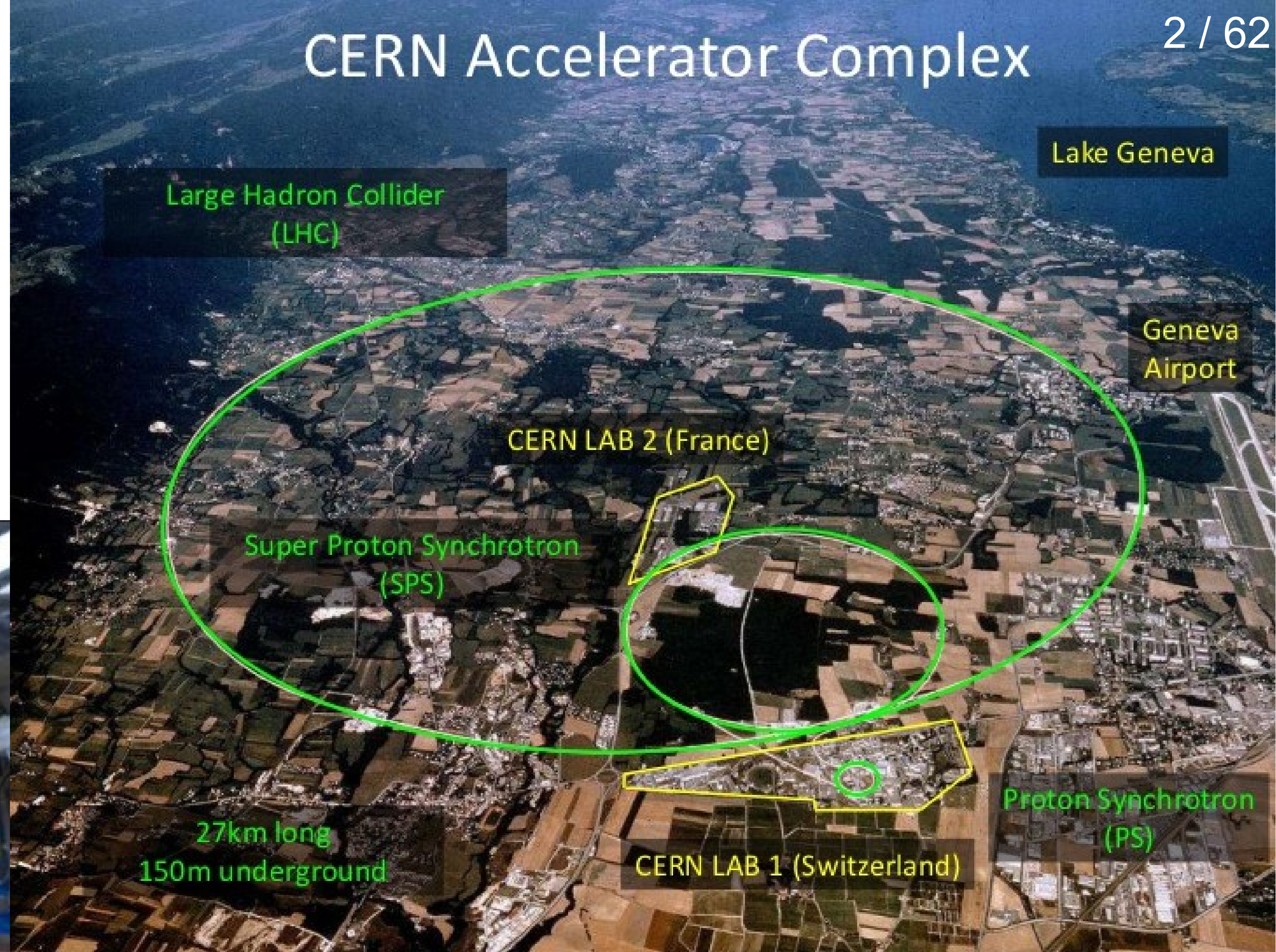
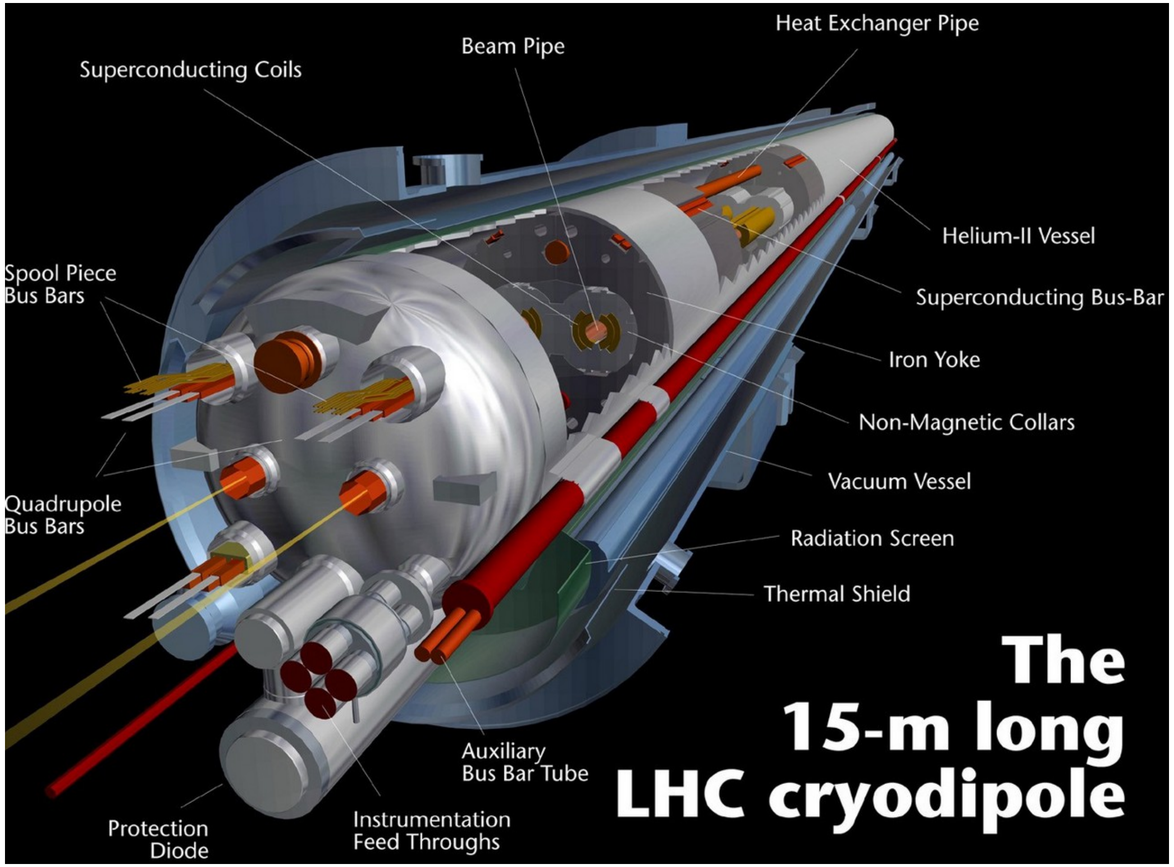
# BSM Higgs Searches at ATLAS

Jana Schaarschmidt (University of Washington)

Bonn – 08 December 2022


# Large Hadron Collider (LHC)



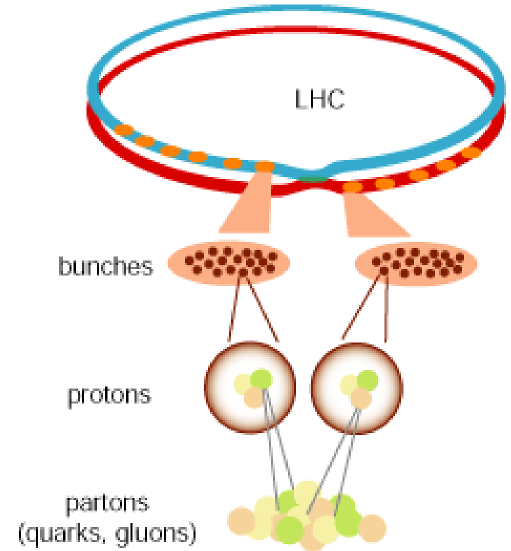

Super-conducting magnets operated with Helium at 1.9 K (colder than space!)

Vacuum in the beam pipe at $10^{-13}$ atm

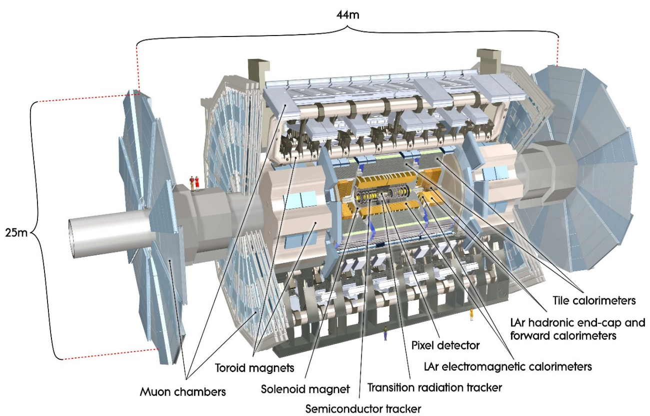
Protons accelerated to 99.999991% of the speed of light

$10^{11}$ protons per bunch,
~2800 bunches per beam

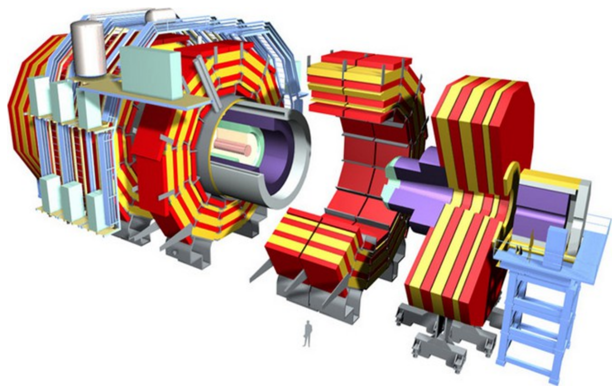
40 M bunch crossings per second



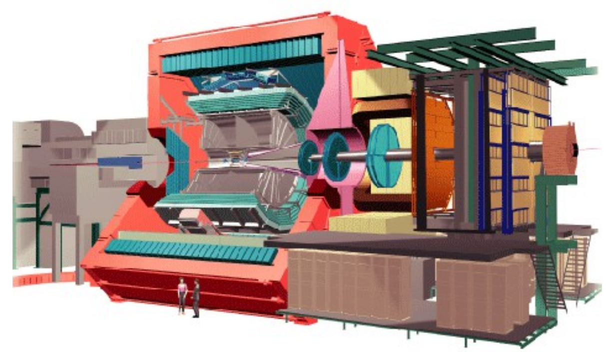

Four large detectors along the ring:



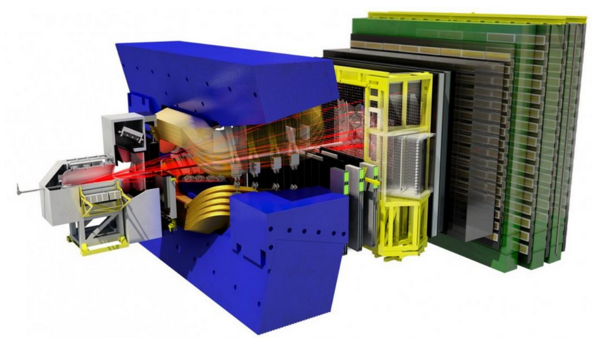

ATLAS



CMS



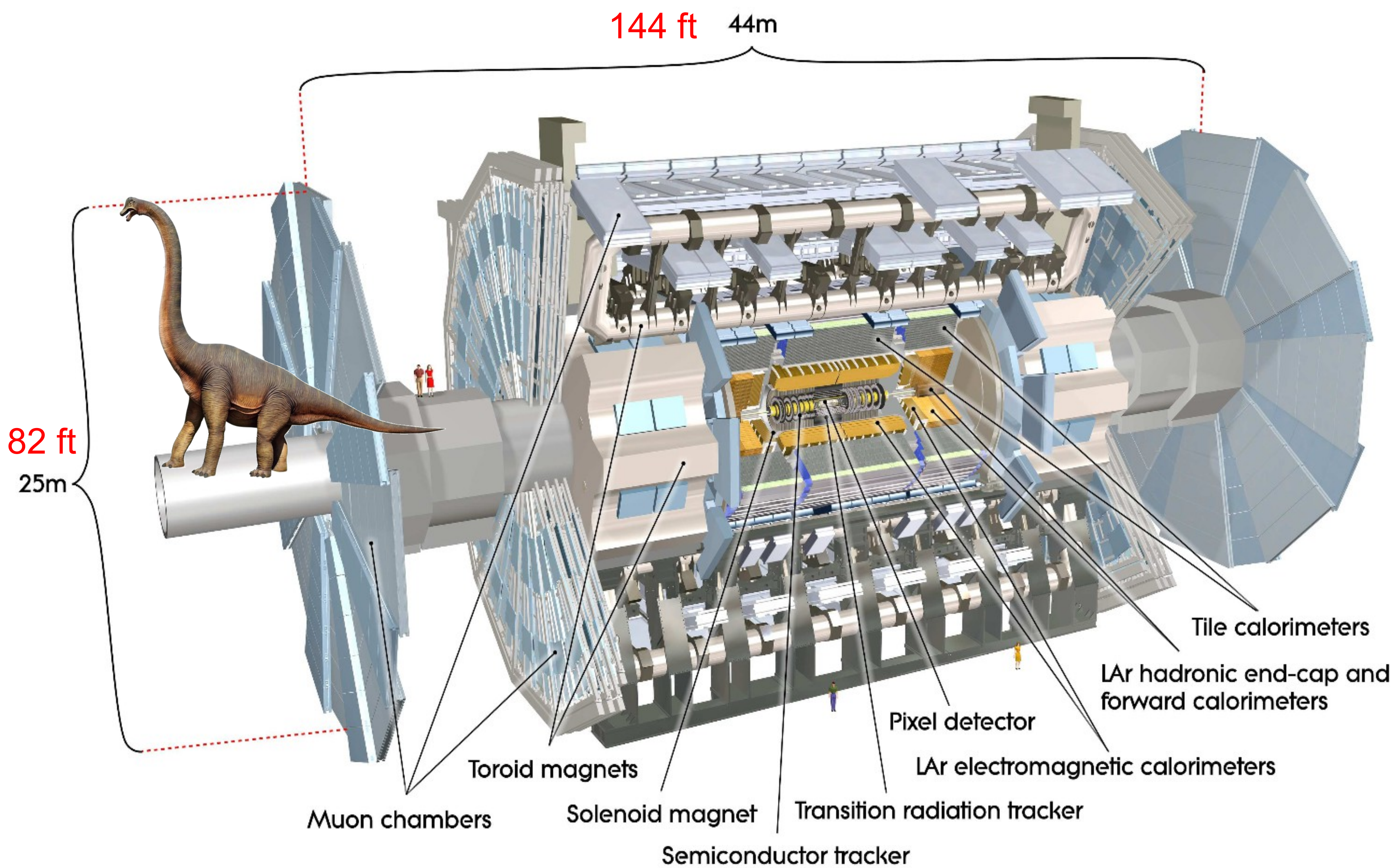
ALICE



LHCb

# The ATLAS Detector



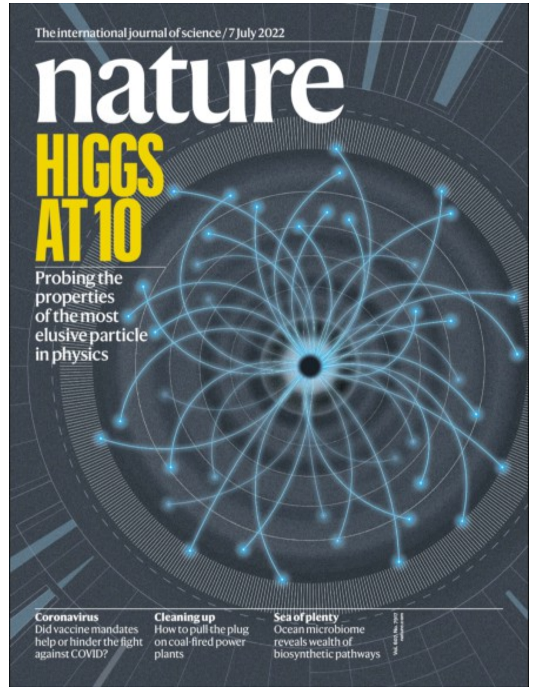



**Rich physics program:**

- Precise Standard Model measurements (EW, top, QCD, ...)
- Study of the electroweak symmetry breaking
- Searches for new physics (new resonances, dark matter, ...)

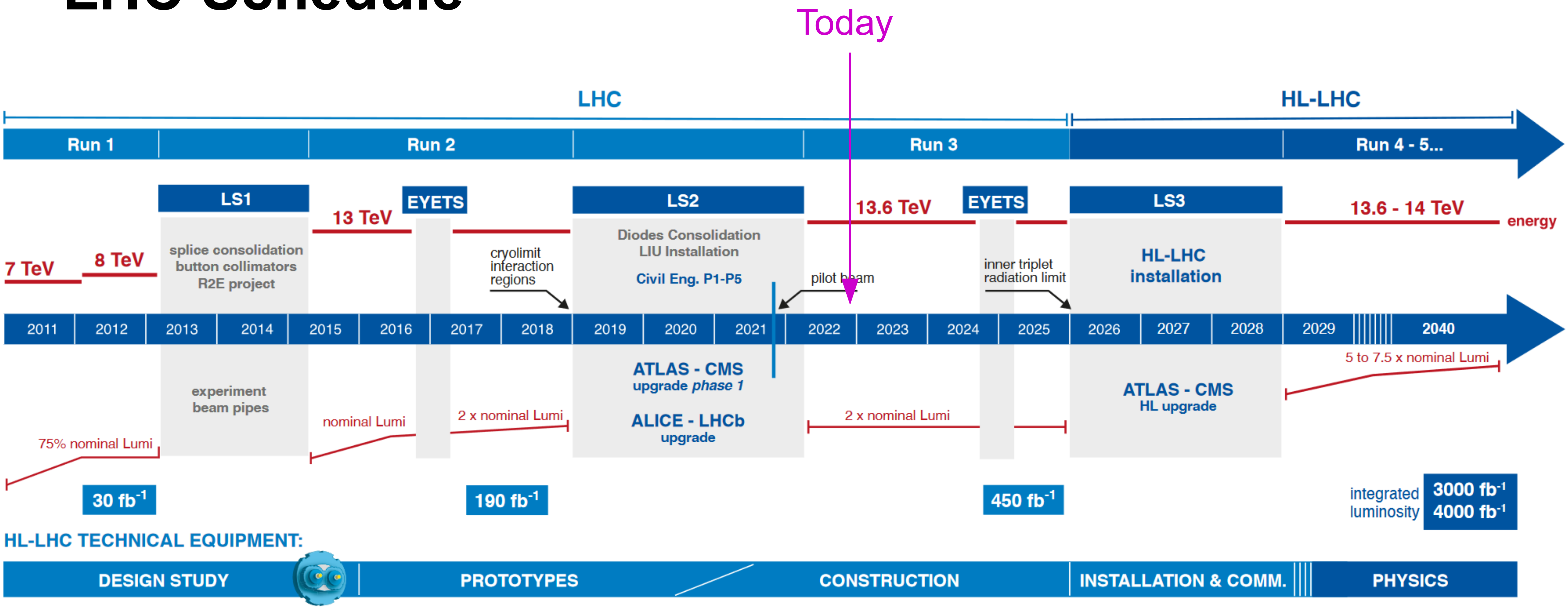

>6000 members, 2600 active authors

CERN 10 years HIGGS boson discovery





# LHC Schedule

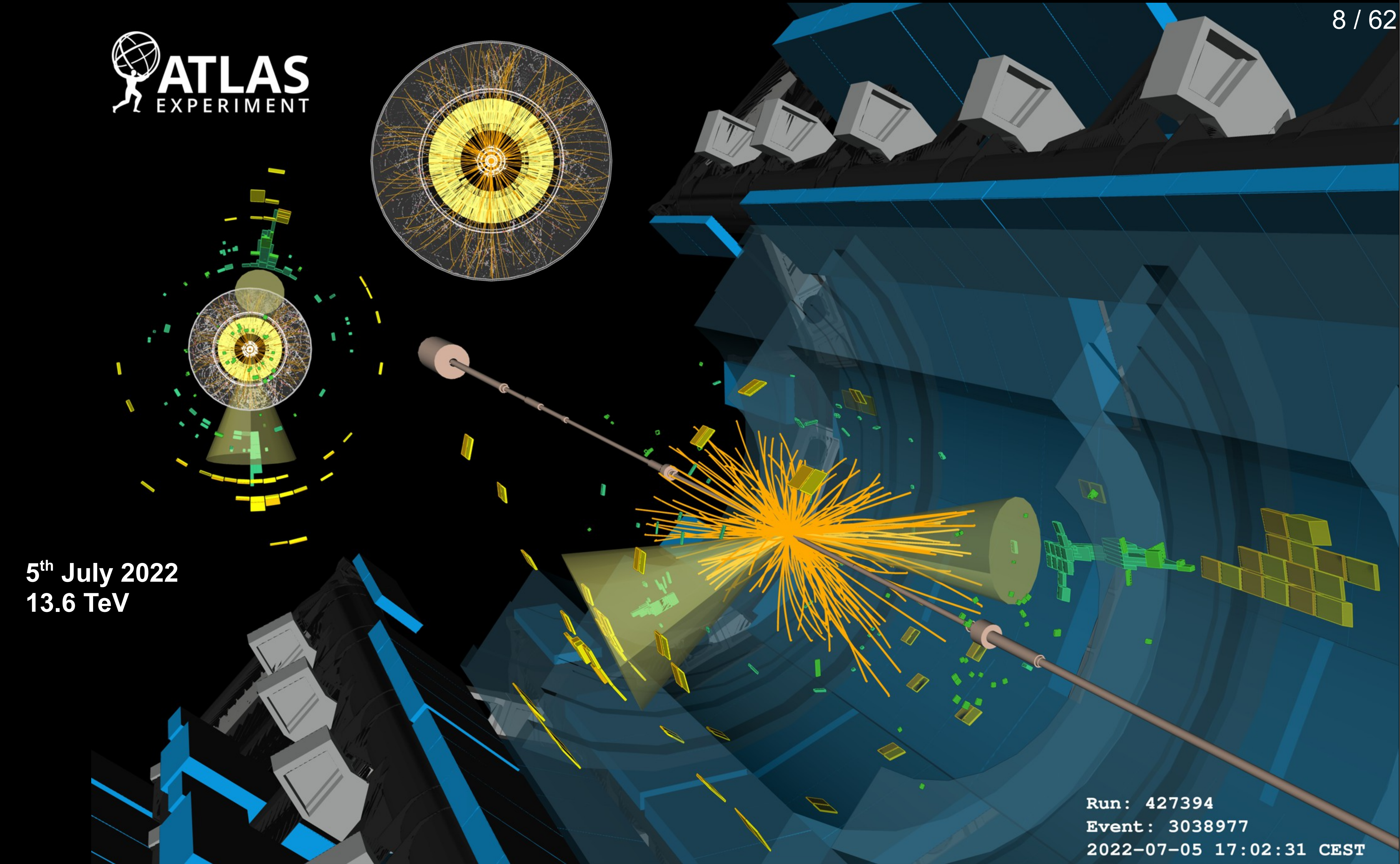



Run1: 25/fb usable data at 7-8 TeV
Run2: 140/fb usable data at 13 TeV
Run3: Expect to take ~250/fb of data at 13.6 TeV

~10% of the total LHC dataset

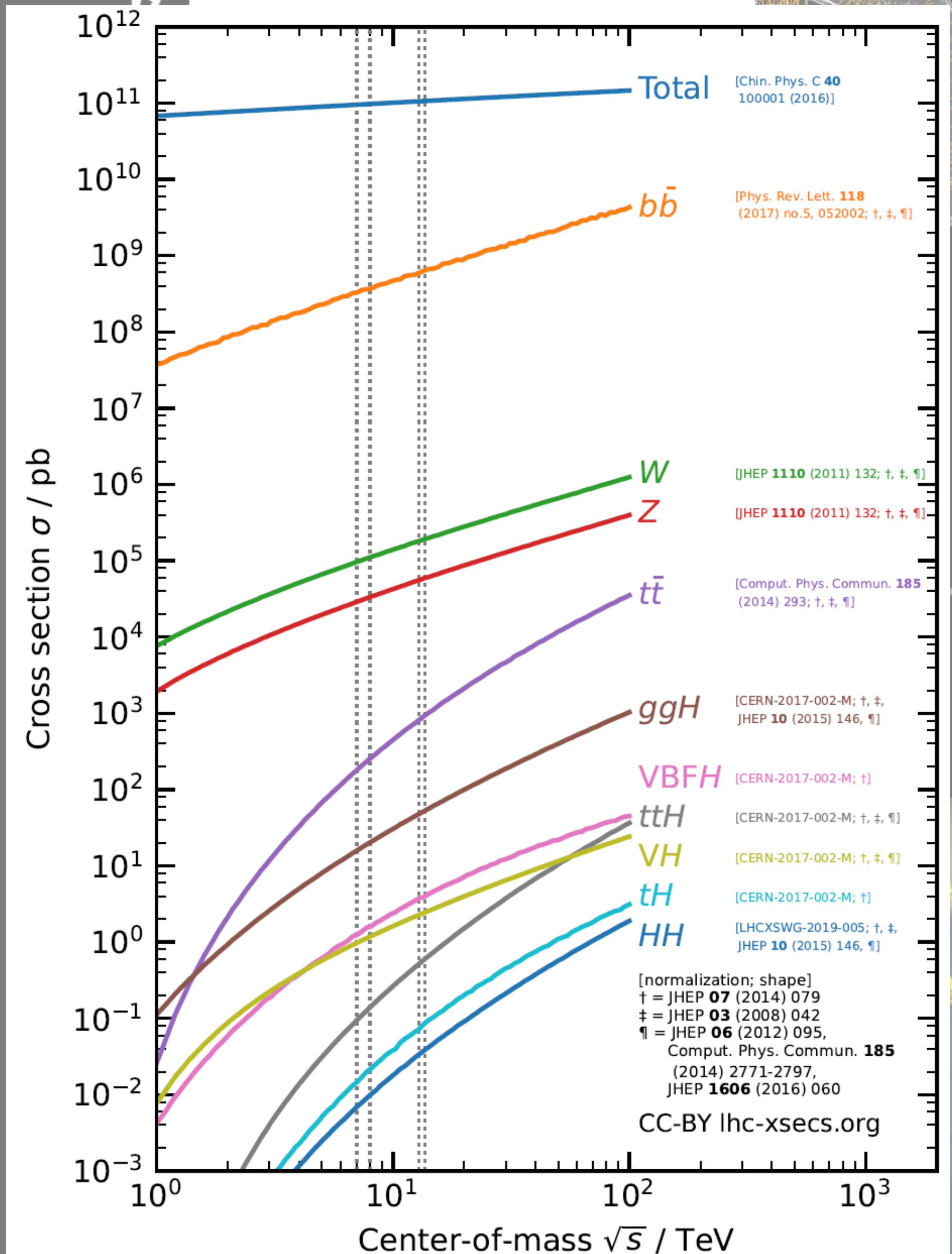
HL-LHC: 3-4/ab at 13.6-14 TeV

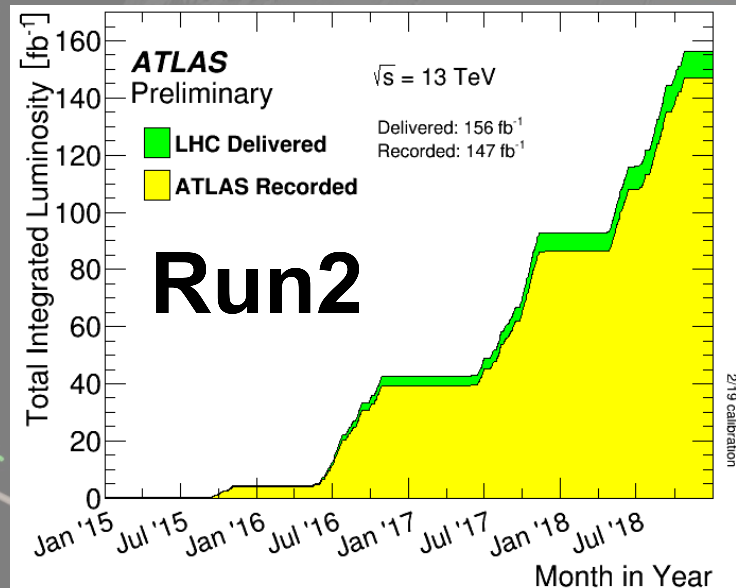
~90% of the total LHC dataset

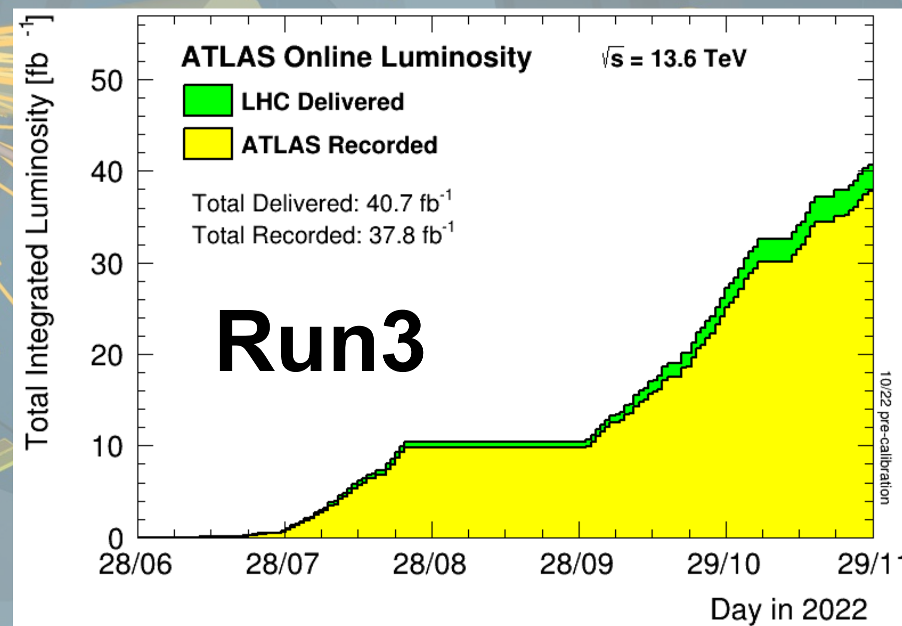

ATLAS
EXPERIMENT
5th July 2022
13.6 TeV
Run: 427394
Event: 3038977
2022-07-05 17:02:31 CEST

# Data Taking: Run2 to Run3

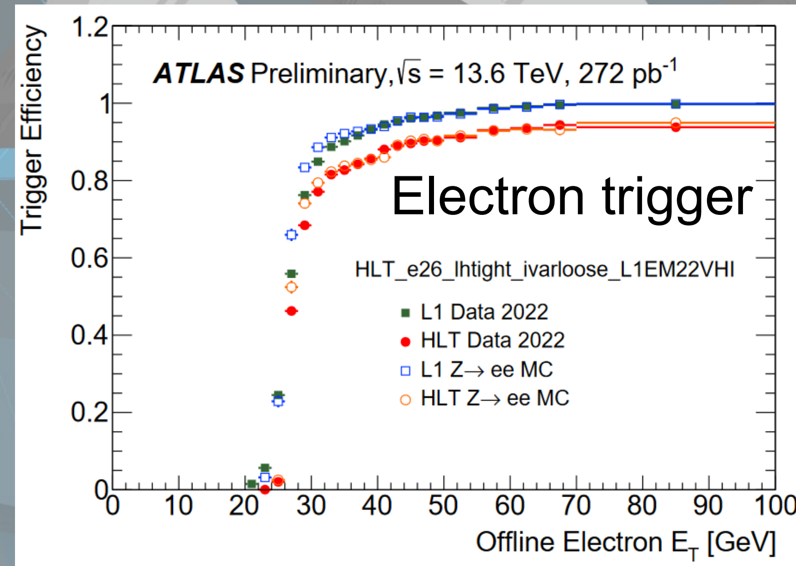
## 13 TeV → 13.6 TeV

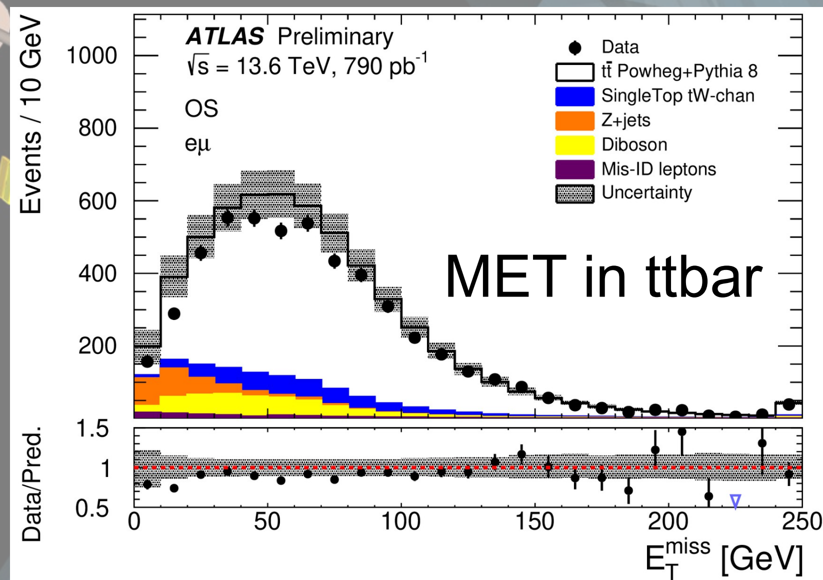


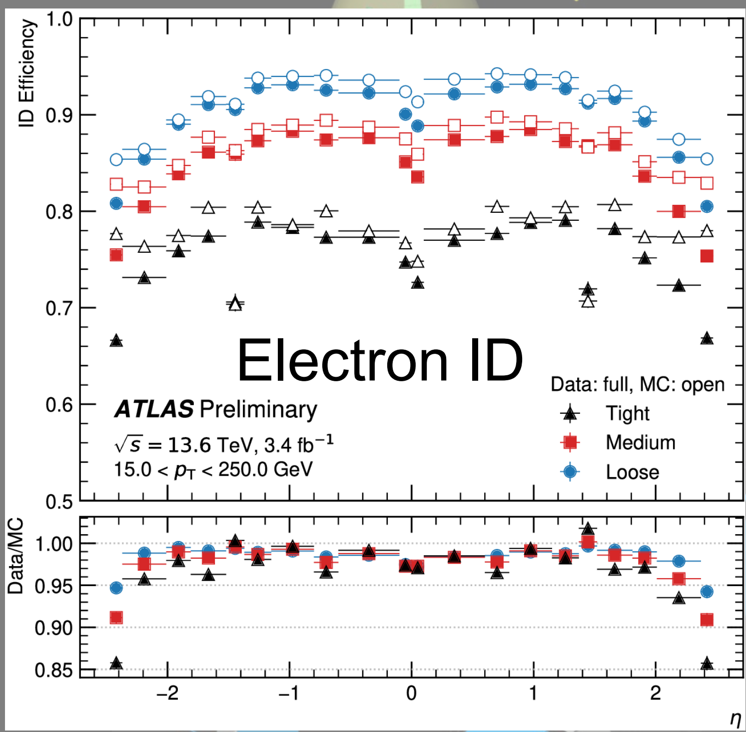



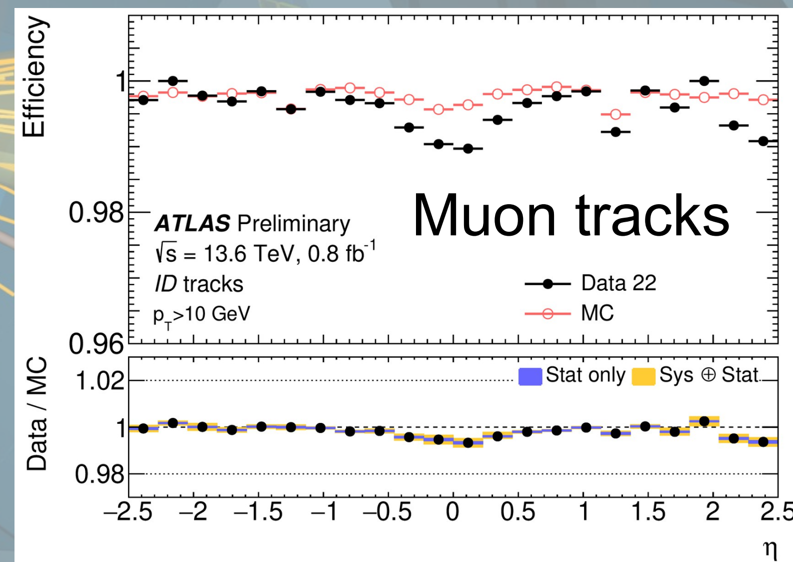



# Run-3 Performance Studies




**All performance results:**
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/WebHome#CPGroups

# Motivation for BSM Higgs Searches

Inflation

Dark matter

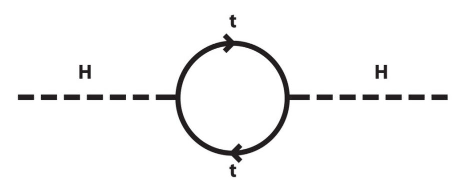
Grand Unified Theory

Neutrino Masses

Gravity

Matter-antimatter asymmetry

Higgs mass fine tuning




SM Parameters

Dark Energy

The Standard Model is not the final answer in physics, but it is a part of a greater theory

# BSM Higgs Models

- Interesting are those models, that have an extended Higgs sector, to which we are sensitive
- Typically we explore models that extend the SM in a minimal way, ie. less model parameters

SM Higgs field: SU(2) doublet: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ — One scalar (125 GeV Higgs)

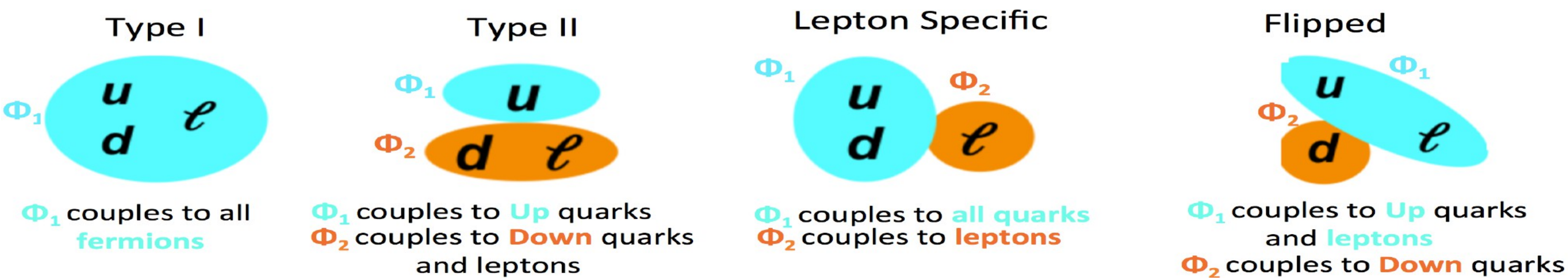
SM + real singlet — 2 scalars: h, H

SM + complex singlet — 3 scalars: $h_1$, $h_2$, $h_3$

Two Higgs Doublet Model: $\phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}$ — 5 scalars: h, H, A, $H^+$, $H^-$

$\tan\beta = vev_2/vev_1$

MSSM (Minimal Supersymmetric extension of the SM): A type-II 2HDM, with SUSY




(S. Semlali)

NMSSM, 2HDM+S: — 7 scalars: h, $H_1$, $H_2$, $A_1$, $A_2$, $H^+$, $H^-$

Georgi-Machacek (1 doublet+2 triplets): — 10 scalars: h, $H_1$, $H_3$, $H_5$, $H_3^+$, $H_3^-$, $H_5^+$, $H_5^-$, $H_5^{++}$, $H_5^{--}$

# LHC Higgs Working Group

Group founded 2010 to bring together theorists and LHC experimentalists, to:

- produce agreement on cross sections, BR and pseudo observables relevant for SM and BSM Higgs bosons
- provide the experimental collaborations with information in various forms (twikis, reports, …)
- Overall twiki: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG
- Last week: 19th Workshop of the LHCHWG https://indico.cern.ch/event/1169286/

WG3 (BSM Higgs) currently has 5 subgroups, everyone is invited to join egroups, come to the meetings and collaborate:

- MSSM
- NMSSM
- Extended Higgs Sector
- Exotic Higgs decays
- bbH

WG3 Twiki: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG3

WG3 mailing list: lhc-higgs-bsm@cern.ch

# Direct searches for BSM associated to the Higgs boson

**Low mass states**
Typically "soft" signatures

**High mass states**
Typically "high-$p_T$" signatures

$m_h$
125 GeV

- Additional (light) Higgs states
- BSM Higgs decays and couplings
  - light resonances
  - enhanced rare decays
  - flavor violating couplings
  - long lived particles
  - invisible decays

- Additional (heavy) Higgs states
  - neutral or charged
  - decays to SM particles, or new scalars (ie. cascades)
  - invisible decays

These efforts are **complementary to measurements of Higgs boson properties** (spin, CP, couplings, decay rates, total width, …) to search for deviations from the SM

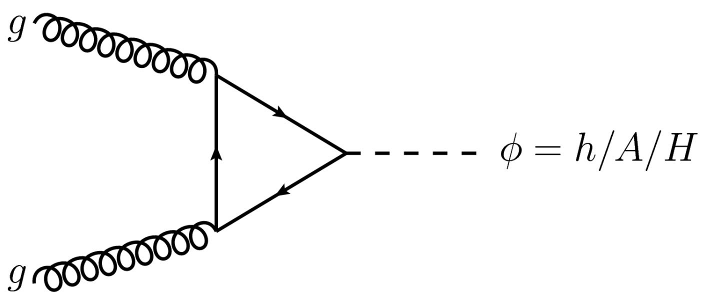
# Searches for additional (heavy) Higgs

| | | |
|---|---|---|
| $A/H \to \tau\tau$ | arXiv:2002.12223 | 139/fb |
| $A/H \to \mu\mu$ | arXiv:1901.08144 | 36/fb |
| (b)A/H $\to$ (b)bb | arXiv:1907.02749 | 28/fb |
| A/H $\to$ ttbar | arXiv:1707.06025 | 8 TeV, 20/fb |
| ttH, A/H $\to$ ttbar | arXiv:2211.01136 | 139/fb |
| H $\to$ ZZ $\to$ 4l or ll$\nu\nu$ | arXiv:1907.02749 | 139/fb |
| X $\to$ VV (Semileptonic) | arXiv:2004.14636 | 139/fb |
| X $\to$ VV (All-hadronic) | arXiv:2004.14636 | 139/fb |
| H $\to$ WW (e$\nu\mu\nu$) | ATLAS-CONF-2022-066 | 139/fb |
| VH, H $\to$ VV $\to$ 2 leptons | arXiv:2211.02617 | 139/fb |
| Heavy H $\to \gamma\gamma$ | arXiv:2102.13405 | 139/fb |
| Intermediate H $\to \gamma\gamma$ | ATLAS-CONF-2018-025 | 80/fb |
| Light H $\to \gamma\gamma$ | arXiv:2211.04172 | 138/fb |
| H $\to$ V$\gamma$ | ATLAS-CONF-2021-041 | 139/fb |
| A $\to$ Zh (125) | arXiv:2207.00230 | 139/fb |
| A $\to$ ZH or H $\to$ ZA (not 125) | arXiv:2011.05639 | 139/fb |
| (Heavy) H $\to$ invisible | arXiv:2202.07953 | 139/fb |

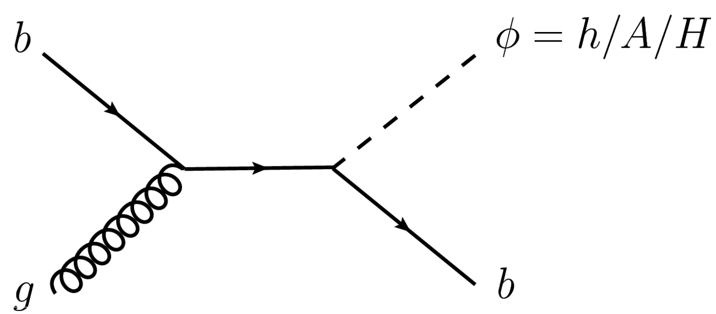
# Searches for additional (heavy) Higgs

| | | |
|---|---|---|
| ggF $H \to hh \to 4b$ | arXiv:2202.07288 | 139/fb |
| VBF $H \to hh \to 4b$ | arXiv:2001.05178 | 126/fb |
| $H \to hh \to bb\tau\tau$ | arXiv:2209.10910 | 139/fb |
| Boosted $H \to hh \to bb\tau\tau$ | arXiv:2007.14811 | 139/fb |
| $H \to hh \to bb\gamma\gamma$ | arXiv:2112.11876 | 139/fb |
| $H \to hh \to bbWW$ | arXiv:1811.04671 | 36/fb |
| $H \to hh/ss \to 4W$ | arXiv:1811.11028 | 36/fb |
| $H \to hh \to WW\gamma\gamma$ | arXiv:1807.08567 | 36/fb |
| $H \to hh$ Combination | arXiv:1906.02025 | 36/fb |
| $H^+ \to WA$ | ATLAS-CONF-2021-047 | 139/fb |
| $H^+ \to cb$ | ATLAS-CONF-2021-037 | 139/fb |
| $H^+ \to cs$ | arXiv:1302.3694 | 5/fb, 7 TeV |
| $H^+ \to tb$ | arXiv:2102.10076 | 139/fb |
| $H^+ \to \tau\nu$ | arXiv:1807.07915 | 36/fb |
| $H^+ \to WZ$ | arXiv:1806.01532 | 36/fb |
| $H^{++} \to WW$ | arXiv:2101.11961 | 139/fb |
| $H^{++} \to ll$ | arXiv:2211.07505 | 139/fb |

# A/H → ττ




Gluon fusion

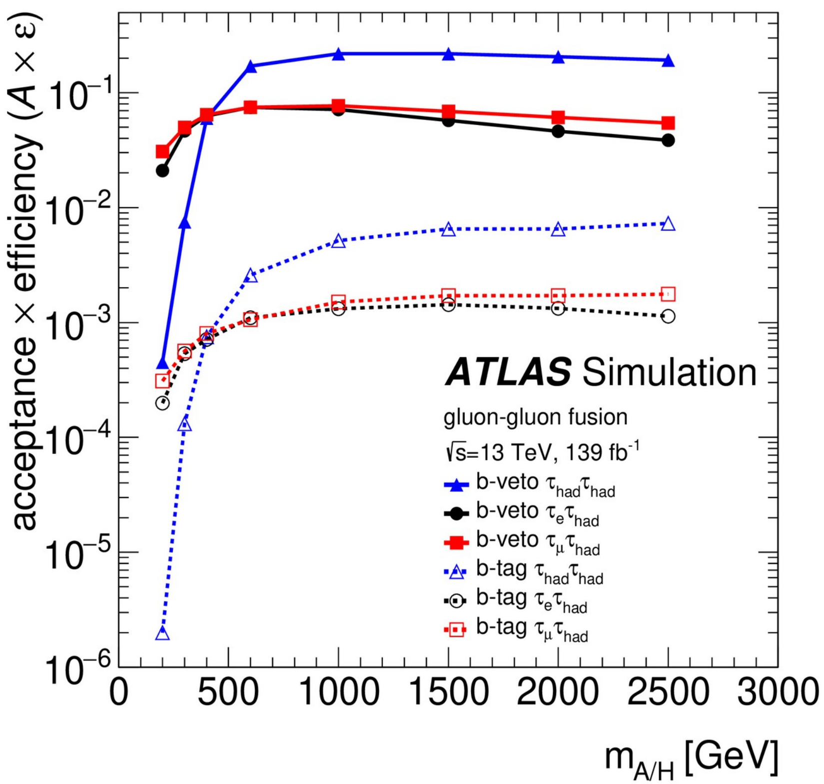


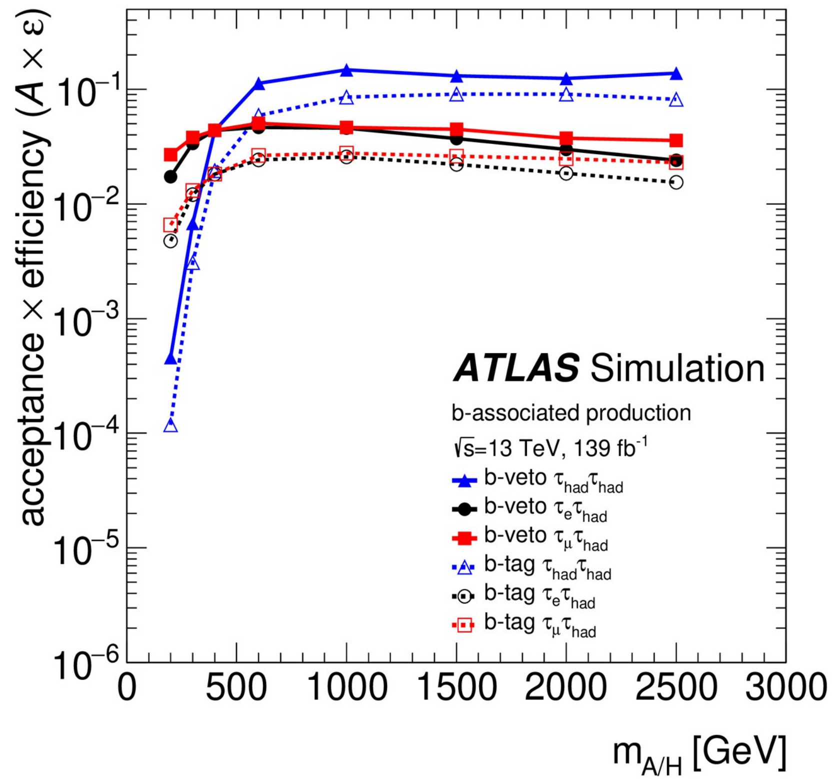

bbH production in the SM mostly negligible

Flagship for high tanβ MSSM Higgs

- Enhanced cross section for b-associated production
- Enhanced decay to τ leptons (can reach ~10%)

- **B-tag** and **b-veto** categories to target gluon-fusion and b-associated production (70% b-tagger efficiency)
- Gluon-fusion signal populates mostly the b-veto categories, but huge fraction of b-associated signal makes it also to the b-veto categories
- τ decay channels: **lep-had**, **had-had**



# A/H → ττ

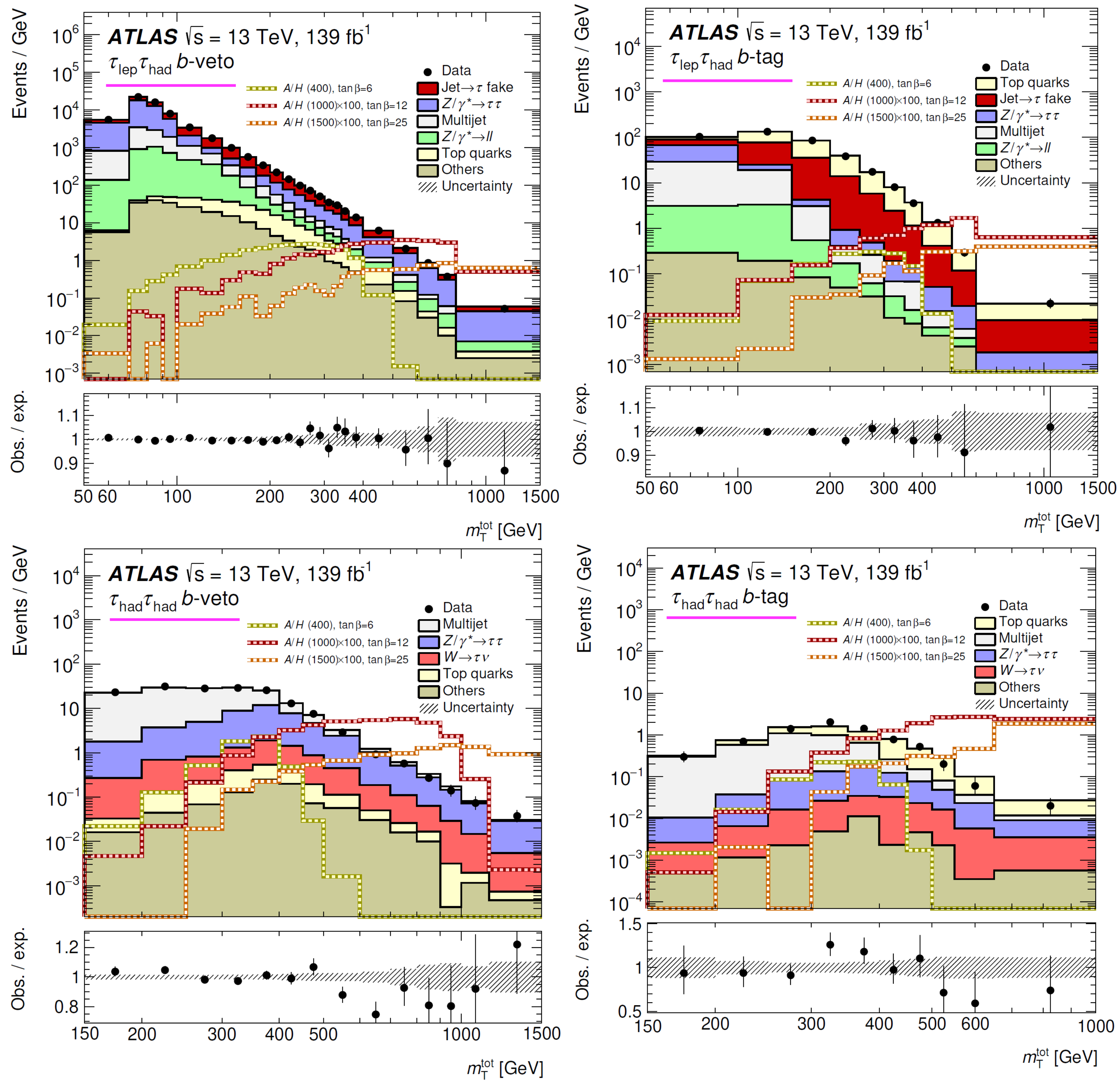
- Cut-based selection, optimized separately for lep-had and had-had

- Main backgrounds:
  - jets faking τ, estimated from data in CRs (multijet, W+jet)
  - ttbar normalisation constrained by top CR included in the fit
  - Z → ττ from MC

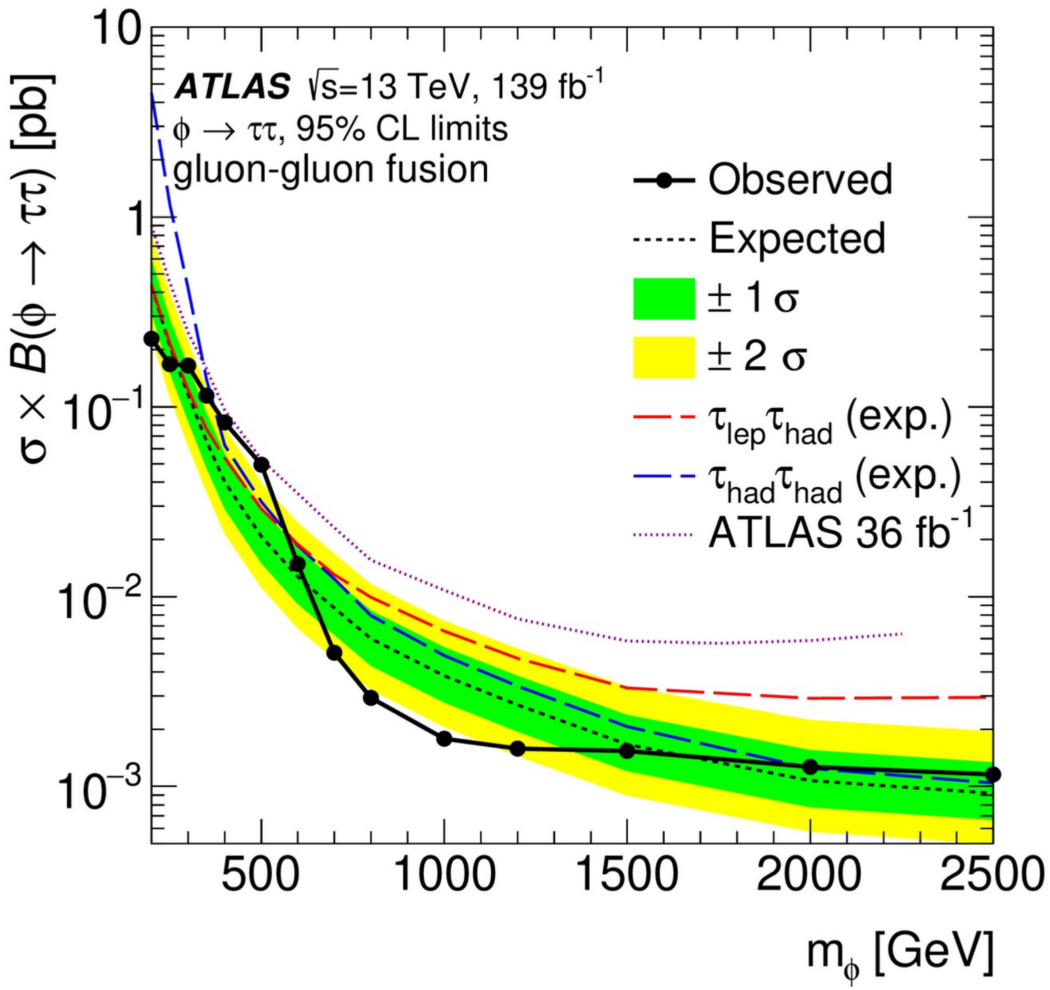
- Leading uncertainties:
  - hadronic τ ID efficiency
  - τ energy scale
  - Background model

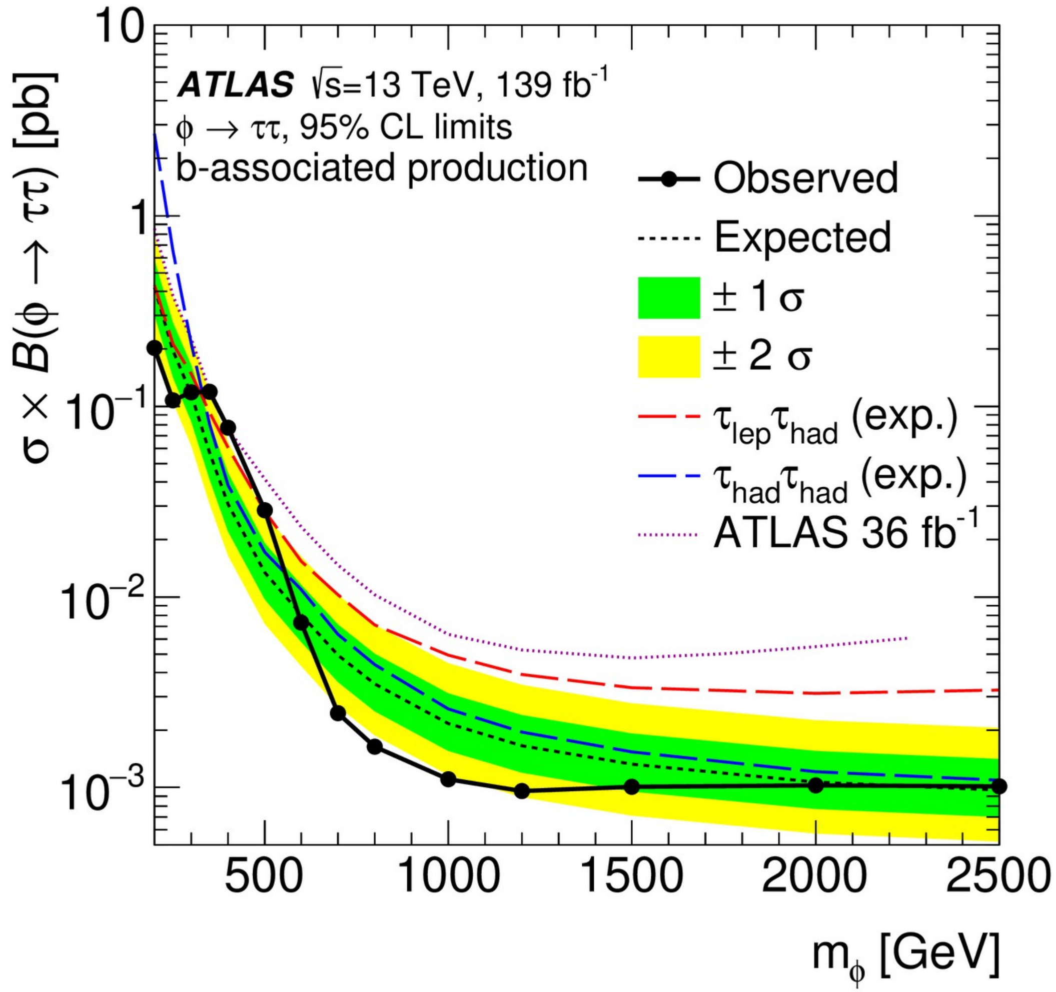
- Final discriminant: transverse mass $m_T$

$$\sqrt{(p_T^{\tau_1} + p_T^{\tau_2} + E_T^{\text{miss}})^2 - (\mathbf{p}_T^{\tau_1} + \mathbf{p}_T^{\tau_2} + \mathbf{E}_T^{\text{miss}})^2}$$



# A/H → ττ

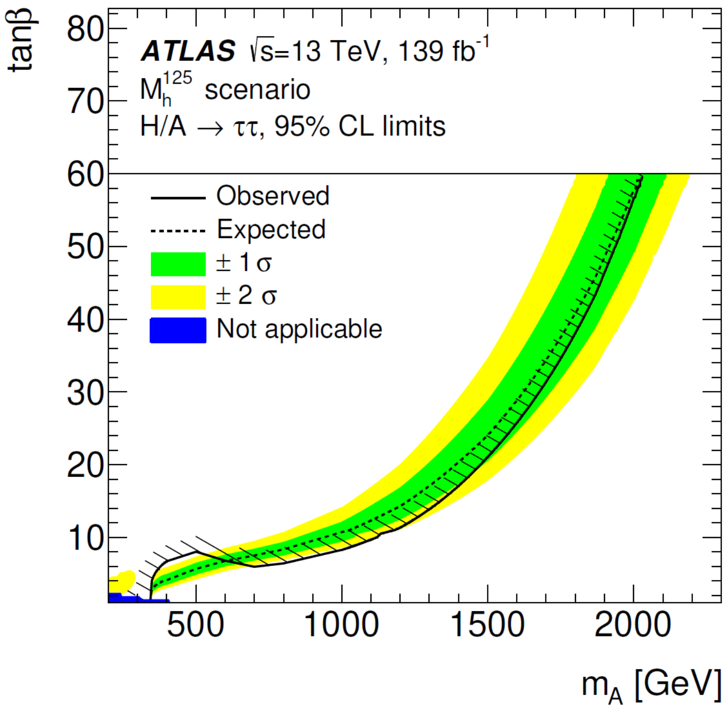


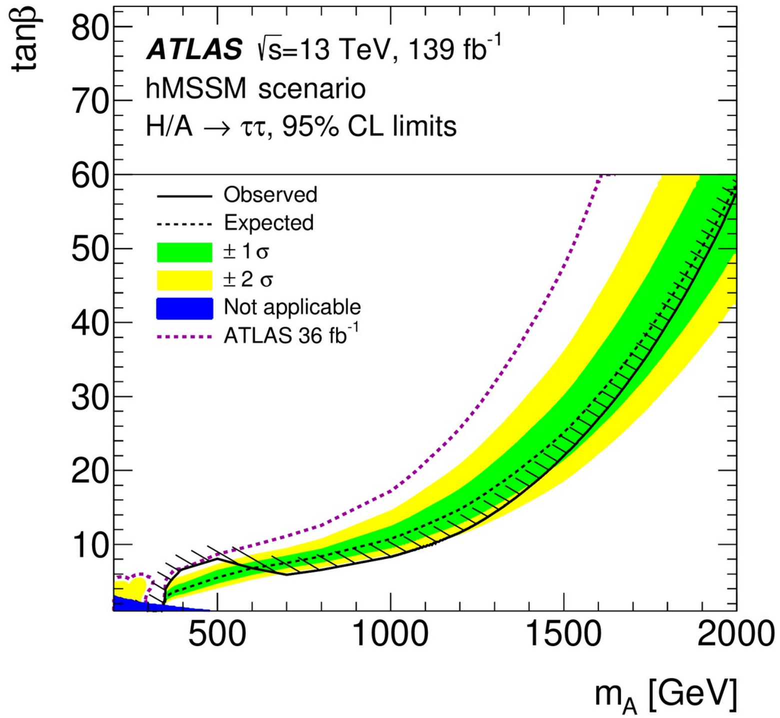



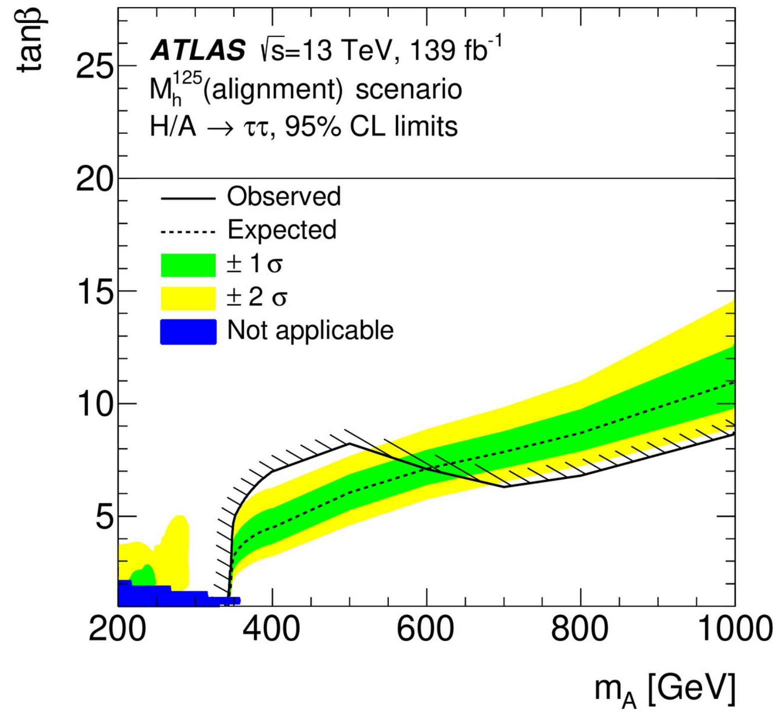

- Moderate excess observed around 400-500 GeV for both production modes
- Local significance 2.9$\sigma$ at 500 GeV for ggF, 2.7$\sigma$ for bbA at 400 GeV
- Global significance 1.9$\sigma$

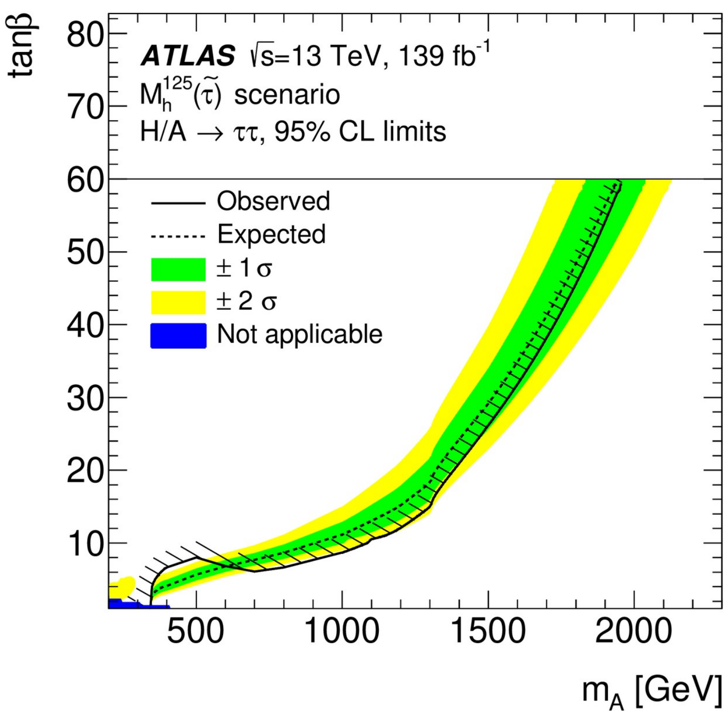
# $A/H \rightarrow \tau\tau$

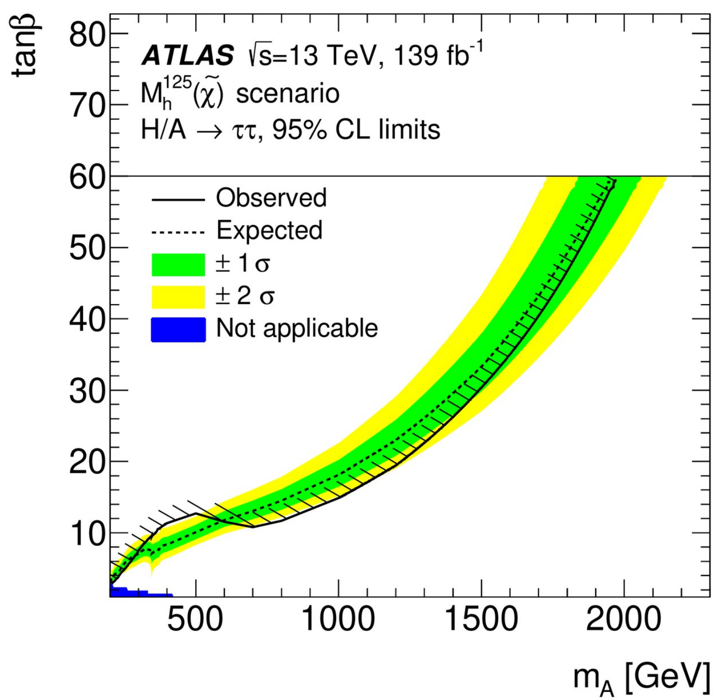
## bbA and ggF combined according to model predictions




Predictions from LHCHWG

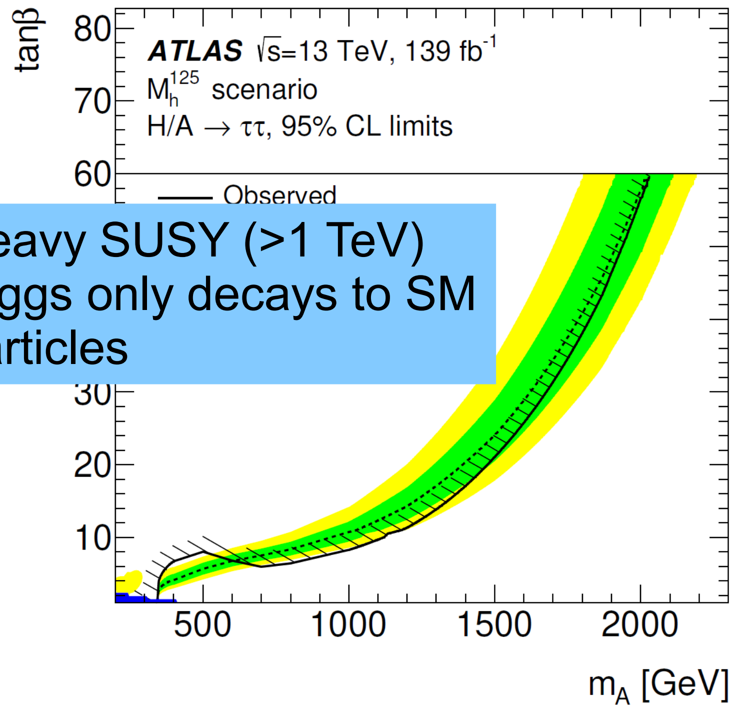
Leading channel in the MSSM
Strong high $\tan\beta$ exclusions

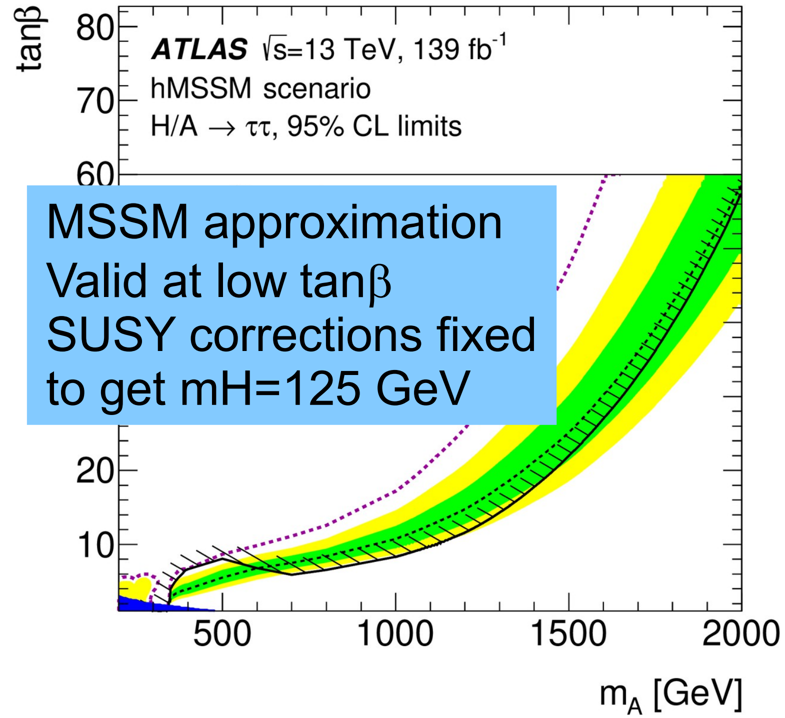
Excess weakens limits

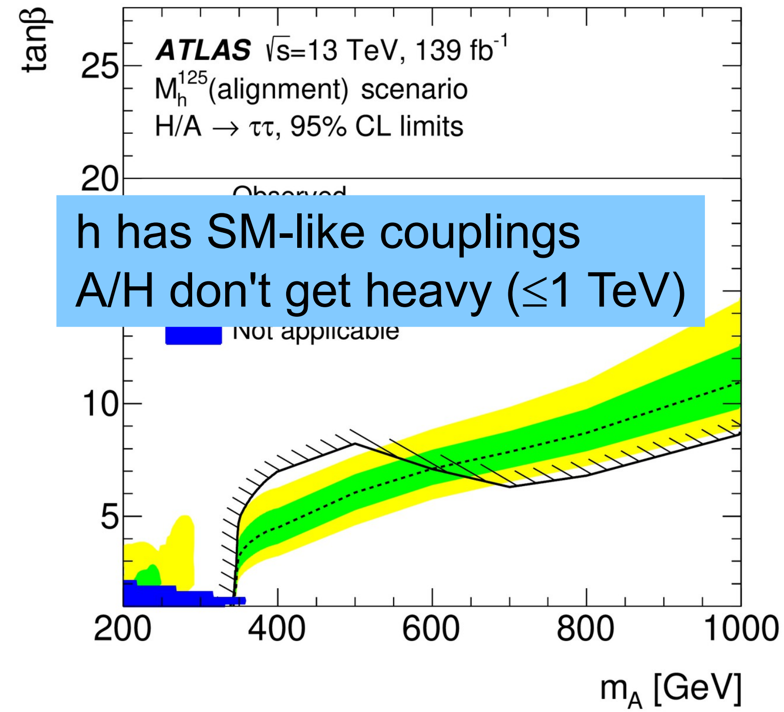
H and A mass degenerate
(except in blue corner)

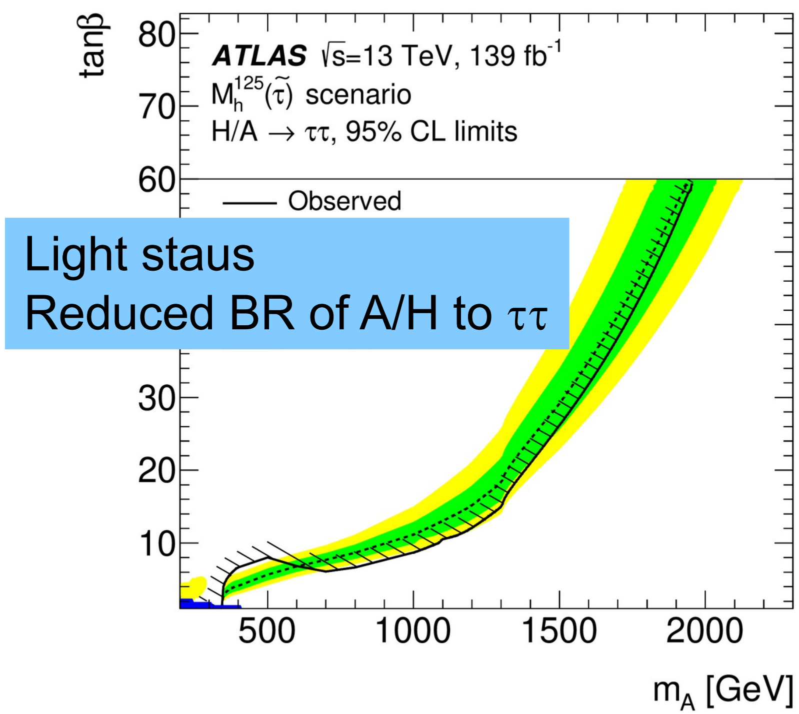
# A/H → ττ

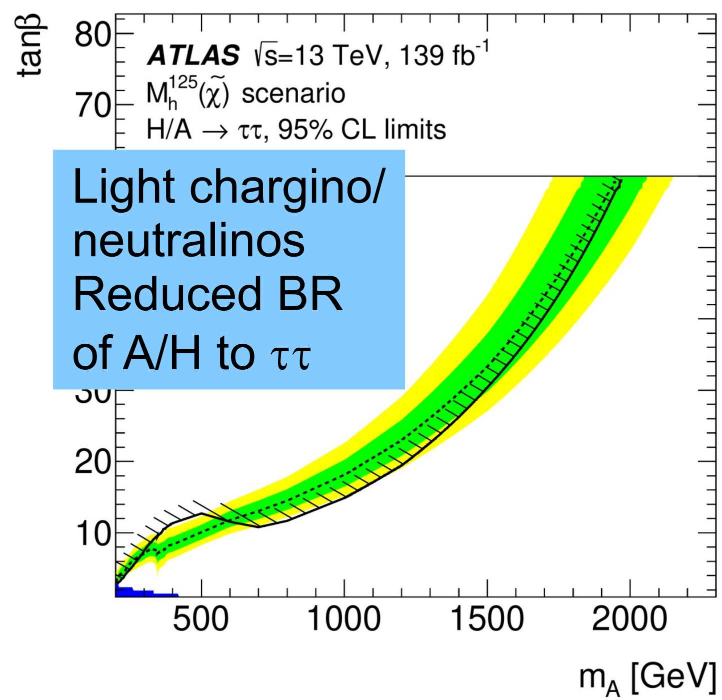
bbA and ggF combined according to model predictions



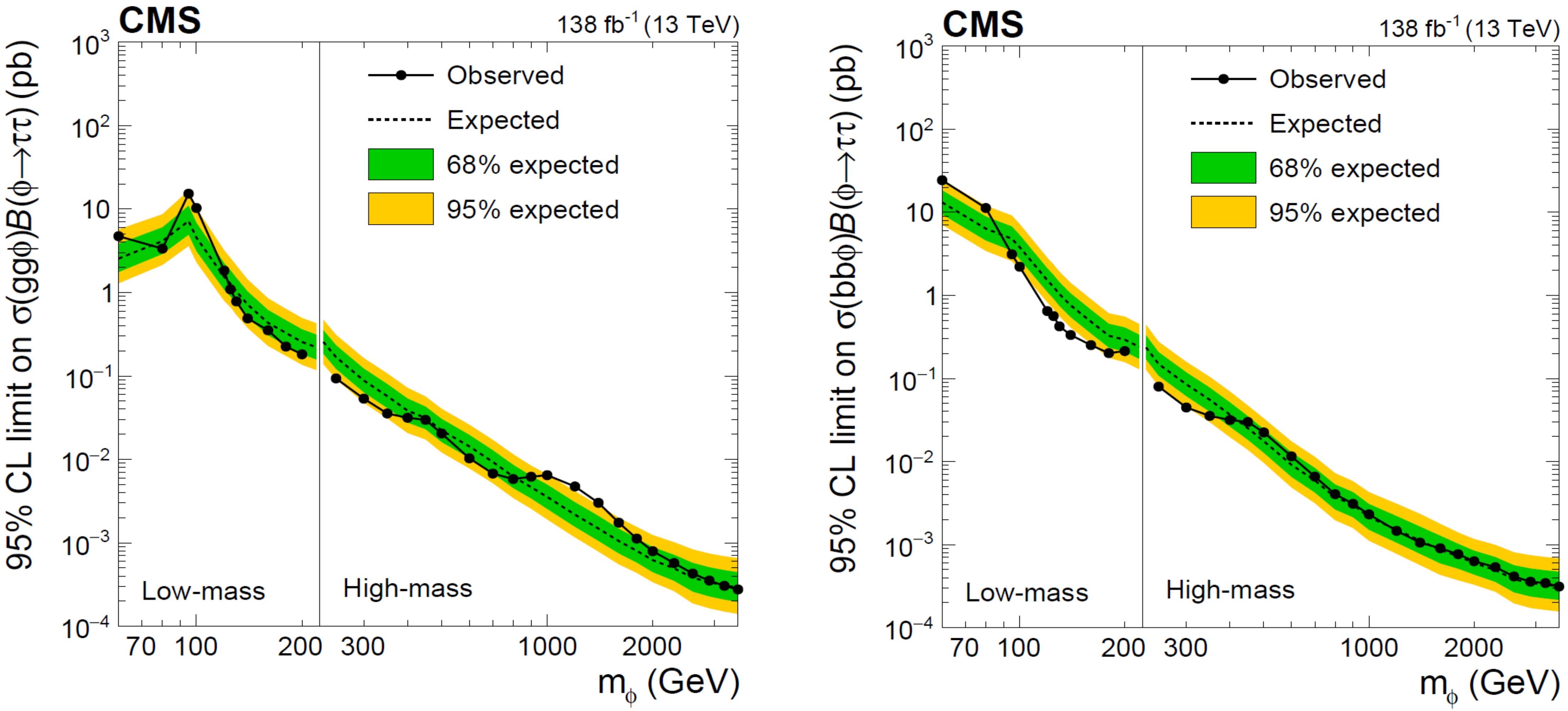

Predictions from LHCHWG

Leading channel in the MSSM
Strong high tanβ exclusions

Excess weakens limits

H and A mass degenerate (except in blue corner)

# A/H/h → ττ in CMS

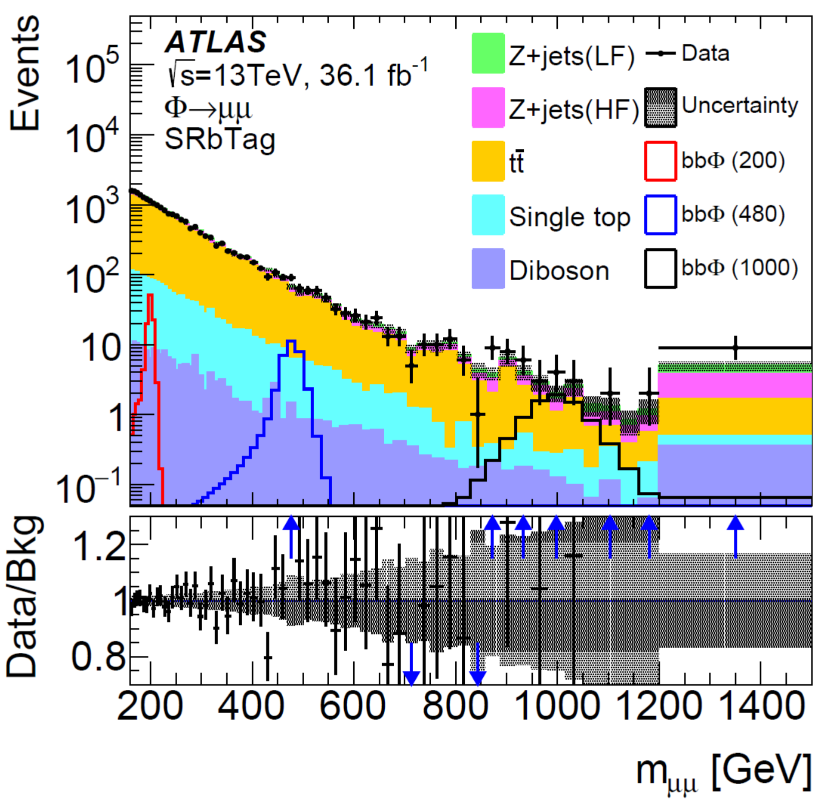


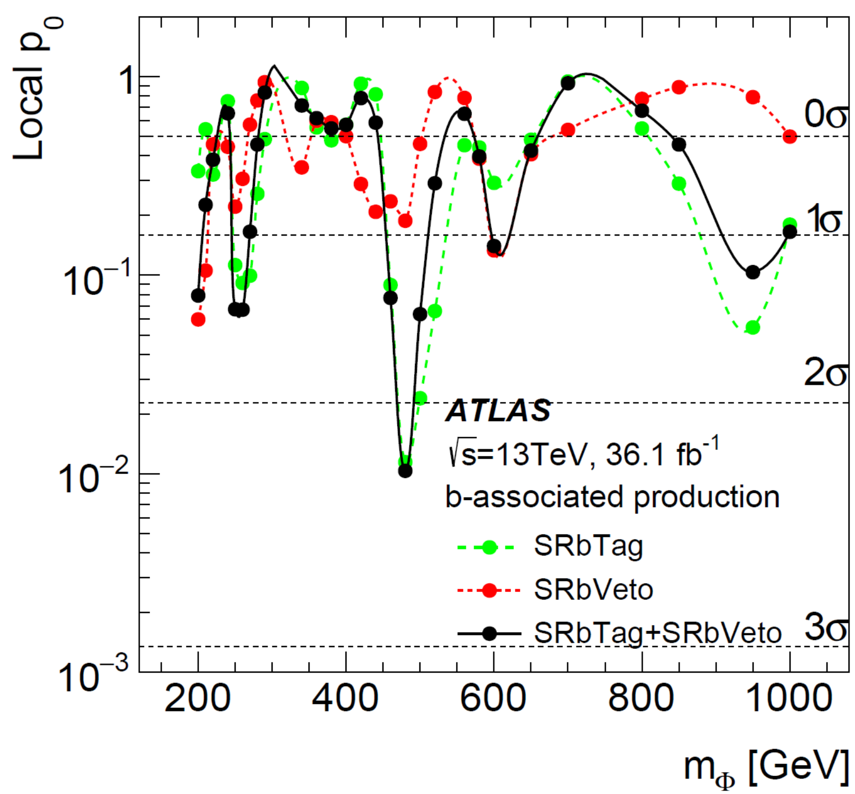

CMS starts at 60 GeV. Like ATLAS, categorizes events in „btag“ and „no-btag“.
Dedicated low mass optimisation ($m_H$<250 GeV), extra categories based on $p_T^{\tau\tau}$.

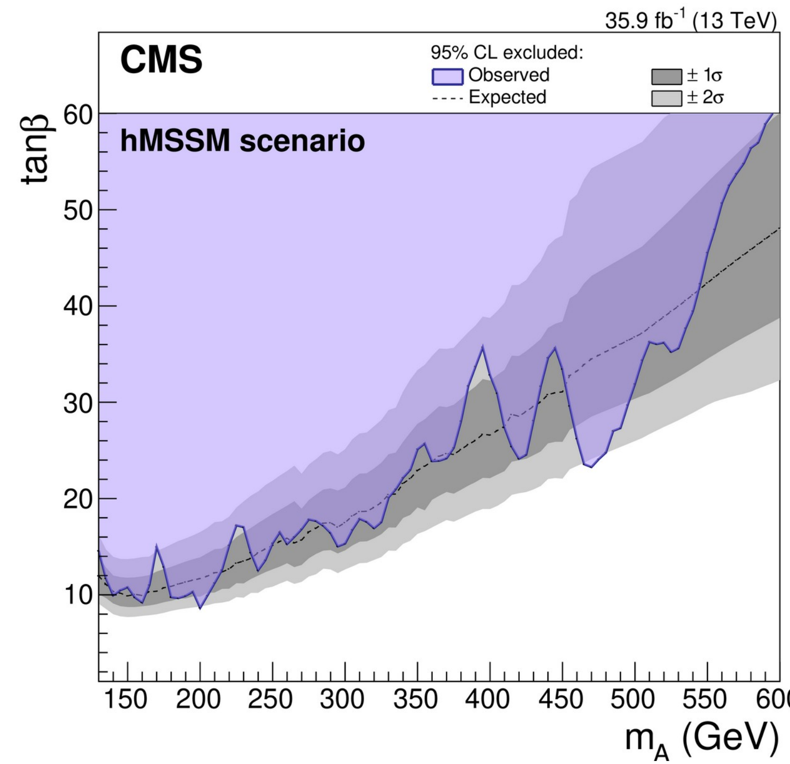
400 GeV excess not confirmed,
But two excesses of each ~3σ (locally) in ggF signal at 100 GeV, and 1200 GeV

# A → μμ

- Targets the same models as A → ττ, has the same enhancement of bbA production and decay
- Much smaller decay rates, but easy mass reconstruction and a smoothly falling background
- Similar analysis strategy: Separating events into b-veto and b-tag categories
- Generic dilepton bump searches typically are not sensitive to the MSSM, as no b-tag is applied
- ATLAS and CMS results only with partial run-2 dataset



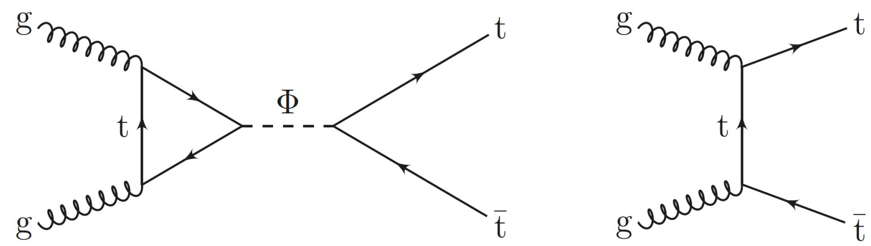



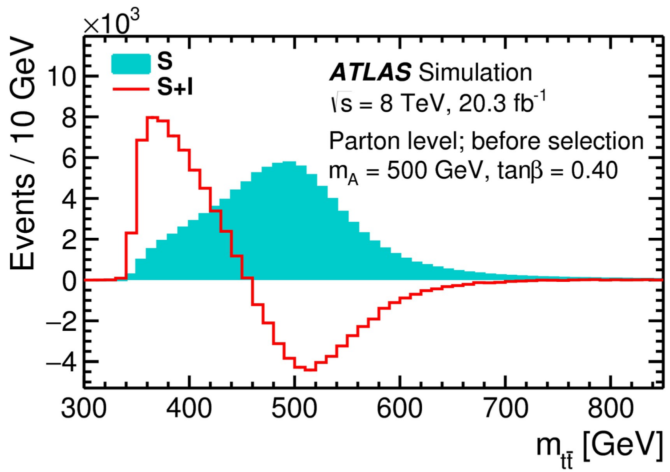

ATLAS has 2.3σ local excess at 480 GeV for b-associated production
Global significance is 0.6σ

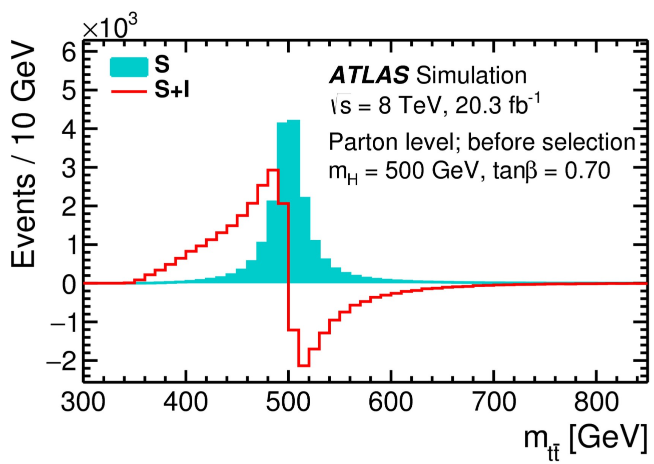
# A/H → tt

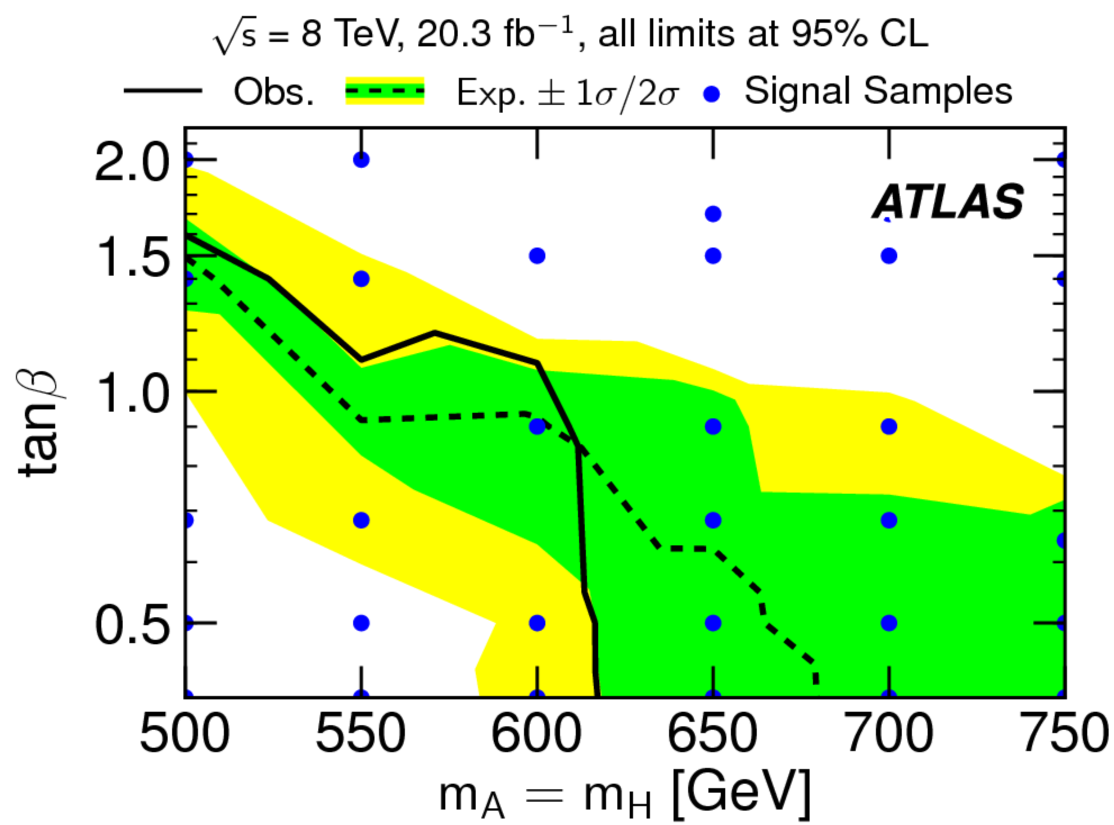
Another flagship channel, but it is much more difficult.
Any Higgs that is produced through ggF will also decay to ttbar, if it is heavy enough (~400 GeV)
Decays to ttbar are dominant for many models, such as MSSM at low tanβ.

Signal gg → A/H → tt and background gg → tt interfere,
and impact is strong, and it depends on the theory parameters.
Need to generate S and I terms for each parameter value.



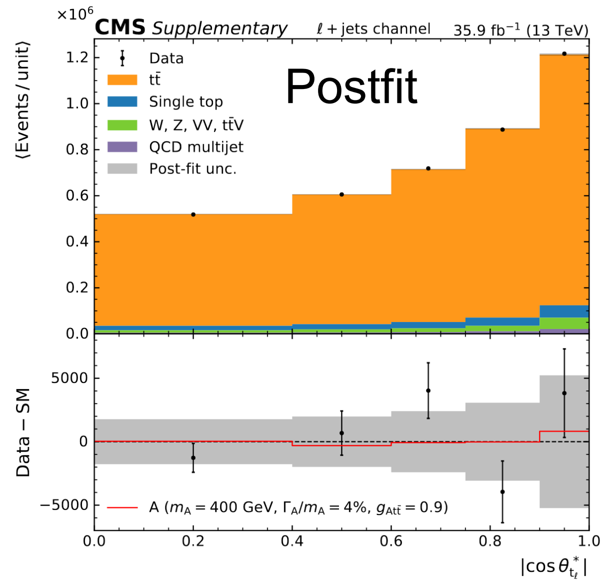




Search for a peak+dip structure, instead of a simple signal bump.
ATLAS pioneered this search at 8 TeV, update still being worked on.

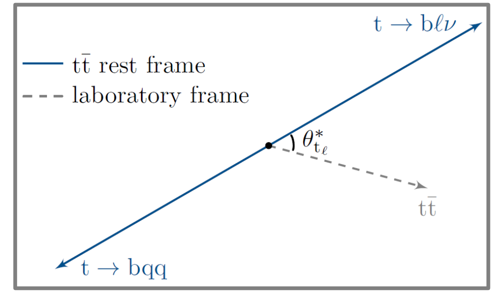
# A/H → tt at CMS

- Single-lepton and di-lepton final states considered
- Single-lepton channel: $t\bar{t}$ mass fully reconstructed with a likelihood technique that chooses the combination of objects most consistent with a top decay.

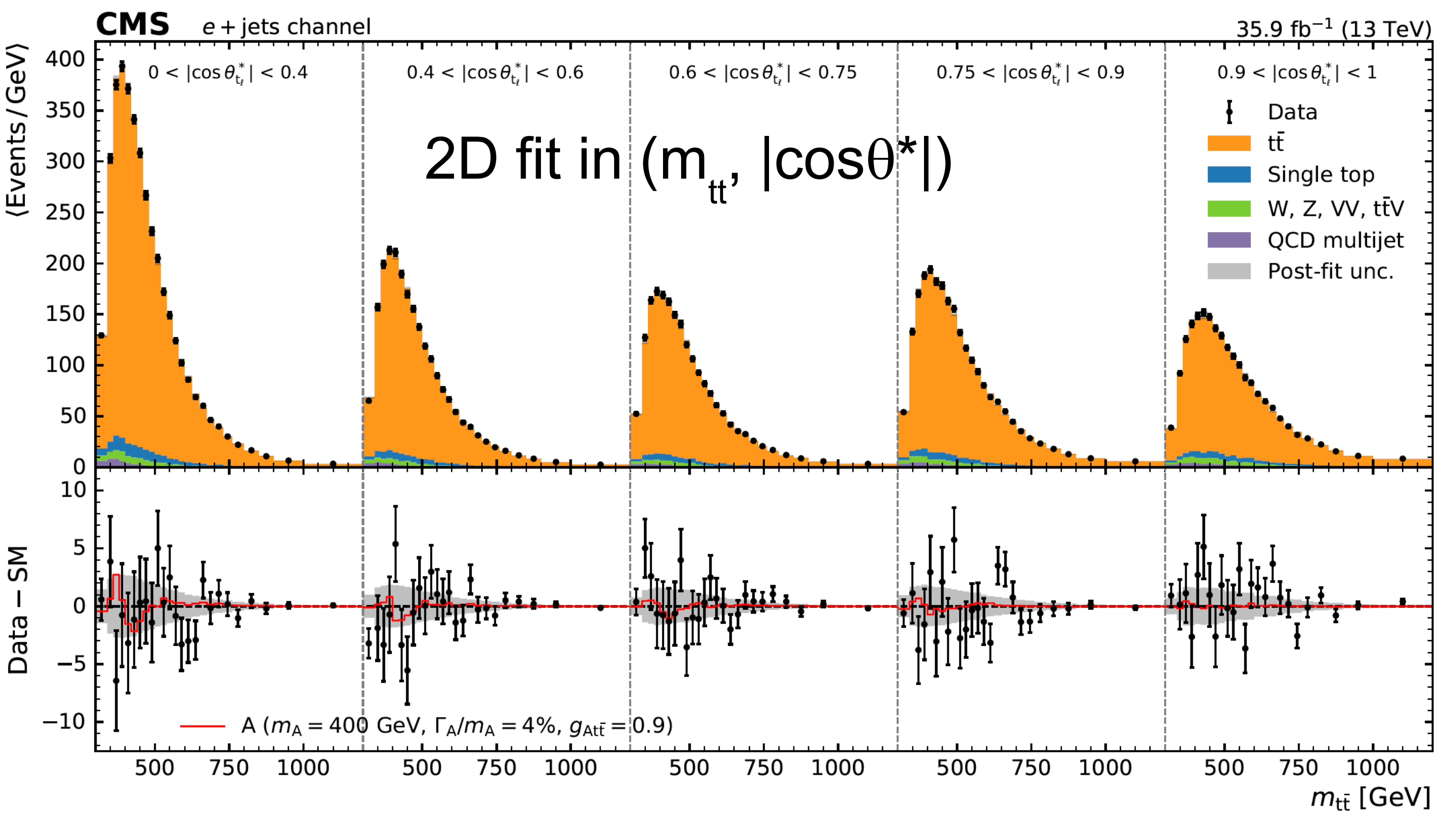
  |cosθ*| used for signal-background discrimination →

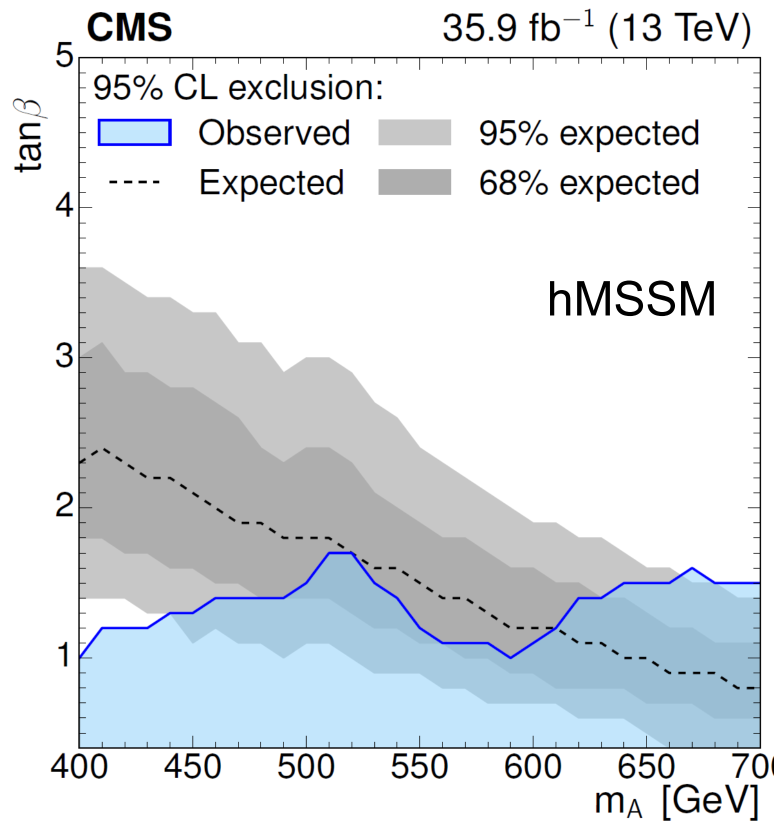



← Signal flat
ttbar peaks towards 1



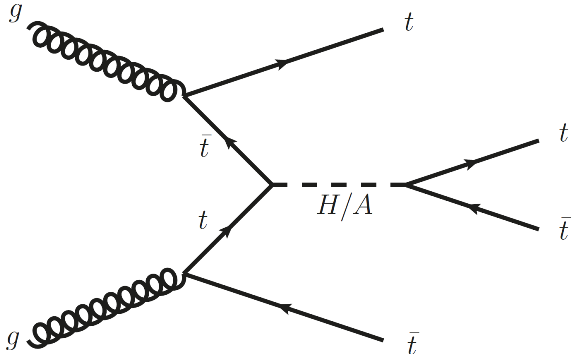

- Moderate excess at 400 GeV (1.9σ global), which however is right at the edge of the acceptance
  *It would be strange to have a real signal in both ttbar and ττ at the same mass.*




Highest sensitivity at low tanβ

# ttH/A, H/A → tt



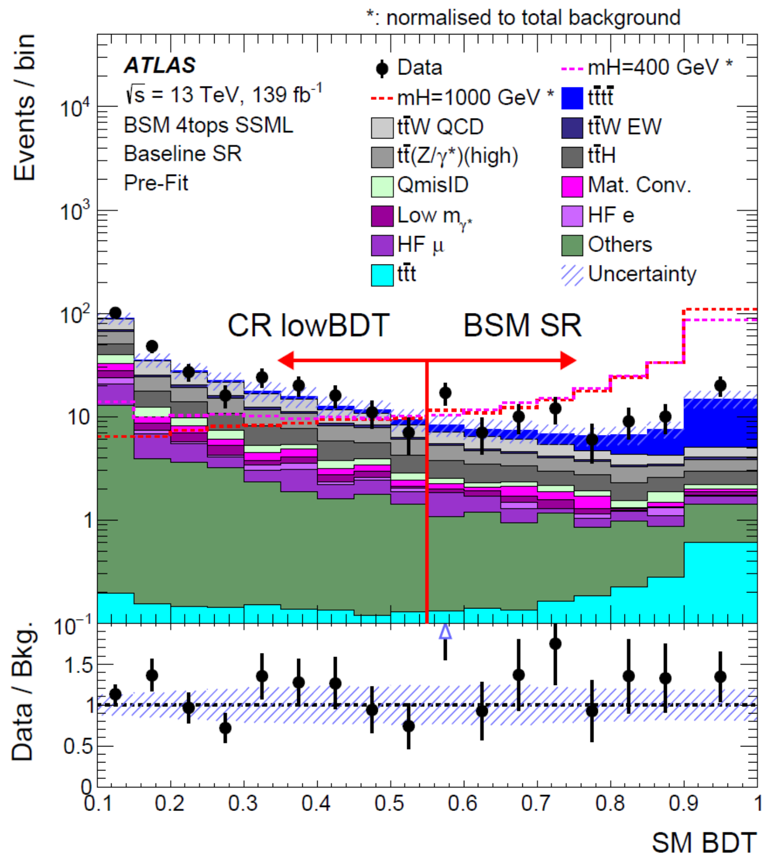

- ttH channel offers a nice, simpler opportunity to search for A/H → tt

- Interference with SM 4tops exists, and it impacts cross section of up to 20%, but kinematics are not affected

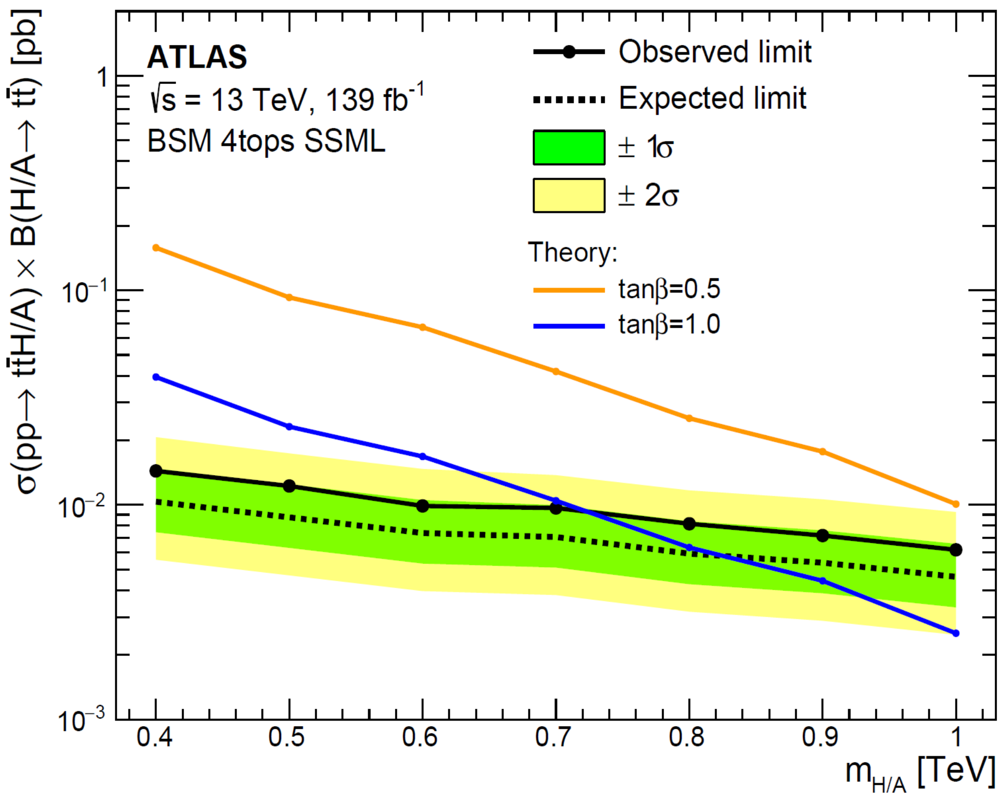
Signal-enriched baseline selection:
- 2 (SS) or ≥3 leptons
- at least 6 jets
- at least 2 of them b-tagged
- $H_T$ > 500 GeV

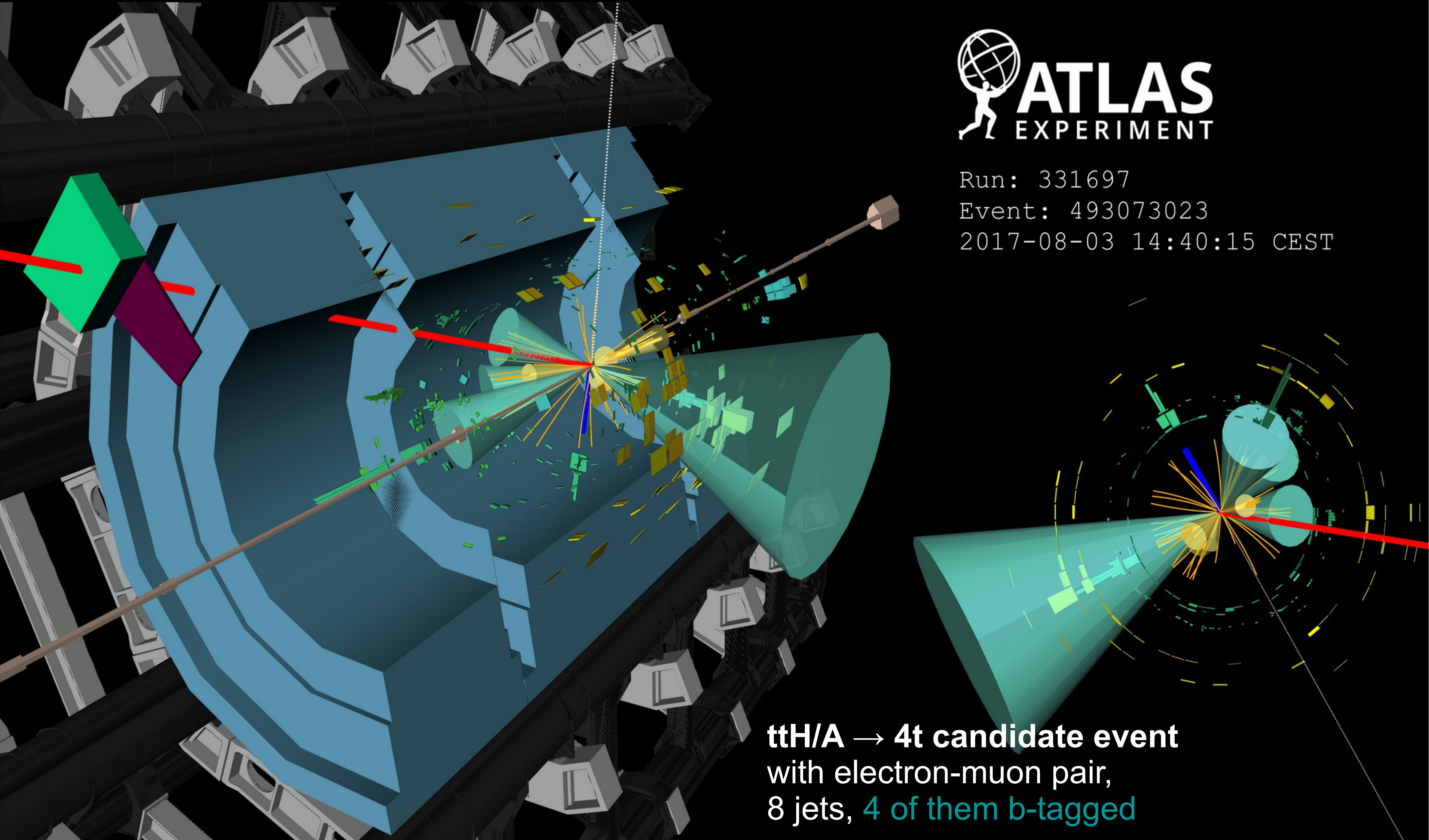
2 BDTs:
(1) Discriminates SM 4tops from other backgrounds

(2) Discriminates signal from all backgrounds




Sensitive to type-II 2HDM:





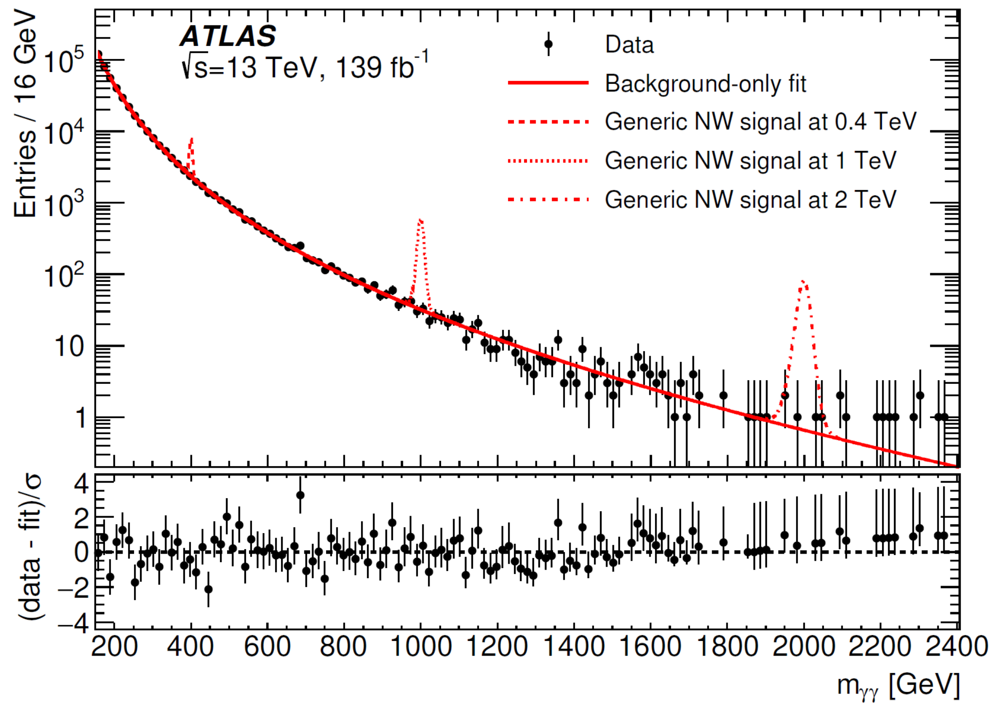

**ttH/A → 4t candidate event**
with electron-muon pair,
8 jets, 4 of them b-tagged

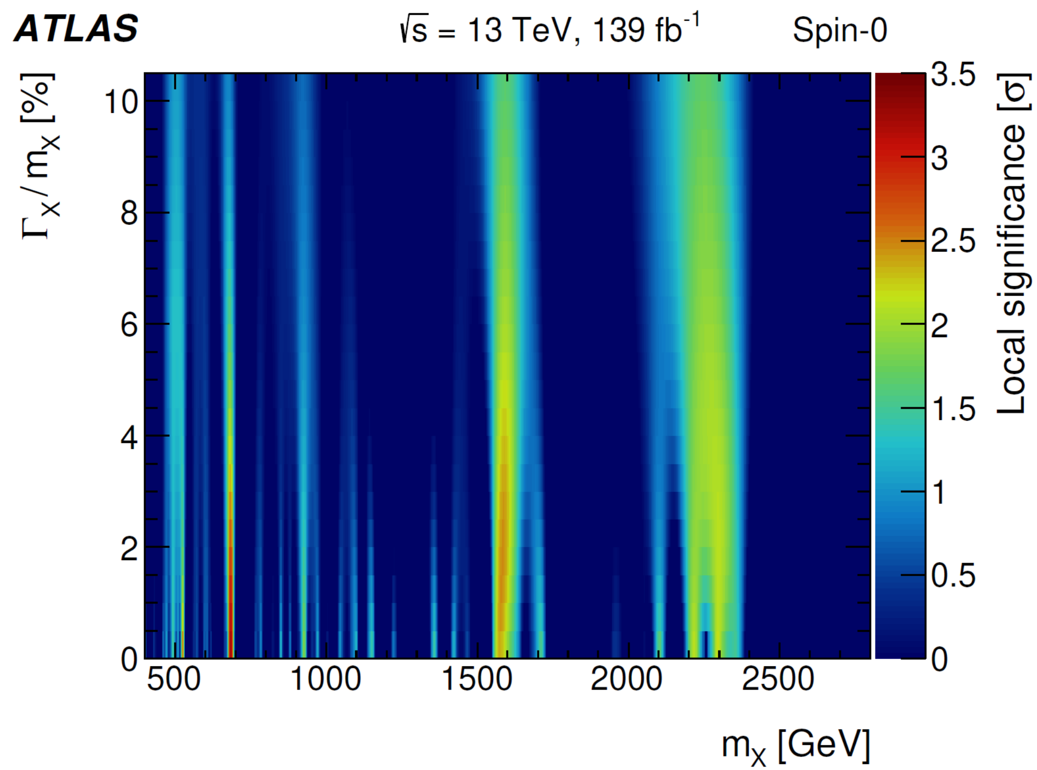
# Heavy H $\rightarrow \gamma\gamma$

- This channel was the source for great hope some time ago, when an excess was found at 750 GeV
- Here: Updated search with the full run-2 dataset
- Selecting events with tightly identified and isolated photons
- $E_T$ requirements on the photons relative to the $m_{\gamma\gamma}$ value: $E_{T,1}>0.3*m_{\gamma\gamma}$, $E_{T,2}>0.25*m_{\gamma\gamma}$
- Largest background is diphoton continuum, also $\gamma$j and jj
- Background template built from simulation (Sherpa) of $\gamma\gamma$ plus data-driven $\gamma$j, then fit with analytical function:

$$f(x;b,a_0,a_1) = N(1-x^{1/3})^b x^{a_0+a_1\log(x)}$$

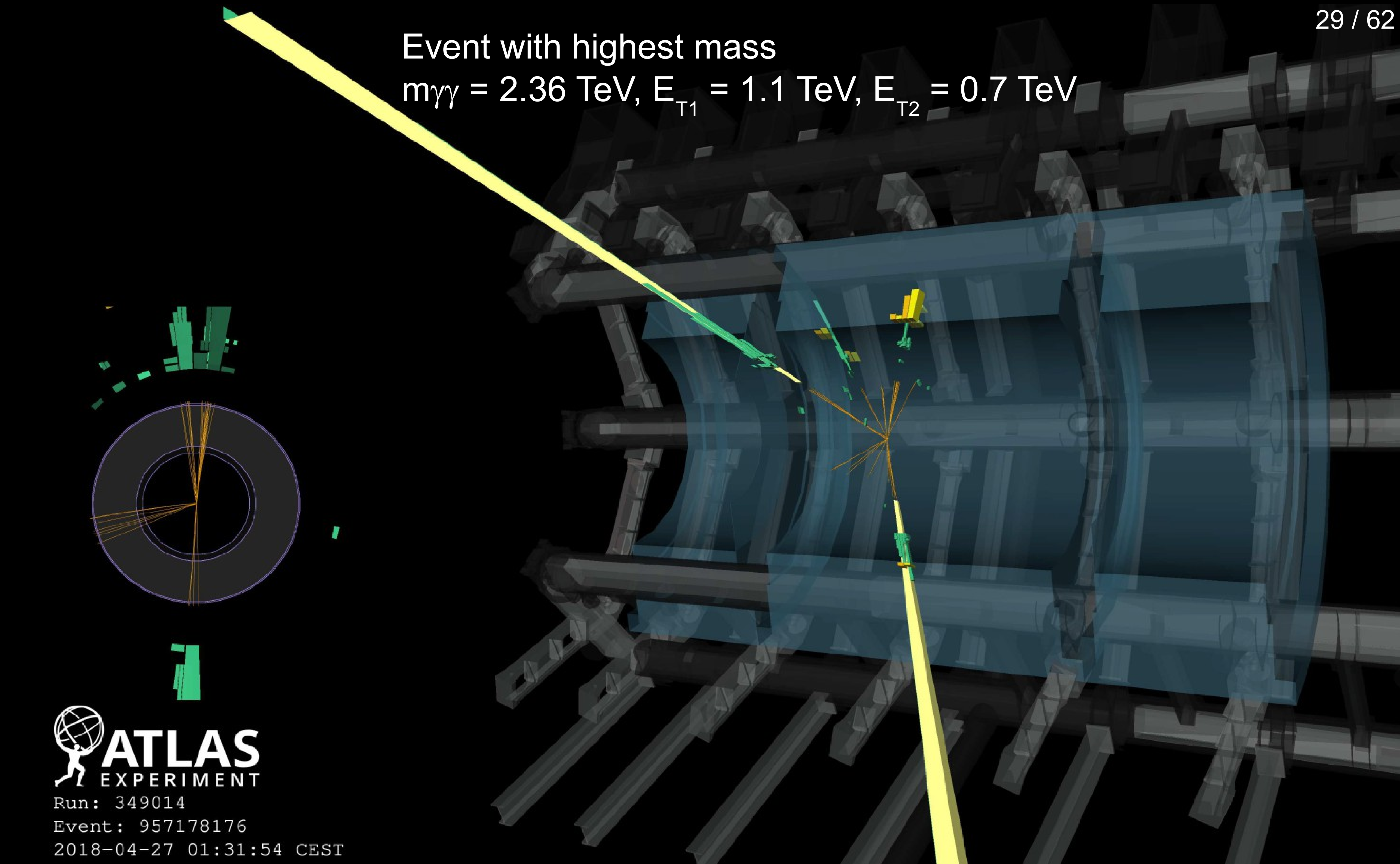
- Largest excess (very narrow) found at 684 GeV (1.3$\sigma$ global)



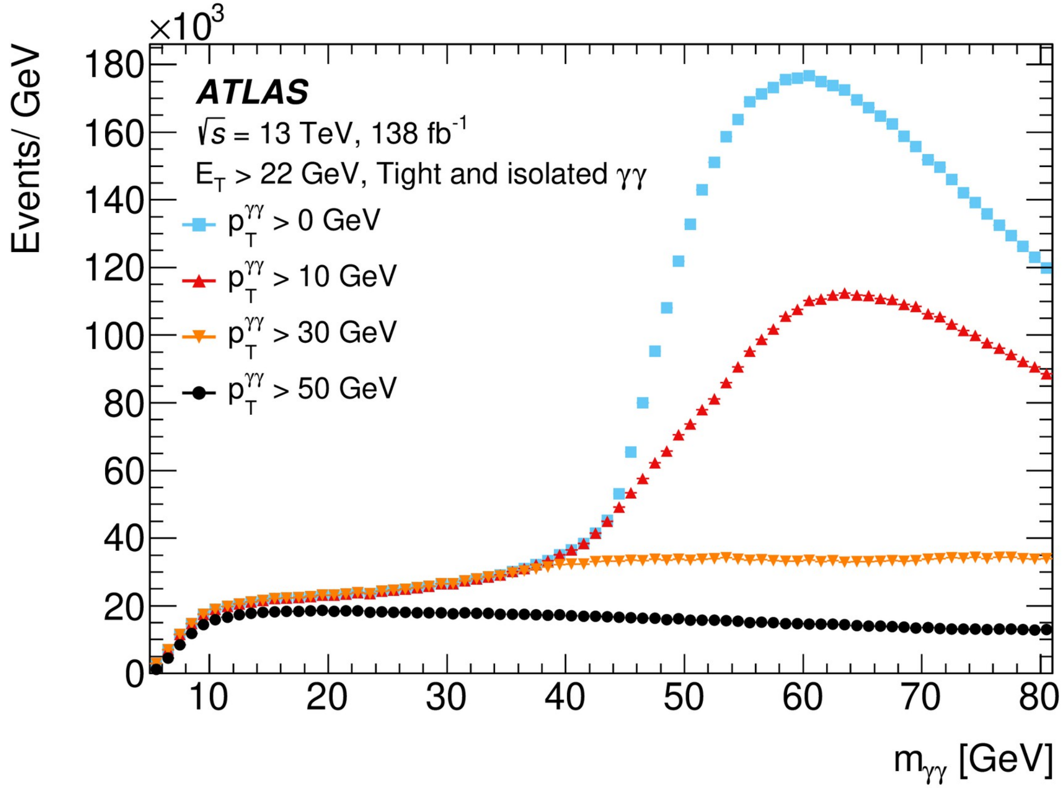
Event with highest mass

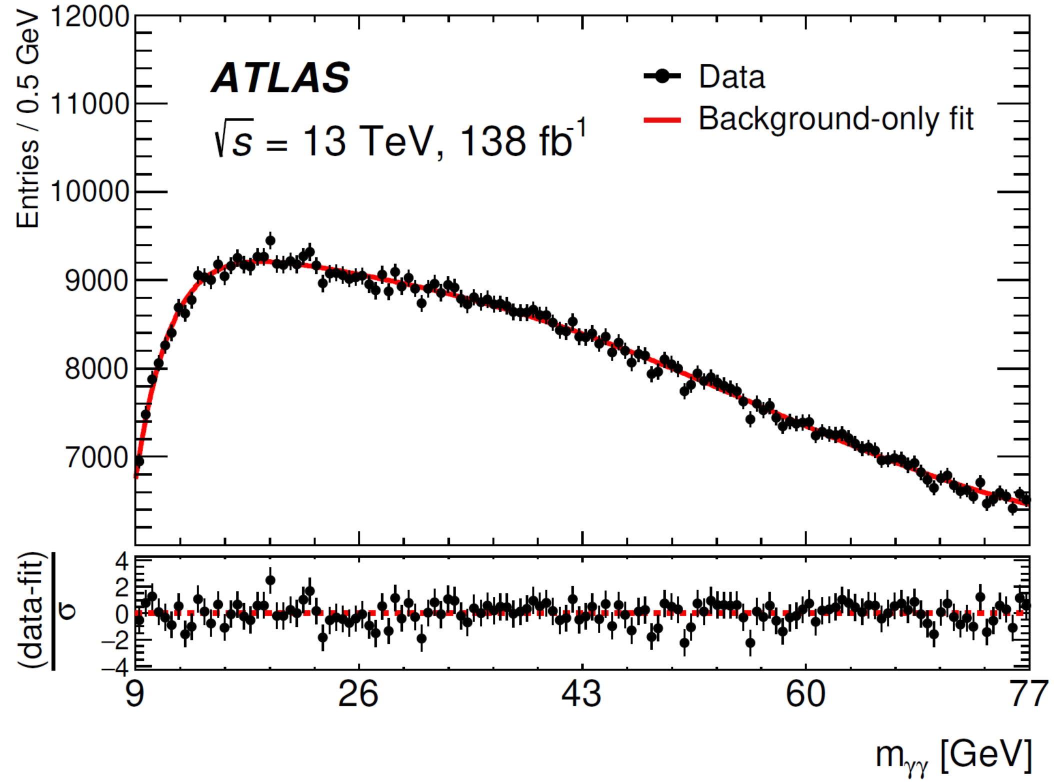
$m_{\gamma\gamma}$ = 2.36 TeV, $E_{T1}$ = 1.1 TeV, $E_{T2}$ = 0.7 TeV

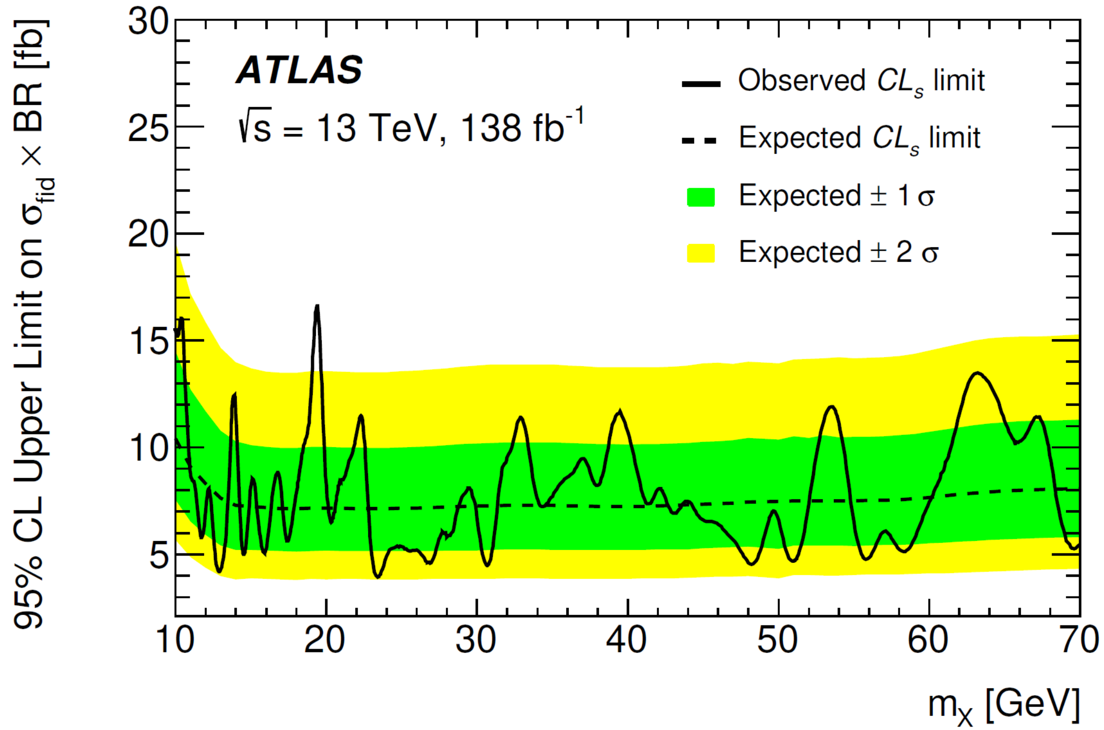


# Light H → γγ

- Diphoton trigger with $E_T$>20-22 GeV
- Cut on $p_T\gamma\gamma$ > 50 GeV to reduce background sculpting effects due to trigger turn-on



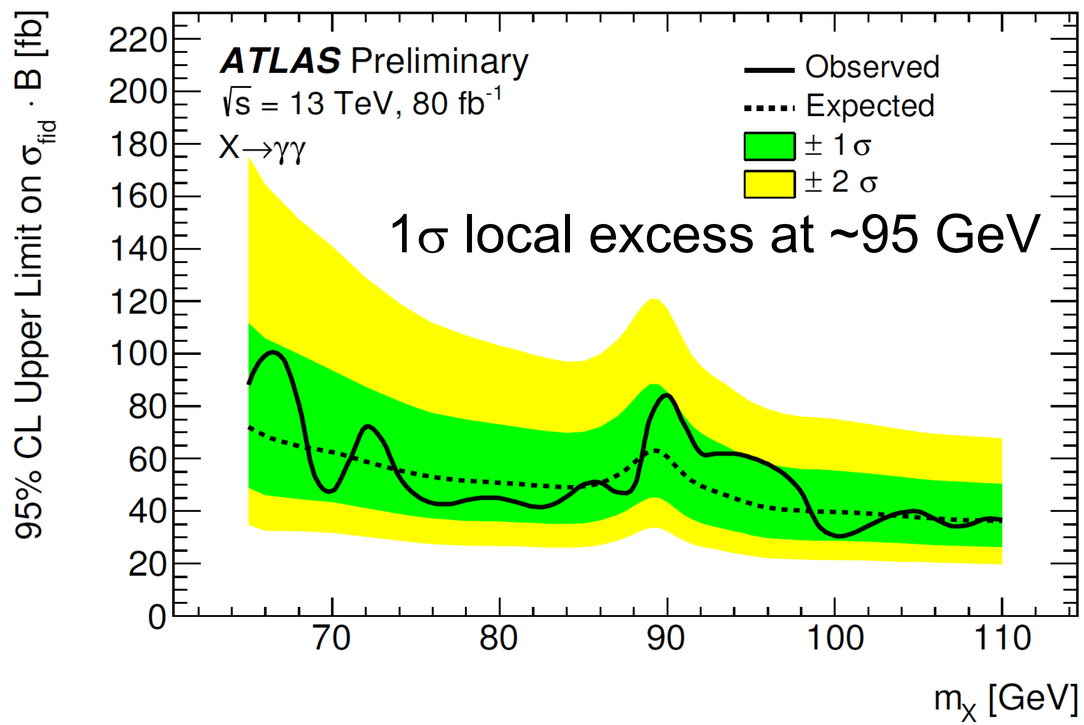



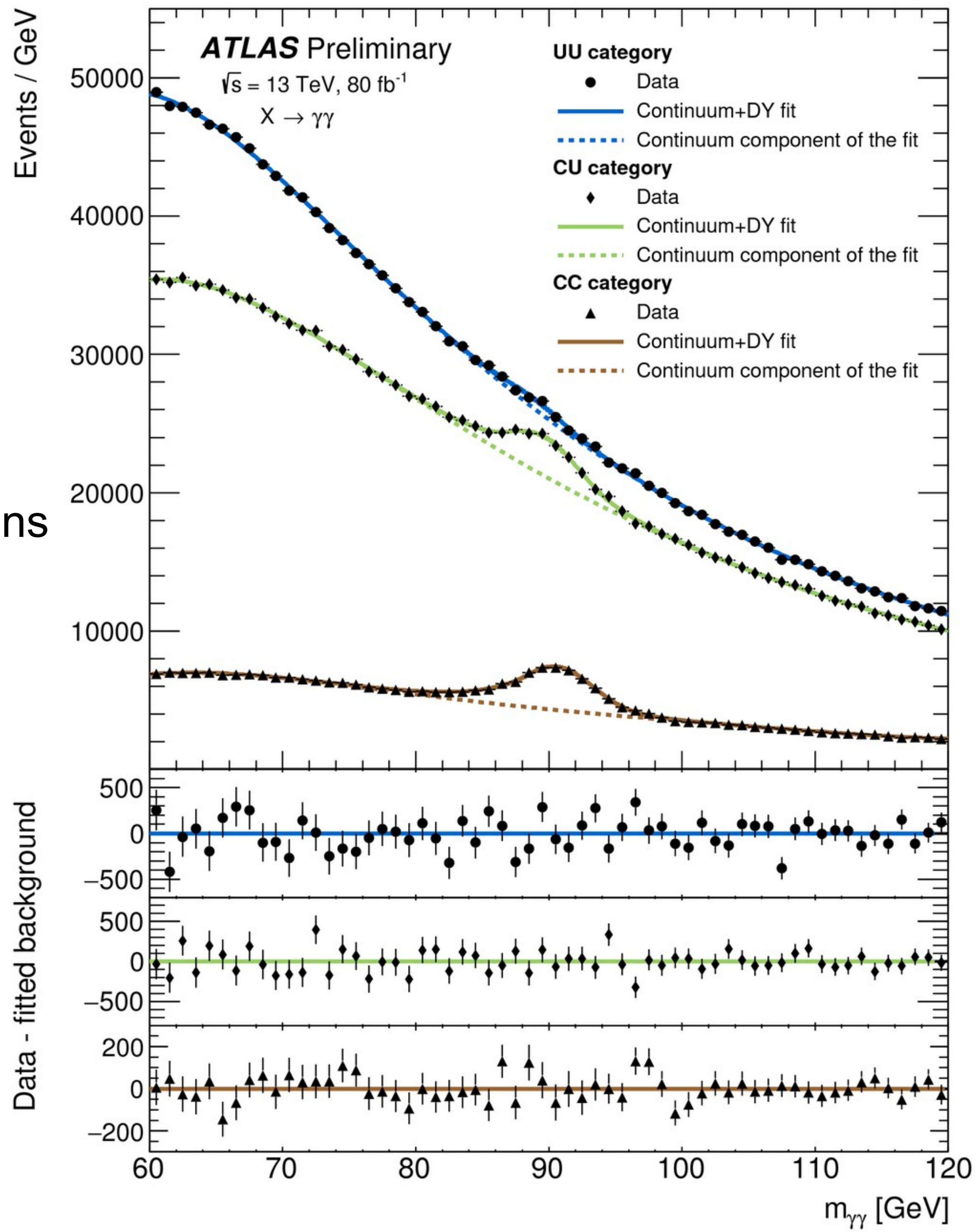




- Background model is the sum of a turn-on function and a smoothly falling function for $m_{\gamma\gamma}$ > 30 GeV
- Largest excess at 19.4 GeV: 3.1σ local, 1.5σ global significance

# Intermediate H → γγ

- Search range: 65 – 110 GeV, 80/fb (partial run-2 dataset), update in the works!
- Difficult due to Z → ee background (both electrons misidentified as photons), and trigger turn-on effects
- Categorized by photon conversion status (impacts eg. mass resolution)
- Z → ee background shape described as double sided Crystal ball, parameters estimated from ee data, electrons are corrected for energy loss due to bremsstrahlung



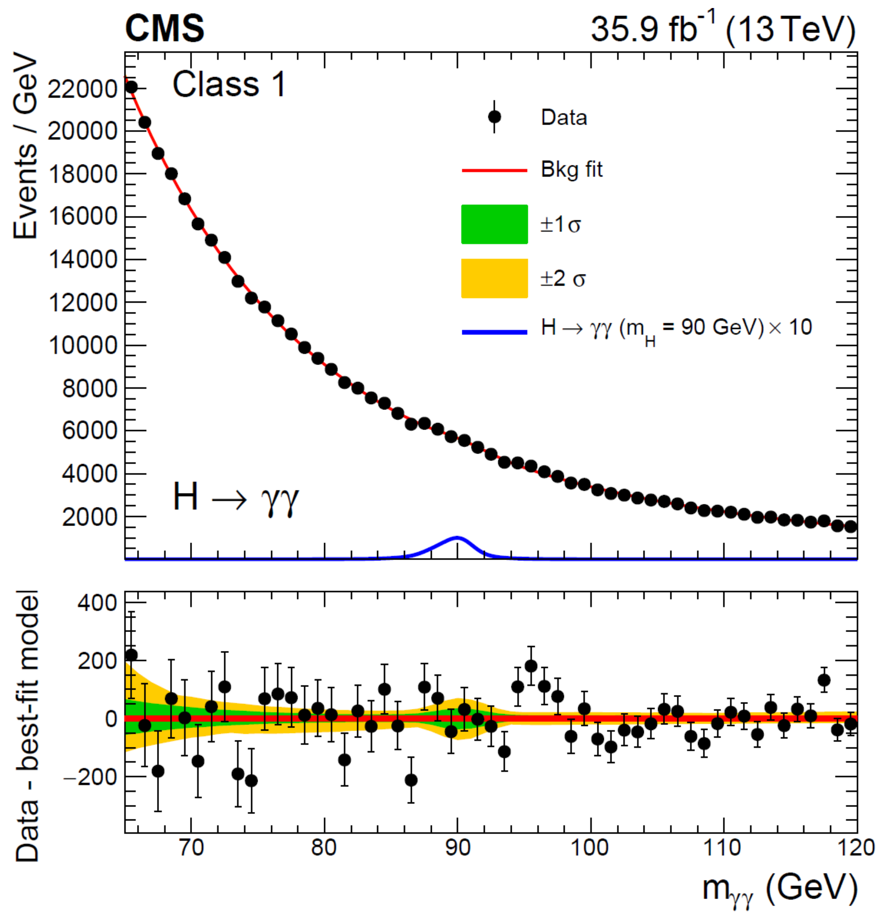
# CMS Intermediate $H \rightarrow \gamma\gamma$

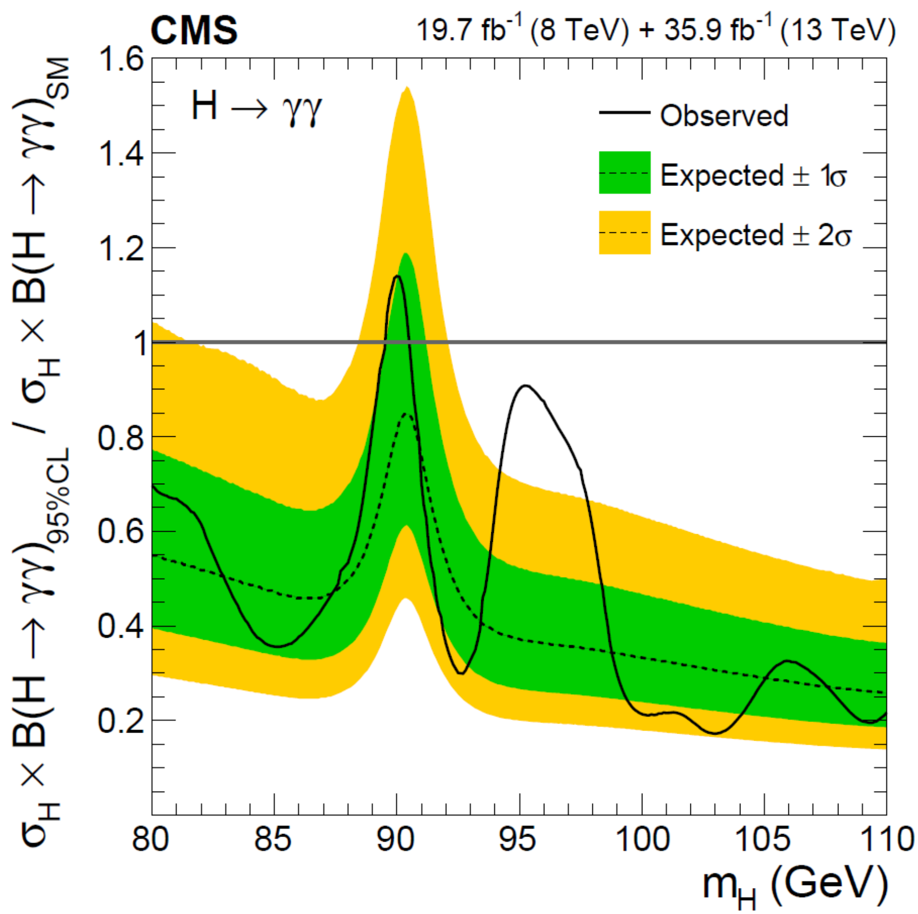
- Search range: 80 – 110 GeV, combination of 20/fb (8 TeV) and 36/fb (13 TeV)
- MVA classifier used to separate signal and diphoton continuum background, categorizing events into 4 (3) classes for 8 (13) TeV
- Shape of the misidentified $Z \rightarrow ee$ background described with a double sided Crystal ball function, parameters fixed using MC

8 TeV data:
Largest excess at 97.7 GeV
(2$\sigma$ local)

13 TeV data:
Largest excess at 95.3 GeV
(2.9$\sigma$ local)

Combination:
Largest excess at 95.3 GeV
(2.8$\sigma$ local, 1.3$\sigma$ global)



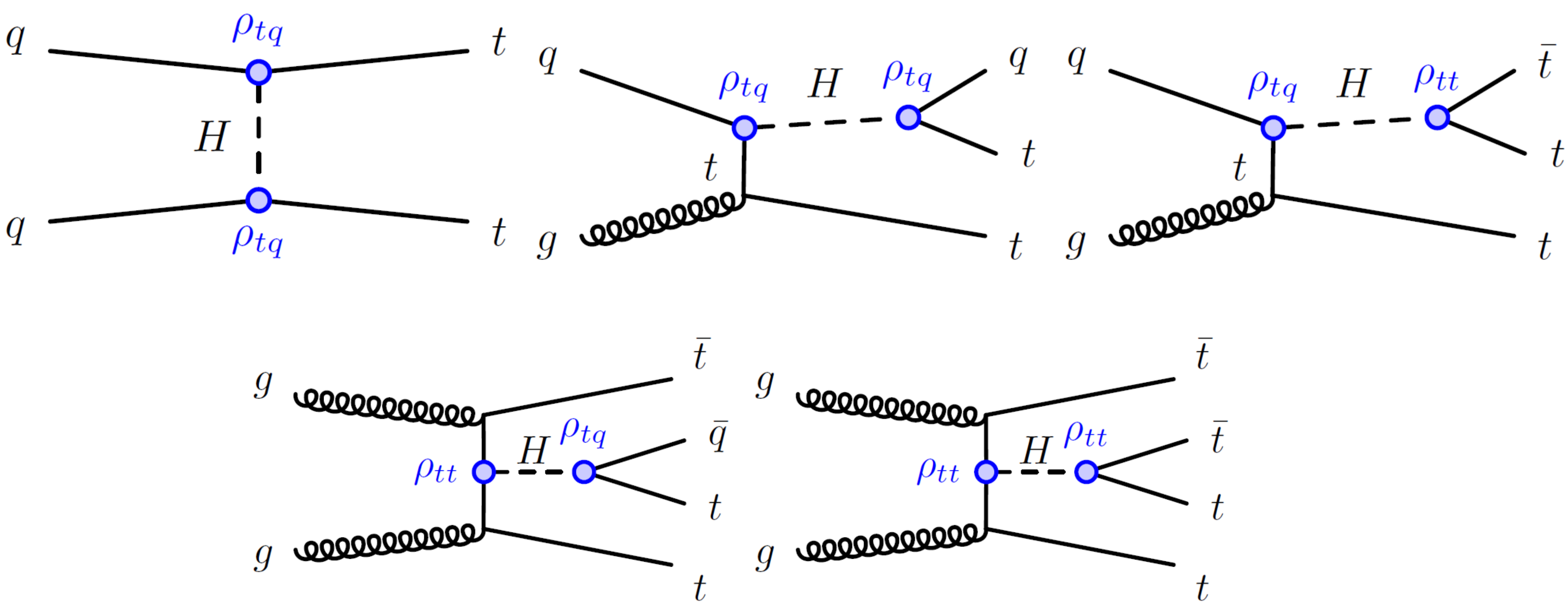



# Heavy Higgs in the general 2HDM

- g2HDM means that usual $Z_2$ symmetry is not imposed → FCNC in the heavy Higgs sector

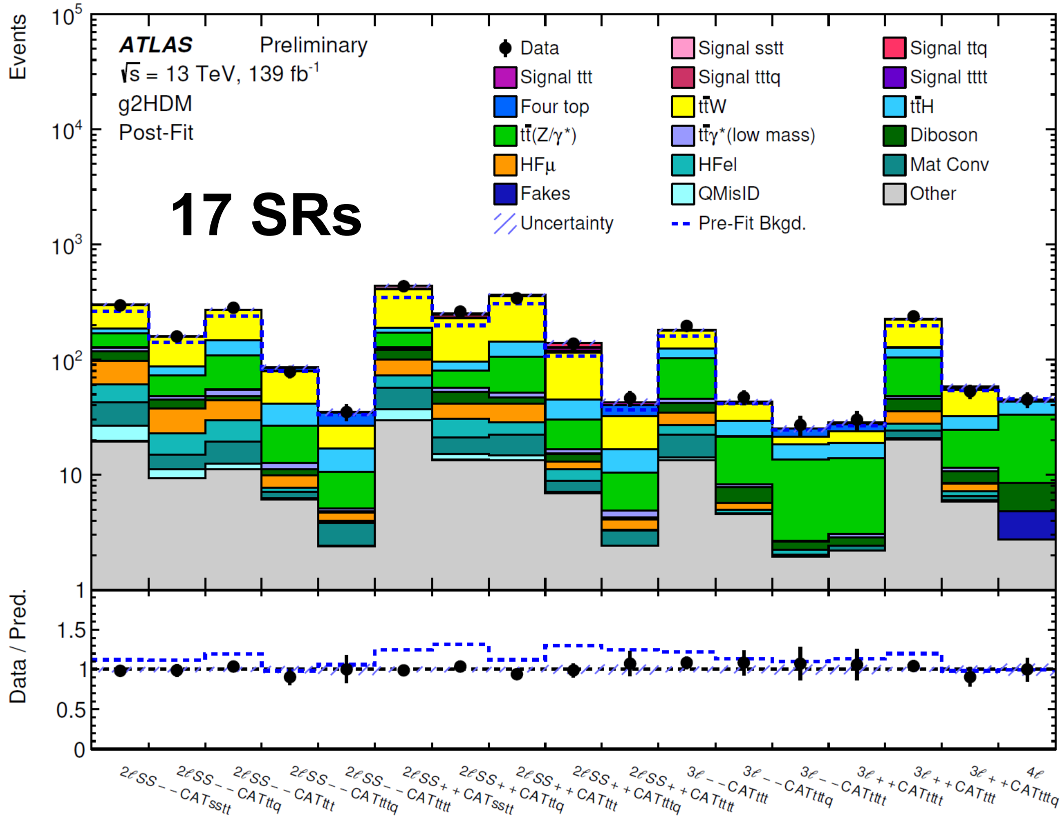
  $Z_2$ symmetry means the Lagrangian is invariant under $\phi_1 \leftrightarrow \phi_1, \phi_2 \leftrightarrow -\phi_2$ or $\phi_1 \leftrightarrow -\phi_1, \phi_2 \leftrightarrow \phi_2$

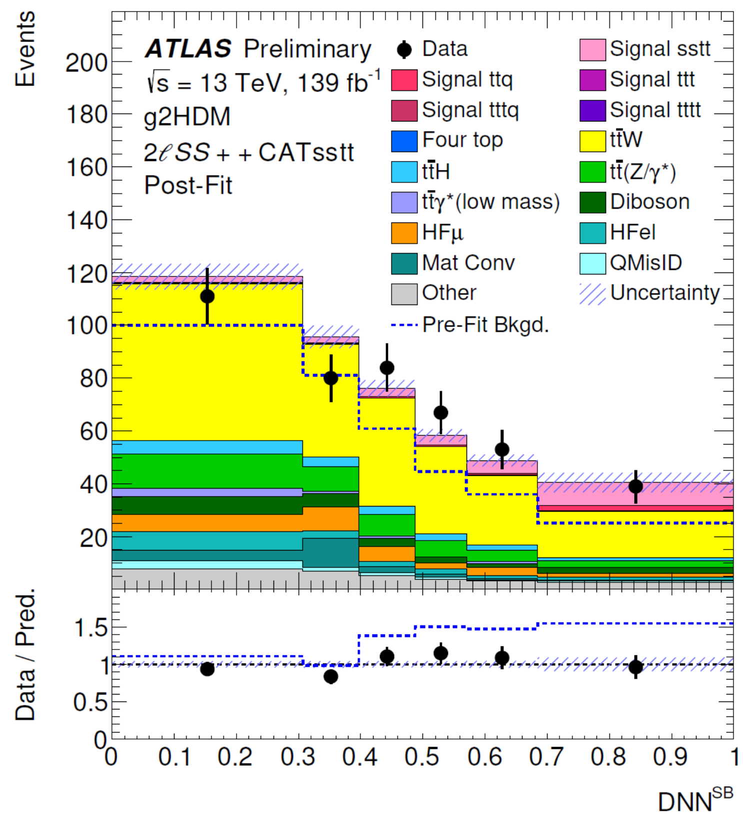
- Extra top Yukawa couplings $\rho_{tt}$, $\rho_{tc}$, $\rho_{tu}$ → heavy Higgs production with 2, 3 or 4 tops

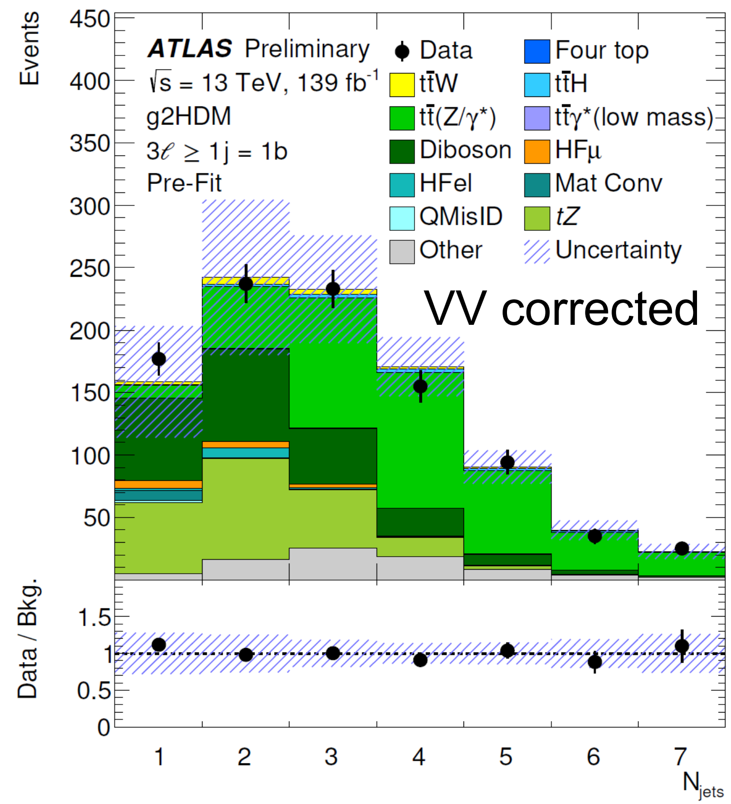


# Heavy Higgs in the g2HDM

- DNN$^{cat}$ classifier has 5 output categories corresponding to 5 signal modes (sstt, ttq, ttt, tttq, tttt)
- Events are categorized by #leptons (2lSS, 3l, 4l), total lepton charge, DNN$^{cat}$ classifier output → in total 17 signal and 10 control regions are defined
- In each signal region, another DNN$^{SB}$ is trained to separate signal from background
- Background estimated mainly from MC, but several corrections obtained from data:
  - VV reweighted to match jet multiplicity seen in a data CR
  - tt+≥1 bjet, ttW, ttZ and VV adjusted via normalization factors from data

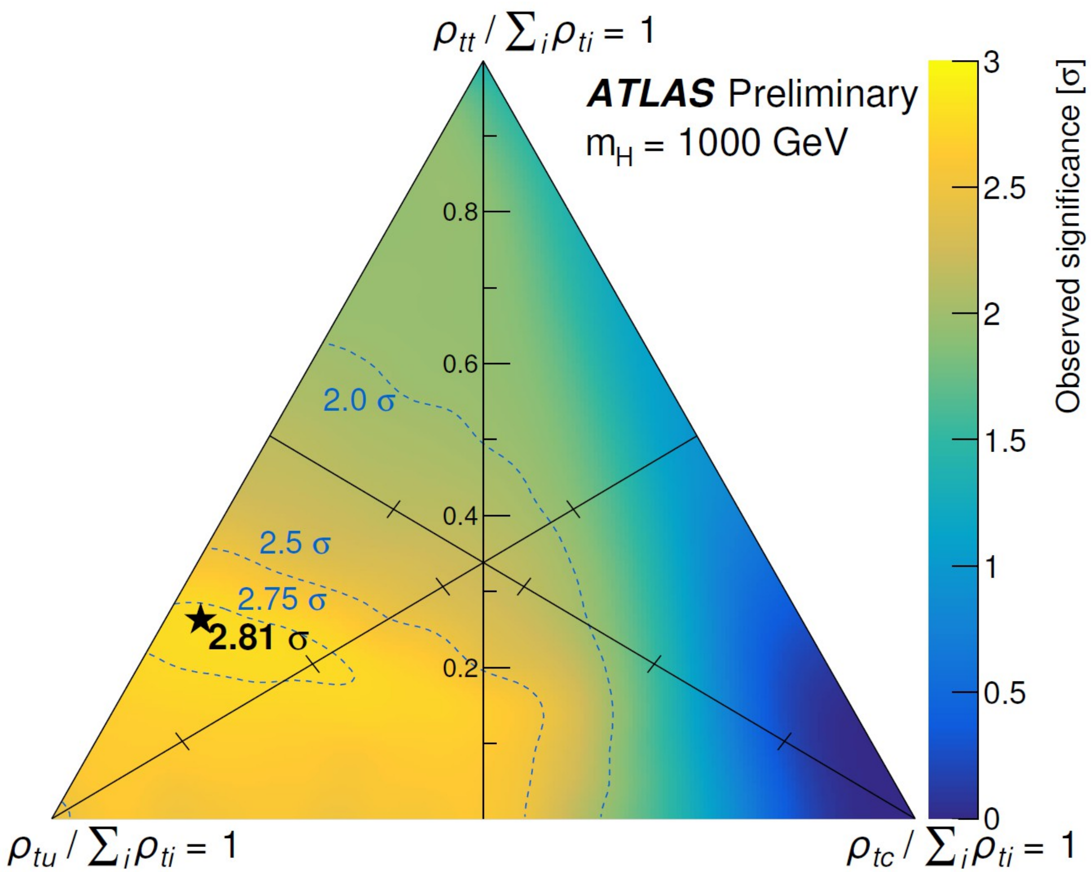


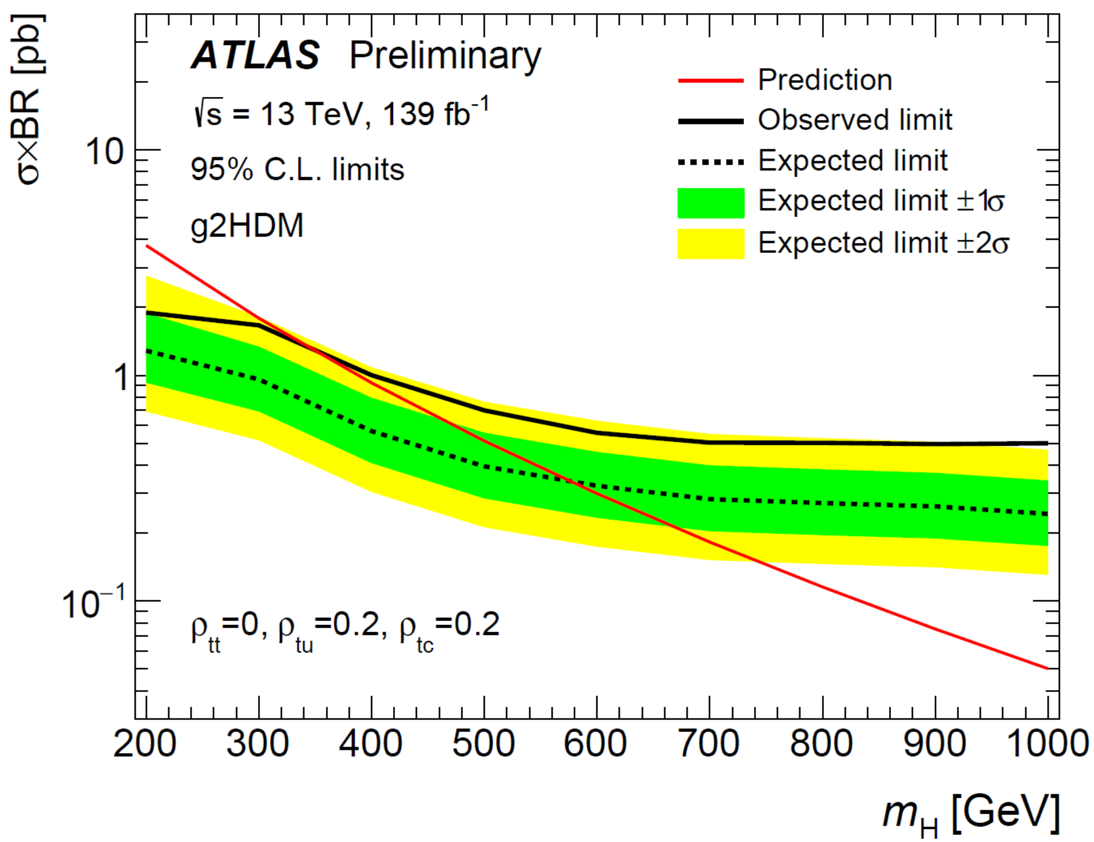



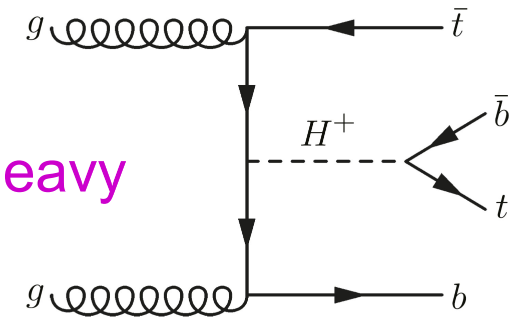
# Heavy Higgs in the g2HDM

- Simultaneous fit to 17 signal regions and 10 control regions
- DNN$^{SB}$ output is the discriminant in the SR; #bjets, sublead. lepton $p_T$ and event yields in the CRs
- Largest excess (2.81σ locally) at $\rho_{tt}$=0.32, $\rho_{tc}$=0.05, $\rho_{tu}$=0.85 and $m_H$=1000 GeV
- Global significance difficult, will be calculated for the paper result
- Depending on the couplings, some values for $m_H$ are excluded by this search

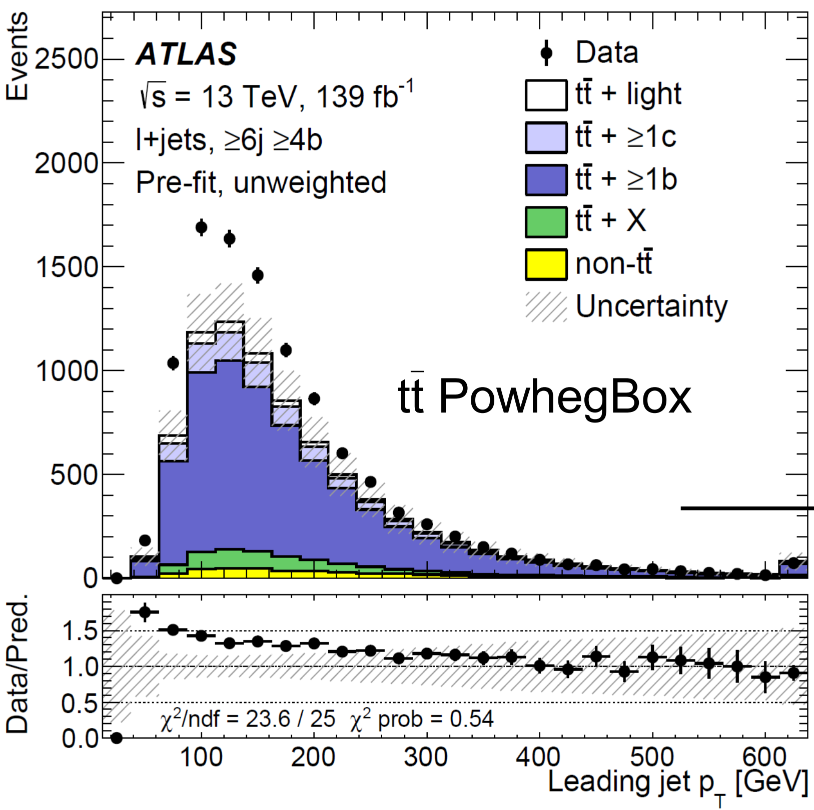


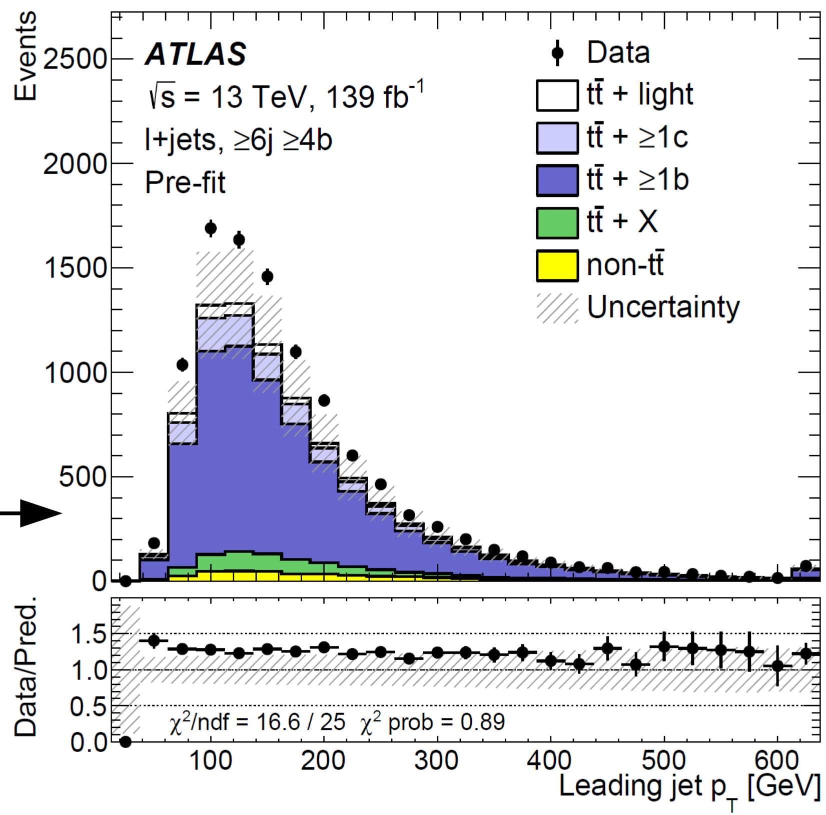



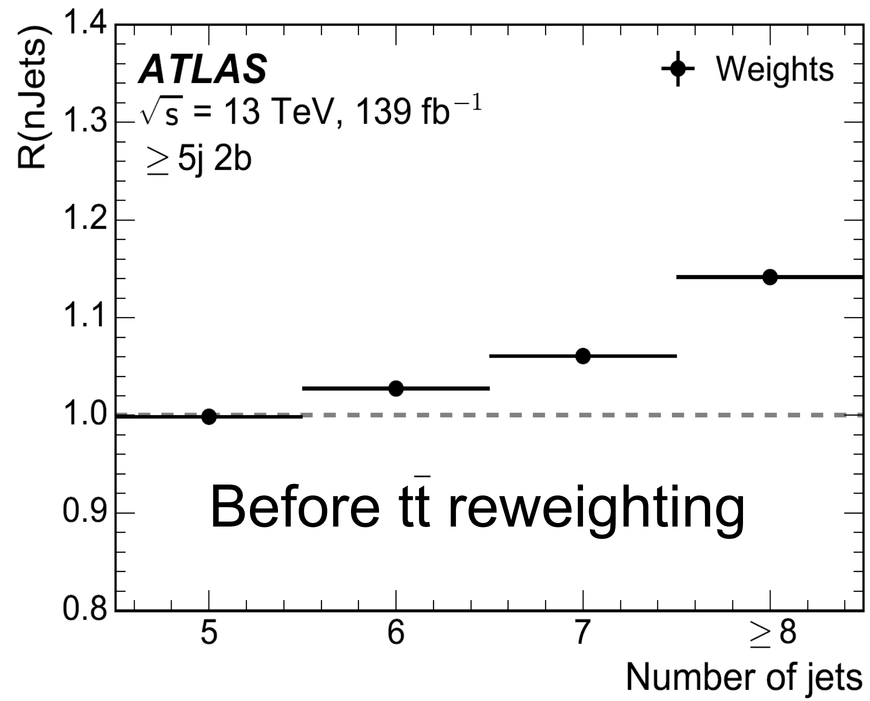
# $H^+ \rightarrow tb$



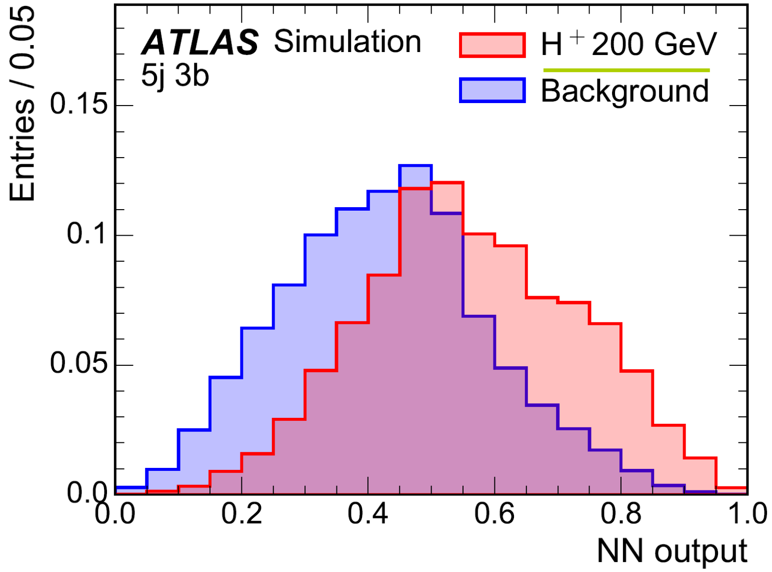

- Golden channel for charged Higgs in the MSSM, largest BR if $H^+$ is heavy
- 1 lepton in the final state (dilepton or all-hadronic not considered)
- ttbar mismodelled for high jet multiplicities, which is independent of presence of b-jets
- Corrections derived from low b-tagged regions and applied to analysis categories: $R(x) = \frac{N_{\mathrm{Data}}(x) - N_{\mathrm{MC}}^{\text{non-}t\bar{t}}(x)}{N_{\mathrm{MC}}^{t\bar{t}}(x)}$
- **Analysis regions: 5j3b, 5j4b, 6j3b, 6j4b** (no CRs included in the fit)

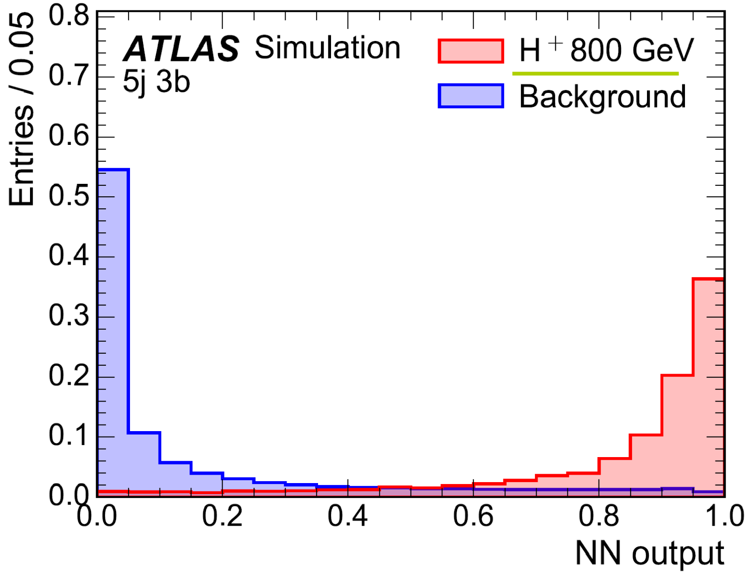


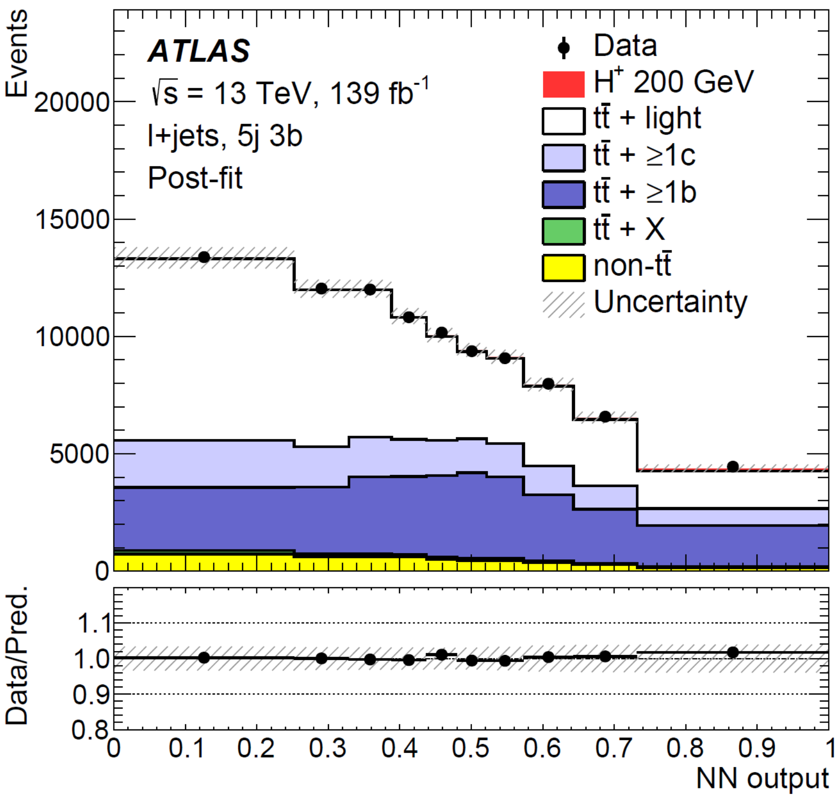
# $H^+ \rightarrow tb$

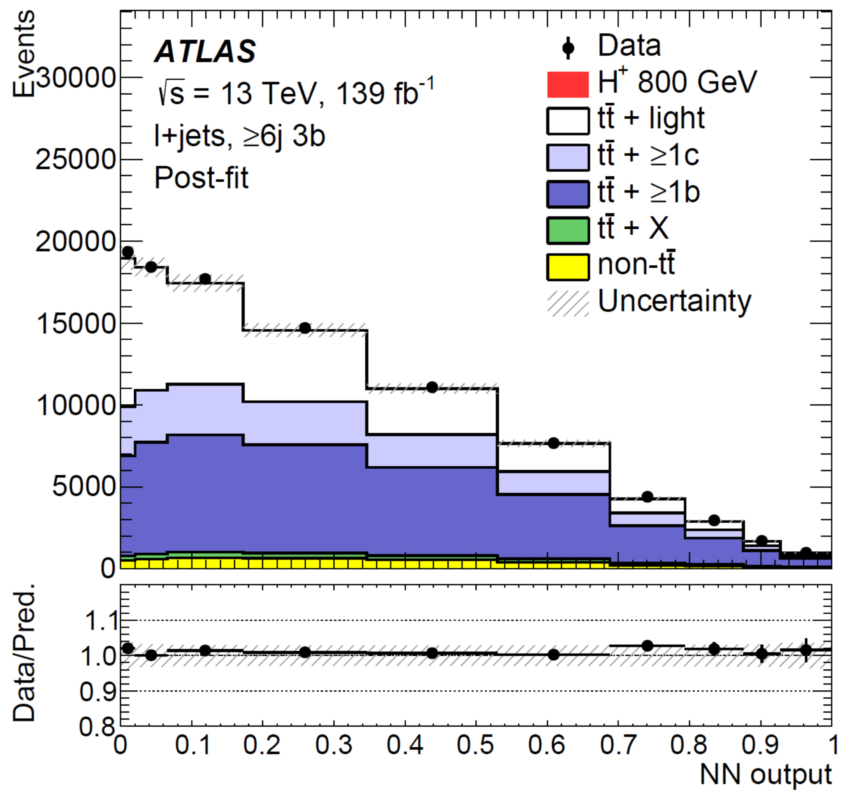


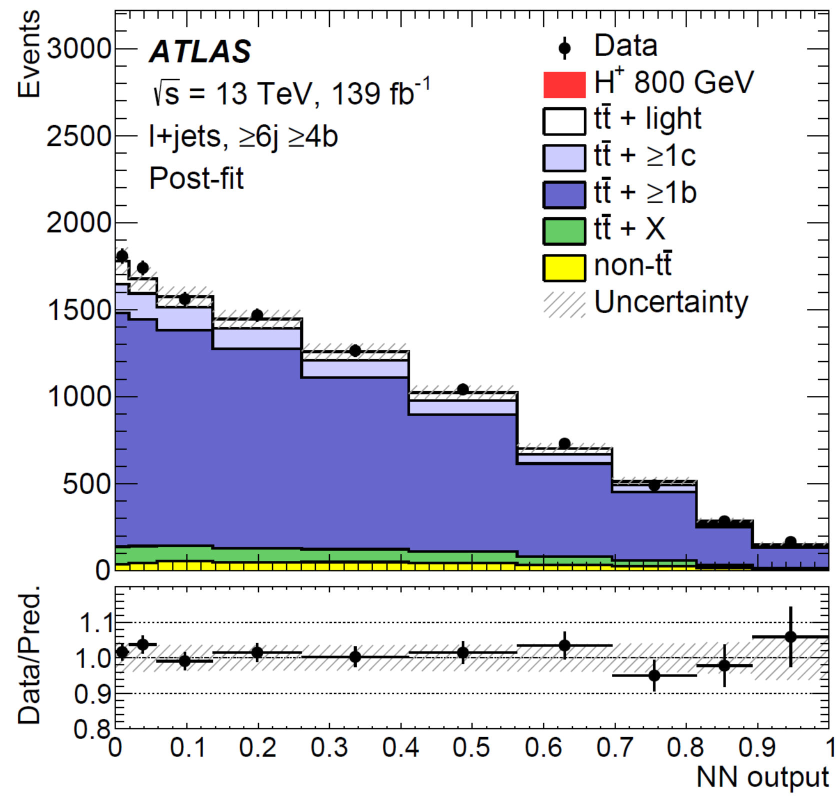




Parametrized NN trained in each category

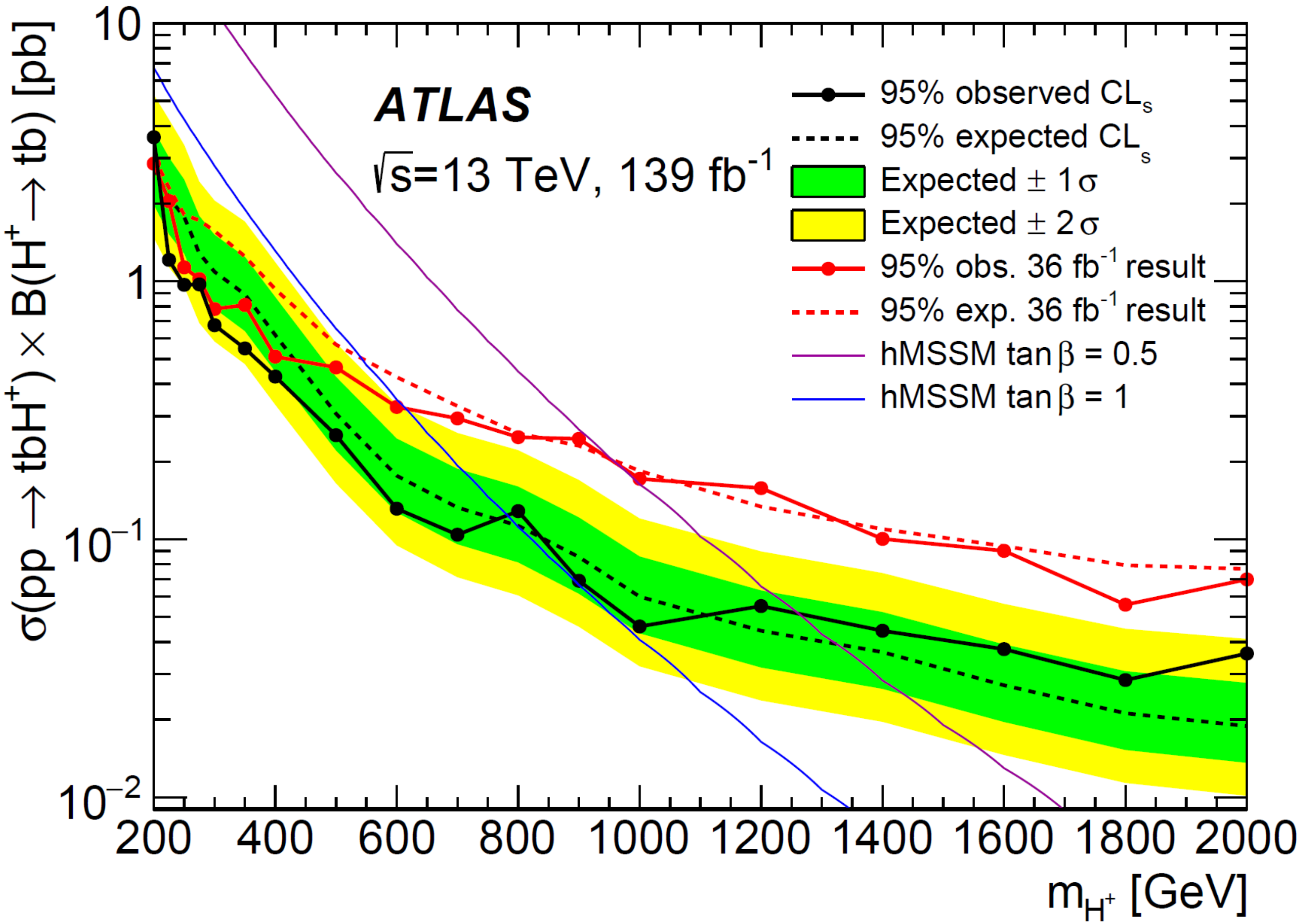
One of the inputs is a discriminant that quantifies consistency with $H^+$ or $t\bar{t}$ event topology, that increases NN performance at low $mH^+$



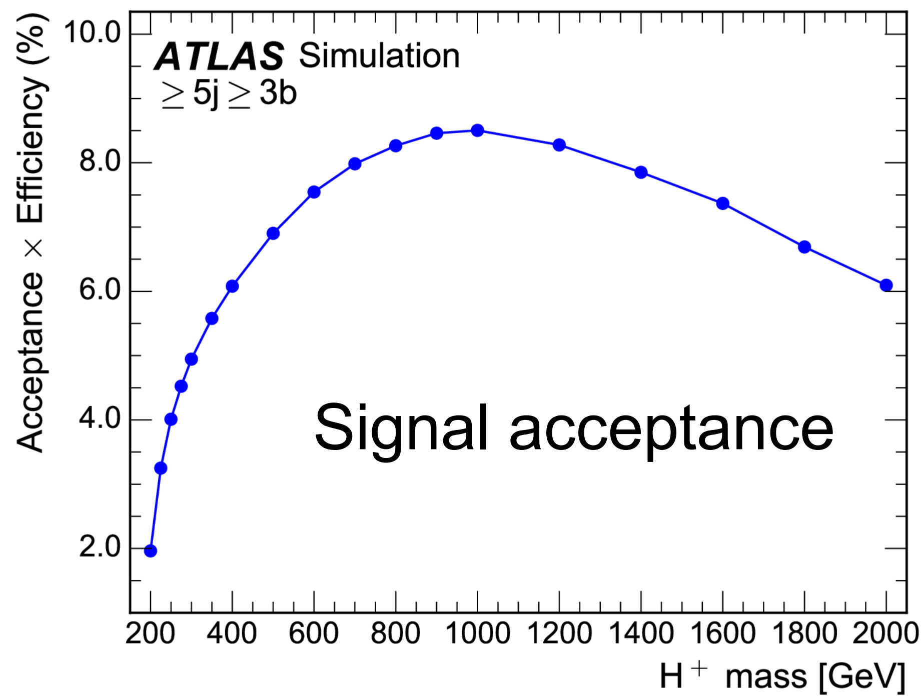



# $H^+ \rightarrow tb$

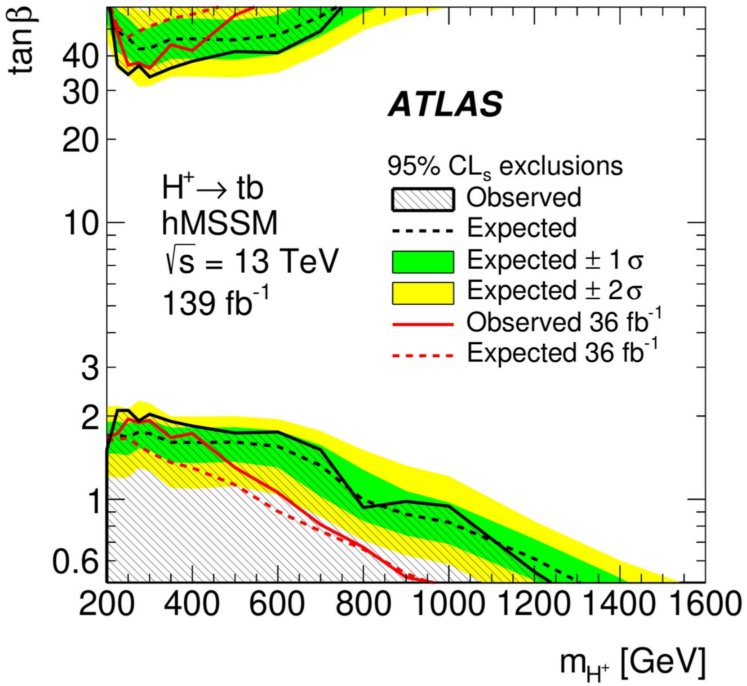


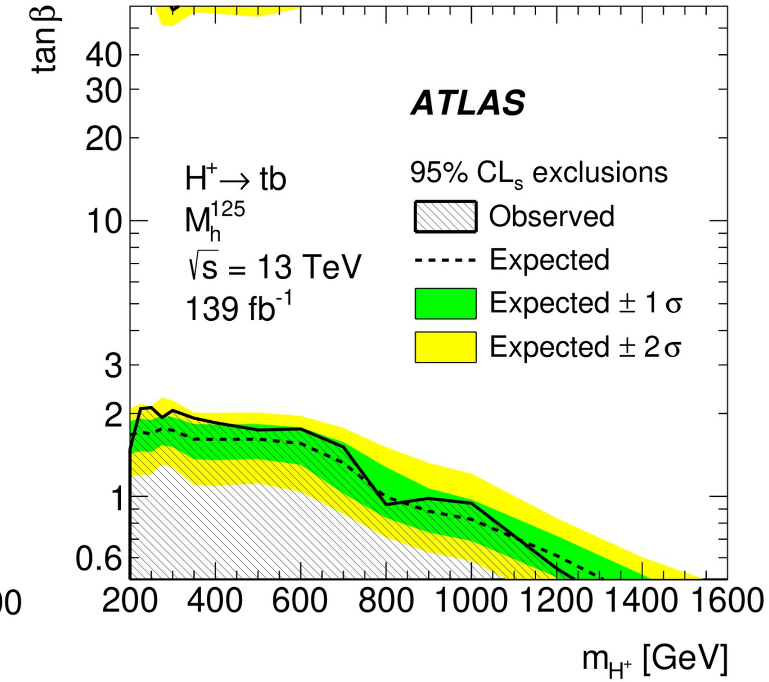

About 170 parameters in the fit (long list of jet-related and bkg. modelling uncertainties)

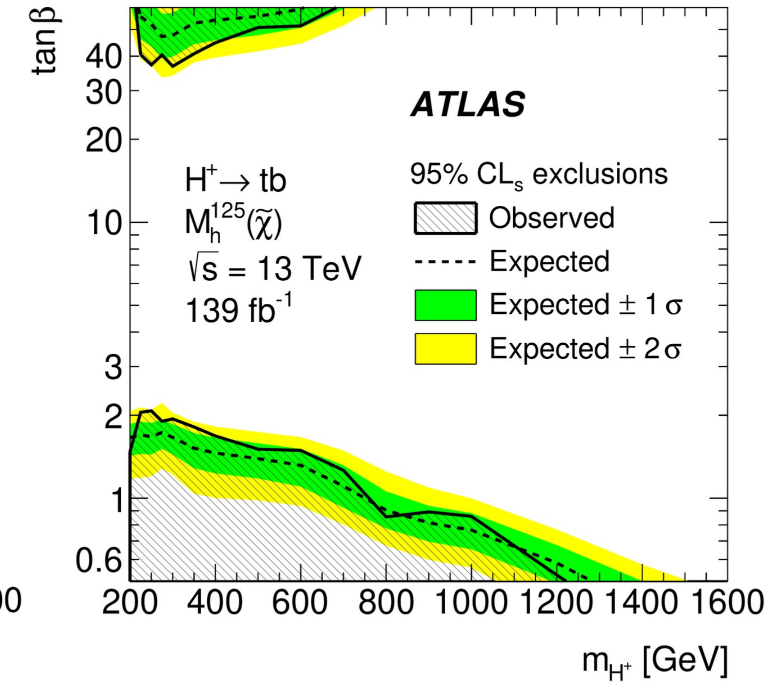


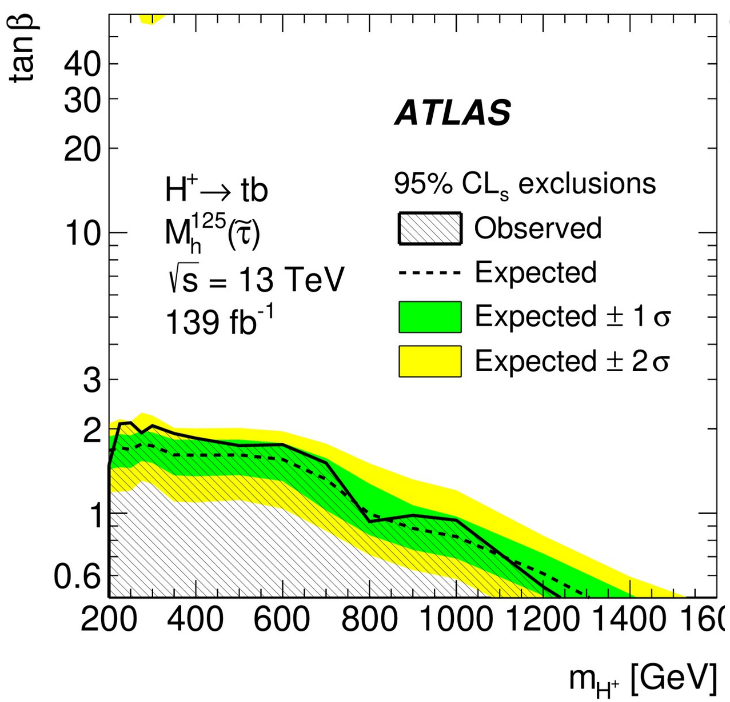

- No excess. Sensitivity at low mass strongly limited by systematics
- Signal acceptance drops for high $H^+$ masses because jets start to merge
- Need dedicated boosted analysis to recover these events

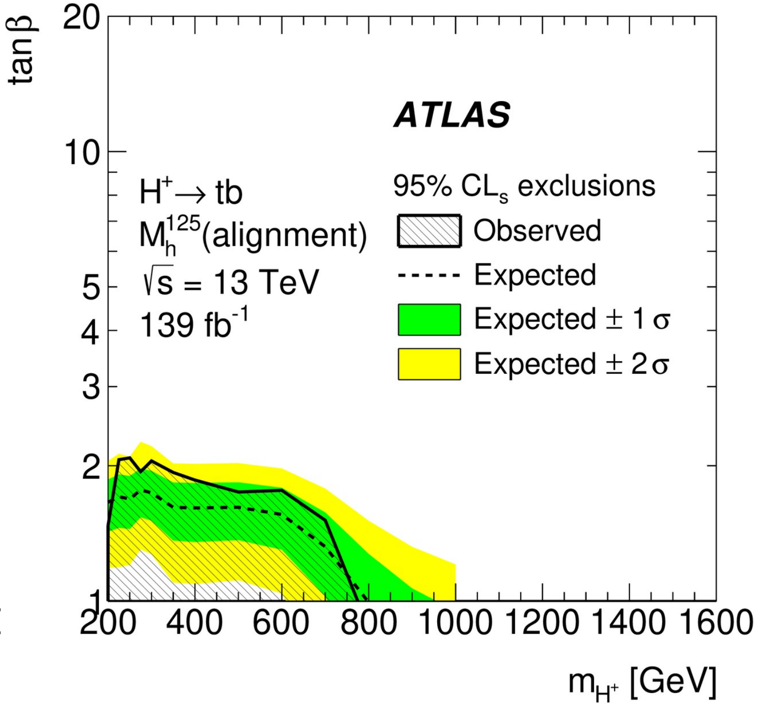
# $H^+ \rightarrow tb$

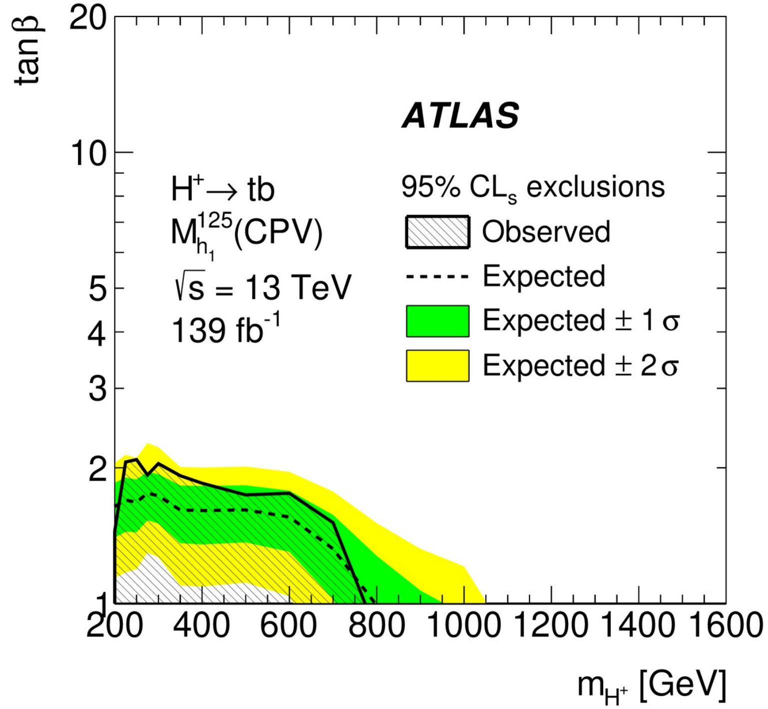


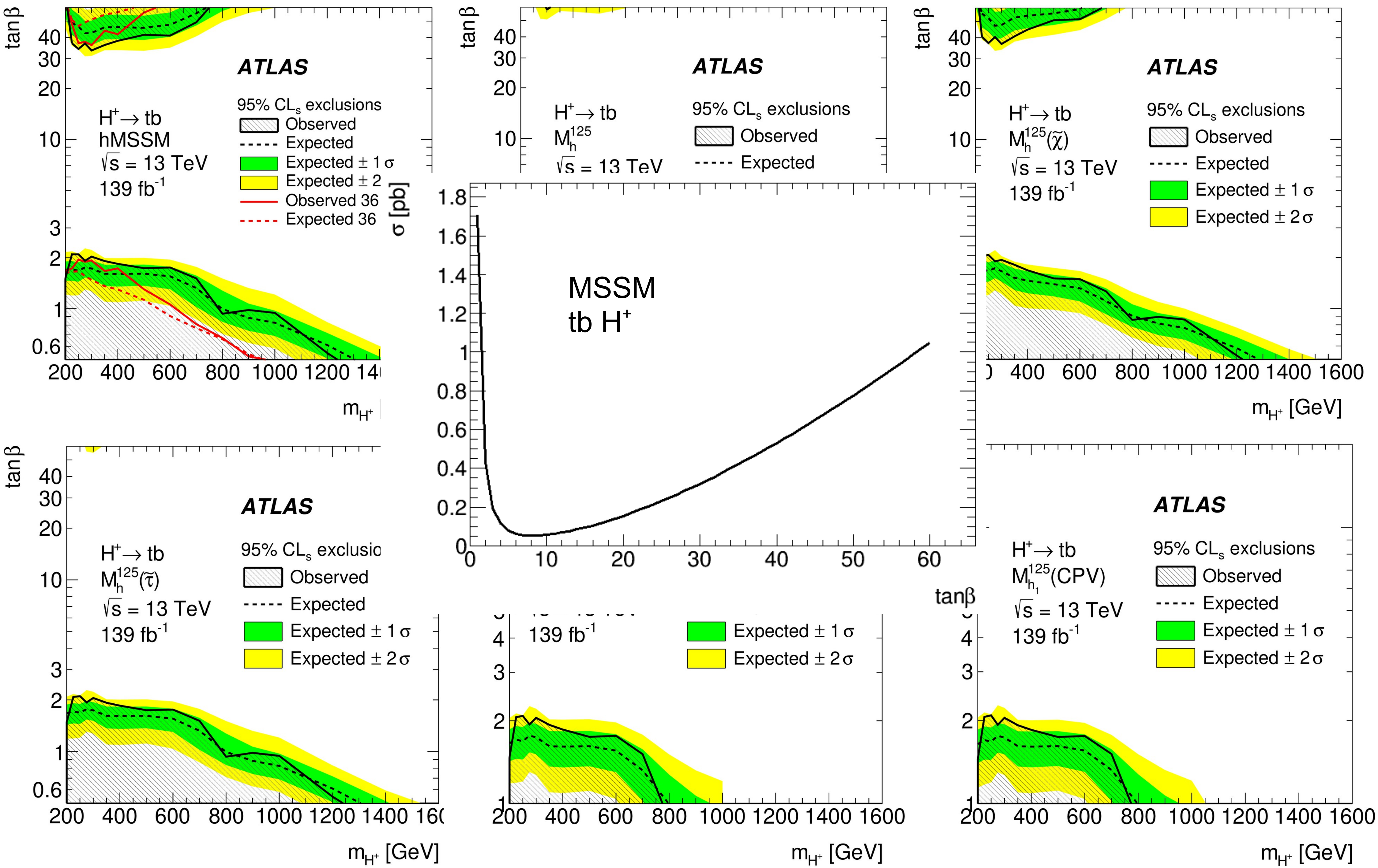



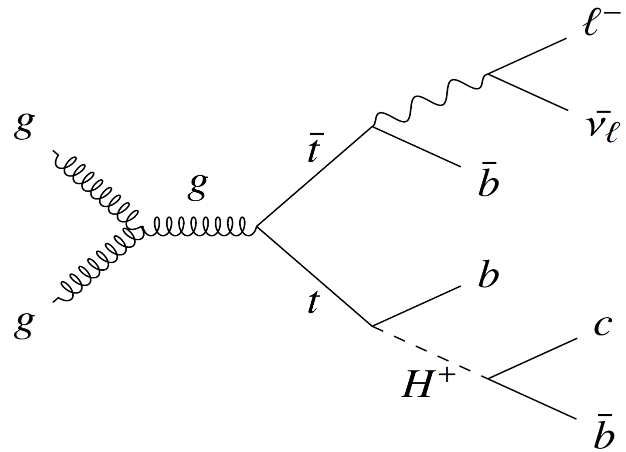



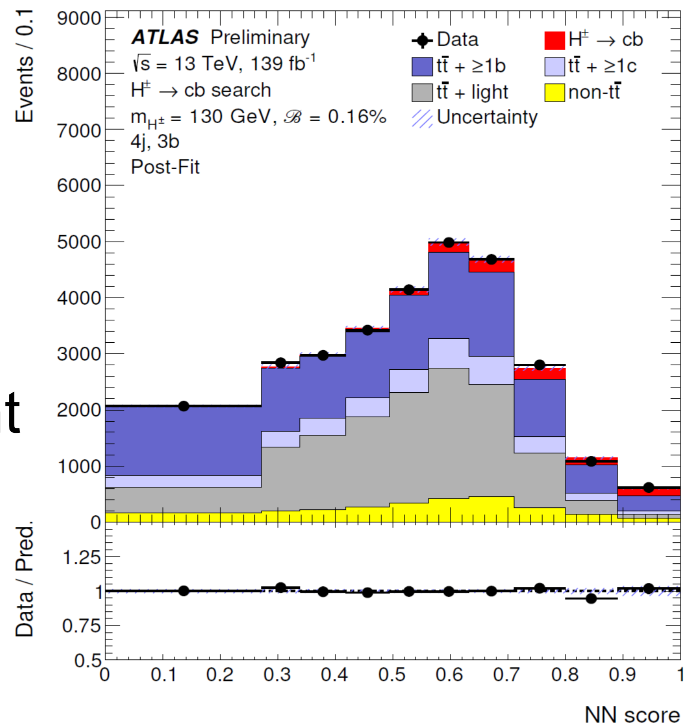
# $H^+ \rightarrow tb$

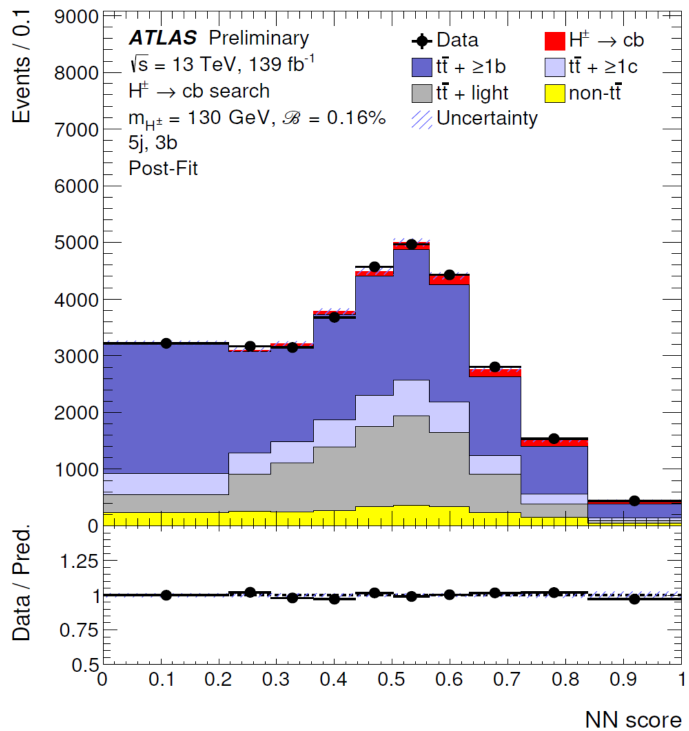


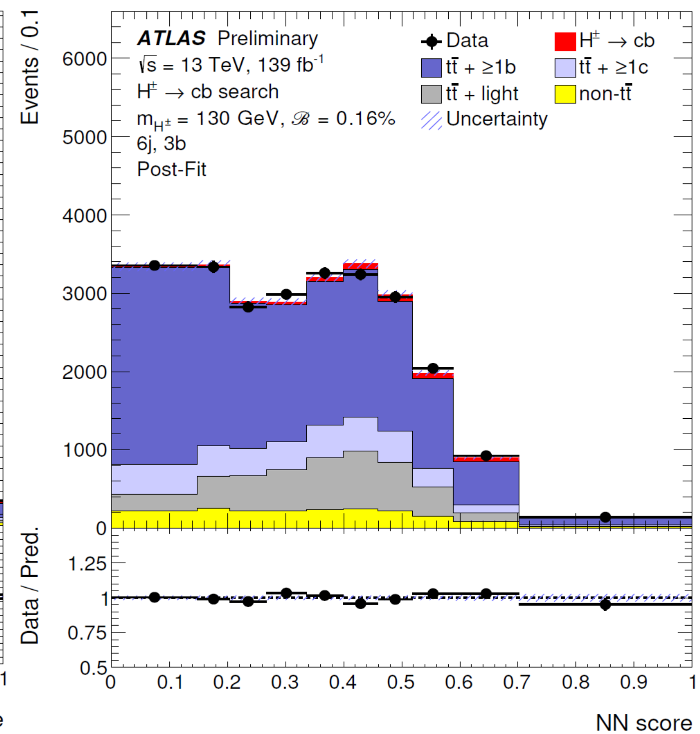
# $H^+ \rightarrow cb$



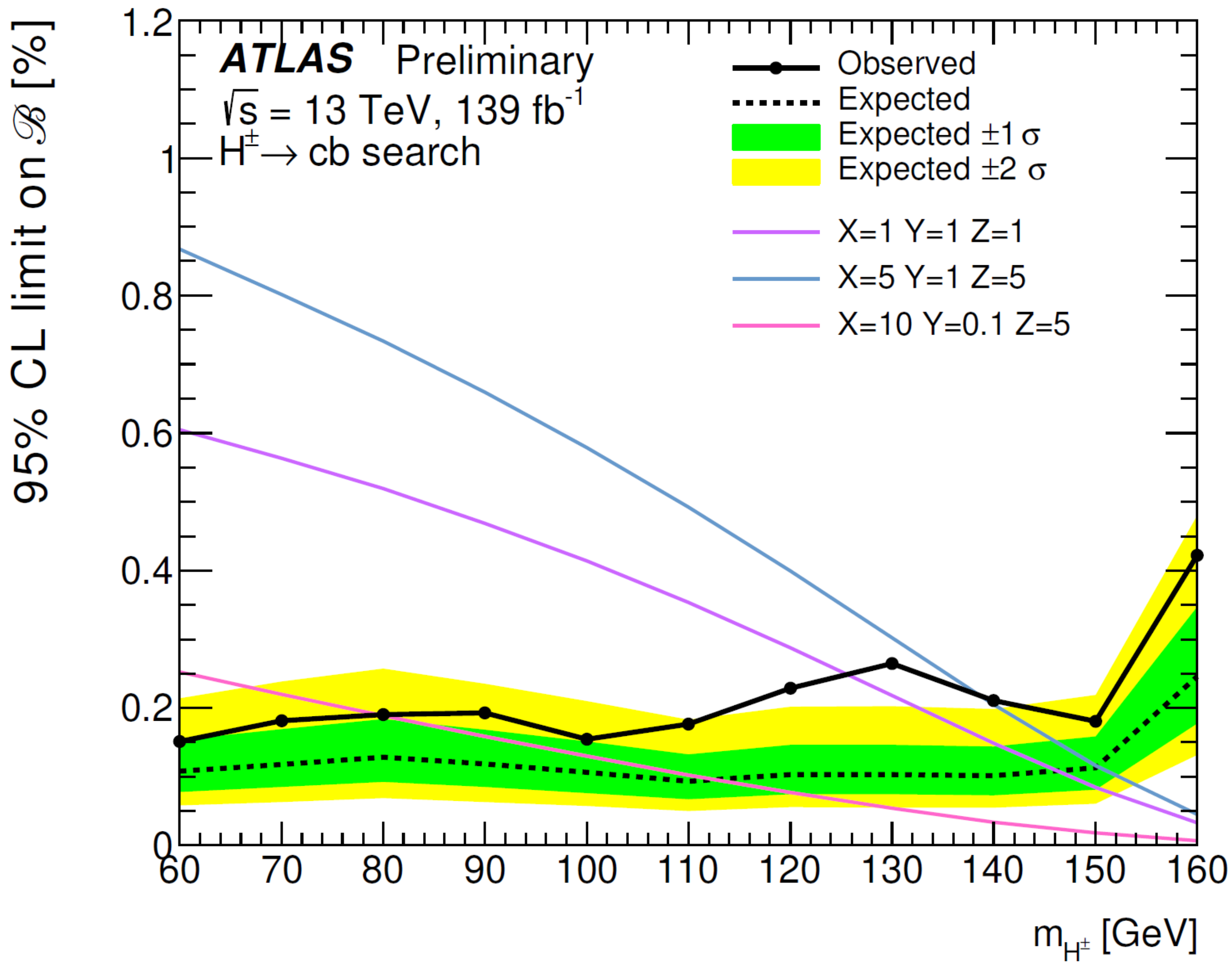

- Strongly motivated in the 3HDM model ($\Phi_1$, $\Phi_2$, $\Phi_3$) (two charged scalars: $H_1^+$, $H_2^+$, couplings X, Y, Z), BR ($H^+ \rightarrow cb$) can get up to 80%
- Final state with high jet/b-jet multiplicities, large ttbar background (tt+light, tt+b, tt+c)
- Very tight b-tagging: 60% WP using „DL1r“ (DNN-based)
- Signal-enriched categories: **4j3b**, **5j3b**, **6j3b**, and 4j4b to recover a bit signal acceptance, 5 signal-depleted categories to correct or control the ttbar background
- Parametrized NN for signal-background separation
- NN score is final discriminant
- Mass range 60-160 GeV



# $H^+ \rightarrow cb$

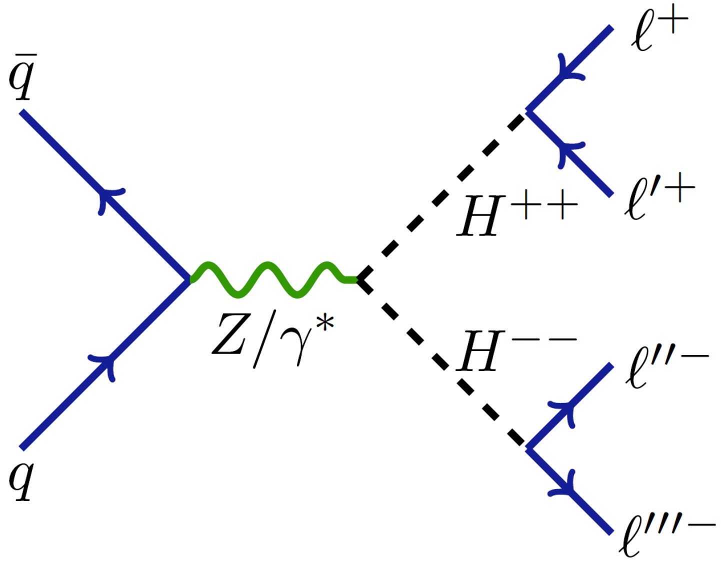



$3\sigma$ local excess ($1.6\sigma$ global) at 130 GeV, broadness compatible with $H^+$ signal

Model predictions in the 3HDM (Predictions from the LHCHXSWG)

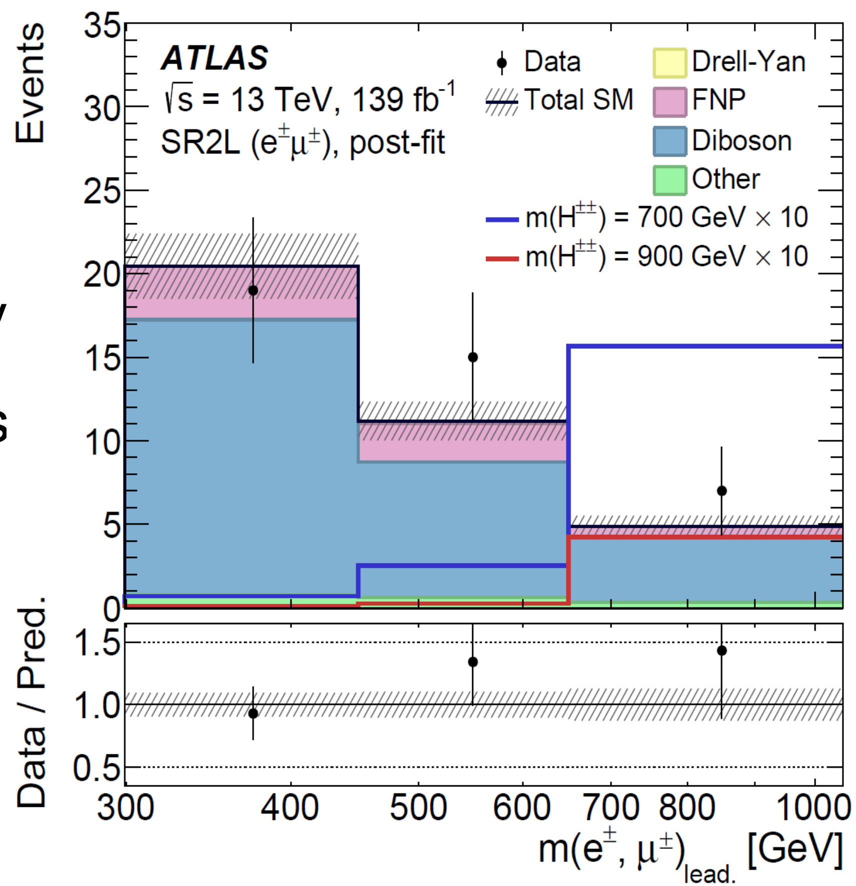
Generated $H^+$ width is much smaller than the resolution

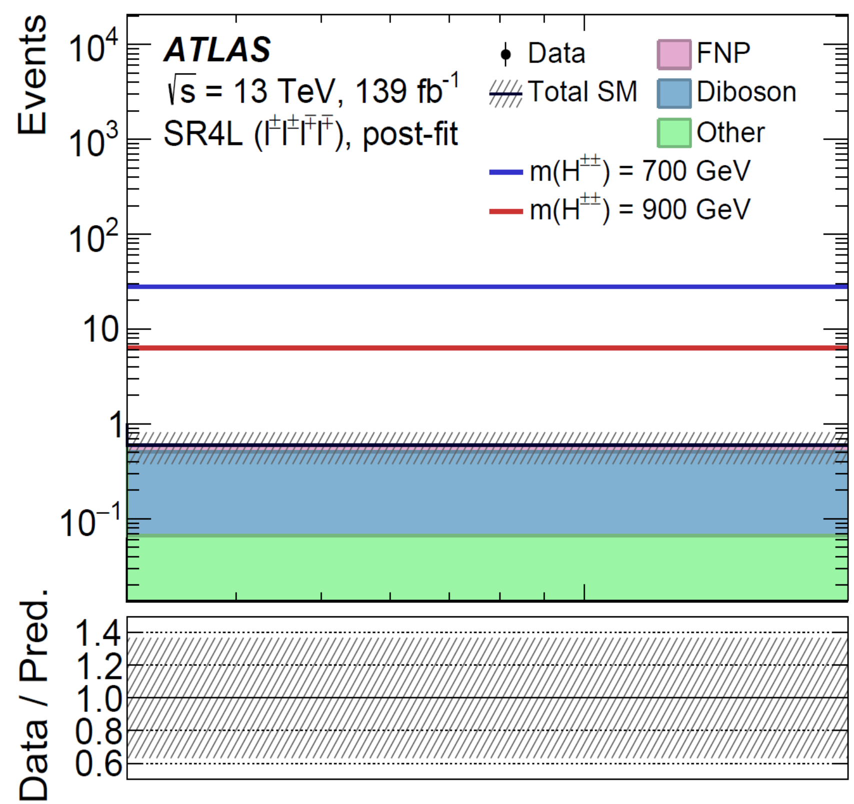
# $H^{++} \rightarrow$ leptons



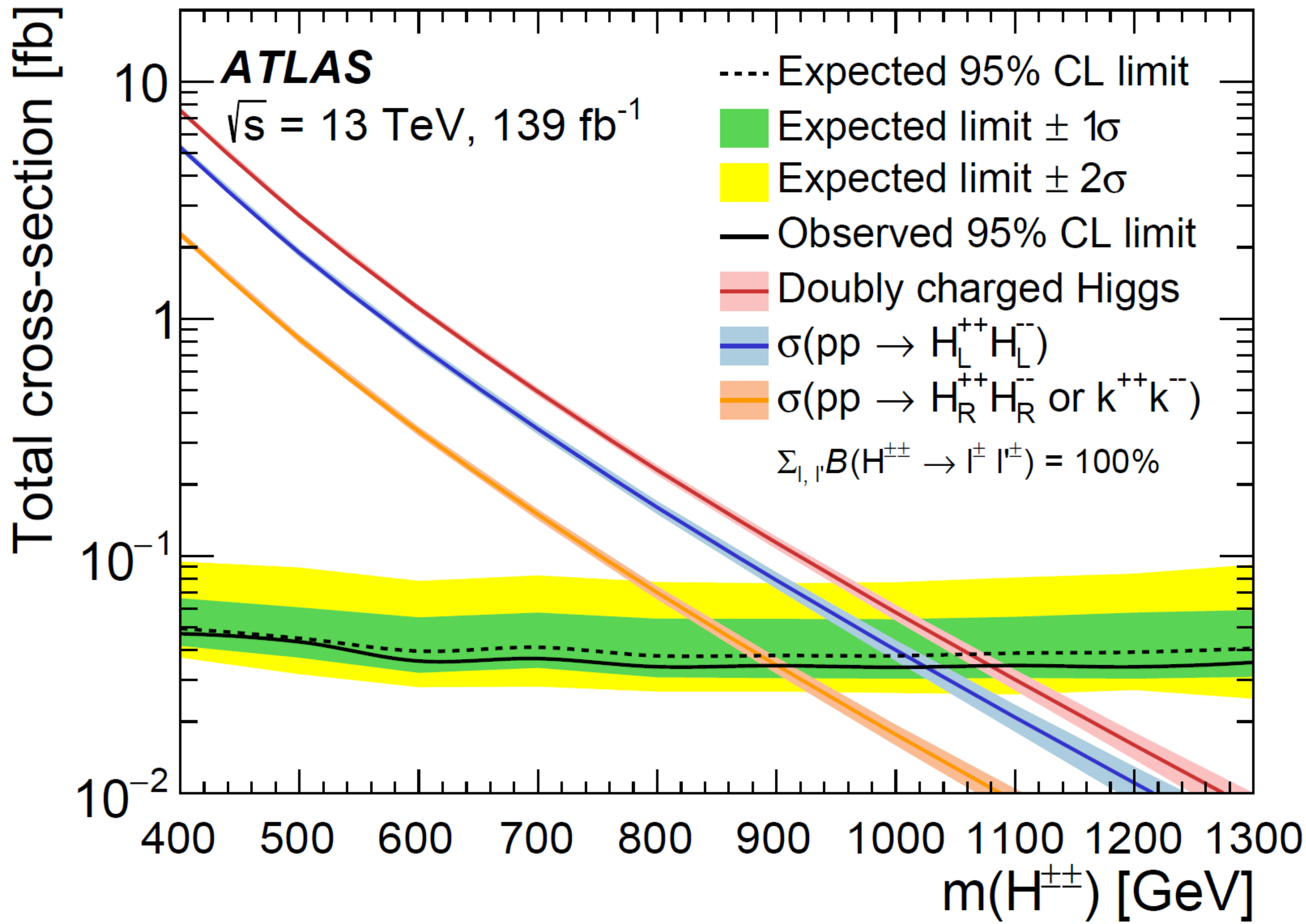

- $H^{++}$ $H^{--}$ pair production
- $H^{++}$ well motivated by many models: type-II seesaw, left-right symmetric models, Zee-Babu, GM, …
- GM favors decay of $H^{++}$ to WW
- Here focus on LRSM, which features $H_L^{++}$ and $H_R^{++}$, which couple to either left-handed or right-handed leptons

- Categories: 2l, 3l, 4l
- 4l category has lowest statistics, but drives sensitivity
- Considered: Electrons, muons leptonic τ decays
- Leptons must pass tight ID
- Same-sign leading lepton pair mass > 300 GeV



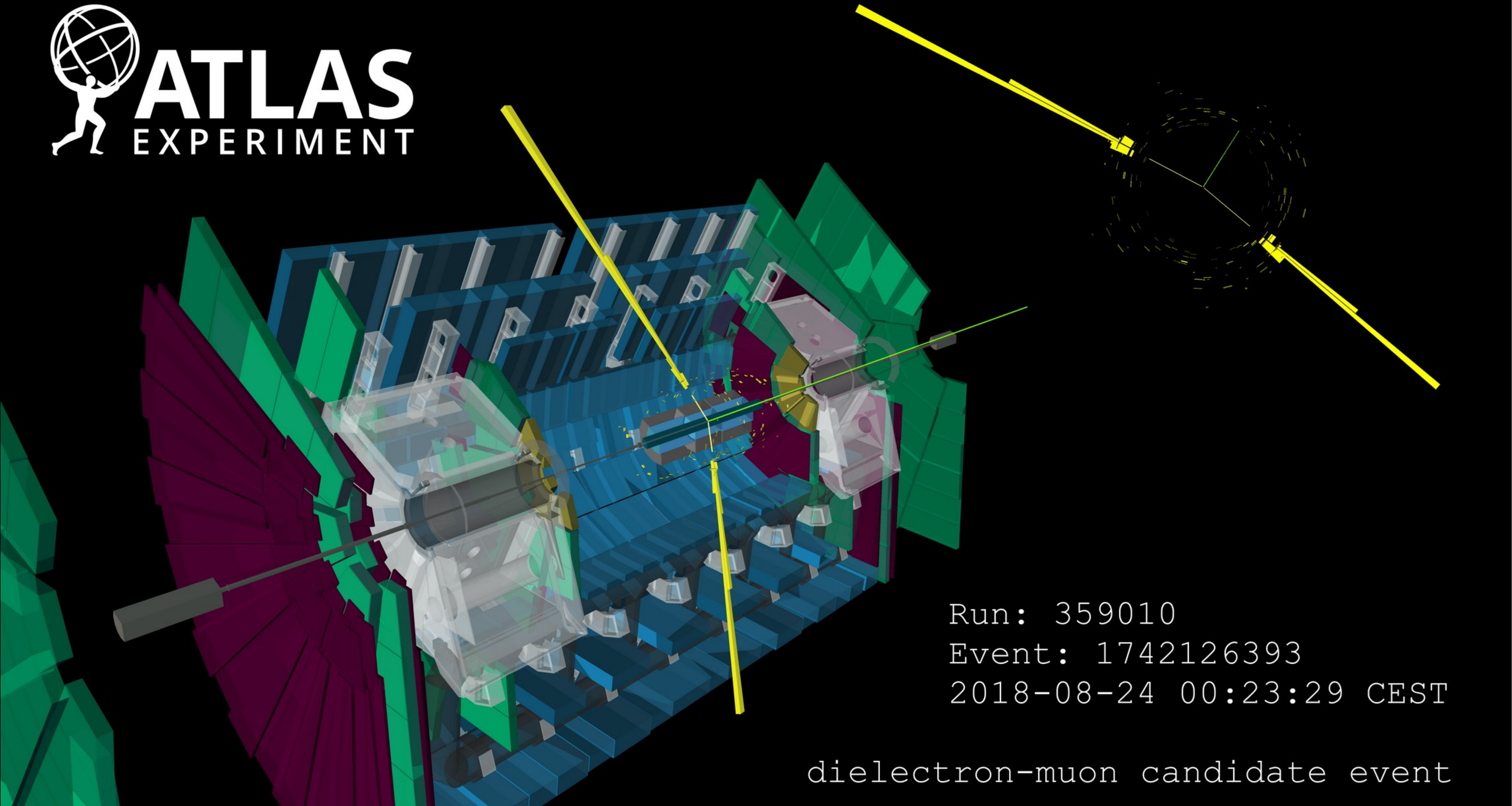
# $H^{++} \rightarrow$ leptons



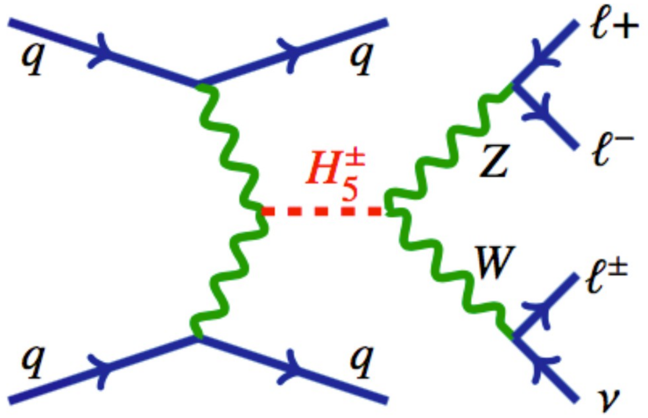

This search can exclude $H^{++}$ in the LRSM with mass below 900 GeV or 1000 GeV depending on their couplings

**H$^{++}$ candidate event** with 2 same-sign electrons and 1 muon

m(ee$\mu$) = 1257 GeV



# VBF $H^+ \rightarrow WZ$

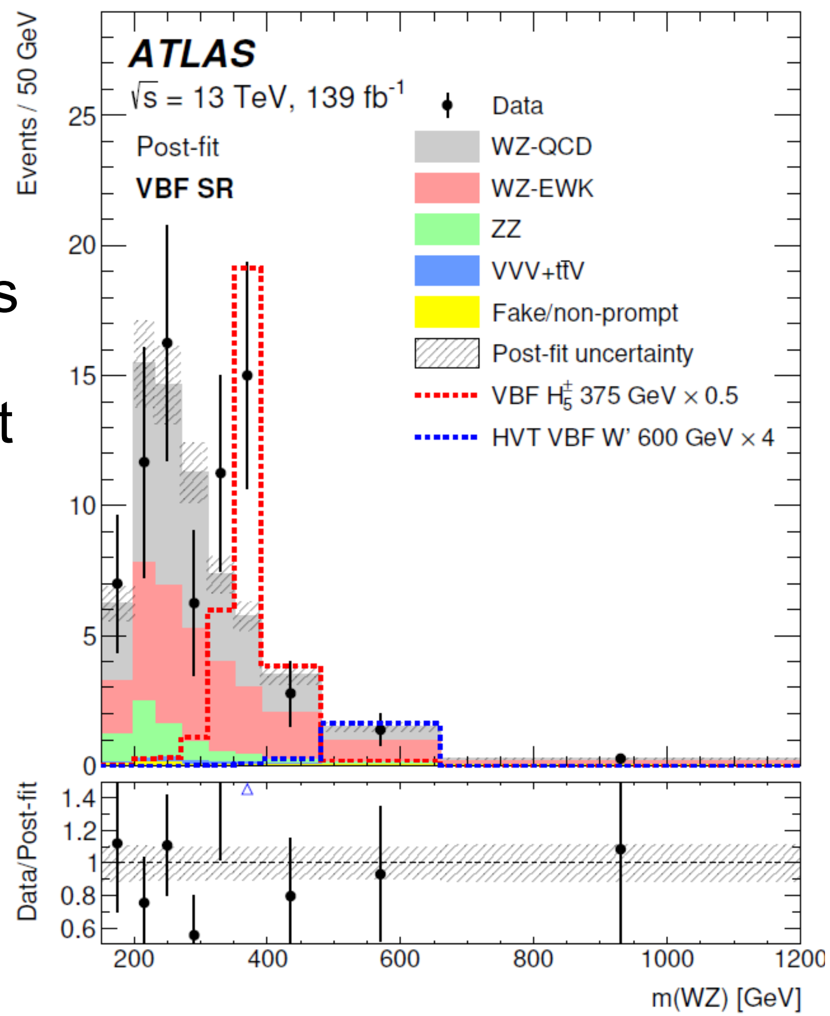


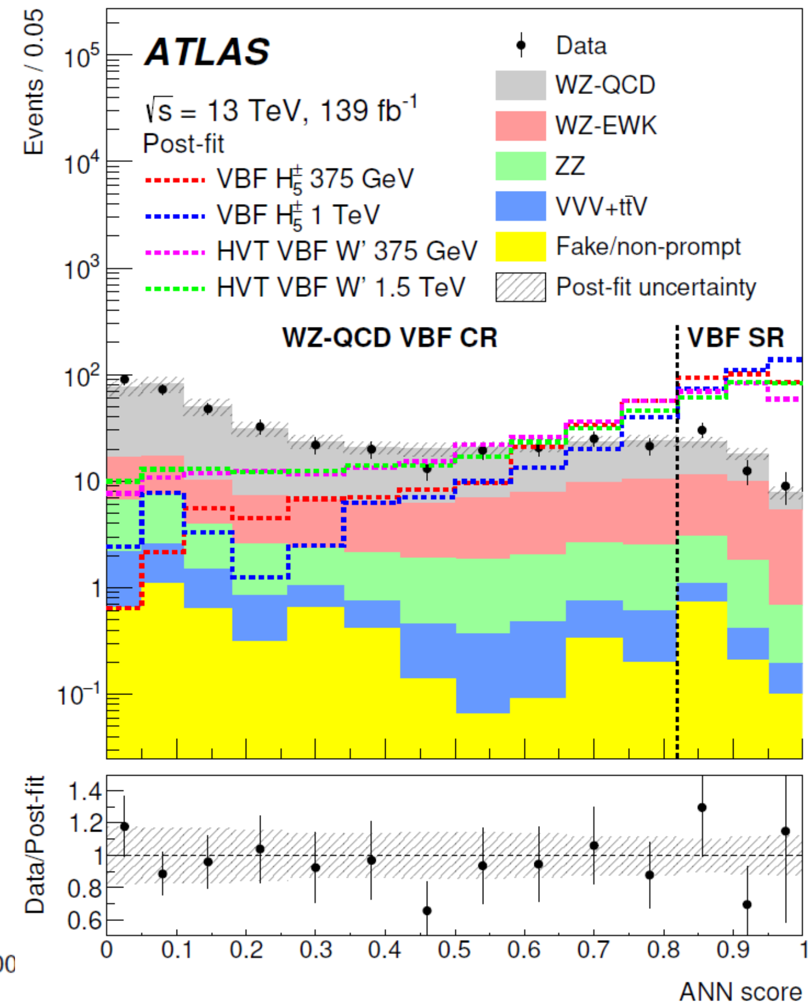

In the 2HDM, this process is suppressed.
But in triplet models, like the Georgi-Machacek, this can have sizable rates.
$H_5^+$ is part of the 5-plet ($H_5^{++}$, $H_5^+$, $H_5^0$), which is fermiophobic.

Neural network classification (either signal- or background like)
NN was trained on the lowest mass point (200 GeV), mass-dependent training would not give significantly better results

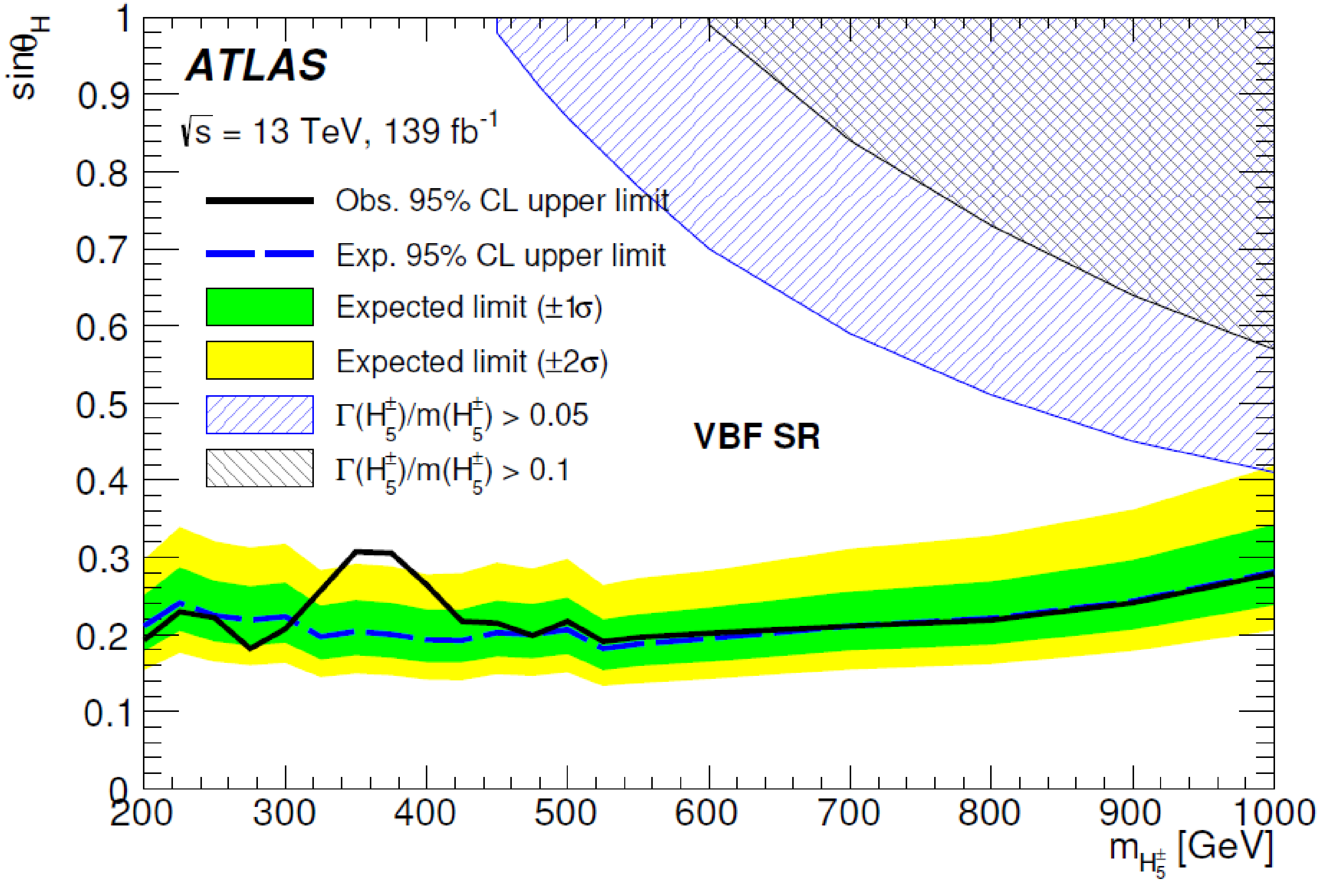
Cut on NN score defines the signal region

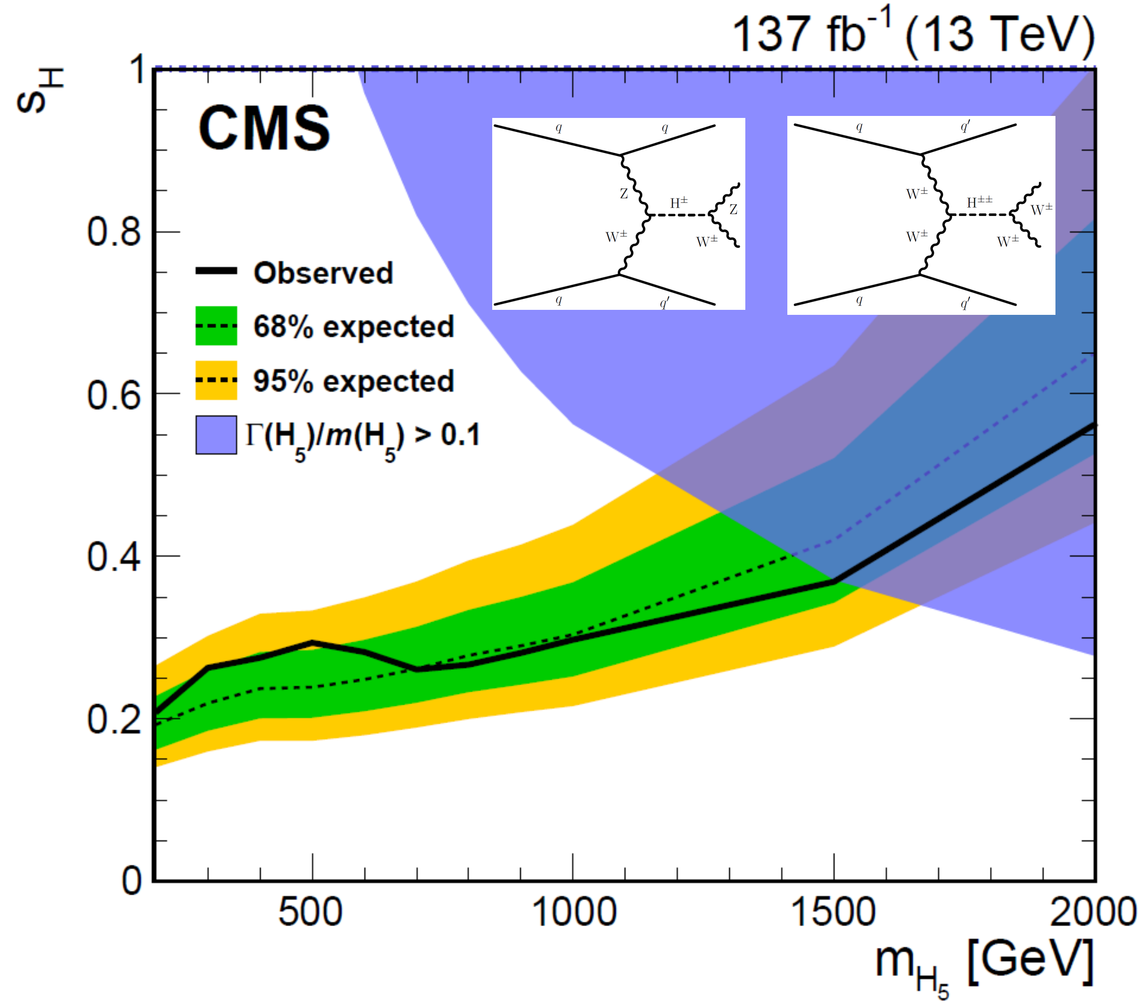
Final discriminant is then the reconstructed WZ mass



# VBF $H^+ \to WZ$ Results



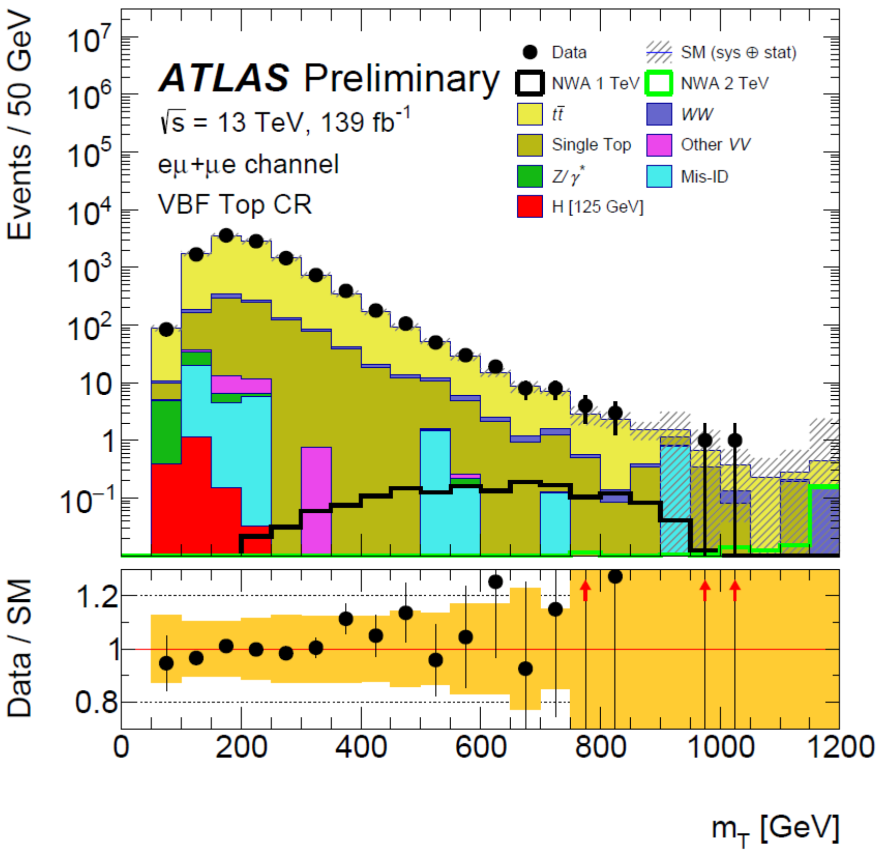

$\sin\theta_H$ is a GM model parameter that controls how much of the W/Z mass is generated by the vacuum expectation value of the triplet fields. The VBF $H^+$ cross section is proportional to $\sin\theta_H{}^2$.

ATLAS has $2.8\sigma$ local excess at 375 GeV.

CMS considers VBF $H^{++} \to WW$ in addition to $H^+ \to WZ$ and covers a search range up to 2 TeV.

# Heavy H → WW

- Brand new result, released only last week!
- WW decays to eμ and neutrinos (→ missing energy)
- Simple event selection based on cuts
- Dedicated background control regions (to control WW and top)



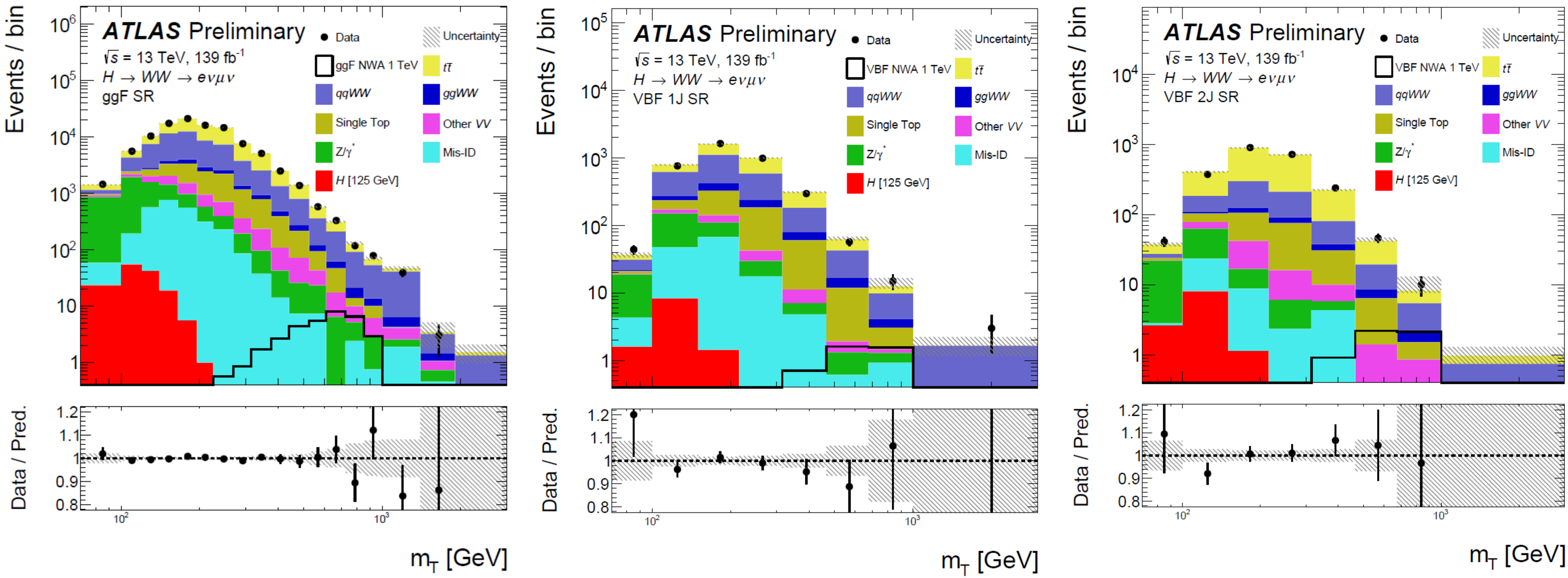

| | | |
|---|---|---|
| Pre-Selection | | |
| Two Different Flavour, Opposite Sign Leptons, $p_T^\ell > 25$ GeV<br>Third lepton veto, $p_T^\ell > 15$ GeV | | |
| Common Selection | | |
| $N_{b-\text{tag}} = 0$<br>$\lvert\Delta\eta_{\ell\ell}\rvert < 1.8$<br>$m_{\ell\ell} > 55$ GeV<br>$p_T^{\ell,\text{lead}} > 45$ GeV<br>$p_T^{\ell,\text{sublead}} > 30$ GeV<br>$\max(m_T^W) > 50$ GeV | | |
| $SC_{ggF}$ | $SC_{VBF1J}$ | $SC_{VBF2J}$ |
| Inclusive in $N_{\text{jet}}$ but excluding $SC_{VBF1J}$ and $SC_{VBF2J}$ | $N_{\text{jet}} = 1$ and $\lvert\eta_j\rvert > 2.4$, $\min(\lvert\Delta\eta_{j\ell}\rvert) > 1.75$ | $N_{\text{jet}} \geq 2$ and $m_{jj} > 500$ GeV, $\lvert\Delta y_{jj}\rvert > 4$ |

| WW $CR_{ggF}$ | Top $CR_{ggF}$ | WW $CR_{VBF1J}$ | Top $CR_{VBF}$ |
|---|---|---|---|
| $N_{b-\text{tag}} = 0$ | $N_{b-\text{tag}} = 1$ | $N_{b-\text{tag}} = 0$ | $N_{b-\text{tag}} \geq 1$ |
| $\lvert\Delta\eta_{\ell\ell}\rvert > 1.8$ | $\lvert\Delta\eta_{\ell\ell}\rvert < 1.8$ | ($\lvert\Delta\eta_{\ell\ell}\rvert > 1.8$ or | $\lvert\Delta\eta_{\ell\ell}\rvert < 1.8$ |
| $m_{\ell\ell} > 55$ GeV | | 10 GeV $< m_{\ell\ell} <$ 55 GeV) | $m_{\ell\ell} > 55$ GeV |
| $p_T^{\ell,\text{lead}} > 45$ GeV | | – | $p_T^{\ell,\text{lead}} > 45$ GeV |
| $p_T^{\ell,\text{sublead}} > 30$ GeV | | – | $p_T^{\ell,\text{sublead}} > 30$ GeV |
| $\max(m_T^W) > 50$ GeV | | – | $\max(m_T^W) > 50$ GeV |
| METSigRatio $> 0.8$ GeV$^{-1}$ | – | – | |
| Excluding VBF1/2J phase space | | VBF1J phase space | VBF1/2J phase space |

Top and WW backgrounds corrected with normalization factors derived from fit to data, top bkg reweighted in $p_T$ of leading lepton

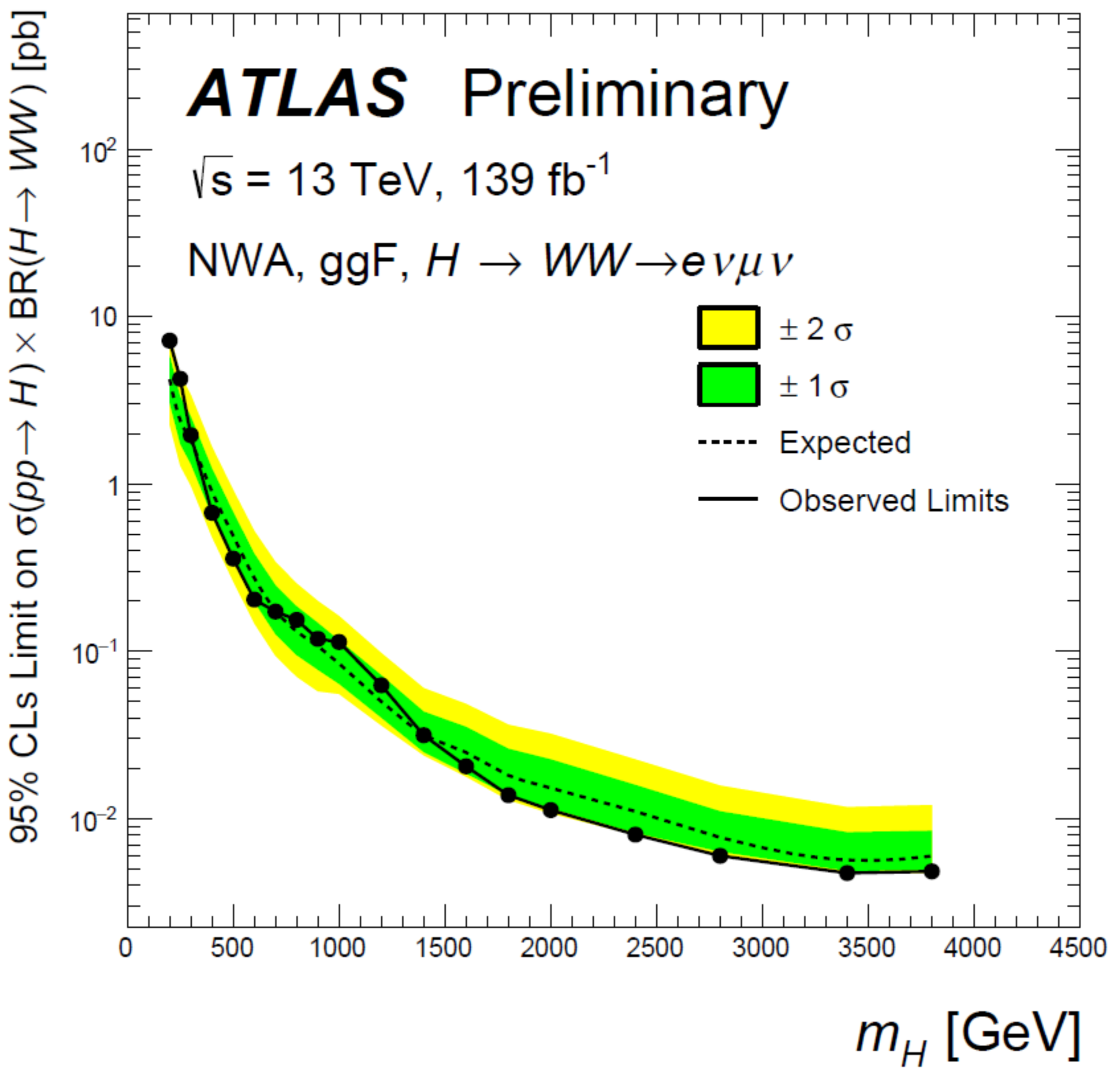
# H → WW

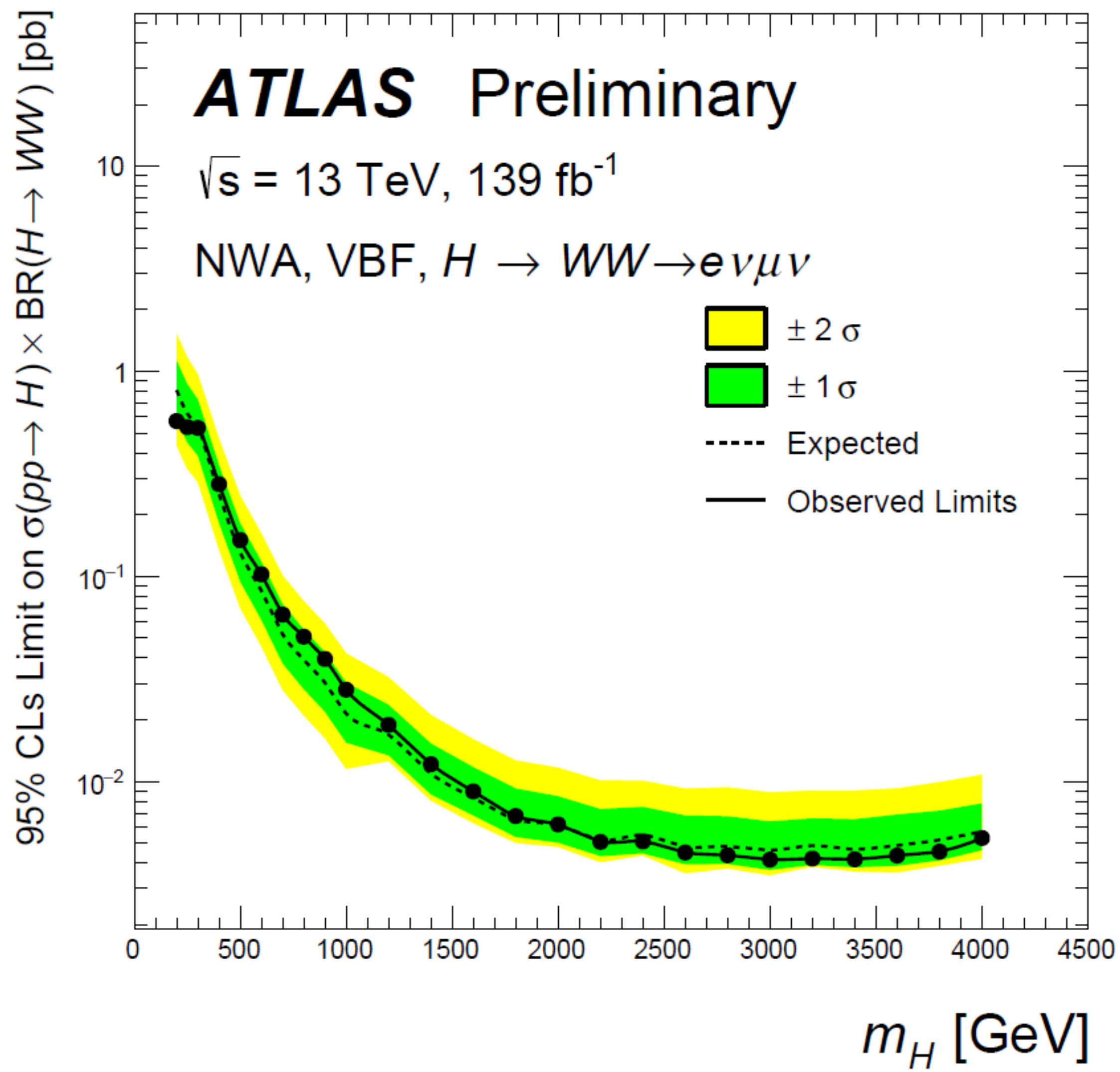
- Three signal regions, one targetting gluon fusion, and two targetting VBF signal
- It can happen, that one of the 2 forward jets is not reconstructed
  (eg. because it is outside of the detector acceptance) → 1-jet category




Final discriminant: $m_T^W = \sqrt{2 p_T^{\ell} E_T^{\text{miss}} \left(1 - \cos(\phi^{\ell} - \phi^{E_T^{\text{miss}}})\right)}$ with $E_T^{\ell\ell} = \sqrt{|\vec{p}_T^{\,\ell\ell}|^2 + m_{\ell\ell}^2}$

# H → WW



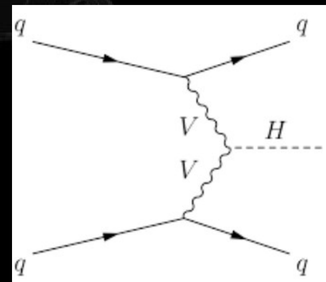




Very good agreement of data with background-only hypothesis for both ggF and VBF

In these plots, a generic narrow-width signal is assumed (other signal models considered in the conf note, and signal-background intereference effects found negligible in any case).

# VBF H → WW candidate event

(2nd jet outside of acceptance)




Run: 362204
Event: 2842448996
2018-09-29 13:15:54 CEST

# $H \rightarrow$ WW in CMS

Mass range: 115 – 5000 GeV

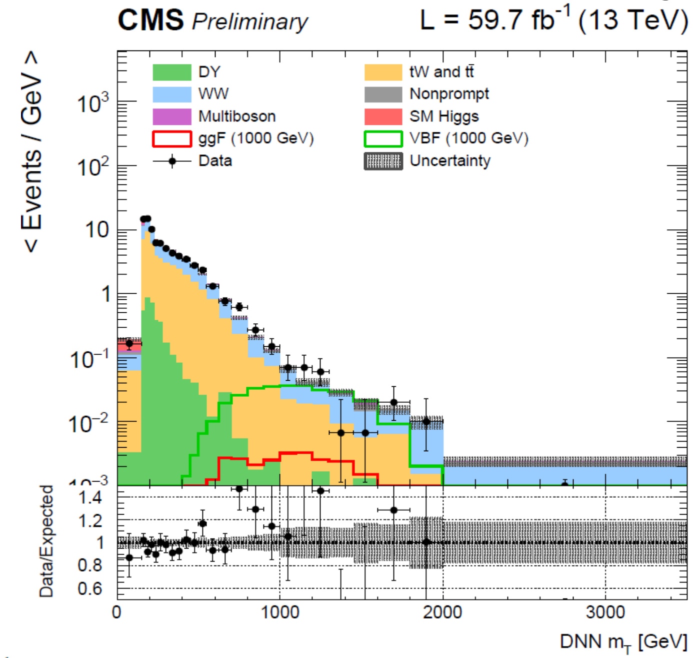
WW decay to ee, $\mu\mu$ end e$\mu$ (and missing energy)

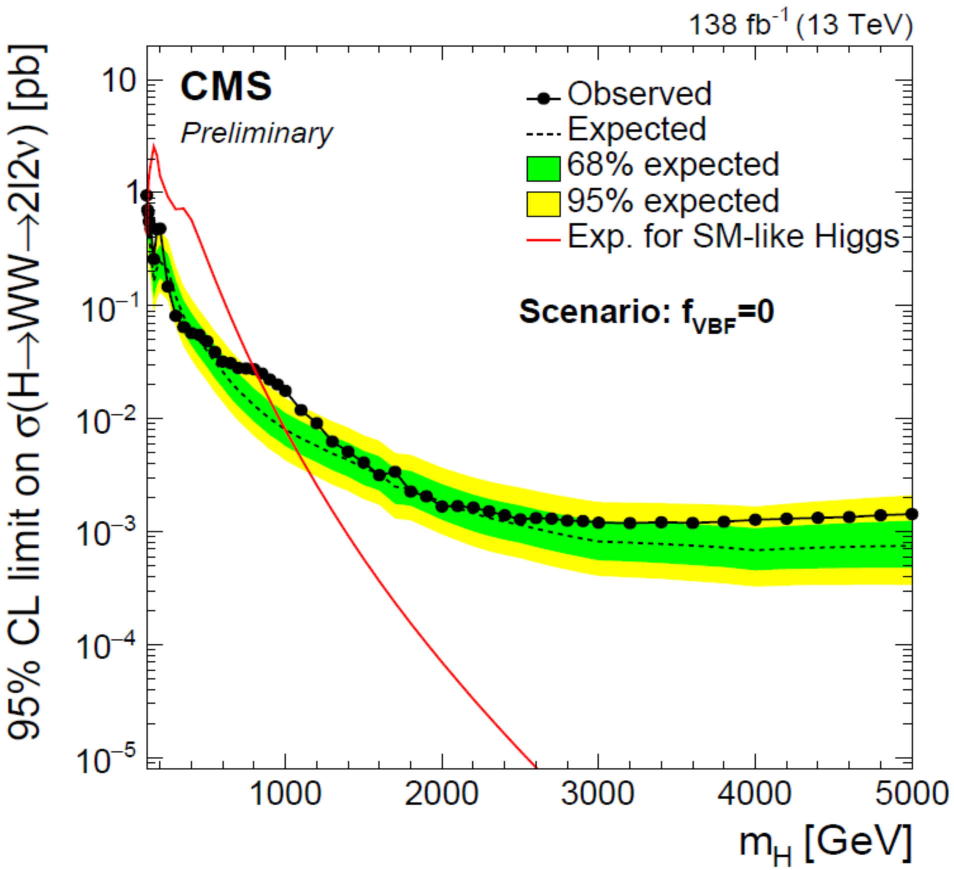
DNN used to classify events as ggF-, VBF-, or background-like

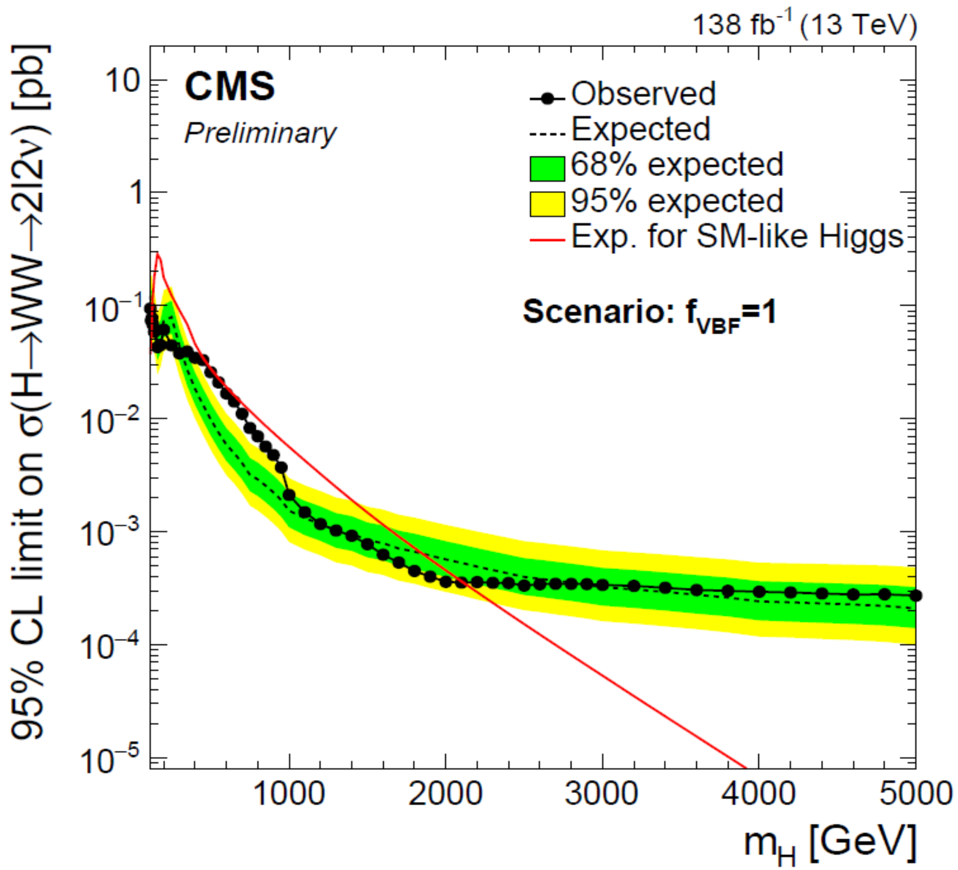
„DNN $m_T$“ is final discriminant (output of mass reconstruction DNN)

Excess of events for 400 GeV < $m_T$ < 1200 GeV

Fraction of VBF signal relative to the total signal $f_{VBF}$ varied



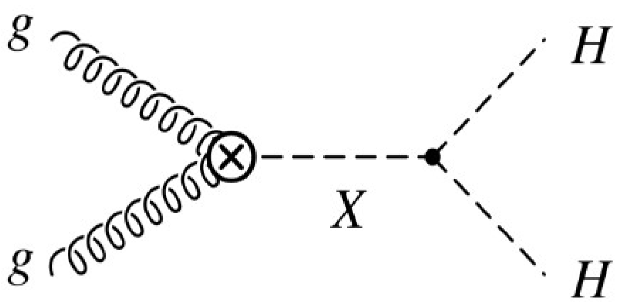



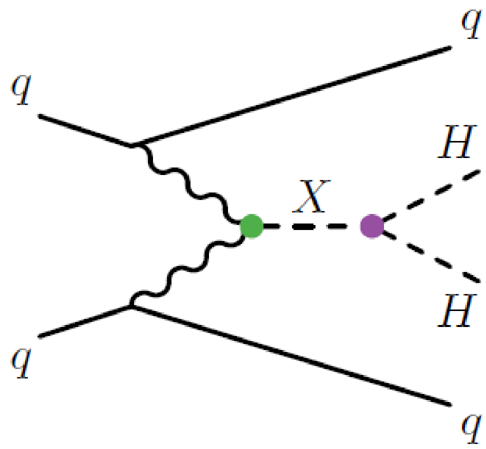




Highest significance: 3.8$\sigma$ for $f_{VBF}$=1 at $m_H$=650 GeV (global 2.6$\sigma$)

CMS analysis more sensitive than ATLAS since ee and $\mu\mu$ are included

# Resonant Higgs Boson Pair Production X → HH/SH




Heavy scalar X decays to two Higgs bosons with each 125 GeV.

Predicted by many models, eg. real or complex singlets, 2HDM, TRSM, NMSSM, GM, ...

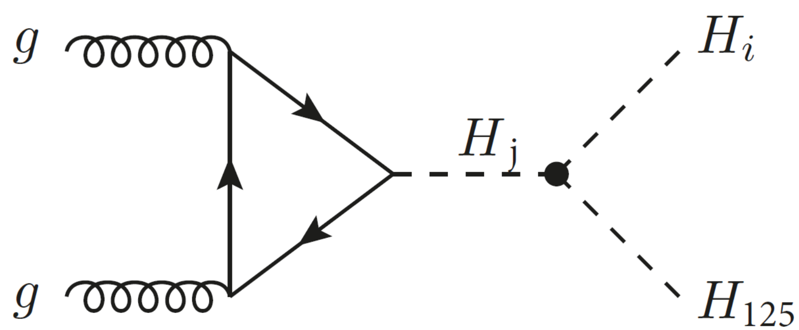
| | bb | WW | ττ | ZZ | γγ |
|---|---|---|---|---|---|
| bb | 34% | | | | |
| WW | 25% | 4.6% | | | |
| ττ | 7.3% | 2.7% | 0.39% | | |
| ZZ | 3.1% | 1.1% | 0.33% | 0.07% | |
| γγ | 0.26% | 0.10% | 0.03% | 0.01% | 0.0005% |

published by ATLAS

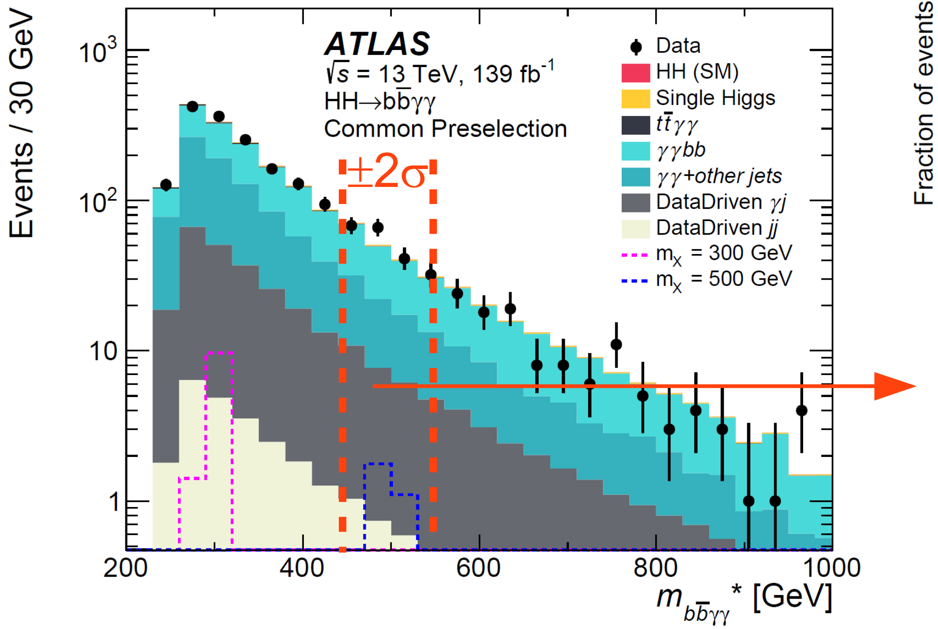
← **Branching ratios of HH decay channels**
(H is the SM Higgs boson)

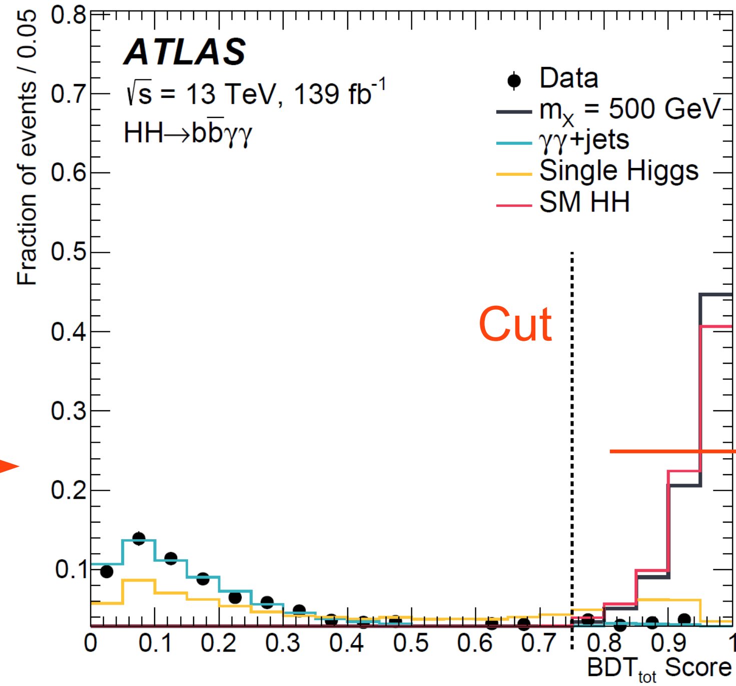
The most sensitive HH channels contain at least one $b\bar{b}$ decay, taking advantage of its large BR.

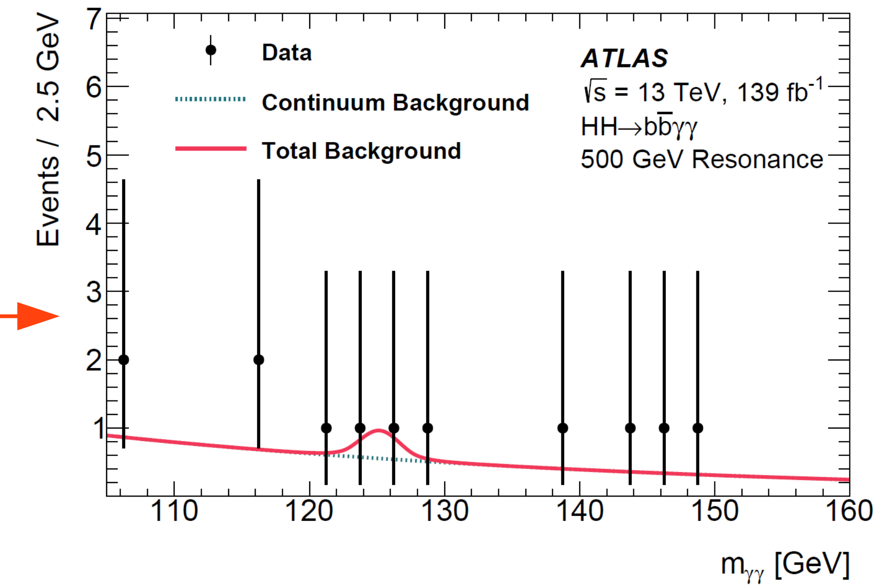
Another possibility is to search for X → SH, with mS ≠ mH. This is predicted by many models, often leading to larger signal rates than HH.



# $X \rightarrow HH \rightarrow bb\gamma\gamma$



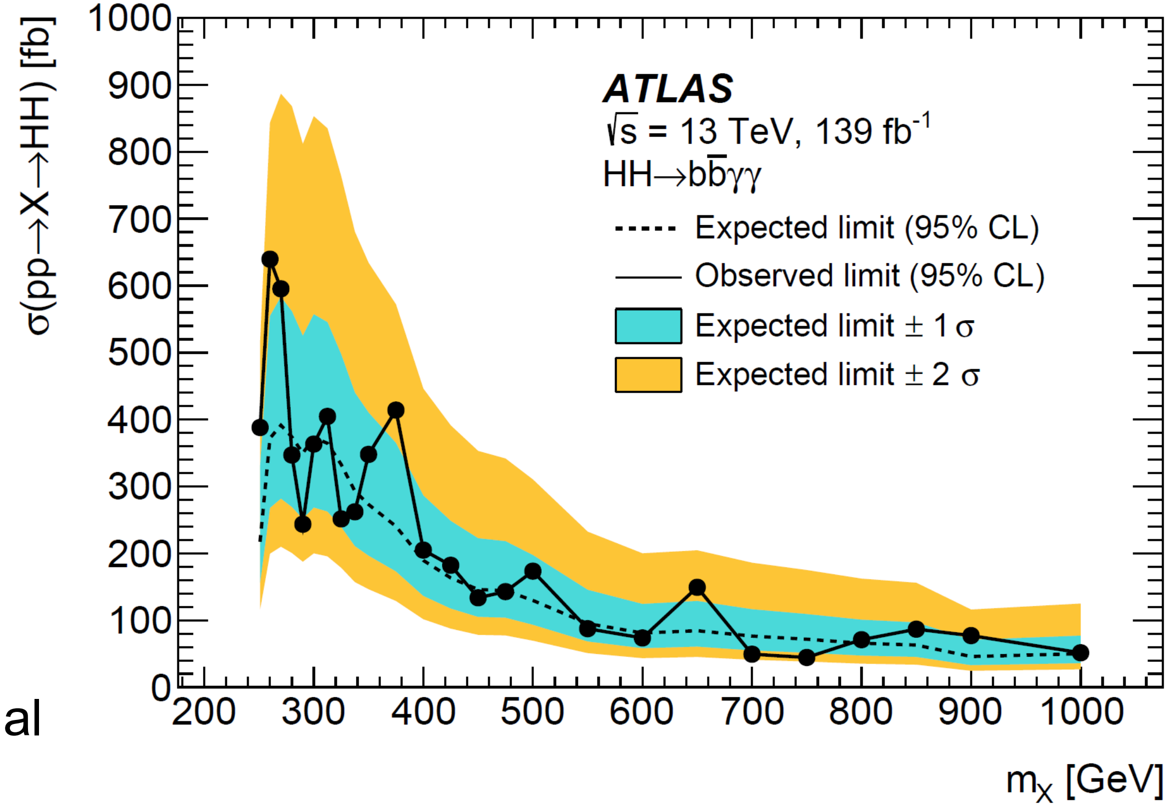

Gluon fusion production only
Signal is a narrow scalar

Cut on $m^{*}_{bb\gamma\gamma}$ ($\pm 2\sigma$),

$m^{*}_{bb\gamma\gamma} = m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250$ GeV

Cut on BDT score to enhance S/B

Final discriminant is $m_{\gamma\gamma}$,
background modelled with exponential

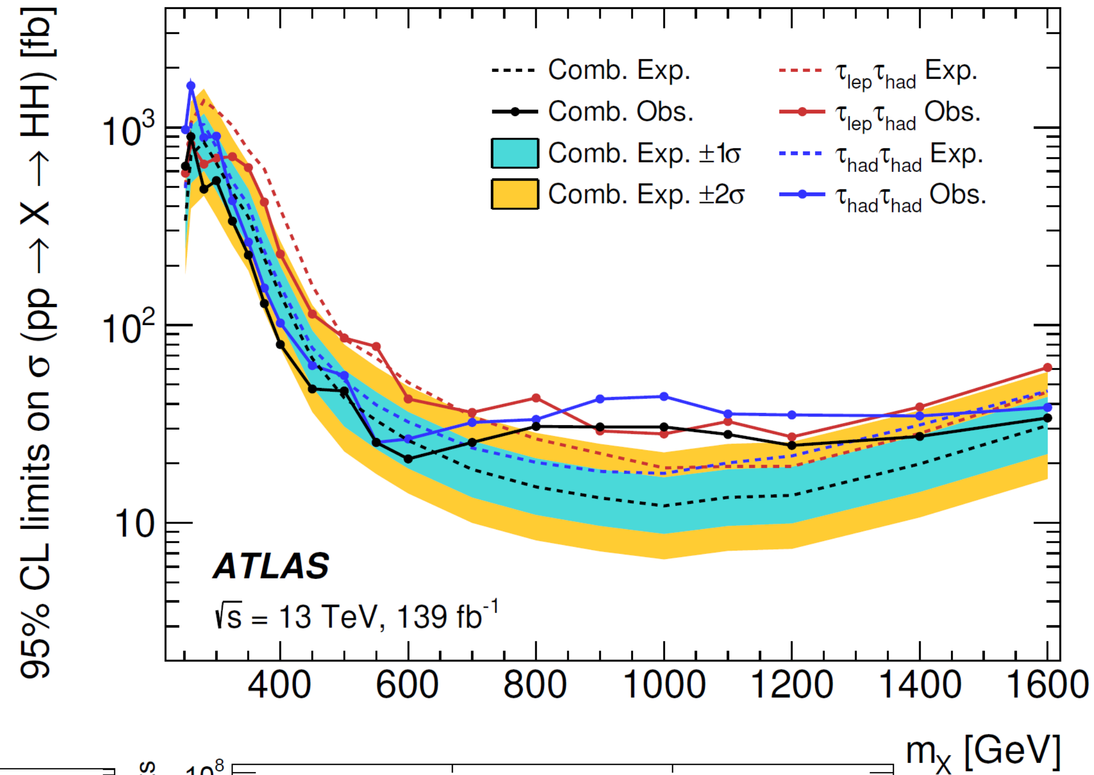


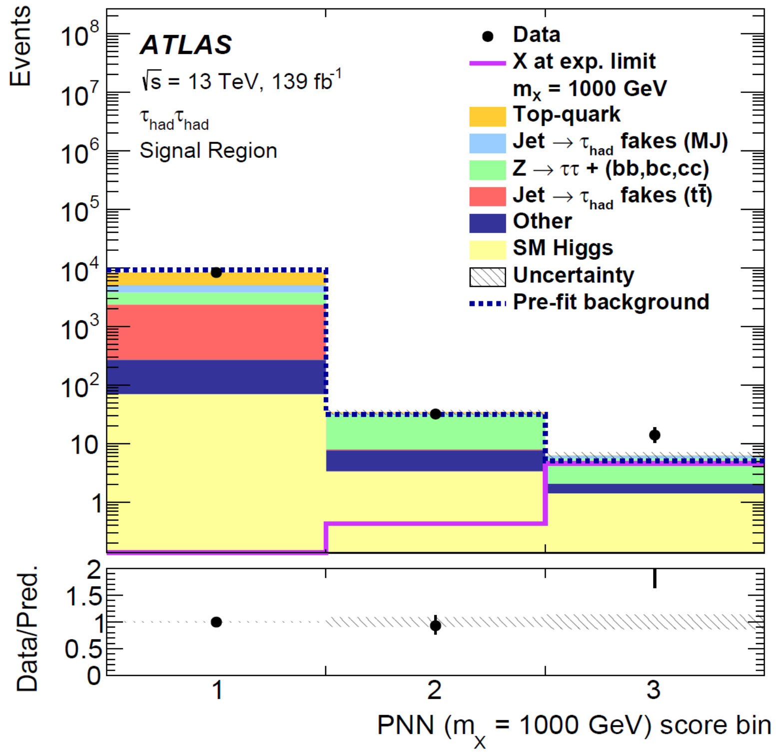

No excess found

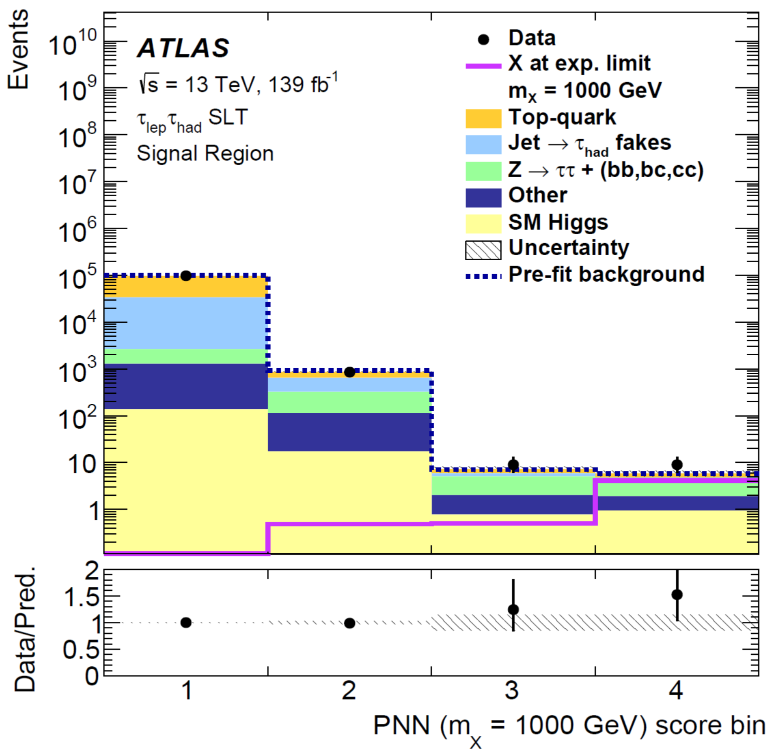
Very strong limits at low $m_X$

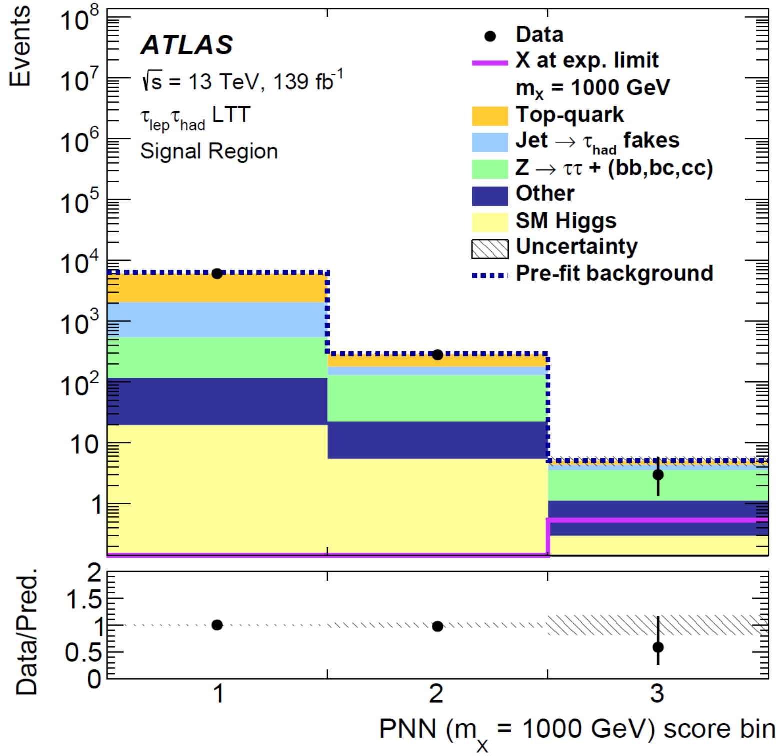
# $X \to HH \to bb\tau\tau$

- Only gluon fusion considered, narrow width scalar
- **3 signal-enriched categories:**
  - had-had channel
  - lep-had channel triggered by single lepton trigger („SLT“)
  - lep-had channel triggered by lepton+tau trigger („LTT“)
- Machine learning techniques for signal enhancement, final fit performed to the MVA output scores
- Excess at 1 TeV (2$\sigma$ global)

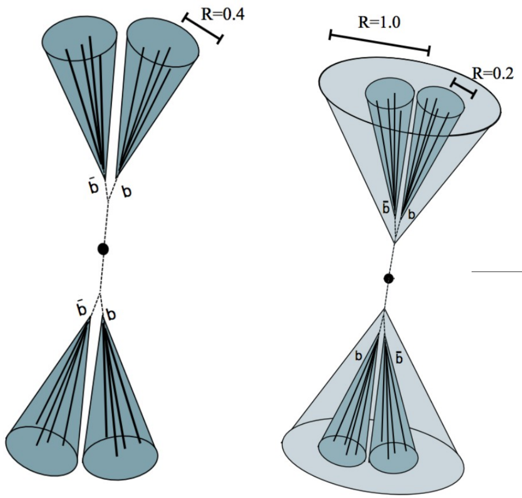


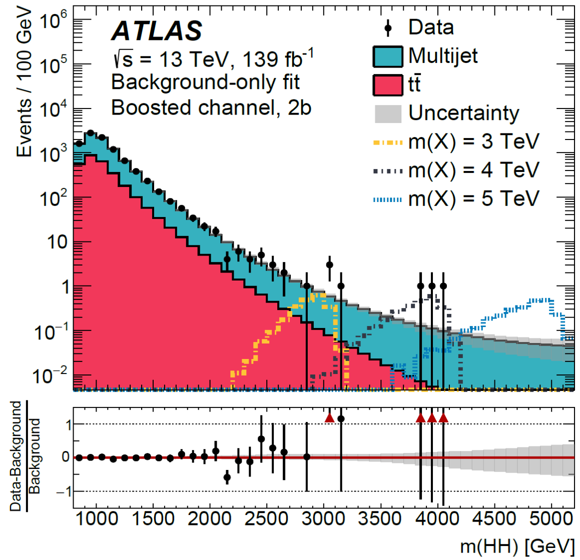



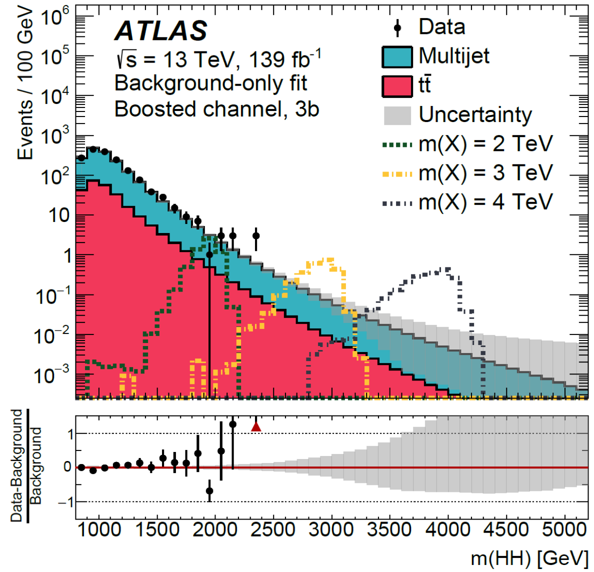



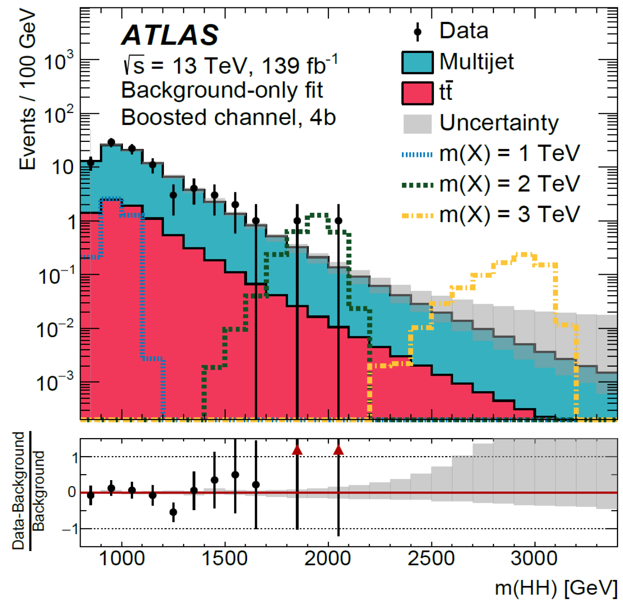



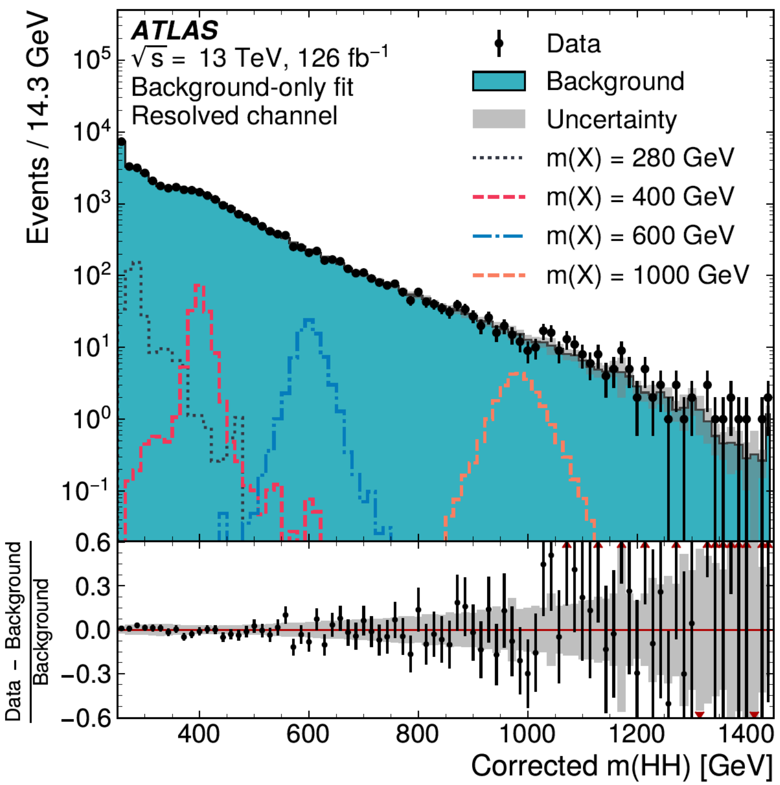
# X → HH → bbbb

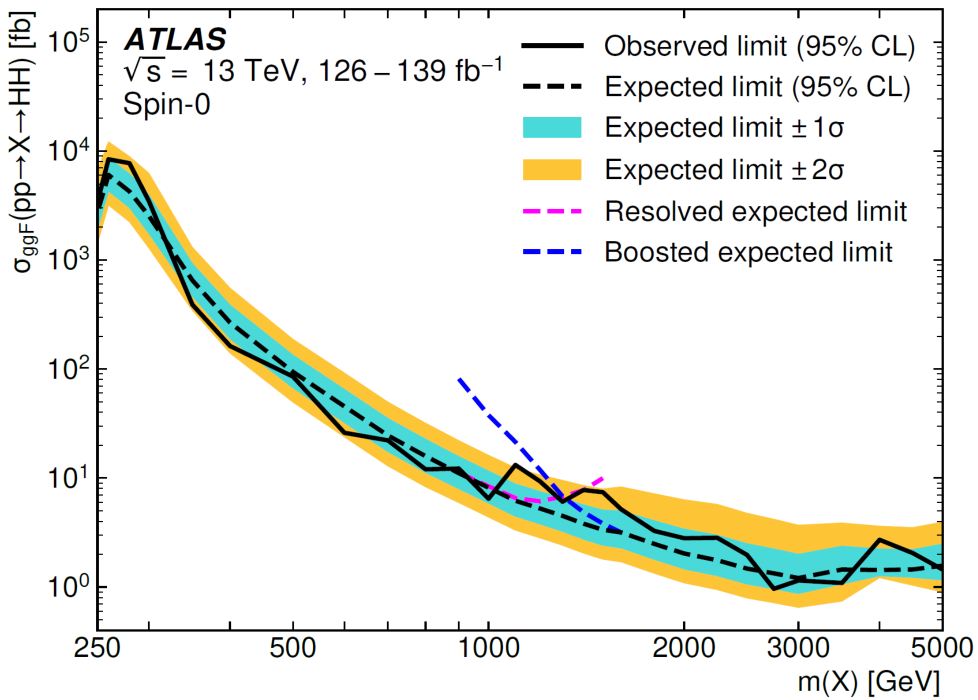



Best HH channel at high mass

Resolved channel:
4 b-tagged small-radius jets

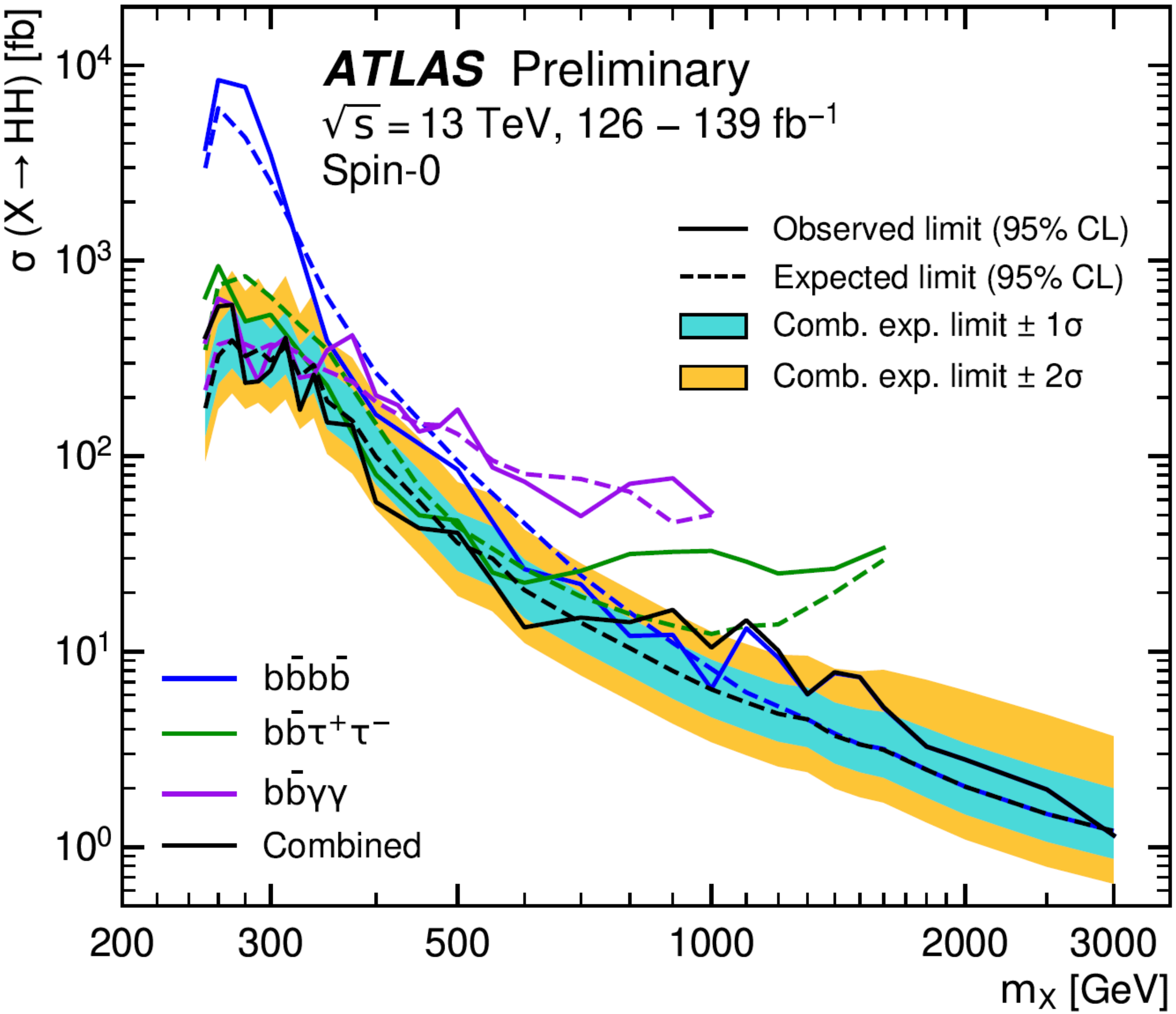
Boosted channel:
2 large-radius jets, with in total 2 or 3 or 4 b-tagged track-jets

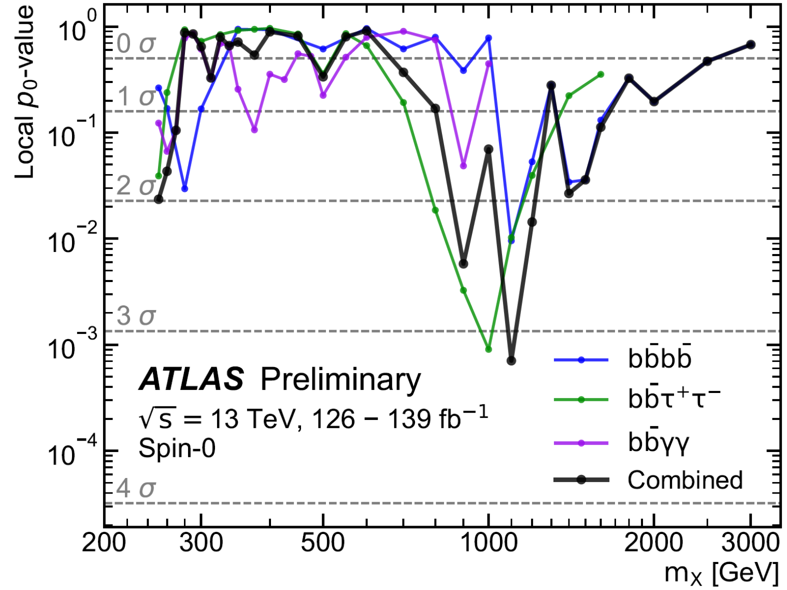
$m_{HH}$ is final discriminant

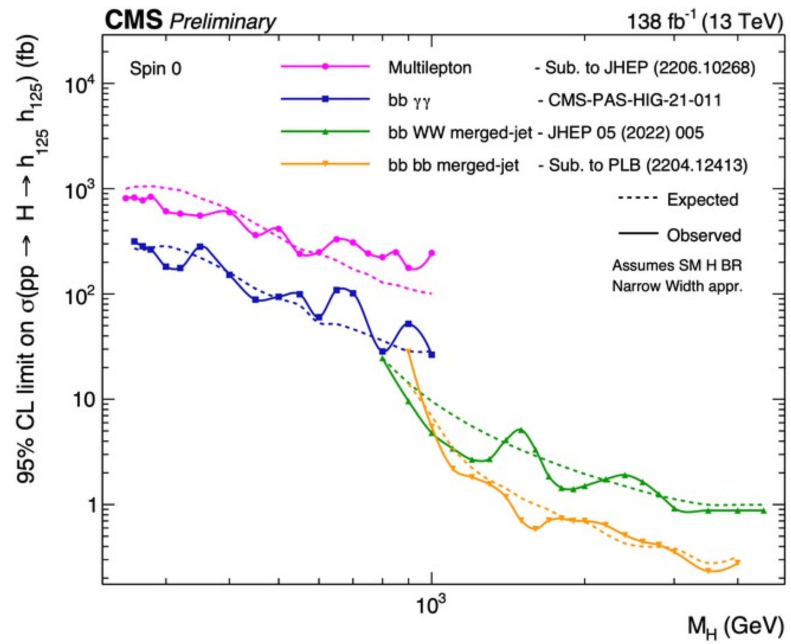
Gluon fusion only
Spin-0 narrow-width

# X → HH Combination

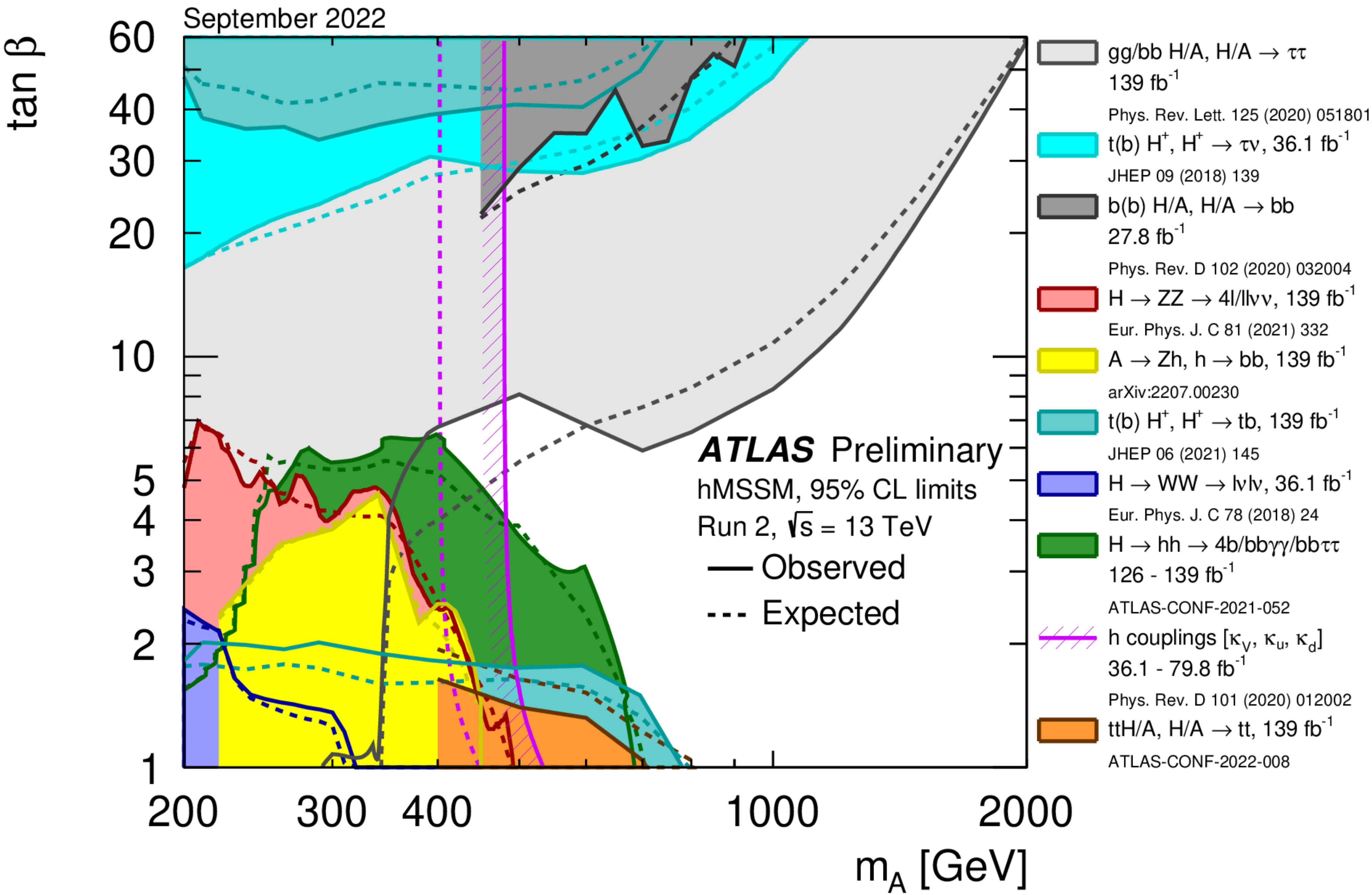
$bb\gamma\gamma$, $bb\tau\tau$ and 4b combined
Largest excess is at 1.1 TeV
with 2.1$\sigma$ global. Not seen by CMS.



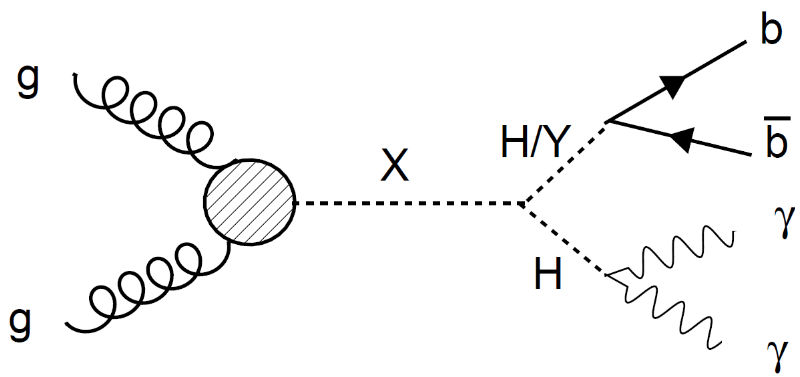



# Summary Plot for the hMSSM



# CMS $X \rightarrow HY \rightarrow bb\gamma\gamma$

CMS-PAS-HIG-21-011



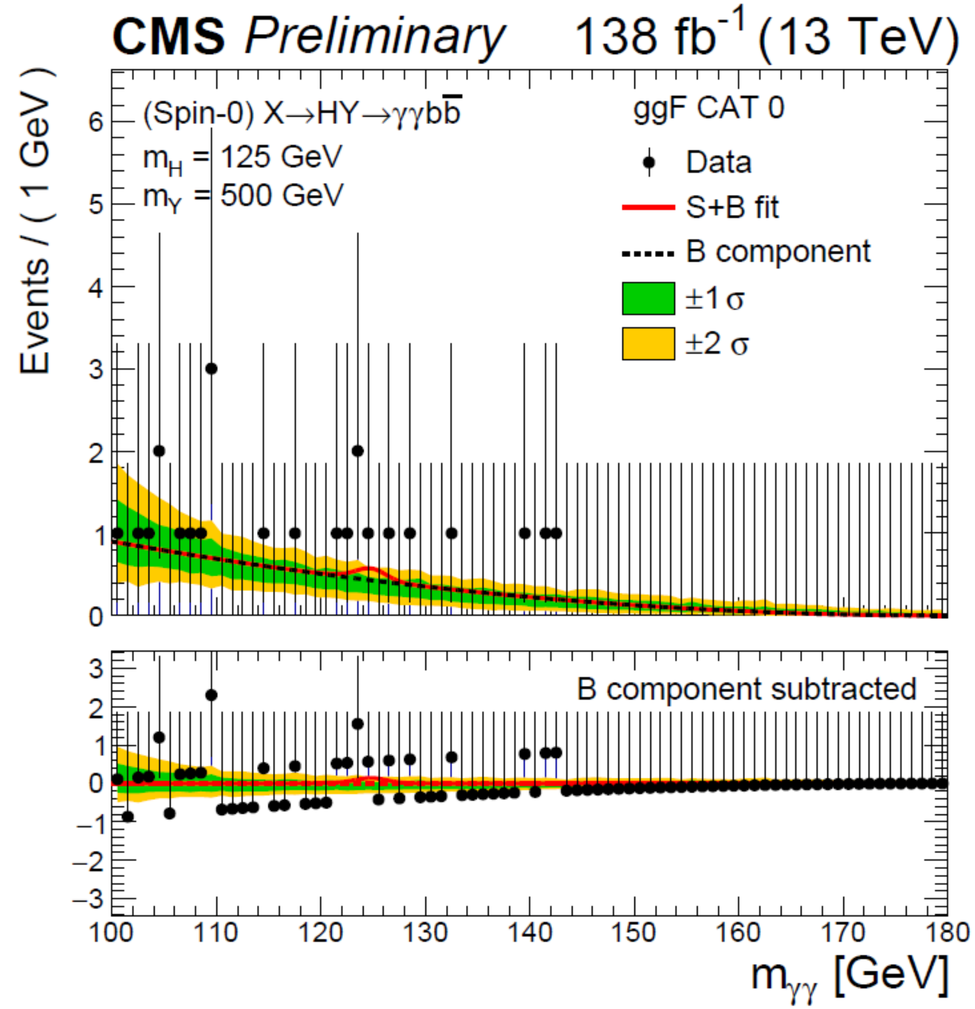

Asymmetric decays are motivated in **extended Higgs models**, for example Two-Real-Singlets model (TRSM), or the Next-to-Minimal-Supersymmetric model (NMSSM)

Search range:
90 < mY < 800 GeV, 300 < mX < 1 TeV

Object selections:

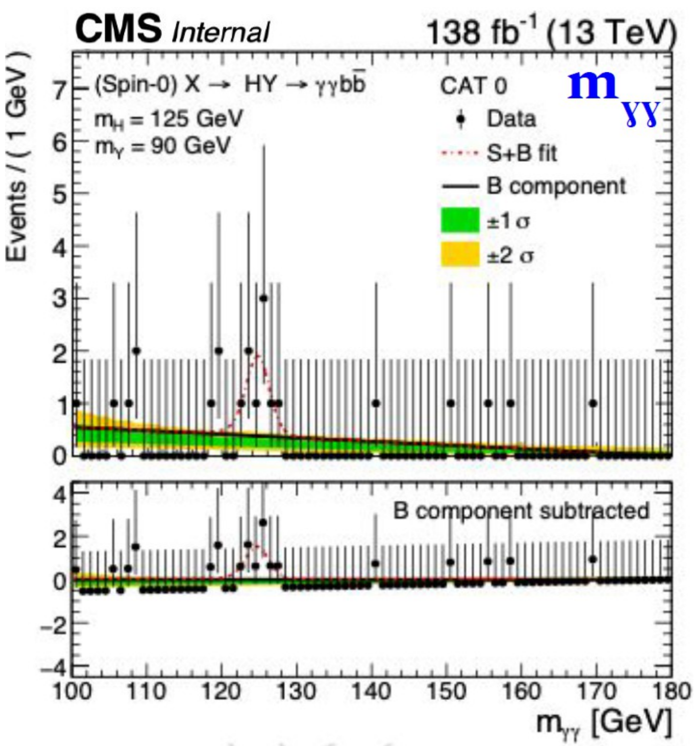
- $p_T(\gamma 1)/m_{\gamma\gamma} > 1/3$, $p_T(\gamma 2)/m_{\gamma\gamma} > 1/4$
- pT(jets) > 25 GeV
- $\Delta R(\text{jet},\gamma) > 0.4$
- Jet pair selected has highest sum of DeepJet score
- Electron veto

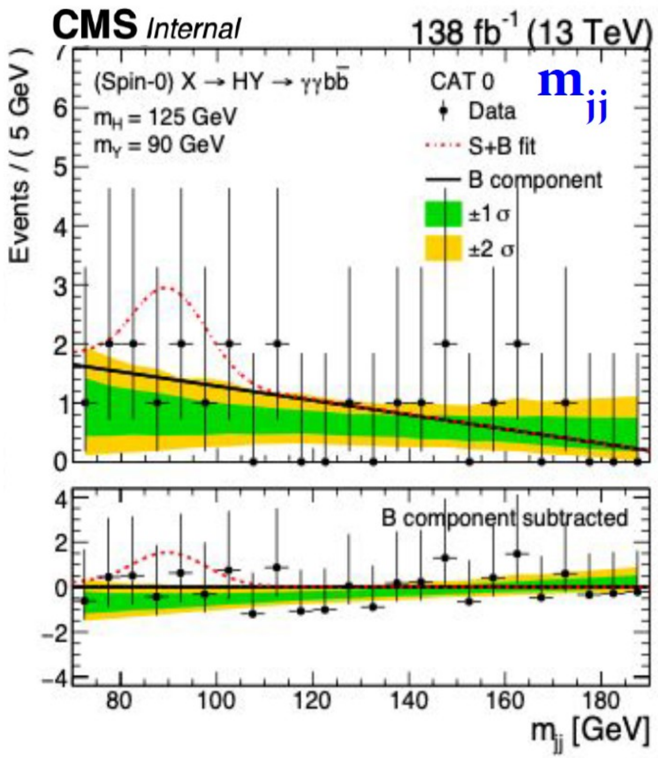
- NN to reject ttH background
- BDT to reject non-resonant background
  → 3 categories defined based on BDT score
- Stringent window in X mass with ~60% signal efficiency
- Signal is extracted with 2D fit in $m_{\gamma\gamma}$-mjj plane



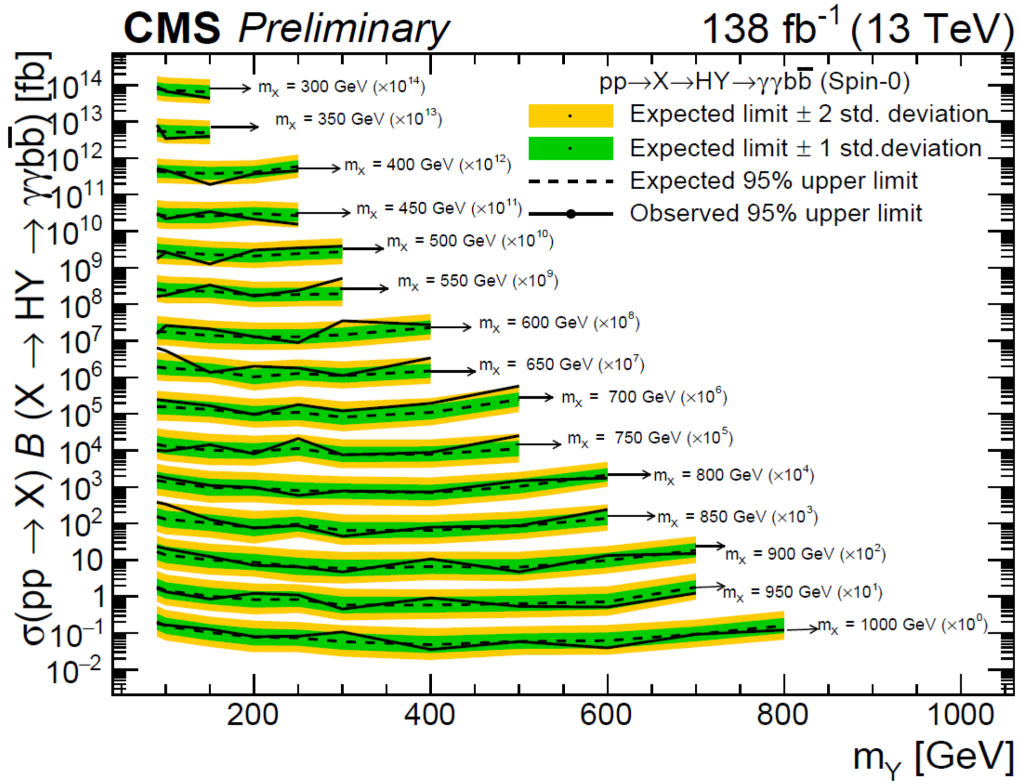
# CMS X → HY → bbγγ

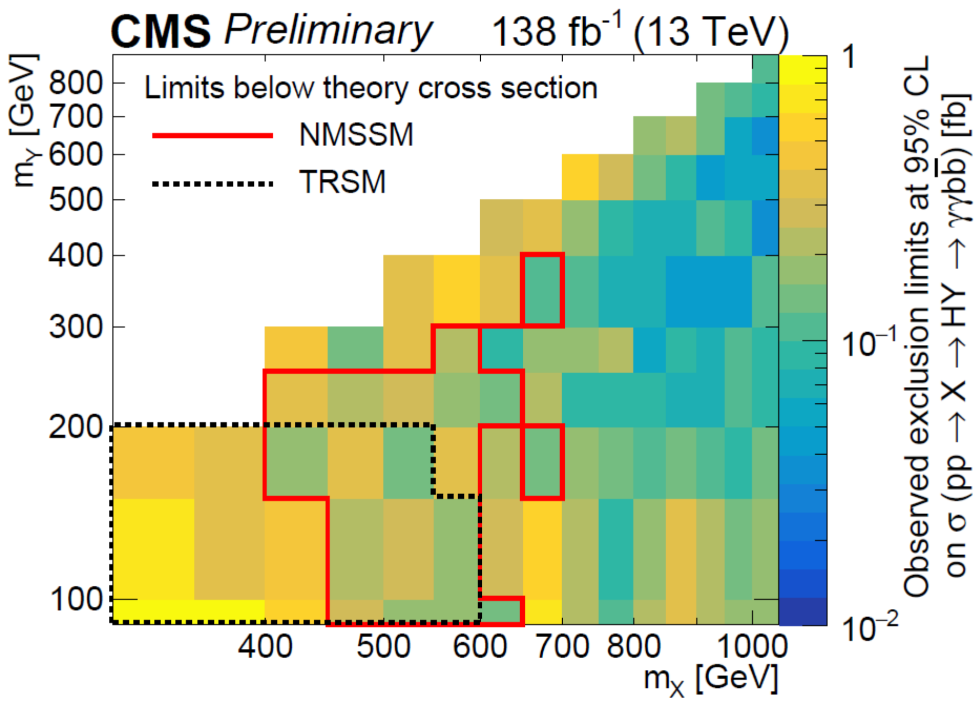
- Resonant background (SM H): from simulation
- Non-resonant background:
  modelled with 2D envelope method (1408.6865), bkg function is labelled by an integer which is treated like a discrete nuisance parameter which is profiled by the fit to the data $m_{\gamma\gamma}$ sidebands



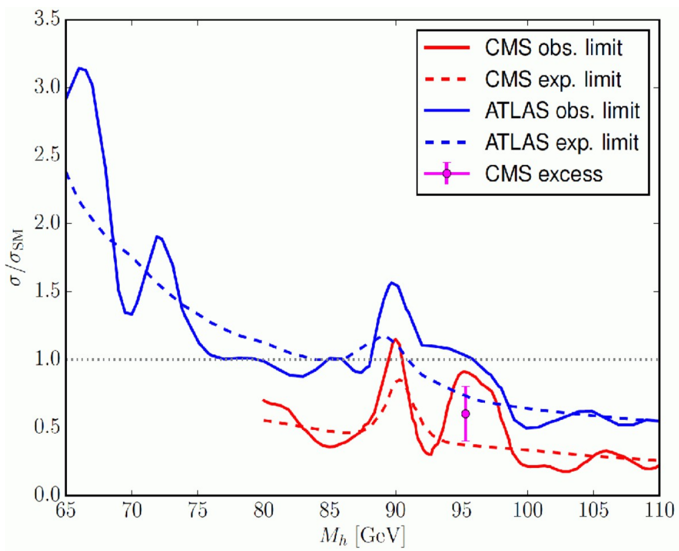

**Huge excess: 3.8σ local, 2.8σ global**
**mX = 650 GeV, mY=90 GeV**

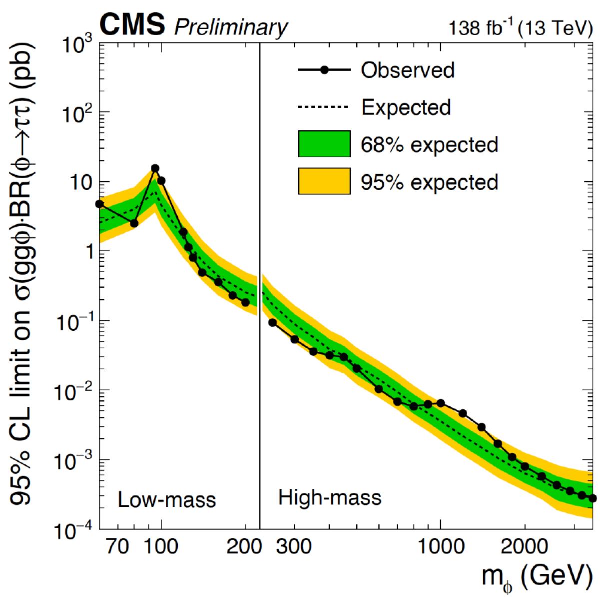


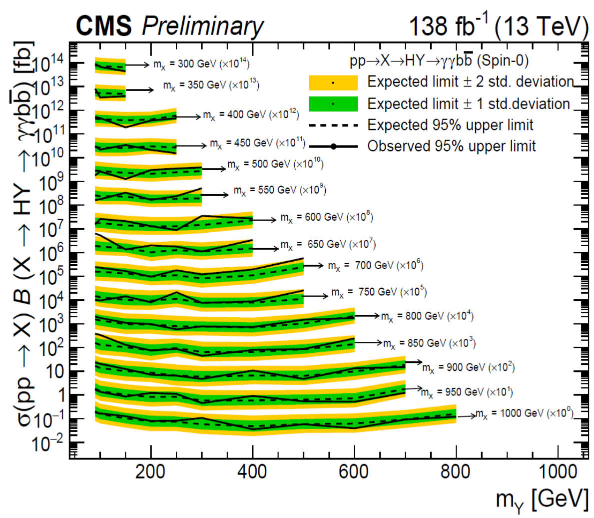



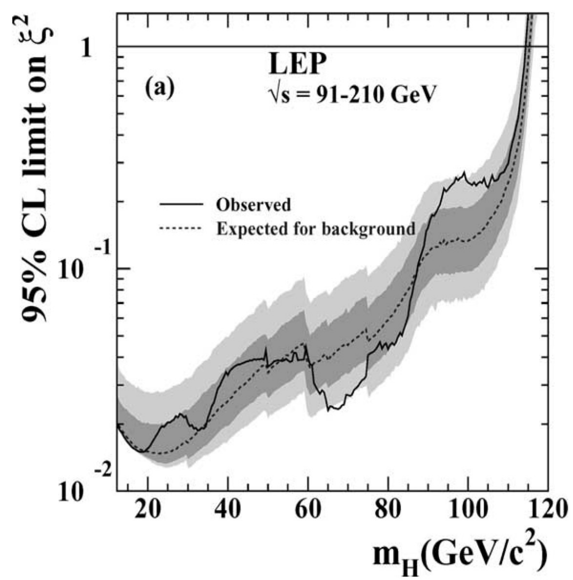
# Excitement about the 95 (or 96) GeV Excess

- **Four occurances:**
  CMS H → γγ (3σ), CMS H → ττ (2.4σ), CMS X → SH → bbγγ (3.8σ),
  LEP H → bb (2σ); not ruled out by ATLAS intermediate H → γγ
- Various theory papers: 2203.13180, 2205.03187, 1908.01668, 2204.07470, 2204.11755, 2002.07697, 1908.07206, ...
- Plenary talk at ICHEP in 2022 by S. Heinemeyer, also discussed at length in Santander
- N2HDM (2HDM+real singlet) can fit this excess
- Everybody is waiting for the ATLAS intermediate H→γγ and H→ττ results and Run 3



# Conclusions

- Many BMS Higgs searches published, more results are in the pipeline!
- Various excesses seen in the run2 dataset (95 GeV, 400 GeV, 650 GeV, ...)
- Super exciting times, what will we see in the run3 data?
- Are we about to approach the golden age for BSM Higgs physics?

# Backup

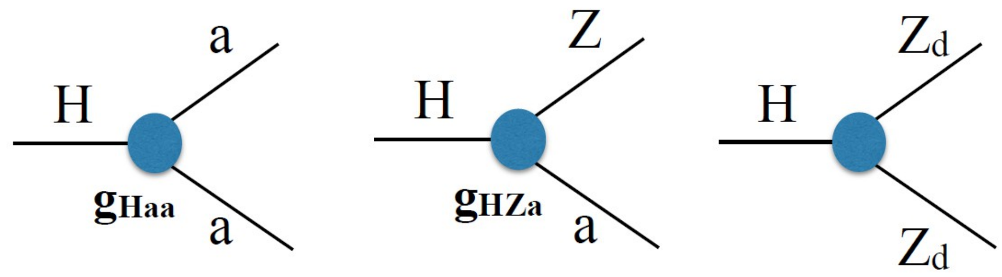
# Exotic Higgs Decays

Higgs boson has a very small total width (~4 MeV)

→ decay to SM particles is supressed (either small Yukawa couplings, or phase space)

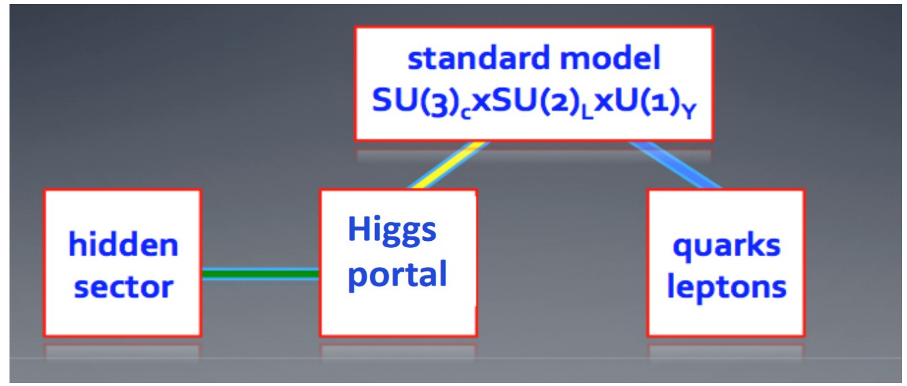
→ dominant decay to bb controlled by a small coupling

→ even very weakly coupled new particles can generate sizable branching ratios

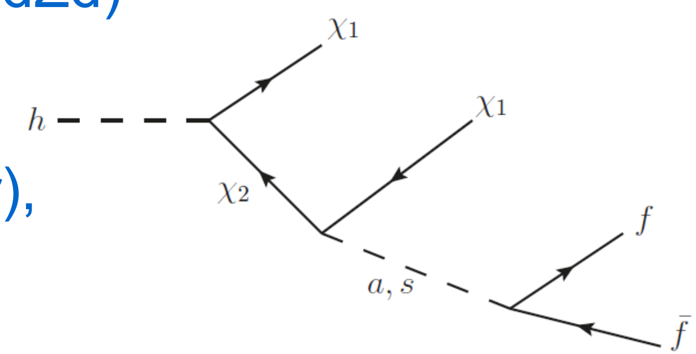



**Search for...**

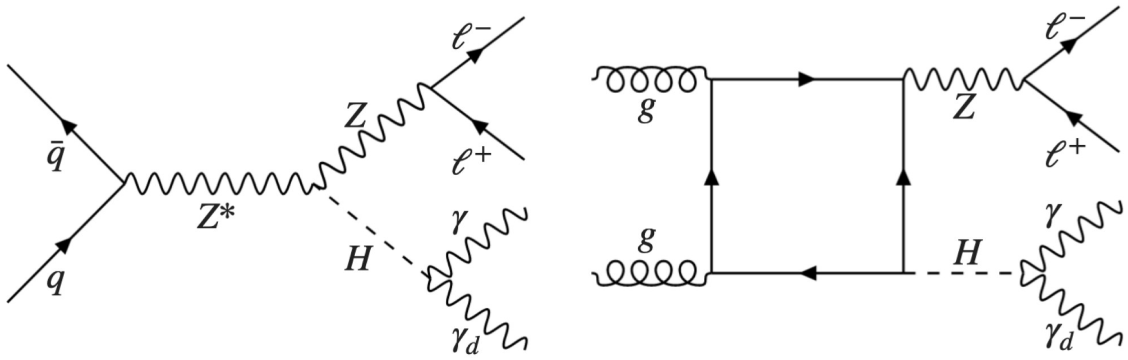
- Rare Higgs decays to SM particles (BSM effects could lead to an enhanced rate)
- Lepton-flavor-violating deacys (eg. $H \rightarrow e\mu$)
- Invisible Higgs decays, or decays with associated MET
- Higgs couplings to dark particles from hidden sectors (eg. $H \rightarrow ZdZd$)
- Higgs decay to long-lived particles
- Higgs decay to new light scalars $H \rightarrow aa$ (scalar or pseudoscalar), also $H \rightarrow ab$ ($m_a \neq m_b$), or $H \rightarrow Za$
- Cascade decays involving new (invisible) particles



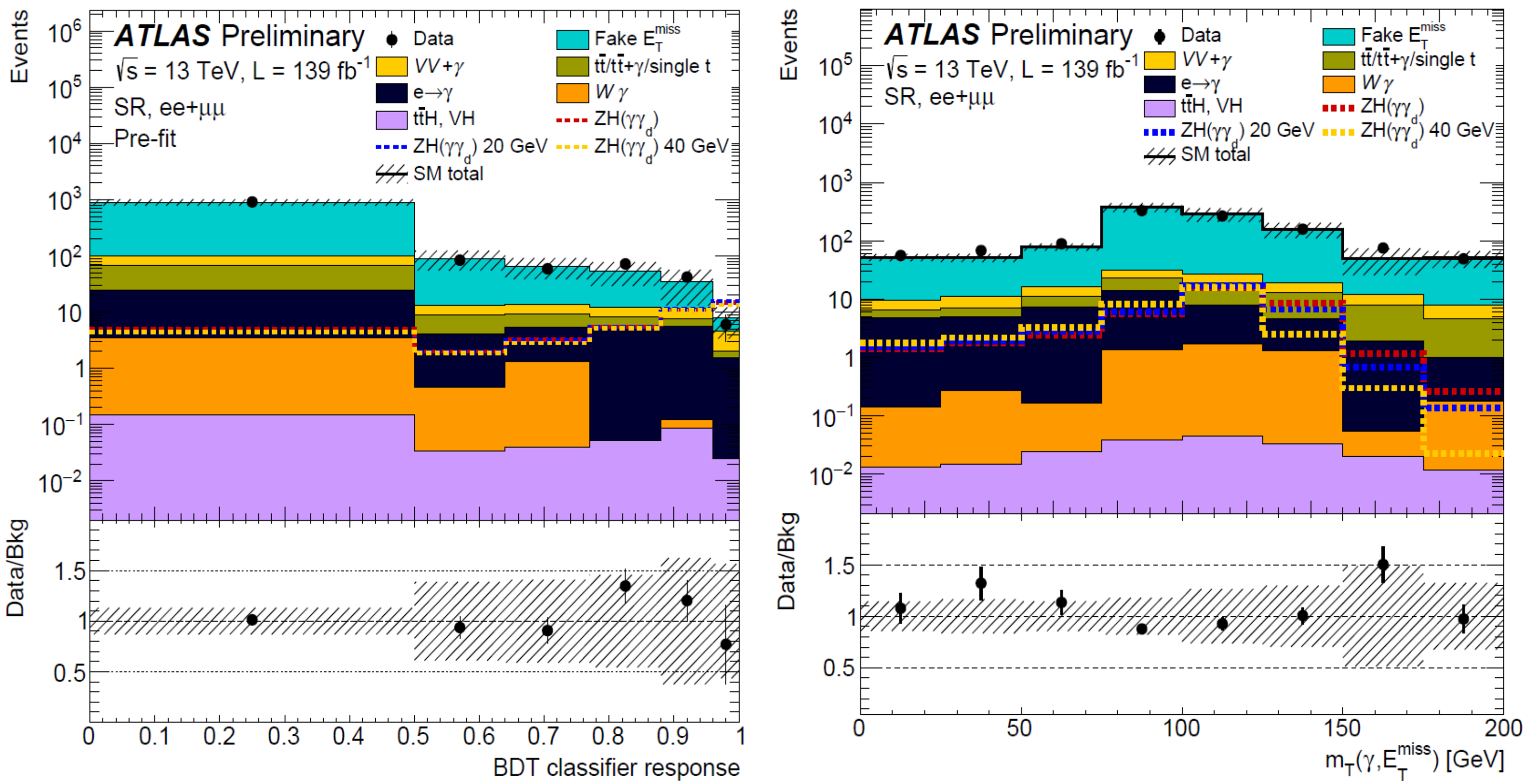

(Theodota Lagouri)



# H → γγ$_{dark}$




- 125 Higgs is produced in association with Z
- Z → ee or μμ
- Dark photon is undetectable, can be massless or massive
- Look for events with lepton pair, MET and a photon
- Veto of events with a third lepton



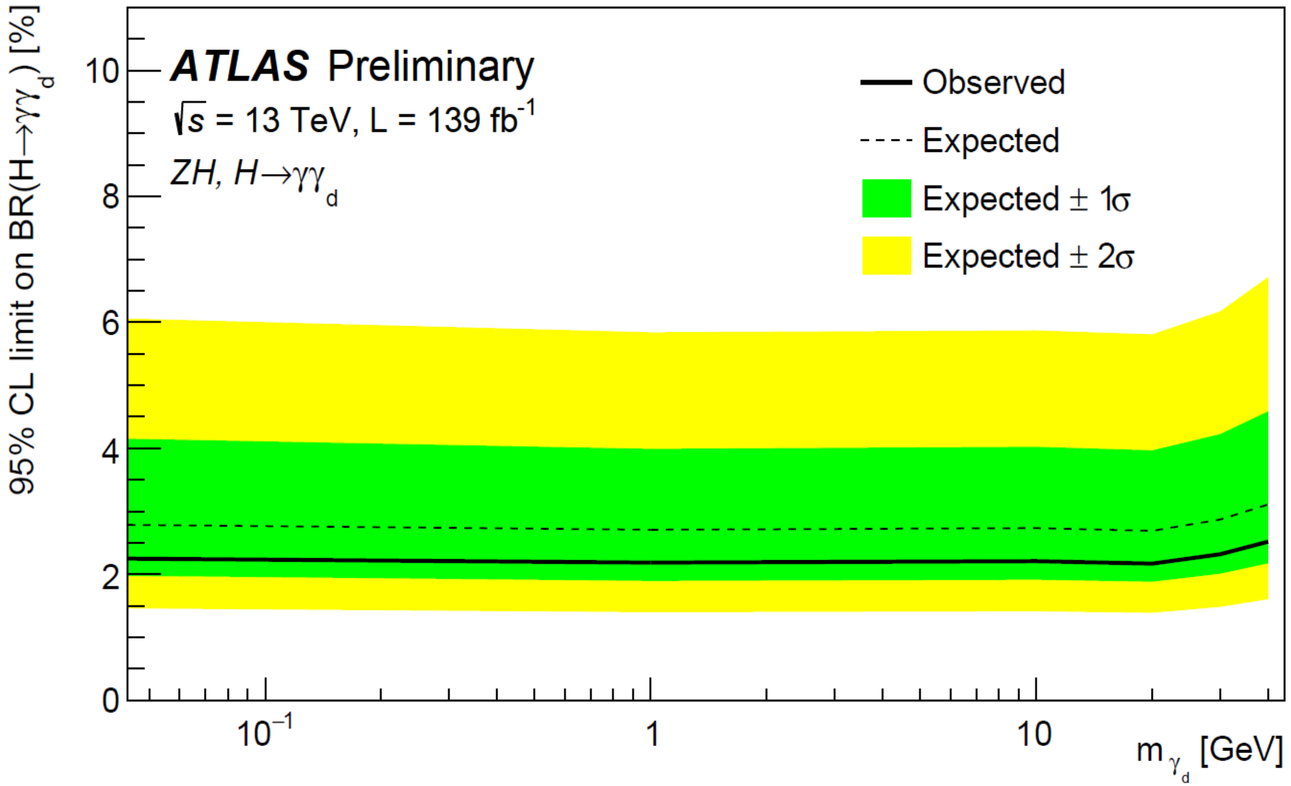

BDT used to separate signal from background

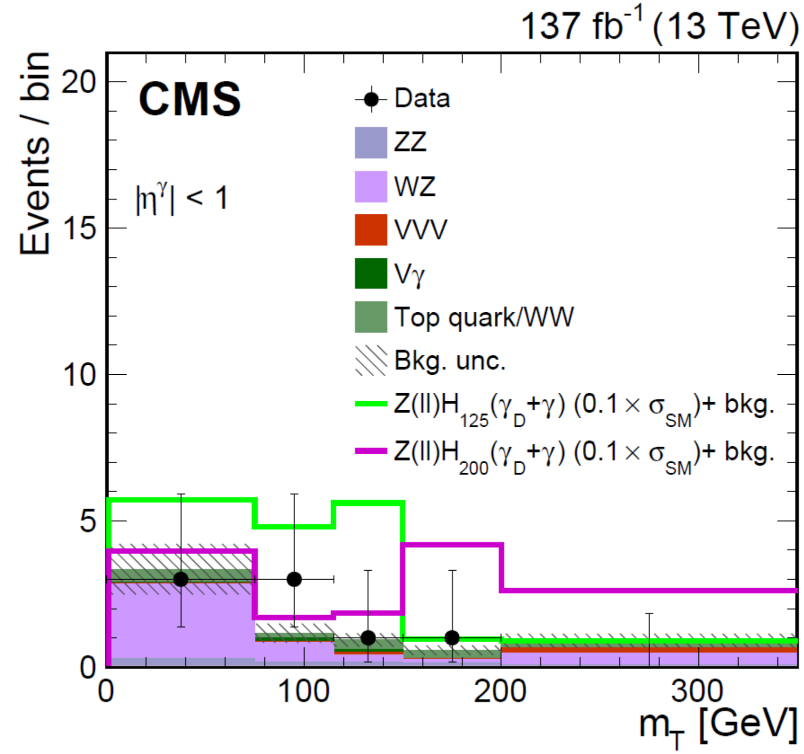
Fake background from jets or leptons misidentified as γ, fake rate estimated from data

BDT score is the final discriminant

← $m_T$ from γ and MET has kinematic edge at 125 GeV

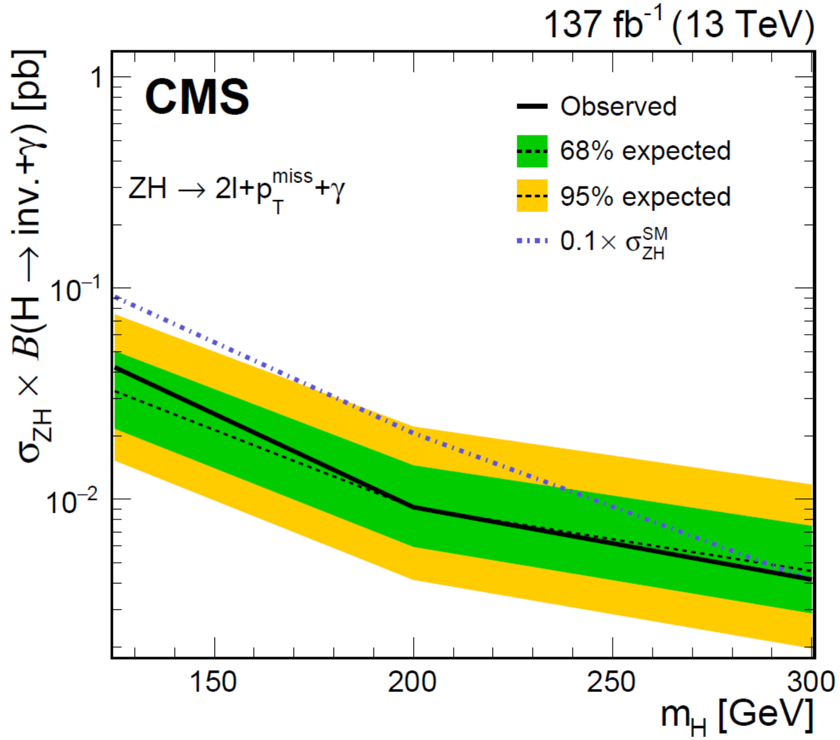
# $H \to \gamma\gamma_{dark}$ Results




ATLAS 95% CL Limit on BR($H \to \gamma\gamma_d$ ) = 2.28%

for massless $\gamma_d$.




CMS considers only massless gd, but varies the mass of H. For $m_H$=125 GeV, limit on BR($H \to \gamma\gamma_d$) = 4.6%.
CMS uses more restrictive event selection cuts, no MVA.

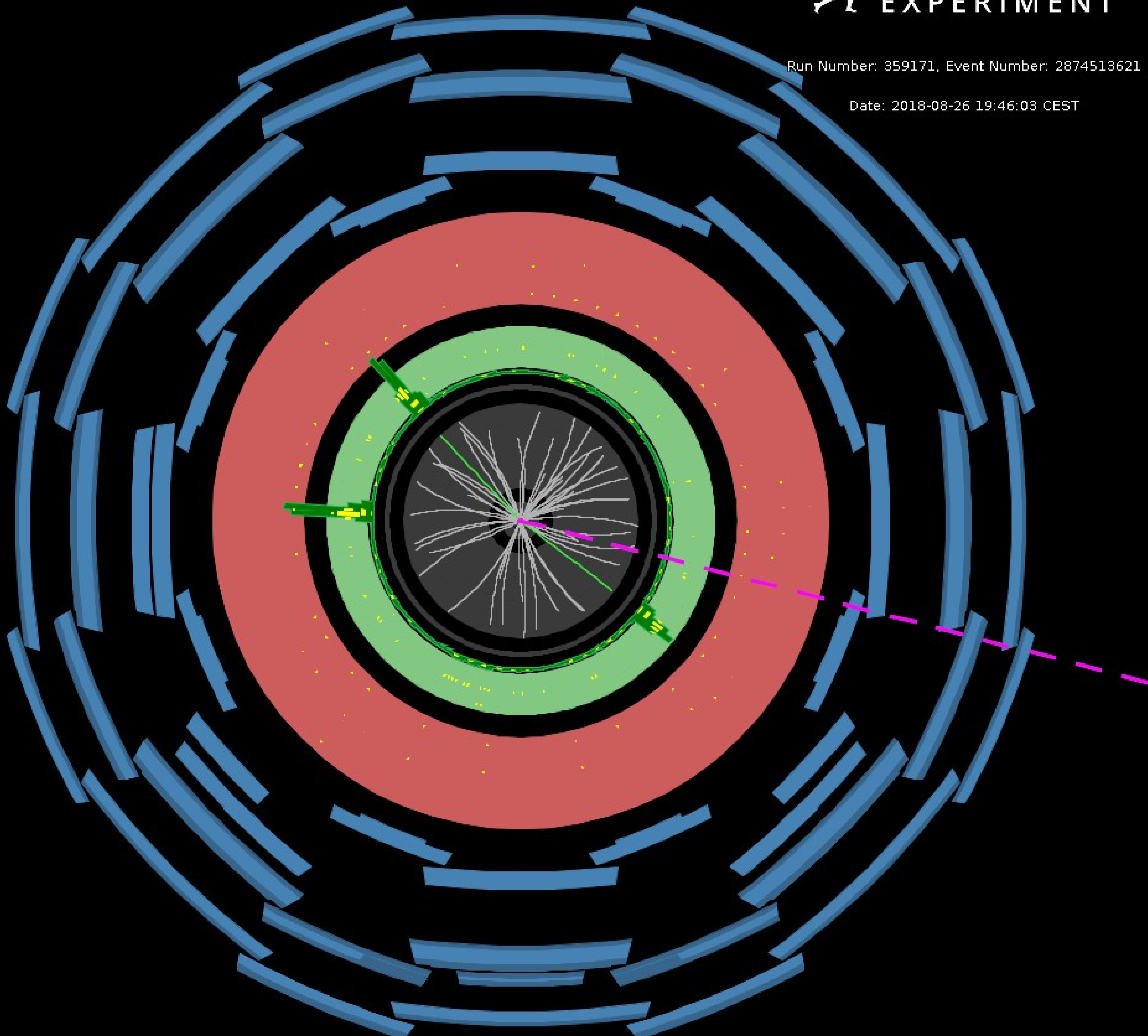
ATLAS EXPERIMENT

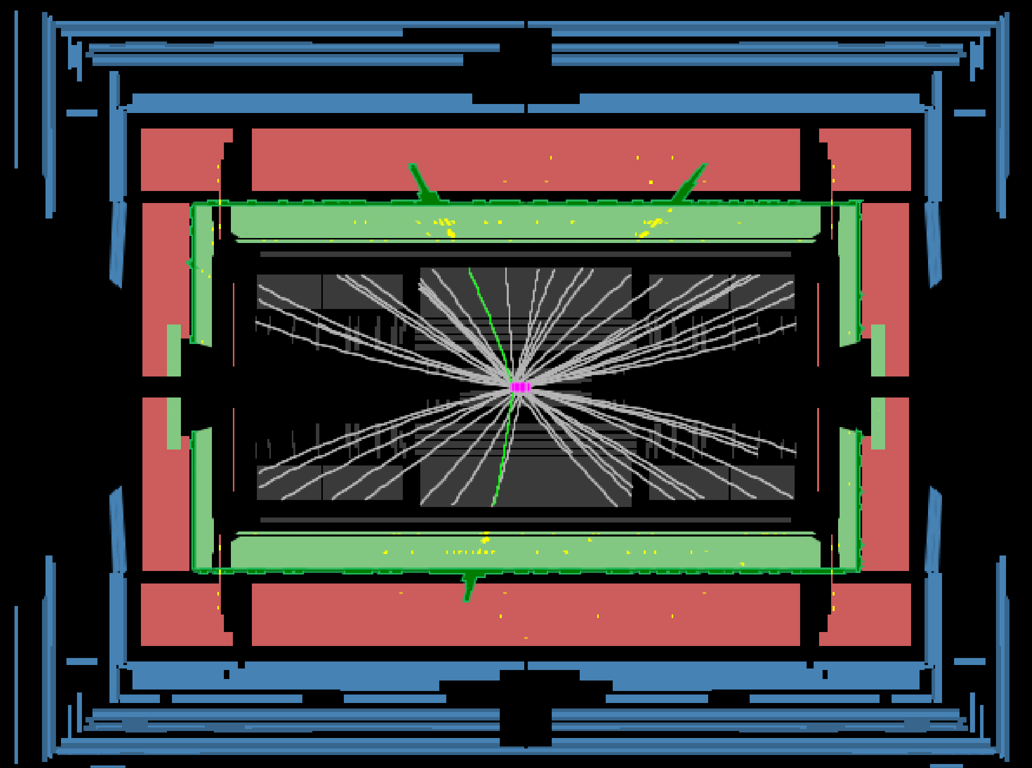
Run Number: 359171, Event Number: 2874513621

Date: 2018-08-26 19:46:03 CEST

# $ZH \rightarrow ee + \gamma\gamma_d$ candidate

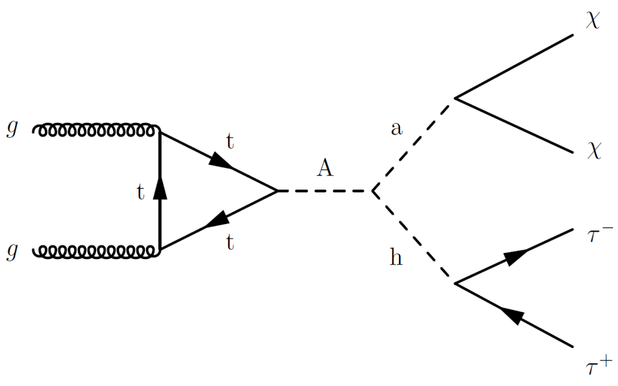
$m(ee) = 92$ GeV
$pT(\gamma) = 62$ GeV
MET $= 63$ GeV

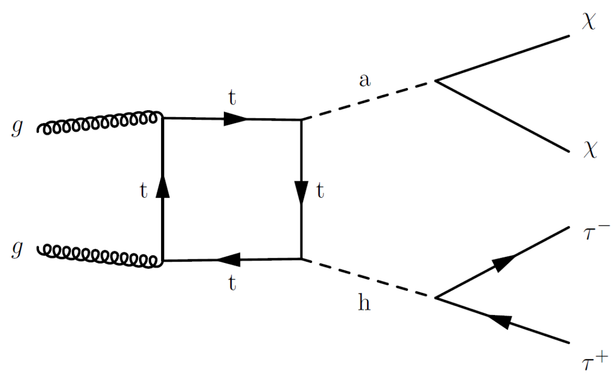


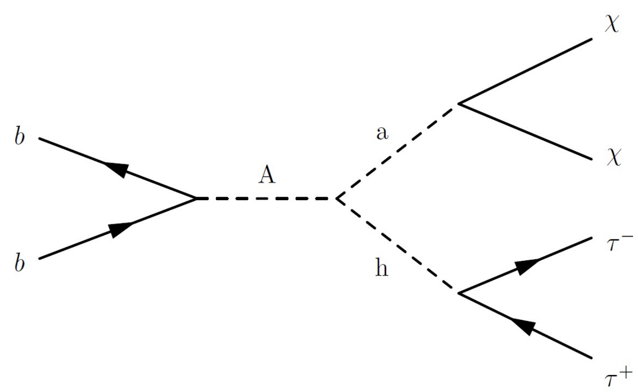


# $H \rightarrow \tau\tau$ + MET

Motivated by the 2HDM+a model



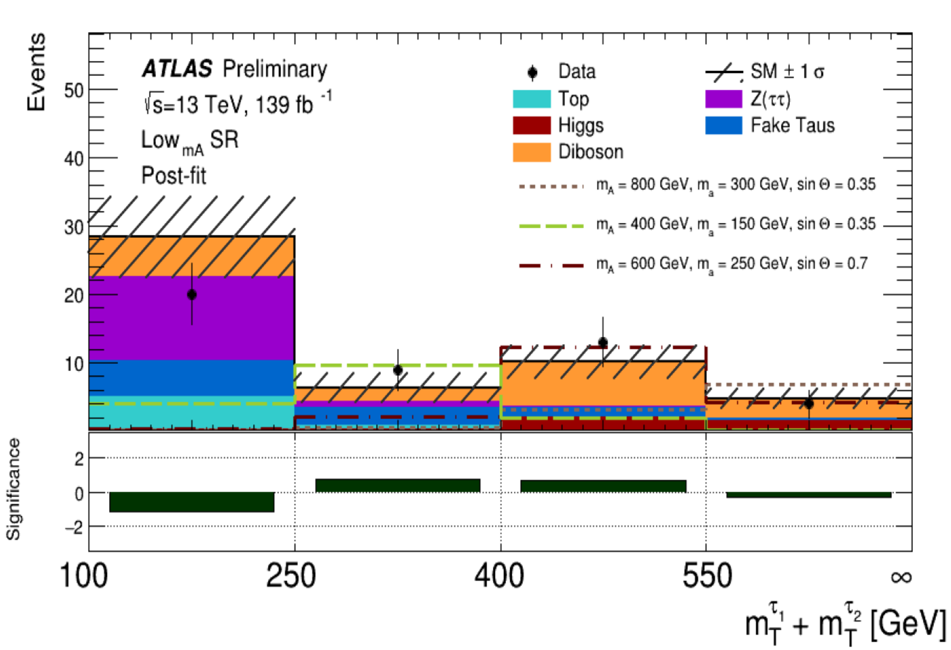



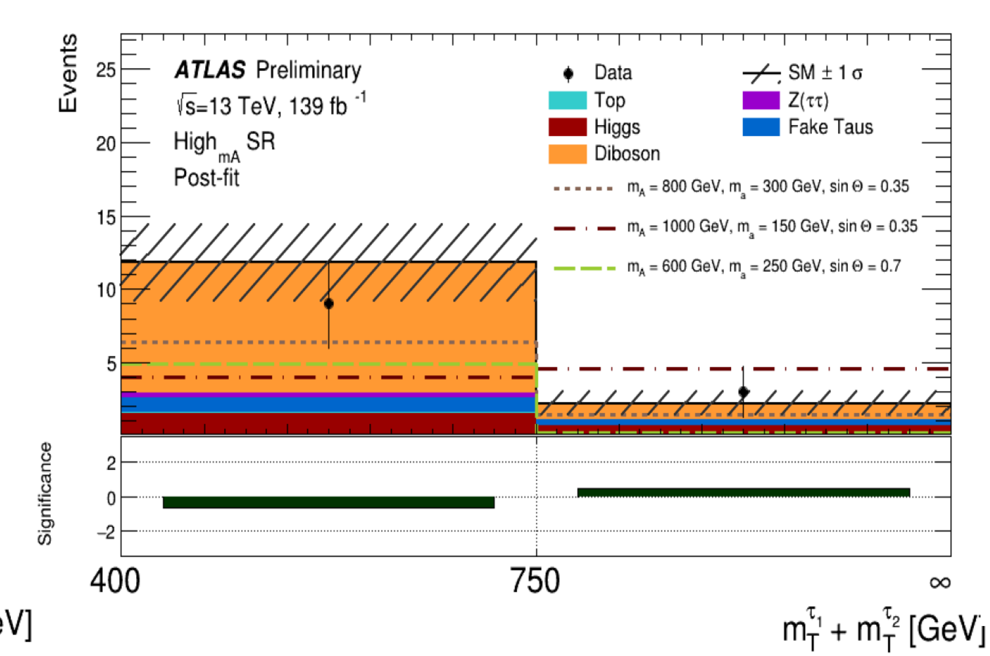

- h is 125 Higgs
- A is heavy pseudoscalar
- a is pseudoscalar that couples to dark matter

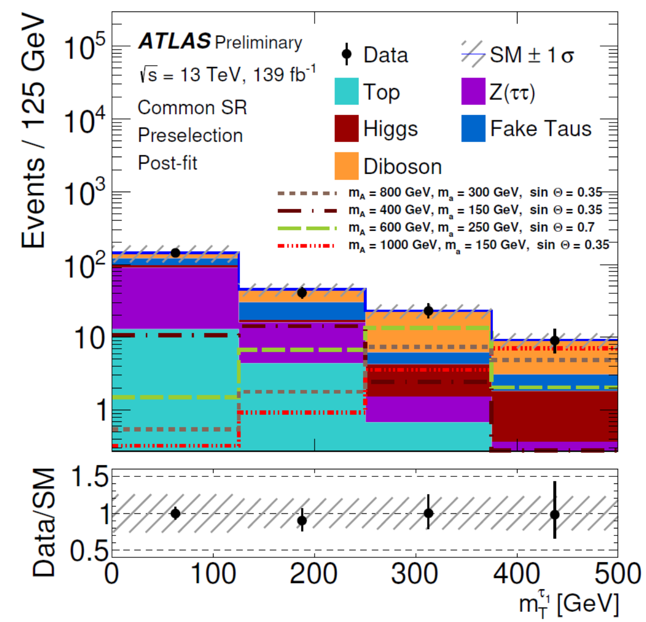
Events contain high pT hadronic taus and large MET (> 150 GeV), some additional cuts

„Low mA“ region targets mA≤800 GeV, „high mA“ region targets A masses above that

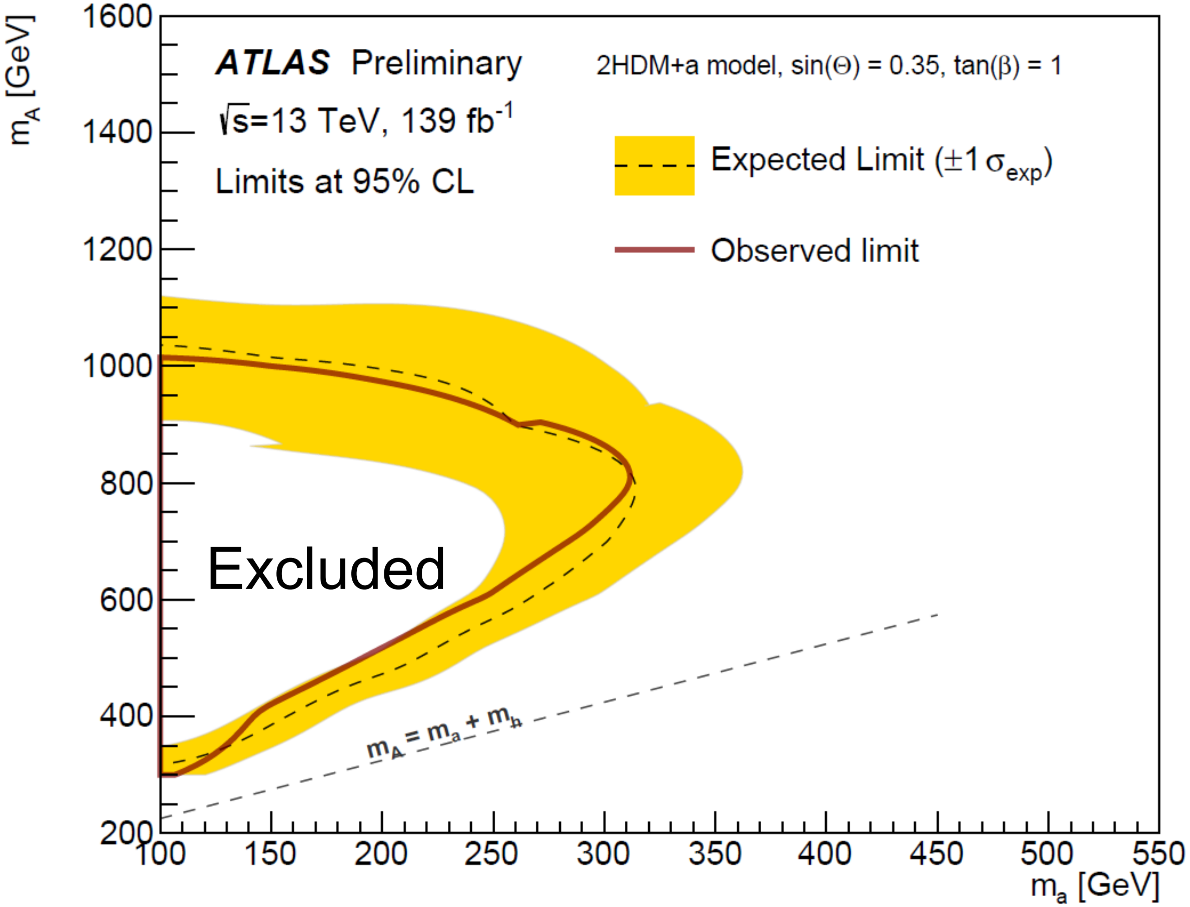
Final discriminant is sum of $m_T(\tau_1$, MET)+$m_T(\tau_2$,MET), with $m_T^{\tau_i} = \sqrt{2 p_T(\tau_i) E_T^{miss}(1 - \cos\Delta\phi(\tau_i, p_T^{miss}))}$

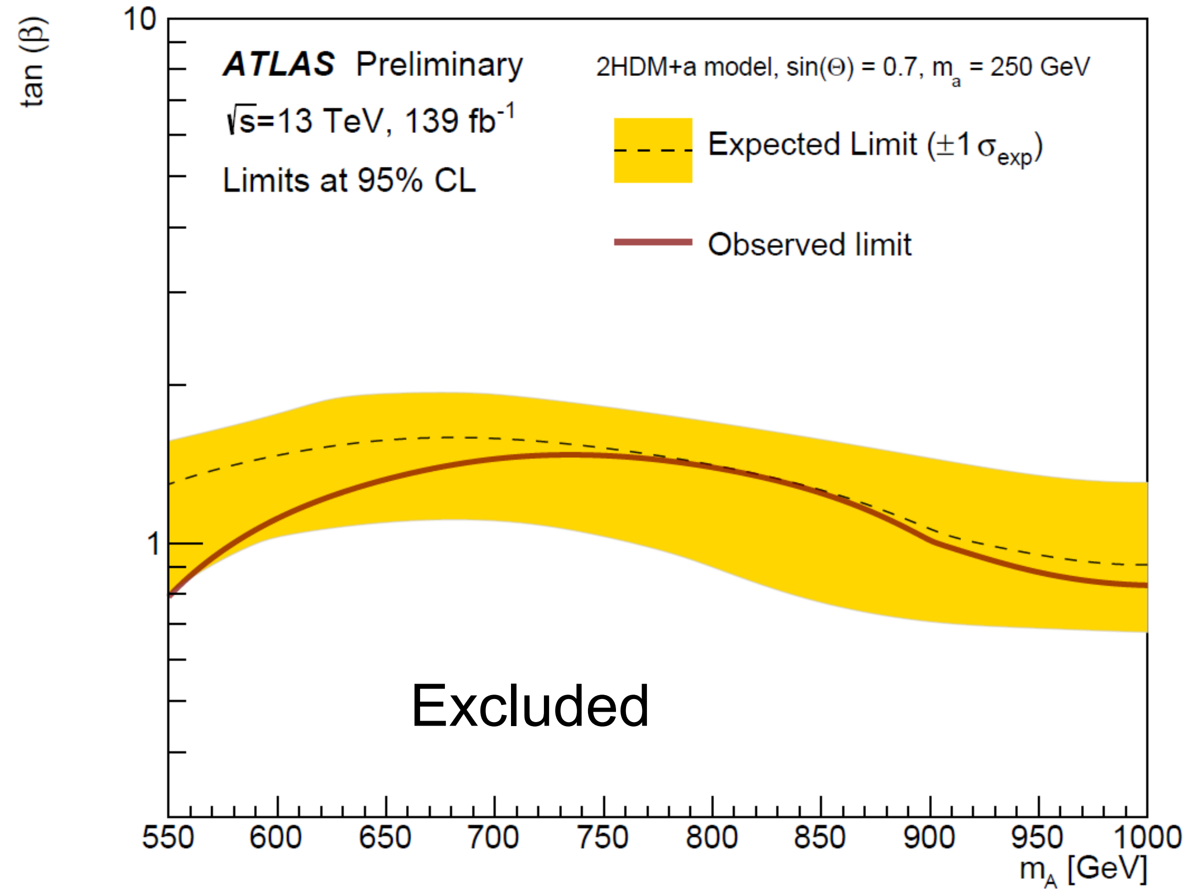


# $H \to \tau\tau$ + MET

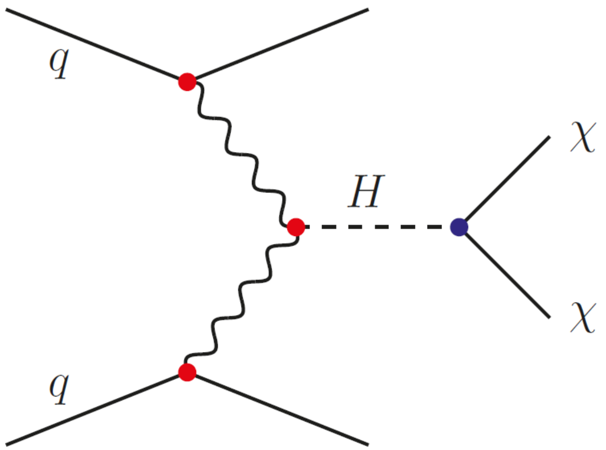



**Assumptions entering in these results:**

- Mass degeneracy between H, A and $H^+$
- Mass of the DM particle $\chi$ is set to 10 GeV
- $\cos(\beta-\alpha)=0$
- Mixing angle $\theta$ between both pseudoscalars fixed to 0.35 (left) or 0.7 (right)

# Higgs to Invisible



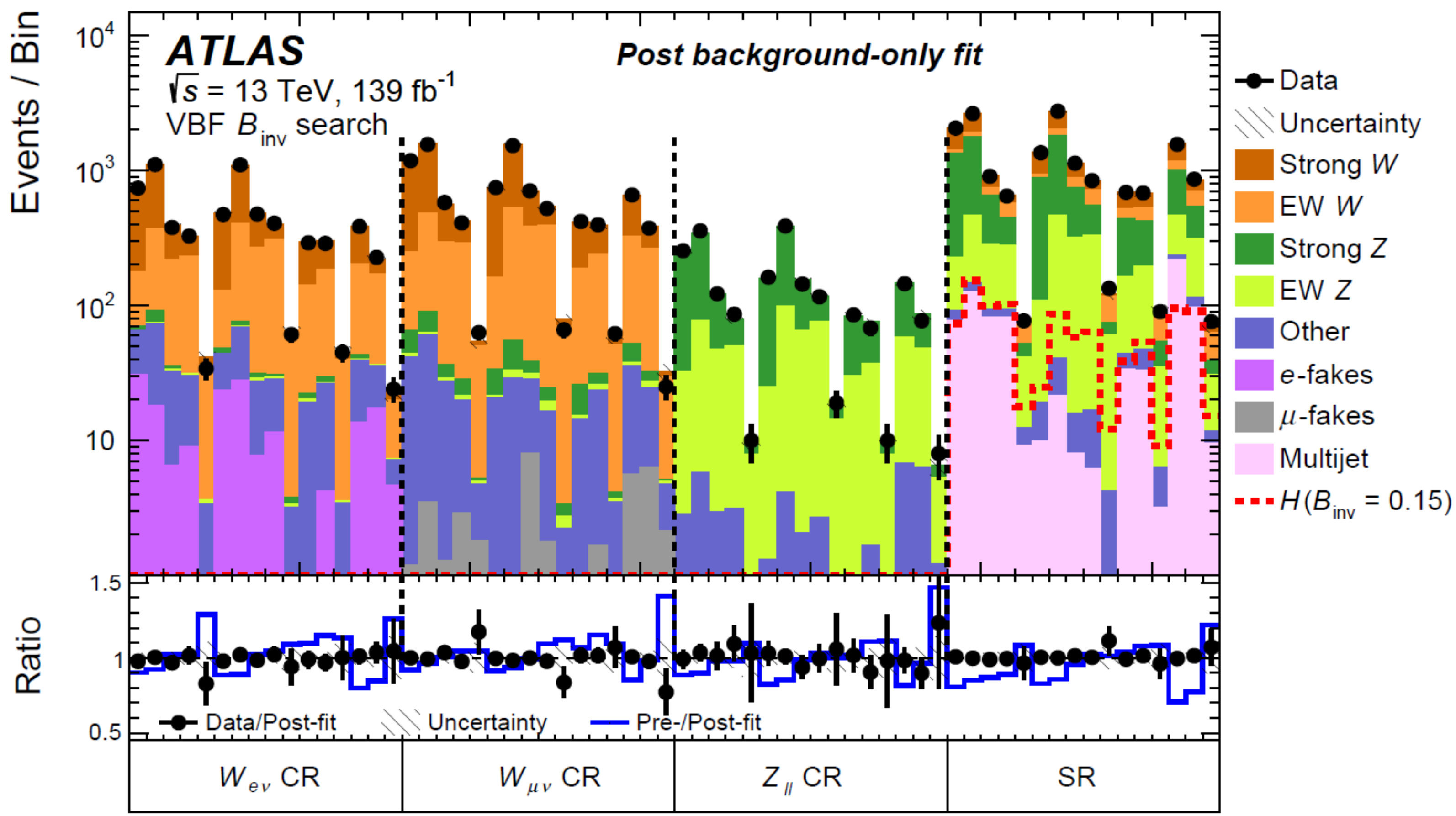

Vector boson fusion signature can be separated from background despite the lack of visible decay products of the Higgs:

- 2 leading jets in foward direction and in opposite hemispheres
- large dijet mass mjj (>0.8 TeV)
- large pseudorapidity separation Δηjj (>3.8)
- smaller values of Δϕjj

SR has 16 bins in mjj and ΔΦjj, depending on the jet multiplicity and MET.

Fit also contains several control regions for V+jets, fakes and pile-up jets.

Total fit contains 105 observed Yields, 58 normalization parameters and many constrained nuisance parameters.



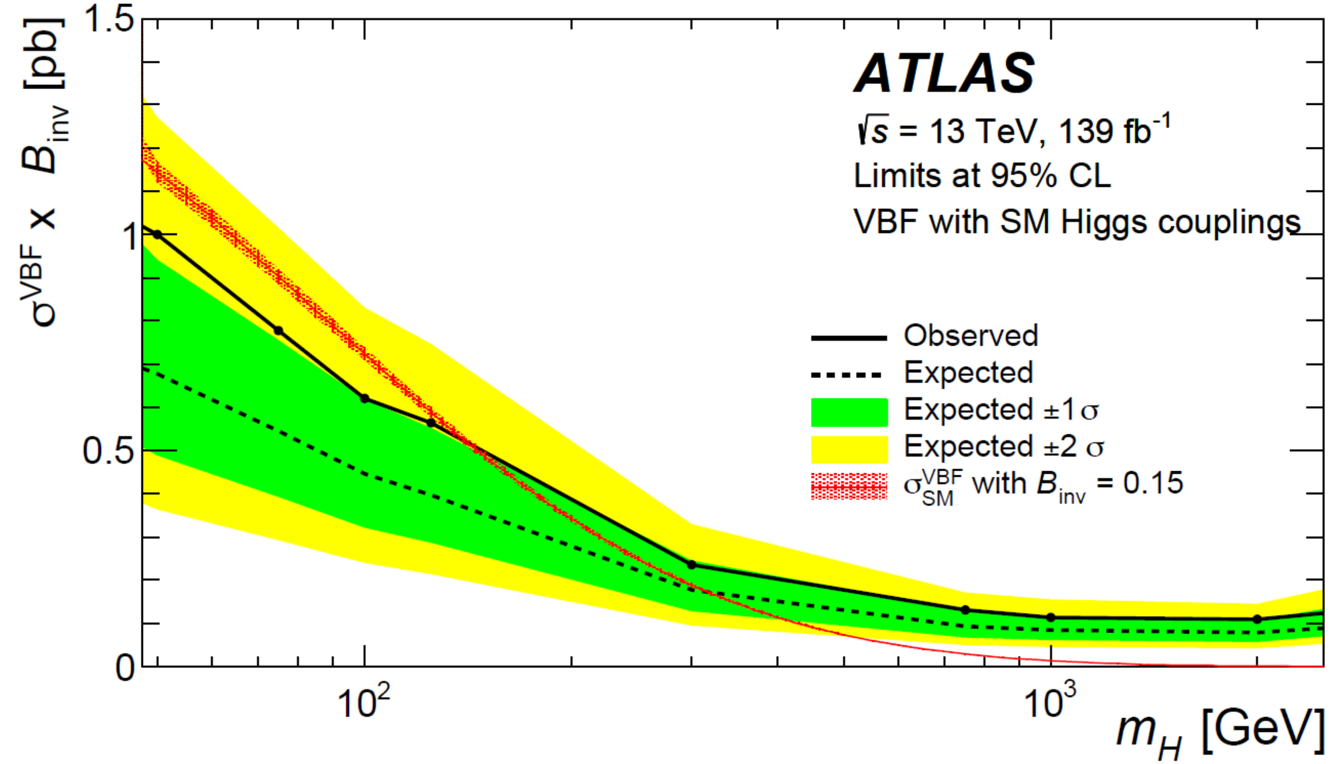
# Higgs to Invisible

Limit on BR (H → invisible)
Observed: 0.145
Expected: 0.103 + 0.041 - 0.028
Best fit value: 0.053 ± 0.052

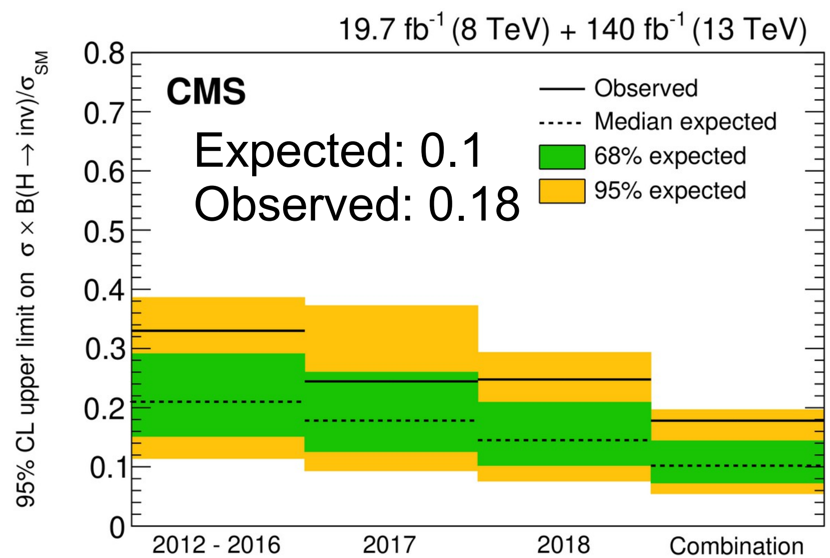
Relative impact of each source of uncertainy on the limit on BR(H→inv):

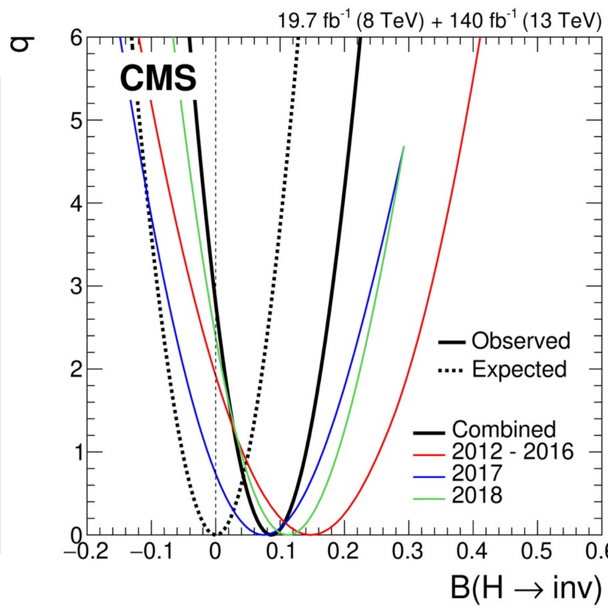
| Source | Δ [%] |
|---|---|
| Jet energy scale | 2.1 |
| Jet energy resolution | 4.2 |
| Fake leptons | 6.5 |
| Lepton ID | 5.3 |
| Multijet | 5.0 |
| Other | 2.8 |
| $V$+jets theory | 4.2 |
| Signal theory | 0.6 |
| MC stats. | 3.8 |
| $V$+jets data stats. | 9.4 |
| Remaining data stats. | 8.7 |

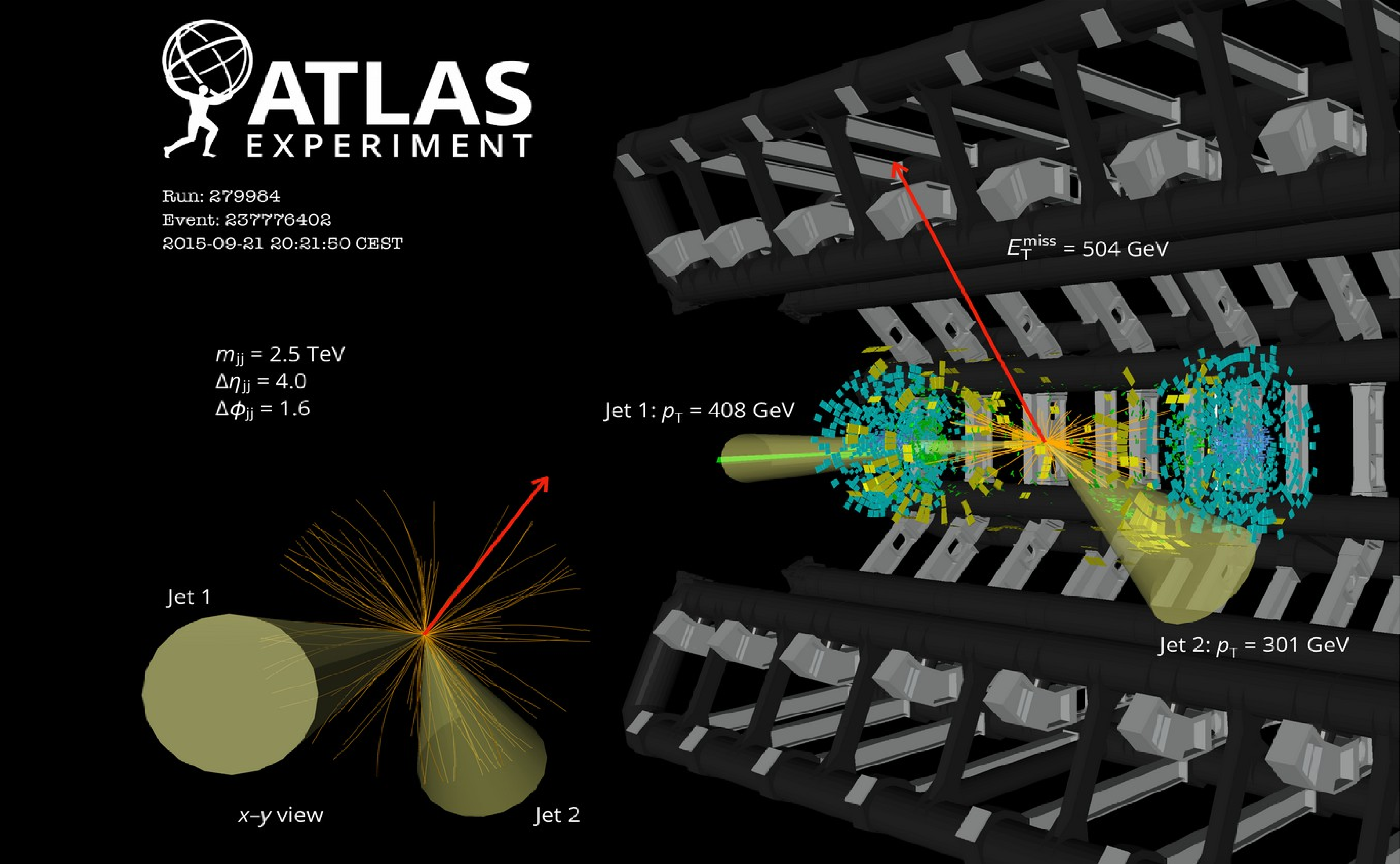
Analysis optimized for SM Higgs is also used to Constrain heavy Higgs → invisible:

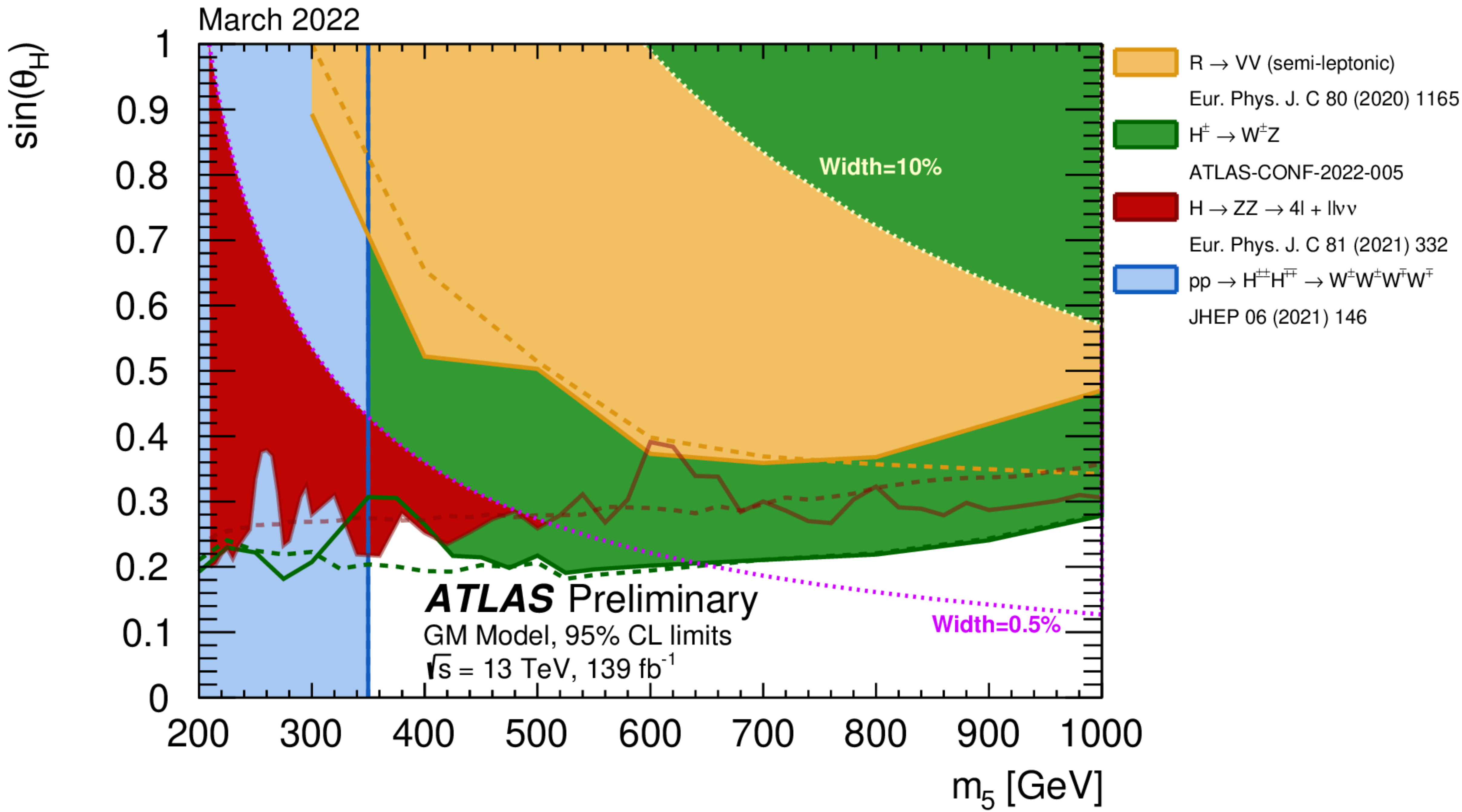



Both ATLAS and CMS have a slight excess each

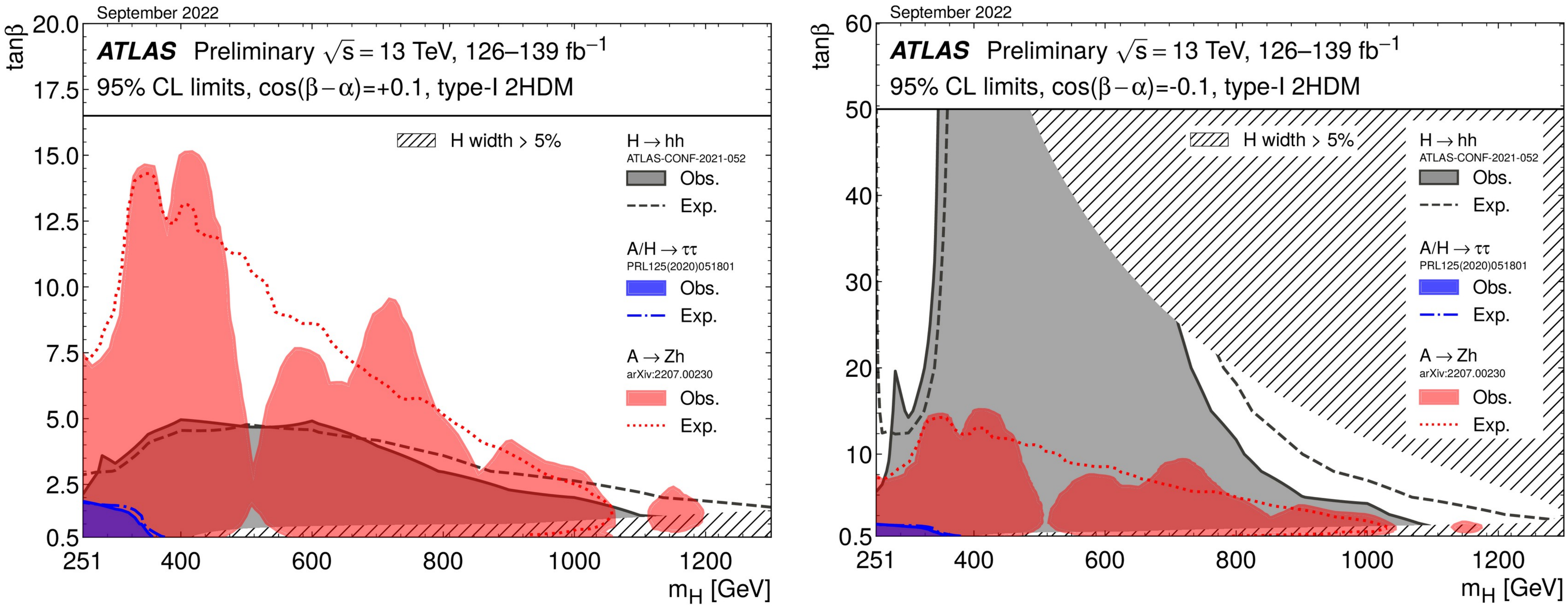



ATLAS EXPERIMENT
Run: 279984
Event: 237776402
2015-09-21 20:21:50 CEST
$E_T^{miss}$ = 504 GeV
$m_{jj}$ = 2.5 TeV
$\Delta\eta_{jj}$ = 4.0
$\Delta\phi_{jj}$ = 1.6
Jet 1: $p_T$ = 408 GeV
Jet 1
Jet 2: $p_T$ = 301 GeV
$x$–$y$ view
Jet 2



March 2022
$\sin(\theta_H)$
$m_5$ [GeV]
Width=10%
Width=0.5%
ATLAS Preliminary
GM Model, 95% CL limits
$\sqrt{s}$ = 13 TeV, 139 fb$^{-1}$
$R \rightarrow VV$ (semi-leptonic)
Eur. Phys. J. C 80 (2020) 1165
$H^{\pm} \rightarrow W^{\pm}Z$
ATLAS-CONF-2022-005
$H \rightarrow ZZ \rightarrow 4l + ll\nu\nu$
Eur. Phys. J. C 81 (2021) 332
$pp \rightarrow H^{\pm\pm}H^{\mp\mp} \rightarrow W^{\pm}W^{\pm}W^{\mp}W^{\mp}$
JHEP 06 (2021) 146


September 2022
ATLAS Preliminary $\sqrt{s} = 13$ TeV, 126–139 fb$^{-1}$
95% CL limits, cos(β − α)=+0.1, type-I 2HDM
H width > 5%
H → hh
ATLAS-CONF-2021-052
Obs.
Exp.
A/H → ττ
PRL125(2020)051801
Obs.
Exp.
A → Zh
arXiv:2207.00230
Obs.
Exp.
tanβ
$m_H$ [GeV]
September 2022
ATLAS Preliminary $\sqrt{s} = 13$ TeV, 126–139 fb$^{-1}$
95% CL limits, cos(β − α)=-0.1, type-I 2HDM
H width > 5%
H → hh
ATLAS-CONF-2021-052
Obs.
Exp.
A/H → ττ
PRL125(2020)051801
Obs.
Exp.
A → Zh
arXiv:2207.00230
Obs.
Exp.
tanβ
$m_H$ [GeV]

# H (and Z) → Quarkonium+γ Results