The Higgs boson and searches for its siblings

Particle Physics Seminar
University of Bonn
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ATLAS EXPERIMENT

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

FSP ErUM

CMS Compact Muon Solenoid

The beating heart of the Standard Model

- Higgs boson: not just another particle!

$$\mathscr{L}_{\text{Higgs}} = T - V$$

(*) simplified

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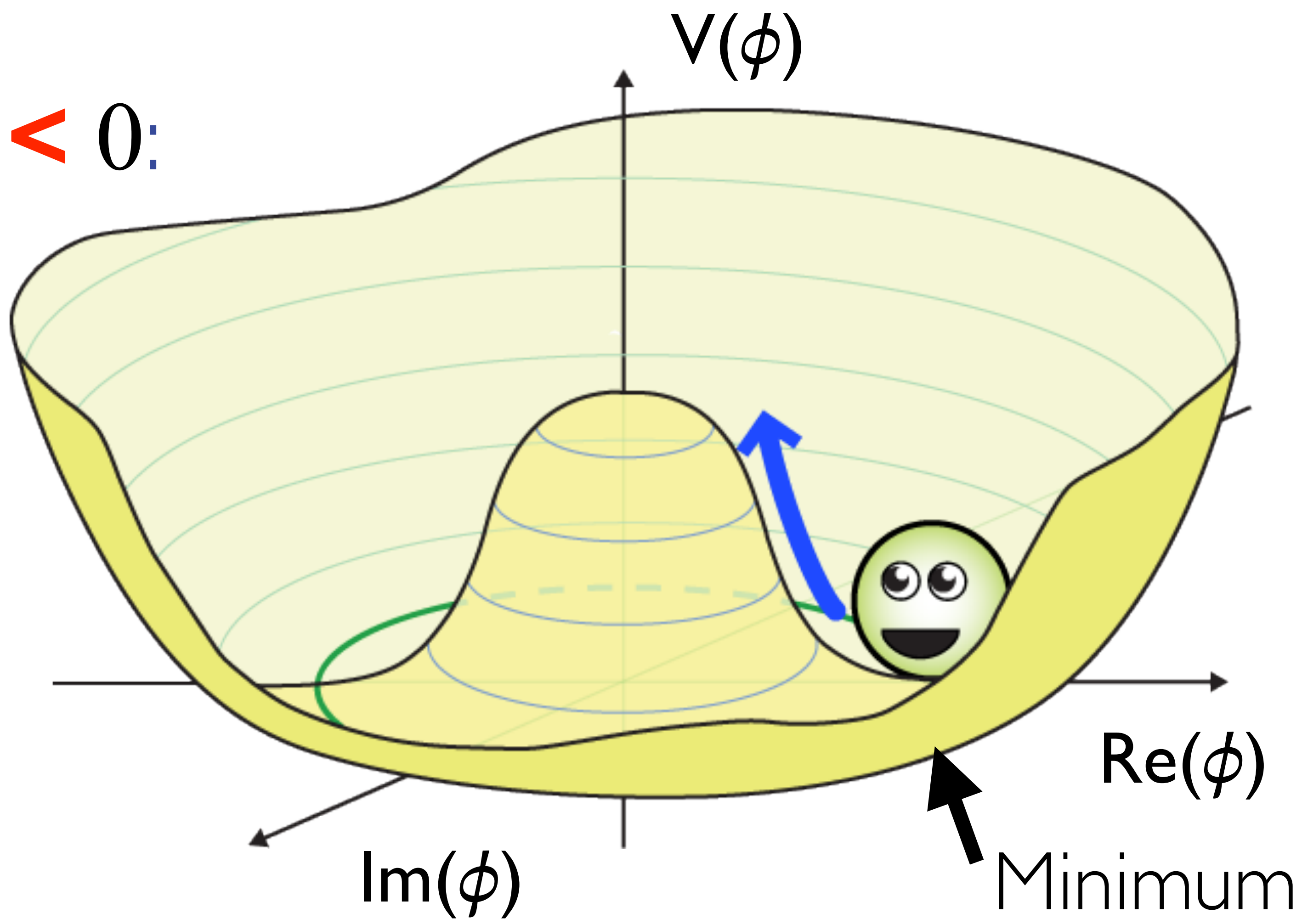
For $\lambda > 0,\ \mu^2 < 0$: Spontaneous symmetry breaking



Minimum at $\langle\phi\rangle = \frac{v}{\sqrt{2}} = \sqrt{-\frac{\mu^2}{2\lambda}},\ v \approx 246\,\mathrm{GeV}$

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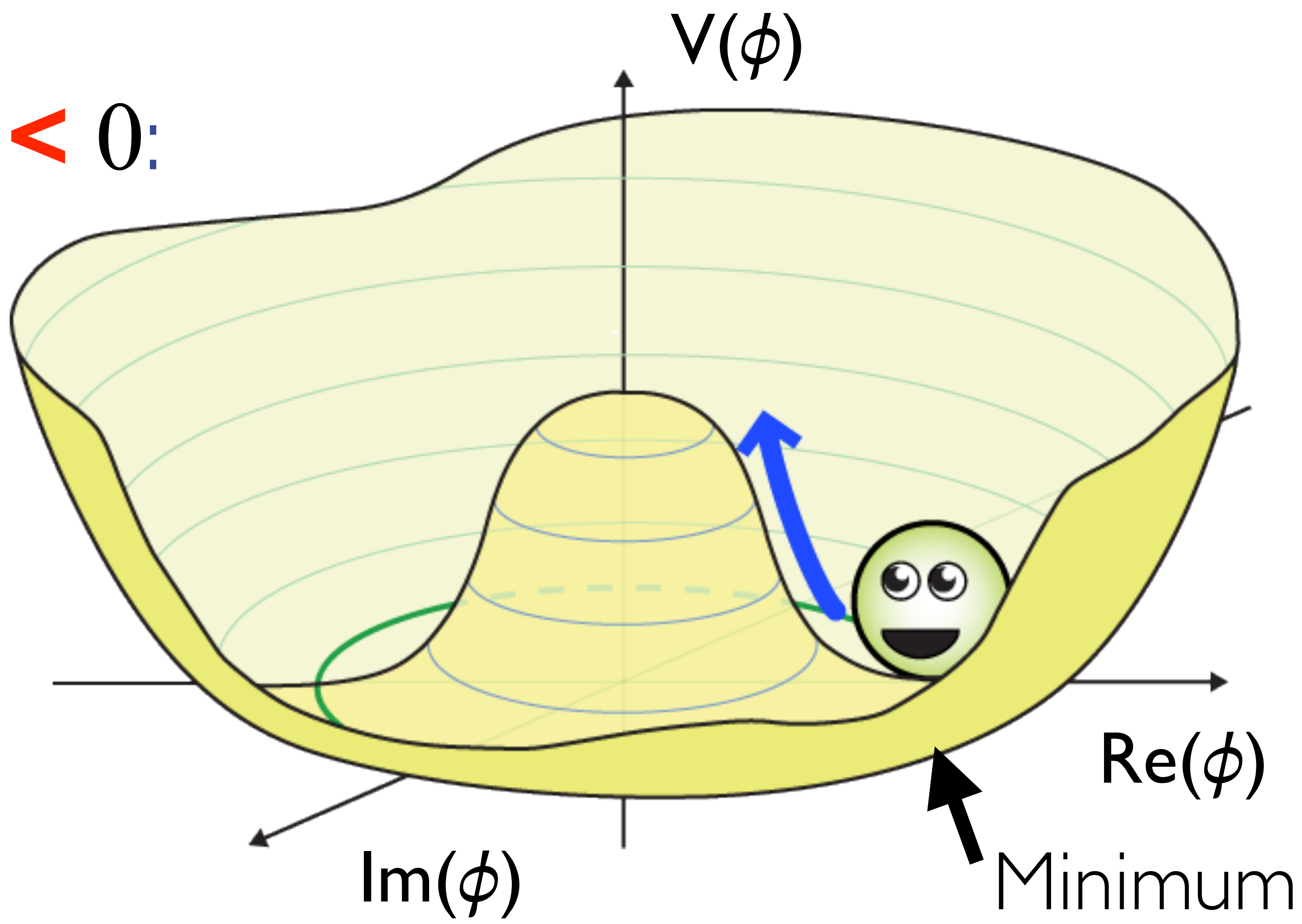

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Kinetic term:
- Masses of W and Z

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Higgs mass

Higgs self-interaction

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Kinetic term:
- Masses of W and Z

- CP violation?
- Dark Matter?

-Higgs potential

Higgs mass

- Naturalness?
- Hierarchy problem

Higgs self-interaction

- Vacuum stability?
- Baryogenesis?

Yukawa term:
- Fermion masses

- Flavor structure
- CP violation?
- Dark Matter?

(*) simplified

Consequences

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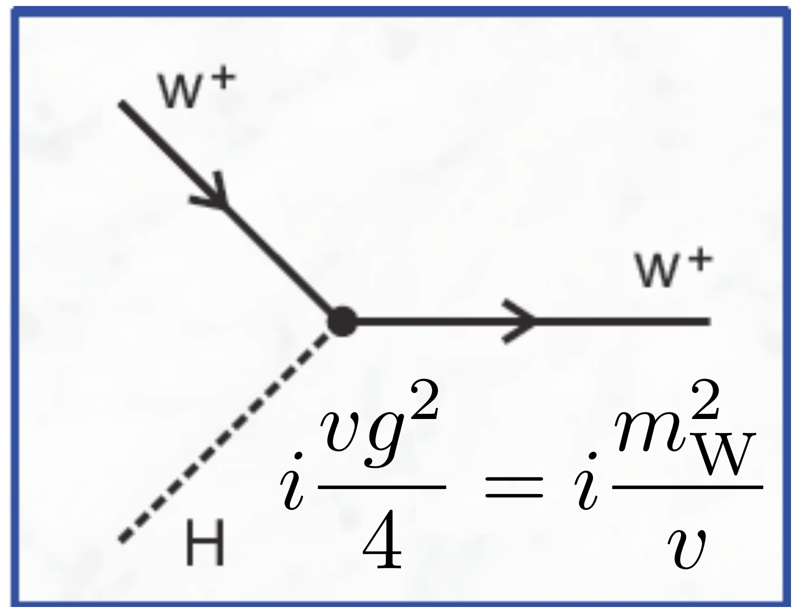
$$m_W = \frac{vg}{2}$$

direct connection ⟷



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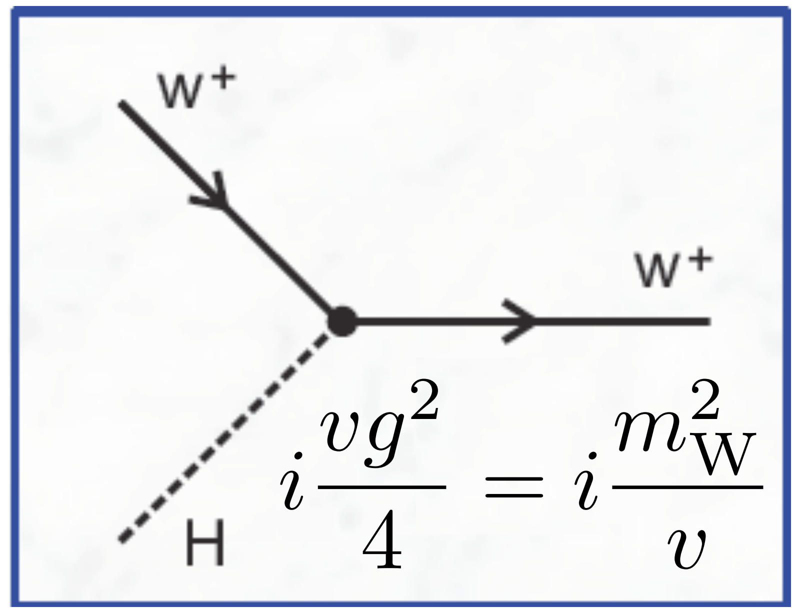

- Fermion masses and Yukawa interactions:

$$m_f = \frac{\lambda_f v}{\sqrt{2}}$$

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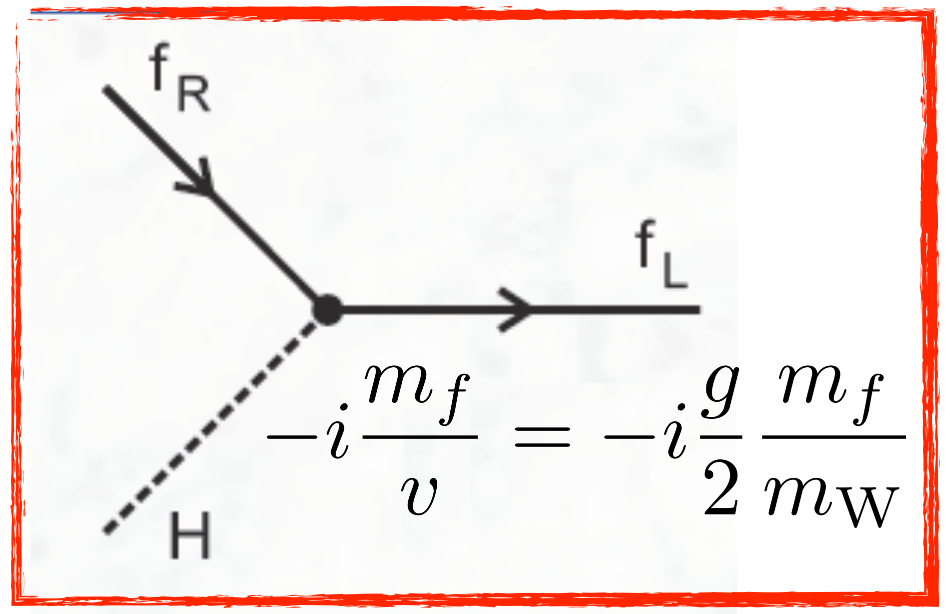

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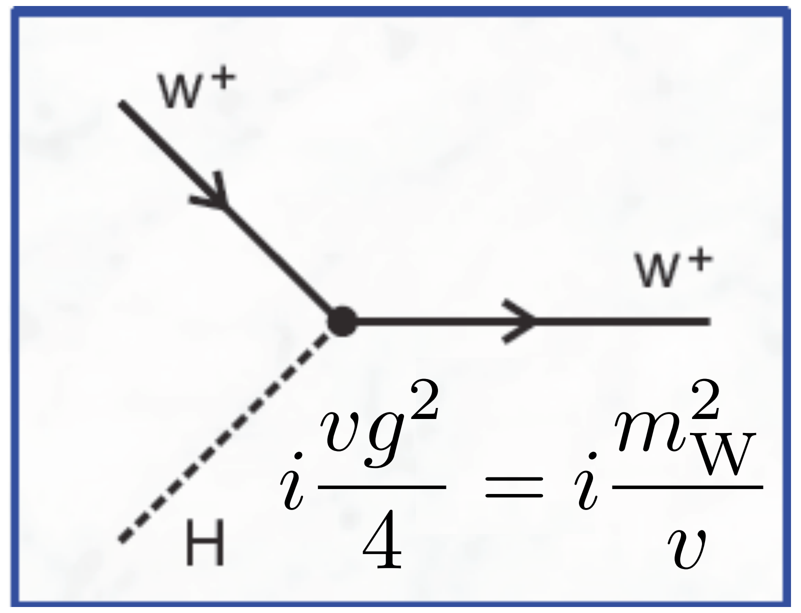

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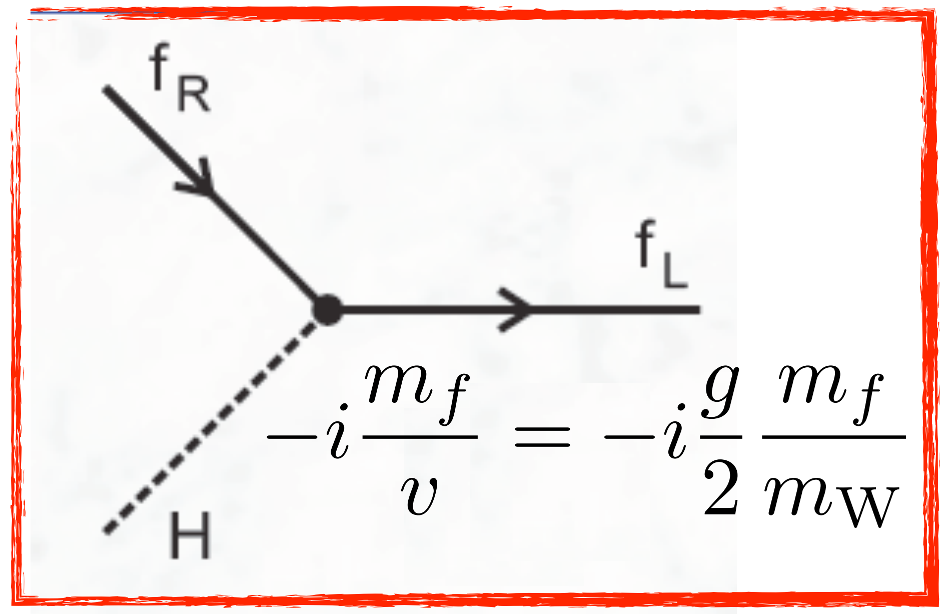
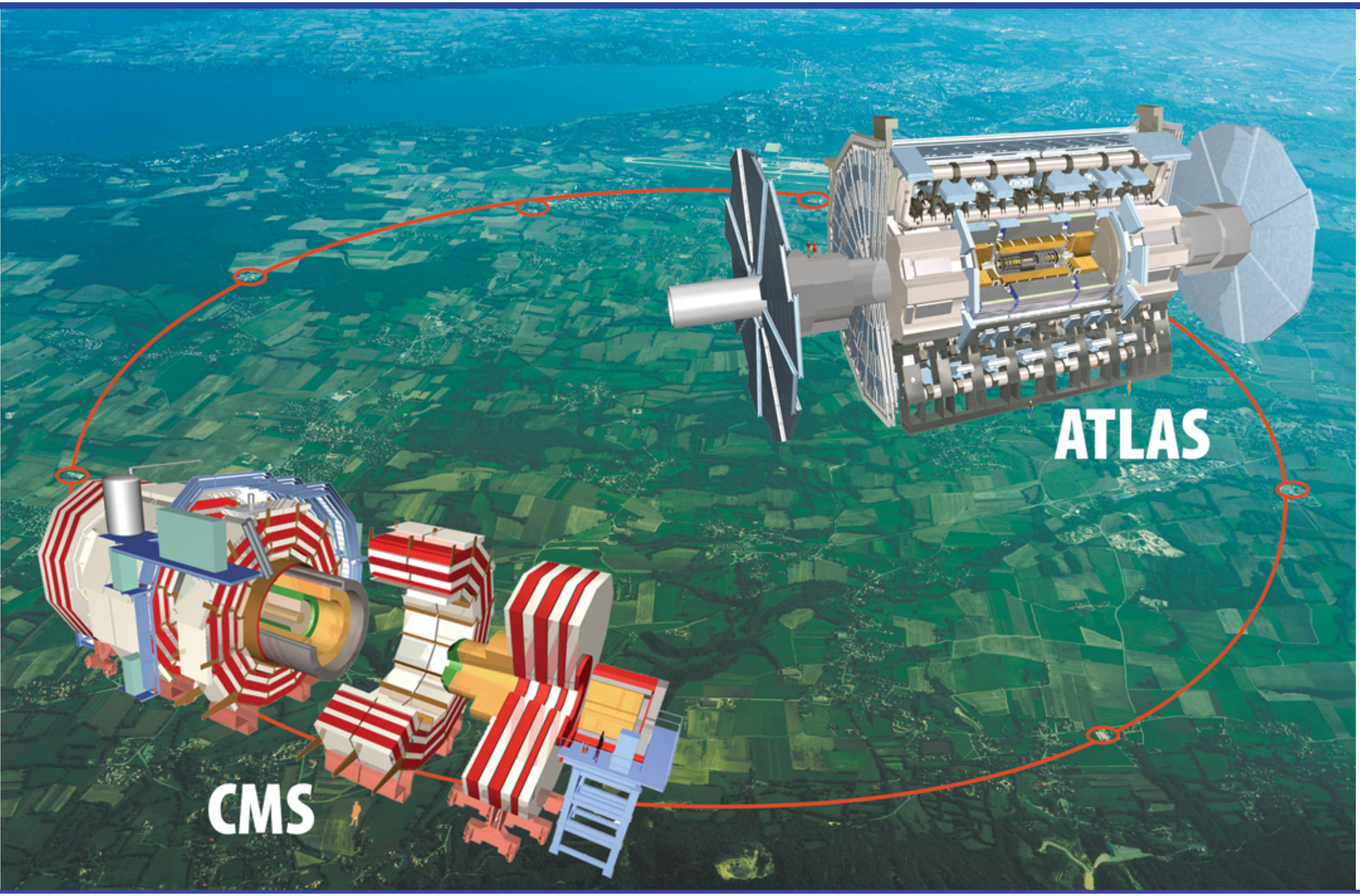
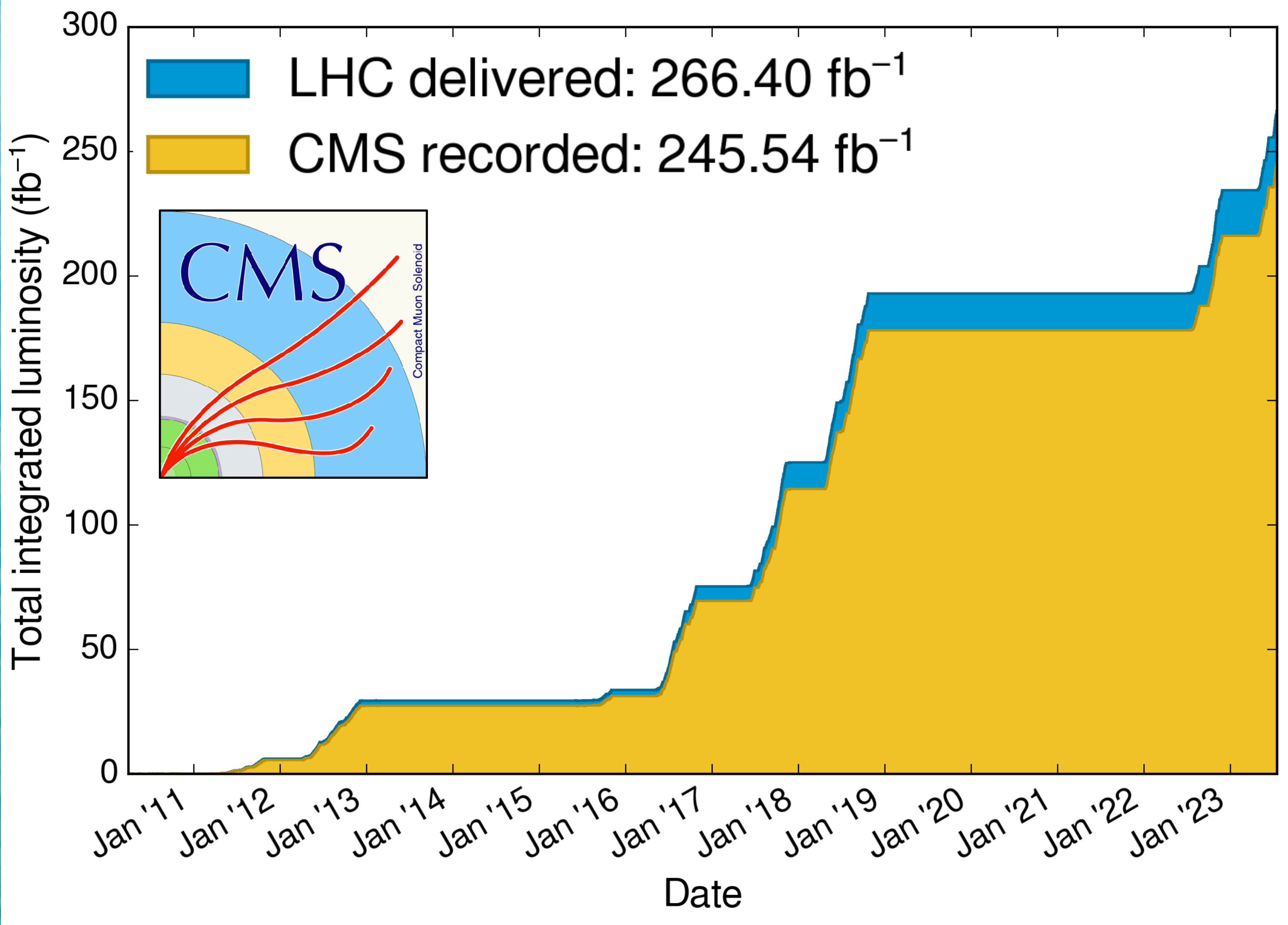


- Higgs potential:

HH production ⟷ **In SM:** $\lambda = \frac{1}{2}m_{\mathrm{H}}^2/v^2$ ⟷ $\mu^2\left(\phi^\dagger\phi\right) + \lambda\left(\phi^\dagger\phi\right)^2$ H potential as in SM?

The LHC with ATLAS & CMS



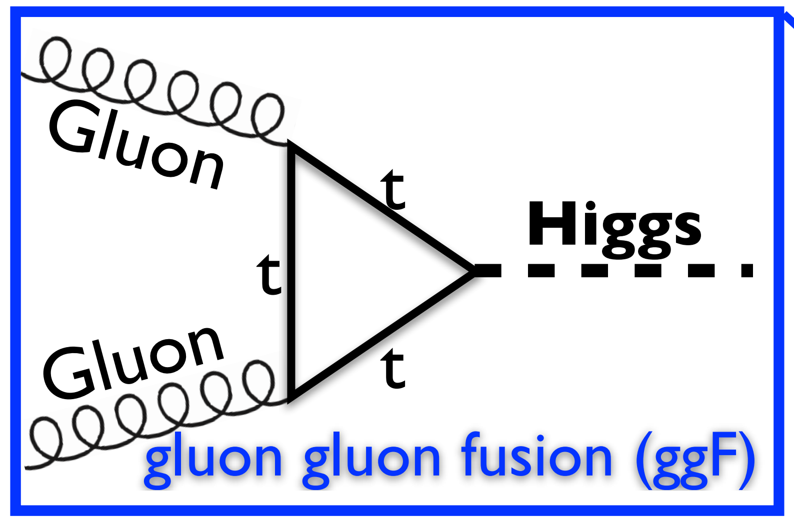


Run 2: 140 fb^{-1}

$\Rightarrow$ **N**$_{\mathbf{Higgs}}$(produced)

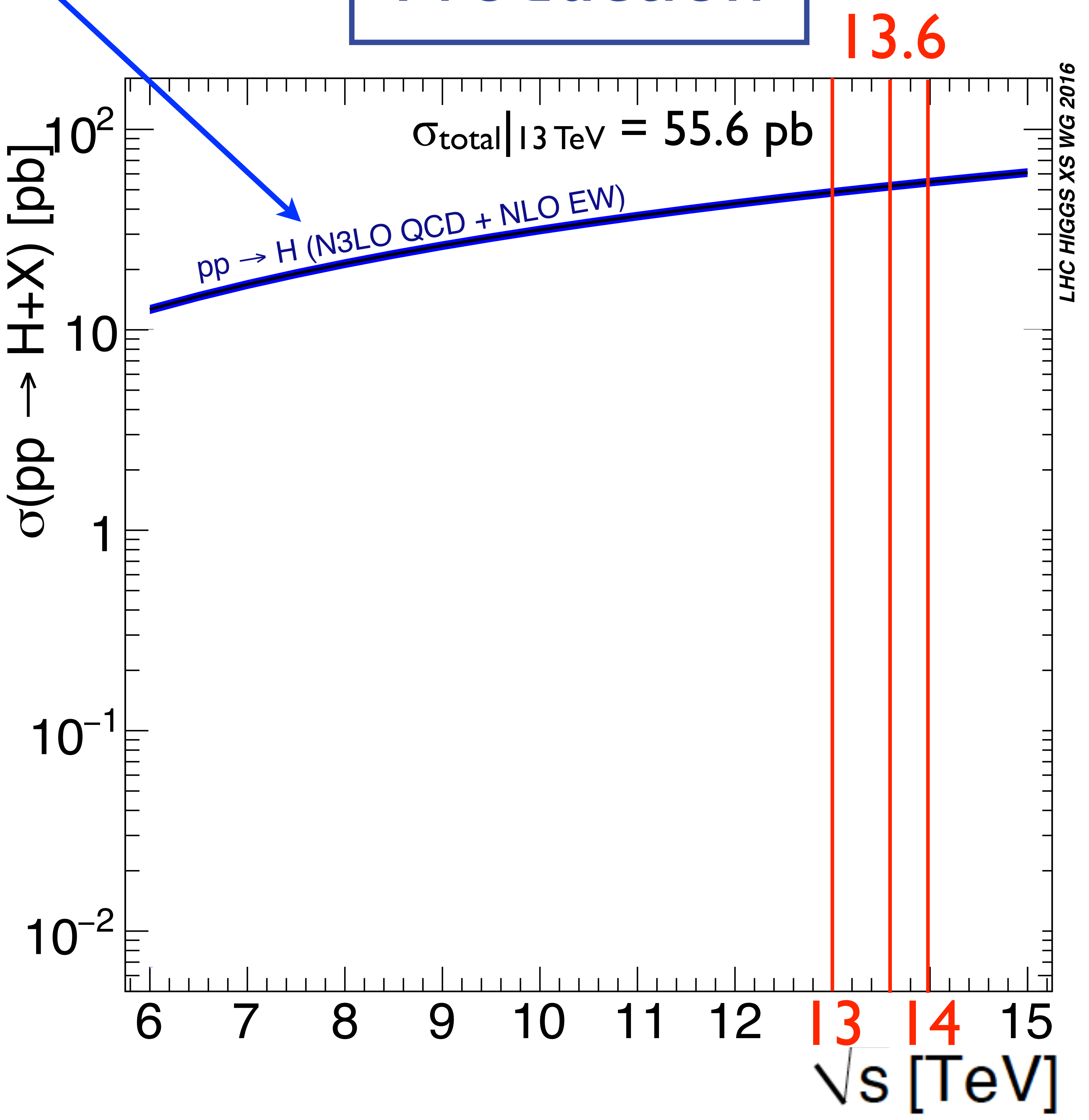
$\approx$ **7 700 000**

Higgs Boson at the LHC



σ_{ggF} = 48.5 pb (87 %)

Production



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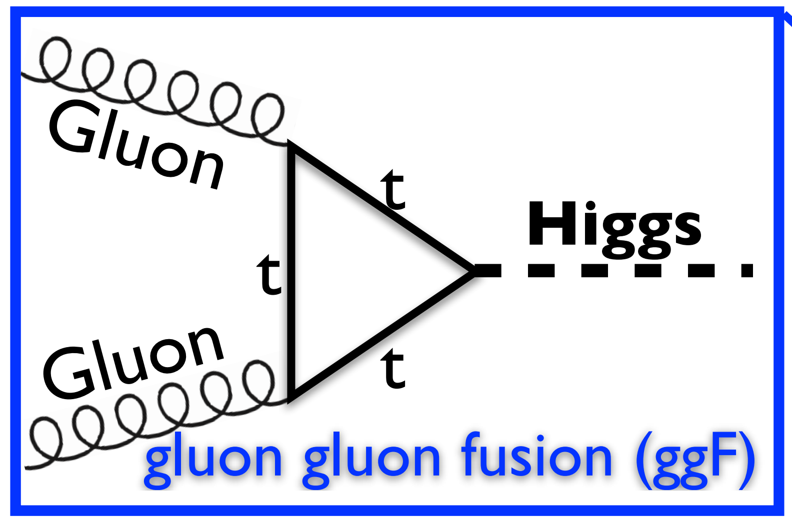

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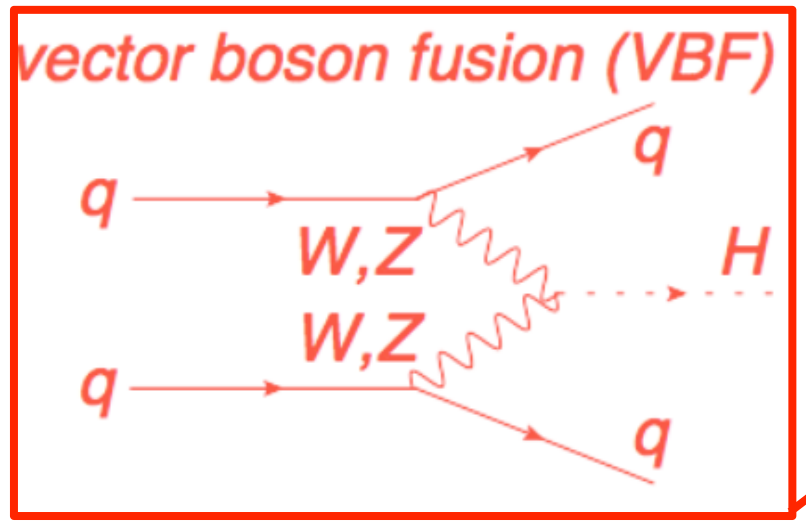

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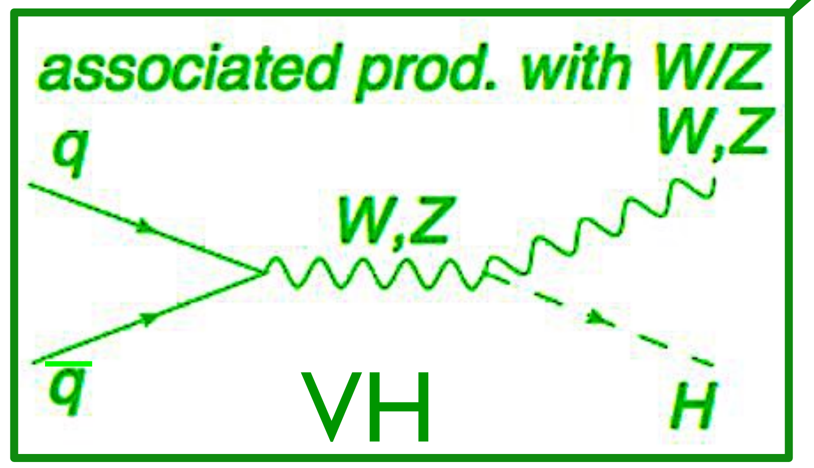

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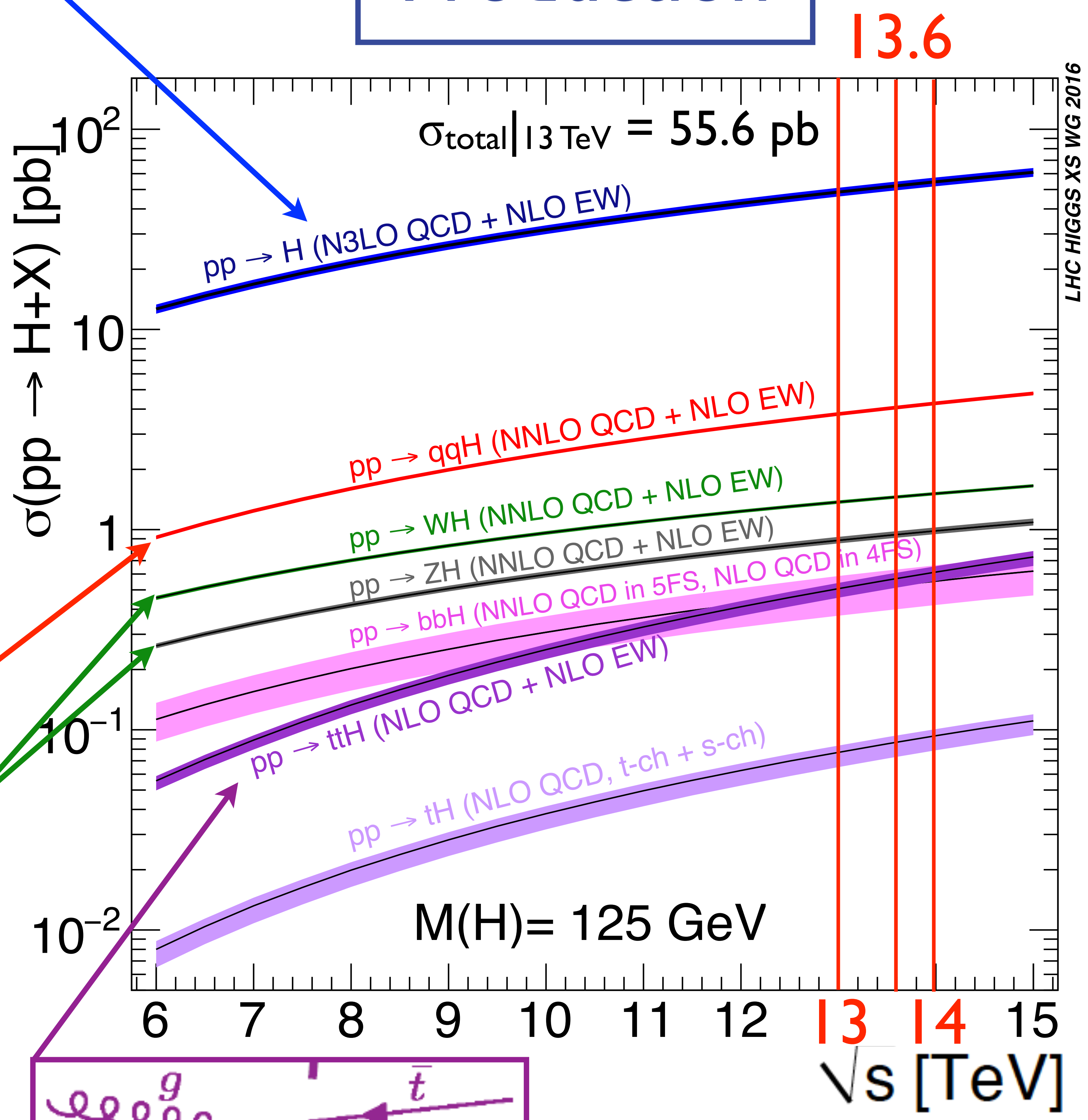

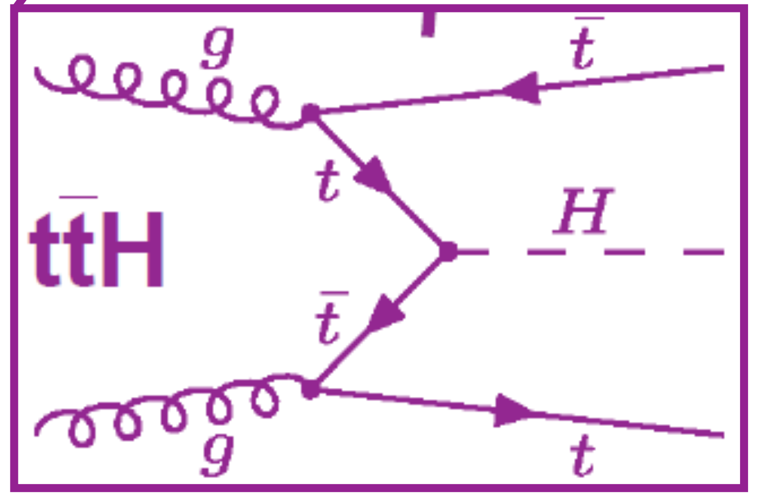

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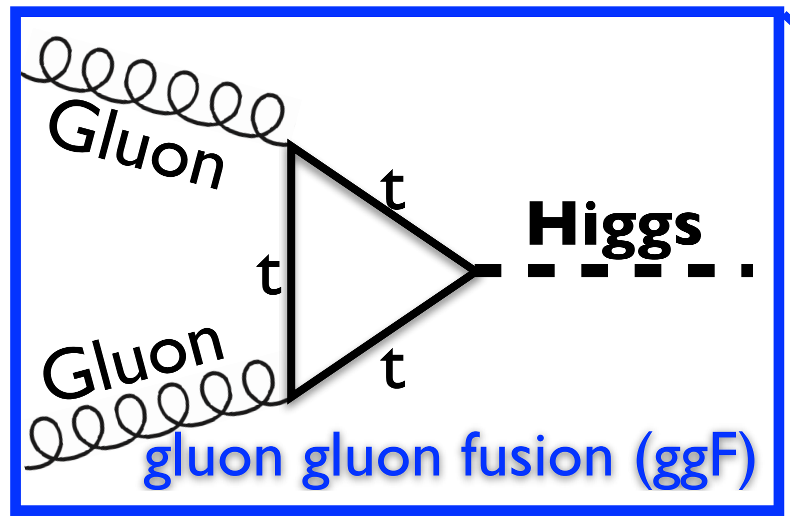

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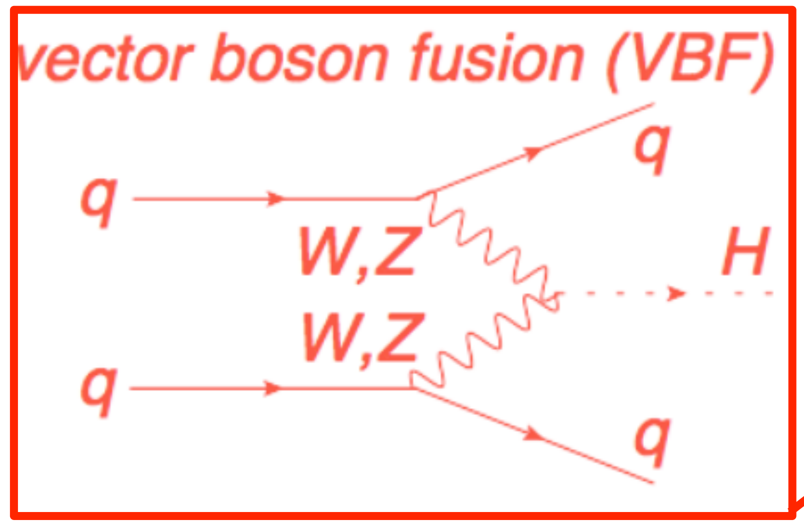

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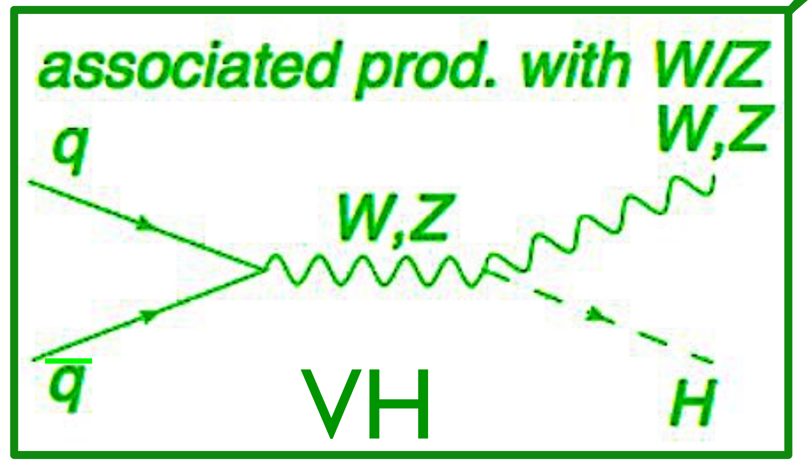

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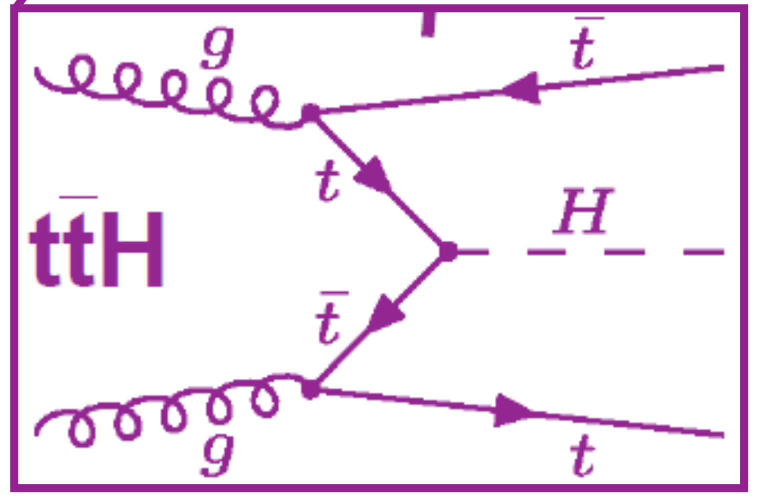

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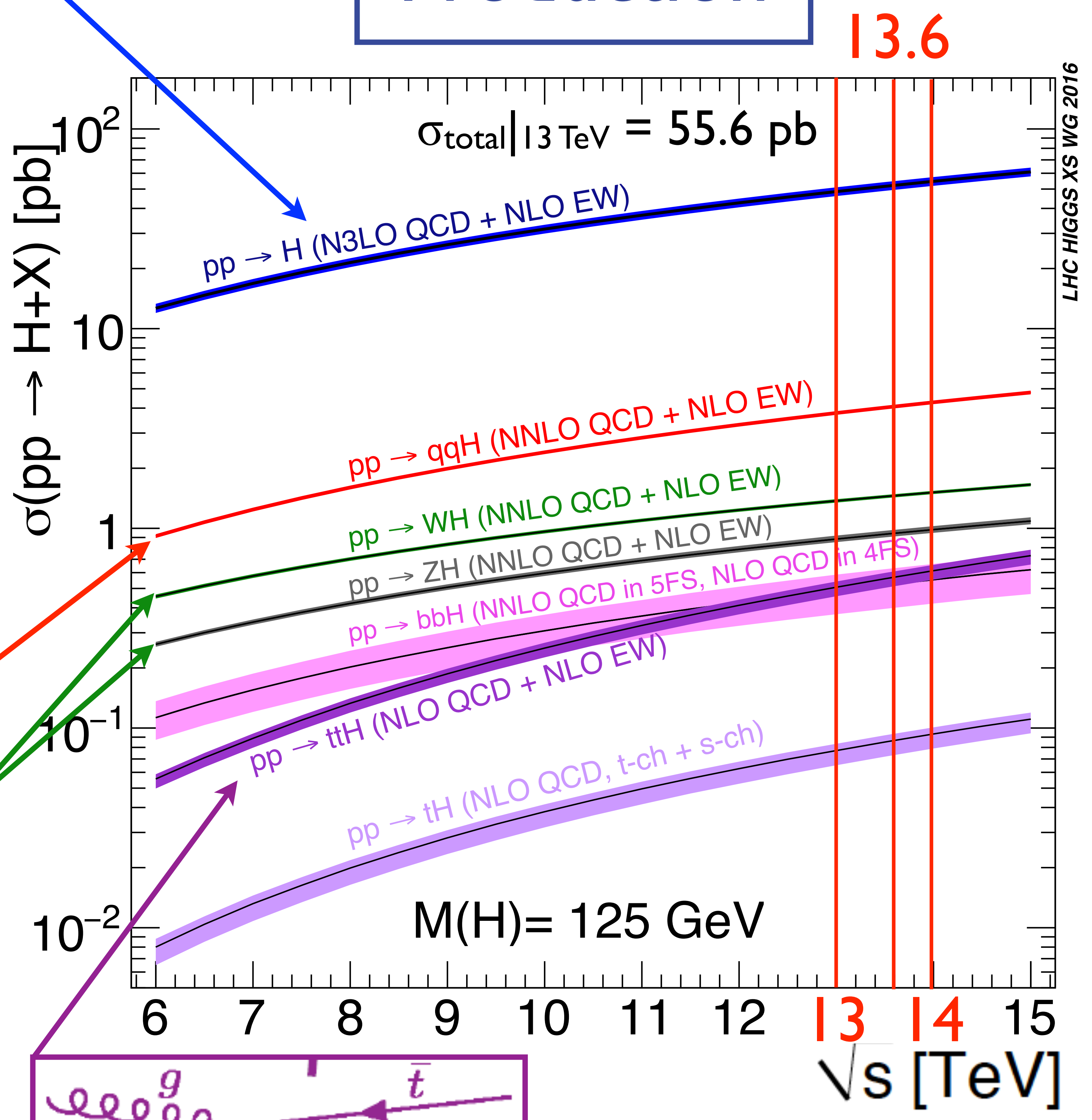

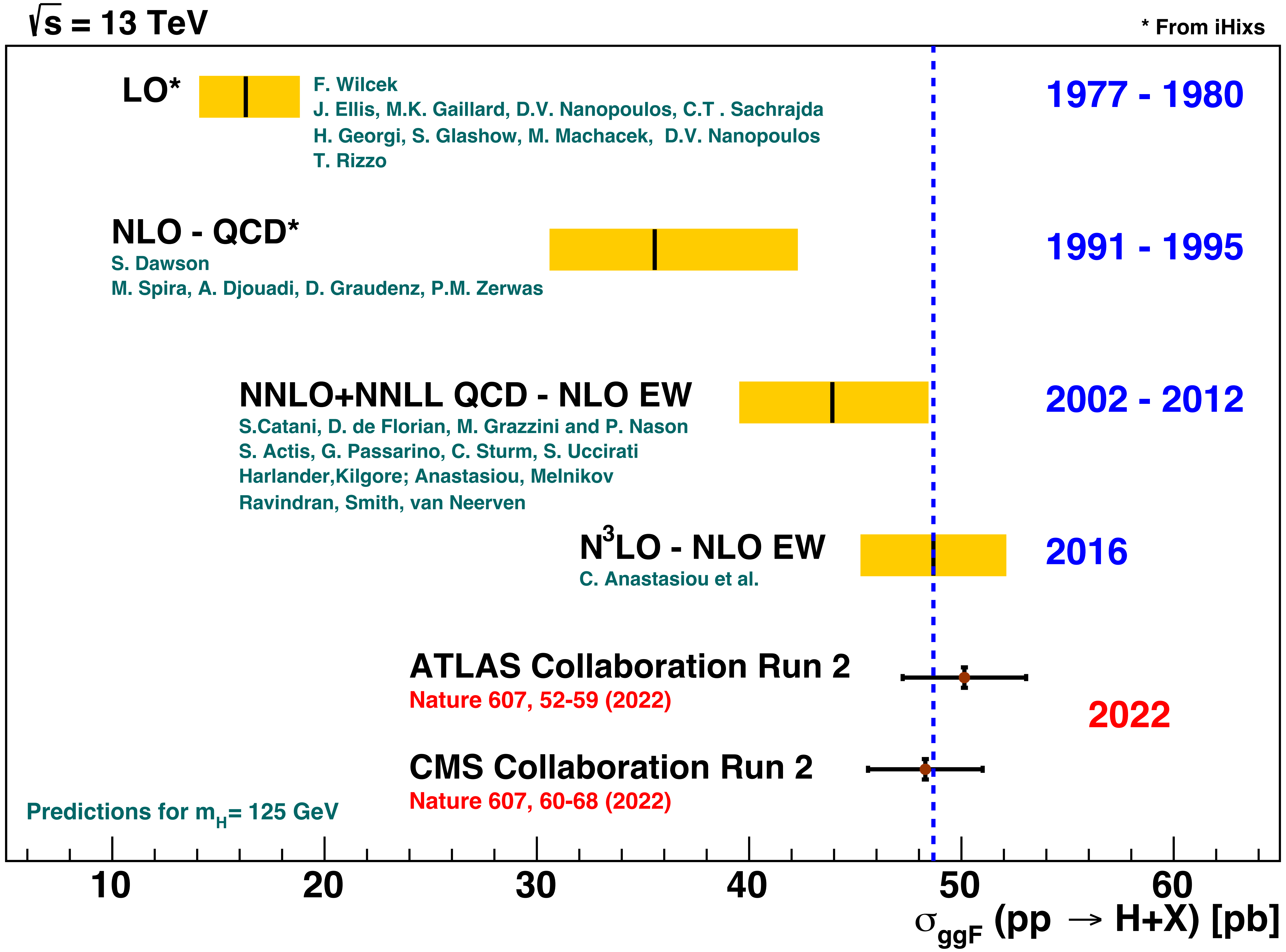

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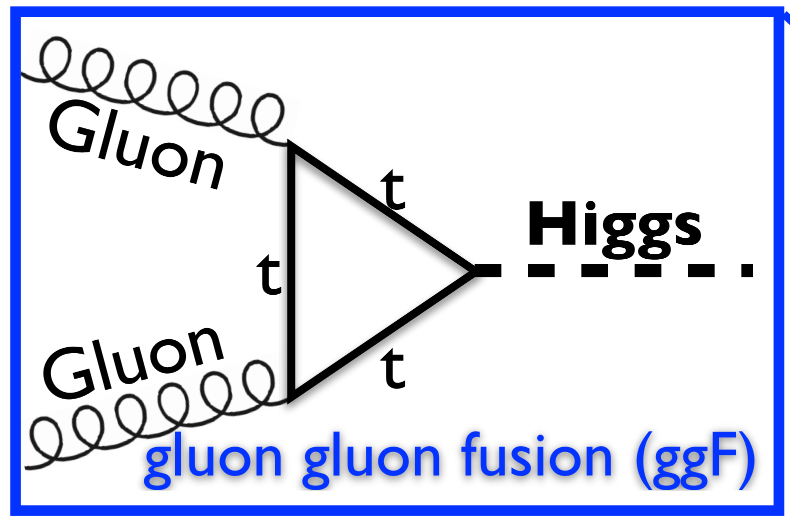

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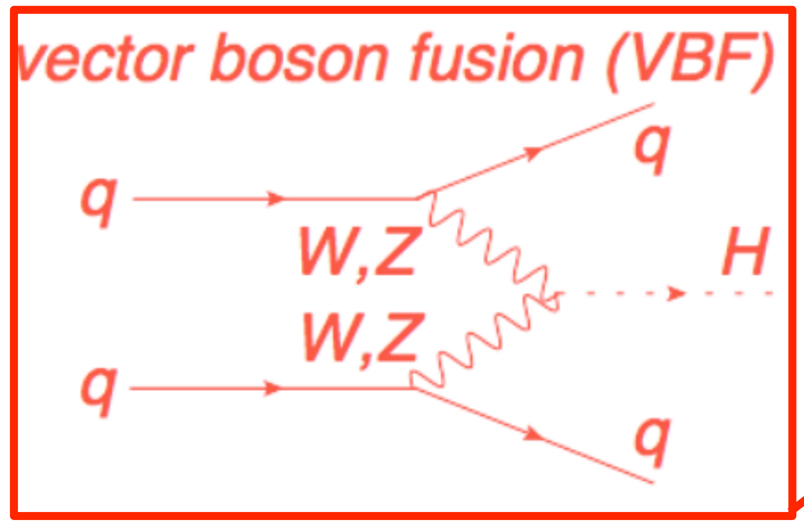

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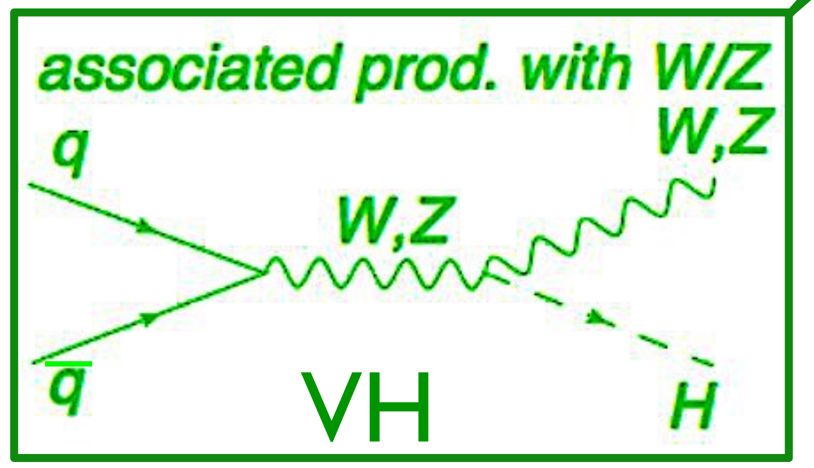

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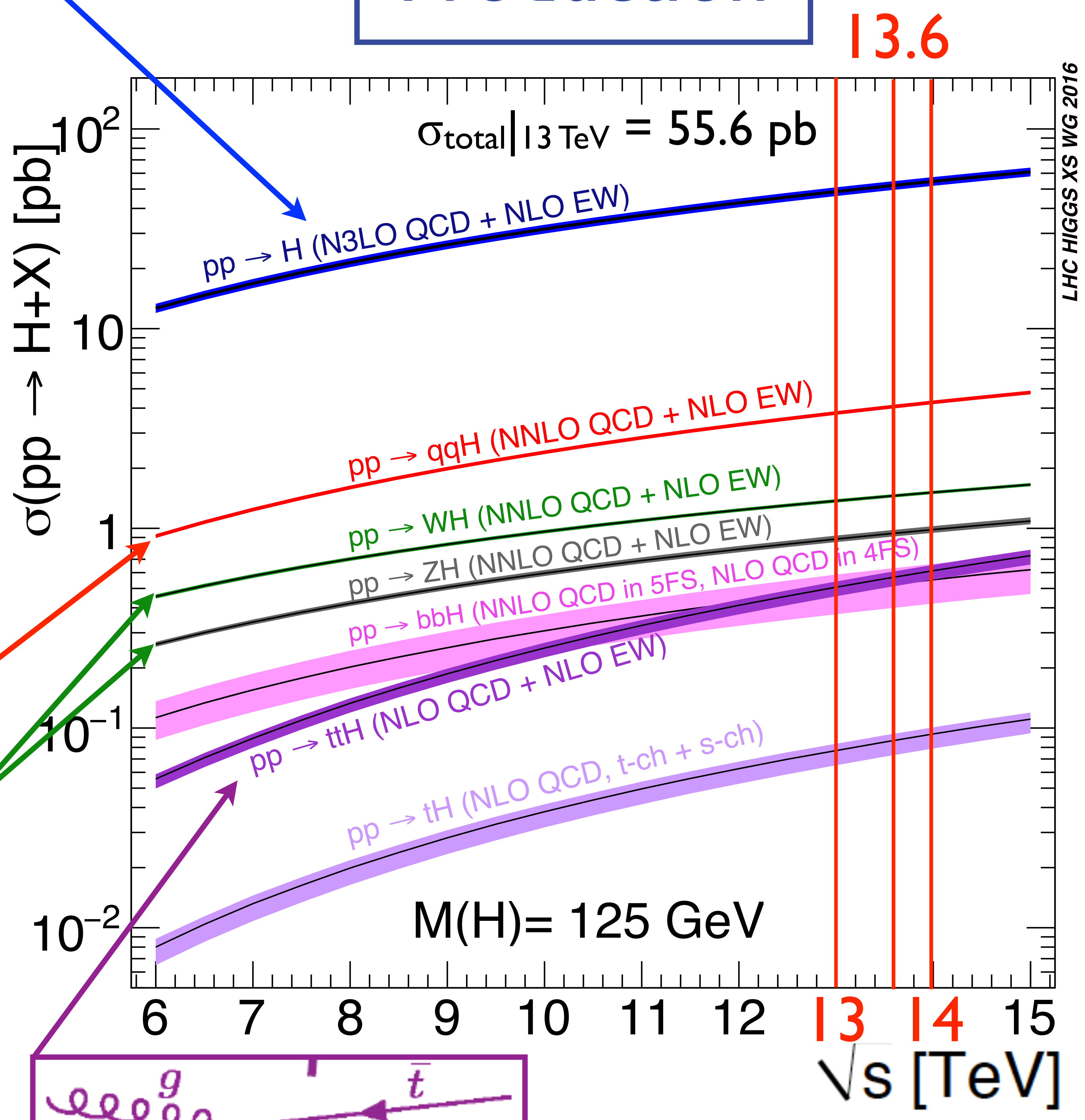

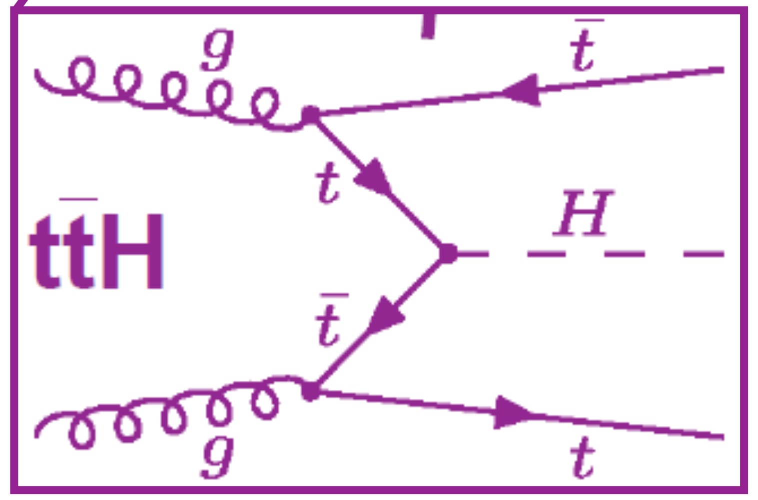

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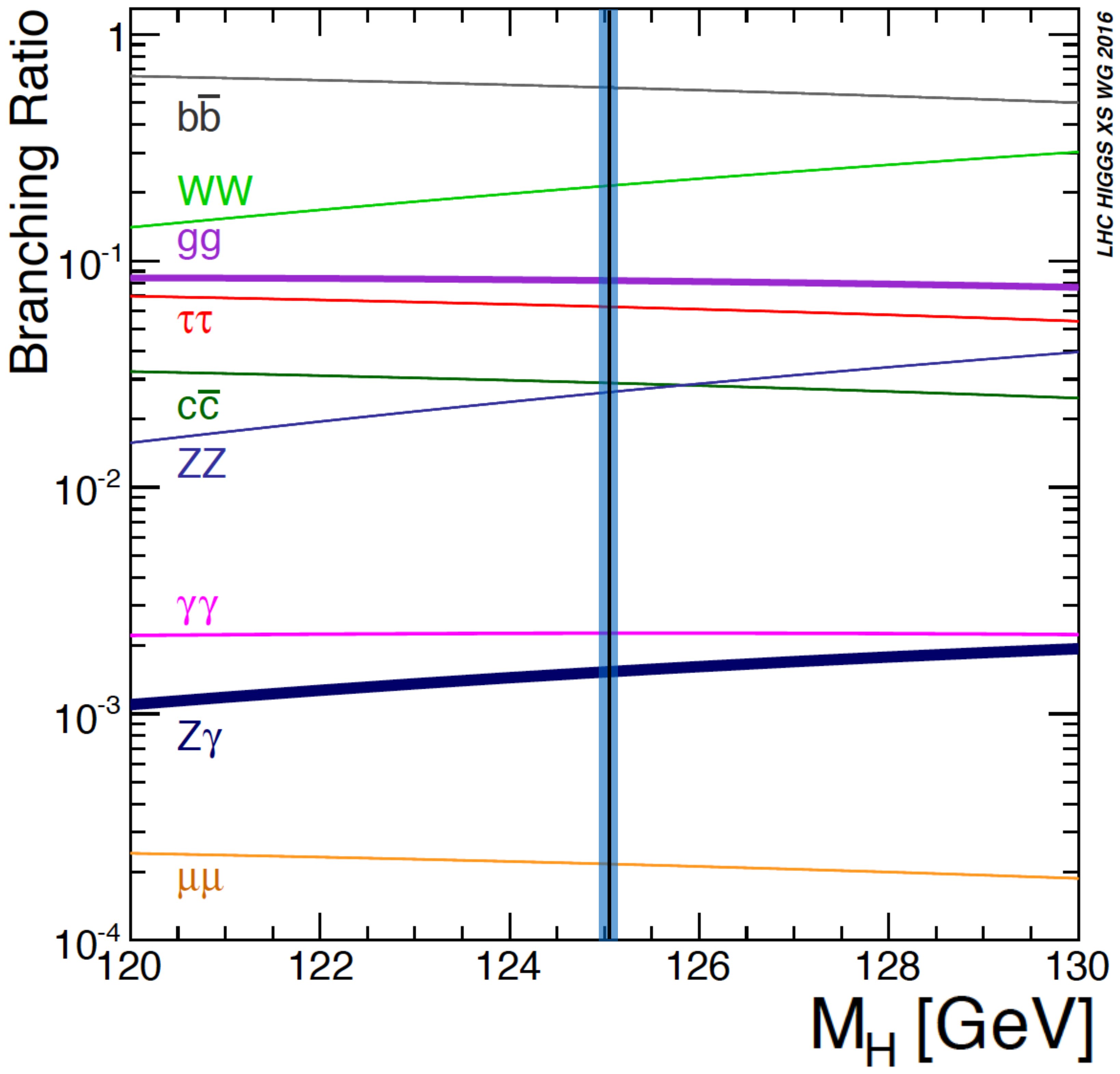
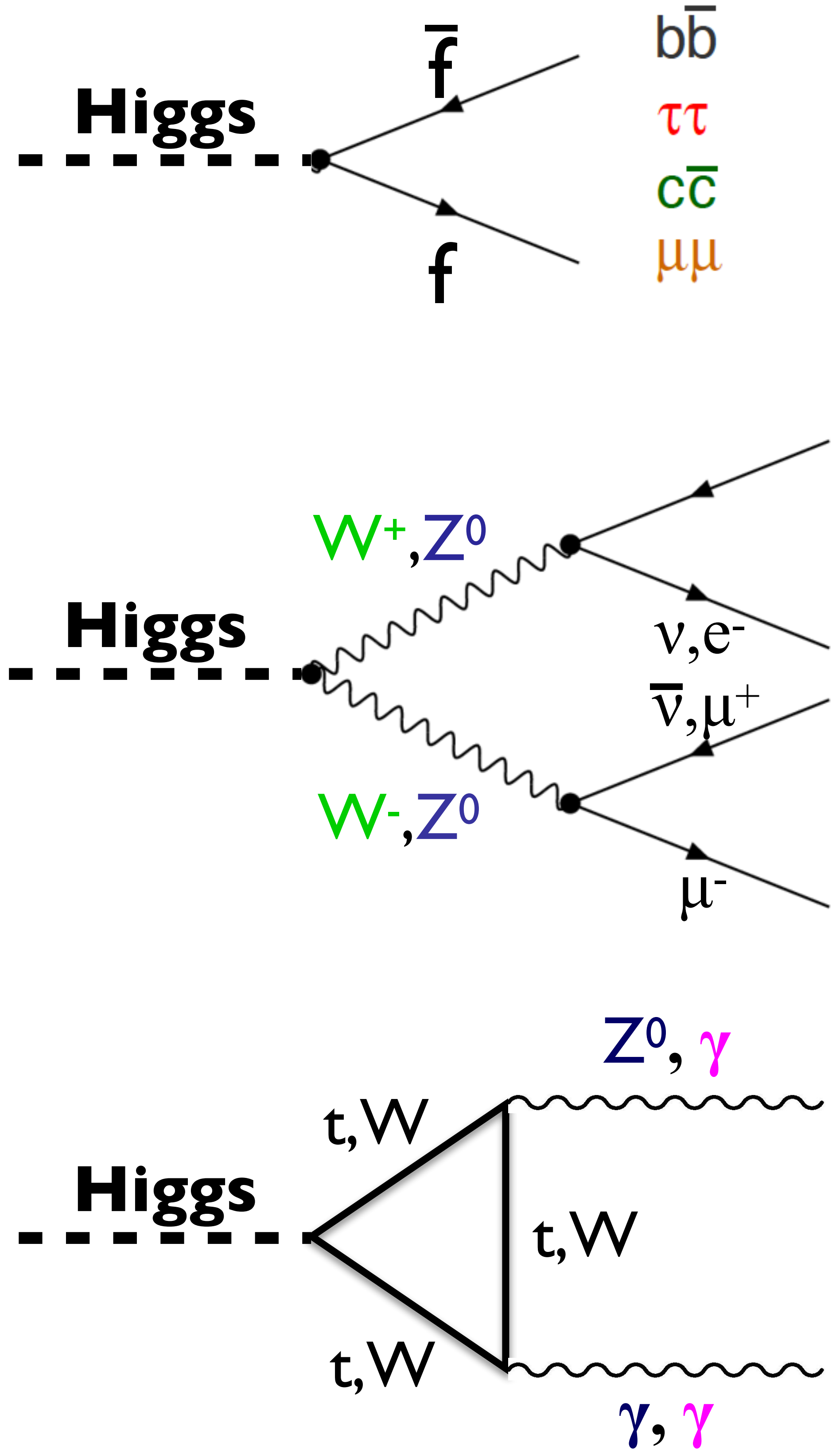
Decay





Observed Production and Decay Modes

Nature 607, 52–59 (2022)

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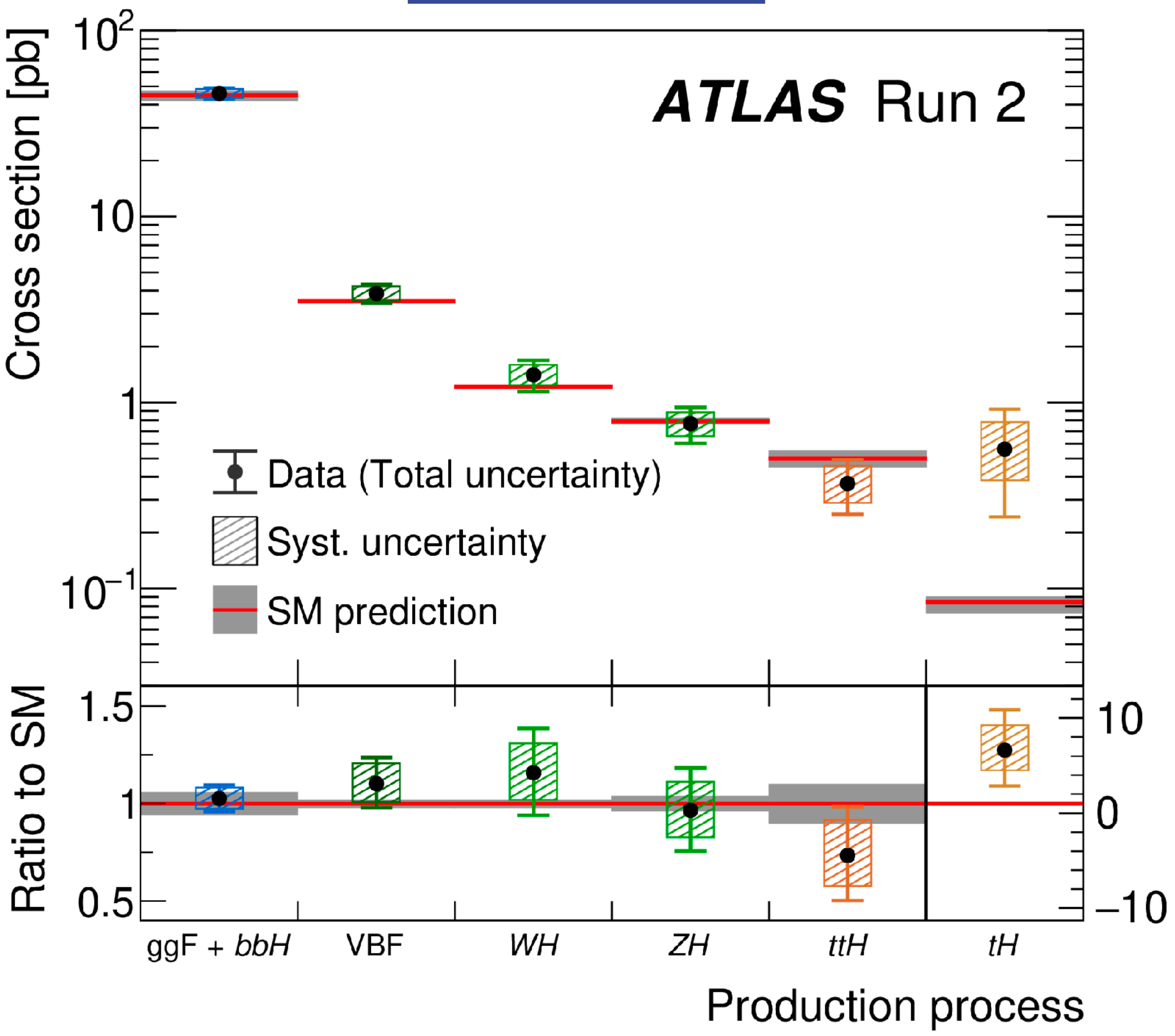

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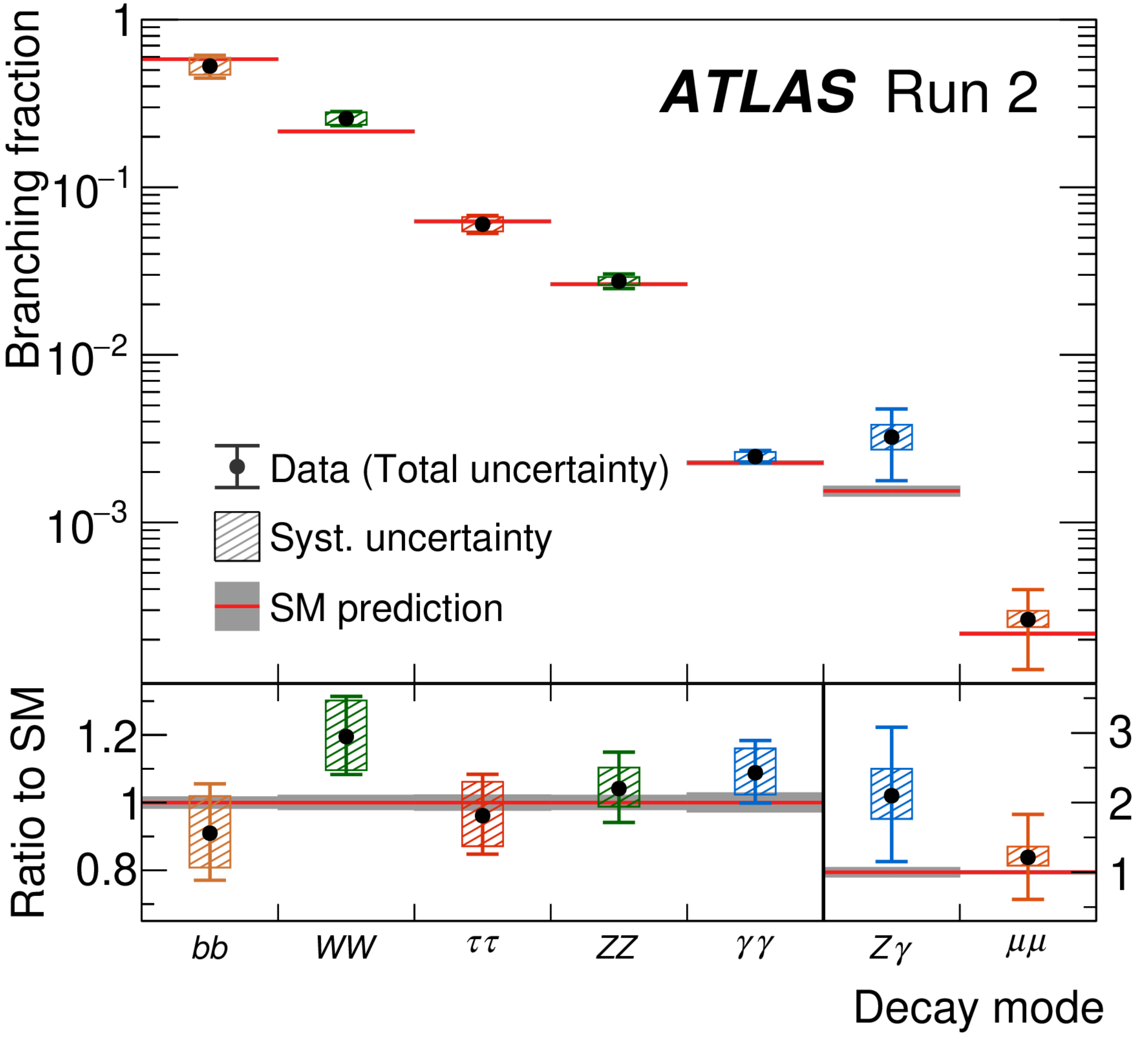
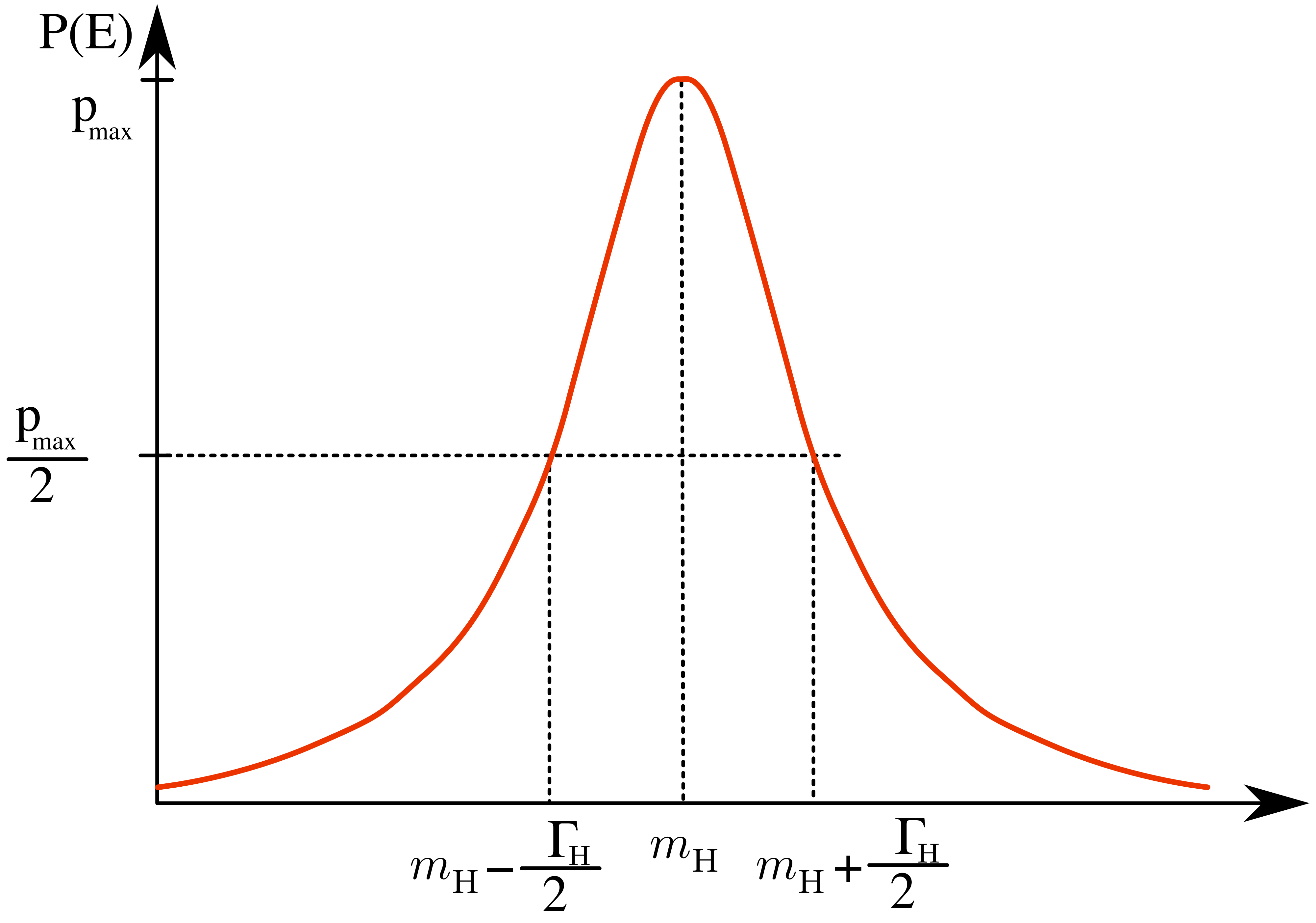


⇒ CMS results

Outline

$$\mathscr{L}_{\text{Higgs}} = (D_\mu \phi)^2 - \mu^2\phi^2 - \lambda\phi^4 + \lambda_f \phi \bar{\psi}\psi$$

1. Higgs boson mass and width



Electroweak Symmetry Breaking

$$\mathscr{L} \ni -\lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4} H^4$$

$$m_H = \sqrt{2\lambda} v$$

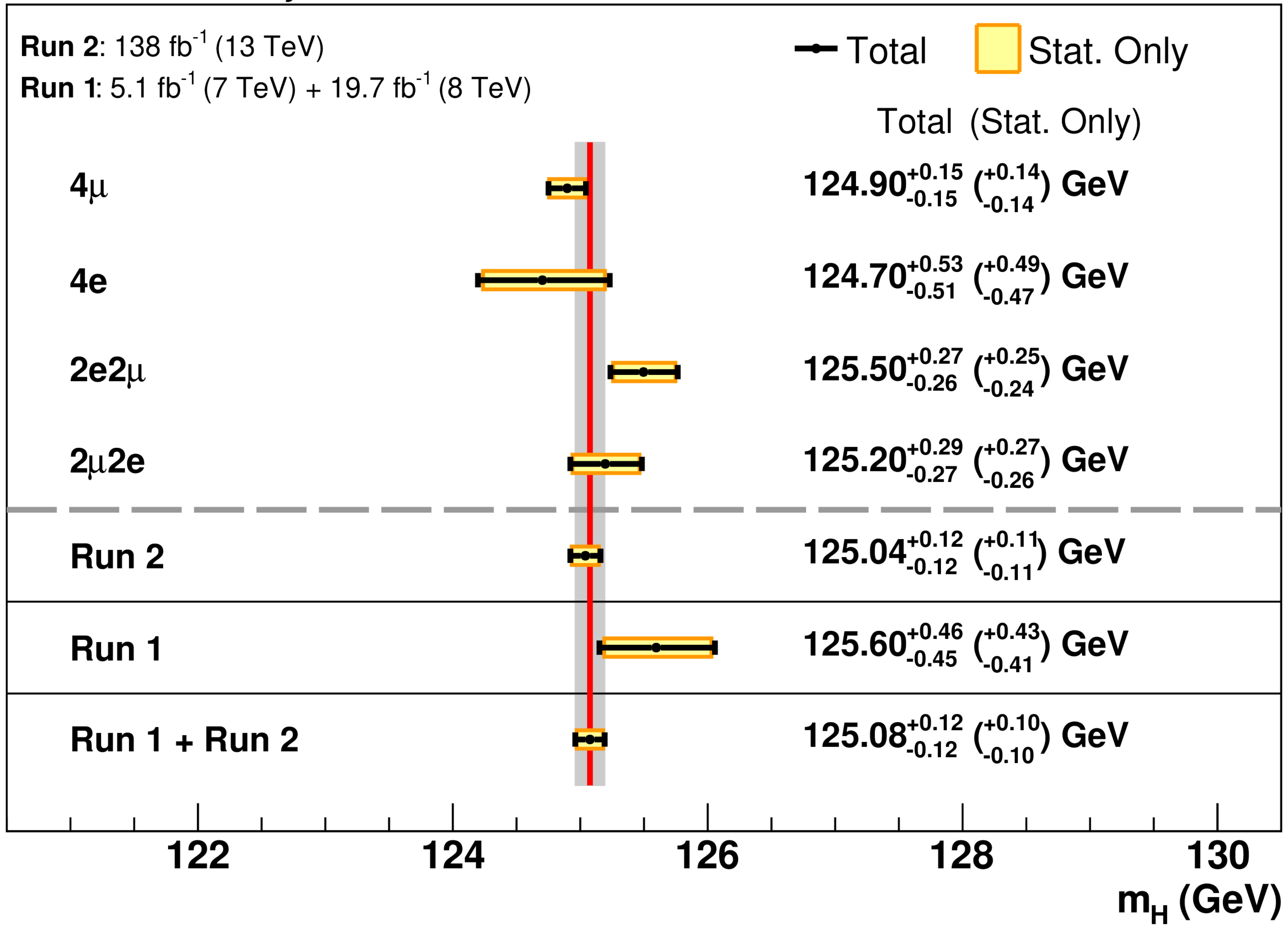
not predicted!

(*) simplified

Higgs Boson Mass

CMS — Sep 2023

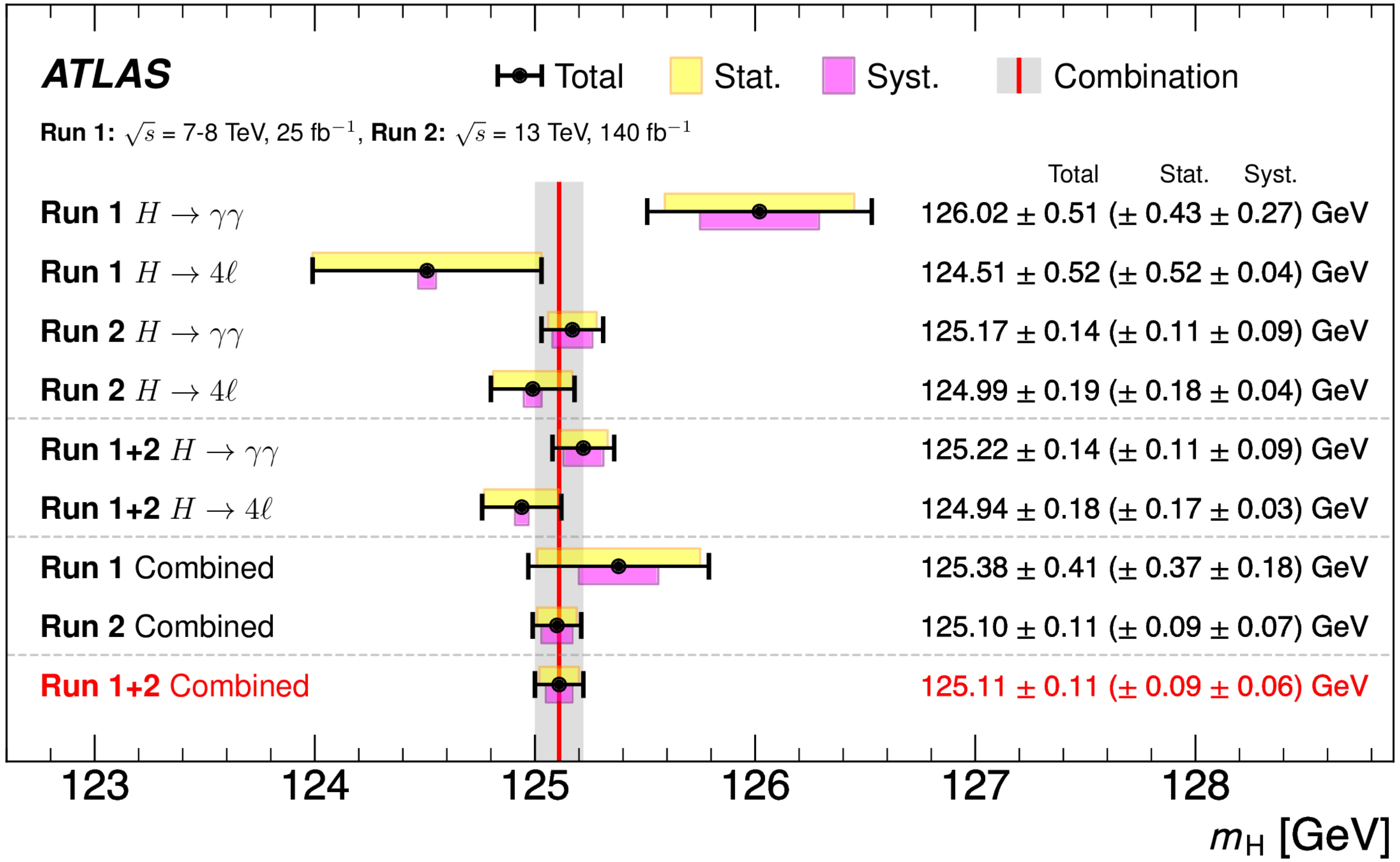
$H \to ZZ^* \to 4\ell$



$$m_H = 125.08 \pm 0.10(\text{stat}) \pm 0.07\ (\text{syst})\ \text{GeV}$$

ATLAS — Aug 2023

$H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$



$$m_H = 125.11 \pm 0.09(\text{stat}) \pm 0.06\ (\text{syst})\ \text{GeV}$$

CMS-PAS-HIG-21-019

Phys. Rev. Lett. 131 (2023) 251802

Higgs Boson Width

- Expected width: $\Gamma_{H,SM} = 4.1$ MeV
  - Direct limit: $\Gamma_H < 60$ MeV @ 68% CL ($\lesssim 320$ MeV @ 95 % C.L.) CMS-PAS-HIG-21-019
  - Lifetime too short to measure: $\Gamma_H > 3.5 \times 10^{-9}$ MeV @ 95% CL Phys. Rev. D 92, 072010 (2015)

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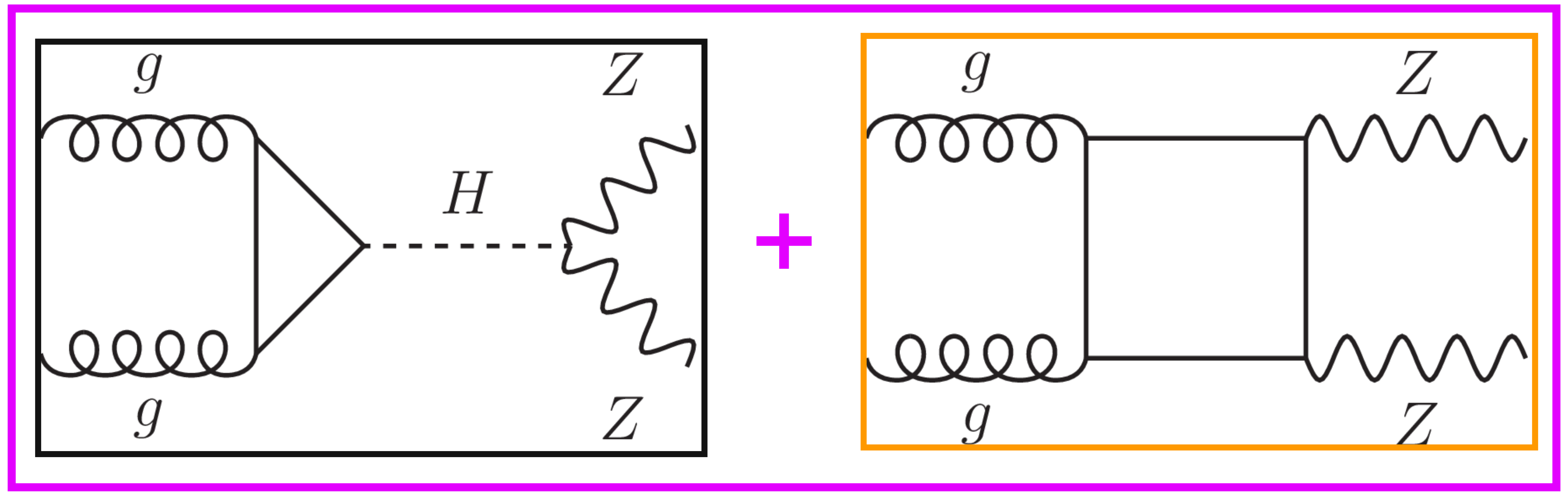
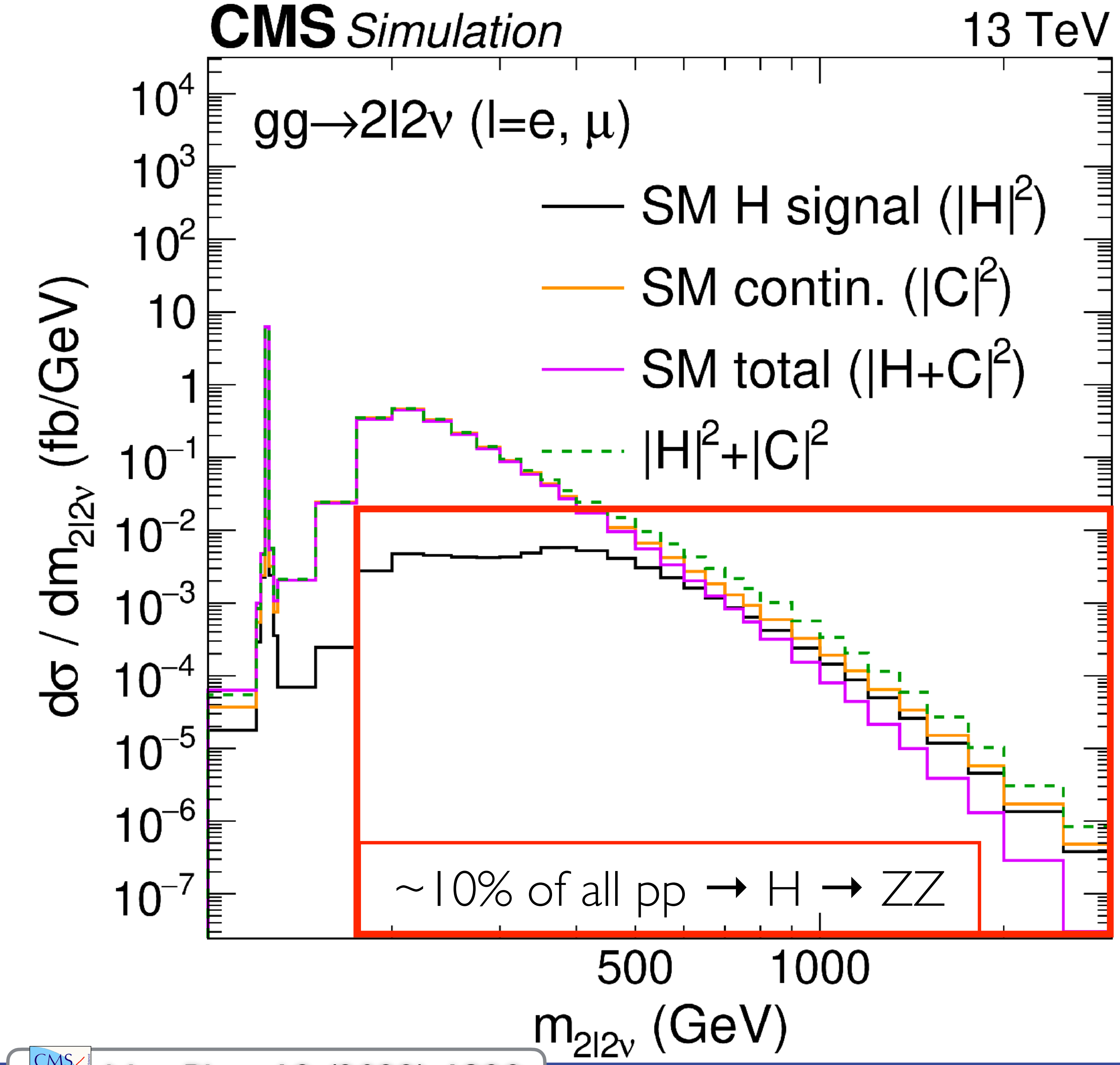
- Use H → $ZZ^{(*)}$ → 4ℓ and $2\ell2\nu$





Nat. Phys. 18 (2022) 1329

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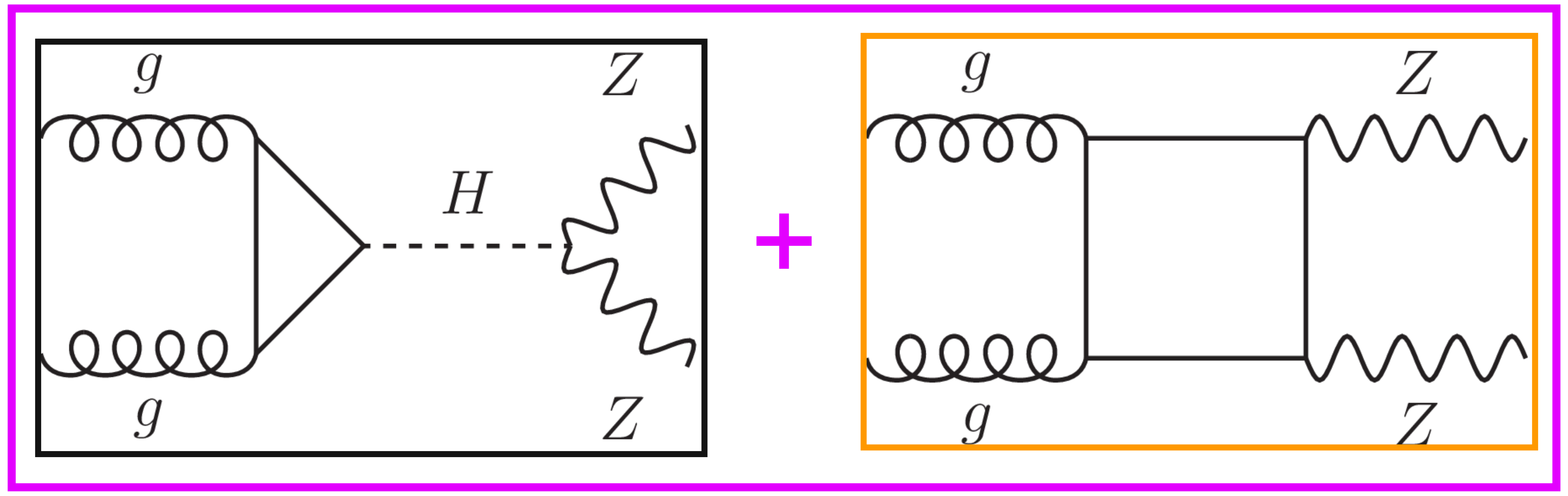
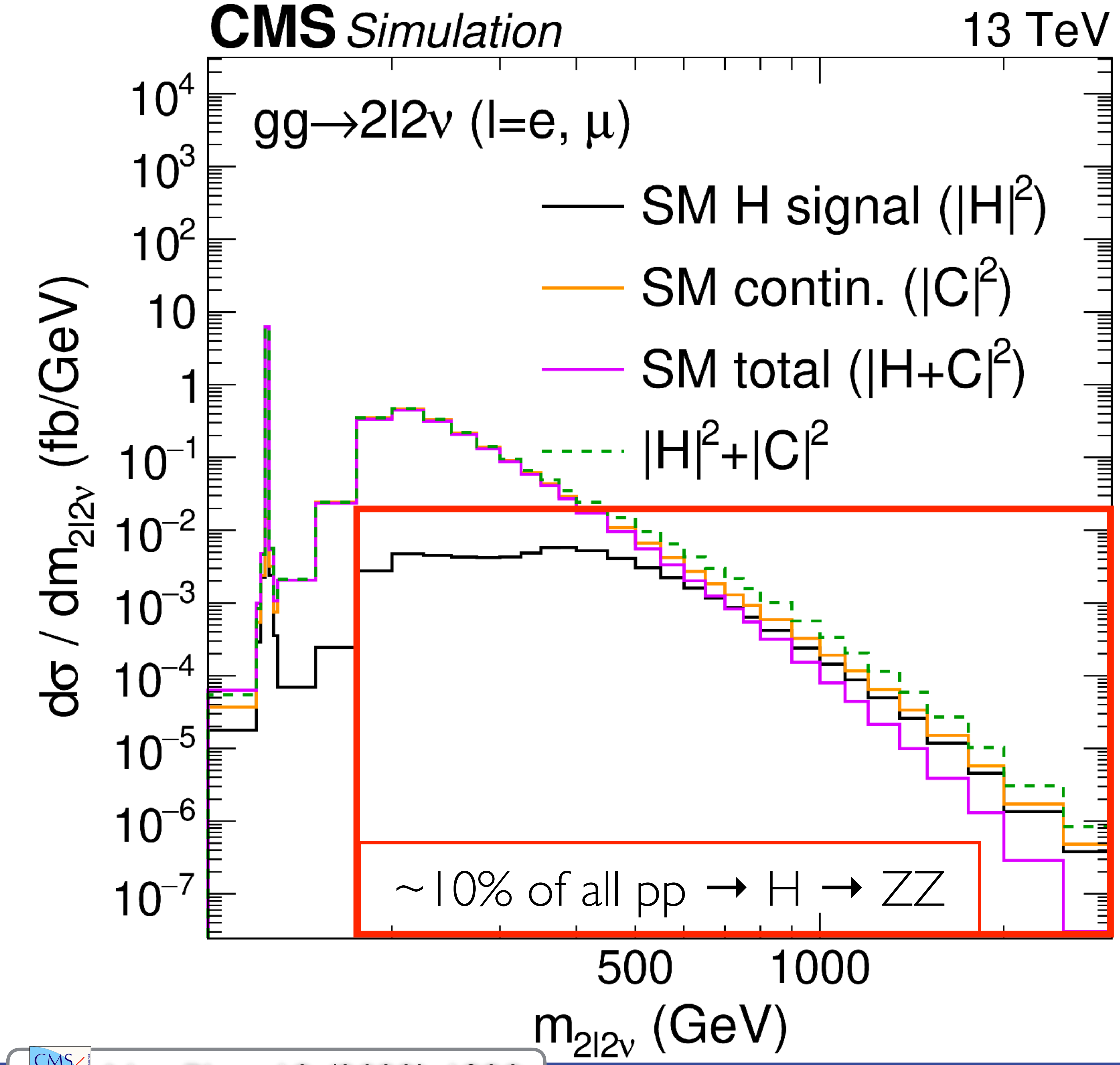


- Use H → ZZ(*) → 4ℓ and 2ℓ2ν
  - CMS: Evidence for off-shell production: **3.6 σ**
  - $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV — Feb 2022
  - ATLAS: Evidence for off-shell production: **3.3 σ**
  - $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV — Apr 2023

Phys. Lett. B 846 (2023) 138223



Nat. Phys. 18 (2022) 1329

Outline

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2. Higgs coupling to bosons
   - Bosonic decays
   - Differential cross sections

Electroweak Symmetry Breaking

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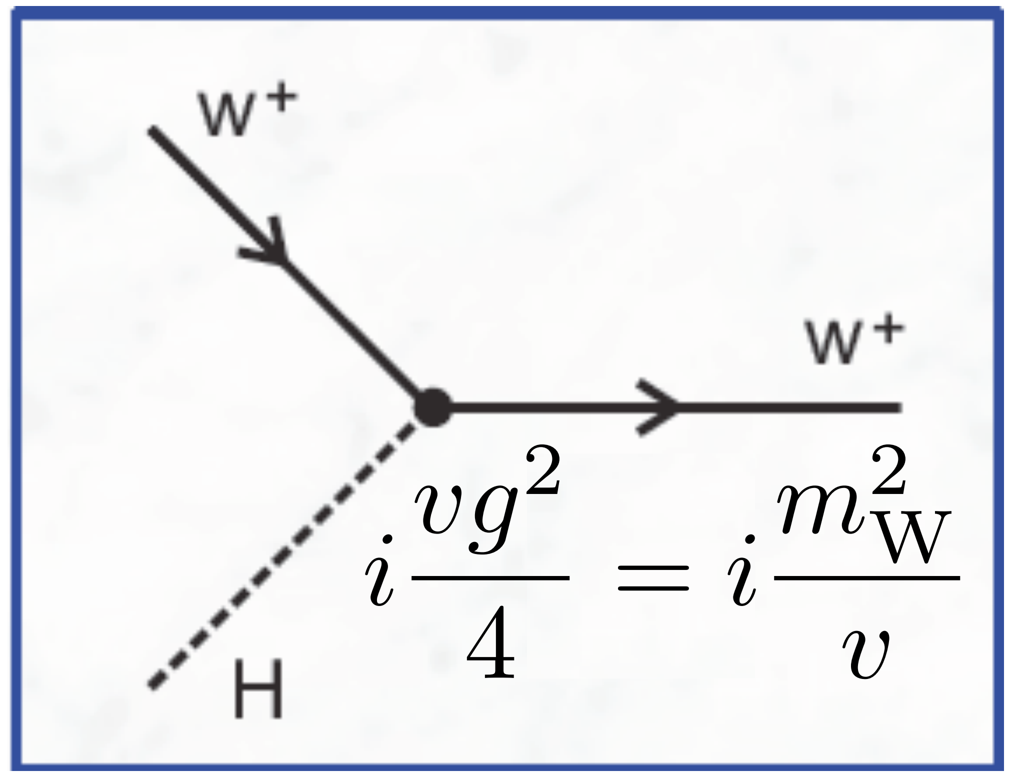
direct connection ⟷



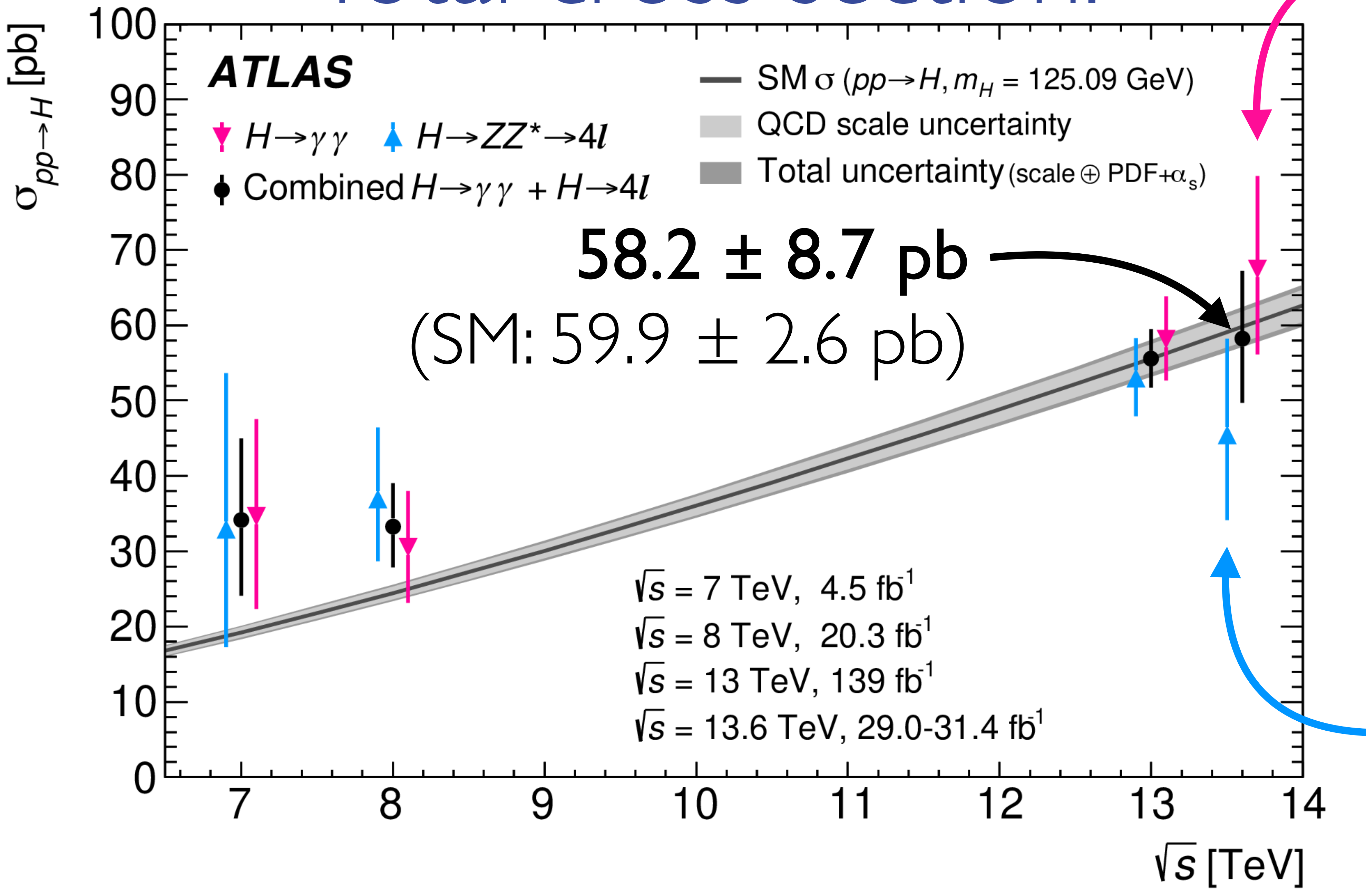
(*) simplified

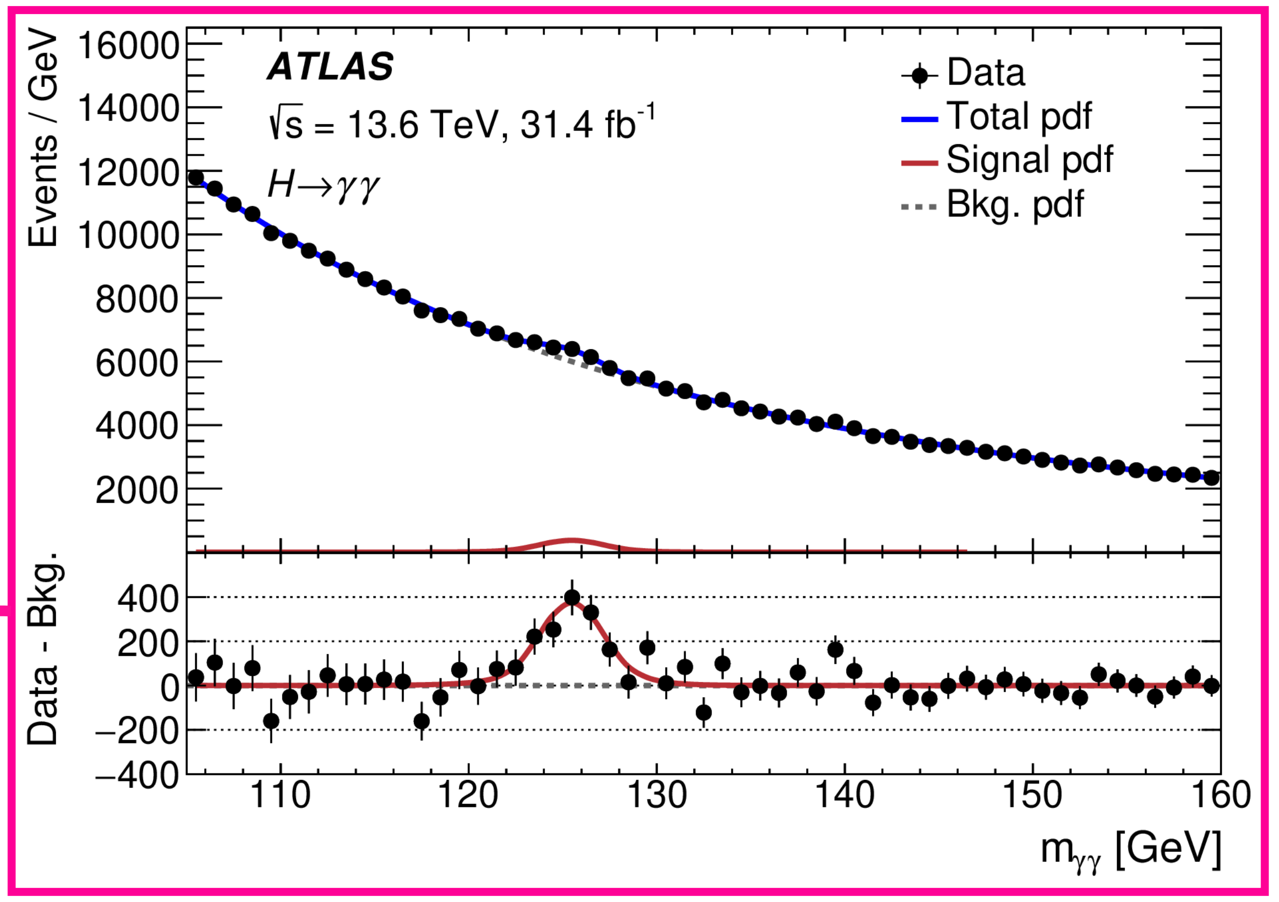
Total and differential cross sections

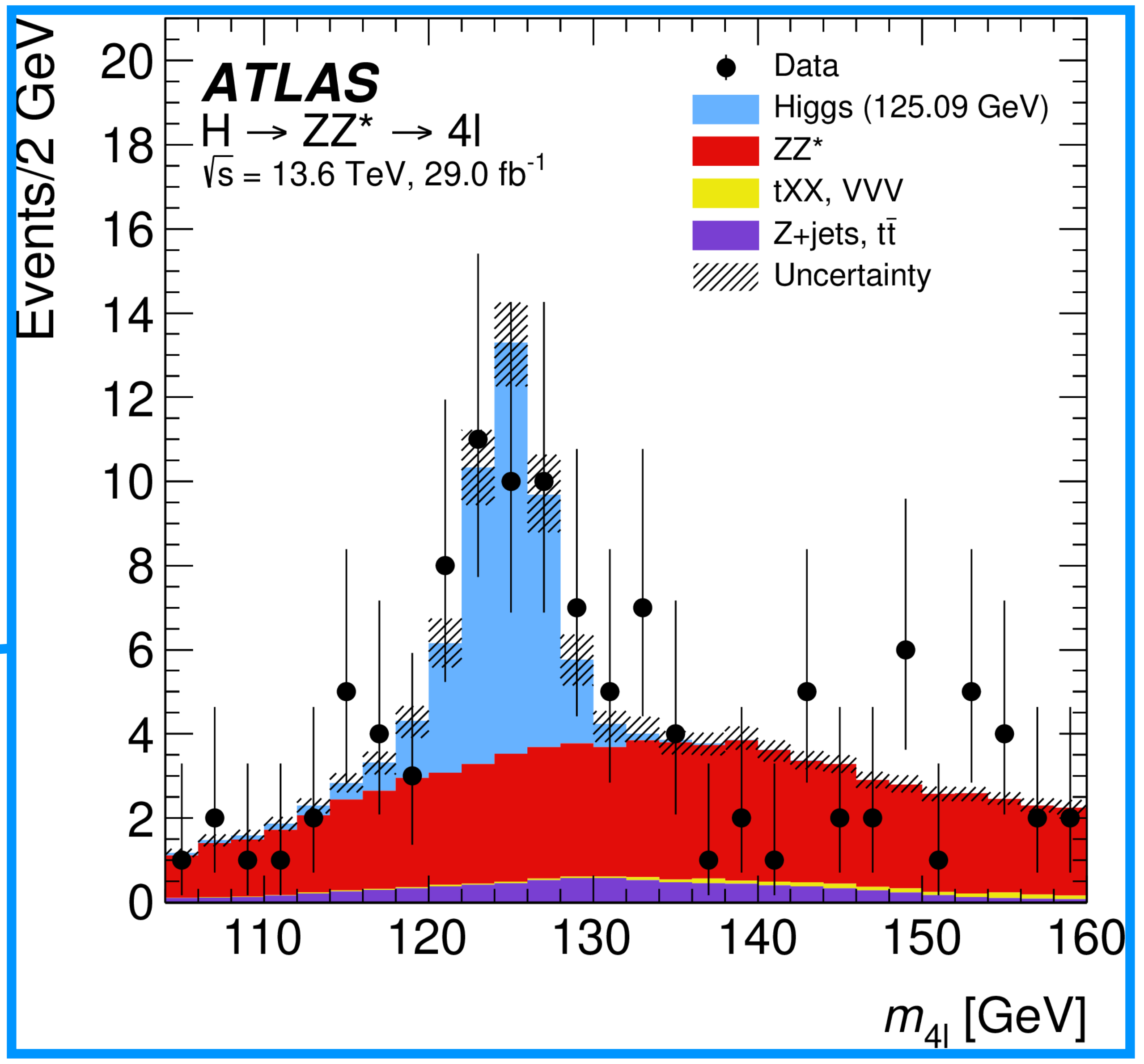
June 2023

$H \to \gamma\gamma$ and
$H \to ZZ^* \to 4\ell$

Total cross section:







Eur. Phys. J. C 84 (2024) 78

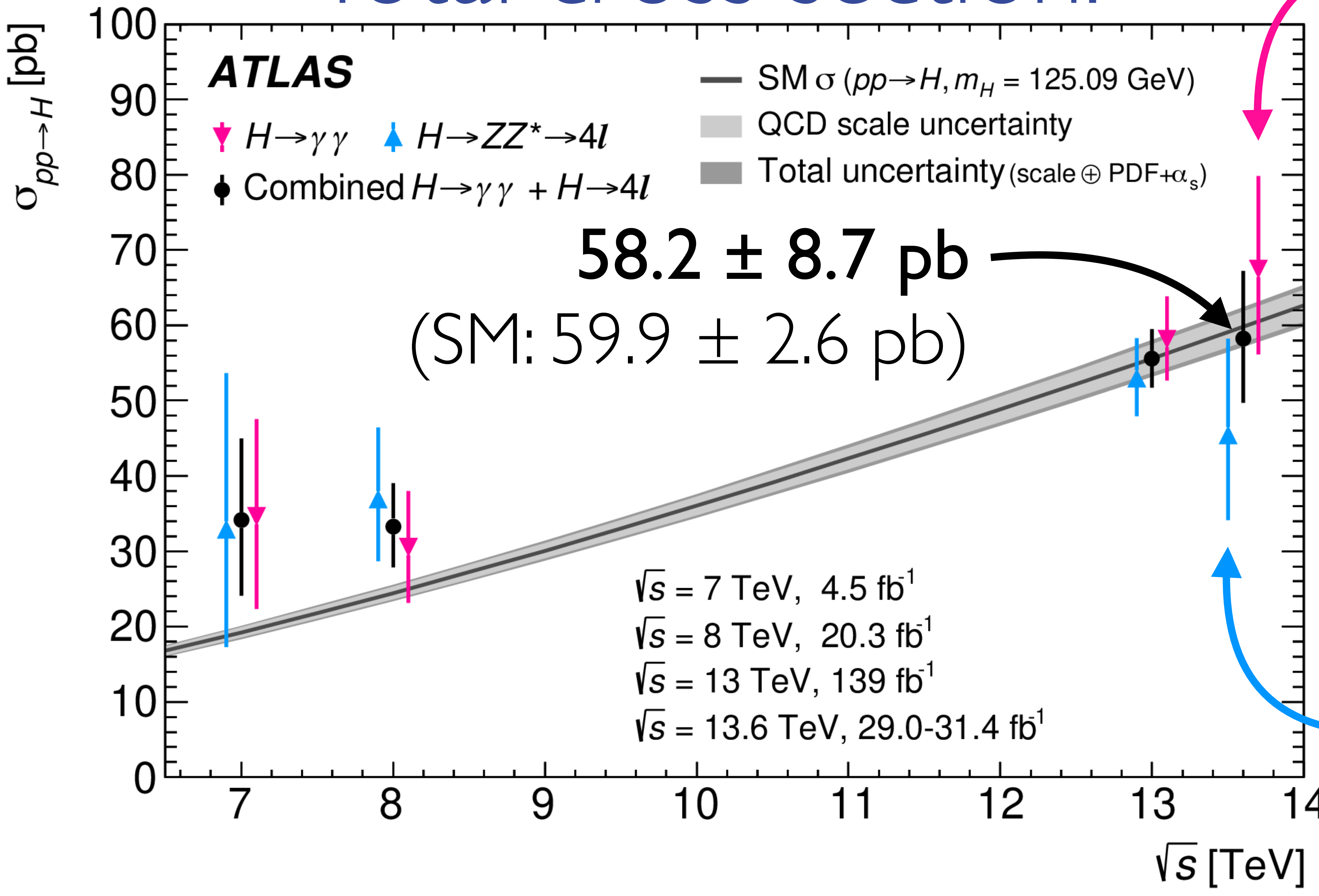
(ℓ = electron or muon)

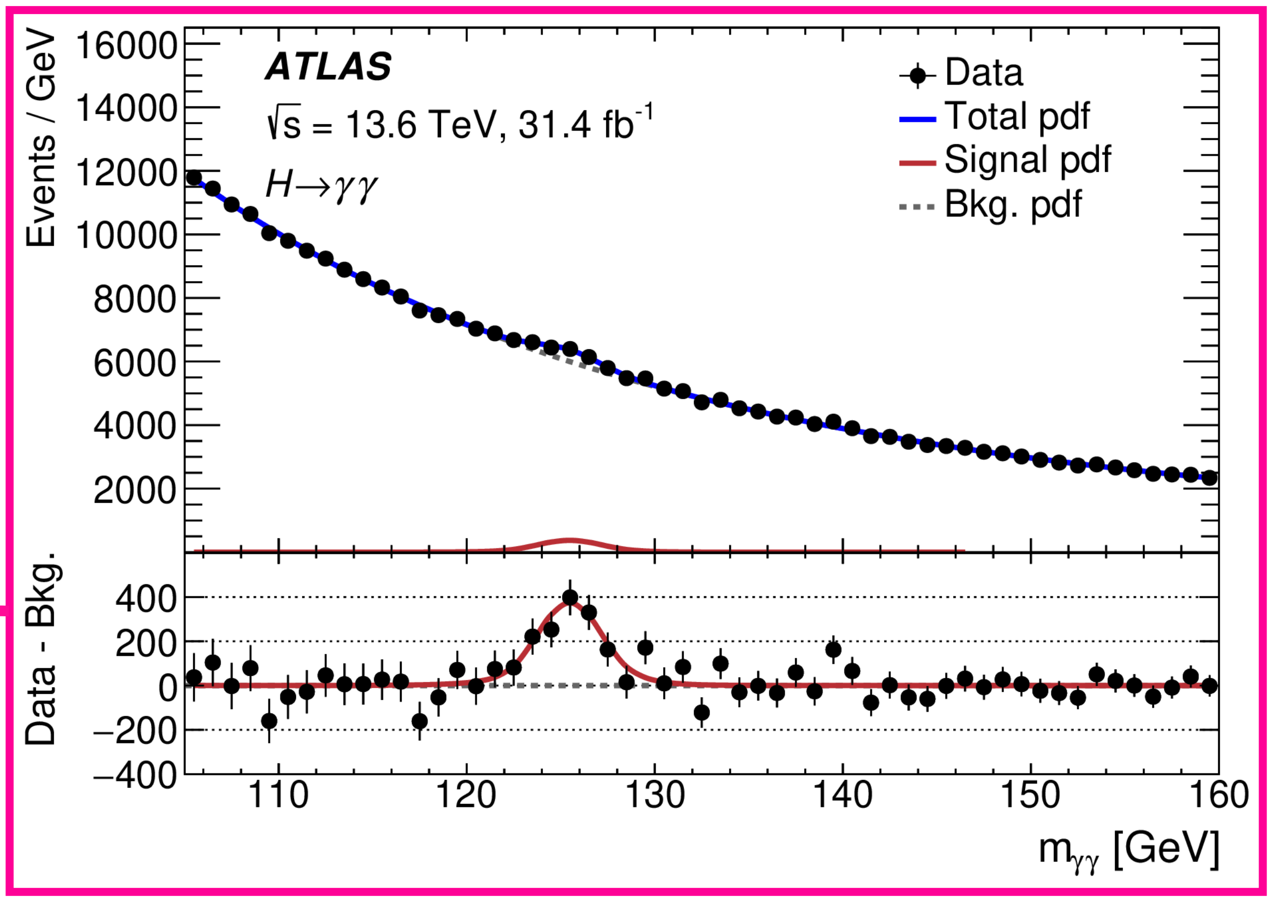
Total and differential cross sections

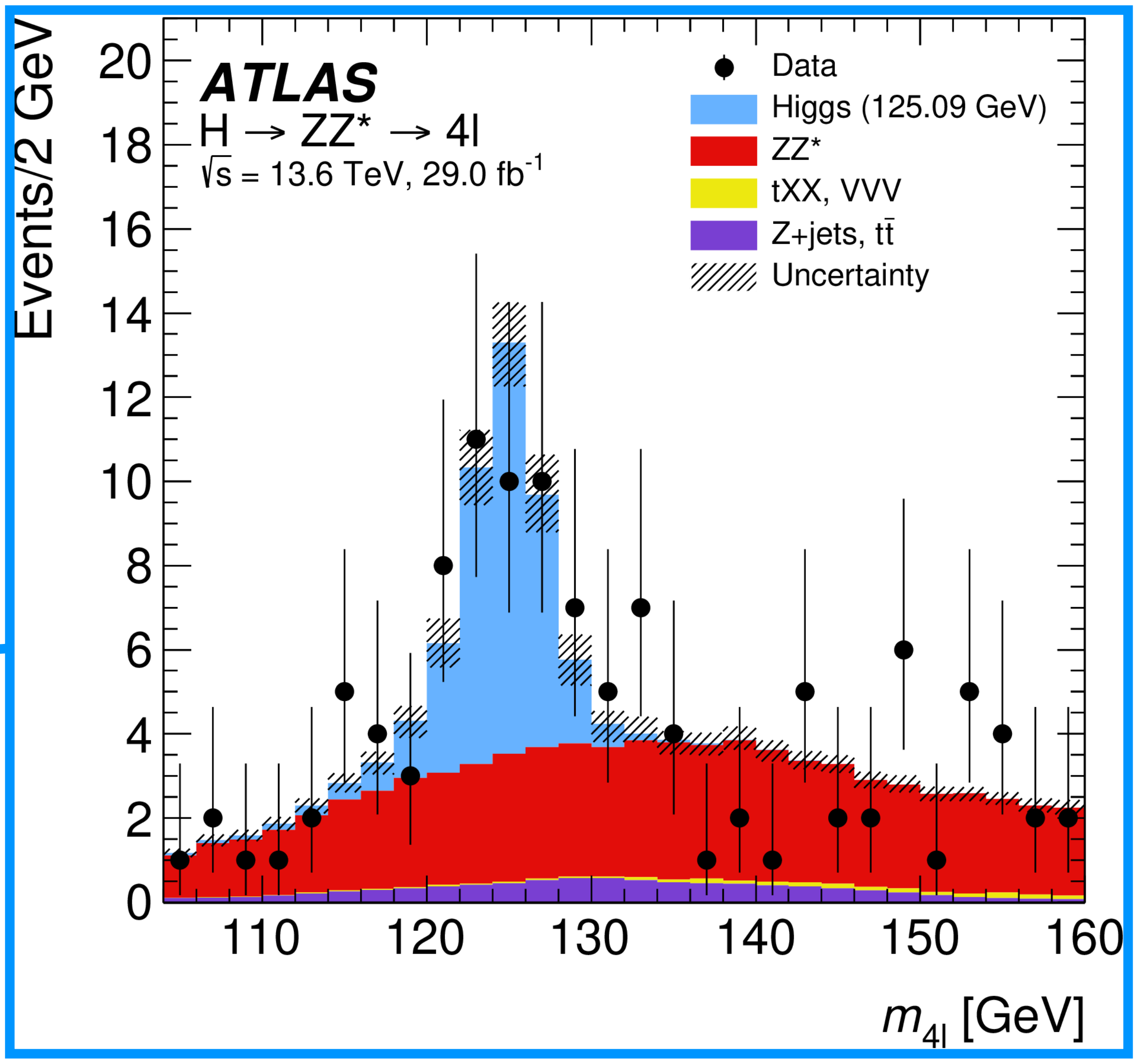
June 2023

H → γγ and H → ZZ* → 4ℓ

Total cross section:



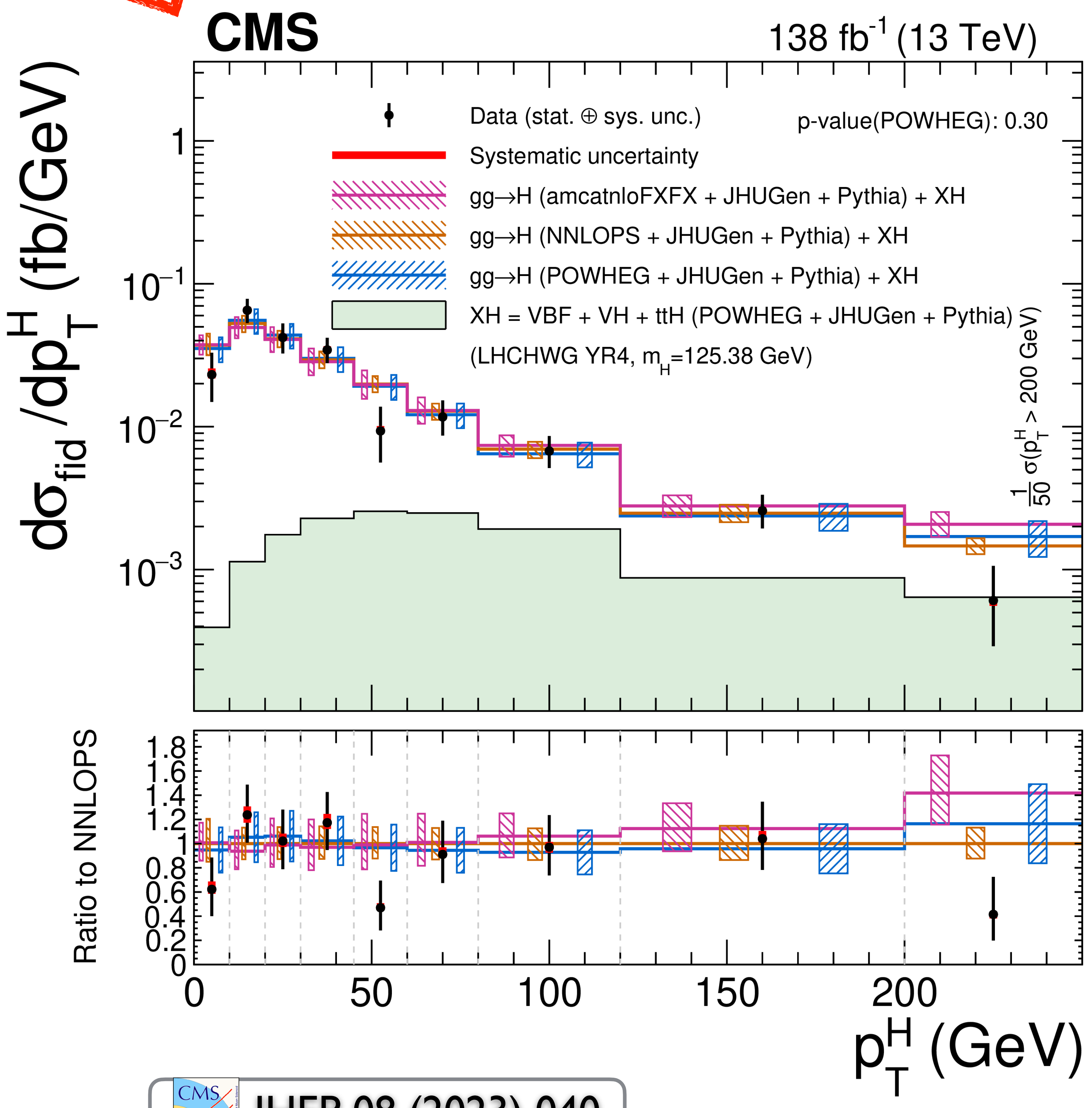




May 2023

H → ZZ* → 4ℓ

Differential cross section:



Eur. Phys. J. C 84 (2024) 78

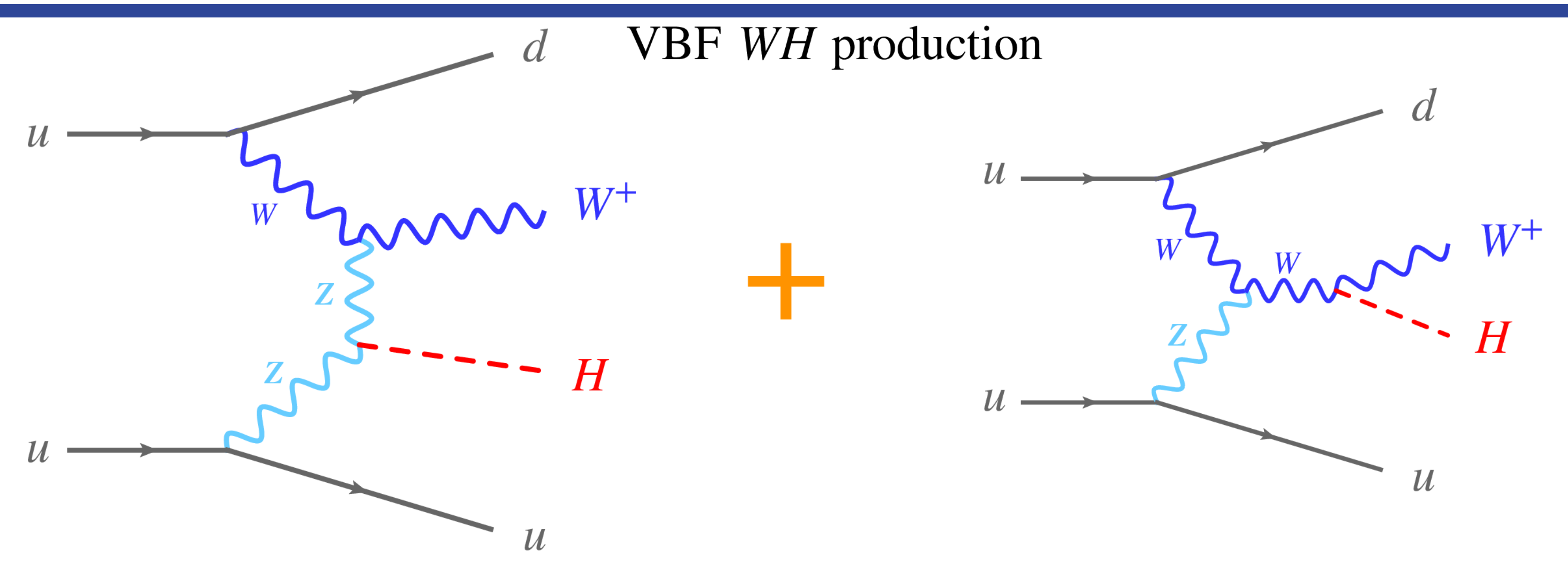
Karsten Köneke

(ℓ = electron or muon)

JHEP 08 (2023) 040

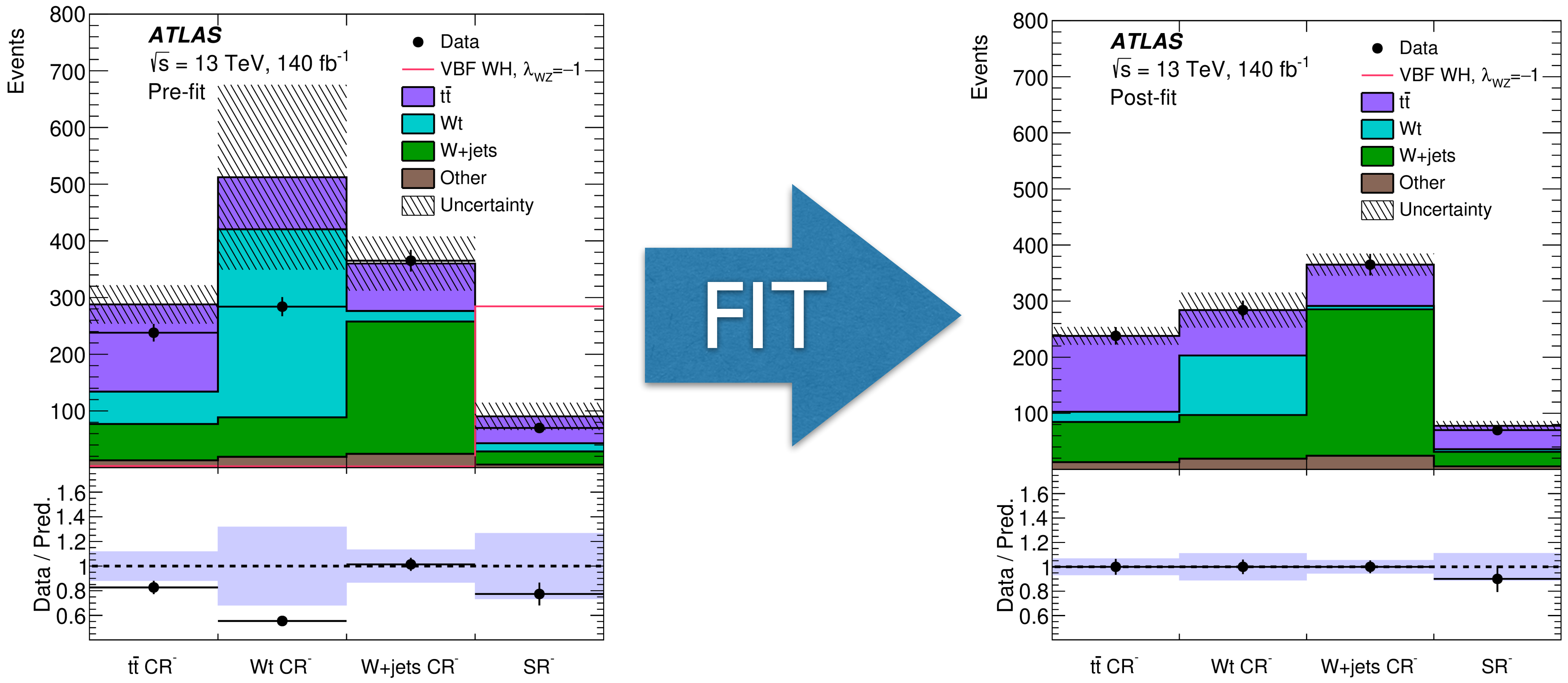
Relative sign between HZZ and HWW coupling

VBF *WH* production



$\sim \kappa_Z^2$ Interference $\sim \kappa_W \kappa_Z$ $\sim \kappa_W^2$

$$\kappa_{W,Z} := \frac{g_{W,Z}}{\left(g_{W,Z}\right)_{SM}}$$



- Use interference in VBF WH production
  - H → bb and W → ℓν
  - Observed (expected) σ(VBF WH) < **9.0 (8.7)** × SM

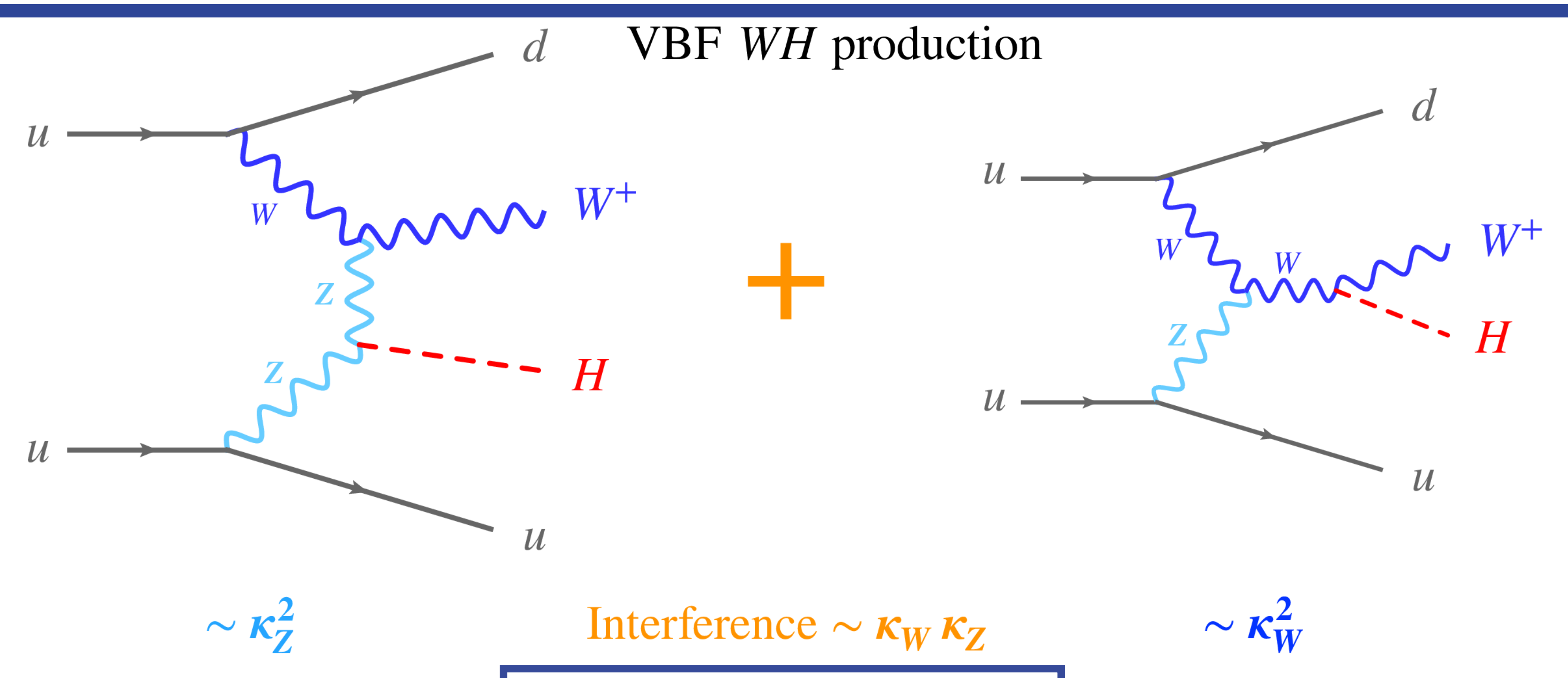
Feb 2024

arXiv:2402.00426

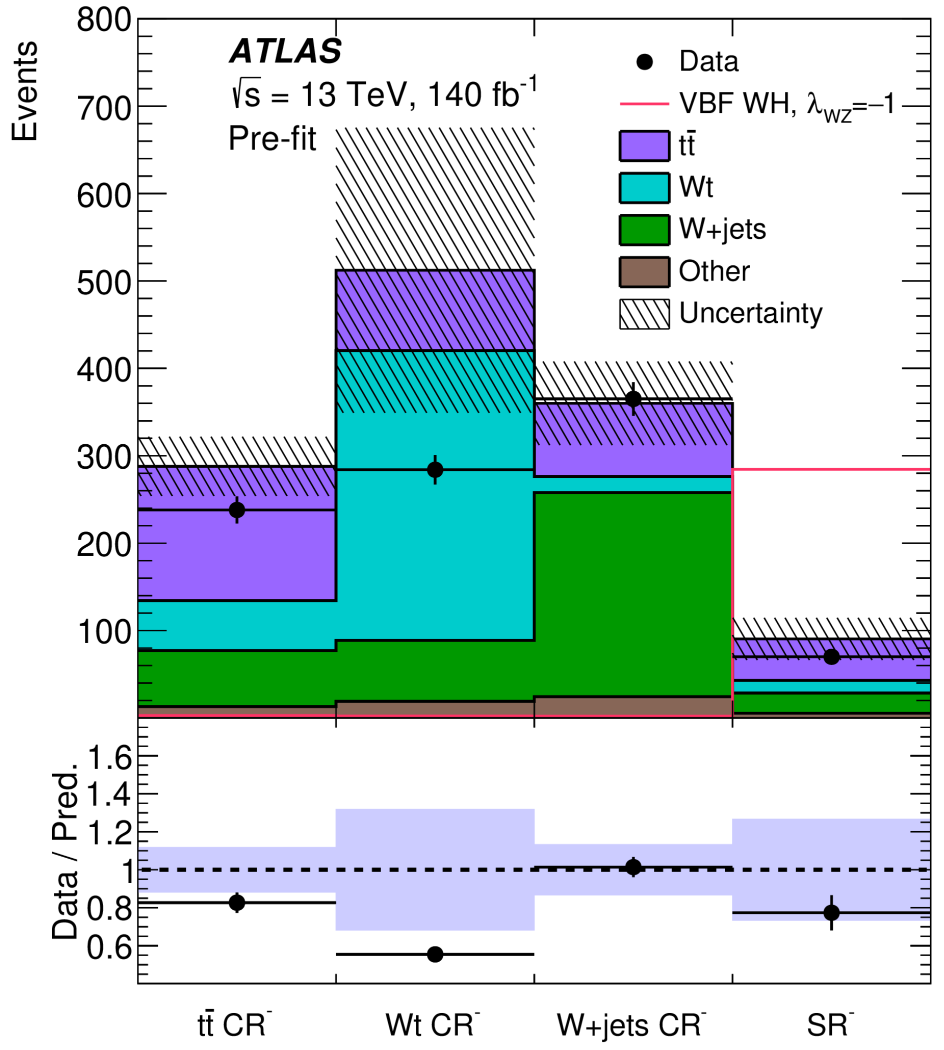
Relative sign between HZZ and HWW coupling

- Use interference in VBF WH production
  - H → bb and W → ℓν
  - Observed (expected) σ(VBF WH) < **9.0 (8.7)** × SM
  - Opposite-sign coupling rejected ≫ **5 σ**

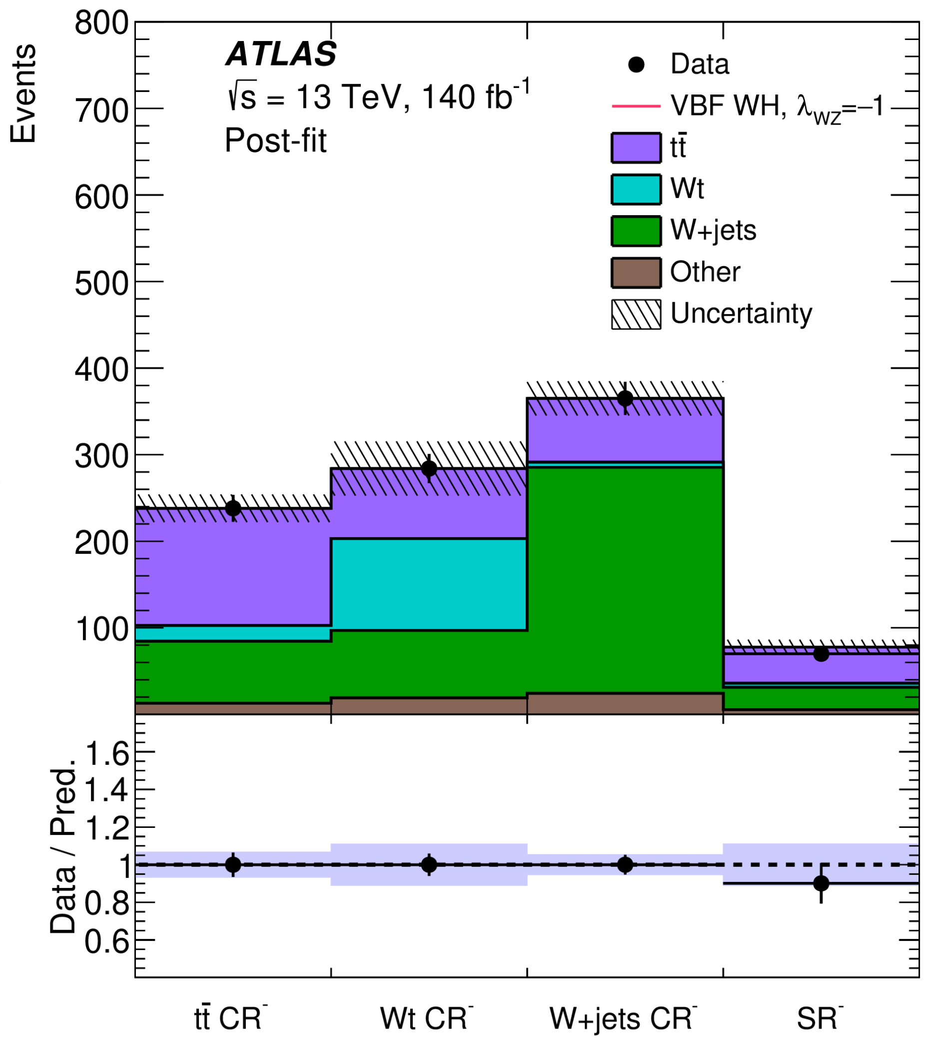
Feb 2024

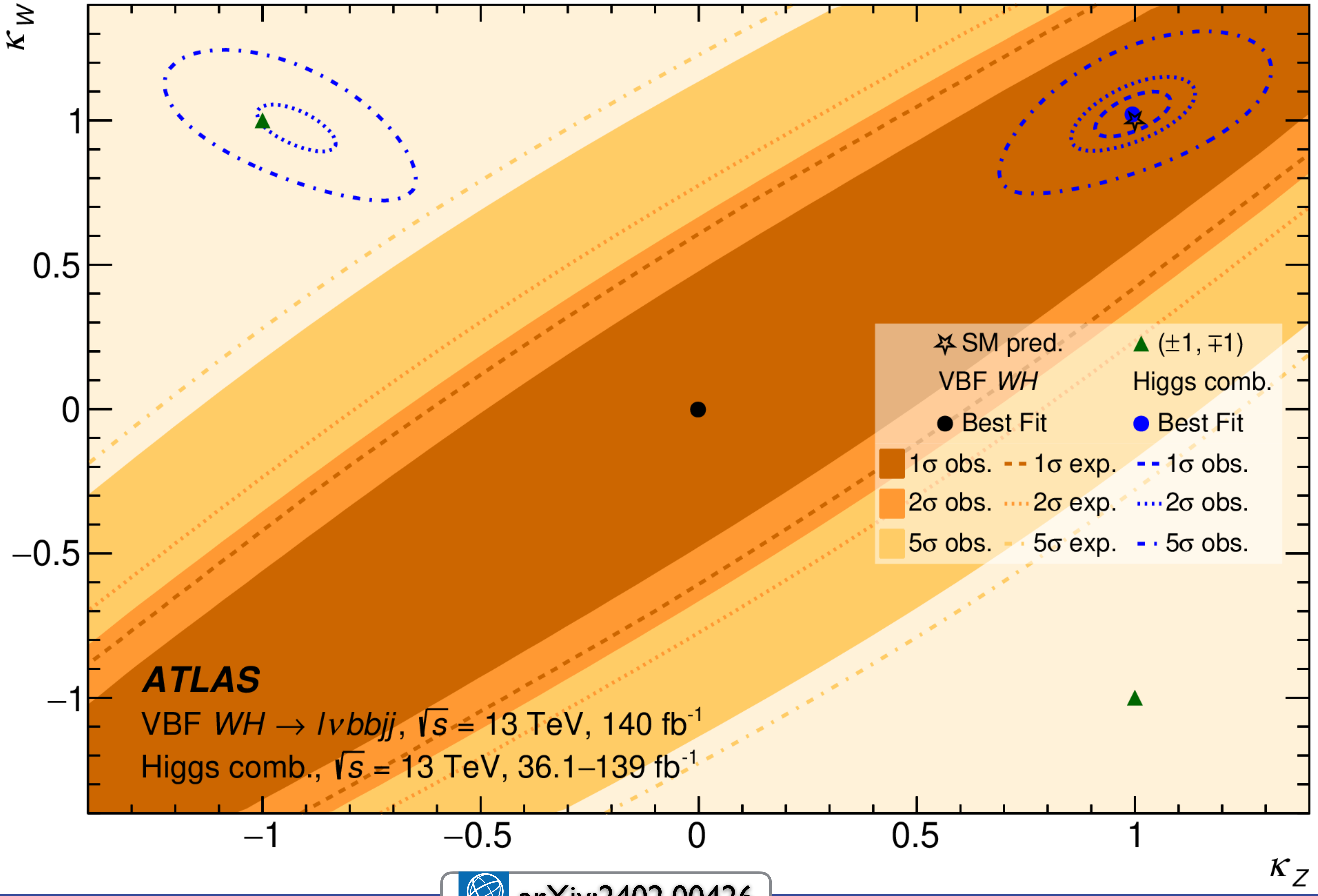


$$\kappa_{W,Z} := \frac{g_{W,Z}}{\left(g_{W,Z}\right)_{SM}}$$



FIT





arXiv:2402.00426

Outline

$$\mathscr{L}_{\text{Higgs}} = (D_\mu \phi)^2 - \mu^2 \phi^2 - \lambda \phi^4 + \lambda_f \phi \bar{\psi} \psi$$

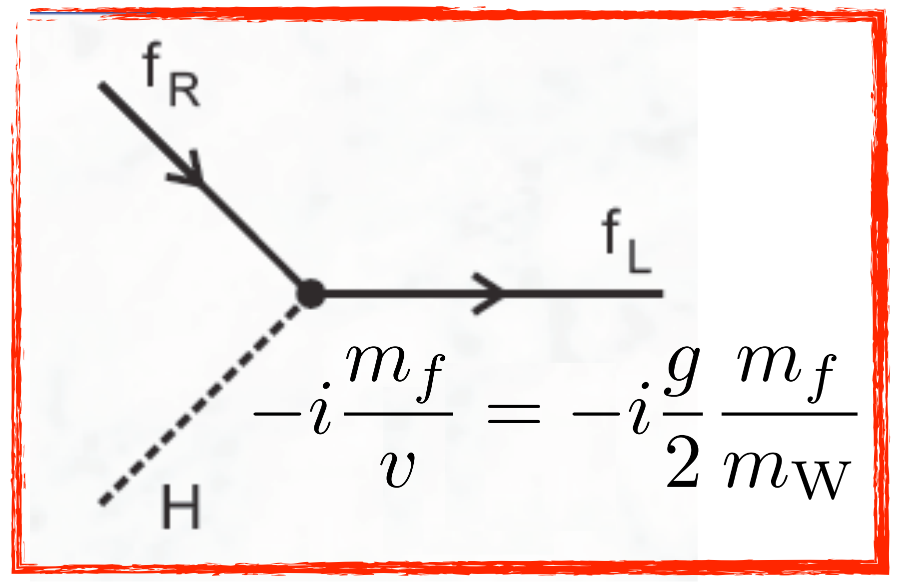
3. Higgs coupling to fermions

- Fermionic decays

Electroweak Symmetry Breaking

$$m_f = \frac{\lambda_f v}{\sqrt{2}}$$

direct connection

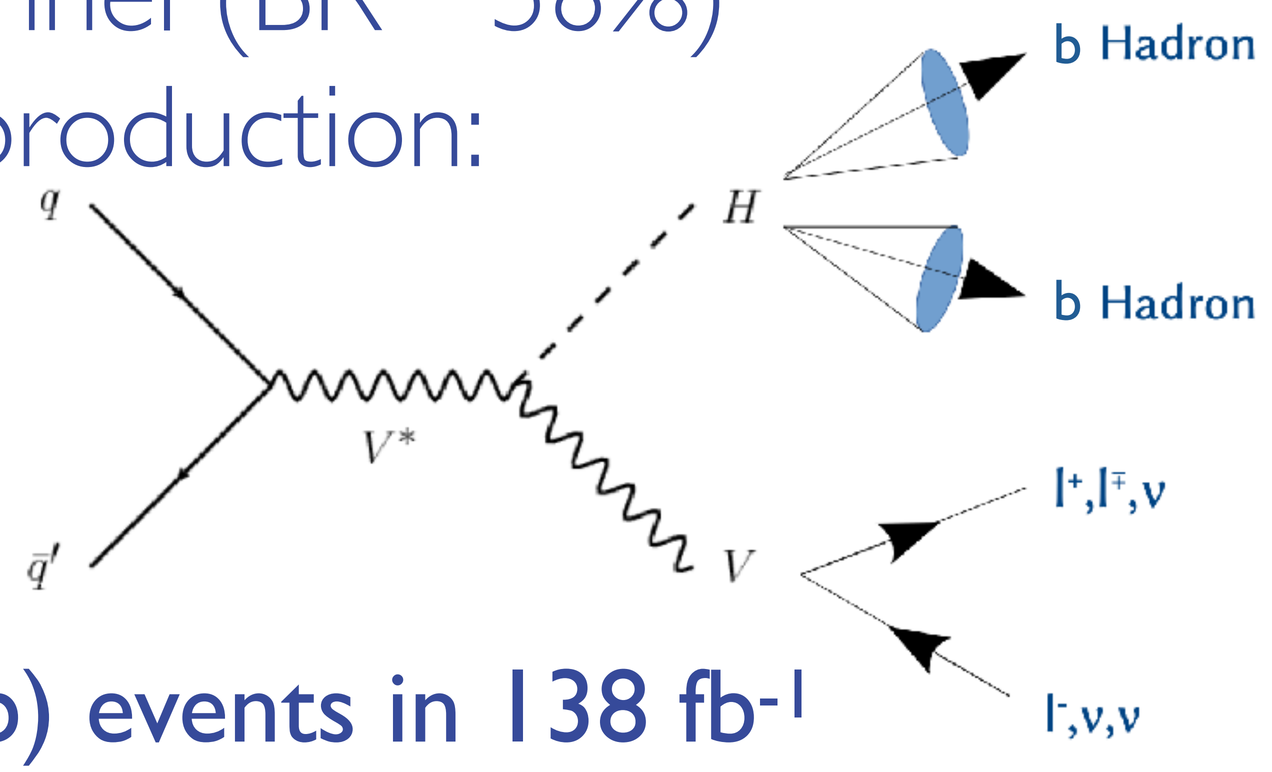


 Karsten Köneke (*) simplified

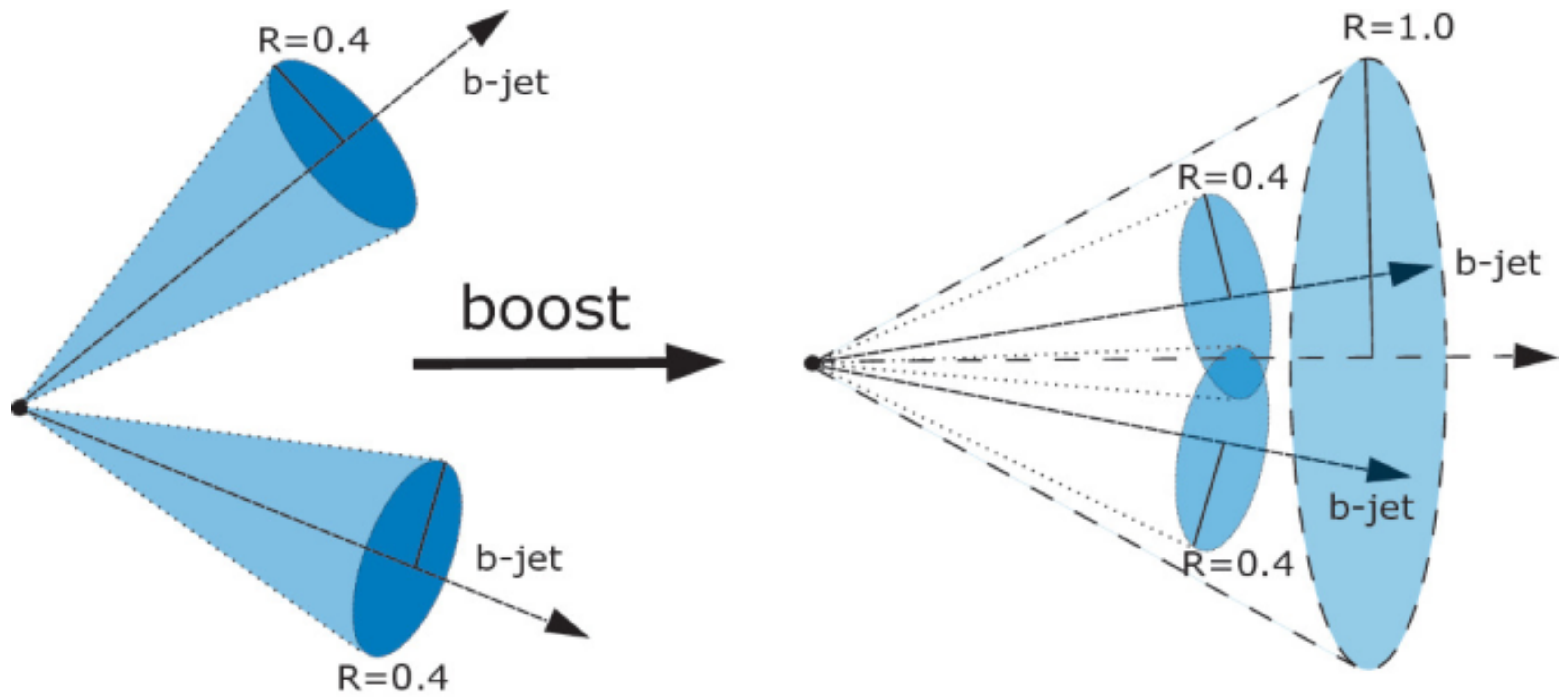
$H \rightarrow b\bar{b}$

- $H \rightarrow b\bar{b}$ dominant decay channel (BR ~58%)
- VH (V=W or Z) associated production:
  - 0 lepton ($Z \rightarrow \nu\nu$)
  - 1 lepton ($W \rightarrow \ell\nu$)
  - 2 lepton ($Z \rightarrow \ell\ell$)

⇒ **~30000 V(→leptons)H(→ bb) events in 138 fb^{-1}**



- First observed in 2018
- Now refined:
  - DNNs & BDTs for signal extraction
  - Resolved & boosted channels



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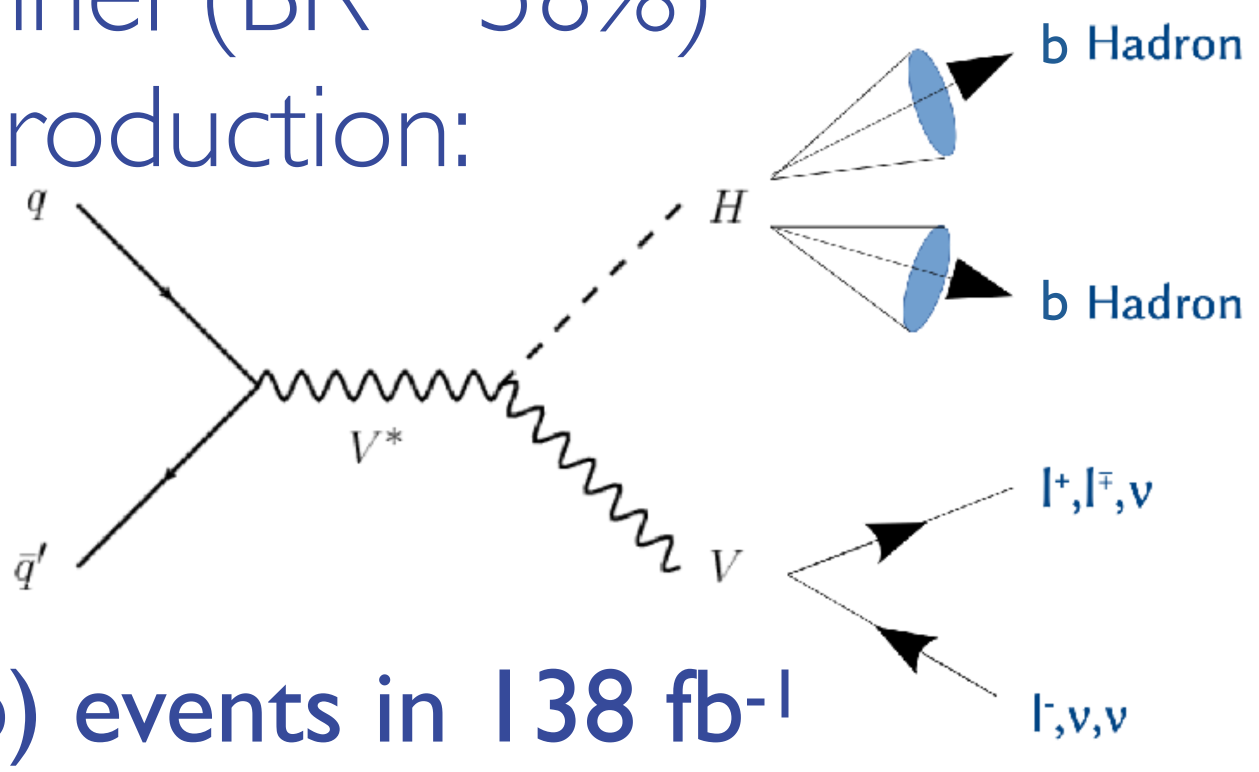

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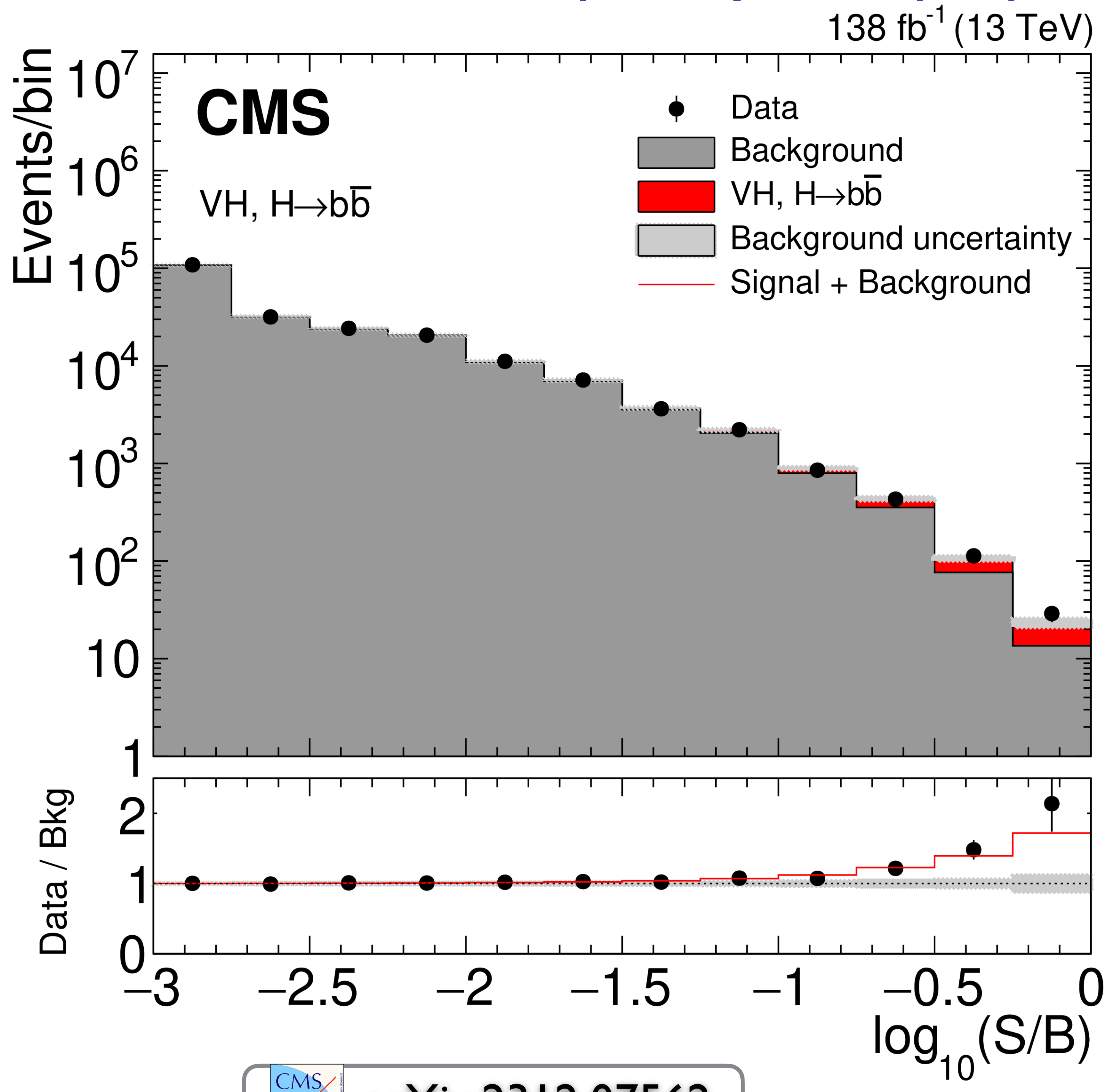

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  - DNNs & BDTs for signal extraction
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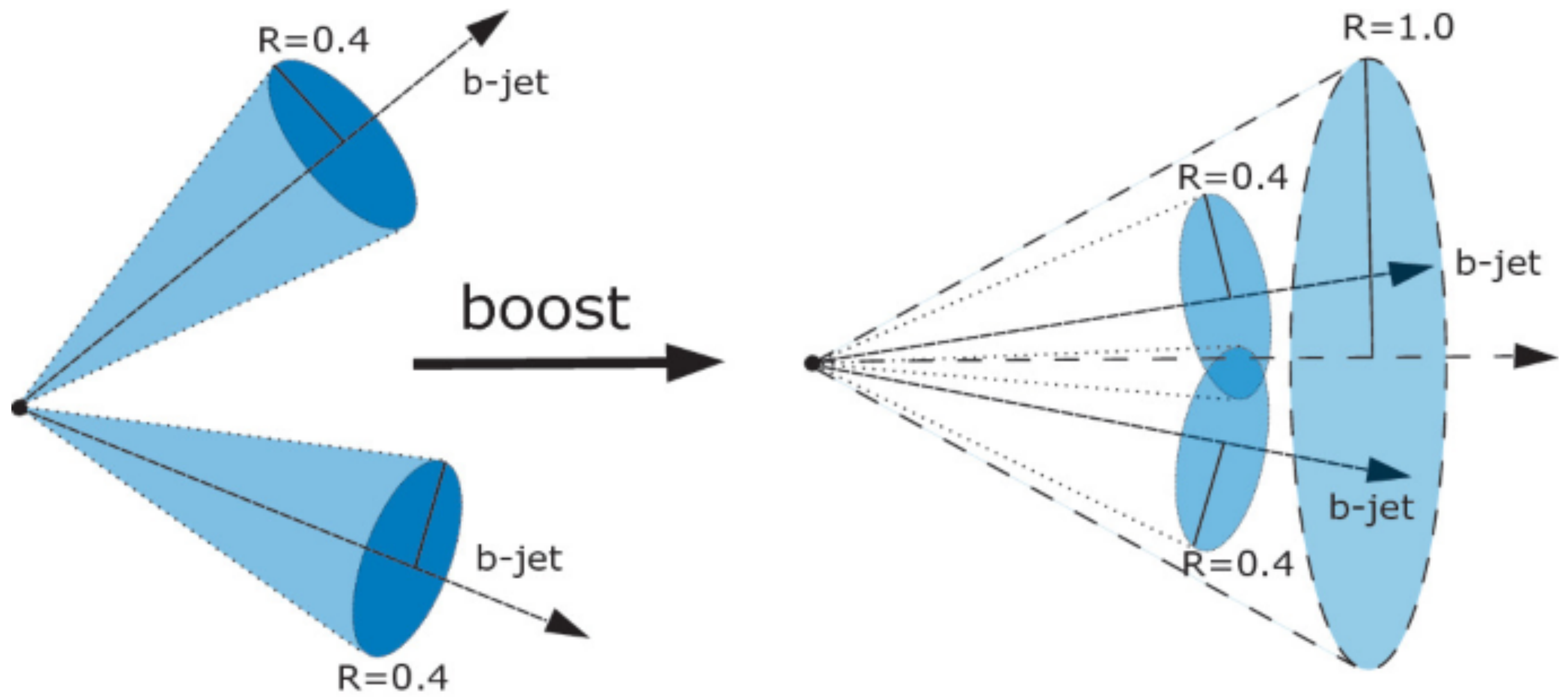

- Obs. (exp.) significance: 6.3 (5.6) σ

arXiv:2312.07562

$H \to b\bar{b}$

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  - 0 lepton ($Z \to \nu\nu$)
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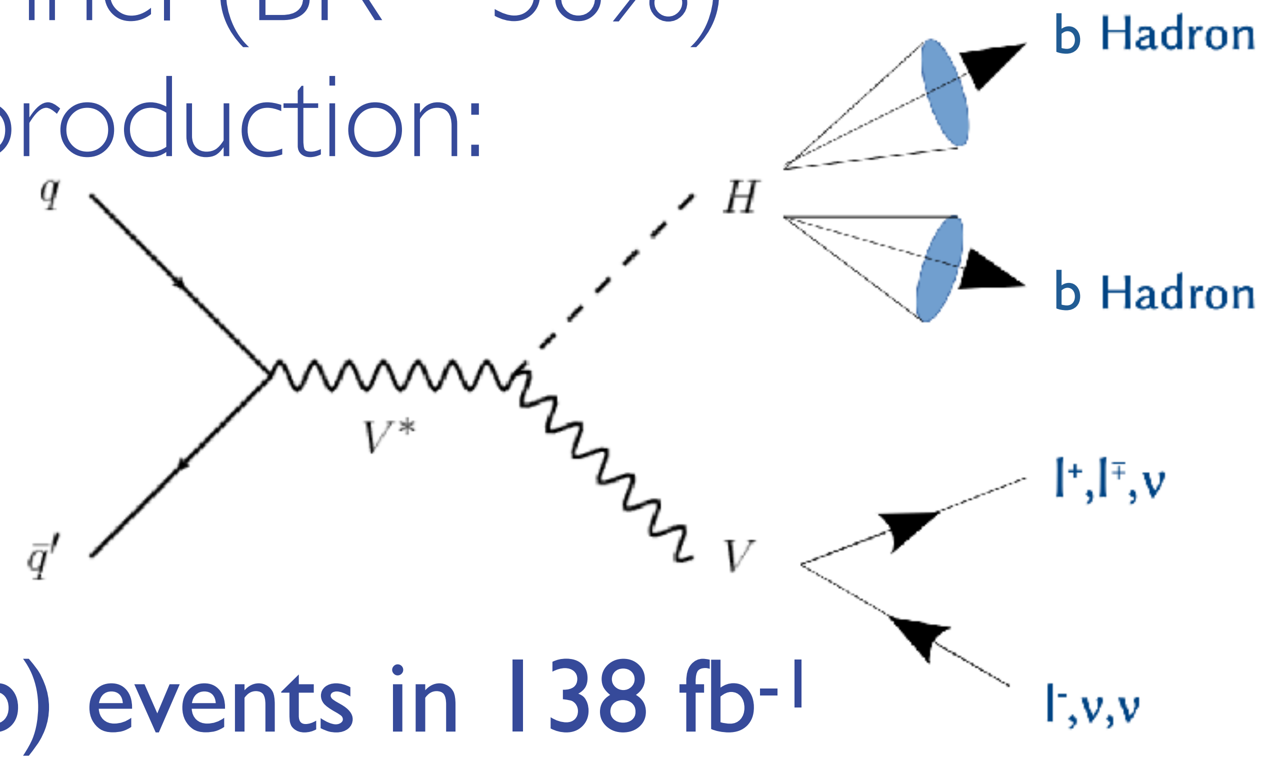
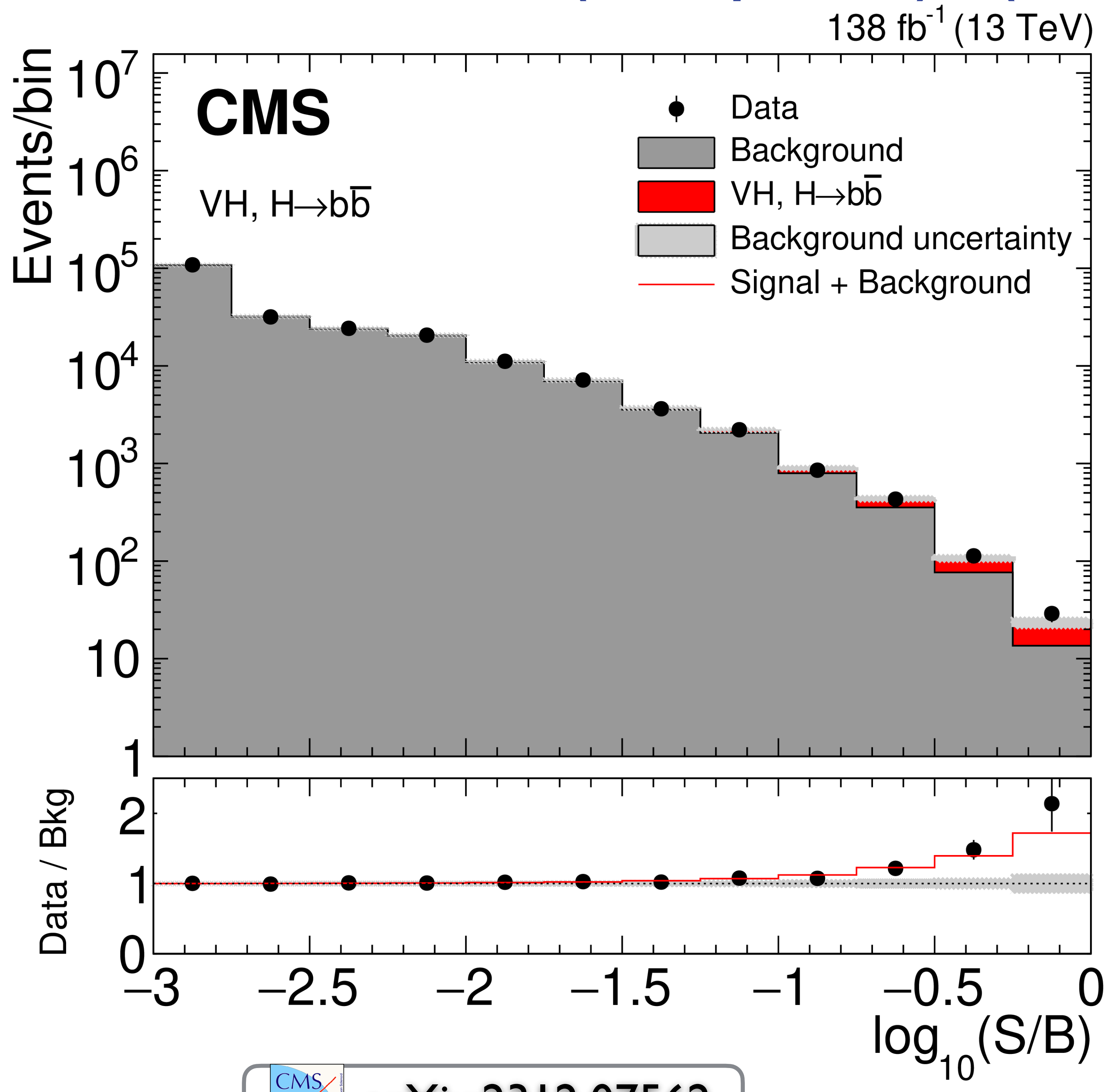


⇒ **~30000 V(→leptons)H(→ bb) events in 138 fb^{-1}**



- First observed in 2018
- Now refined:
  - DNNs & BDTs for signal extraction
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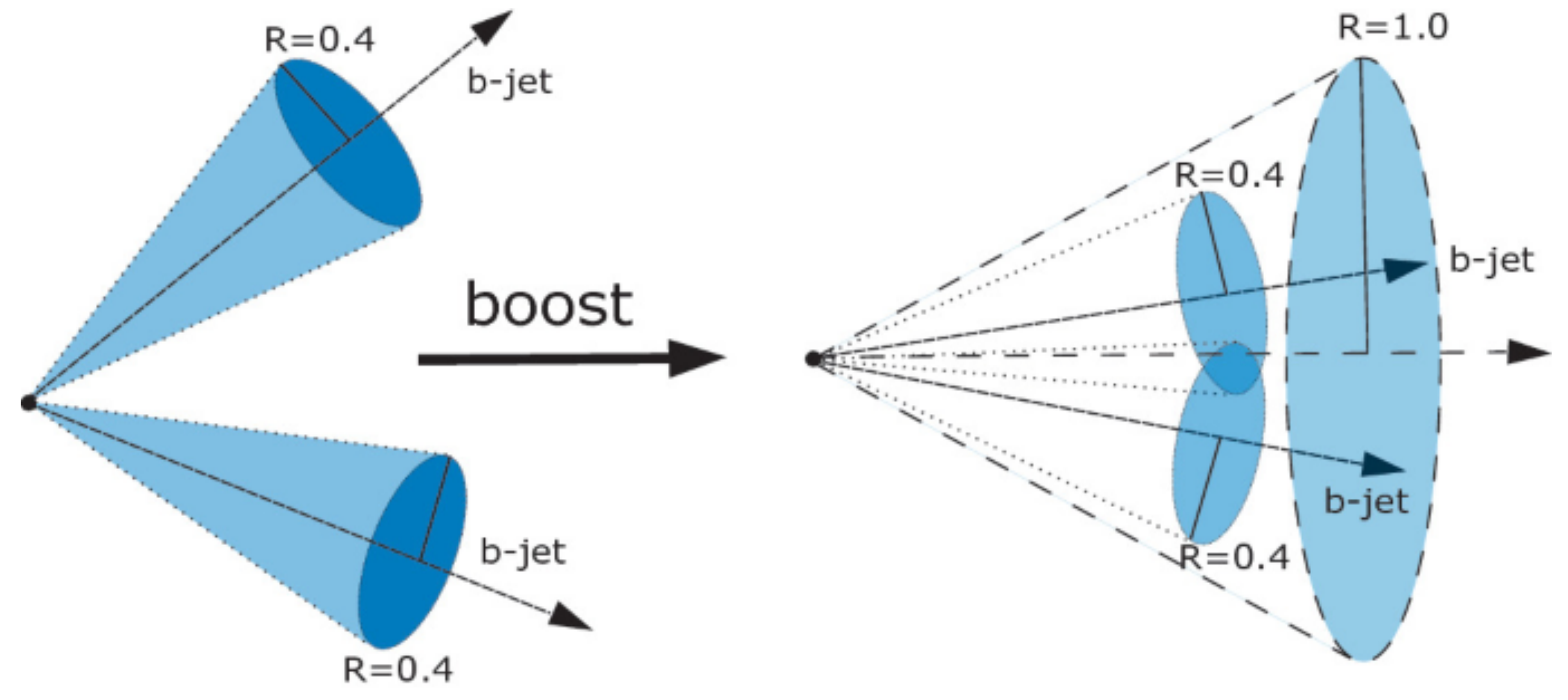

  - Obs. (exp.) significance: 6.3 (5.6) σ

Signal strength $\mu := \frac{\sigma_i \cdot \mathcal{B}^f}{(\sigma_i \cdot \mathcal{B}^f)_{\text{SM}}} = \frac{\text{observed rate}}{\text{expected rate}}$

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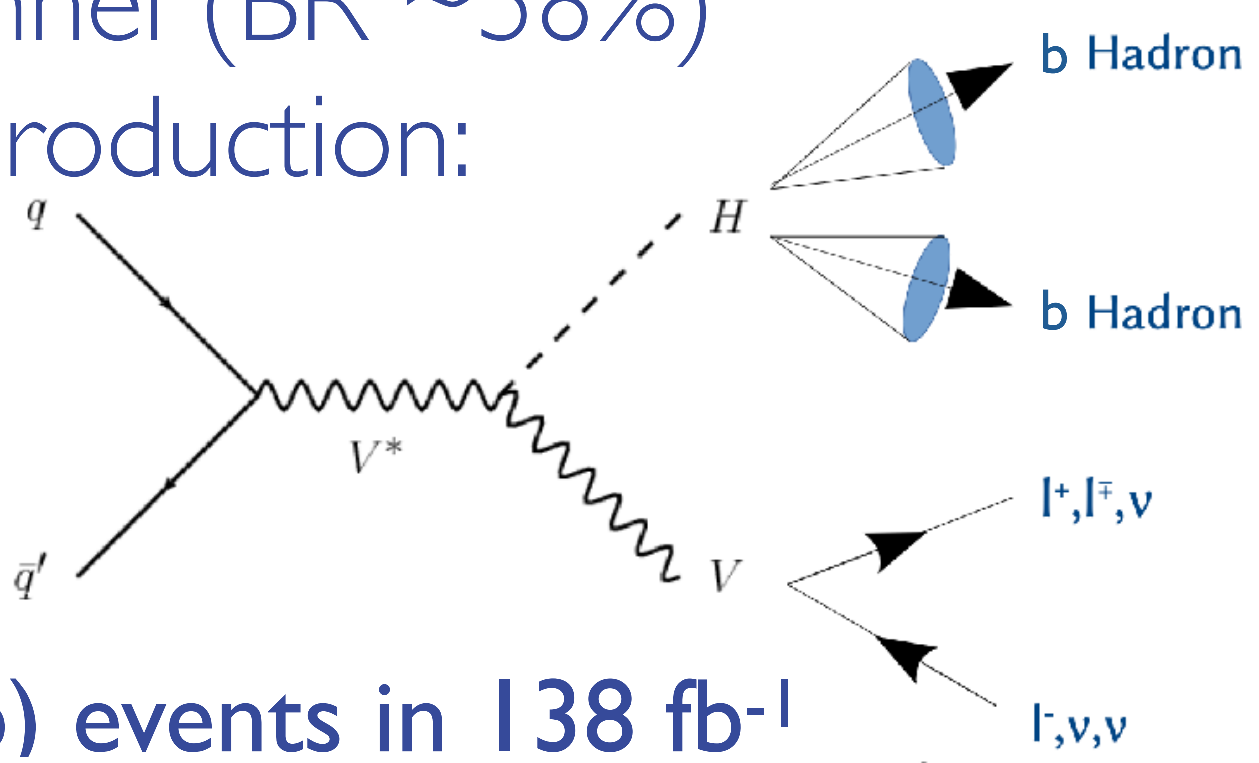
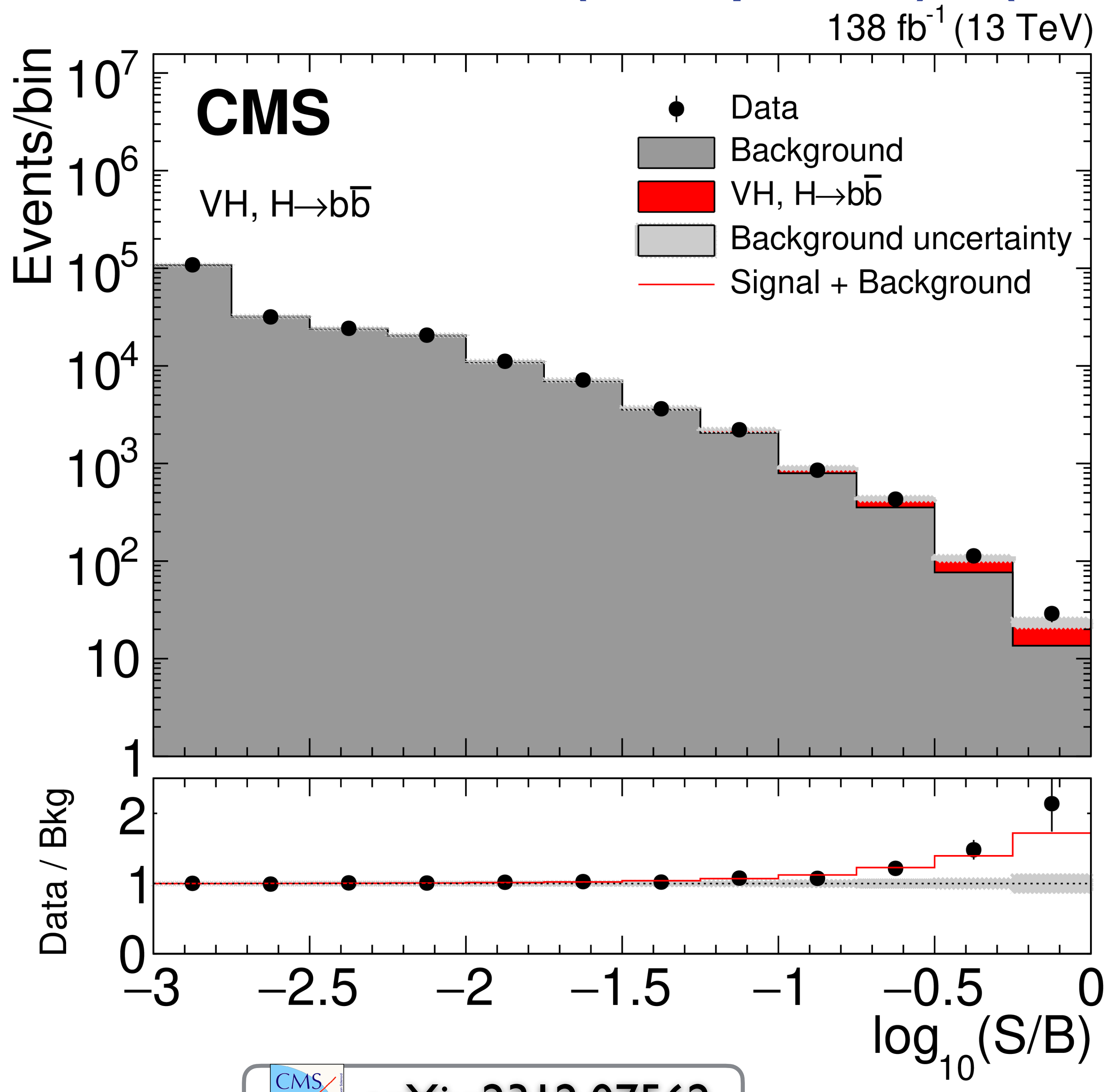
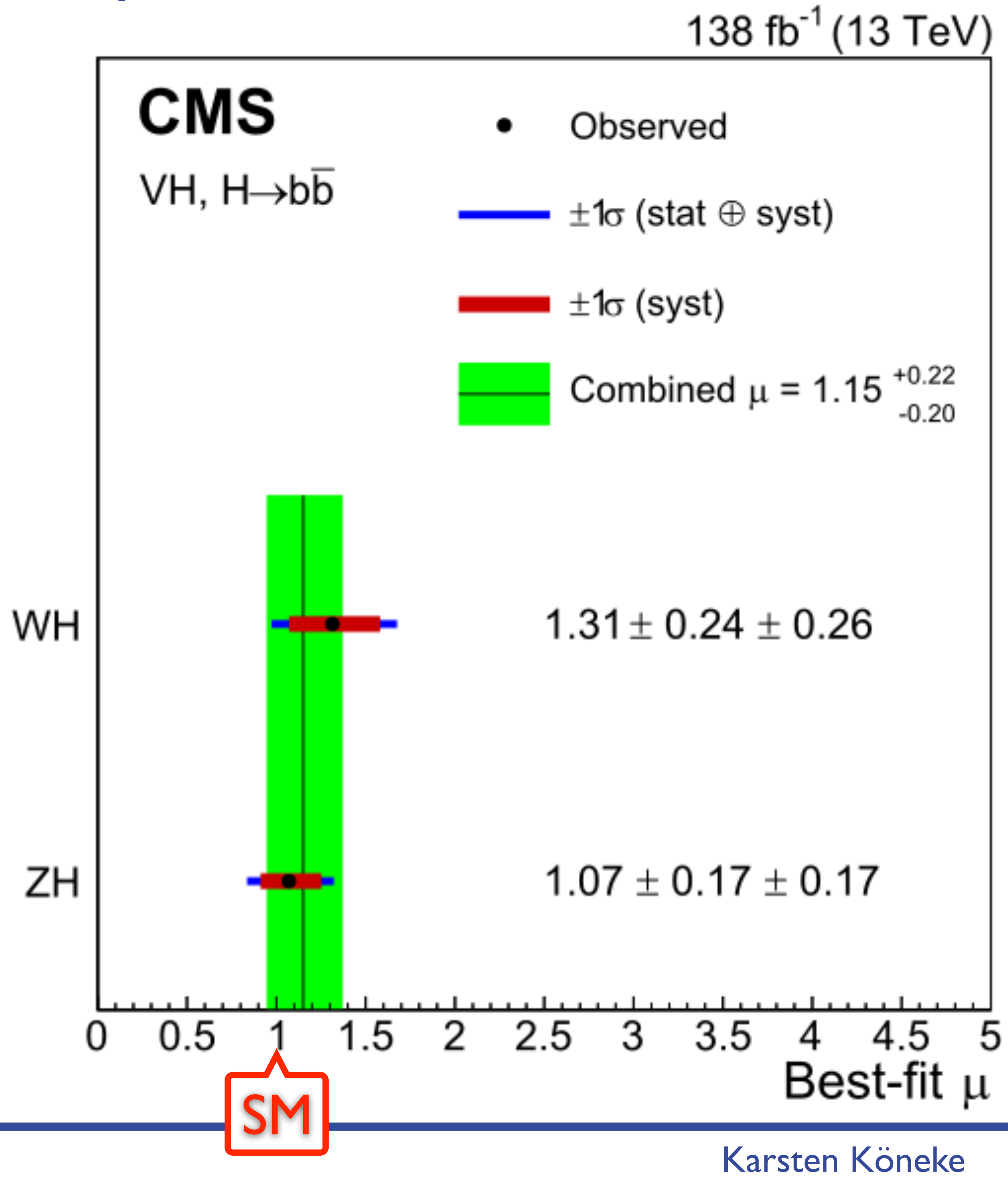
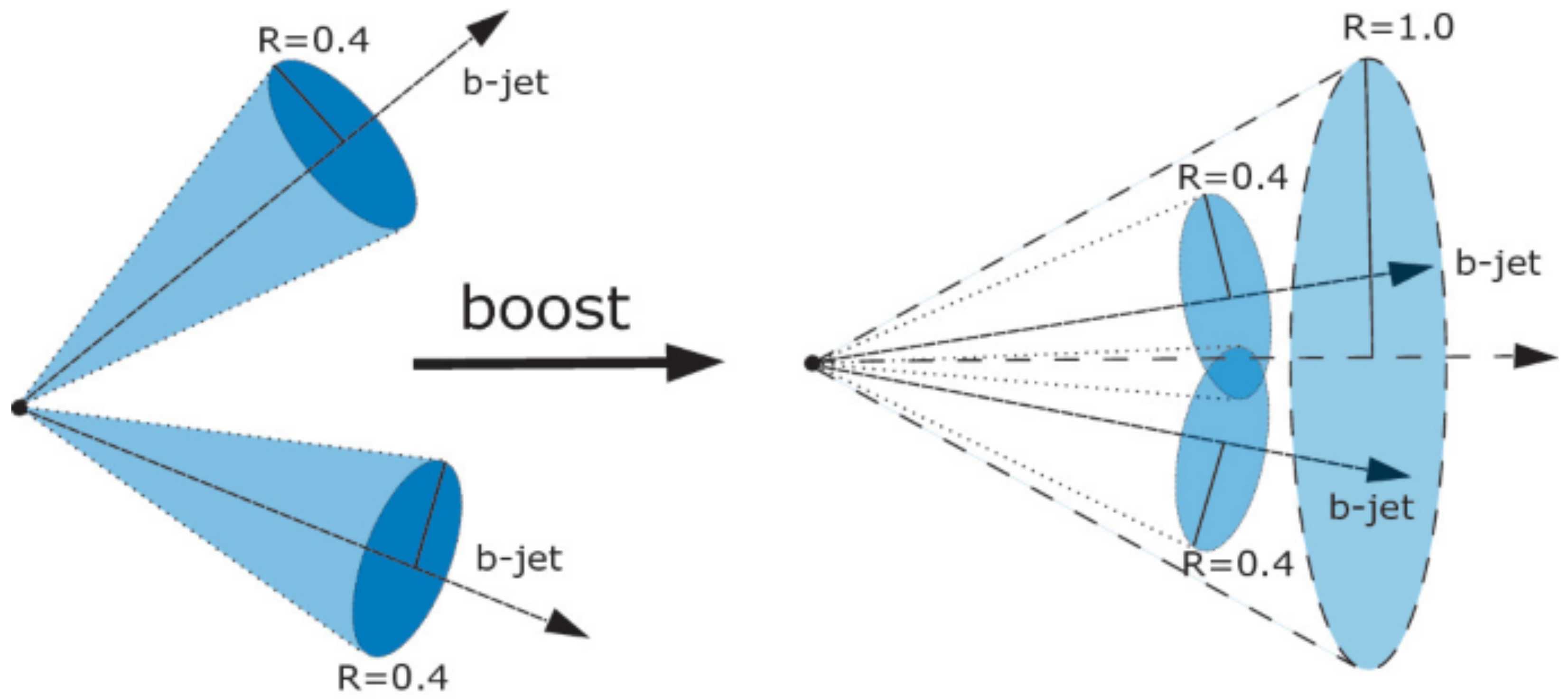


⇒ ~30000 V(→leptons)H(→ bb) events in 138 fb^{-1}





- First observed in 2018
- Now refined:
  - DNNs & BDTs for signal extraction
  - Resolved & boosted channels



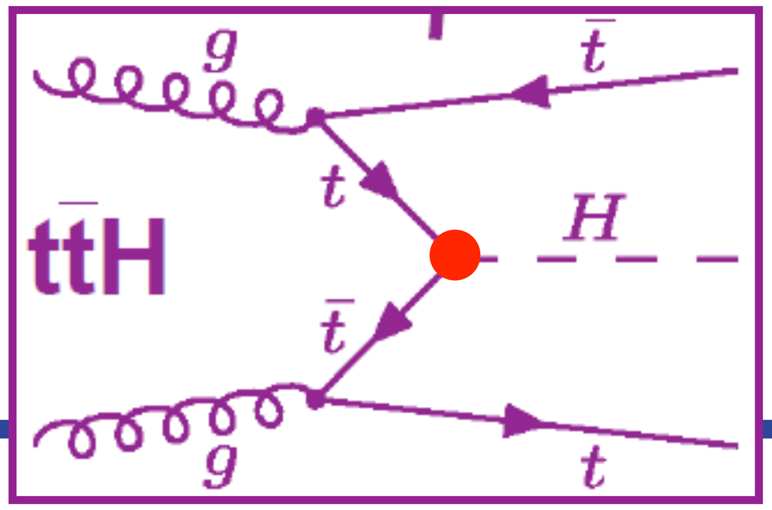
- Obs. (exp.) significance: 6.3 (5.6) σ

Signal strength $\mu := \frac{\sigma_i \cdot \mathcal{B}^f}{(\sigma_i \cdot \mathcal{B}^f)_{\mathrm{SM}}} = \frac{\text{observed rate}}{\text{expected rate}}$

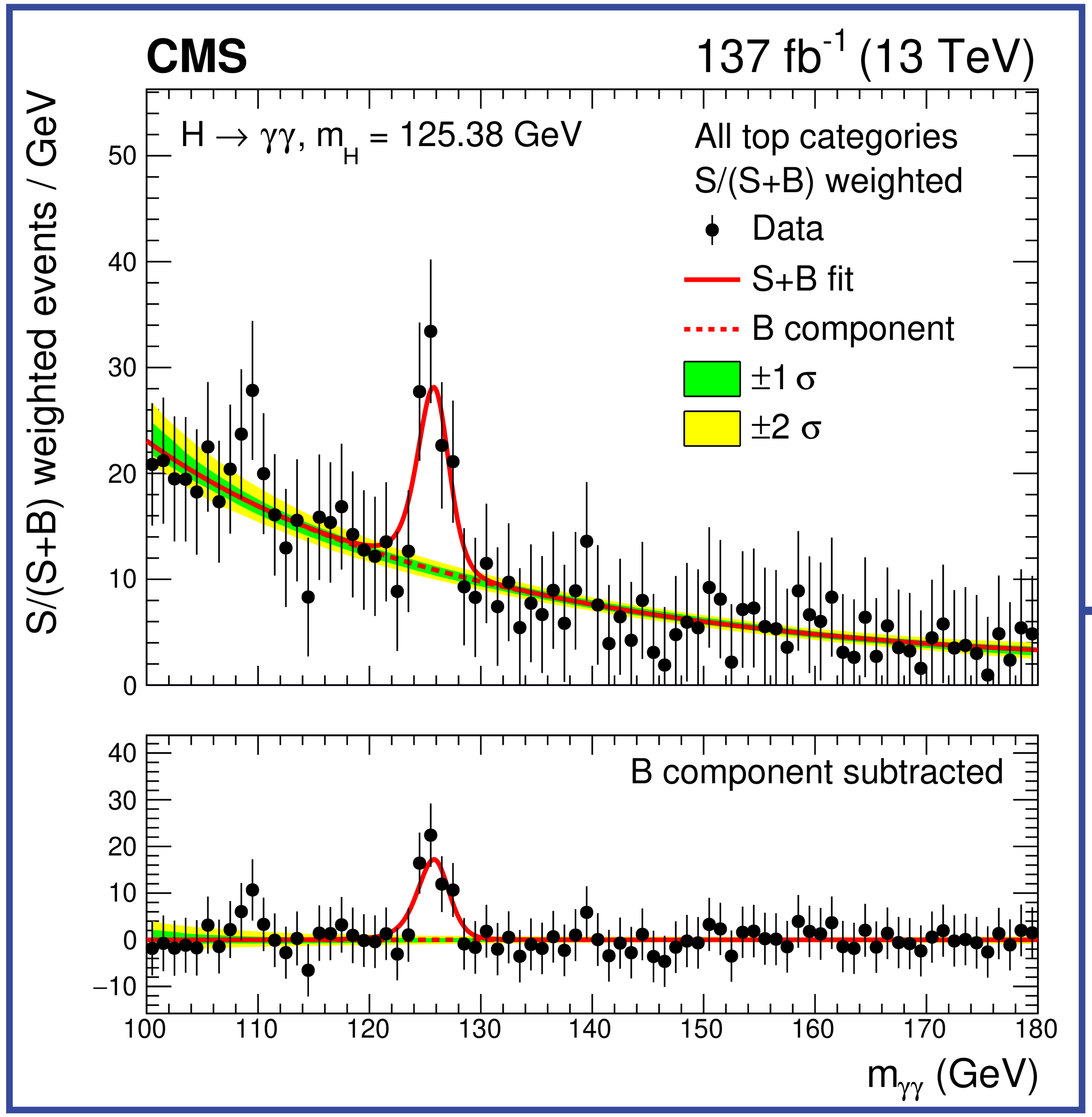
- Obs. signal strength: $\mu = 1.15^{+0.22}_{-0.20}$

arXiv:2312.07562

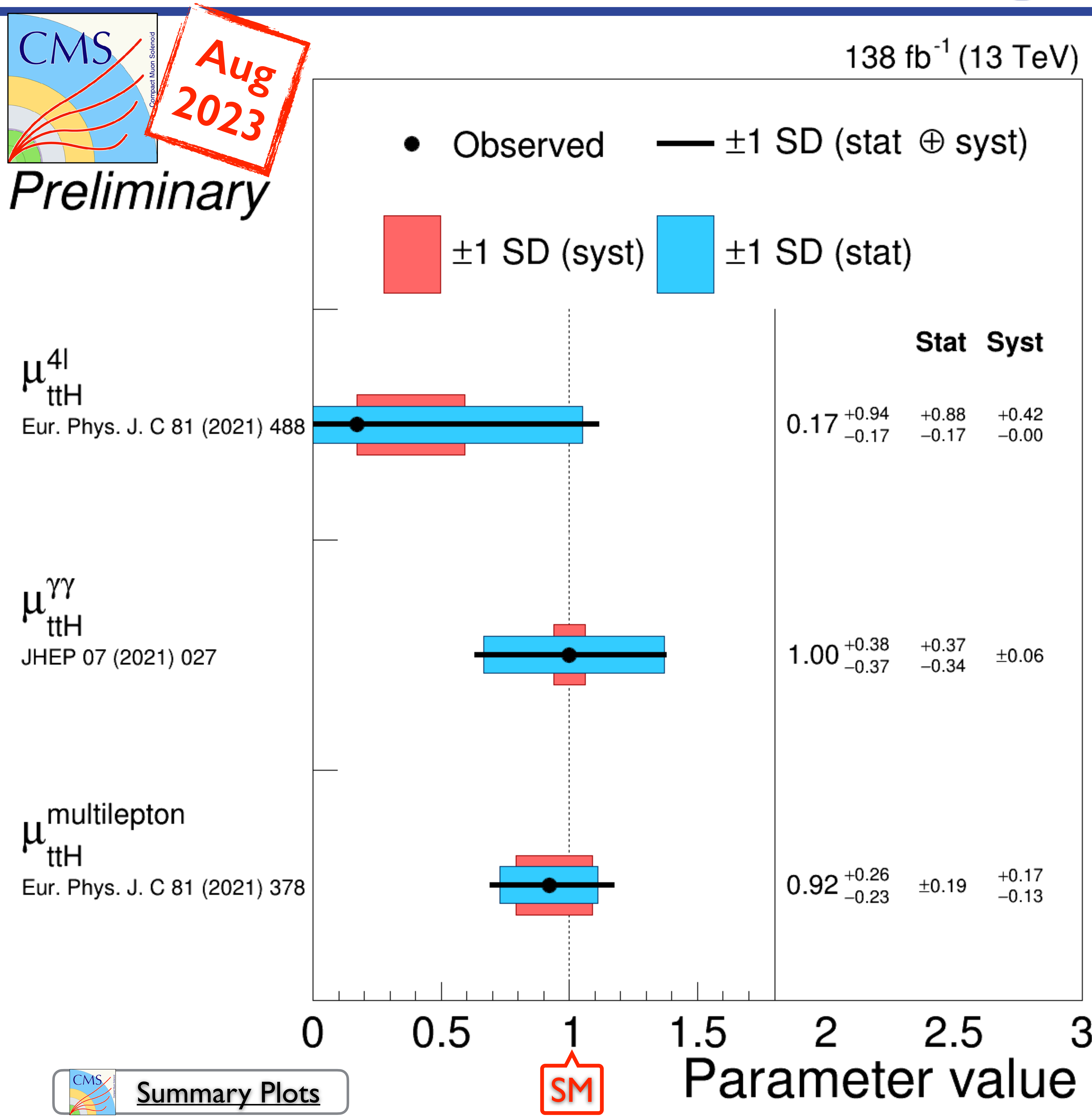
ttH Production



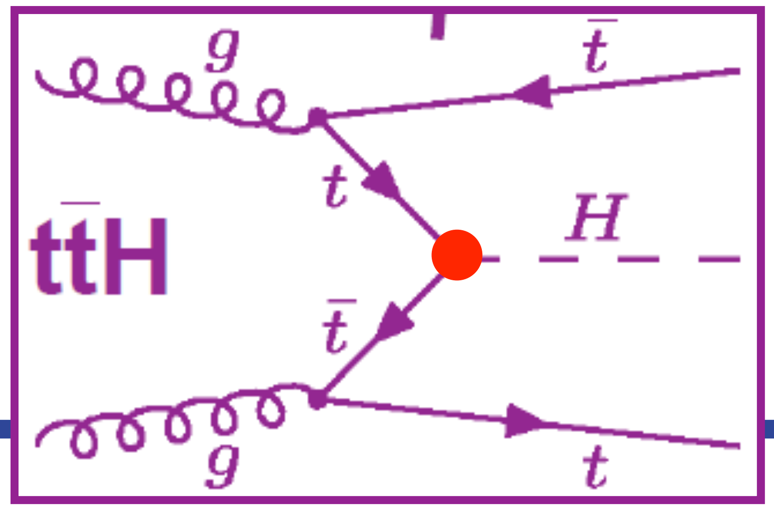
- Tree-level **top-Yukawa** measurement



JHEP 07 (2021) 027

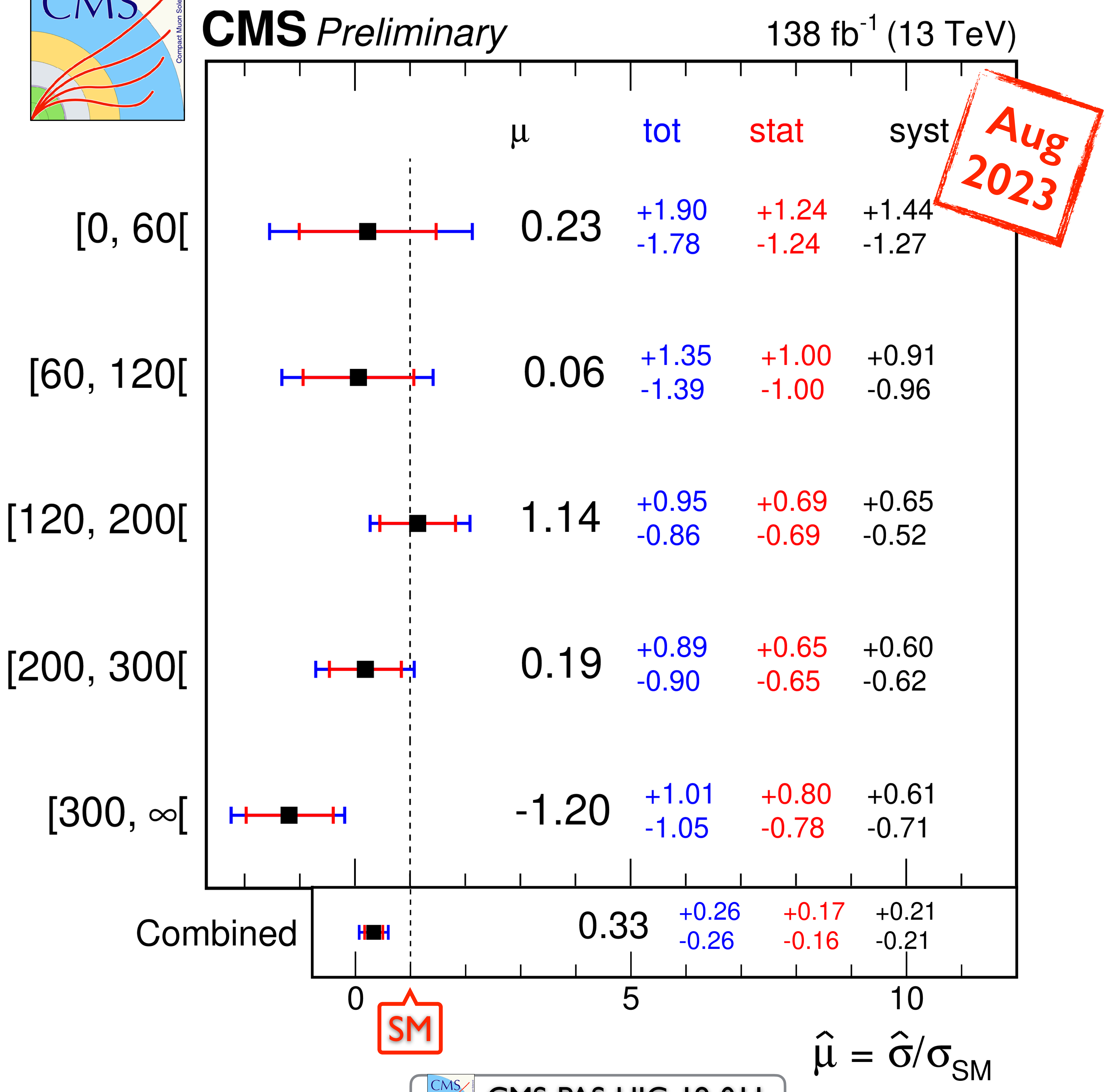


Summary Plots

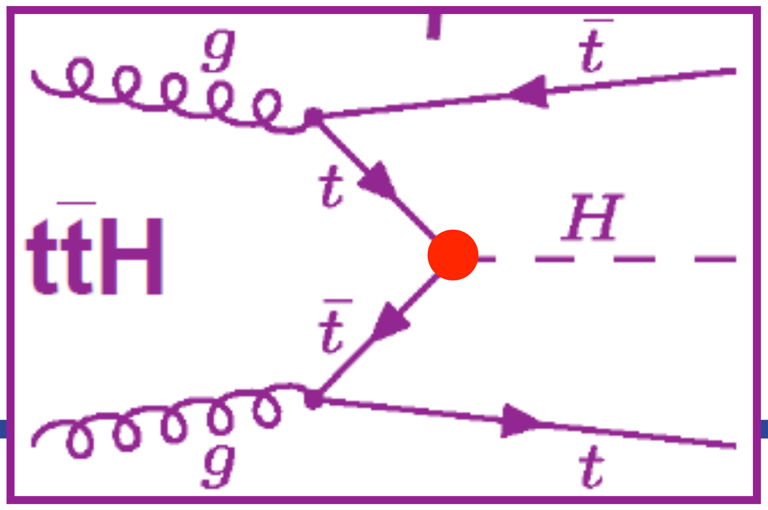


ttH, H → $b\bar{b}$

- Tree-level **top-Yukawa** measurement
  - Very difficult to predict and model dominant ttbb background
  - **CMS** obs. (exp.) significance: **1.3 (4.1)** σ



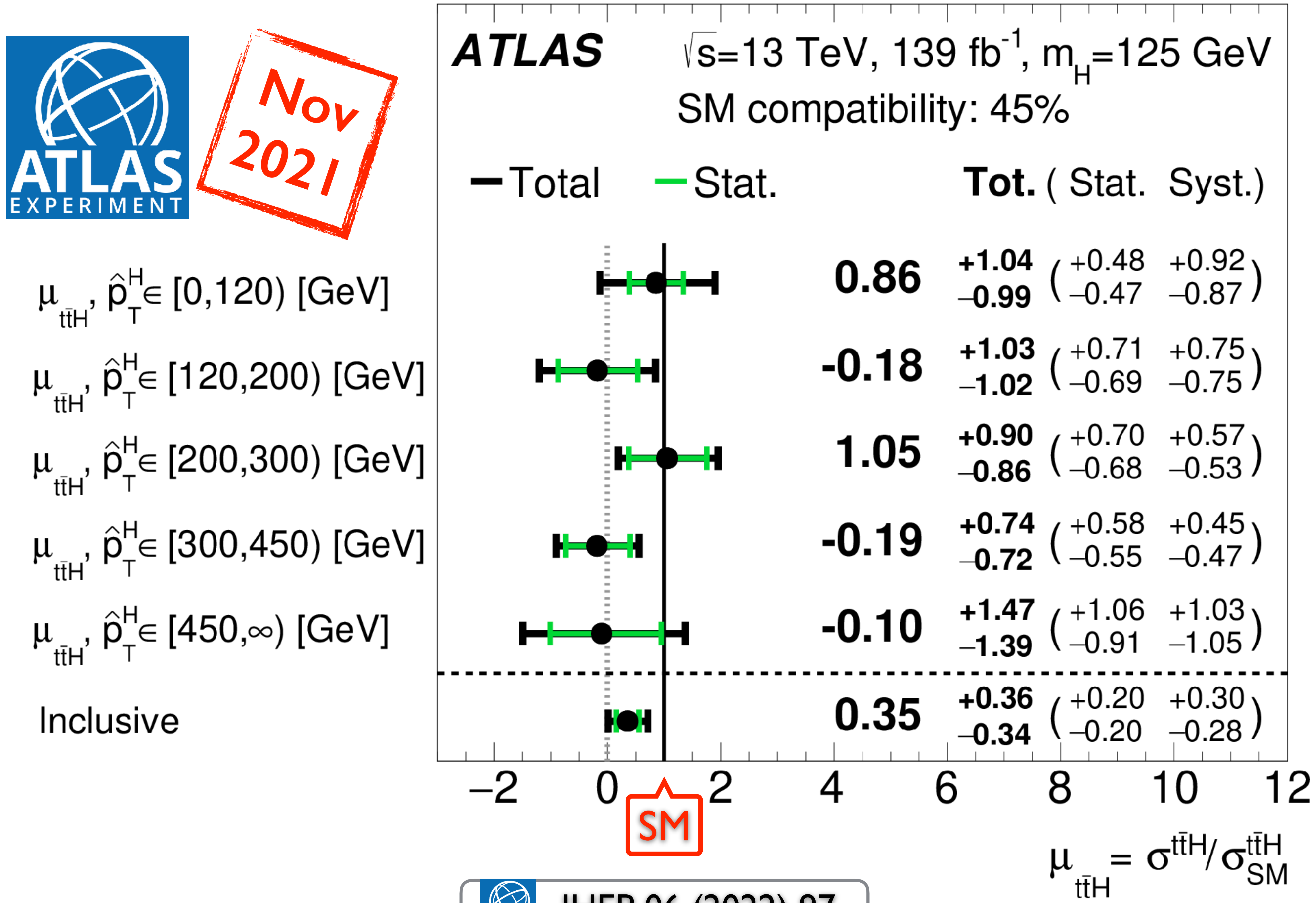
CMS-PAS-HIG-19-011



ttH, H → bb̄

- Tree-level **top-Yukawa** measurement
  - Very difficult to predict and model dominant ttbb background
  - **CMS** obs. (exp.) significance: **1.3 (4.1) σ**
  - **ATLAS** obs. (exp.) significance: **1.0 (2.7) σ**

Nov 2021



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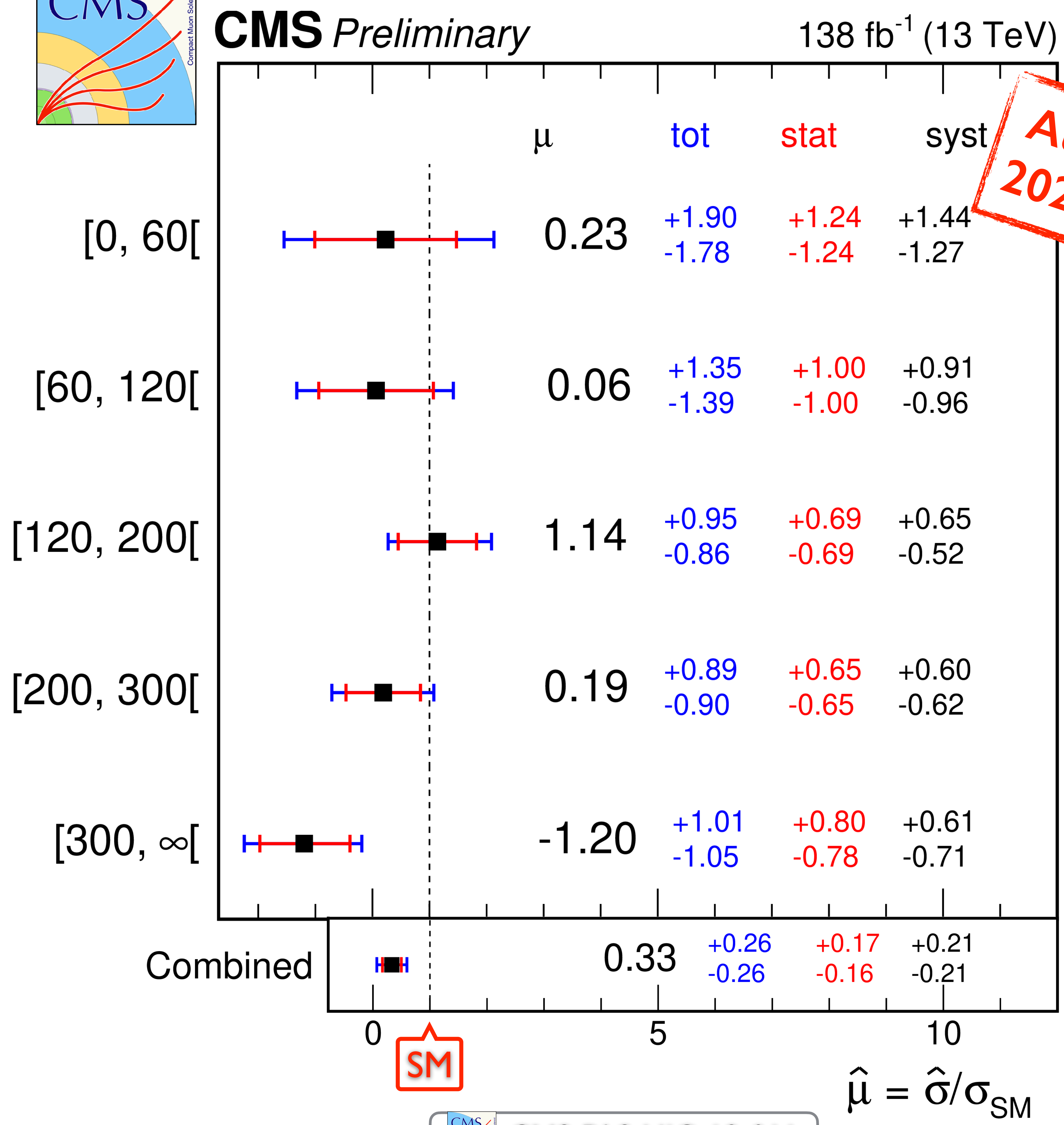
Aug 2023

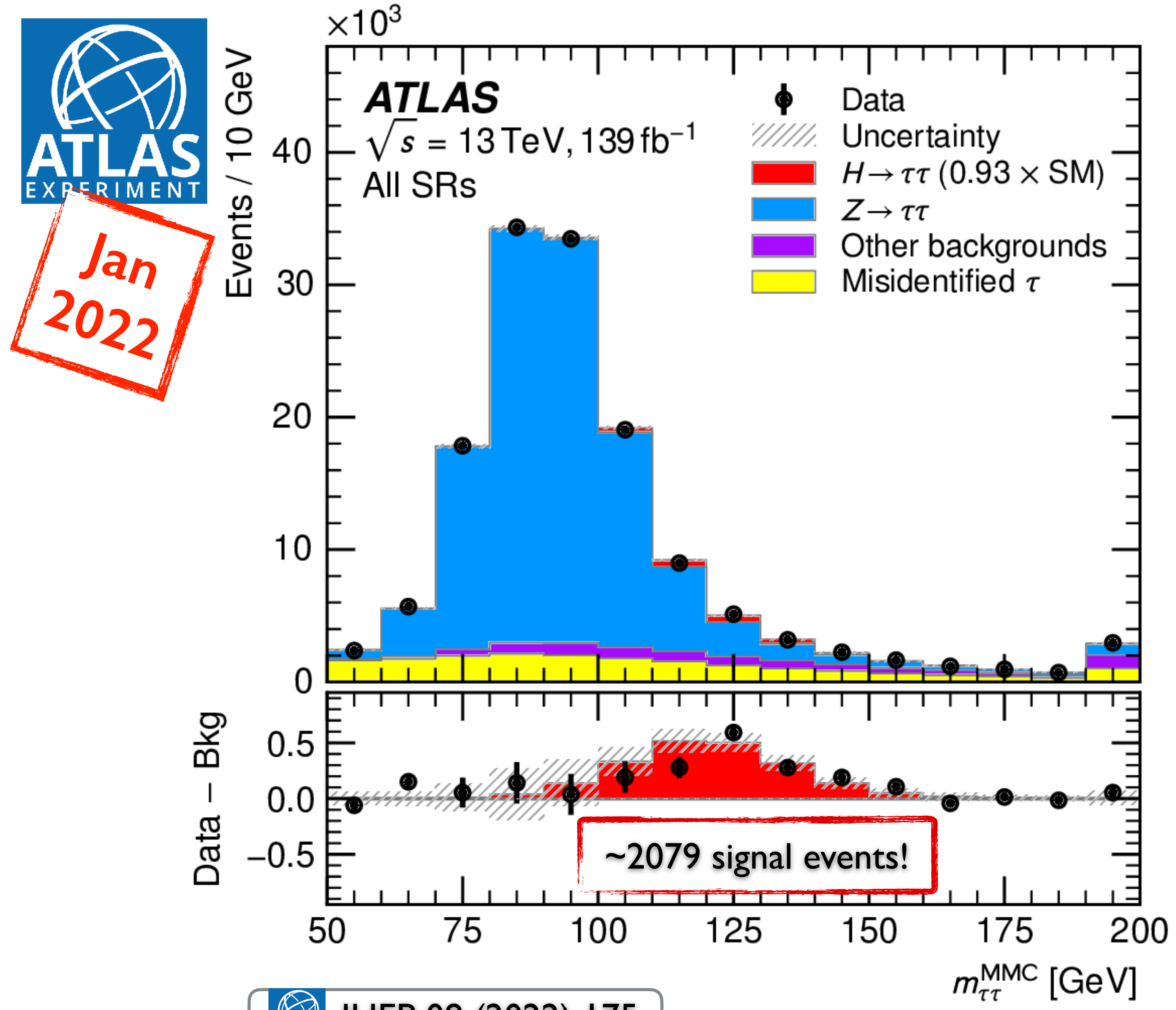


CMS-PAS-HIG-19-011

$H \to \tau\tau$

- Strongest coupling to leptons
  - $BR_{SM}(H \to \tau\tau) = 6.3\%$

⇒ ~480 000 $H \to \tau\tau$ events in 139 fb^{-1}

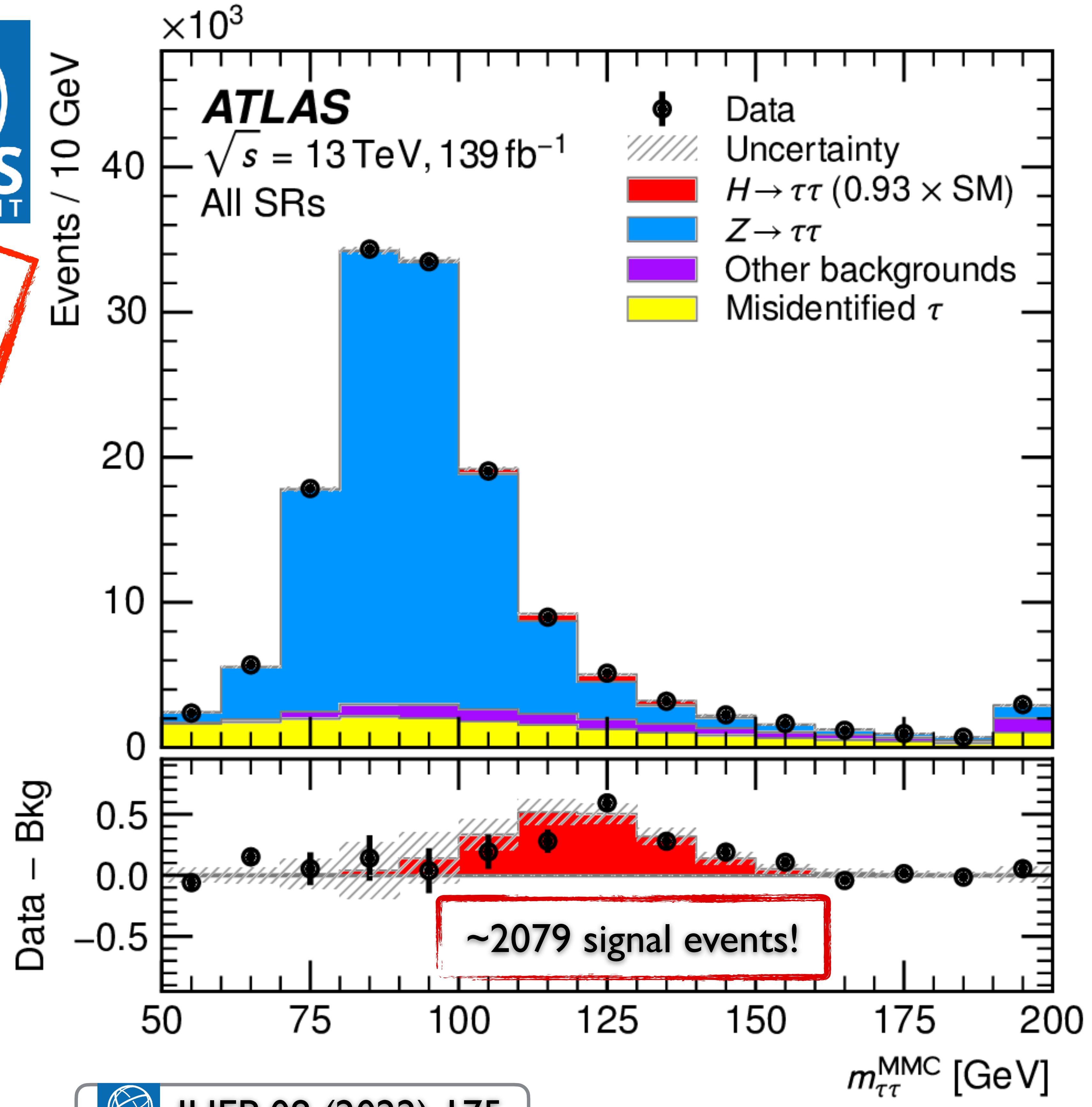


JHEP 08 (2022) 175

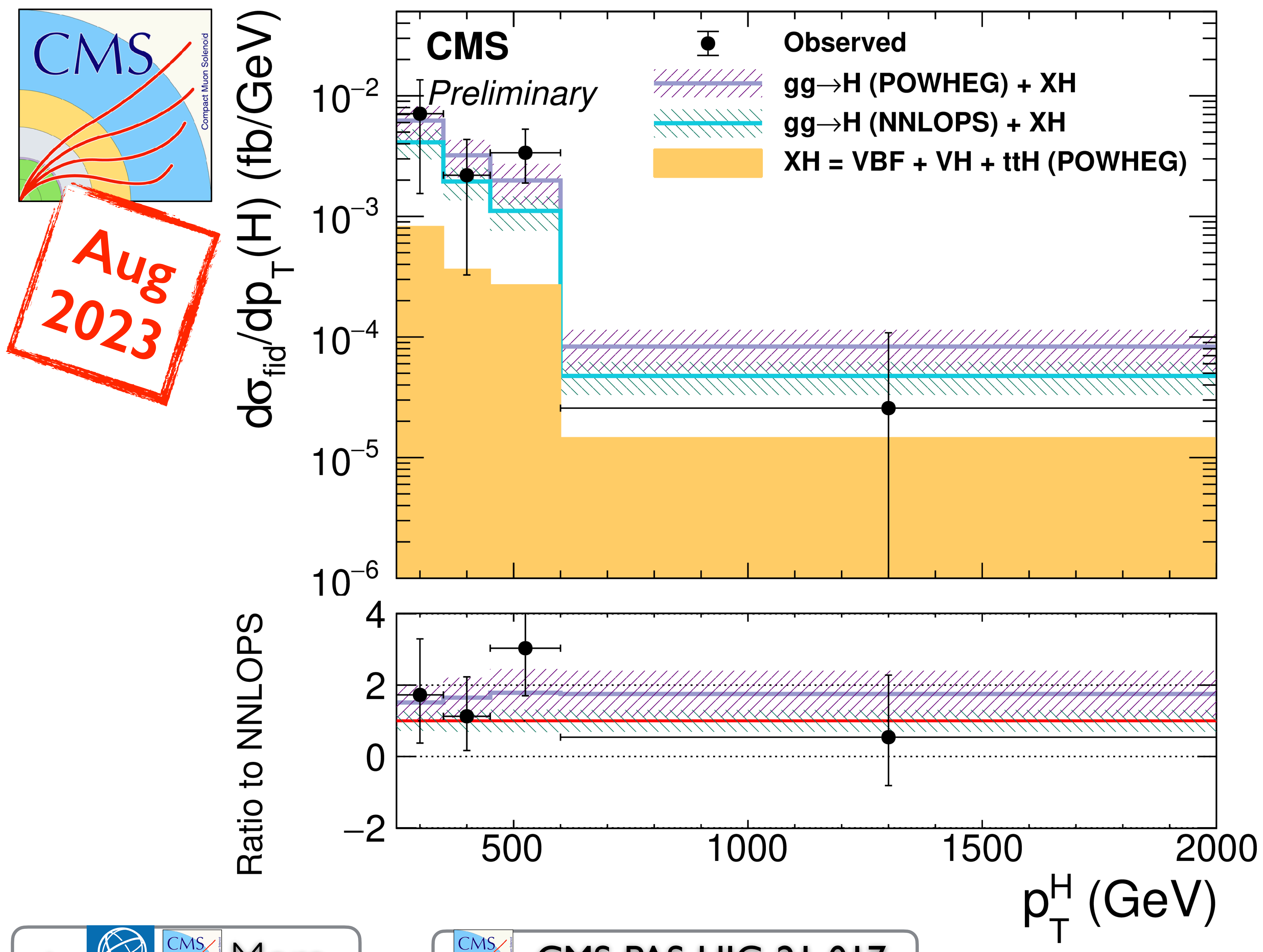
$H \to \tau\tau$

- Strongest coupling to leptons
  - $BR_{SM}(H \to \tau\tau) = 6.3\%$

$\Rightarrow$ **~480 000 $H \to \tau\tau$ events in 139 fb^{-1}**



- Highly boosted $p_T(H) > 250$ GeV
  - Dedicated boosted di-tau algorithm
- Observed (expected) significance: **3.5 (2.2) σ**
- $\mu = 1.64^{+0.68}_{-0.54}$



JHEP 08 (2022) 175

⇒ More
CMS-PAS-HIG-21-017

Outline

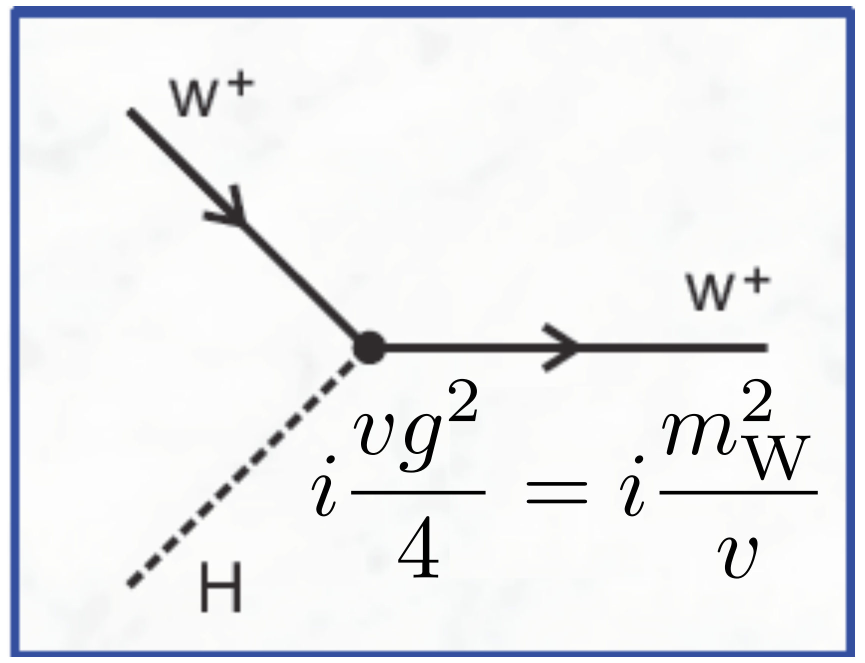
$$\mathcal{L}_{\text{Higgs}} = (D_\mu\phi)^2 - \mu^2\phi^2 - \lambda\phi^4 + \lambda_f\phi\bar{\psi}\psi$$

4. Rare decays

- 2nd generation
- Loop-induced

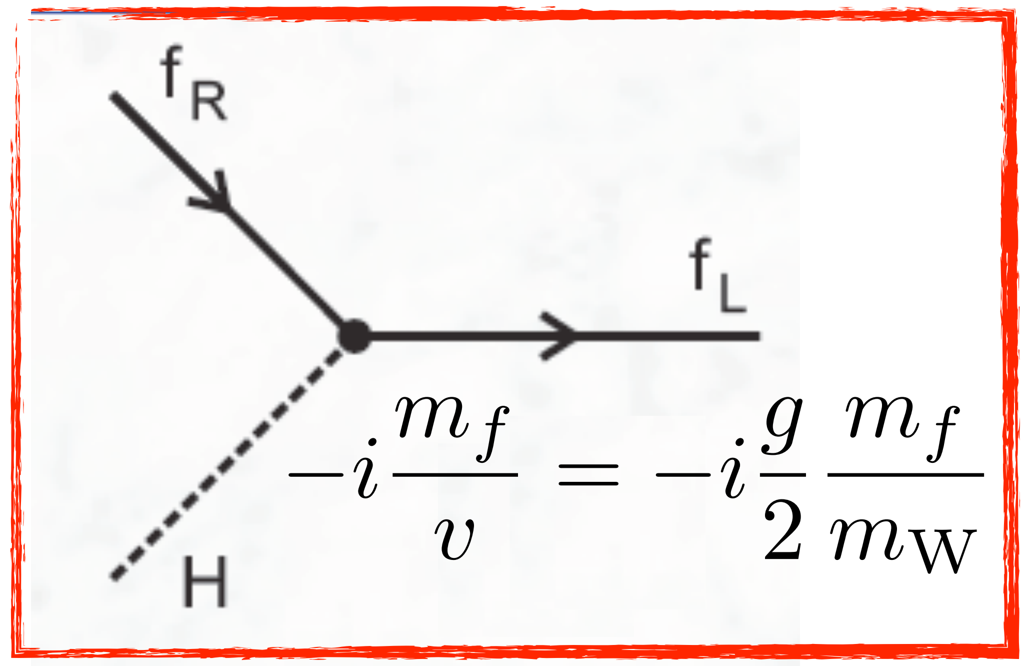
$$m_W = \frac{vg}{2}$$

direct connection



$$m_f = \frac{\lambda_f v}{\sqrt{2}}$$

direct connection



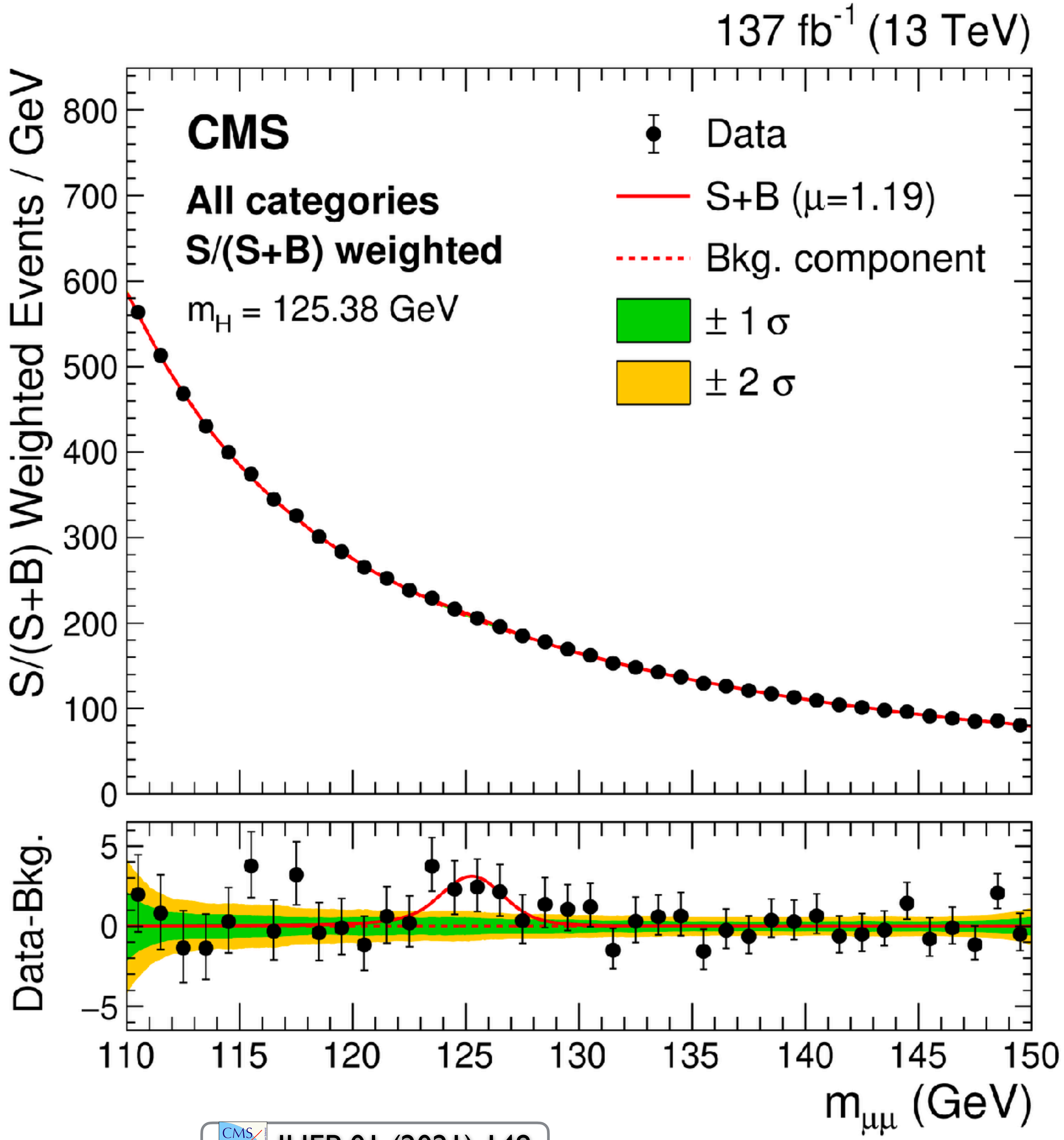
(*) simplified

H → μμ

- SM branching ratio:
  - $BR_{SM}(H \rightarrow \mu\mu) = 2.18 \times 10^{-4}$

⇒ **~1700 H → μμ events in 137 fb^{-1}**, huge $Z/\gamma^* \rightarrow \mu\mu$ background

- Results:
  - Signal strength $\mu = 1.19^{+0.44}_{-0.42}$
  - Observed (expected) significance: **3.0 (2.5) σ**



JHEP 01 (2021) 148

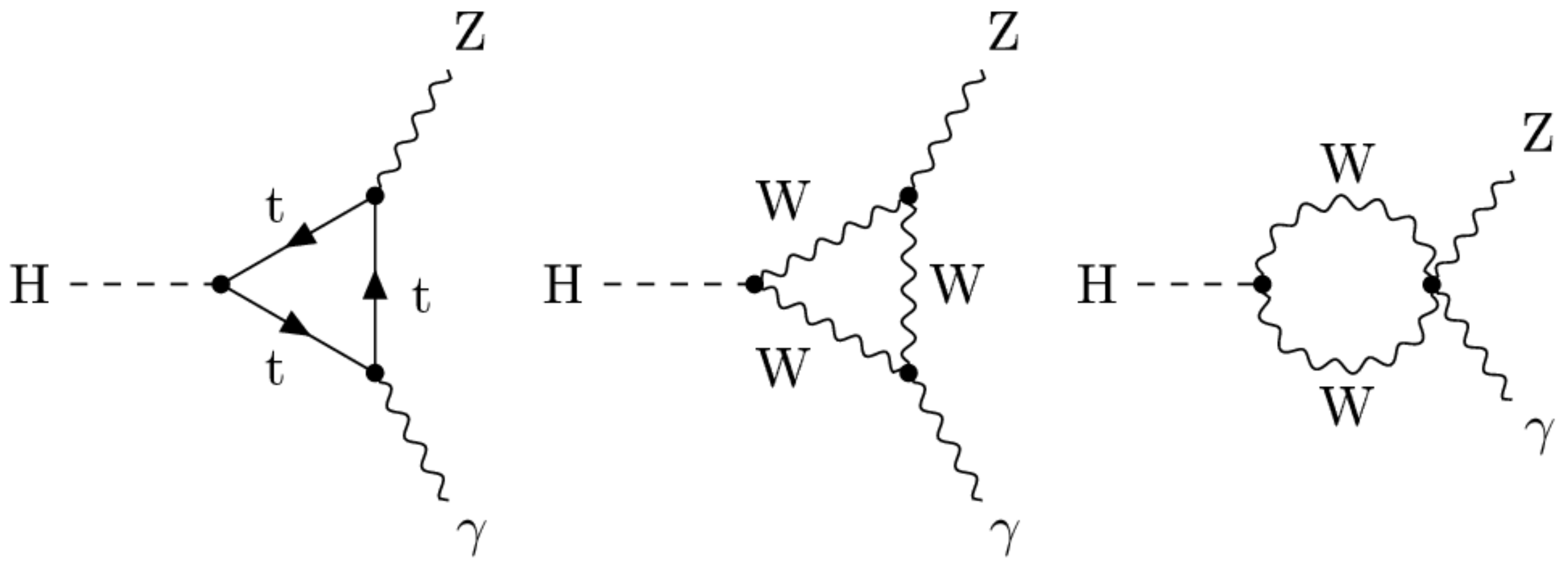
Phys. Lett. B 812 (2021) 135980

ATLAS result:
- Signal strength μ =**1.2 ± 0.6**
- Observed (expected) significance: **2.0 (1.7) σ**
- Observed (expected) upper limit on BR: **2.2 (1.1) × SM** (95% C.L.)

$H \rightarrow Z\gamma$

- **Small $BR_{SM}(H \rightarrow Z\gamma) \approx 0.15\%$**
  - $BR_{SM}(Z \rightarrow \ell\ell) \approx 3.4\%$

    $\Rightarrow BR_{SM}(H \rightarrow Z\gamma \rightarrow \ell\ell\gamma) = \mathbf{0.01\%}$



$\Rightarrow$ **~765 $H \rightarrow Z\gamma \rightarrow \ell\ell\gamma$ events in 140 fb^{-1}**

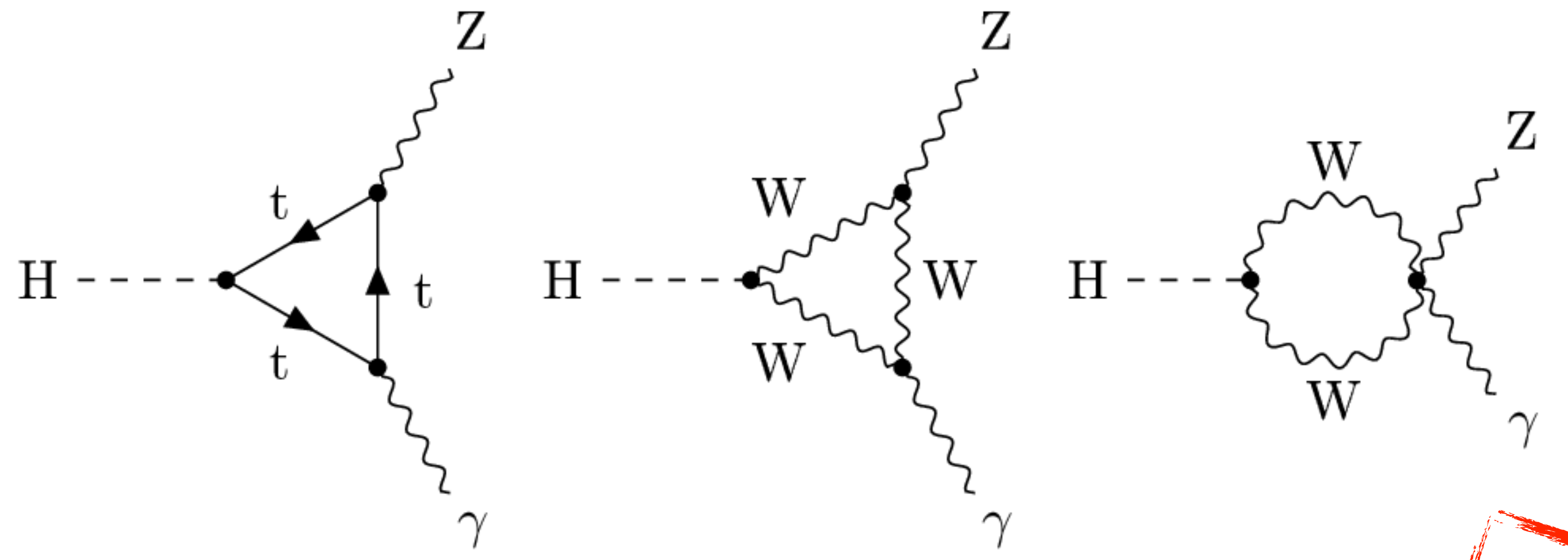
and difficult kinematics

 (ℓ = electron or muon)

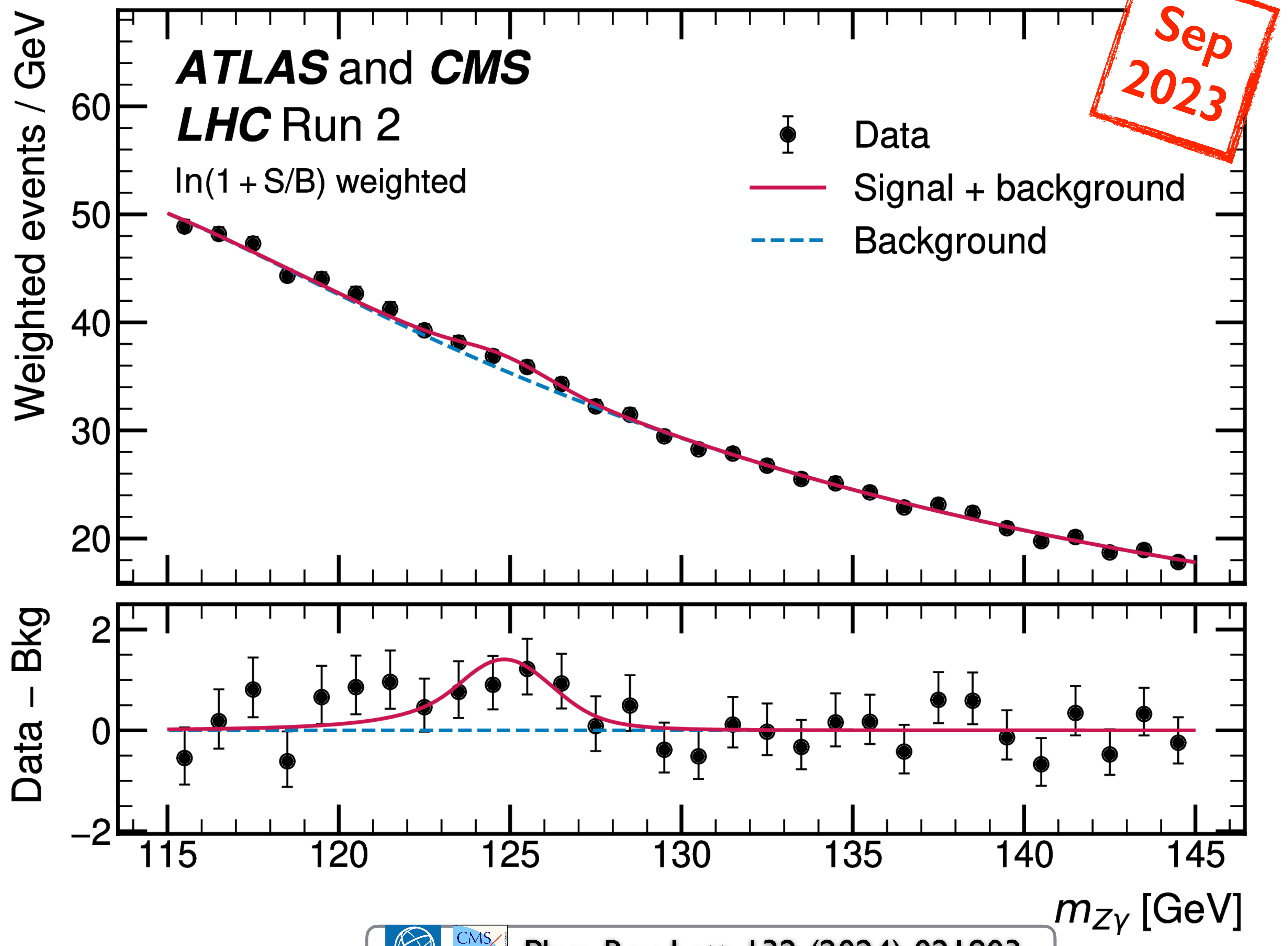
$H \rightarrow Z\gamma$

- **Small $BR_{SM}(H \rightarrow Z\gamma) \approx 0.15\%$**
  - $BR_{SM}(Z \rightarrow \ell\ell) \approx 3.4\%$
    $\Rightarrow BR_{SM}(\mathbf{H} \rightarrow Z\gamma \rightarrow \ell\ell\gamma) =$ **0.01%**

$\Rightarrow$ **~765 $H \rightarrow Z\gamma \rightarrow \ell\ell\gamma$ events in 140 fb^{-1}**
and difficult kinematics



- First evidence from ATLAS+CMS combination:
  - Observed signal strength $\mu = 2.2 \pm 0.7$
  - Observed (expected) significance: $3.4\,\sigma$ ($1.6\,\sigma$)



$\Rightarrow$ ATLAS $H \rightarrow \ell\ell\gamma$ result: obs. (exp.): $3.2\,\sigma$ ($2.1\,\sigma$)

Phys. Rev. Lett. 132 (2024) 021803

(ℓ = electron or muon)

Outline

$$\mathscr{L}_{\text{Higgs}} = (D_\mu\phi)^2 - \mu^2\phi^2 - \boxed{\lambda\phi^4} + \lambda_f\phi\bar{\psi}\psi$$

5. HH

HH production

In SM: $\lambda = \frac{1}{2}m_{\mathrm{H}}^2/v^2$

$\mu^2\left(\phi^\dagger\phi\right) + \lambda\left(\phi^\dagger\phi\right)^2$

H potential as in SM?

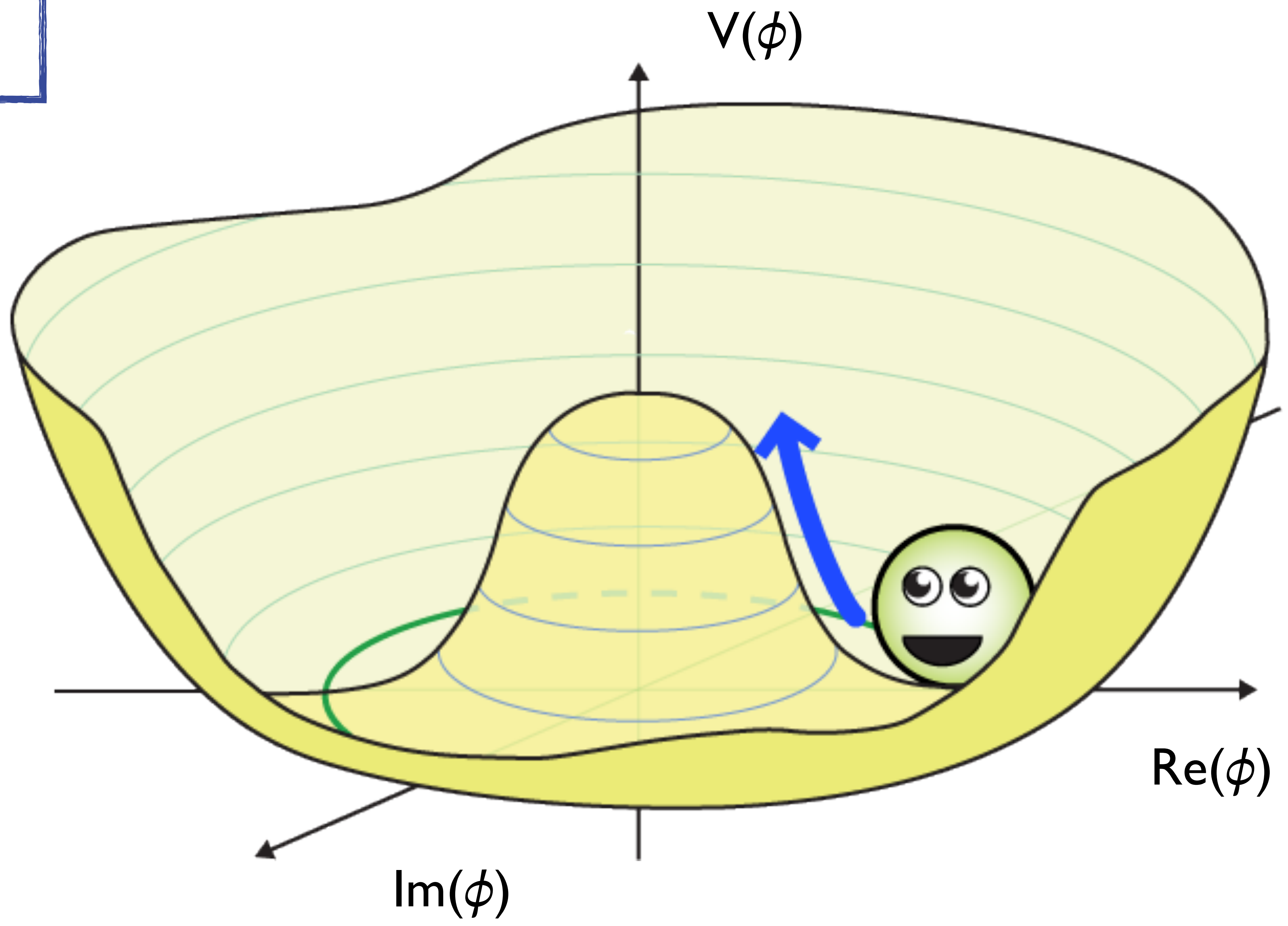
(*) simplified

HH Production

- Map out Higgs potential

H self interactions

$$\mathscr{L} \ni -\lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4} H^4$$



arXiv:1401.7340

HH Production

- Map out Higgs potential

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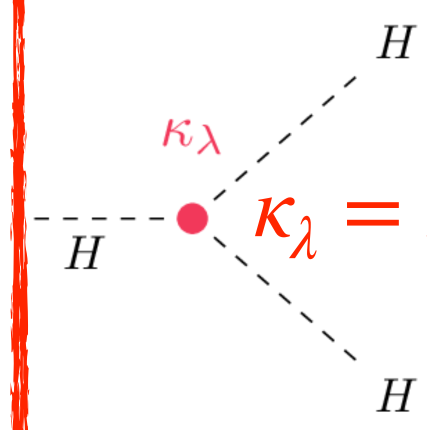
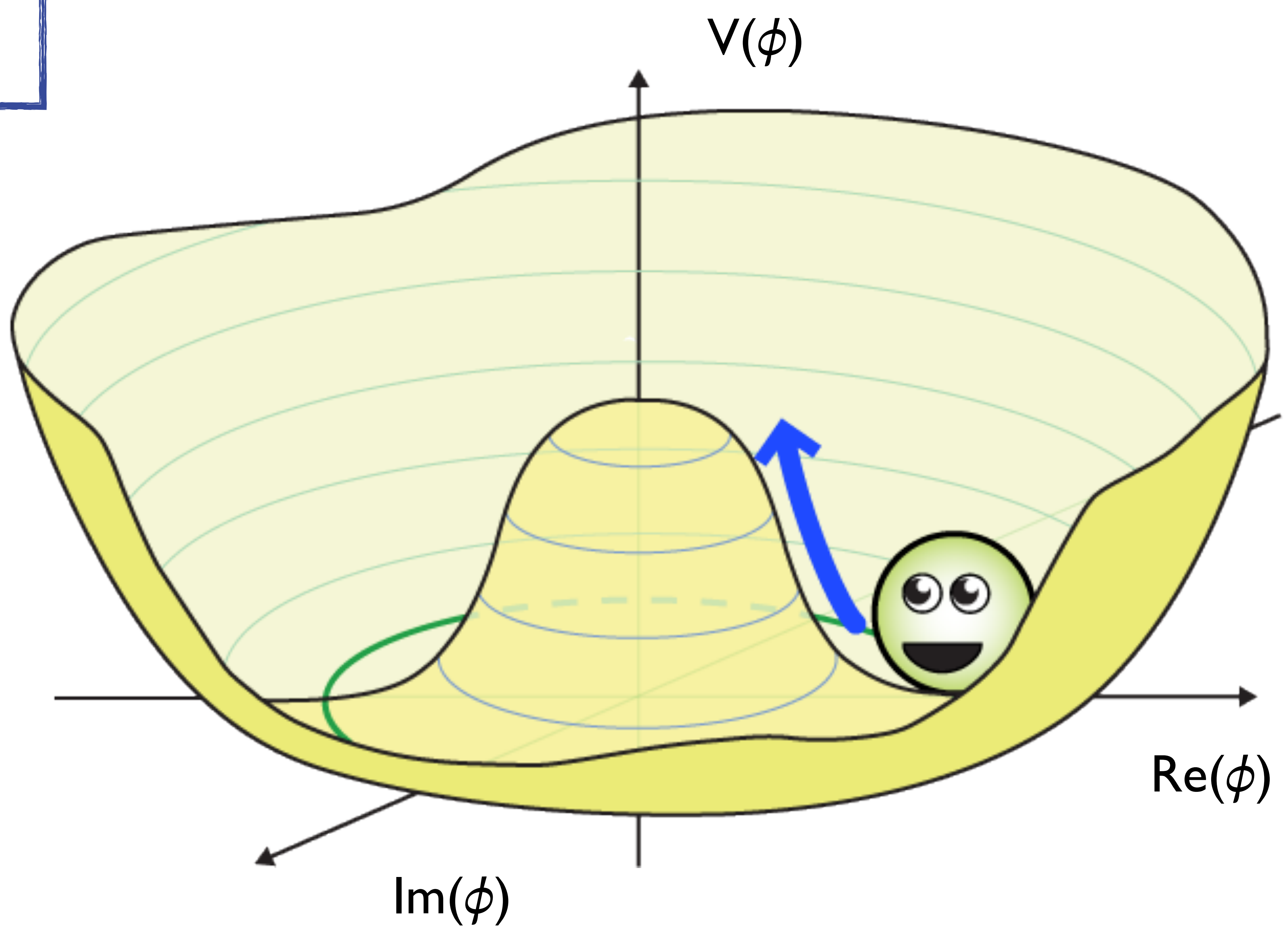


$\kappa_\lambda = \lambda/\lambda_{SM}$



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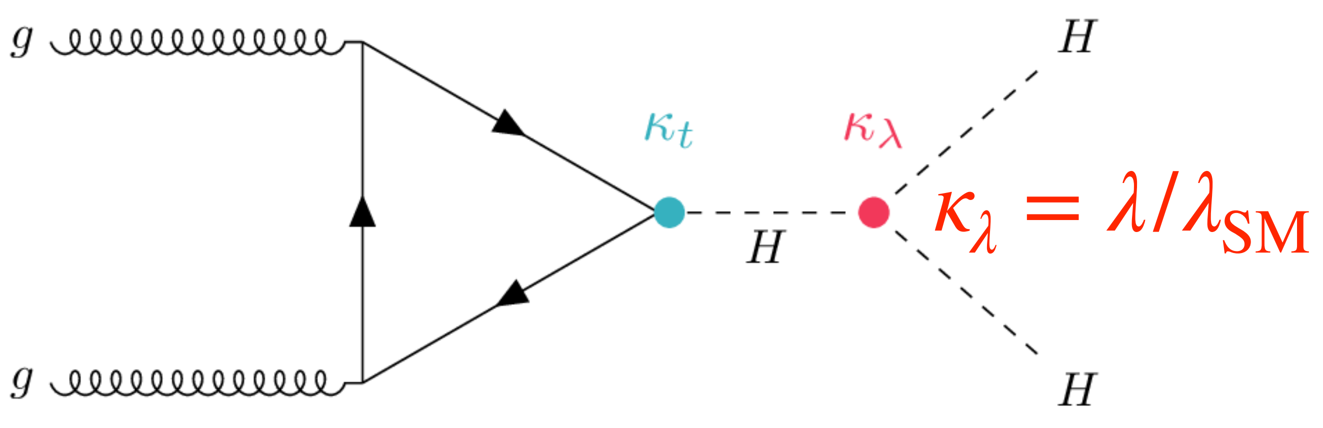

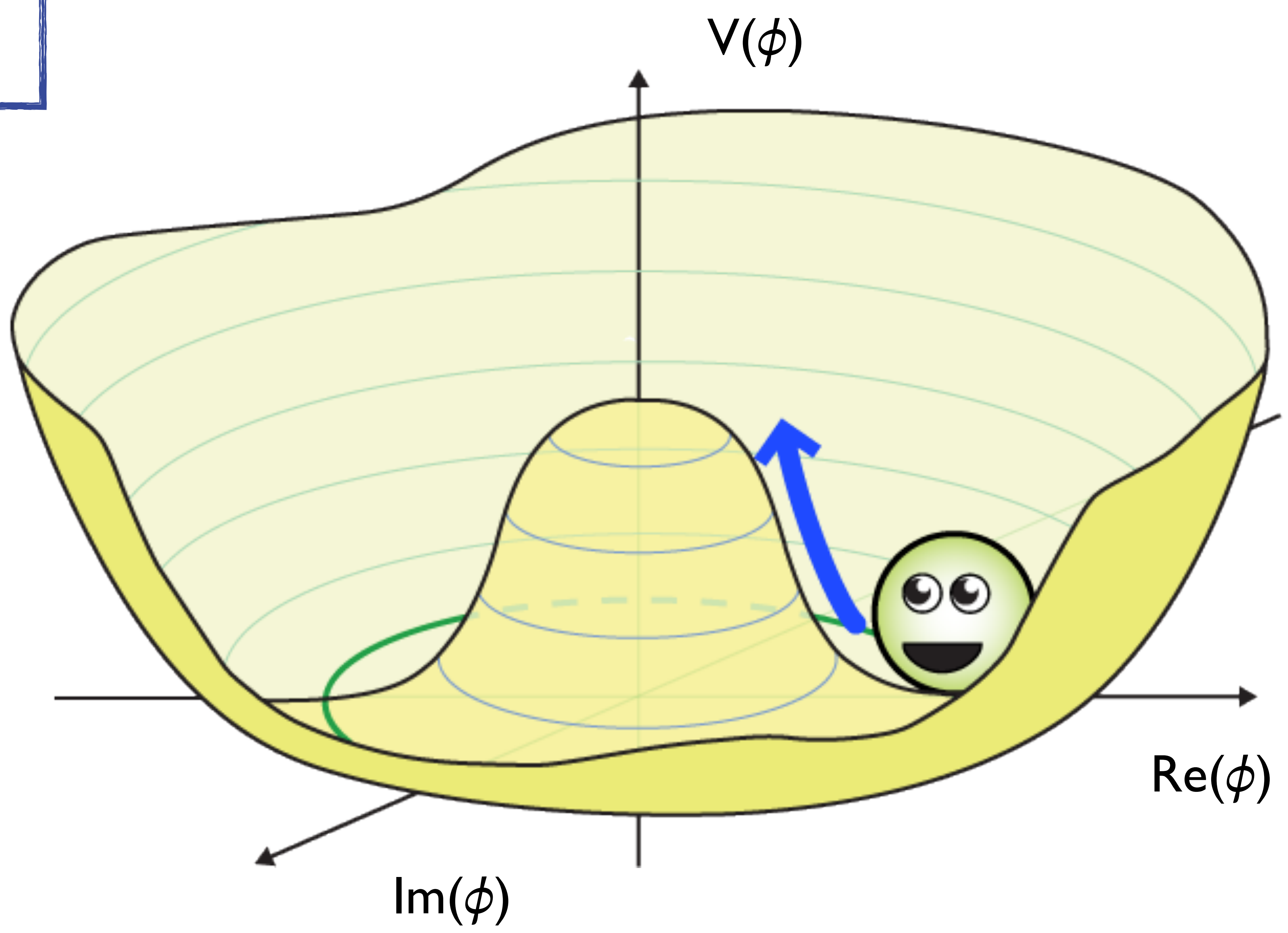

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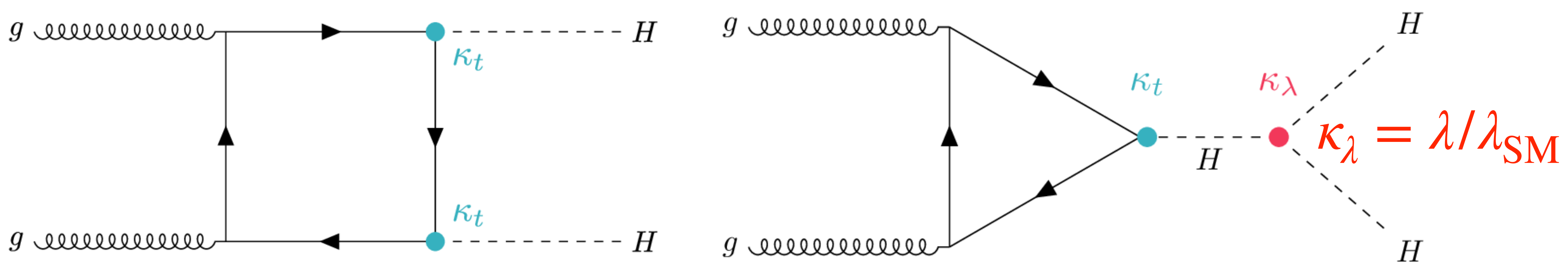
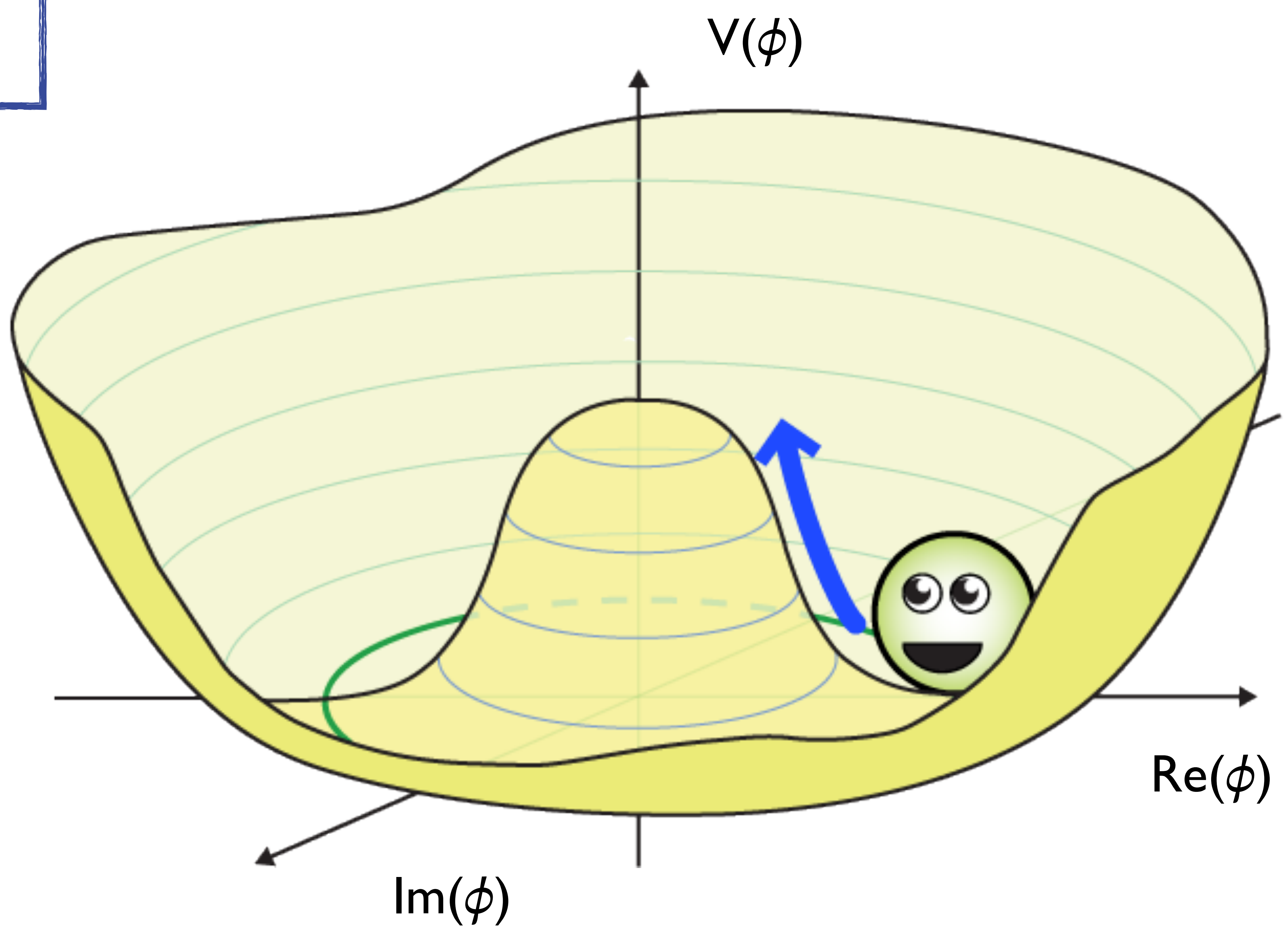




arXiv:1401.7340

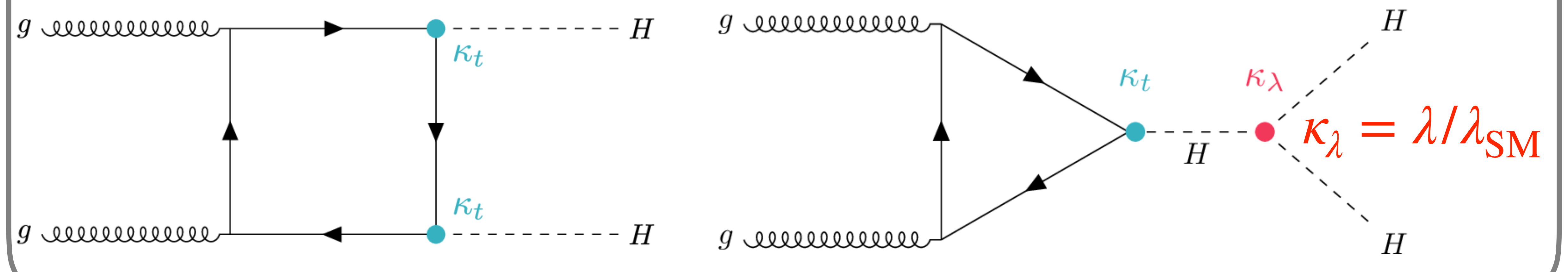
HH Production

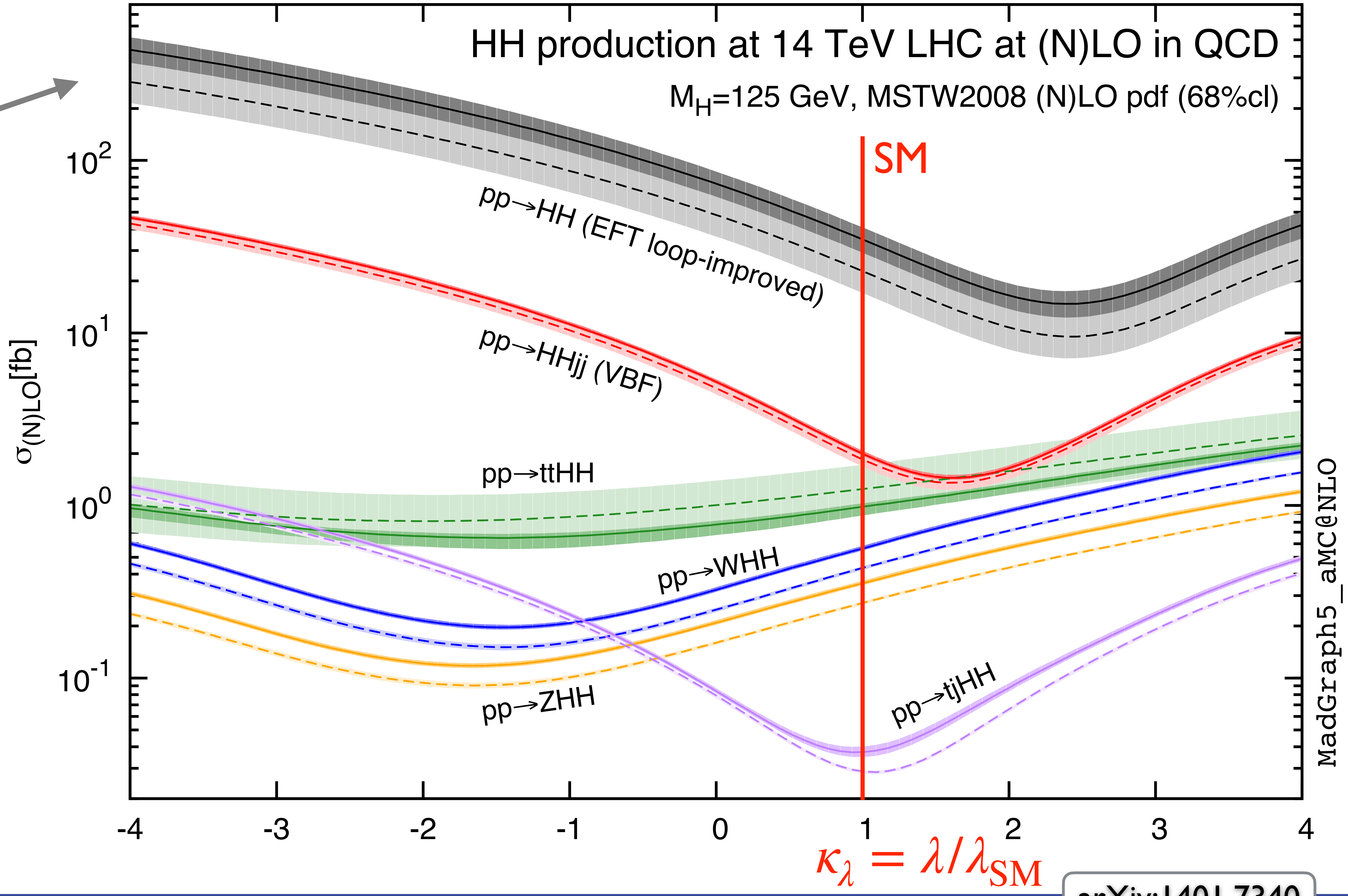
- Map out Higgs potential

H self interactions

$$\mathscr{L} \ni -\lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4} H^4$$

$\sigma(gg \to HH) = 31.05$ fb ⇒ ~4300 events in 140 fb^{-1}





arXiv:1401.7340

HH Production

- Map out Higgs potential

H self interactions

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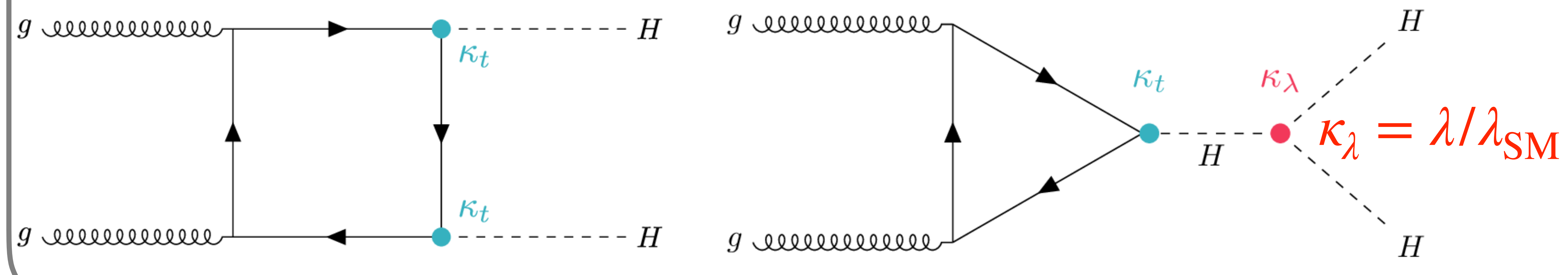
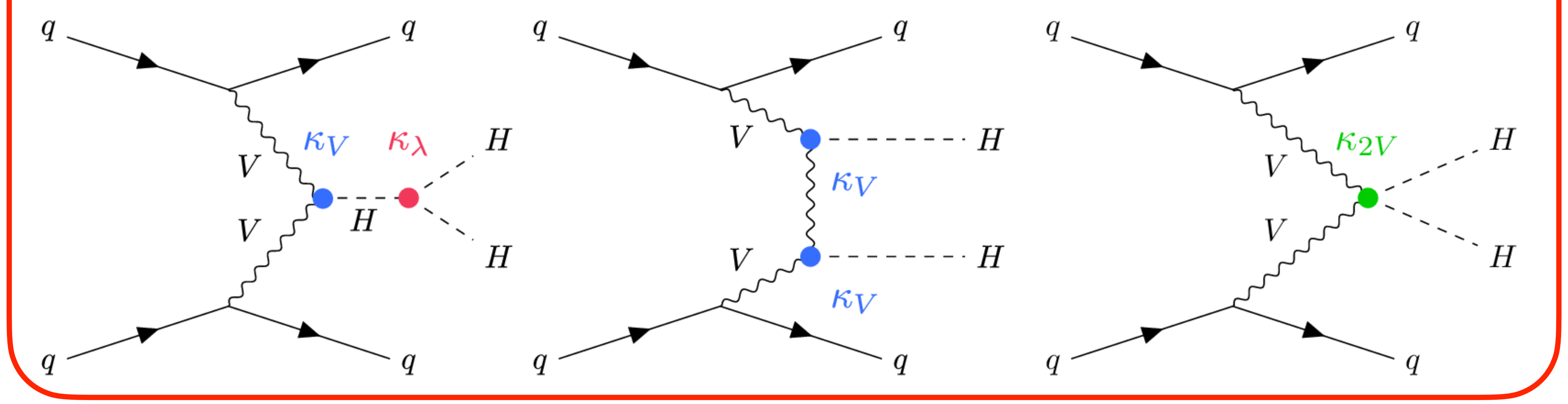
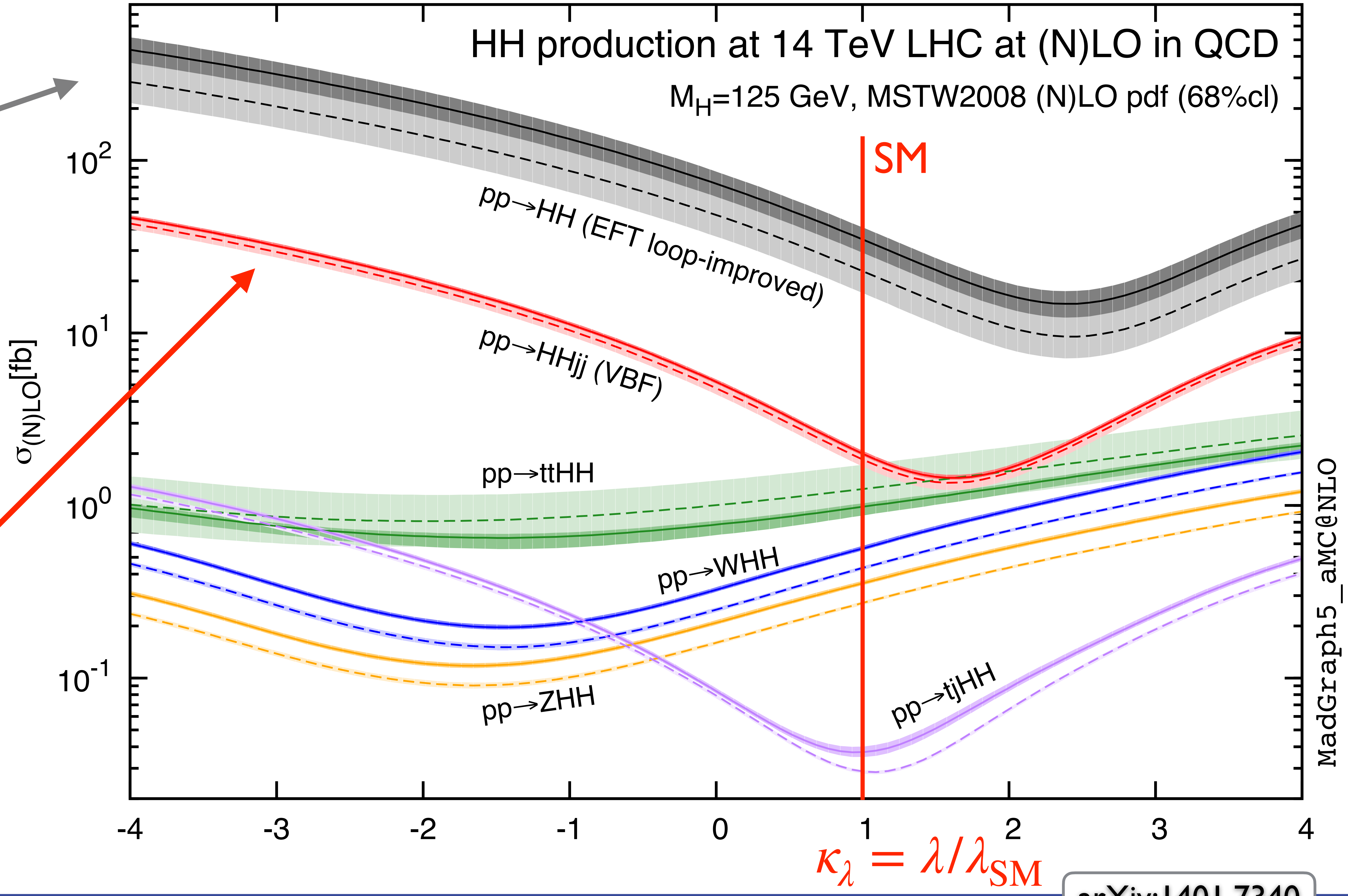
σ(gg → HH) = 31.05 fb ⇒ ~4300 events in 140 fb^{-1}



σ(VBF HH) = 1.726 fb ⇒ ~240 events in 140 fb^{-1}





arXiv:1401.7340

Di-Higgs Decays and Results

	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.3%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

- "Large" BR & clean signatures:
  - BR_{SM}(**HH → bbbb**) = 33% ⇒ **~1430** events in 140 fb^{-1}
  - BR_{SM}(**HH → bbττ**) = 7.3% ⇒ **~320** events in 140 fb^{-1}
  - BR_{SM}(**HH → bbγγ**) = 0.26% ⇒ **~11** events in 140 fb^{-1}

Di-Higgs Decays and Results

	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.3%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

- "Large" BR & clean signatures:
  - BR_{SM}(**HH → bbbb**) = 33% ⇒ **~1430** events in 140 fb^{-1}
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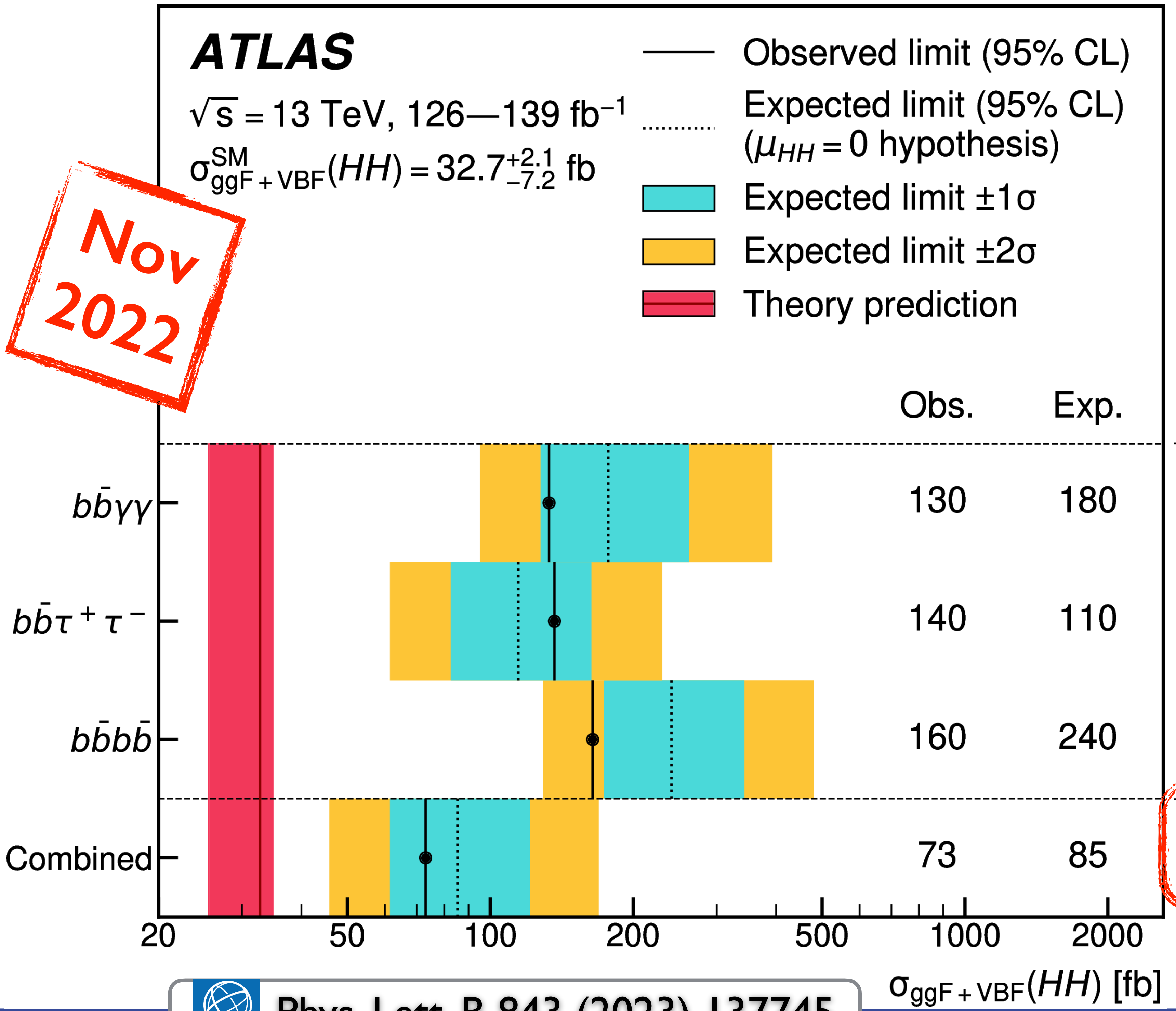
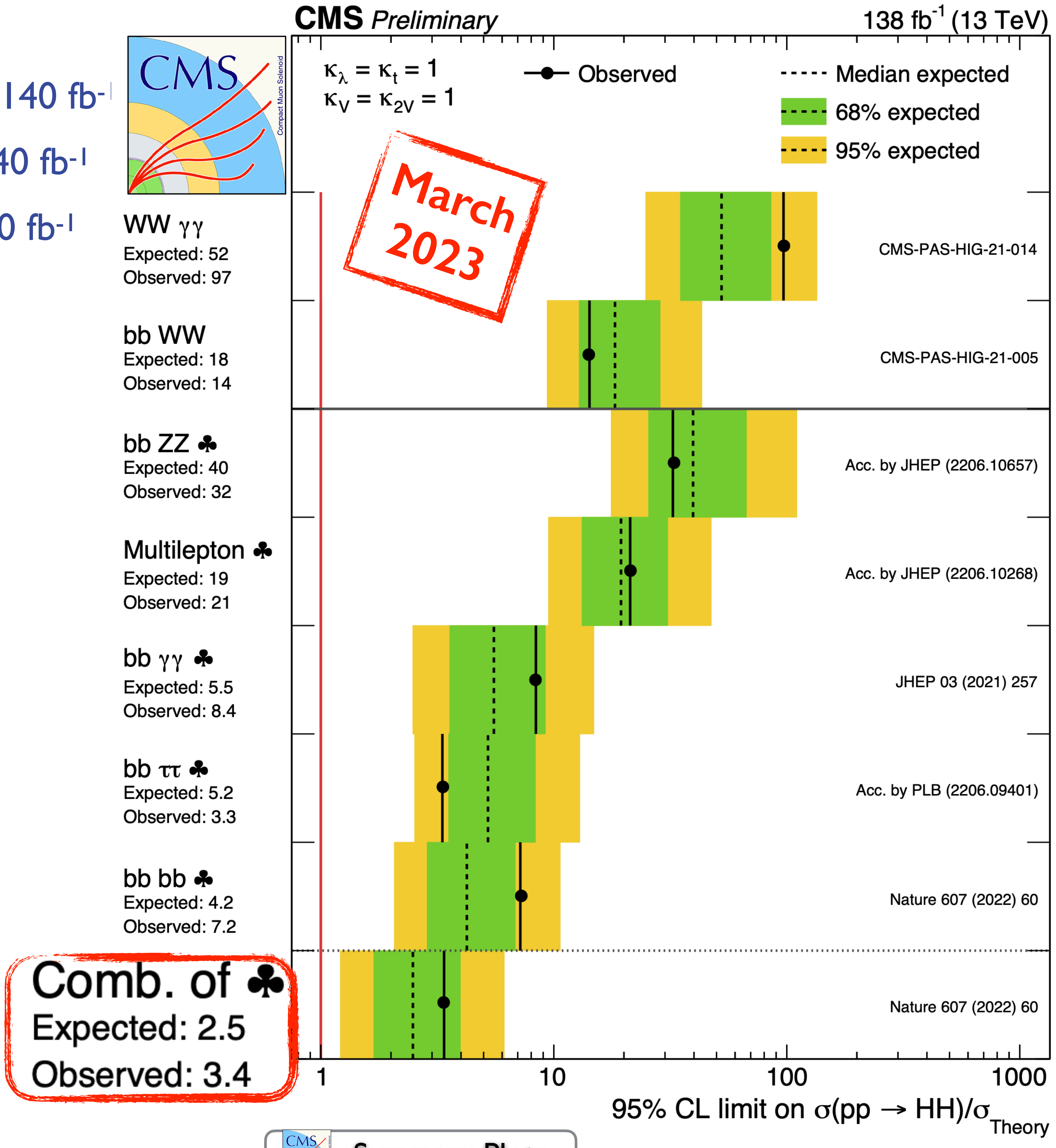


Signal strength μ

	Obs.	Exp.
bb̄γγ	4.2	5.7
bb̄τ⁺τ⁻	4.7	3.9
bb̄bb̄	5.4	8.1
Combined	2.4	2.9



Phys. Lett. B 843 (2023) 137745

Summary Plots

Di-Higgs Decays and Results

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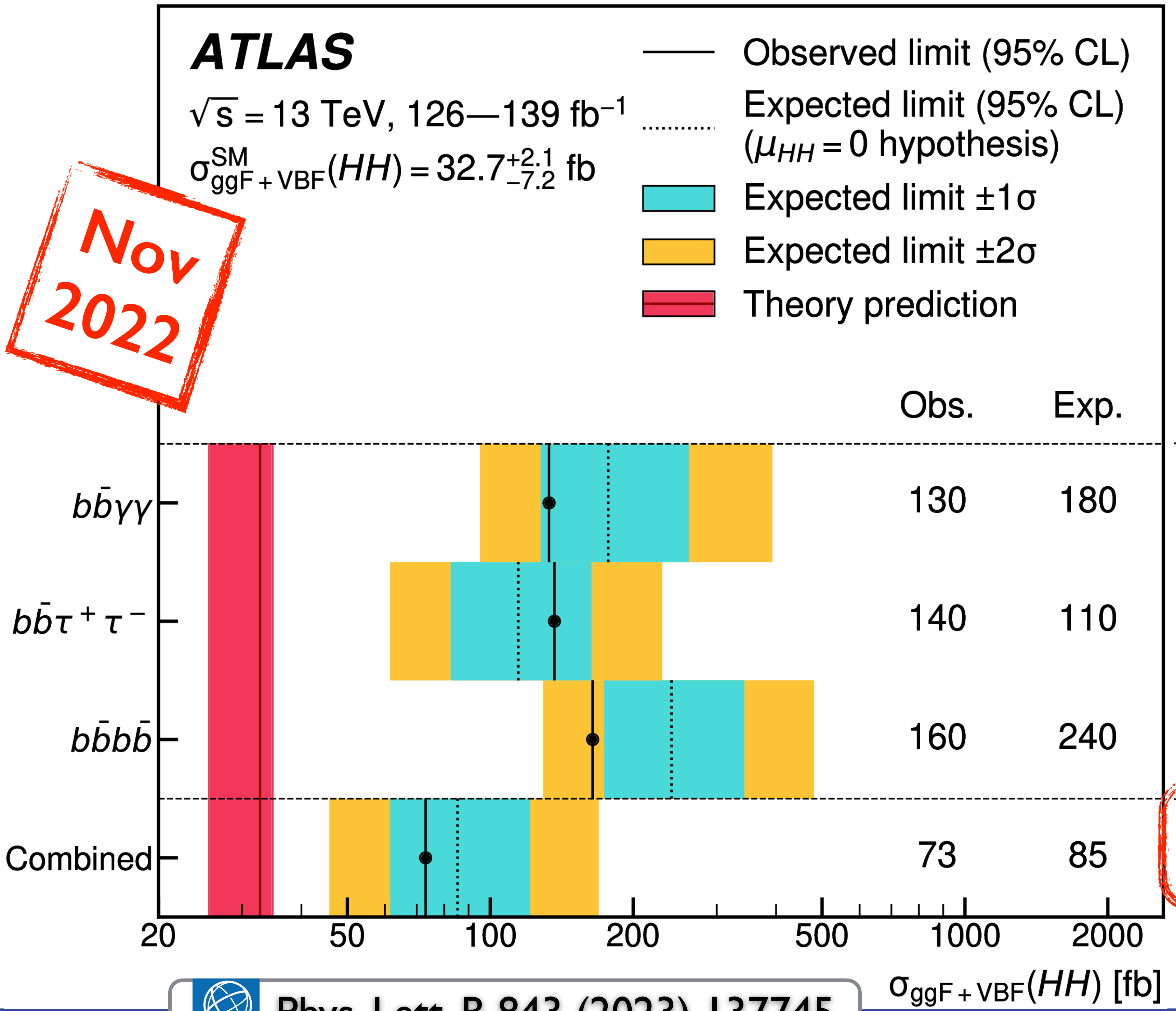
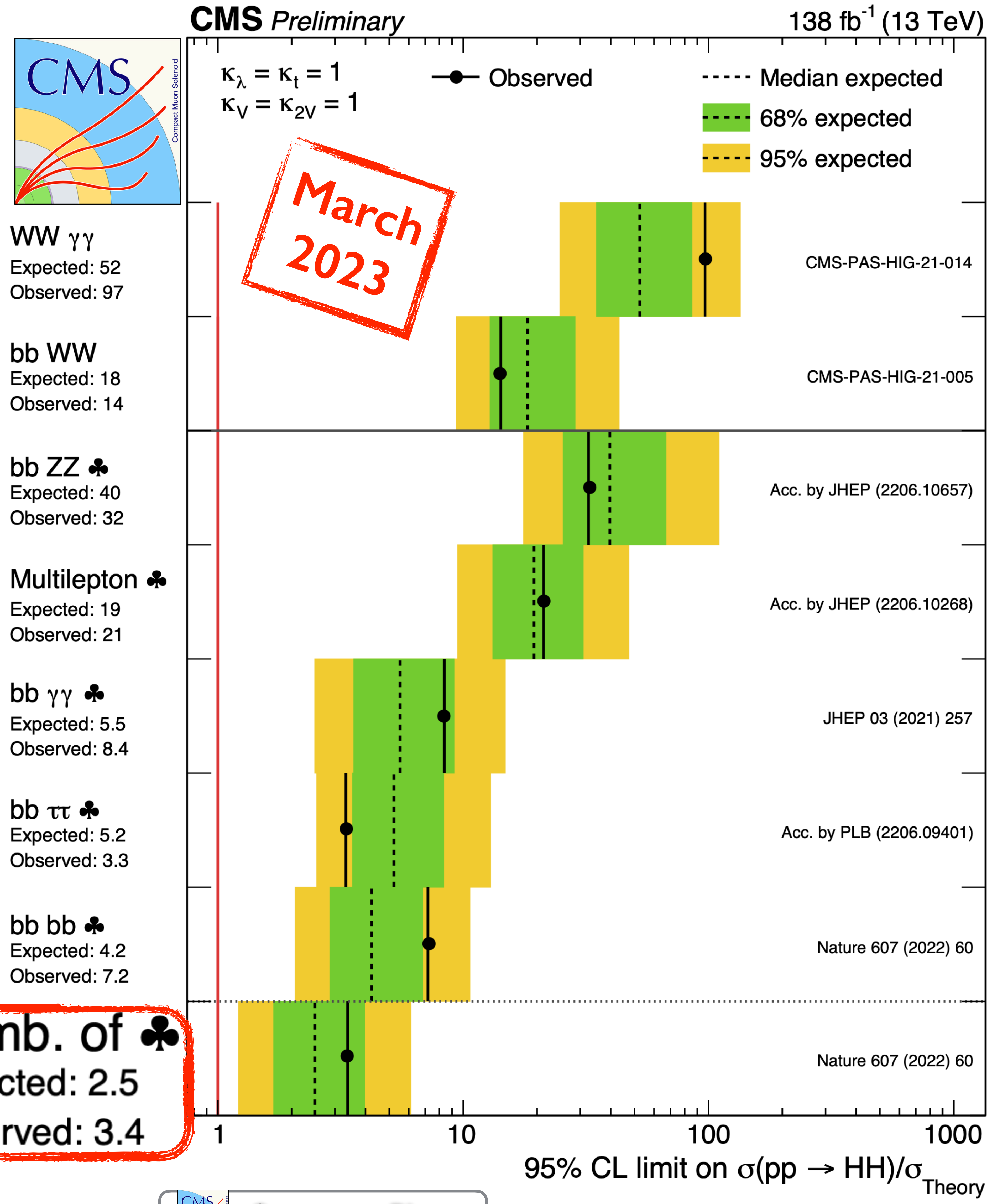


Signal strength μ

	Obs.	Exp.
$b\bar{b}\gamma\gamma$	4.2	5.7
$b\bar{b}\tau^+\tau^-$	4.7	3.9
$b\bar{b}b\bar{b}$	5.4	8.1
Combined	2.4	2.9

Improved results:

Obs.	Exp.	
4.0	5.0	Oct 2023 — JHEP 01 (2024) 066
5.9	3.3	April 2024 — arXiv:2404.12660



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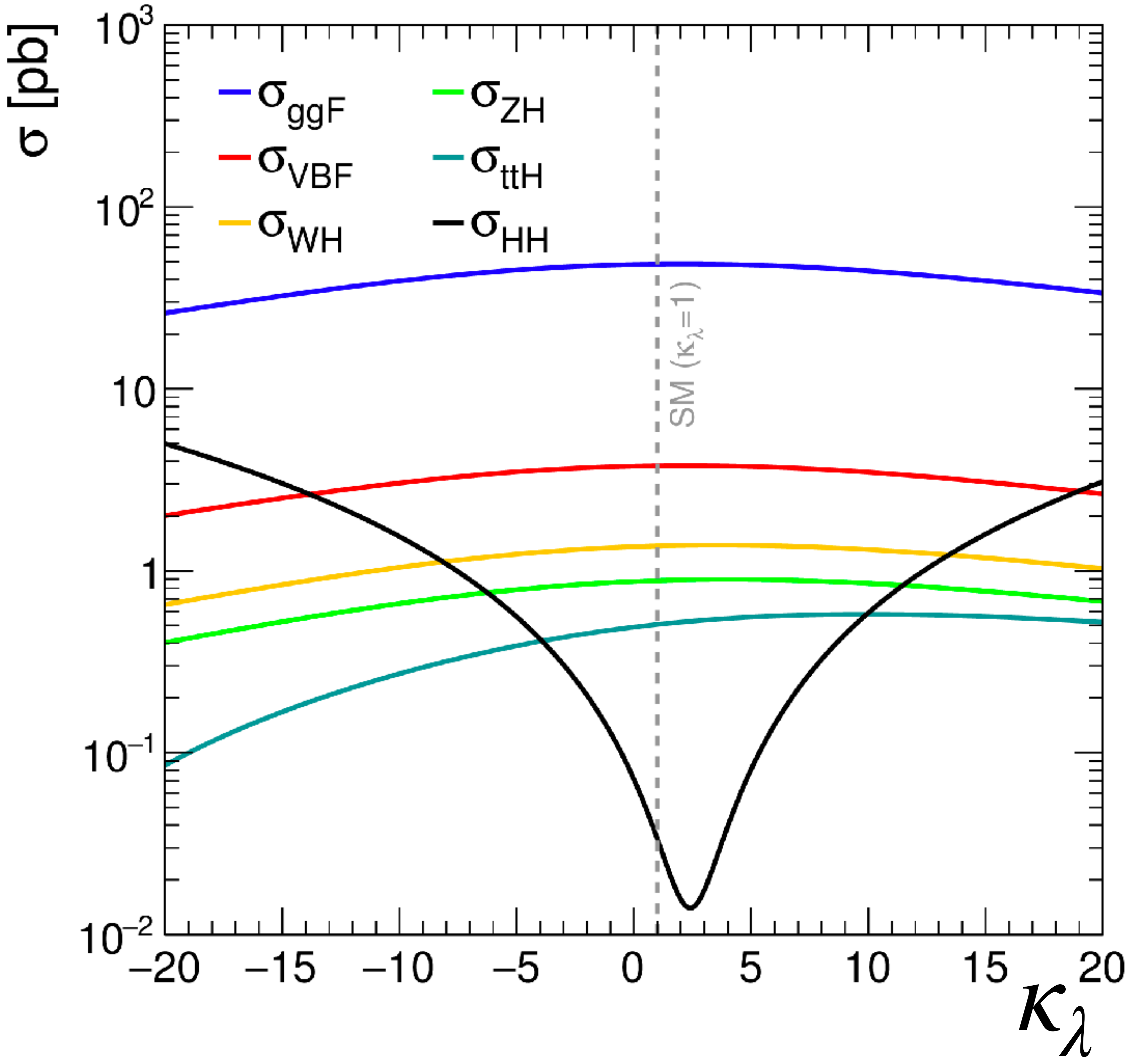
⇒ More

Summary Plots

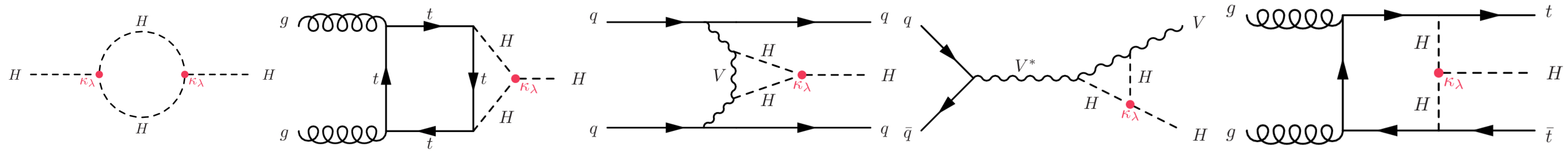
Extracting Trilinear Higgs Coupling λ_{HHH}

- Strong sensitivity of $\sigma(HH)$ on κ_λ:

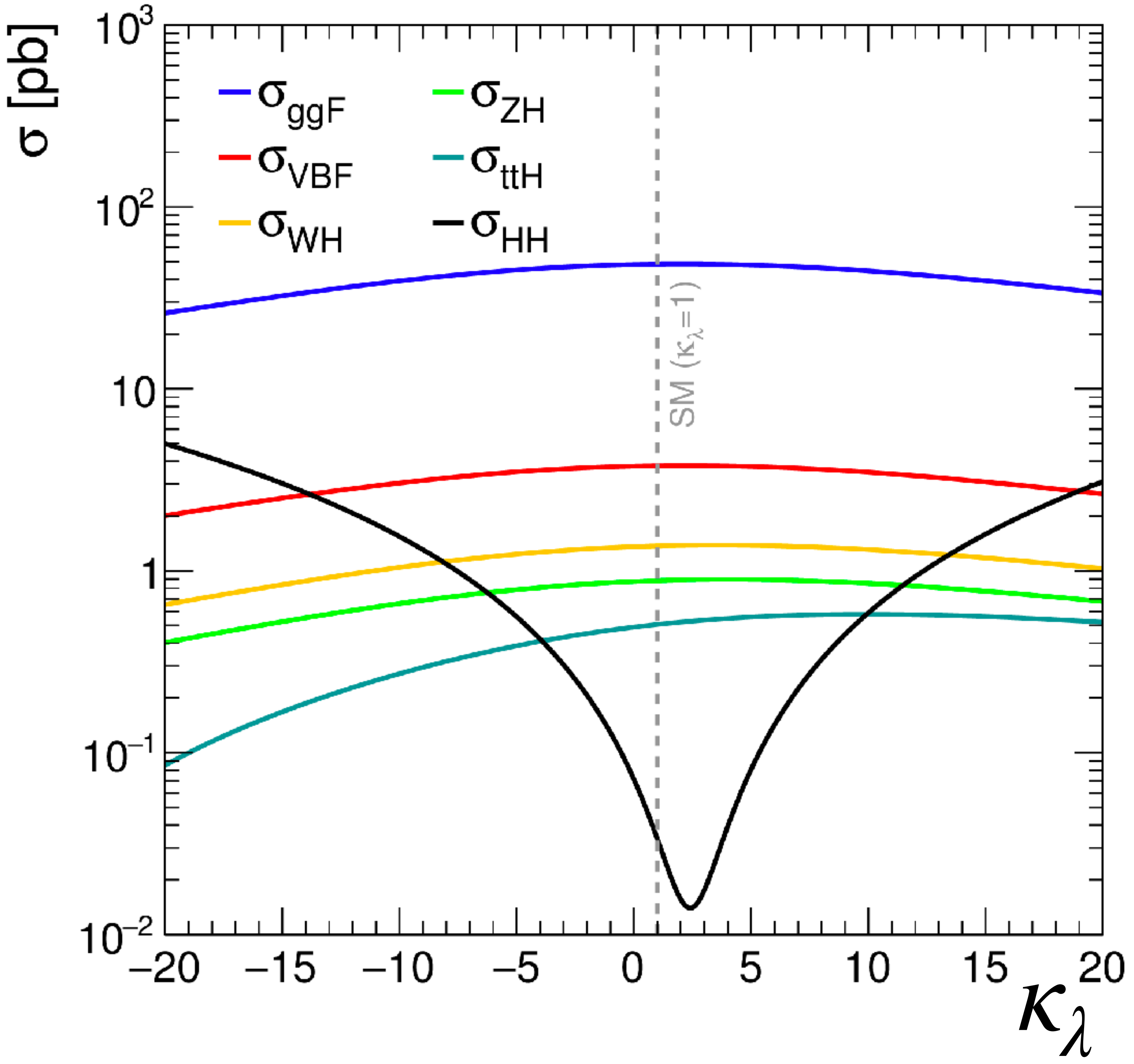


Extracting Trilinear Higgs Coupling λ_{HHH}

- Strong sensitivity of σ(HH) on κ_λ:
  - Single-Higgs sensitivity via higher-order corrections:



  - Low sensitivity, but high measurement precision



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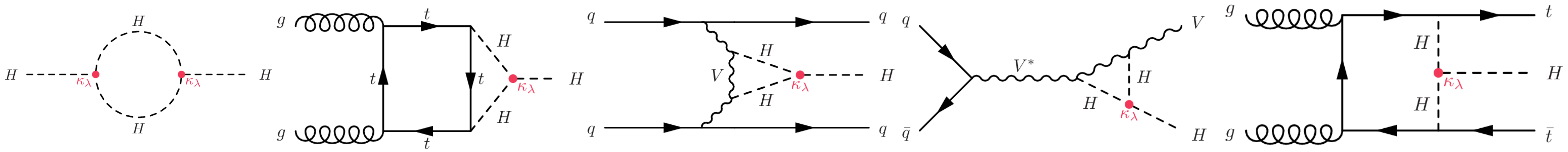

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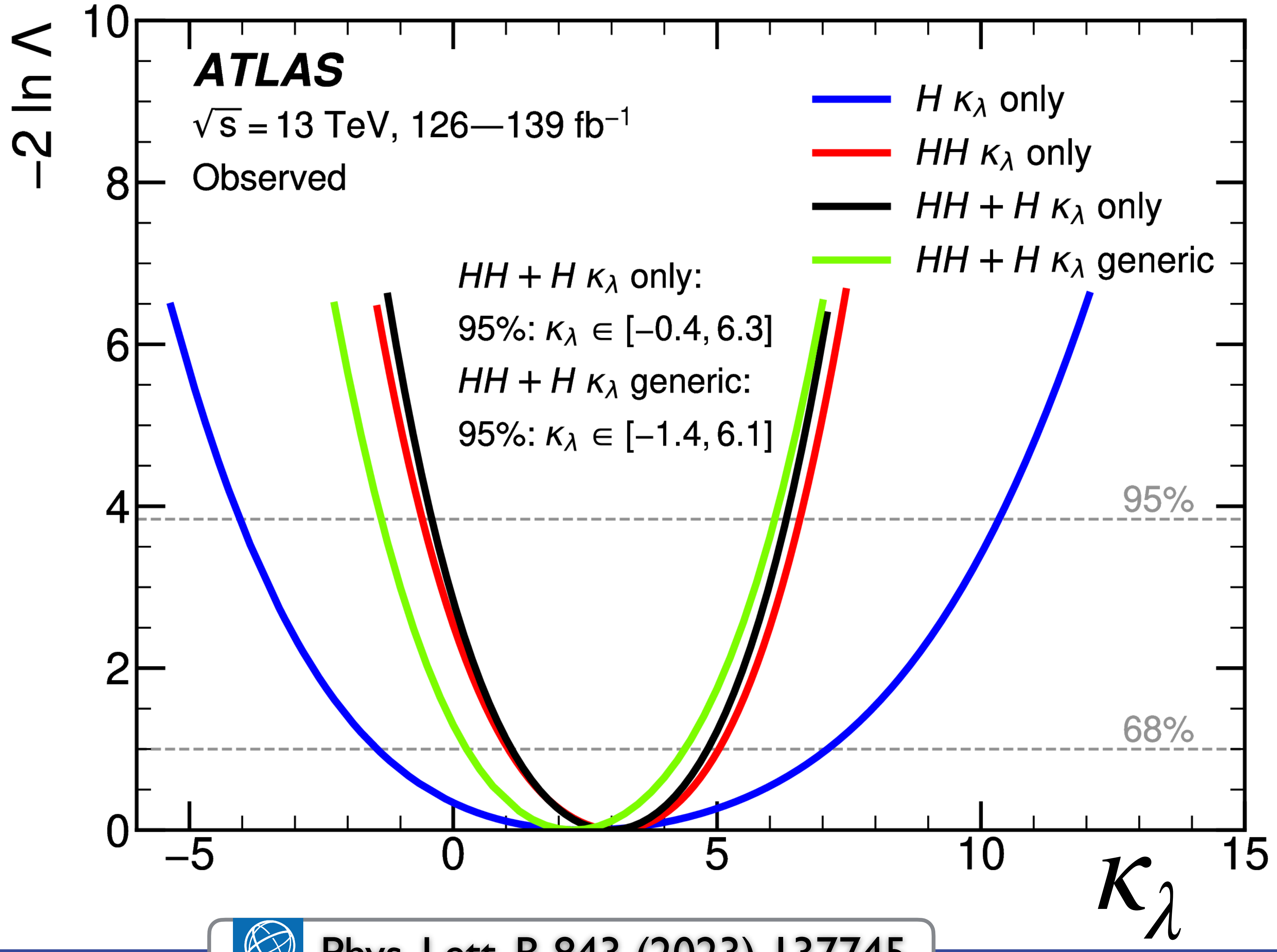

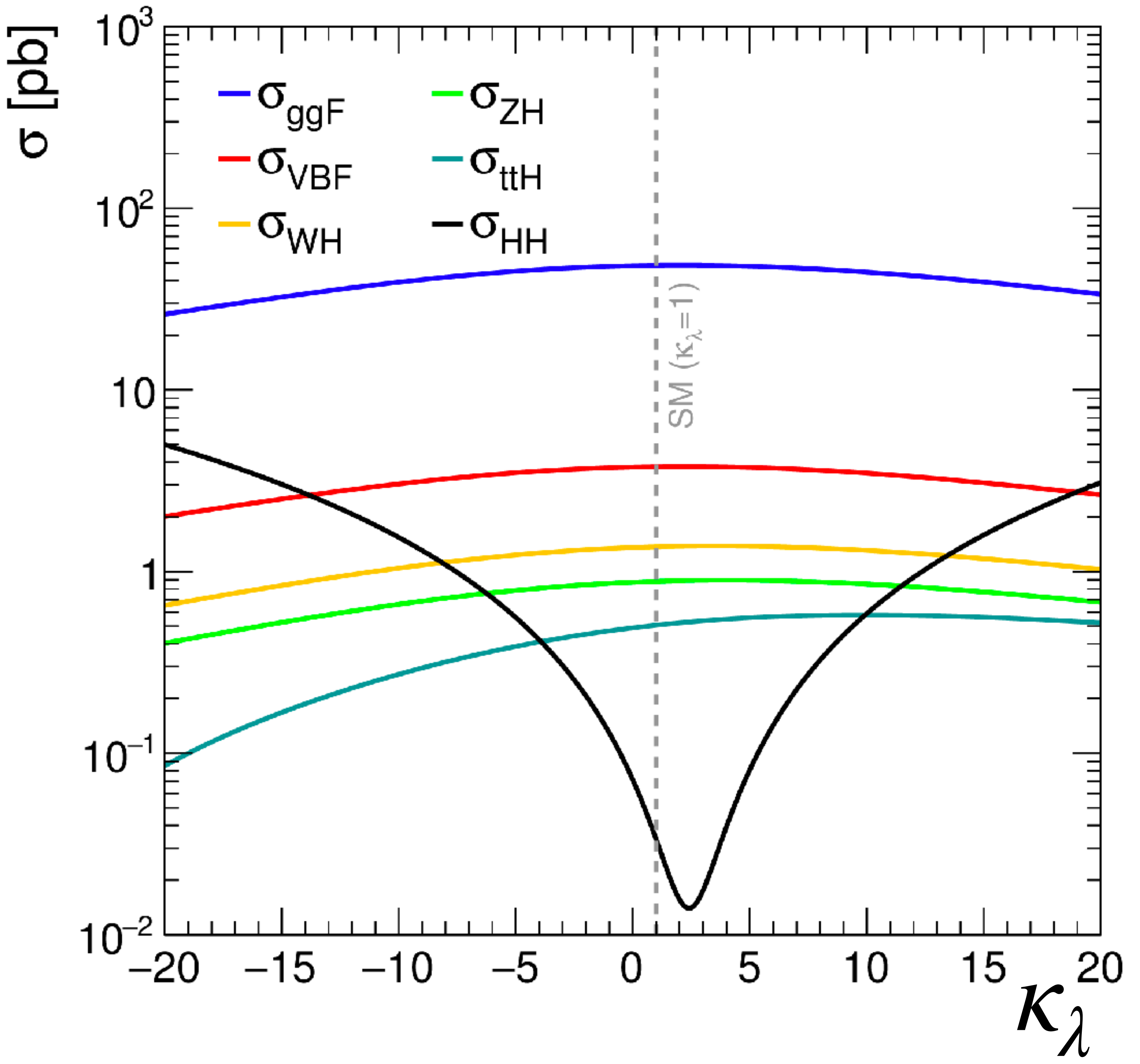

Phys. Lett. B 843 (2023) 137745

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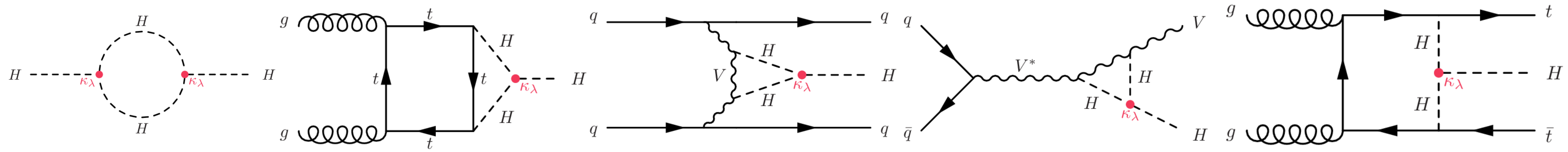

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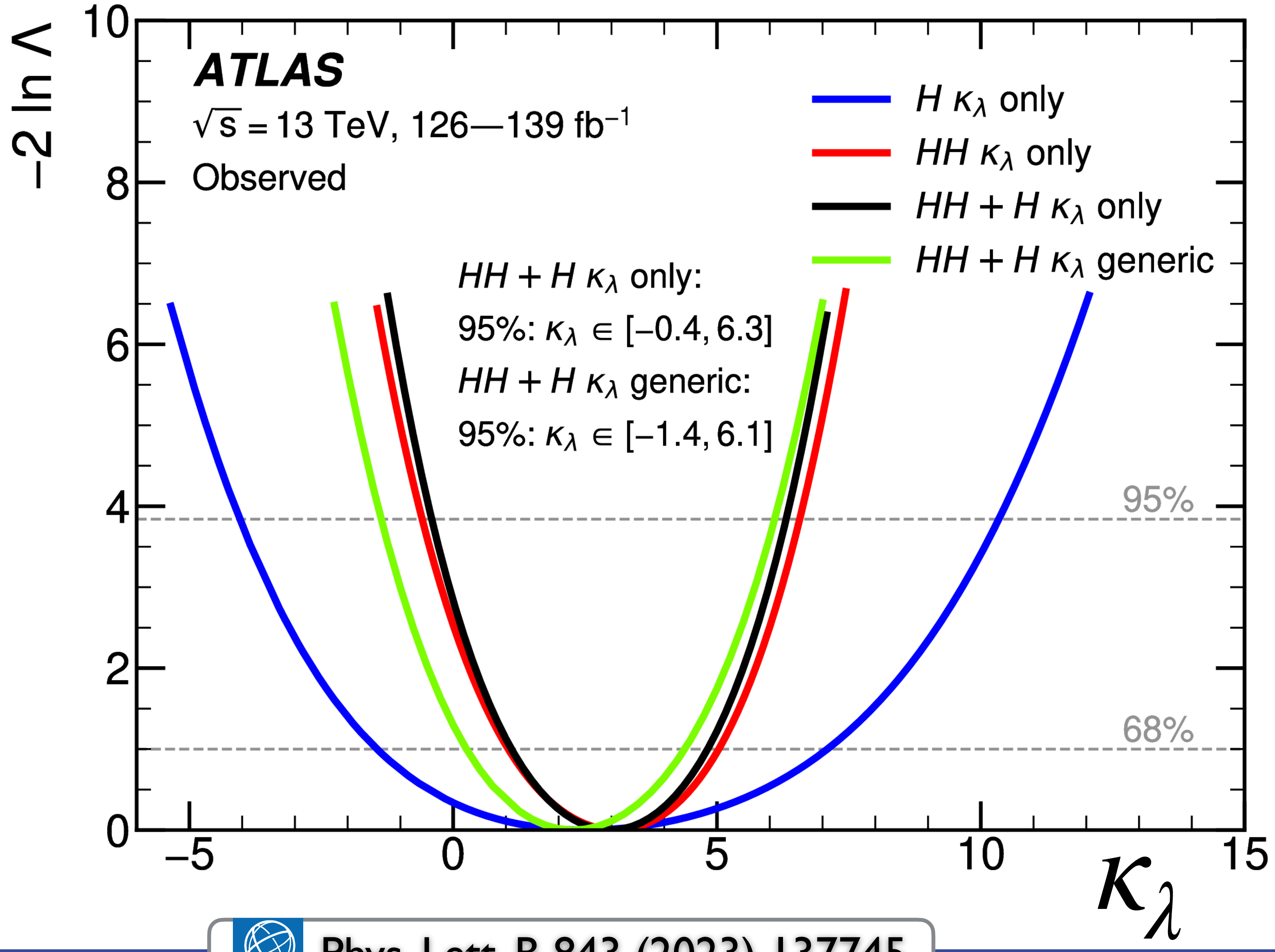
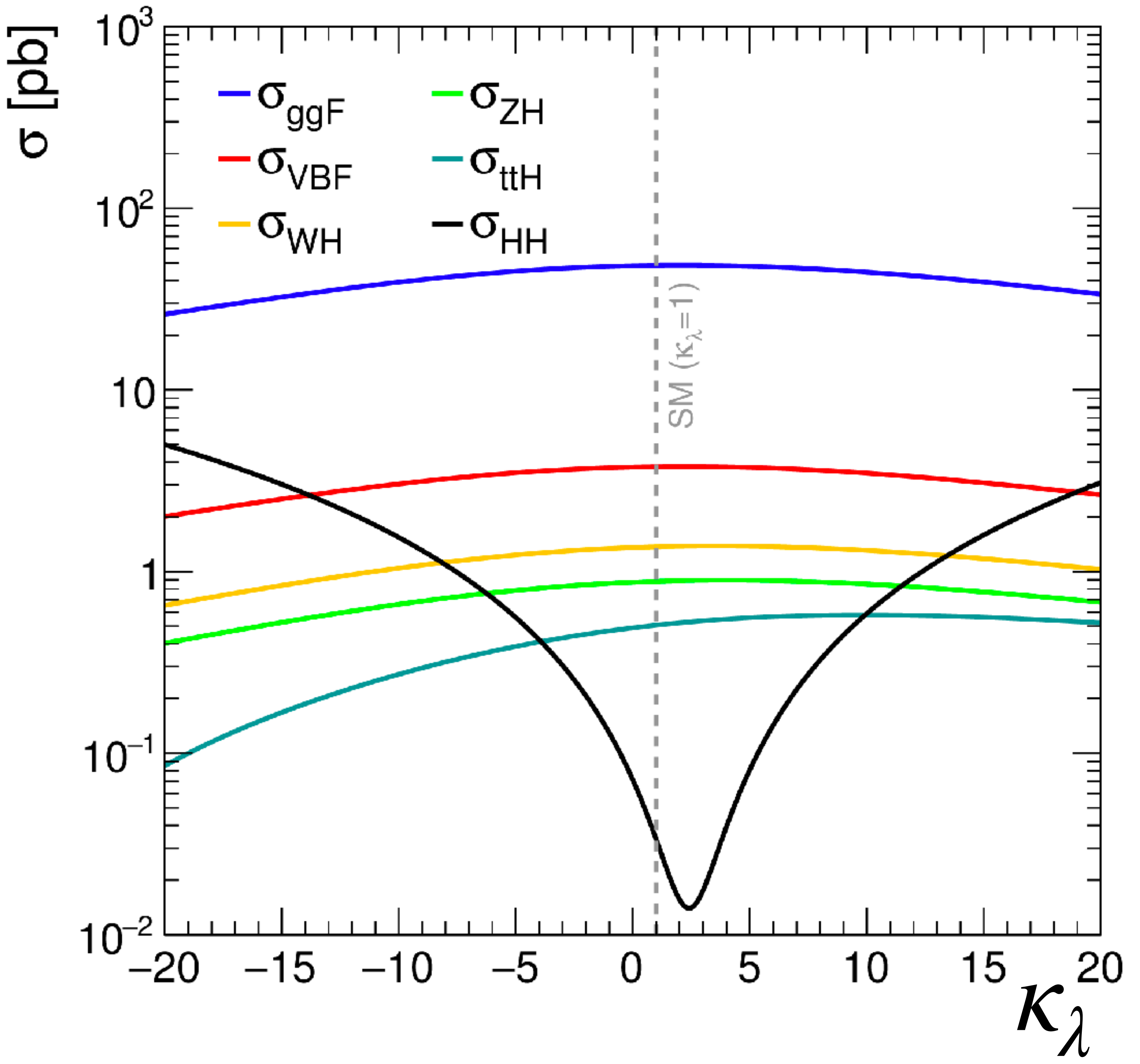


Phys. Lett. B 843 (2023) 137745



95% C.L. constraints on κ_λ obs. (exp.):

ATLAS, Nov 2022:
$$-0.4 < \kappa_\lambda < 6.3$$
$$(-1.3 < \kappa_\lambda < 6.1)$$

CMS, Nov 2023:
$$-1.2 < \kappa_\lambda < 7.5$$
$$(-2.0 < \kappa_\lambda < 7.7)$$

CMS-PAS-HIG-23-006

Extracting Trilinear Higgs Coupling λ_{HHH}

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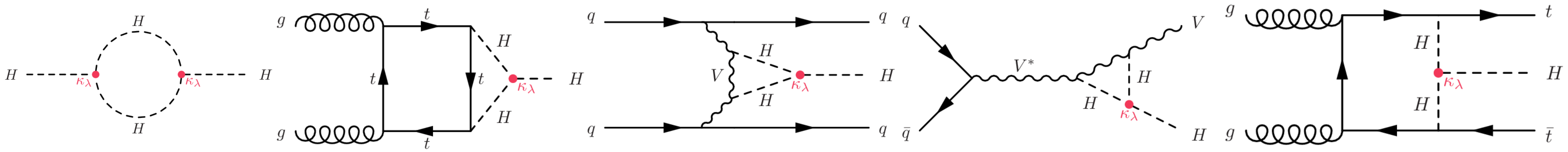

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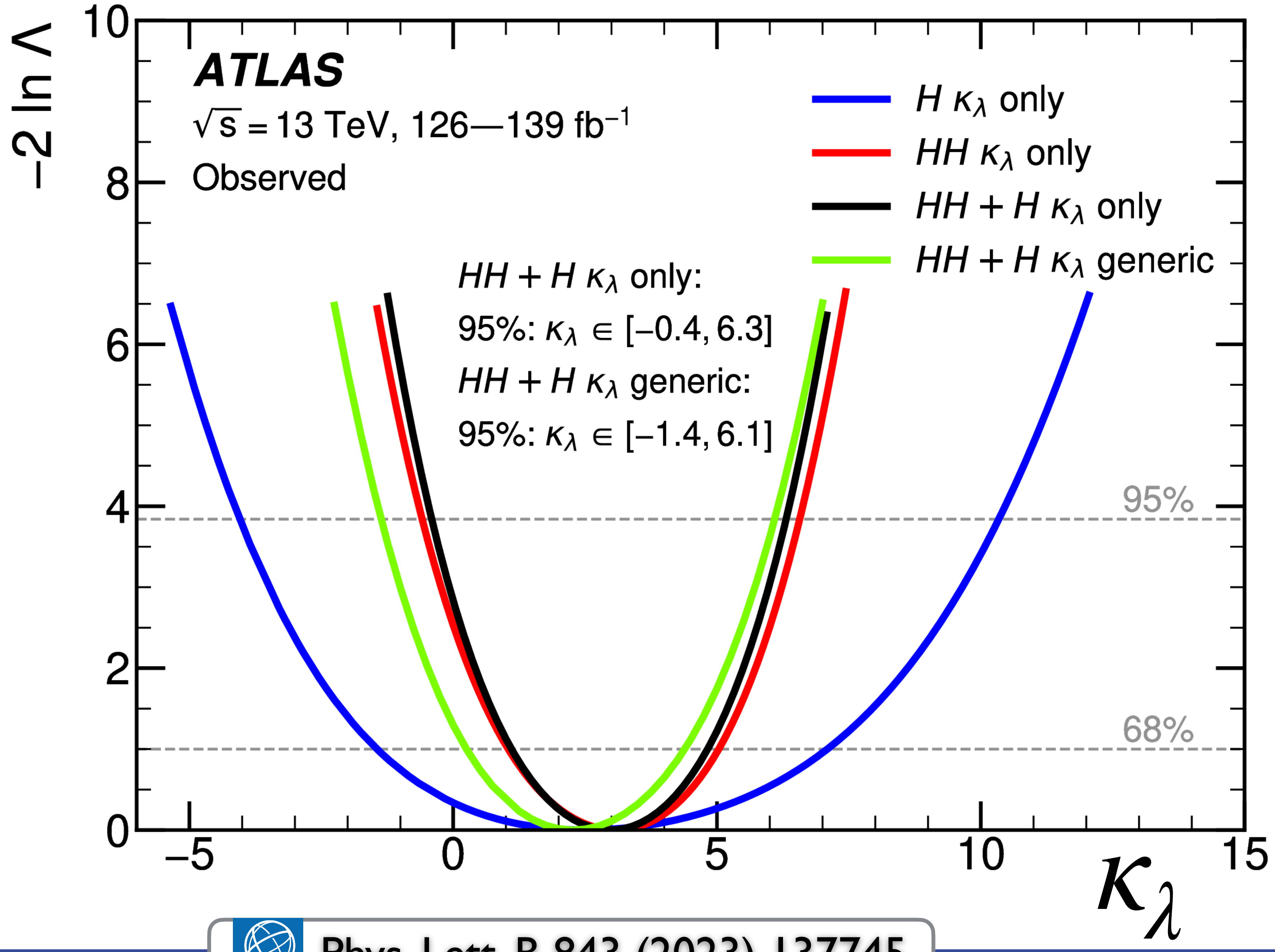

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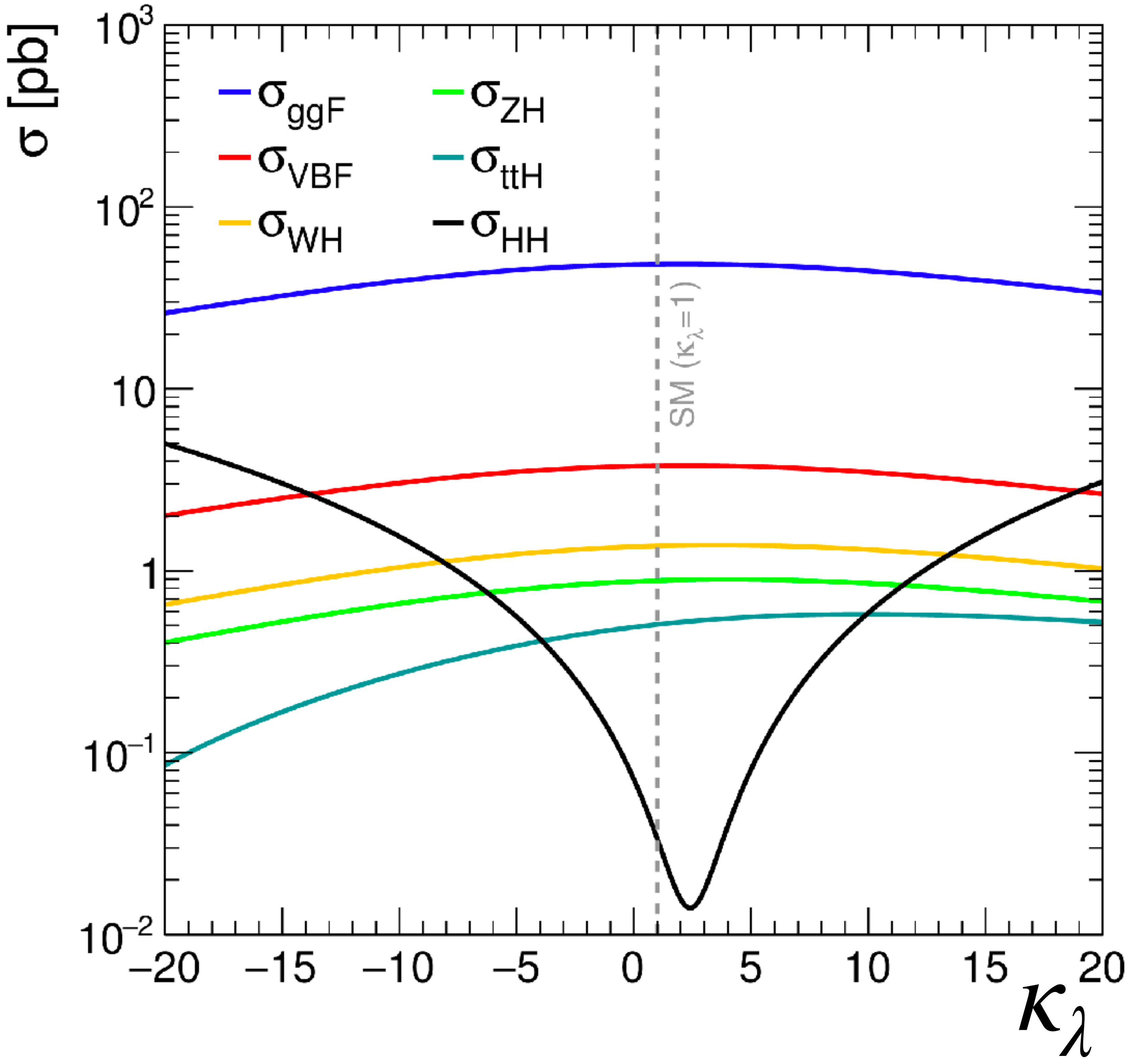
CMS-PAS-HIG-23-006



Projected results:
(3000 fb^{-1}, with systematics)
- HH significance: 3.4 σ
- $0.5 < \kappa_\lambda < 1.6$

⇒ More

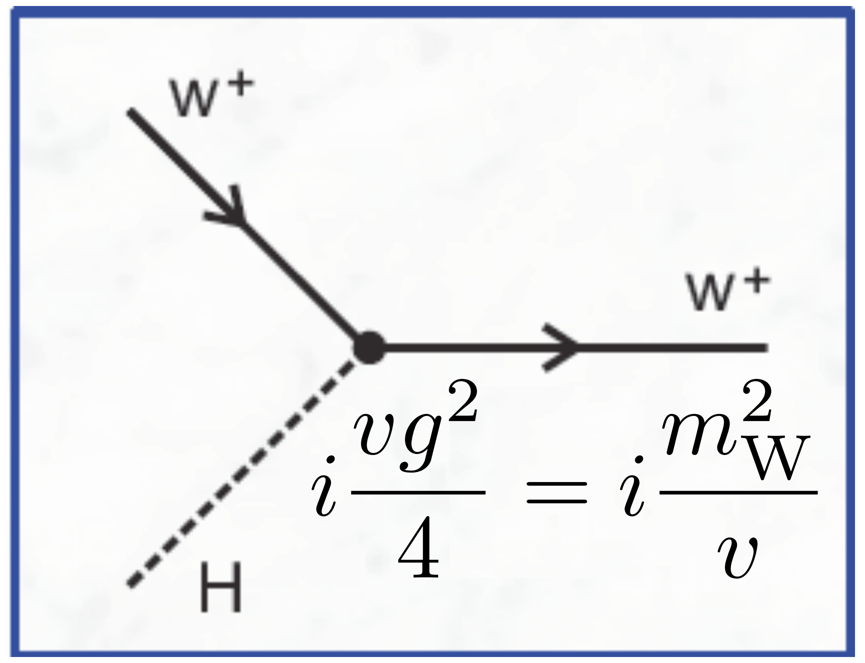
Outline

$$\mathscr{L}_{\text{Higgs}} = (D_\mu\phi)^2 - \mu^2\phi^2 - \lambda\phi^4 + \lambda_{\text{f}}\phi\bar{\psi}\psi$$

6. Combined interpretations

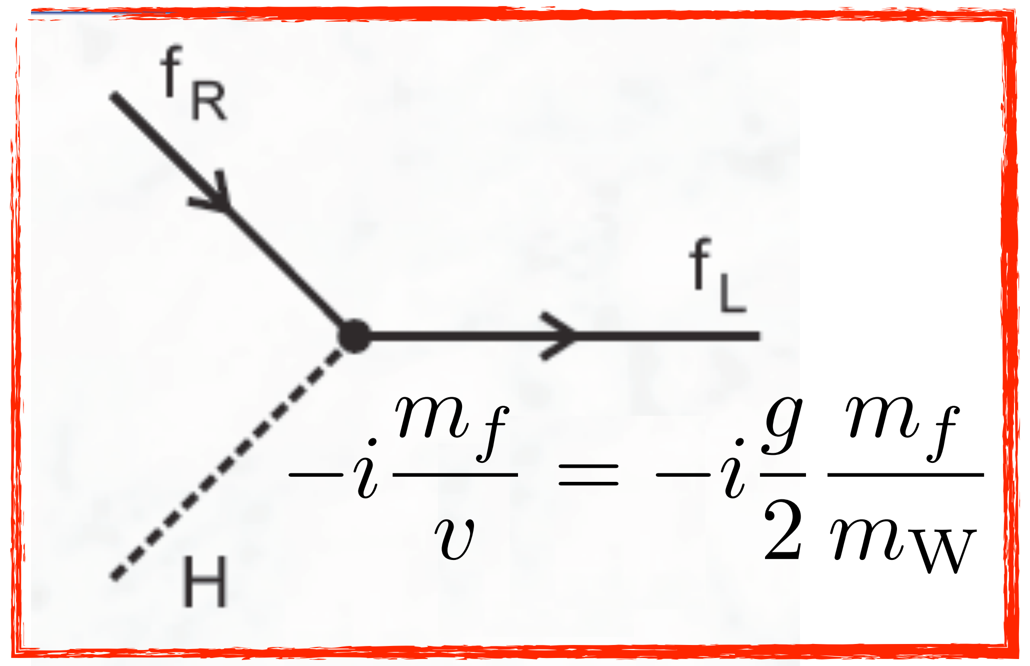
$$m_{\text{W}} = \frac{vg}{2}$$

direct connection



$$m_f = \frac{\lambda_f v}{\sqrt{2}}$$

direct connection



(*) simplified

Effective Field Theory Interpretations

Extend SM with new physics operators:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i c_i^{(6)} \mathcal{O}_i^{(6)} / \Lambda^2$$

(assumes no new particles below Λ = 1 TeV)

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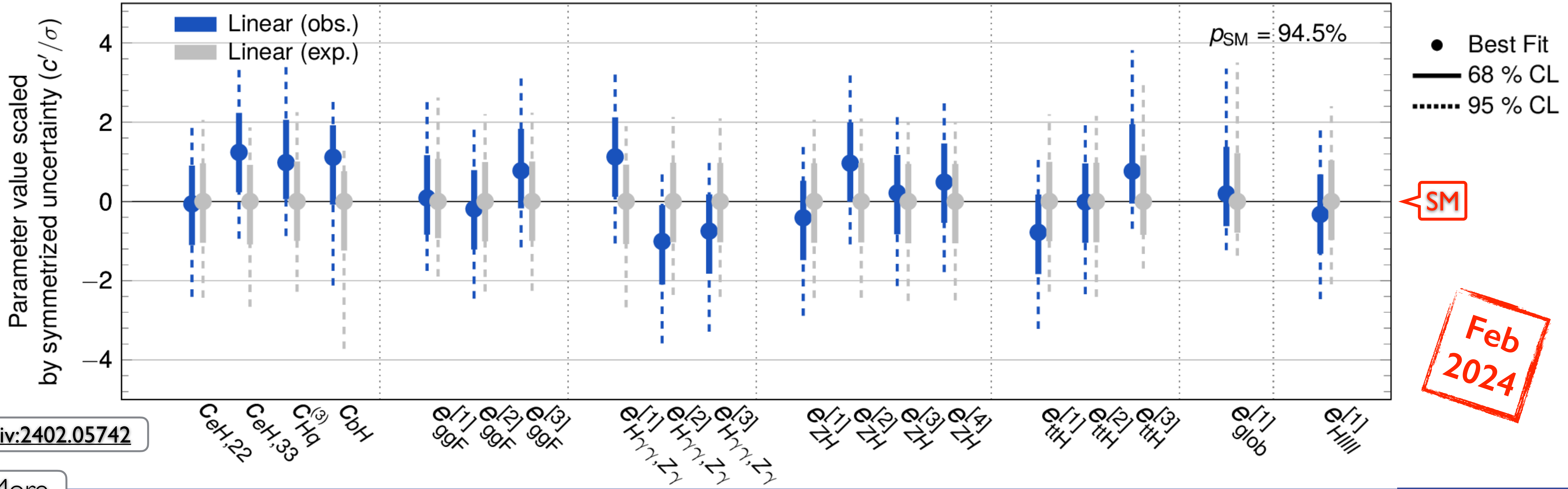
- EFT interpretation of "Nature" combination
- 19 EFT parameters fitted simultaneously!
  - Eigenvector rotation (to remove insensitive directions)

Opens the window to global combined analyses!



arXiv:2402.05742

⇒ More

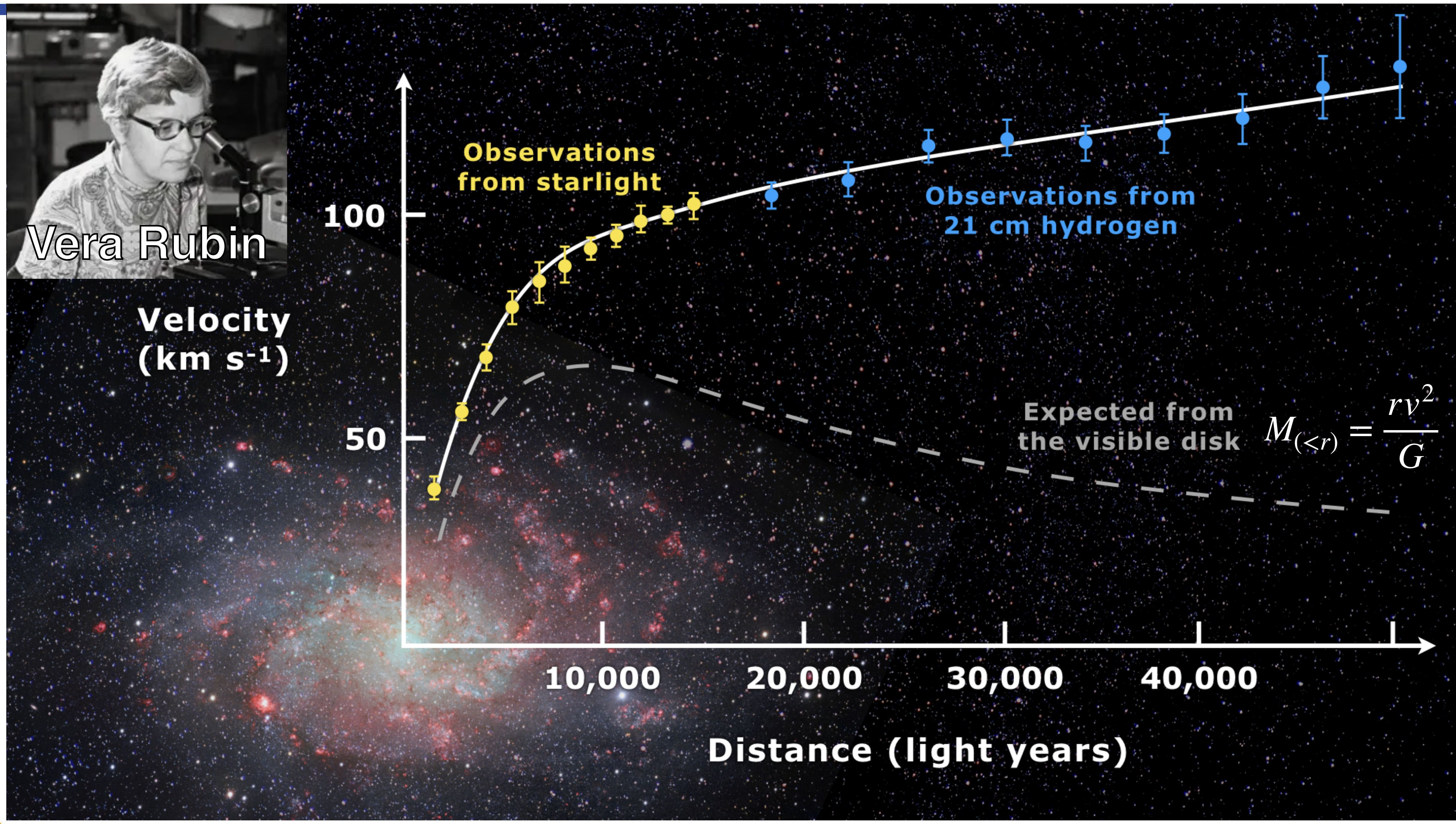
Outline

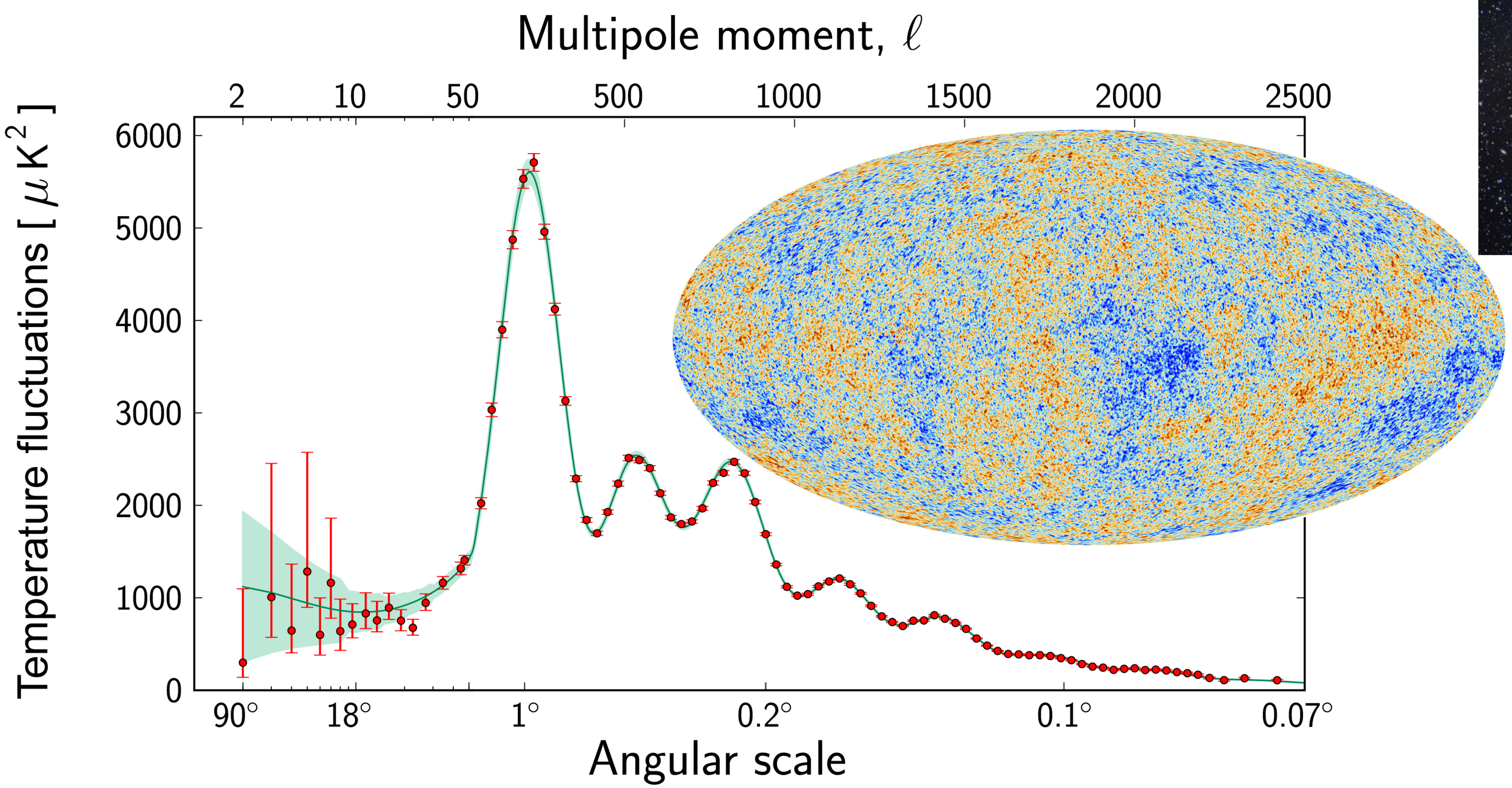
$$\mathscr{L}_{\text{Nature}} = \mathscr{L}_{\text{SM}} + \boxed{\mathscr{L}_{???}}$$

7. Search for other Scalars/Higgses

Motivation

- Many signs for physics Beyond the Standard Model (BSM), only one example:
  - Ample signs for Dark Matter (DM) in the Universe
    - Galaxy rotation curves (discovered by Vera Rubin)
    - Cosmic Microwave Background anisotropies
    - ~27% of total energy in Universe is DM
  - No perfect DM candidate in SM!





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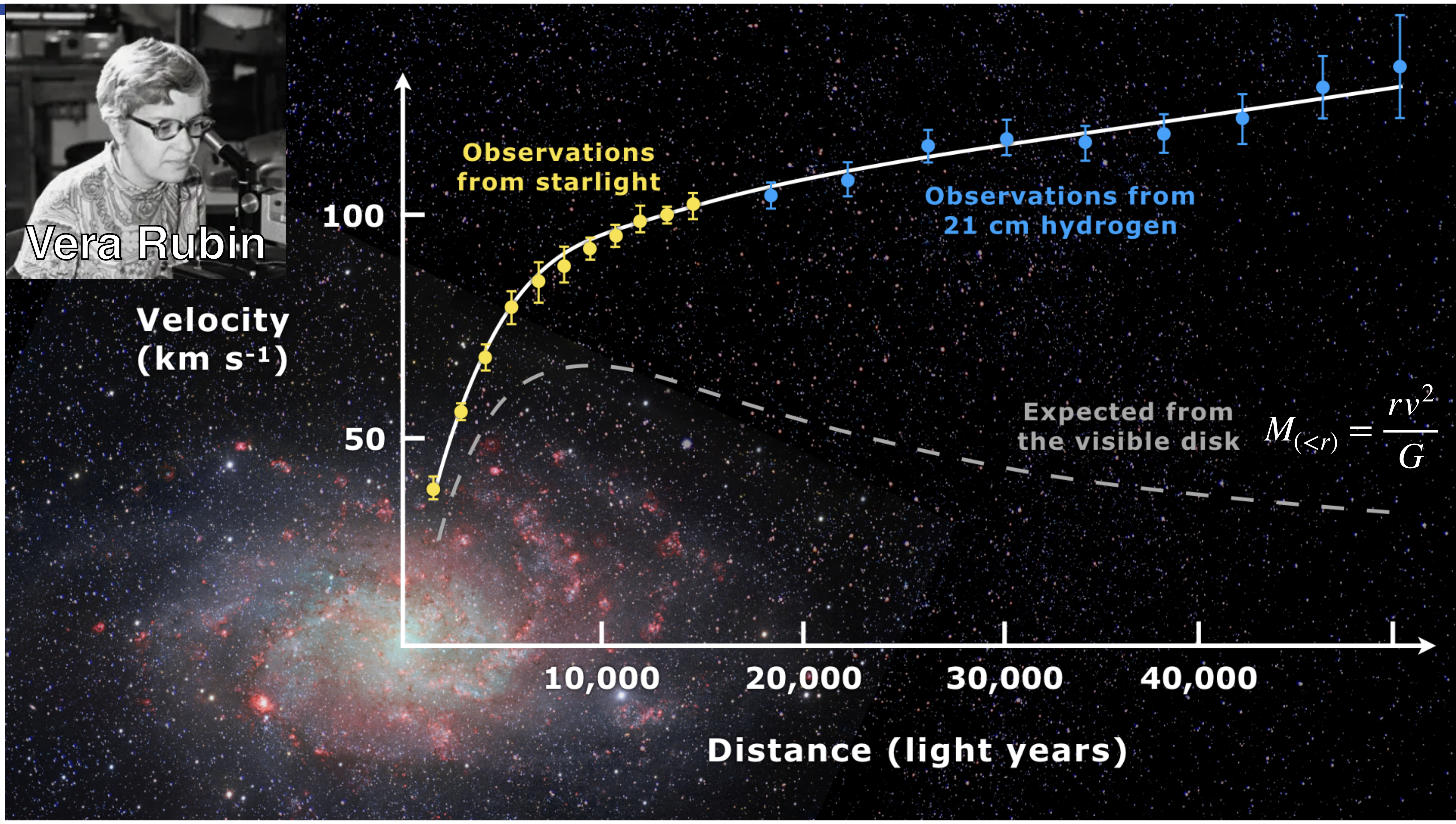

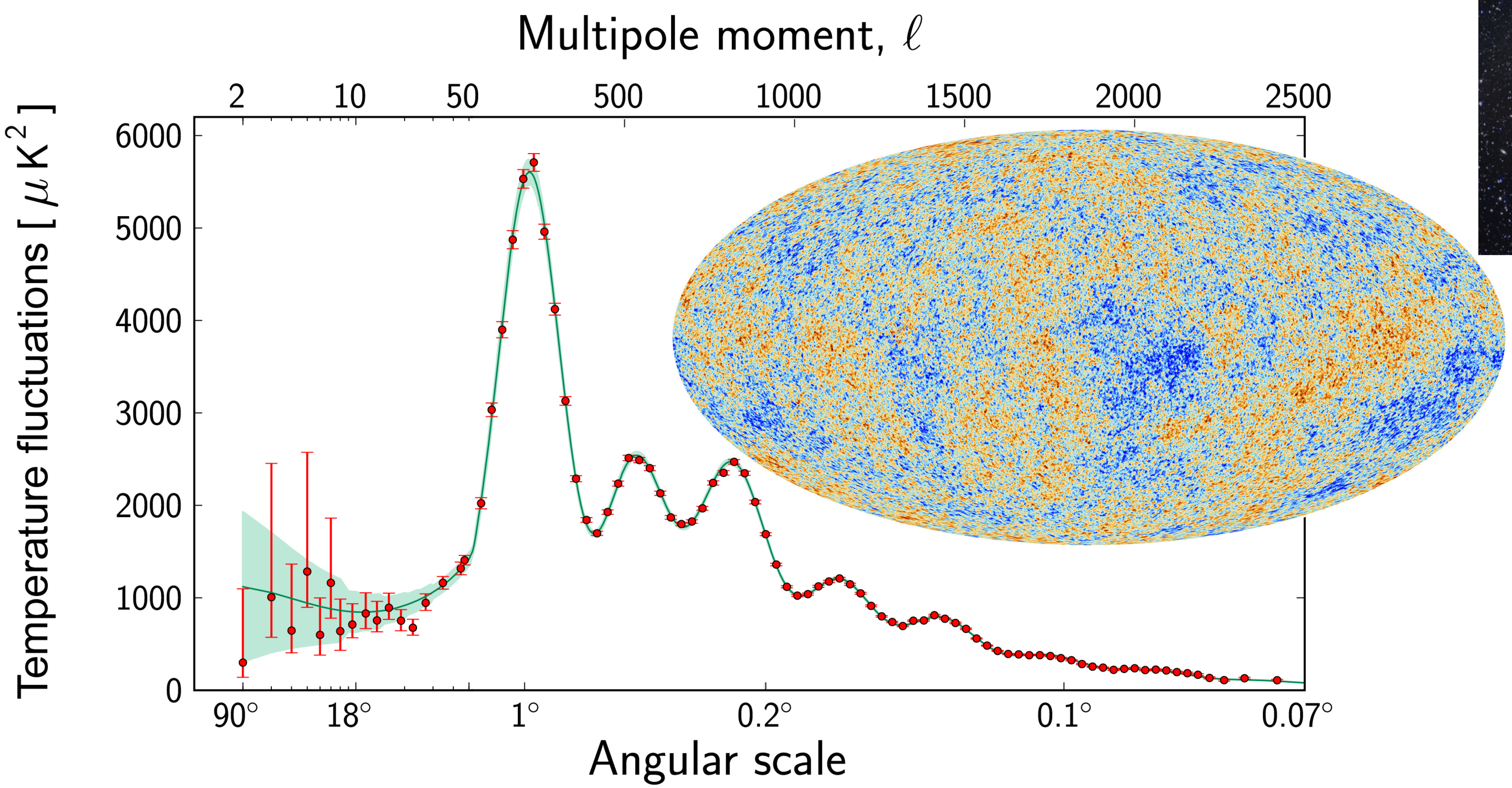

- Possible solutions:
  - R-parity conserving SUSY → DM candidate
  - 2 Higgs Doublet Model (2HDM), 3HDM, Higgs triplets,...

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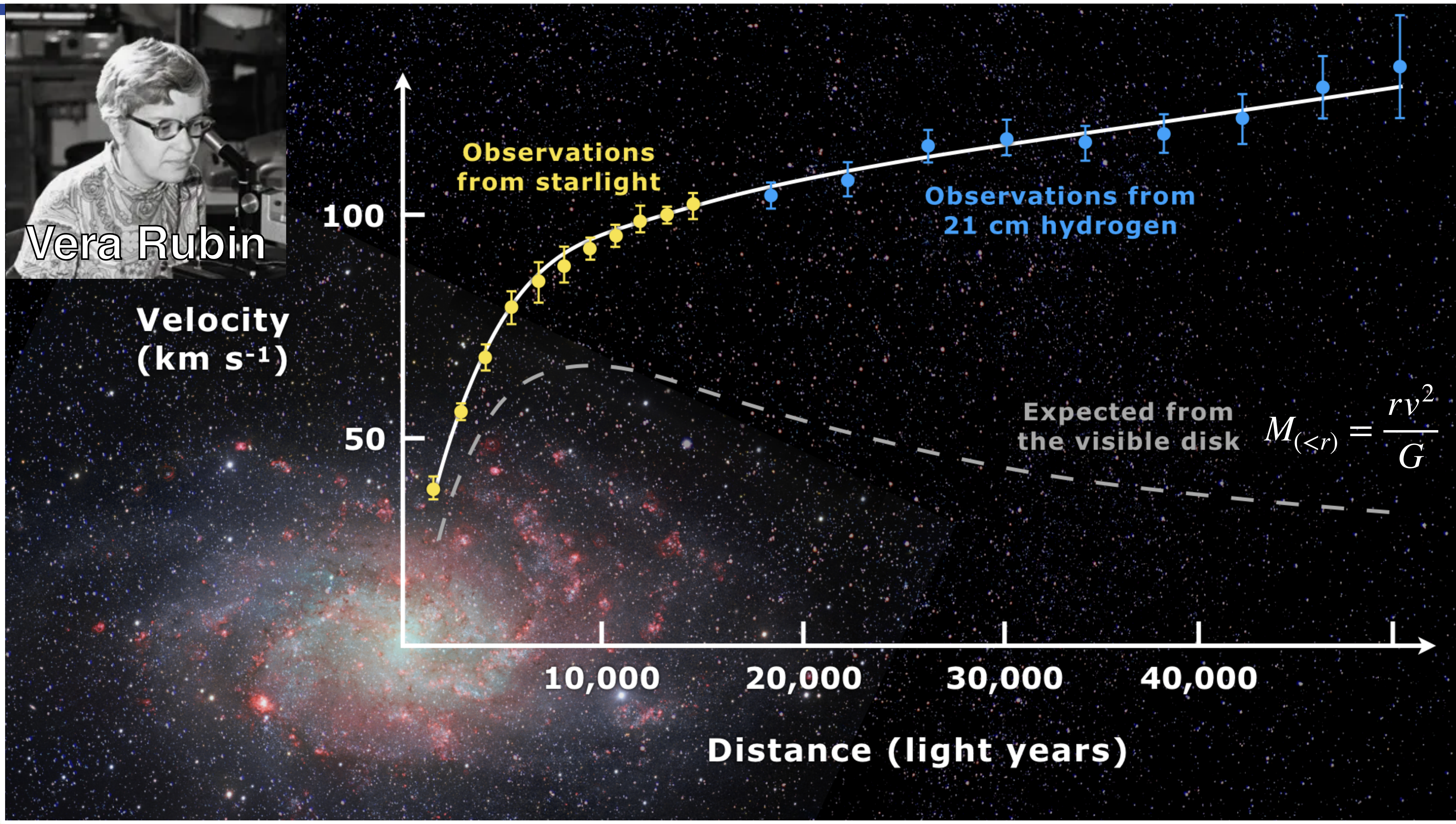

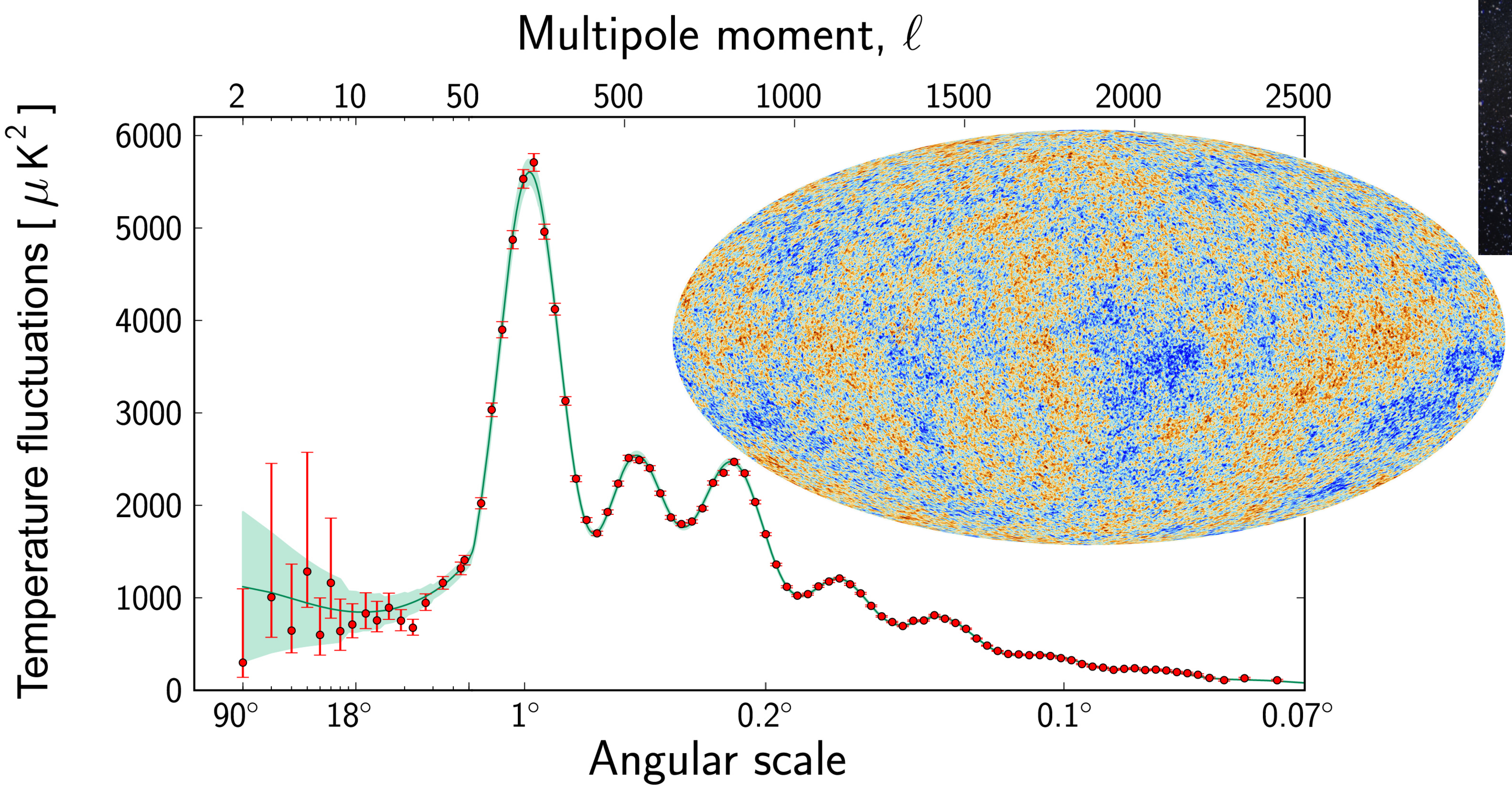

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  - $\mathscr{L}_{???} \in c_\chi \, \bar{\chi}_{DM} \, \phi_{new} \, \chi_{DM}$

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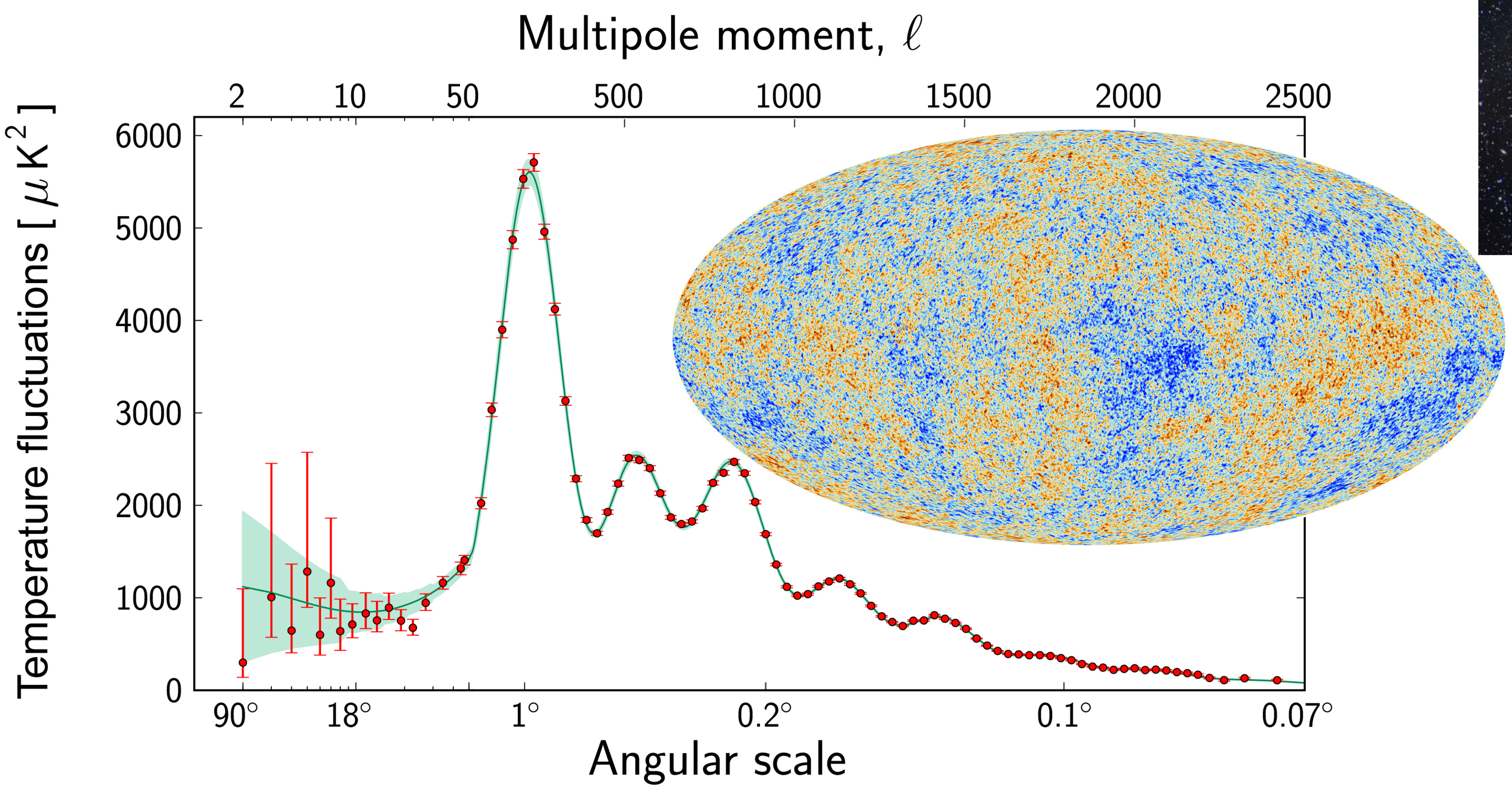

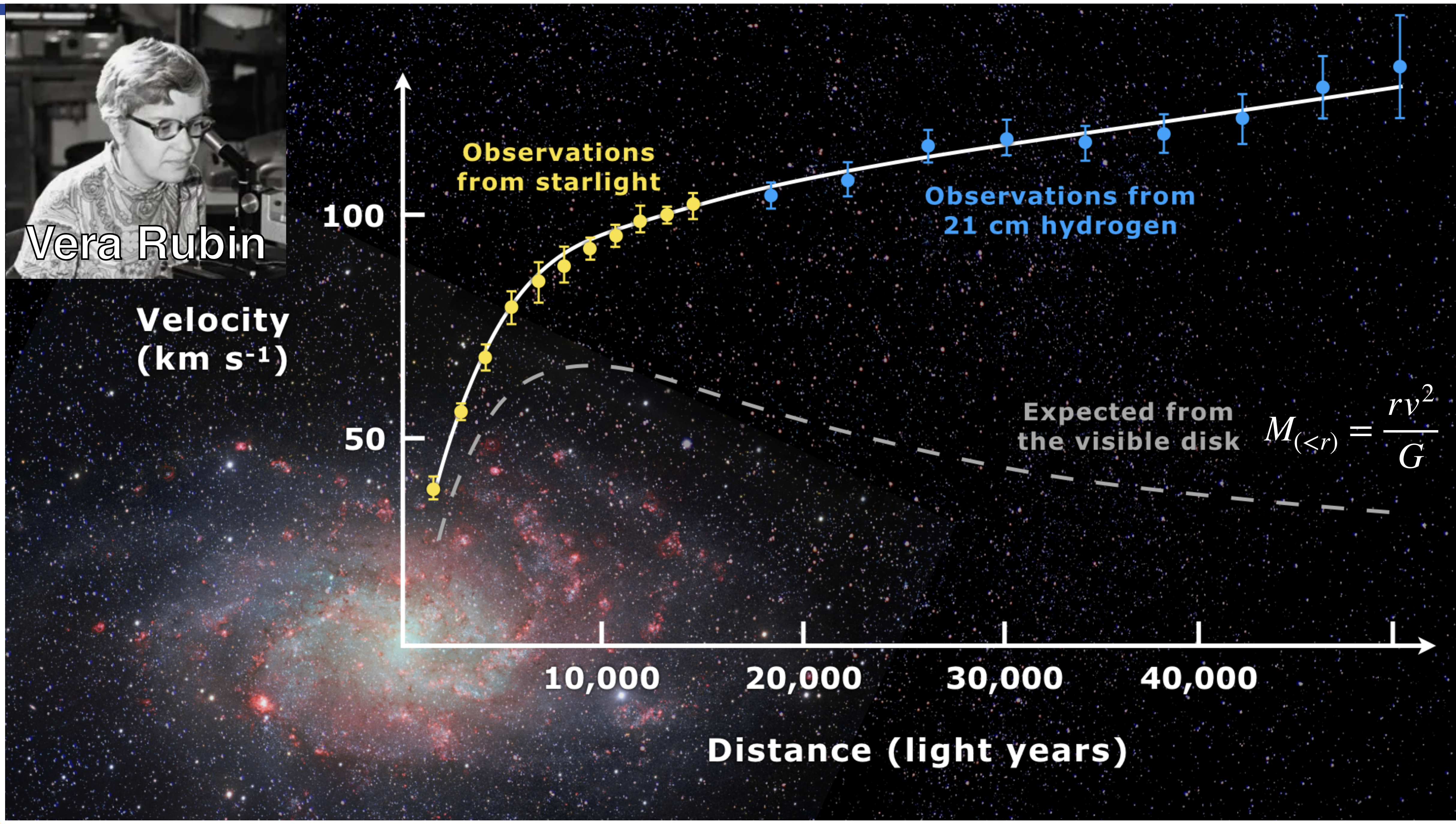

- Possible solutions:
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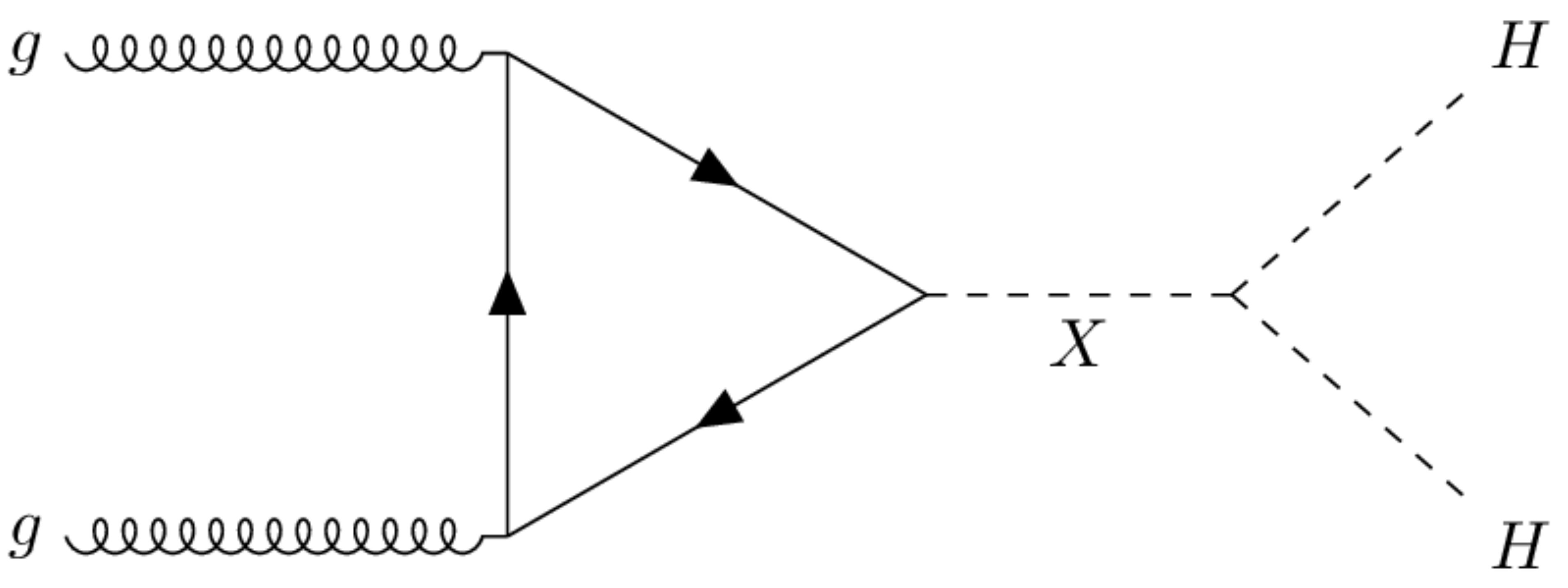
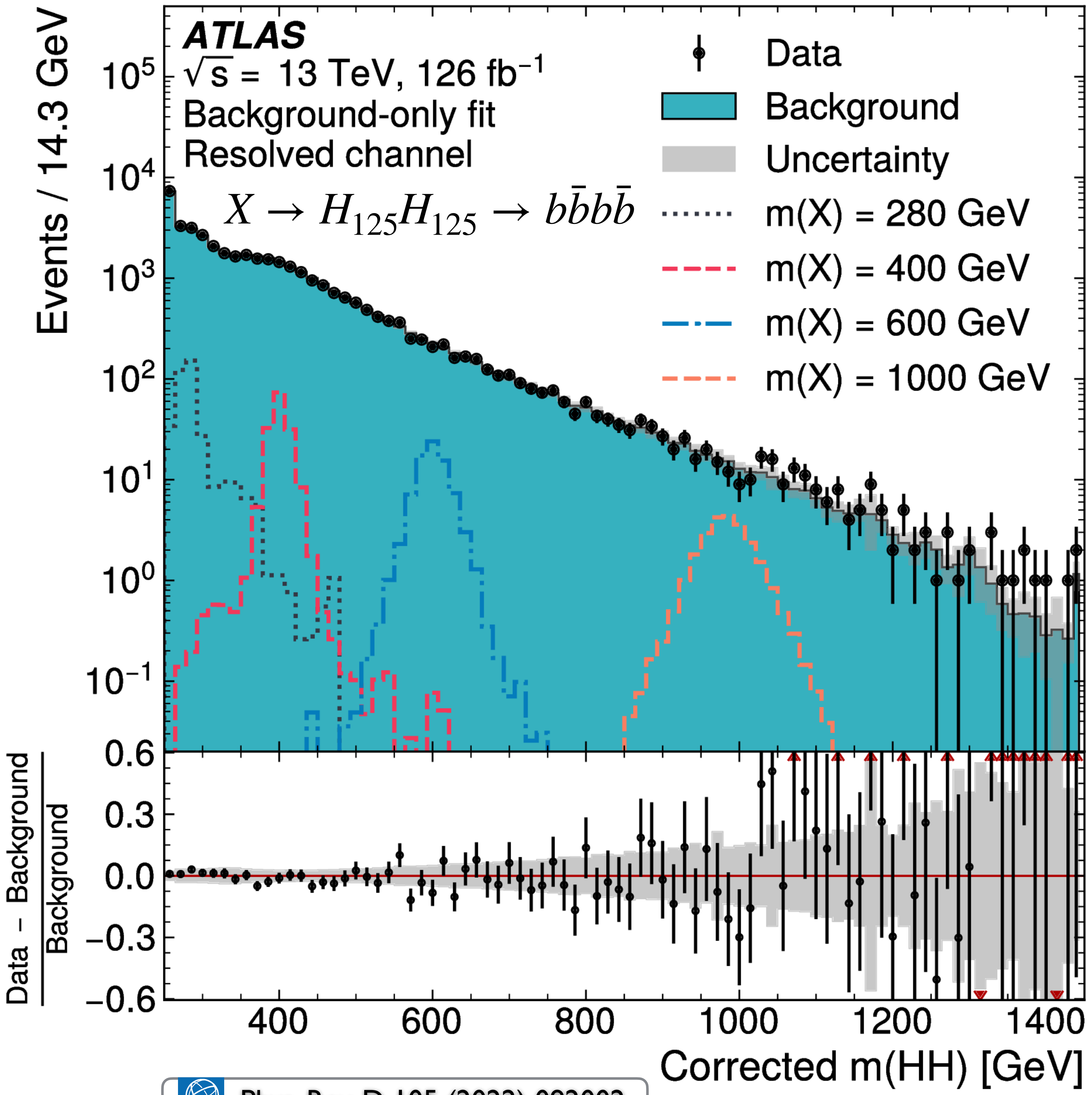
  - 2 Higgs Doublet Model (2HDM), 3HDM, Higgs triplets,...
  - $\mathscr{L}_{???} \in c_\chi \, \bar{\chi}_{DM} \, \phi_{new} \, \chi_{DM}$
- Or just search for any new scalar

Resonant $X \to H_{125}H_{125}$ Production





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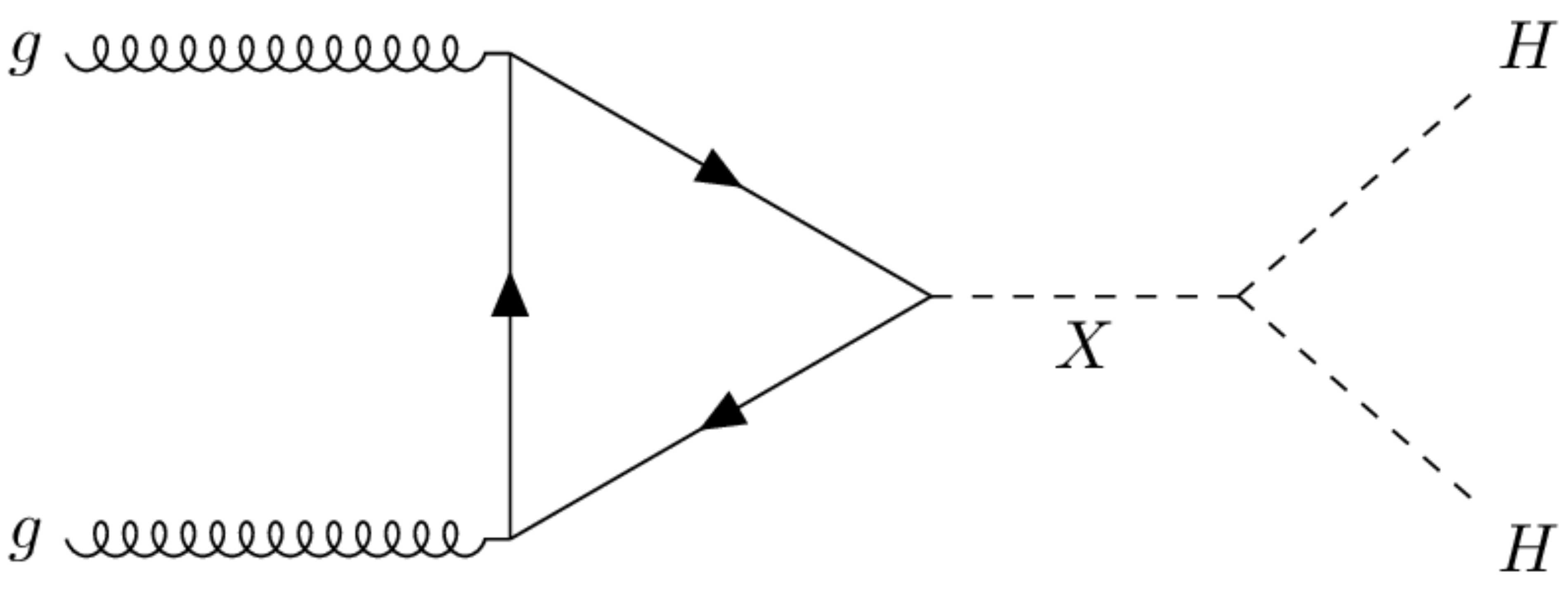
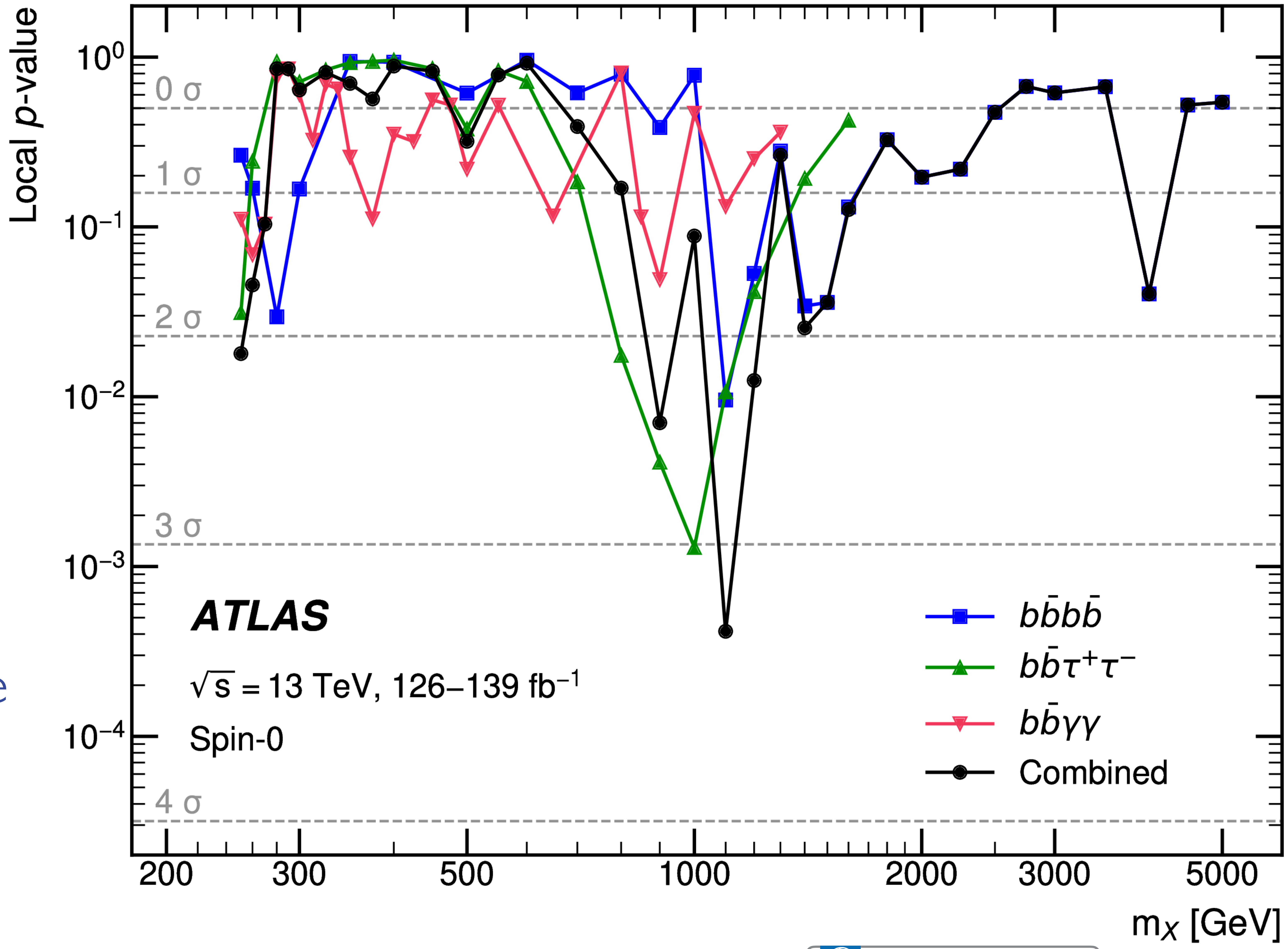
Resonant $X \to H_{125}H_{125}$ Production

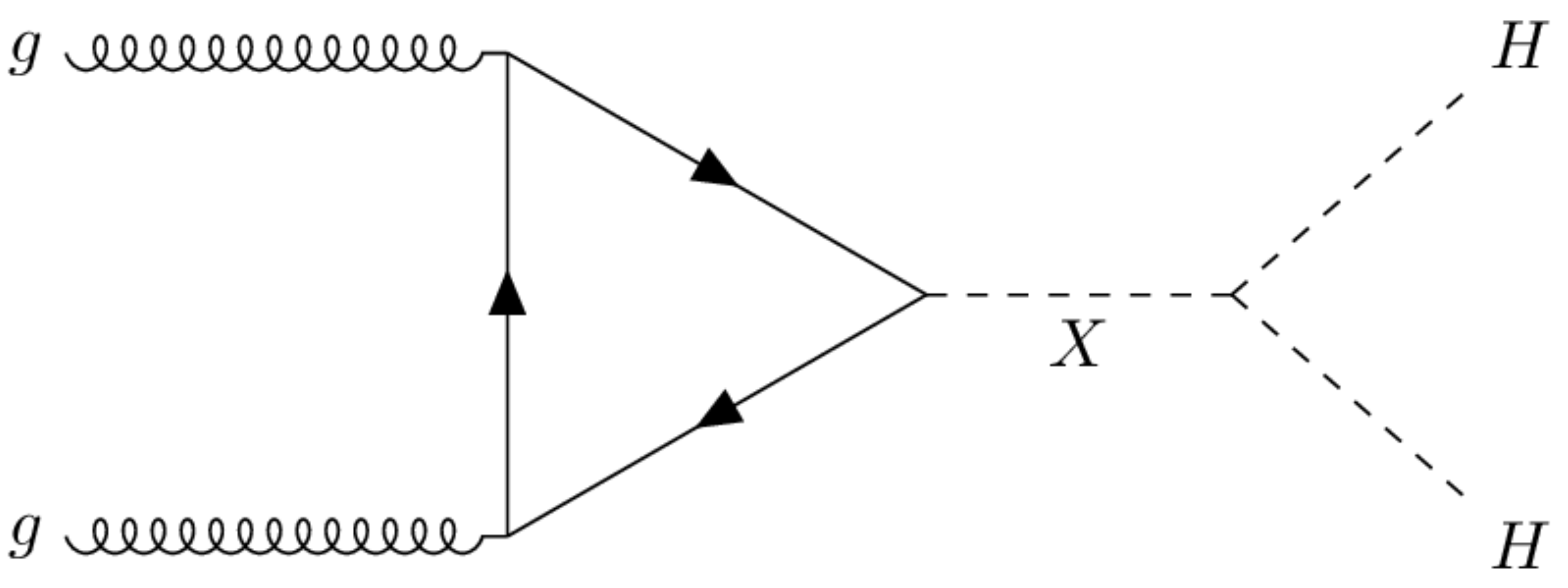


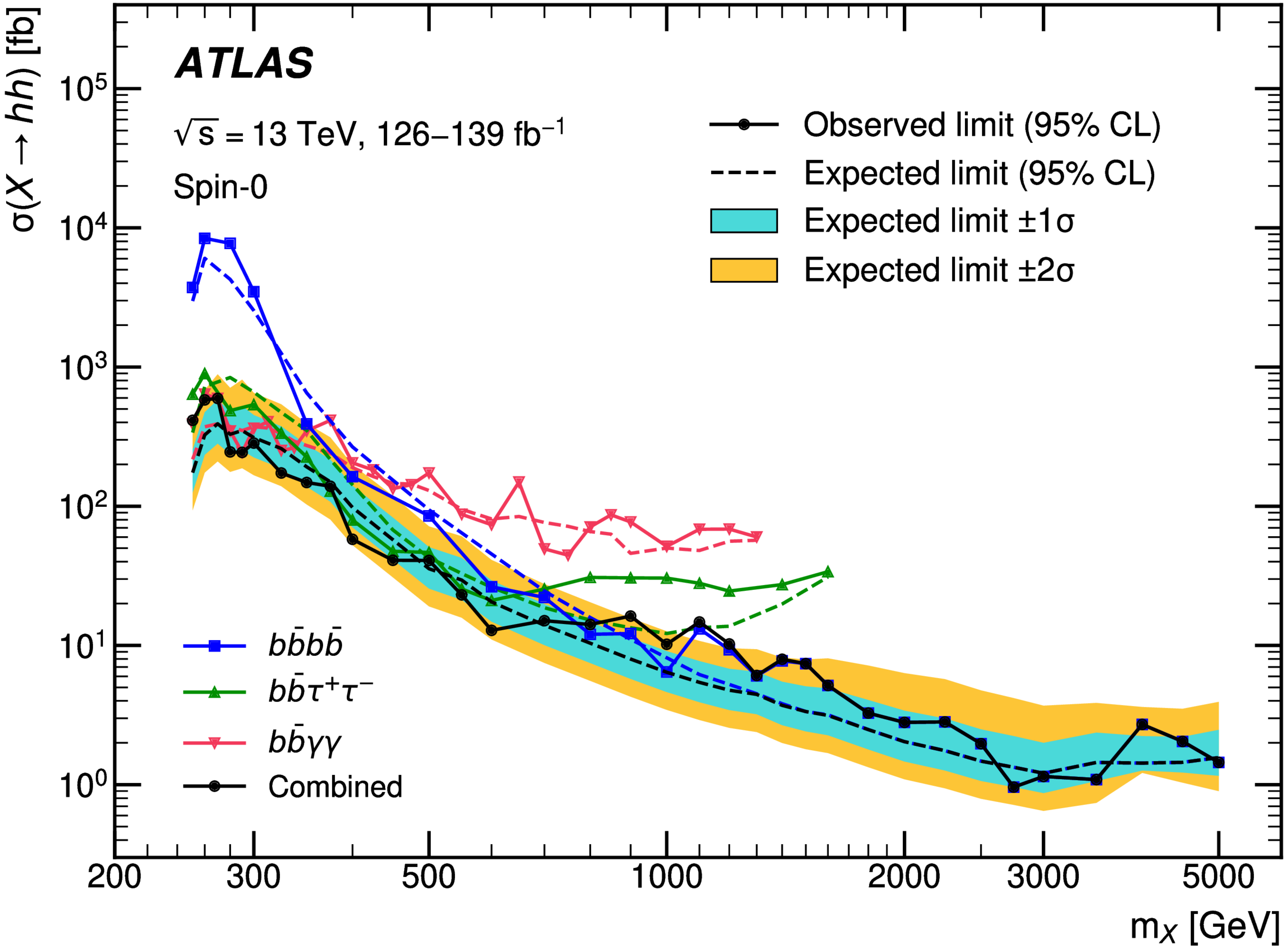
- Small excesses:
  - ≈ 1 TeV in $b\bar{b}\tau^+\tau^-$
  - ≈ 1.1 TeV in $b\bar{b}b\bar{b}$
  - nothing in $b\bar{b}\gamma\gamma$, but less sensitive
- Combined:
  - 1.1 TeV: 3.3 σ local, 2.1 σ global



arXiv:2311.15956

Resonant $X \to H_{125}H_{125}$ Production

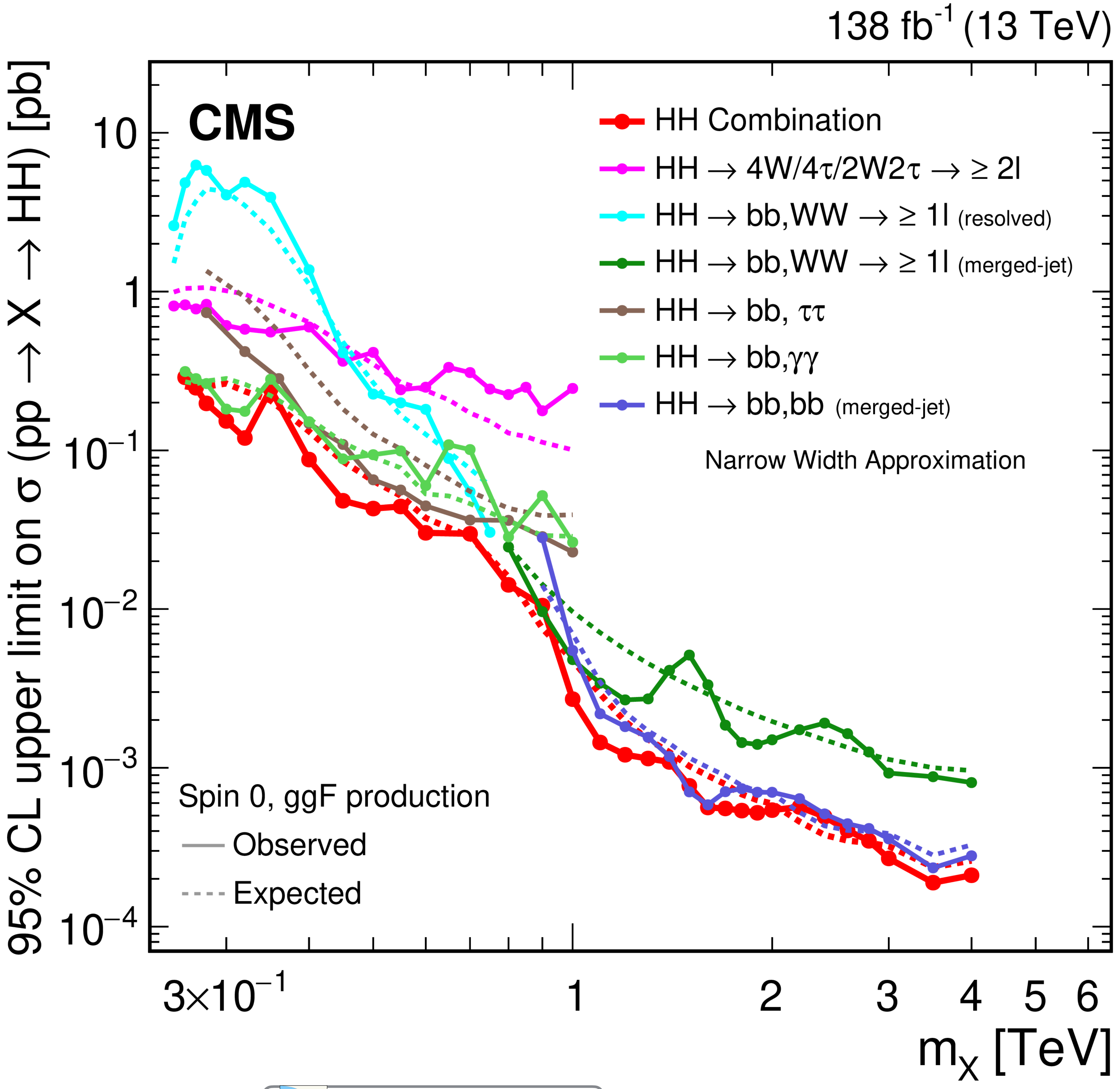


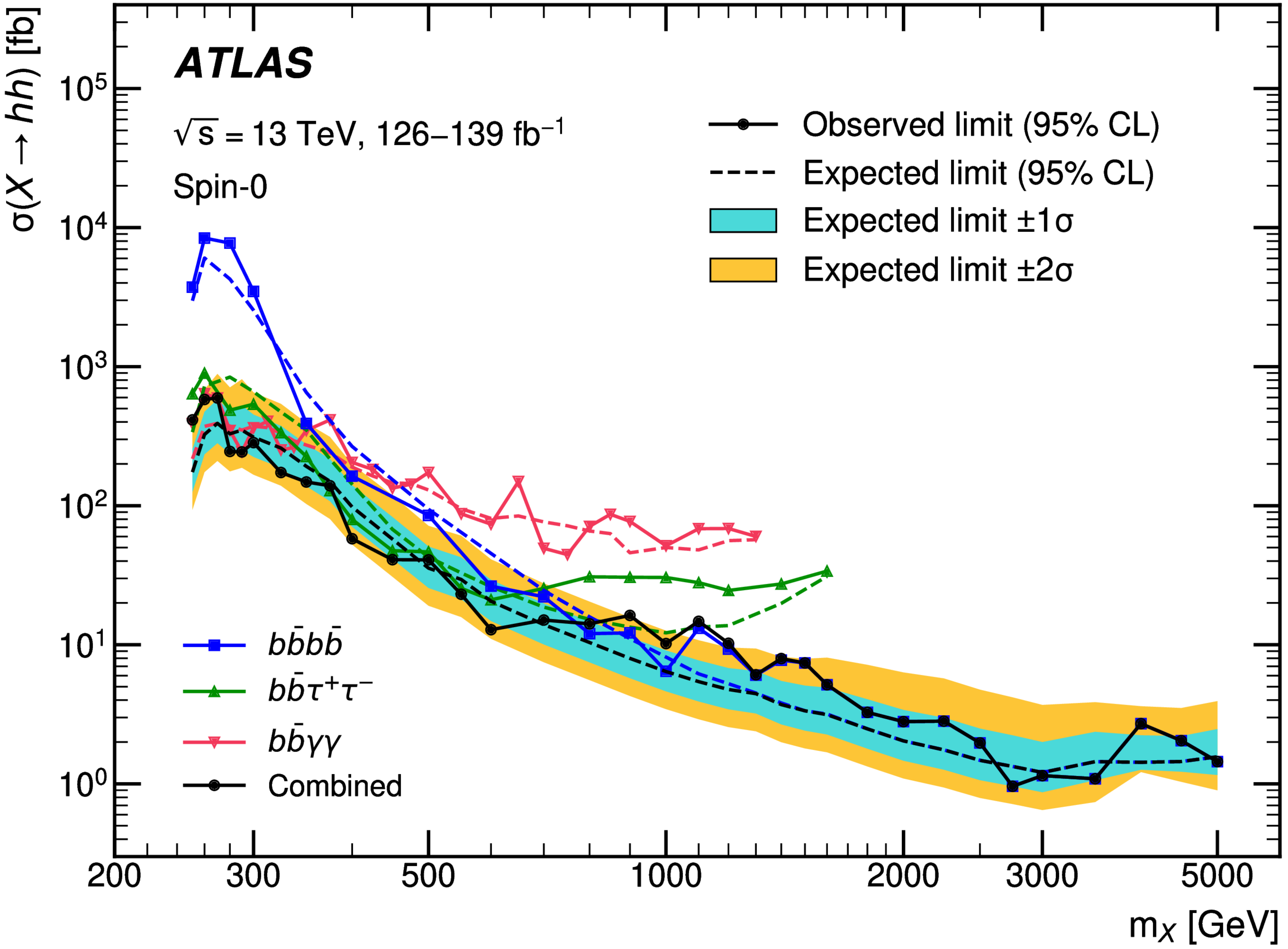


- Small excesses:
  - $\approx 1\,\mathrm{TeV}$ in $b\bar{b}\tau^+\tau^-$
  - $\approx 1.1\,\mathrm{TeV}$ in $b\bar{b}b\bar{b}$
  - nothing in $b\bar{b}\gamma\gamma$, but less sensitive
- Combined:
  - $1.1\,\mathrm{TeV}$: $3.3\,\sigma$ local, $2.1\,\sigma$ global

arXiv:2311.15956

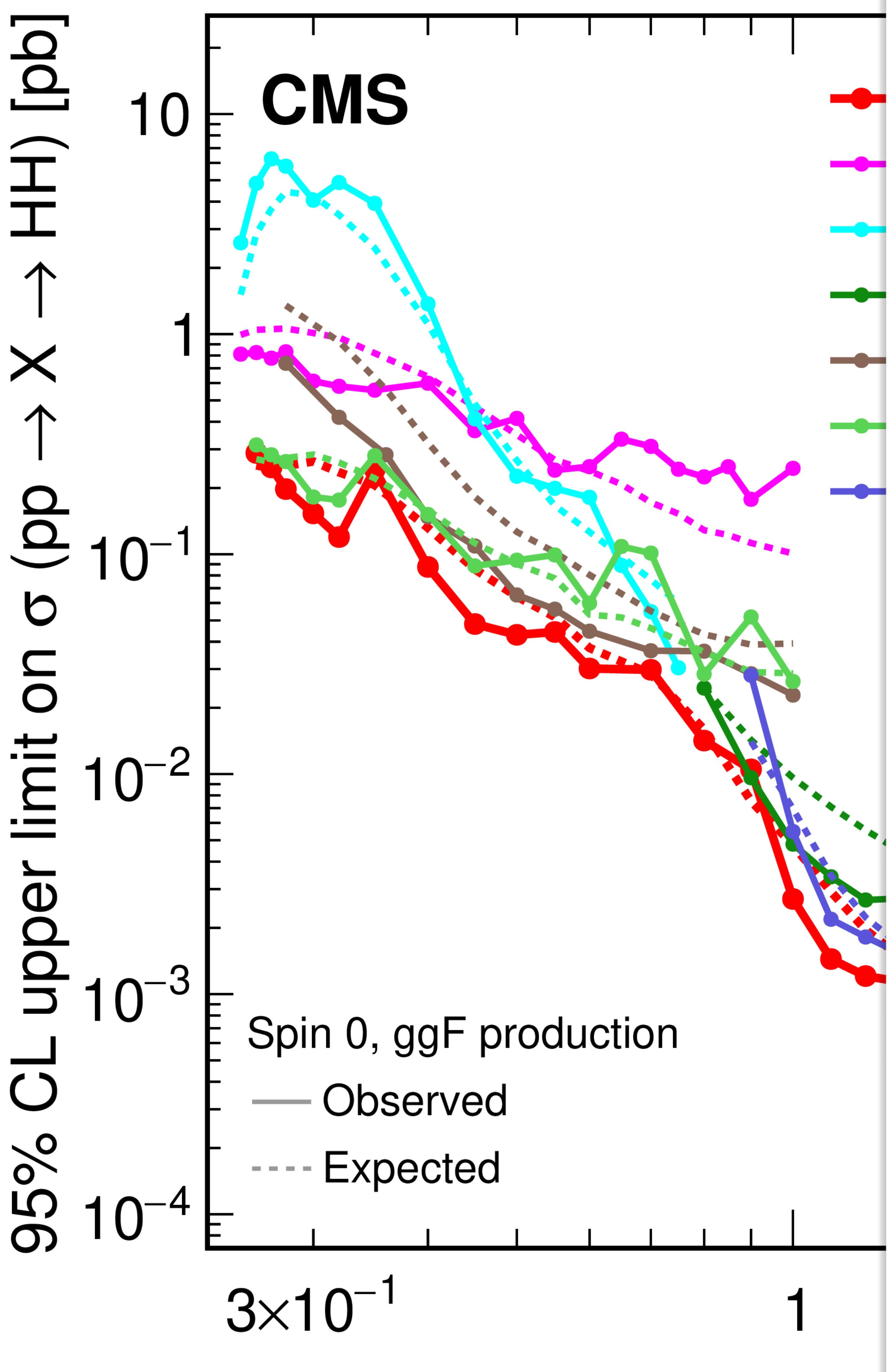
Resonant $X \to H_{125}H_{125}$ Production

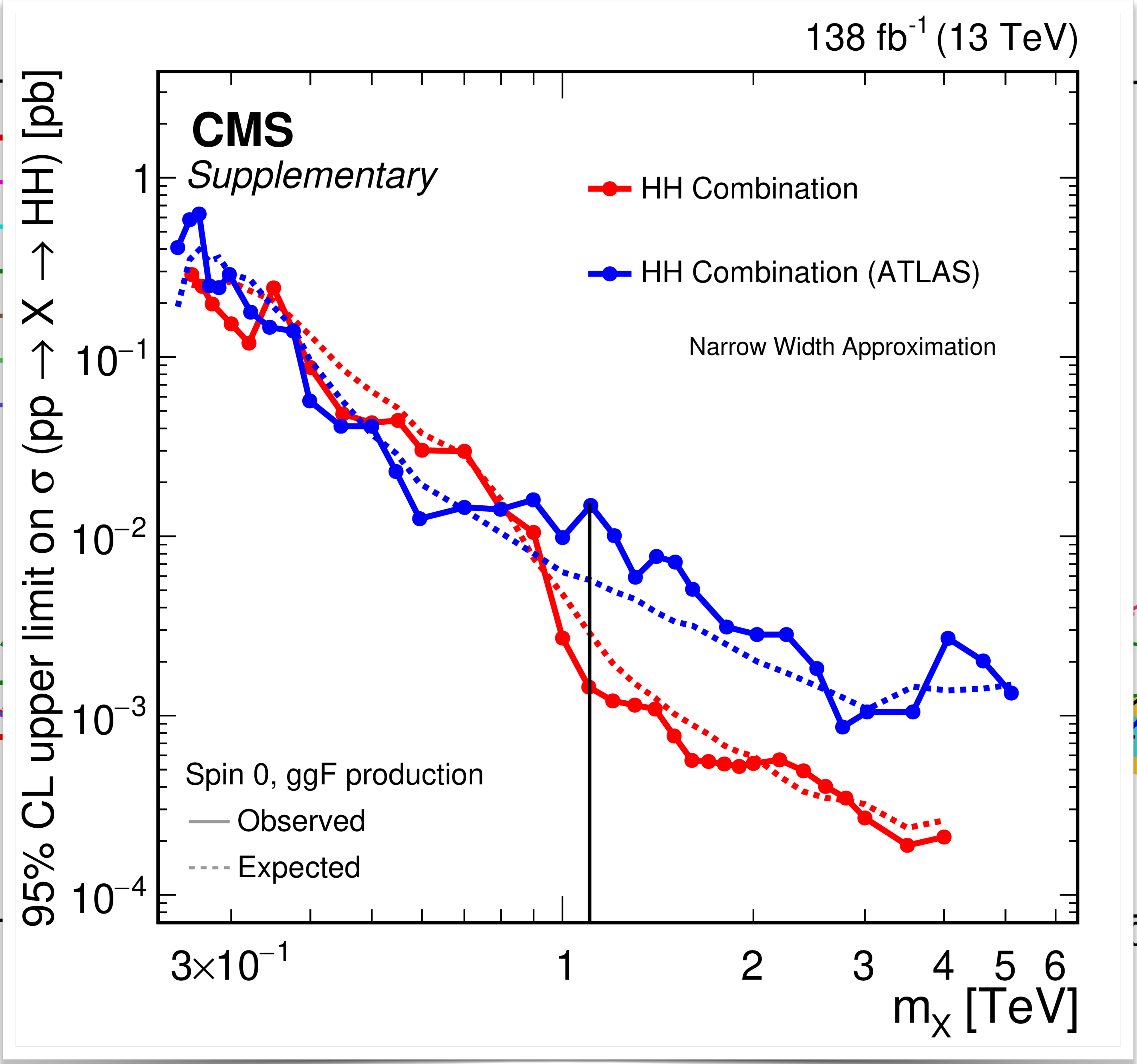


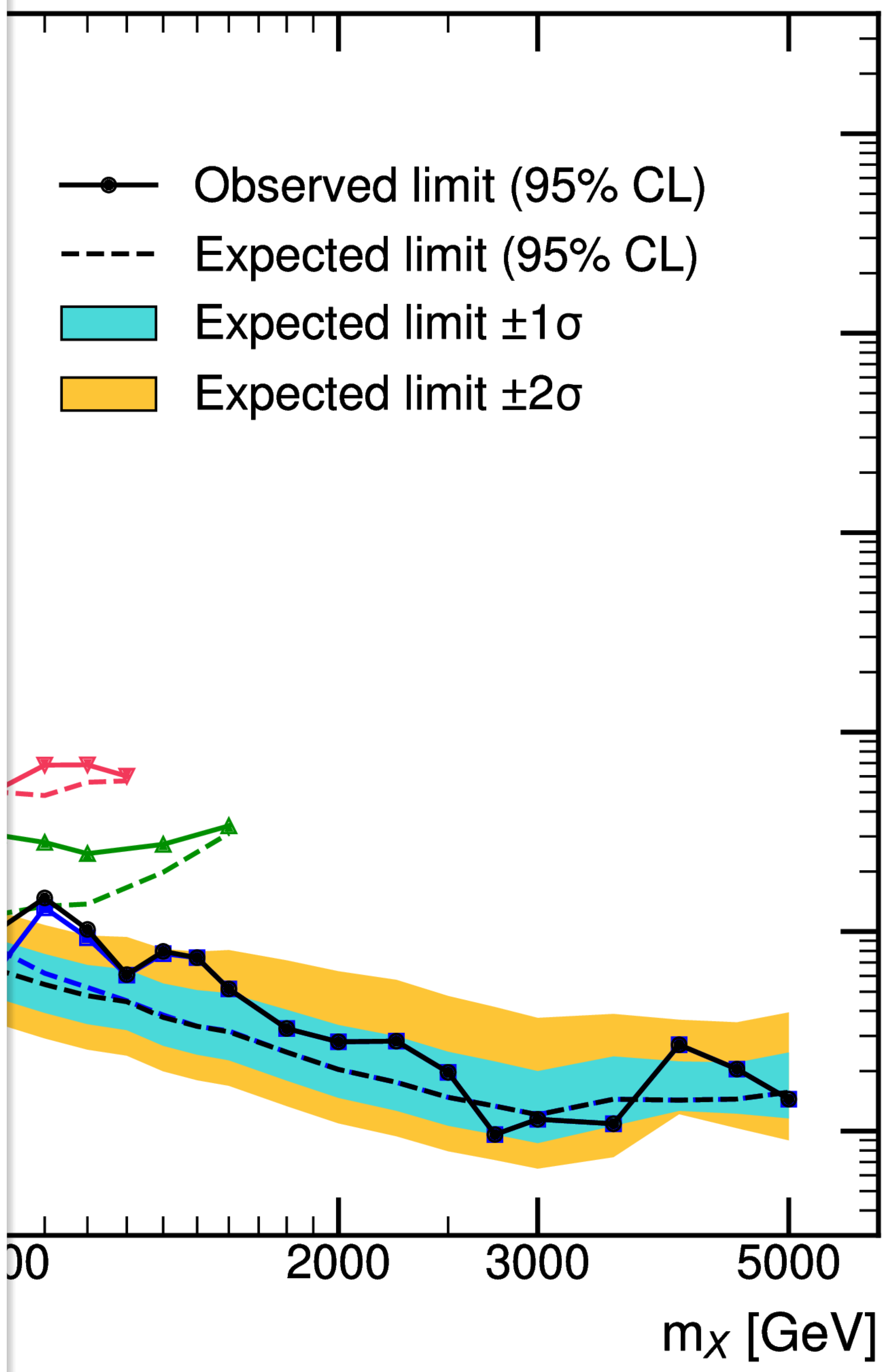


arXiv:2403.16926 arXiv:2311.15956

Resonant $X \rightarrow H_{125}H_{125}$ Production



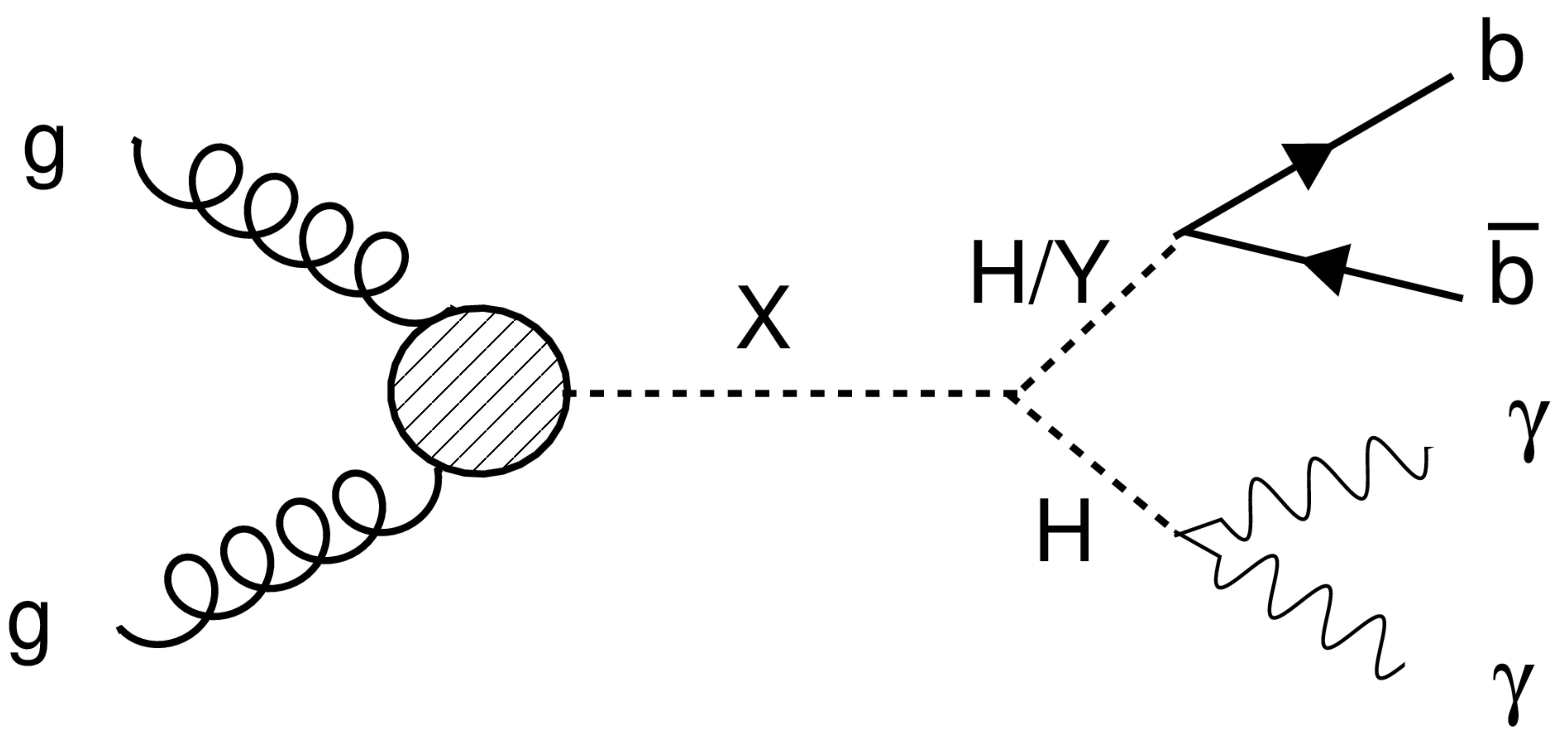




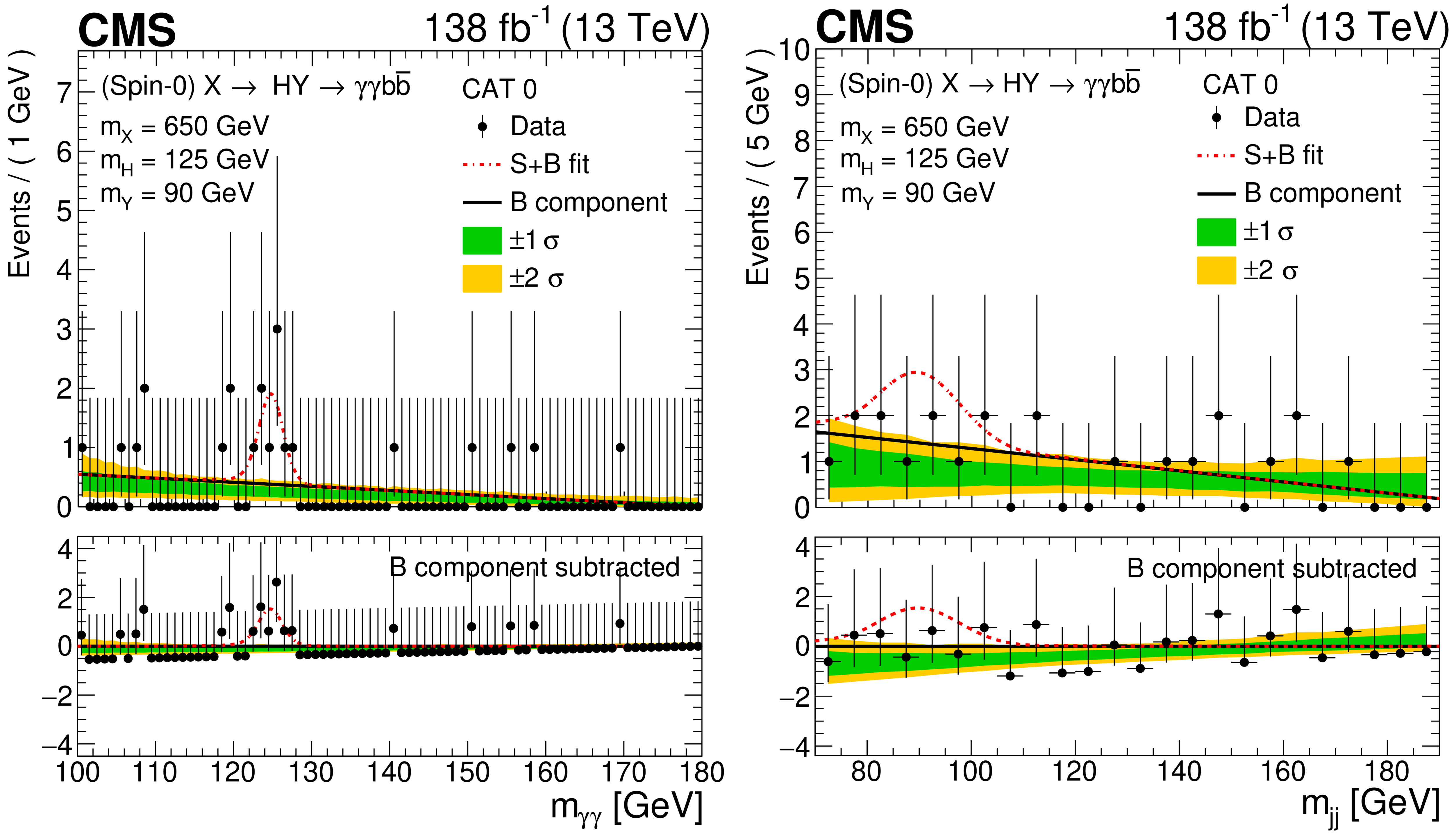
arXiv:2403.16926

arXiv:2311.15956

Resonant $X \to YH_{125}$ Production



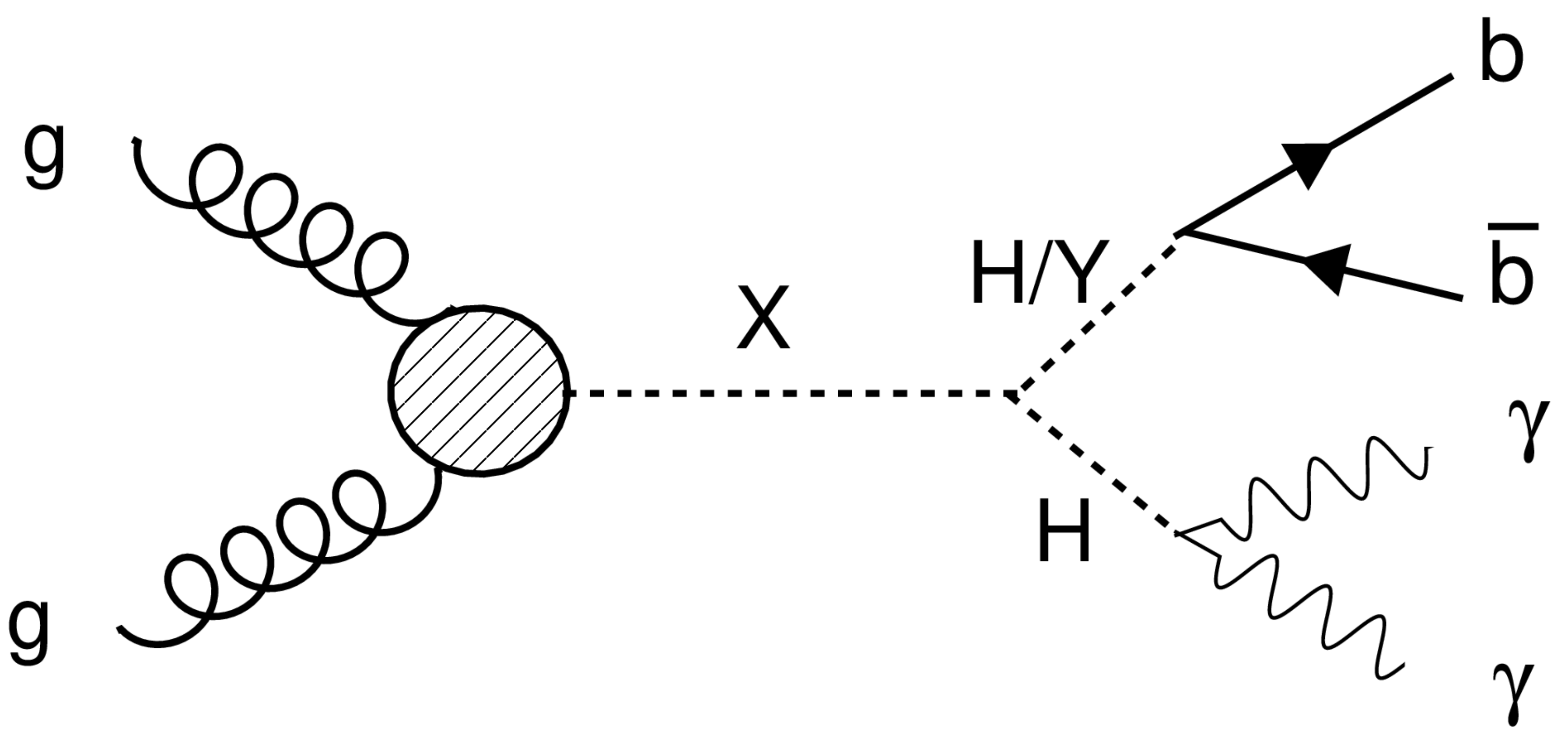
- Pair production of asymmetric-mass Higgs bosons
  - Typical BSM scenarios are beyond MSSM and/or beyond CP-conserving 2HDM



- Largest CMS excess:
  - $m_X = 650\,\mathrm{GeV}$ and $m_Y = 90\,\mathrm{GeV}$
  - $3.8\,\sigma$ local, $2.8\,\sigma$ global
  - Best fit cross section: $0.35^{+0.17}_{-0.13}\,\mathrm{fb}$

arXiv:2310.01643

Resonant $X \to YH_{125}$ Production



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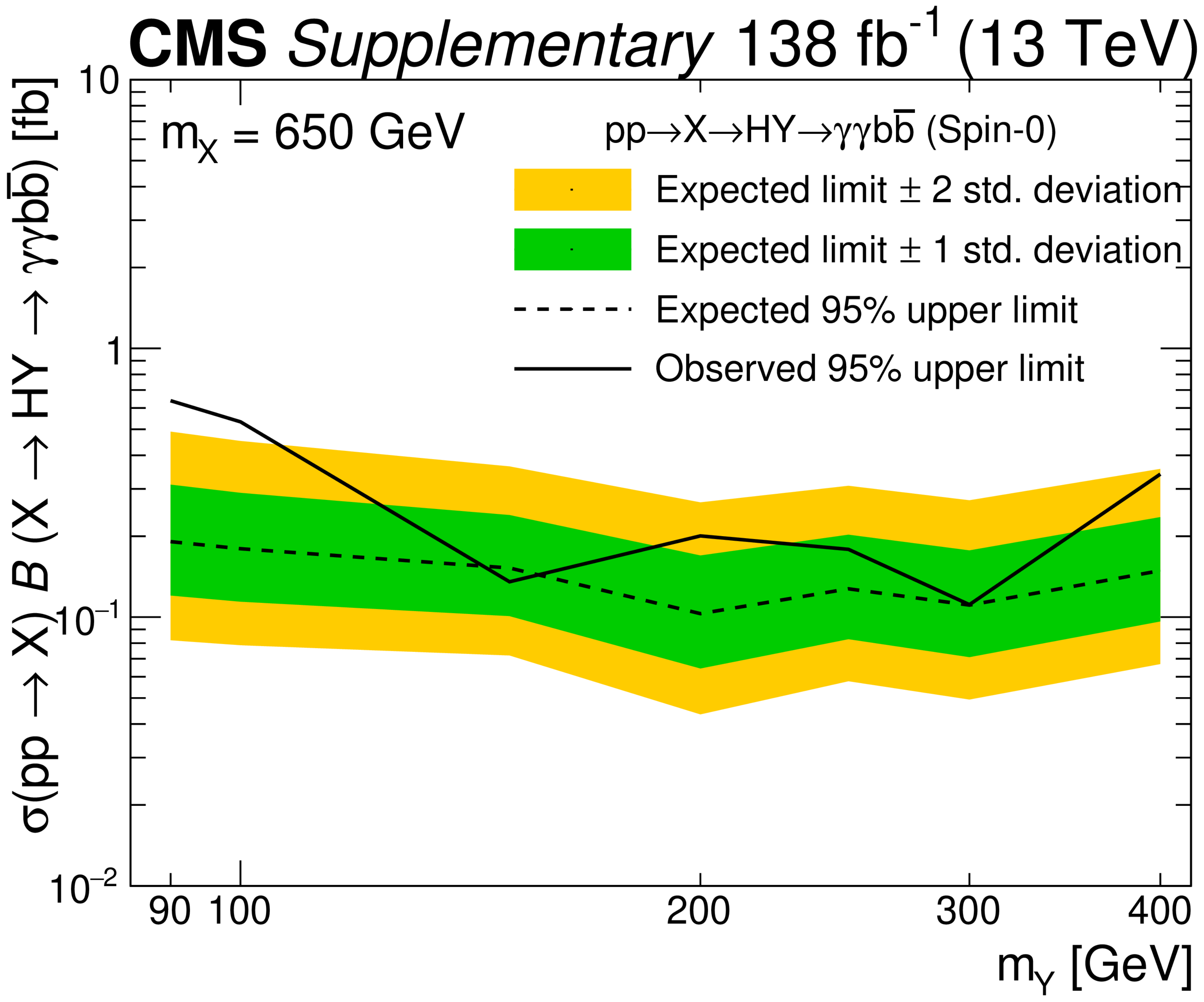

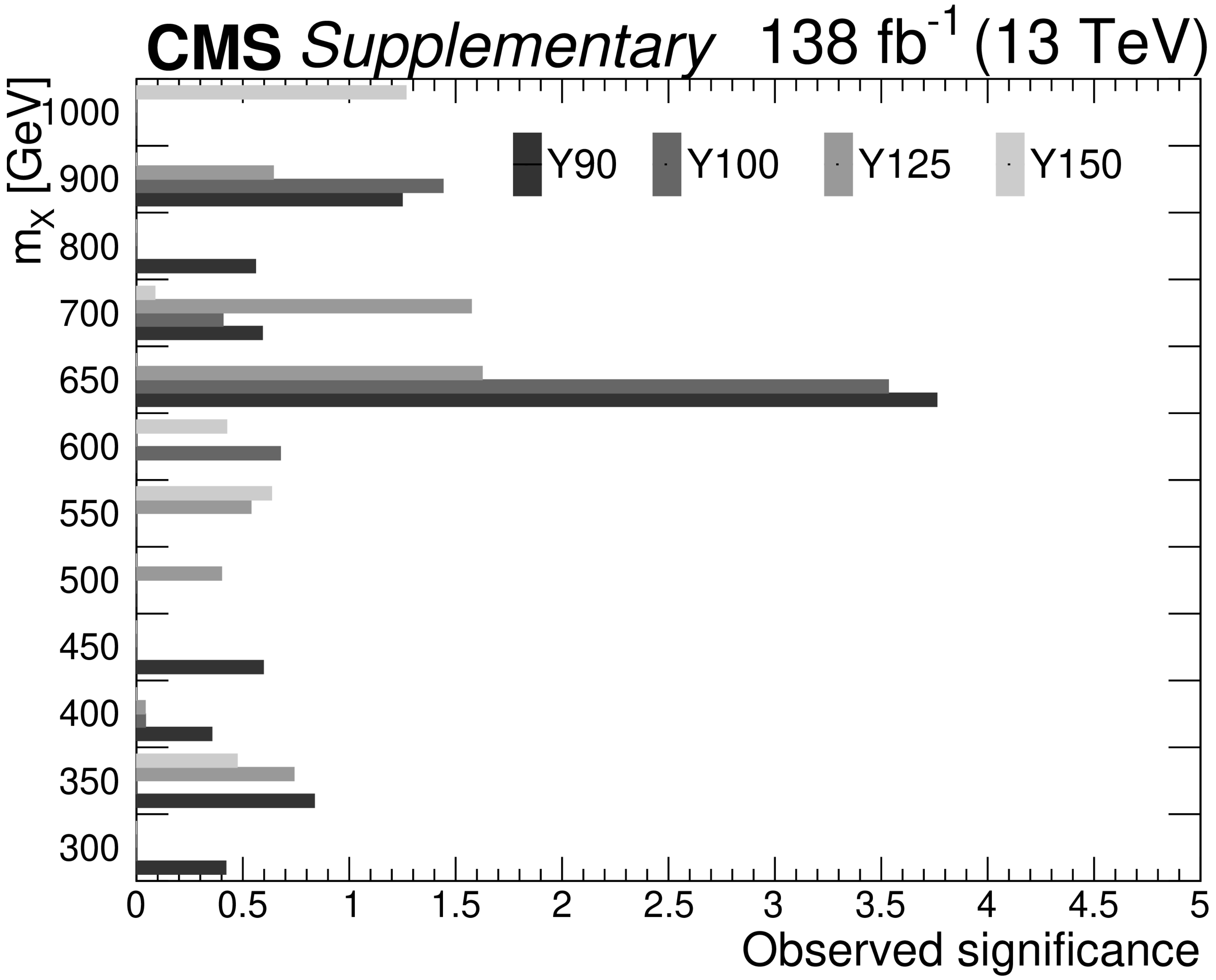

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  - $m_X = 650\,\mathrm{GeV}$ and $m_Y = 90\,\mathrm{GeV}$
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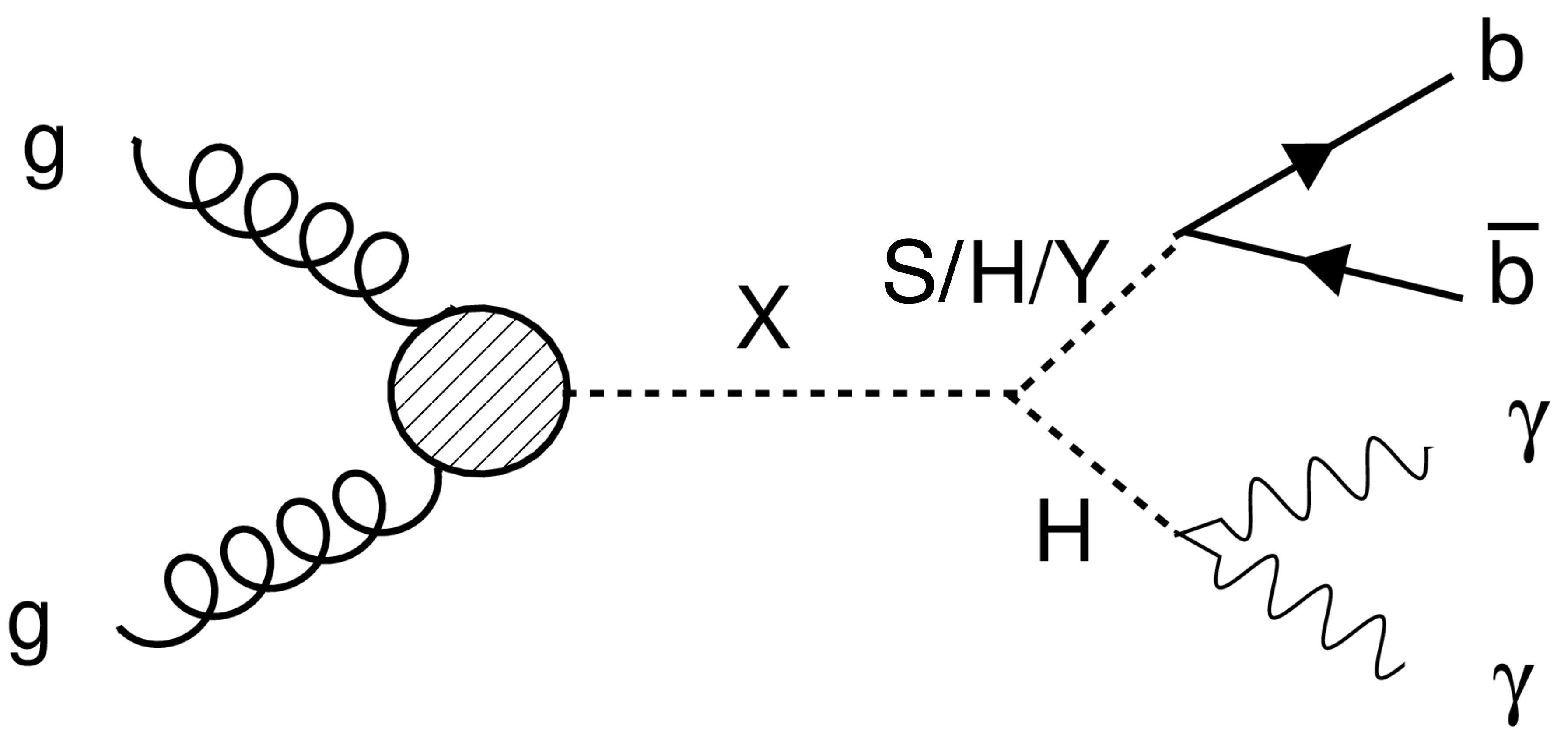
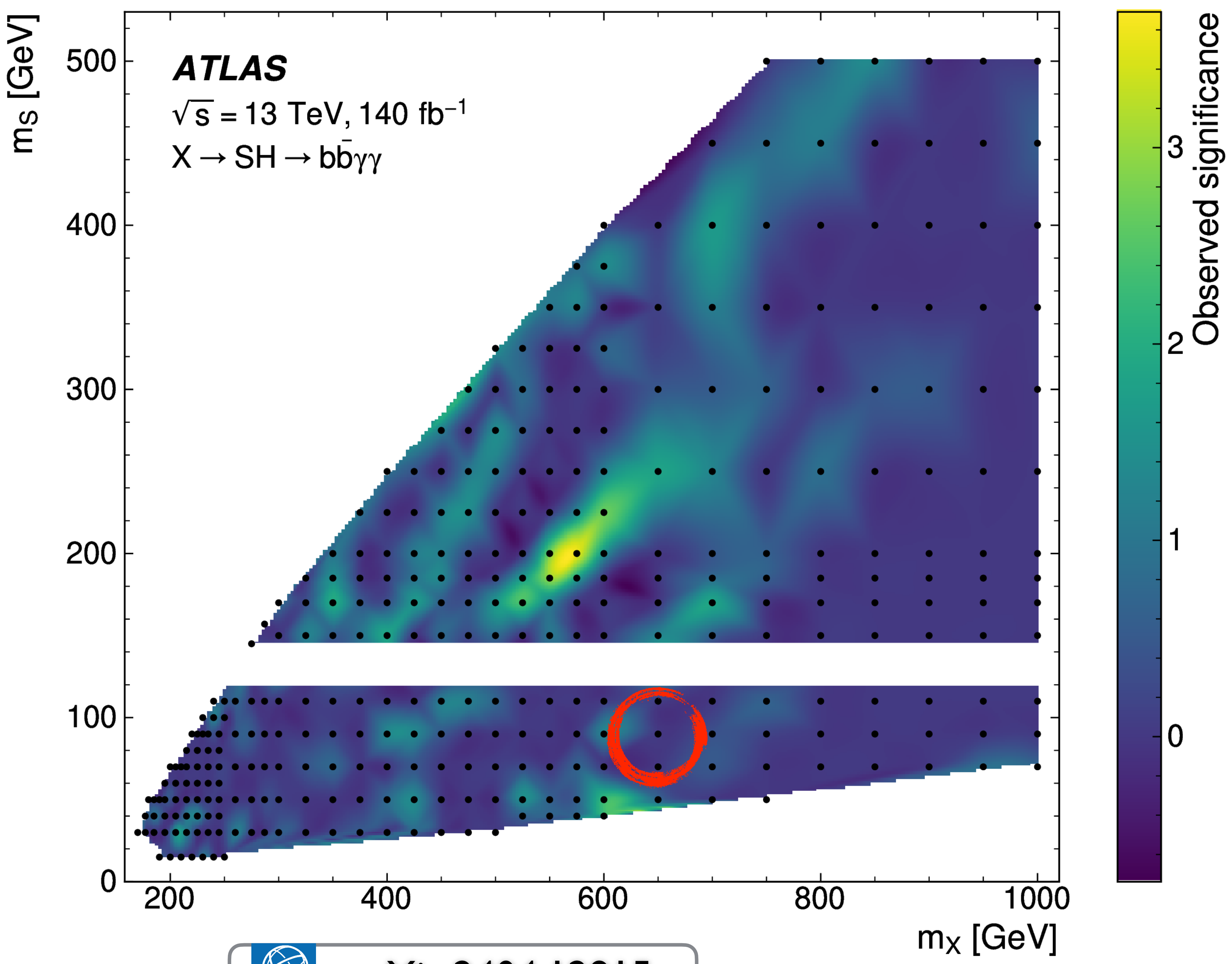
  - Best fit cross section: $0.35^{+0.17}_{-0.13}\,\mathrm{fb}$

arXiv:2310.01643

Resonant $X \to SH_{125}$ Production



- Pair production of asymmetric-mass Higgs bosons
  - Typical BSM scenarios are beyond MSSM and/or beyond CP-conserving 2HDM

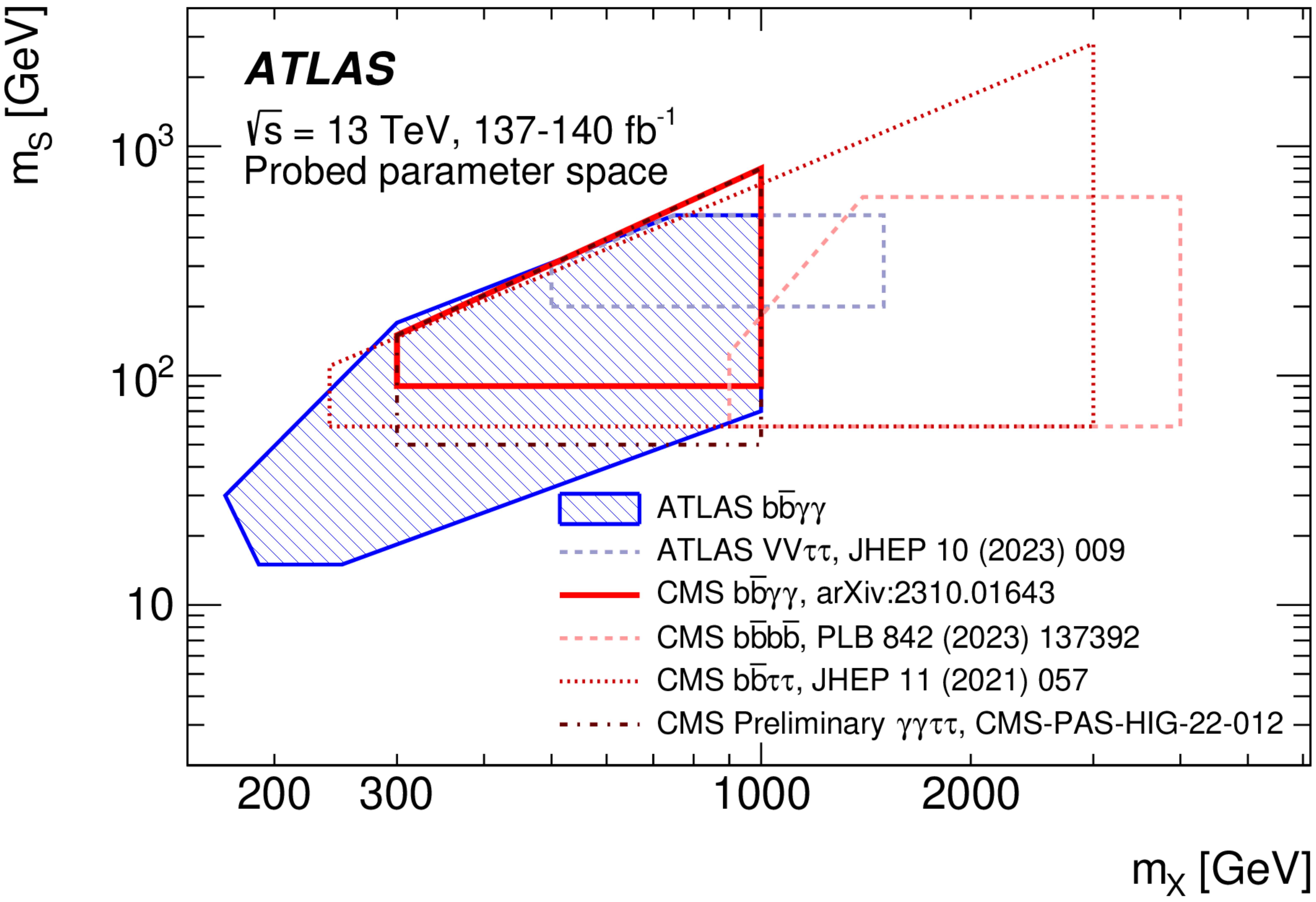


- Largest ATLAS excess:
  - $m_X = 575\,\text{GeV}$ and $m_S = 200\,\text{GeV}$
  - $3.5\,\sigma$ local, $2.0\,\sigma$ global, $\sigma \lesssim 0.97\,\text{fb}$ @ 95% C.L.
    - CMS: $\sigma \lesssim 0.2\,\text{fb}$ @ 95% C.L.
  - Test of CMS excess: Injecting signal with $0.35\,\text{fb}$ would yield $2.7\,\sigma$ local. $\sigma < 0.2\,\text{fb}$ @ 95% C.L.

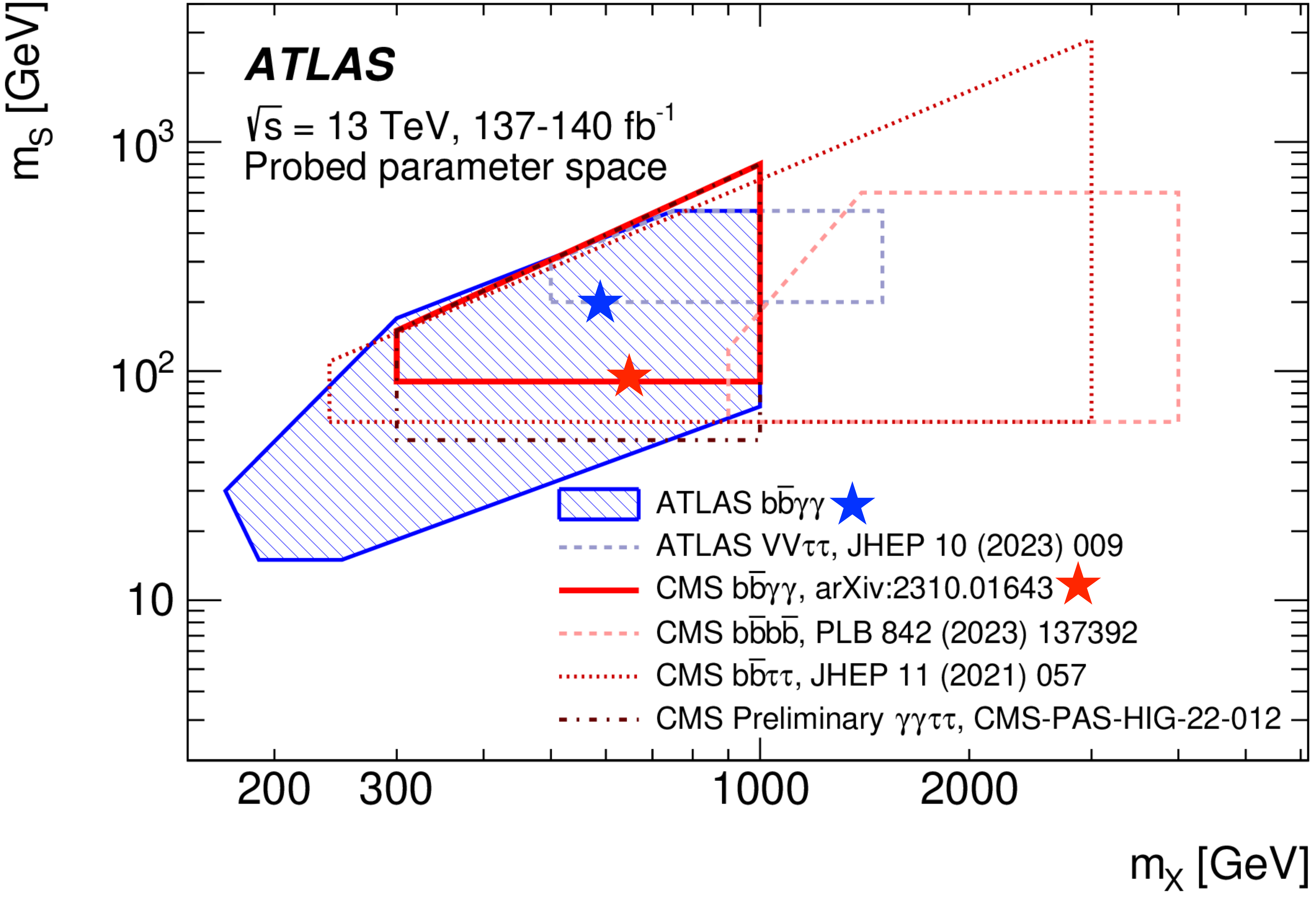
- Largest CMS excess:
  - $m_X = 650\,\text{GeV}$ and $m_Y = 90\,\text{GeV}$
  - $3.8\,\sigma$ local, $2.8\,\sigma$ global
  - Best fit cross section: $0.35^{+0.17}_{-0.13}\,\text{fb}$

arXiv:2404.12915

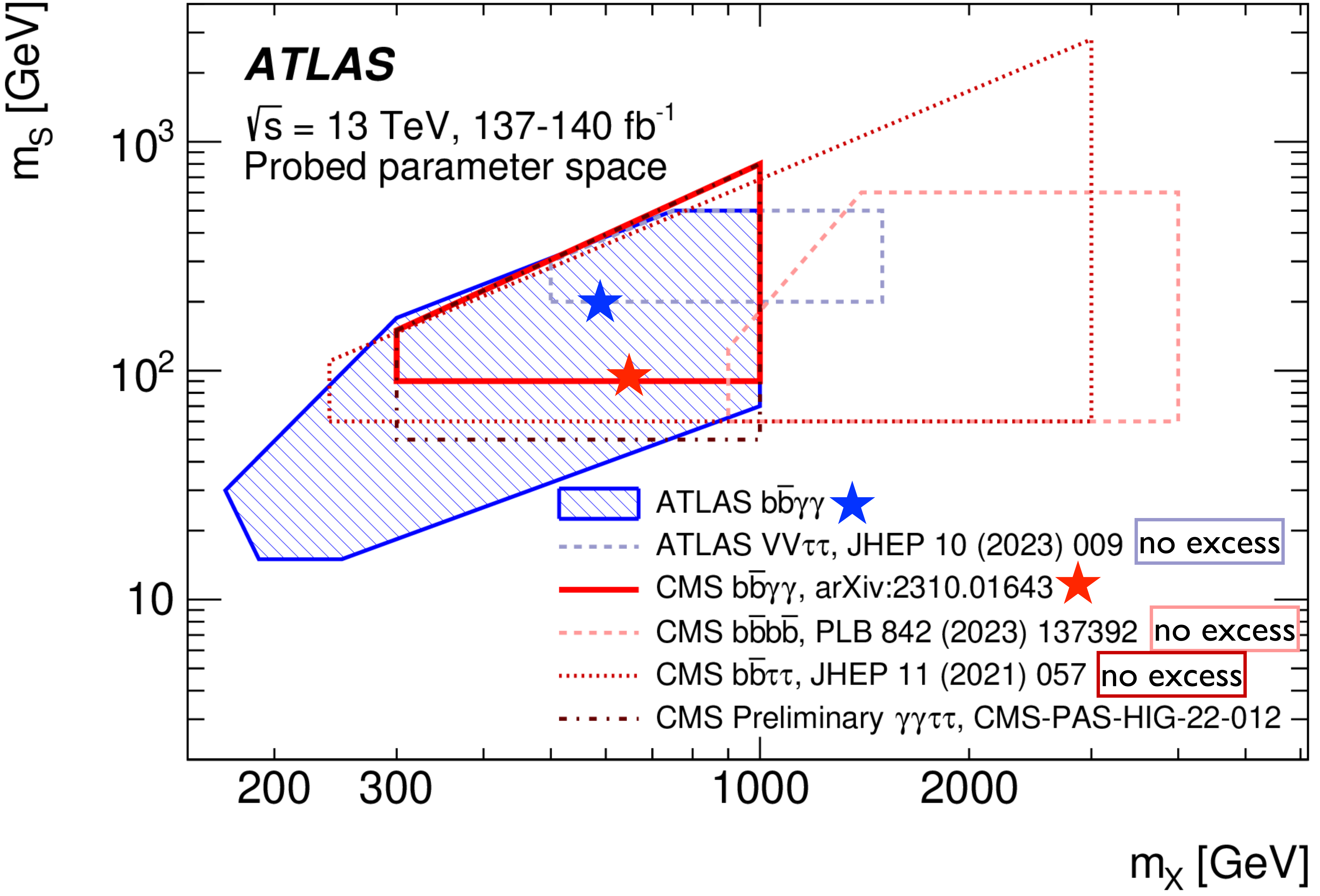
arXiv:2310.01643


ATLAS
√s = 13 TeV, 137-140 fb-1
Probed parameter space
ATLAS bb̄γγ
ATLAS VVττ, JHEP 10 (2023) 009
CMS bb̄γγ, arXiv:2310.01643
CMS bb̄bb̄, PLB 842 (2023) 137392
CMS bb̄ττ, JHEP 11 (2021) 057
CMS Preliminary γγττ, CMS-PAS-HIG-22-012
mS [GeV]
mX [GeV]
10
10^2
10^3
200
300
1000
2000

Resonant $X \to SH_{125}$ Production: Related channels

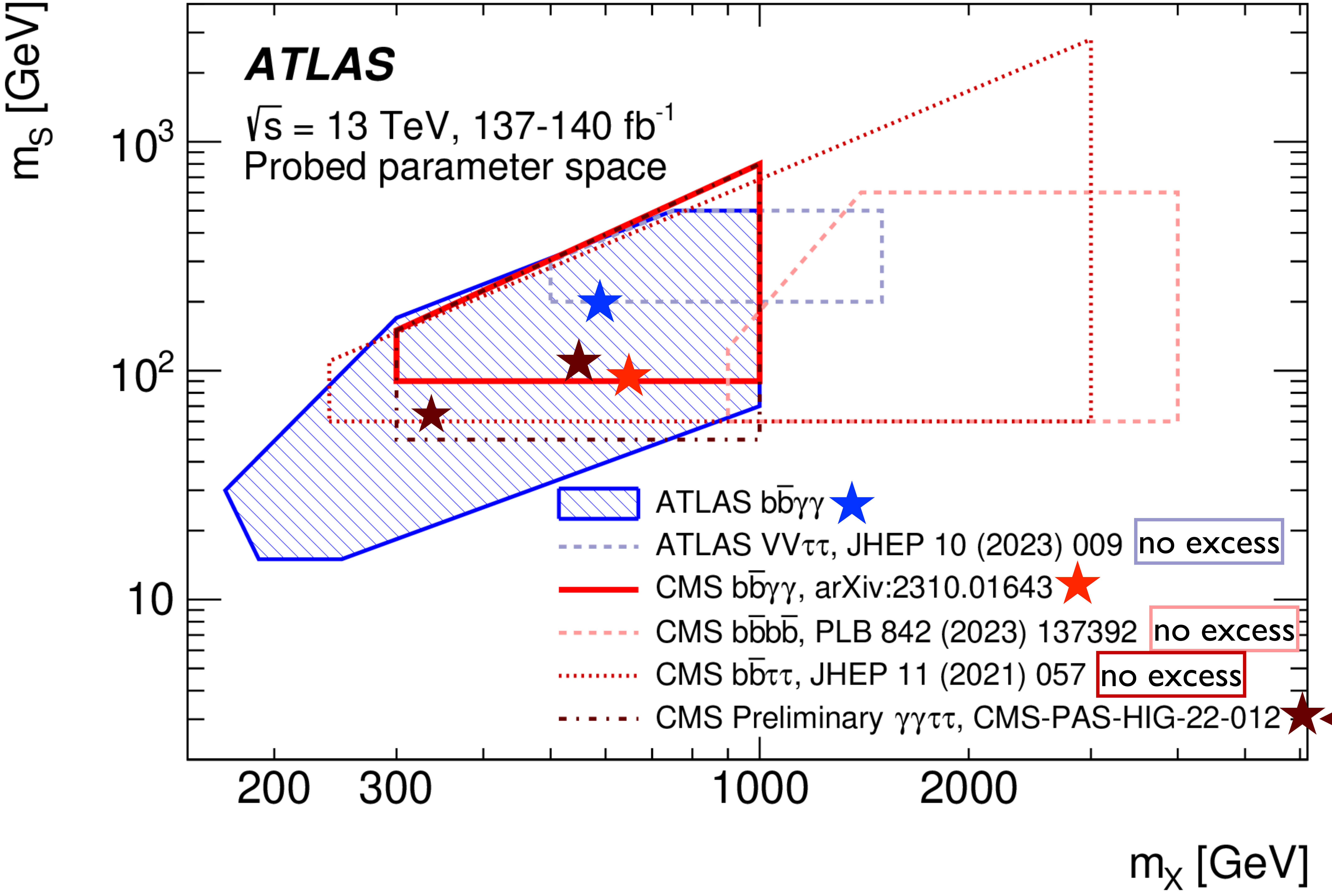


Resonant $X \to SH_{125}$ Production: Related channels



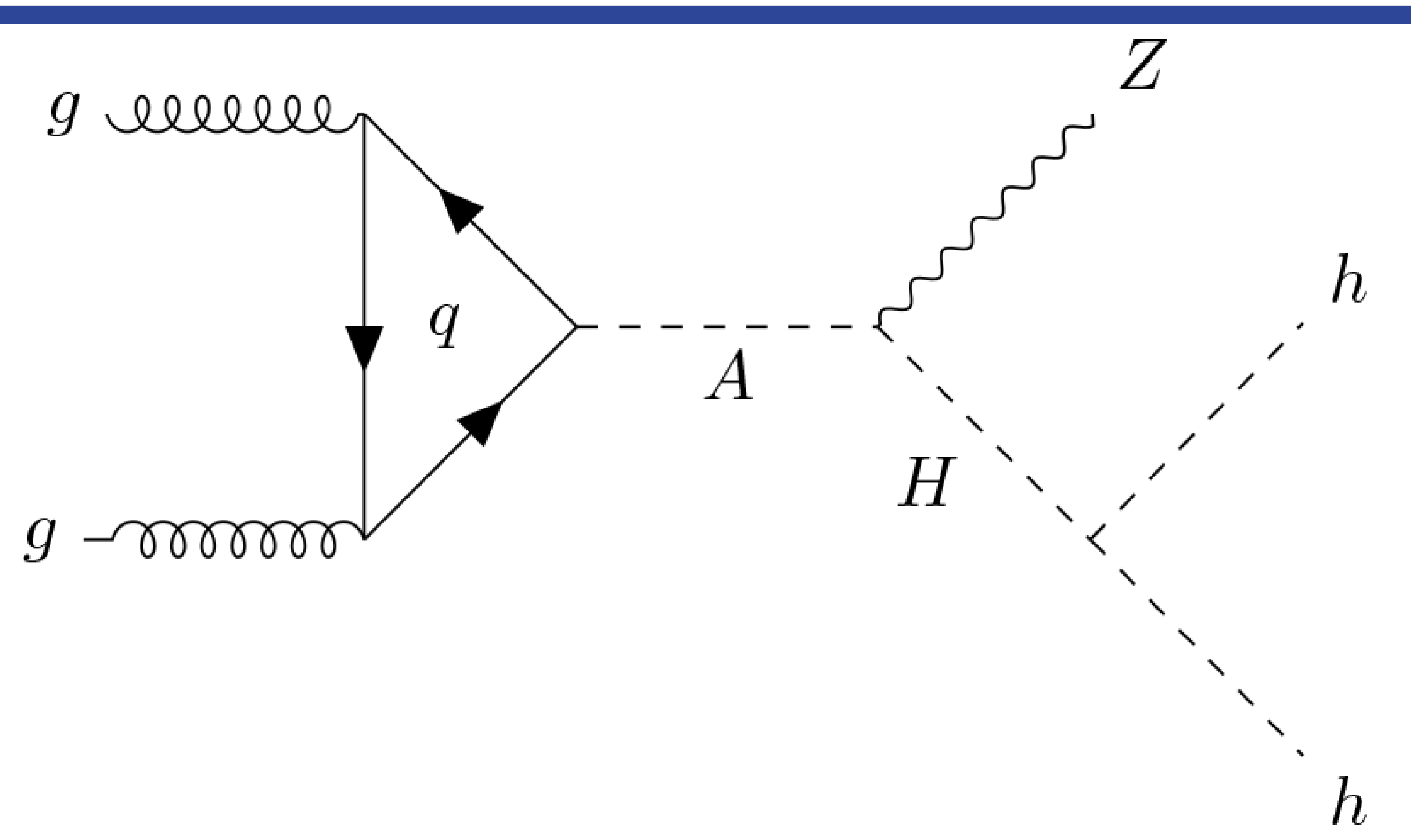
 Karsten Köneke

Resonant $X \to SH_{125}$ Production: Related channels

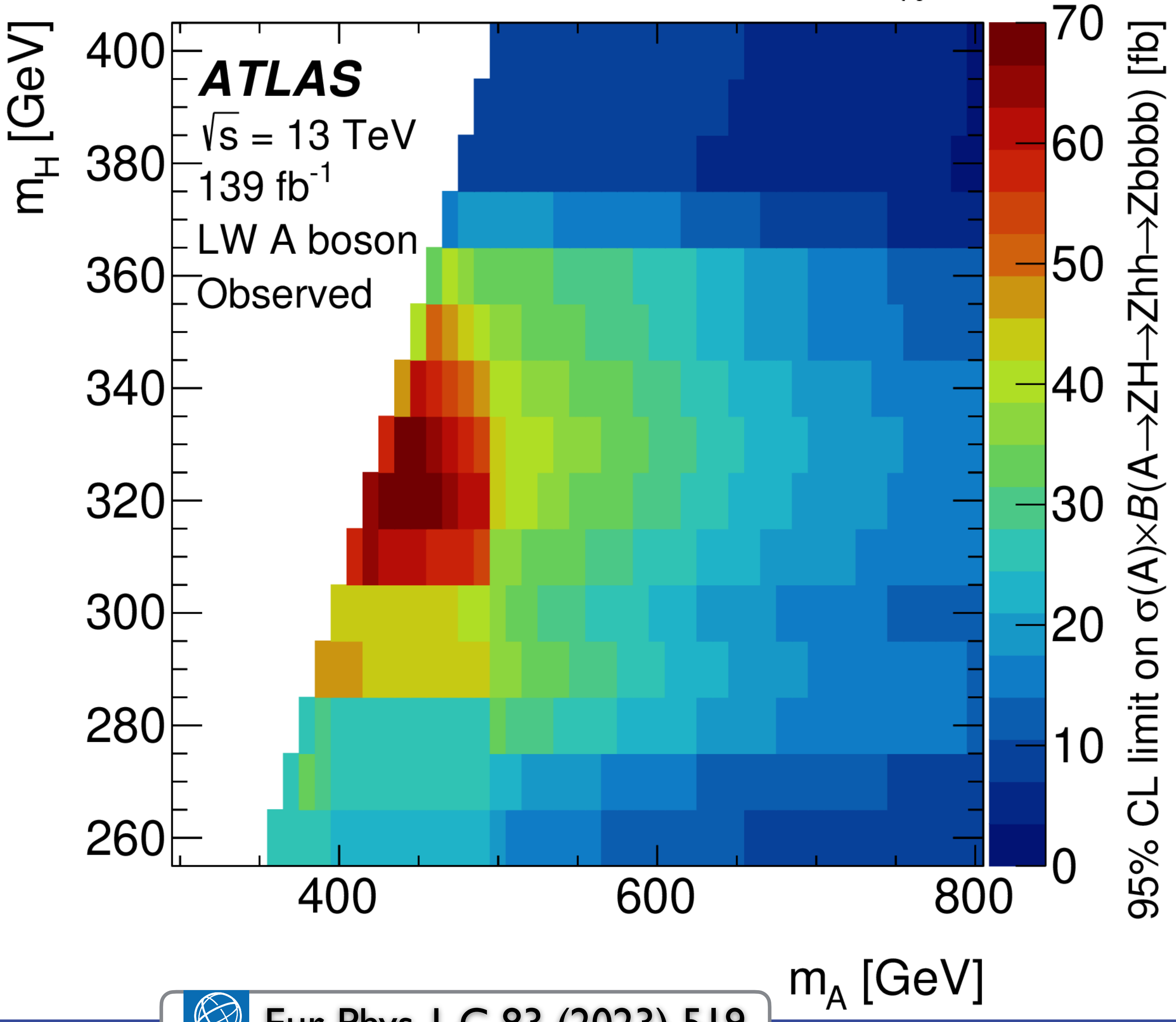


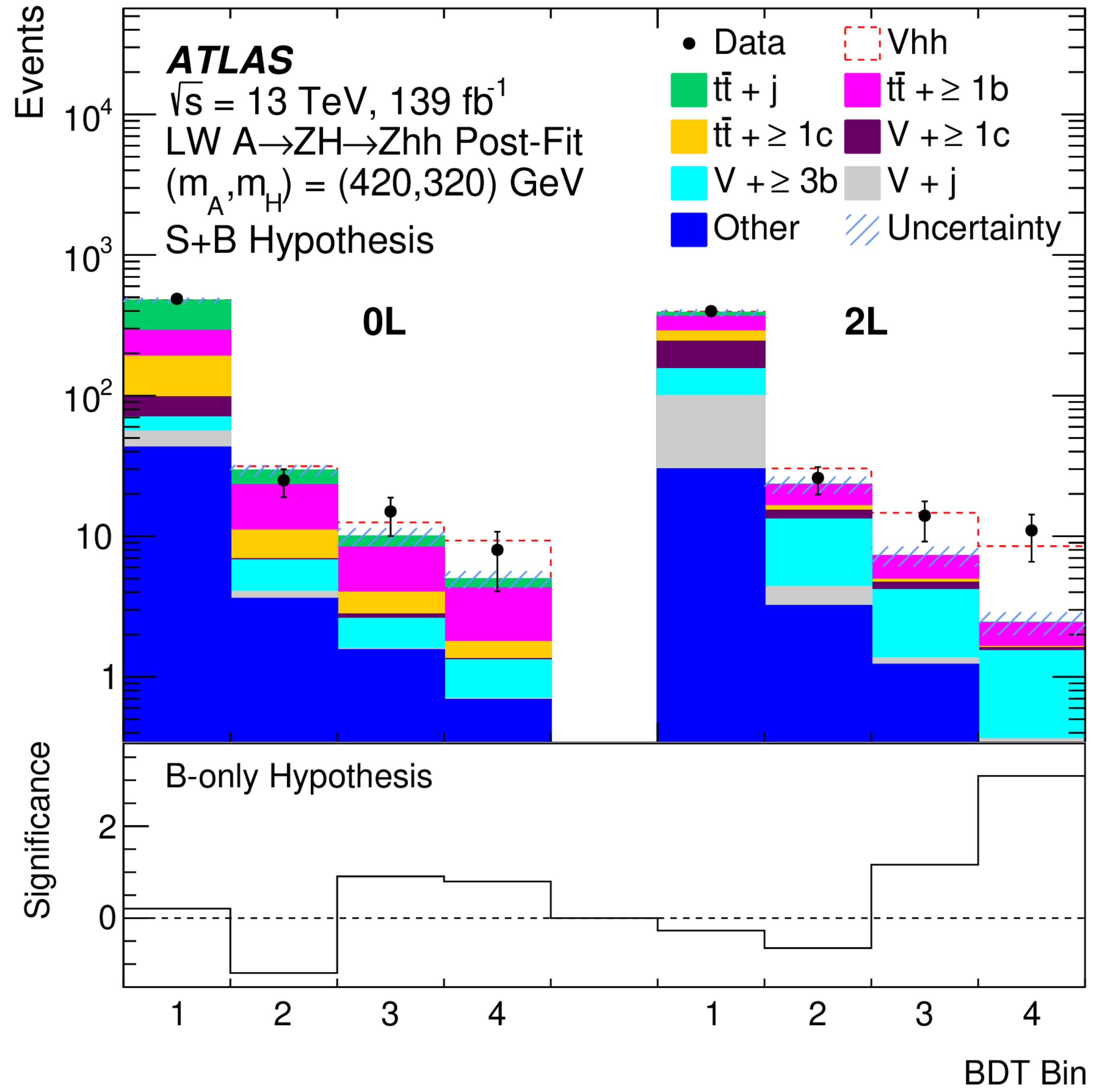
- $m_X = 525$ GeV and $m_{Y\to\gamma\gamma} = 115$ GeV, $3.4\,\sigma$ local, $0.1\,\sigma$ global
- $m_X = 462$ GeV and $m_{Y\to\gamma\gamma} = 161$ GeV, $3.2\,\sigma$ local, $0.3\,\sigma$ global
- $m_X = 320$ GeV and $m_{Y\to\tau\tau} = 60$ GeV, $2.6\,\sigma$ local, $2.2\,\sigma$ global

$A \to ZH \to Zh_{125}h_{125} \to Zb\bar{b}b\bar{b}$



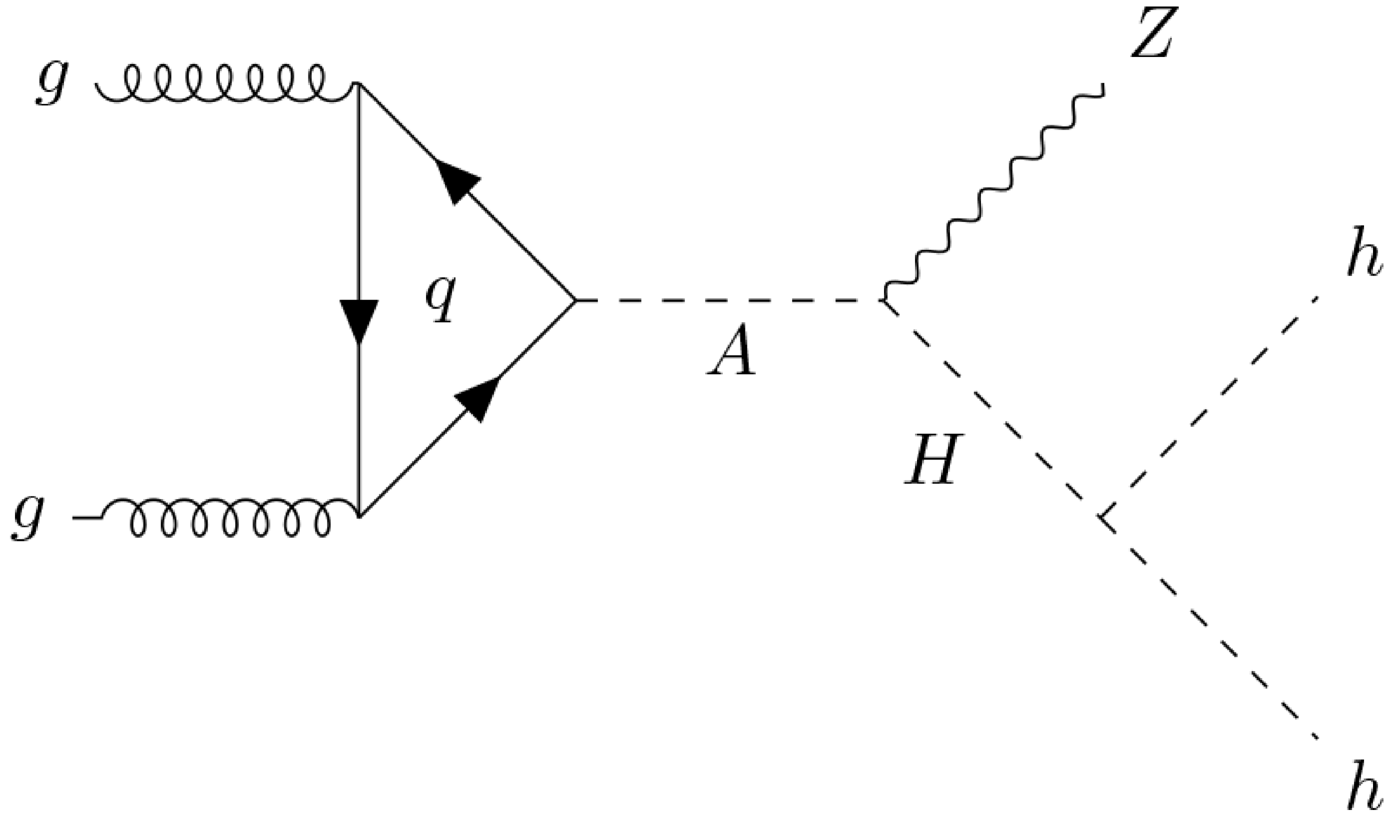
- Search narrow and large width of A boson
  - Largest excess for large width (20% of mass) A boson scenario:
    - $(m_\mathrm{A}, m_\mathrm{H}) = (420, 320)$ GeV:
    - 3.8σ (2.8σ) local (global) significance



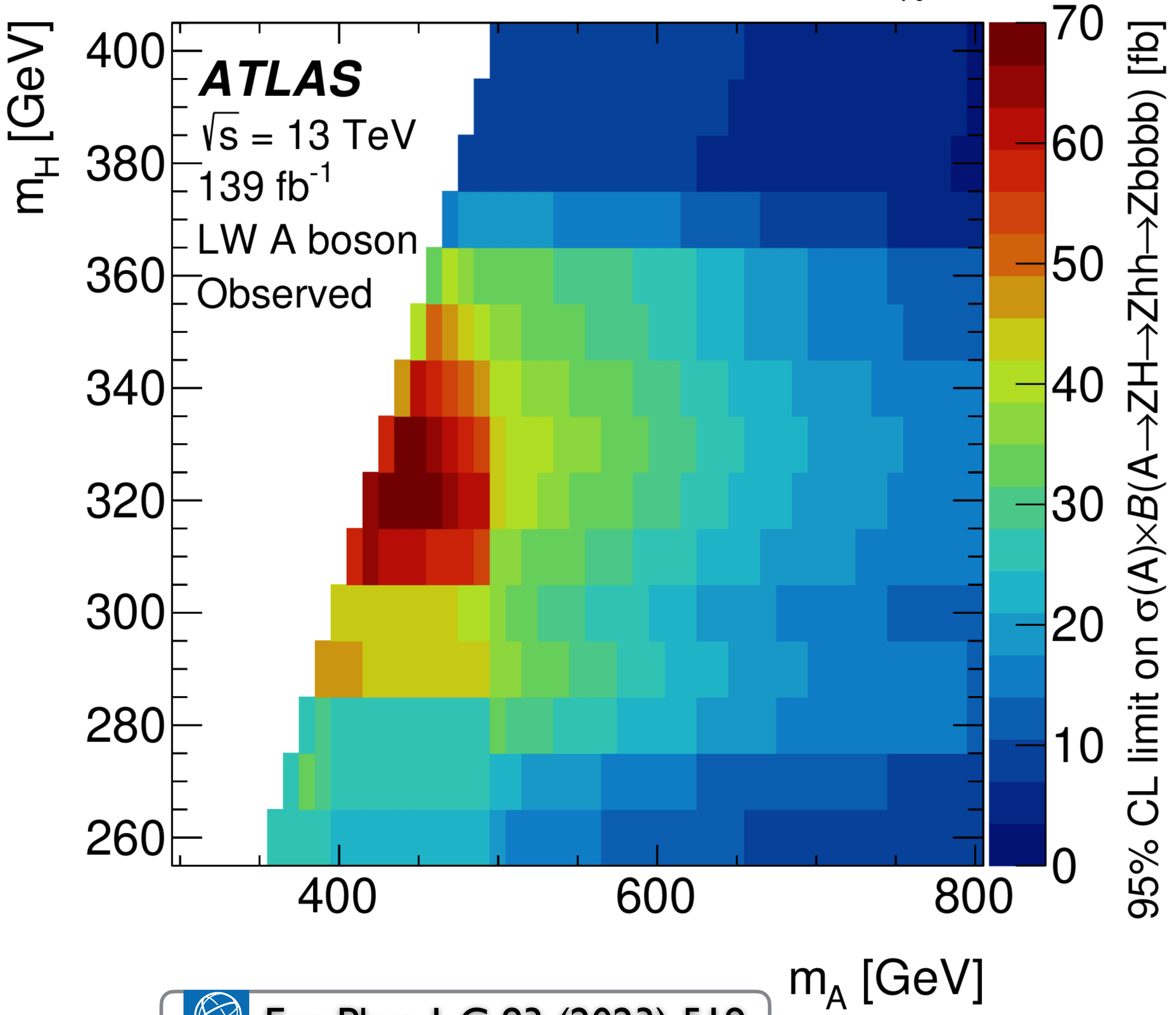


Eur. Phys. J. C 83 (2023) 519

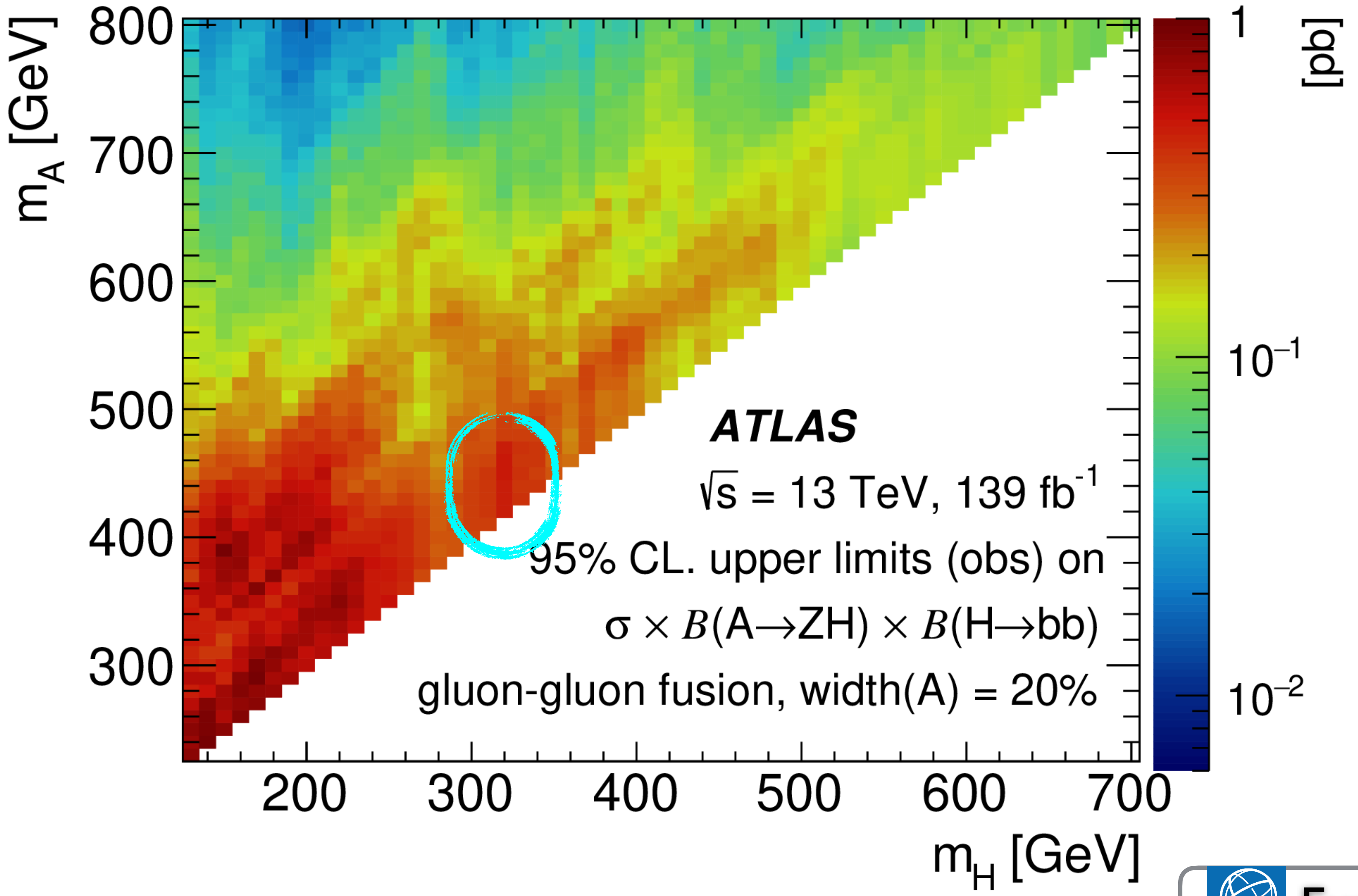
$A \rightarrow ZH \rightarrow Zh_{125}h_{125} \rightarrow Zb\bar{b}b\bar{b}$

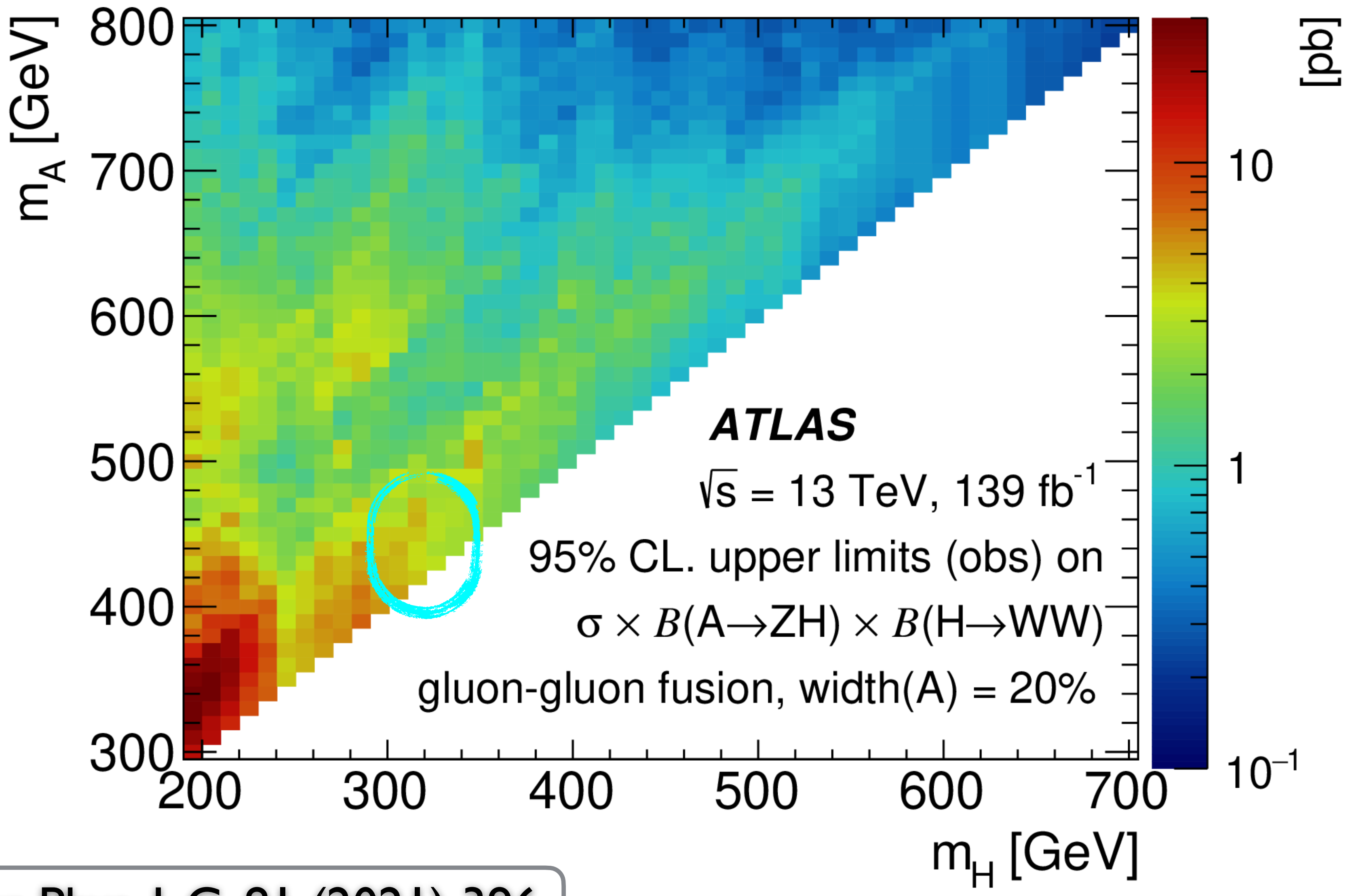


- Search narrow and large width of A boson
  - Largest excess for large width (20% of mass) A boson scenario:
    - $(m_A, m_H) = (420, 320)$ GeV:
    - 3.8σ (2.8σ) local (global) significance
- ATLAS searches for $A \rightarrow ZH \rightarrow Zbb$ and $A \rightarrow ZH \rightarrow ZWW$ do not show pronounced excess



Eur. Phys. J. C 83 (2023) 519

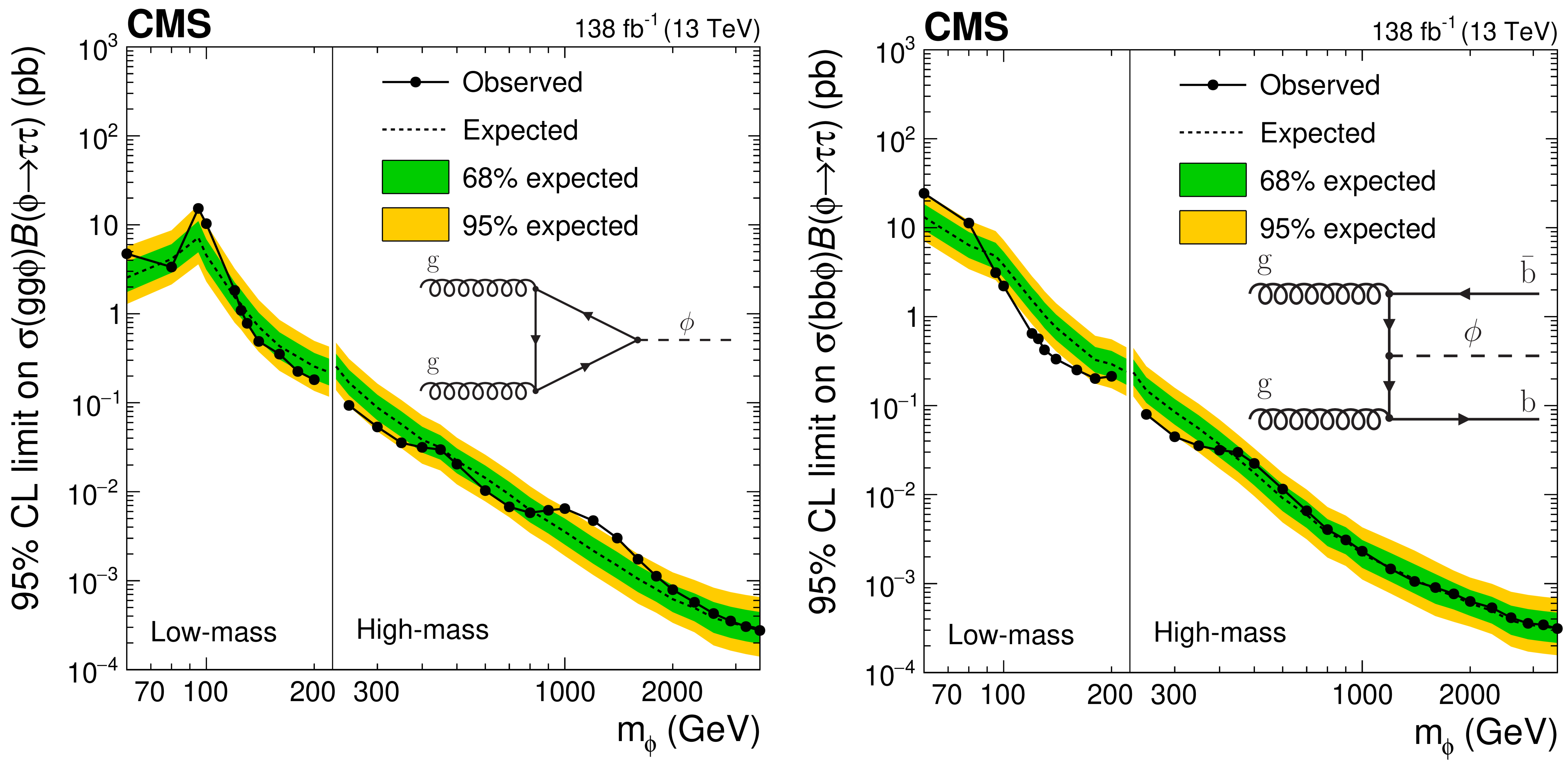




Eur. Phys. J. C. 81 (2021) 396

$\phi \to \tau^+\tau^-$

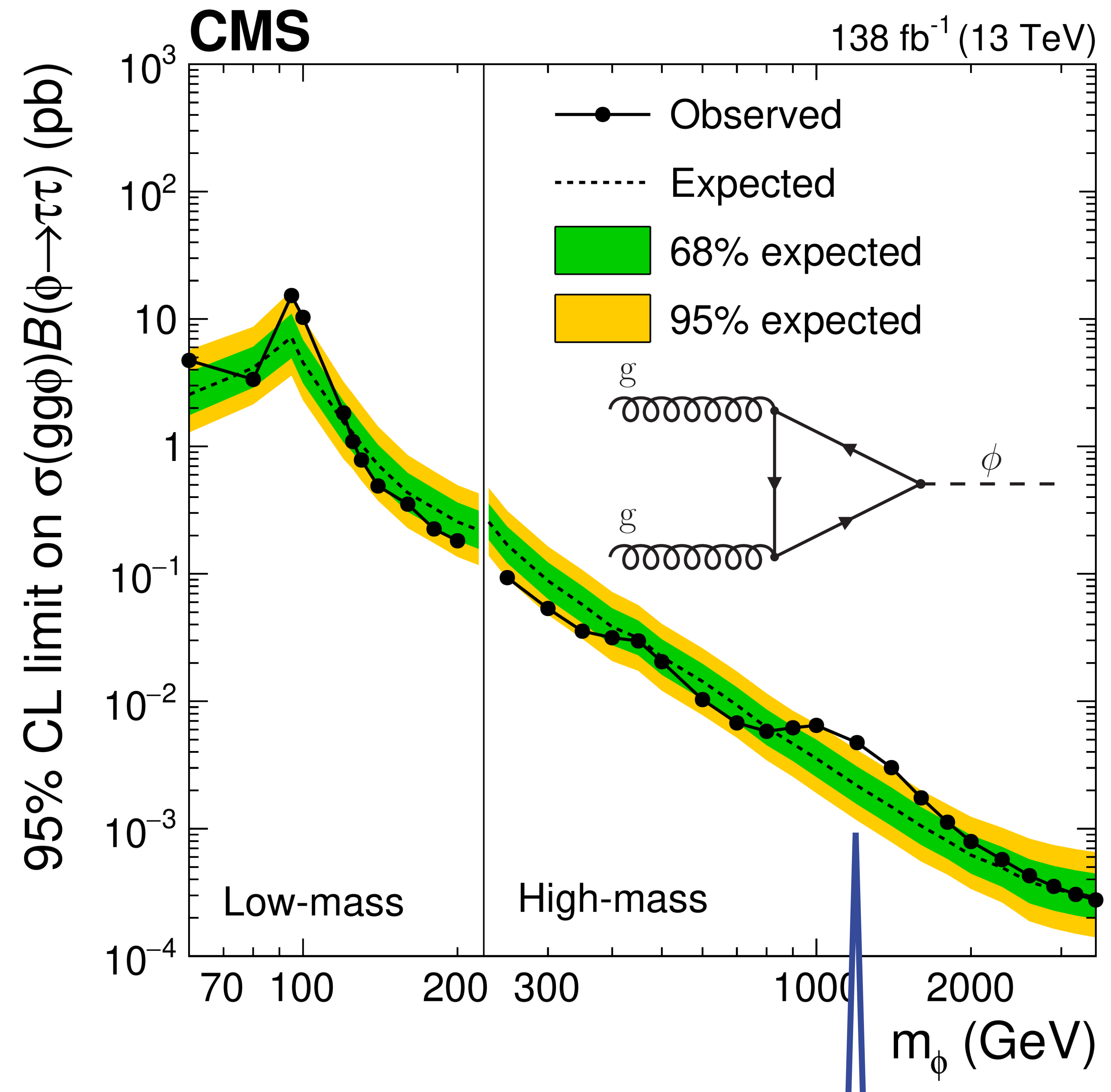
- $\phi \to \tau\tau$ search, 60-3500 GeV:
  - Final states: $e\mu, e\tau_{\text{had}}, \mu\tau_{\text{had}}, \tau_{\text{had}}\tau_{\text{had}}$

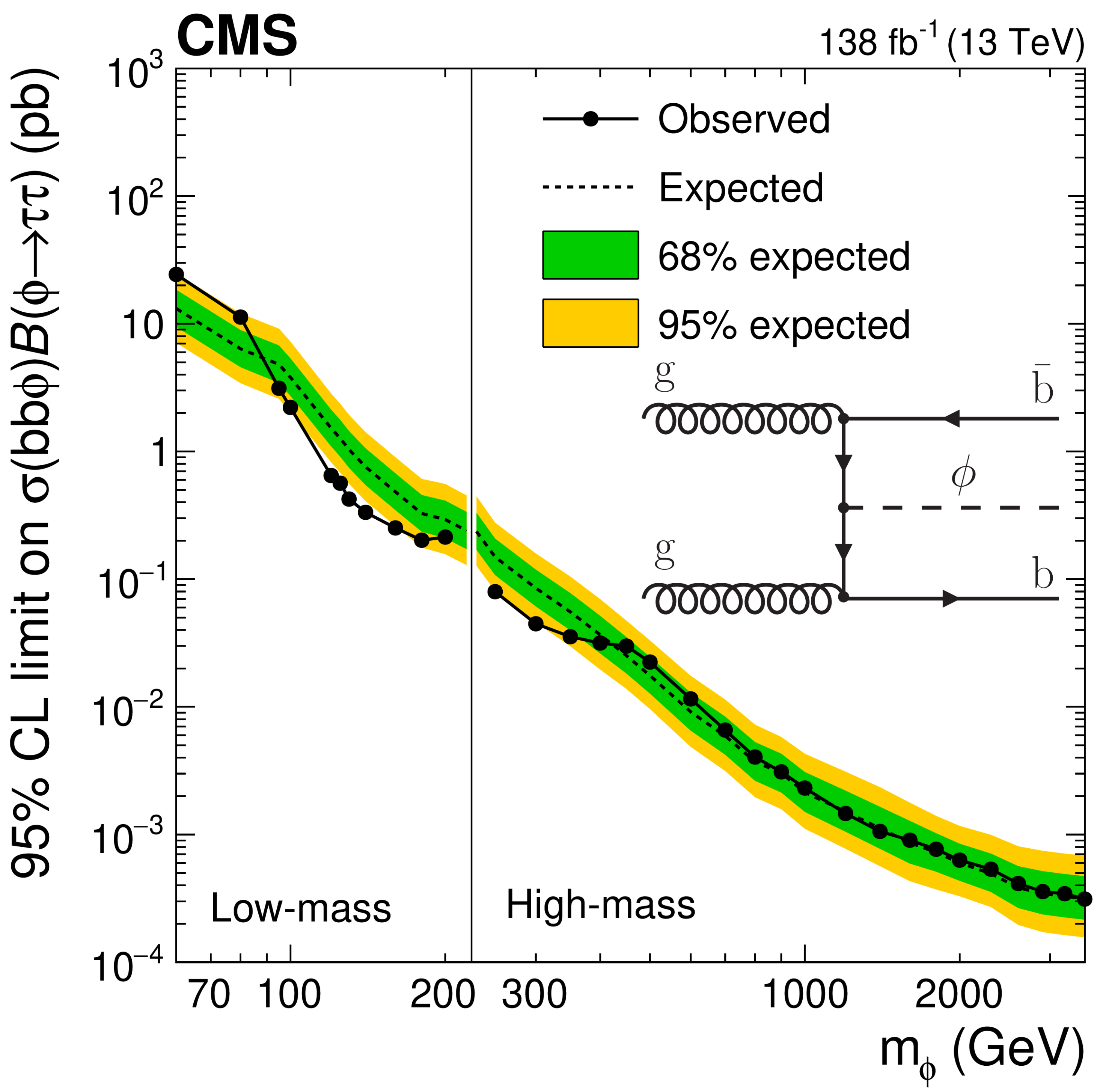


JHEP 07 (2023) 073

$\phi \to \tau^+\tau^-$

- $\phi \to \tau\tau$ search, 60-3500 GeV:
  - Final states: $e\mu$, $e\tau_{\text{had}}$, $\mu\tau_{\text{had}}$, $\tau_{\text{had}}\tau_{\text{had}}$





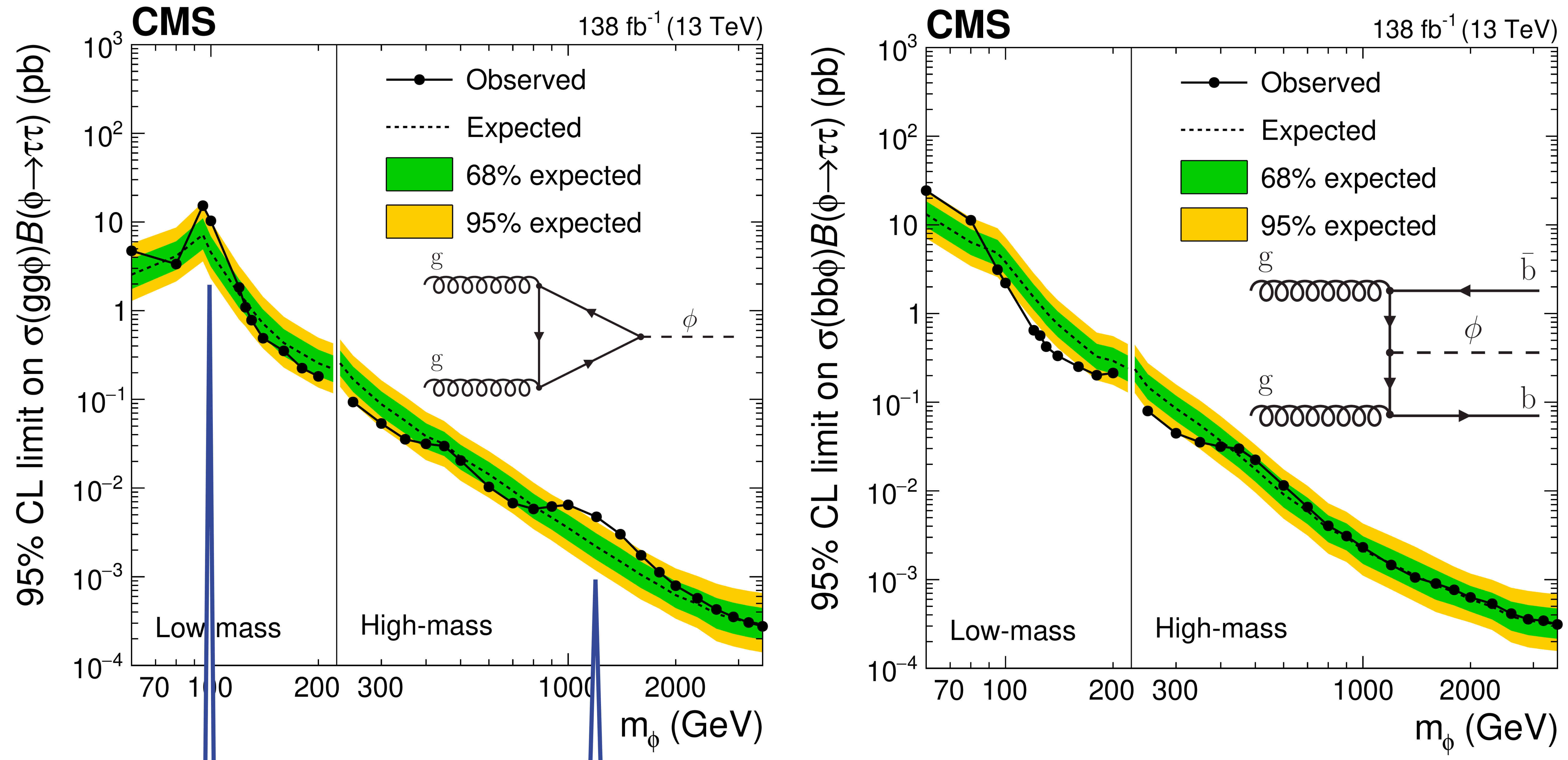
$m_\phi = 1200\,\text{GeV}$:

- $2.8\,\sigma$ local, $2.2\,\sigma$ global;
- Best fit $\sigma_{gg\phi}\mathcal{B}\left(\phi \to \tau\tau\right) = \left(3.1^{+1.0}_{-1.1}\right)$ fb
- p-value 11% (63%) for compatibility across $\tau\tau$ final states (data-taking years).
- Excluded by **ATLAS** full Run-2 $(200 < m_\phi < 2500\,\text{GeV})$ [Phys. Rev. Lett. 125 (2020) 051801]; 95% C.L. obs. (exp.) upper limit: ~1.7 fb (~2.7 fb)

JHEP 07 (2023) 073

$\phi \to \tau^+\tau^-$

- $\phi \to \tau\tau$ search, 60-3500 GeV:
  - Final states: $e\mu, e\tau_{had}, \mu\tau_{had}, \tau_{had}\tau_{had}$



$m_\phi = 100\,\mathrm{GeV}$:
- $3.1\,\sigma$ local, $2.7\,\sigma$ global;
- Best fit $\sigma_{gg\phi}\mathscr{B}\left(\phi \to \tau\tau\right) = \left(5.8^{+2.5}_{-2.0}\right)$ pb
- p-value 50% (58%) for compatibility across $\tau\tau$ final states (data-taking years).

$m_\phi = 1200\,\mathrm{GeV}$:
- $2.8\,\sigma$ local, $2.2\,\sigma$ global;
- Best fit $\sigma_{gg\phi}\mathscr{B}\left(\phi \to \tau\tau\right) = \left(3.1^{+1.0}_{-1.1}\right)$ fb
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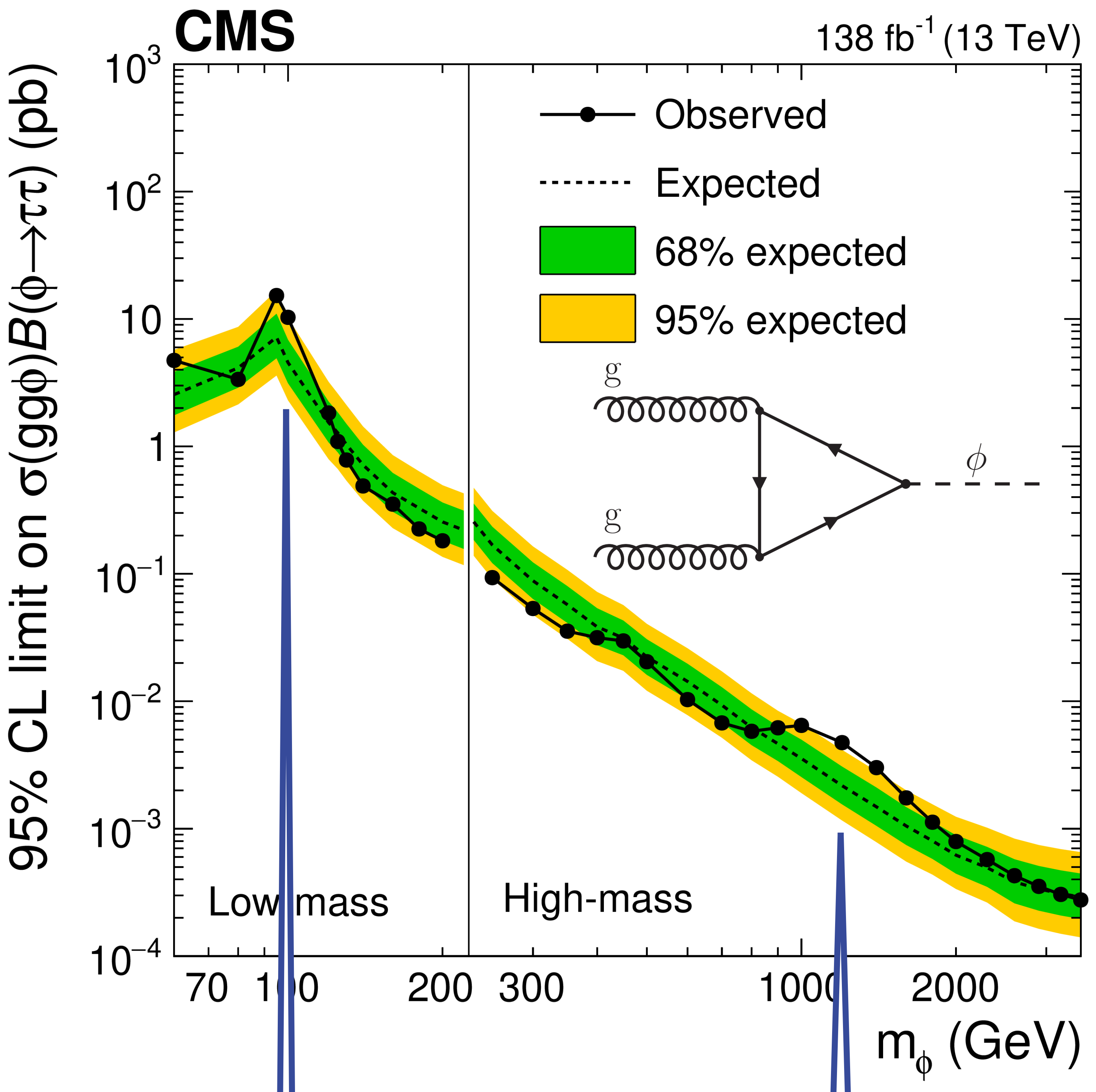
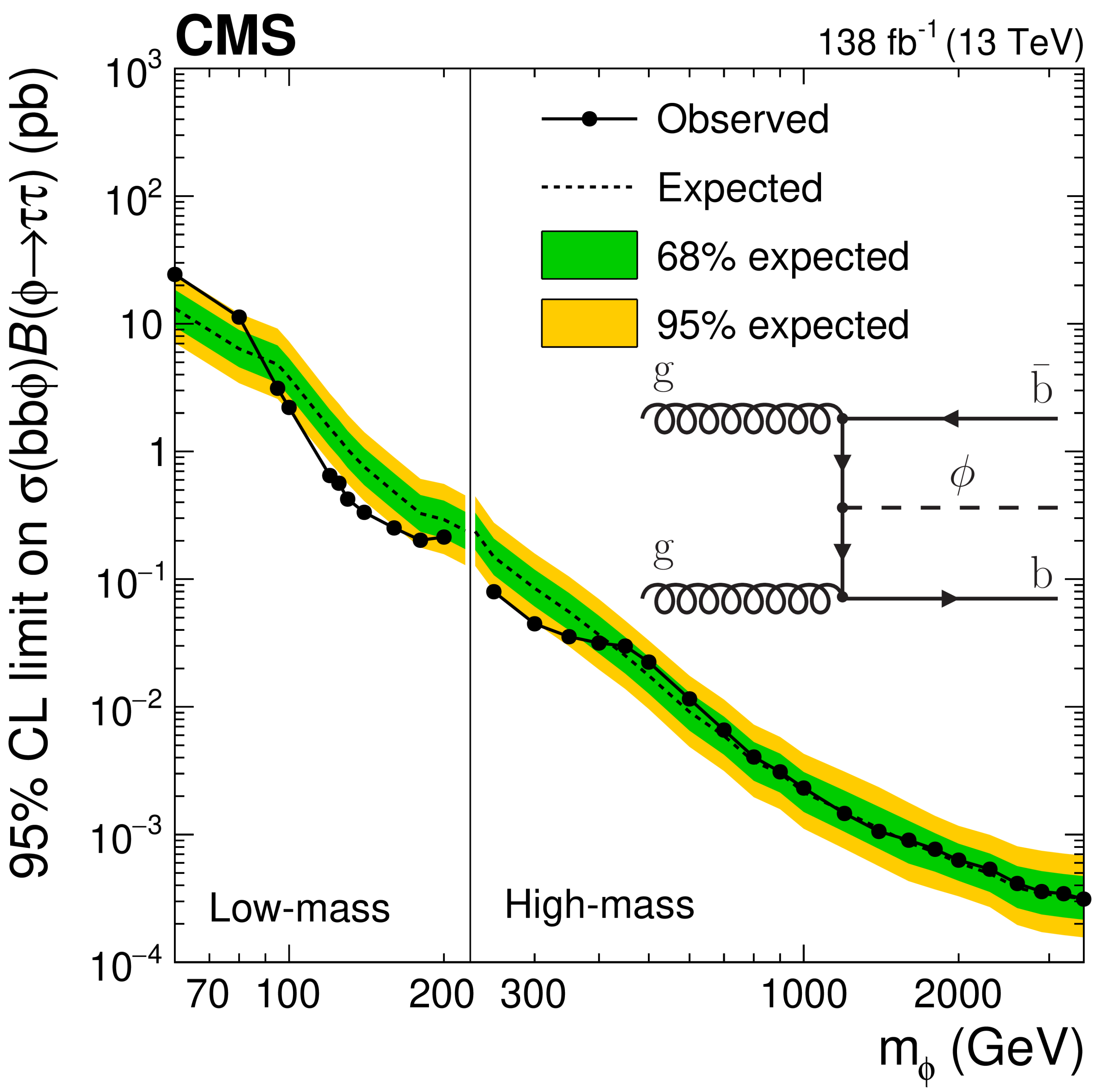
JHEP 07 (2023) 073

$\phi \rightarrow \tau^+\tau^-$

- $\phi \rightarrow \tau\tau$ search, 60-3500 GeV:
  - Final states: $e\mu, e\tau_{had}, \mu\tau_{had}, \tau_{had}\tau_{had}$

$m_\phi = 95\,\text{GeV}$:
- $2.6\,\sigma$ local, $2.3\,\sigma$ global;
- Best fit $\sigma_{gg\phi}\mathscr{B}\left(\phi \rightarrow \tau\tau\right) = \left(7.8^{+3.9}_{-3.1}\right)$ pb





$m_\phi = 100\,\text{GeV}$:
- $3.1\,\sigma$ local, $2.7\,\sigma$ global;
- Best fit $\sigma_{gg\phi}\mathscr{B}\left(\phi \rightarrow \tau\tau\right) = \left(5.8^{+2.5}_{-2.0}\right)$ pb
- p-value 50% (58%) for compatibility across $\tau\tau$ final states (data-taking years).

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JHEP 07 (2023) 073

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- $\phi \to \tau\tau$ search, 60-3500 GeV:
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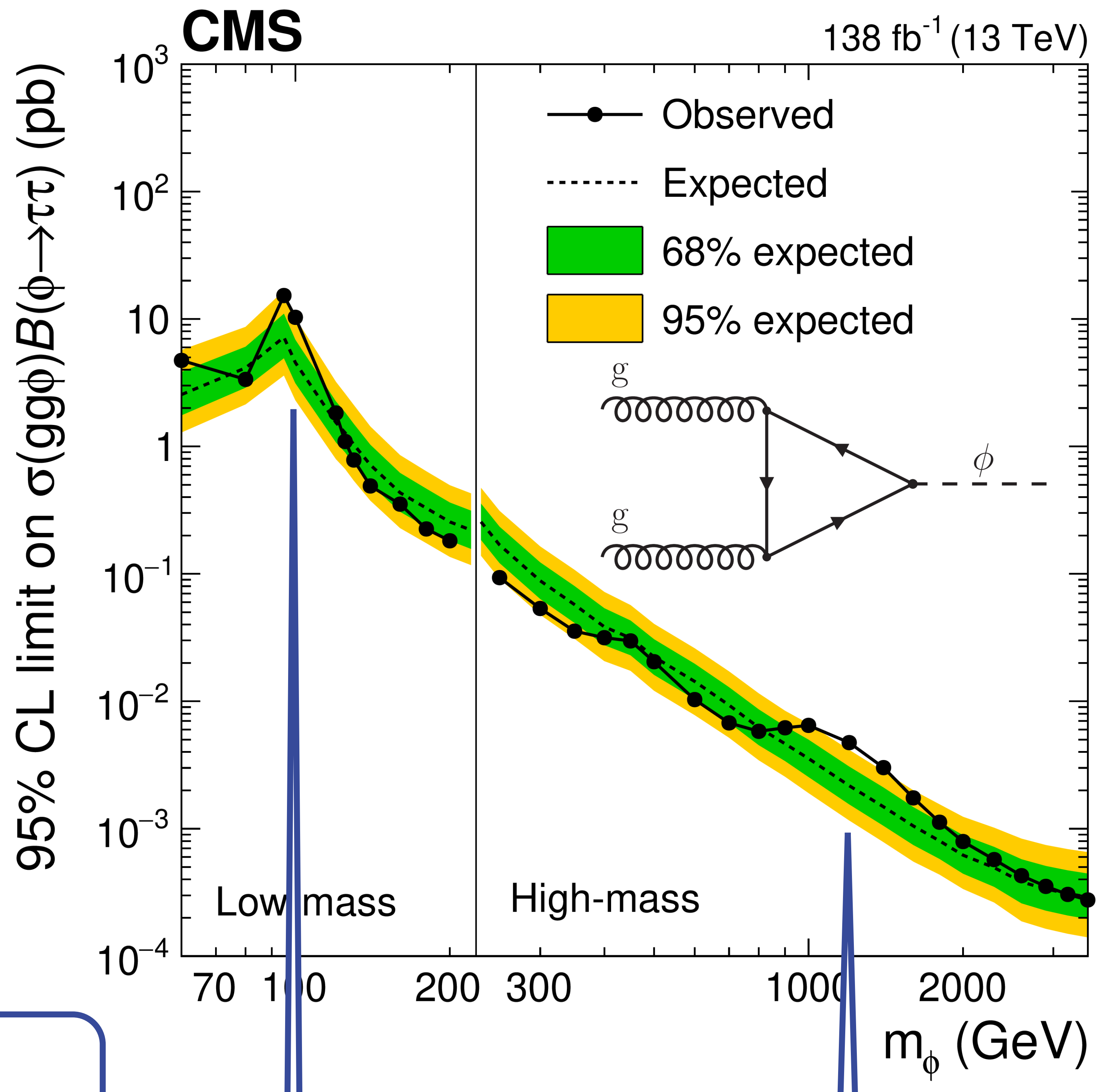

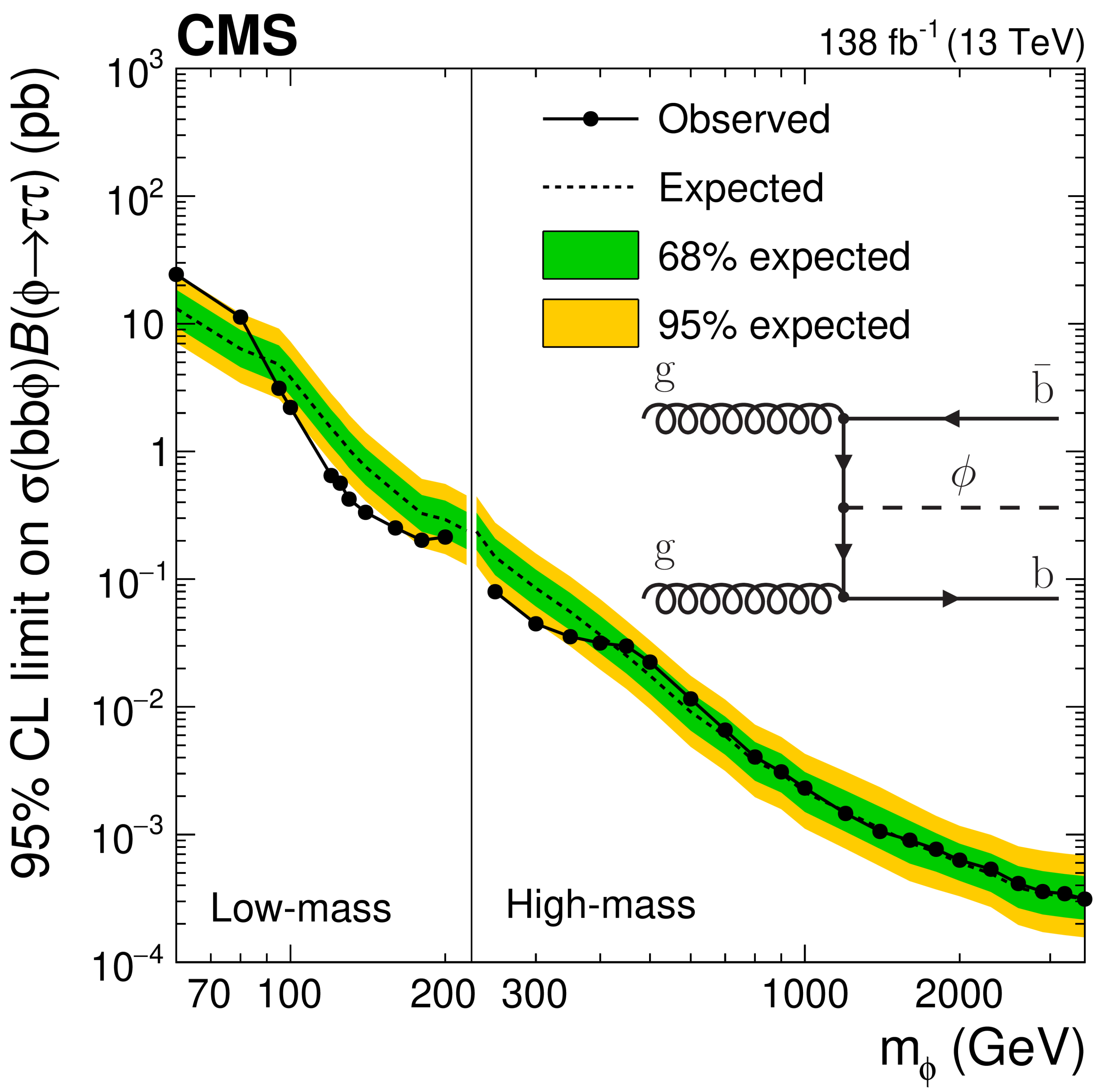

$m_\phi = 95\,\mathrm{GeV}$:
- $2.6\,\sigma$ local, $2.3\,\sigma$ global;
- Best fit $\sigma_{gg\phi}\mathcal{B}\left(\phi \to \tau\tau\right) = \left(7.8^{+3.9}_{-3.1}\right)$ pb

- Not seen in $bb\phi$ production
- No ATLAS counterpart yet (also not clearly seen in SM $H \to \tau\tau$ measurement)

$m_\phi = 100\,\mathrm{GeV}$:
- $3.1\,\sigma$ local, $2.7\,\sigma$ global;
- Best fit $\sigma_{gg\phi}\mathcal{B}\left(\phi \to \tau\tau\right) = \left(5.8^{+2.5}_{-2.0}\right)$ pb
- p-value 50% (58%) for compatibility across $\tau\tau$ final states (data-taking years).

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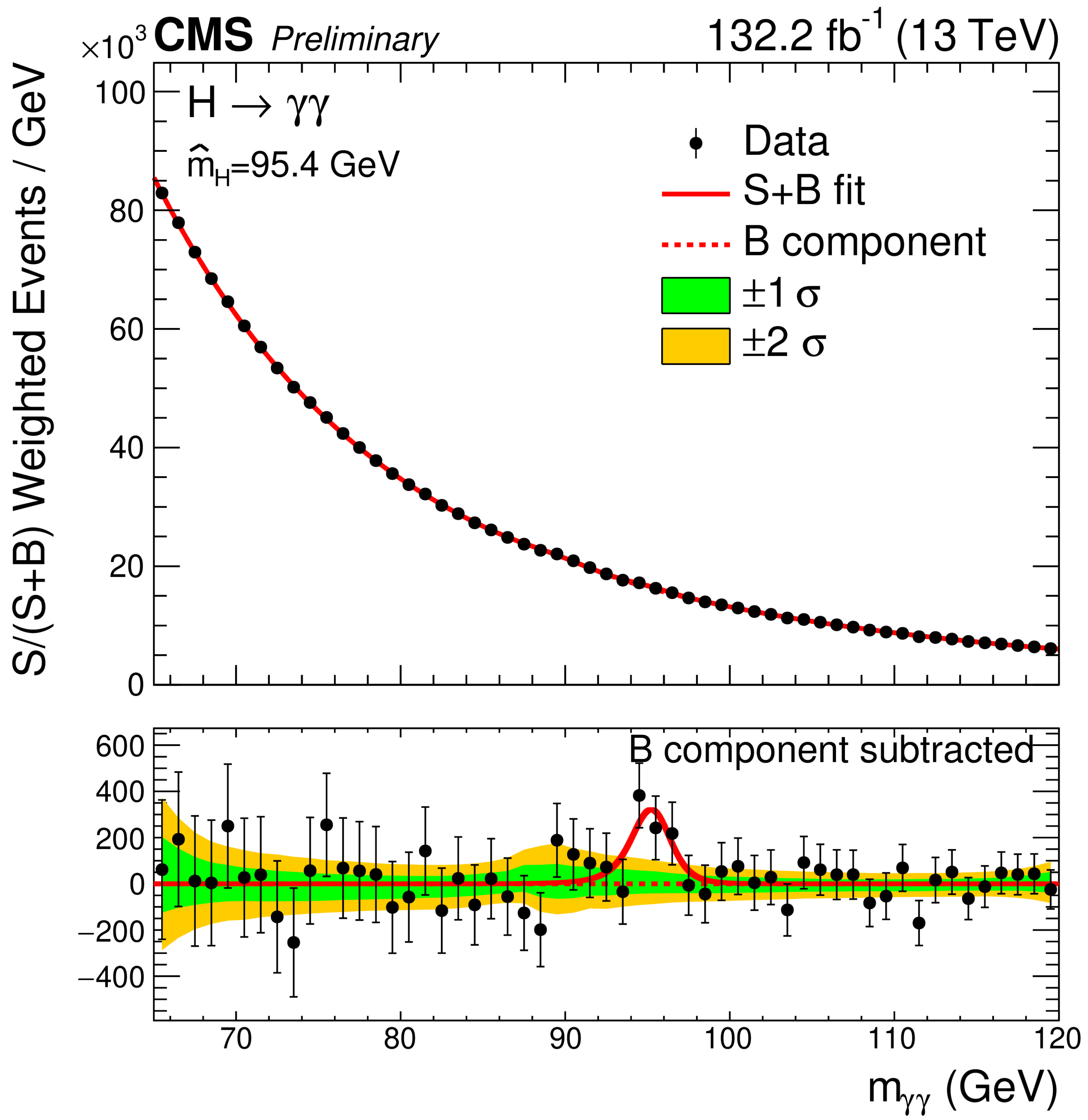
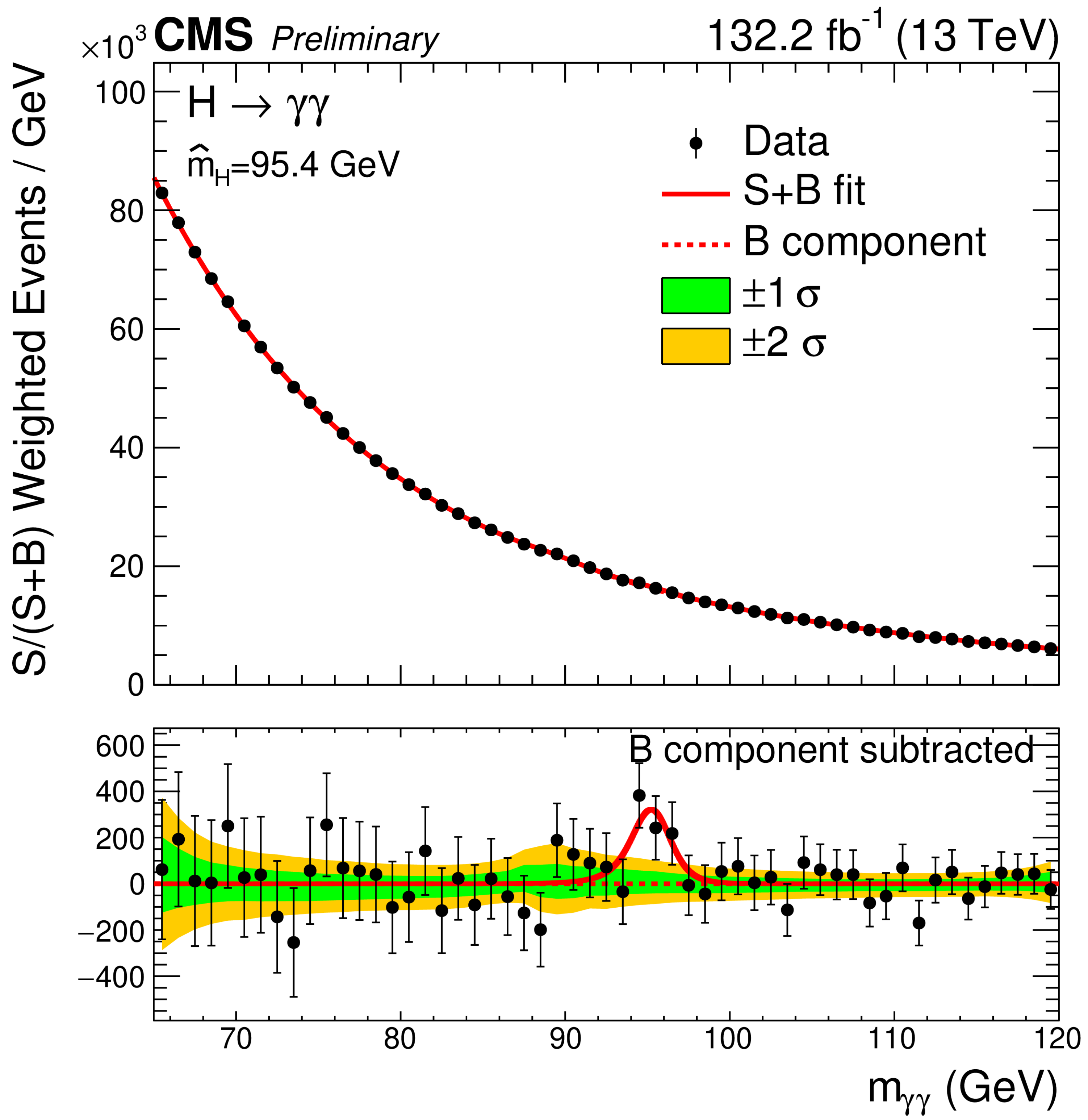
JHEP 07 (2023) 073

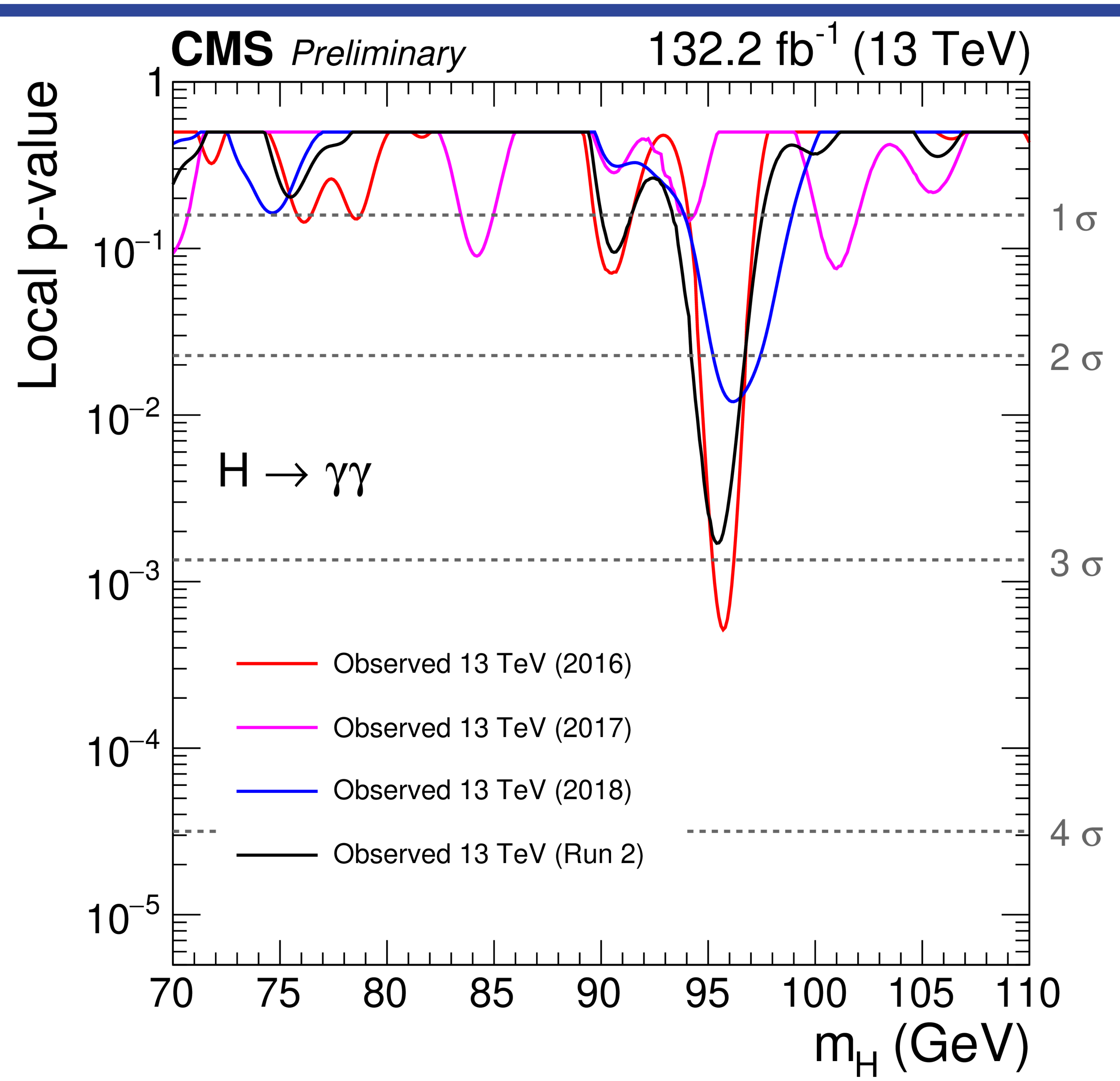
$H \to \gamma\gamma$



CMS-PAS-HIG-20-002

$H \to \gamma\gamma$

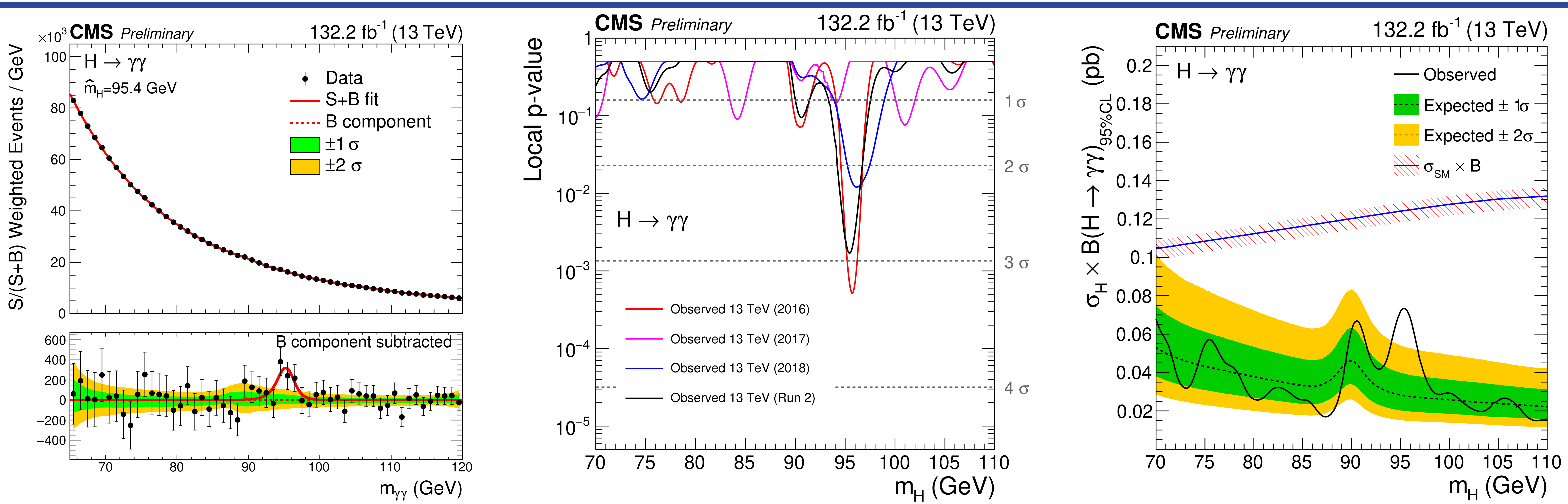




- Largest excess at $m_{\mathrm{H}} = 95.4\,\mathrm{GeV}$: $2.9\,\sigma$ local, $1.3\,\sigma$ global

CMS-PAS-HIG-20-002

$H \to \gamma\gamma$

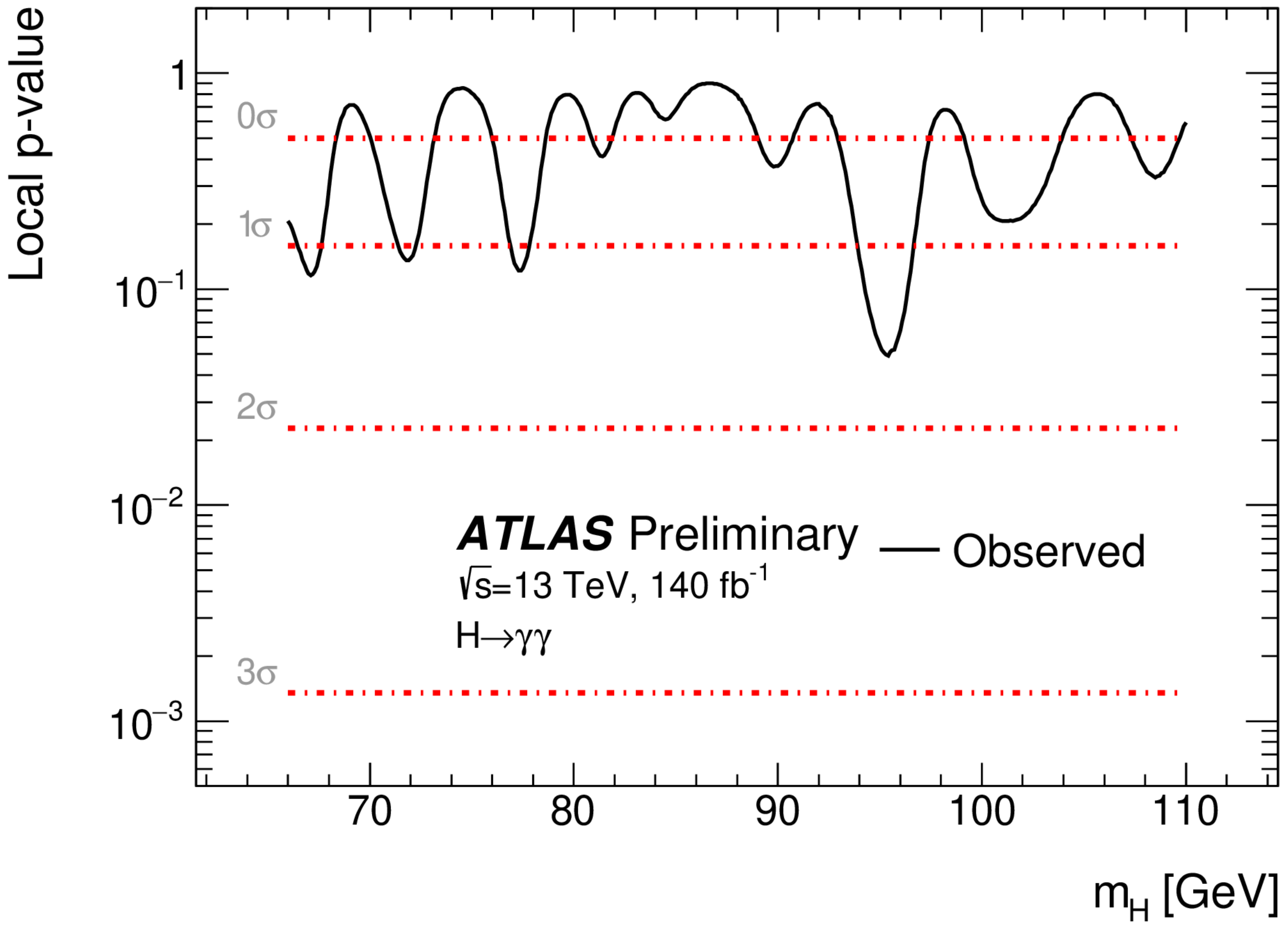


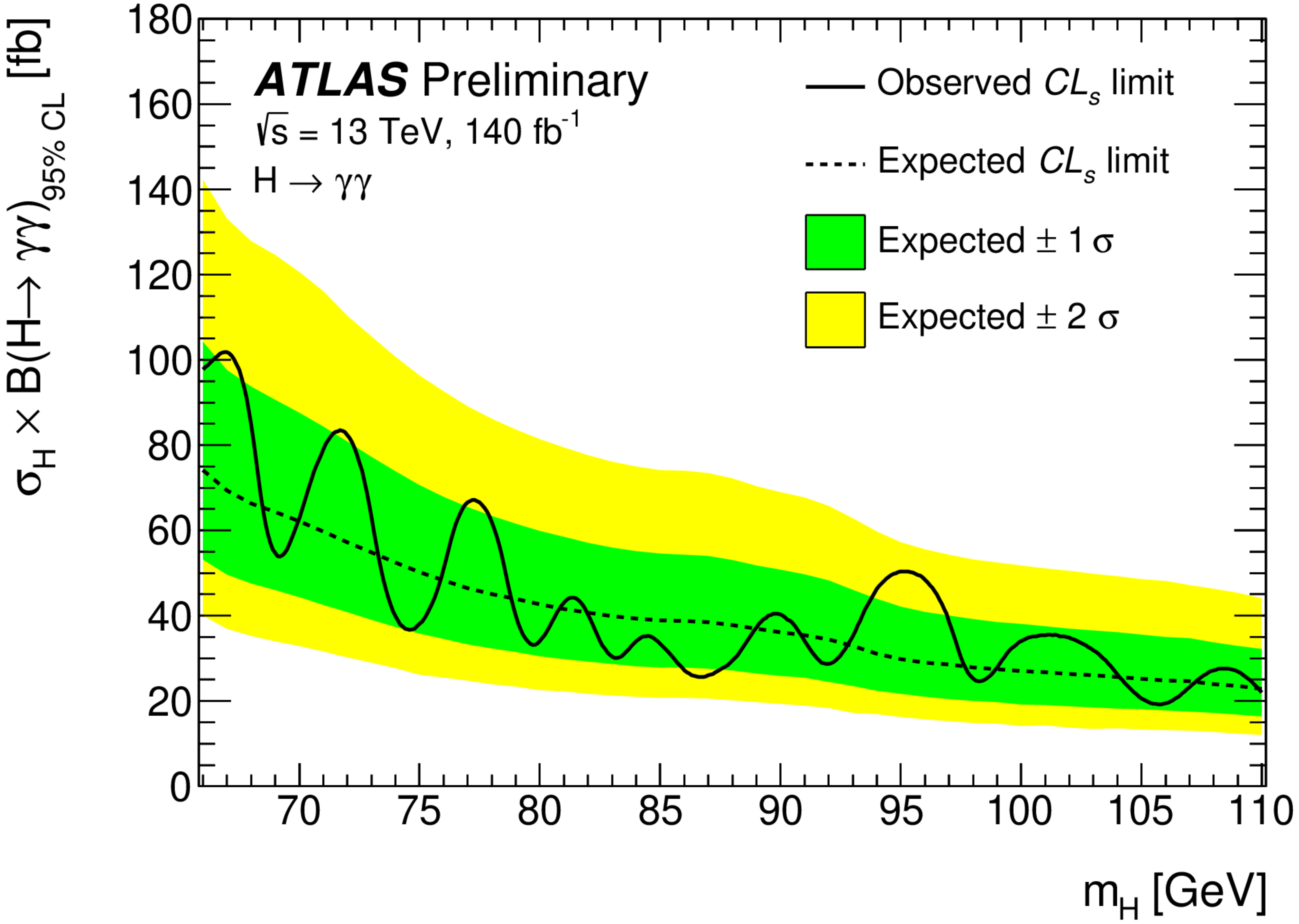
- Largest excess at $m_{\mathrm{H}} = 95.4\,\mathrm{GeV}$: $2.9\,\sigma$ local, $1.3\,\sigma$ global
  - $\sigma \times BR\,(H \to \gamma\gamma)\Big|_{m_{\mathrm{H}}=95.4\,\mathrm{GeV}} < 73\,\mathrm{fb}$ @ 95% C.L.
  - Present in different production modes: ggF+ttH, VBF, VH

CMS-PAS-HIG-20-002

$H \to \gamma\gamma$

- Model independent (generic spin-0, fiducial σ) and model dependent (SM-like Higgs, total σ) search in 66-110 GeV
  - 3 categories of un/converted photons
  - MVAs used for SM-like analysis to both mitigate background processes and classify events



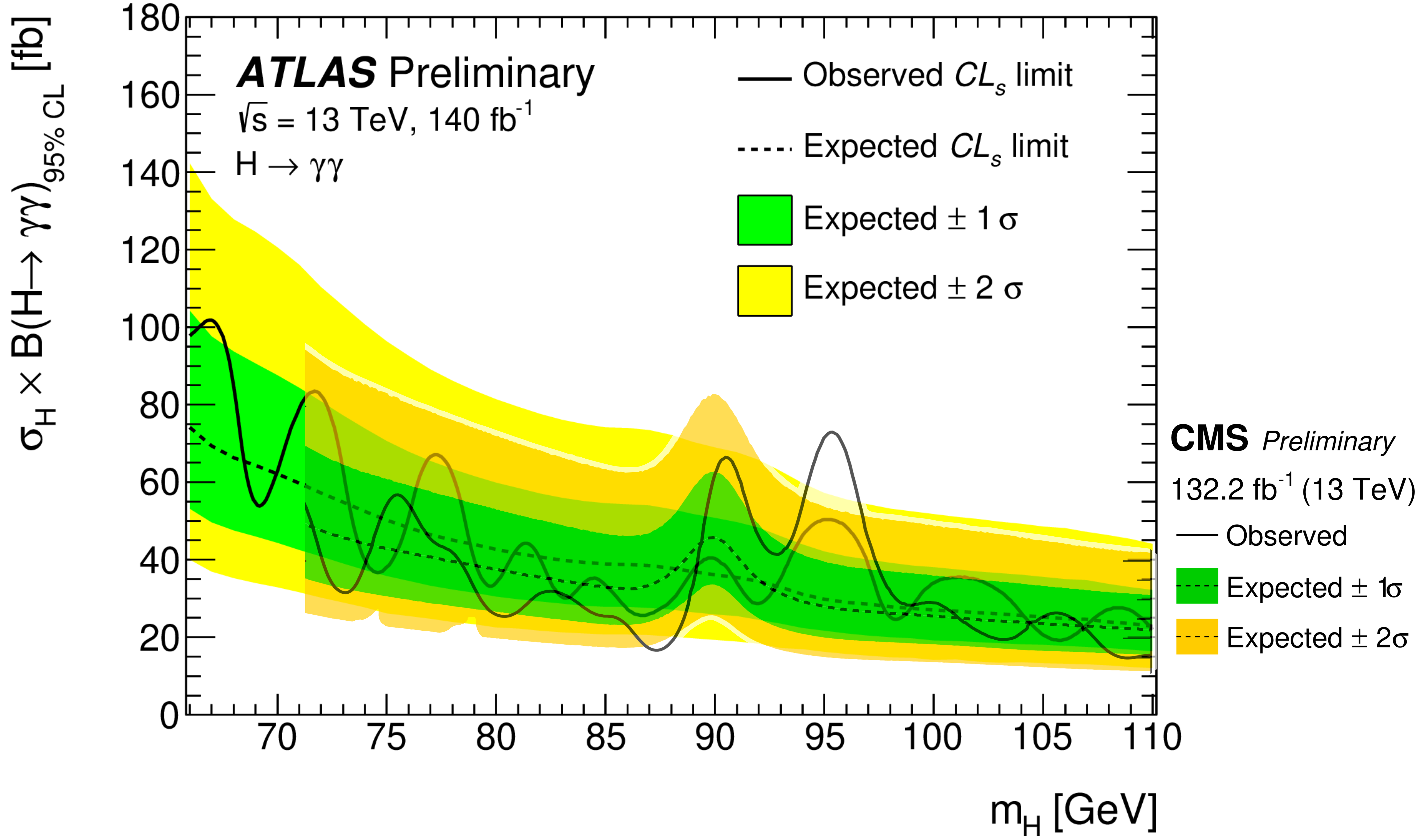


- Largest excess at $m_{\mathrm{H}} = 95.4\,\mathrm{GeV}$: $1.7\,\sigma$ local
  - $\sigma \times BR\left(H \to \gamma\gamma\right)\Big|_{m_{\mathrm{H}}=95.4\,\mathrm{GeV}} \lessapprox 50\,\mathrm{fb}$ @ 95% C.L.

ATLAS-CONF-2023-035

$H \rightarrow \gamma\gamma$

- Model independent (generic spin-0, fiducial σ) and model dependent (SM-like Higgs, total σ) search in 66-110 GeV
  - 3 categories of un/converted photons
  - MVAs used for SM-like analysis to both mitigate background processes and classify events



- Largest excess at $m_H = 95.4\,\text{GeV}$: $2.9\,\sigma$ local, $1.3\,\sigma$ global
  - $\sigma \times BR\,(H \rightarrow \gamma\gamma)\Big|_{m_H=95.4\,\text{GeV}} < 73\,\text{fb}$ @ 95% C.L.

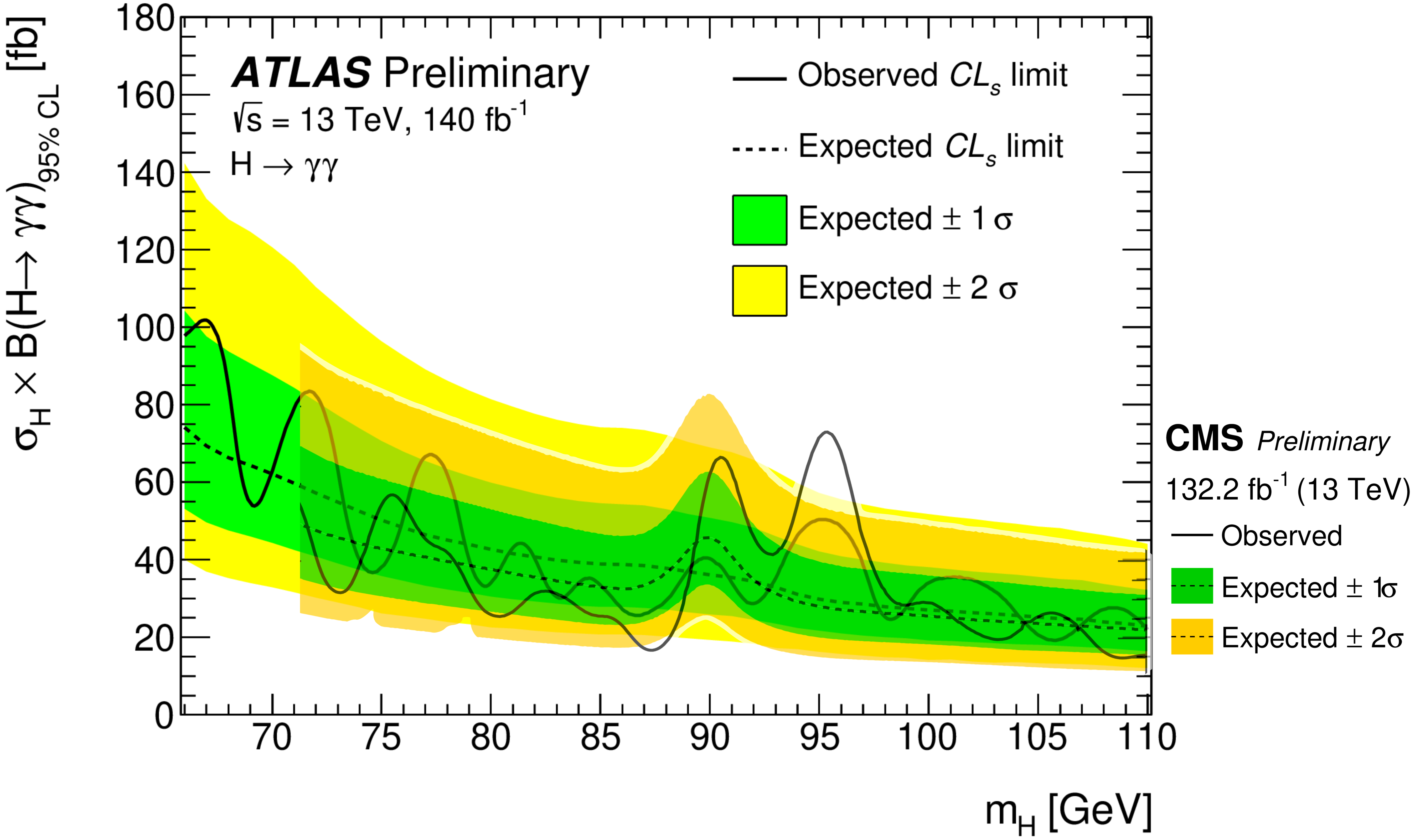
- Largest excess at $m_H = 95.4\,\text{GeV}$: $1.7\,\sigma$ local
  - $\sigma \times BR\,(H \rightarrow \gamma\gamma)\Big|_{m_H=95.4\,\text{GeV}} \lesssim 50\,\text{fb}$ @ 95% C.L.

CMS-PAS-HIG-20-002 ATLAS-CONF-2023-035

$H \to \gamma\gamma$

- Model independent (generic spin-0, fiducial σ) and model dependent (SM-like Higgs, total σ) search in 66-110 GeV
  - 3 categories of un/converted photons
  - MVAs used for SM-like analysis to both mitigate background processes and classify events

- Intriguing to see small bump at same mass…
  - Quite low significances though…
- Both results are preliminary
  - Let's see the published results
  - And see what Run 3 has to say…



- Largest excess at $m_H = 95.4\,\mathrm{GeV}$: $2.9\,\sigma$ local, $1.3\,\sigma$ global
  - $\sigma \times BR\,(H \to \gamma\gamma)\big|_{m_H=95.4\,\mathrm{GeV}} < 73\,\mathrm{fb}$ @ 95% C.L.

- Largest excess at $m_H = 95.4\,\mathrm{GeV}$: $1.7\,\sigma$ local
  - $\sigma \times BR\,(H \to \gamma\gamma)\big|_{m_H=95.4\,\mathrm{GeV}} \lessapprox 50\,\mathrm{fb}$ @ 95% C.L.

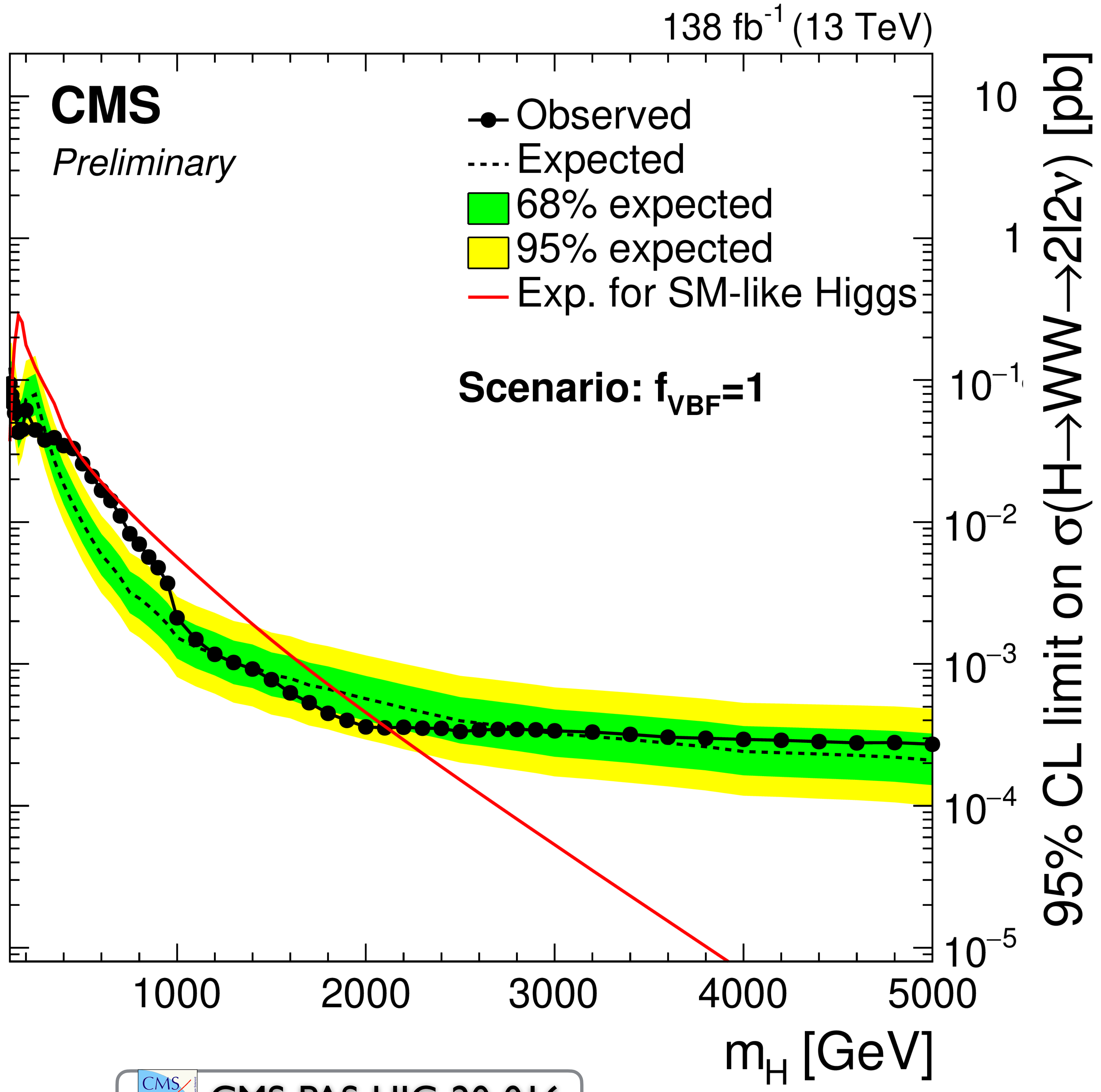
CMS-PAS-HIG-20-002

ATLAS-CONF-2023-035

$H \rightarrow W^+W^- \rightarrow \ell\nu\ell\nu$

- Search range 115 GeV — 5 TeV, various width hypotheses
- S-B interference taken into account
- ggF and VBF (and relative variations) tested

- Largest excess at $m_X = 650\,\mathrm{GeV}$ and $f_{VBF} = 1$
  - $3.8\,\sigma$ local, $2.6\,\sigma$ global
  - Best fit cross section: $160\,\mathrm{fb}$

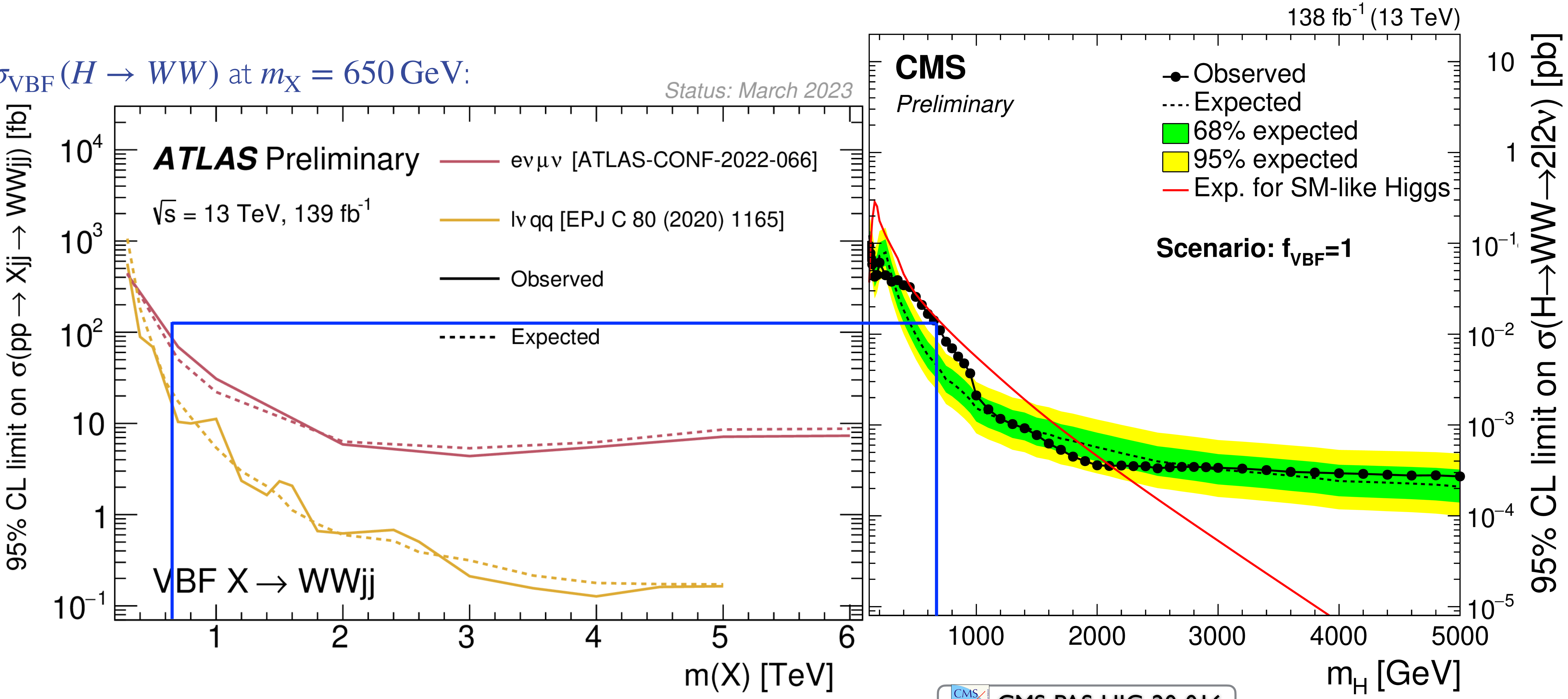


CMS-PAS-HIG-20-016

$H \to W^+W^- \to \ell\nu\ell\nu$

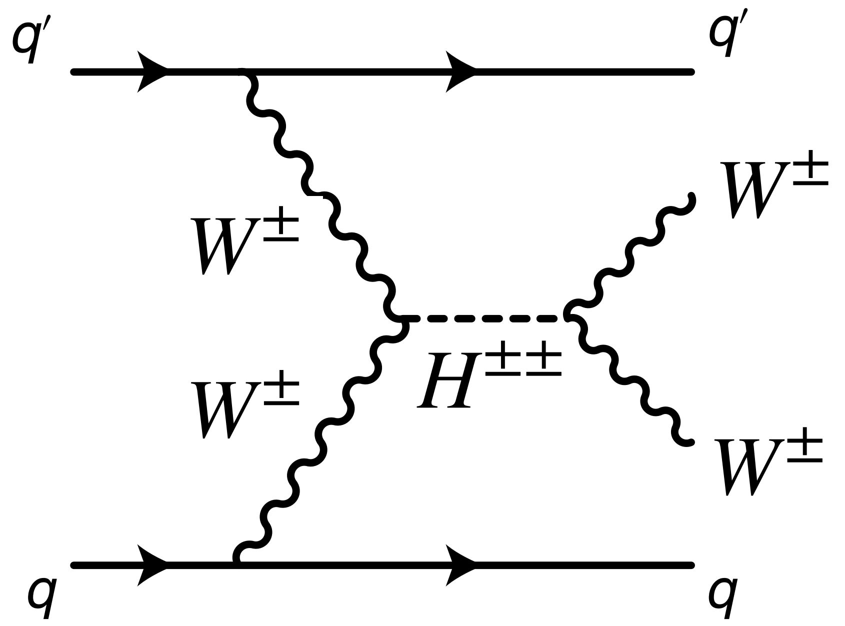
- Search range 115 GeV — 5 TeV, various width hypotheses
- S-B interference taken into account
- ggF and VBF (and relative variations) tested
- ATLAS: No excess
  - 95% C.L. upper limit on $\sigma_{\rm VBF}(H \to WW)$ at $m_X = 650\,{\rm GeV}$:
    - $e\nu\mu\nu$ decay: $\approx 80\,{\rm fb}$
    - $\ell\nu qq$ decay: $\approx 15\,{\rm fb}$

- Largest excess at $m_X = 650\,{\rm GeV}$ and $f_{\rm VBF} = 1$
  - $3.8\,\sigma$ local, $2.6\,\sigma$ global
  - Best fit cross section: $160\,{\rm fb}$

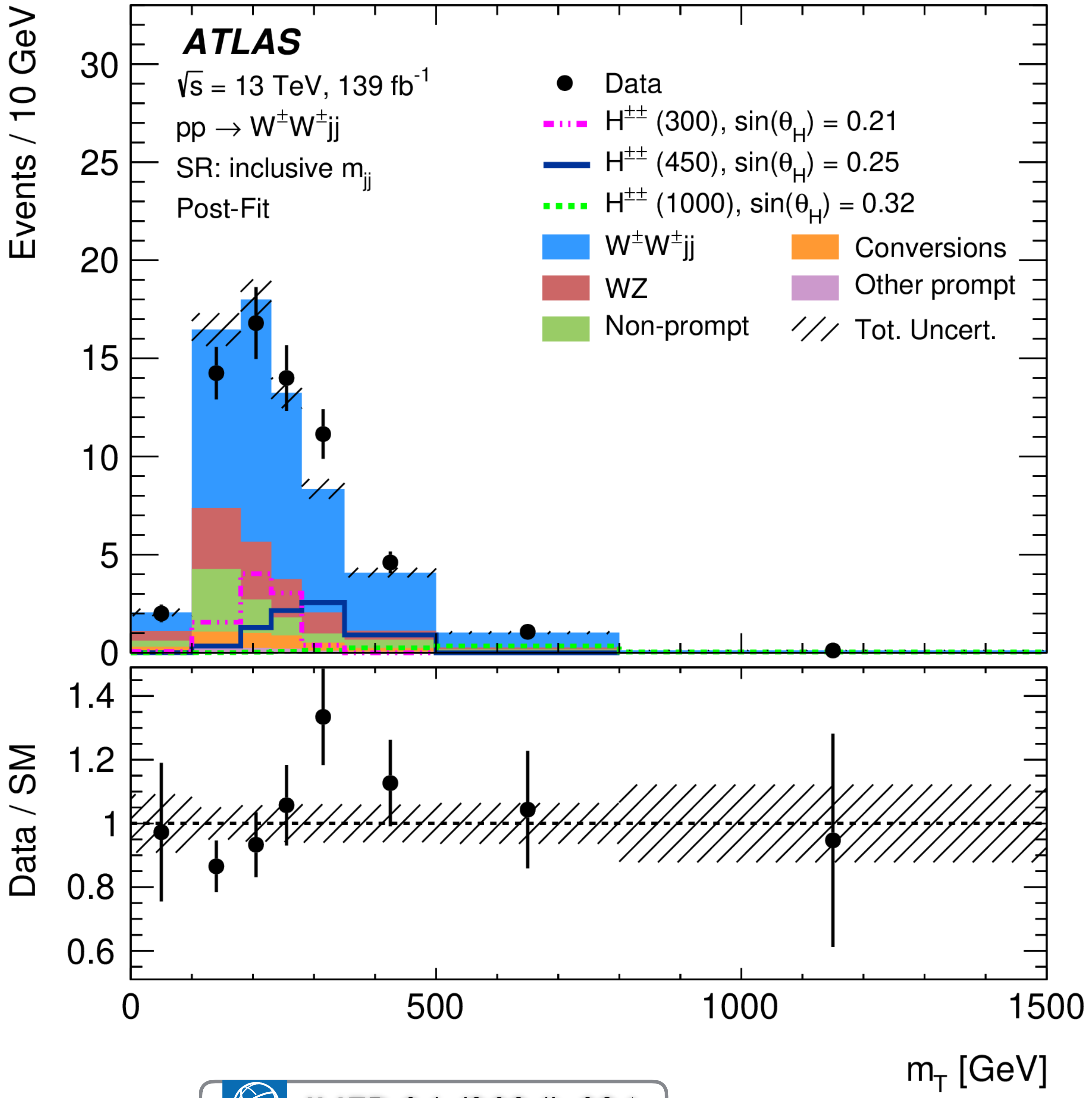


CMS-PAS-HIG-20-016

$H^{++}jj \to W^+W^+jj \to \ell\nu\ell\nu jj$

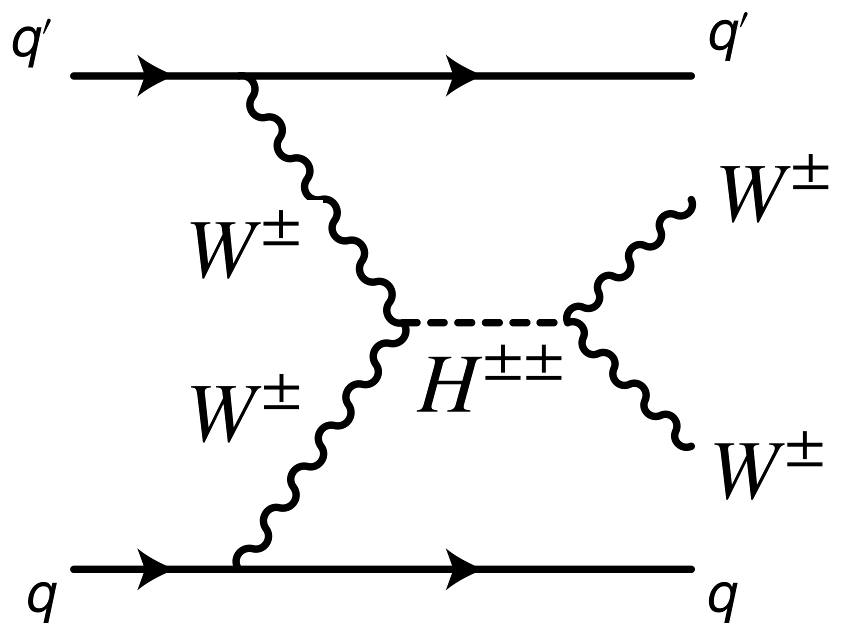


- Use SM measurement of EW $W^\pm W^\pm jj$ production
- Search for $H^{\pm\pm}$ production in context of Georgi-Machacek model
  - Assume $BR\left(H_5^{\pm\pm} \to W^\pm W^\pm\right) = 100\,\%$

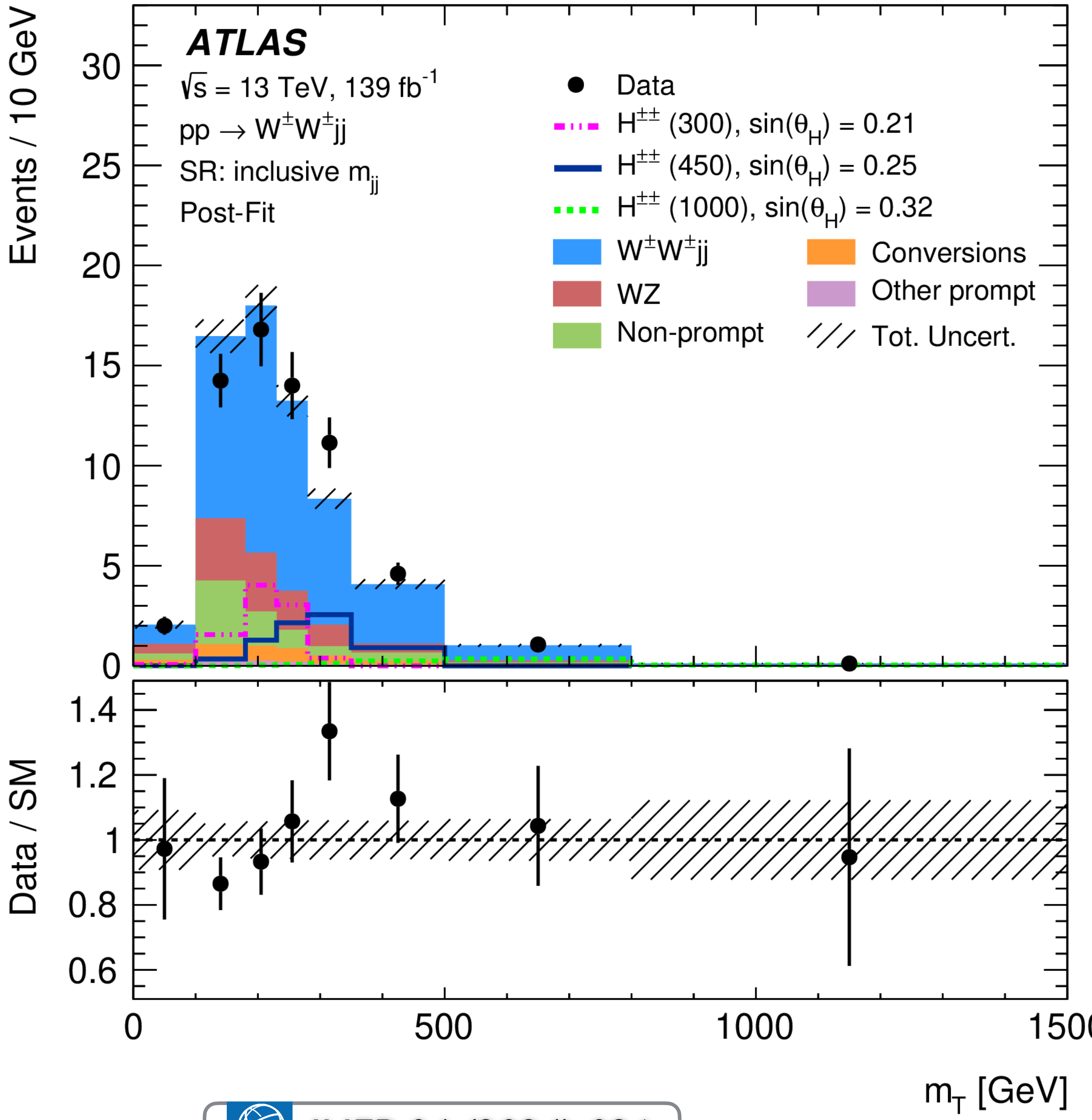


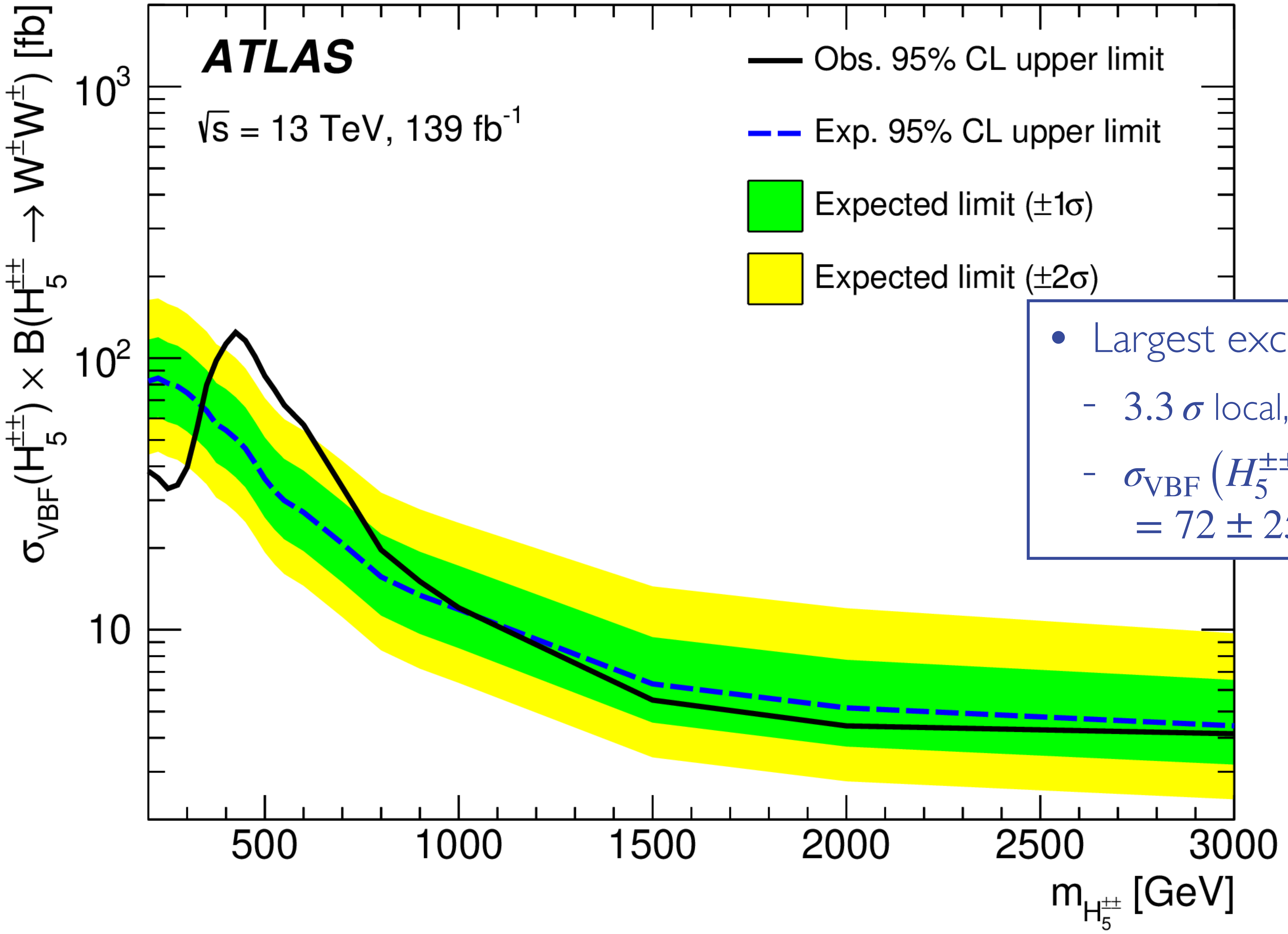
JHEP 04 (2024) 026

$H^{++}jj \to W^+W^+jj \to \ell\nu\ell\nu jj$



- Use SM measurement of EW $W^{\pm}W^{\pm}jj$ production
- Search for $H^{\pm\pm}$ production in context of Georgi-Machacek model
  - Assume $BR\left(H_5^{\pm\pm} \to W^{\pm}W^{\pm}\right) = 100\,\%$

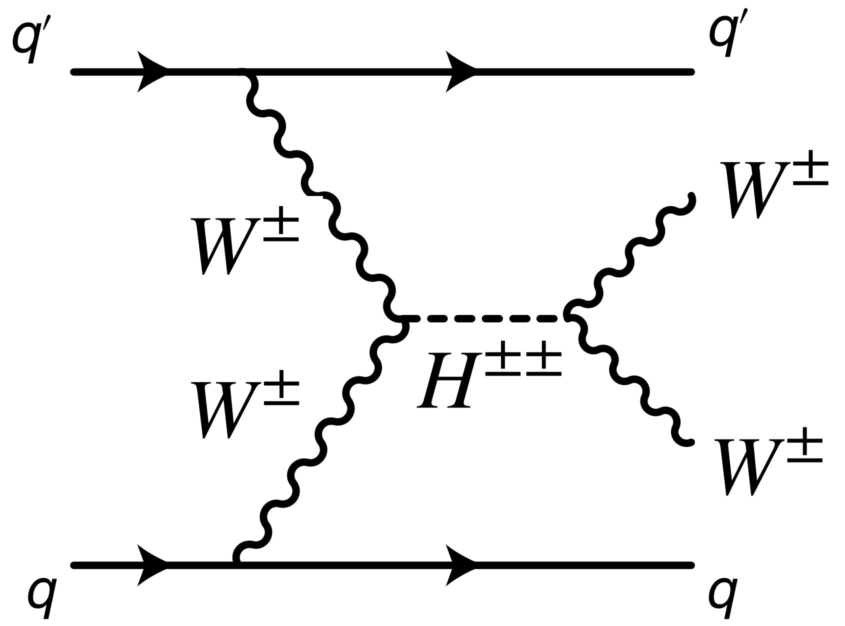




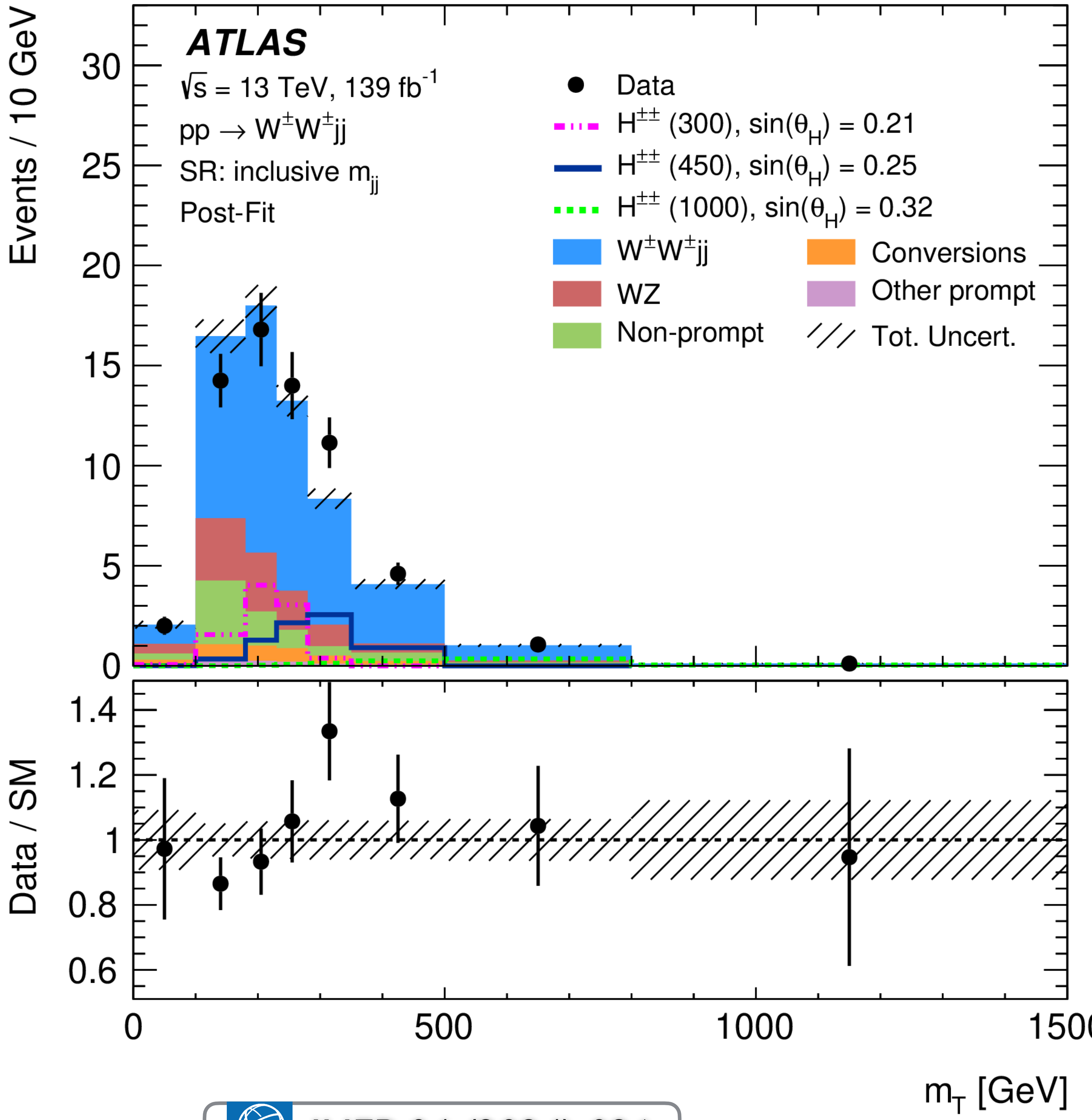
- Largest excess at $m_{H^{++}} = 450\,\text{GeV}$
  - $3.3\,\sigma$ local, $2.5\,\sigma$ global
  - $\sigma_{\text{VBF}}\left(H_5^{\pm\pm}\right) \times BR\left(H_5^{\pm\pm} \to W^{\pm}W^{\pm}\right) = 72 \pm 25\,\text{fb}$

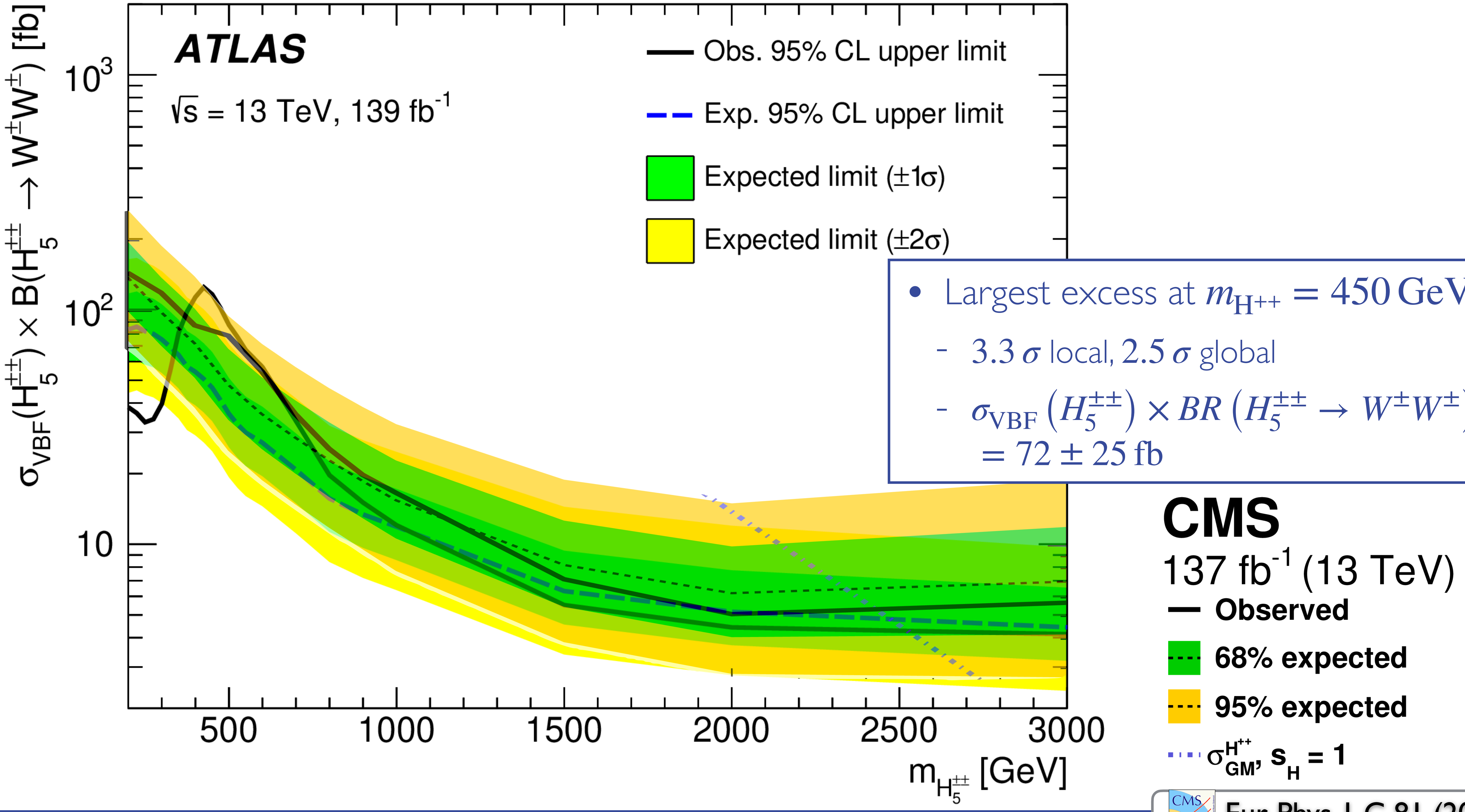
JHEP 04 (2024) 026

$H^{++}jj \to W^+W^+jj \to \ell\nu\ell\nu jj$



- Use SM measurement of EW $W^\pm W^\pm jj$ production
- Search for $H^{\pm\pm}$ production in context of Georgi-Machacek model
  - Assume $BR\left(H_5^{\pm\pm} \to W^\pm W^\pm\right) = 100\,\%$



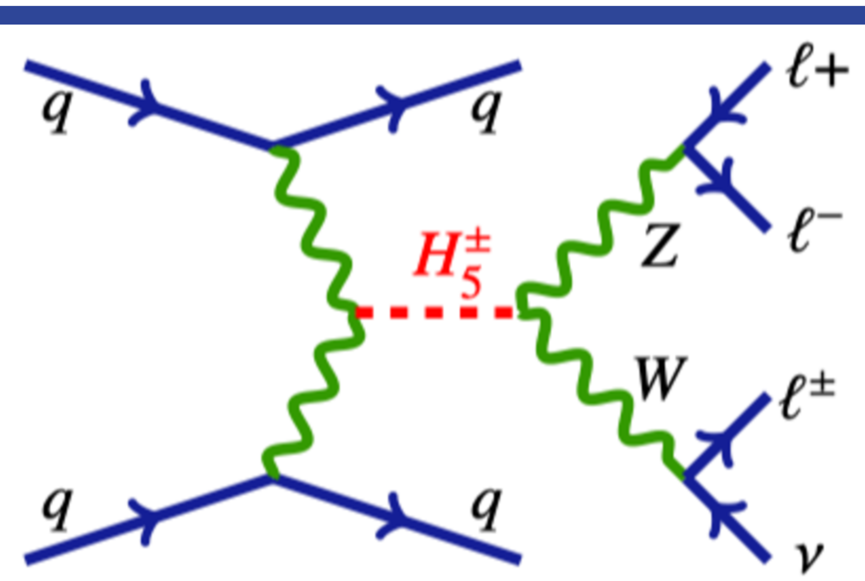


- Largest excess at $m_{\mathrm{H}^{++}} = 450\,\mathrm{GeV}$
  - $3.3\,\sigma$ local, $2.5\,\sigma$ global
  - $\sigma_{\mathrm{VBF}}\left(H_5^{\pm\pm}\right) \times BR\left(H_5^{\pm\pm} \to W^\pm W^\pm\right) = 72 \pm 25\,\mathrm{fb}$

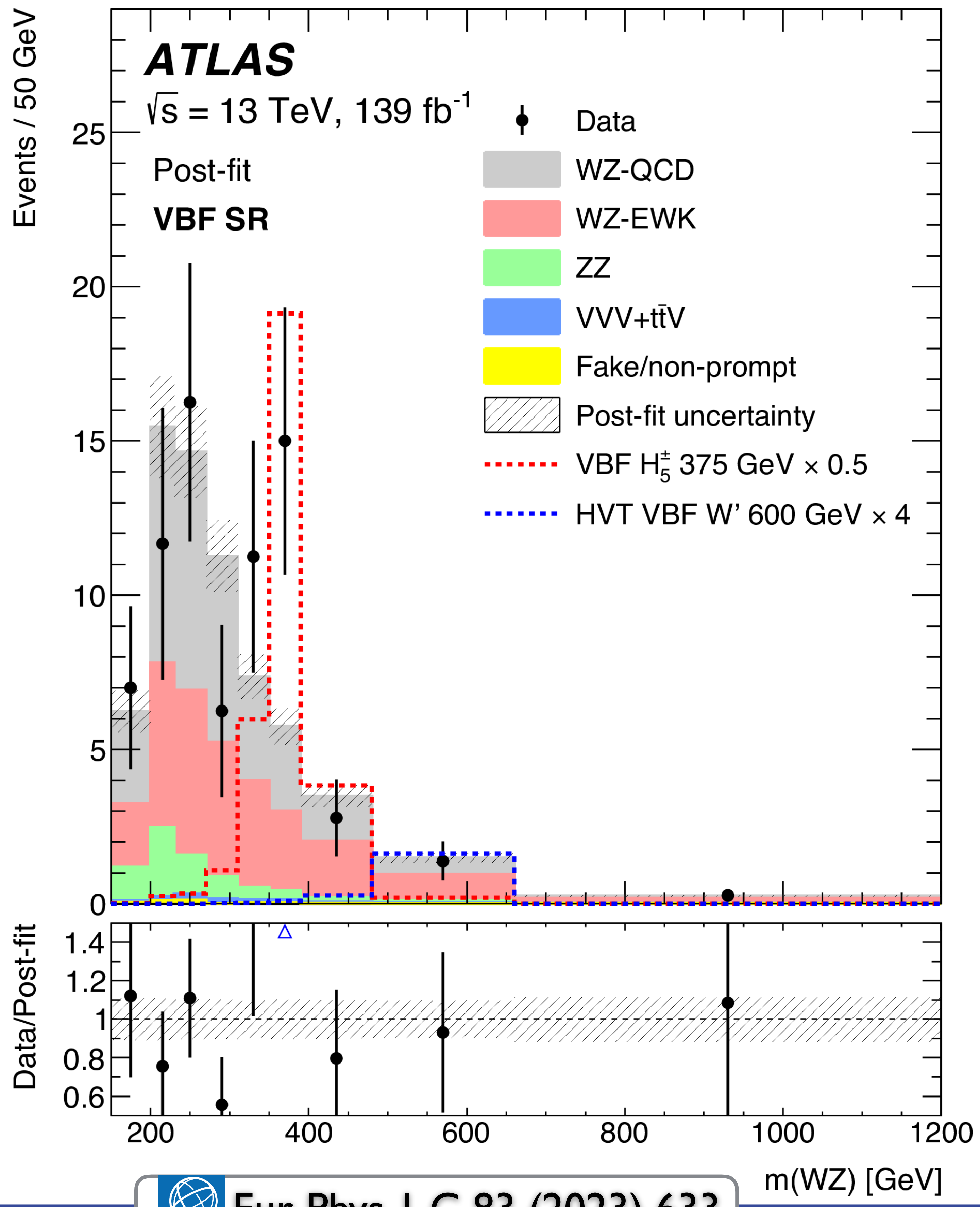
JHEP 04 (2024) 026

Eur. Phys. J. C 81 (2021) 723

$H^+jj \to W^+Z^0jj \to \ell\nu\ell'\ell'jj$

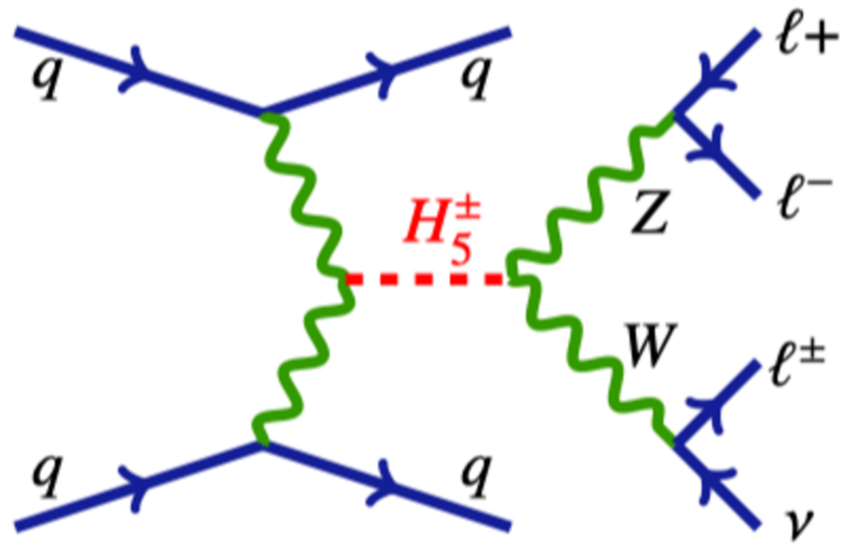


- Search for $H^\pm$ production in context of Georgi-Machacek model
  - $H^\pm$ is fermiophobic, assume BR to VV = 100%

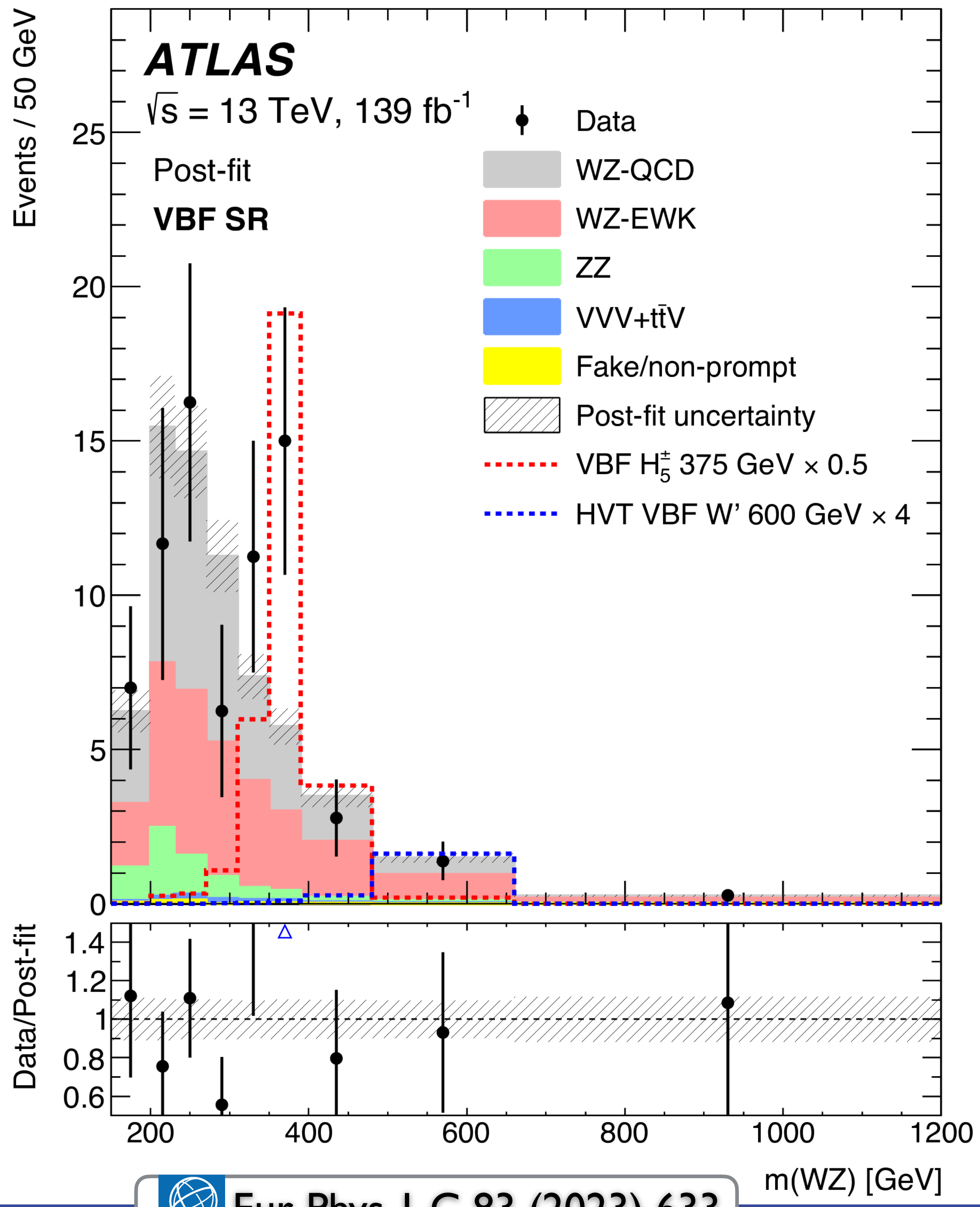


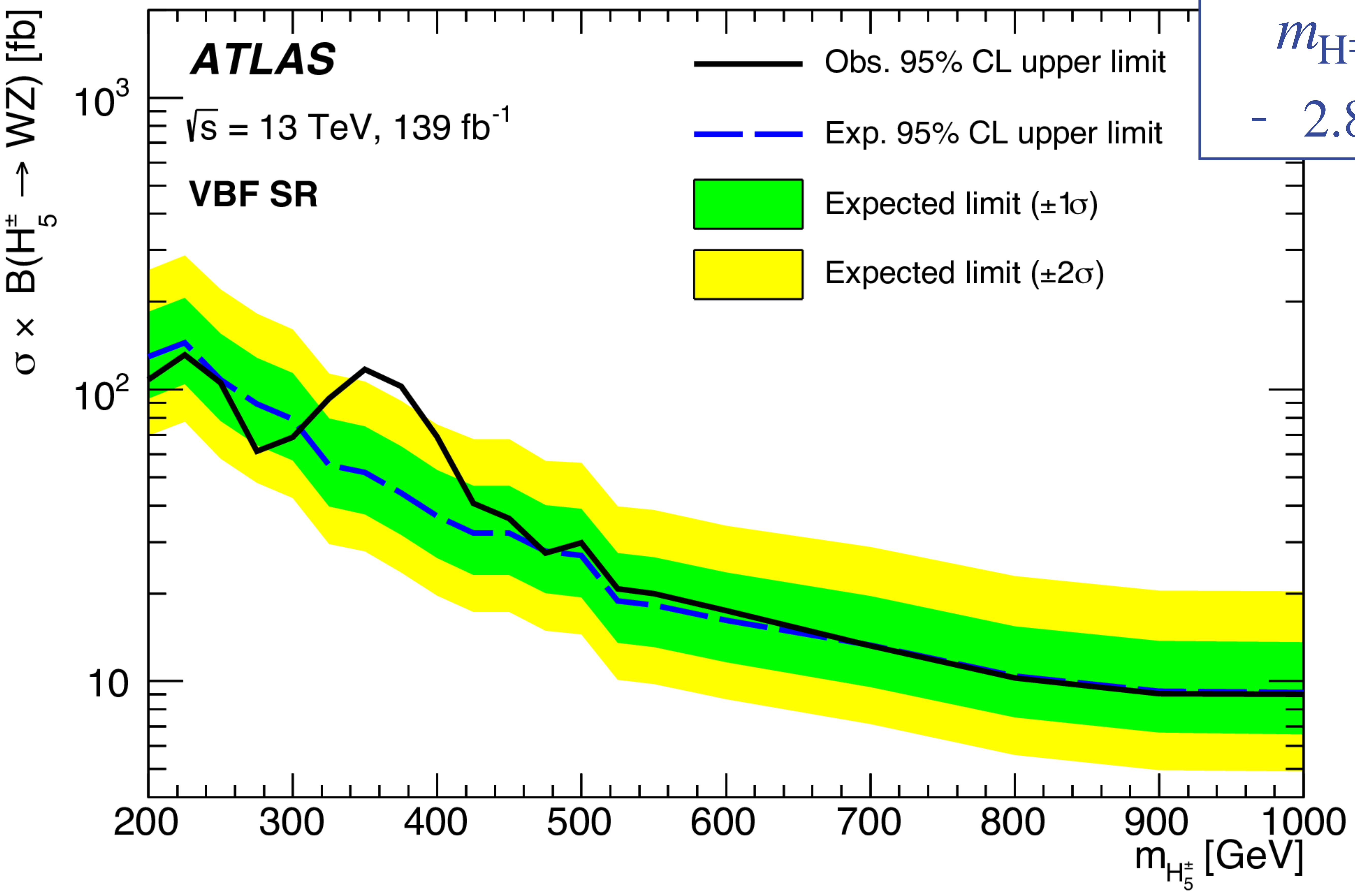
Eur. Phys. J. C 83 (2023) 633

$H^+jj \to W^+Z^0jj \to \ell\nu\ell'\ell'jj$



- Search for $H^\pm$ production in context of Georgi-Machacek model
  - $H^\pm$ is fermiophobic, assume BR to VV = 100%





- Largest excess at $m_{H^\pm} = 375$ GeV
  - $2.8\,\sigma$ local, $1.6\,\sigma$ global

Eur. Phys. J. C 83 (2023) 633

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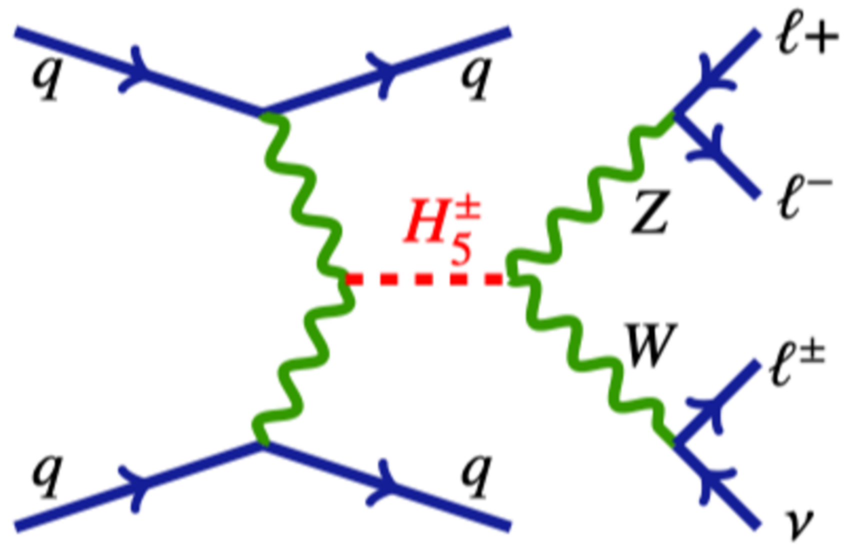

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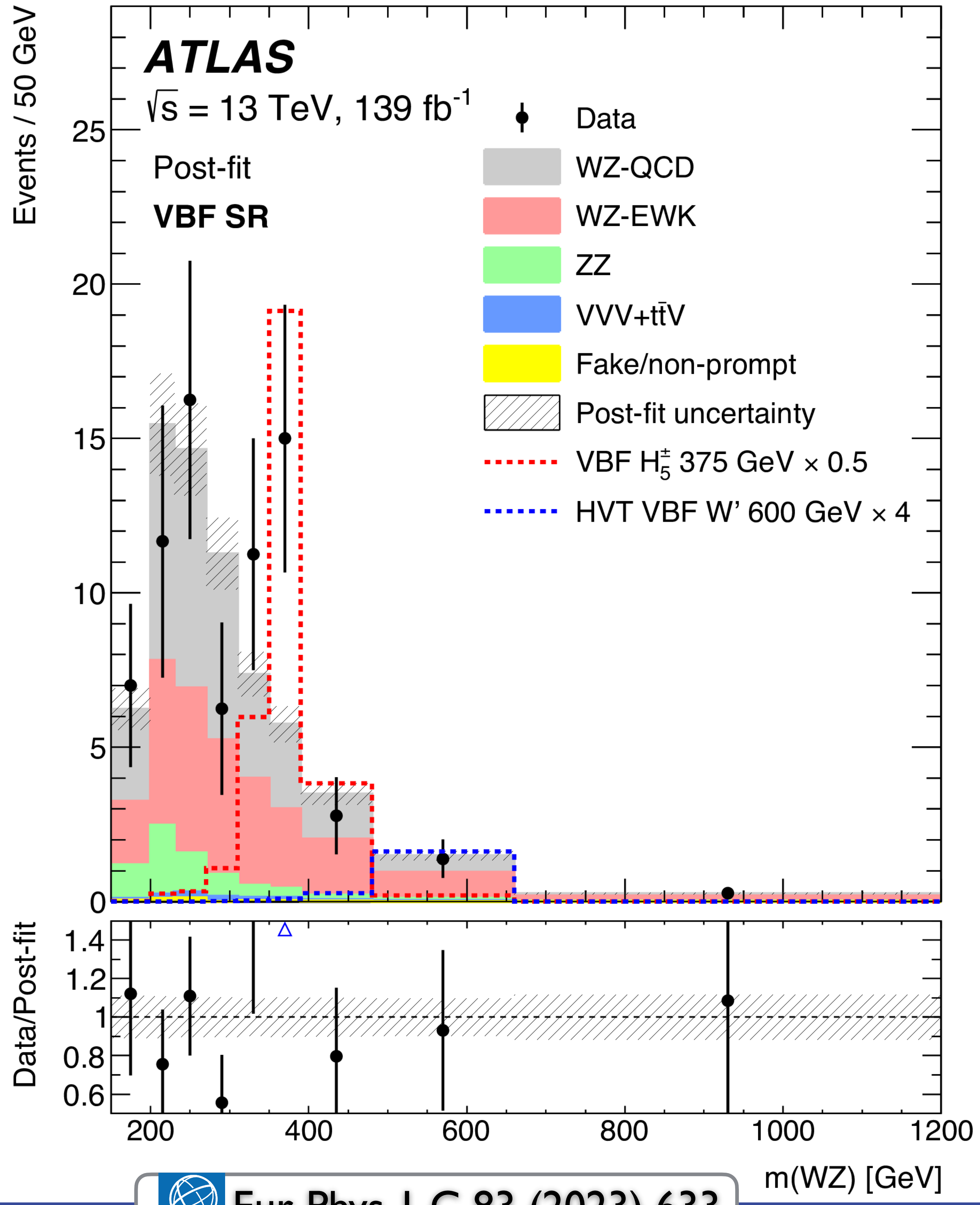
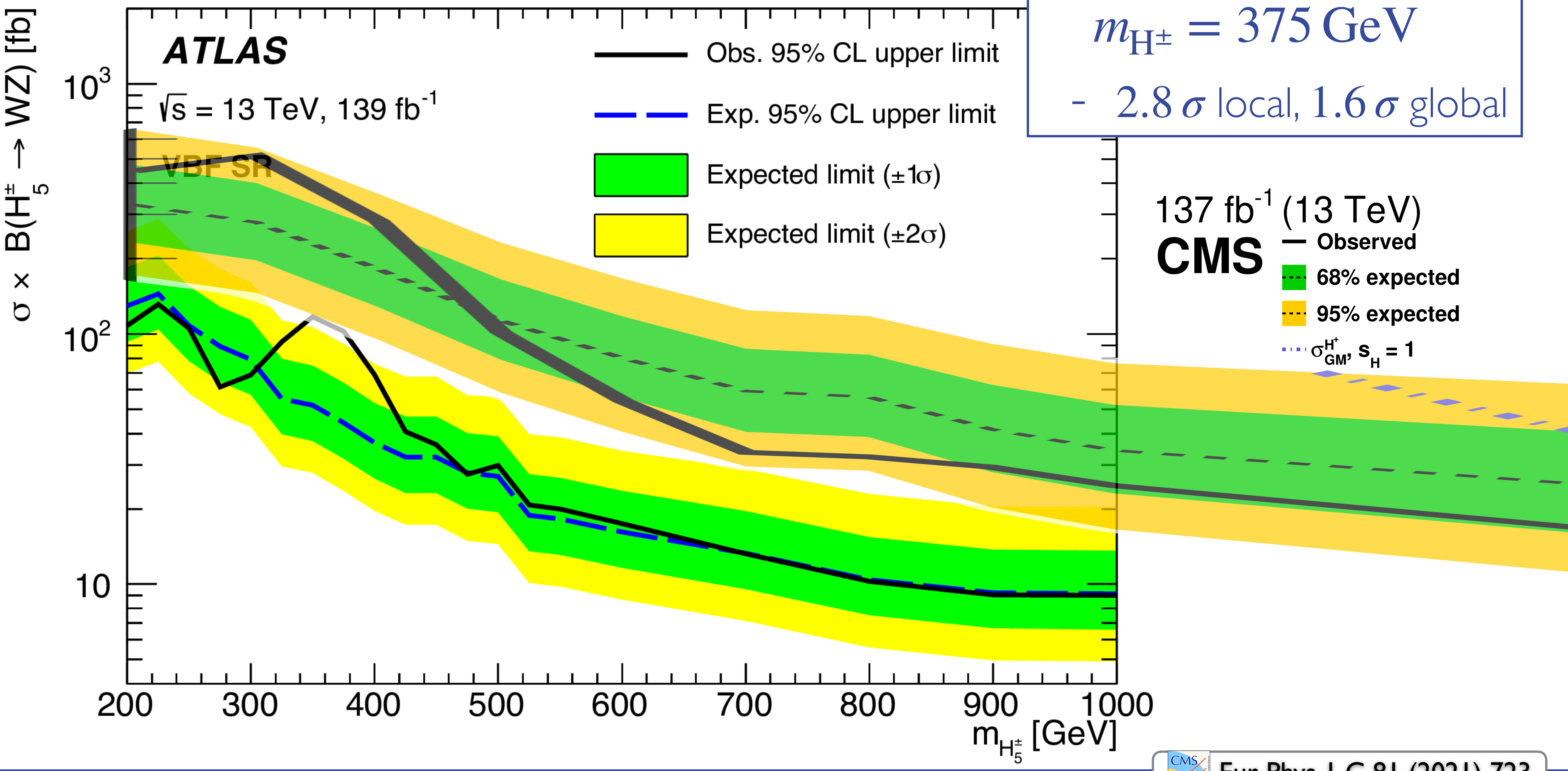
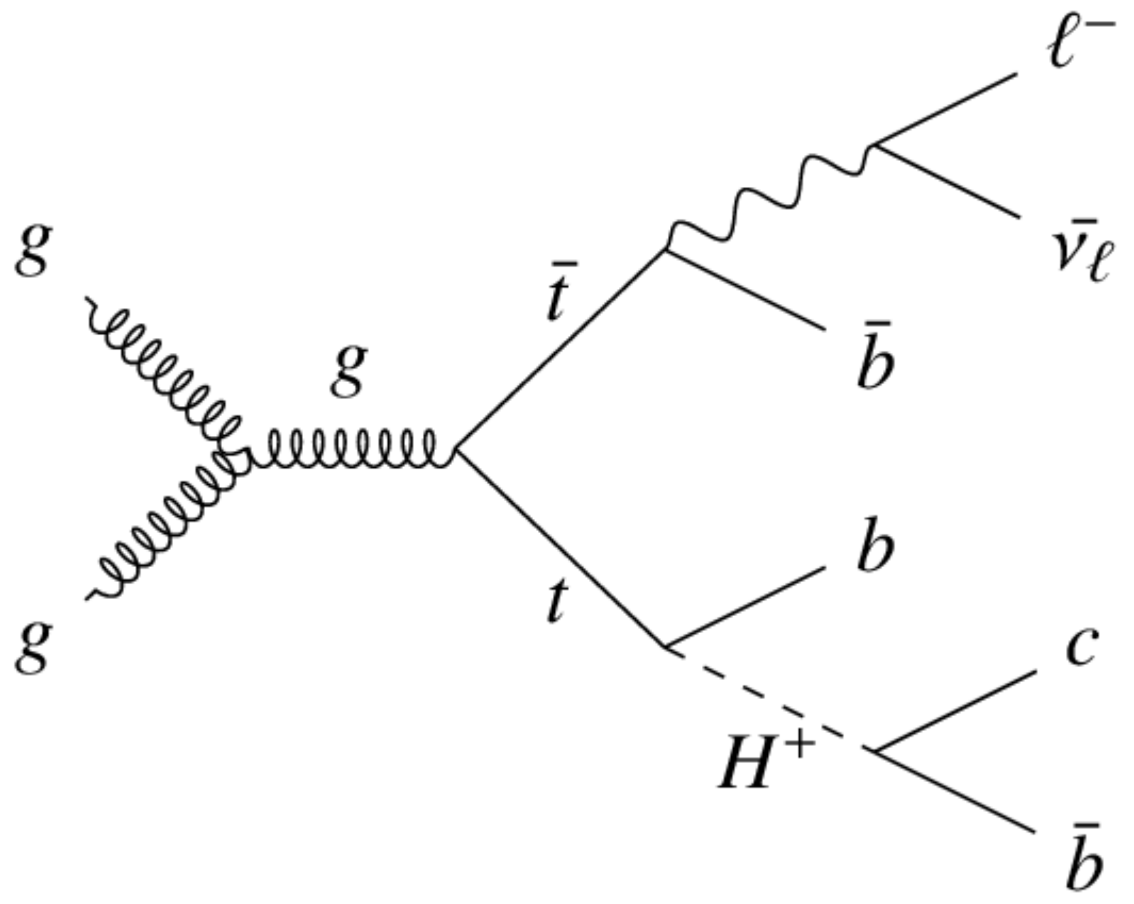




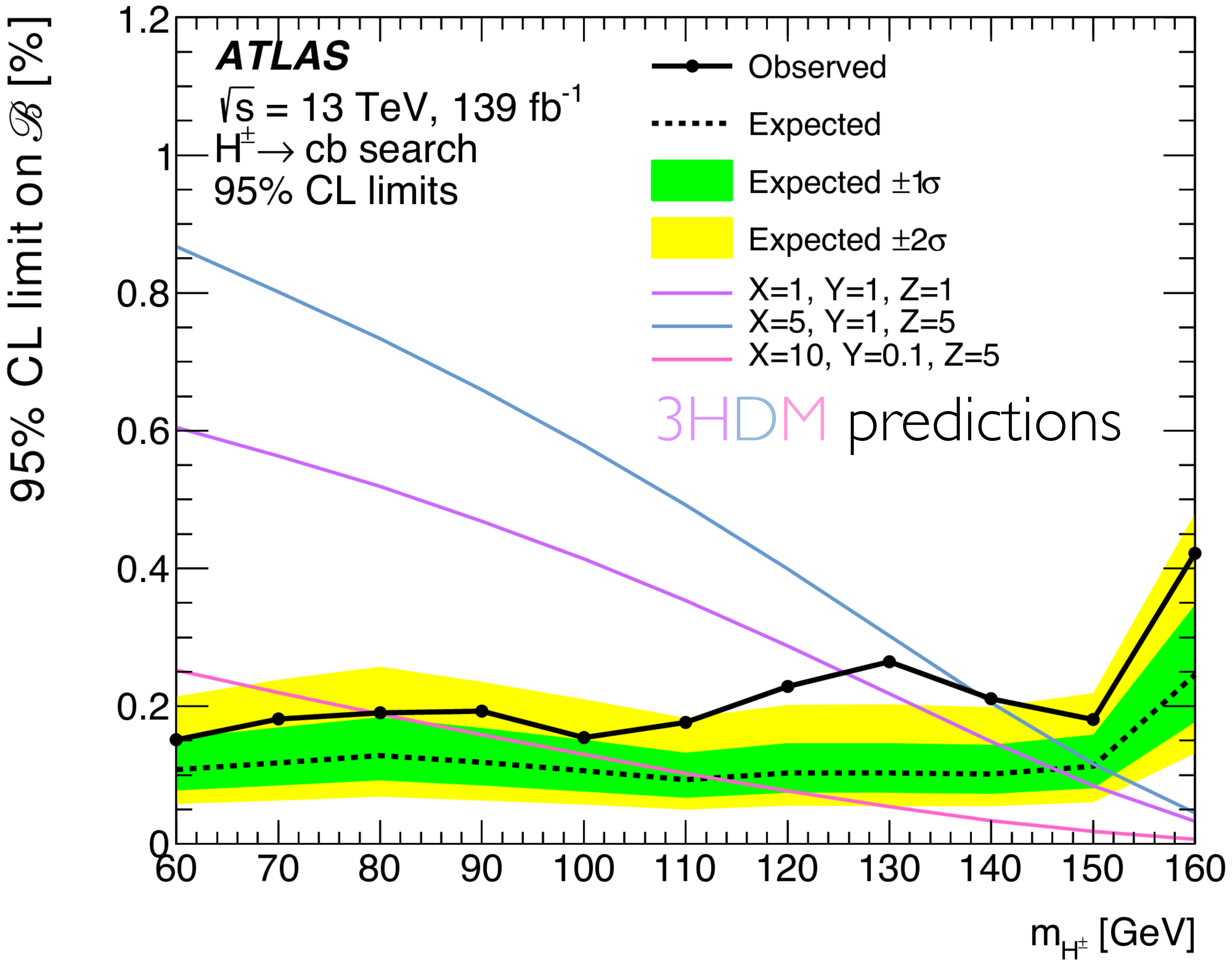
Eur. Phys. J. C 83 (2023) 633

Eur. Phys. J. C 81 (2021) 723

Charged Higgs in Top Decays

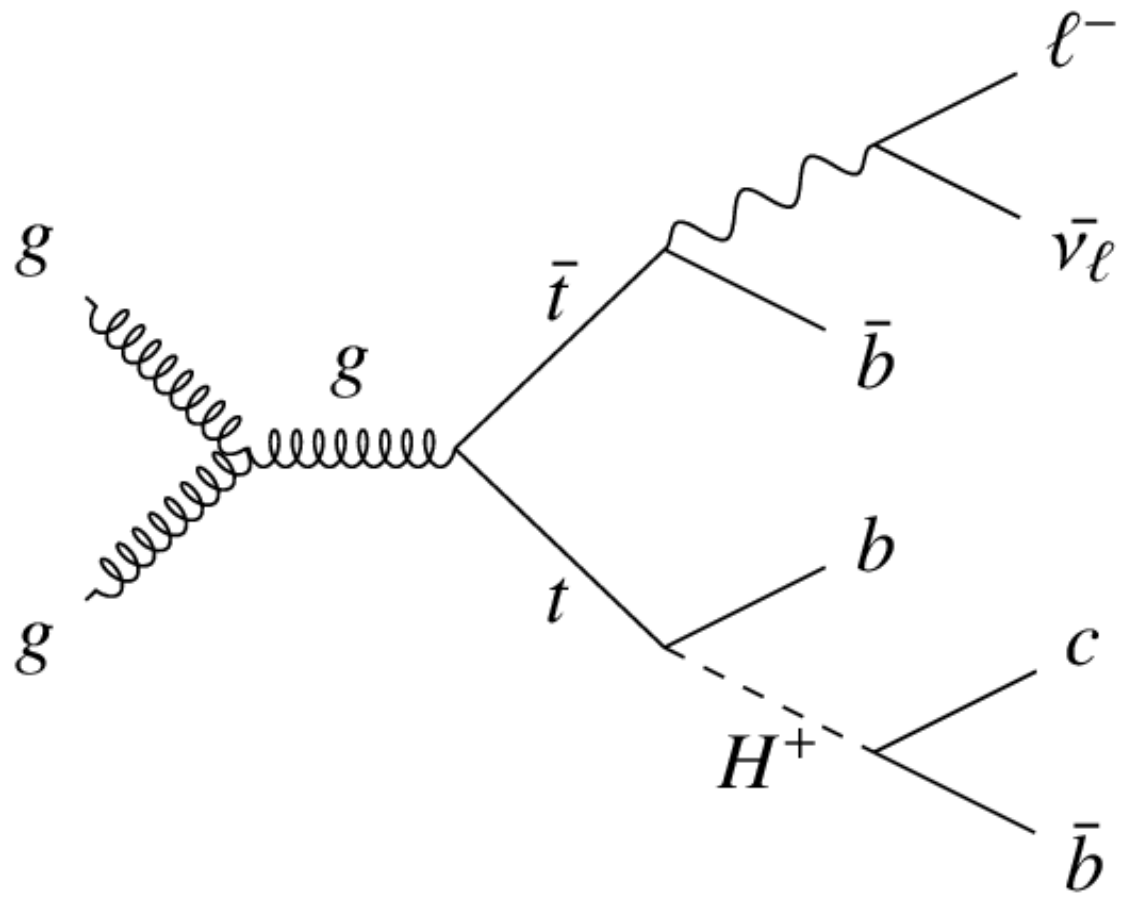


- Search for H^+ instead of W^+ in $t\bar{t}$ decays
  - NN to isolate signal jets from SM background
  - Largest excess for $m_{H^\pm} = 130\,\mathrm{GeV}$:
    - Best-fit $\mathcal{B}\left(t \to bH^\pm\right) \times \mathcal{B}\left(H^\pm \to cb\right) = \left(0.16 \pm 0.06\right)\%$
    - $\approx 3\sigma$ (2.5σ) local (global) significance



Karsten Köneke

Charged Higgs in Top Decays



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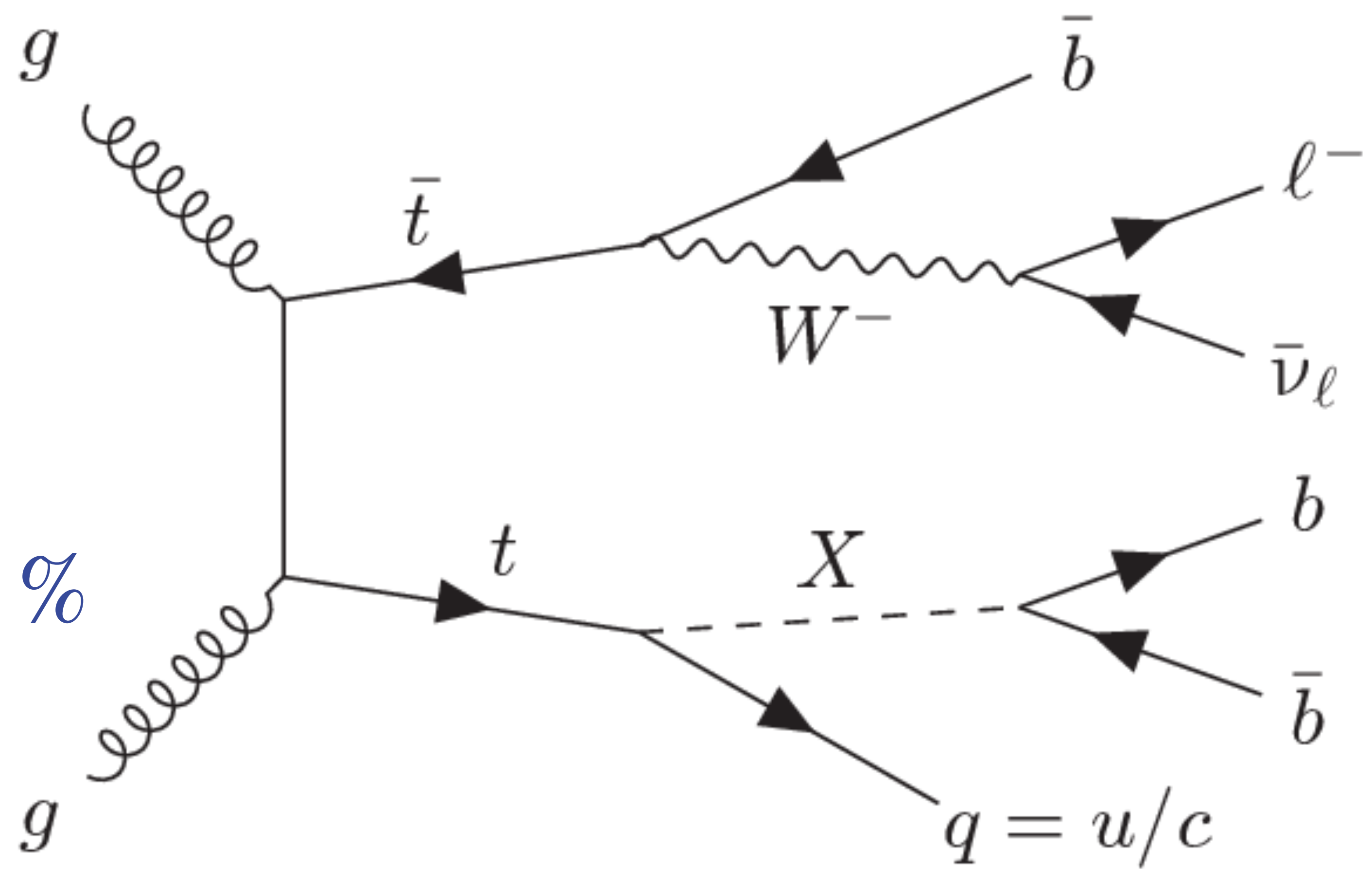
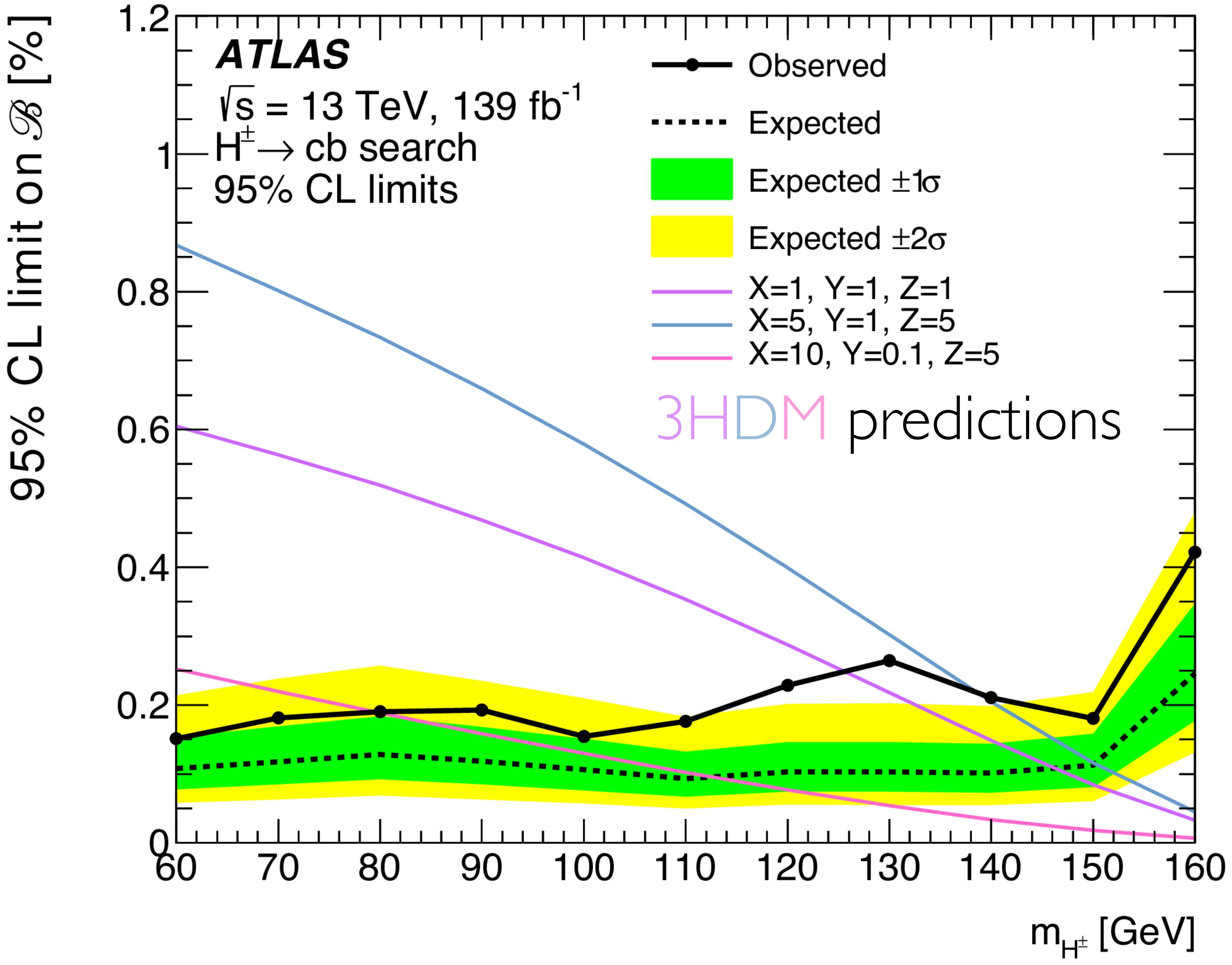
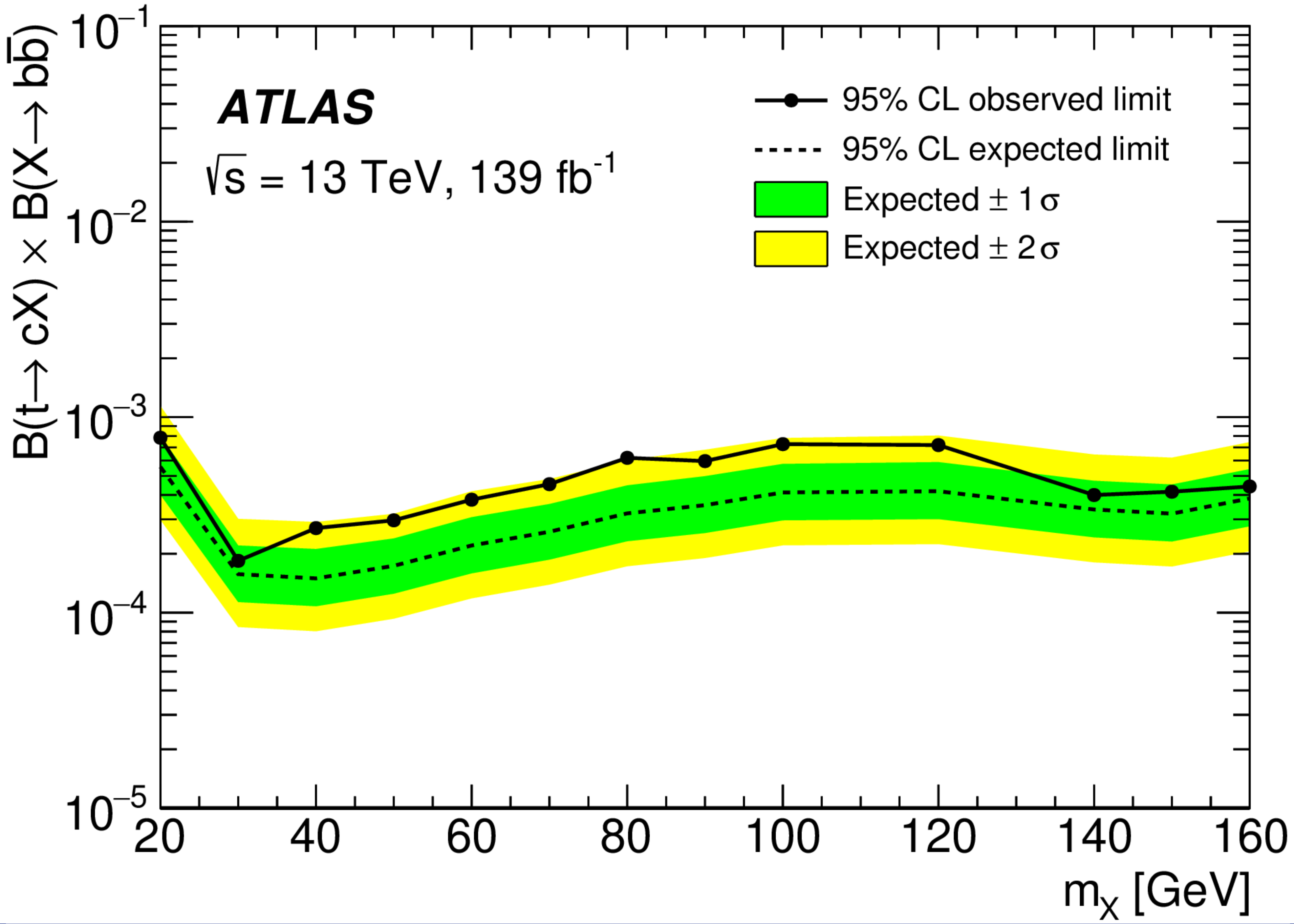




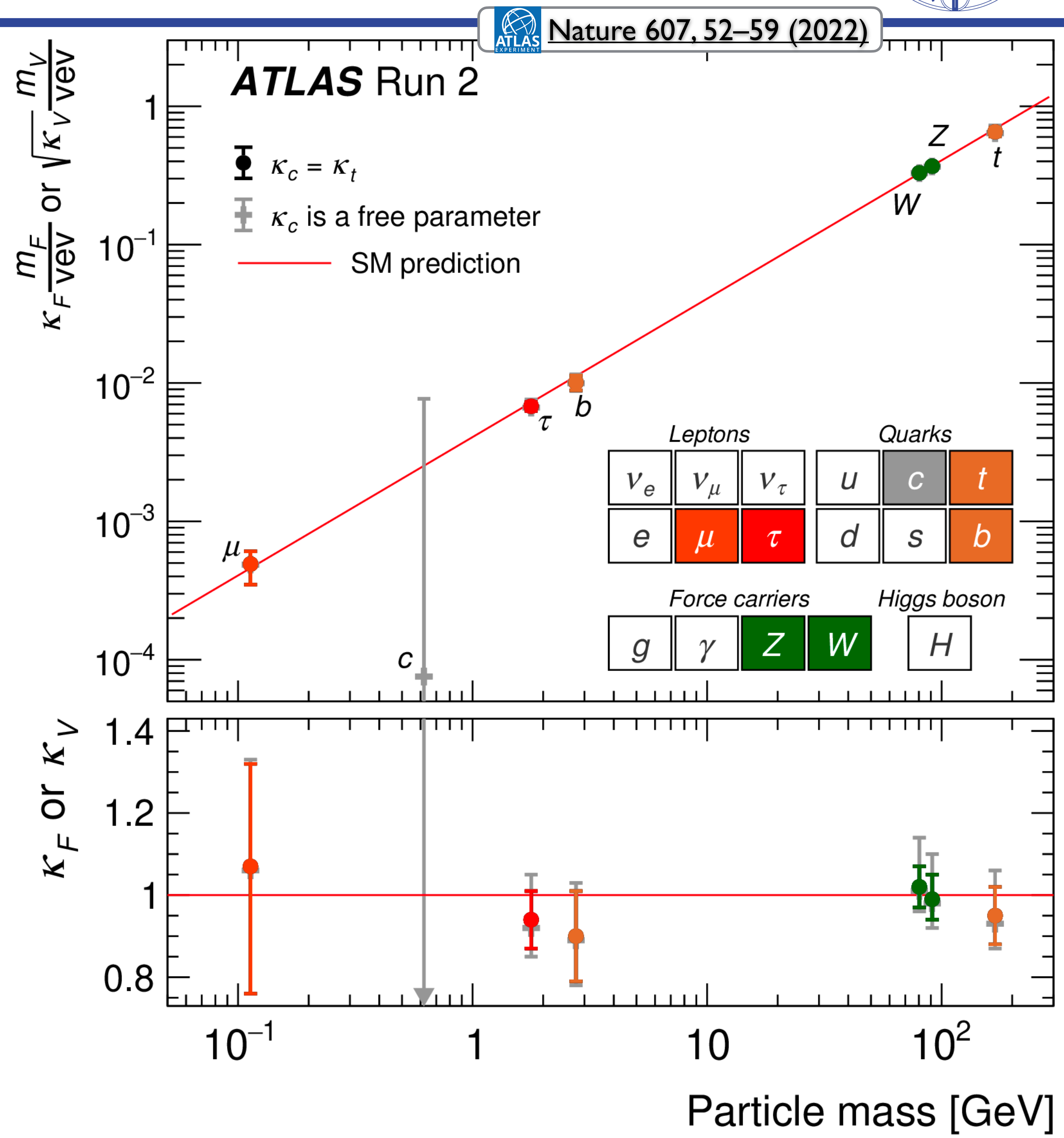
- Related search with similar final state: $t \to cX\left(b\bar{b}\right)$
  - $\approx 2\,\sigma$ local broad excess
  - Not compatible with narrow $X \to b\bar{b}$,
  - But $H^\pm \to cb$ could cause this



 Karsten Köneke

Concluding Remarks

Mass ~ Coupling Strength?

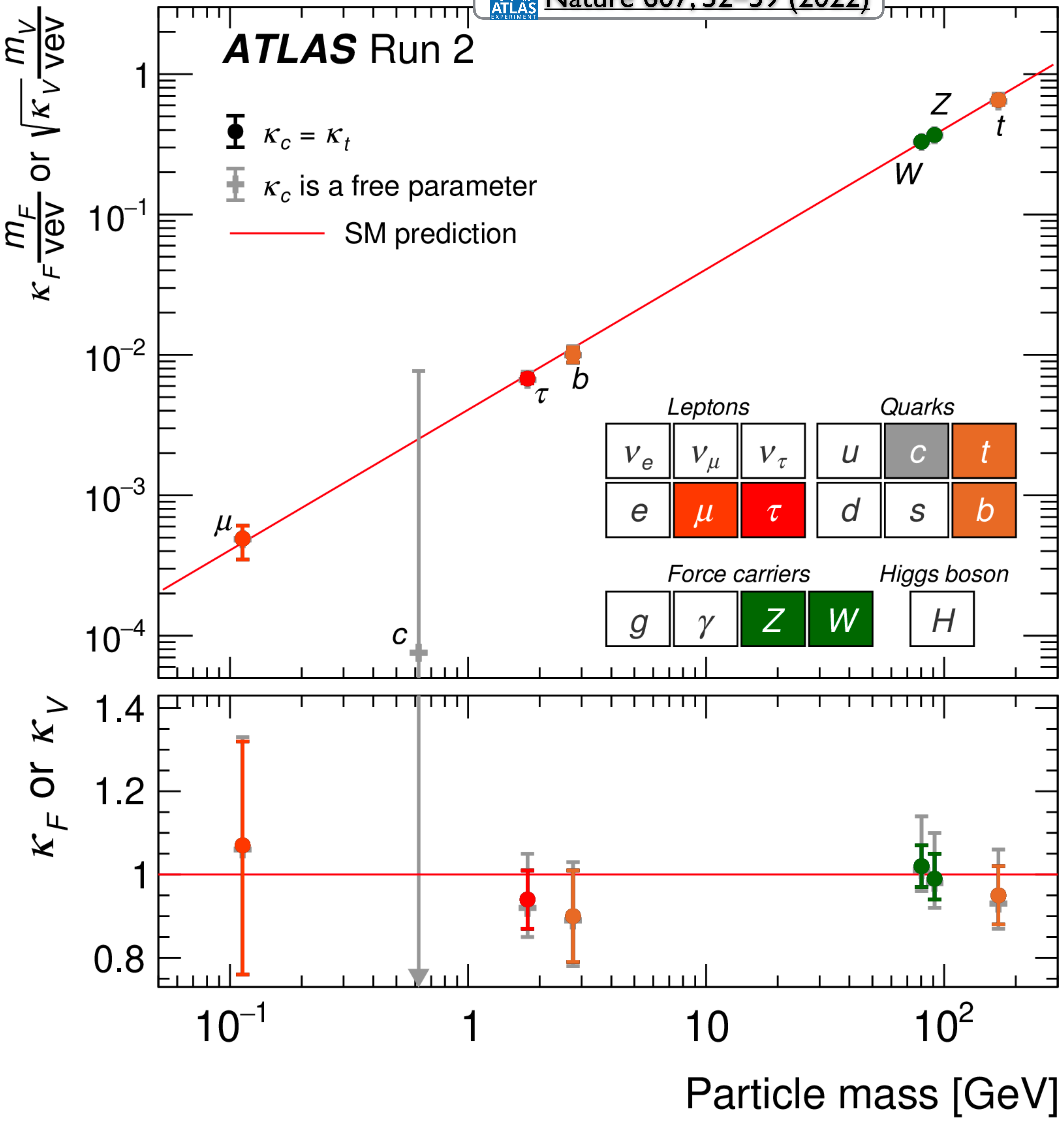


(*) simplified

Concluding Remarks

$$\mathscr{L}_{\text{Higgs}} = (D_\mu\phi)^2 - \mu^2\phi^2 - \lambda\phi^4 + \lambda_f\phi\bar{\psi}\psi$$

Nature 607, 52–59 (2022)



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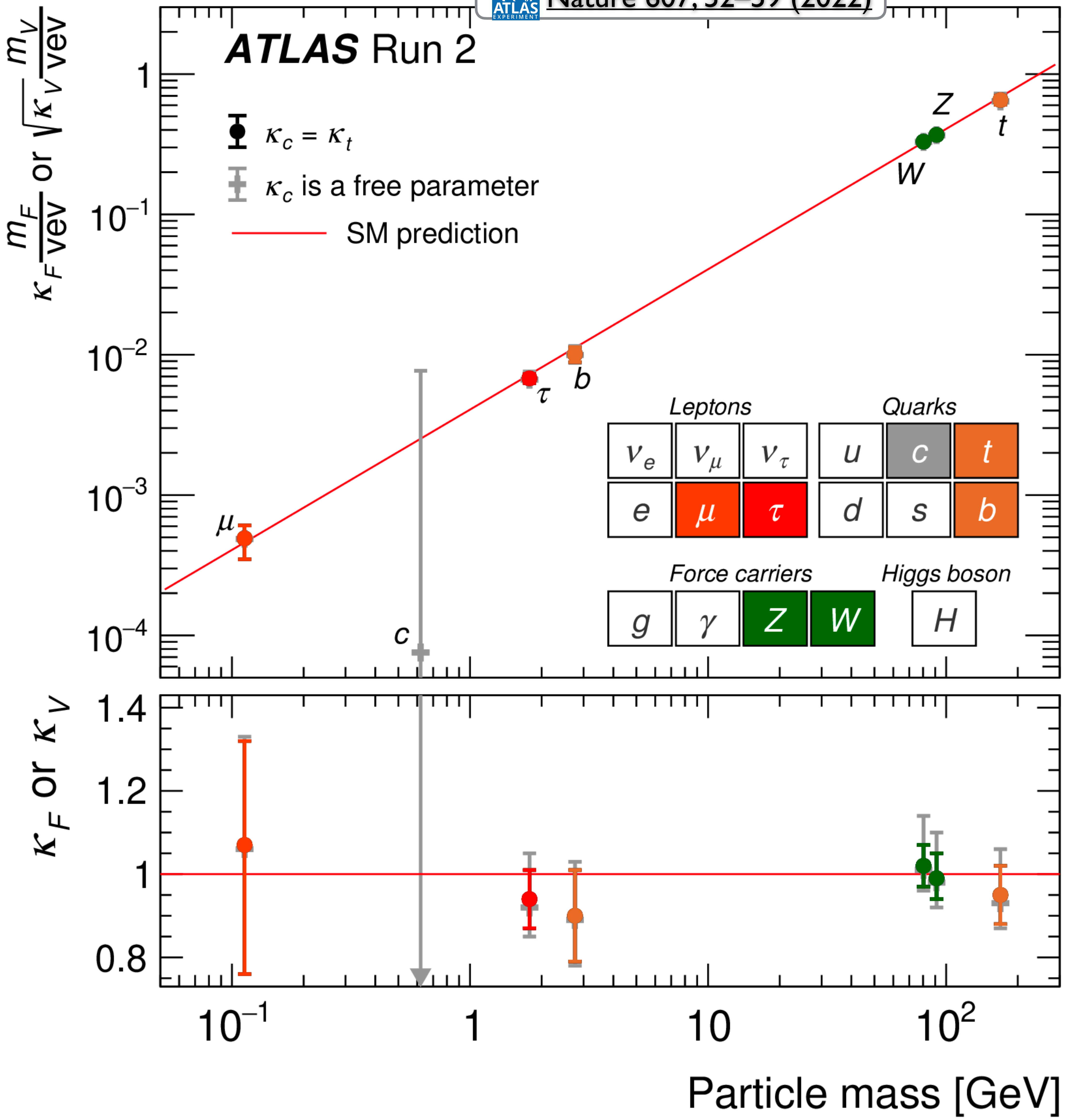
The heart of the Standard Model is beating strong

- Plethora of new results improves our understanding of nature

Nature 607, 52–59 (2022)



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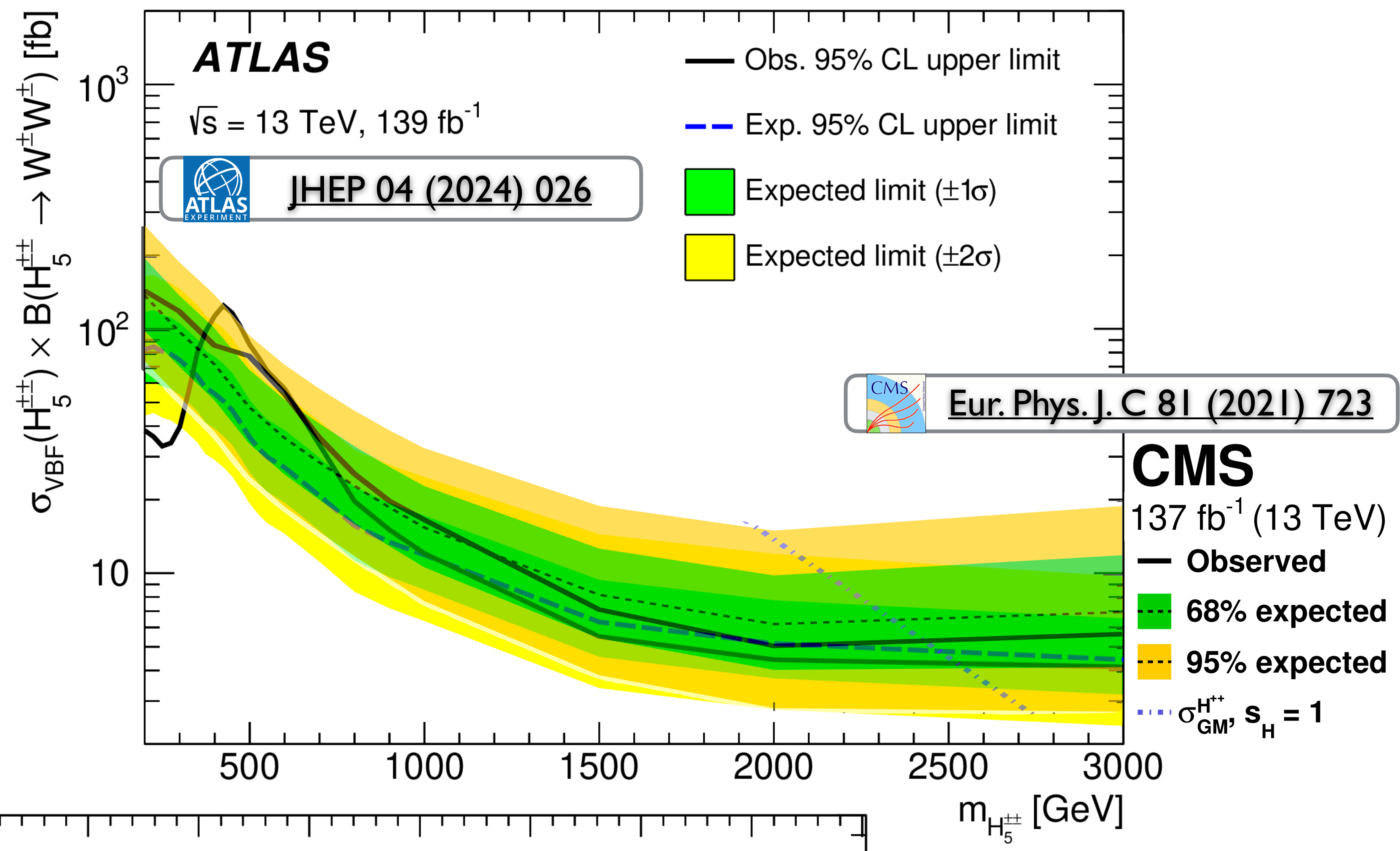
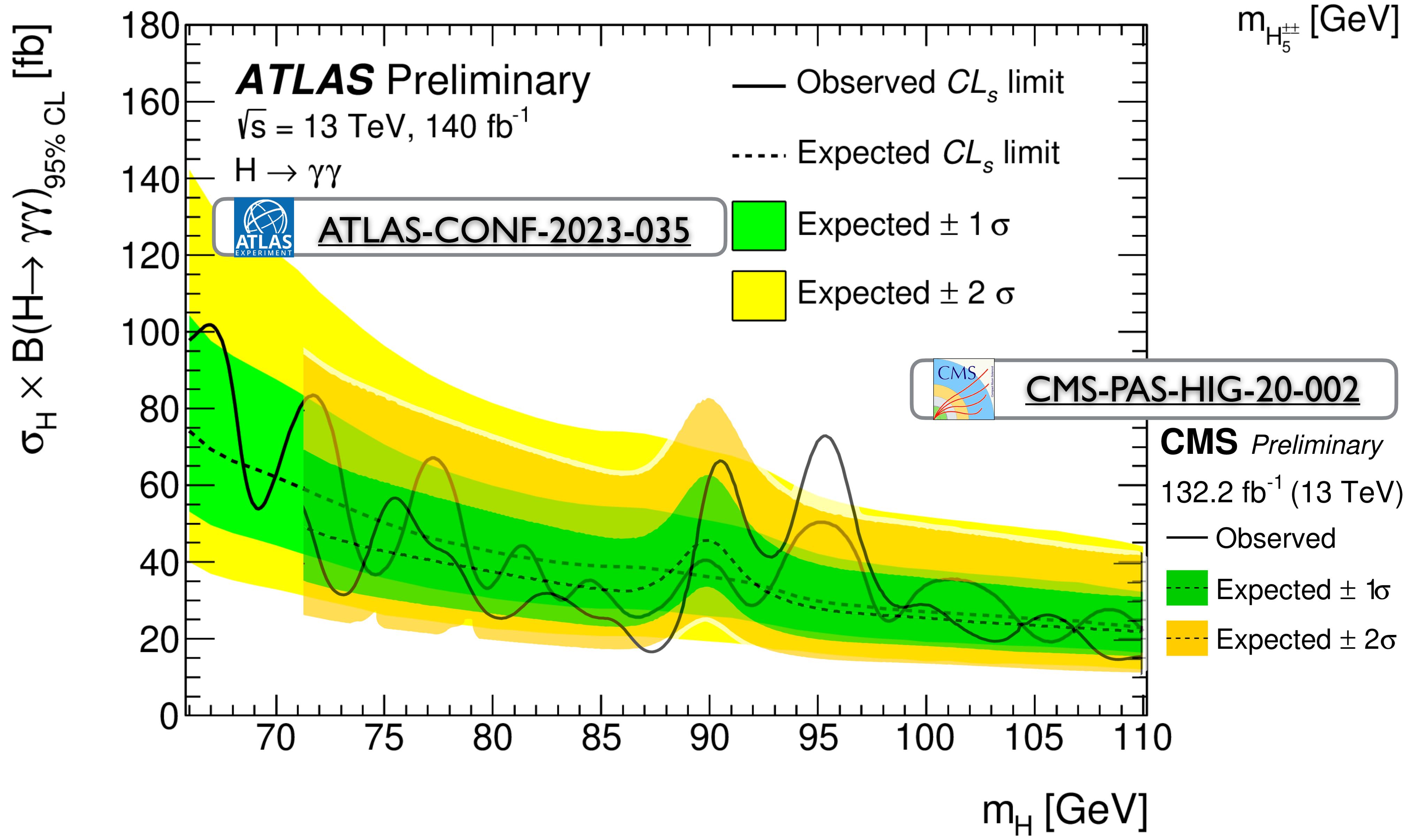
$$\mathscr{L}_{\text{Nature}} = \mathscr{L}_{\text{SM}} + \mathscr{L}_{???}$$

Many small scalar-like excesses seen in Run 2 data

- But $\mathscr{L}_{???}$ still remains $\mathscr{L}_{???}$





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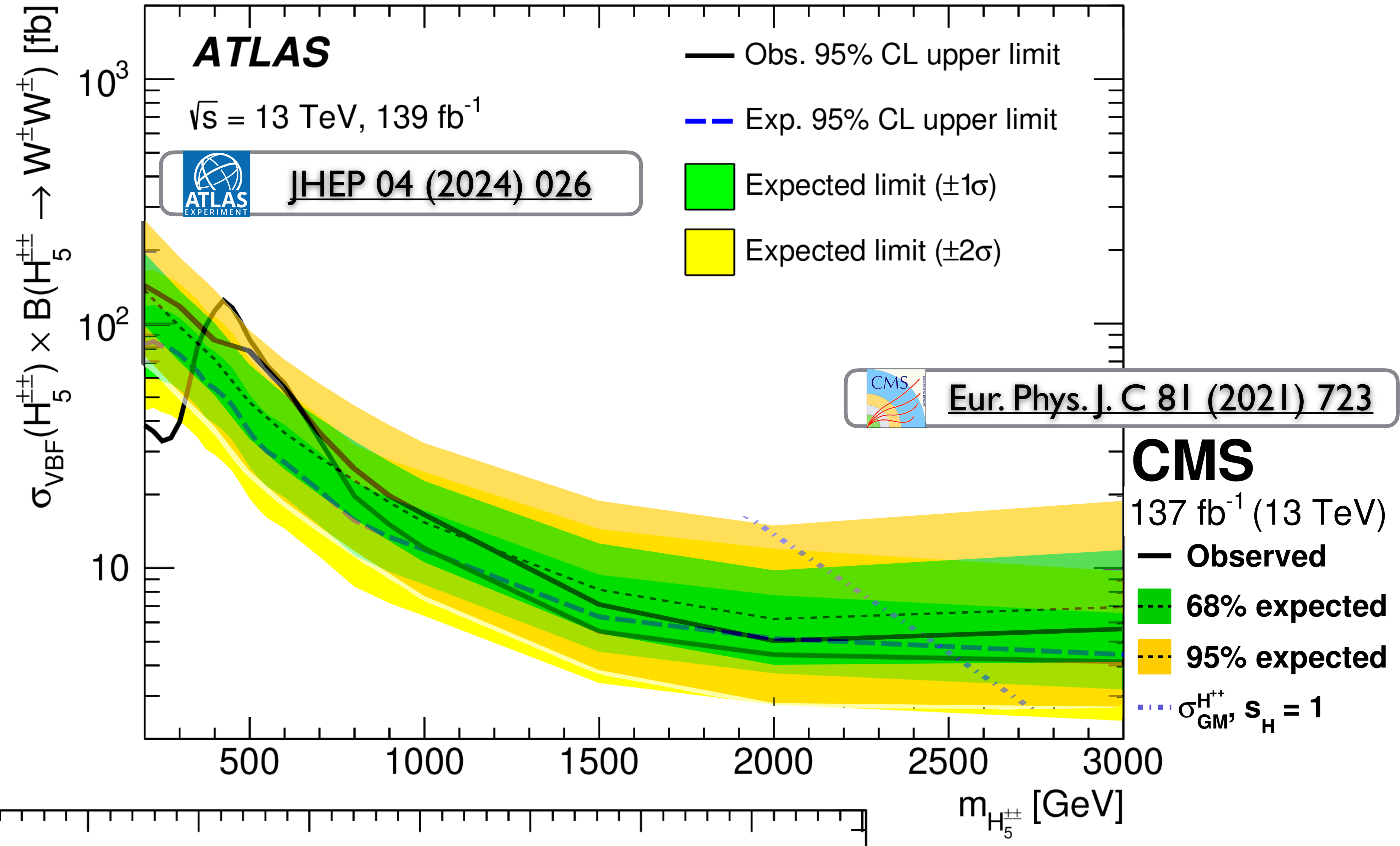
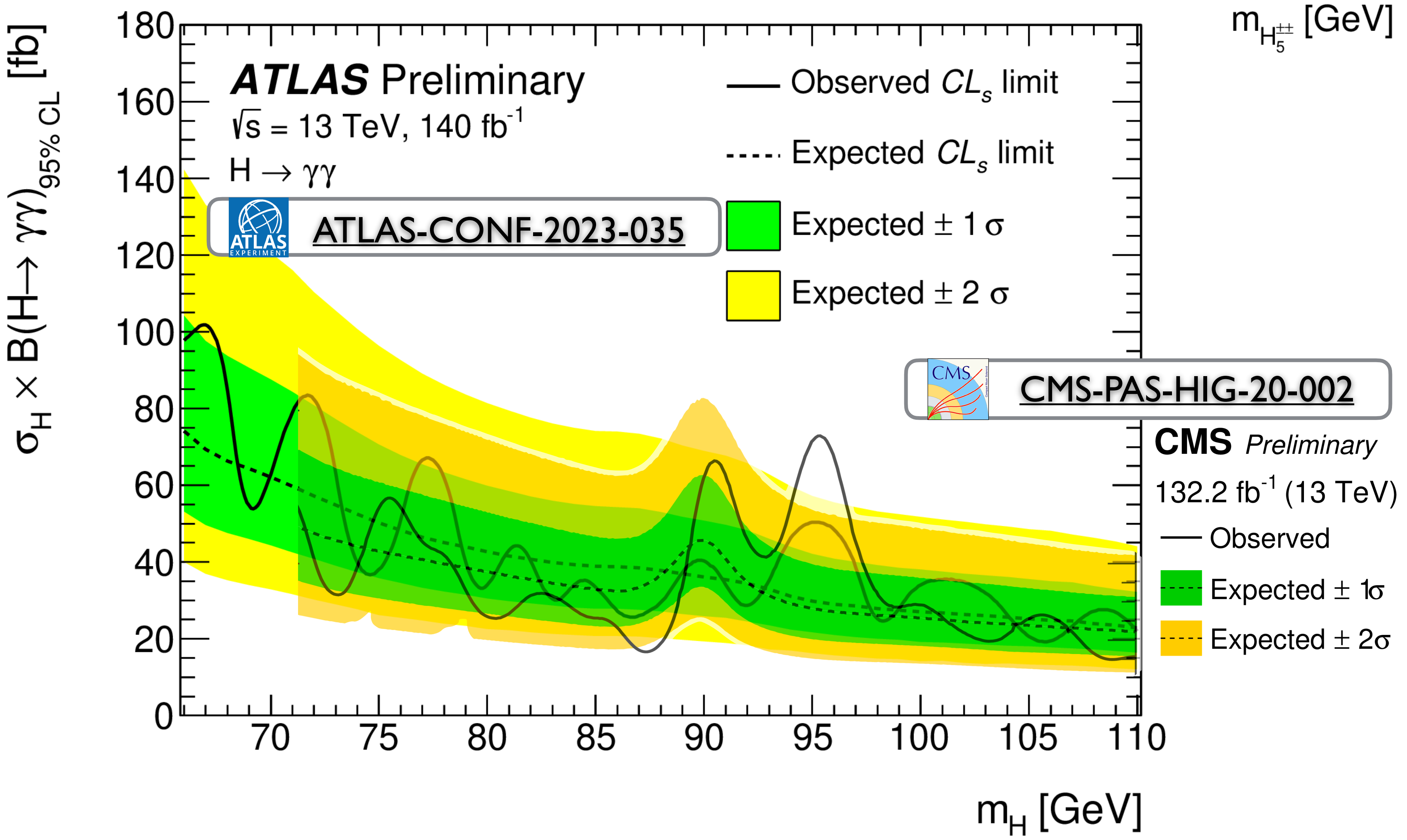
LHC Run 3: another boost in our understanding

- Not only due to higher statistical precision, but also due to the **ingenuity of people**!





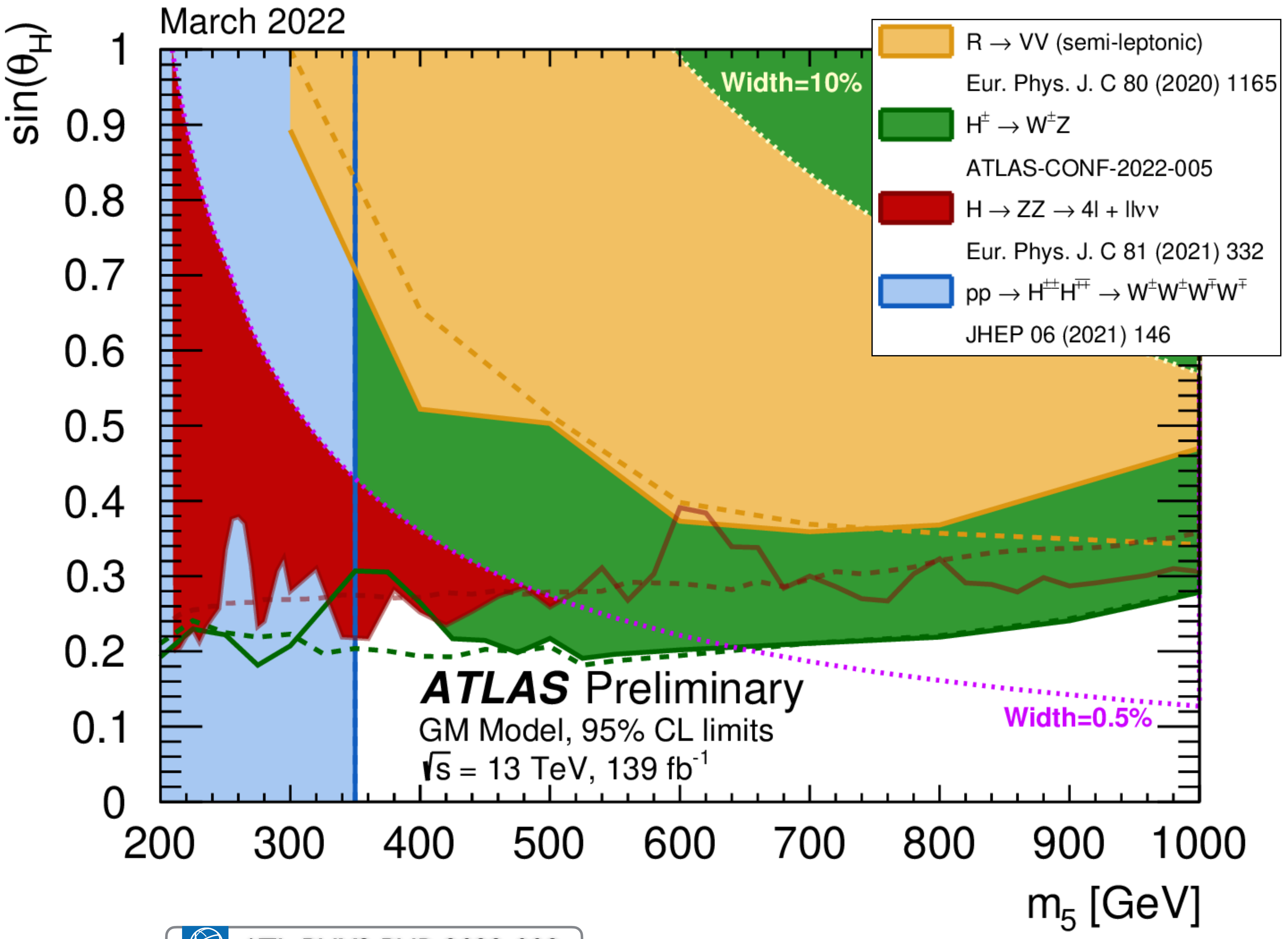
(*) simplified

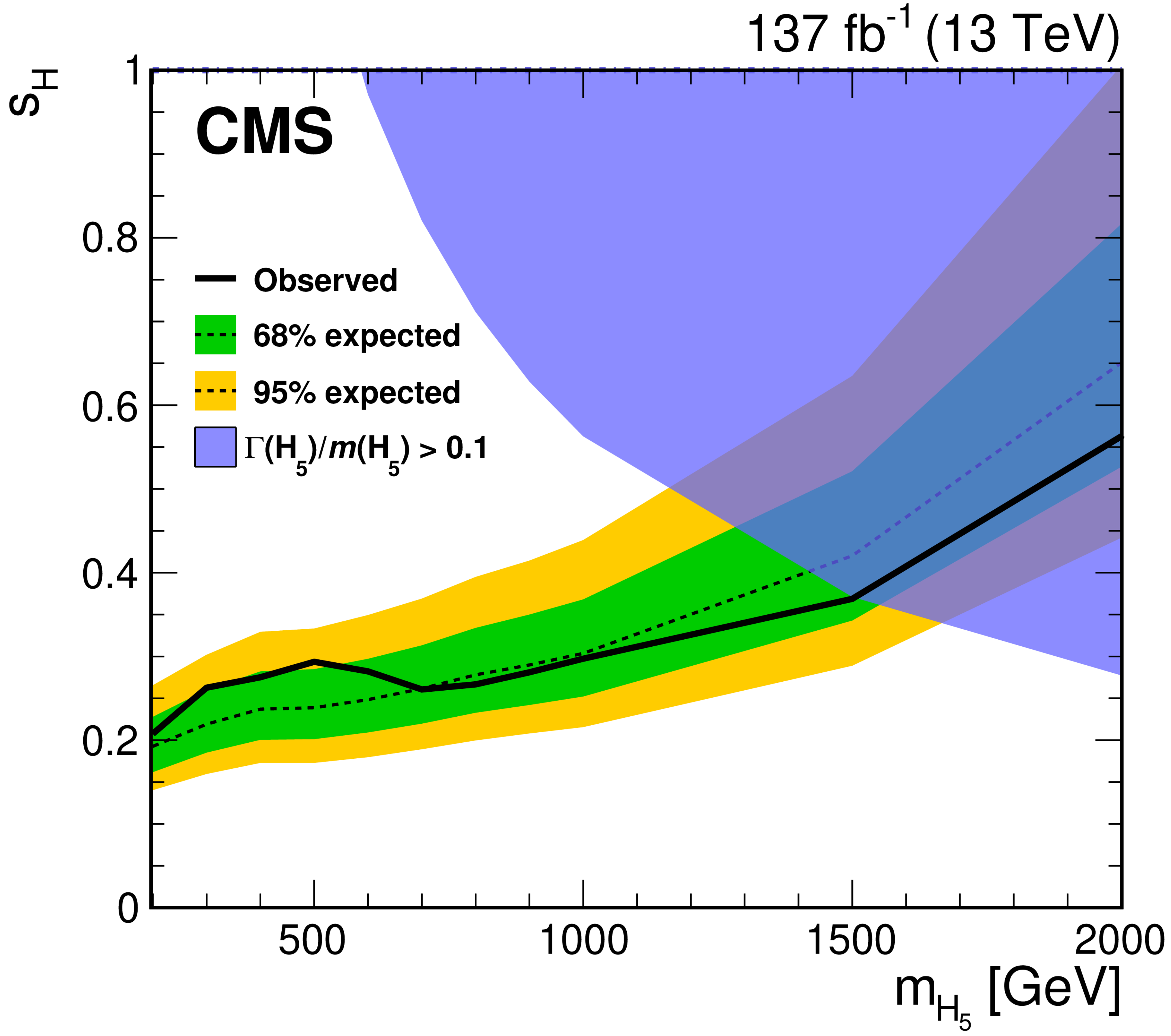
Look elsewhere effect: Local vs. Global significance

- Significance:
  - How likely does the background fluctuate to the observed (or more extreme) value ⇒ ***p-value***
  - Transform p-value into (local) significance assuming Gaussian probability distribution ⇒ $Z\sigma$
    - $3 \leq Z < 4$: "evidence"; $4 \leq Z < 5$: "strong evidence"; $Z \geq 5$: "observation"
  - Depends on background
- When there is another unknown signal parameter, e.g., unknown mass m_X of a resonance: what to do?
  - How to claim "*observation*" for any value of m_X within a search range?
    - Much larger chance to find an excess in a narrow mass window if we scan this narrow window over a very wide mass range ⇒ "***look elsewhere effect***"
  - Correct p-value by scaling it by the "*number of places we have looked*", or a "***trials factor***"
    - ***Trials factor*** could, e.g., be simply $\frac{\text{wide mass search range}}{\text{mass resolution}}$
  - Often called "*Bonferroni-type* correction"

Georgi-Machacek model

- $\sin\theta_H = s_H$: characterizes the contribution of the isotriplet scalar fields to the masses of the W and Z bosons





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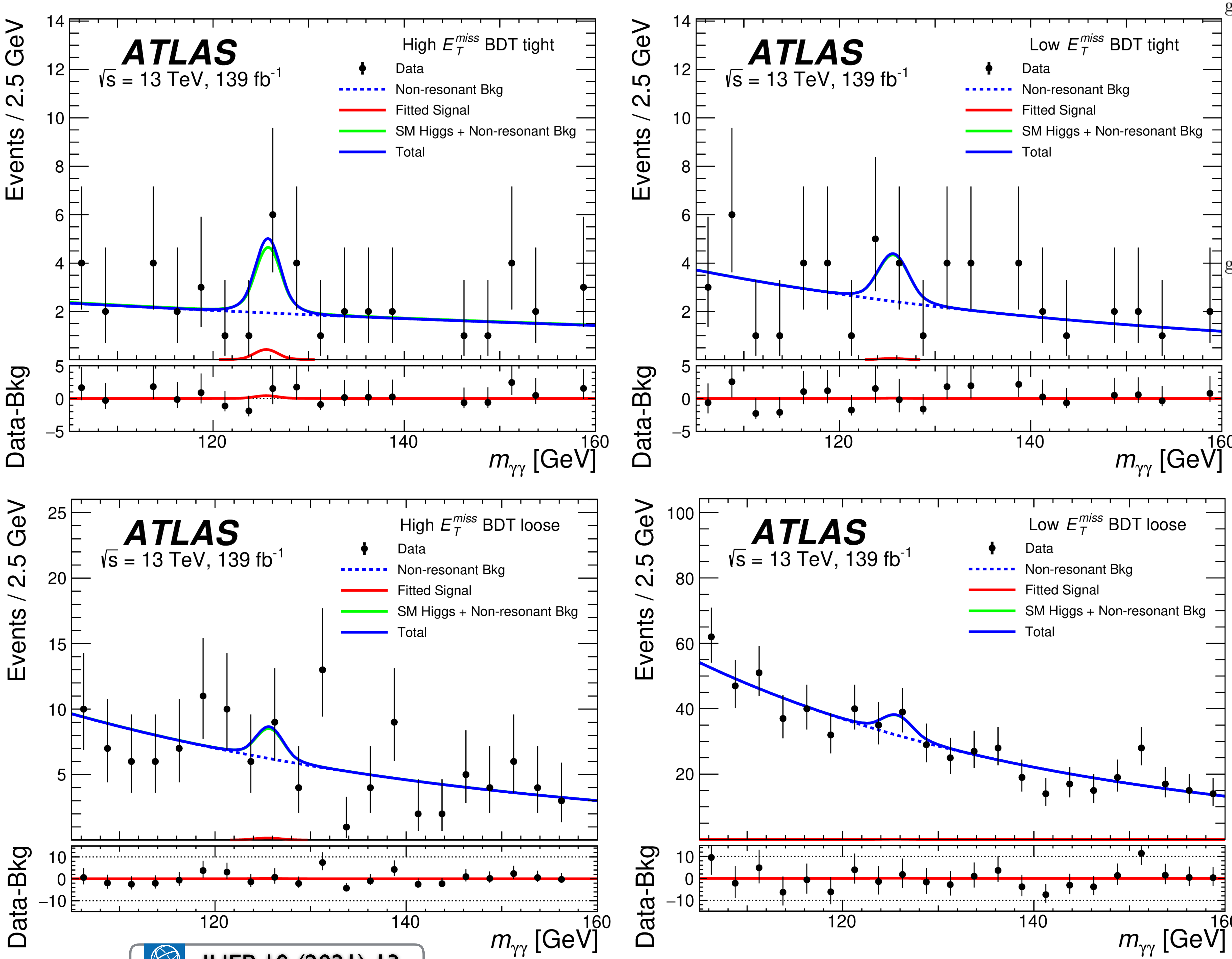
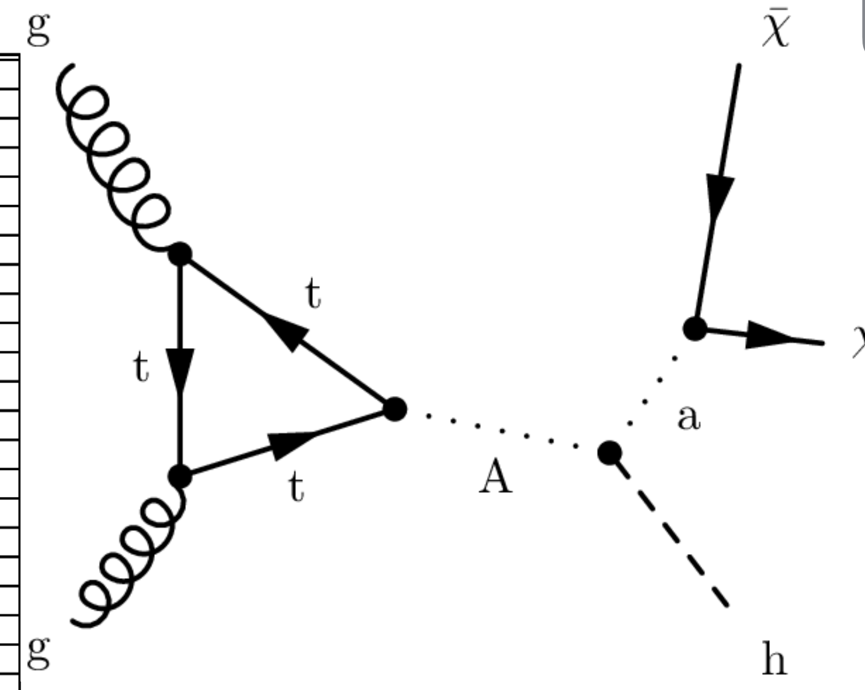
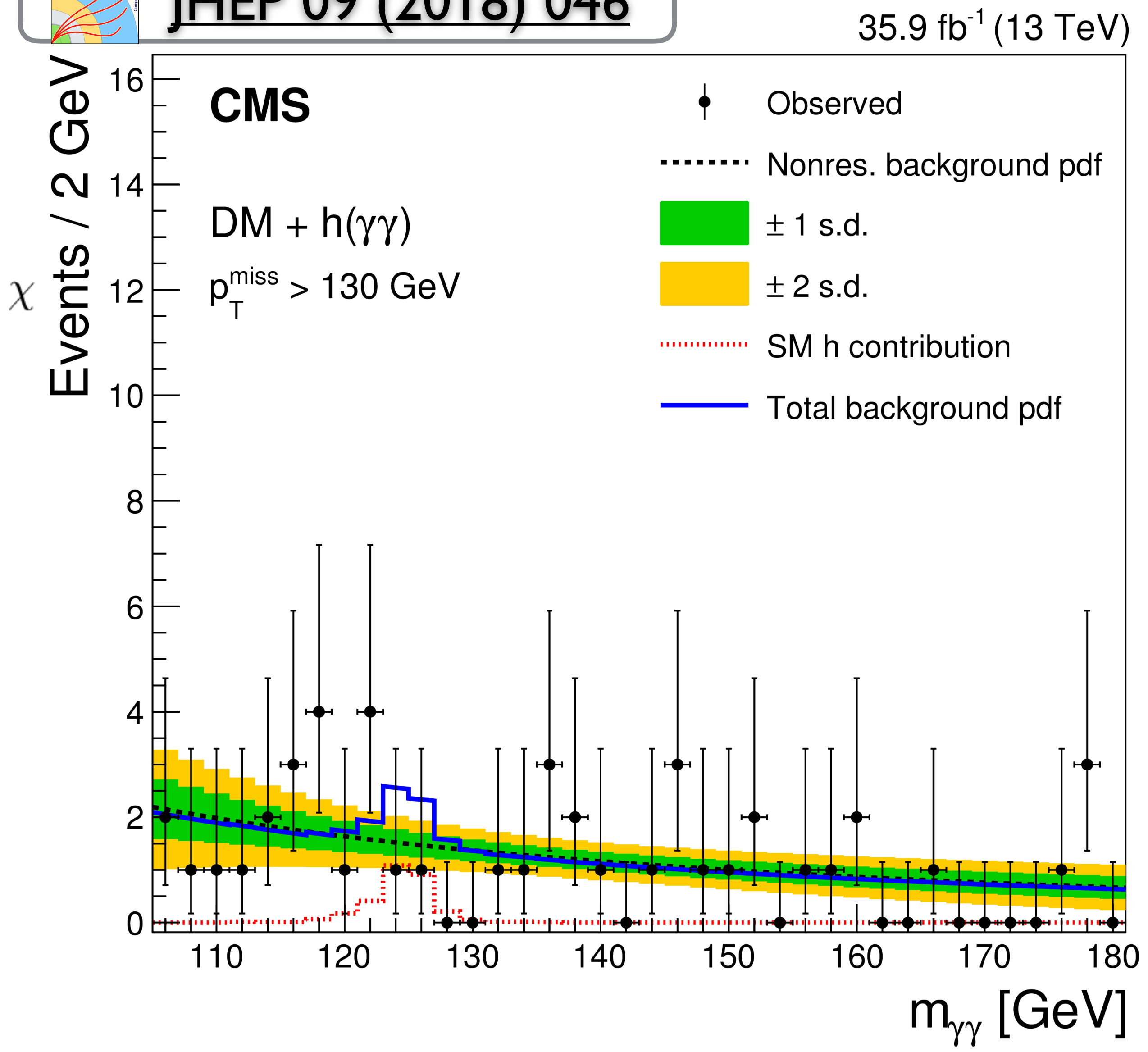
$S \to \gamma\gamma$ near 152 GeV?



JHEP 10 (2021) 13

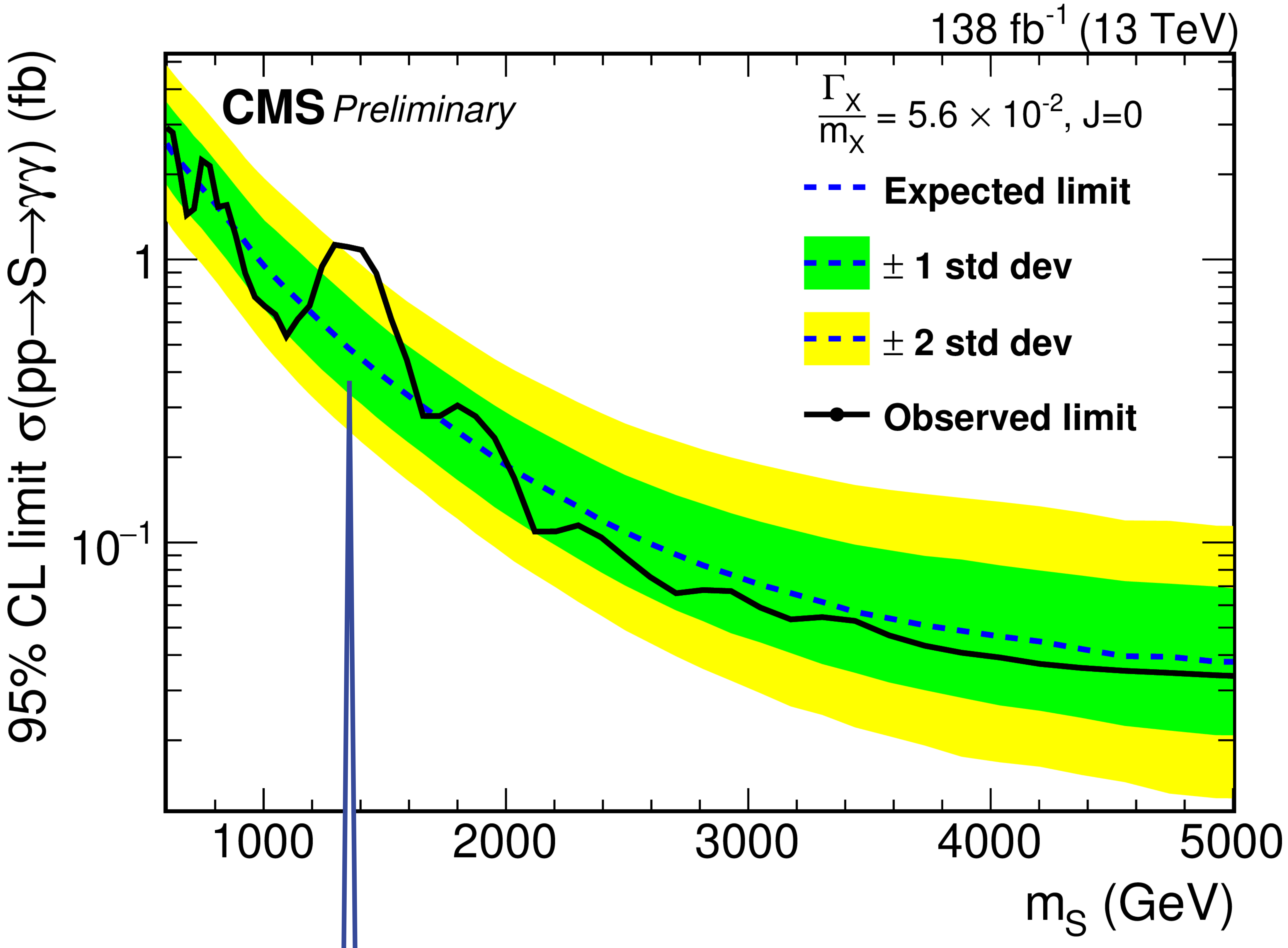


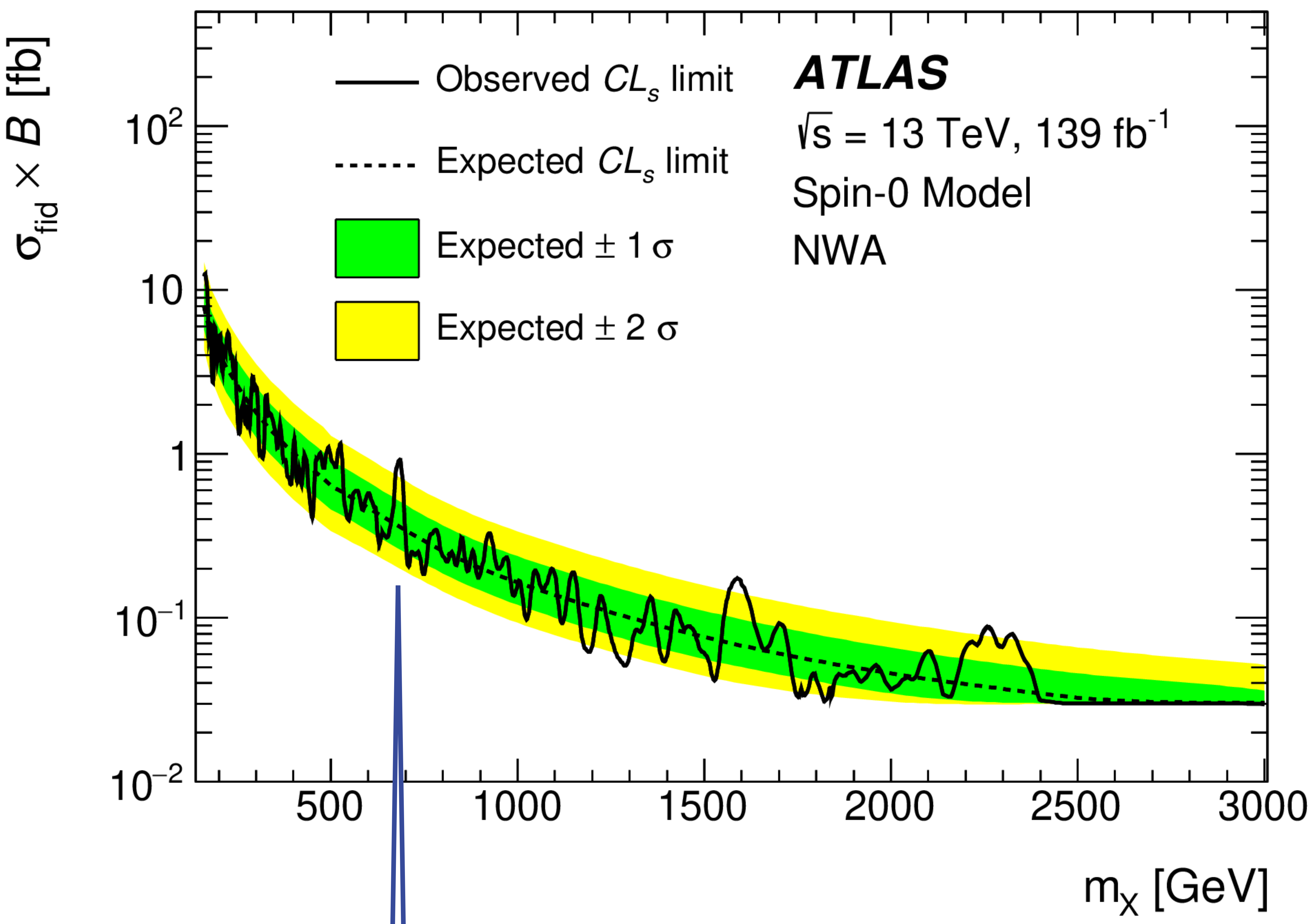
JHEP 09 (2018) 046



- I am not excited…

$H \to \gamma\gamma$ high mass





Largest excess at $m_S = 1320\,\mathrm{GeV}$:

- $\Gamma_X/m_X = 5.6\,\%$
- $2.6\,\sigma$ local, $0.8\,\sigma$ global;

CMS-PAS-EXO-22-024

Largest excess at $m_S \approx 684\,\mathrm{GeV}$:

- $3.29\,\sigma$ local, $1.30\,\sigma$ global;
- Nothing near 1320 GeV

Phys. Lett. B 822 (2021) 136651

Outline

$$\mathscr{L}_{\text{Higgs}} = \boxed{(D_\mu\phi)^2} - \mu^2\phi^2 - \lambda\phi^4 + \boxed{\lambda_f\phi\bar{\psi}\psi}$$

2. CP coupling structure

- in Higgs coupling to bosons
- in Higgs coupling to fermions

(*) simplified

CP Measurement in HVV Coupling

CP-violation through interference of SM $\mathscr{M}_{\mathrm{SM}}$ (CP-even) with dim-6 CP-odd $\mathscr{M}_{CP-\mathrm{odd}}$:

$$|\mathscr{M}|^2 = |\mathscr{M}_{\mathrm{SM}}|^2 + 2c_i \mathrm{Re}(\mathscr{M}^*_{\mathrm{SM}} \mathscr{M}_{CP\text{-odd}}) + c_i^2 |\mathscr{M}_{CP\text{-odd}}|^2$$

(ℓ = electron or muon)

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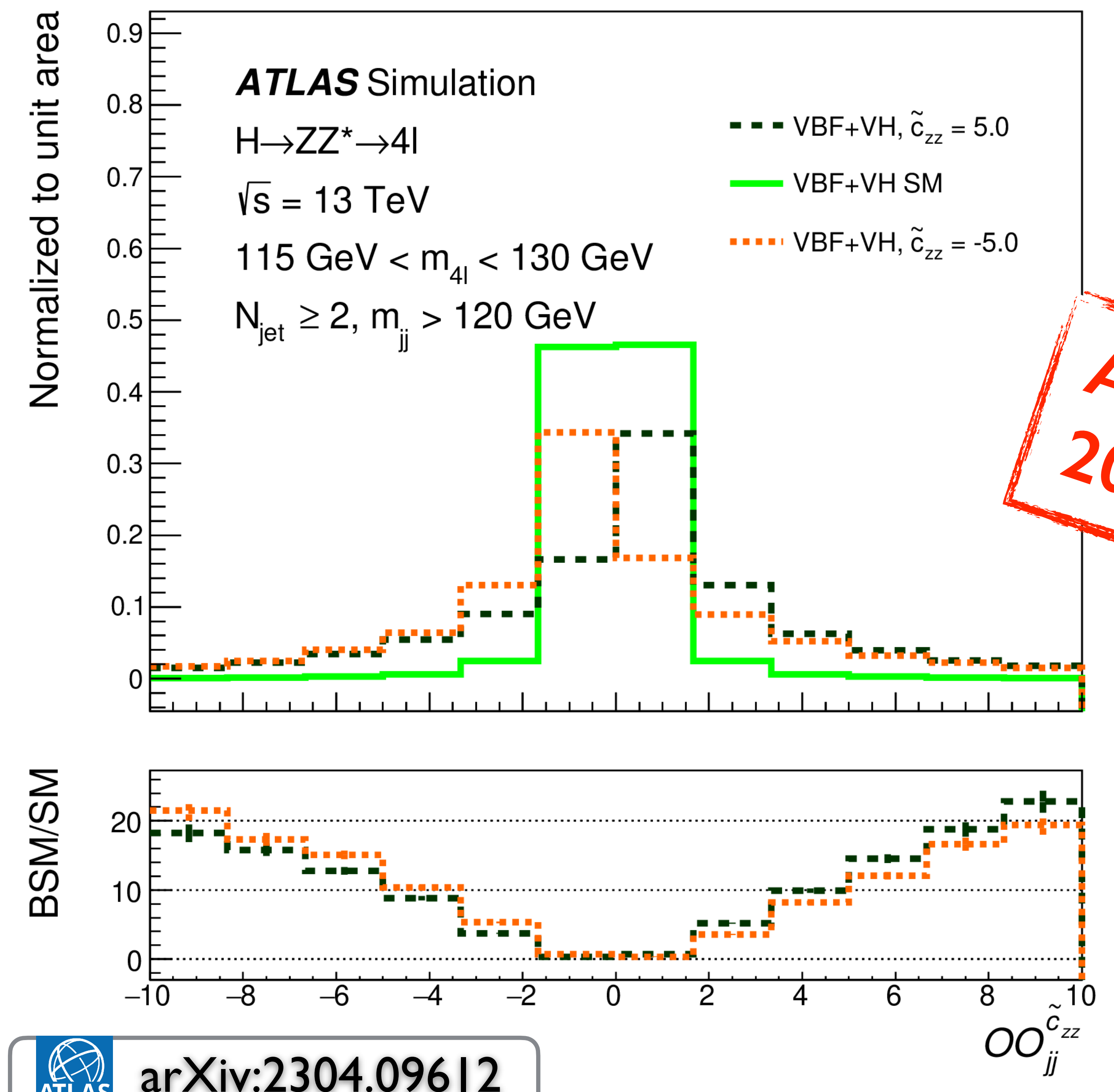
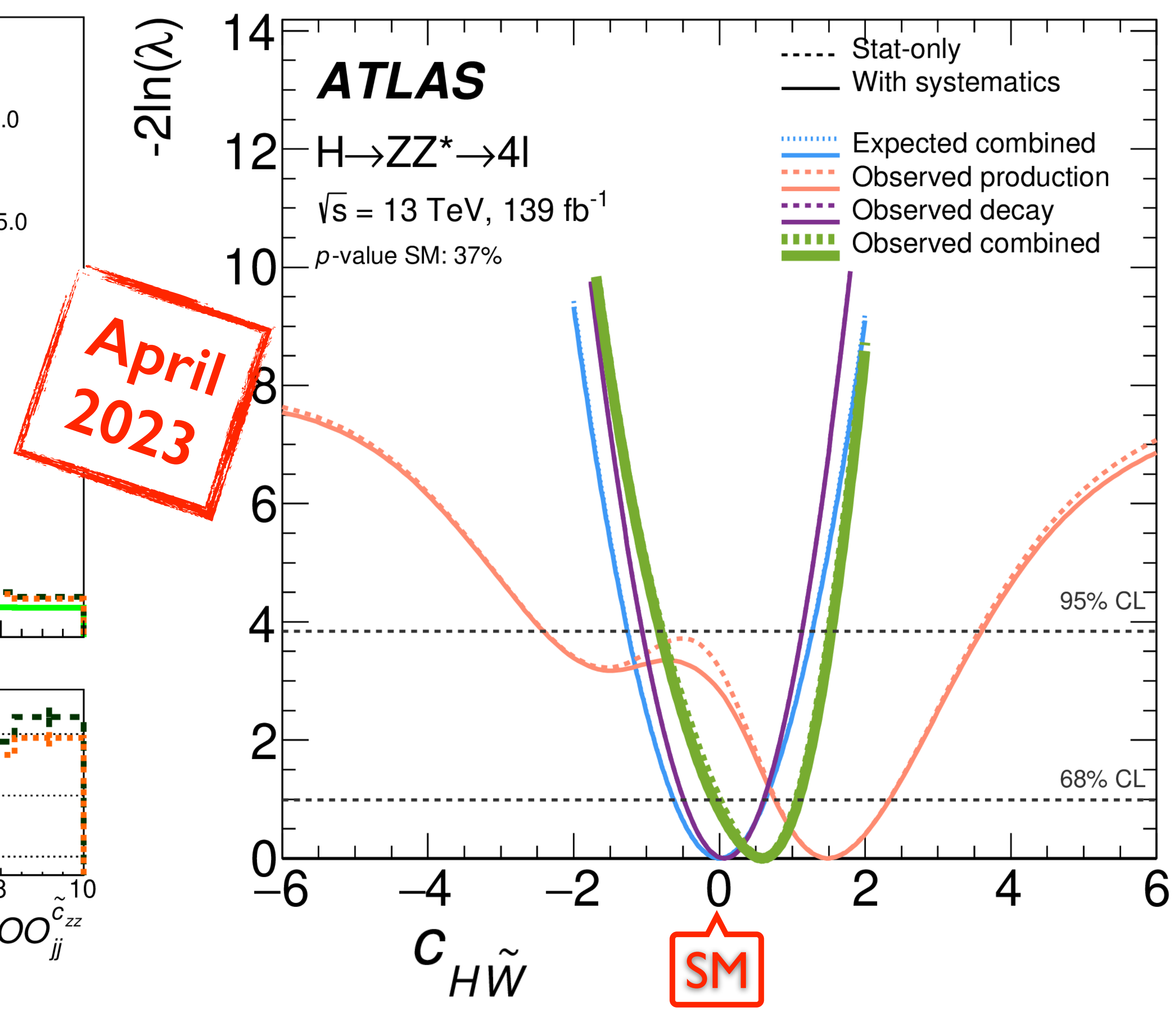
Optimal Observable:
$OO = 2\mathrm{Re}(\mathscr{M}^*_{\mathrm{SM}}\mathscr{M}_{\mathrm{CP-odd}})/|\mathscr{M}_{\mathrm{SM}}|^2$

VBF production and $H \to ZZ^* \to 4\ell$ decay



arXiv:2304.09612



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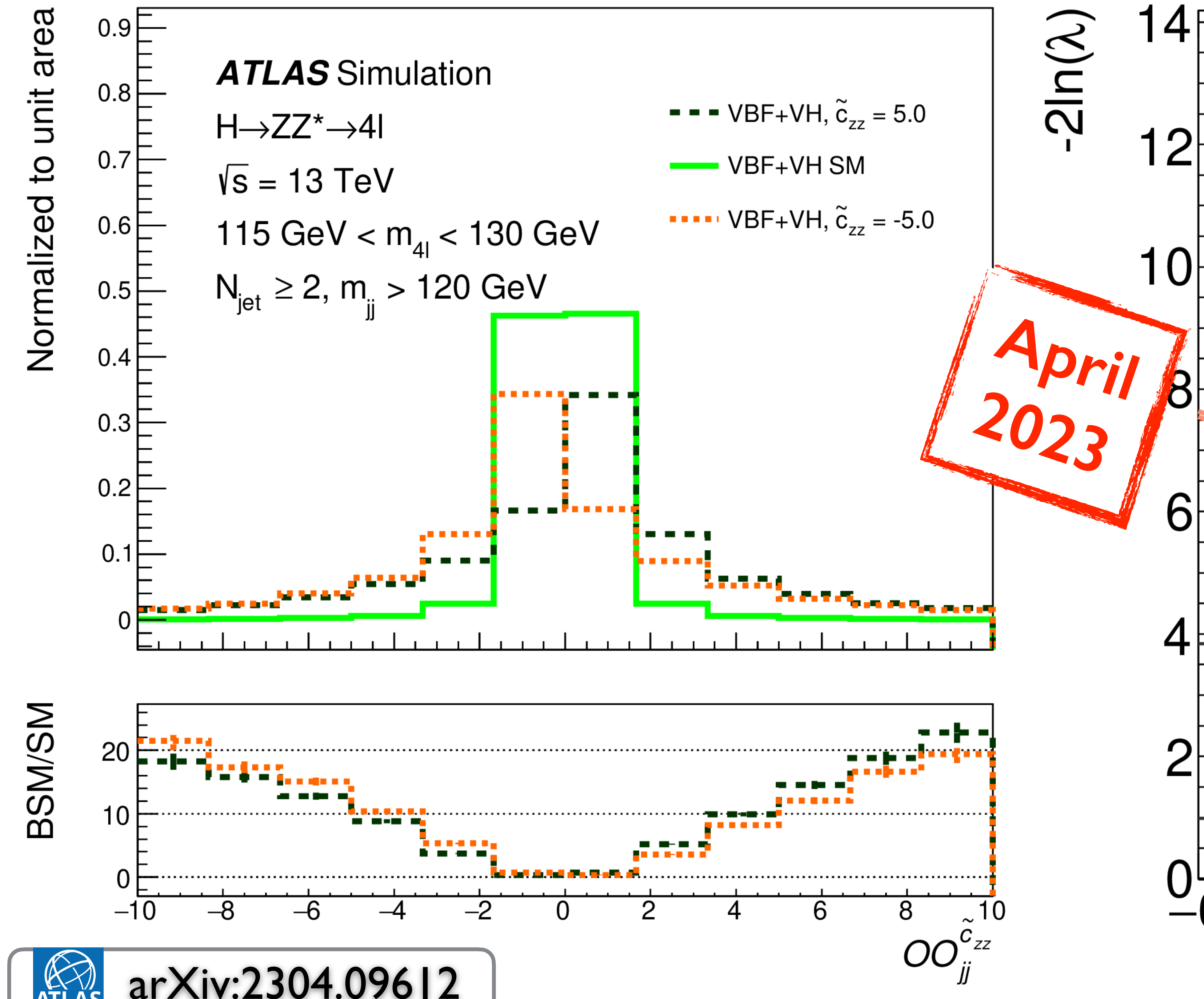

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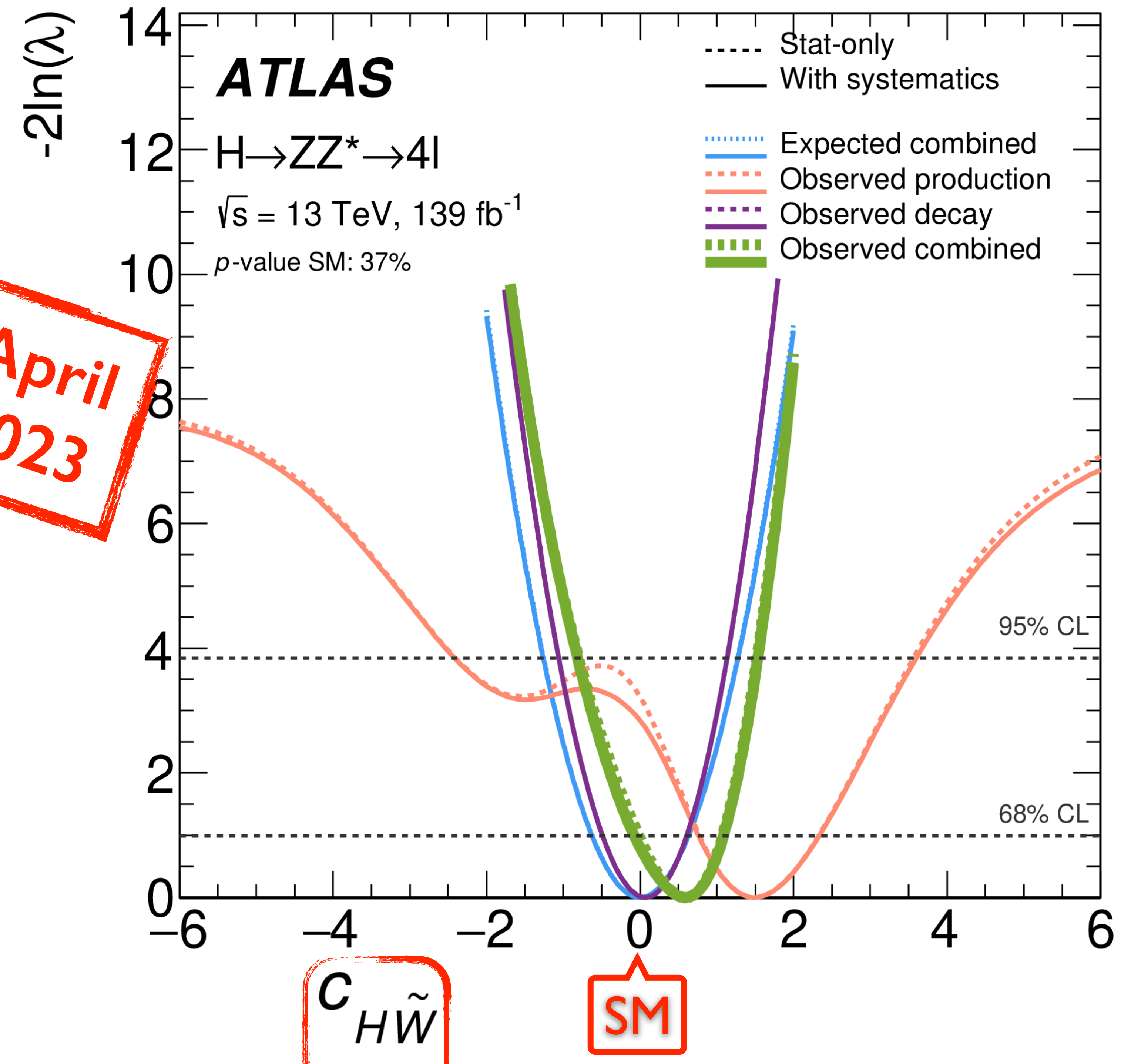

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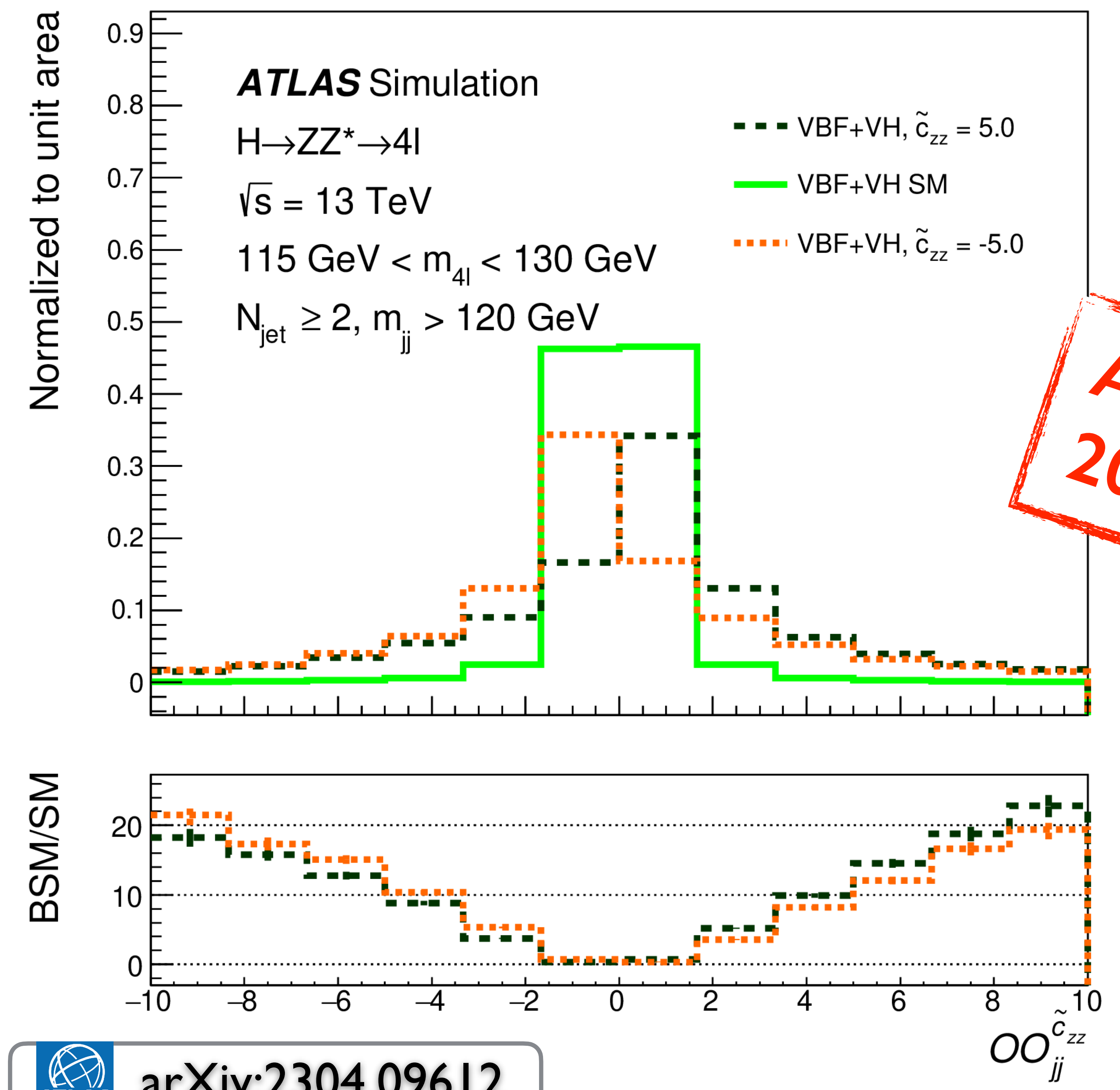
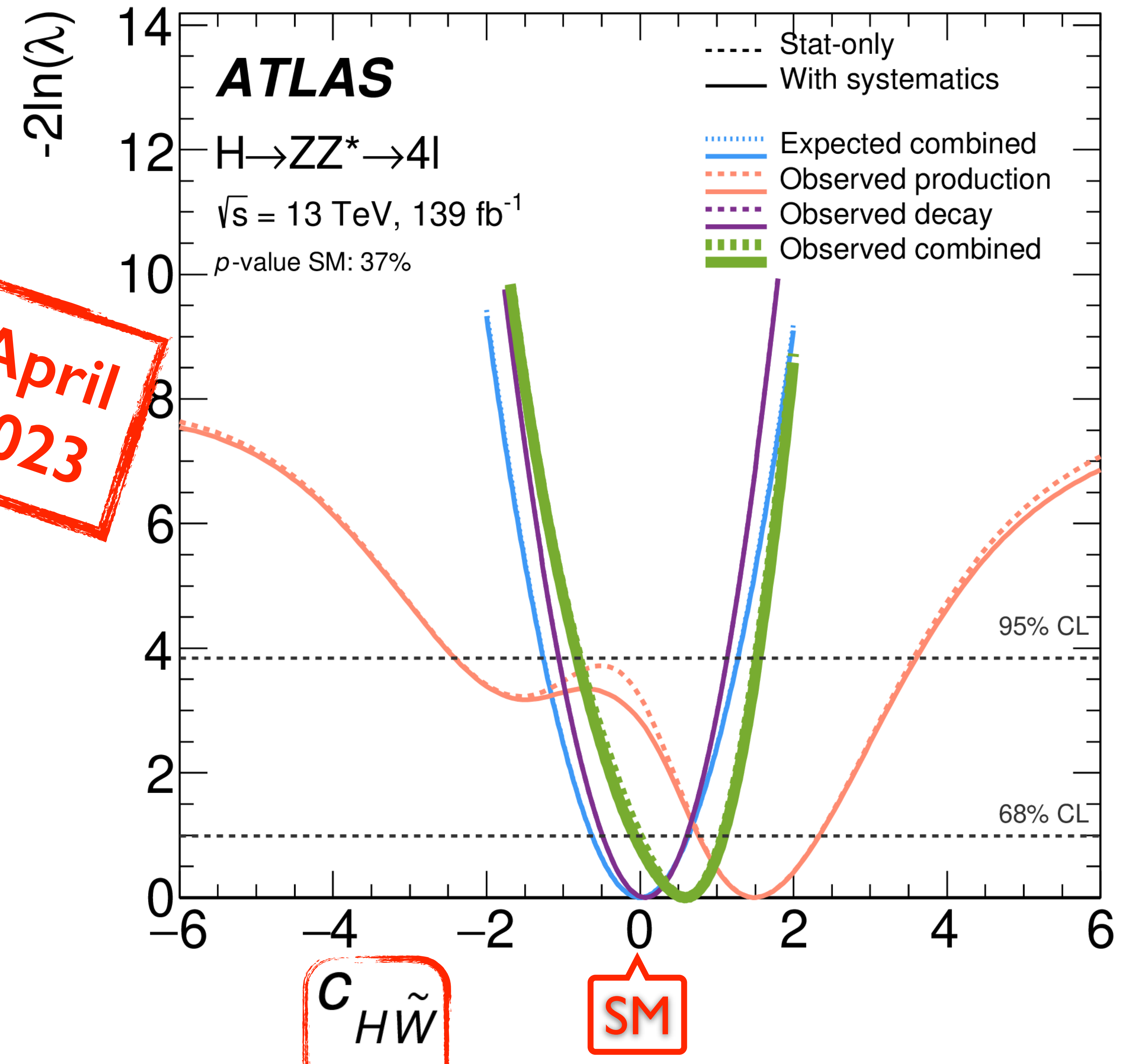
VBF production and $H \to ZZ^* \to 4\ell$ decay

ggF, VBF, VH production and $H \to WW^* \to e\nu\mu\nu$ decay

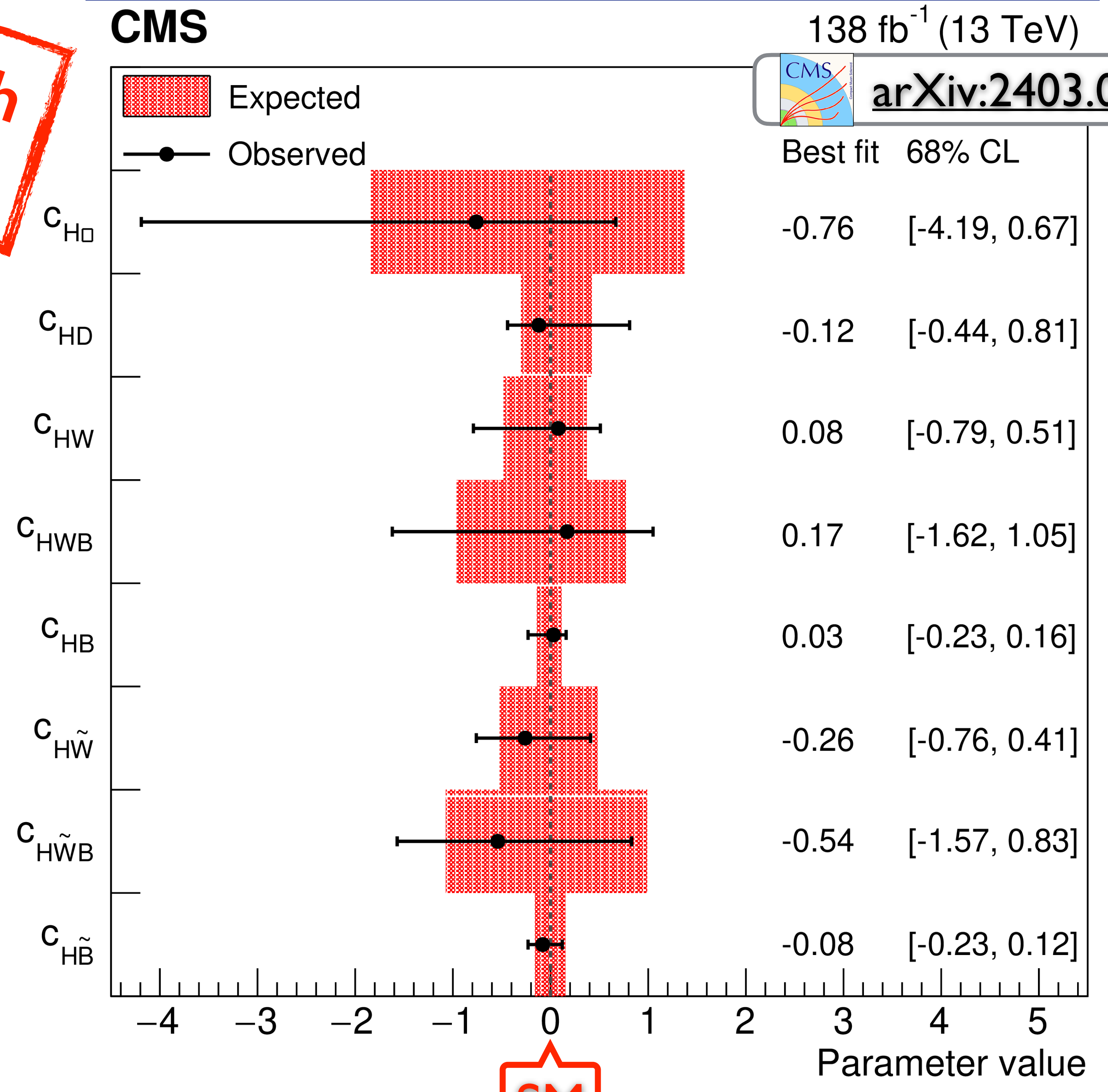


arXiv:2304.09612

April 2023



March 2024



arXiv:2403.00657

Parameter	Best fit	68% CL
$c_{H\Box}$	-0.76	[-4.19, 0.67]
c_{HD}	-0.12	[-0.44, 0.81]
c_{HW}	0.08	[-0.79, 0.51]
c_{HWB}	0.17	[-1.62, 1.05]
c_{HB}	0.03	[-0.23, 0.16]
$c_{H\tilde{W}}$	-0.26	[-0.76, 0.41]
$c_{H\tilde{W}B}$	-0.54	[-1.57, 0.83]
$c_{H\tilde{B}}$	-0.08	[-0.23, 0.12]

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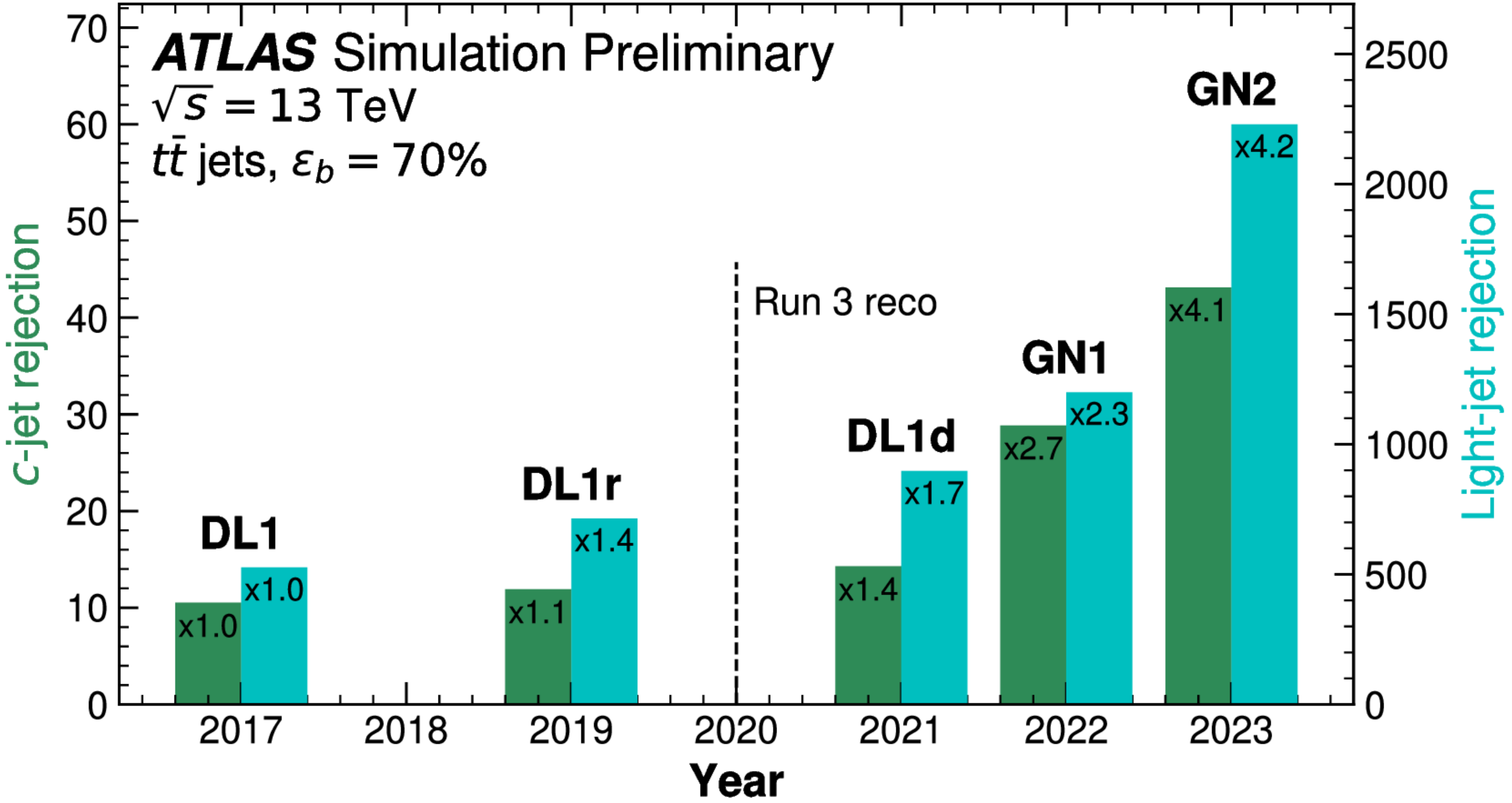
More: CP measurements in Higgs-Fermion couplings

(ℓ = electron or muon)

Progress in Experimental Techniques (in a tiny Nutshell)

FTAG-2023-01

- Example: Jet flavor tagging with better and better machine learning



Higgs Couplings at HL-LHC

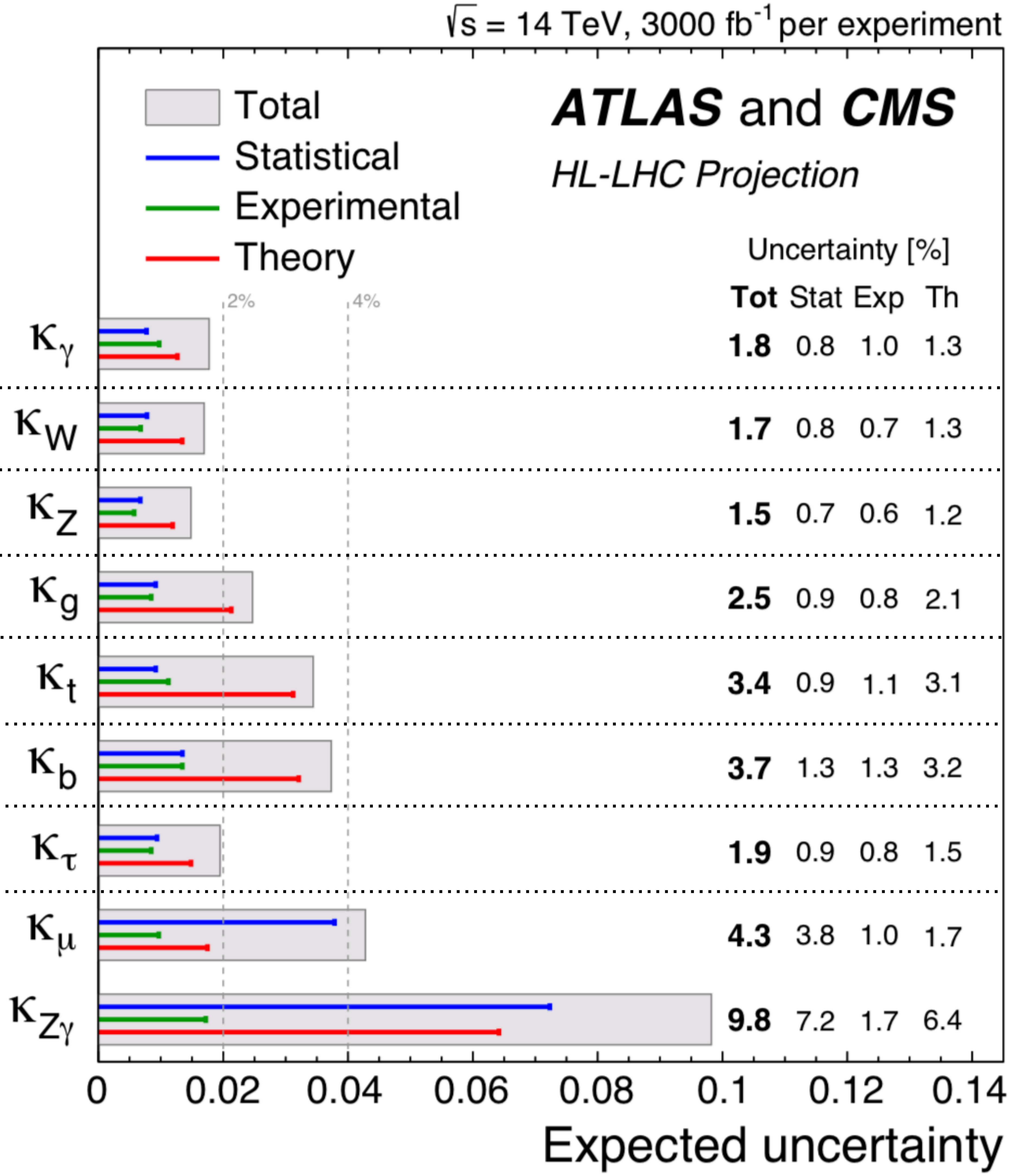
Higgs couplings strength with respective particles

	ATLAS - CMS Run 1 combination	Current precision
κ_γ	13%	6%
κ_W	11%	6%
κ_Z	11%	6%
κ_g	14%	7%
κ_t	30%	11%
κ_b	26%	13%
κ_τ	15%	8%

JHEP 08 (2016) 045

Nature 607, 52–59 (2022)

Nature 607 (2022) 60-68



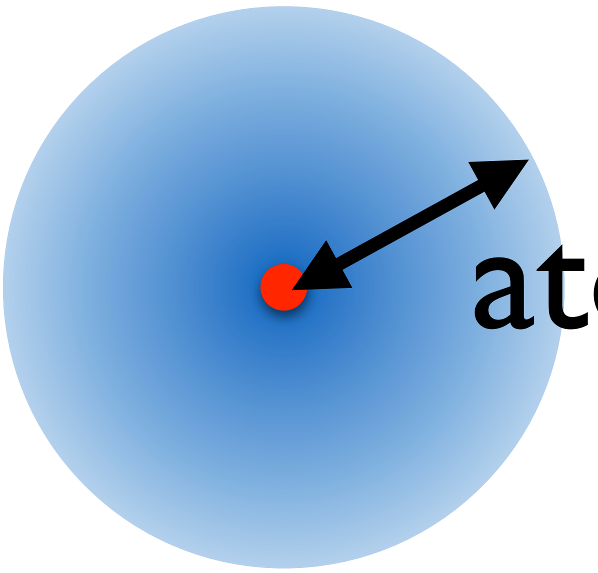
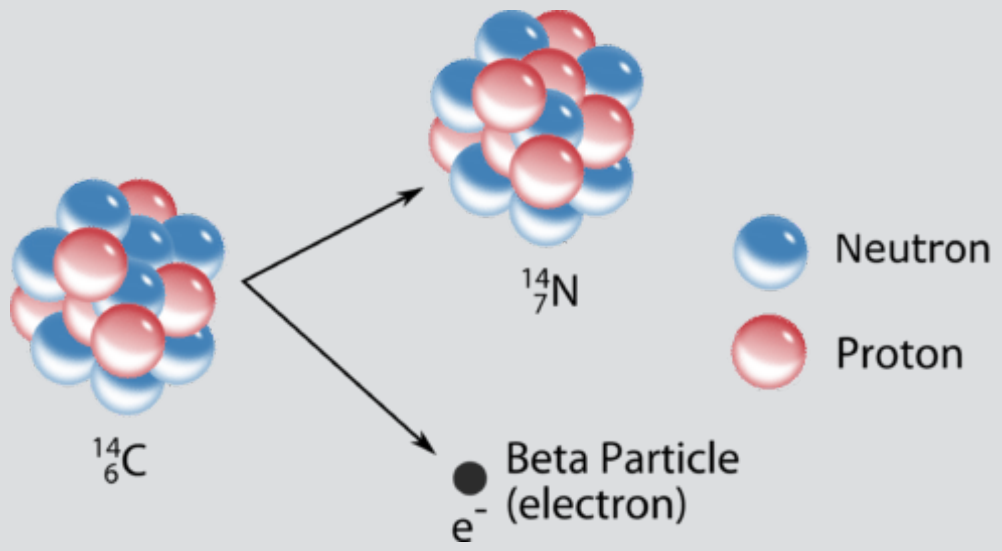
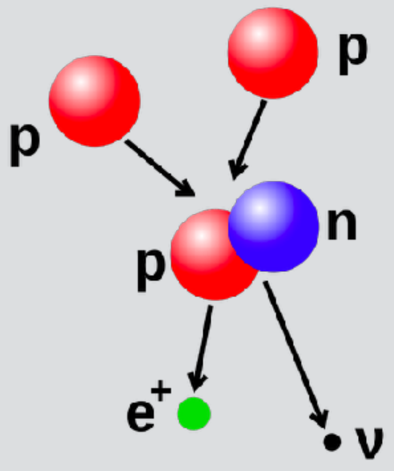
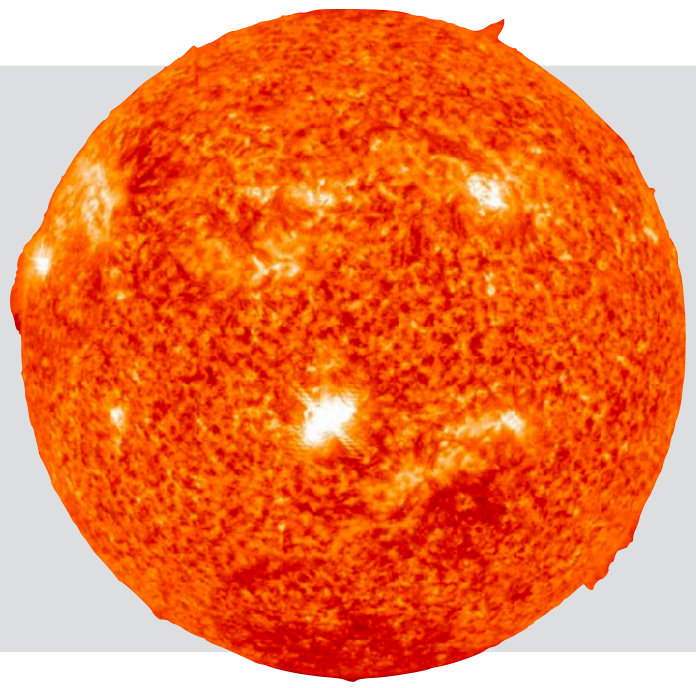
- Dataset 25× larger
- Uncertainty reduction by factor 3
- Theory uncertainties dominant

Measurements here assume no BSM in Higgs width

Higgs and our Universe

- Higgs-boson interactions set the quark, electron, and W-boson masses with important consequences

<table>
<tr><th>Role of elementary particle masses</th><th>Consequence</th><th>Higgs role established?</th></tr>
<tr><td>Up quarks (mass ~2.2 MeV) lighter than down quarks (mass ~ 4.7 MeV)

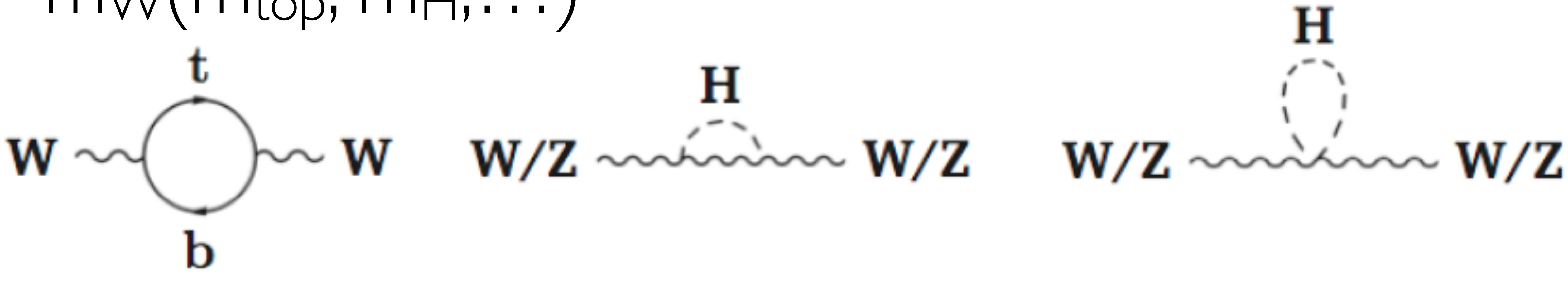
Proton (up|up|down): 2.2 + 2.2 + 4.7 MeV + EM+strong force = 938.3 MeV
Neutron (up|down|down): 2.2 + 4.7 + 4.7 MeV + EM+strong force = 939.6 MeV</td><td>Proton lighter than Neutron
⇒ Protons are stable
⇒ Hydrogen atom</td><td>No</td></tr>
<tr><td>
$$\text{atomic radius} \propto \frac{1}{m_e}$$</td><td>Electron mass (m_e) sets size of atoms & energy levels of chemical reactions</td><td>No</td></tr>
<tr><td>
$$\text{rate} \propto \frac{1}{m_W^4}$$

</td><td>W-boson mass (m_W) sets rate of radioactive β-decay and burning of the sun</td><td>Yes</td></tr>
</table>

Adapted from Salam, Wang, Zanderighi, Nature 607 (2022) 7917


H → ZZ* → 4ℓ
Gluon
Gluon
t
t
t
Higgs
Z0
Z0
e+
e-
μ+
μ-
ATLAS
EXPERIMENT
http://atlas.ch
Run: 182796
Event: 74566644
2011-05-30 07:54:29 CEST

Impact of m_H

- In SM: $m_W = m_W(m_{top}, m_H, \ldots)$



- Measurement uncertainty: Δm_W = **9** MeV
- Impact on m_W in electroweak fit: Δm_W(Top) = **±2.7** MeV, **Δm_W(H) = ±0.1 MeV**

- Impact of Δm_H on cross-sections and branching fractions very small:

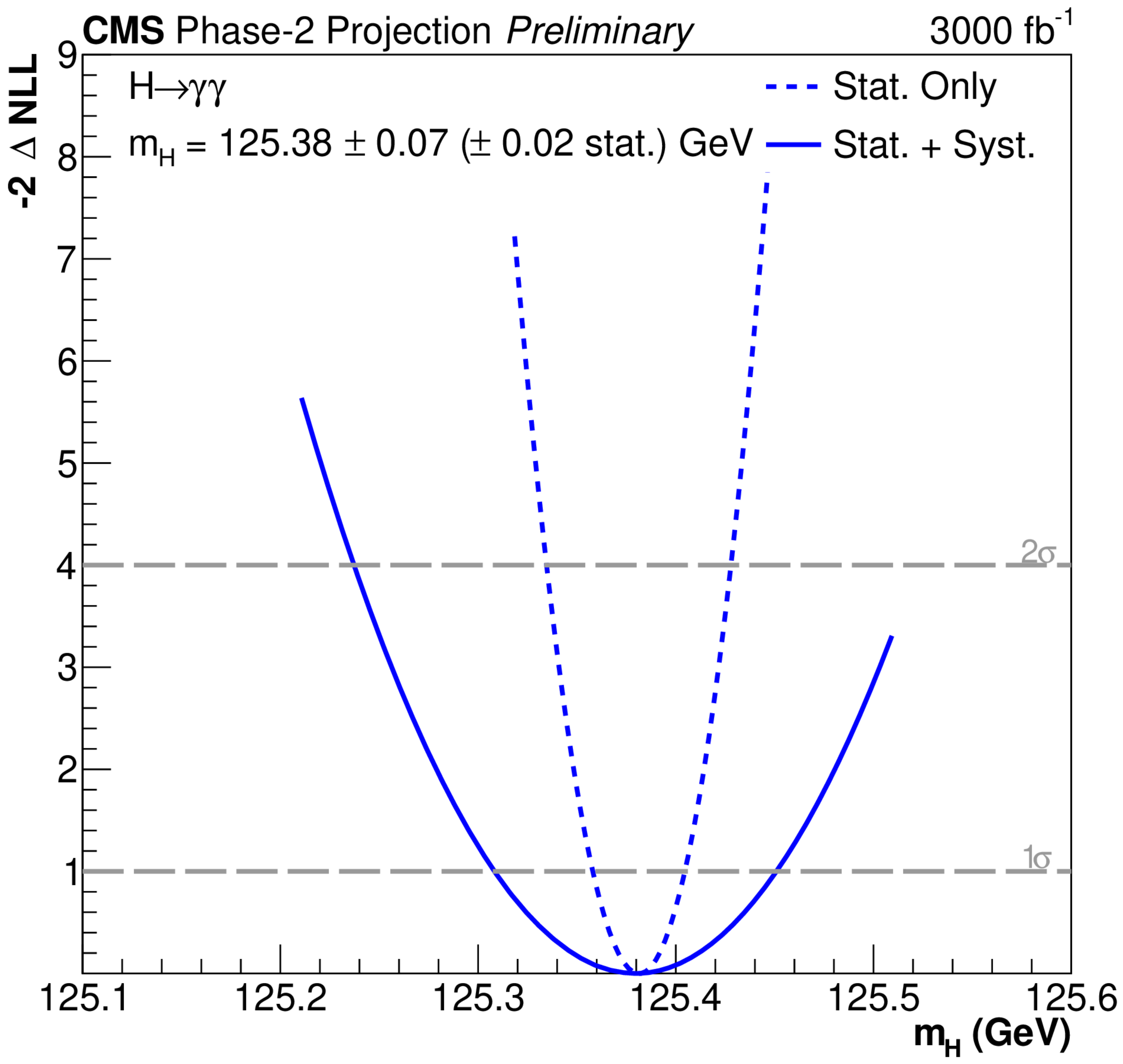
	Δ_{theo}	Δ_{exp}	Δm_H
BR(ZZ)	±1%	~10%	±1%
σ_{VBF}	±2%	~11%	±0.1%

⇒ Measurement precision of m_H good enough for this

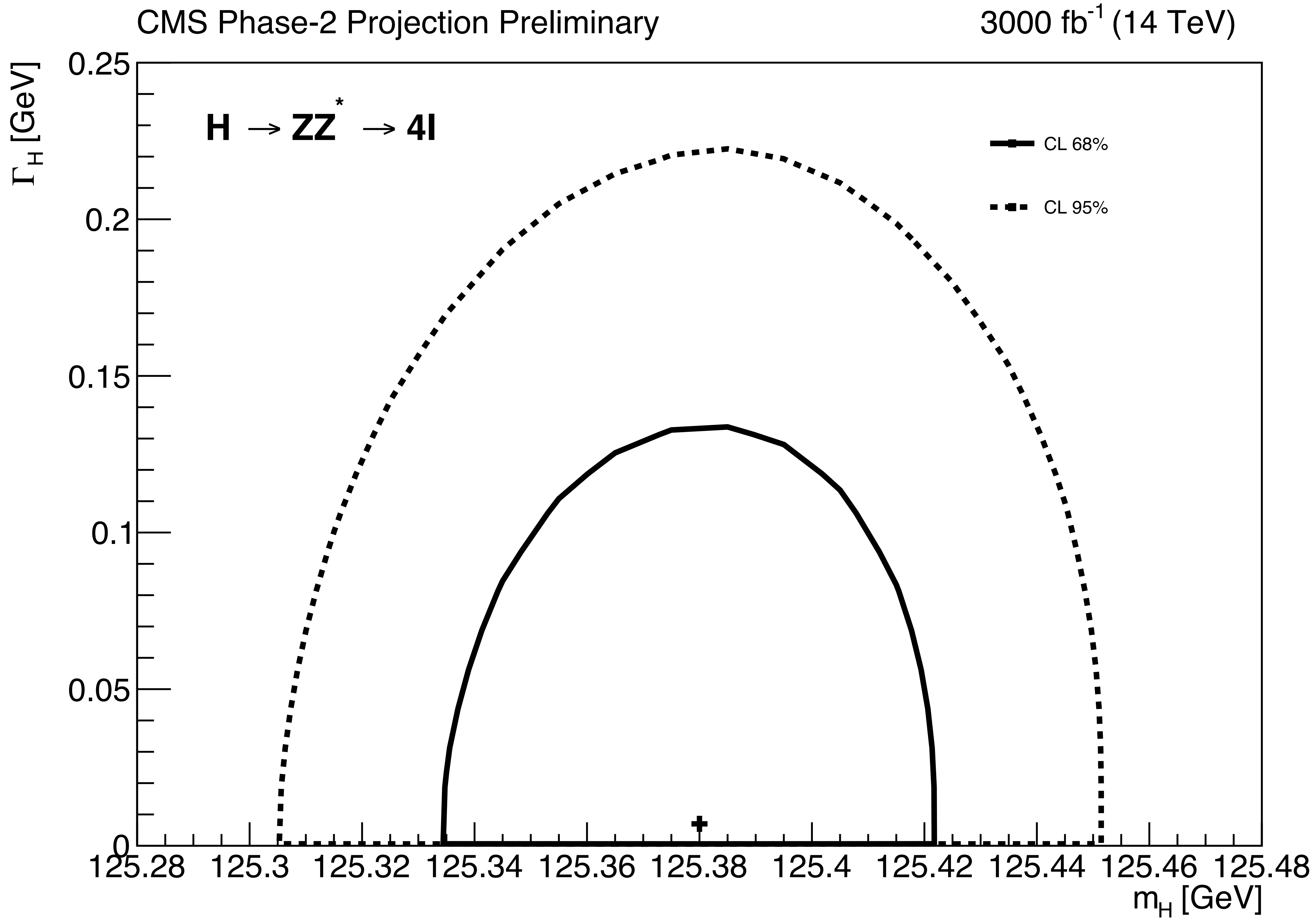
- but precise measurement important!

HL-LHC Higgs Boson Mass

$H \to \gamma\gamma$



$H \to ZZ^* \to 4\ell$:



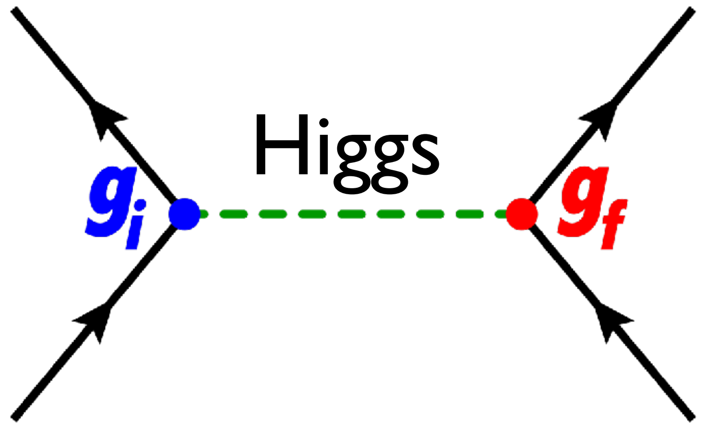
	Mass uncertainty (MeV)					Width upper limit at 95 % CL (MeV)
	Combined	4μ	4e	$2e2\mu$	$2\mu 2e$	Combined
Stat. uncertainty	22	28	83	51	59	94
Syst. uncertainty	20	15	189	94	95	150
Total	30	32	206	107	112	177

CMS-PAS-FTR-21-008 CMS-PAS-FTR-21-007

⇒ Back

Higgs Boson Width

- Expected width: $\Gamma_{H,SM}$ = 4.1 MeV
  - Direct limit: Γ_H < 60 MeV @ 68% CL (~15 × $\Gamma_{H,SM}$) CMS-PAS-HIG-21-019
  - Lifetime too short to measure: $\Gamma_H > 3.5 \times 10^{-9}$ MeV @ 95% CL Phys. Rev. D 92, 072010 (2015)
- Idea:



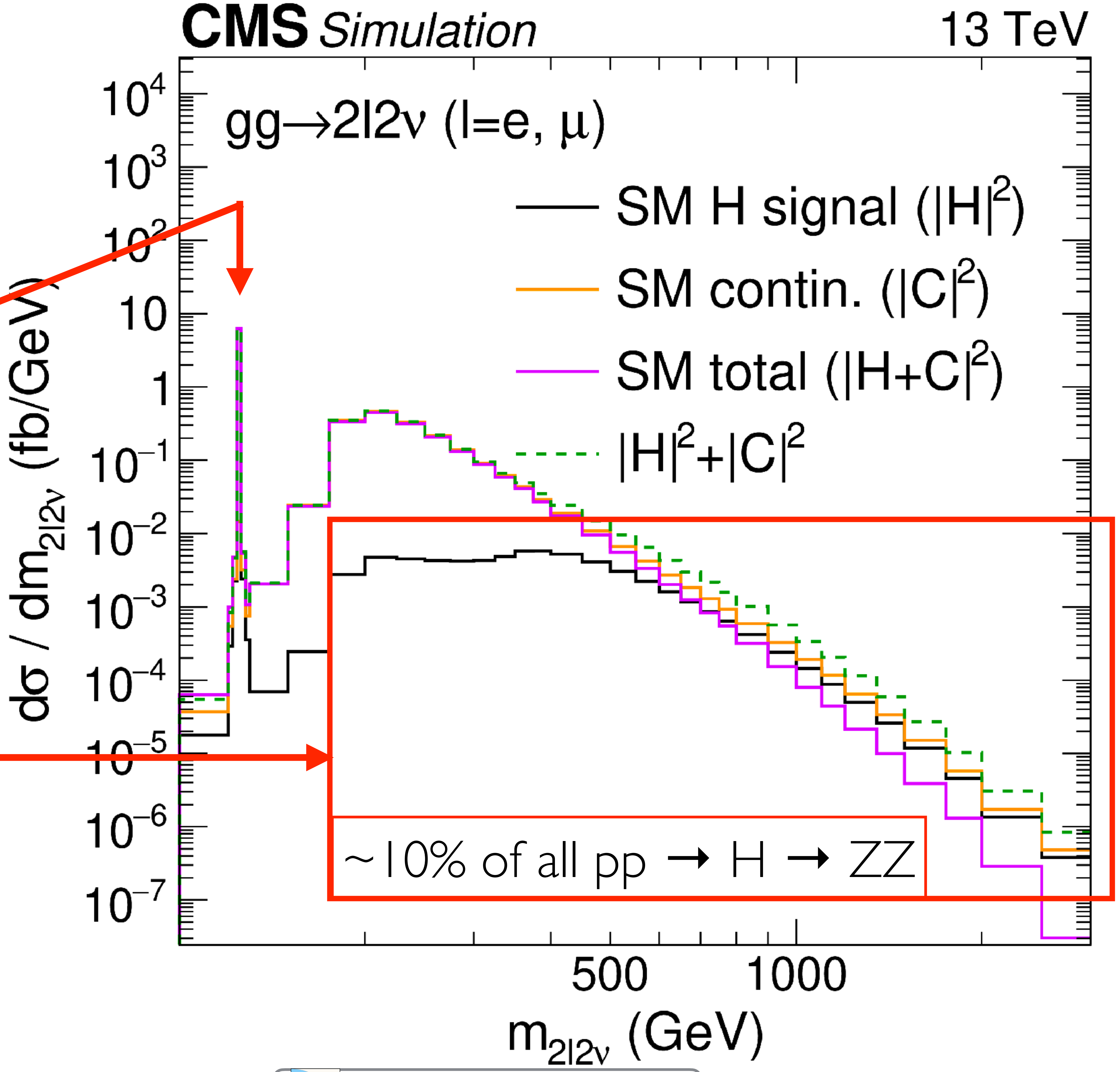
  - Cross-section on-resonance:

$$\sigma_{i\to H\to f} = \int \frac{g_i^2 g_f^2}{(s-m_H^2)^2 + \Gamma_H^2 m_H^2} ds \propto \frac{g_i^2 g_f^2}{\Gamma_H}$$

  - Cross section far above resonance ("off-shell"):

$$\sigma^{\text{off}}_{i\to H\to f} = \int \frac{g_i^2 g_f^2}{(s-m_H^2)^2 + \Gamma_H^2 m_H^2} ds \propto g_i^2 g_f^2$$

  - Measure ratio of both: $\Gamma_H \propto \frac{\sigma_{\text{off}}}{\sigma_{\text{on}}}$

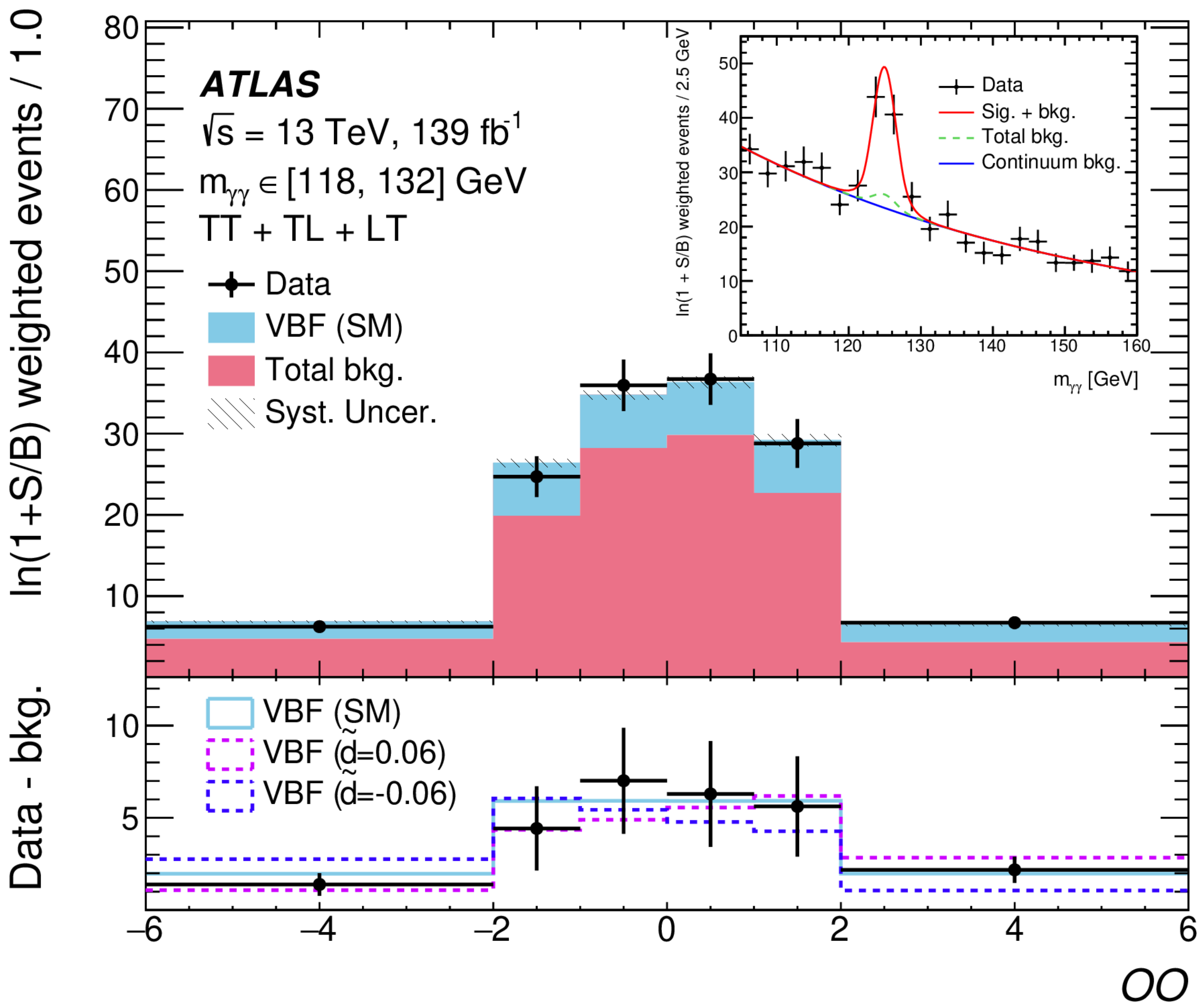


Nat. Phys. 18 (2022) 1329

CP Measurement in HVV Coupling

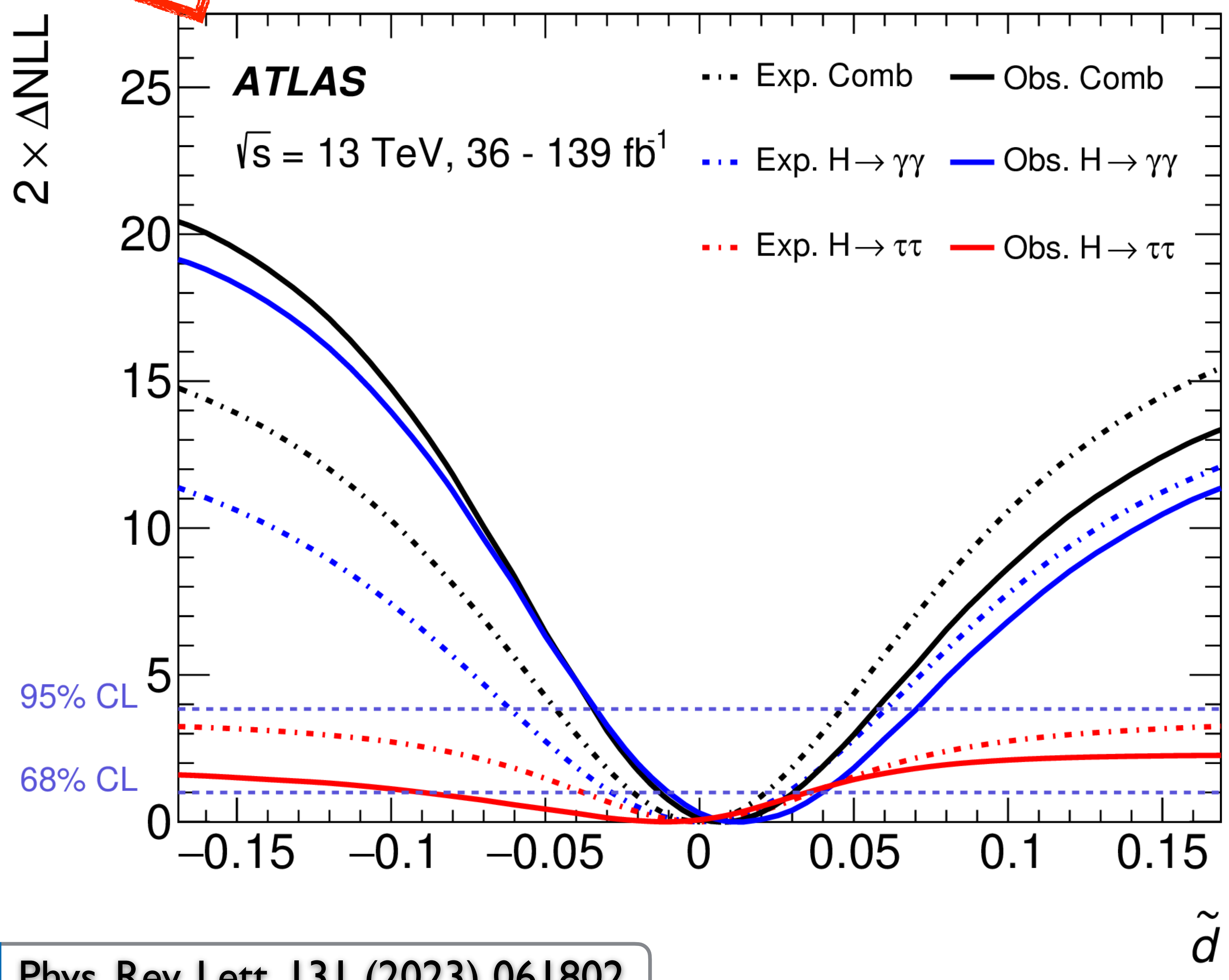
CP-odd through interference of SM with dim-6 CP-odd: $|\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + 2c_i \mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}} \mathcal{M}_{CP\text{-odd}}) + c_i^2 |\mathcal{M}_{CP\text{-odd}}|^2.$

Optimal Observable:
$$OO = 2\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}} \mathcal{M}_{\mathrm{CP-odd}})/|\mathcal{M}_{\mathrm{SM}}|^2$$



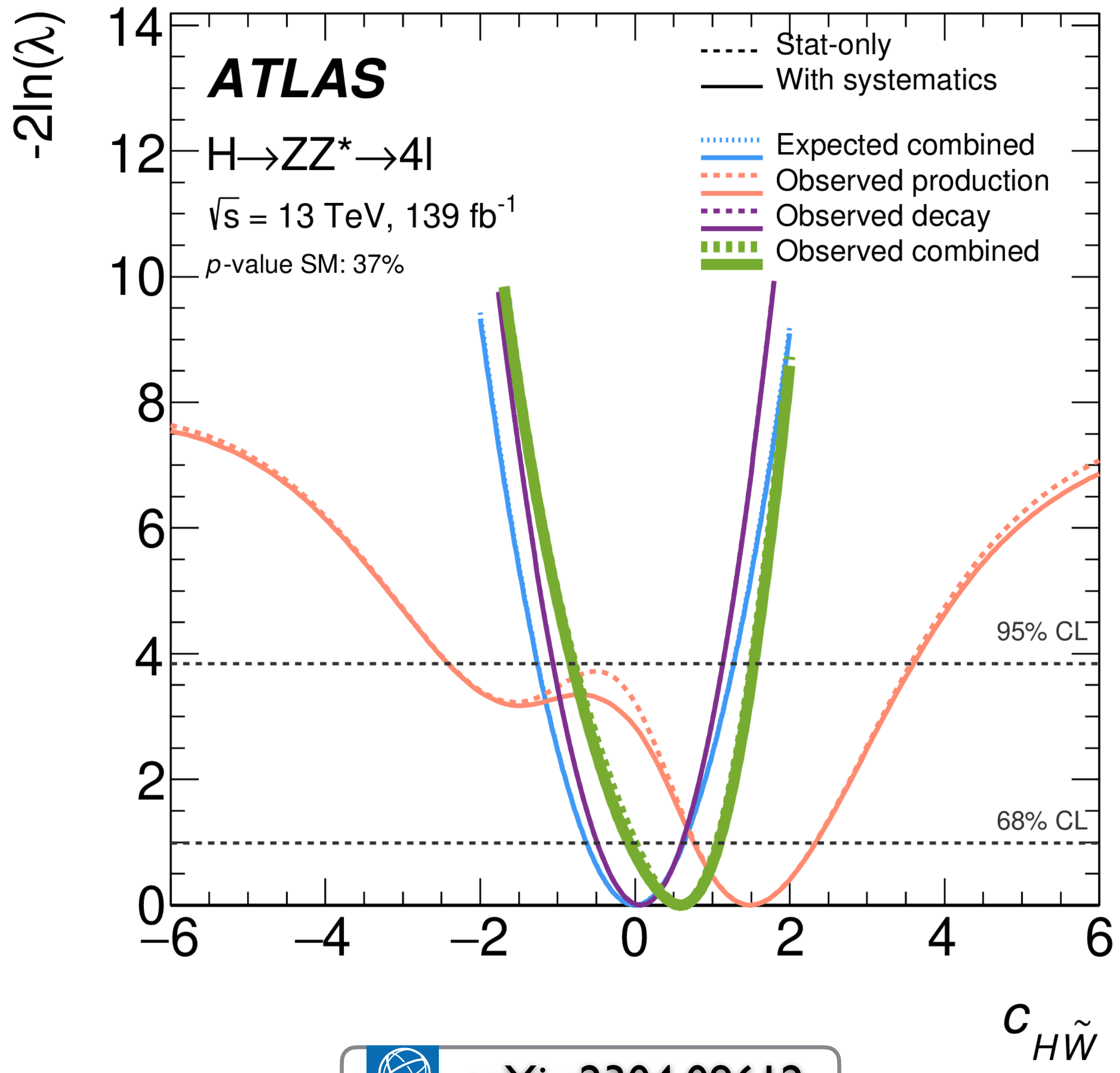
Aug 2022

VBF production (H → γγ)



April 2023

VBF production and H → ZZ* → 4ℓ decay



⇒ Back

Phys. Rev. Lett. 131 (2023) 061802

arXiv:2304.09612

CP Measurement in t(t)H Production

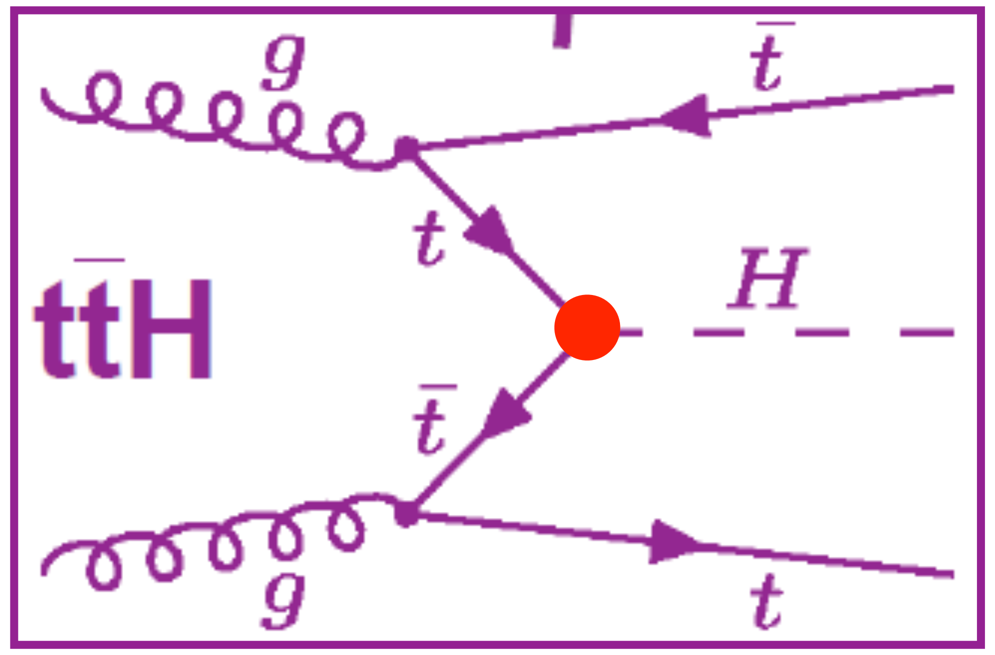
Phys. Lett. B 849 (2024) 138469

- CP-odd in Higgs-Gauge interactions need higher-order operators
- CP-odd in **top-Yukawa** can be **tree-level**

SM ttH coupling: CP-even
($\tilde{\kappa}_t = 0$ or $\alpha = 0°$)

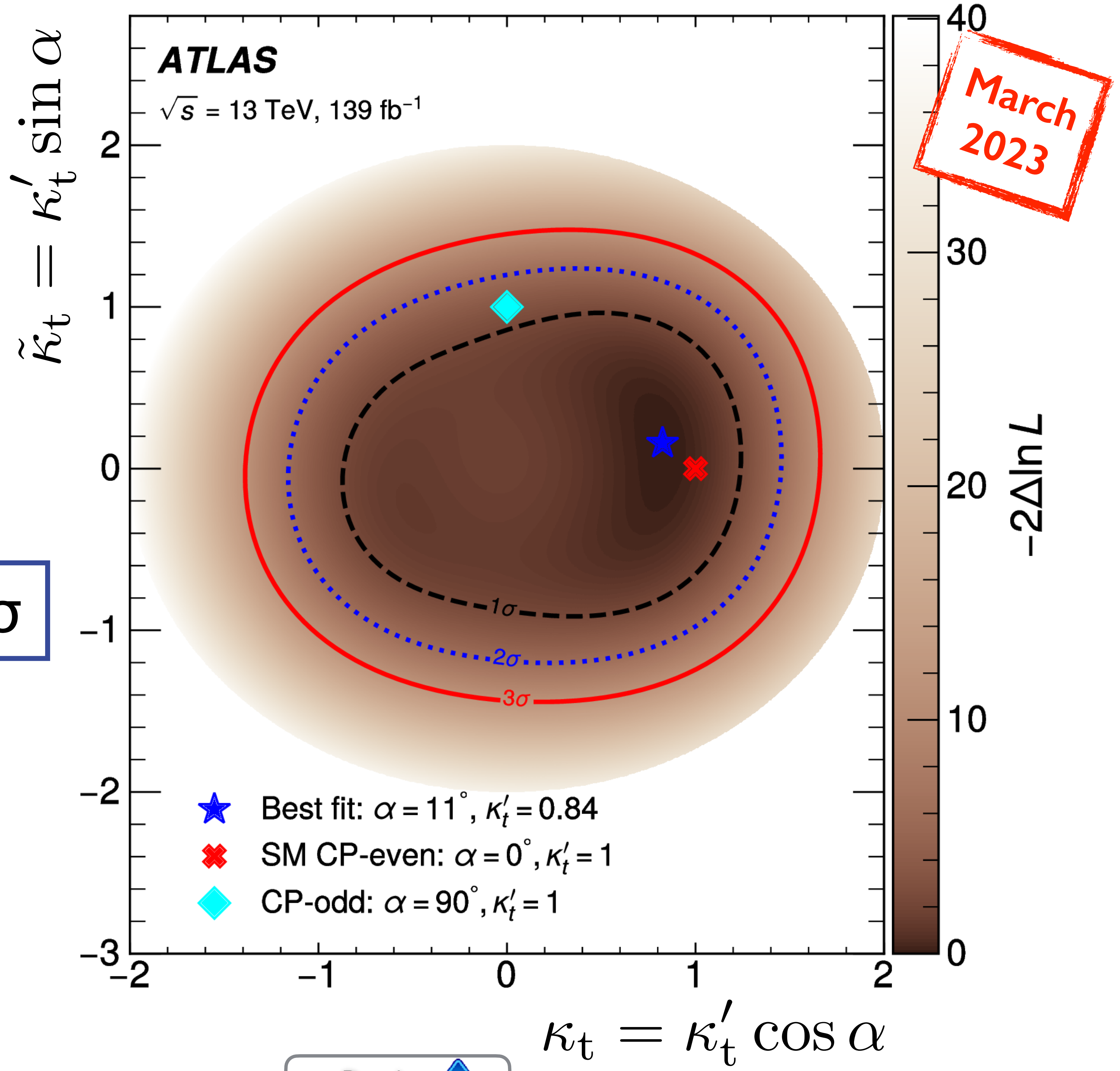
$$\mathcal{L}_{t\bar{t}H} = \frac{-y_t}{2}\bar{\psi}_t(\kappa_t + i\gamma_5\tilde{\kappa}_t)\psi_t H = -\kappa_t' y_t \phi \bar{\psi}_t(\cos\alpha + i\gamma_5 \sin\alpha)\psi_t$$

ttH, H → bb topology
Dominant ttbb background difficult to model



$$\alpha = 11°^{+55°}_{-77°}$$

Pure CP-odd coupling excluded at **1.2 σ**



ttH, H → γγ topology:
Pure CP-odd coupling excluded at **3.9** σ, |α| **< 43° @ 95%** C.L.

Phys. Rev. Lett. 125 (2020) 061802

ttH multilepton combined w/ **H** → γγ and **H → ZZ**:
Pure CP-odd coupling excluded at **3.7** σ, |α| **< 48° @ 68%** C.L.

JHEP 07 (2023) 092

⇒ Back

CP Measurement in t(t)H Production

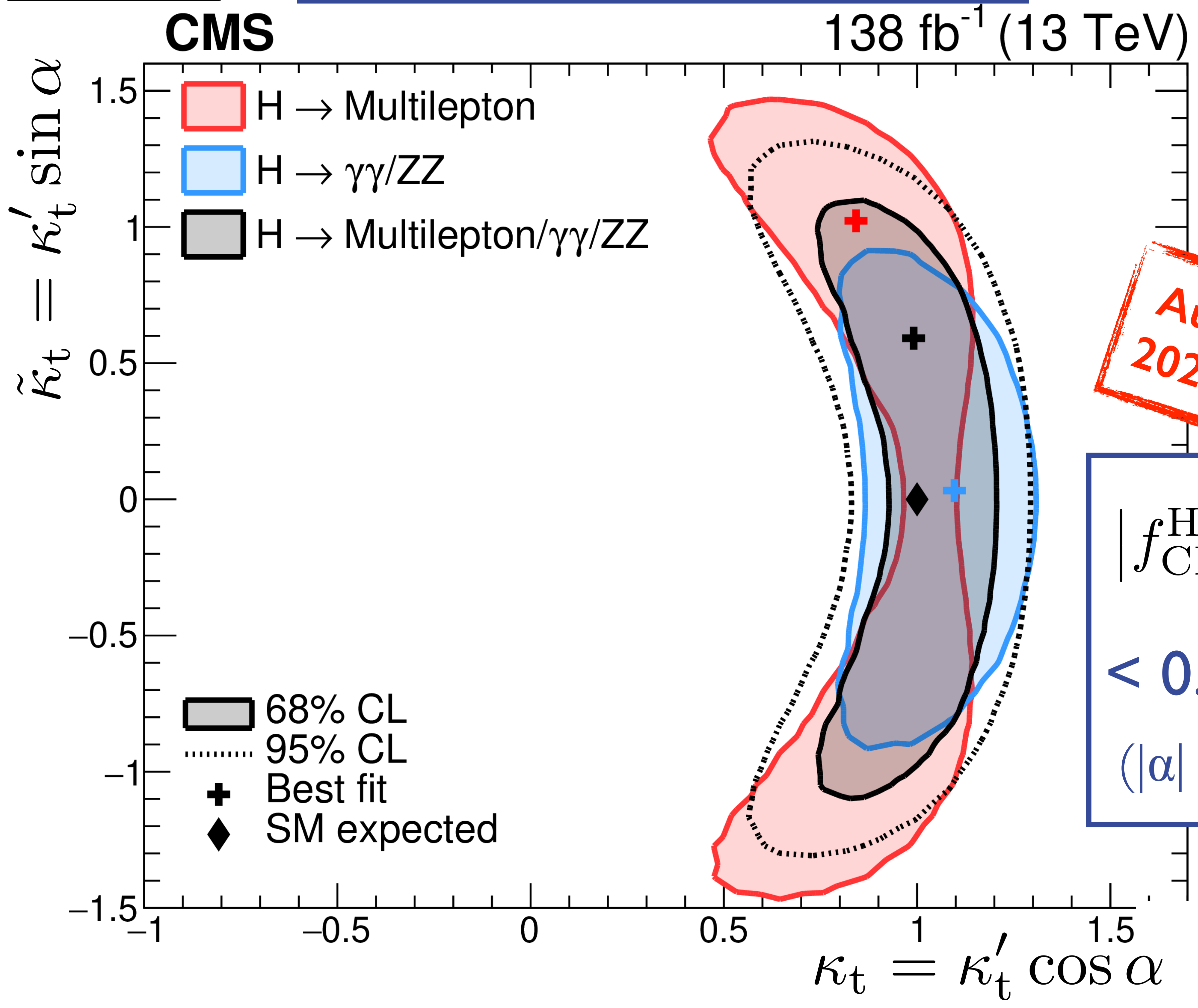
- CP-odd in Higgs-Gauge interactions need higher-order operators
- CP-odd in Higgs-fermion interactions (**top-Yukawa**) can be **tree-level**

$$\mathcal{L}_{t\bar{t}H} = \frac{-y_t}{2}\bar{\psi}_t(\kappa_t + i\gamma_5\tilde{\kappa}_t)\psi_t H = -\kappa_t' y_t \phi \bar{\psi}_t(\cos\alpha + i\gamma_5 \sin\alpha)\psi_t$$

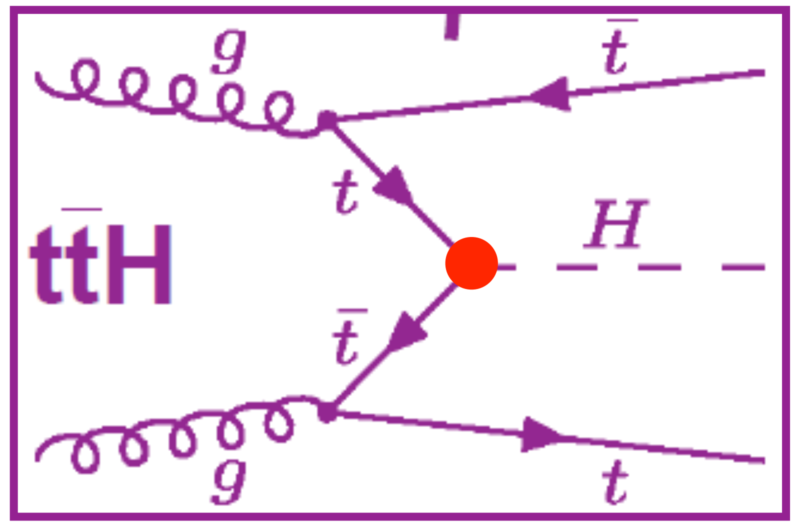
"**multilepton**" topology
Combine with γγ and ZZ*

SM ttH coupling: CP-even
($\tilde{\kappa}_t = 0$ or $\alpha = 0°$)

ttH, H → γγ topology



Aug 2022

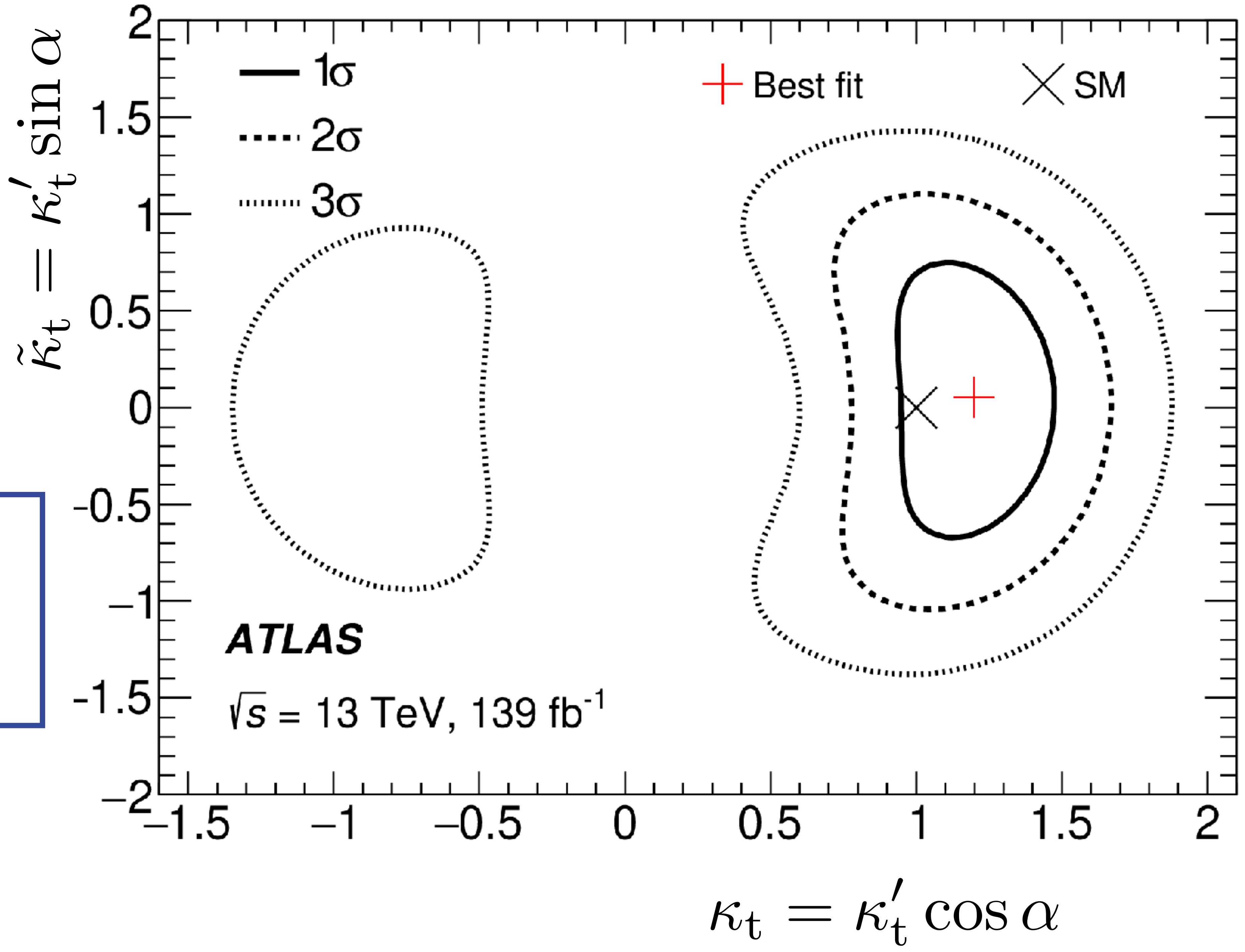


$$|f_{CP}^{Htt}| = \left|\frac{\tilde{\kappa}_t^2}{\tilde{\kappa}_t^2 + \kappa_t^2}\right|$$

< 0.55 @ 68% C.L.

(|α| < 48° @ 68% C.L.)

|α| < 43°
@ 95% C.L.



- Pure CP-odd coupling excluded at **3.7 σ** … …at **3.9 σ**

JHEP 07 (2023) 092

Phys. Rev. Lett. 125 (2020) 061802

⇒ Back

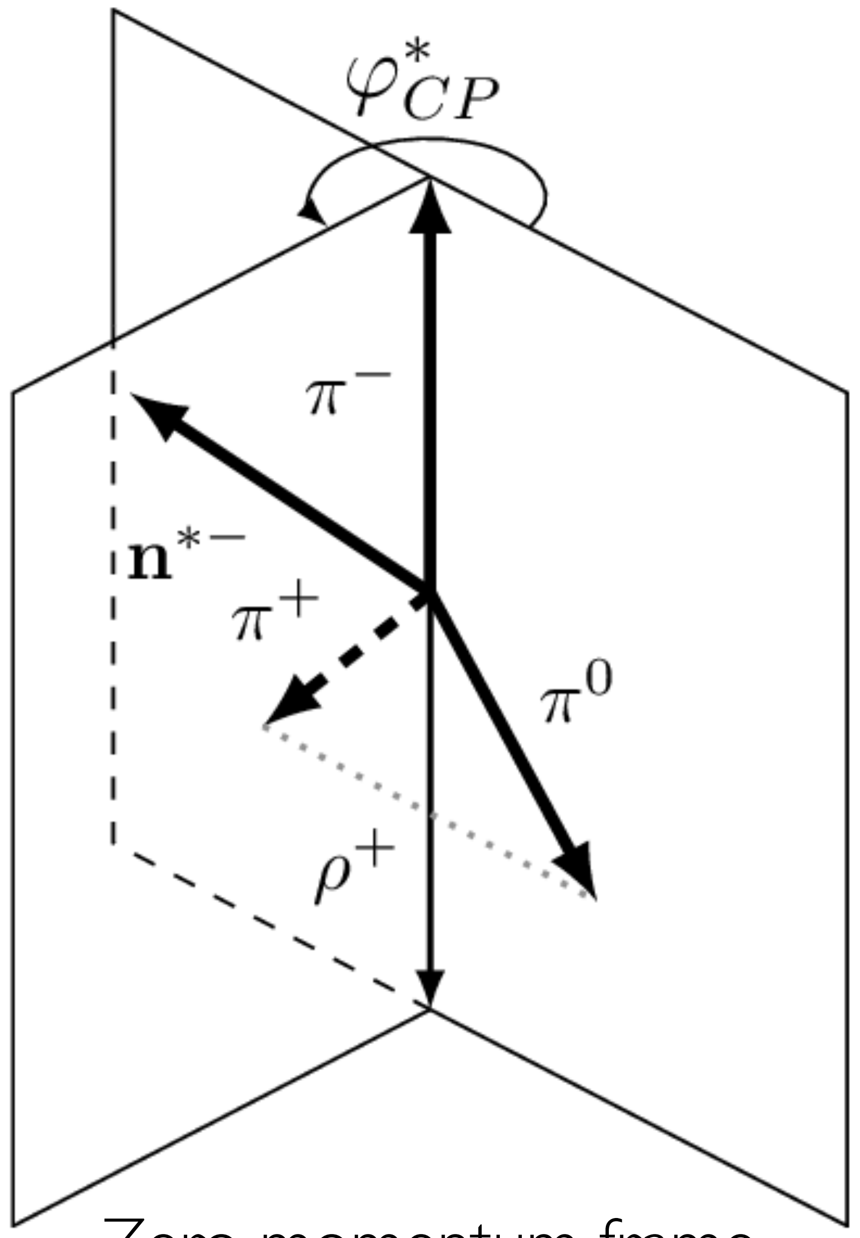
CP Measurement in H → ττ Decay

Parametrize **τ-Yukawa** coupling: $\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)H$ SM Hττ coupling: CP-even ($\phi_\tau = 0°$)

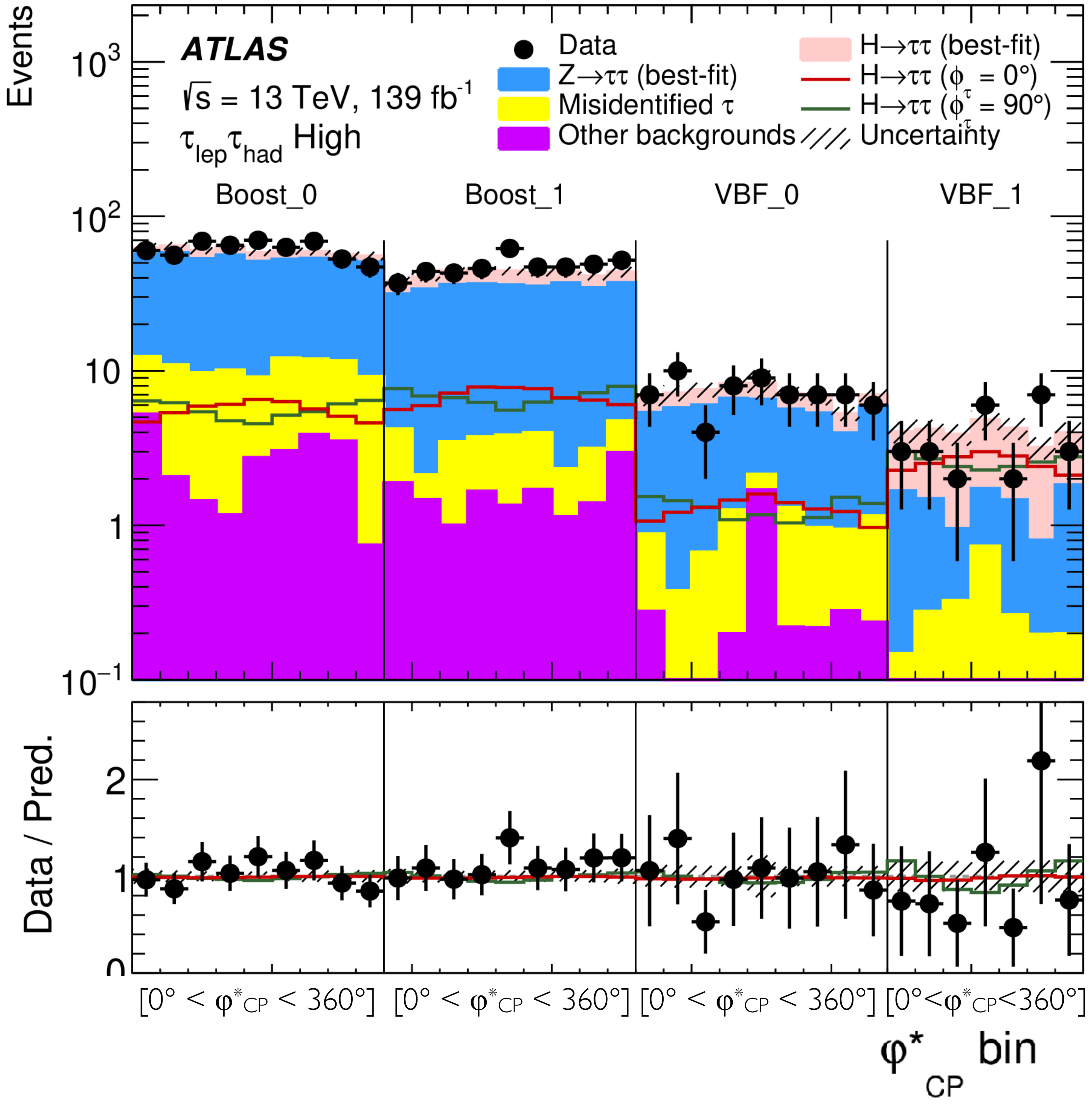
- CP-odd in Higgs-Gauge interactions need higher-order operators
- CP-odd in Higgs-fermion interactions (**τ-Yukawa**) can be **tree-level!**
- Reconstruct τ decay modes
- Observable: signed acoplanarity angle between τ decay planes
  - spanned by impact parameter and/or decay products ($\pi^\pm$, π^0)

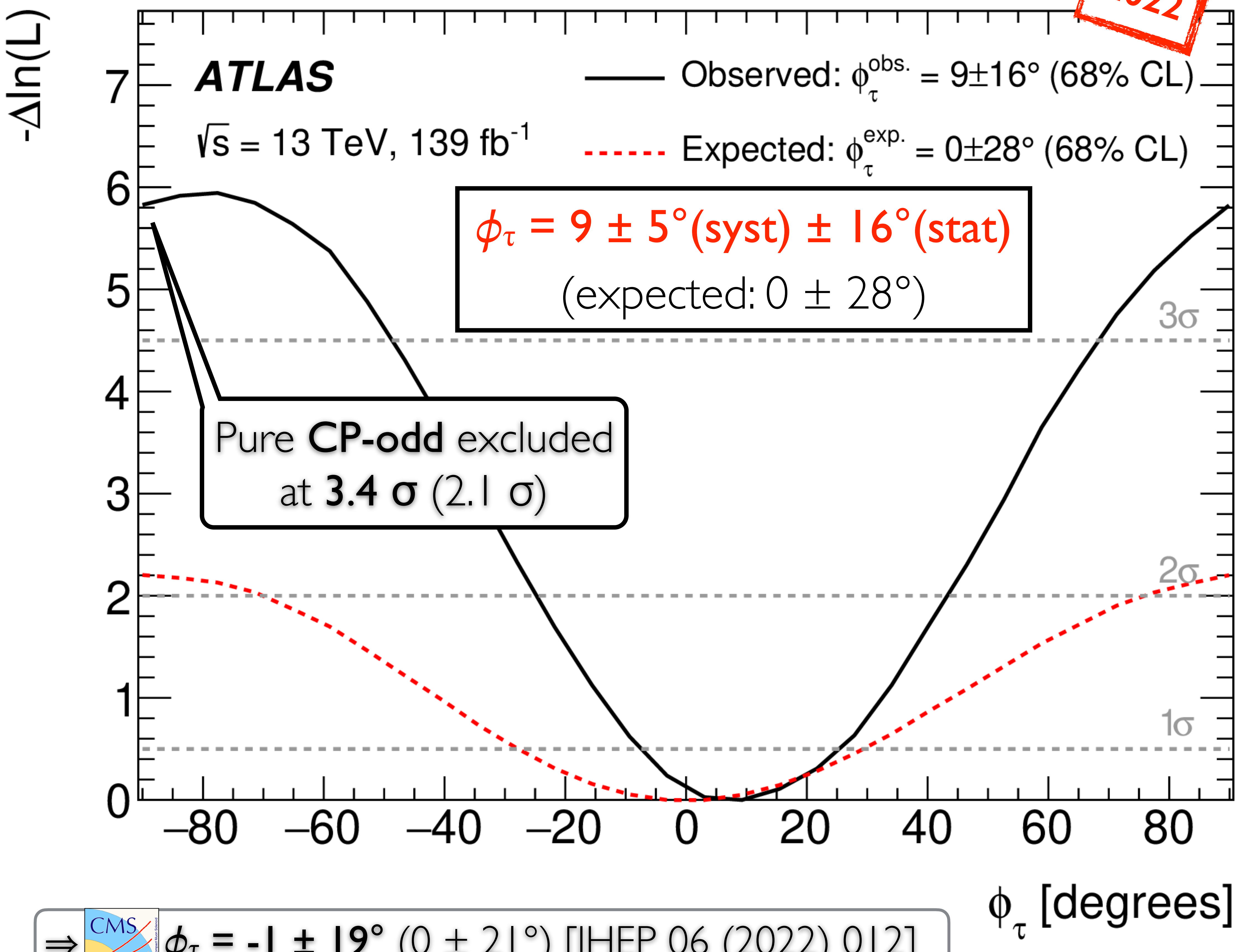
Dec 2022

$H \to \tau^+\tau^- \to \pi^+\pi^0\nu\ \pi^-\nu$



Zero momentum frame





ϕ_τ = 9 ± 5°(syst) ± 16°(stat)
(expected: 0 ± 28°)

Pure **CP-odd** excluded at **3.4 σ** (2.1 σ)

⇒ CMS ϕ_τ **= -1 ± 19°** (0 ± 21°) [JHEP 06 (2022) 012]

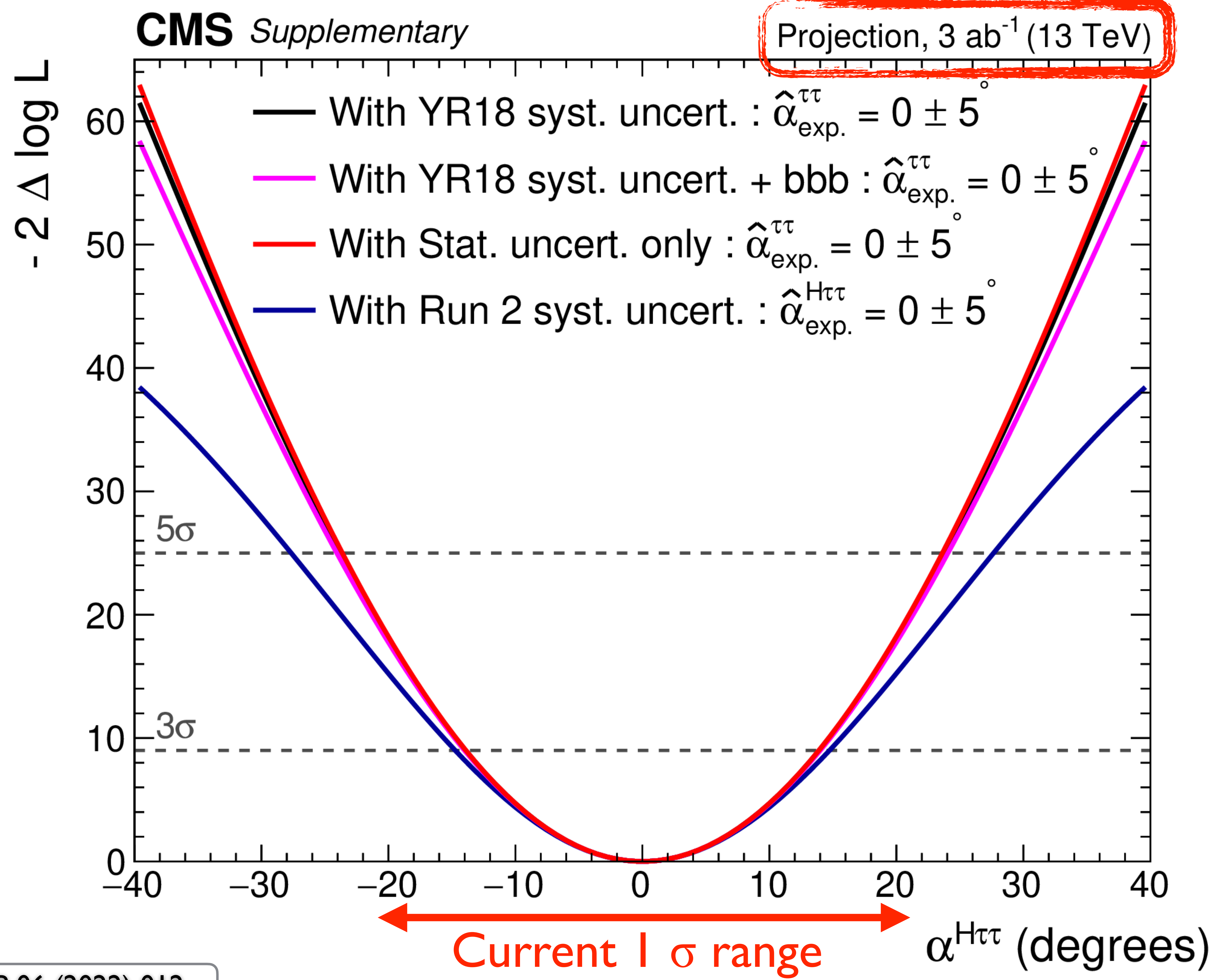
⇒ CMS Projection to 3000 fb-1

Eur. Phys. J. C 83 (2023) 563

⇒ Back

HL-LHC CP Measurement in H → ττ Decay

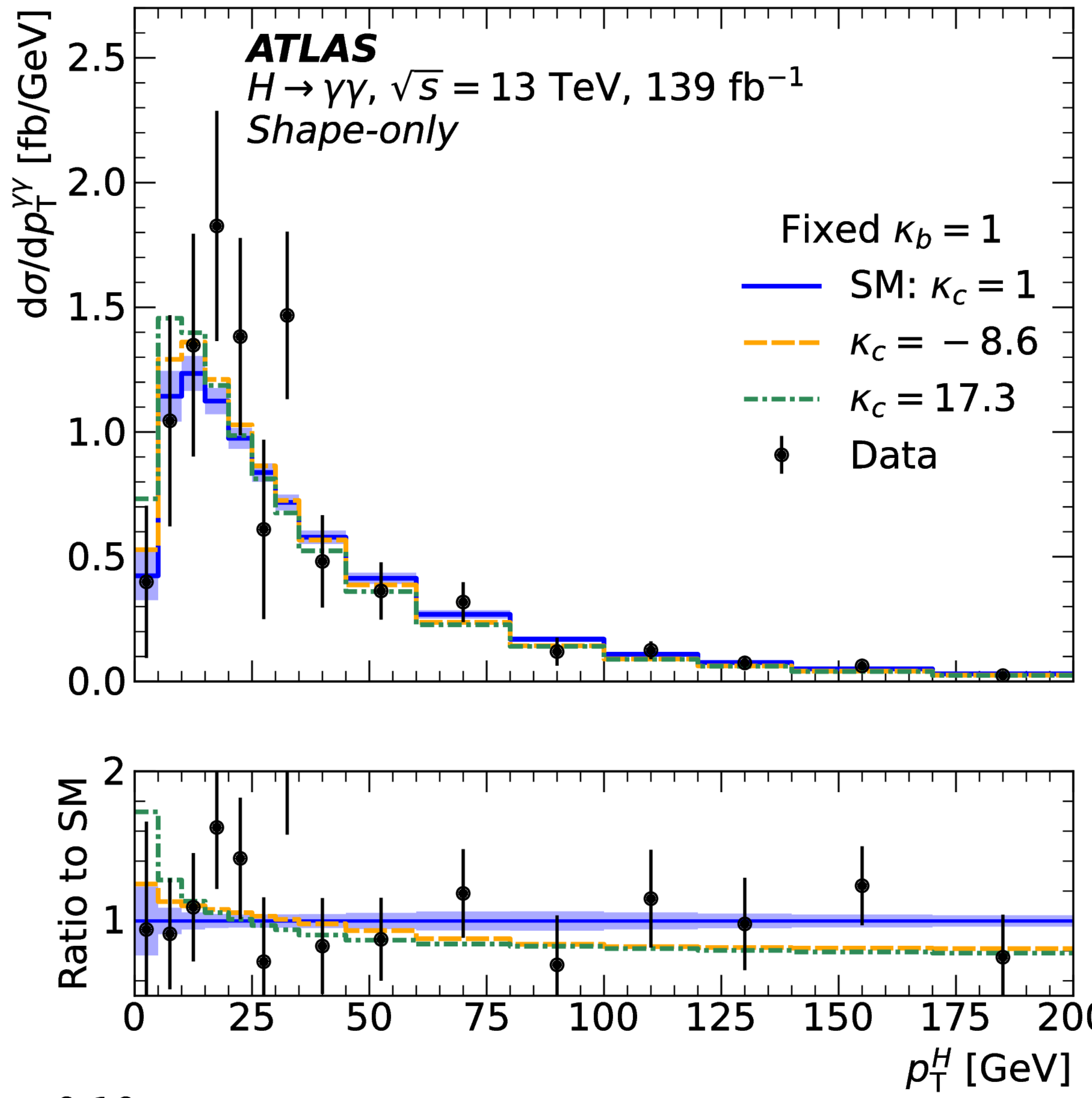
Parametrize **τ-Yukawa** coupling: $\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)H$ SM Hττ coupling: CP-even (ϕ_τ = 0°)

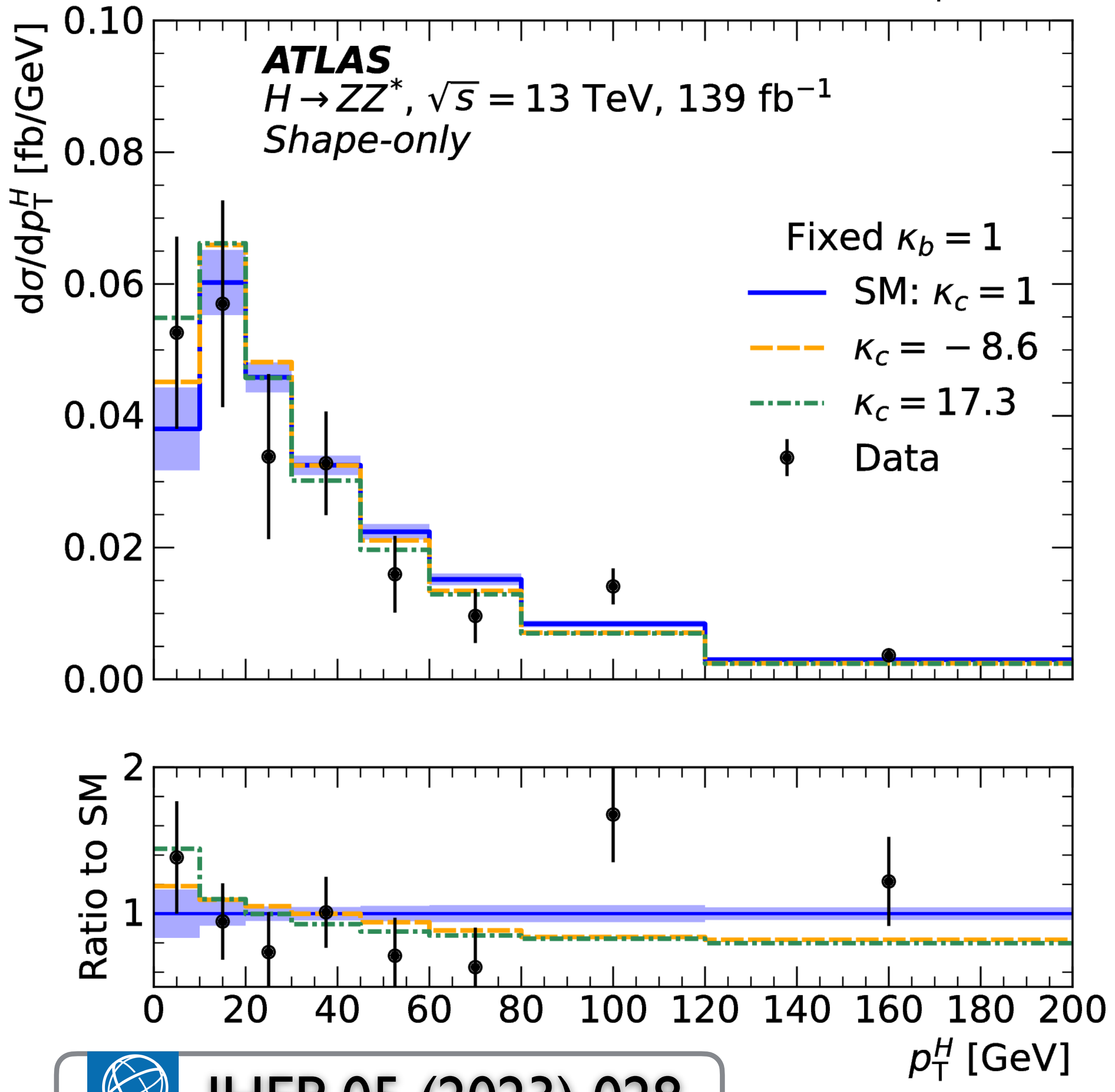


JHEP 06 (2022) 012

Combination: H → γγ and H → ZZ* → 4ℓ

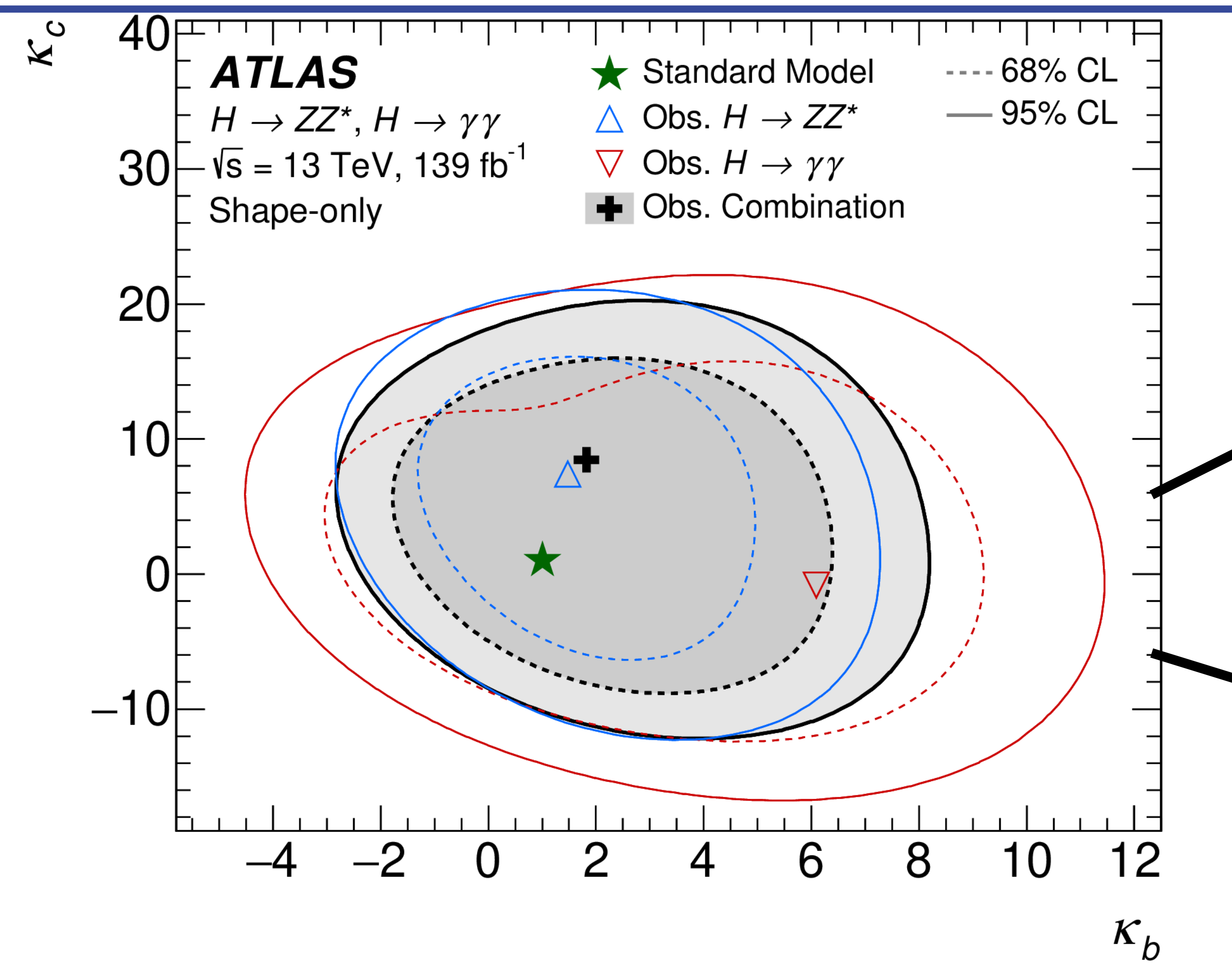
July 2022



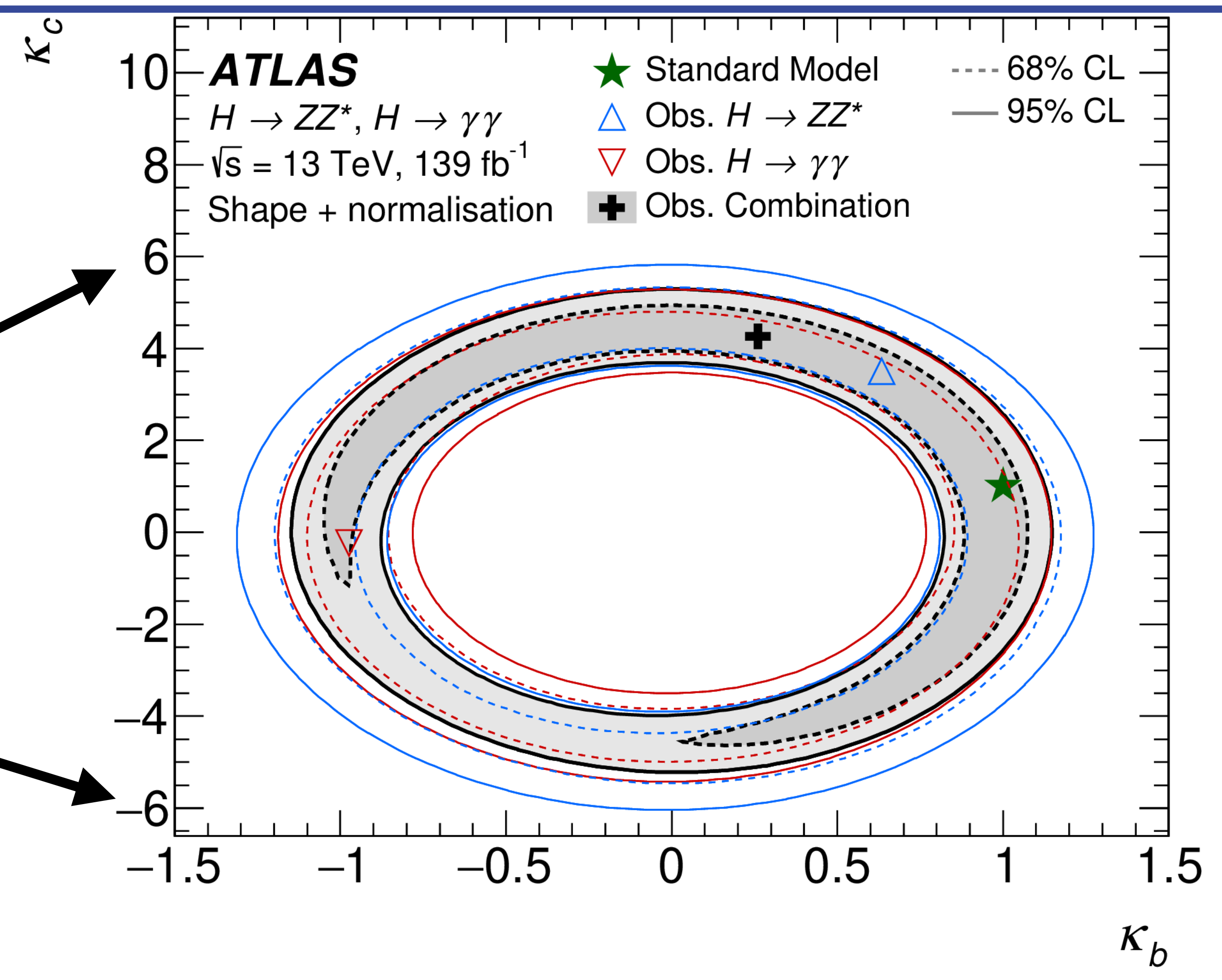


- Measure σ_{tot}, y_H, N_{jet}, p_T(jet 1), p_T(H) ⇒ More
- Combined interpretation from separate **p_T(H)** distributions

Only modifications to p_T(H) shape



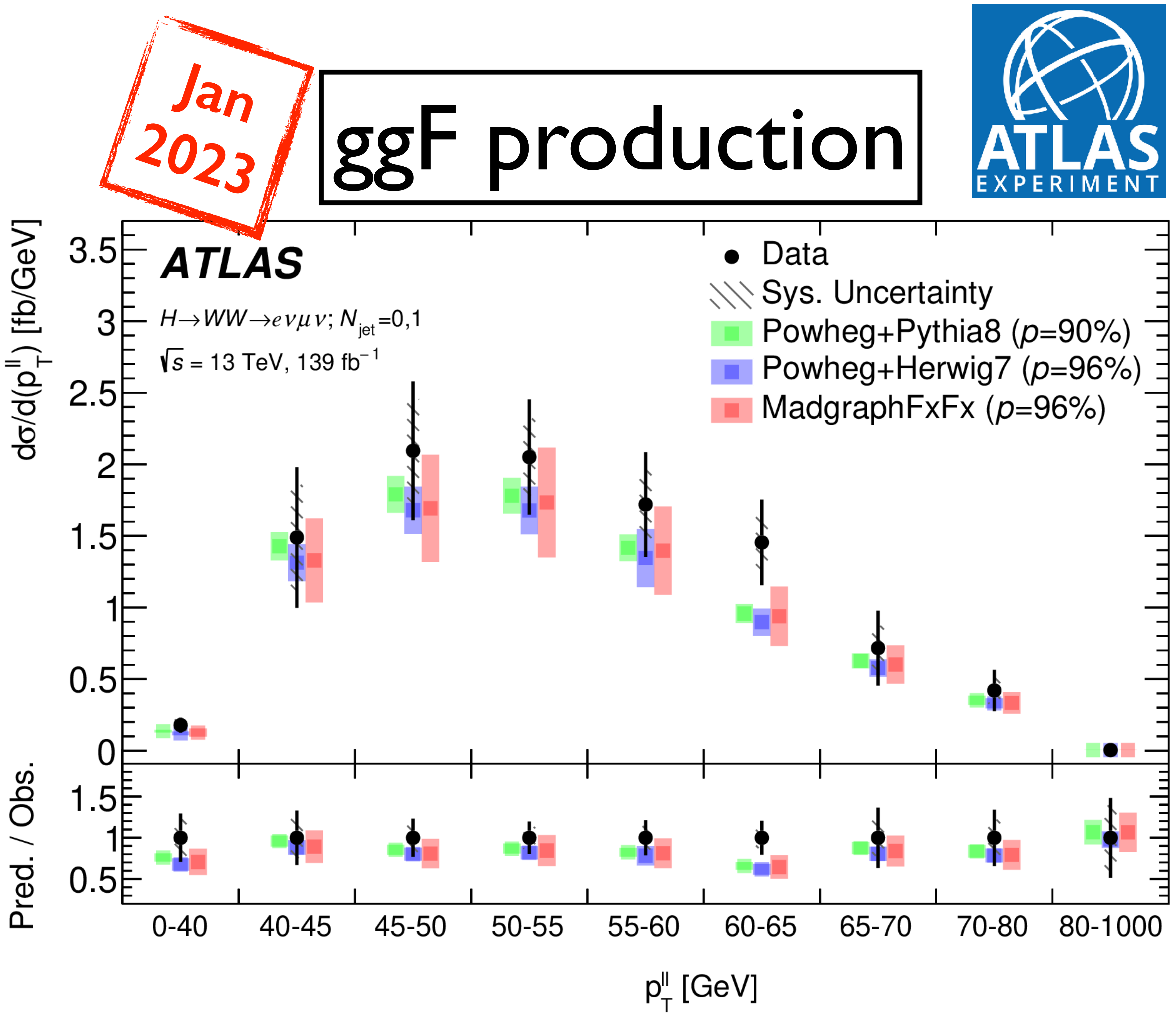
Shape & coupling dependent on BR



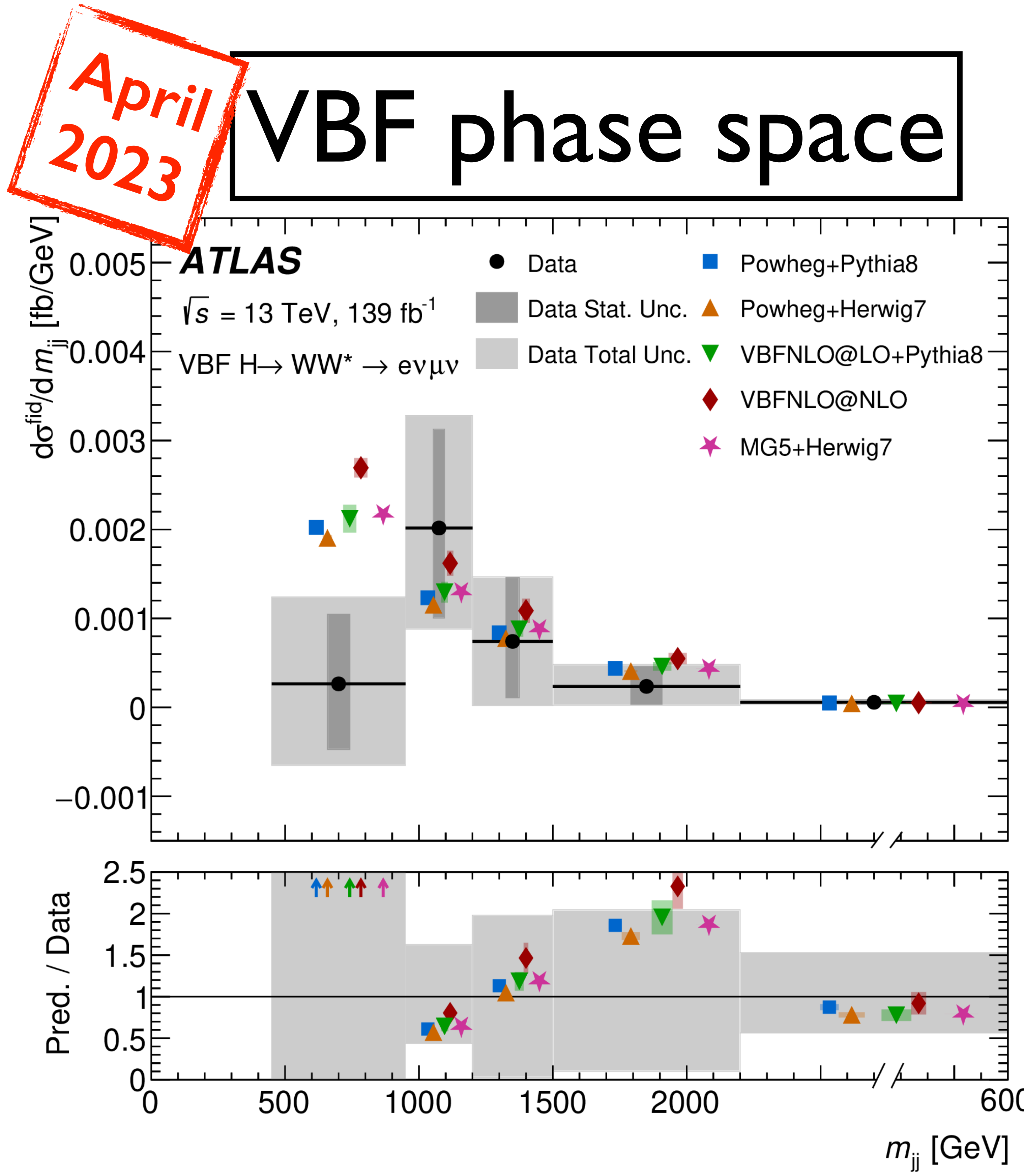
Channel	Parameter	Observed 95% confidence interval	Expected 95% confidence interval	Observed 95% confidence interval	Expected 95% confidence interval
$H\to ZZ^*\to 4\ell$	κ_b	[−2.1, 6.1]	[−3.6, 9.3]	[−1.14, −0.88] ∪ [0.80, 1.17]	[−1.23, −0.87] ∪ [0.82, 1.20]
	κ_c	[−9.4, 18.5]	[−14.3, 19.6]	[−2.94, 2.99]	[−3.33, 3.14]
$H\to\gamma\gamma$	κ_b	[−3.8, 10.2]	[−2.8, 8.0]	[−1.12, −0.78] ∪ [0.78, 1.07]	[−1.18, −0.87] ∪ [0.83, 1.19]
	κ_c	[−14.5, 18.9]	[−12.1, 17.8]	[−2.46, 2.32]	[−3.03, 3.09]
Combined	κ_b	[−2.3, 7.3]	[−2.2, 7.4]	[−1.09, −0.86] ∪ [0.81, 1.09]	[−1.14, −0.92] ∪ [0.86, 1.15]
	κ_c	[−10.5, 18.0]	[−10.4, 16.6]	[−2.27, 2.27]	[−2.77, 2.75]

JHEP 05 (2023) 028

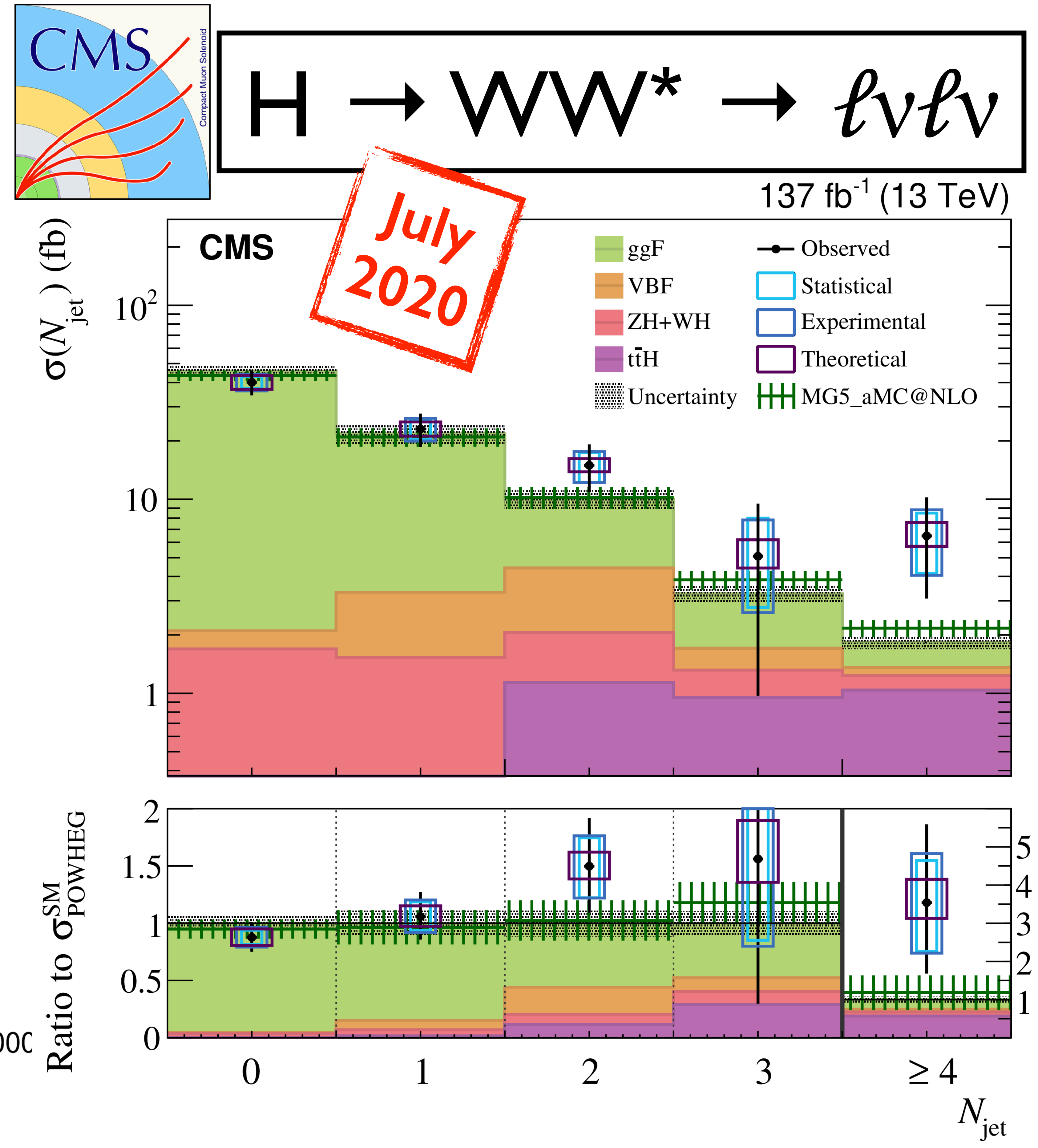
Differential cross sections with H → WW* → ℓνℓν



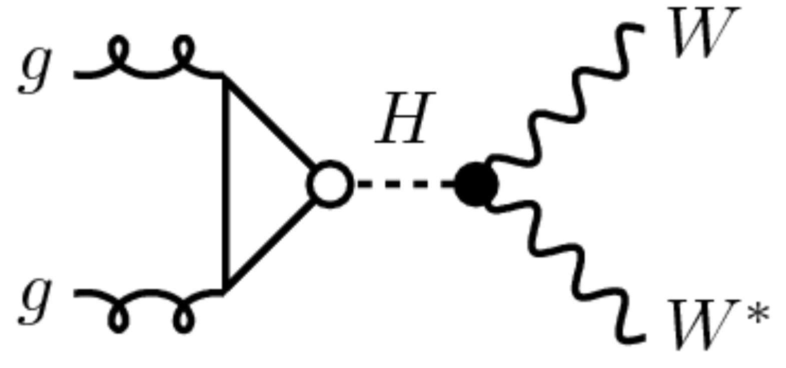
Eur. Phys. J. C 83 (2023) 774



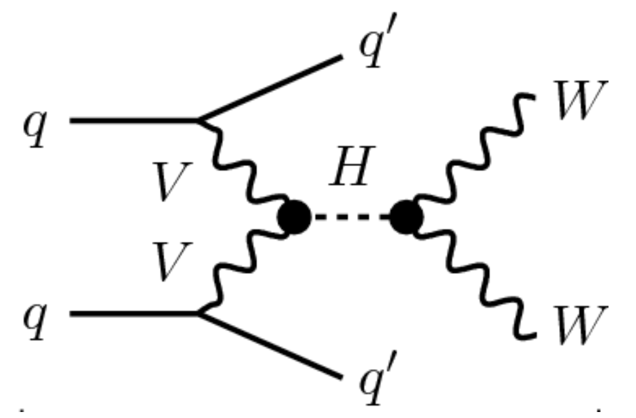
Phys. Rev. D 108 (2023) 072003

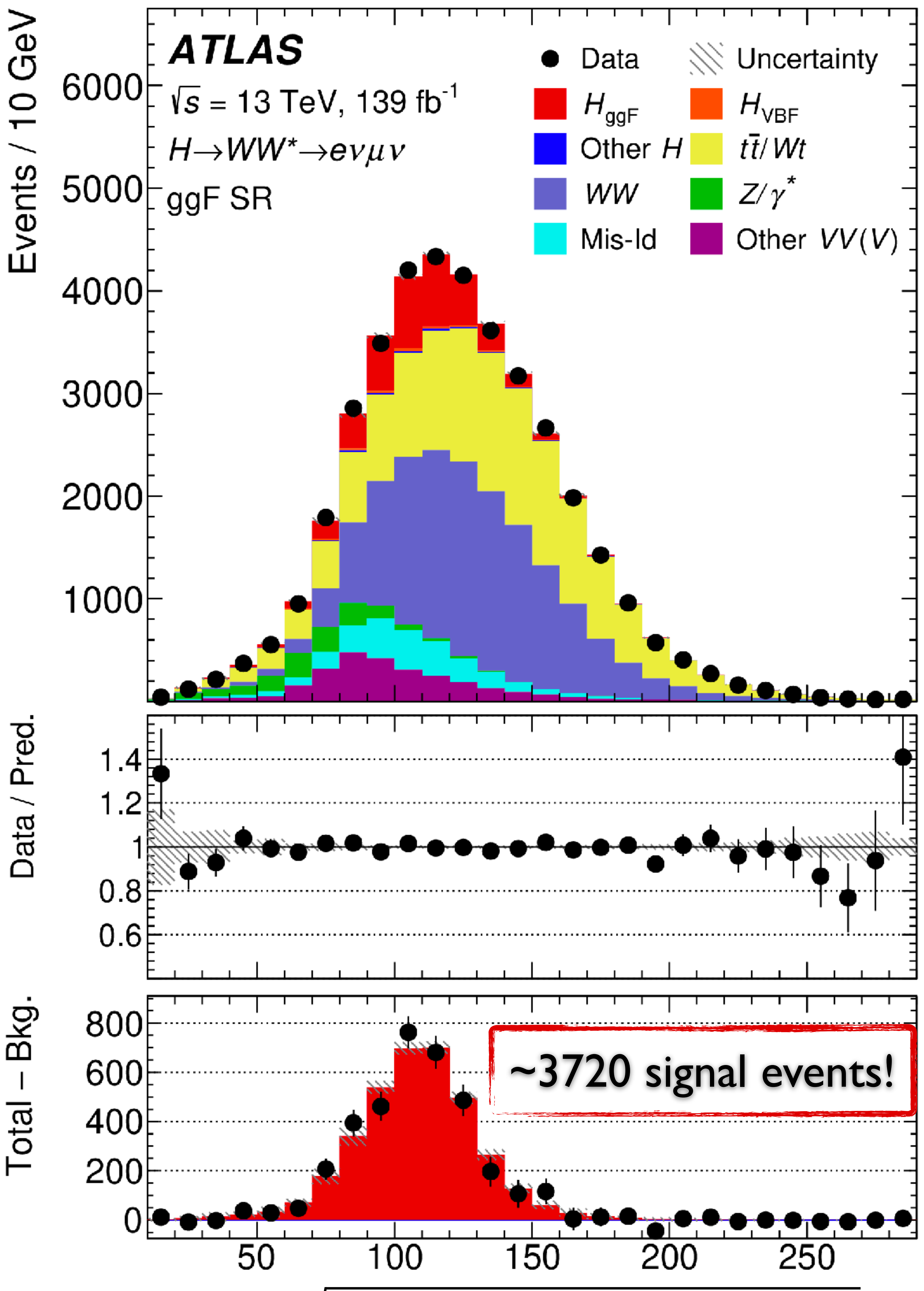


JHEP 03 (2021) 003



H → WW* → eνμν





$$m_T = \sqrt{\left(E_T^{\ell\ell} + E_T^{miss}\right)^2 - \left|\boldsymbol{p}_T^{\ell\ell} + \boldsymbol{E}_T^{miss}\right|^2}$$

- **Large $BR_{SM}(H \to WW^*) \approx 22\%$**
  - $BR_{SM}(W \to \ell\nu) \approx 10.8\%$
    $\times\ BR_{SM}(H \to WW^* \to e\nu\mu\nu) = 0.5\%$

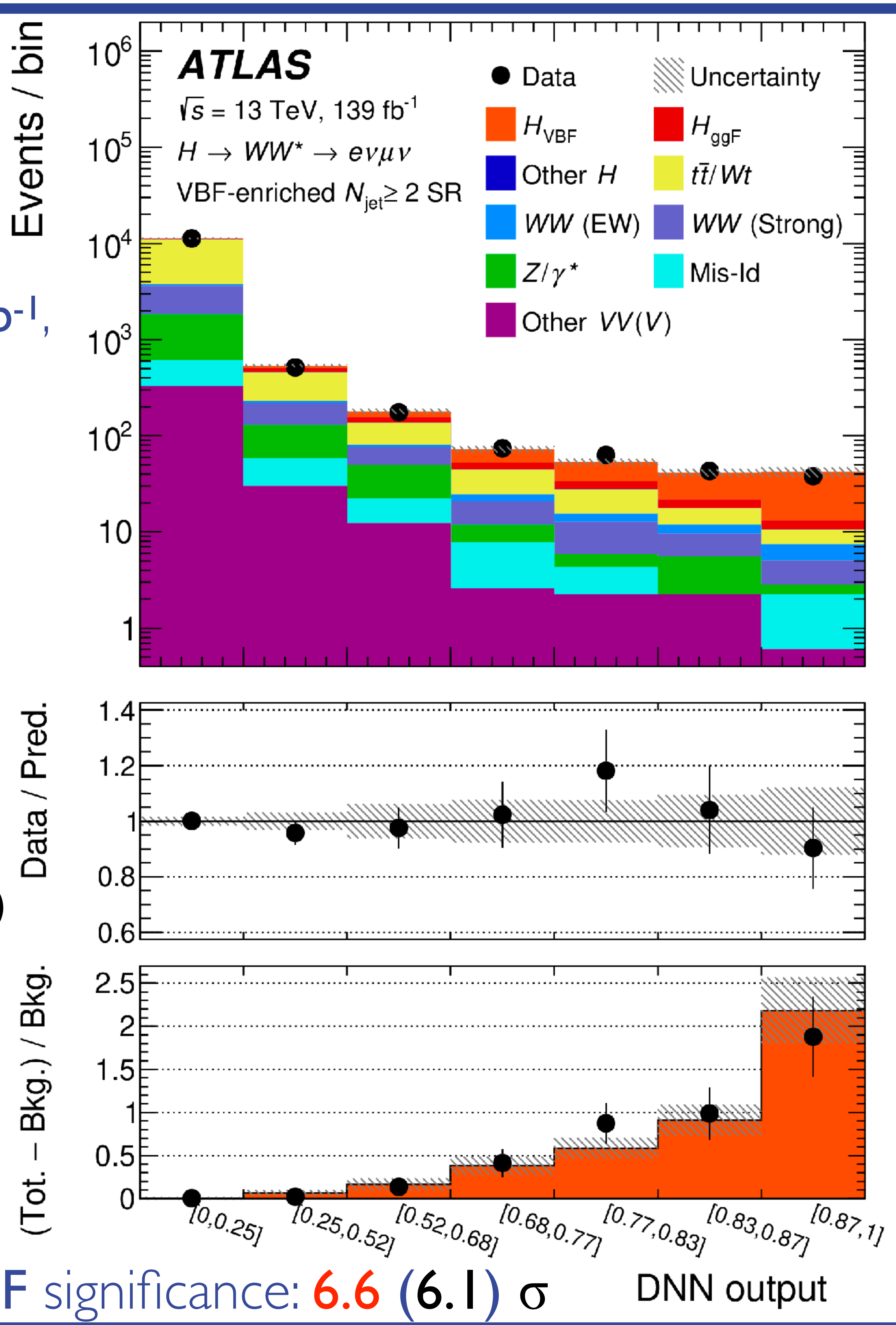
⇒ **~40 000 $H \to WW^* \to e\nu\mu\nu$ events in 139 fb^{-1}**,
but difficult backgrounds…

Signal strength:

$$\mu := \frac{\sigma_i \cdot \mathcal{B}^f}{(\sigma_i \cdot \mathcal{B}^f)_{SM}} = \frac{\text{observed rate}}{\text{expected rate}}$$

$$\mu_{ggF} = 1.20\ ^{+0.16}_{-0.15}$$
$$= 1.20 \pm 0.05\ (\text{stat.})\ ^{+0.09}_{-0.08}\ (\text{exp syst.})\ ^{+0.10}_{-0.08}\ (\text{sig theo.})\ ^{+0.12}_{-0.11}\ (\text{bkg theo.})$$

$$\mu_{VBF} = 0.99\ ^{+0.24}_{-0.20}$$
$$= 0.99\ ^{+0.13}_{-0.12}\ (\text{stat.})\ ^{+0.07}_{-0.06}\ (\text{exp syst.})\ ^{+0.17}_{-0.12}\ (\text{sig theo.})\ ^{+0.10}_{-0.08}\ (\text{bkg theo.}).$$

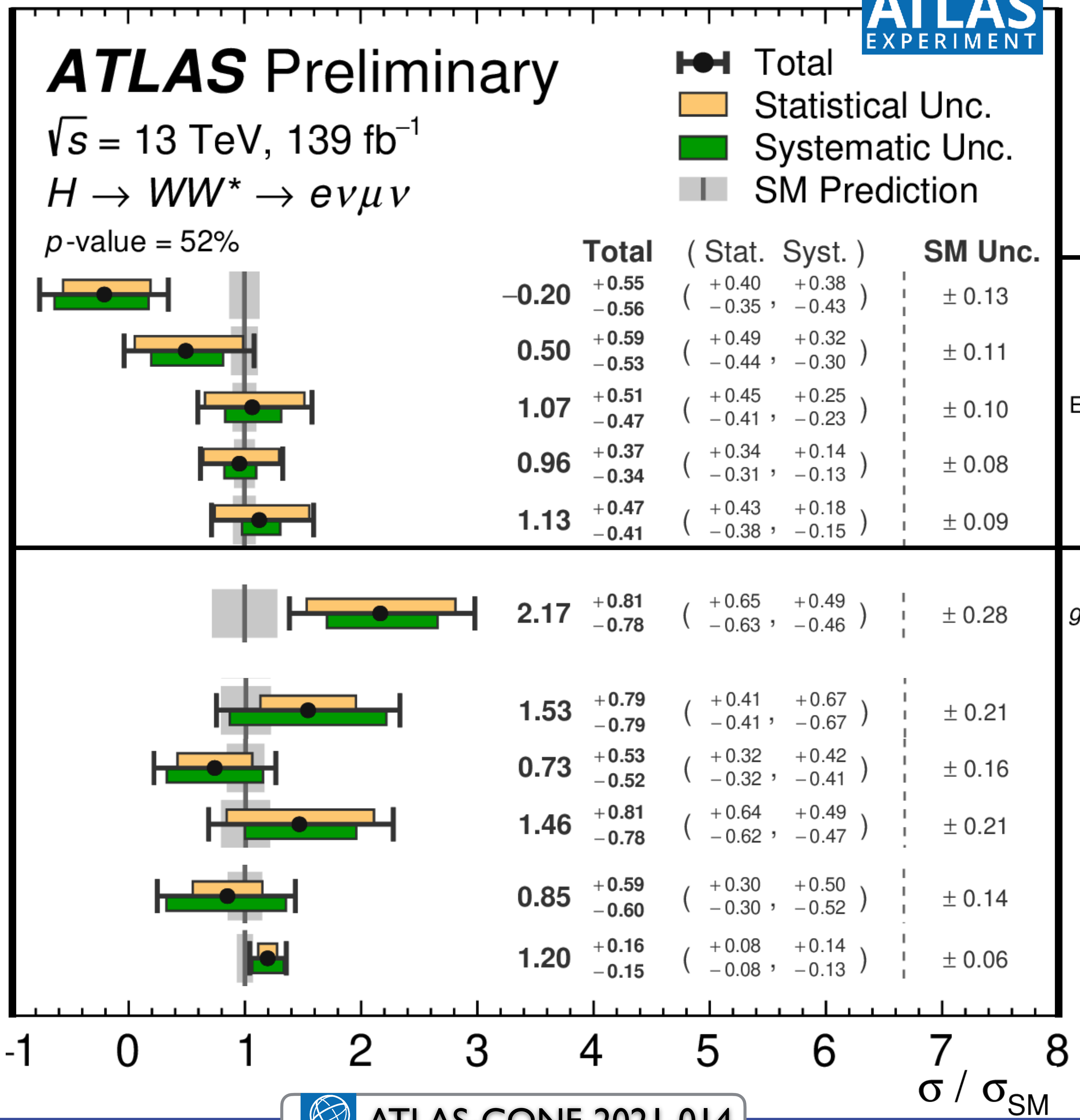


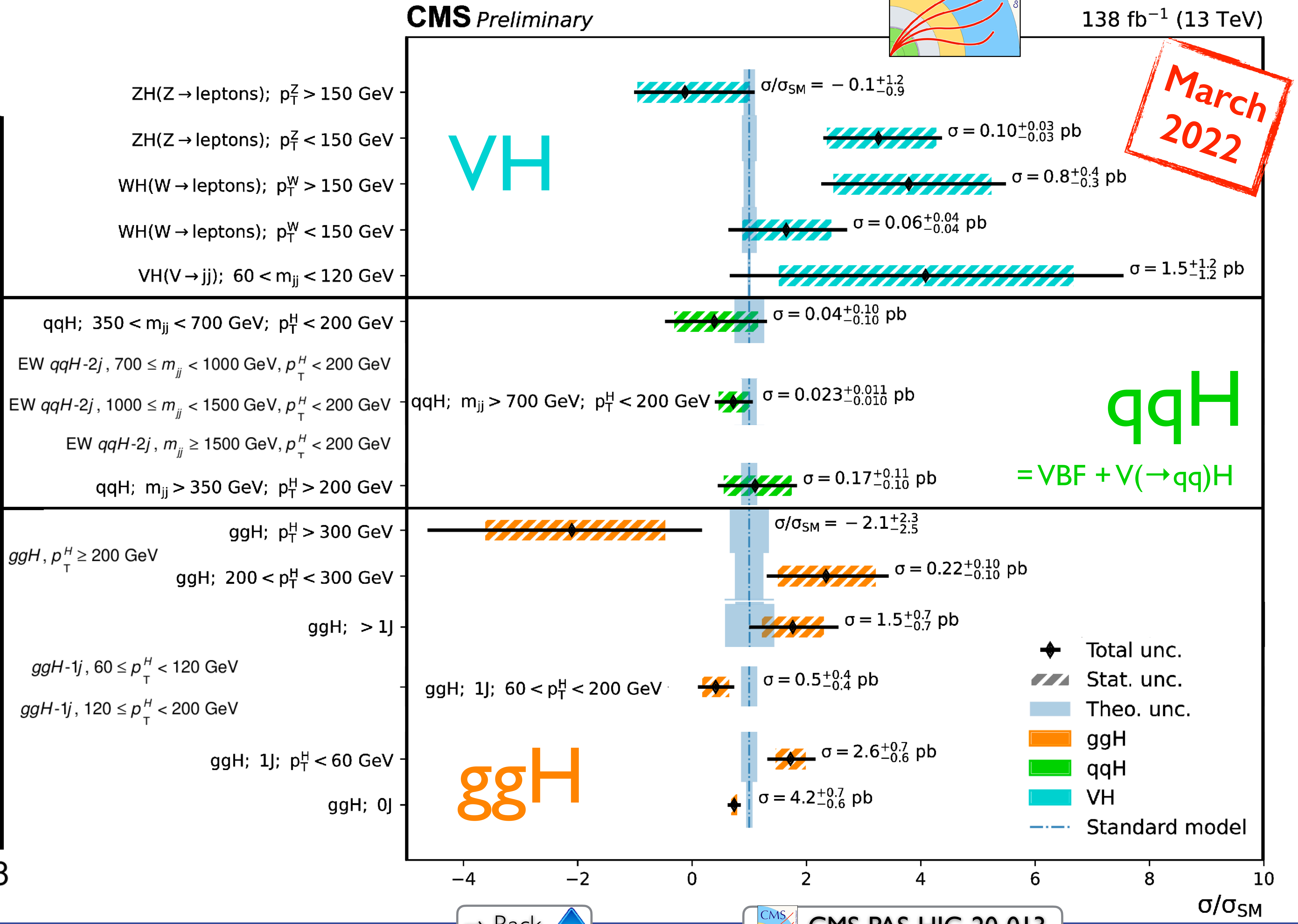
Observed (expected) **VBF** significance: 6.6 (6.1) σ

arXiv:2207.00338

$H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$

- STXS comparison

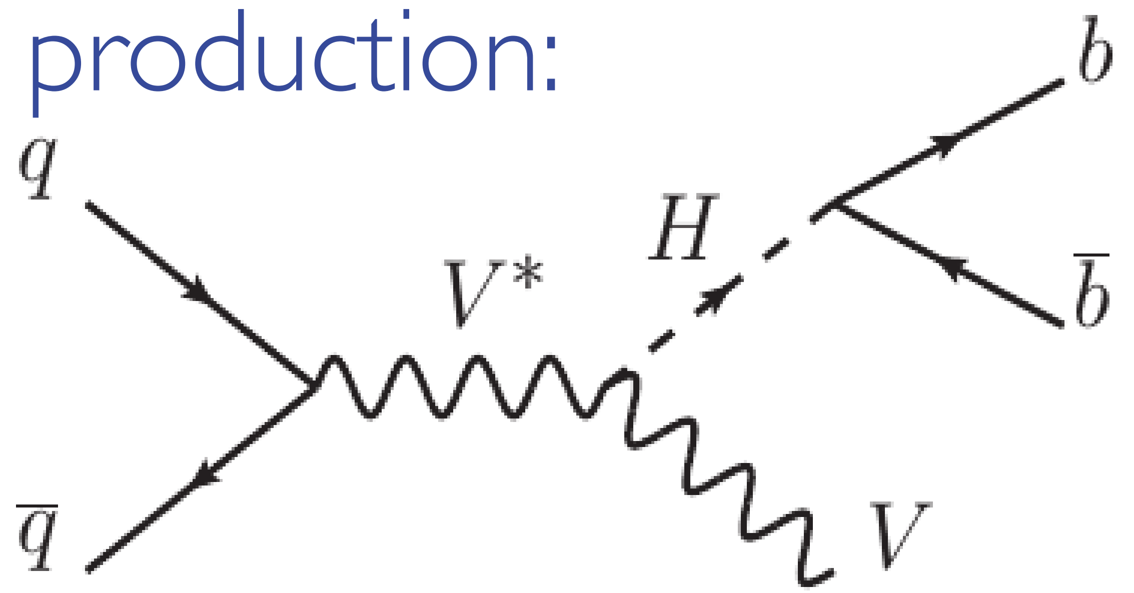




 ATLAS-CONF-2021-014 ⇒ Back CMS-PAS-HIG-20-013

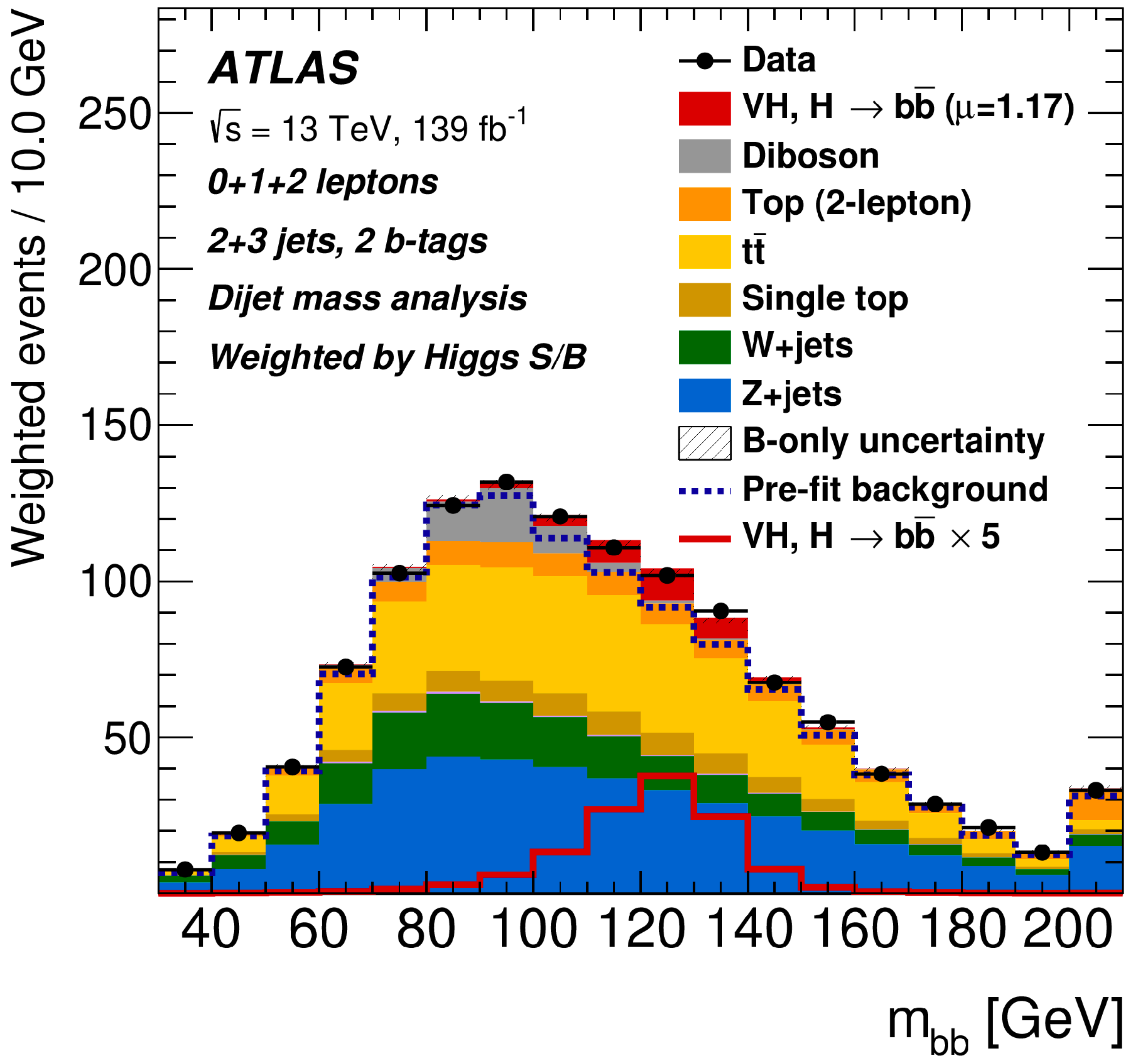
H → $b\bar{b}$

- H → bb dominant decay channel (BR ~58%)
- VH (V=W or Z) associated production:
  - 0 lepton (Z → νν)
  - 1 lepton (W → ℓν)
  - 2 lepton (Z → ℓℓ)



⇒ ~30000 V(→leptons)H(→ bb) events in 139 fb^{-1}

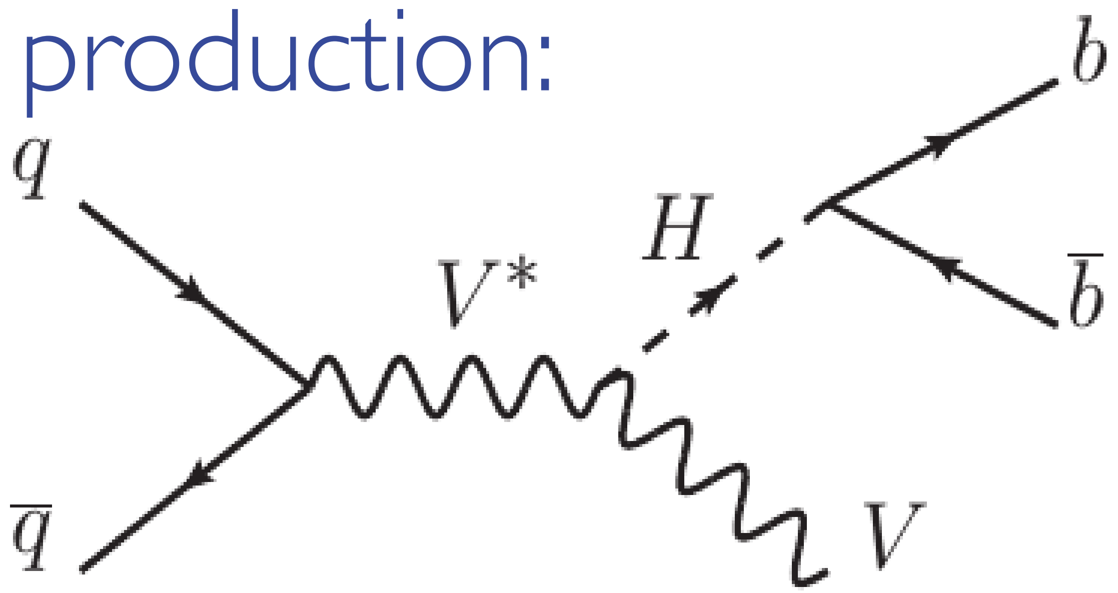
July 2020



Eur. Phys. J. C 81 (2021) 178

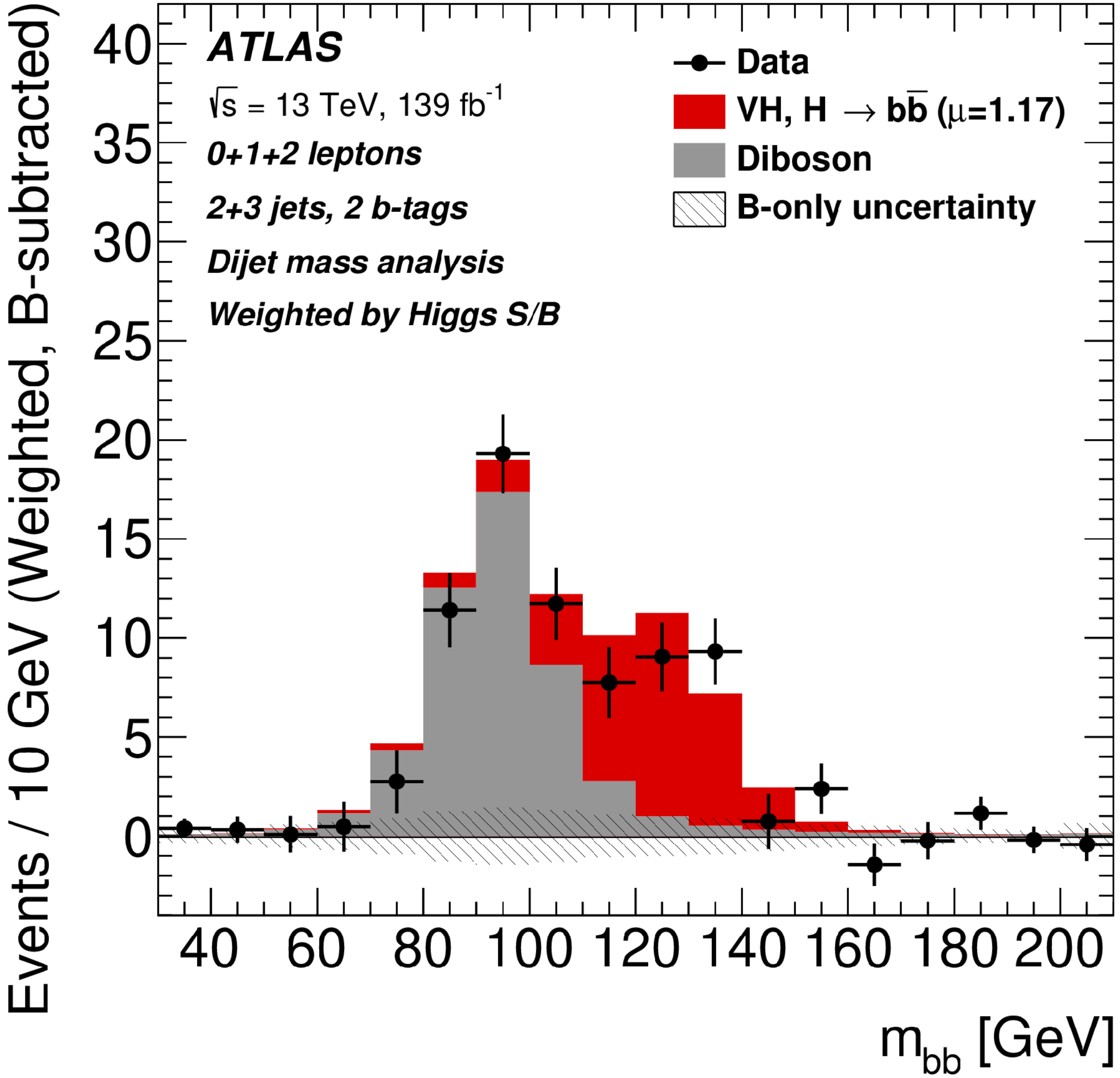
$H \to b\bar{b}$

- $H \to bb$ dominant decay channel (BR ~58%)
- VH (V=W or Z) associated production:
  - 0 lepton ($Z \to \nu\nu$)
  - 1 lepton ($W \to \ell\nu$)
  - 2 lepton ($Z \to \ell\ell$)



⇒ ~30000 V(→leptons)H(→ bb) events in 139 fb^{-1}

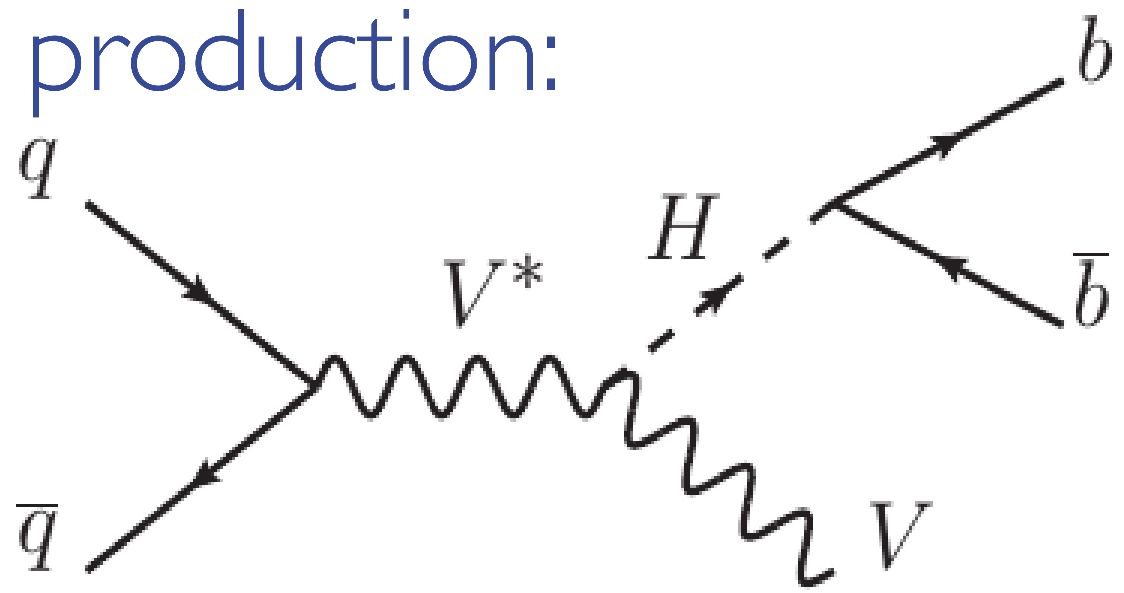
July 2020



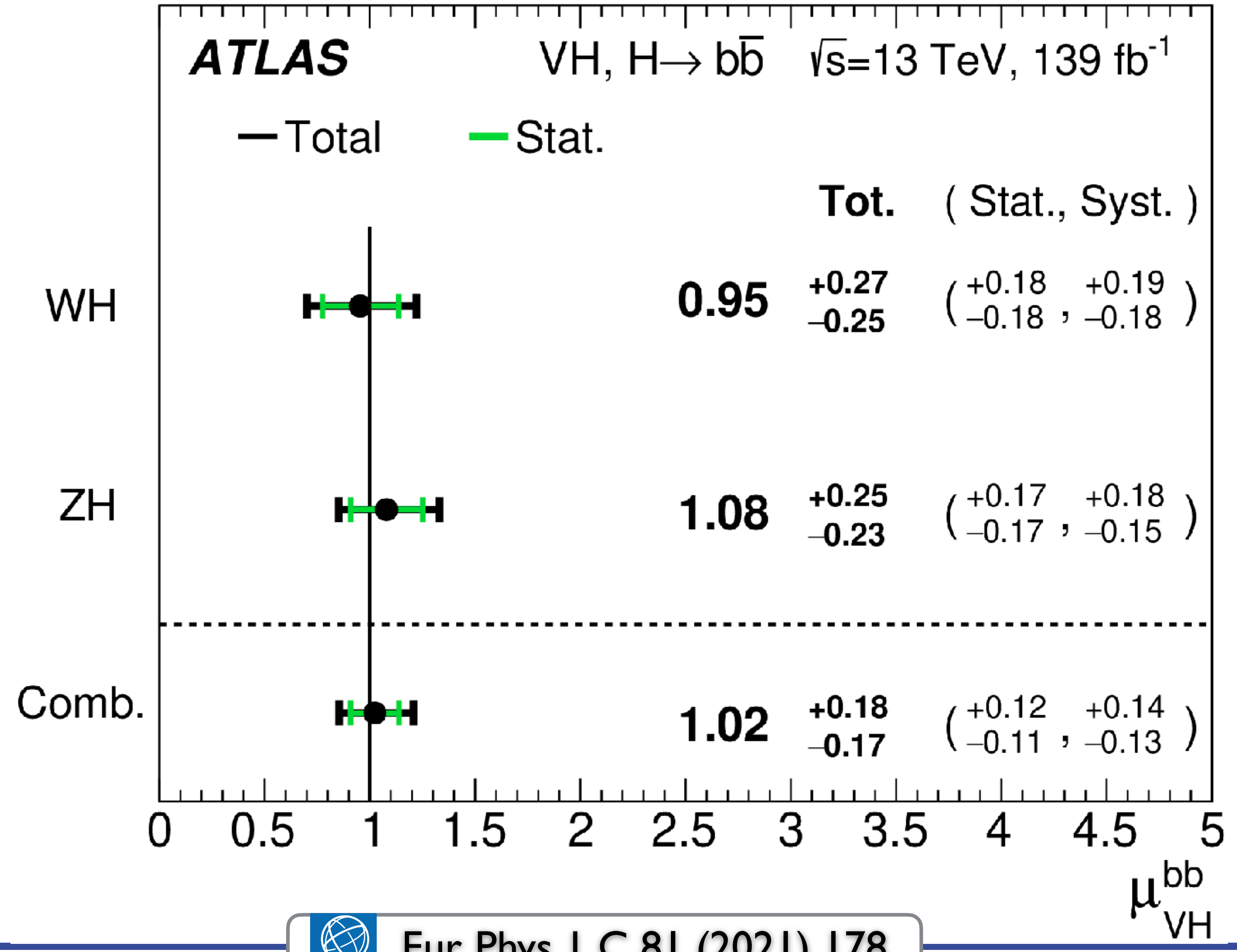
Eur. Phys. J. C 81 (2021) 178

$H \rightarrow b\bar{b}$

- $H \rightarrow bb$ dominant decay channel (BR ~58%)
- VH (V=W or Z) associated production:
  - 0 lepton ($Z \rightarrow \nu\nu$)
  - 1 lepton ($W \rightarrow \ell\nu$)
  - 2 lepton ($Z \rightarrow \ell\ell$)



⇒ ~30000 V(→leptons)H(→ bb) events in 139 fb^{-1}

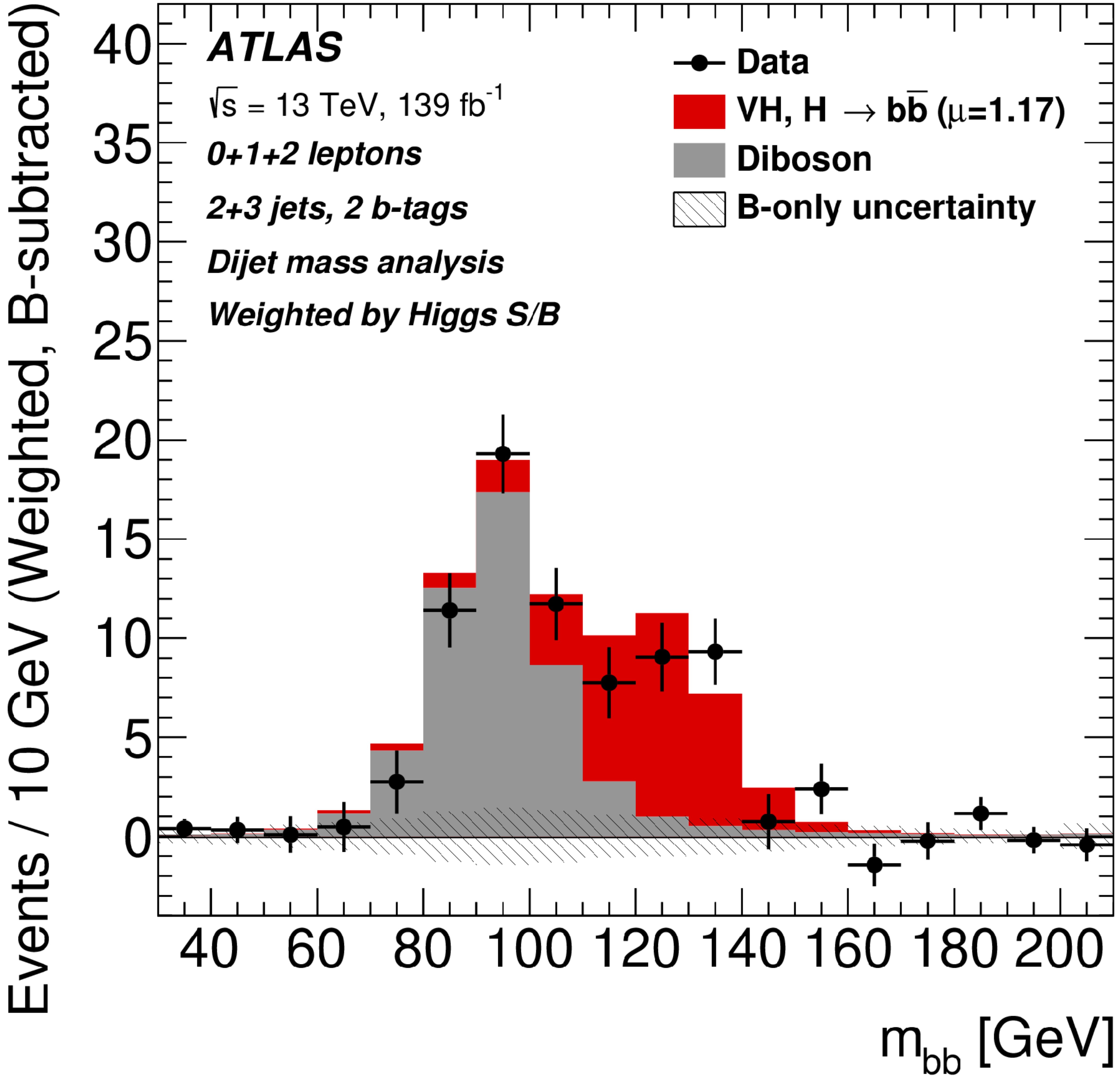


4.0 σ

5.3 σ

6.7 σ

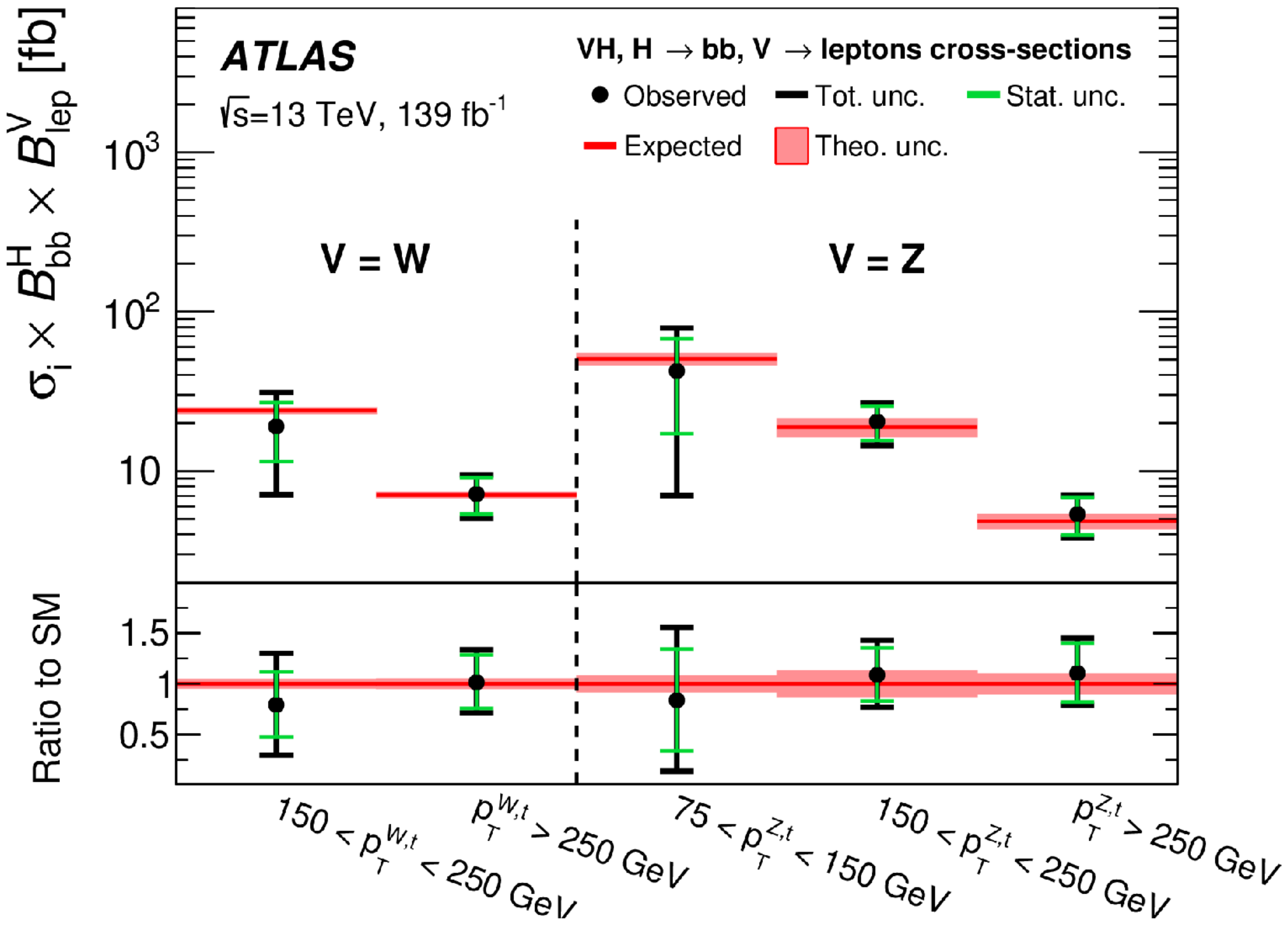
July 2020



Eur. Phys. J. C 81 (2021) 178

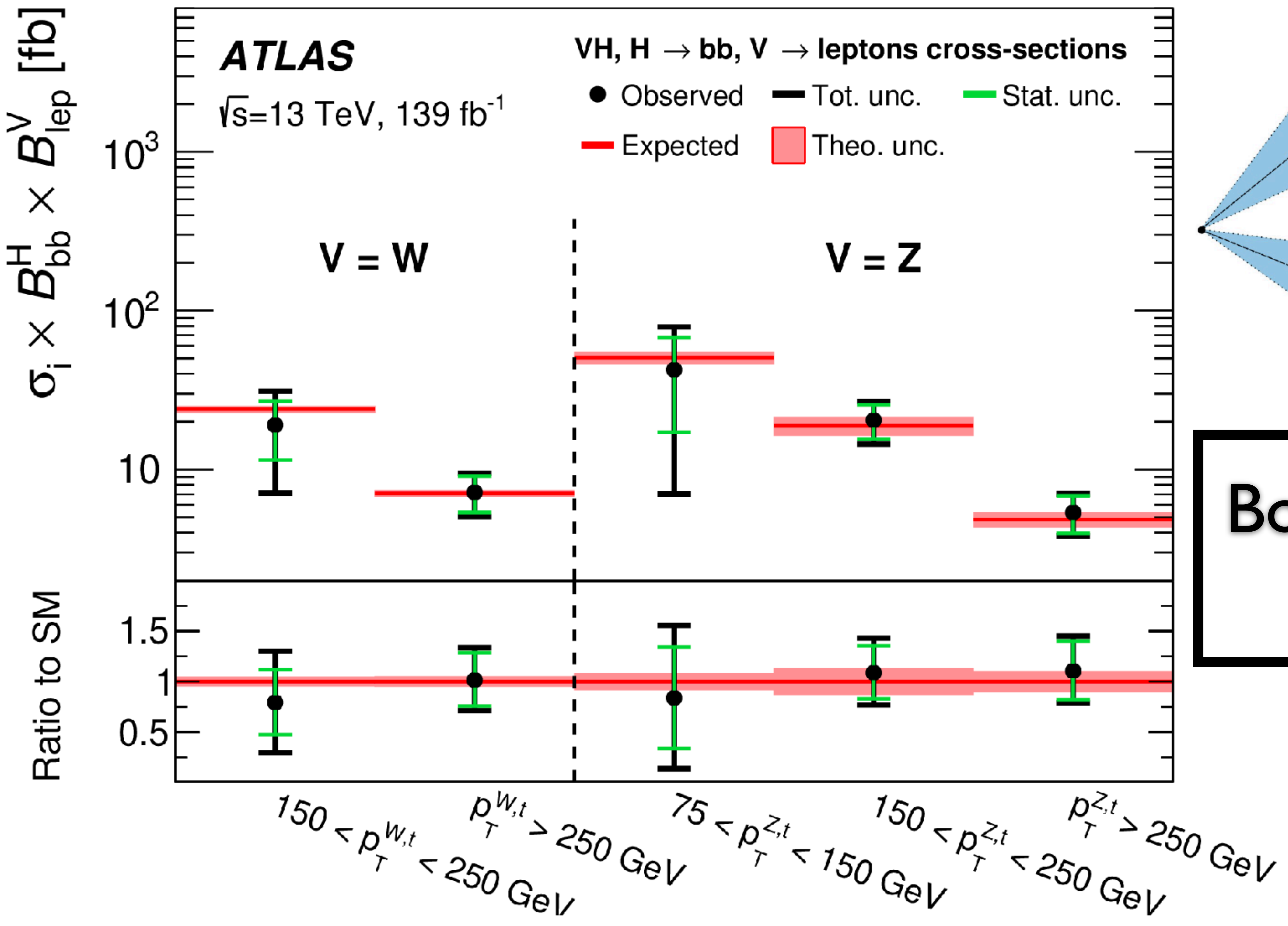
$H \rightarrow b\bar{b}$

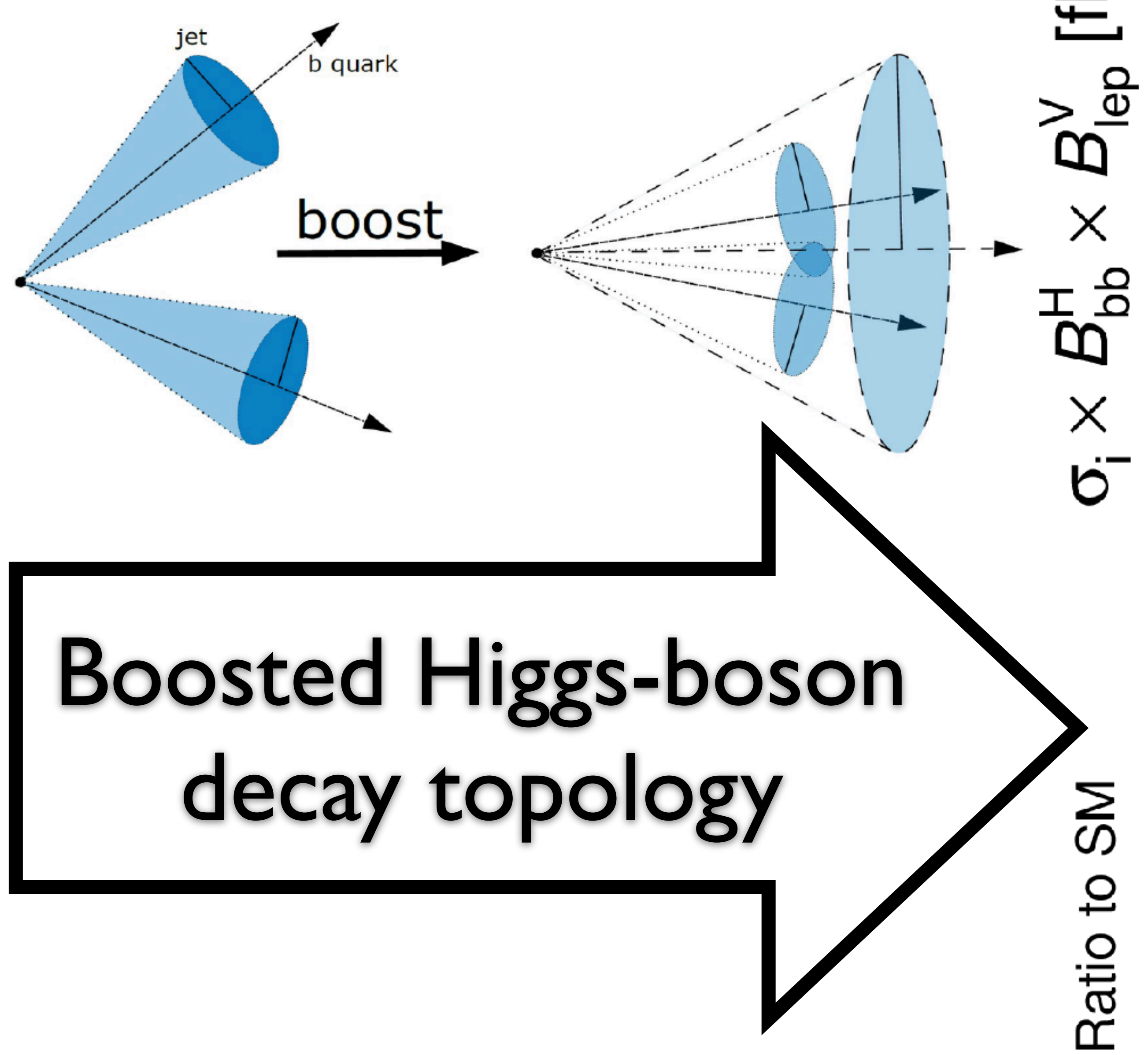
- Cross-section measurements as function of $p_T(V)$

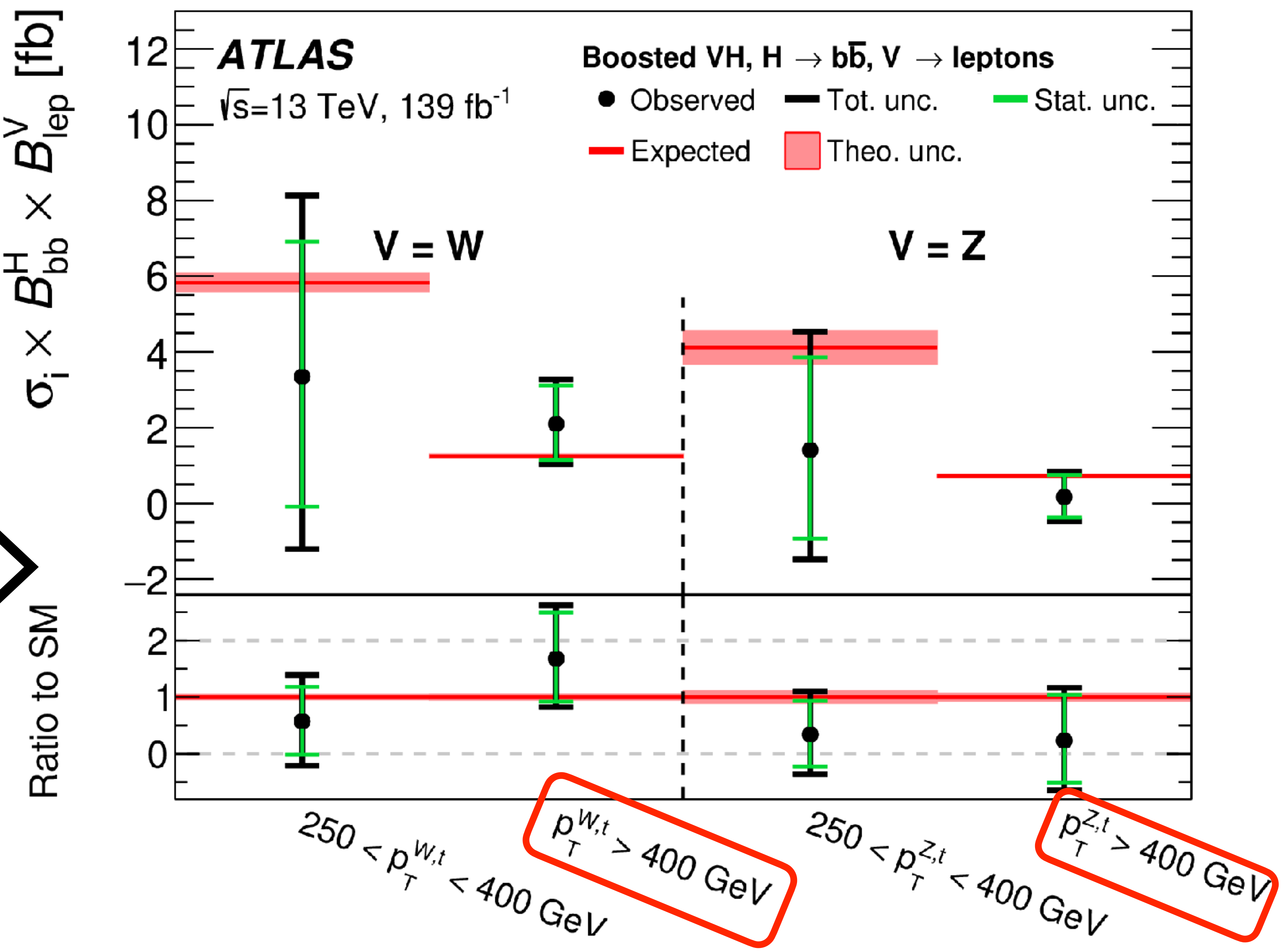


Eur. Phys. J. C 81 (2021) 178

- Cross-section measurements as function of $p_T(V)$







- Explores higher $p_T(V)$

  ⇒ Increase sensitivity to BSM

Eur. Phys. J. C 81 (2021) 178

Phys. Lett. B 816 (2021) 136204

H → b$\bar{b}$

- Cross-section

... her $p_T(V)$

→ increase sensitivity to BSM

ATLAS-CONF-2021-051

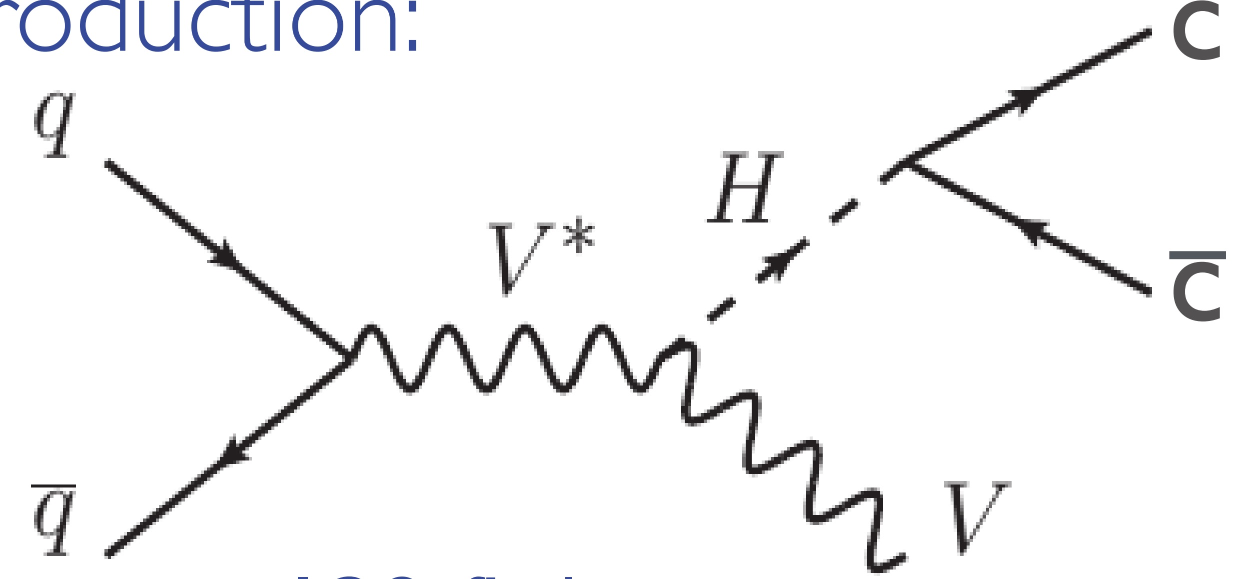
Eur. Phys. J. C 81 (2021) 178

Phys. Lett. B 816 (2021) 136204

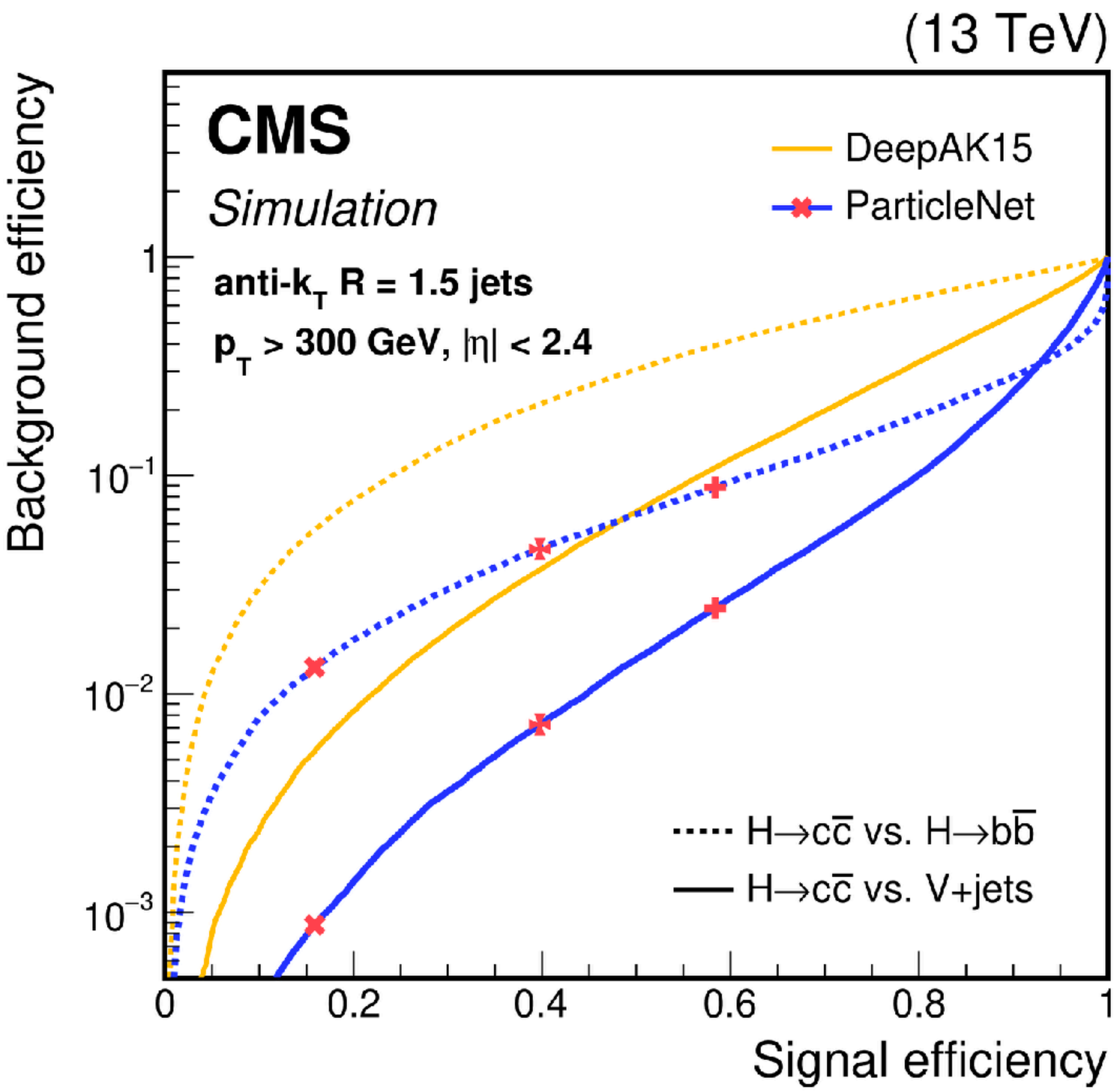
H → $c\bar{c}$

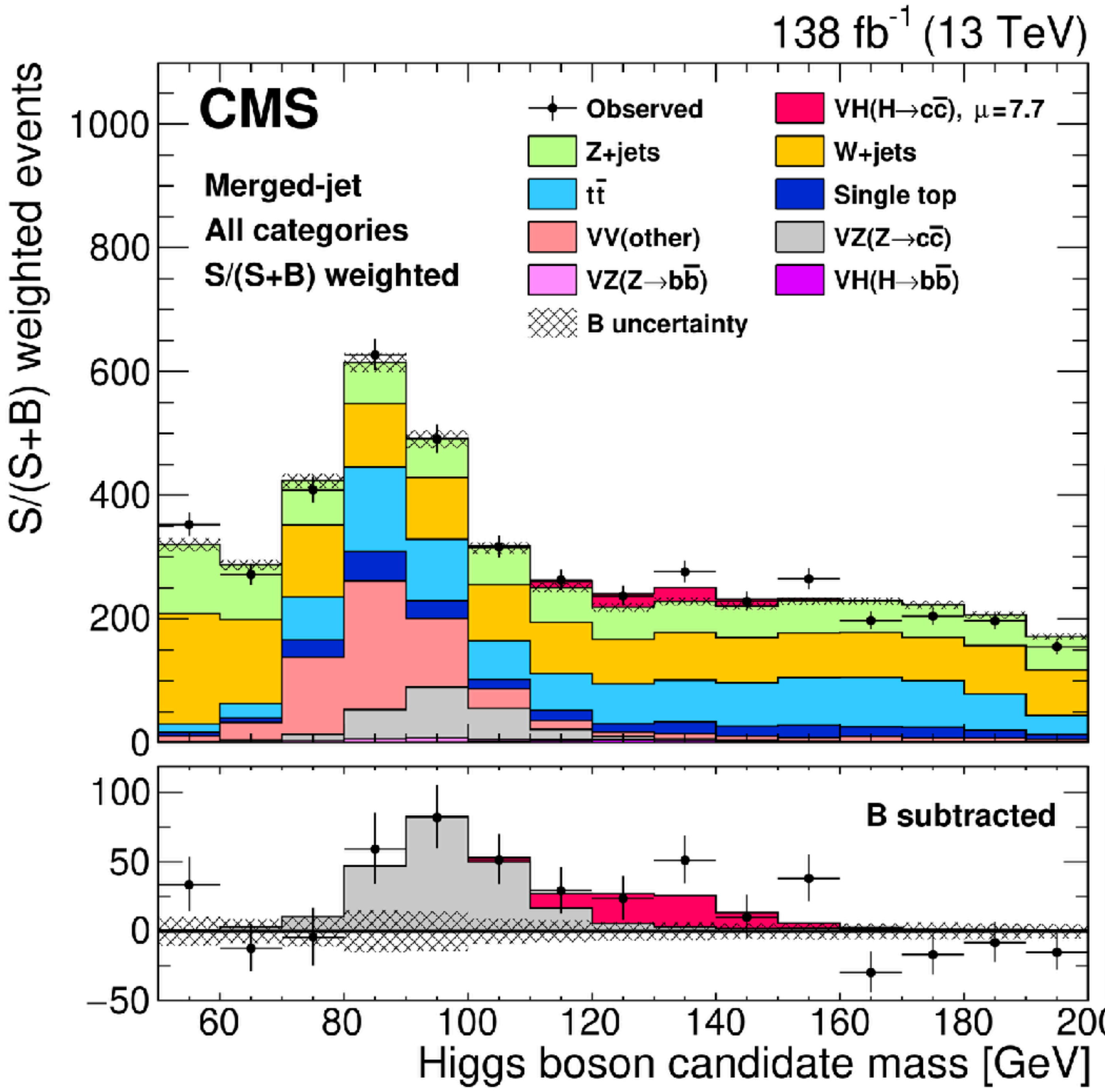
Phys. Rev. Lett. 131 (2023) 061801

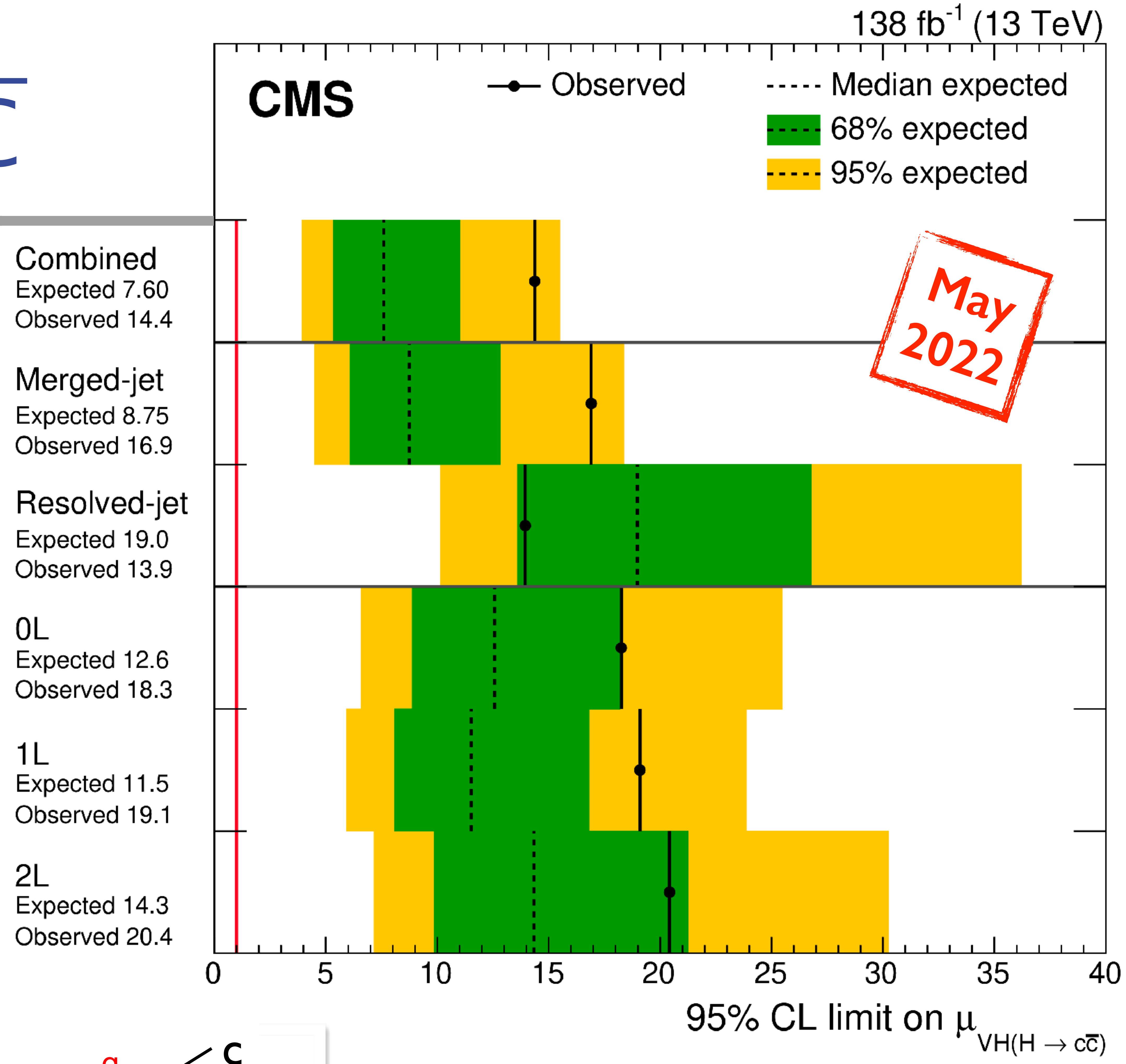
- H → cc 2nd generation decay channel (**BR ~2.9%**)
- VH (V=W or Z) associated production:
  - 0 lepton ($Z \to \nu\nu$)
  - 1 lepton ($W \to \ell\nu$)
  - 2 lepton ($Z \to \ell\ell$)



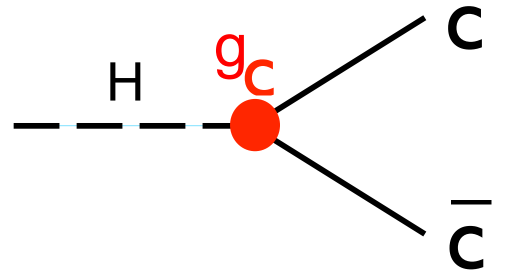
⇒ **~1500 V(→leptons)H(→cc) events in 139 fb⁻¹**







$$\mu := \frac{\sigma_i \cdot \mathcal{B}^f}{(\sigma_i \cdot \mathcal{B}^f)_{SM}} = \frac{\text{observed rate}}{\text{expected rate}}$$



$$\kappa_c := \frac{g_c}{(g_c)_{SM}}$$

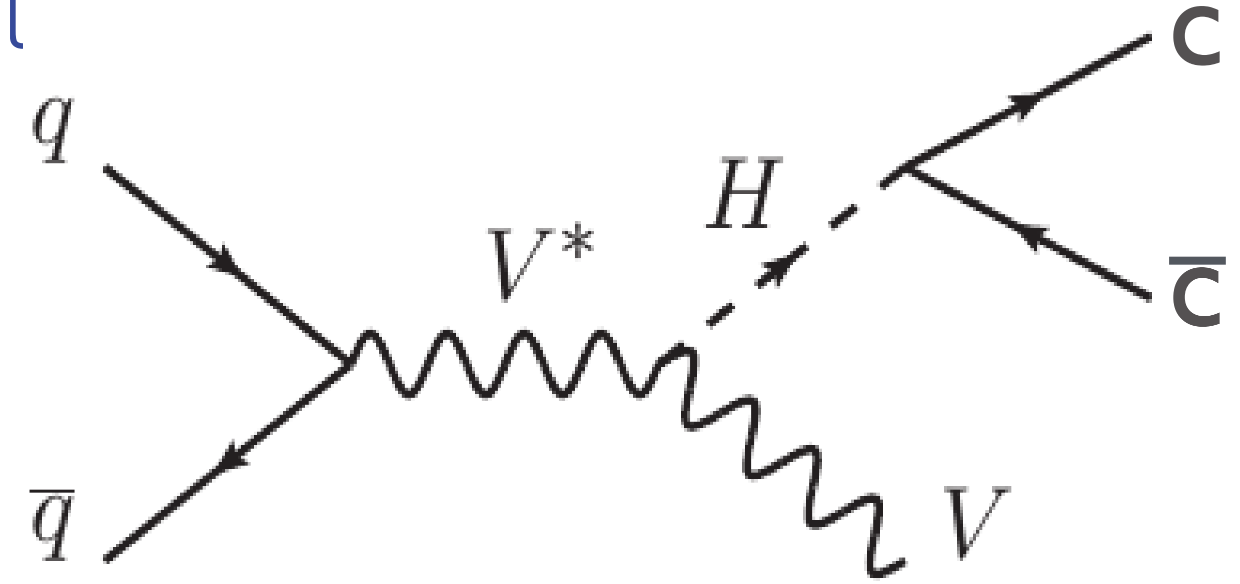
Observed (expected) limit on Higgs-charm coupling modifier:

1.1 < |κc| < 5.5 (|κc| < 3.4) (95% C.L.)

⇒ ATLAS result

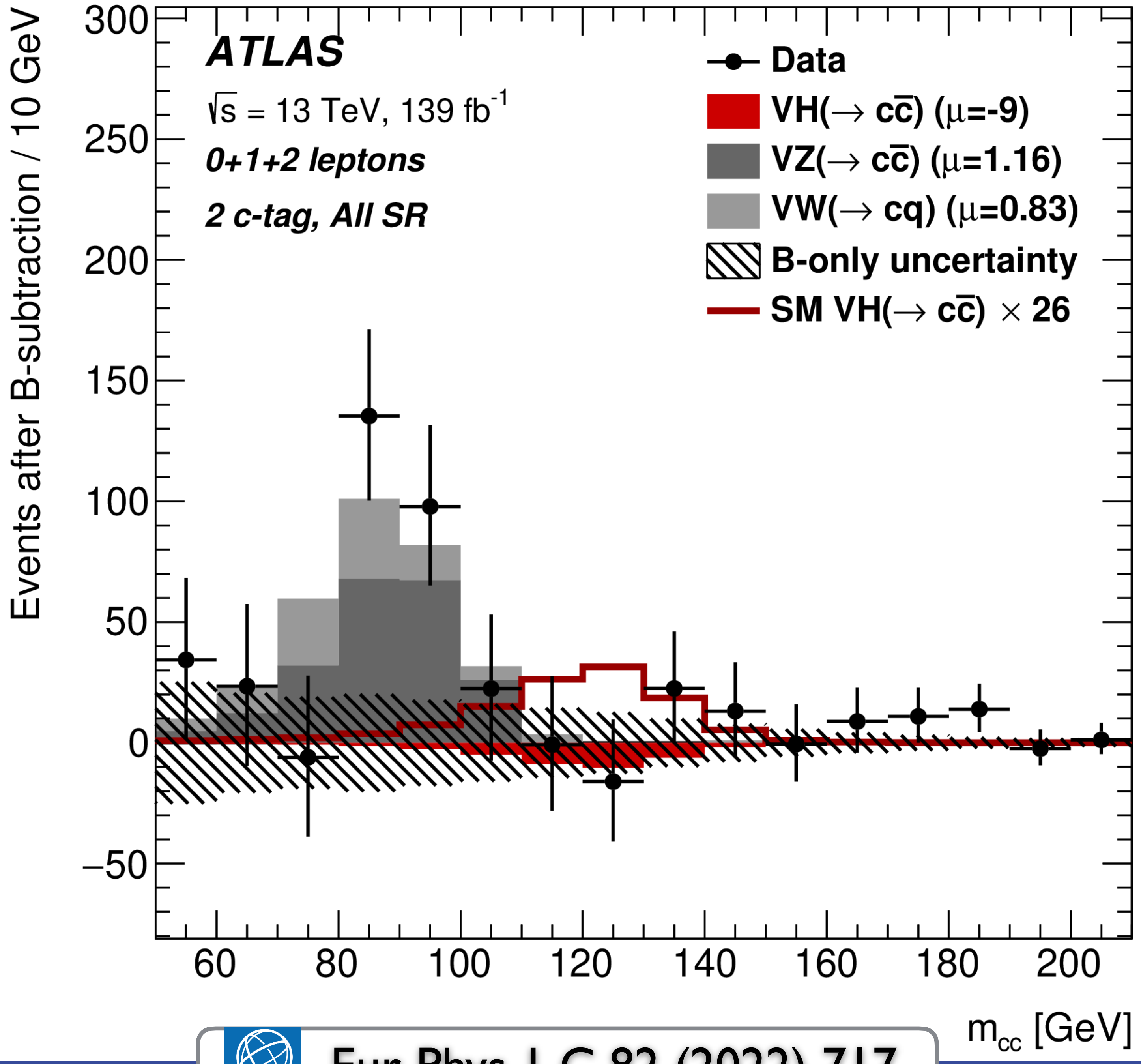
H → $c\bar{c}$

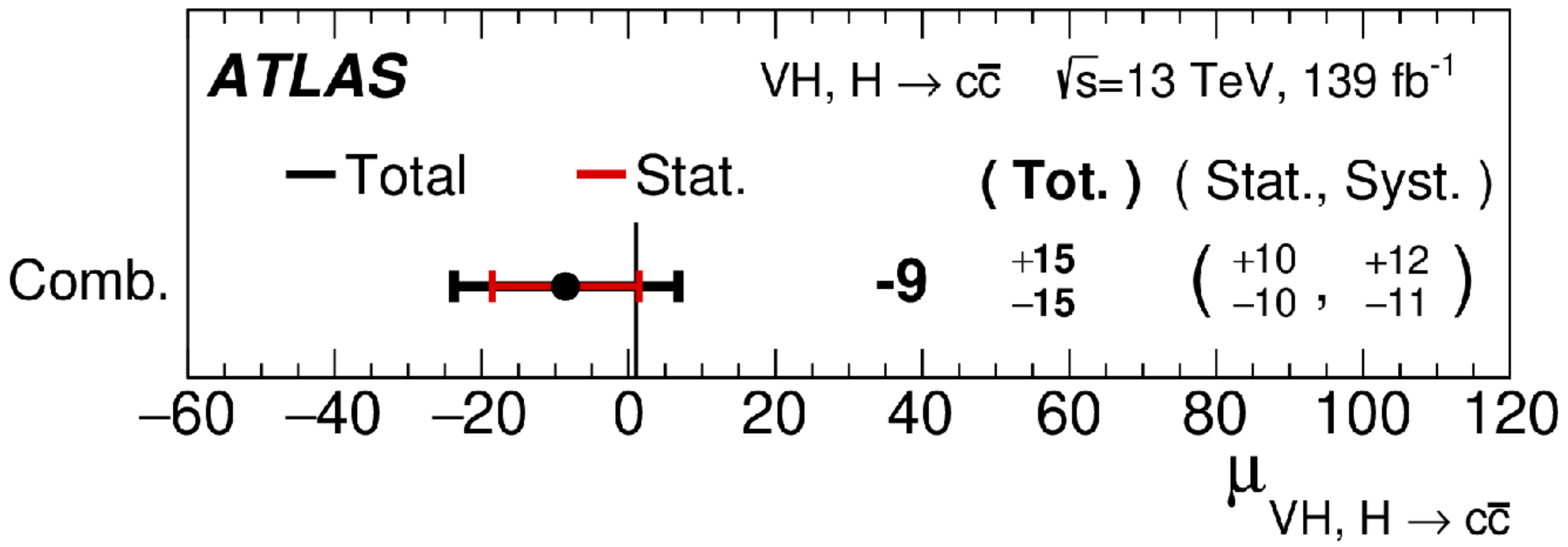
- H → cc 2nd generation decay channel (BR ~2.9%)
- VH (V=W or Z) associat
  - 0 lepton (Z → νν)
  - 1 lepton (W → ℓν)
  - 2 lepton (Z → ℓℓ)

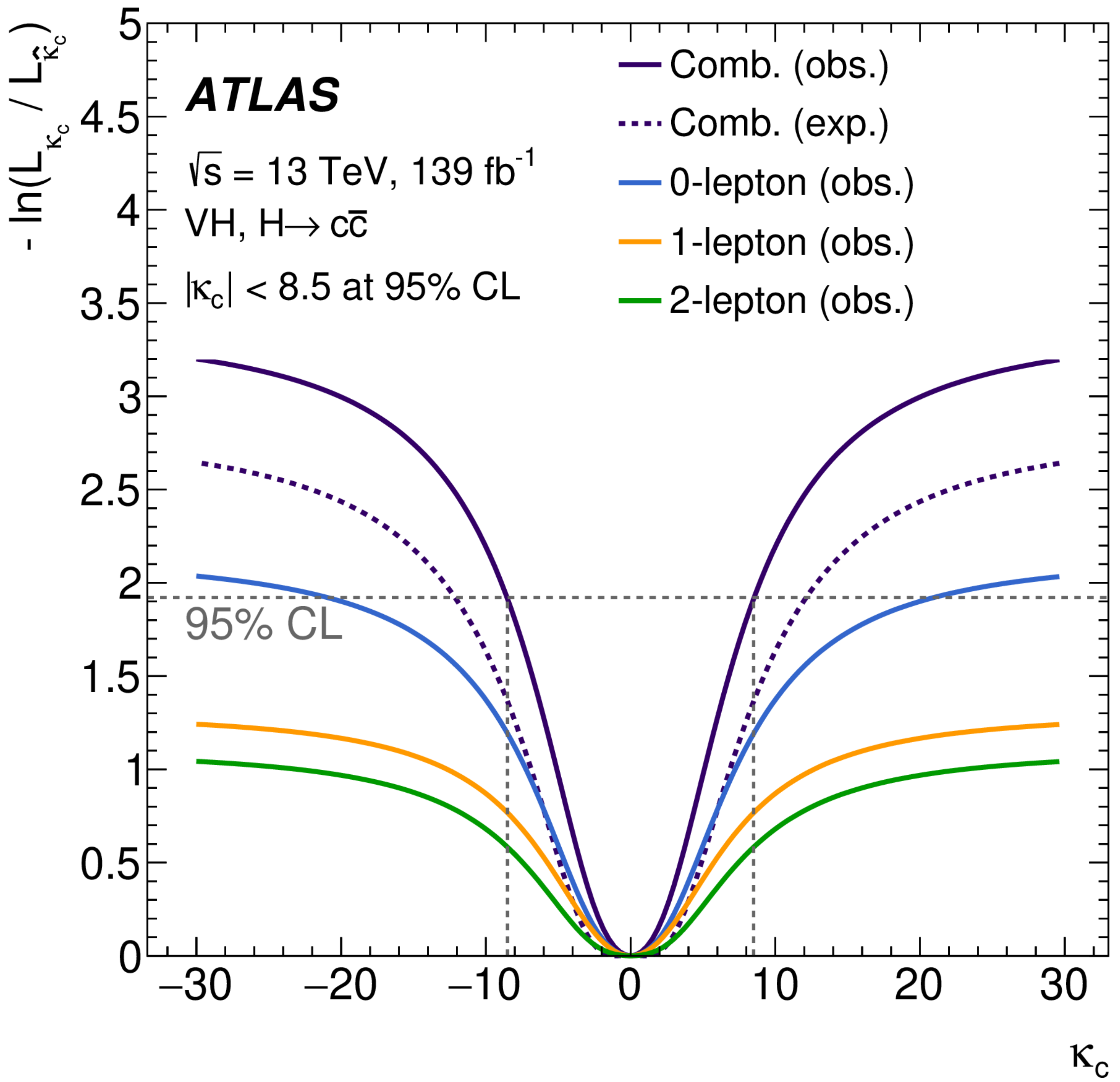


Jan 2022

⇒ ~1500 V(→leptons)H(→cc) events in 139 fb^{-1}







- Observed (expected) upper limit on σ·BR **26 (31) × SM** (95% C.L.)

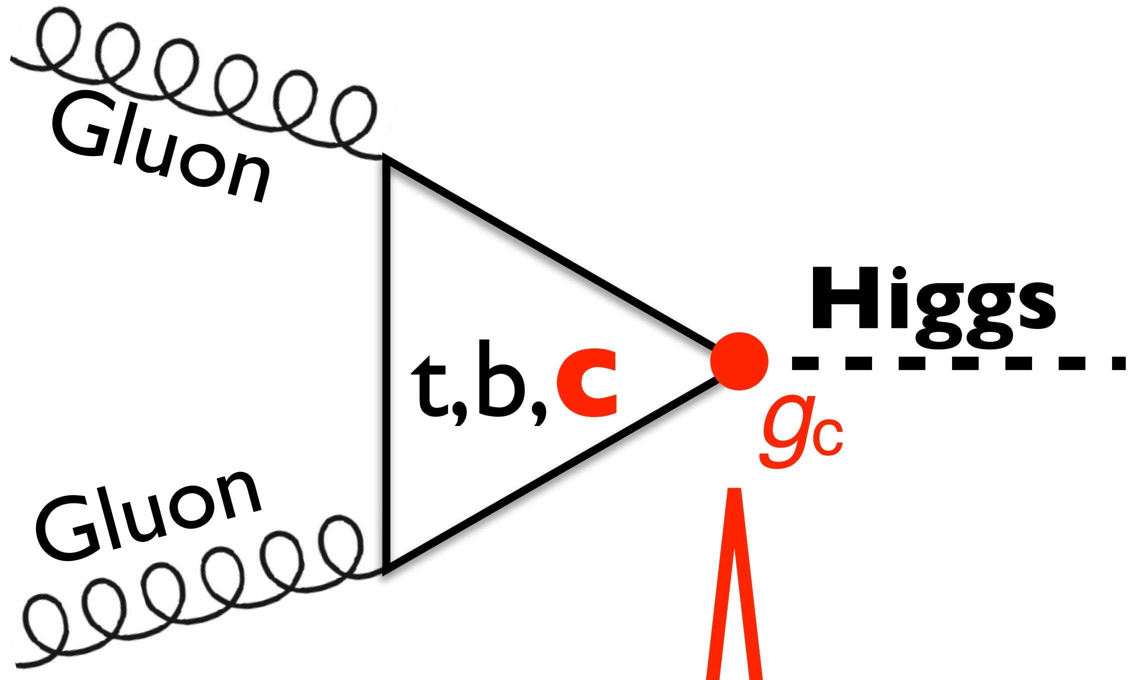
- Observed (expected) upper limit on Higgs-charm-coupling: **8.5 (12.4) × SM** (95% C.L.)

Eur. Phys. J. C 82 (2022) 717

⇒ Back

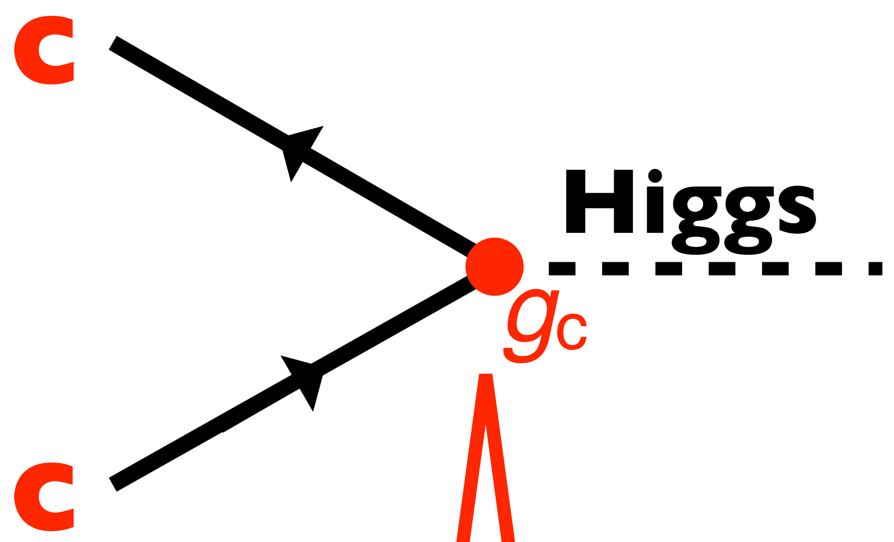
Extracting coupling modifiers

- **Idea**: $p_T(H)$ sensitiv to Charm-Yukawa coupling:
  - Interference between Charm-, Bottom-, and Top-quark loop in ggF



Charm-Higgs coupling strength modifier κ_c

  - Direct cc → H production

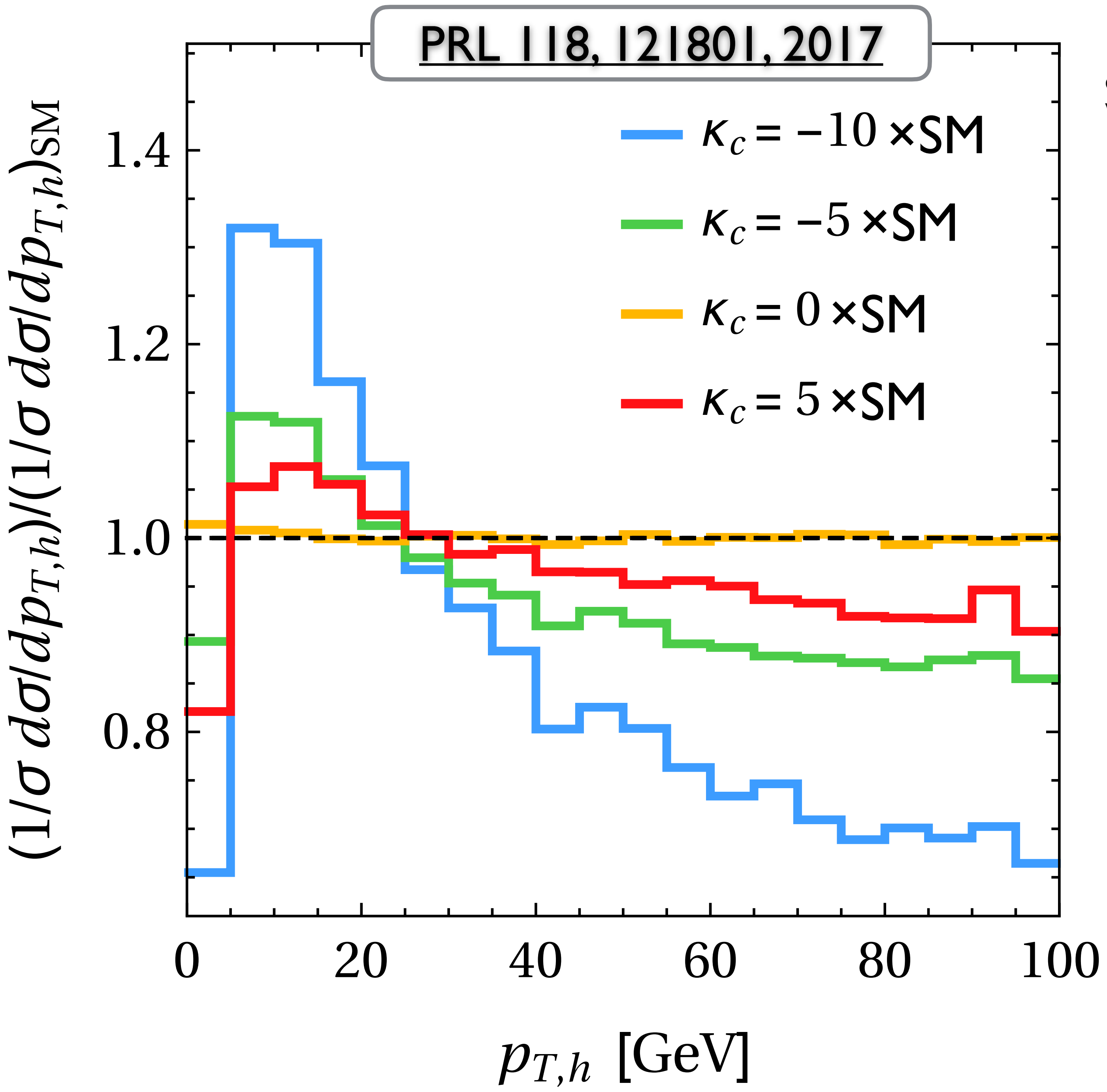


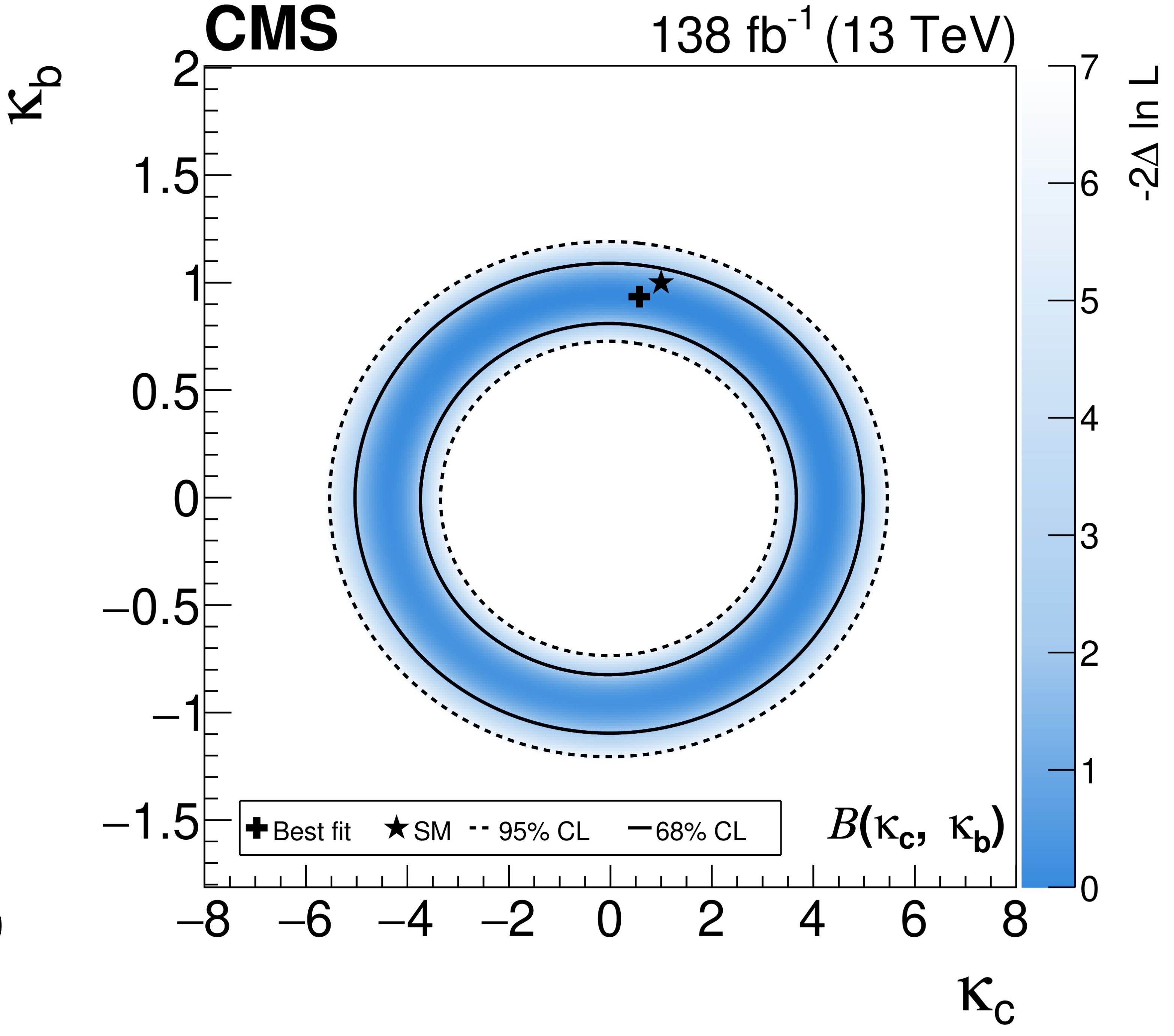
Charm-Higgs coupling strength modifier κ_c

$$\kappa_c := \frac{g_c}{(g_c)_{SM}}$$

Interpretation from $p_T(H)$ distributions with $H \to ZZ^* \to 4\ell$ (May 2023)

Shape & coupling dependent on BR

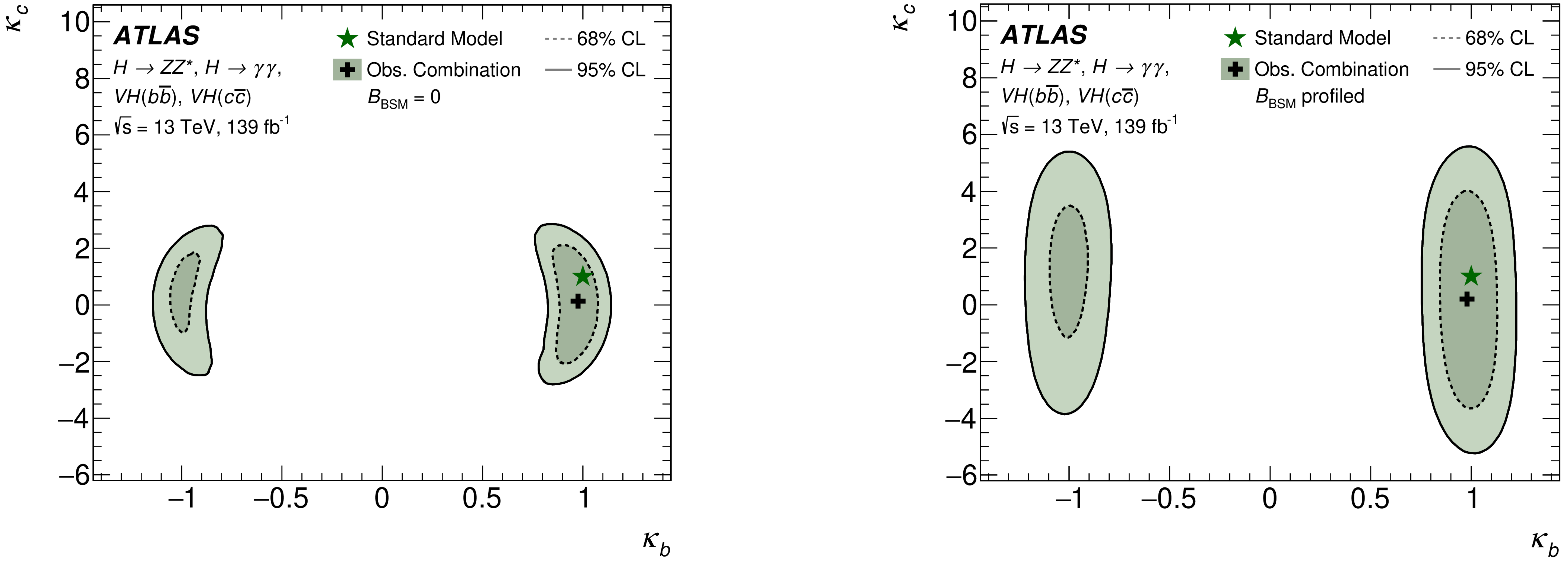




JHEP 08 (2023) 040

Combined κ_b and κ_c extraction

- Combine information from $p_T(H)$ with VH(bb) and VH(cc):



July 2022

Scenario	Observed 68% confidence interval	Observed 95% confidence interval
$B_{BSM} = 0$	[−1.61, 1.70]	[−2.47, 2.53]
No assumption on B_{BSM}	[−2.63, 3.01]	[−4.46, 4.81]

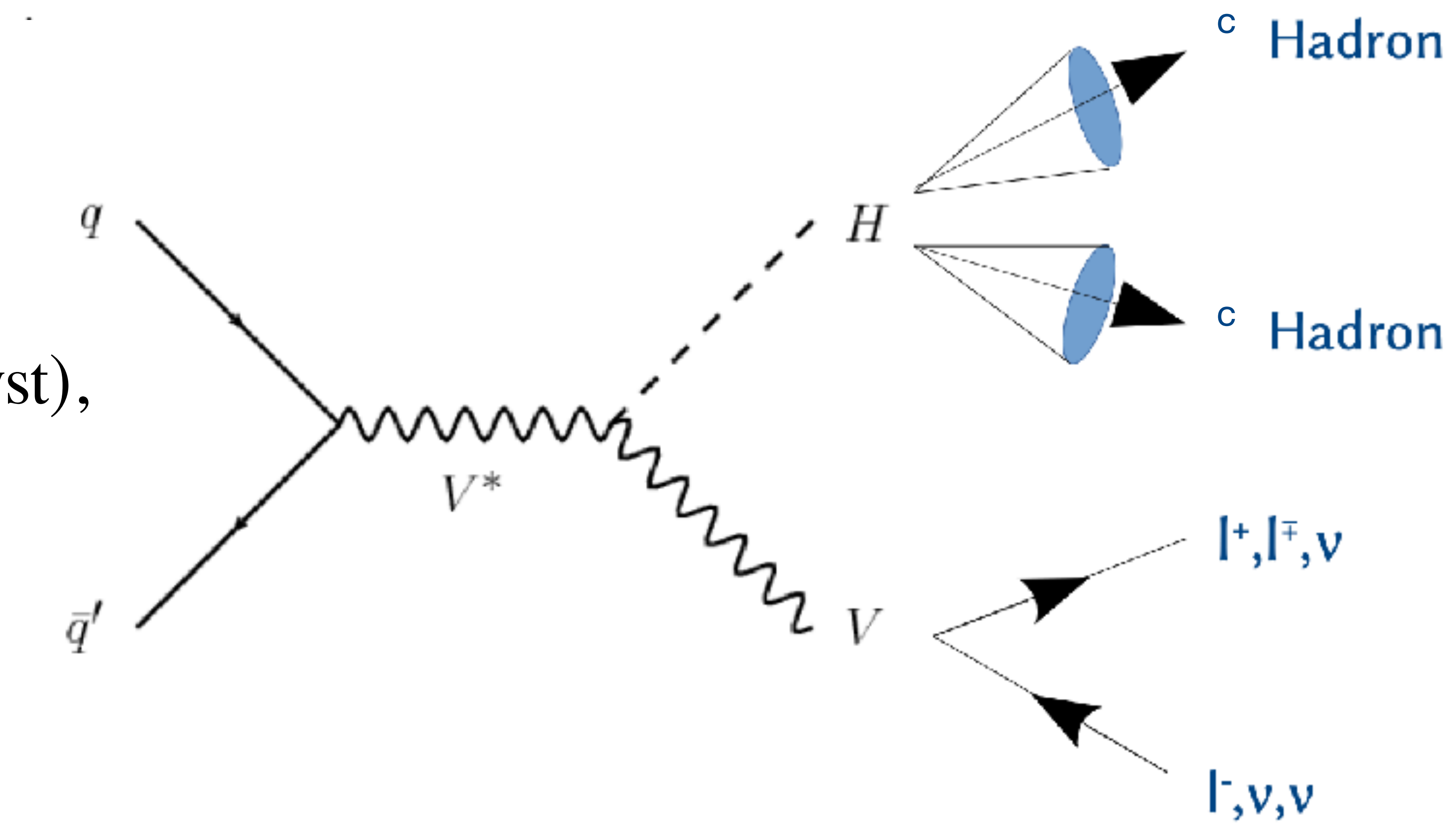
JHEP 05 (2023) 028

HL-LHC Combination: H → bb and H → cc

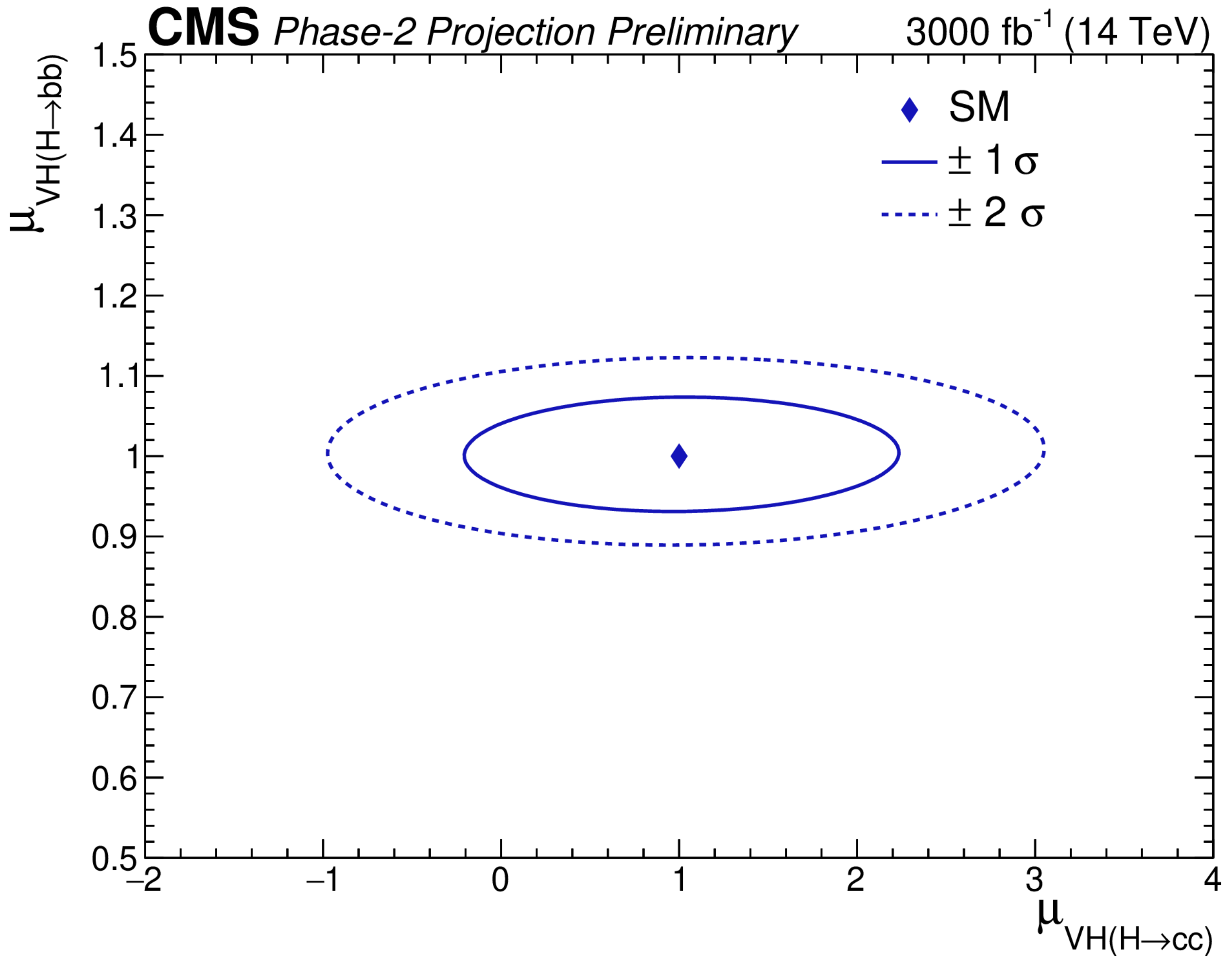
CMS-PAS-FTR-22-001 — Aug 2022

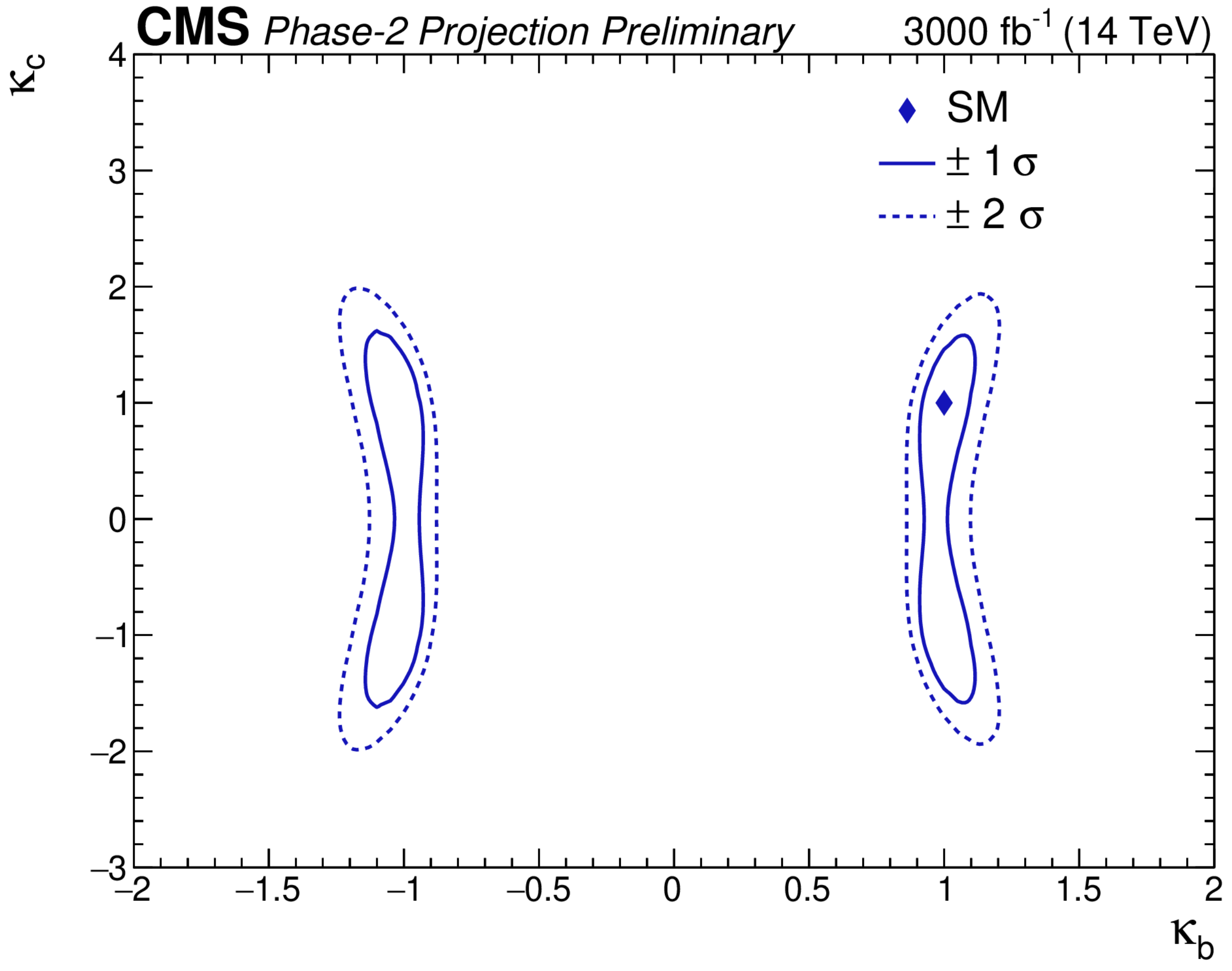
ATL-PHYS-PUB-2021-039 — Nov 2021

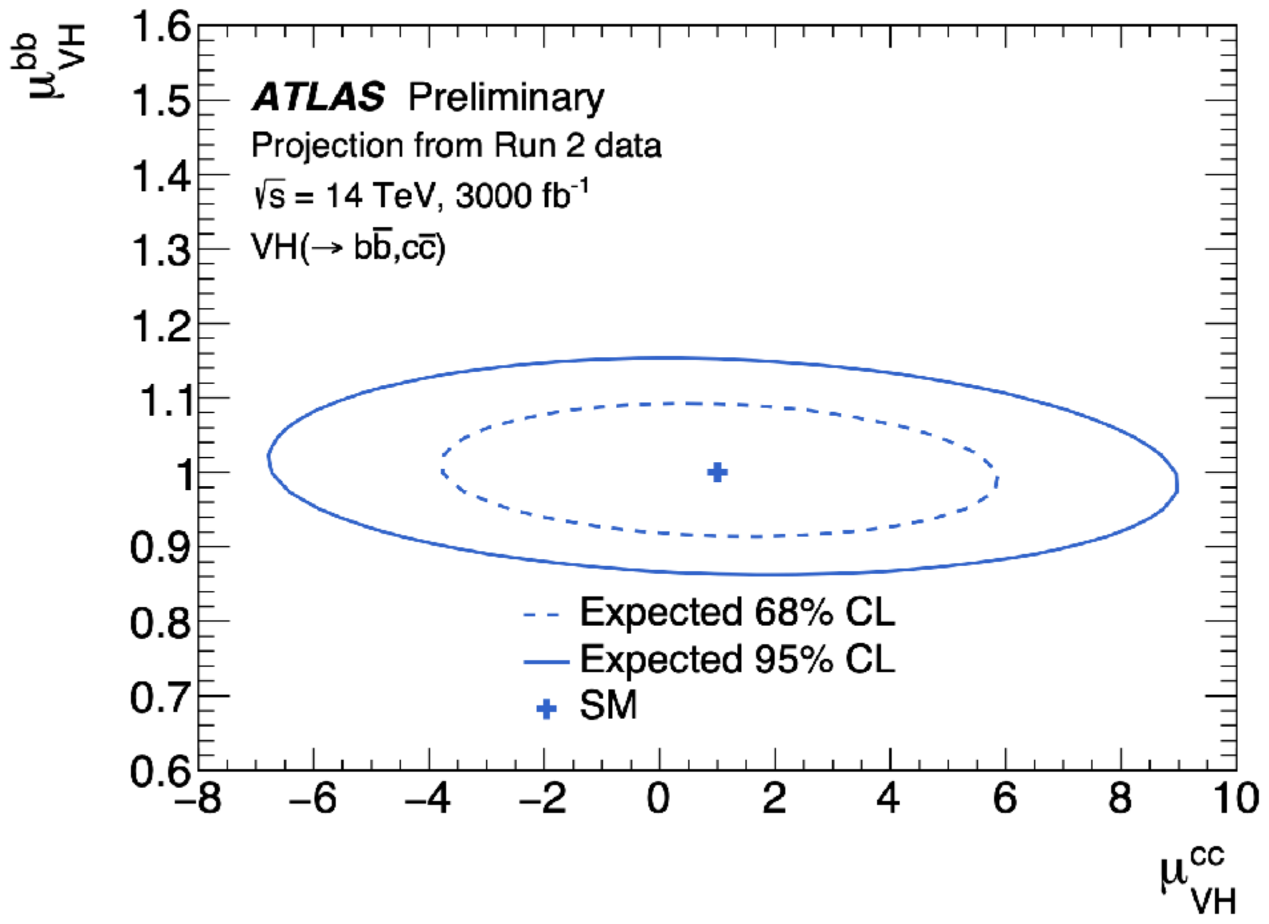
$$\mu_{VH(H\to b\bar{b})} = 1.00 \pm 0.03(\text{stat}) \pm 0.04(\text{syst}),$$
$$\mu_{VH(H\to c\bar{c})} = 1.0 \pm 0.6(\text{stat}) \pm 0.5(\text{syst}).$$



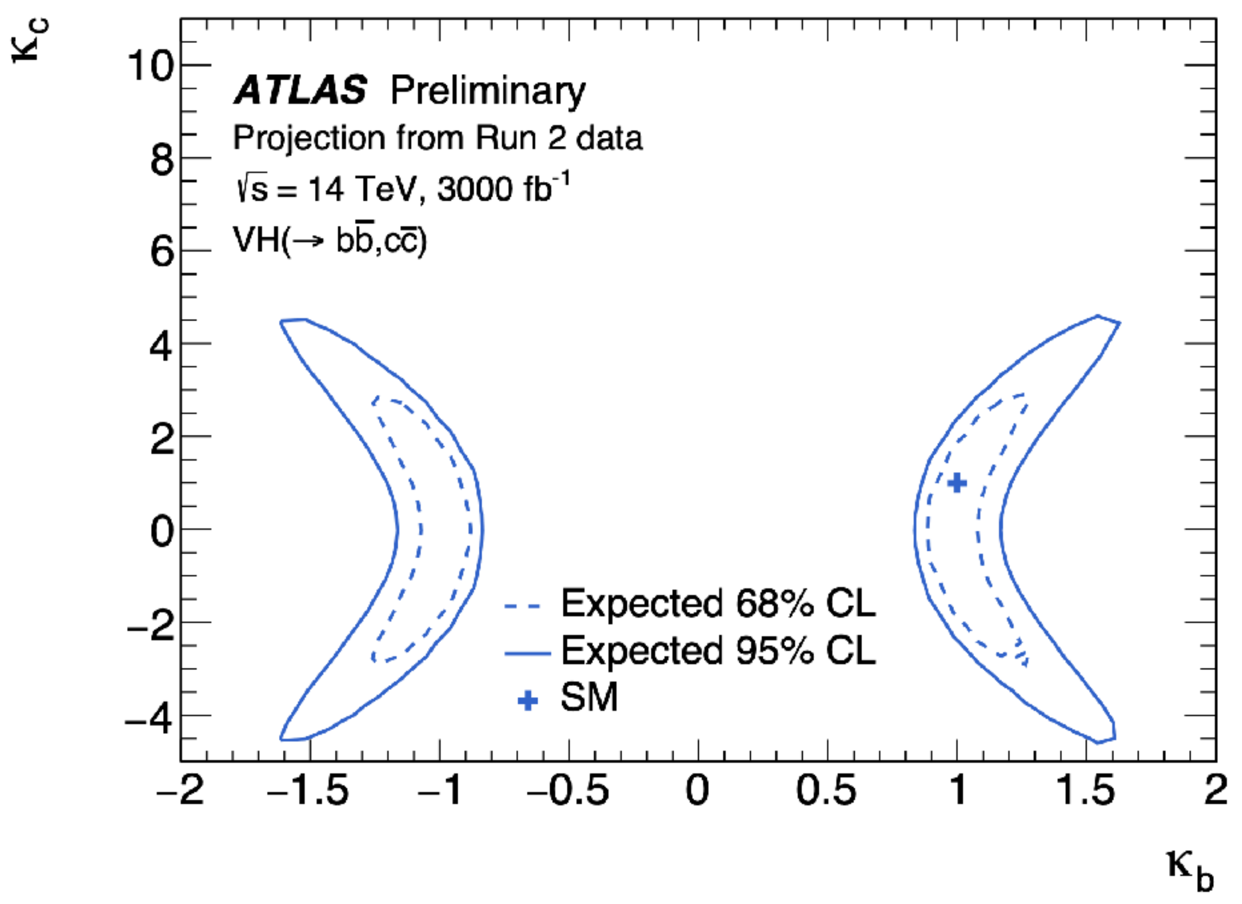
$$\mu^{b\bar{b}}_{VH} = 1.00 \pm 0.06,$$
$$\mu^{c\bar{c}}_{VH} = 1.00 \pm 3.20$$







Moderate correlation of -11%

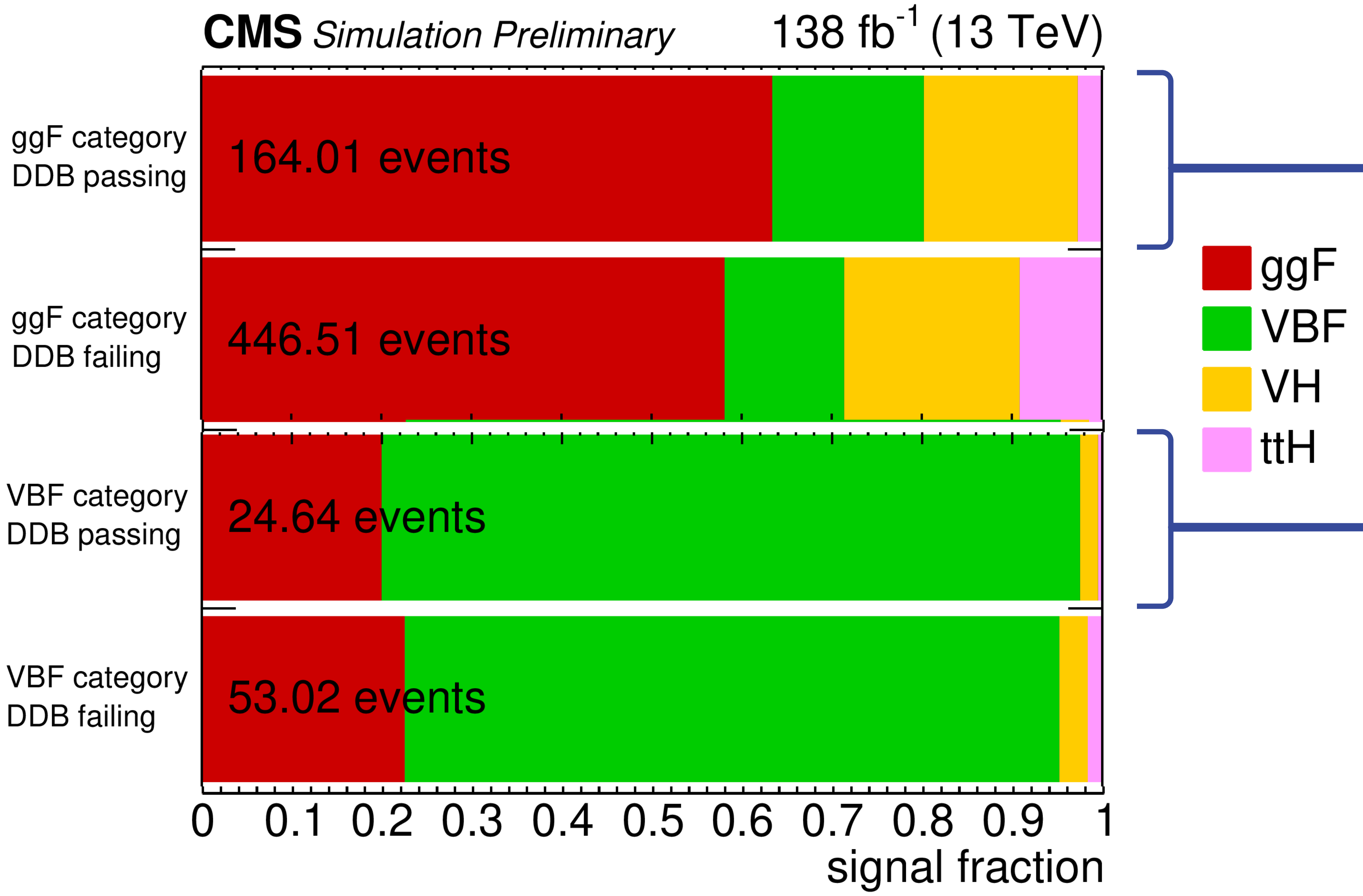


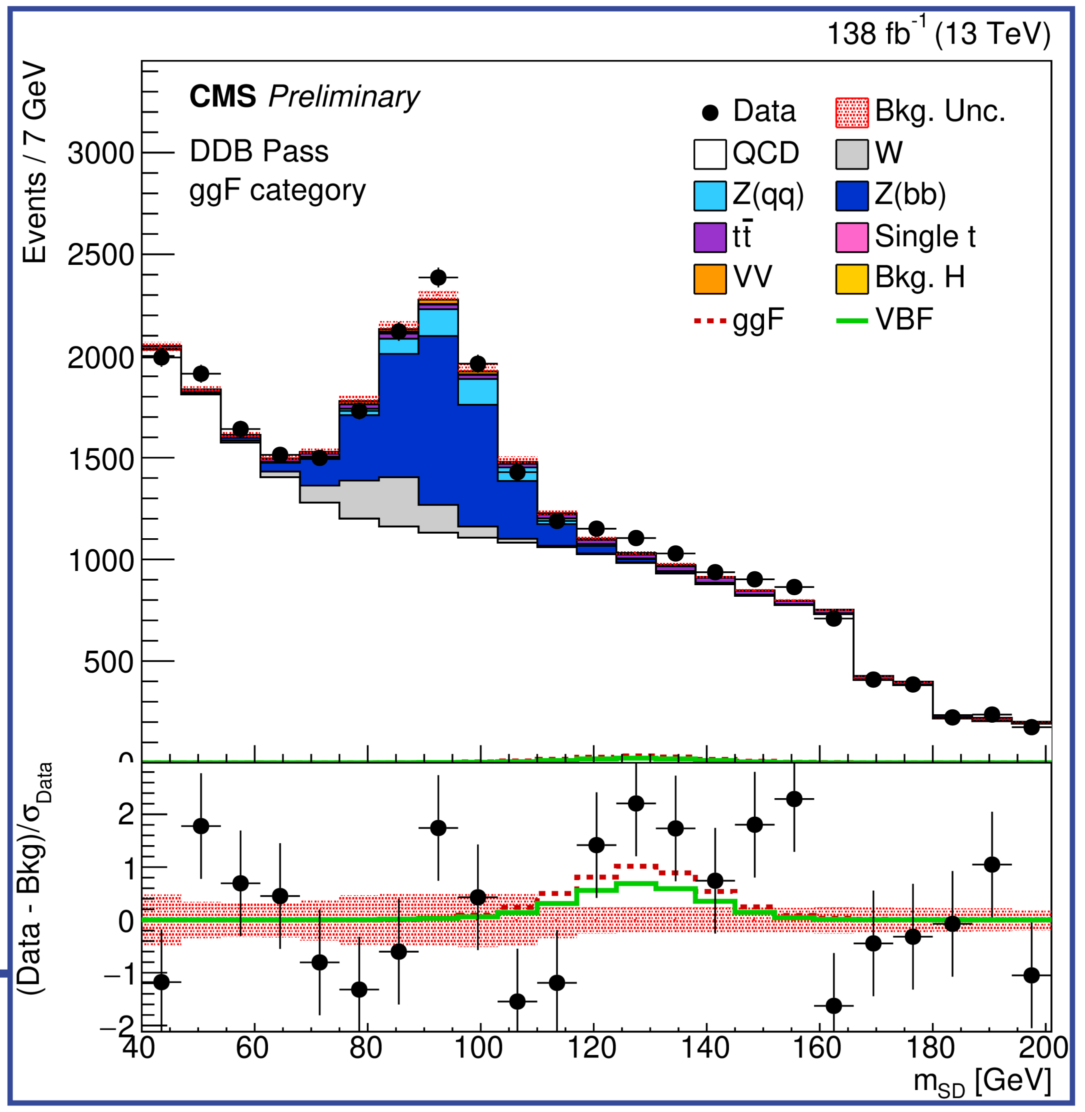
$|\kappa_c| < 3.0 \qquad |\kappa_c/\kappa_b| < 2.7$

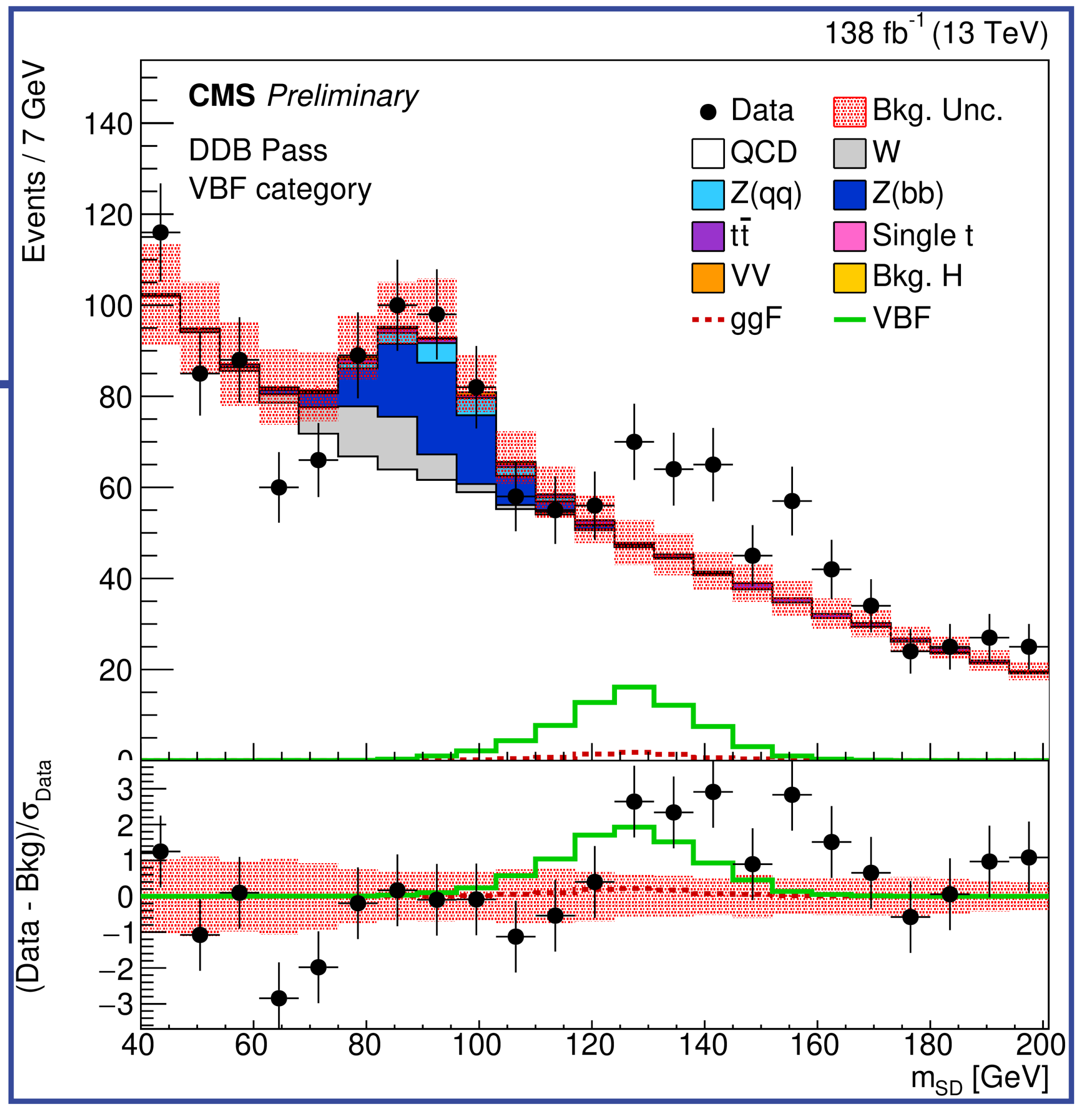
VBF Production with boosted H → $b\bar{b}$ Decays

Aug 2023

- Boosted:
  - Improved H → bb boosted tagger (DBB)
  - 1st measurement of VBF at high p_T,
  - Most precise measurement of boosted ggF to date





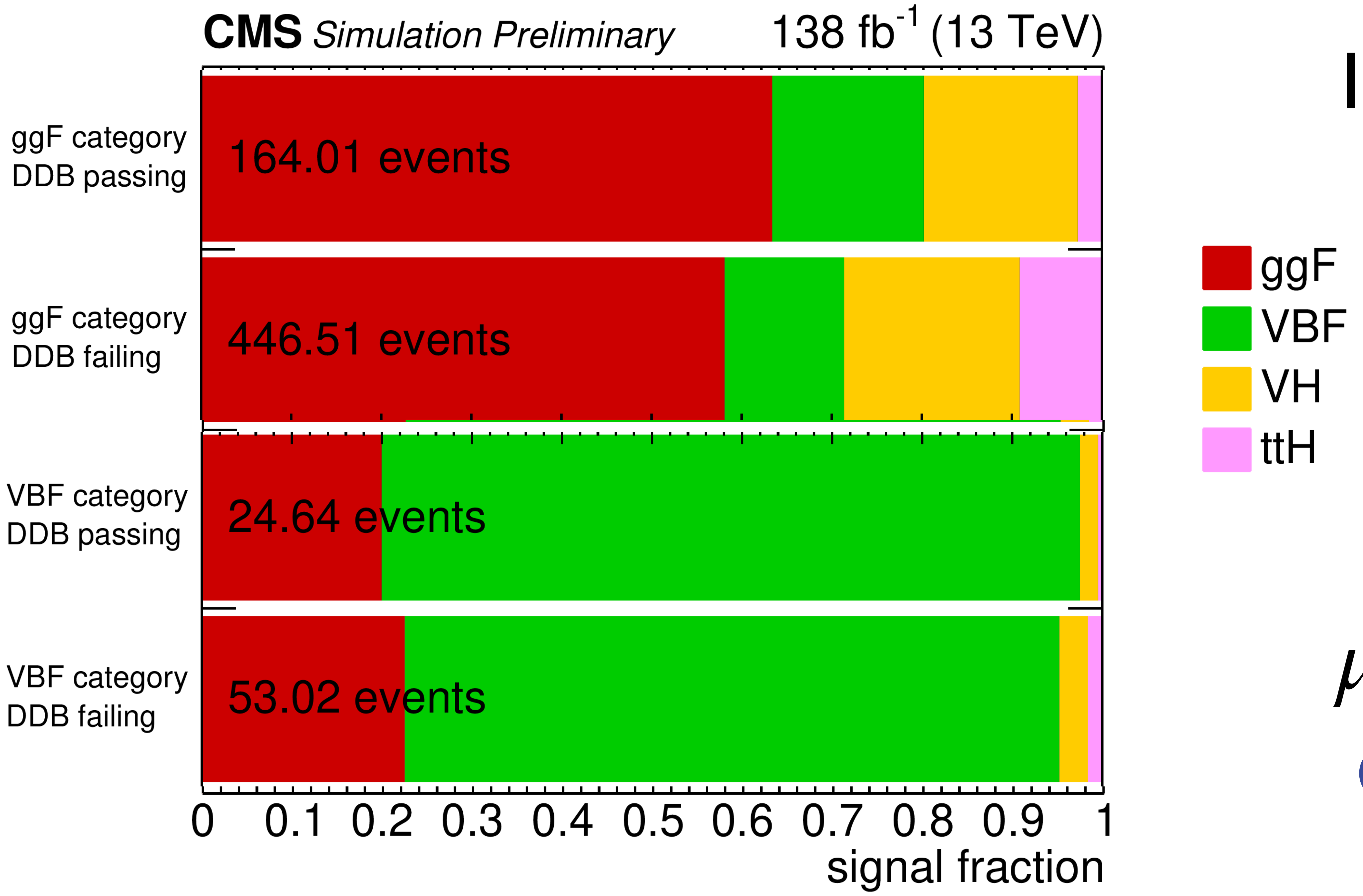


CMS-PAS-HIG-21-020

VBF Production with boosted H → b$\bar{b}$ Decays

- Boosted:
  - Improved H → bb boosted tagger (DBB)
  - 1st measurement of VBF at high p_T,
  - Most precise measurement of boosted ggF to date

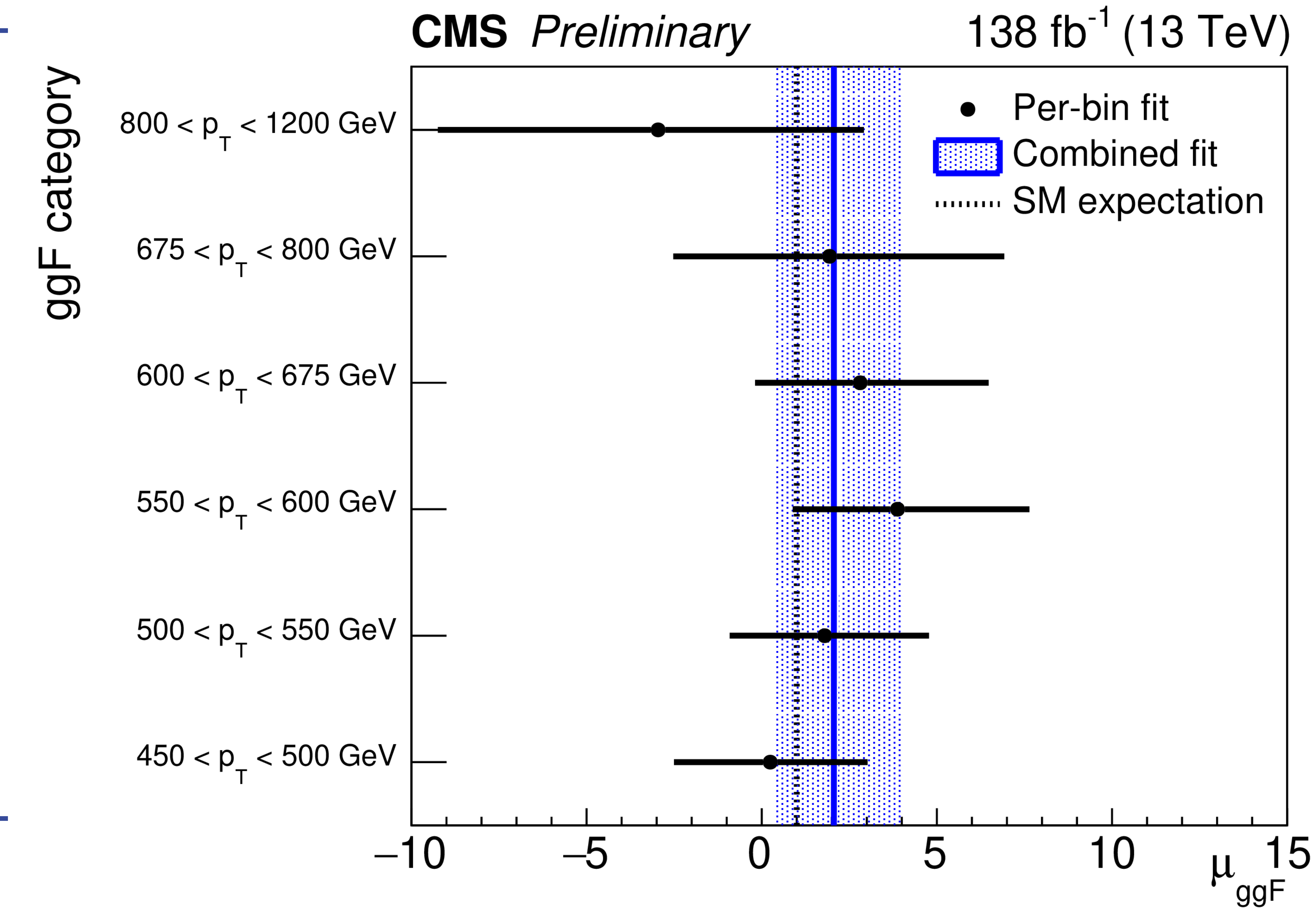
Aug 2023



$\mu = 2.1^{+1.9}_{-1.7}$

Obs. (exp.):

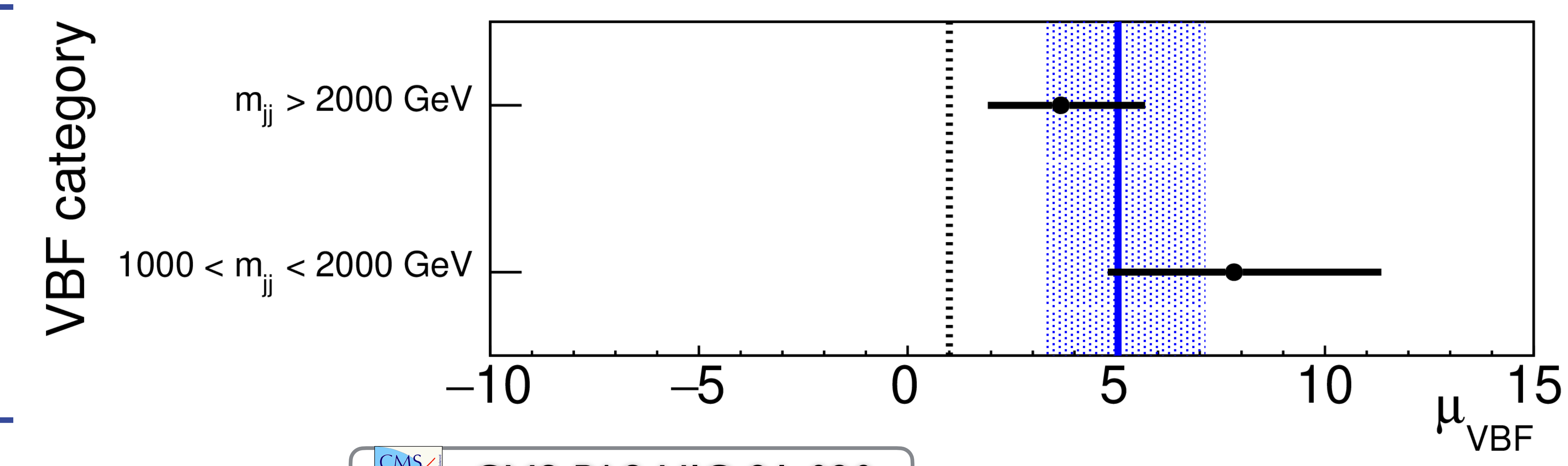
1.2 σ (0.9 σ)



$\mu = 5.0^{+2.1}_{-1.8}$

Obs. (exp.):

3 σ (0.9 σ)

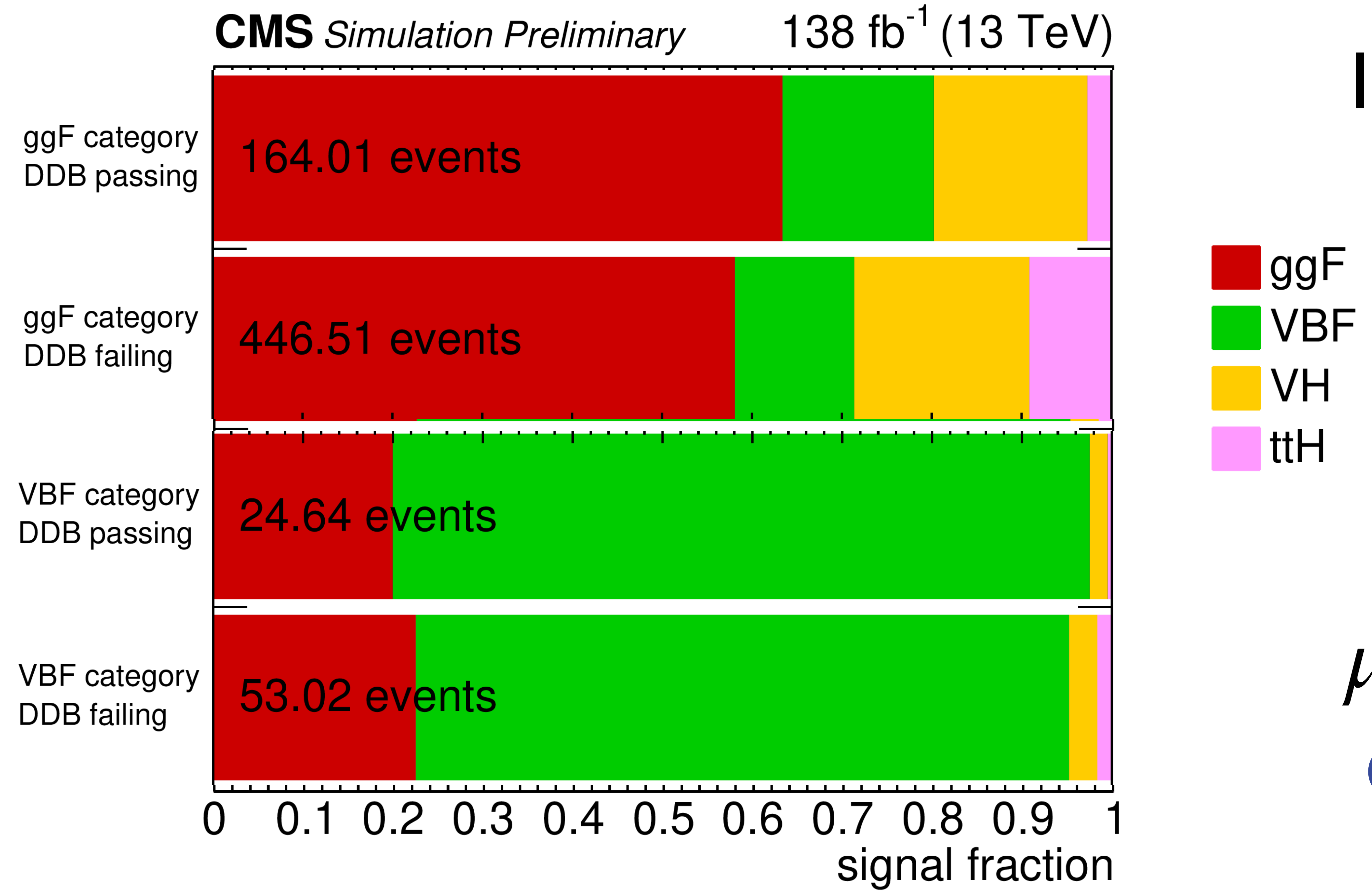


CMS-PAS-HIG-21-020

VBF Production with boosted H → b$\bar{b}$ Decays

- Boosted:
  - Improved H → bb boosted tagger (DBB)
  - 1st measurement of VBF at high p_T,
  - Most precise measurement of boosted ggF to date

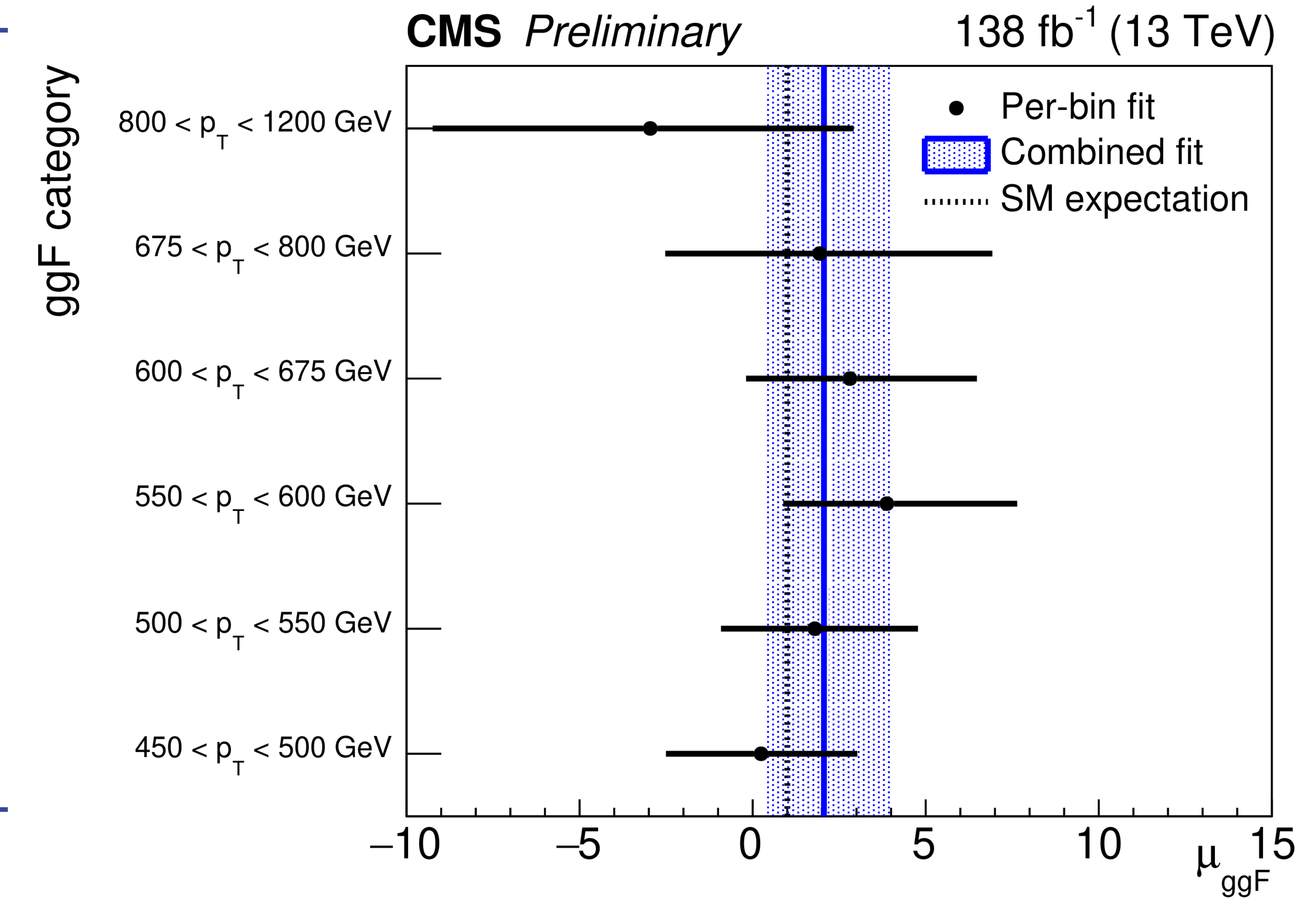
Aug 2023



$\mu = 2.1^{+1.9}_{-1.7}$

Obs. (exp.):

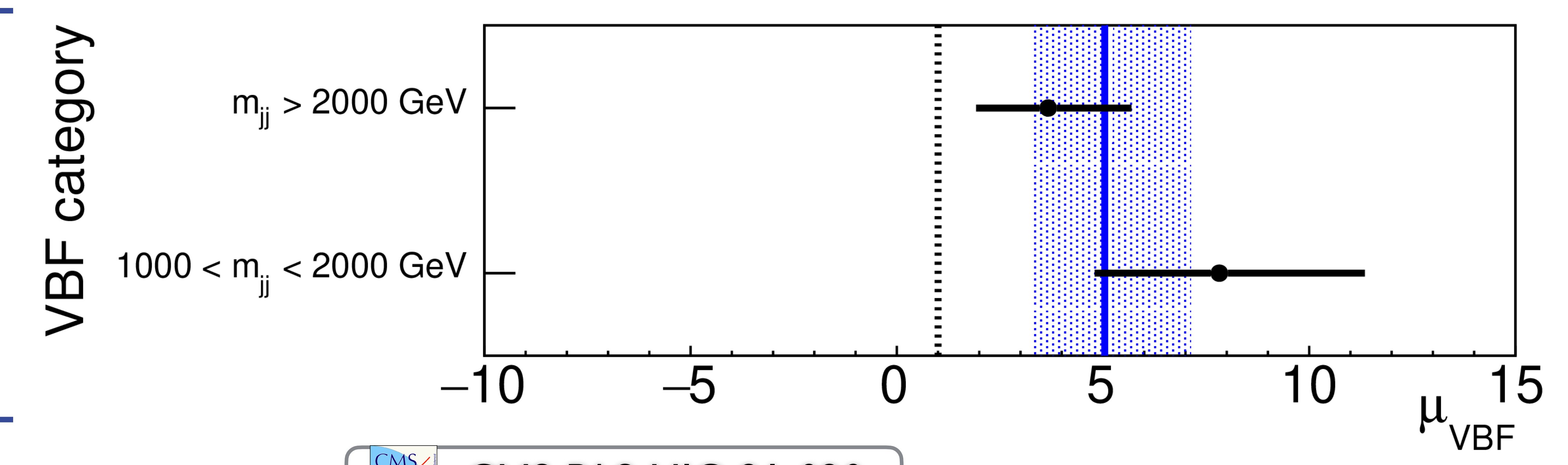
1.2 σ (0.9 σ)



$\mu = 5.0^{+2.1}_{-1.8}$

Obs. (exp.):

3 σ (0.9 σ)



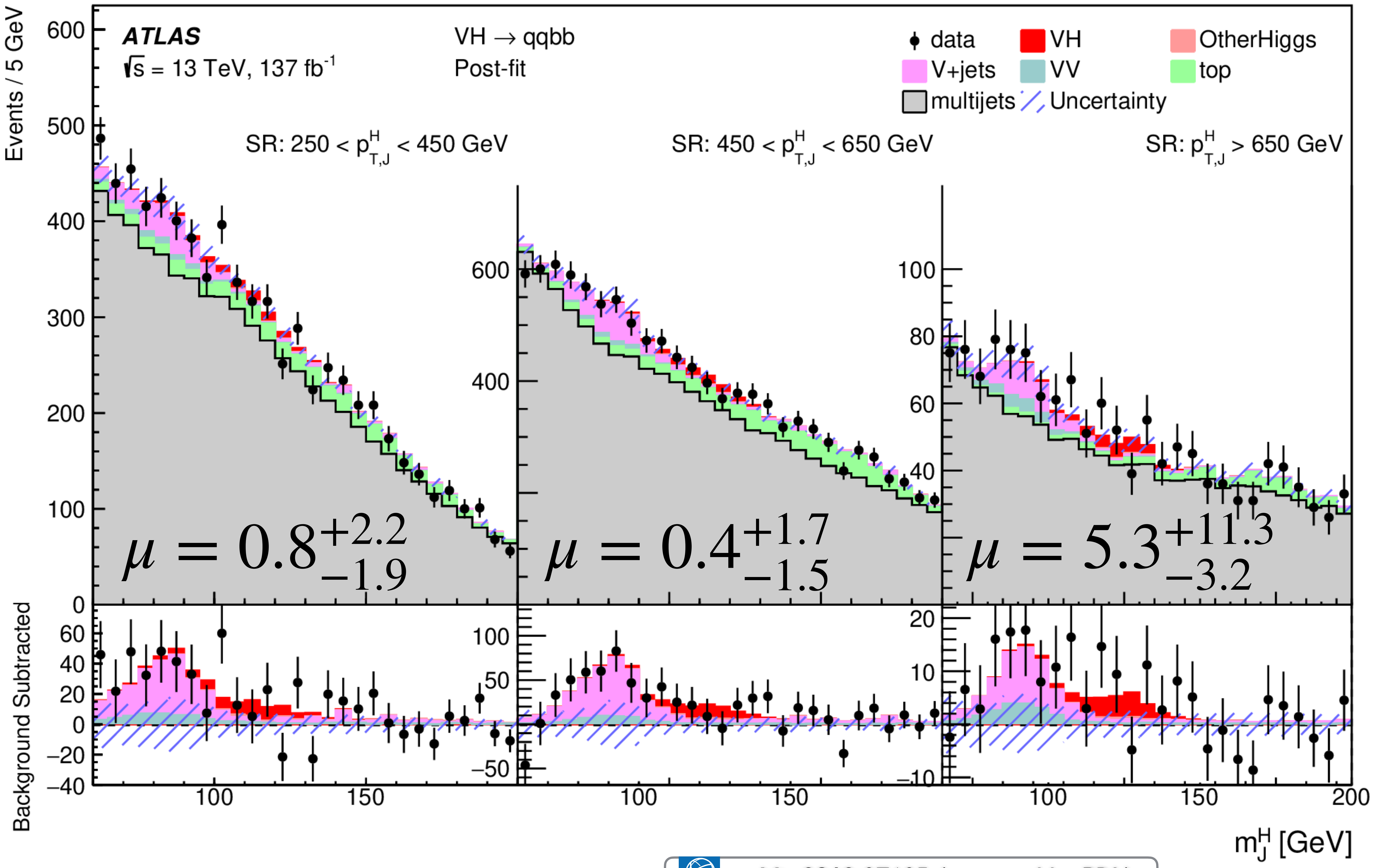
⇒ ATLAS VBF(γ) production in H → bb decays: Eur. Phys. J. C. 81 (2021) 537
Incl. production obs. (exp.) significance: 3.0 (3.0) σ

CMS-PAS-HIG-21-020

V(q$\bar{q}$)H(b$\bar{b}$) at high p_T(H)

Dec 2023

- Fully-hadronic final state
  - Challenging at pp collider!
  - 2 boosted large-R jets
- Inclusive result:
  - $\mu = 1.4^{+1.0}_{-0.9}$
  - Obs. (exp.) significance: **1.7 σ** (1.2 σ)

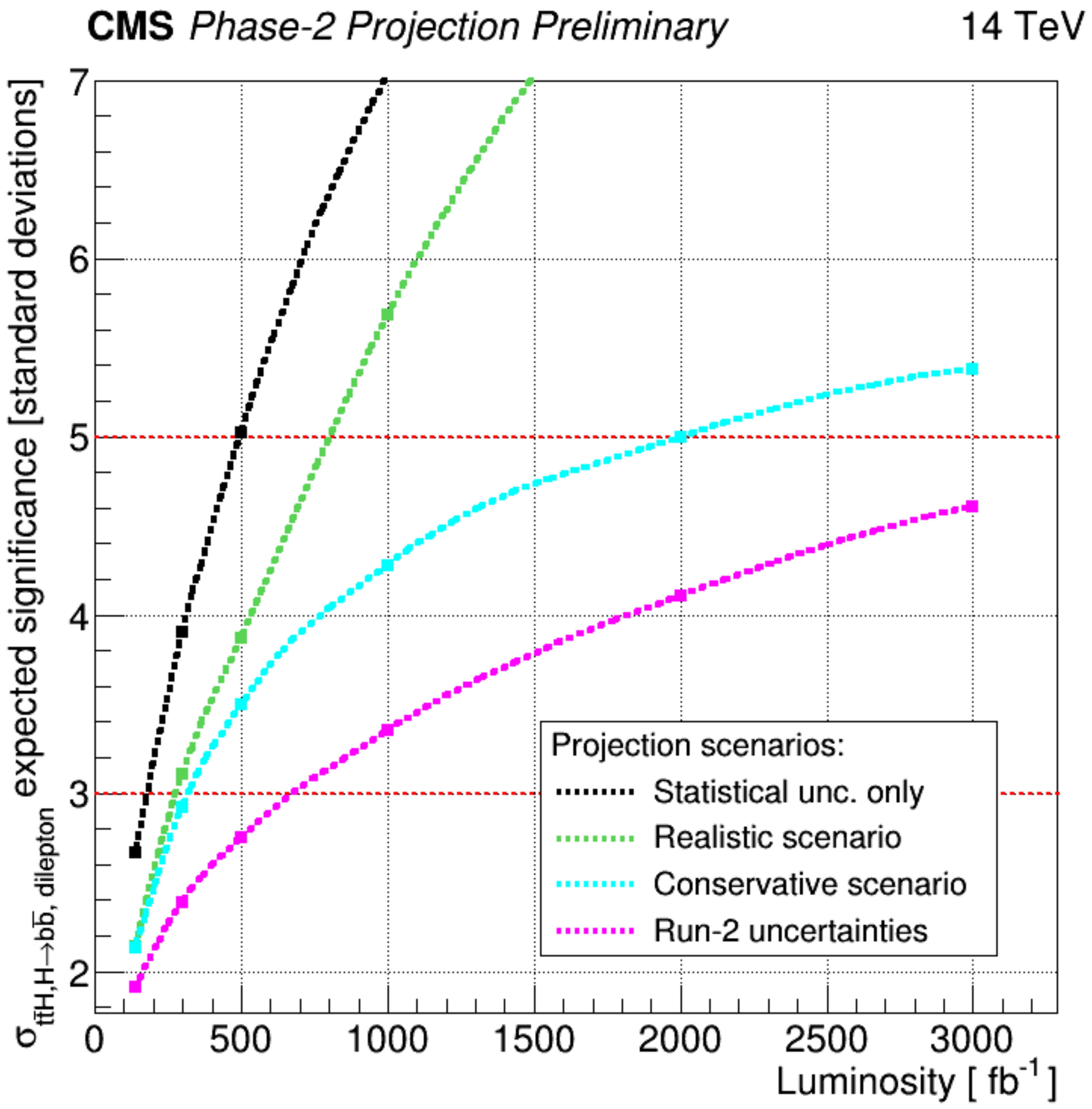


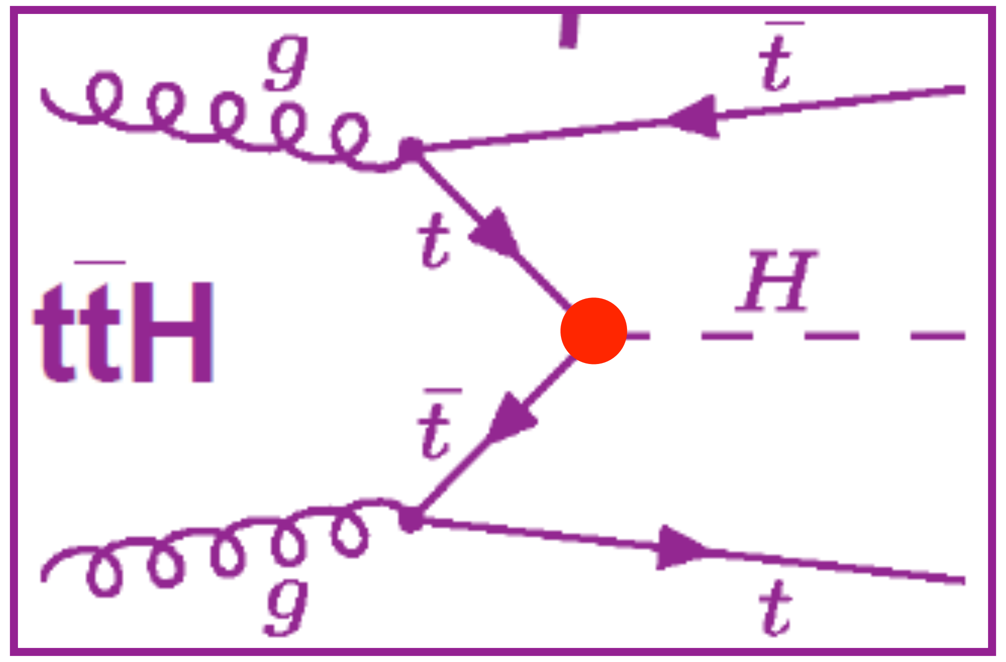
arXiv:2312.07605 (accepted by PRL)

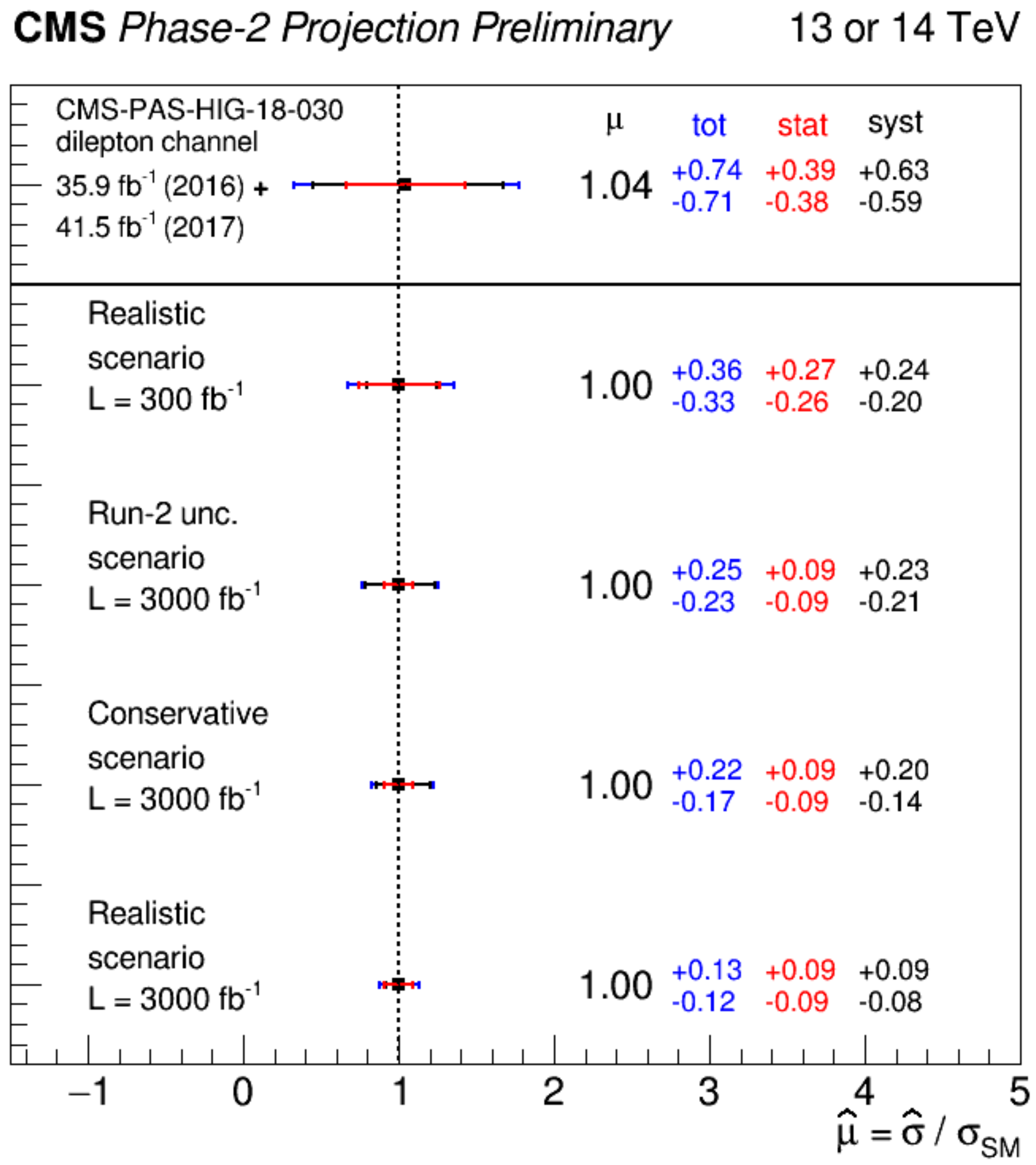
HL-LHC ttH, H → $b\bar{b}$

CMS-PAS-FTR-21-002

- Projection from analysis of 2016+2017 data in the opposite-sign di-leptonic







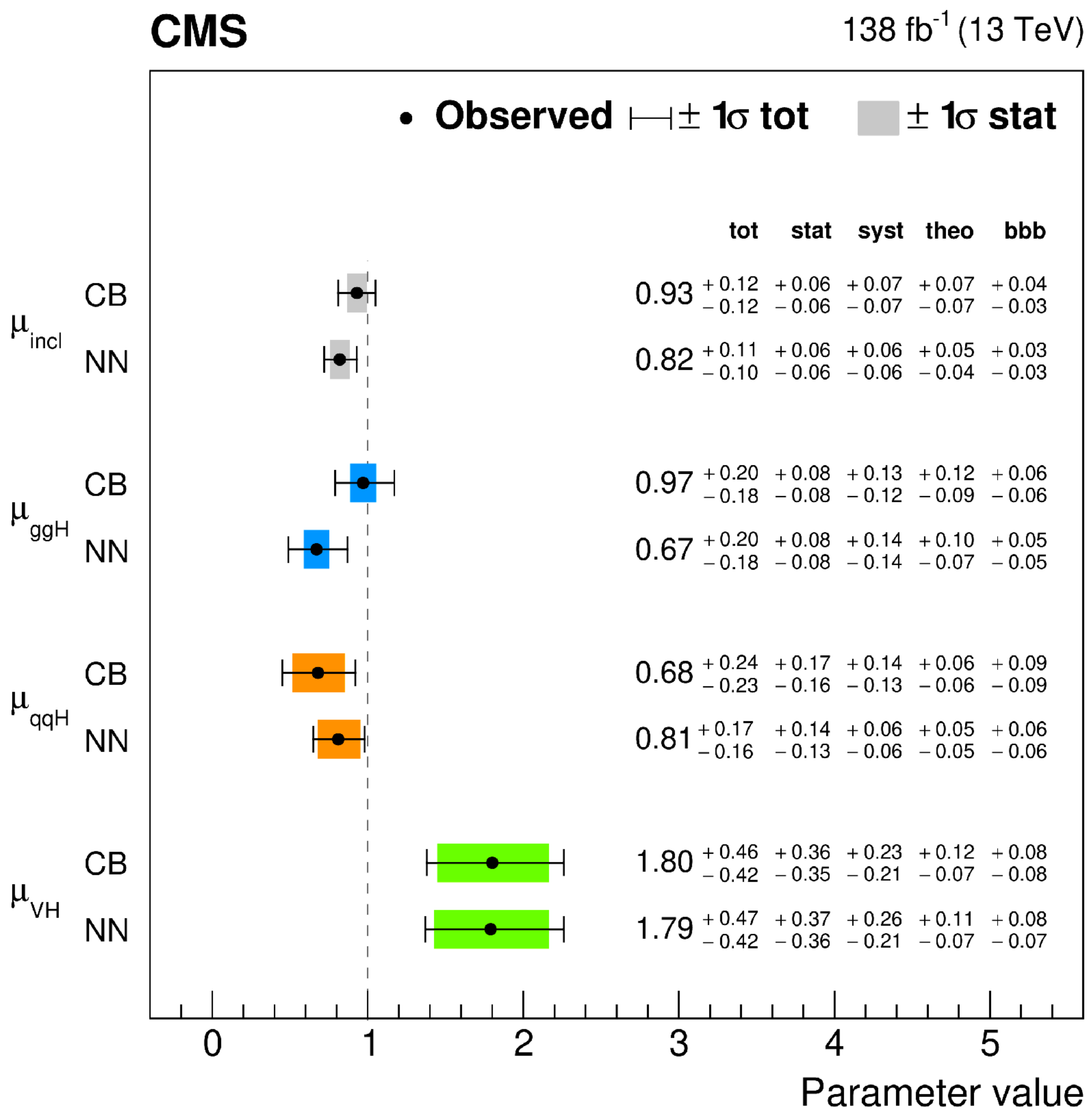
⇒ Back

April 2022

H → ττ

Eur. Phys. J. C 83 (2023) 562

- Strongest coupling to leptons
  - $BR_{SM}(H \rightarrow \tau\tau) = 6.3\% \Rightarrow$ **~485 000 H → ττ events**
- Cut-based (CB) & **multiclass neural-network** (NN) analyses
- 16 (15) STXS bins in NN (CB) analysis



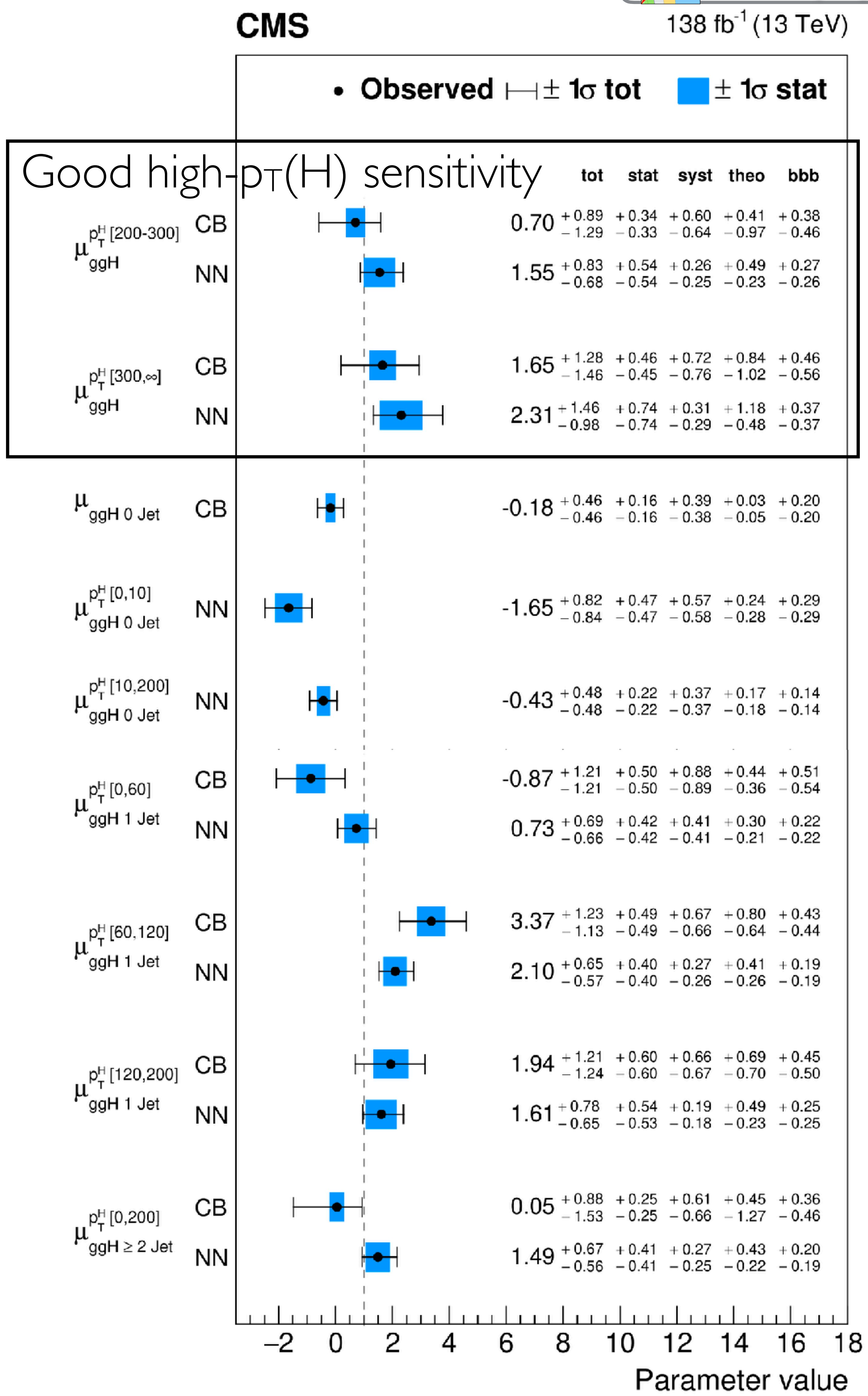
Expected uncertainty NN (CB) [symmetrized]

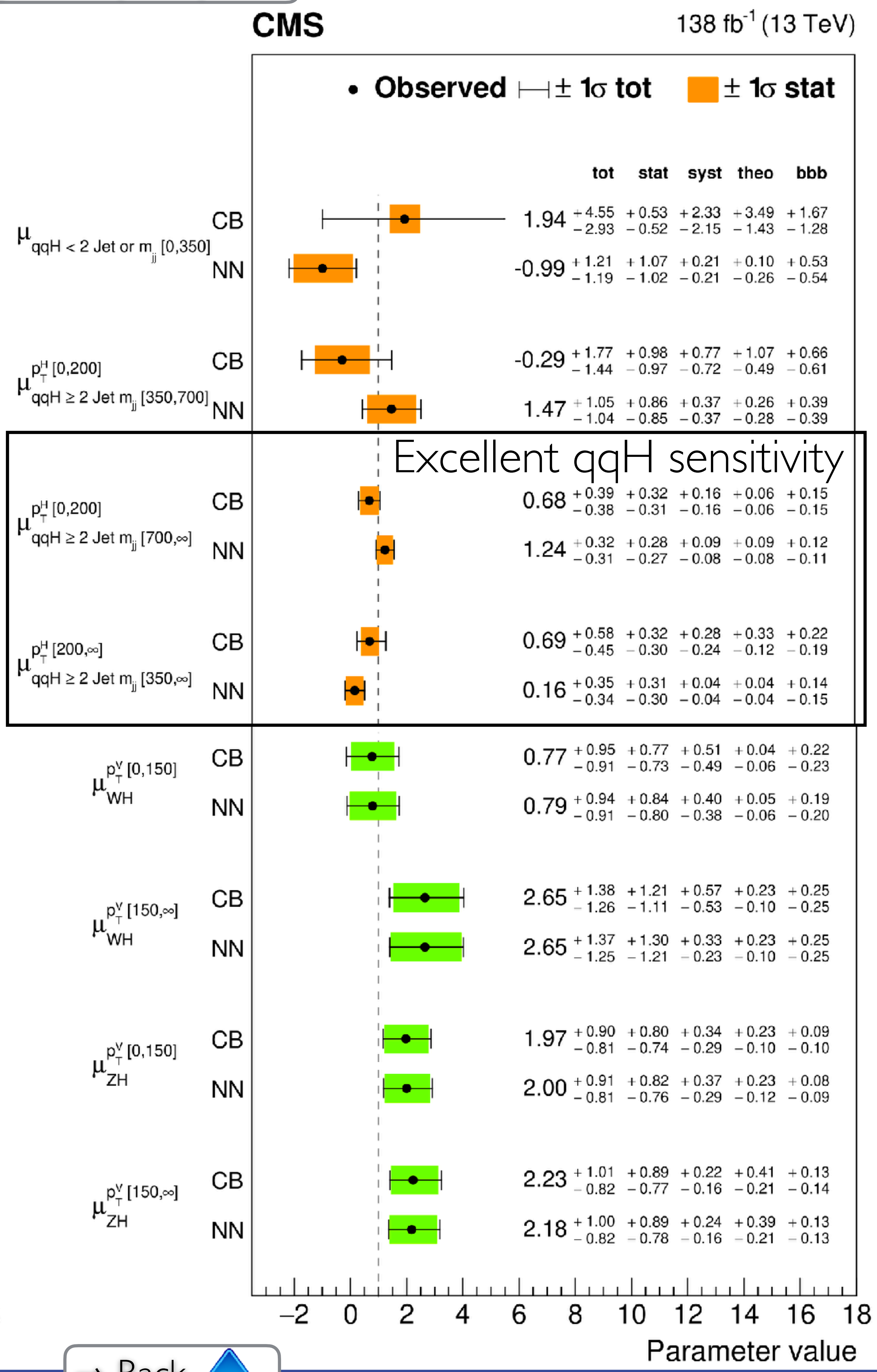
12% (13%)

25% (23%)

17% (24%)

39% (39%)





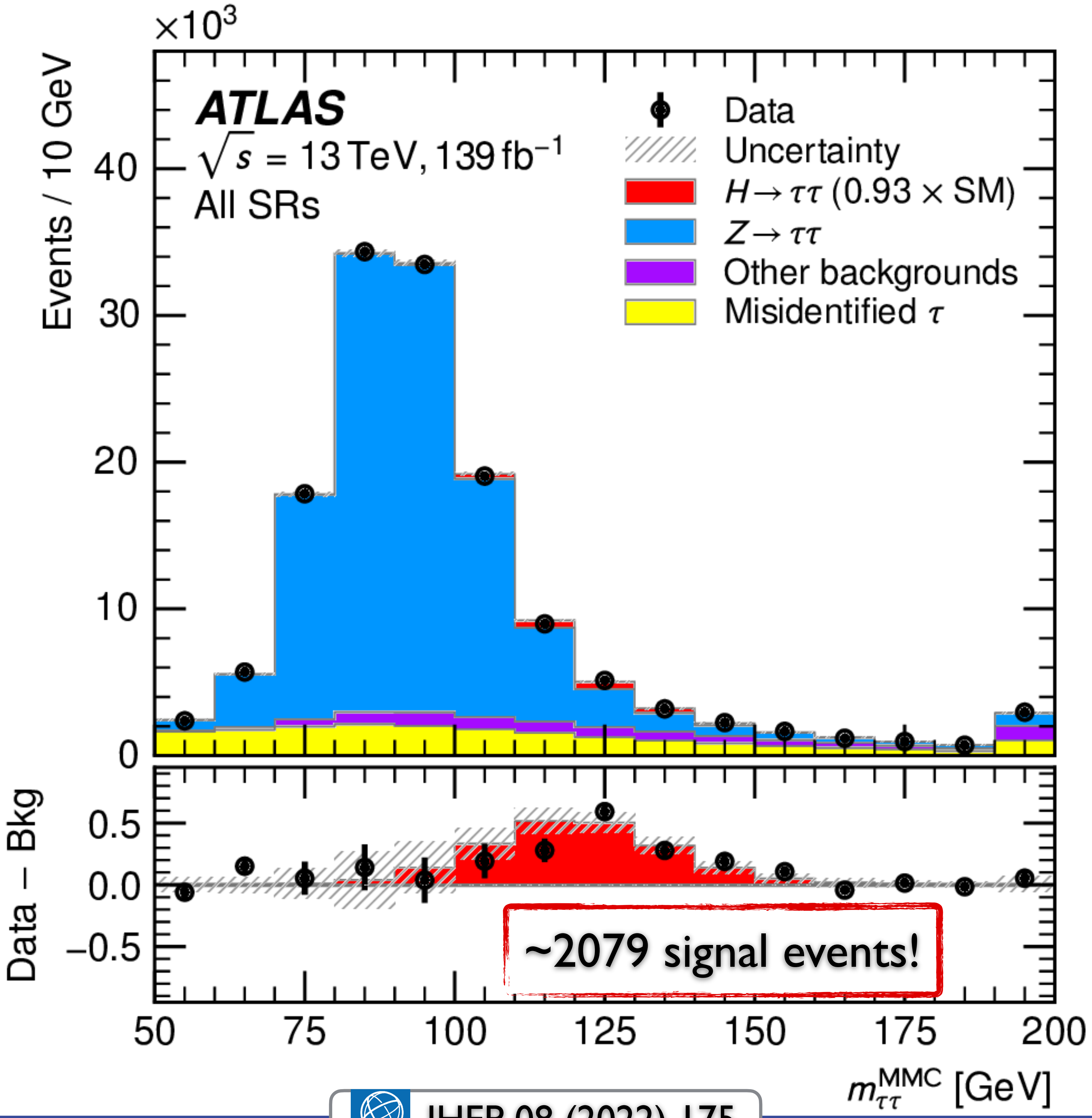
⇒ Back

H → ττ

- Strongest coupling to leptons
  - $BR_{SM}(H \to \tau\tau) = 6.3\%$

⇒ **~480 000 H → ττ events in 139 fb^{-1}**

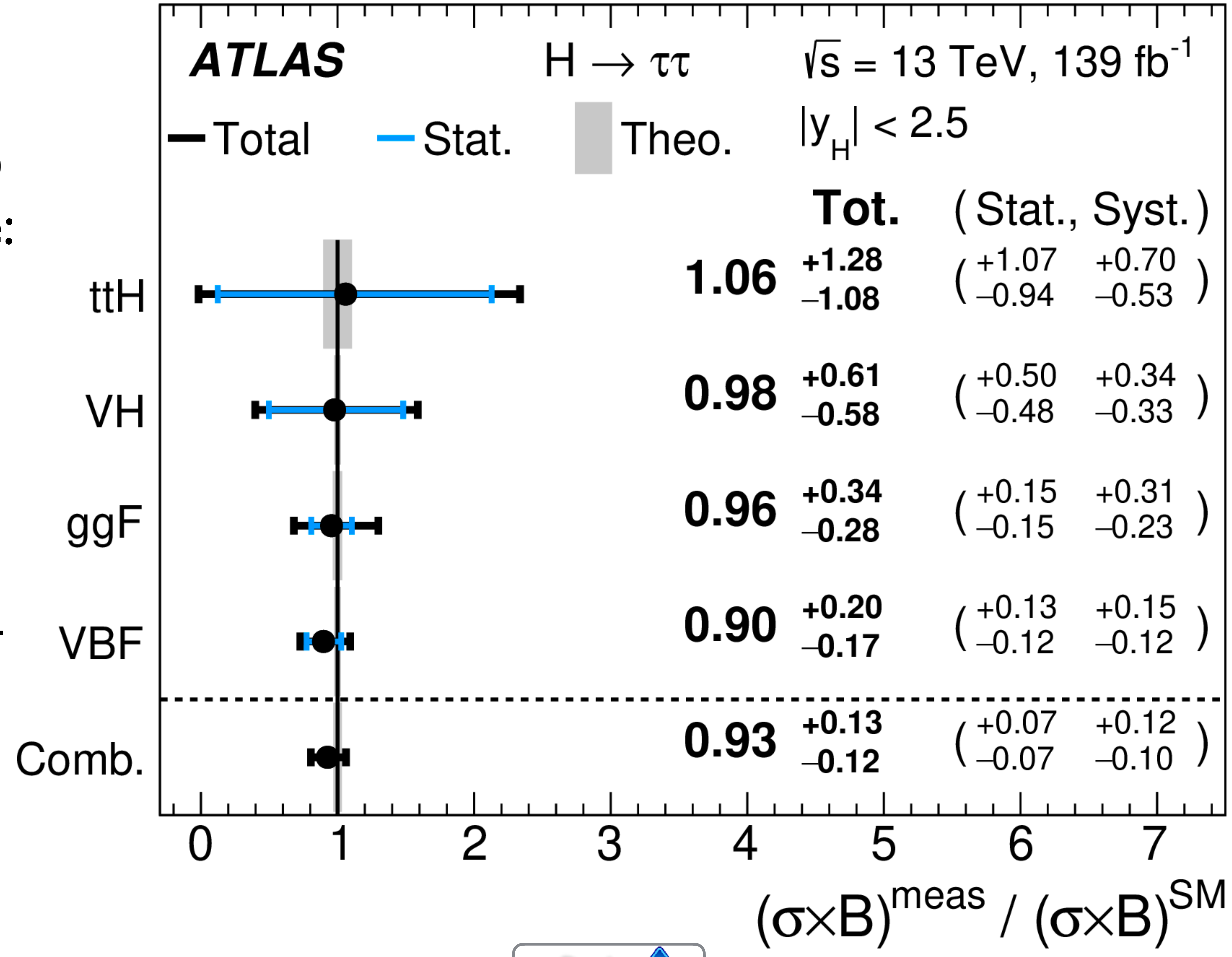
Jan 2022



Observed (expected) significance:

ggF: 3.9 (4.6) σ

VBF: 5.3 (6.2) σ



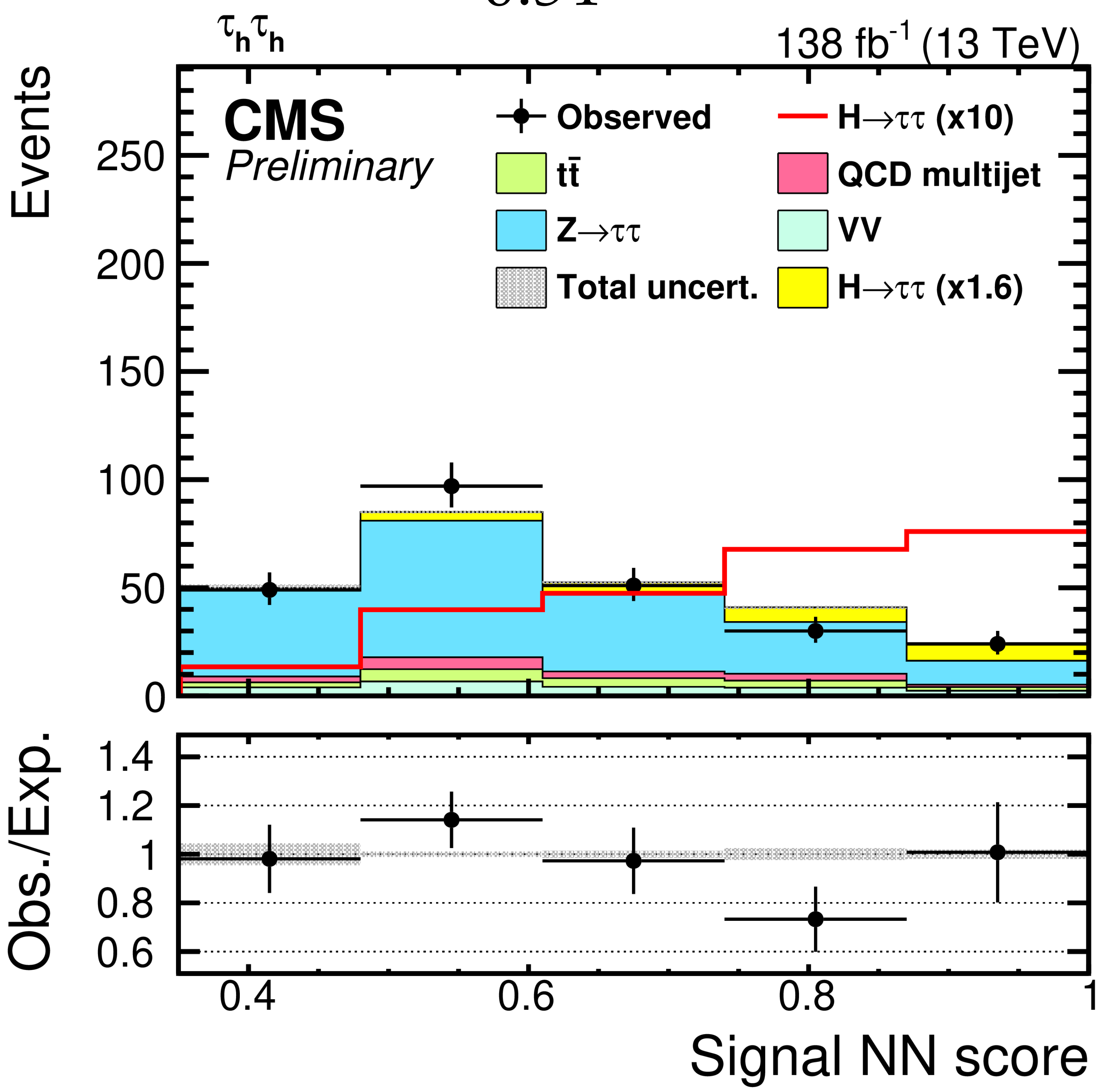
JHEP 08 (2022) 175

⇒ Back

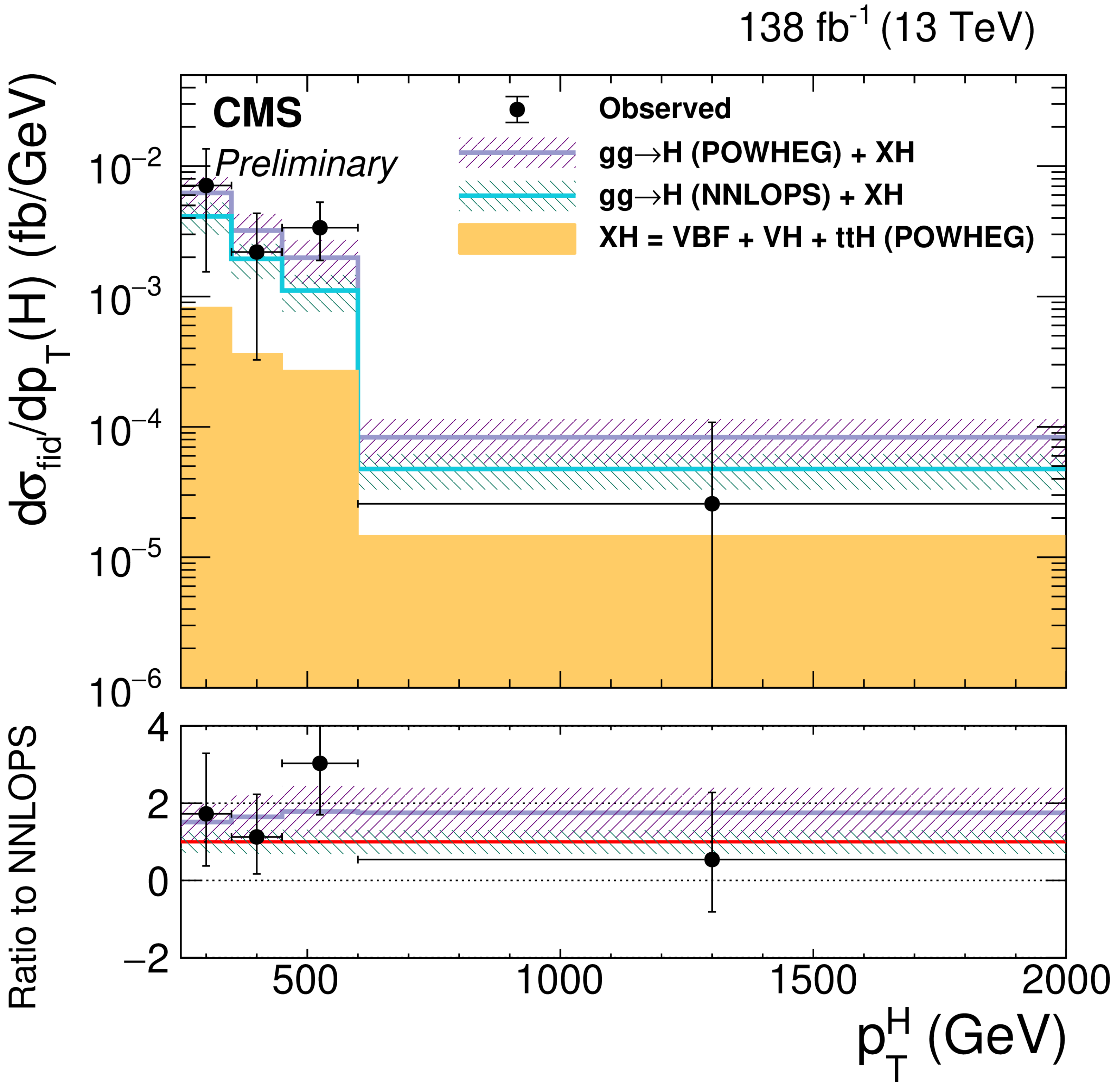
Boosted H → ττ

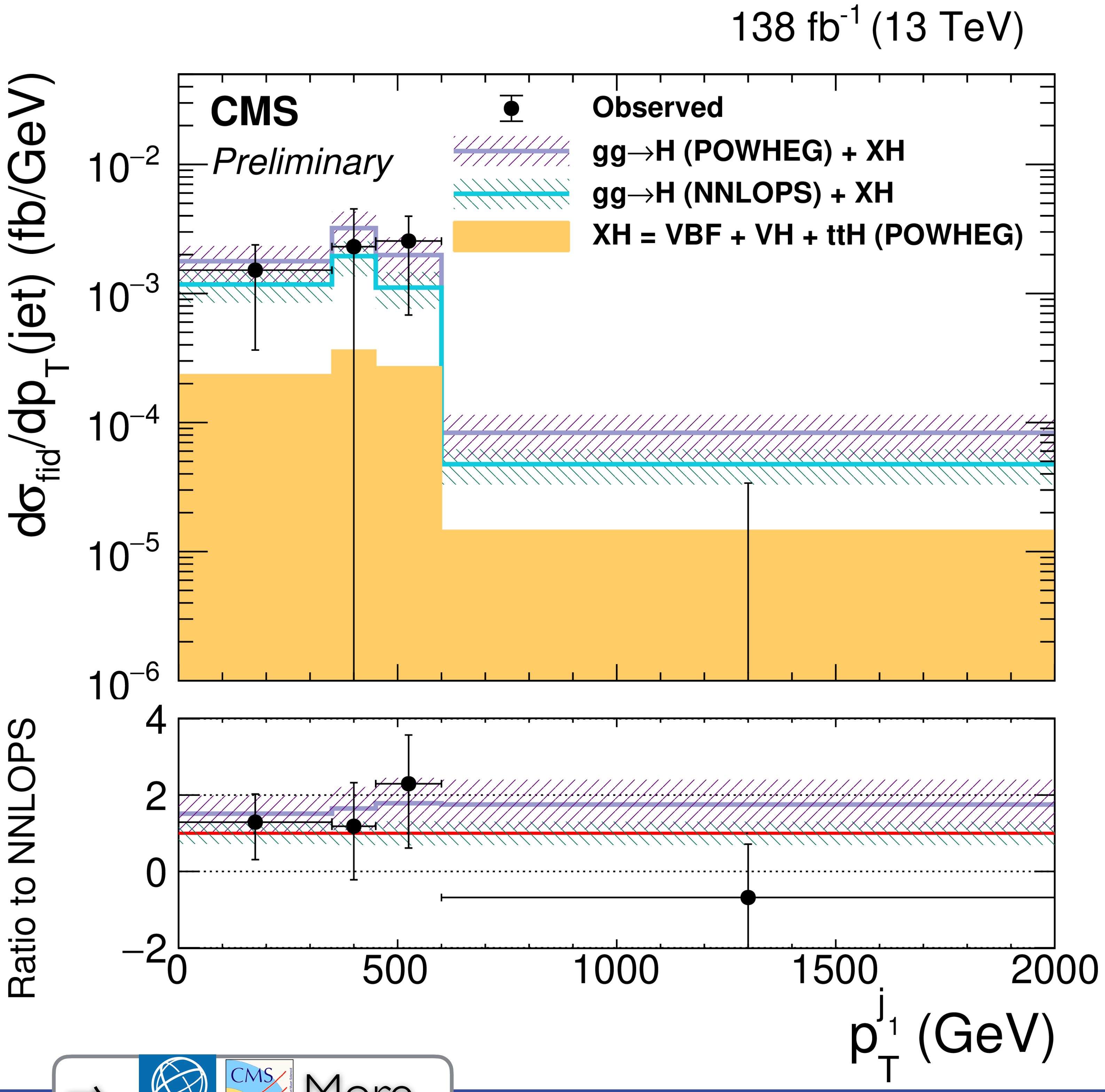
CMS-PAS-HIG-21-017

- Highly boosted $p_T(H) > 250$ GeV
  - Dedicated boosted di-tau algorithm
- Observed (expected) significance: **3.5 (2.2) σ**
- $\mu = 1.64^{+0.68}_{-0.54}$



- Fiducial differential measurements of $p_T(H)$ and p_T(lead-jet)





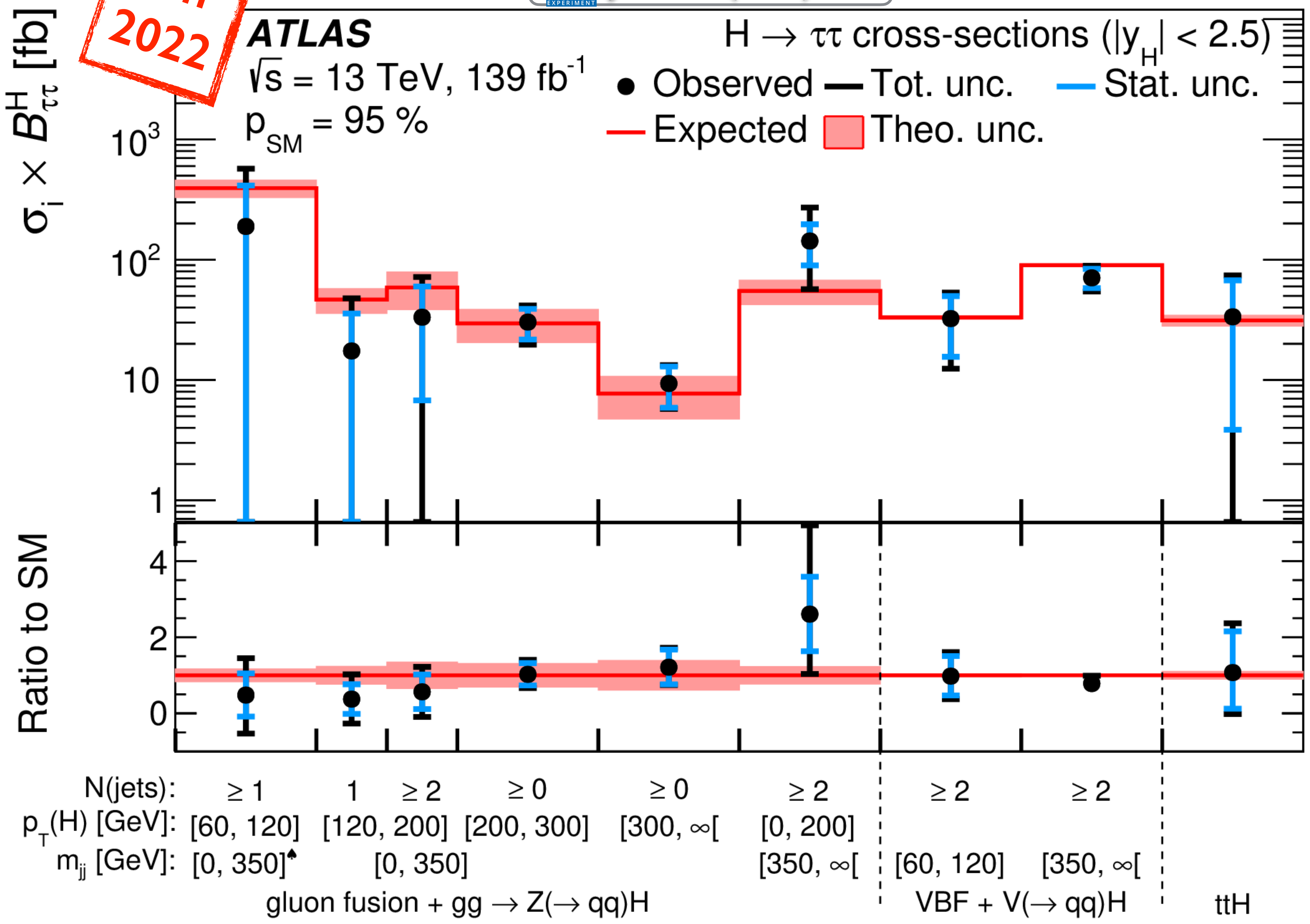
⇒ More

H → ττ and HL-LHC

- Strongest coupling to leptons
  - $BR_{SM}(H \rightarrow \tau\tau)$ = **6.3% ⇒ ~485 000 H → ττ events in 139 fb^{-1}; ~12.6 M in 3 ab^{-1}**

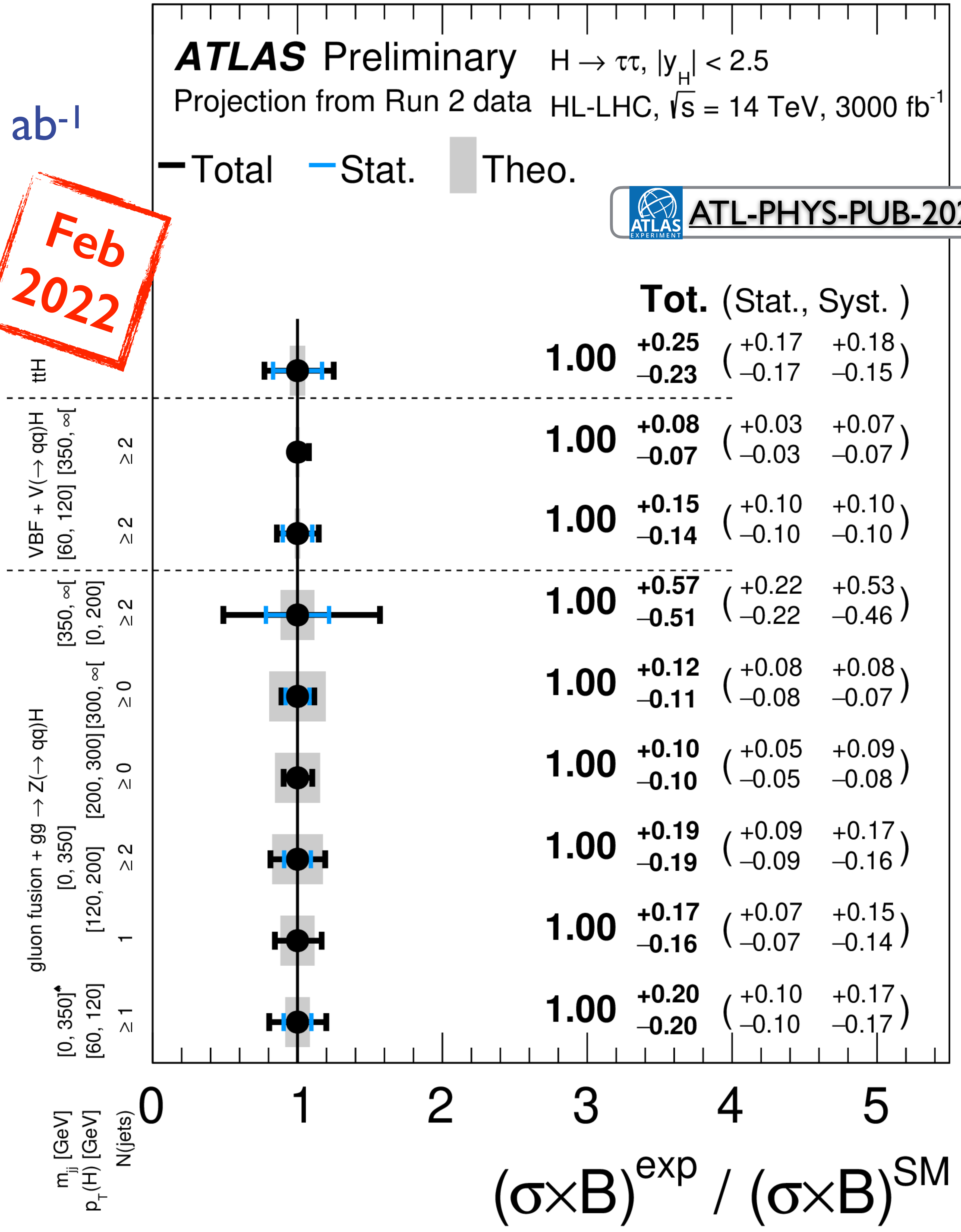
Jan 2022

JHEP 08 (2022) 175



Feb 2022

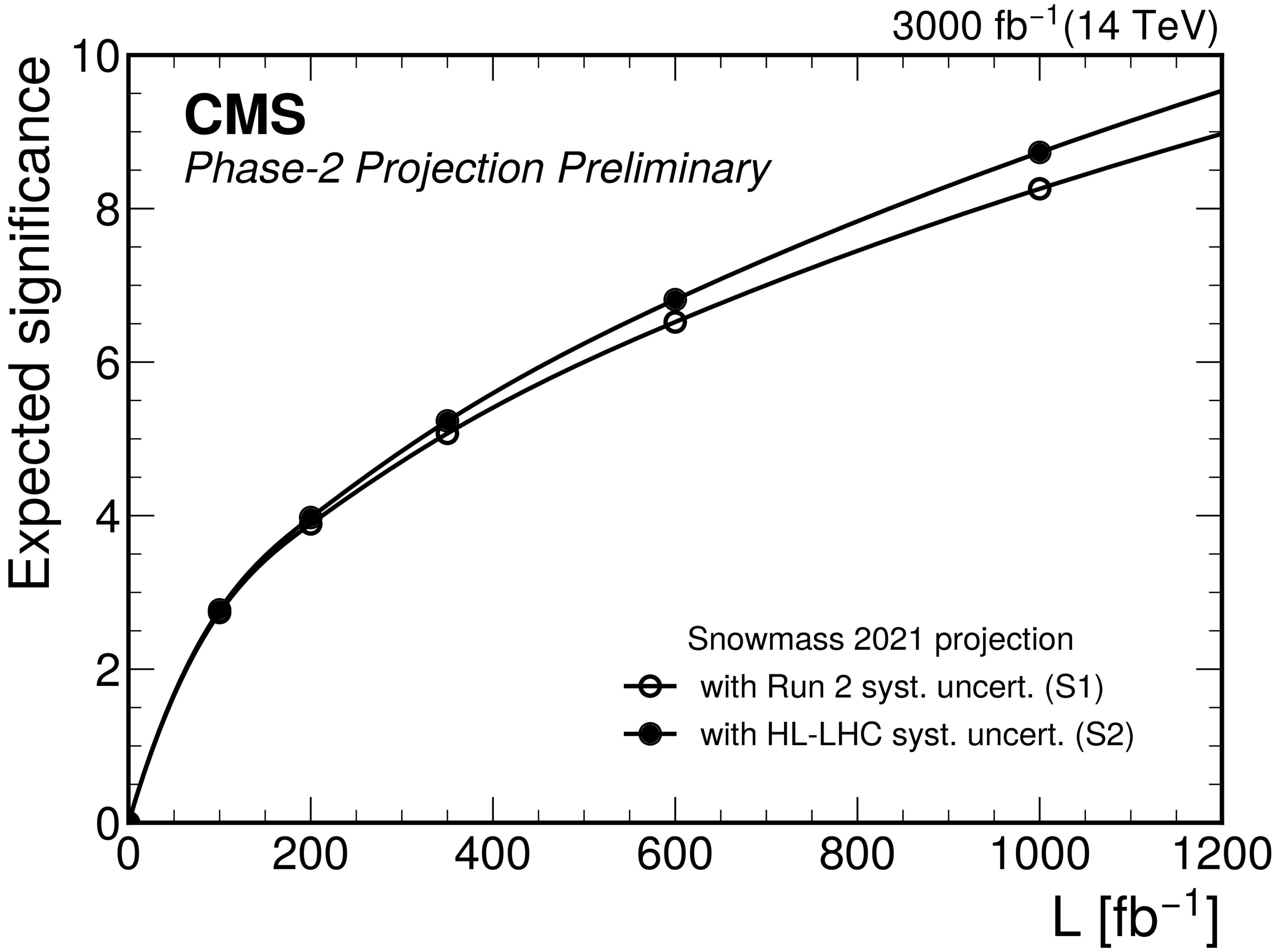
ATL-PHYS-PUB-2022-003

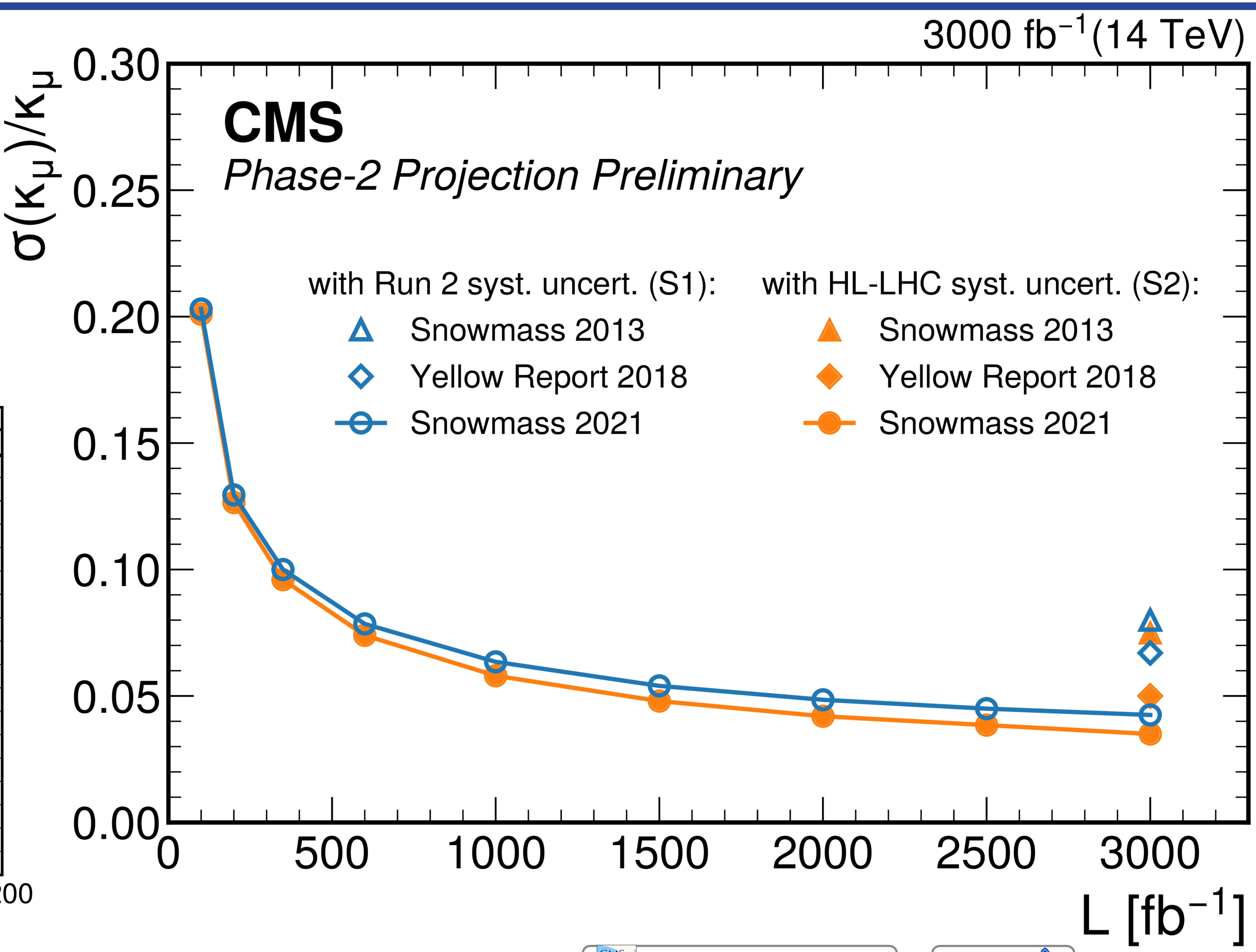


⇒ Back

HL-LHC H → μμ

- Takes into account expected CMS Phase-2 detector upgrades
- Based on 137 fb^{-1} result!
  - κ_μ uncertainty 30-35% smaller w.r.t. previous projections





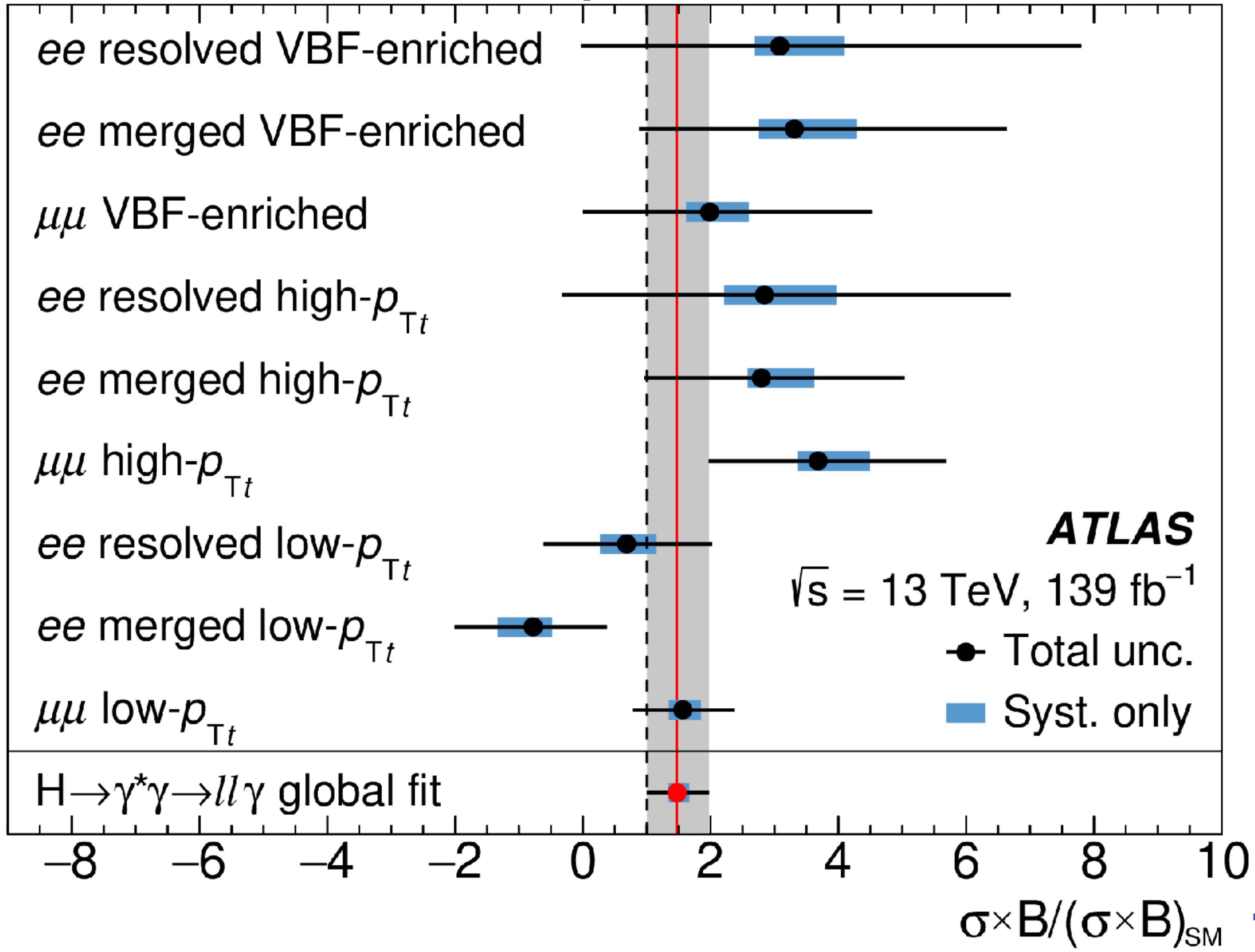
CMS-PAS-FTR-21-006

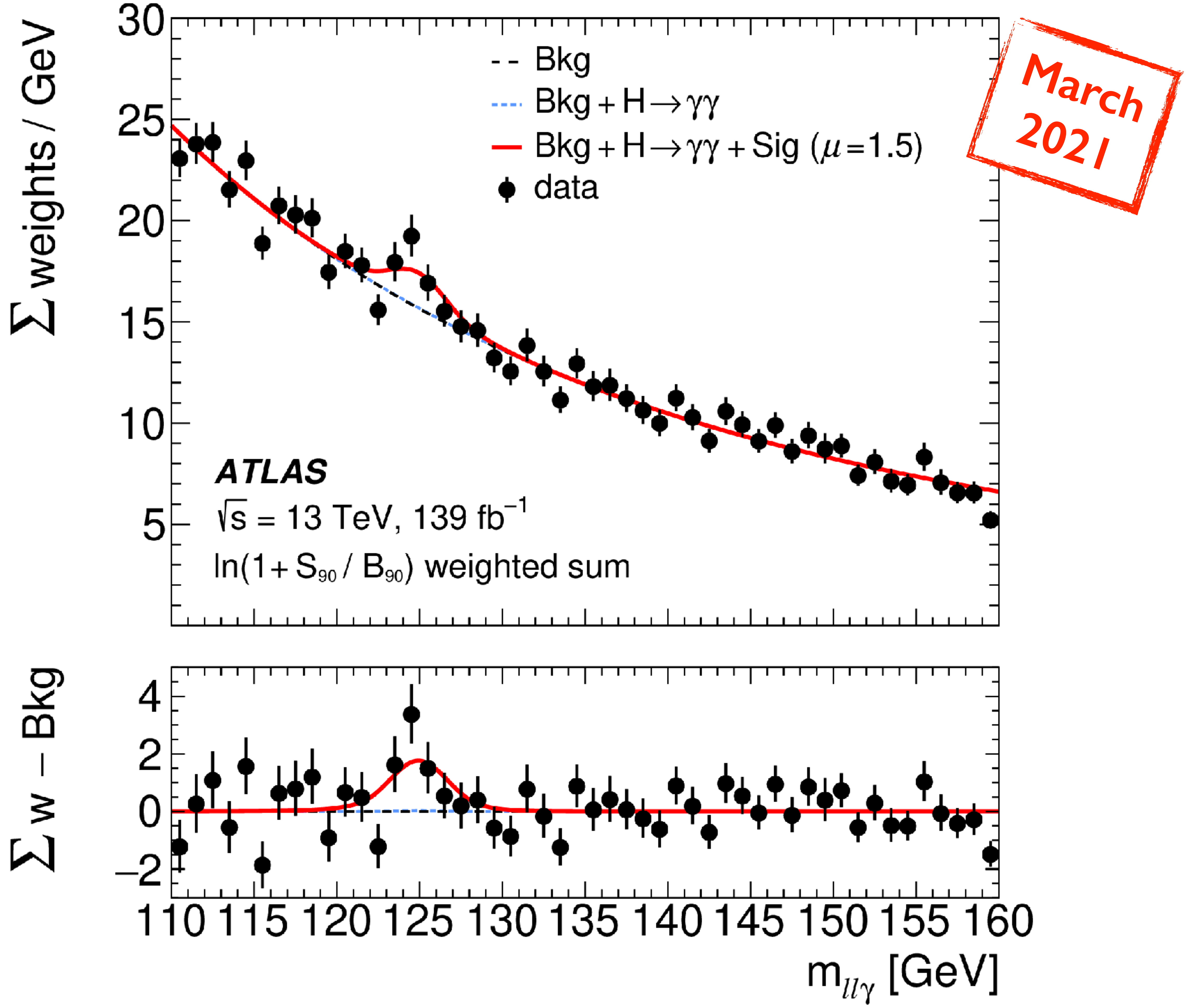
⇒ Back

H → $\ell\ell\gamma$

- Tiny branching fractions:
  - $BR_{SM}(H \to ee\gamma)|_{m_{\ell\ell}<30\ GeV} = 7.20 \times 10^{-5}$

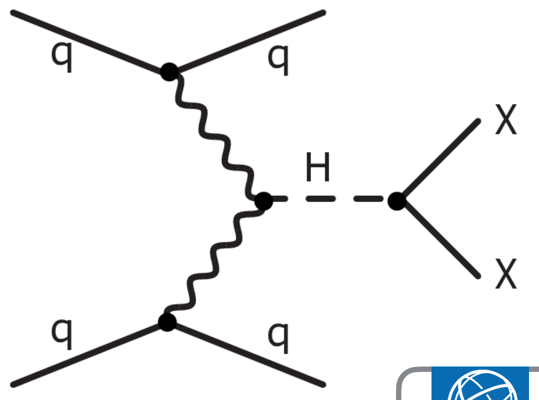
    $BR_{SM}(H \to \mu\mu\gamma)|_{m_{\ell\ell}<30\ GeV} = 3.42 \times 10^{-5}$
  - ~1200 H → $\ell\ell\gamma$ events in 139 fb^{-1}





- Observed (expected) significance: 3.2 σ (2.1 σ)

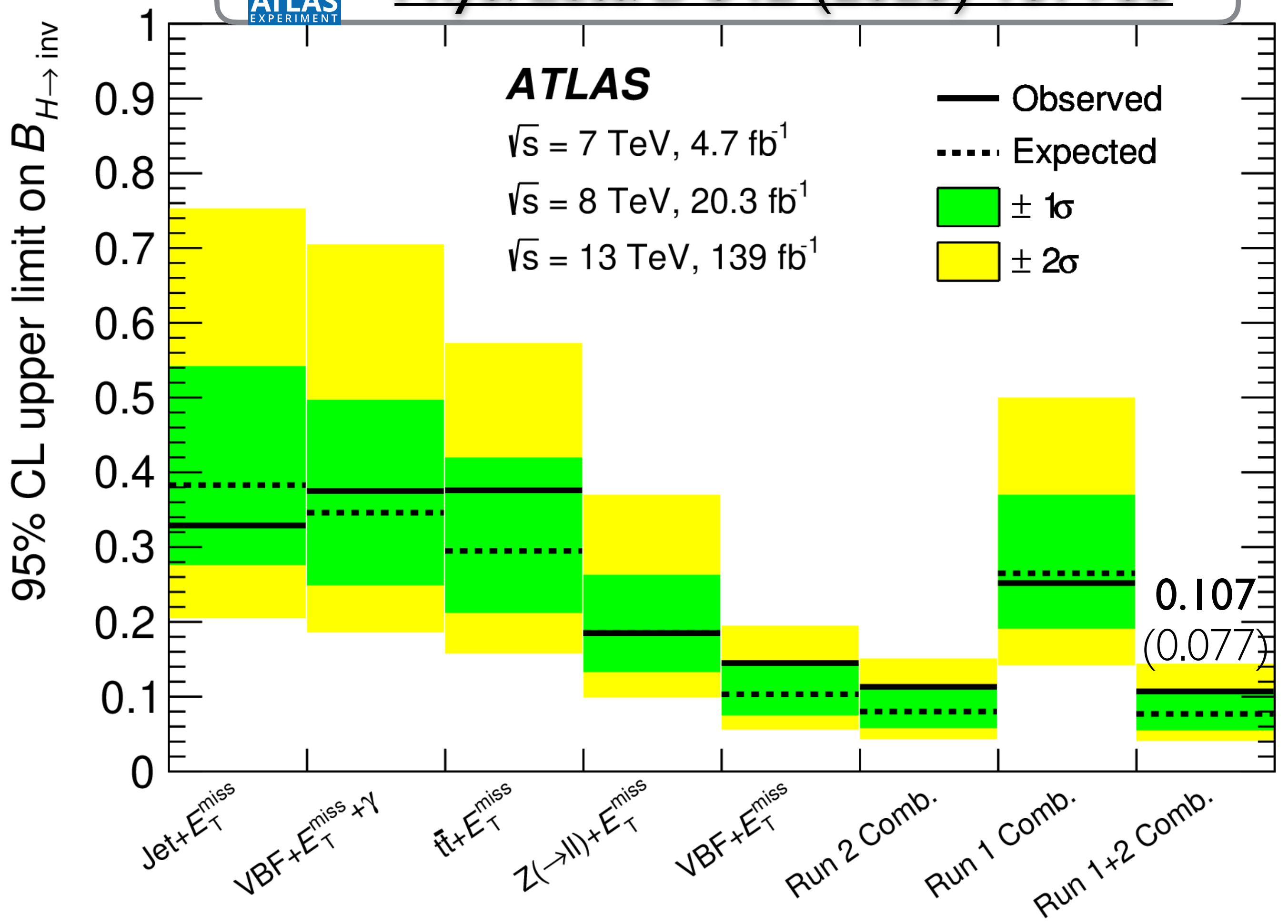
Phys. Lett. B 819 (2021) 136412



Invisible Higgs Boson Decays

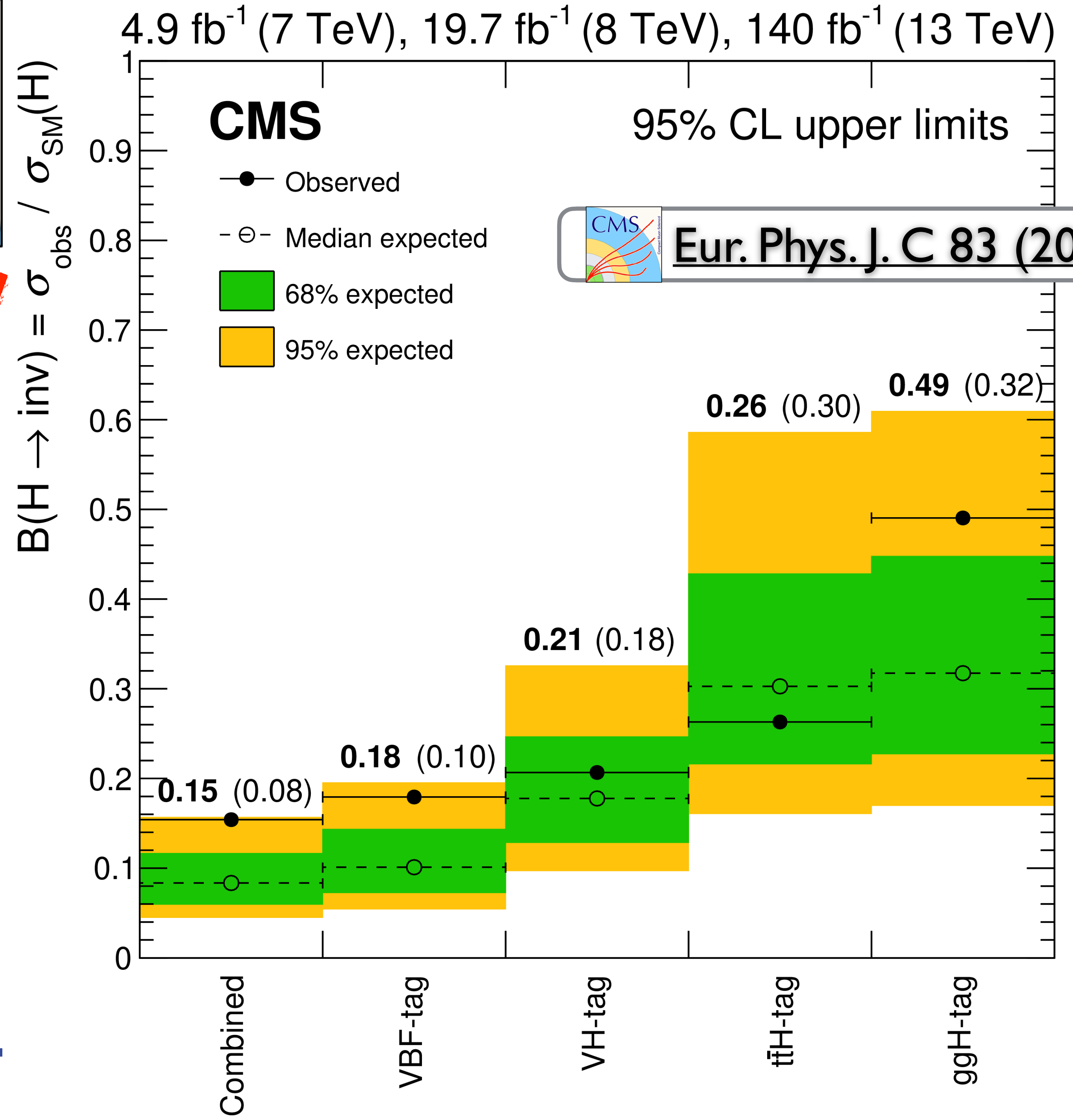
Phys. Lett. B 842 (2023) 137963

Jan 2023

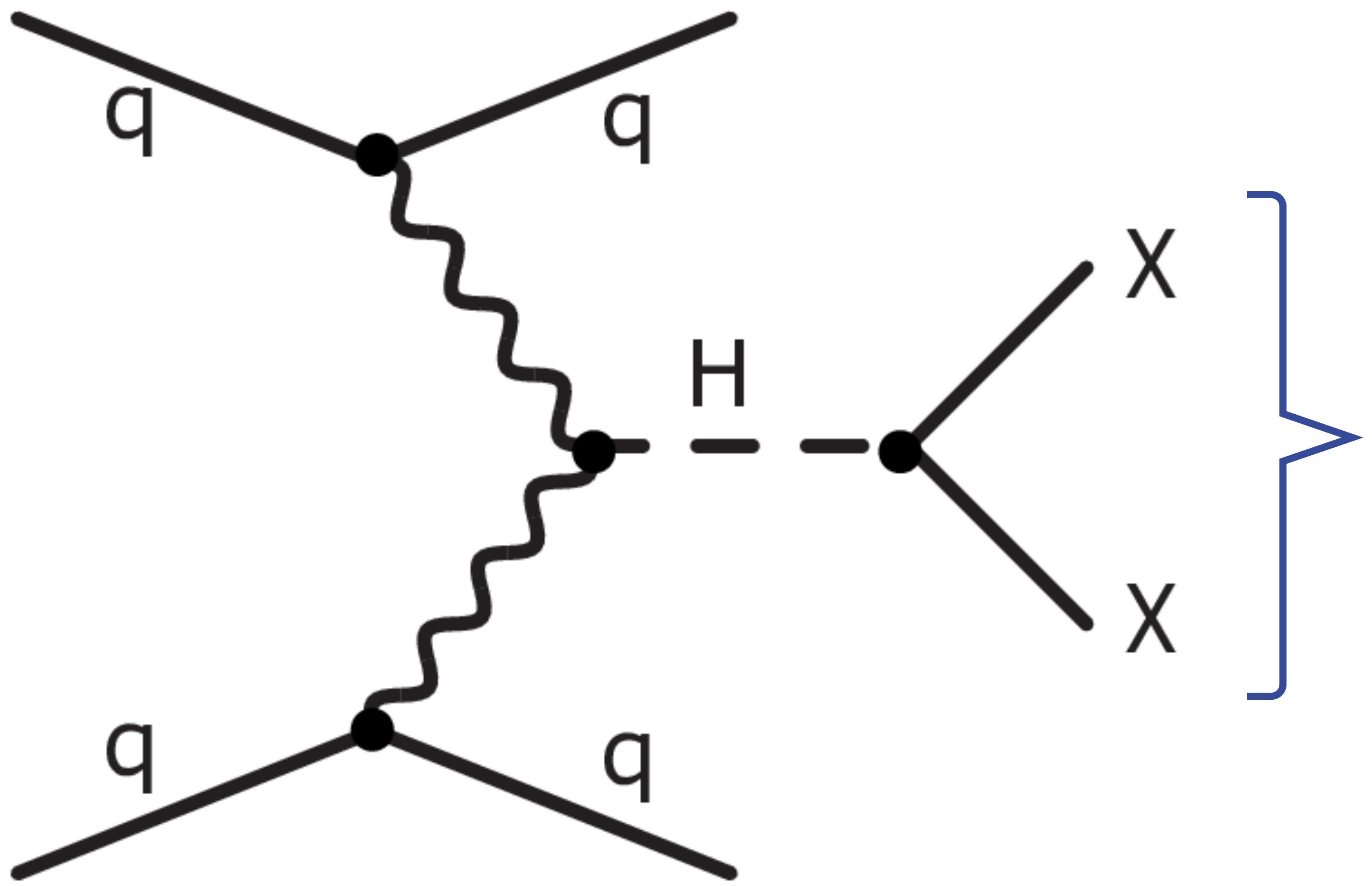


Mar 2023

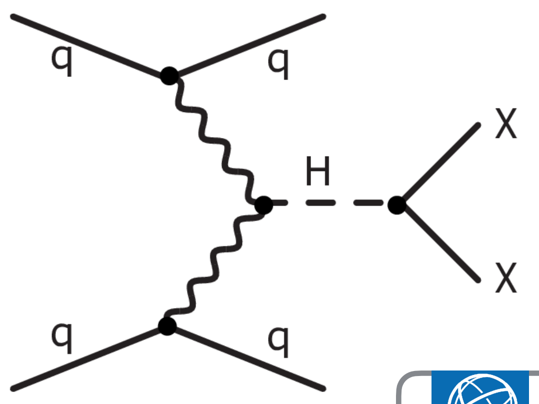
Eur. Phys. J. C 83 (2023) 933



- Search for invisible decays of Higgs boson: addition to Γ_H ?
  - SM: BR(H → $ZZ^{(*)}$ → 4ν) ≈ 0.1 %



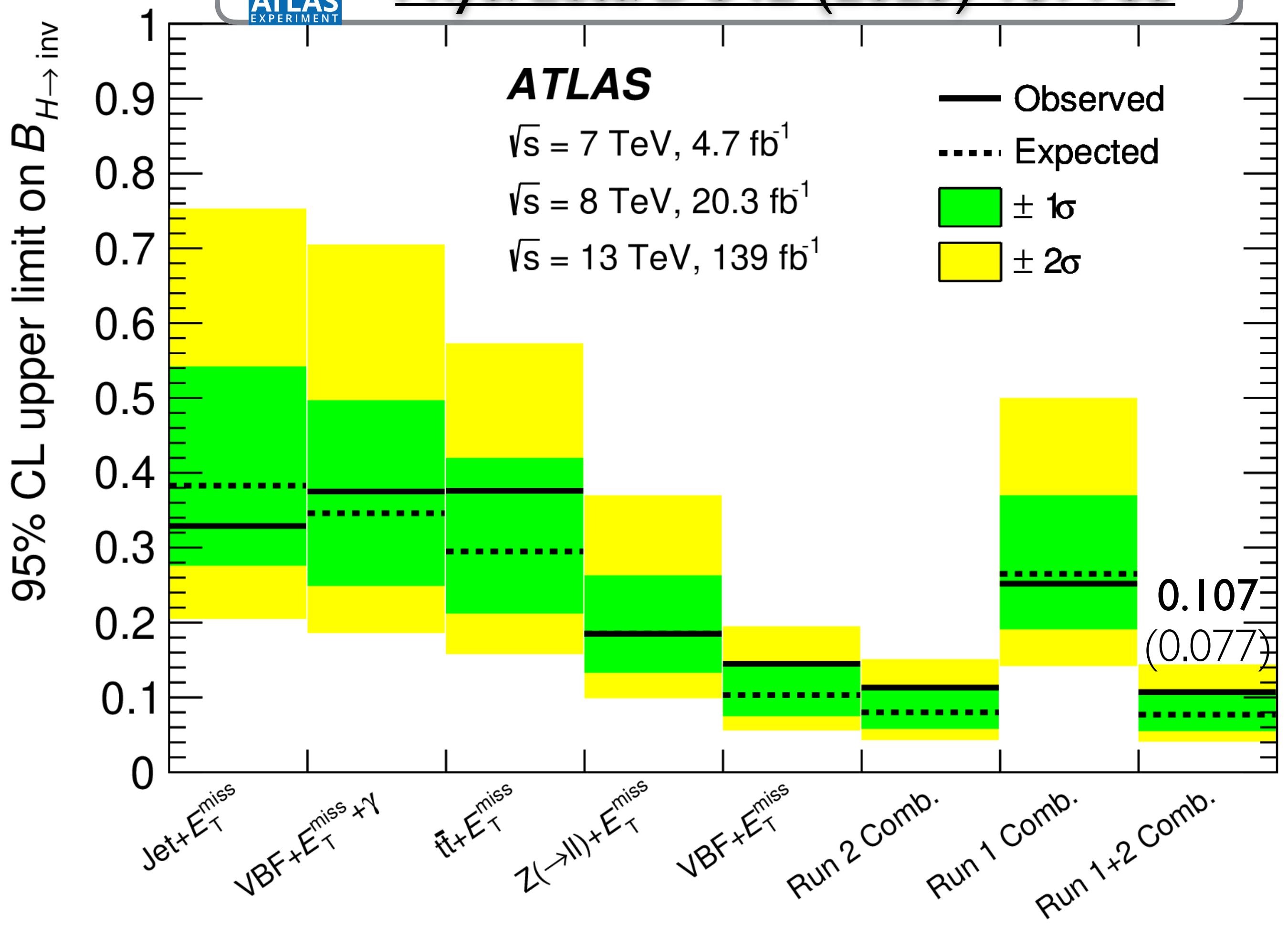
Dark Matter ⇒ E_T^{miss}



Invisible Higgs Boson Decays

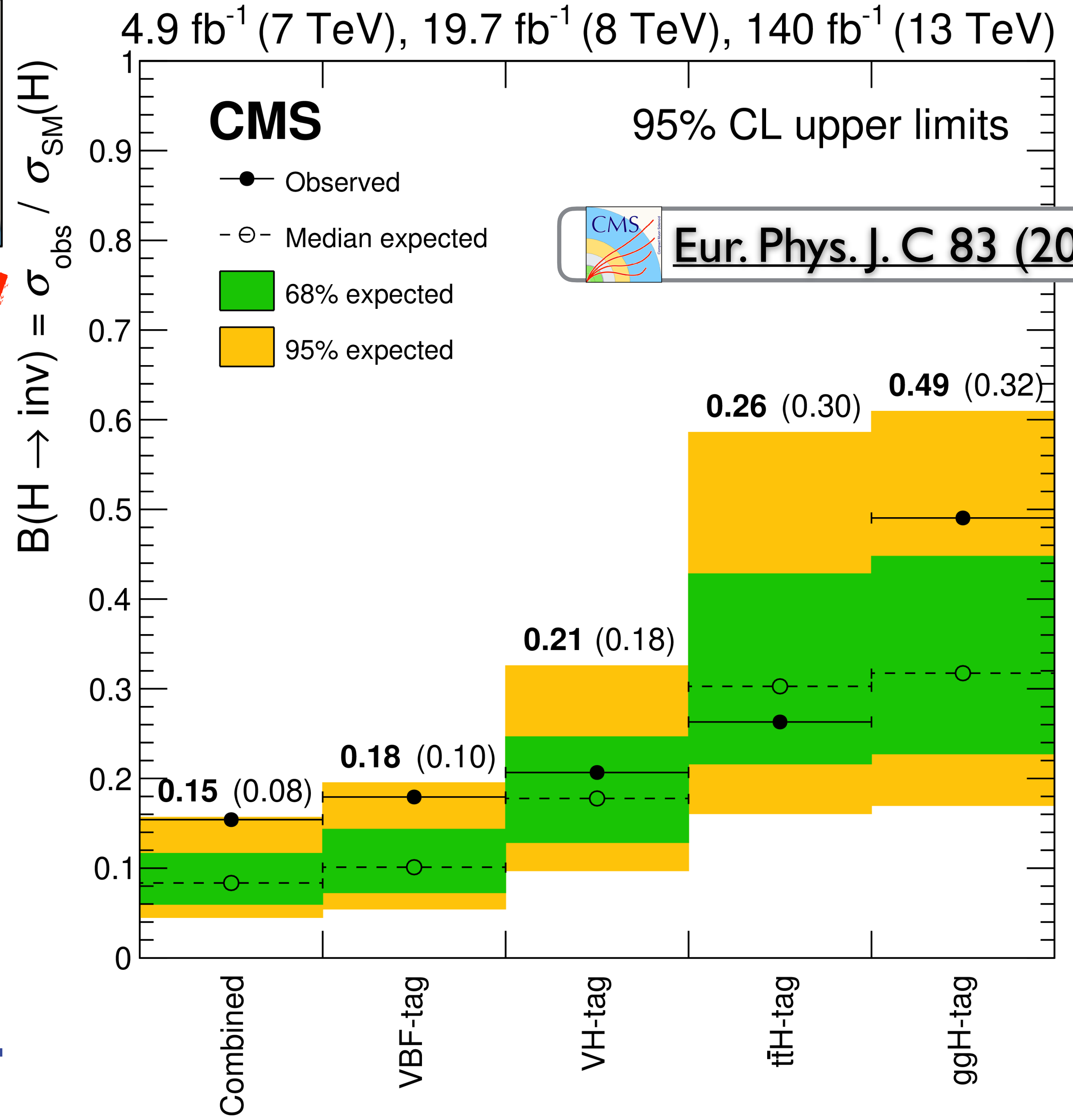
Jan 2023

Phys. Lett. B 842 (2023) 137963

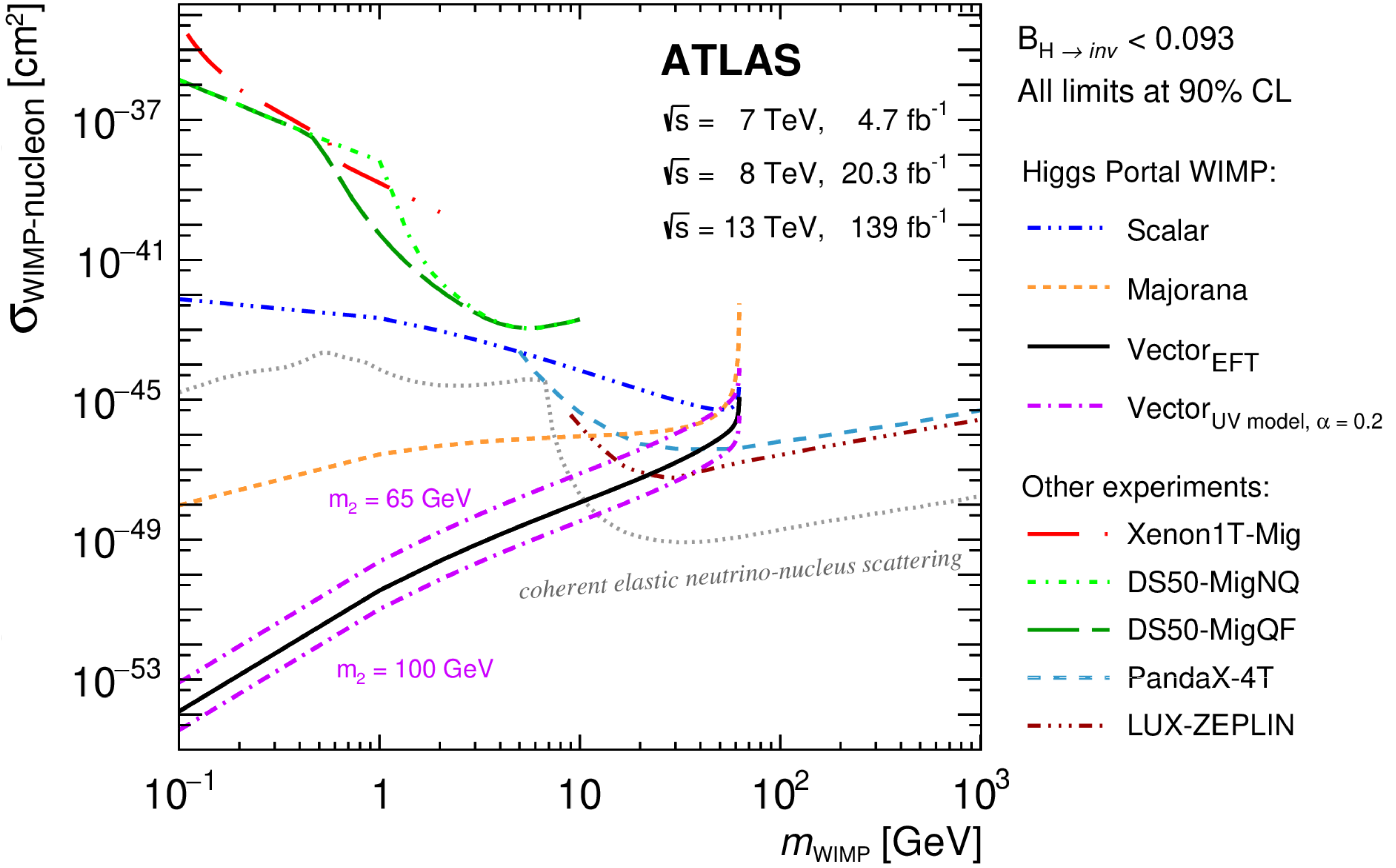


Mar 2023

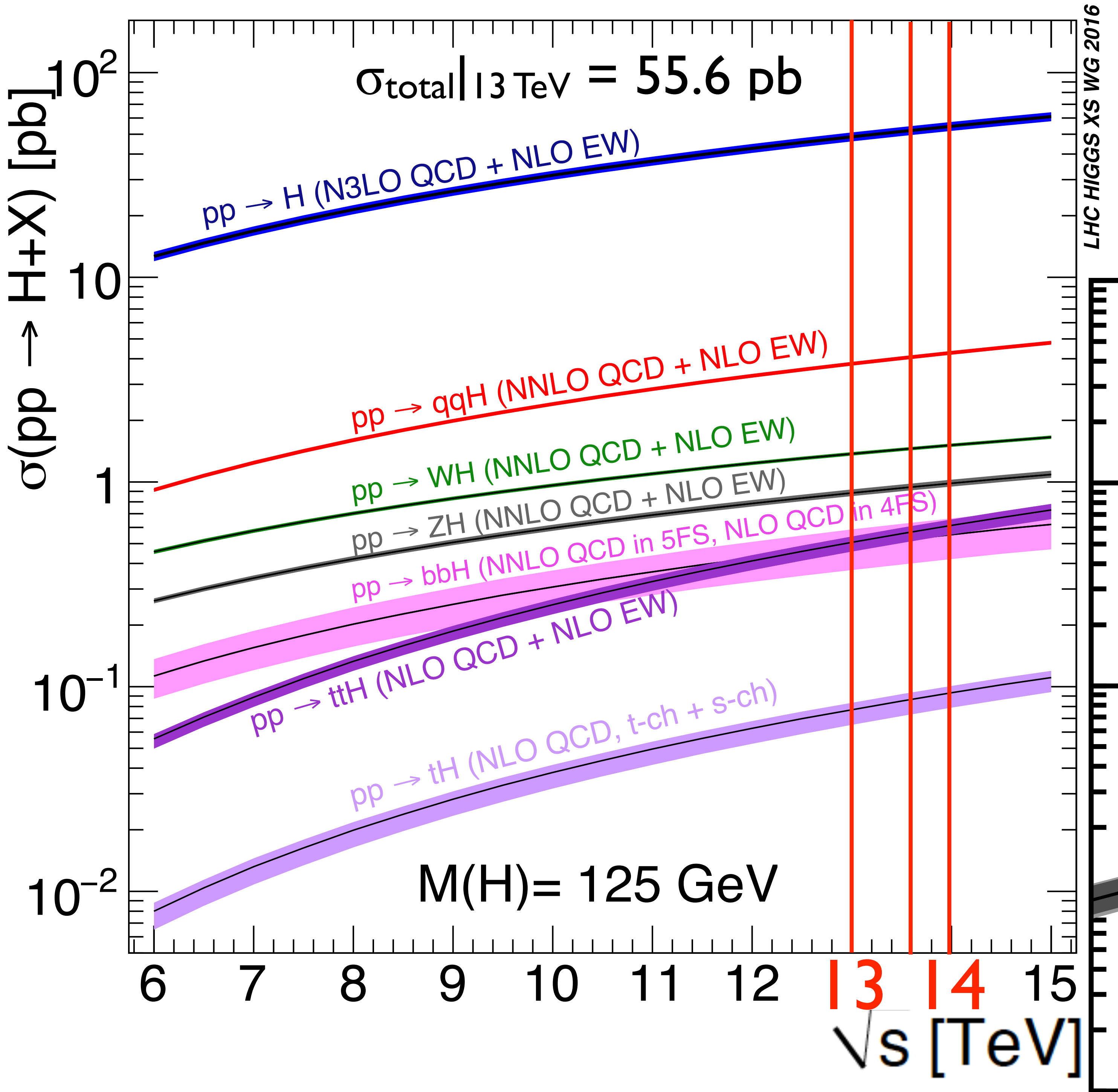
Eur. Phys. J. C 83 (2023) 933

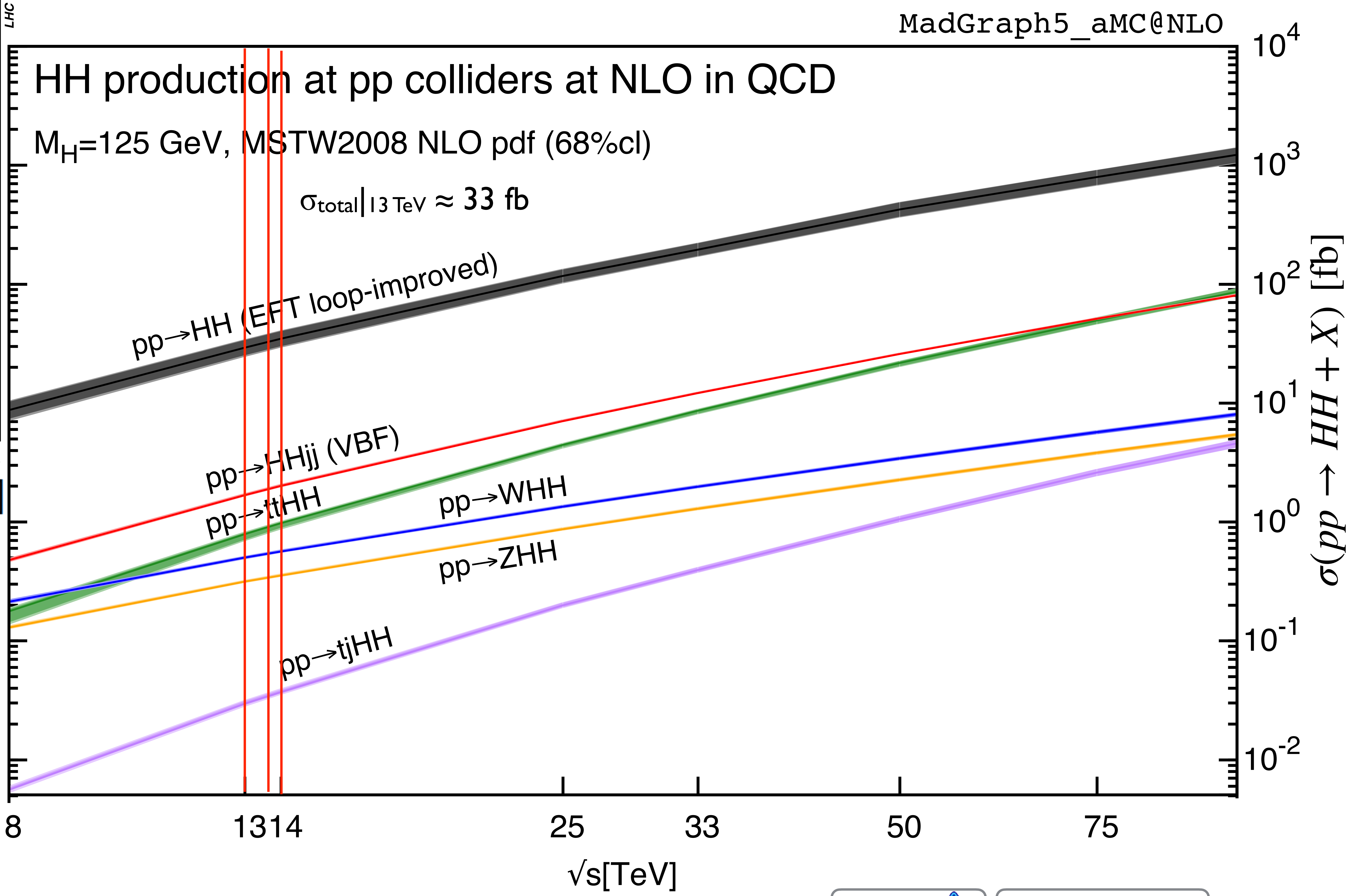


- Search for invisible decays of Higgs boson: addition to Γ_H ?
  - SM: BR($H \rightarrow ZZ^{(*)} \rightarrow 4\nu$) ≈ 0.1 %
  - Interpretation as decay into Dark Matter



H and HH cross sections





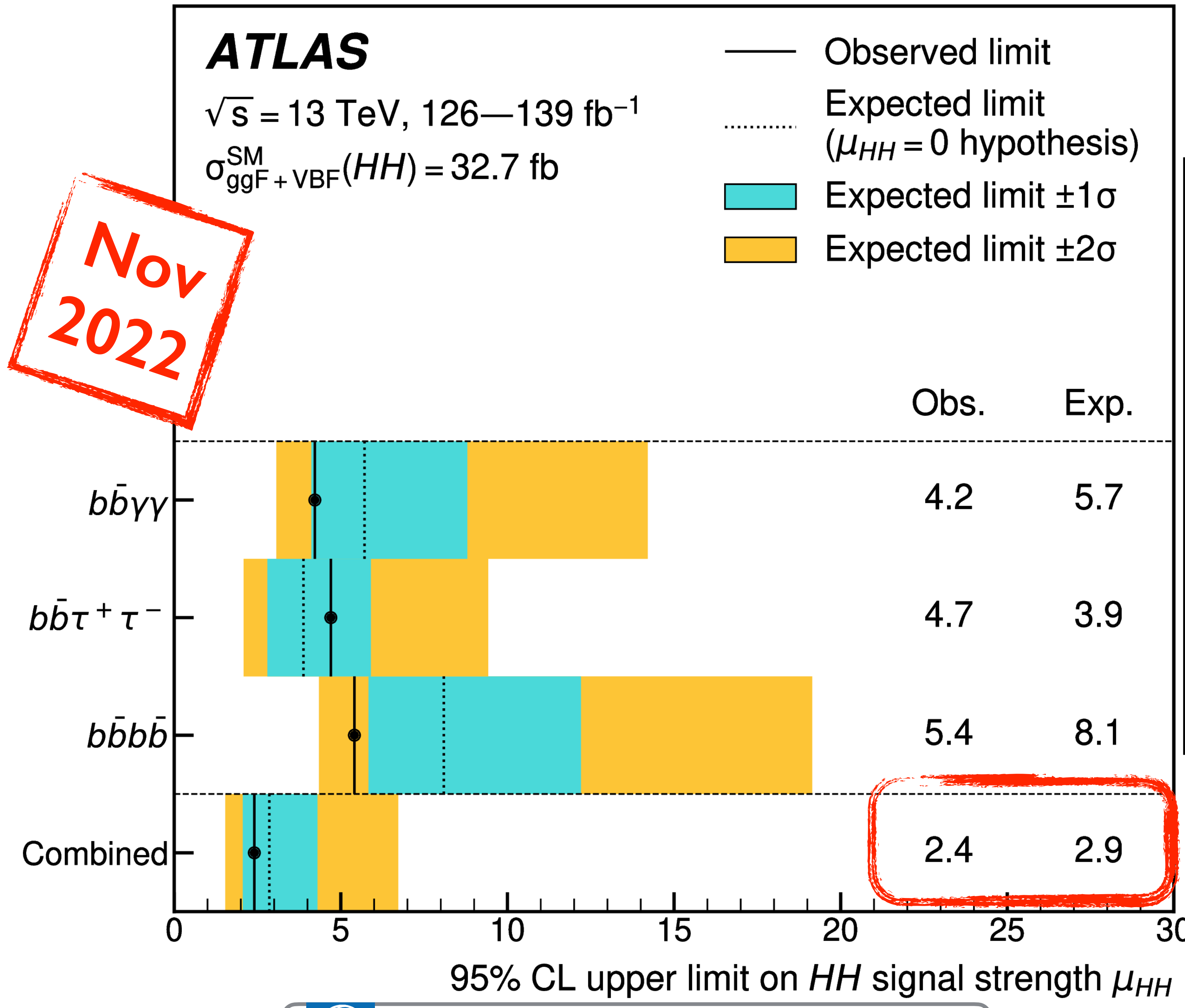
⇒ Back

arXiv:1401.7340

Di-Higgs Production

- "Large" BR & clean signatures:
  - $BR_{SM}(HH \rightarrow bbbb) = 33\% \Rightarrow \sim 1430$ events in 139 fb^{-1}
  - $BR_{SM}(HH \rightarrow bb\tau\tau) = 7.4\% \Rightarrow \sim 320$ events in 139 fb^{-1}
  - $BR_{SM}(HH \rightarrow bb\gamma\gamma) = 0.26\% \Rightarrow \sim 11$ events in 139 fb^{-1}

	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.3	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%



Phys. Lett. B 843 (2023) 137745

Improved results:

Obs.	Exp.	
4.0	5.0	JHEP 01 (2024) 066
5.9	3.1	ATLAS-CONF-2023-071

observed (expected) constraints at 95% C.L.:

$-1.4 < \kappa_\lambda < 6.9$ $(-2.8 < \kappa_\lambda < 7.8)$

$-0.5 < \kappa_{2V} < 2.7$ $(-1.1 < \kappa_{2V} < 3.3)$

$-3.2 < \kappa_\lambda < 9.1$ $(-2.5 < \kappa_\lambda < 9.2)$

$-0.4 < \kappa_{2V} < 2.6$ $(-0.2 < \kappa_{2V} < 2.4)$

⇒ Back

Combination of H and HH

CMS H+HH Combination

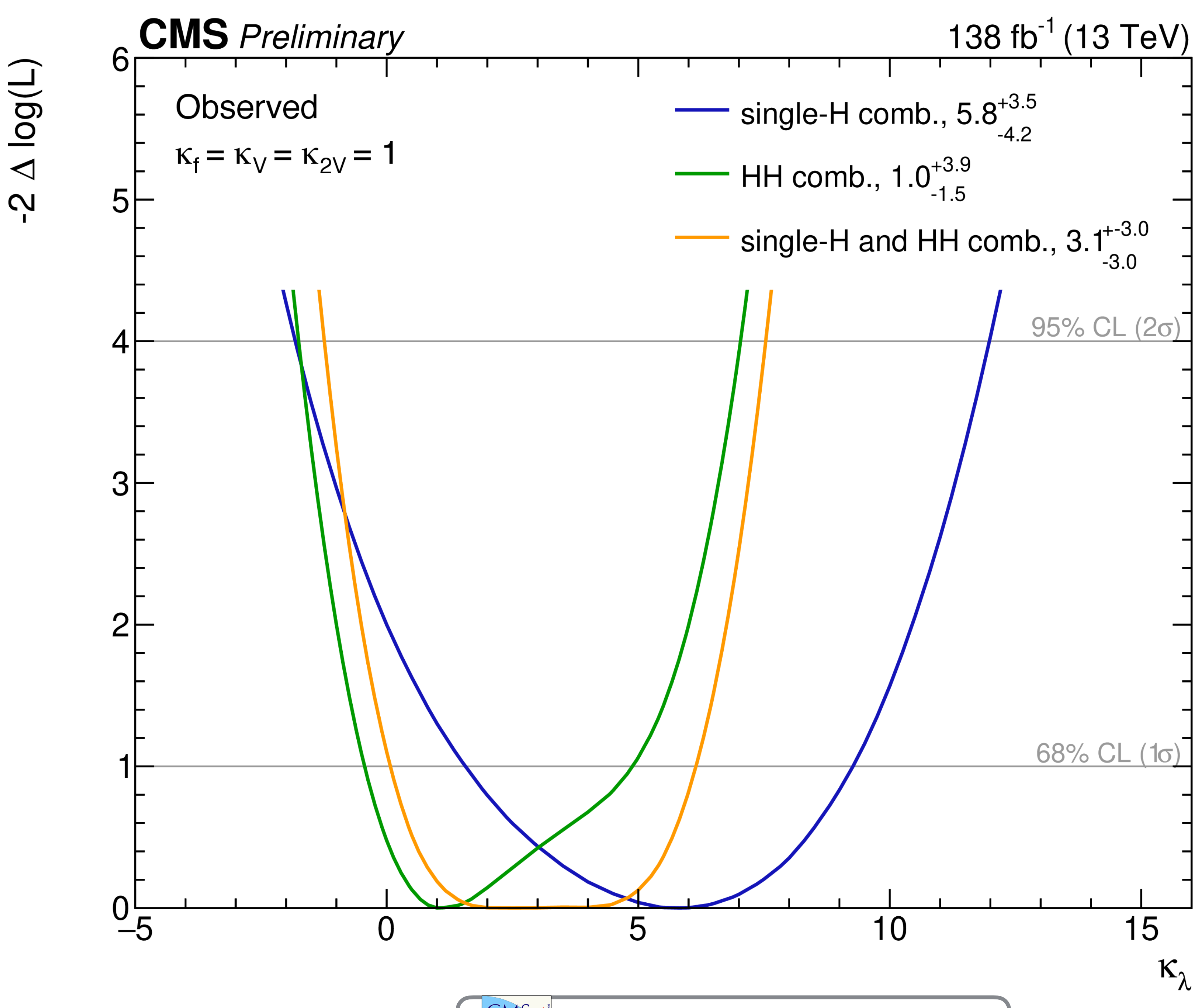
Observed constraint on trilinear coupling at 95% CL:

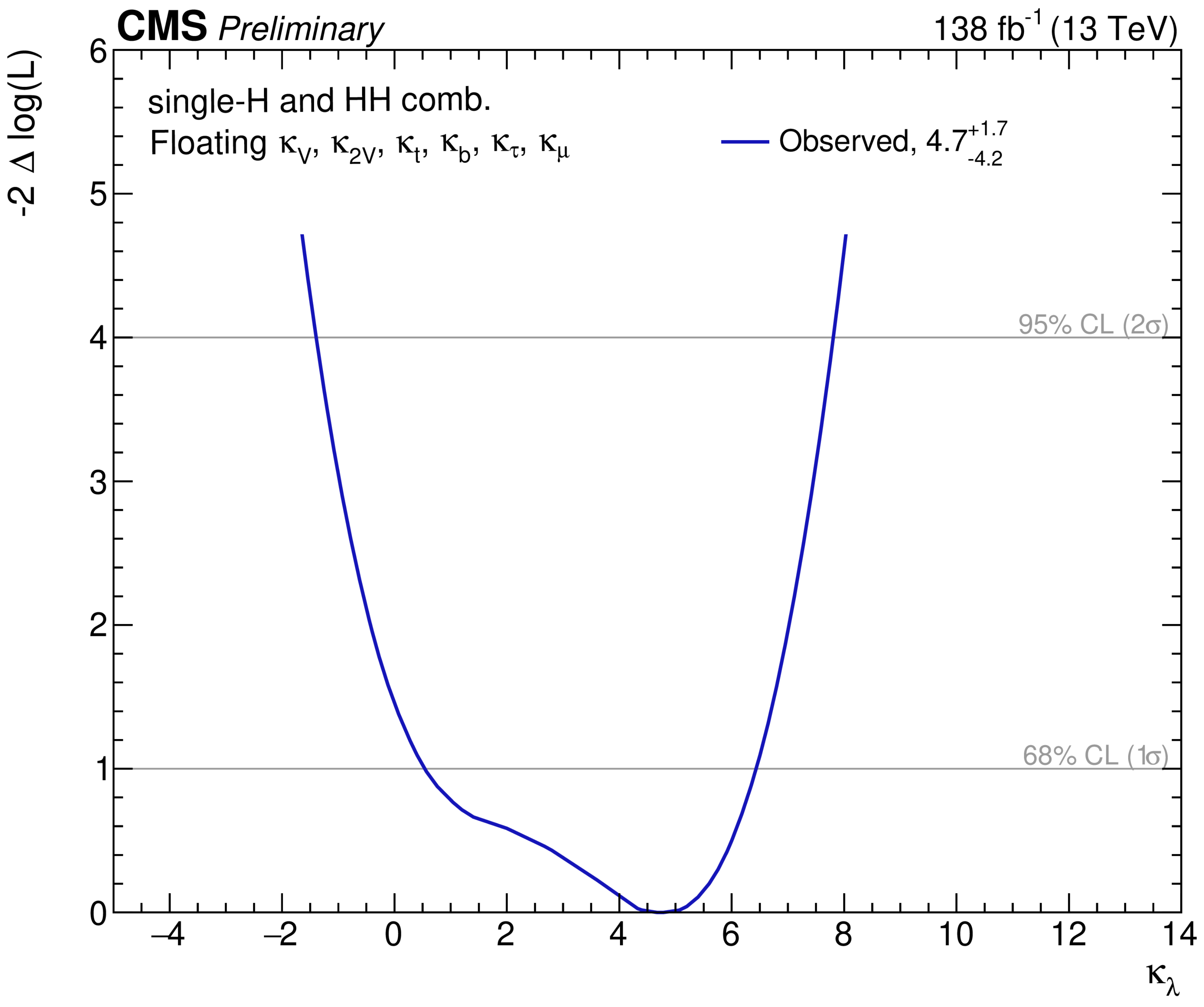
$$-1.2 < \kappa_\lambda < 7.5$$

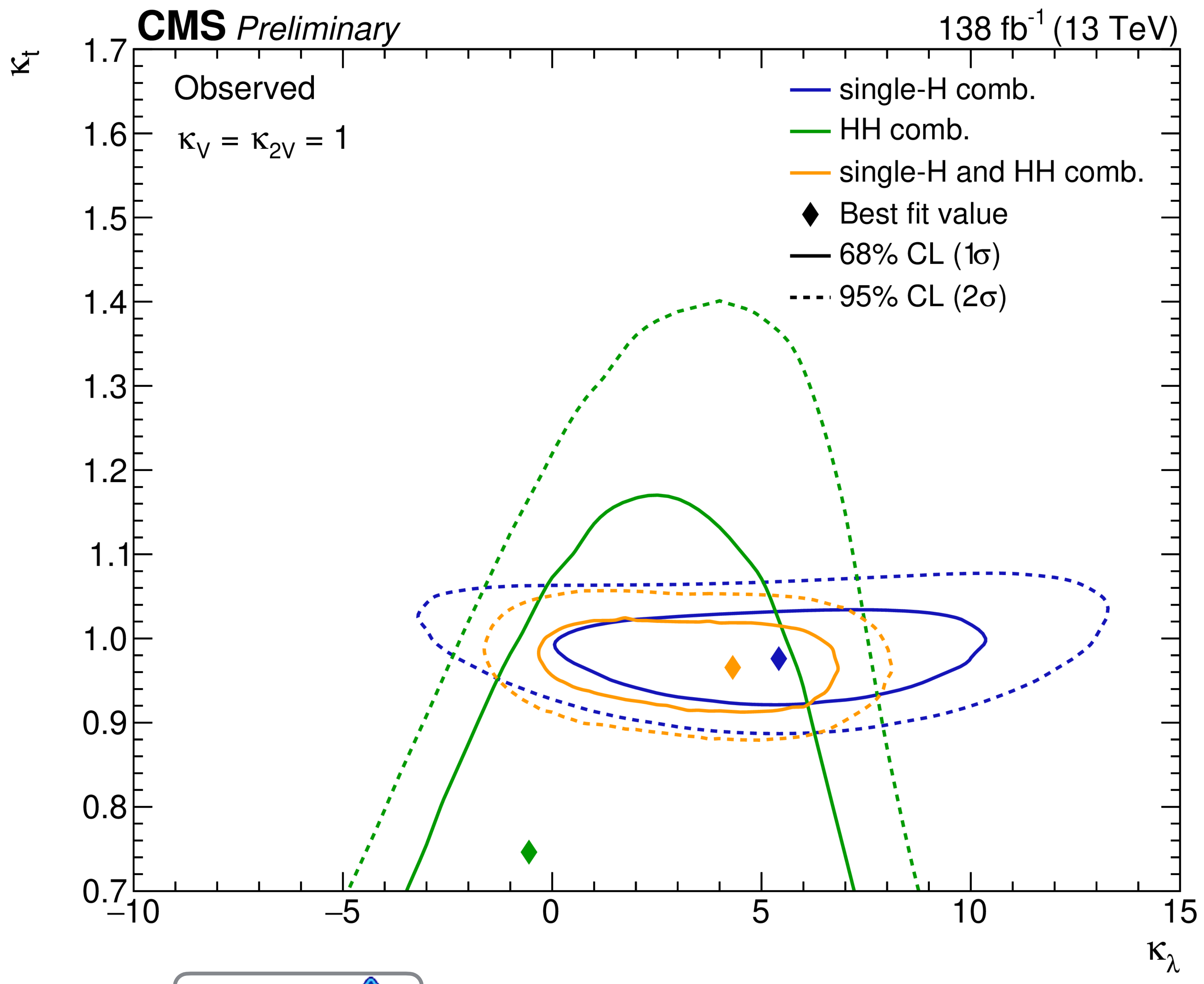
Expected range:

$$-2.0 < \kappa_\lambda < 7.7$$

Nov 2023







CMS-PAS-HIG-23-006

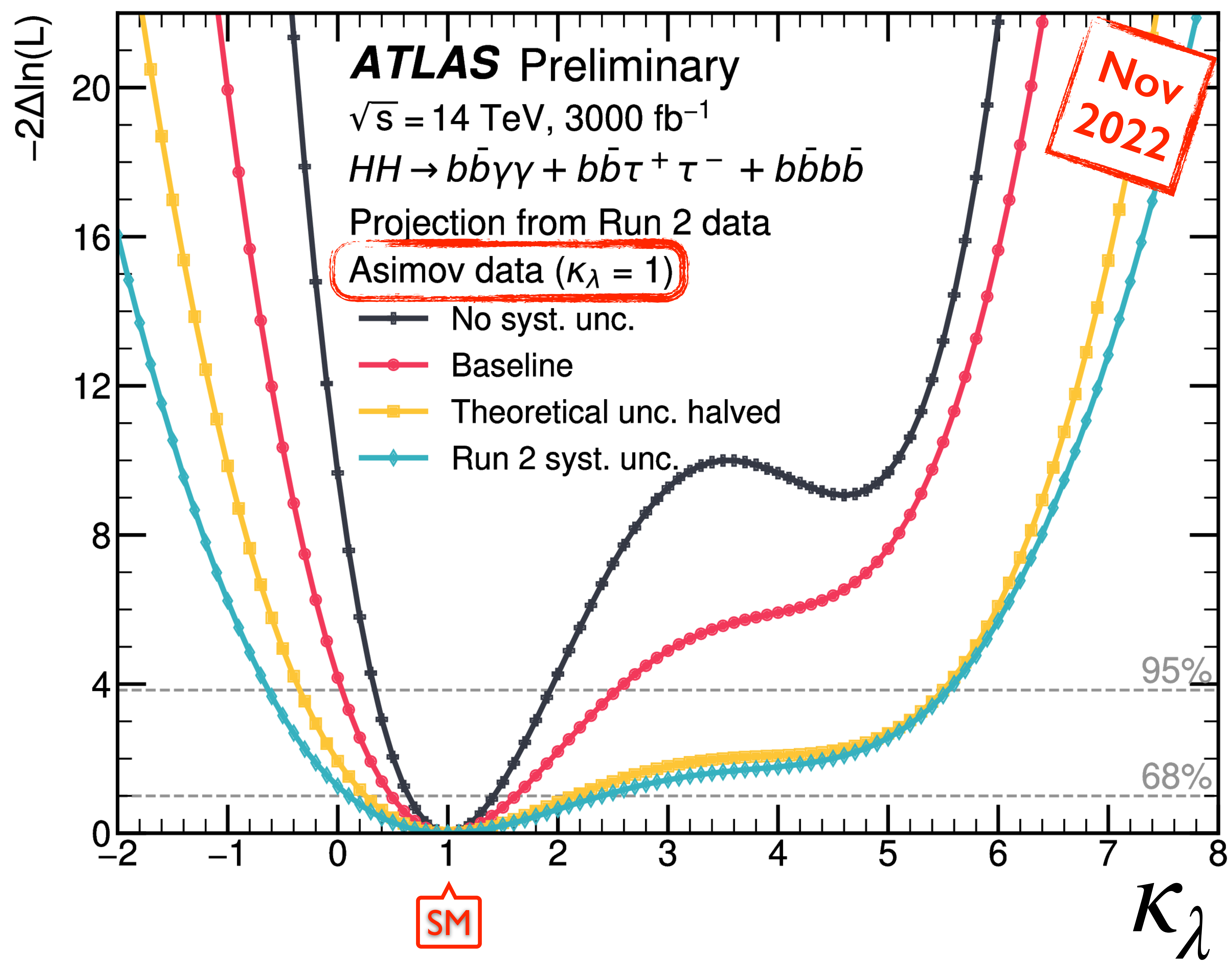
⇒ Back

HH at HL-LHC

ATL-PHYS-PUB-2022-053

- HL-LHC extrapolation from full Run 2 combination of:
  - BR_{SM}(HH → bbbb) = 33% ⇒ ~38400 events in 3000 fb^{-1}
  - BR_{SM}(HH → bbττ) = 7.3% ⇒ ~6900 events in 3000 fb^{-1}
  - BR_{SM}(HH → bbγγ) = 0.26% ⇒ ~240 events in 3000 fb^{-1}

Projected results:
(3000 fb^{-1}, with systematics)
- **HH** significance: **3.4 σ**
- **0.5 < κ_λ < 1.6**



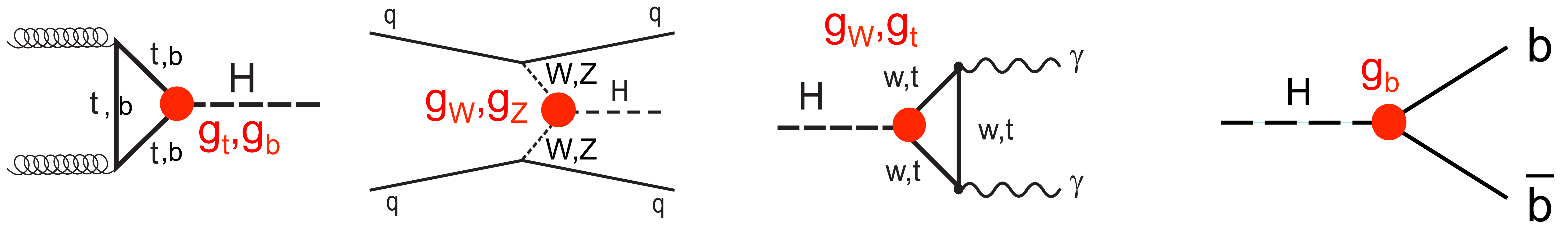
⇒ bbγγ expected significance at 3000 fb^{-1}: **2.16 σ** [CMS-PAS-FTR-21-004]

⇒ ATLAS + CMS (3+3 ab^{-1}, all channels) from CERN HL-LHC Yellow Report (w/ systematics): HH significance: **4.0 σ** and **0.52 < κ_λ < 1.5** @ 68% C.L.

⇒ Back

The κ Framework

- Once Higgs boson mass is known, all other Higgs-boson parameters are fixed in the SM
- To allow for measurement deviations from SM rates, introduce coupling modifiers:



$$\kappa_a := \frac{g_a}{(g_a)_{\mathrm{SM}}}$$

$$(\sigma \cdot \mathrm{BR})\,(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

$$= \sigma_{\mathrm{SM}}\,(i \to H) \cdot \mathrm{BR}_{\mathrm{SM}}\,(H \to f) \cdot \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

Assumption:

- Only one SM Higgs-like state at ~125 GeV with negligible width

LHC Higgs XS WG (arxiv:1307.1347)

⇒ Back

Production and Decay Modes

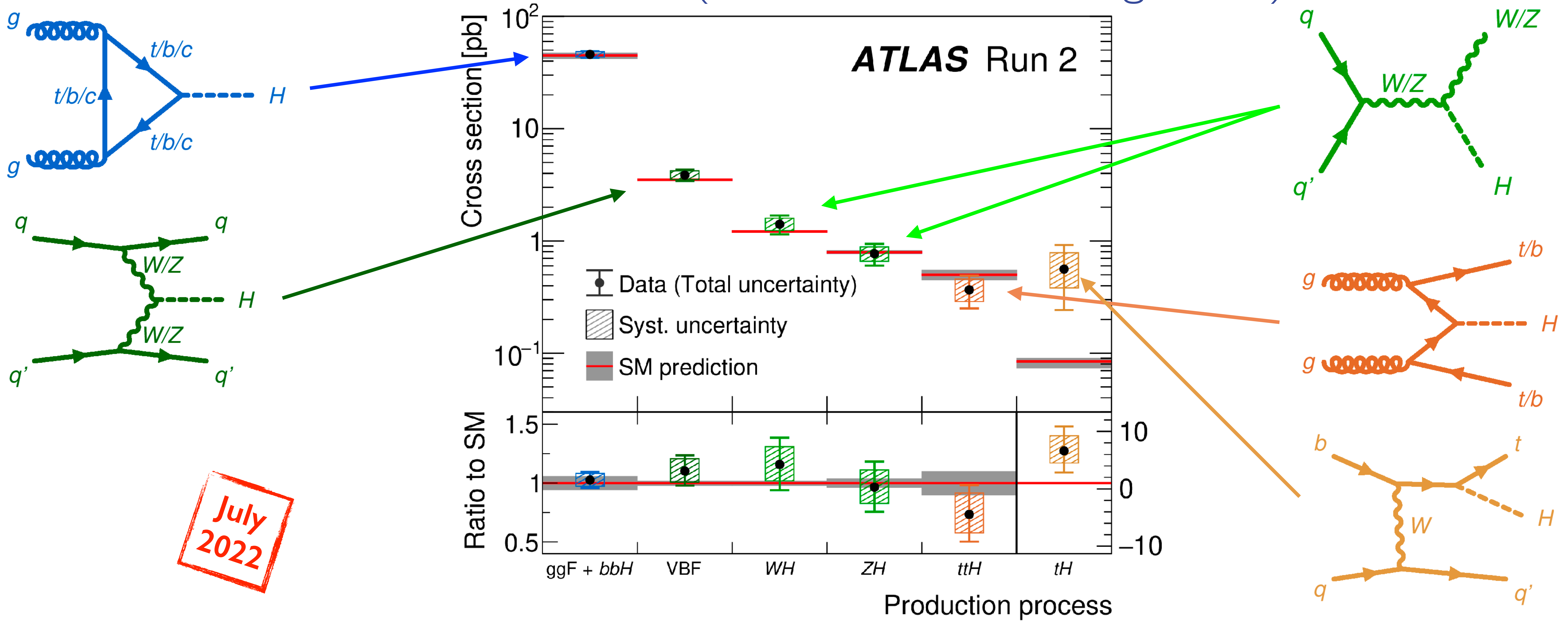
Nature 607, 52–59 (2022)

Decay modes

Production Modes

Nature 607, 52–59 (2022)

Main production modes observed (assume SM branching ratios)



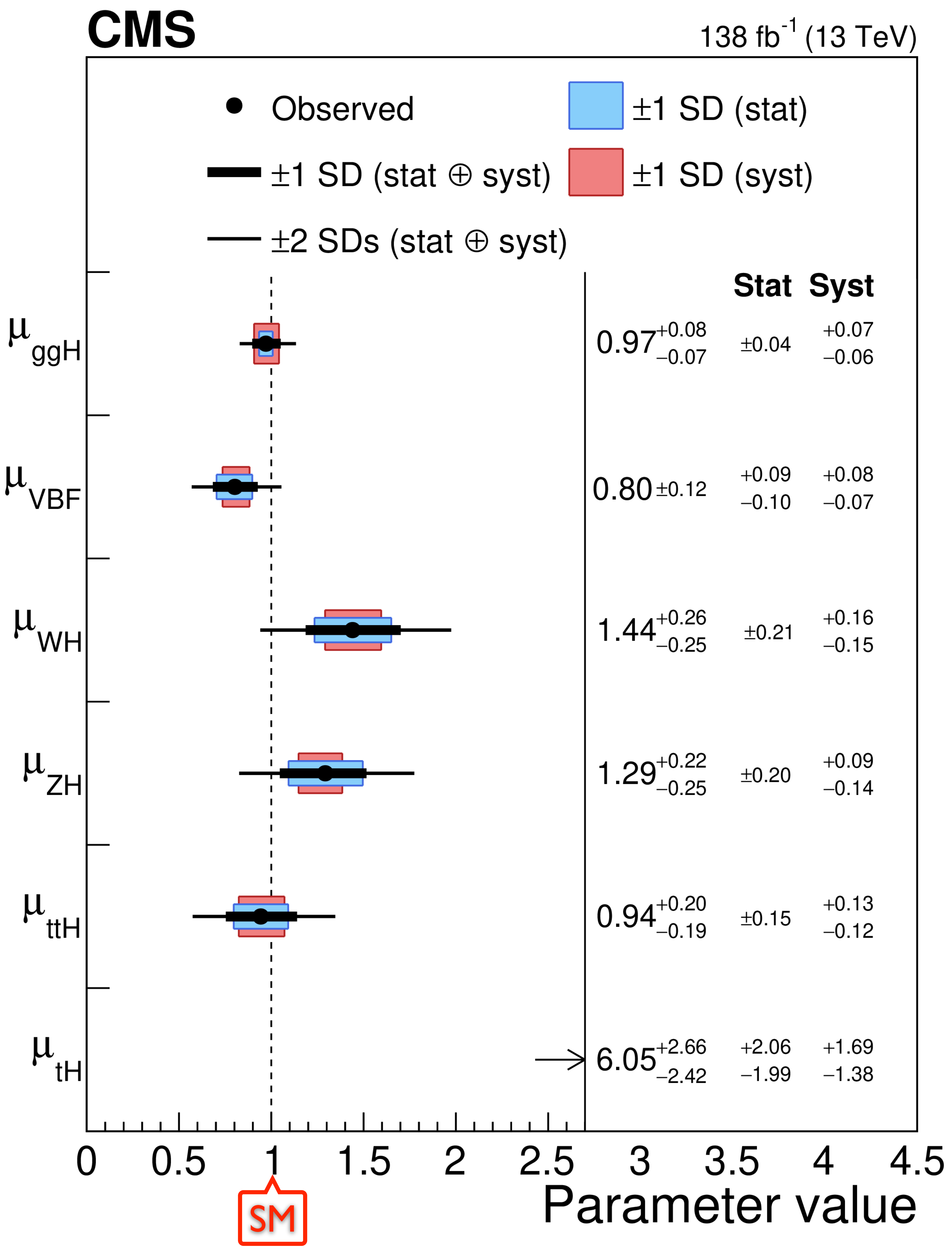
Global $\mu = 1.05 \pm 0.06 = 1.05 \pm 0.03\,(\text{stat.}) \pm 0.03\,(\text{exp.}) \pm 0.04\,(\text{sig. th.}) \pm 0.02\,(\text{bkg. th.})$

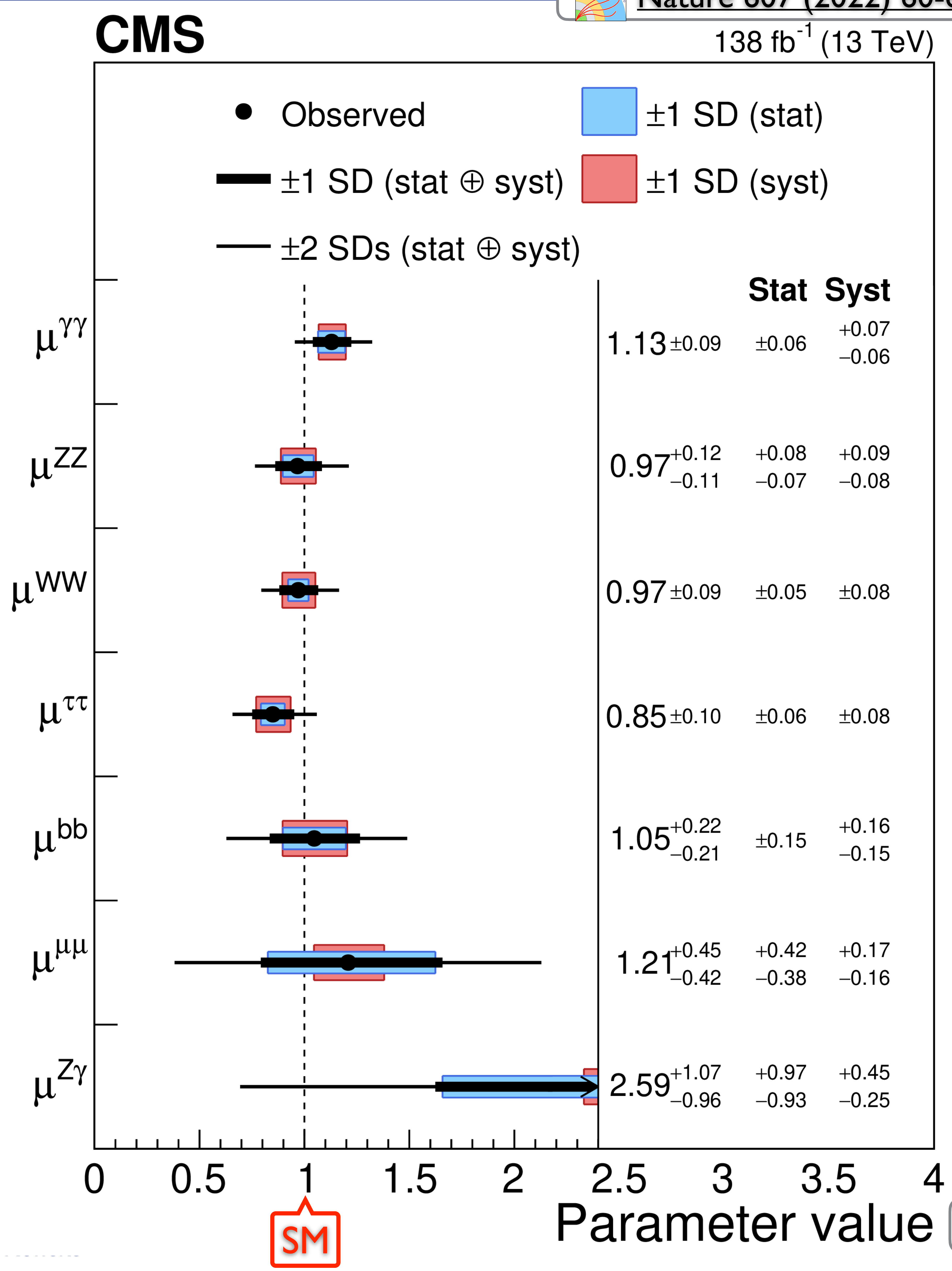
⇒ Back

⇒ CMS results

Production Modes

Nature 607 (2022) 60-68





⇒ ATLAS result

κ Coupling Modifiers

Nature 607, 52–59 (2022)

Assume:

No BSM contributions

($B_{inv} = B_{undet} = 0$)

≈6% κ_Z

≈6% κ_W

≈11% κ_t

≈13% κ_b

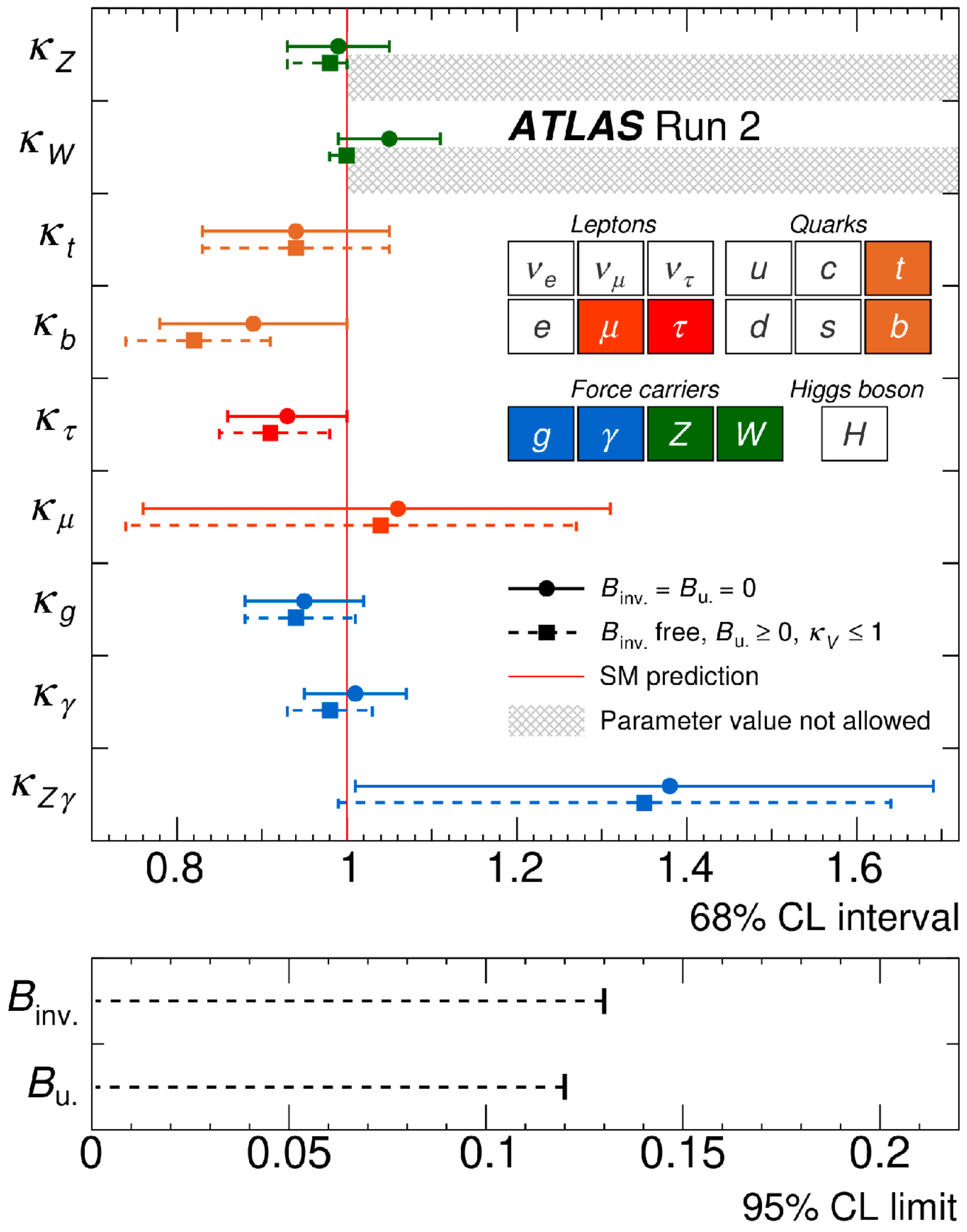
≈8% κ_τ

≈25% κ_μ

≈7% κ_g

≈6% κ_γ

≈25% $\kappa_{Z\gamma}$



Assume:

B_{inv} and B_{undet} are free parameters.

Constrain $\kappa_W \leq 1$ and $\kappa_Z \leq 1$

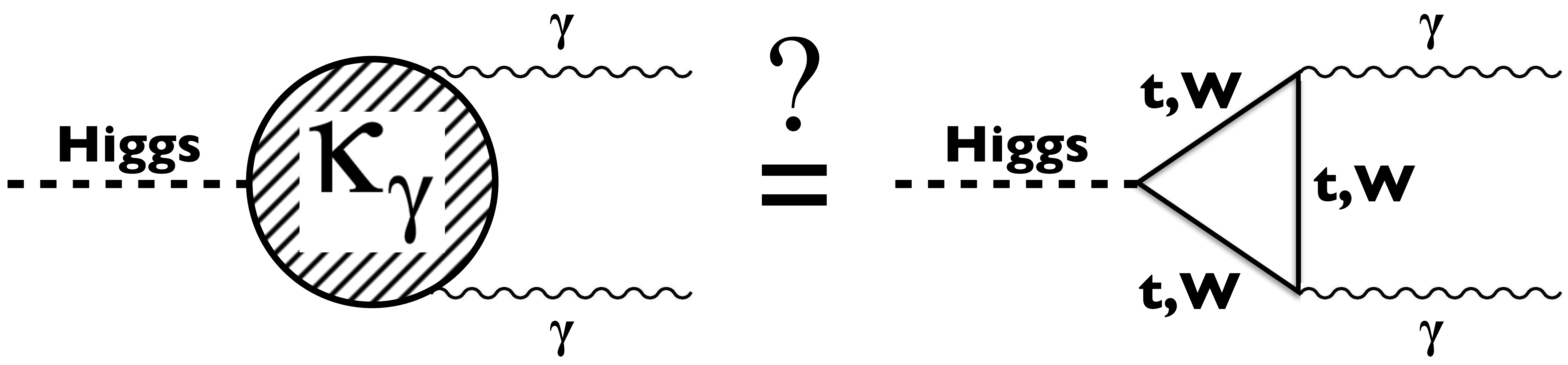
Add:

VBF H → invisible

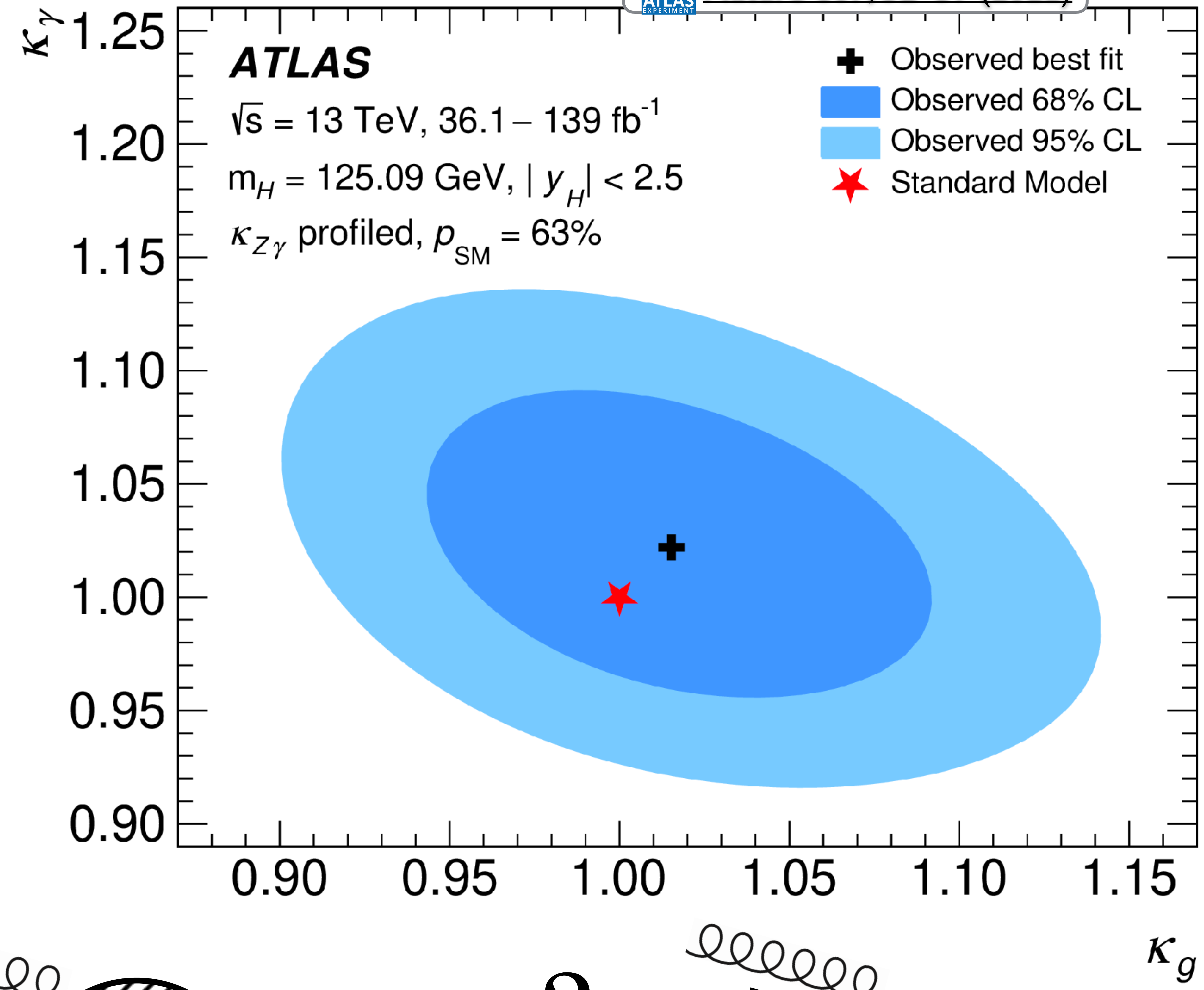
⇒ Back

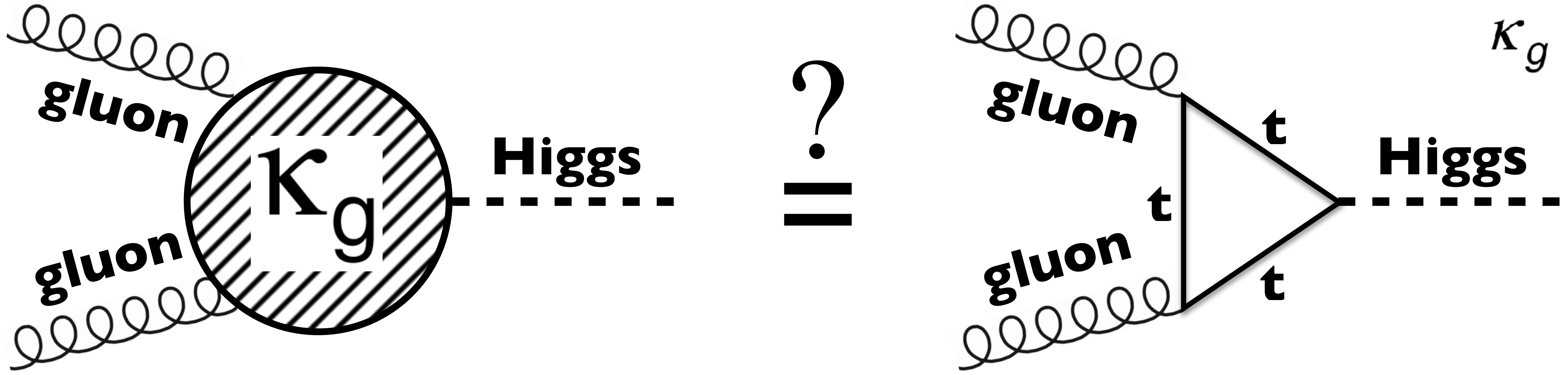
Loop-induced Couplings

- SM: ggF and H → γγ are loop-induced
  - New particles could participate in the loop
  - ⇒ Contributions of BSM?
  - ⇒ Test effective coupling factors for photons (κ_γ) and gluons (κ_g)



Nature 607, 52–59 (2022)

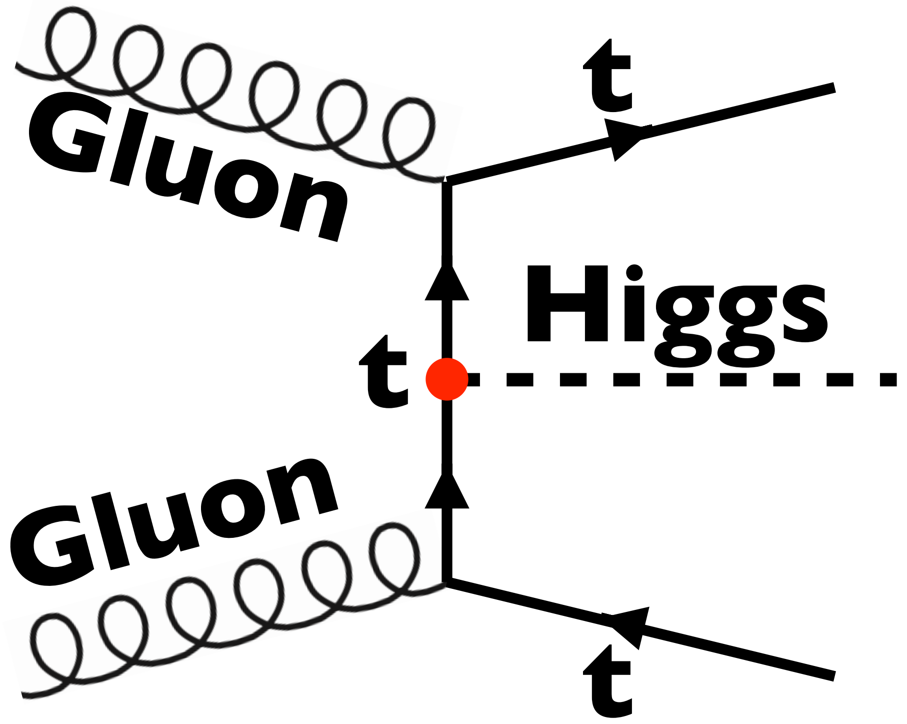


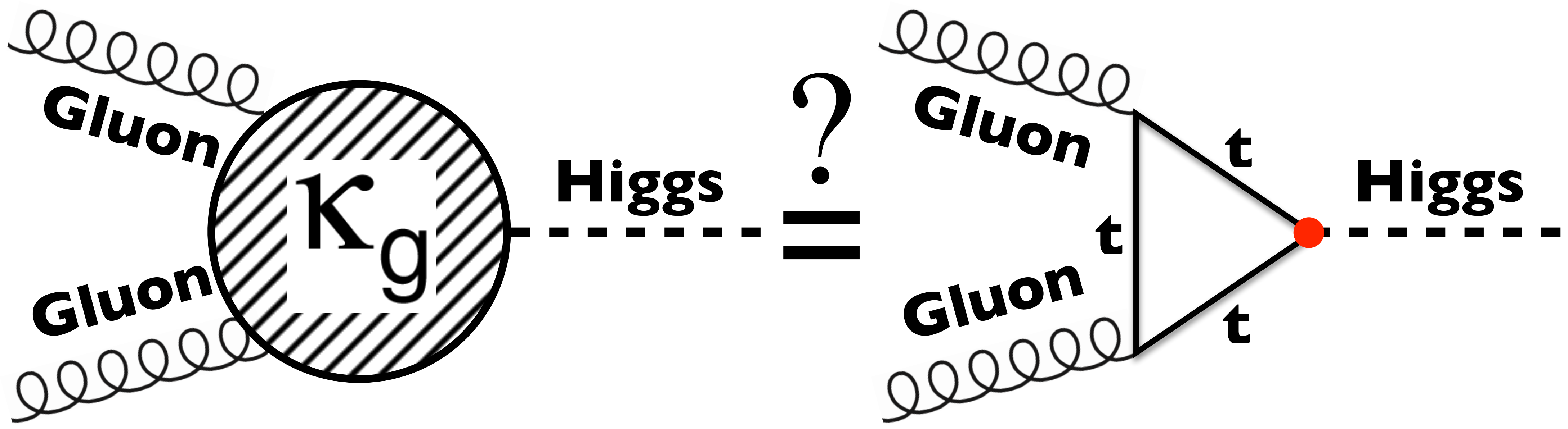


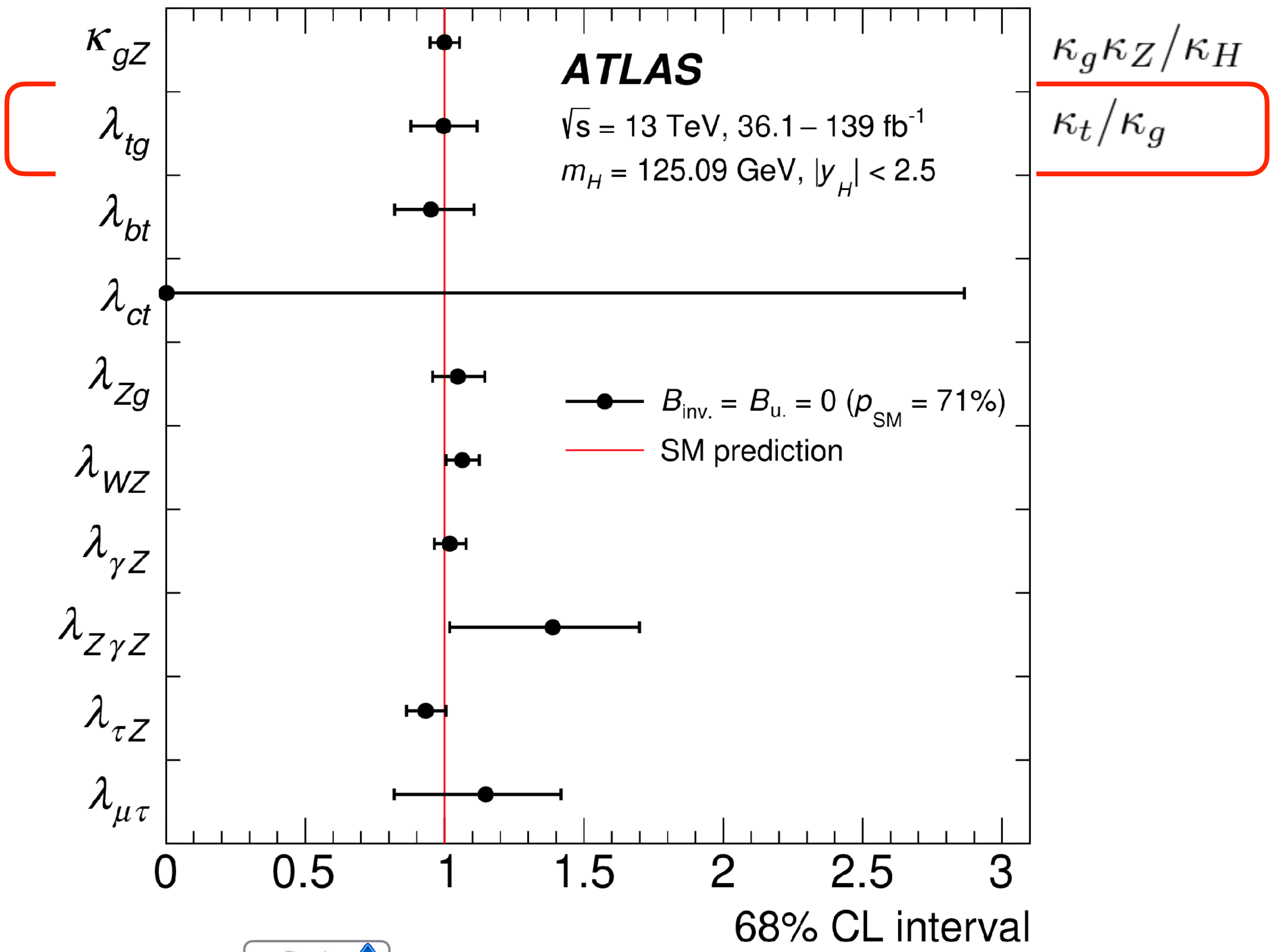
Ratio of Coupling Modifiers

Nature 607, 52–59 (2022)

- No assumption on total width needed; assume all parameters >0
- With ttH measurement:
  ⇒ Test compatibility between
  - direct ttH coupling (κ_t) and
  - coupling in ggF loop, i.e. effective coupling modifier for gluons (κ_g)

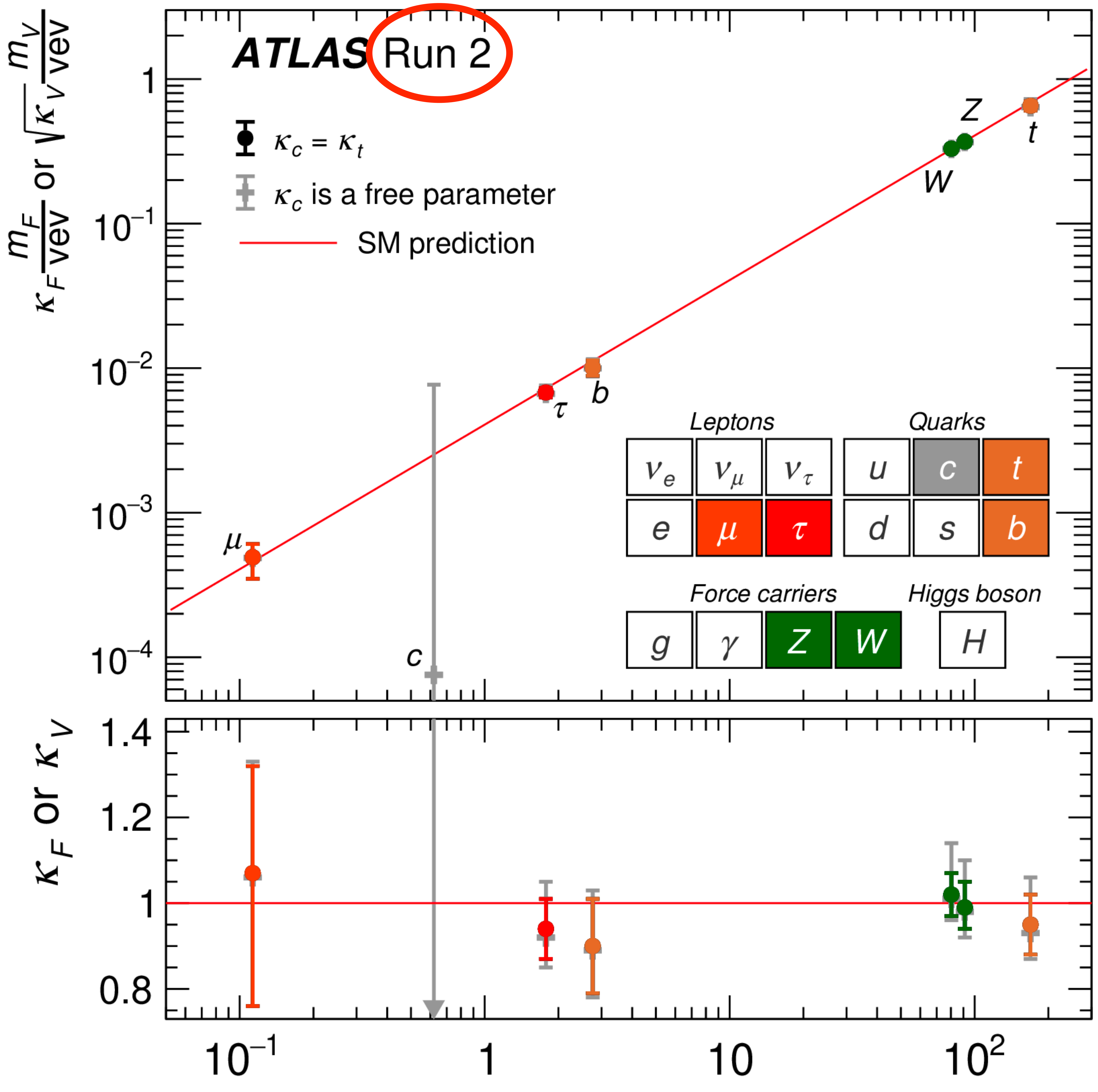




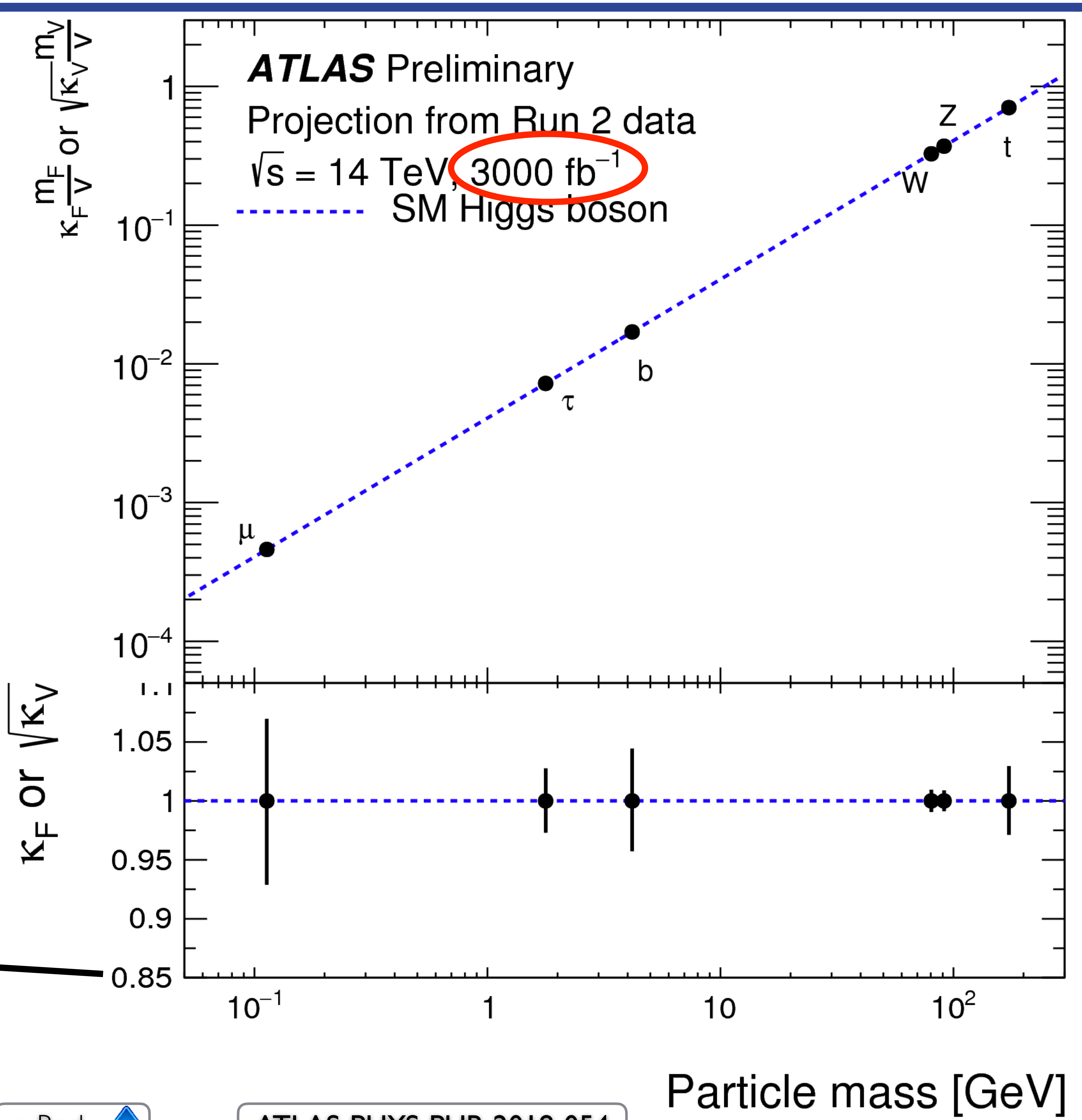


Karsten Köneke
⇒ Back

Extrapolations



⟹



Nature 607, 52–59 (2022)

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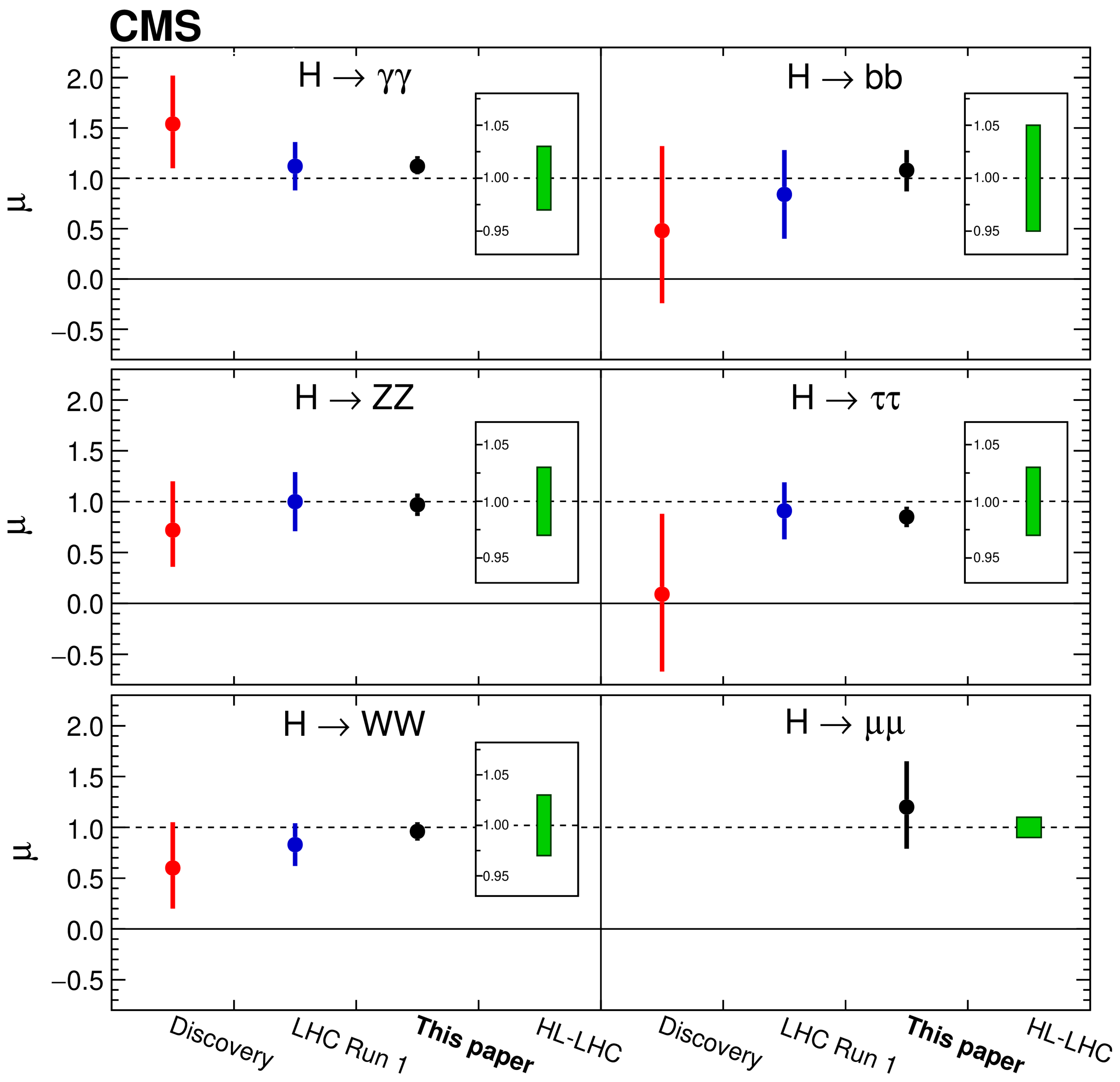
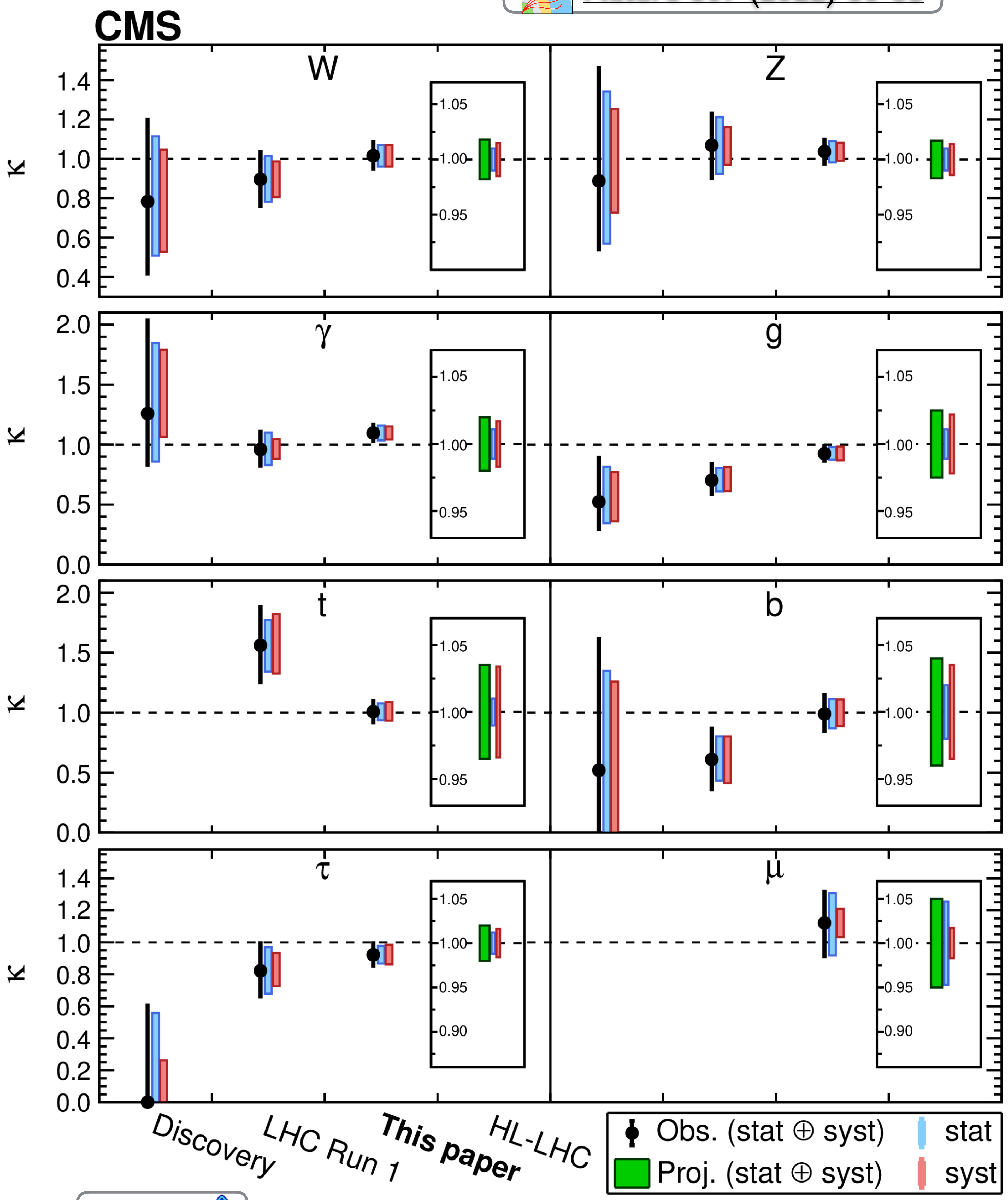
ATLAS-PHYS-PUB-2018-054

Coupling Combination and HL-LHC

Nature 607 (2022) 60-68





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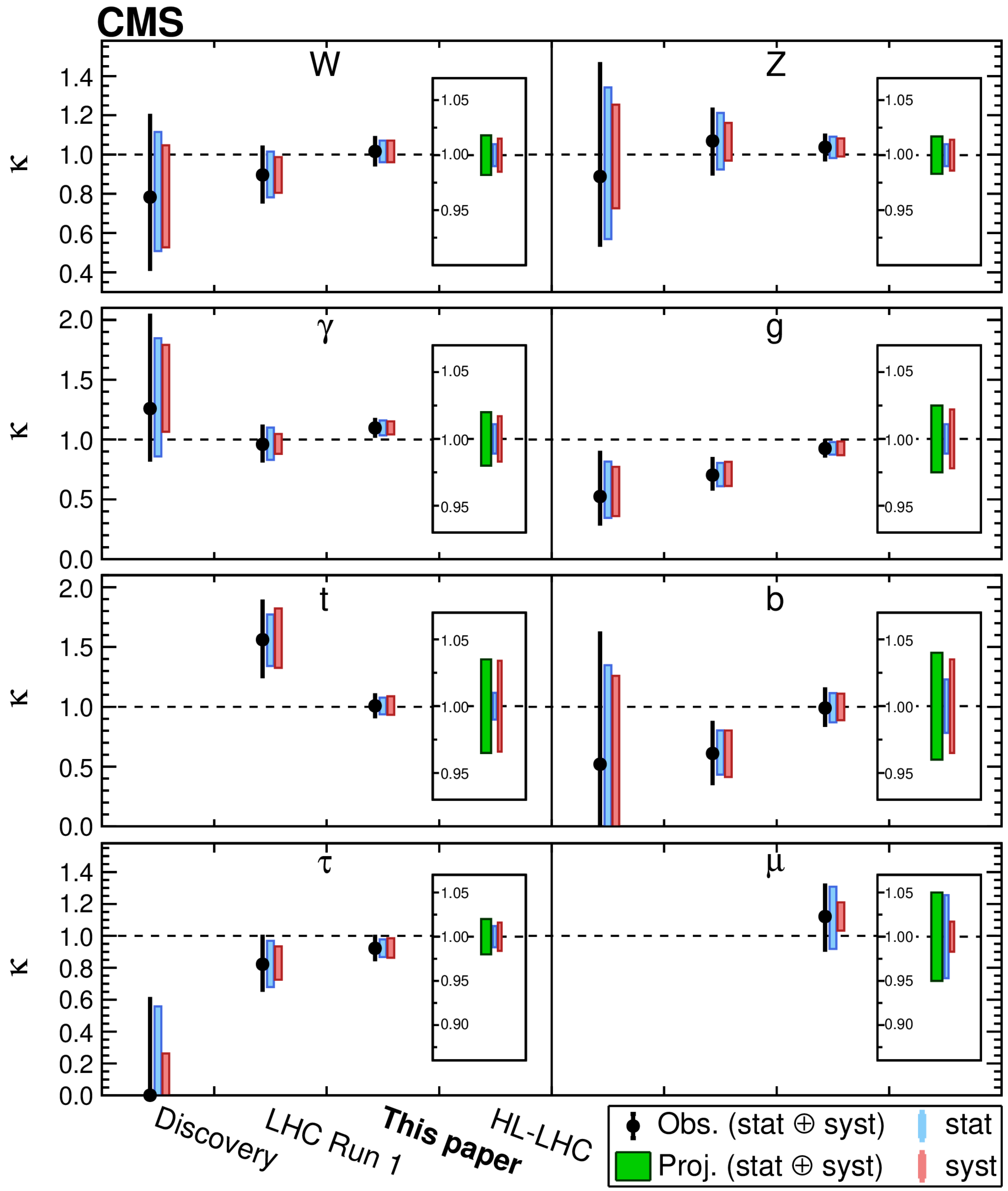
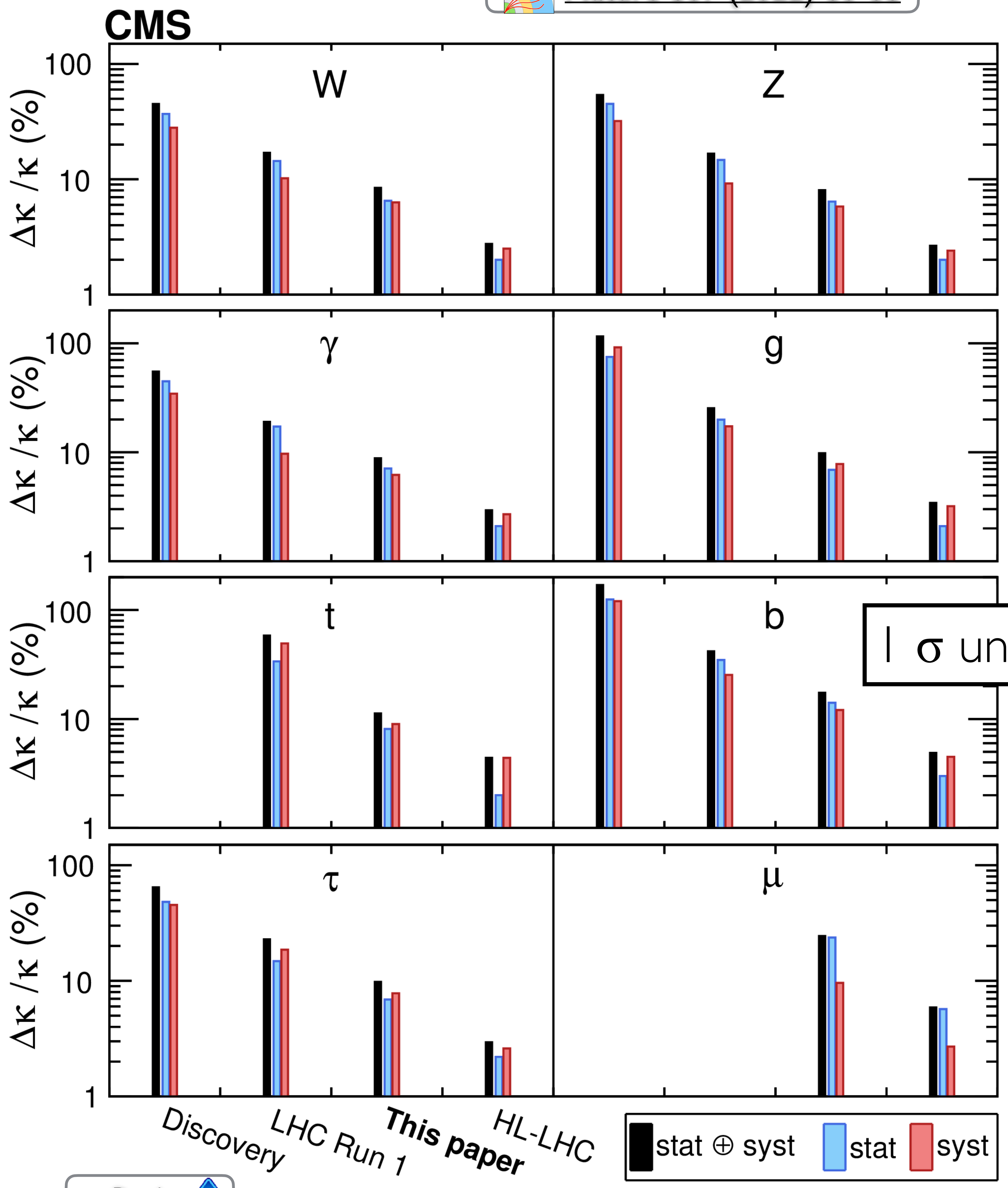
Coupling Combination and HL-LHC

Nature 607 (2022) 60-68





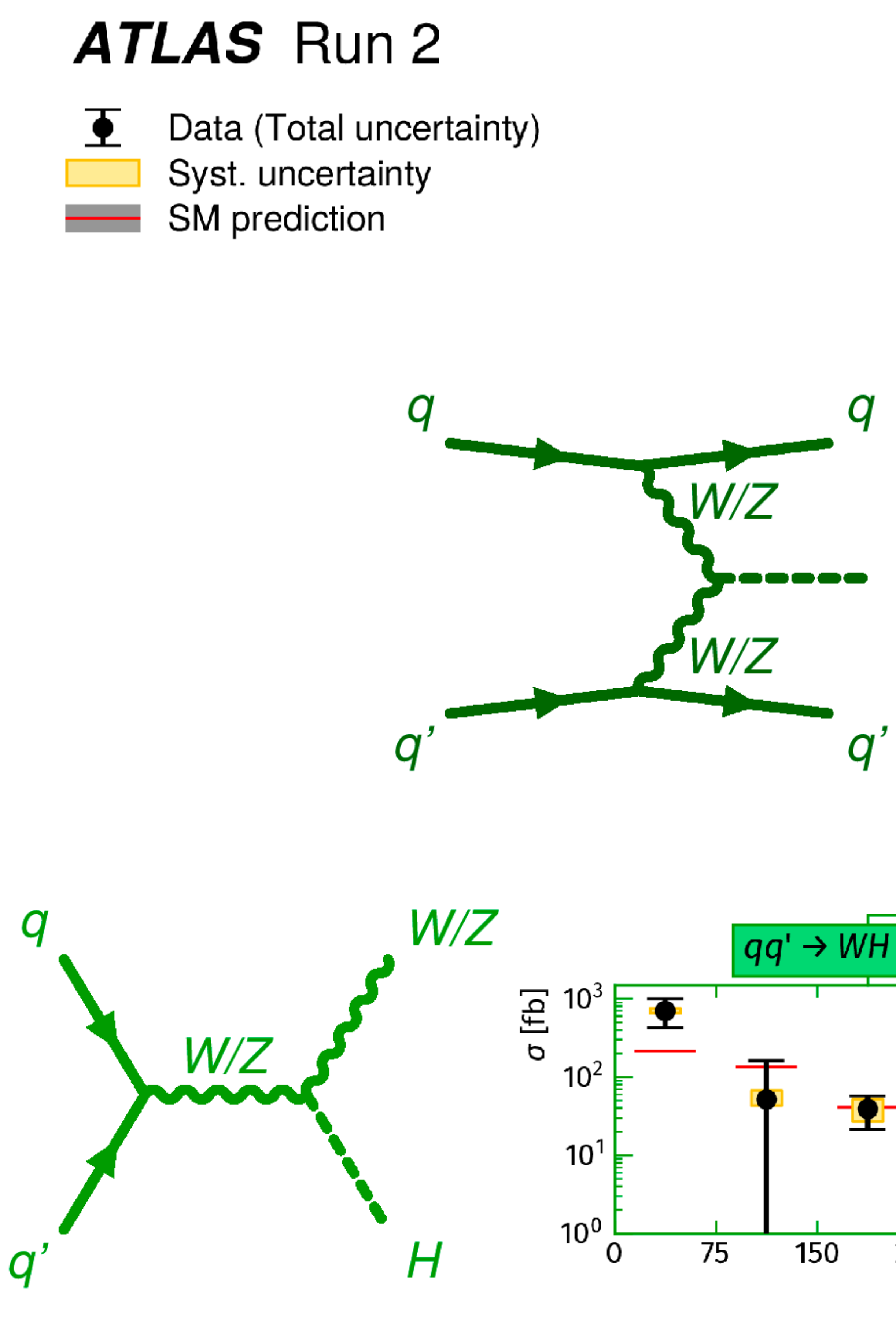
1 σ uncertainties

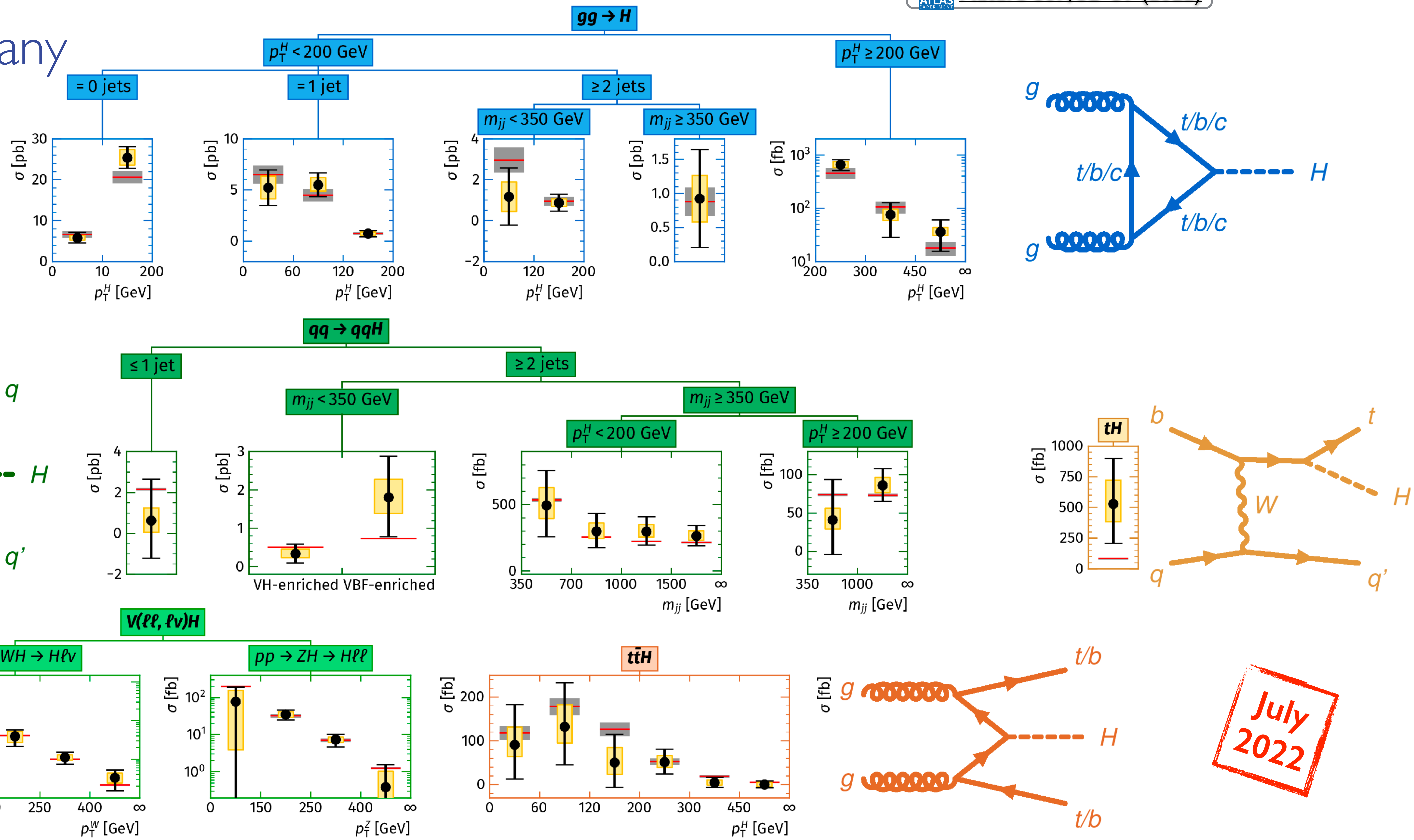
⇒ Back

Combined STXS Measurement

Nature 607, 52–59 (2022)

Measurements in many kinematic regions



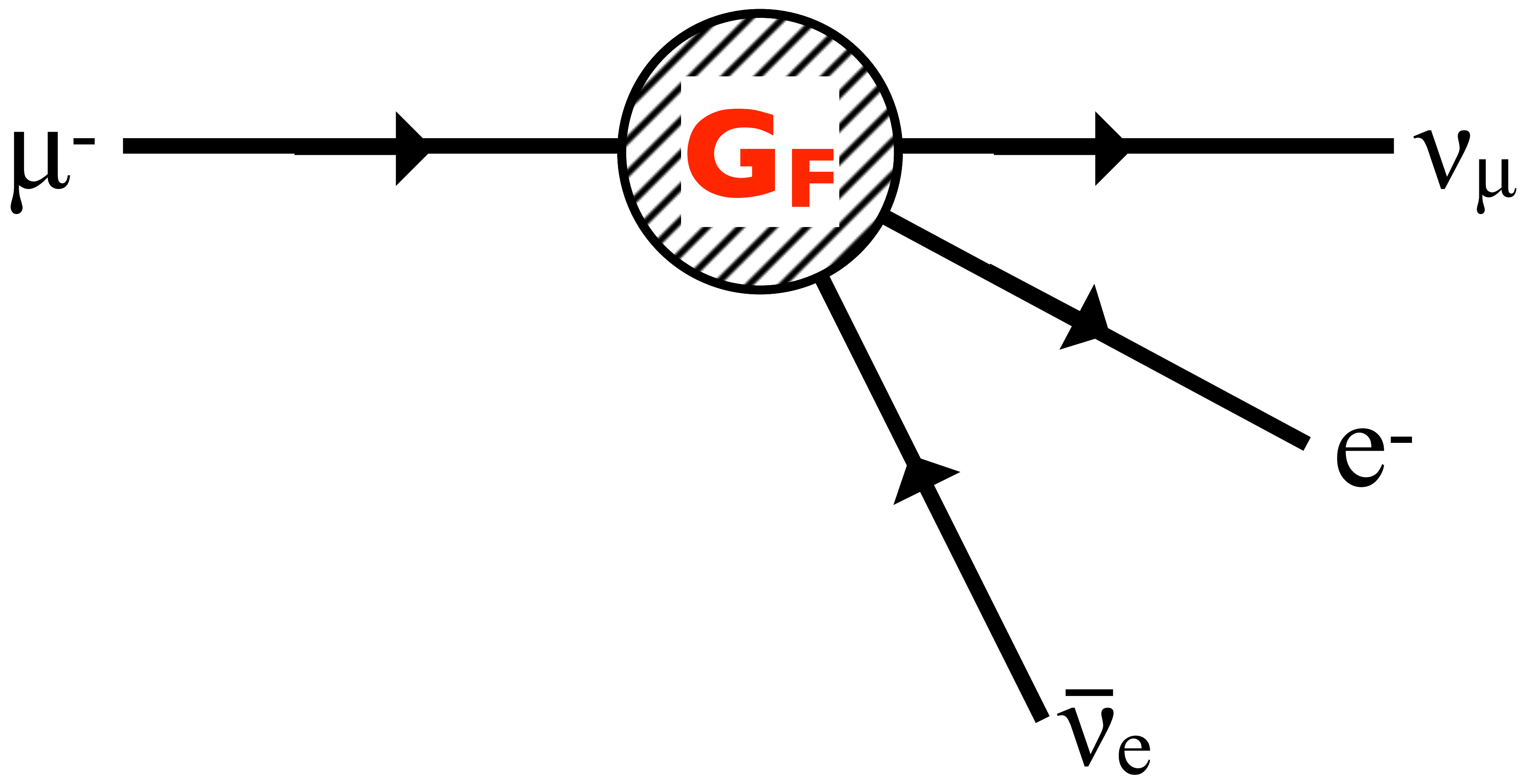


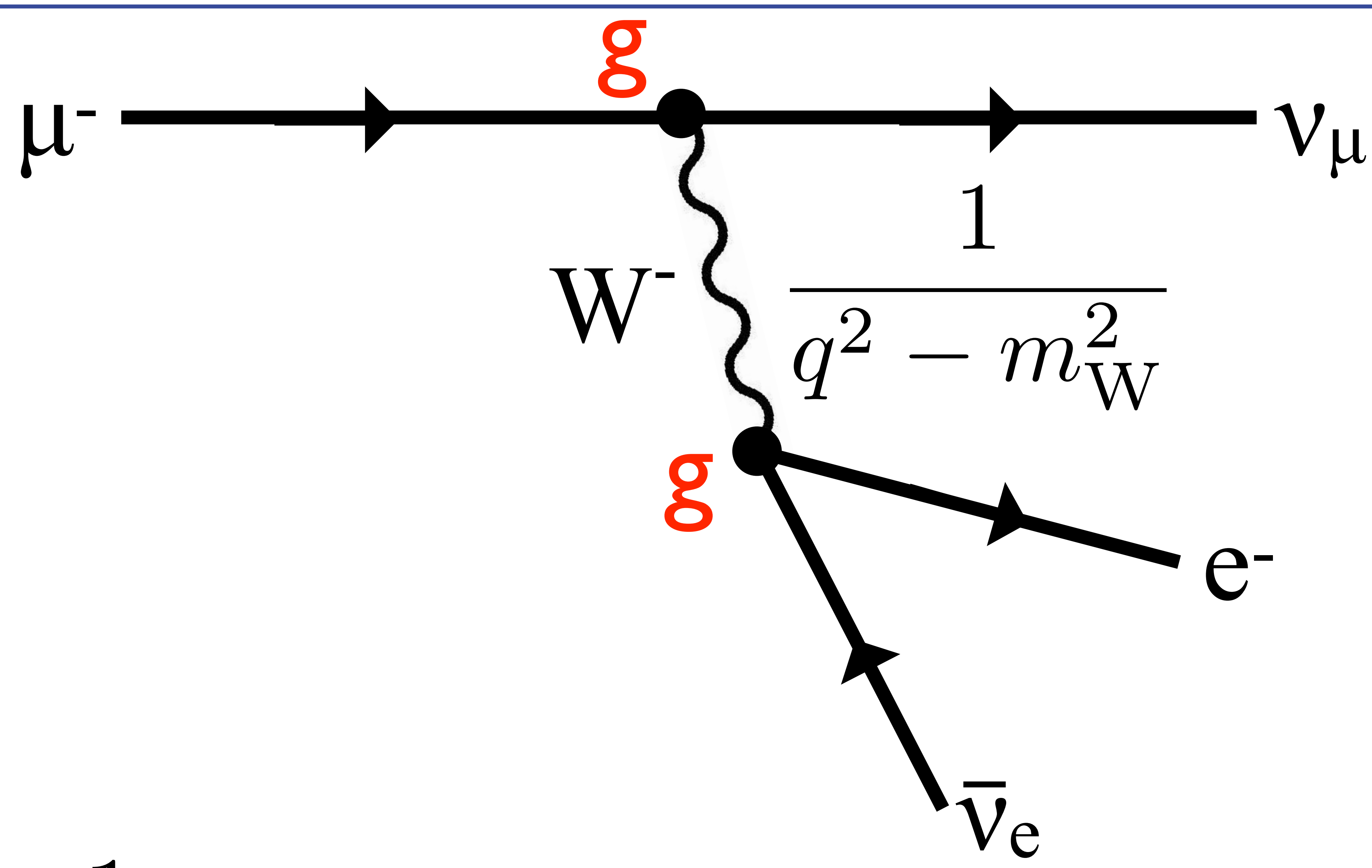
Karsten Köneke

Effective Field Theories: Muon Decay

Fermi-Theory (1933)
Effective Field Theory

Theory of Weak Interaction
"Full" Field Theory





For $q^2 << m_W^2$ is $\frac{1}{q^2 - m_W^2} \rightarrow \frac{1}{-m_W^2}$ and $\frac{g^2}{8m_W^2} \rightarrow \frac{G_F}{\sqrt{2}}$

- Extend SM with new BSM operators:
  - Assume: No new particles below Λ = 1 TeV

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i c_i^{(6)} \mathcal{O}_i^{(6)} / \Lambda^2$$

⇒ Back

Effective Field Theory Interpretations

arXiv:2402.05742

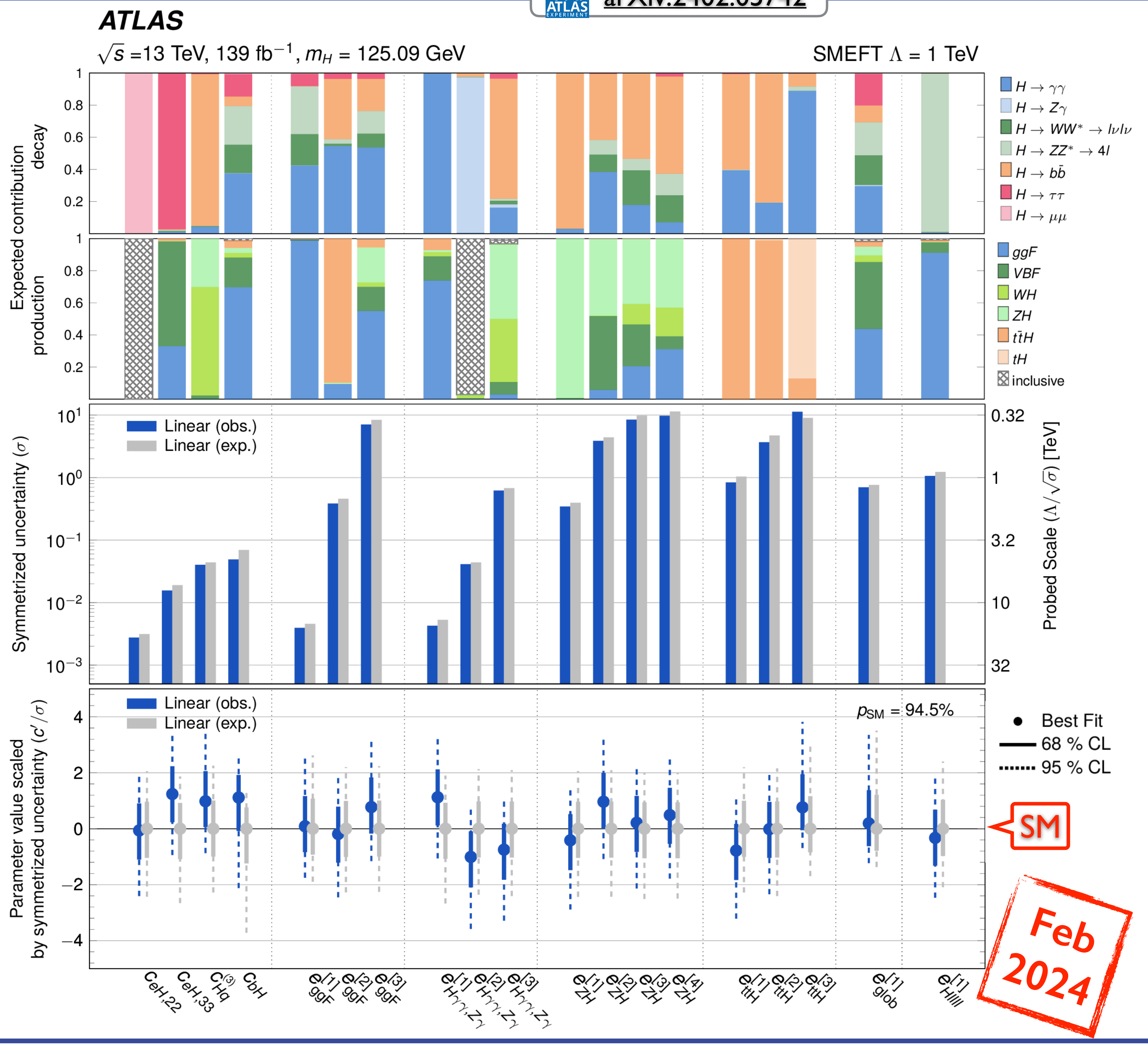
Extend SM with new physics operators:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i c_i^{(6)} O_i^{(6)} / \Lambda^2$$

(assumes no new particles below $\Lambda = 1$ TeV)

- EFT interpretation of Nature combination
- 19 EFT parameters fitted simultaneously!
  - Eigenvector rotation
    (to remove insensitive directions)

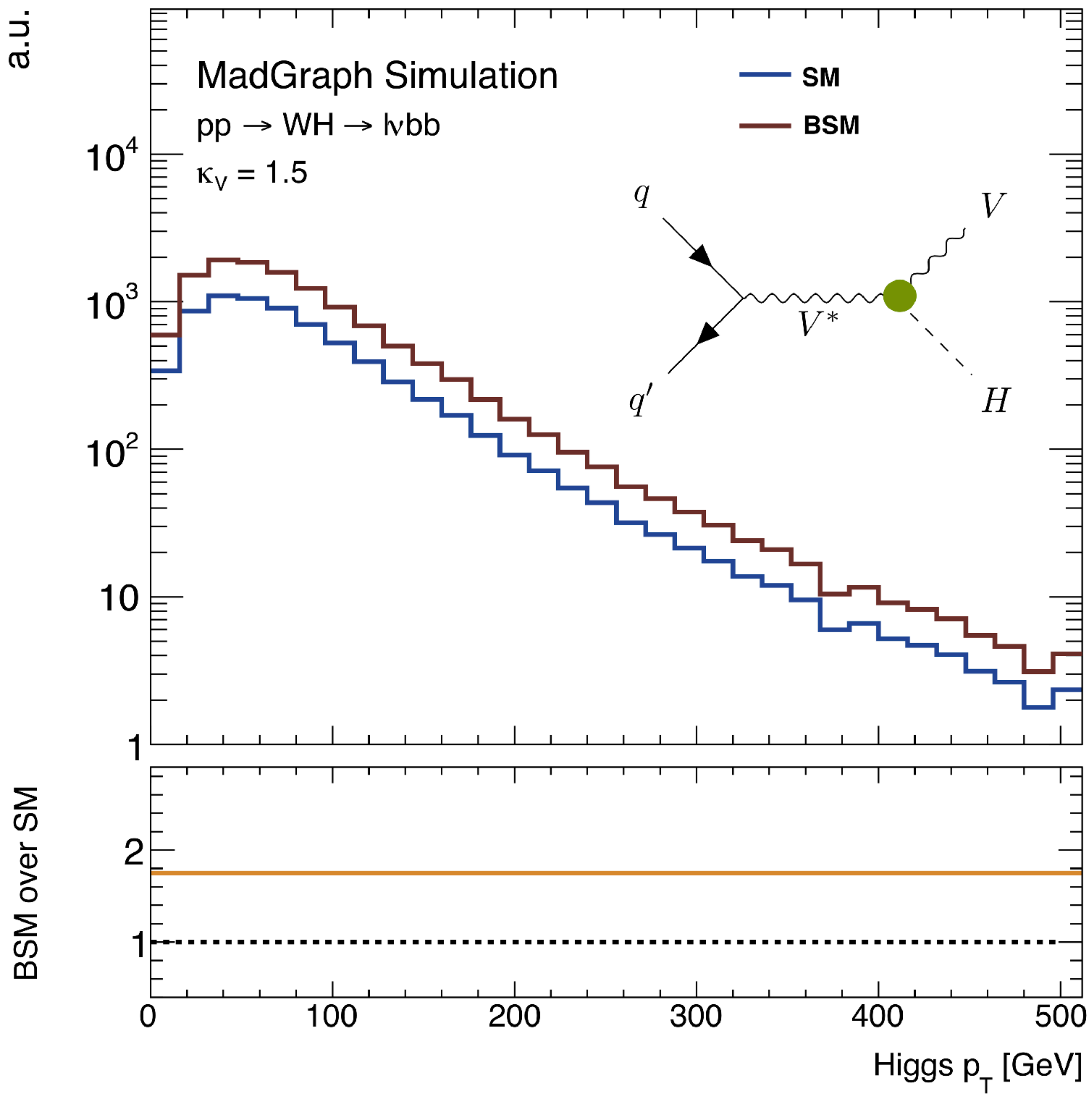
Opens the window to global combined analyses!



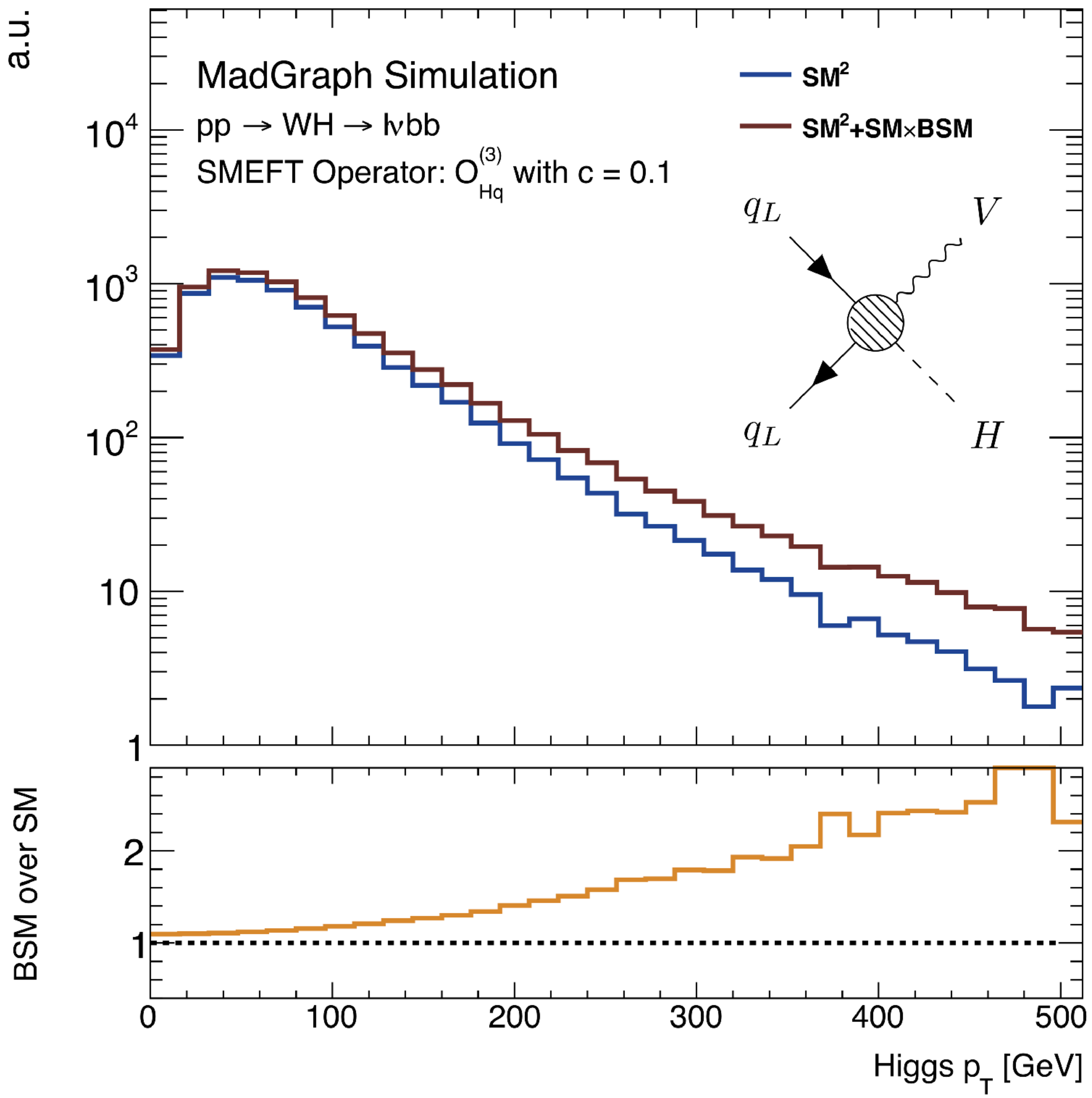
⇒ More

κ Framework vs. EFT Example

κ-framework: κ_V = 1.5



SMEFT: $O_{Hq}^{(3)}$ = 0.1



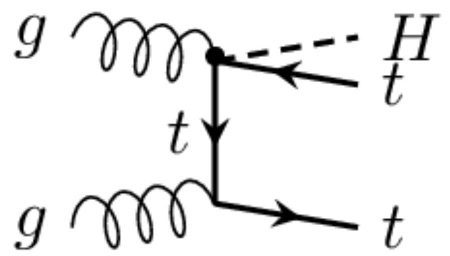
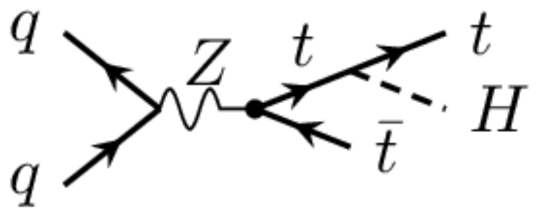
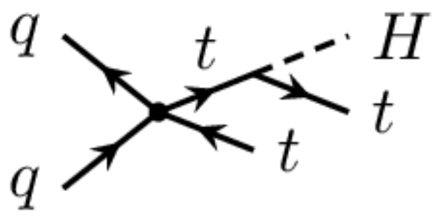
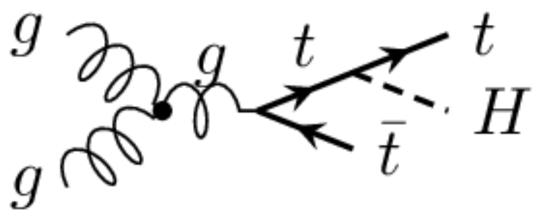
Graphics courtesy of Brian Moser at Higgs 2020

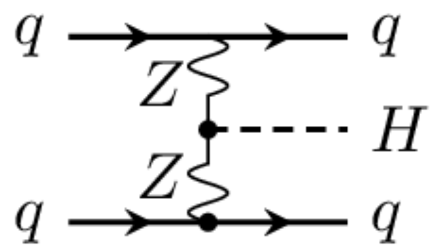
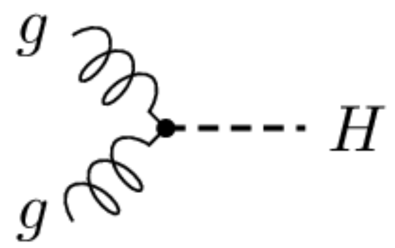
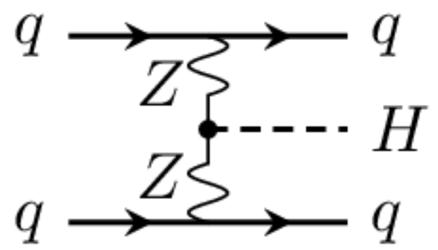
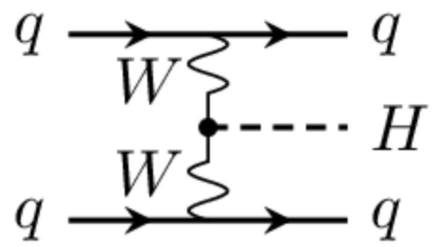
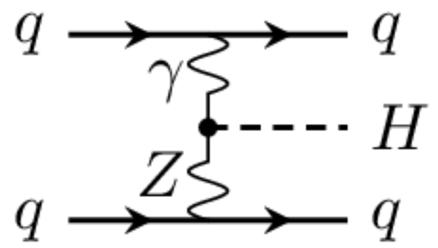
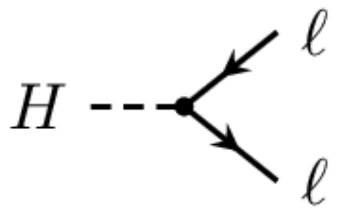
SMEFT

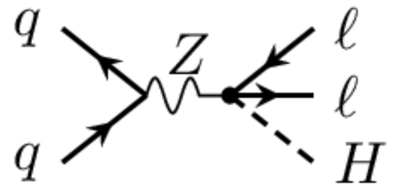
arXiv:2004.03447

CP-even			CP-odd			Impact on	
Operator	Structure	Coeff.	Operator	Structure	Coeff.	production	decay
O_{uH}	$HH^\dagger \bar{q}_p u_r \tilde{H}$	c_{uH}	O_{uH}	$HH^\dagger \bar{q}_p u_r \tilde{H}$	$c_{\tilde{u}H}$	ttH	-
O_{HG}	$HH^\dagger G^A_{\mu\nu} G^{\mu\nu A}$	c_{HG}	$O_{H\tilde{G}}$	$HH^\dagger \tilde{G}^A_{\mu\nu} G^{\mu\nu A}$	$c_{H\tilde{G}}$	ggF	Yes
O_{HW}	$HH^\dagger W^l_{\mu\nu} W^{\mu\nu l}$	c_{HW}	$O_{H\widetilde{W}}$	$HH^\dagger \widetilde{W}^l_{\mu\nu} W^{\mu\nu l}$	$c_{H\widetilde{W}}$	VBF, VH	Yes
O_{HB}	$HH^\dagger B_{\mu\nu} B^{\mu\nu}$	c_{HB}	$O_{H\tilde{B}}$	$HH^\dagger \tilde{B}_{\mu\nu} B^{\mu\nu}$	$c_{H\tilde{B}}$	VBF, VH	Yes
O_{HWB}	$HH^\dagger \tau^l W^l_{\mu\nu} B^{\mu\nu}$	c_{HWB}	$O_{H\widetilde{W}B}$	$HH^\dagger \tau^l \widetilde{W}^l_{\mu\nu} B^{\mu\nu}$	$c_{H\widetilde{W}B}$	VBF, VH	Yes

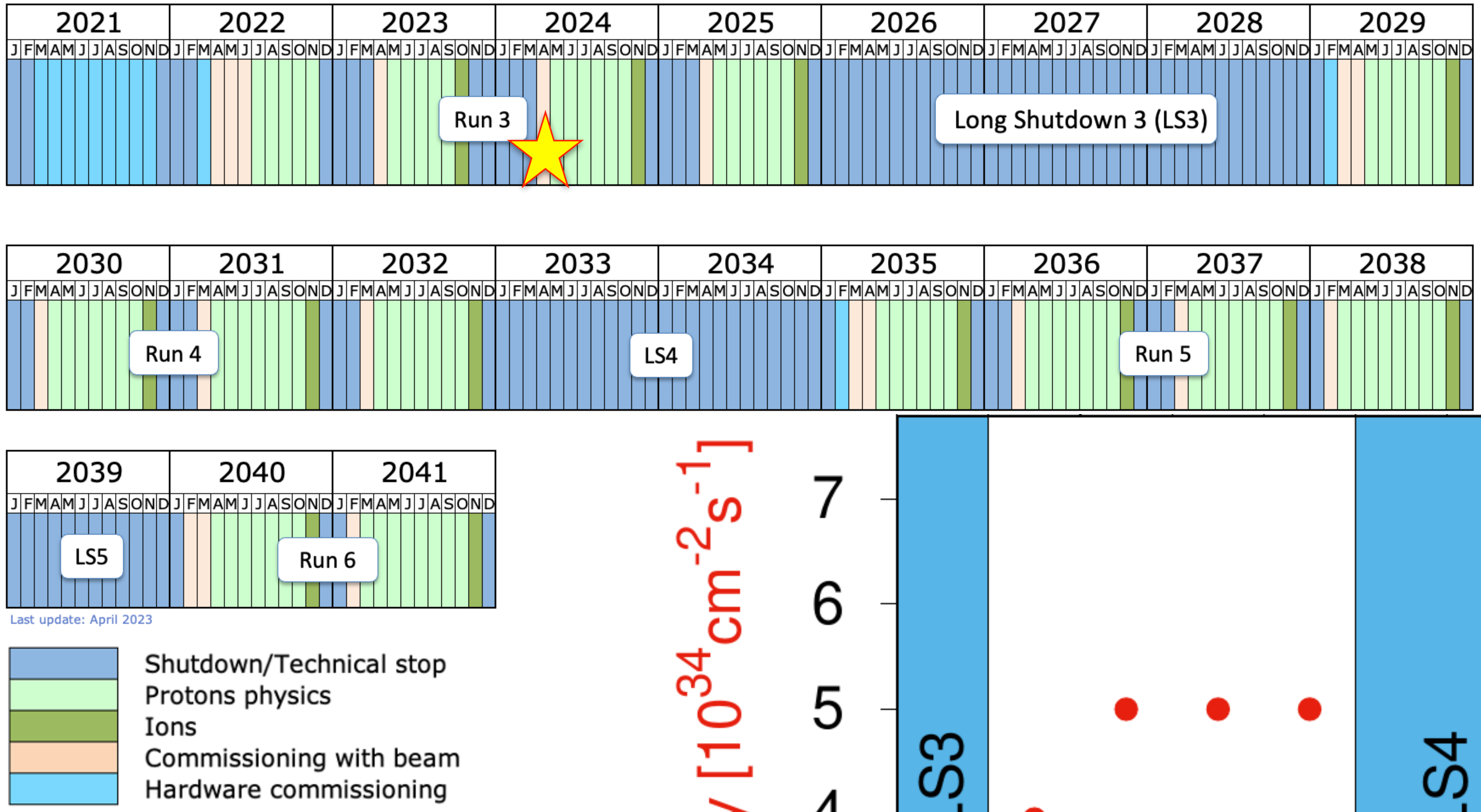
SMEFT

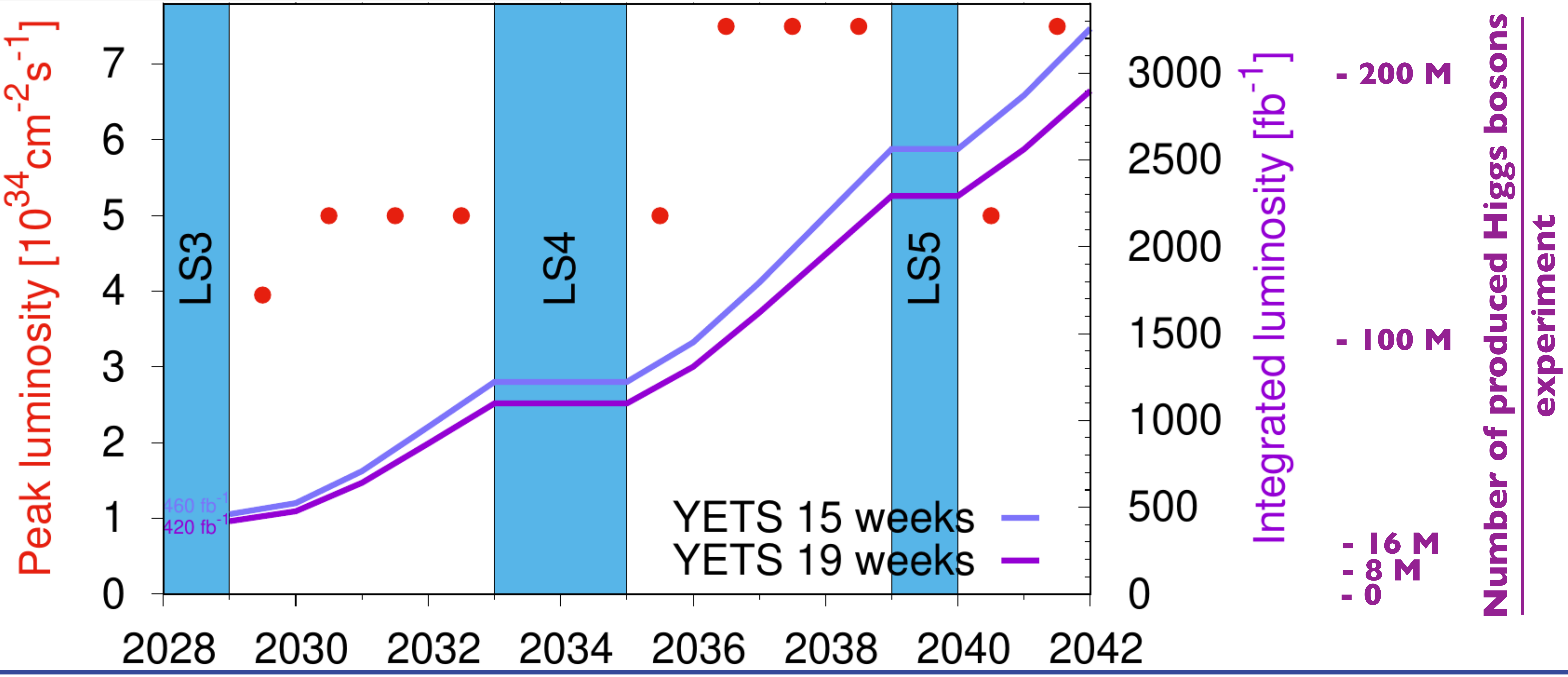
Coefficient	Operator	Example process
c_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H} \, G^A_{\mu\nu}$	
c_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H} \, W^I_{\mu\nu}$	
c_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H} \, B_{\mu\nu}$	
$c^{(1)}_{qq}$	$(\bar{q}_p \gamma_\mu q_t)(\bar{q}_r \gamma^\mu q_s)$	
$c^{(3)}_{qq}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	
c_{qq}	$(\bar{q}_p \gamma_\mu q_t)(\bar{q}_r \gamma^\mu q_s)$	
$c^{(31)}_{qq}$	$(\bar{q}_p \gamma_\mu \tau^I q_t)(\bar{q}_r \gamma^\mu \tau^I q_s)$	
c_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	
$c^{(1)}_{uu}$	$(\bar{u}_p \gamma_\mu u_t)(\bar{u}_r \gamma^\mu u_s)$	
$c^{(1)}_{qu}$	$(\bar{q}_p \gamma_\mu q_t)(\bar{u}_r \gamma^\mu u_s)$	
$c^{(8)}_{ud}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	
$c^{(8)}_{qu}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$	
$c^{(8)}_{qd}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$	
c_G	$f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	

Coefficient	Operator	Example process
c_{HDD}	$\left(H^\dagger D^\mu H\right)^* \left(H^\dagger D_\mu H\right)$	
c_{HG}	$H^\dagger H \, G^A_{\mu\nu} G^{A\mu\nu}$	
c_{HB}	$H^\dagger H \, B_{\mu\nu} B^{\mu\nu}$	
c_{HW}	$H^\dagger H \, W^I_{\mu\nu} W^{I\mu\nu}$	
c_{HWB}	$H^\dagger \tau^I H \, W^I_{\mu\nu} B^{\mu\nu}$	
c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$	

Coefficient	Operator	Example process
$c^{(1)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$	
$c^{(3)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	
c_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$	
$c^{(1)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	
$c^{(3)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$	
c_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$	
c_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$	

High Luminosity LHC (HL-LHC)





Karsten Köneke

A bright Future…

arXiv:1905.03764

A bright Future…

arXiv:1905.03764

A bright Future…

- k combination with next colliders (initial stages only)

arXiv:2209.07510