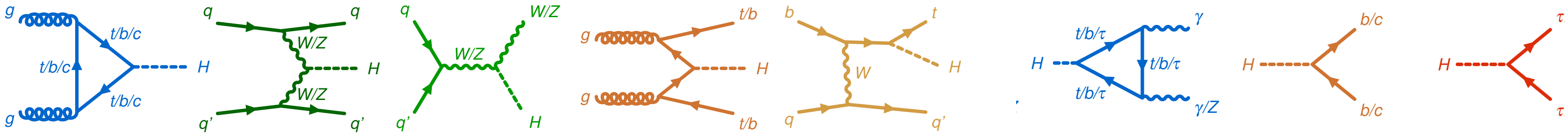


TOWARDS HIGH PRECISION MEASUREMENTS OF HIGGS BOSON PROPERTIES IN THE DI-TAU DECAY WITH THE ATLAS DETECTOR

DISSERTATIONSKOLLOQUIUM

Lena Herrmann

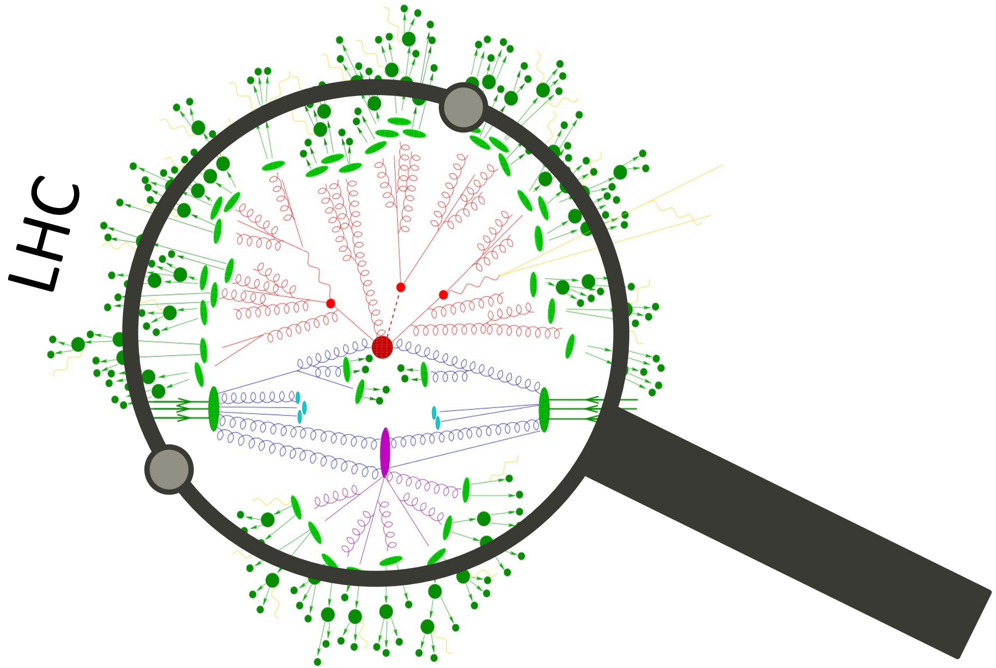
UNIVERSITÄT BONN

02.12.2024

ATLAS EXPERIMENT

TREMENDOUS EFFORTS FOR TINY PARTICLES:

„Exploring the Invisibly Small in a Quest to Understand the Universe“



adapted from arxiv.1411.4085

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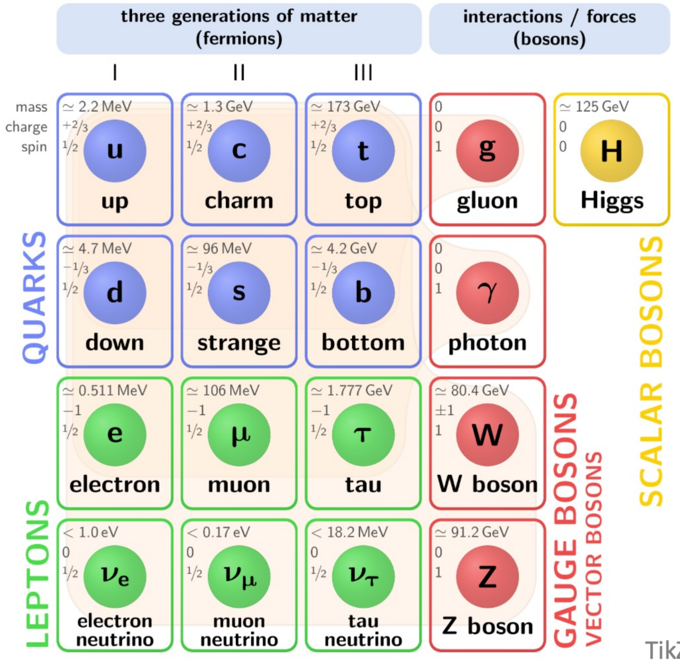

TikZ

Standard Model:

→ Description of Fundamental Particles

+ Particle Interactions

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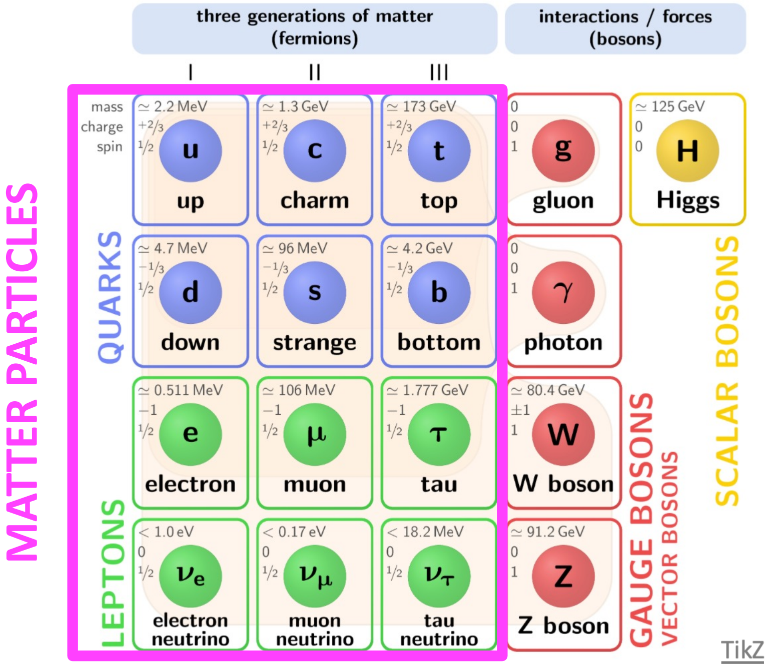

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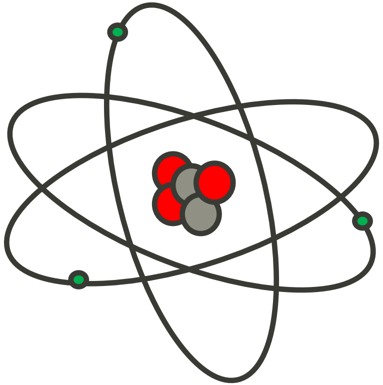

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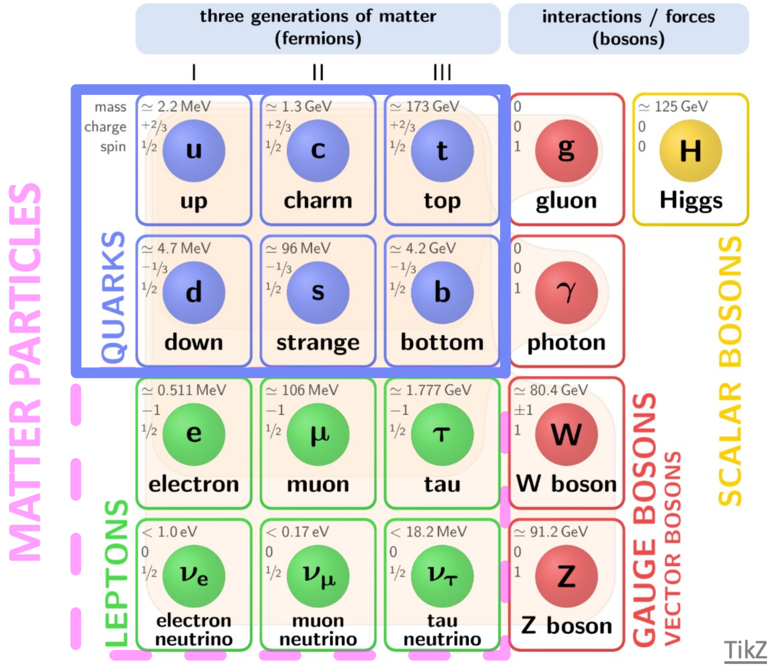

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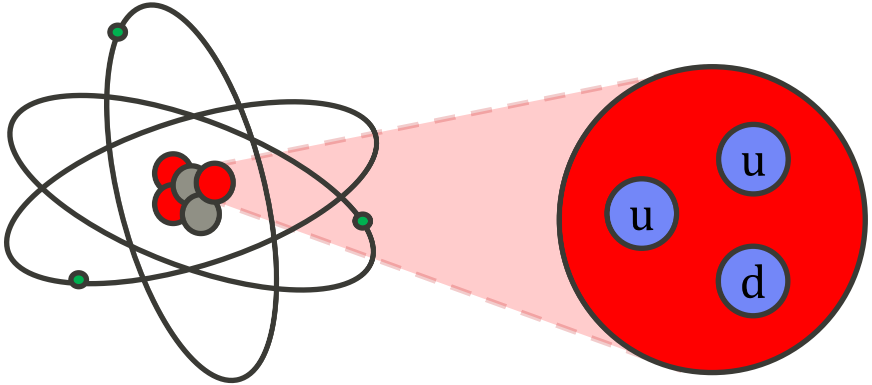

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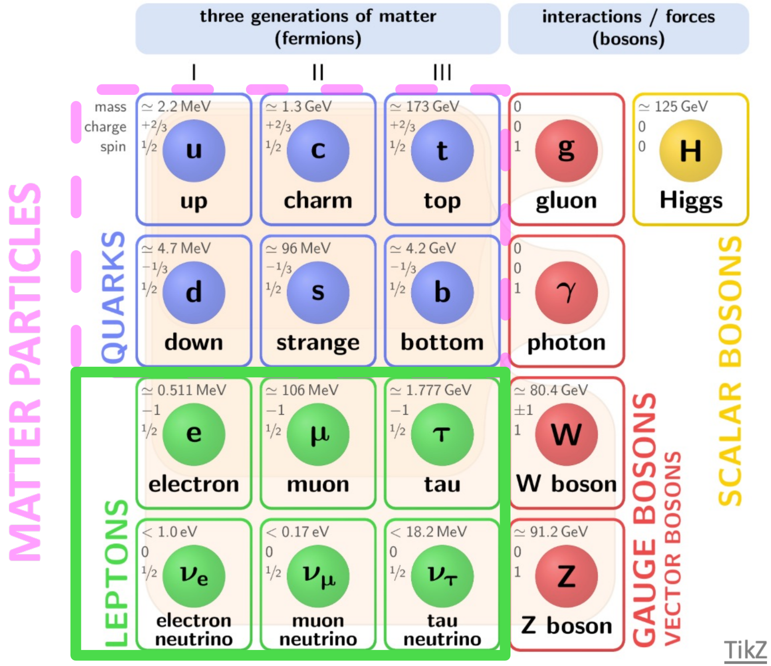

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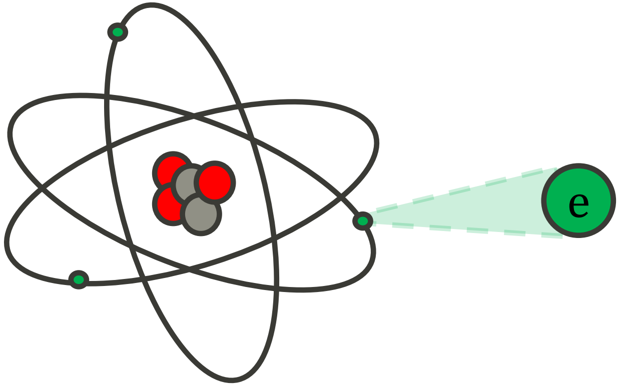

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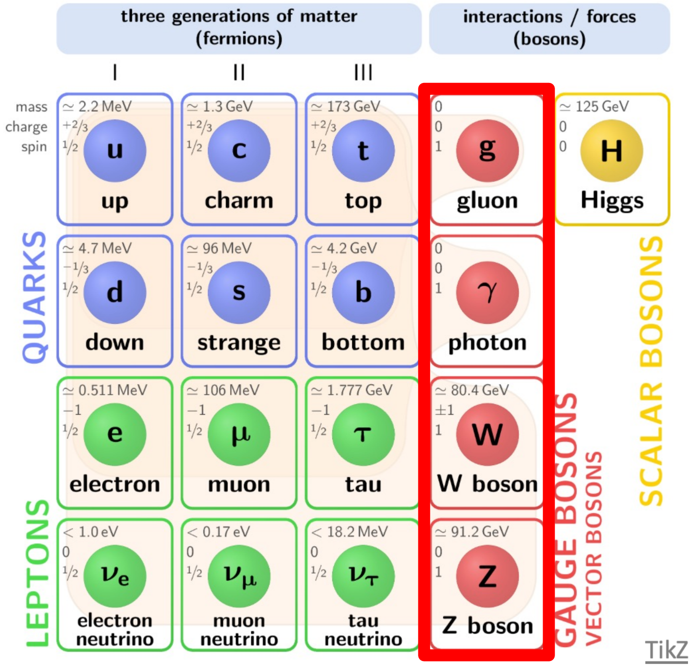

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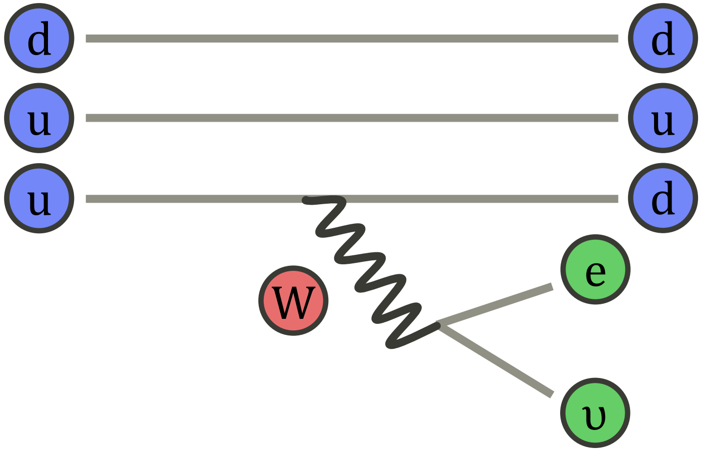

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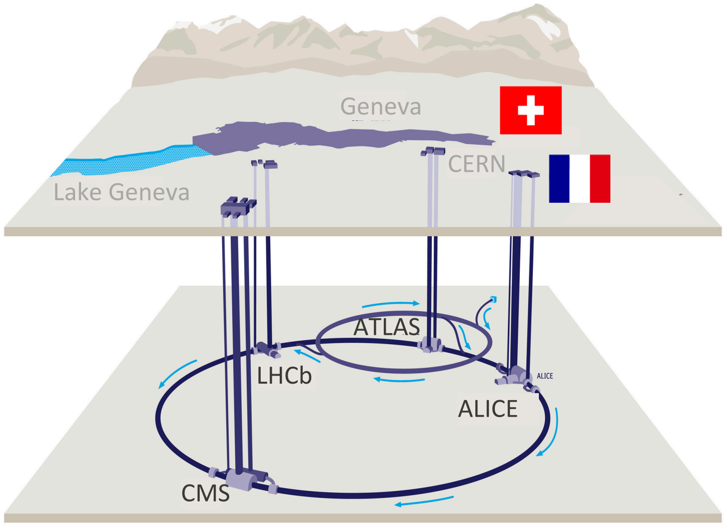

Weltmaschine

Standard Model (SM):

→ Description of
- + Fundamental Particles
- + Particle Interactions

Experimental Methodology:

→ Collide protons near the speed of light

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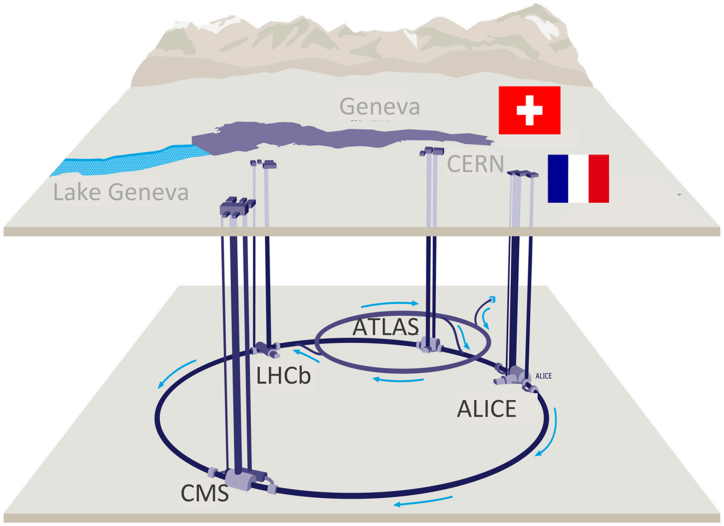

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STANDARD MODEL CONFIRMED

robust & successful theory

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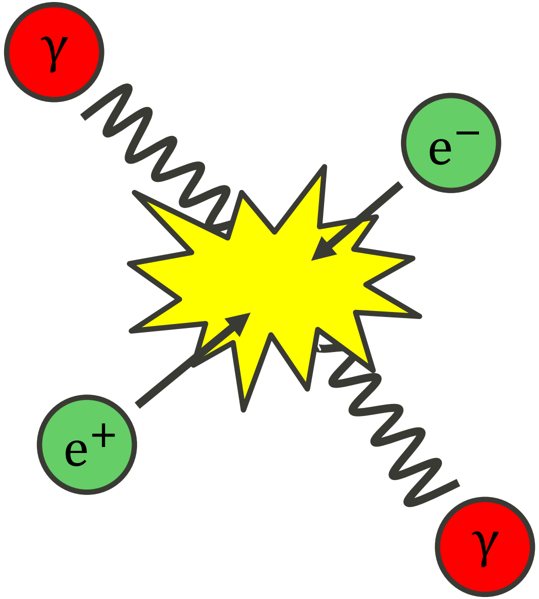

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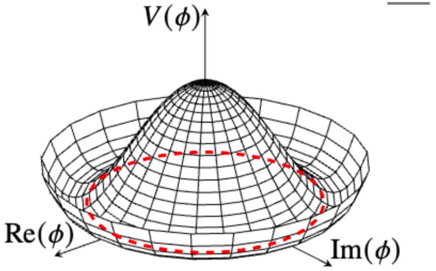
BUT: **Beyond the Standard Model Physics** required to answer open questions

THE HIGGS - THE KEY PLAYER



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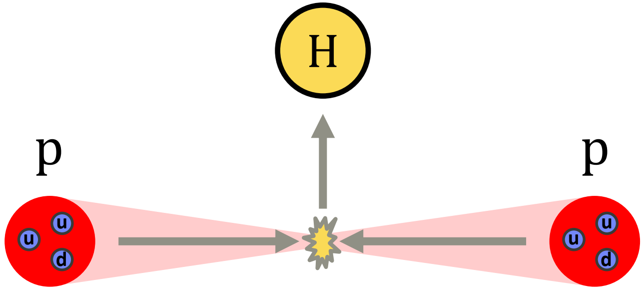
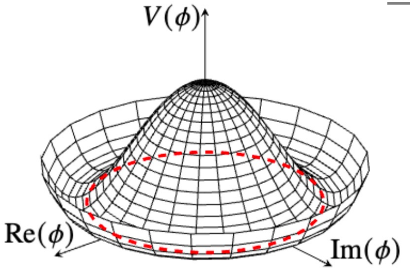


TikZ



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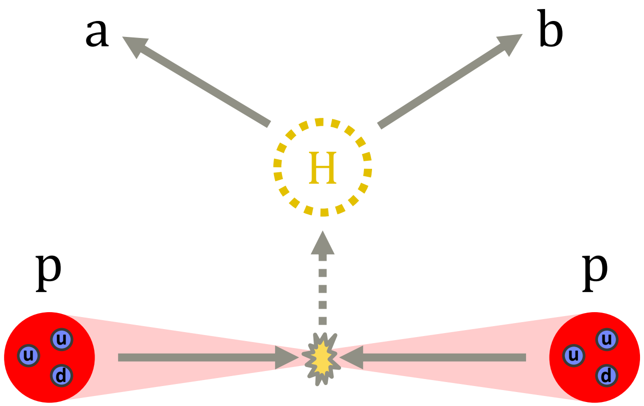

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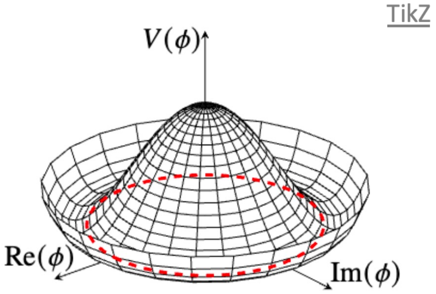

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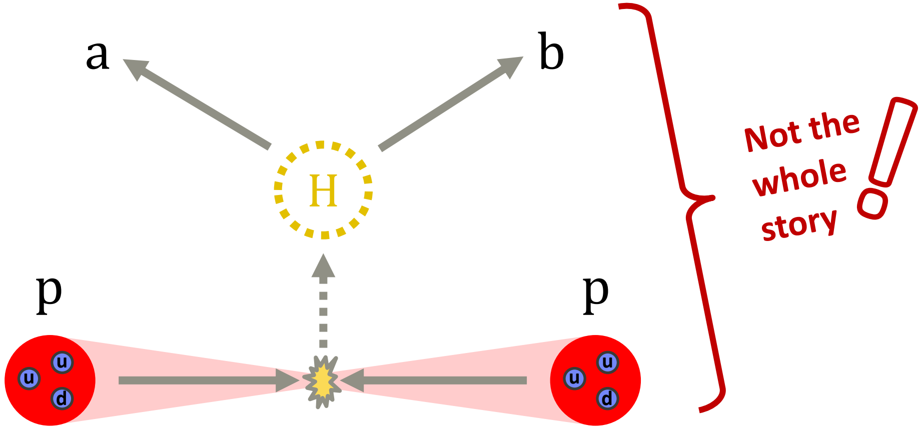

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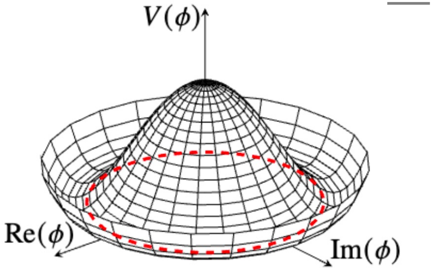

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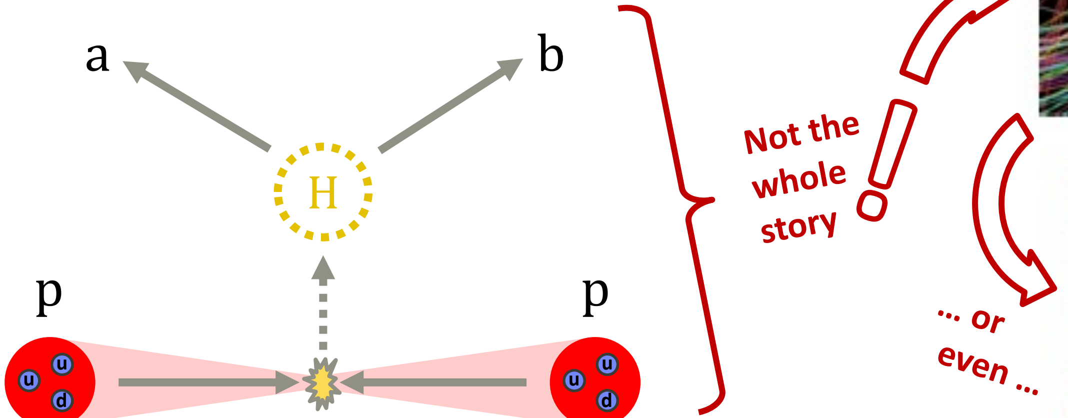

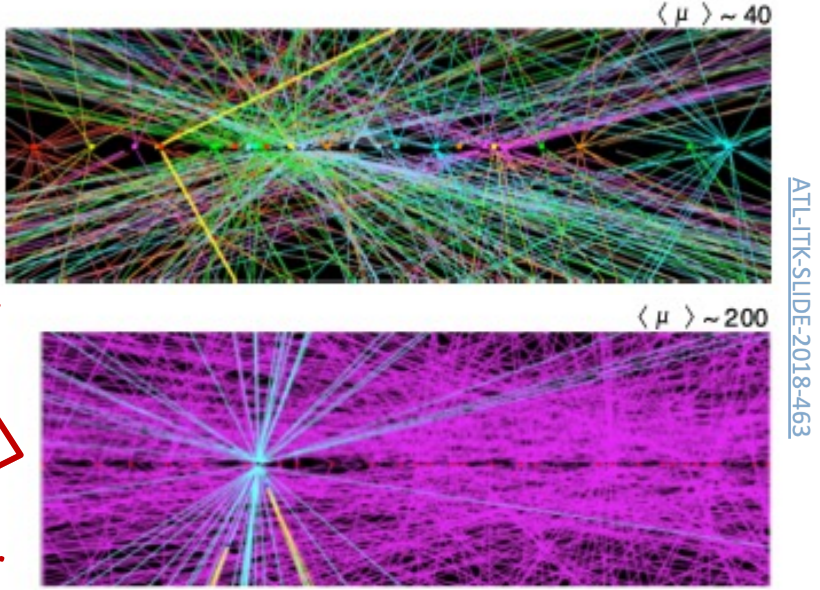

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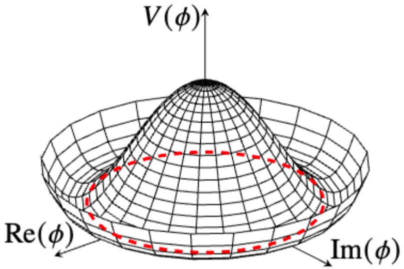

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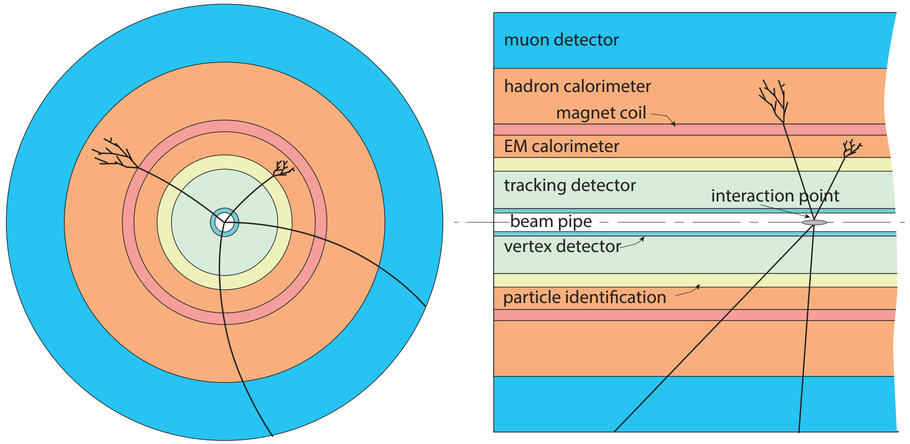
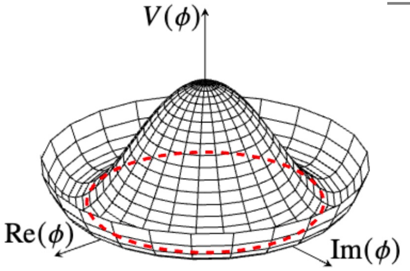


Particle Detectors - Kolanoski, Wermes

TikZ



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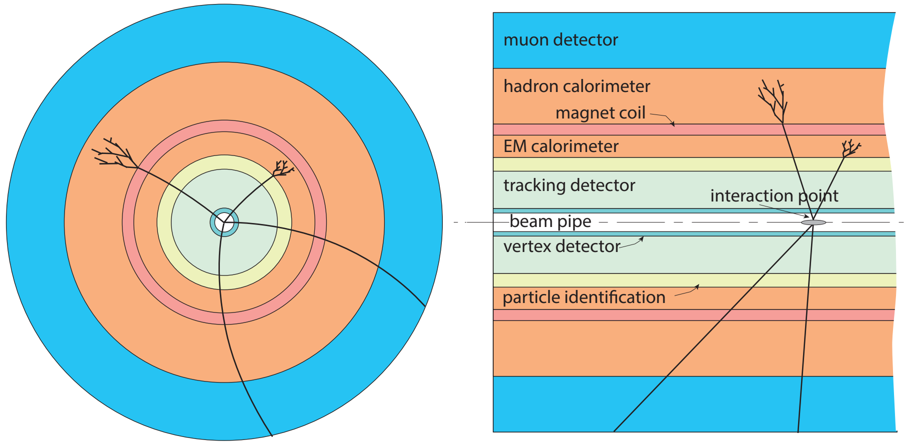

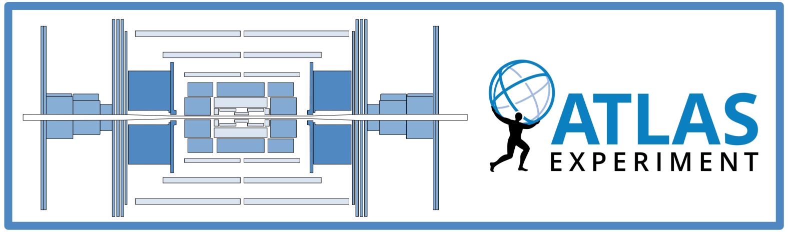

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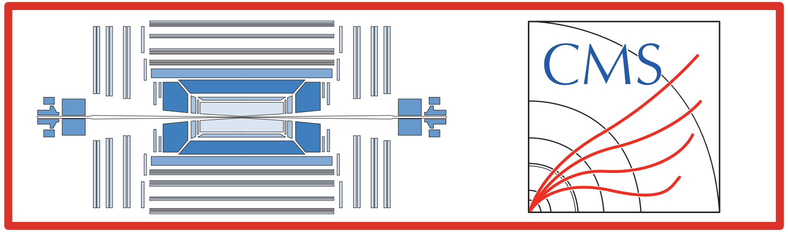

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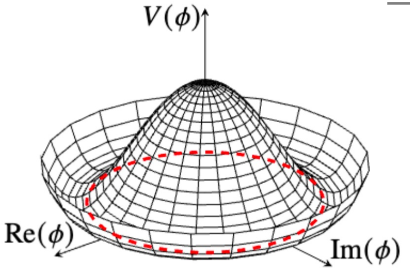
TikZ



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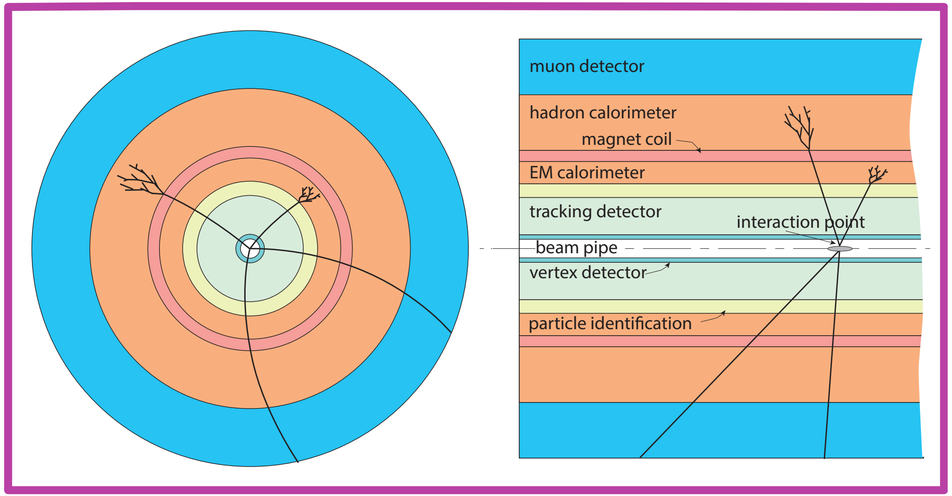

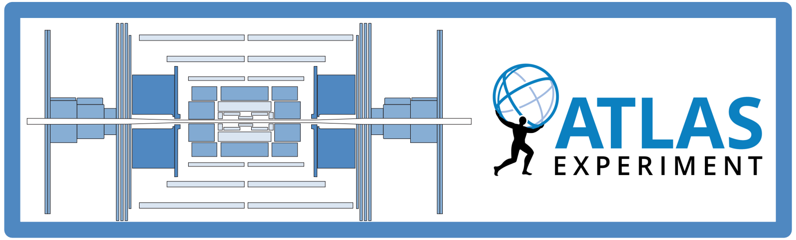

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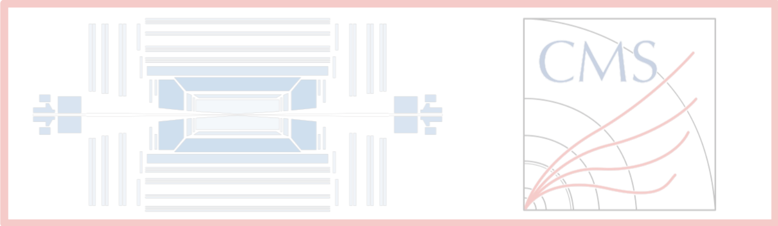

cds.record.2809003

THE STANDARD MODEL

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$
$$+ \; i\bar{\chi} \not{D} \chi$$
$$+ \; \chi_i Y_{ij} \chi_j \phi + h.c.$$
$$+ \; |D_\mu \phi|^2 - V(\phi)$$

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THE STANDARD MODEL

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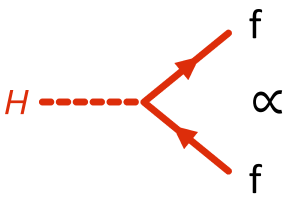
Yukawa Coupling



$\propto m_f$

Nature 607, 52–59 (2022)

THE STANDARD MODEL

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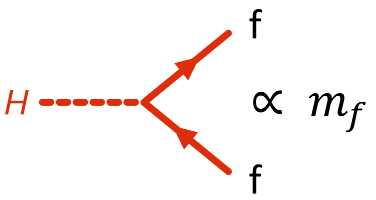
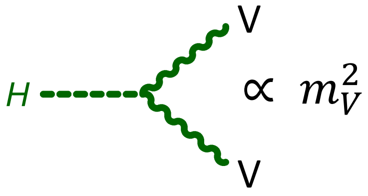


Gauge Coupling



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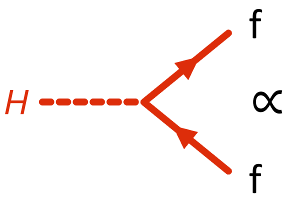

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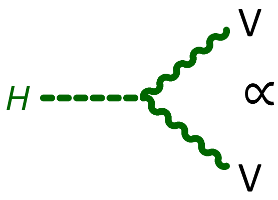
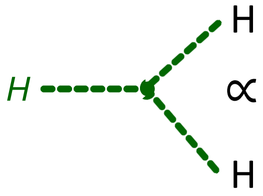


$\propto m_V^2$

Higgs Self-Coupling



$\propto m_H^2$

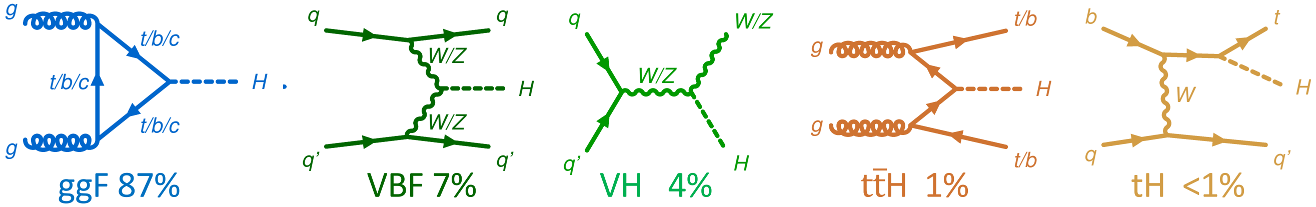
Nature 607, 52–59 (2022)

COUPLINGS MEASUREMENTS

Nature 607, 52–59 (2022)

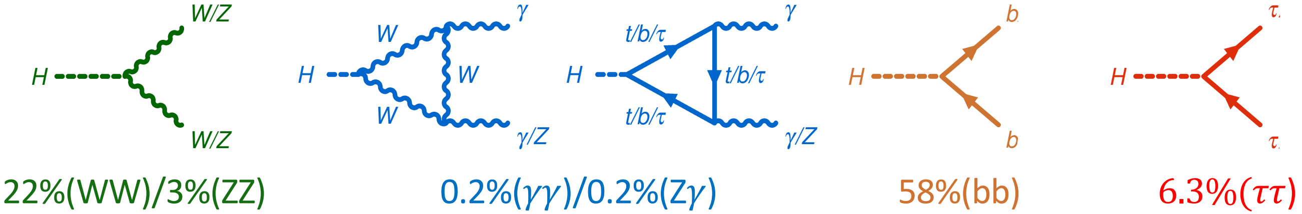
Production

@13TeV



Decay

@125GeV



Ambitious program measuring all accessible combinations

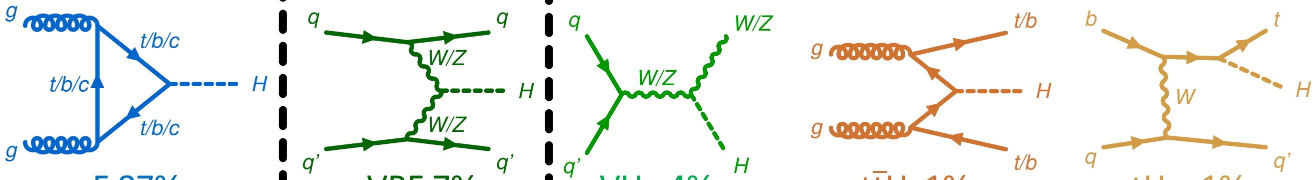
Relevant factors: cross-section, branching ratio, background contamination, selection efficiency

Statistics & analysis strategies essential

COUPLINGS MEASUREMENTS

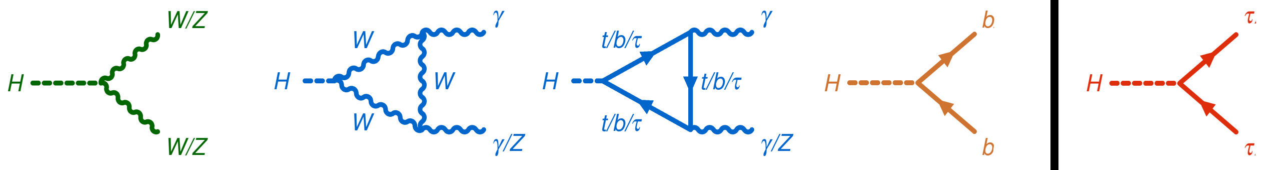
Nature 607, 52–59 (2022)

Production @13TeV



ggF 87% | VBF 7% | VH 4% | $t\bar{t}$H 1% | tH <1%

Decay @125GeV



22%(WW)/3%(ZZ) | 0.2%($\gamma\gamma$)/0.2%($Z\gamma$) | 58%(bb) | 6.3%($\tau\tau$)

Ambitious program measuring all accessible combinations

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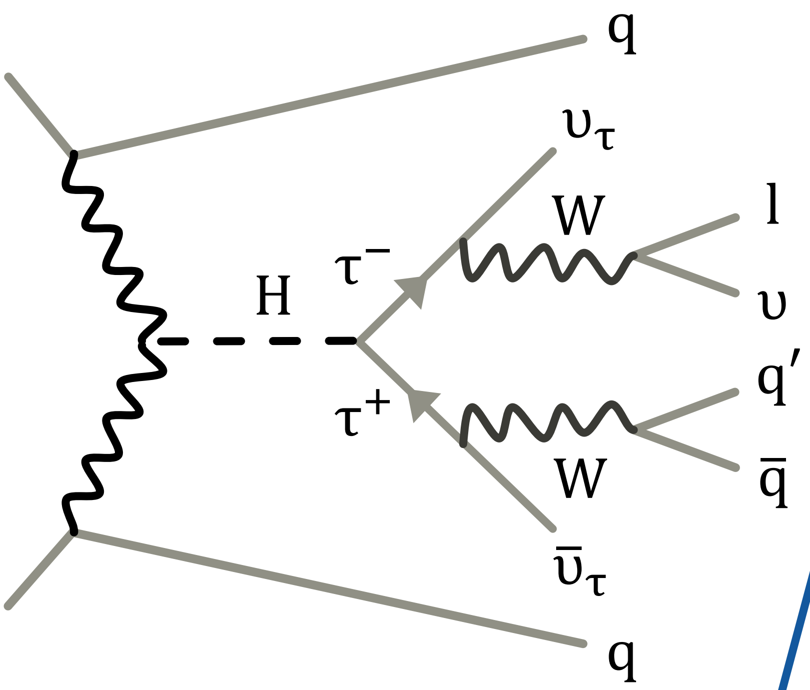
$H \to \tau\tau$



The ττ-Channel

- Best probe for lepton **Yukawa-coupling**
- **High branching ratio** of 6.3%
- Especially **sensitive to BSM** extensions
- Promising sensitivity in VBF production mode

$$N = \sigma \cdot L = 3.78\ \text{pb} \cdot 140\ \text{fb}^{-1} = 53000$$

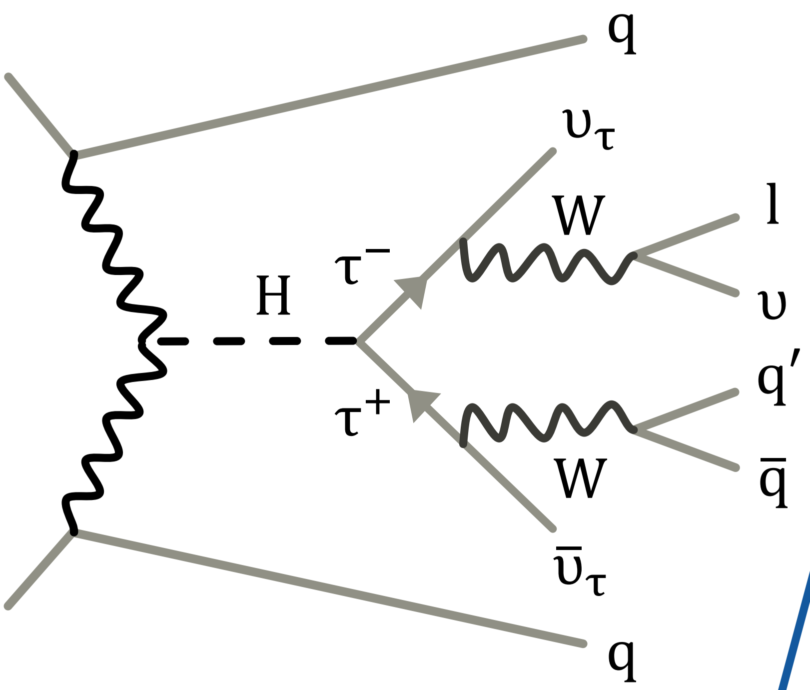
$$\text{BR}(6.3\%) \longrightarrow 33400$$

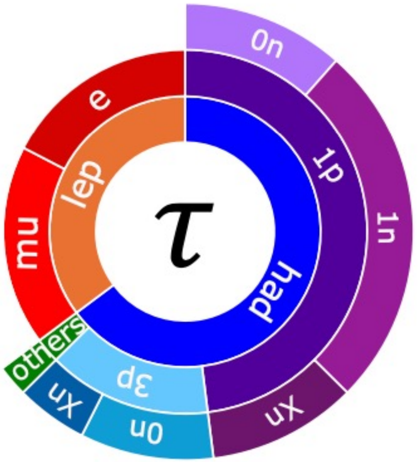
Rich Signature

= Jets
+ light leptons
+ MET

CHALLENGING RECONSTRUCTION

$H \rightarrow \tau\tau$





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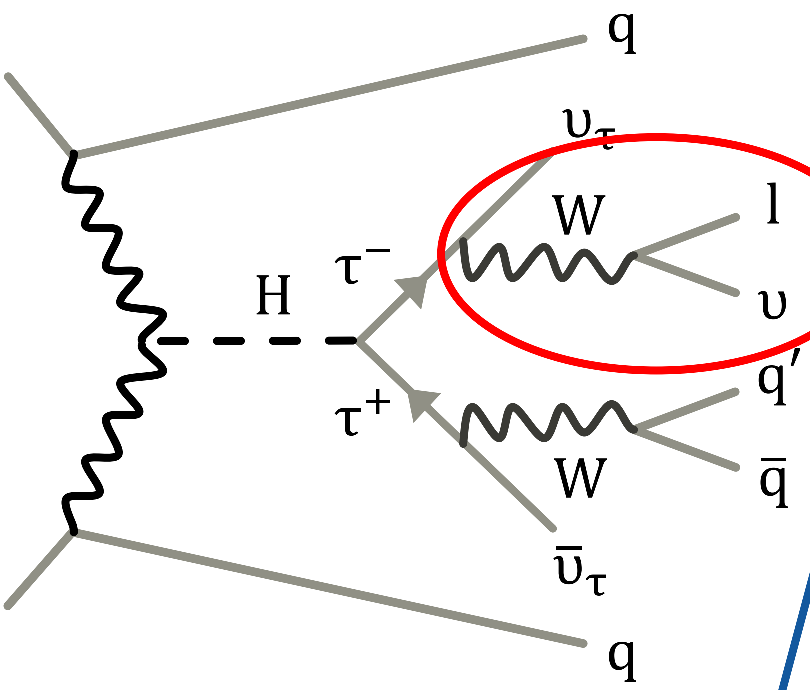

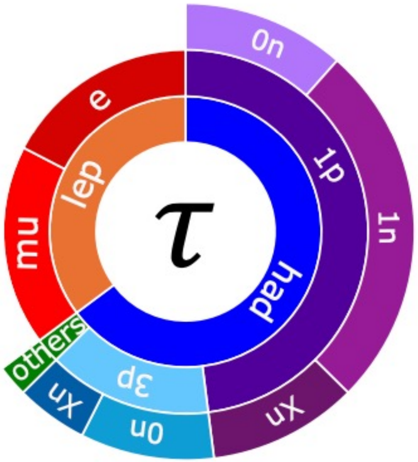

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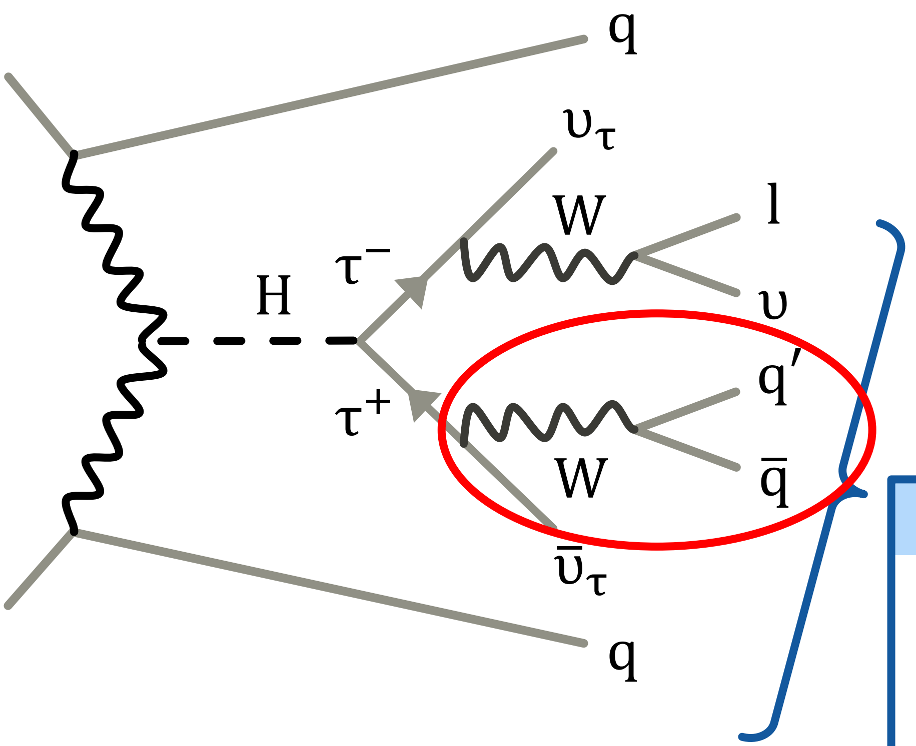

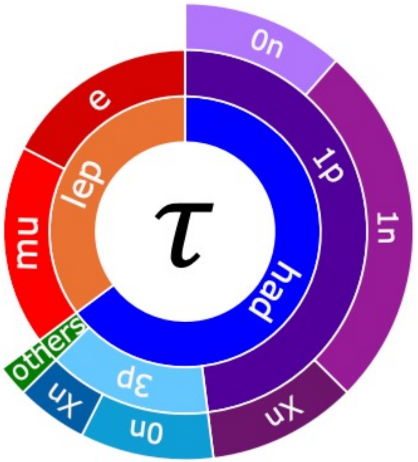

1p0n	$\tau^{\pm} \to \upsilon_{\tau}\pi^{\pm}$
1p1n	$\tau^{\pm} \to \upsilon_{\tau}\pi^{\pm}\pi^{0}$
1pXn	$\tau^{\pm} \to \upsilon_{\tau}\pi^{\pm} > 1\pi^{0}$
3p0n	$\tau^{\pm} \to \upsilon_{\tau}\pi^{\pm}\,\pi^{\pm}\,\pi^{\mp}$
3pXn	$\tau^{\pm} \to \upsilon_{\tau}\pi^{\pm}\,\pi^{\pm}\,\pi^{\mp} > 0\pi^{0}$

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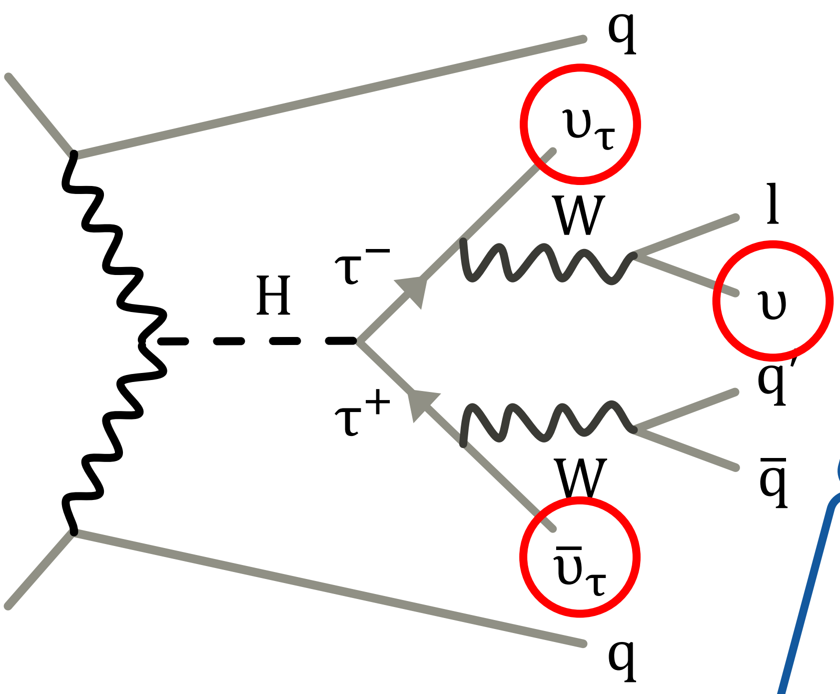
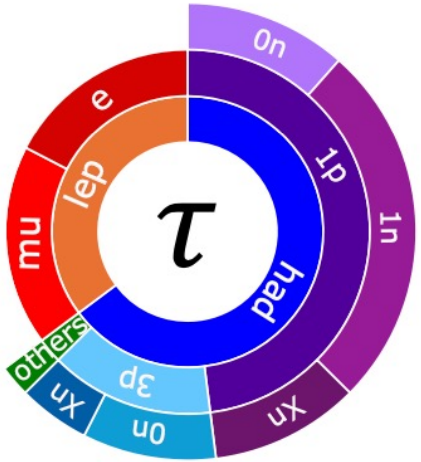
CHALLENGING RECONSTRUCTION

$H \rightarrow \tau\tau$





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1p1n	$\tau^\pm \rightarrow \upsilon_\tau \pi^\pm \pi^0$
1pXn	$\tau^\pm \rightarrow \upsilon_\tau \pi^\pm > 1\pi^0$
3p0n	$\tau^\pm \rightarrow \upsilon_\tau \pi^\pm \pi^\pm \pi^\mp$
3pXn	$\tau^\pm \rightarrow \upsilon_\tau \pi^\pm \pi^\pm \pi^\mp > 0\pi^0$

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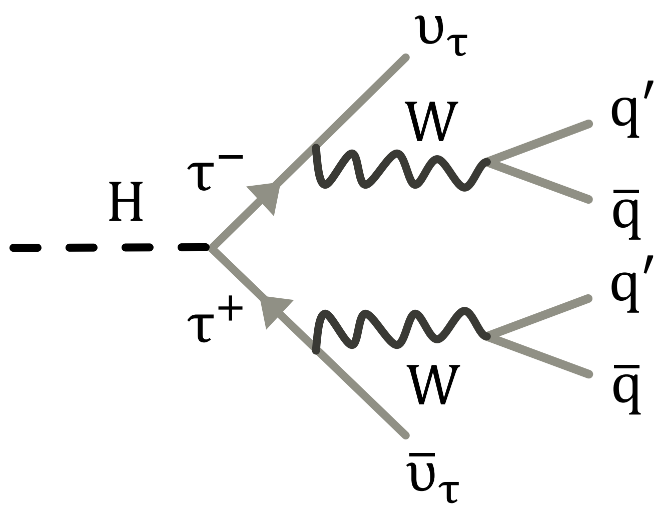
CHALLENGING RECONSTRUCTION

SELECTION

	$\tau_{had}\tau_{had}$
Object Counting	$\# e/\mu = 0$, $\# \tau_{had} = 2$
Charge product	opposite charge
p_T cut	τ_{had}: $p_T > 40{,}30$ GeV
ID	τ_{had}: RNN medium
E_T^{miss}	$E_T^{miss} > 20$ GeV
b-veto	$\#$ b-jets $= 0$
…	…

⇢ **Emphasizes** expected **physics** signatures
⇢ **Reduces** complex **background**



SELECTION

	$\tau_{had}\tau_{had}$
Object Counting	$\# e/\mu = 0, \# \tau_{had} = 2$
Charge product	opposite charge
p_T cut	τ_{had}: $p_T > 40{,}30$ GeV
ID	τ_{had}: RNN medium
E_T^{miss}	$E_T^{miss} > 20$ GeV
b-veto	$\#$ b-jets $= 0$
…	…

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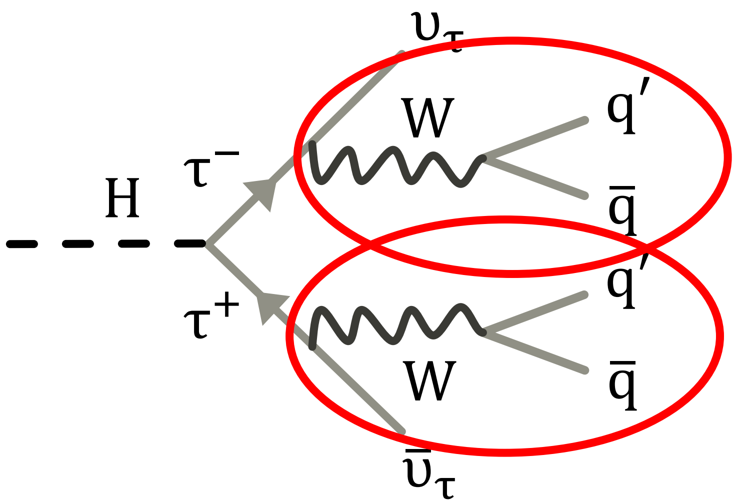

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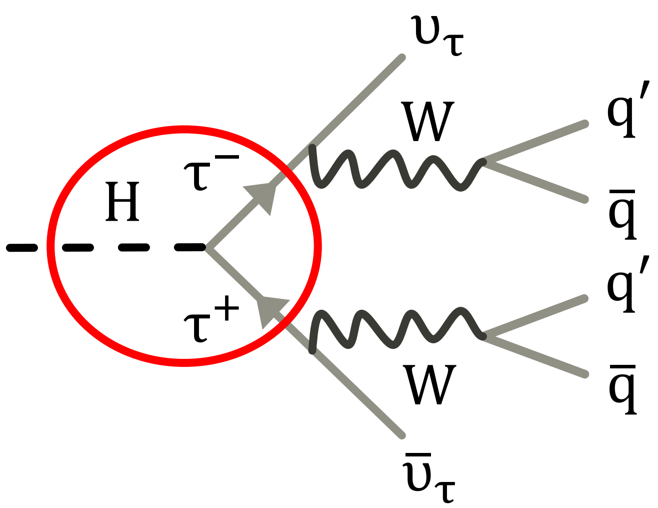

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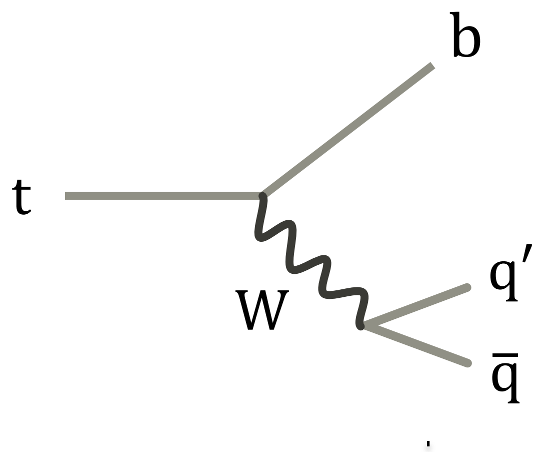
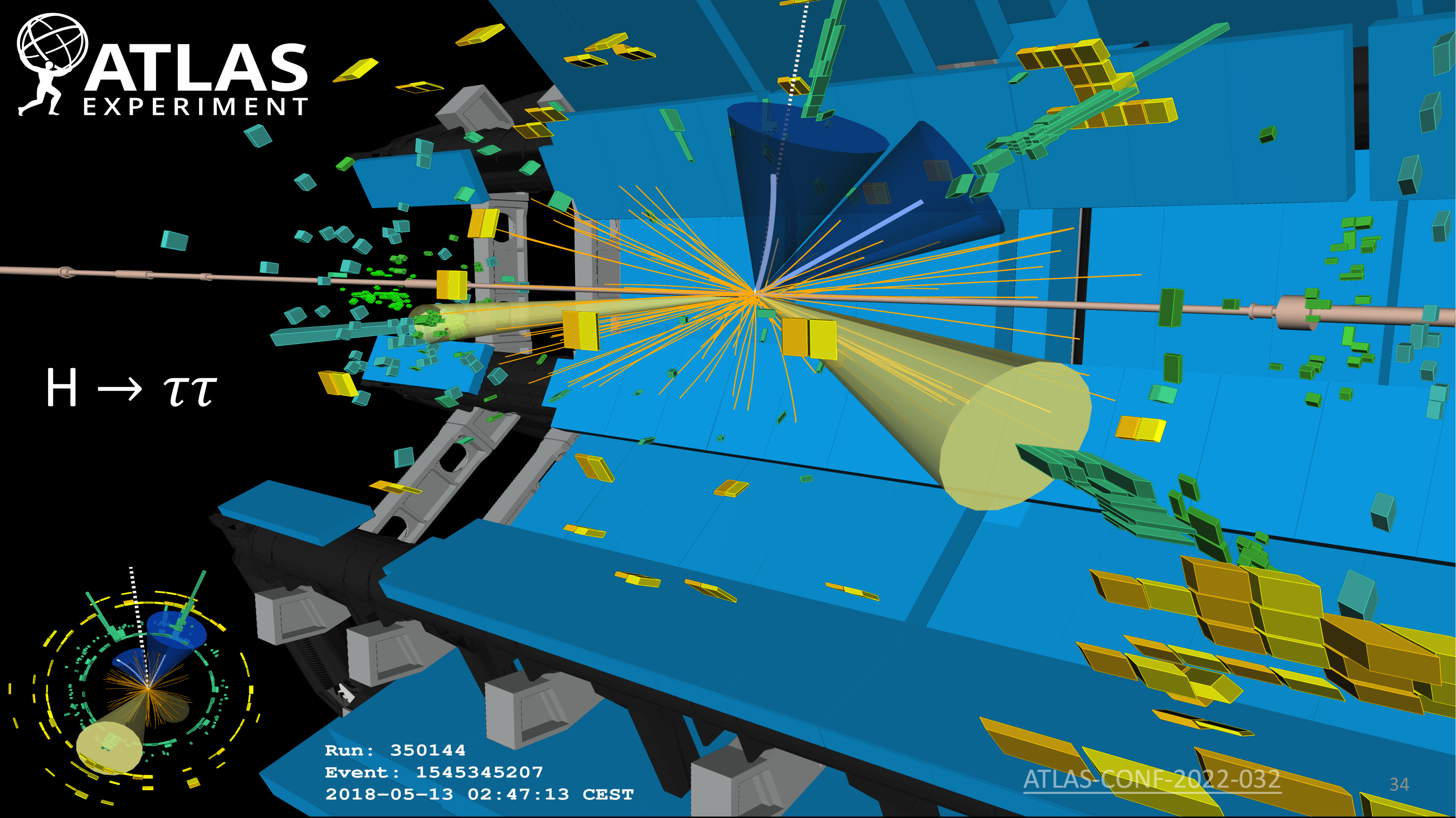
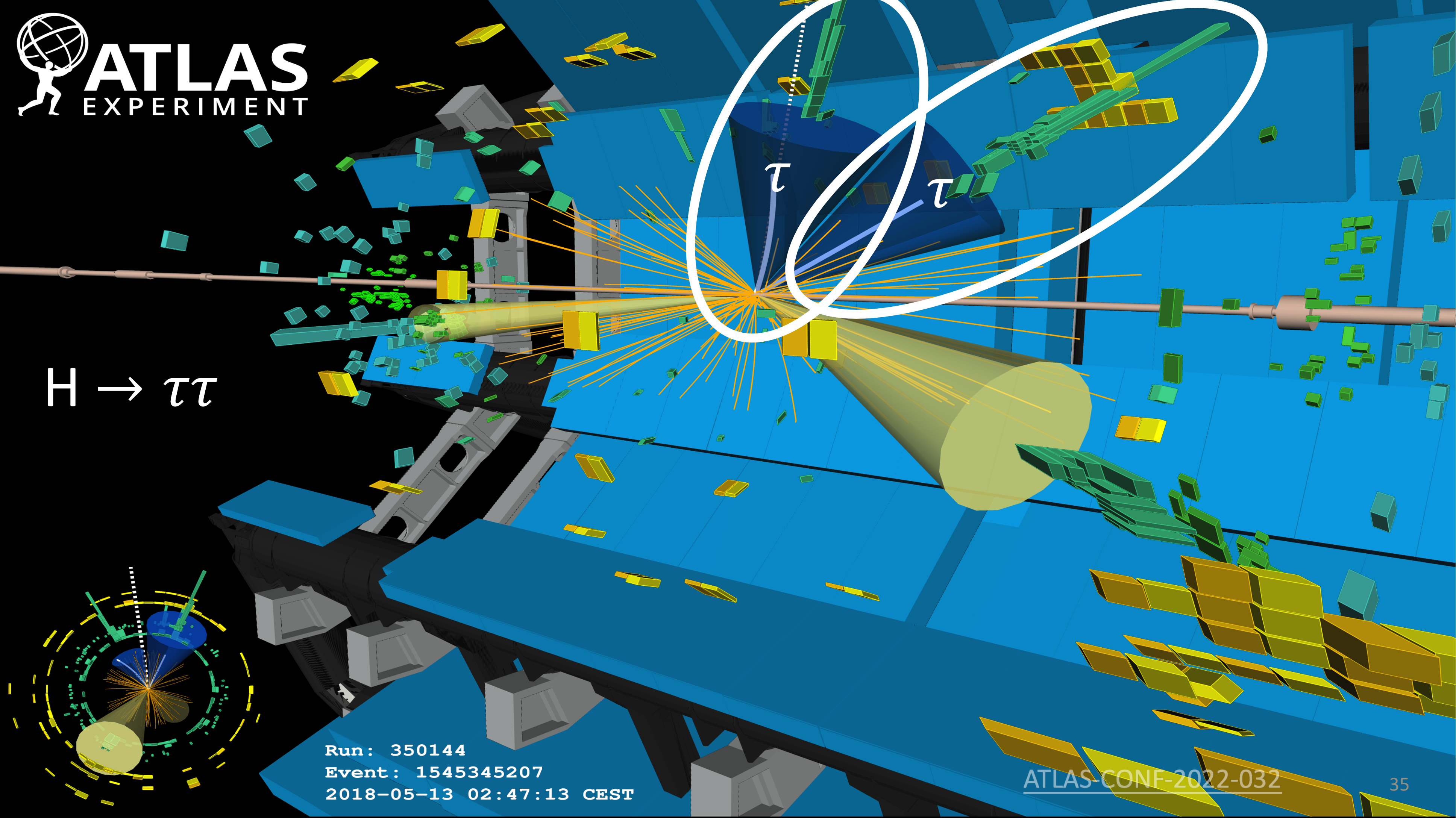
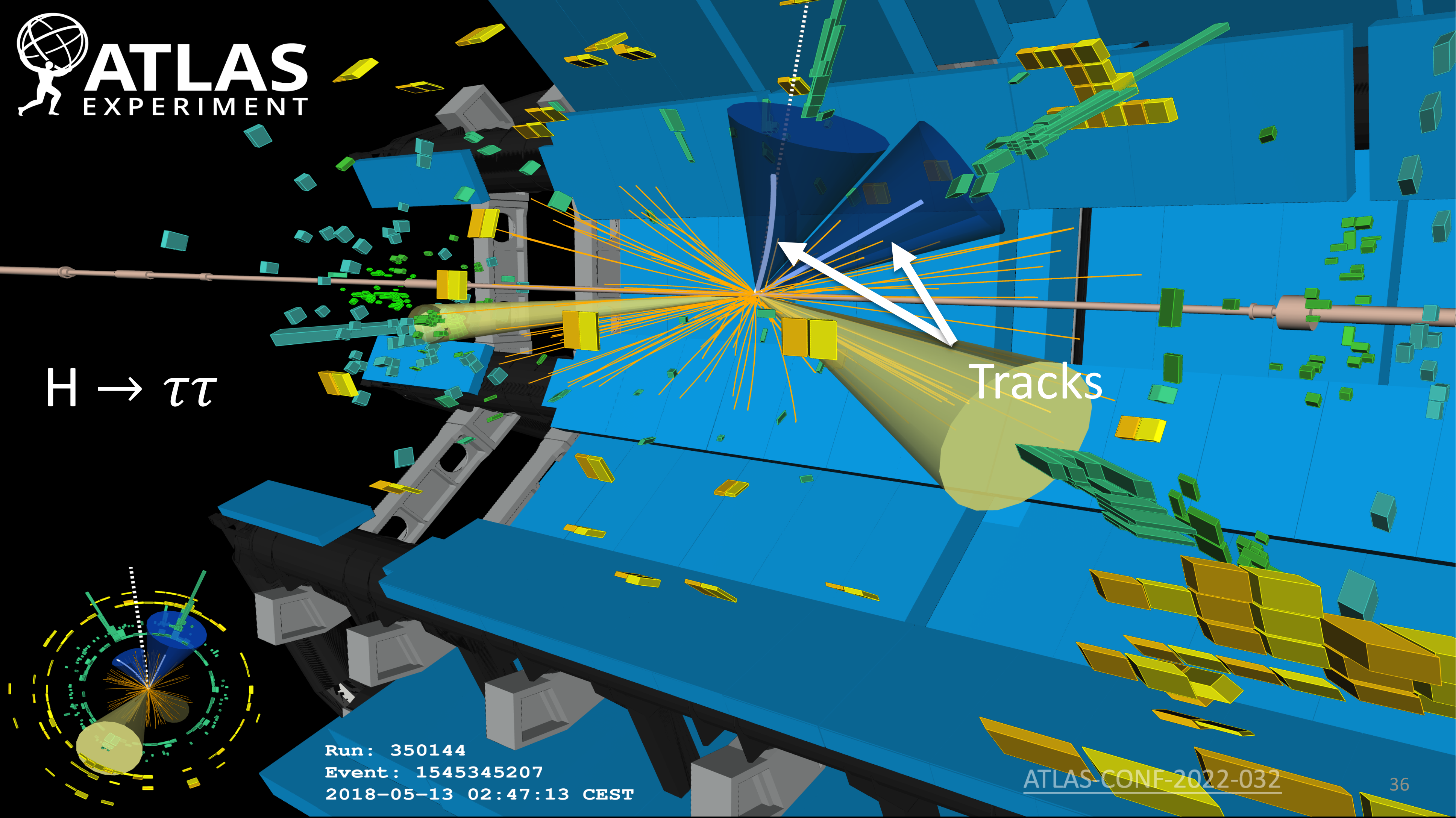


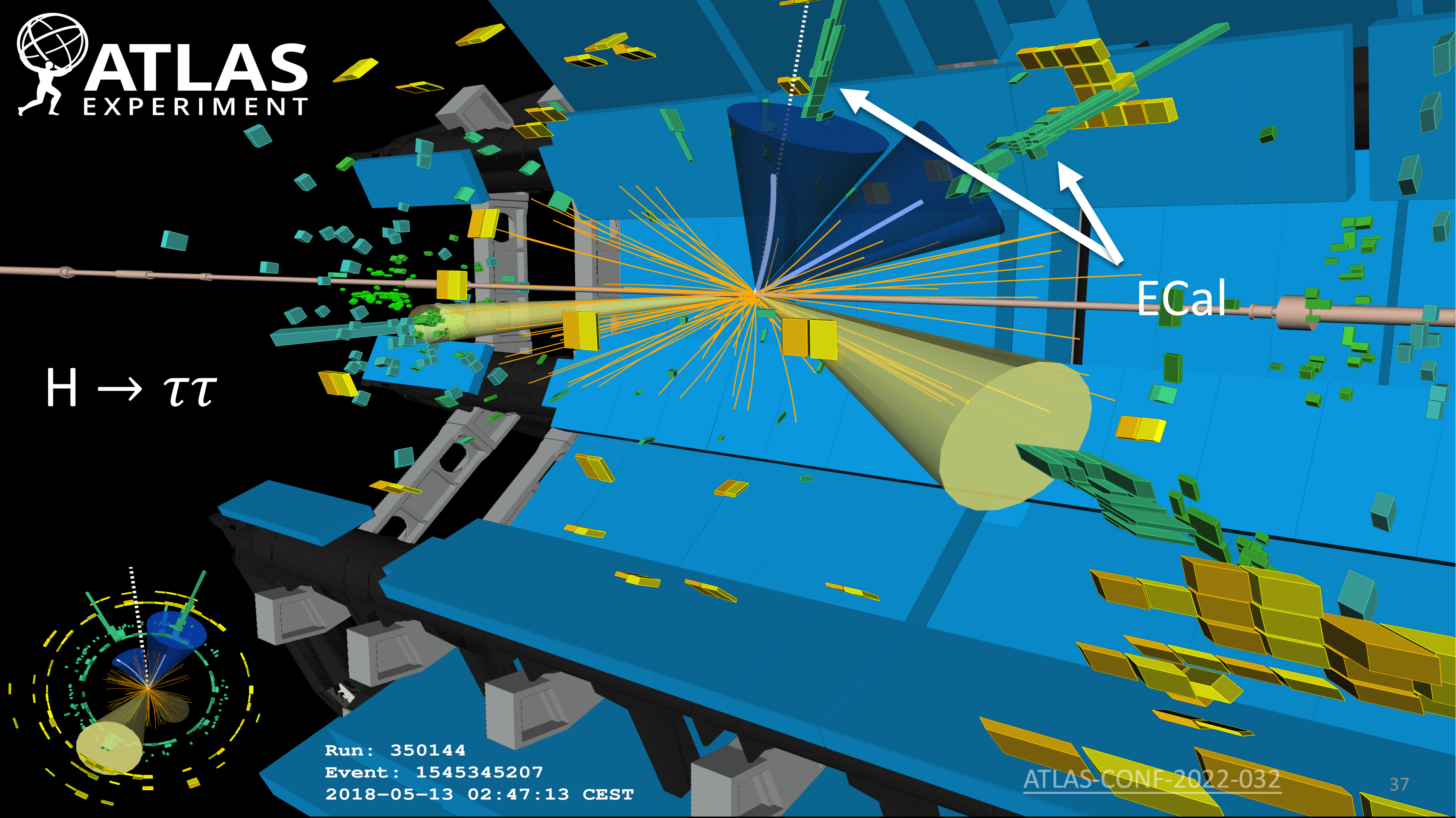

ATLAS
EXPERIMENT
$H \rightarrow \tau\tau$
Run: 350144
Event: 1545345207
2018-05-13 02:47:13 CEST
ATLAS-CONF-2022-032

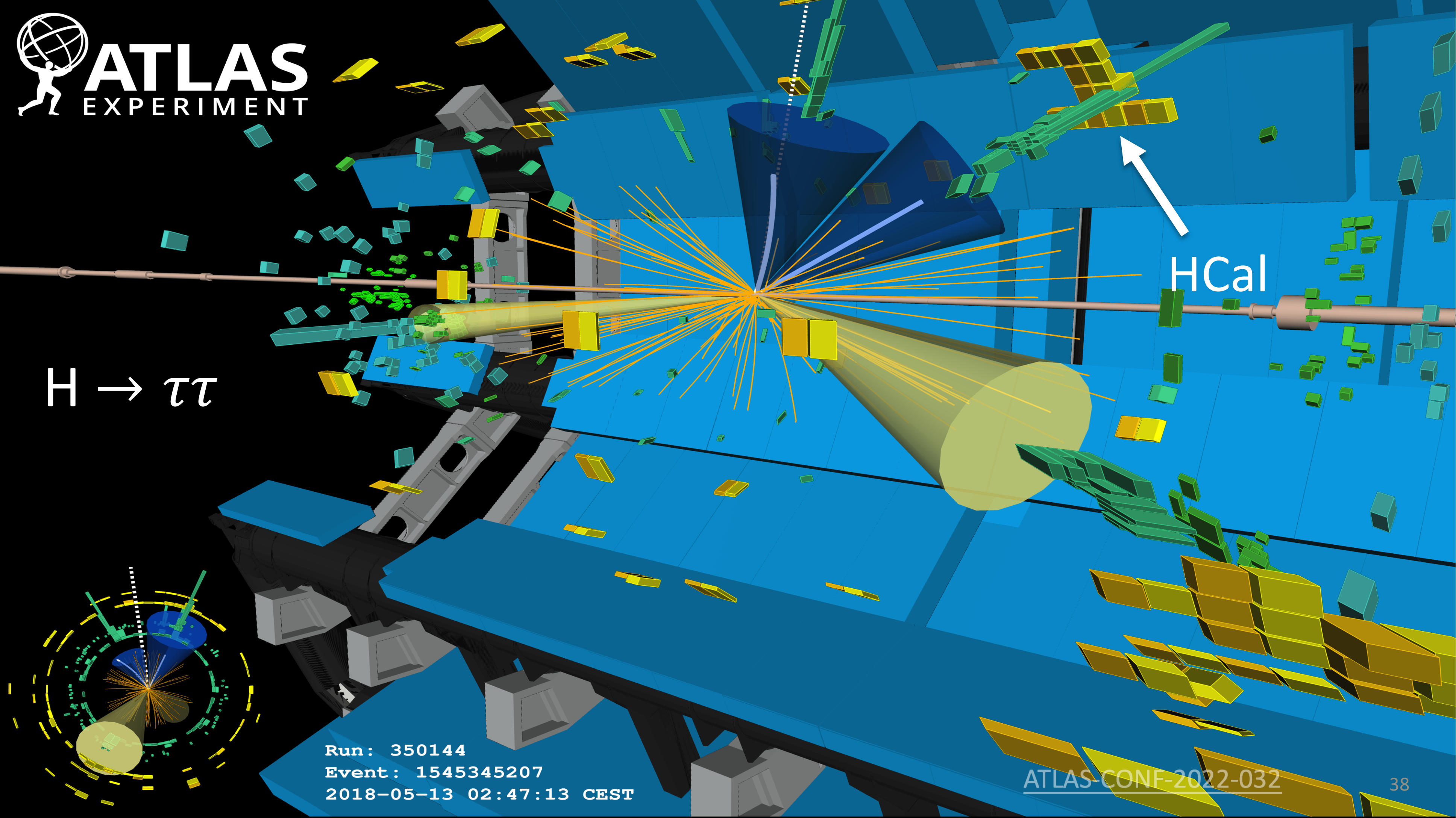


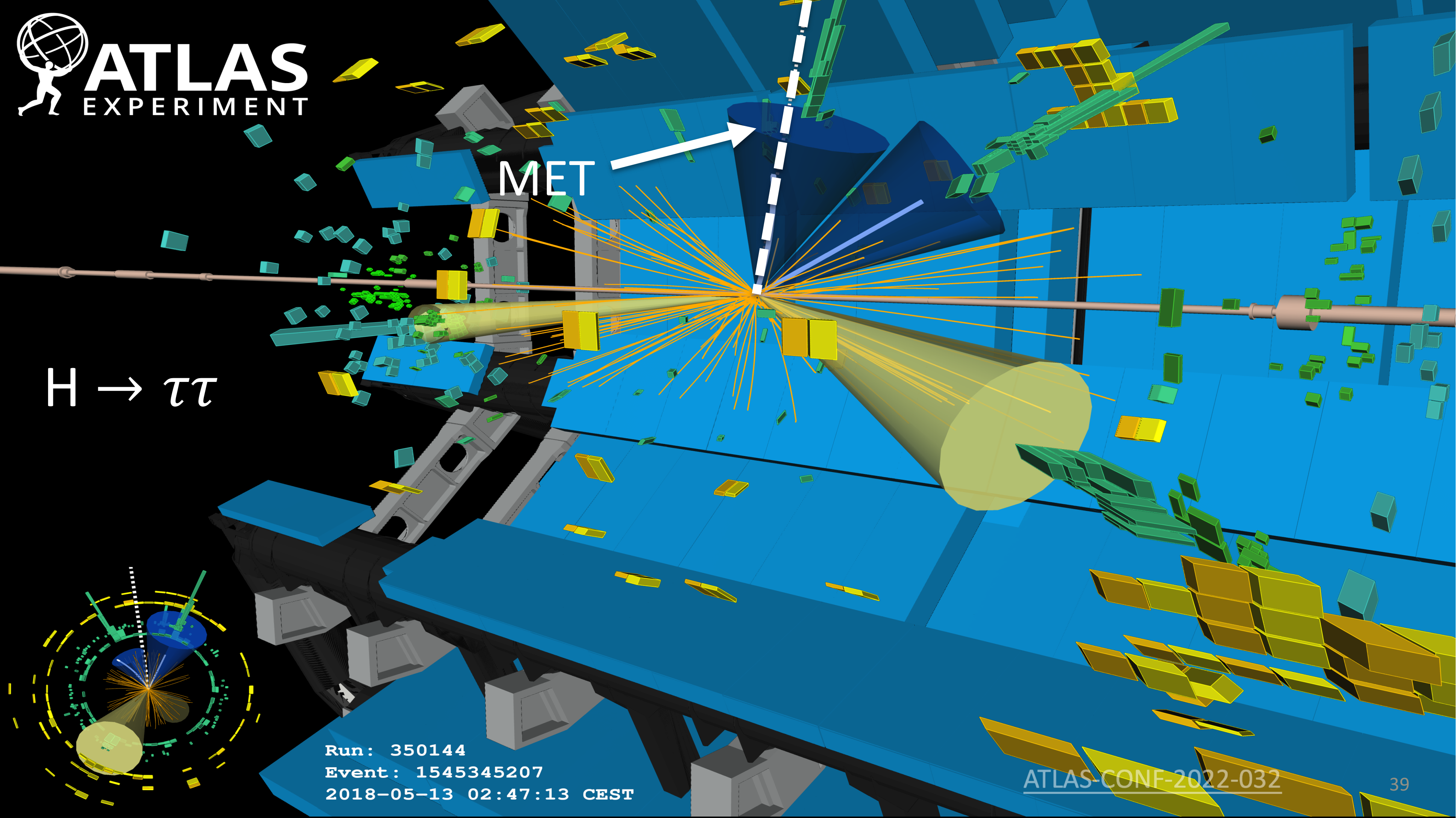
ATLAS
EXPERIMENT
τ
τ
H → ττ
Run: 350144
Event: 1545345207
2018-05-13 02:47:13 CEST
ATLAS-CONF-2022-032



ATLAS-CONF-2022-032


ATLAS
EXPERIMENT
ECal
H → ττ
Run: 350144
Event: 1545345207
2018-05-13 02:47:13 CEST
ATLAS-CONF-2022-032


ATLAS
EXPERIMENT
HCal
$H \to \tau\tau$
Run: 350144
Event: 1545345207
2018-05-13 02:47:13 CEST
ATLAS-CONF-2022-032


ATLAS
EXPERIMENT
MET
H → ττ
Run: 350144
Event: 1545345207
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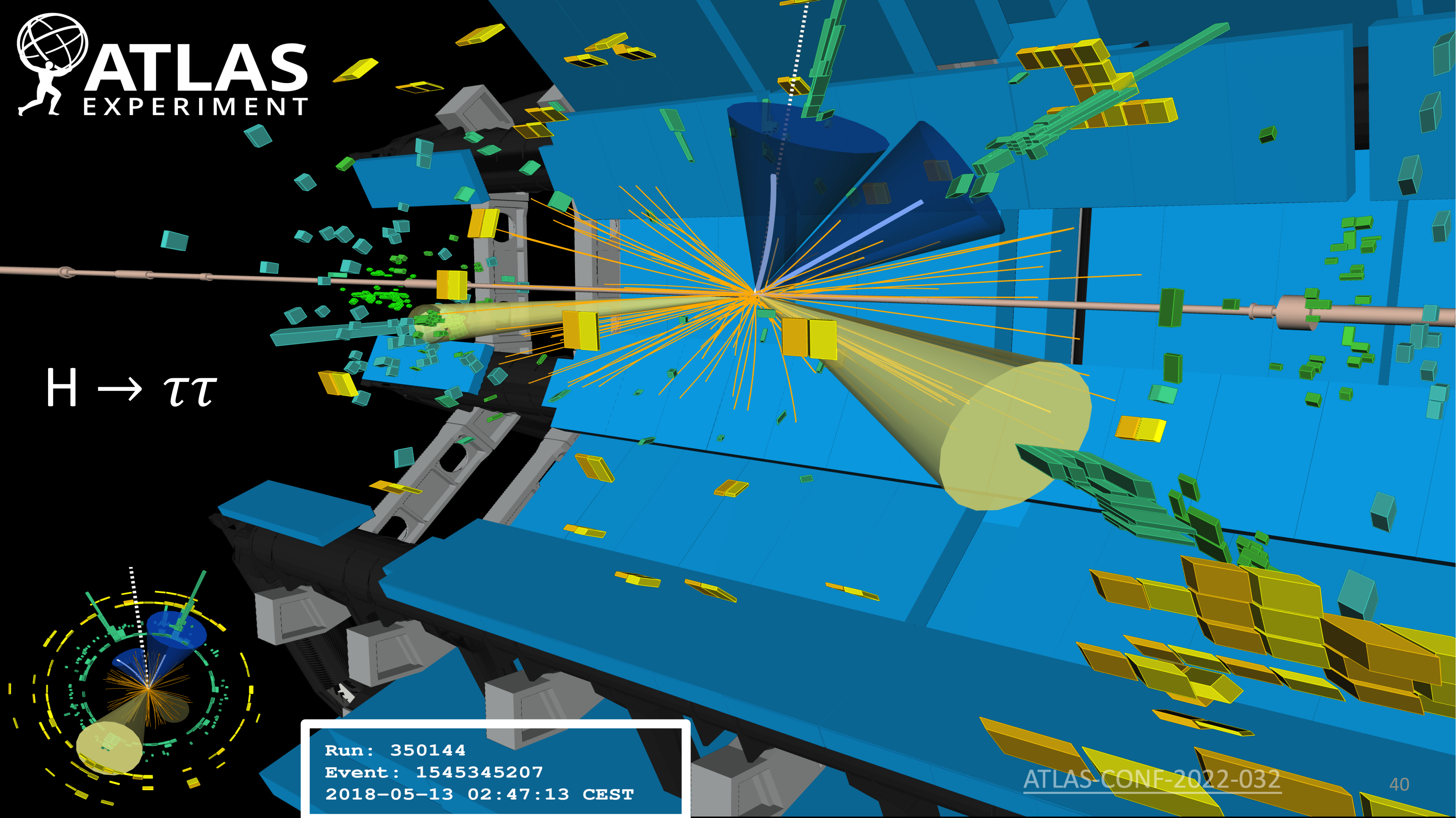
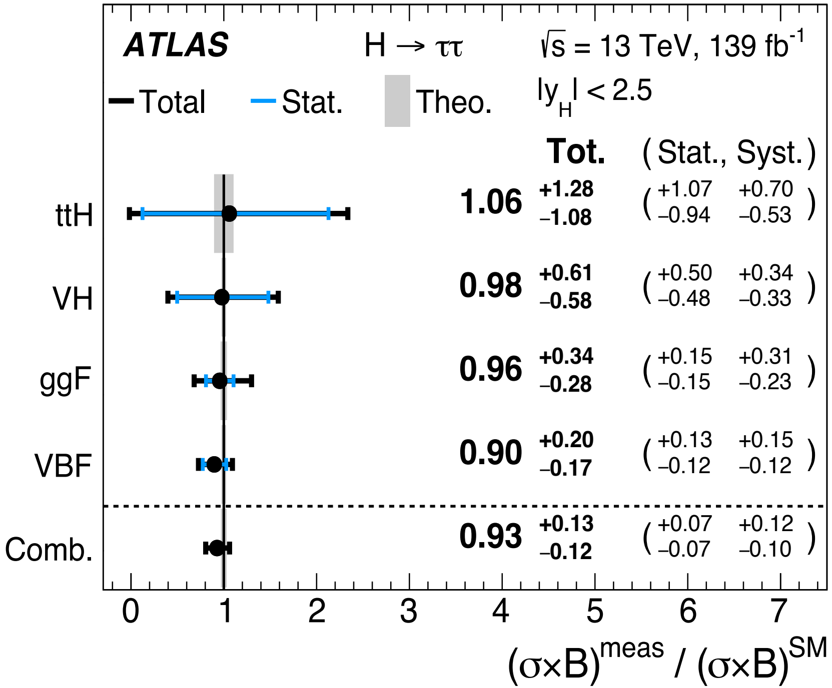
ATLAS-CONF-2022-032



ATLAS-CONF-2022-032

RECENT FINDINGS FROM THE ATLAS COLLABORATION

2022 Analysis: JHEP08(2022)175



RECENT FINDINGS FROM THE ATLAS COLLABORATION

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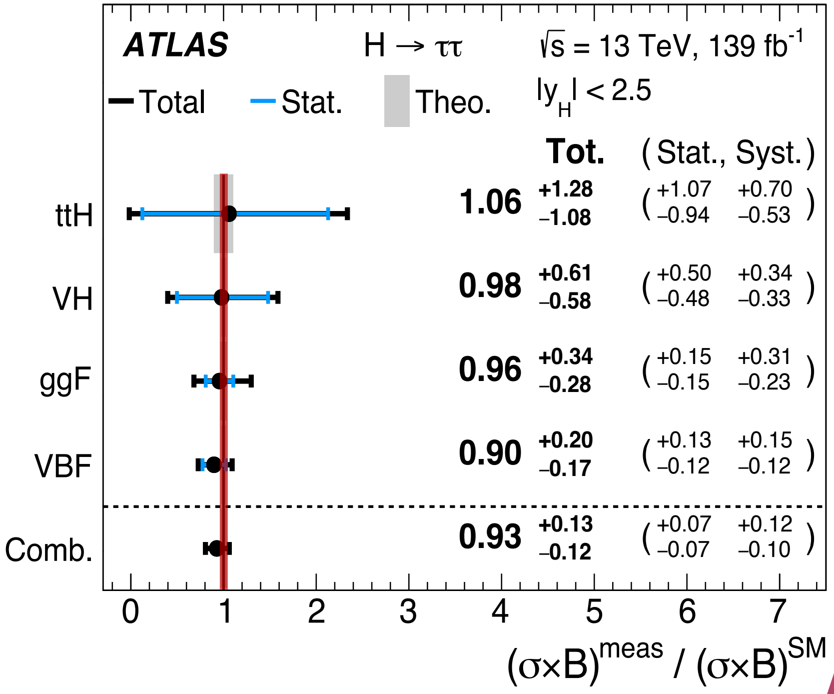

STANDARD MODEL REAFFIRMED

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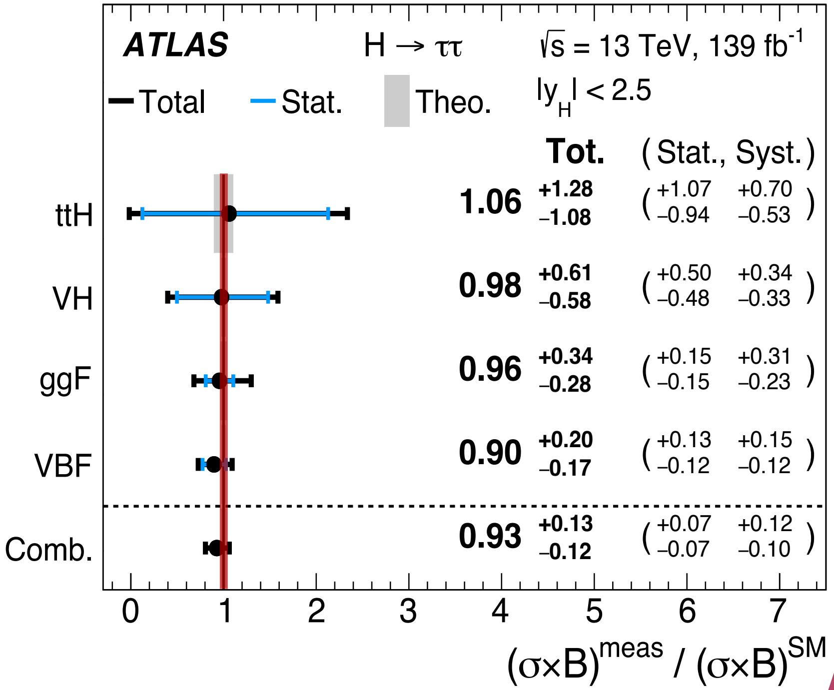

STANDARD MODEL REAFFIRMED

Two-Track Strategy

→ Investigate BSM-sensitive phase-space

→ Improve precision

- Background contamination
- Sources of uncertainty

RECENT FINDINGS FROM THE ATLAS COLLABORATION

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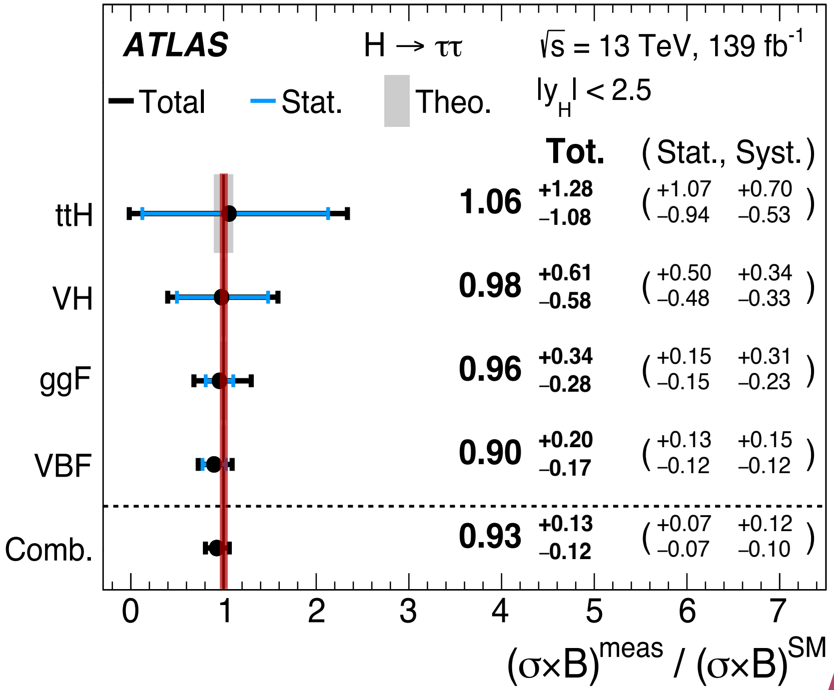

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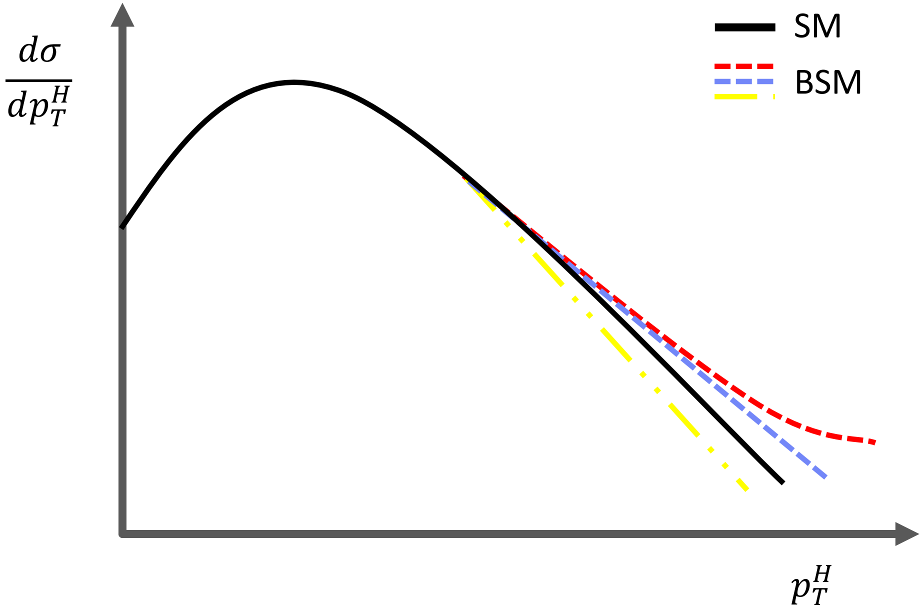

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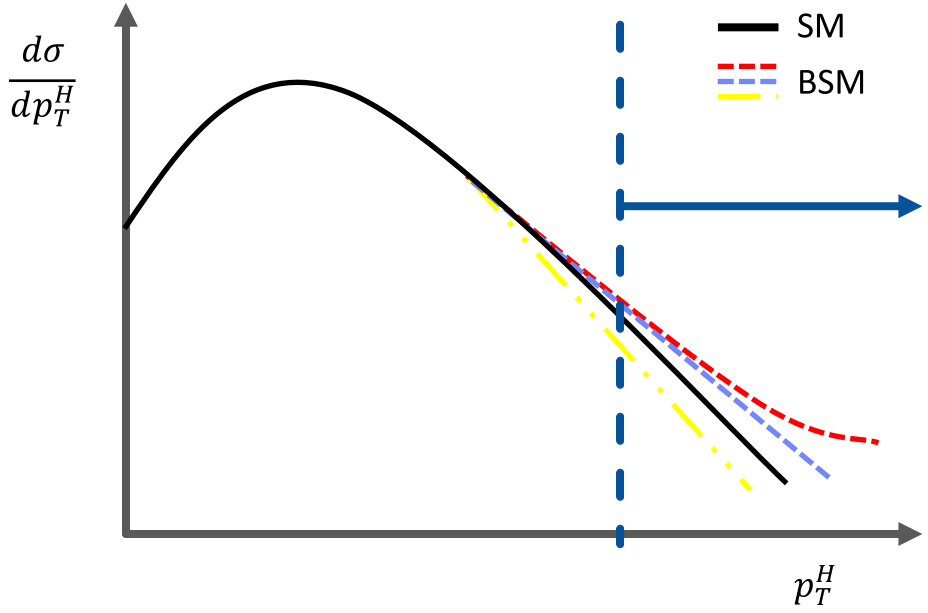

STANDARD MODEL REAFFIRMED

Two-Track Strategy

→ **Investigate BSM-sensitive phase-space**

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STXS: SIMPLIFIED TEMPLATE CROSS-SECTION

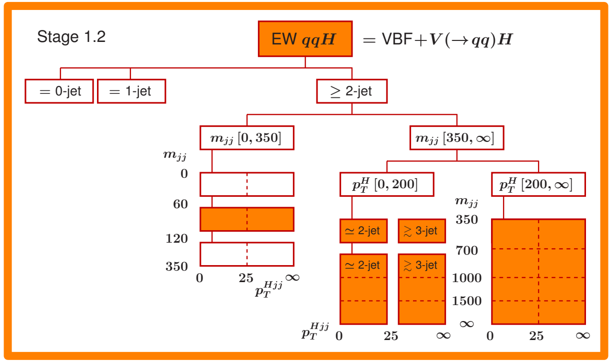
Phase-space regions split by true production modes/kinematics

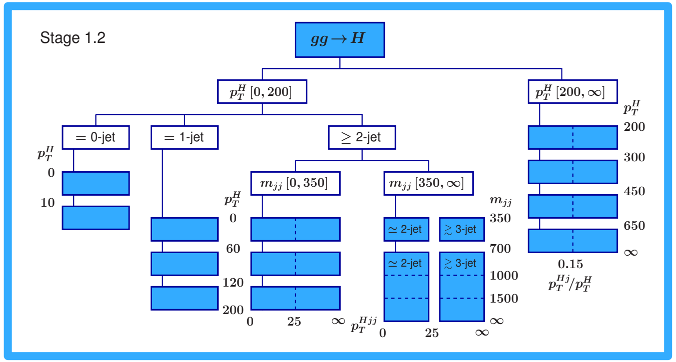
→ reduction of theoretical uncertainties

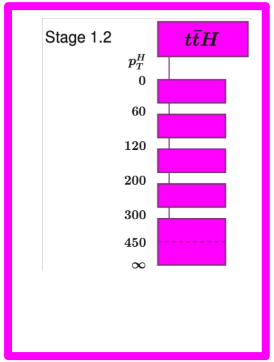
→ emphasize prospective regions for BSM (high p_T^H /m_{jj})

→ facilitate combination of regions

LHCHWGFiducialAndSTXS



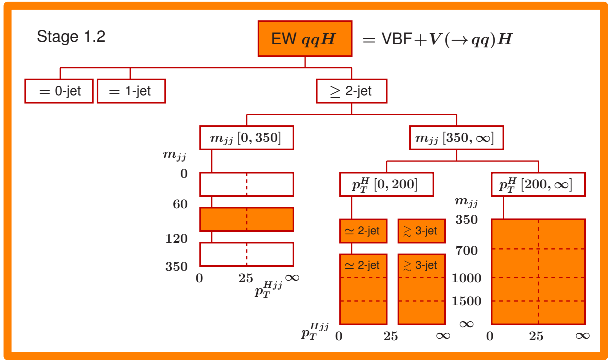


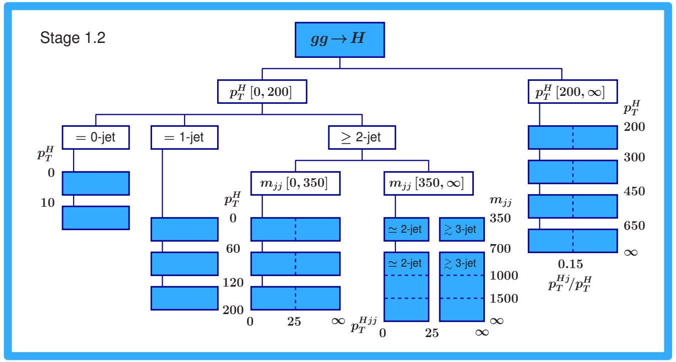


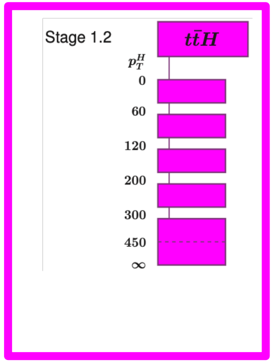
STXS:

- 8 bins in VBF
- 1 bin in VH
- 3 bins in tt̄H
- 6 bins in ggH

LHCHWGFiducialAndSTXS







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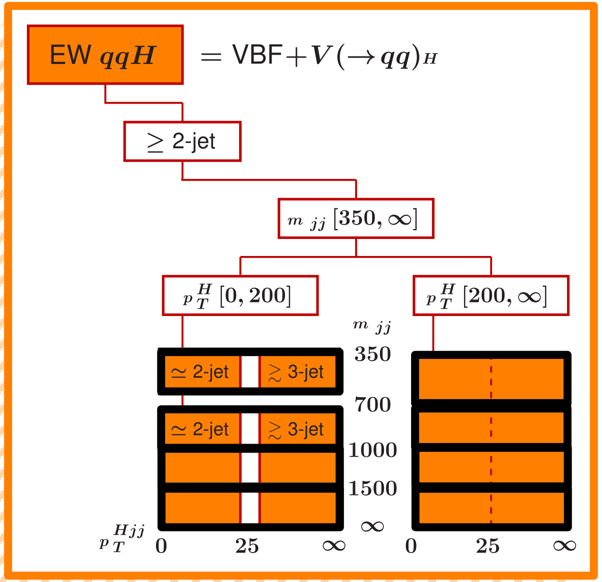
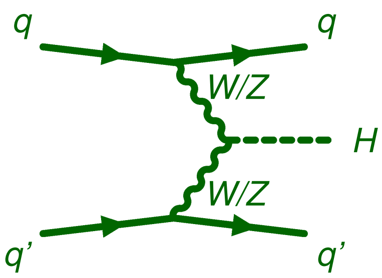
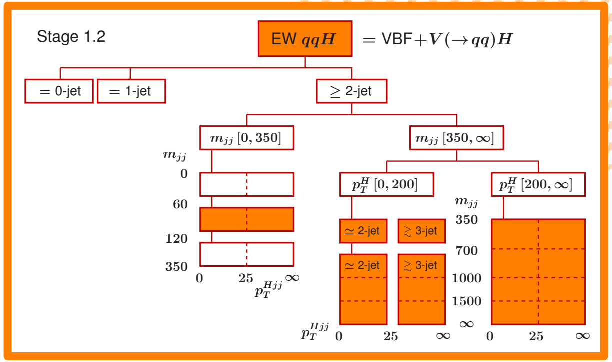
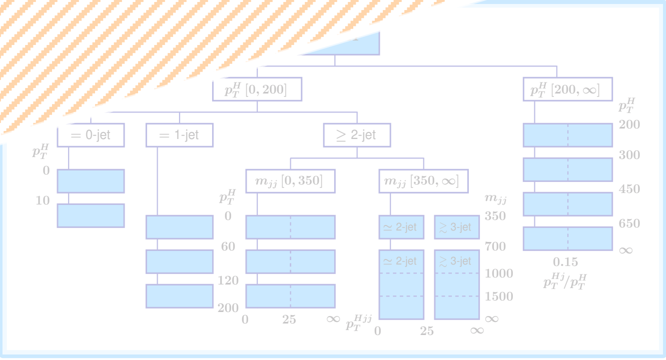
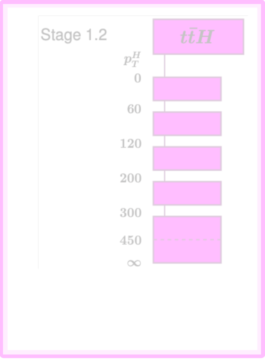




LHCHWGFiducialAndSTXS







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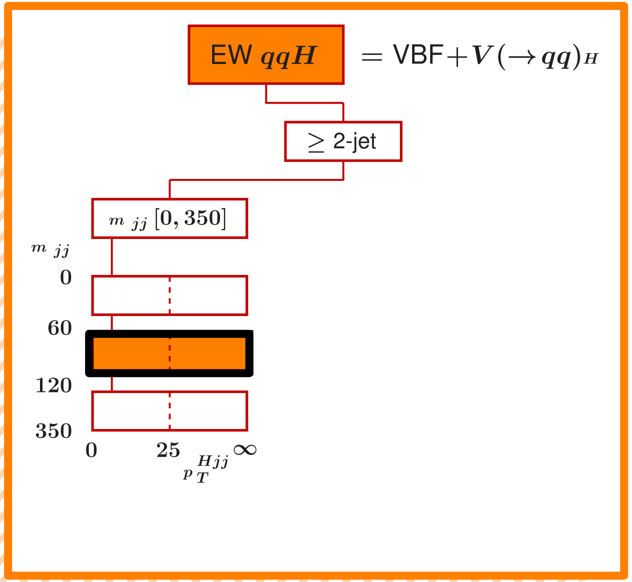
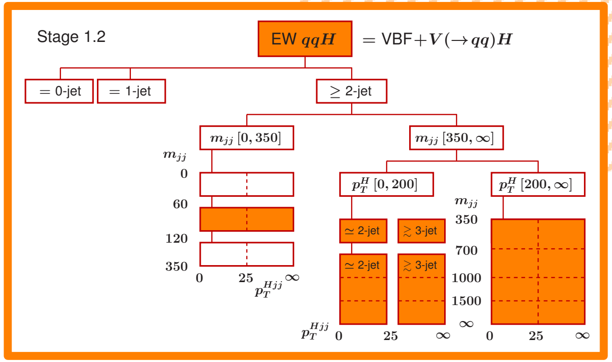
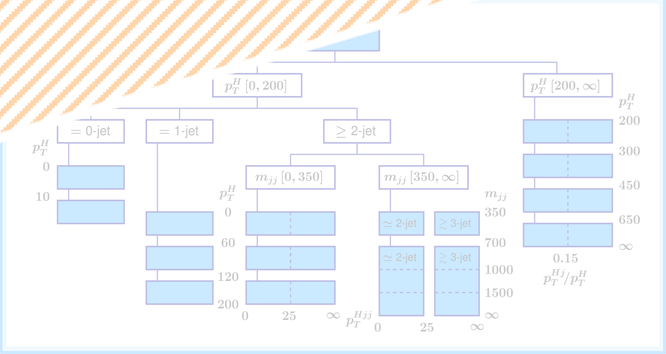
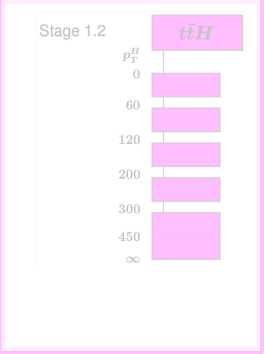


LHCHWGFiducialAndSTXS







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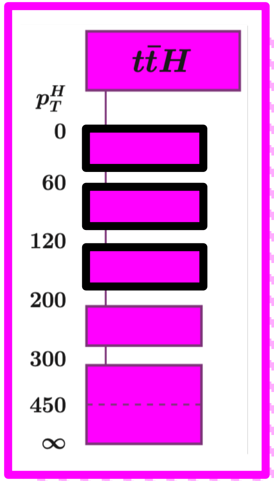

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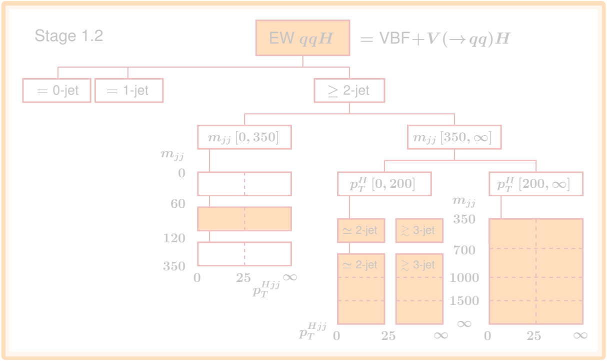

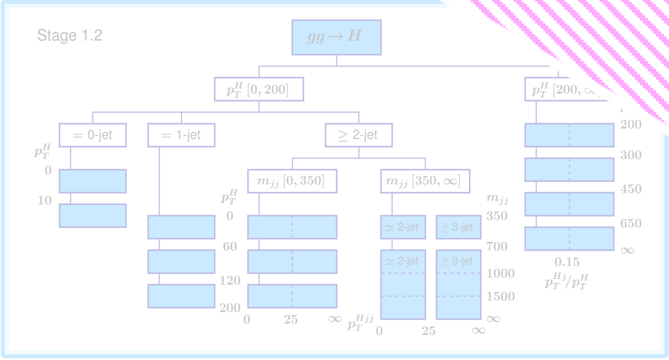

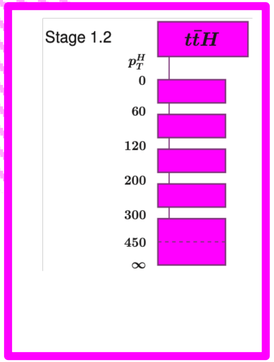

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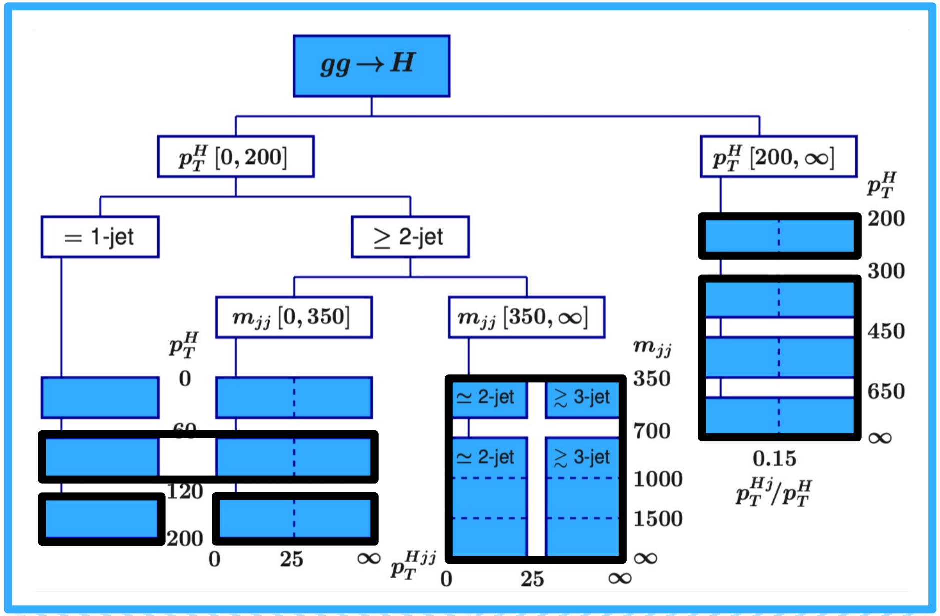

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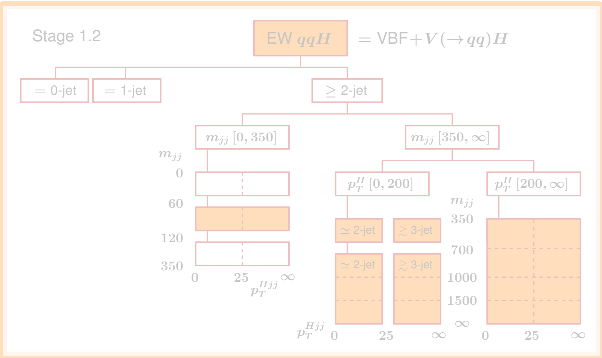
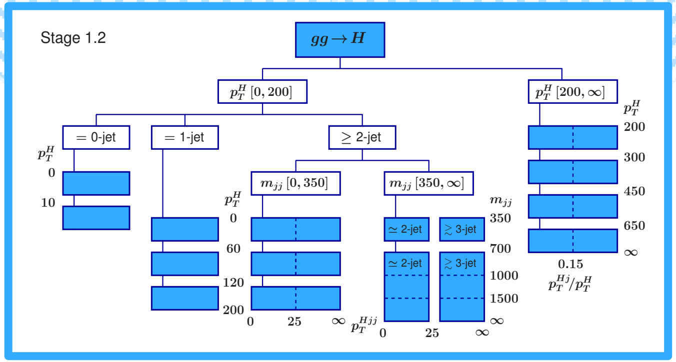
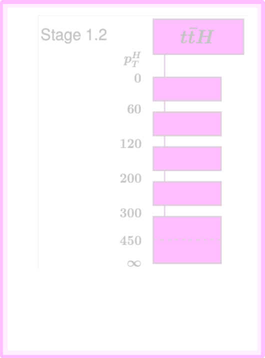
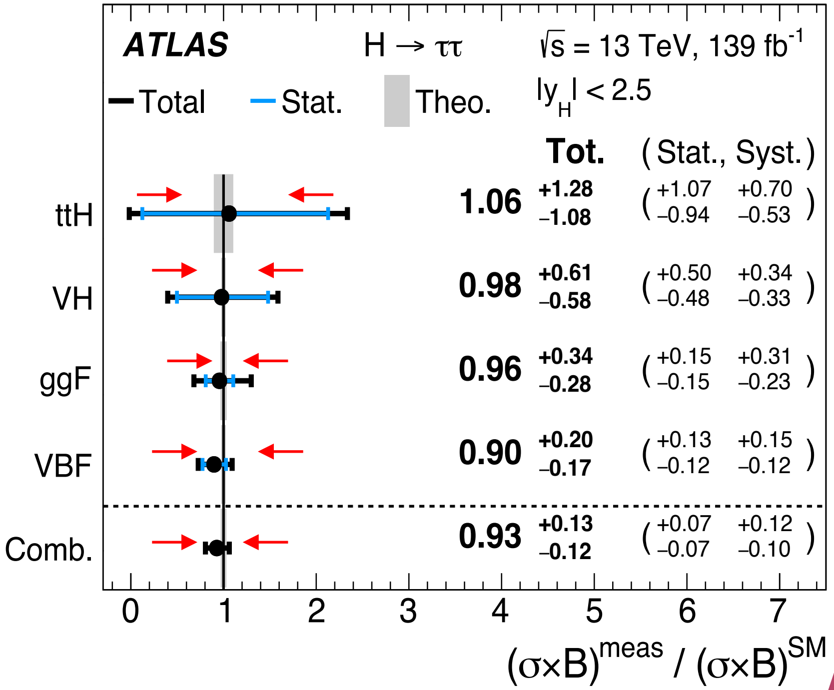






RECENT FINDINGS FROM THE ATLAS COLLABORATION

2022 Analysis: JHEP08(2022)175



STANDARD MODEL REAFFIRMED

Two-Track Strategy

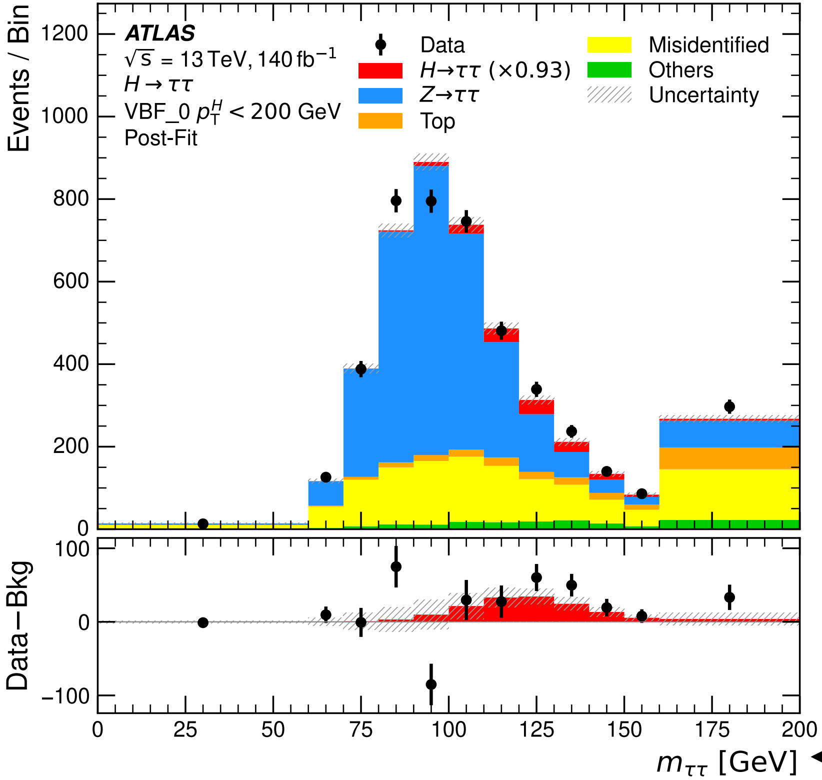
→ Investigate BSM-sensitive phase-space

→ **Improve precision**

- Background contamination
- Sources of uncertainty

PROCESSES

2024 Analysis: arxiv 2407.16320

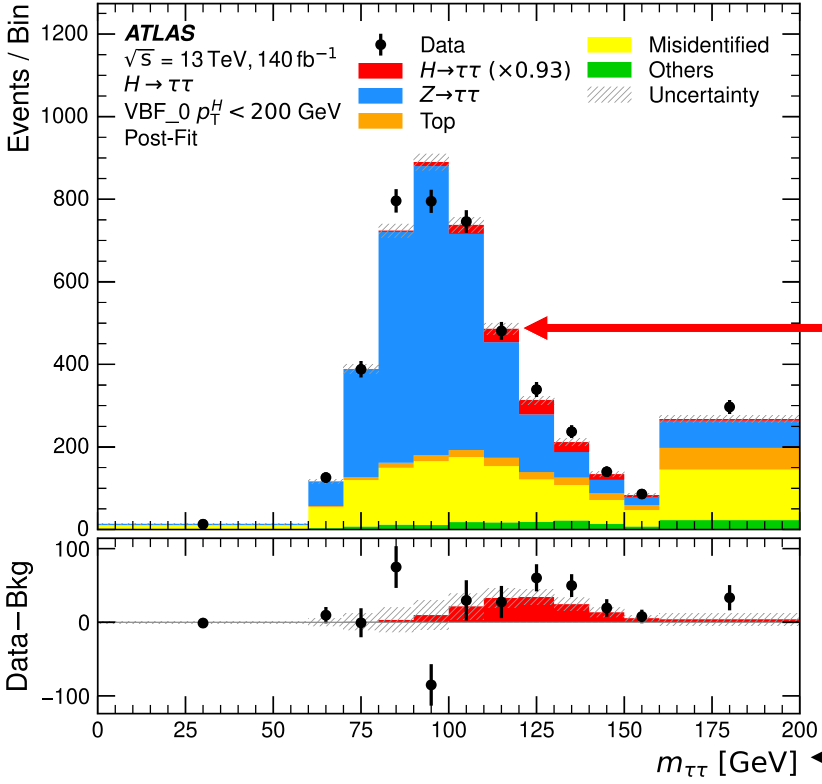


Invariant Di-tau Mass

$$m_{\tau\tau} = (P_{\tau_1} + P_{\tau_2})^2$$

PROCESSES

2024 Analysis: arxiv 2407.16320



$H \rightarrow \tau\tau$ Signal

Invariant Di-tau Mass

$$m_{\tau\tau} = (P_{\tau_1} + P_{\tau_2})^2$$

PROCESSES

$Z \rightarrow \tau\tau$

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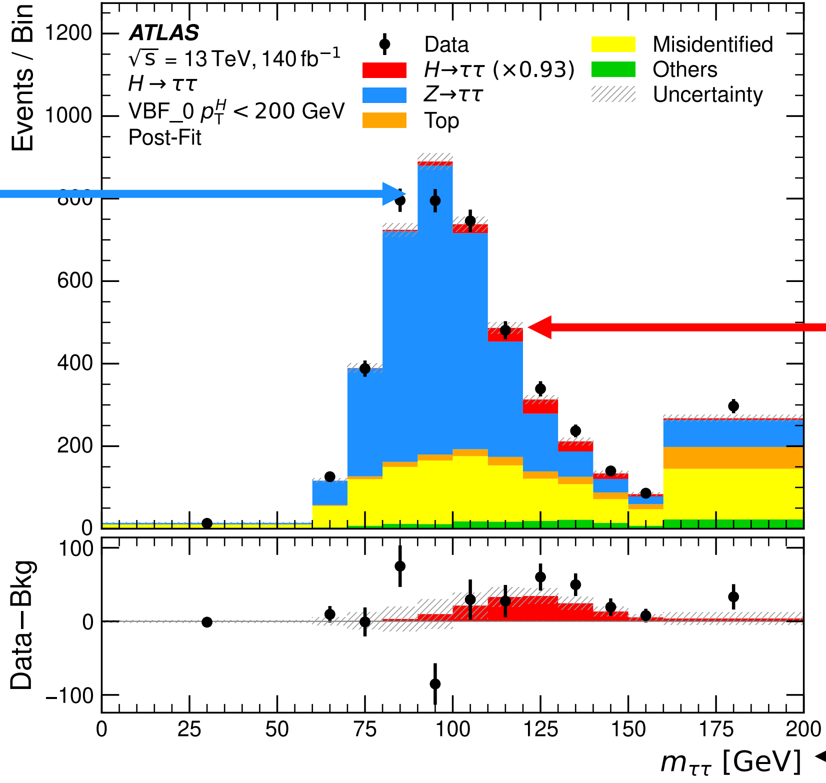

$H \rightarrow \tau\tau$ Signal

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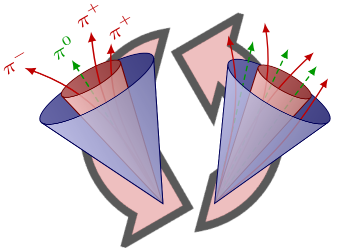
PROCESSES

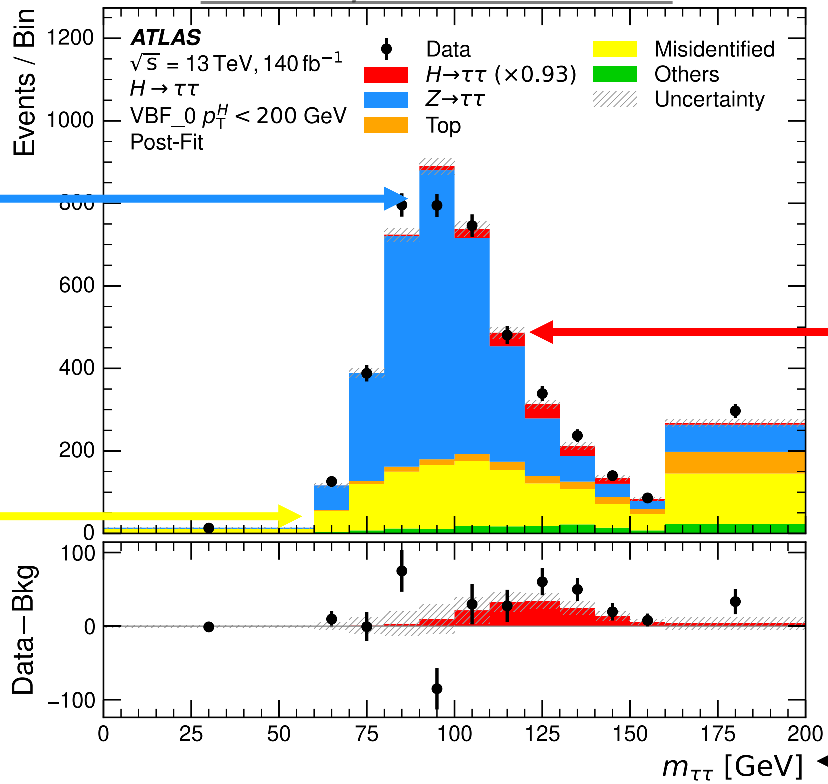
$Z \rightarrow \tau\tau$

Misidentified τ-leptons (fakes)



adapted from tikz

2024 Analysis: arxiv 2407.16320



$H \rightarrow \tau\tau$ **Signal**

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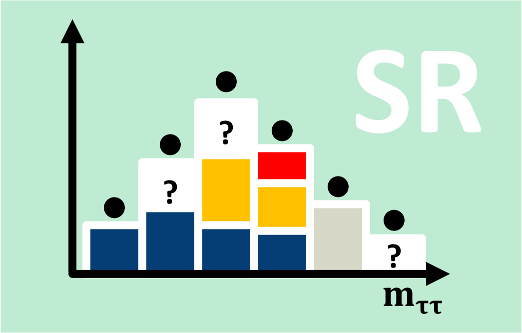
FAKE FACTOR METHOD



What is the contribution of fakes?

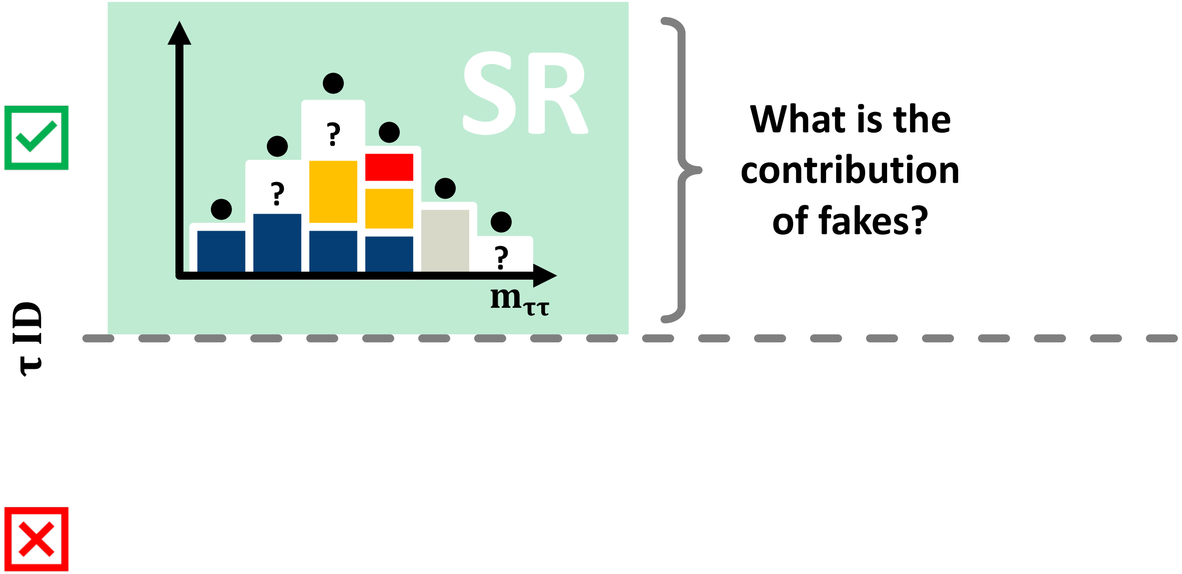
Fake Background …

… is suppressed in genuine τ selection

… depends on kinematic variables

… estimation in SR biases measurement

FAKE FACTOR METHOD



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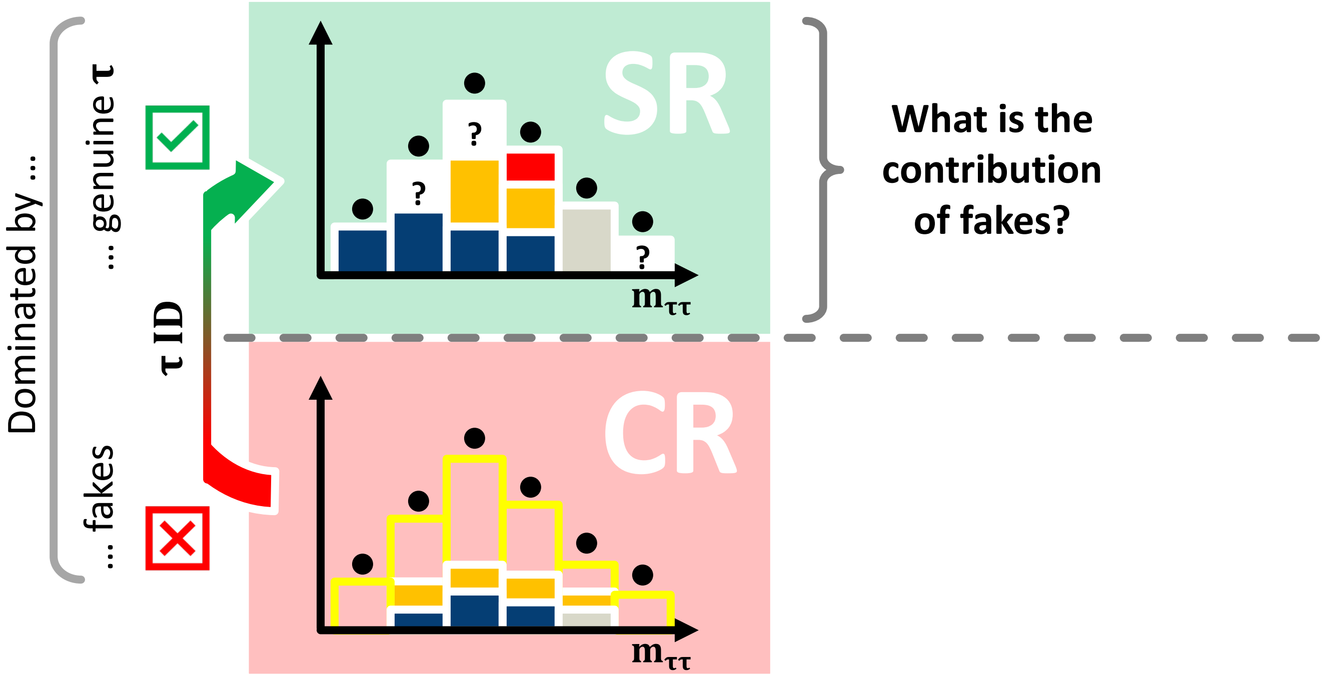
FAKE FACTOR METHOD



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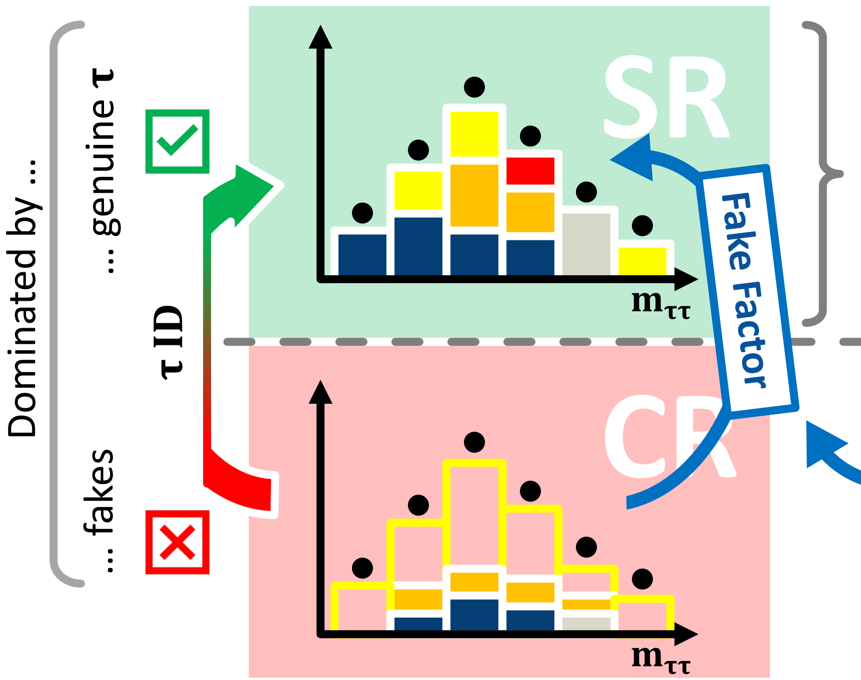
FAKE FACTOR METHOD

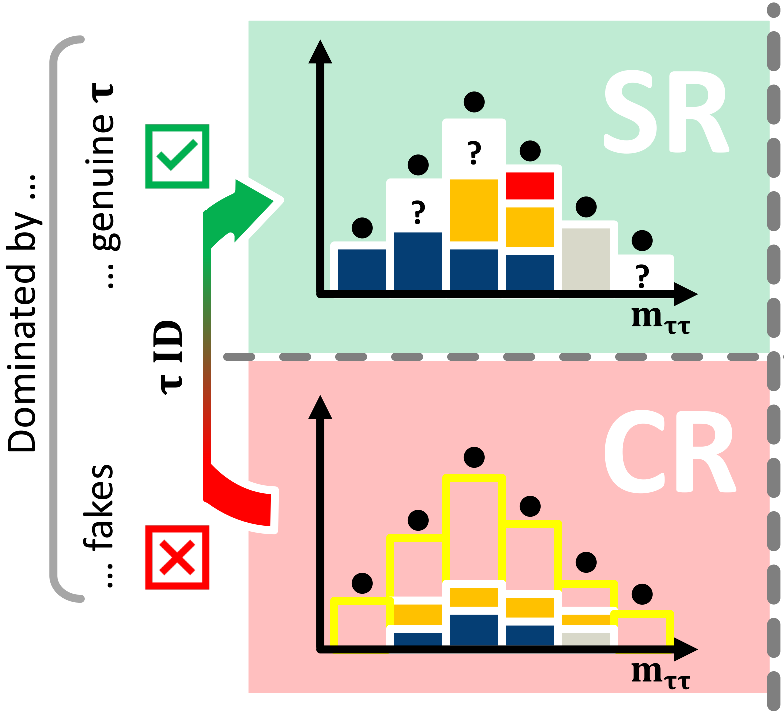


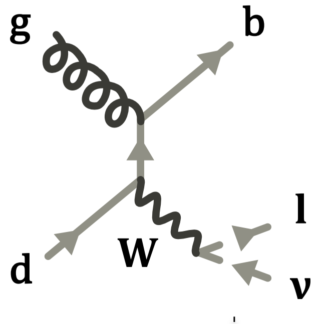
What is the contribution of fakes?

Fake Factor · fakes failing $\boldsymbol{\tau}$ **ID** = fakes fulfilling $\boldsymbol{\tau}$ **ID**

FAKE FACTOR METHOD

Fake Factor = $\frac{\text{fakes fulfilling } \tau \text{ ID}}{\text{fakes failing } \tau \text{ ID}}$

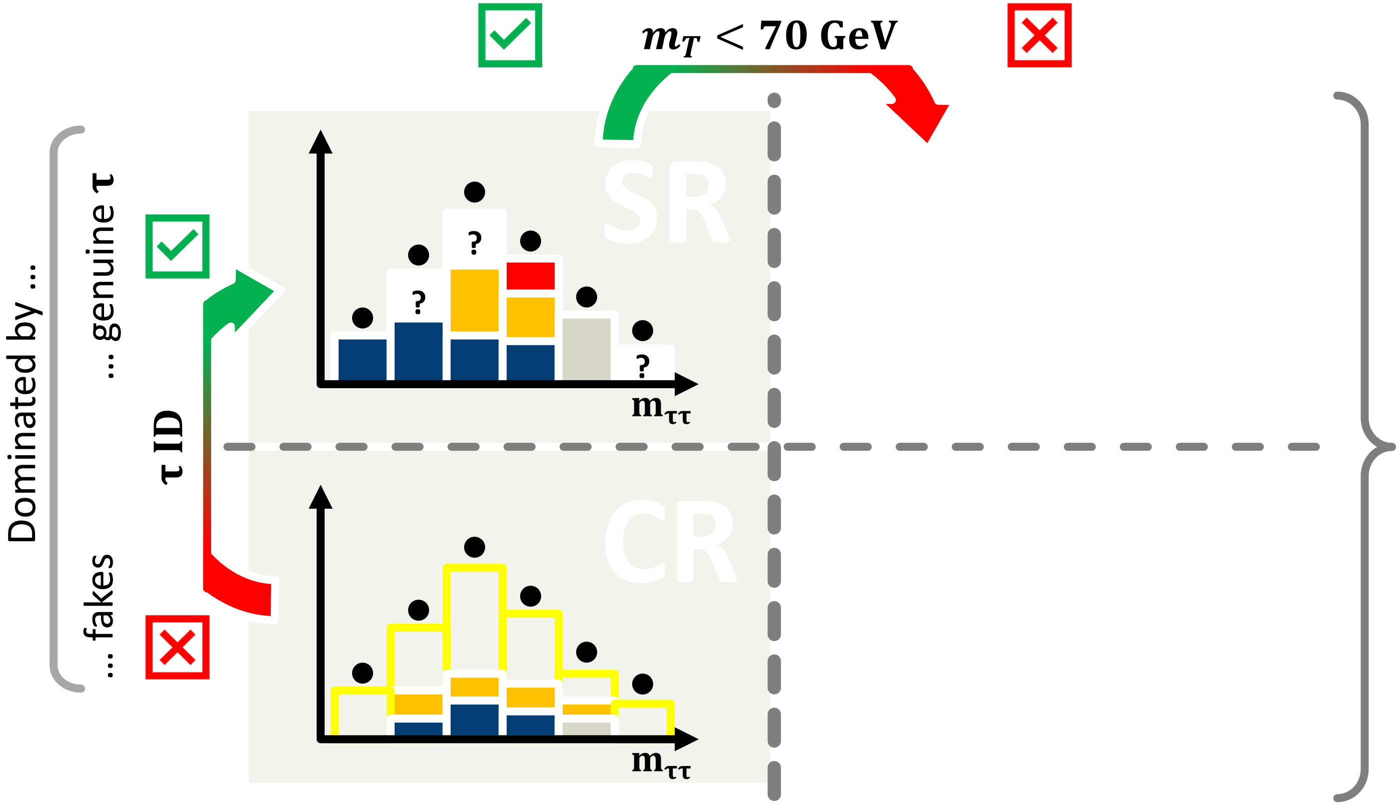


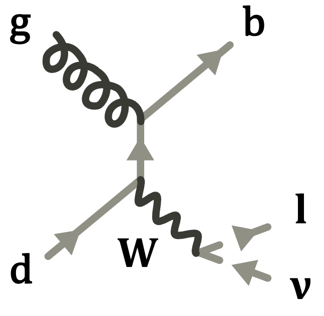


Determine Fake Factor
in fake-enriched region

FAKE FACTOR METHOD

Fake Factor $= \dfrac{\text{fakes fulfilling } \tau\,\mathbf{ID}}{\text{fakes failing } \tau\,\mathbf{ID}}$





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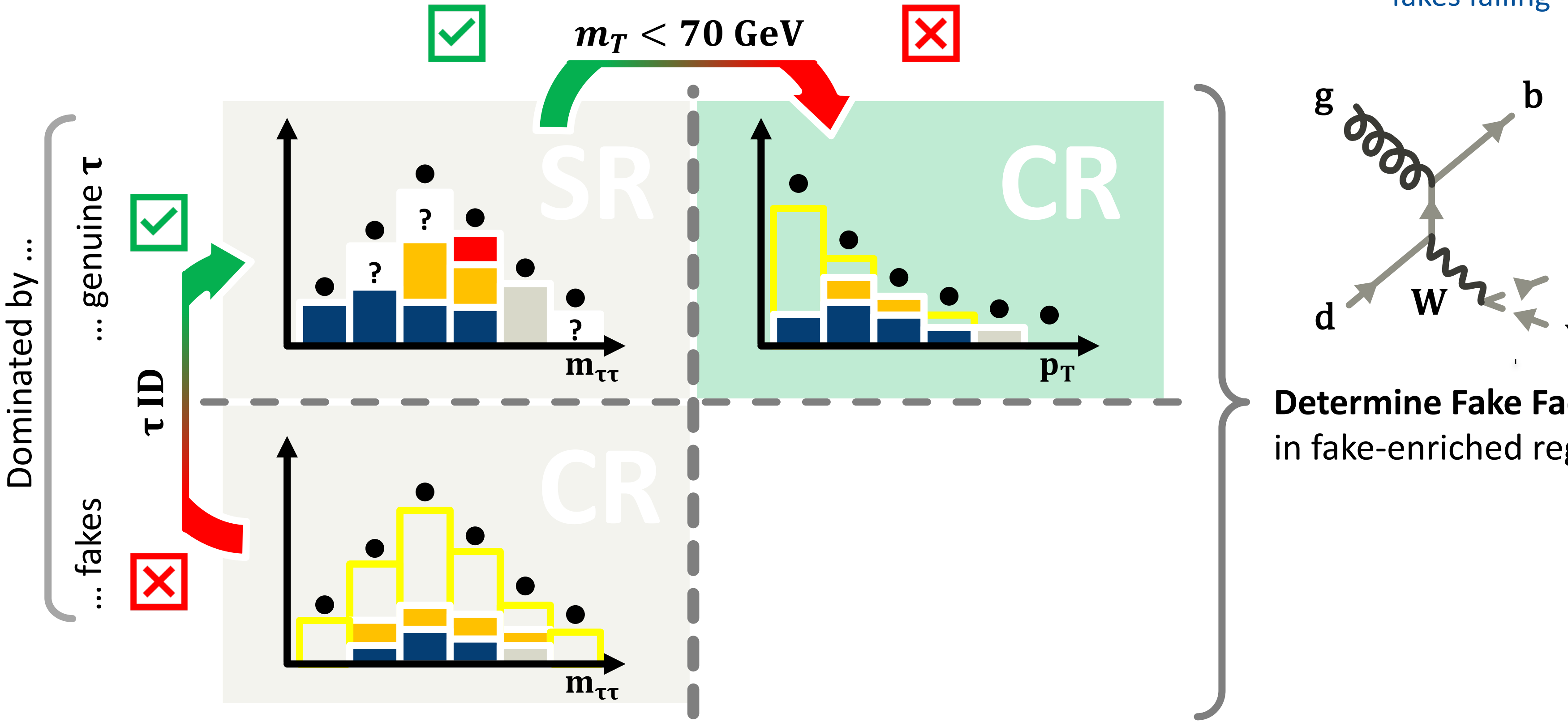

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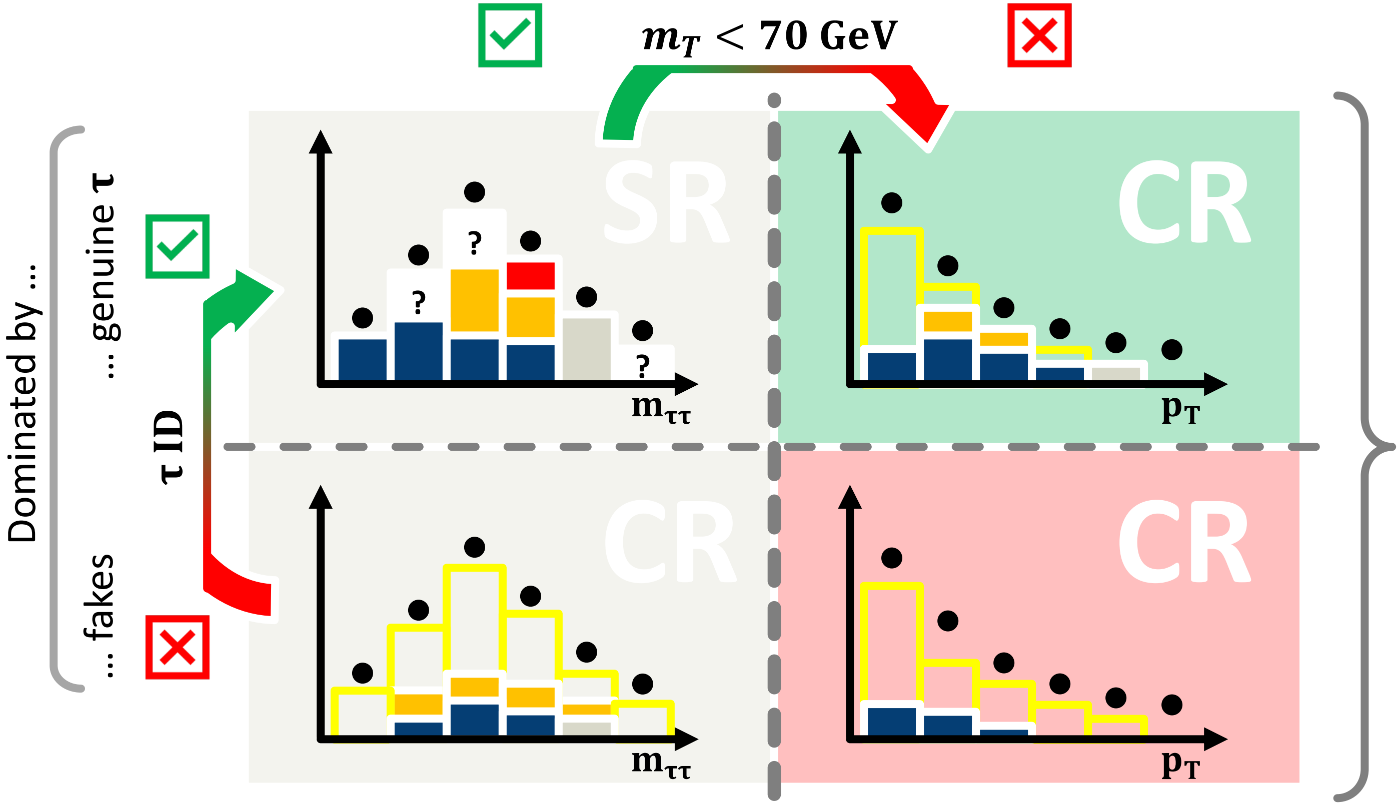

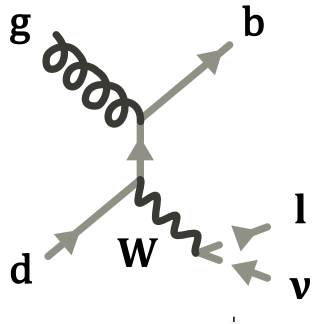

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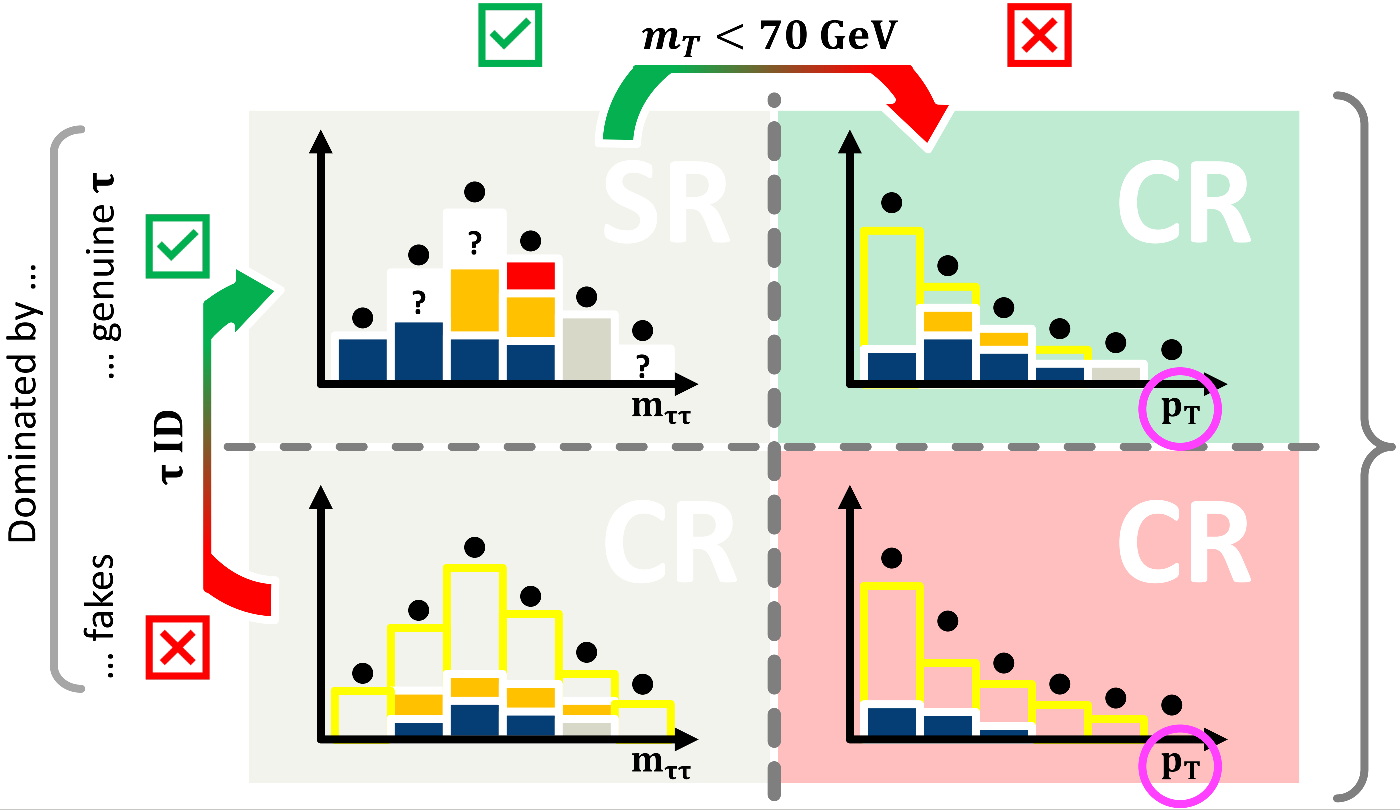
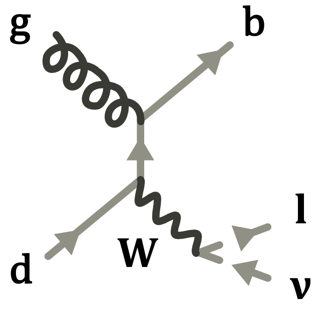
FAKE FACTOR METHOD

Fake Factor = $\frac{\text{fakes fulfilling } \tau \text{ ID}}{\text{fakes failing } \tau \text{ ID}}$





Determine Fake Factor in fake-enriched region

→ Capture fake rate dependencies

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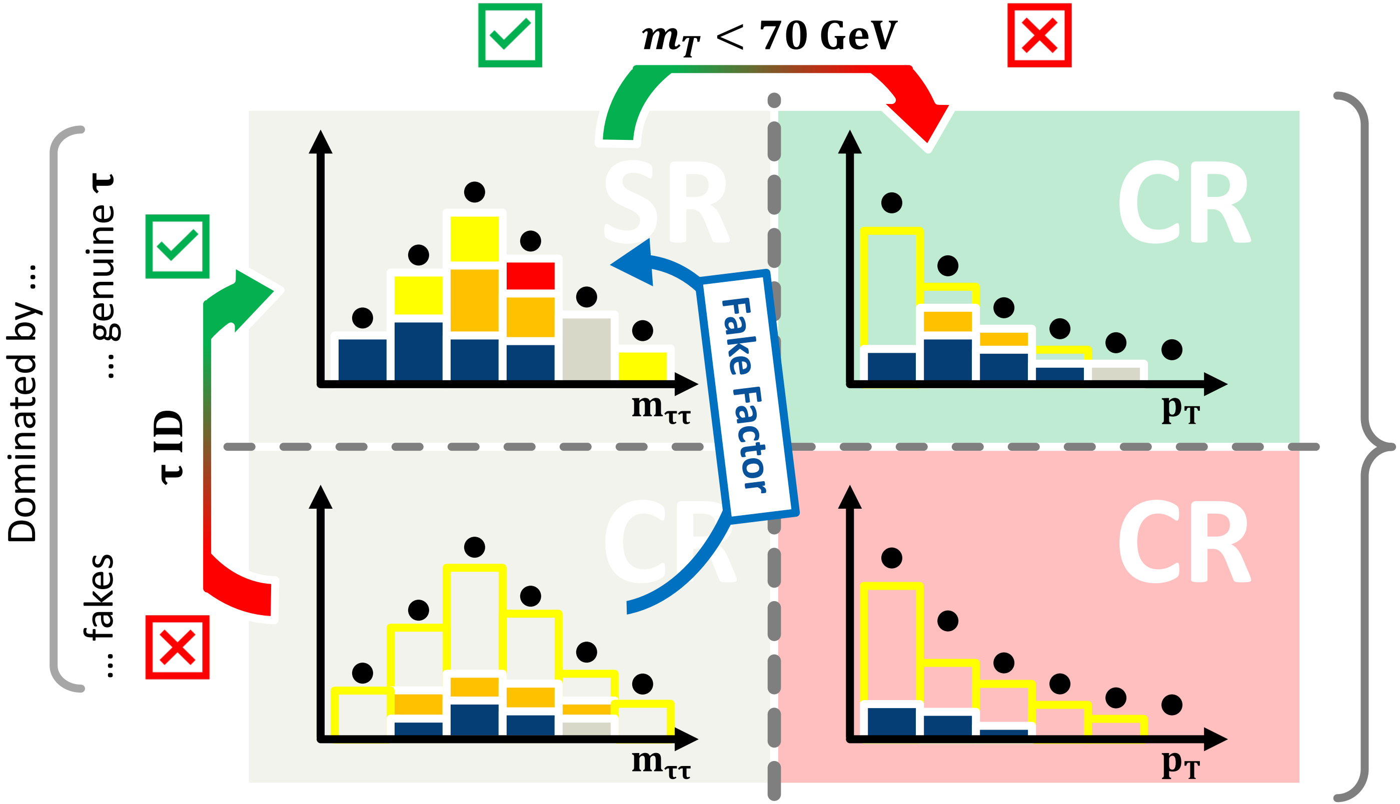
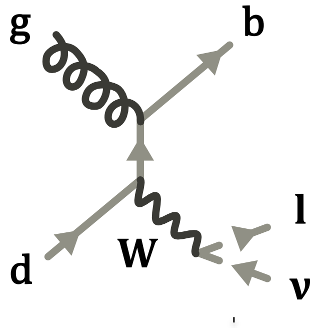
Fake Factor = $\frac{\text{fakes fulfilling } \tau \text{ ID}}{\text{fakes failing } \tau \text{ ID}}$





Determine Fake Factor in fake-enriched region

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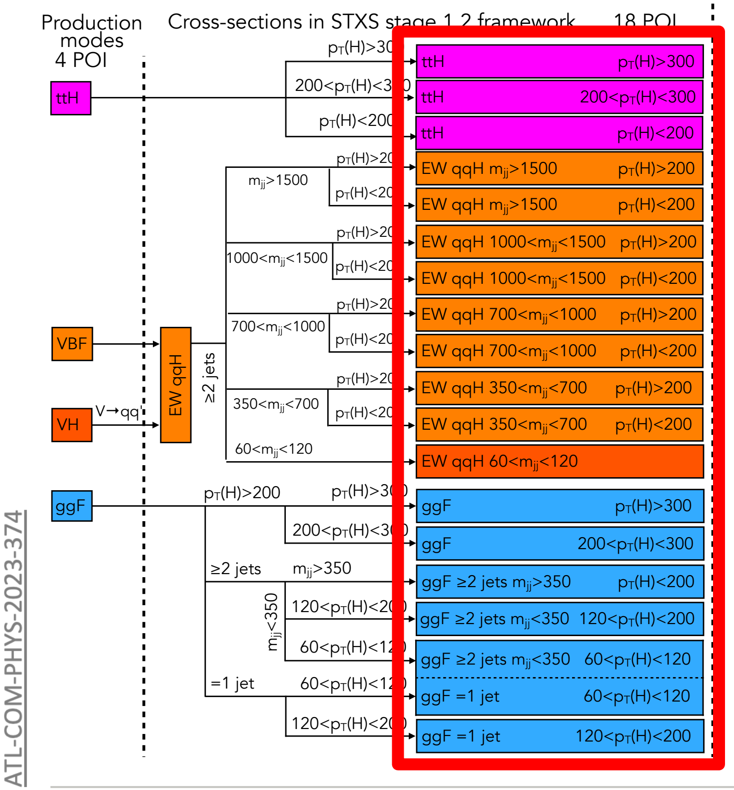
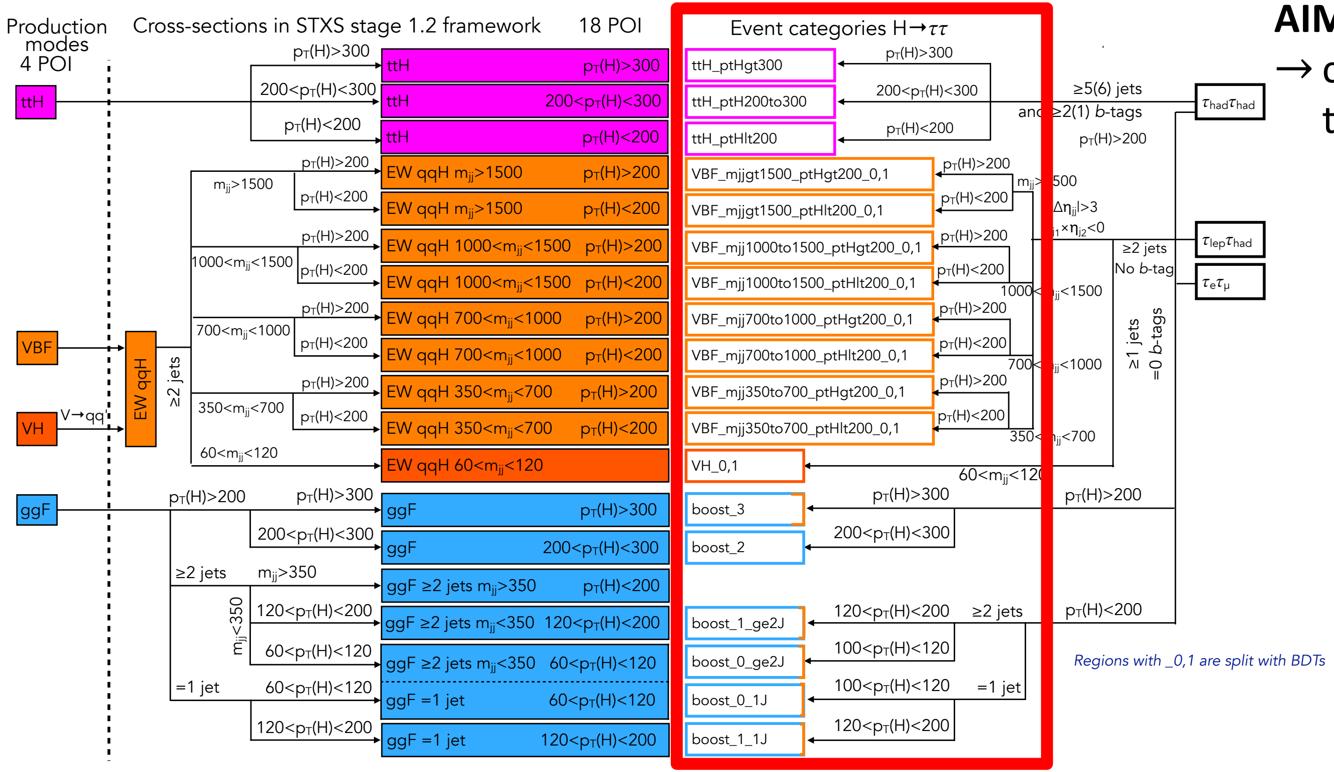
FAKE TEMPLATE BUILDING



AIM: 18 parameters of interest

FAKE TEMPLATE BUILDING

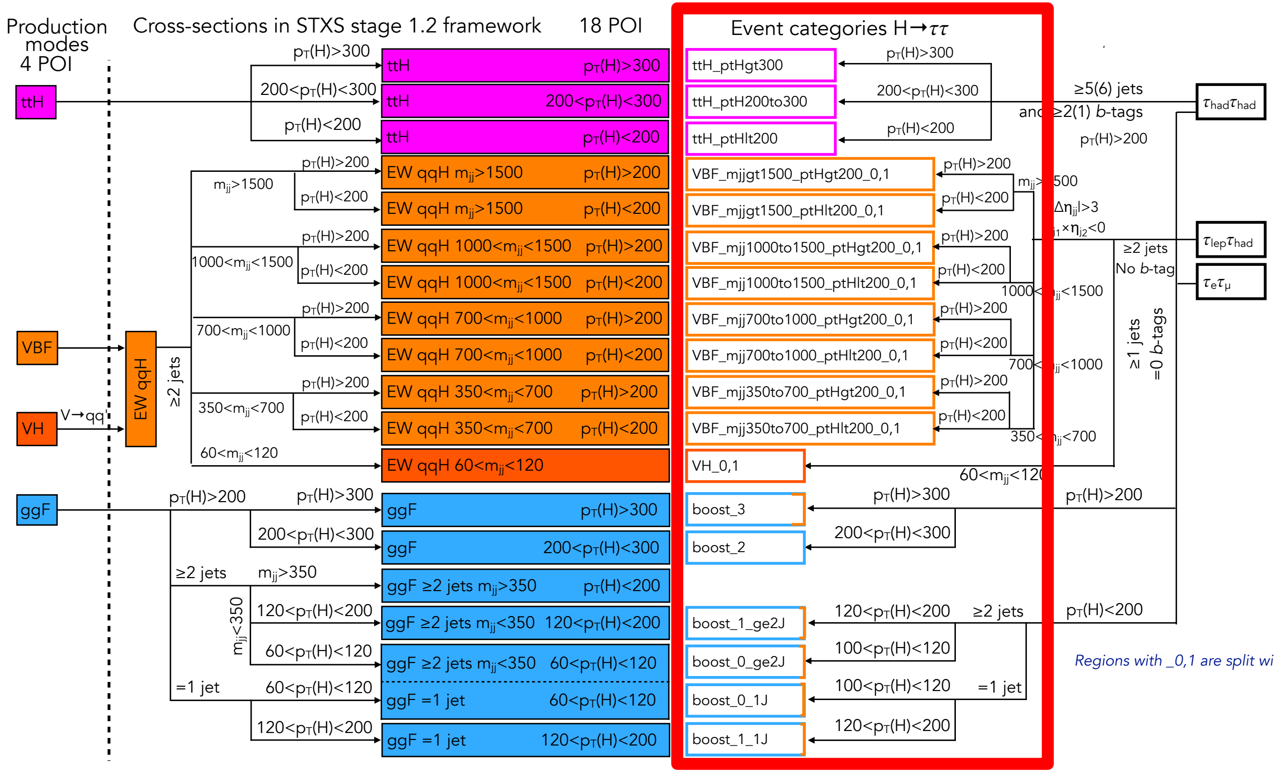


ATL-COM-PHYS-2023-374

AIM: 18 parameters of interest

→ categorize events to match the phase-space

FAKE TEMPLATE BUILDING



Regions with _0,1 are split with BDTs

AIM: 18 parameters of interest

→ categorize events to match the phase-space

→ Total of **78 signal regions**

(3 · 6 ggH, 3 · 16 VBF, 3 · 2VH, 3 · 2 ttH)

Detailed phase-space split

→ low statistics

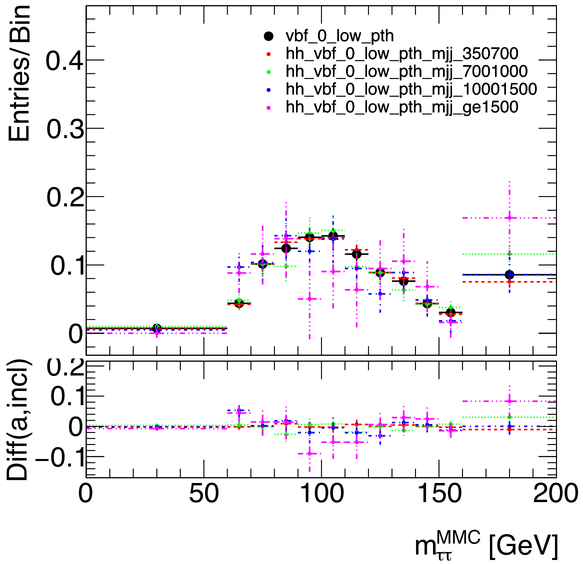
→ large statistical uncertainties

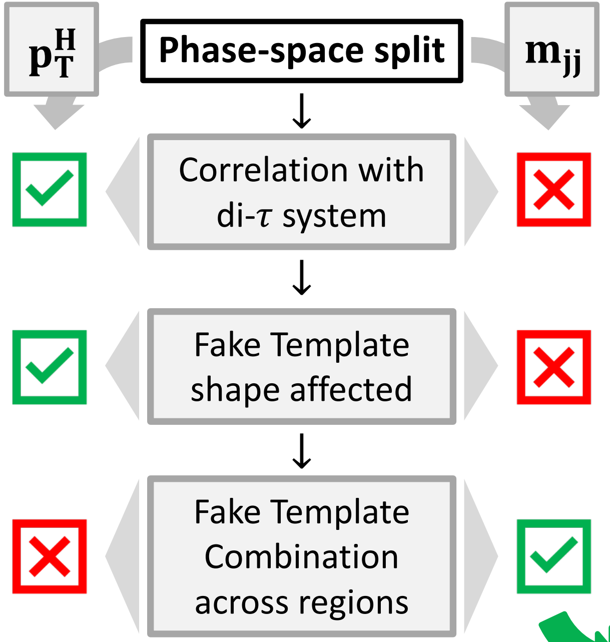
ATL-COM-PHYS-2023-374

FAKE TEMPLATE COMBINATION

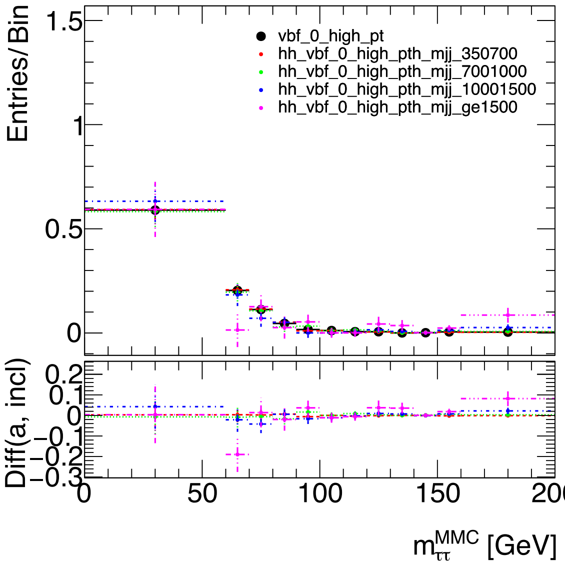
→ Individual fake templates affected by large statistical uncertainties

Fake Templates **High p_T^H**





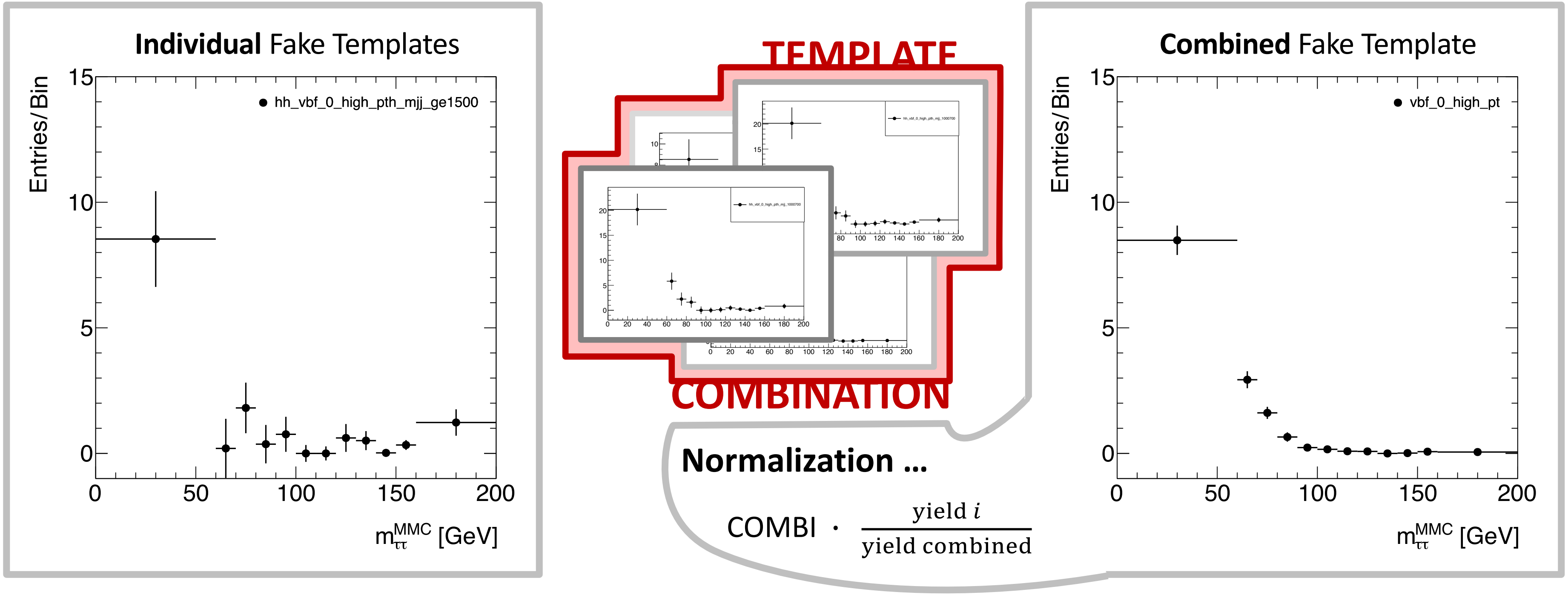
Fake Templates **Low p_T^H**



Better statistical uncertainty on shape

INCLUSIVE REPLACEMENT

→ Replace template by combined version scaled to original yield

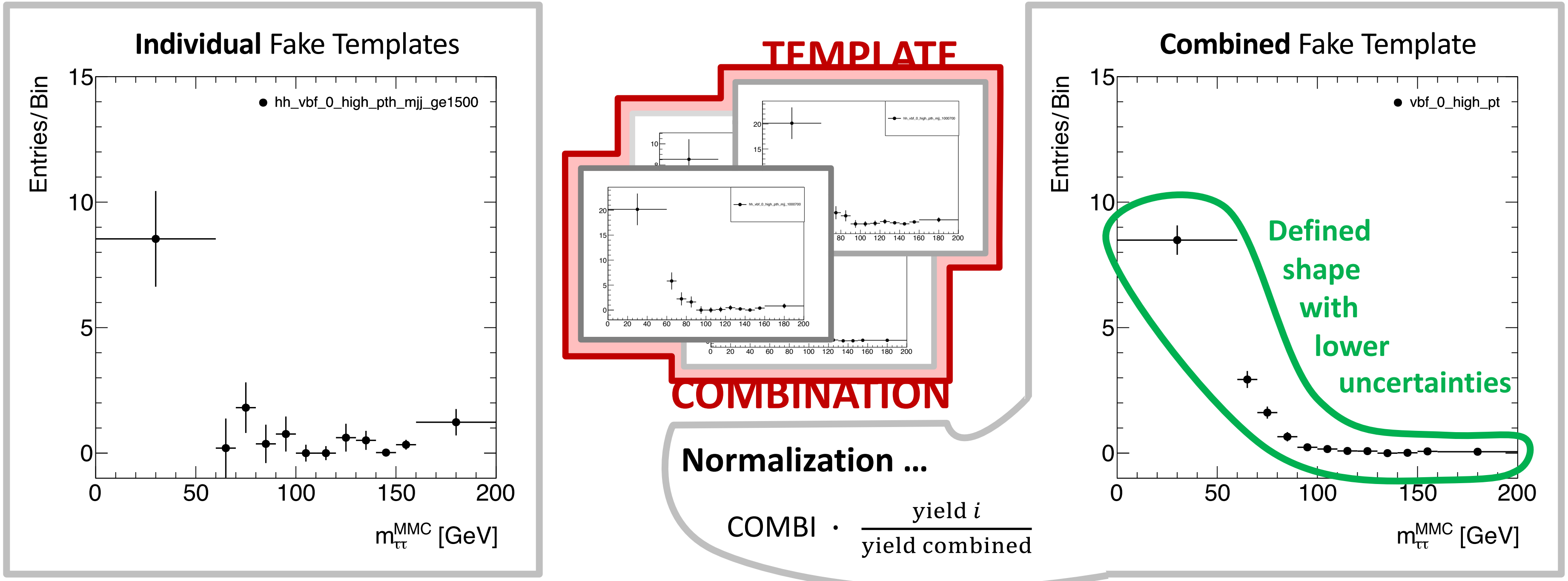


Normalization …

$$\text{COMBI} \cdot \frac{\text{yield } i}{\text{yield combined}}$$

INCLUSIVE REPLACEMENT

→ Replace template by combined version scaled to original yield



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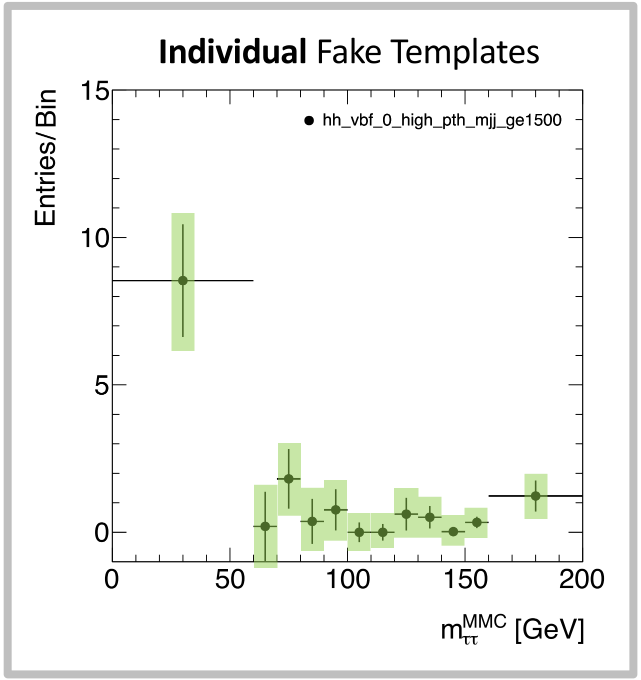
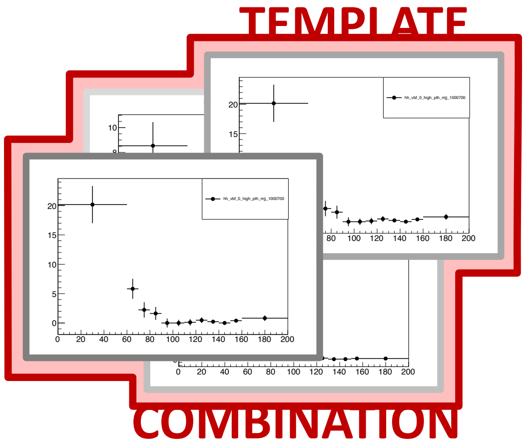
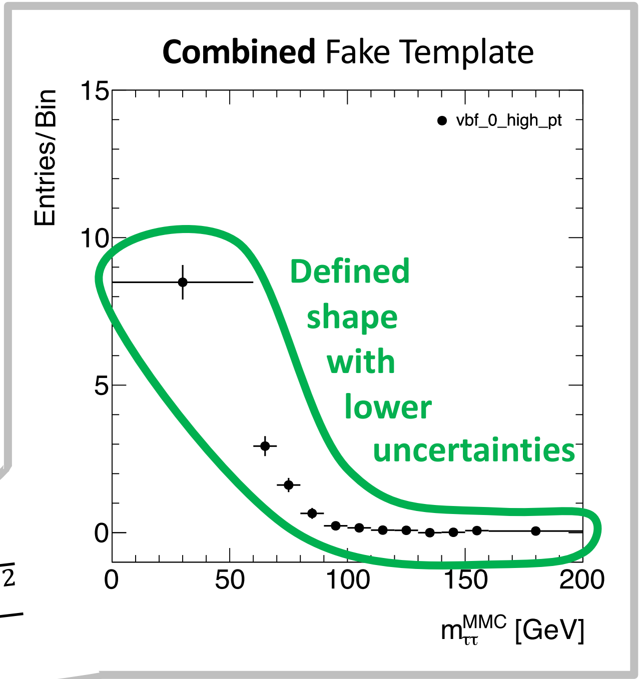




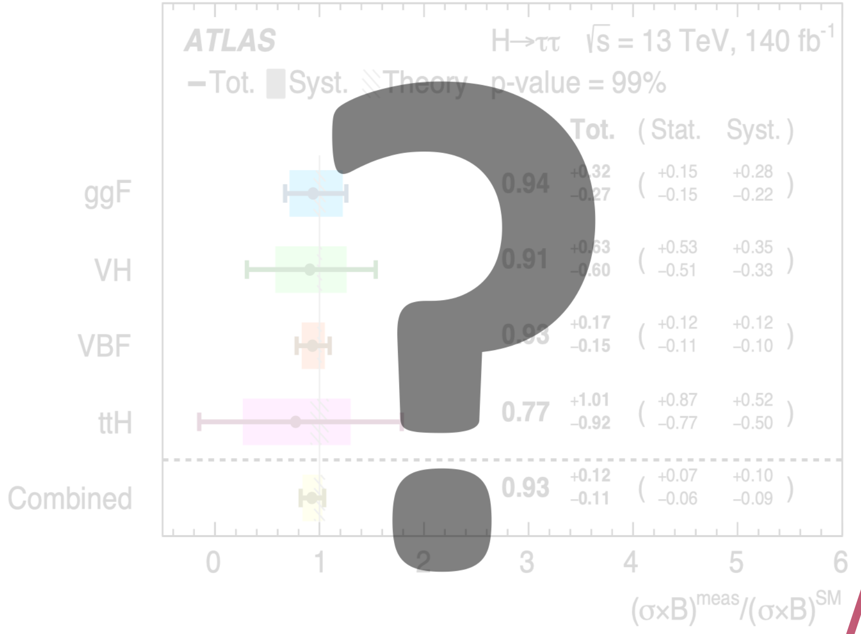


Normalization uncertainty

$$\sigma_N = \frac{\sqrt{\Sigma(\Delta o_i)^2}}{\Sigma o_i}$$

RECENT FINDINGS FROM THE ATLAS COLLABORATION

2024 Analysis: arxiv 2407.16320



STANDARD MODEL REAFFIRMED ???

Two-Track Strategy

→ Check for validity

→ Does the Standard Model withstand?

THE ANALYSIS: BINNED PROFILE LIKELIHOOD FIT

- **Likelihood fit** → find parameter set that optimizes modeling of data
- **Validation** of model **crucial** → investigate parameter dependencies

$$\mathcal{L}\left(\vec{n}, \vec{a} | \vec{\theta}, \vec{k}\right) = \prod_{i \in \text{bins}} \text{Pois}\left(n_i | \mu \times S_i(\vec{\theta}) + B_i(\vec{k}, \vec{\theta})\right) \times \prod_{j \in \text{sys}} c_j\left(a_j | \theta_j\right)$$

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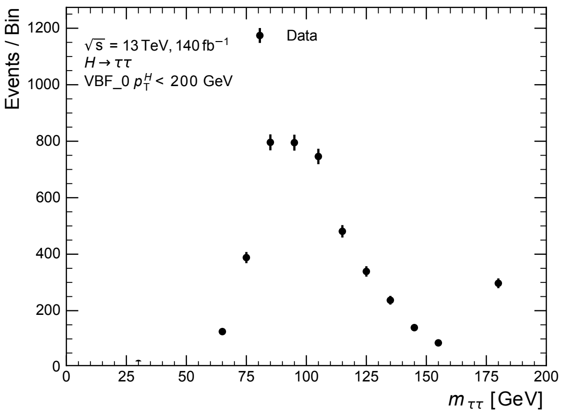
adapted from arxiv 2407.16320



- $\vec{n}$ number of events
- μ signal strength
- Θ systematic uncertainties
- $\vec{a}$ auxiliary measurements
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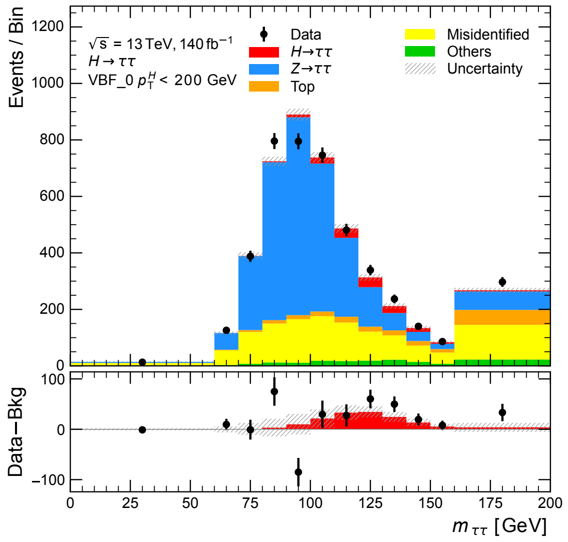

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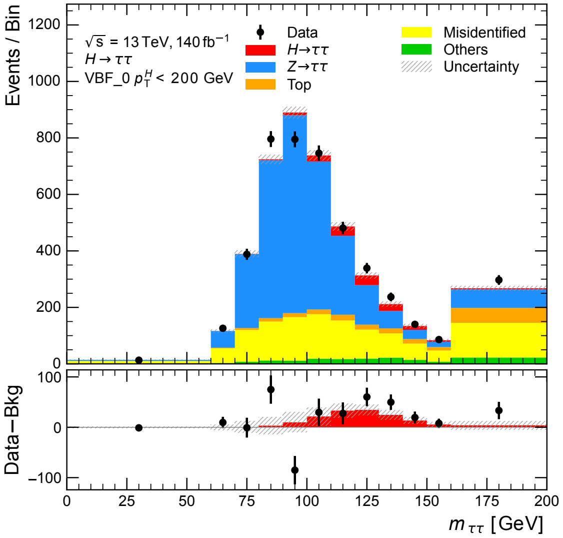

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$$\mu = \frac{\sigma_H}{\sigma^{SM}} \cdot \frac{BR_{\tau\tau}}{BR_{\tau\tau}^{SM}}$$

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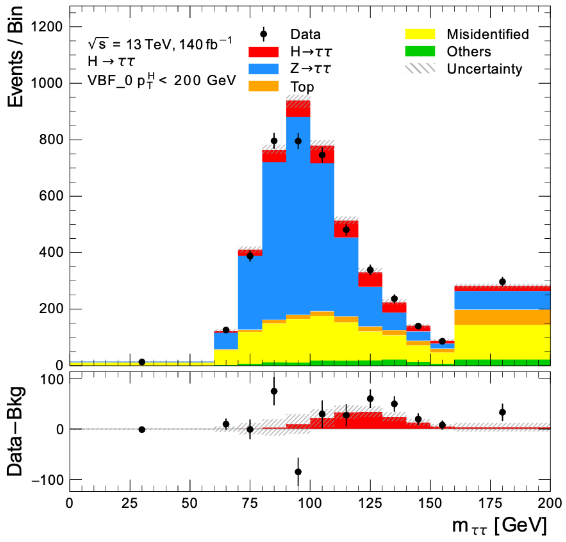

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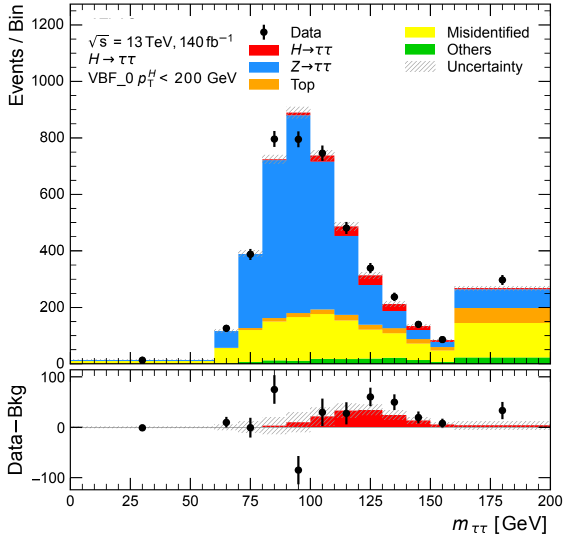

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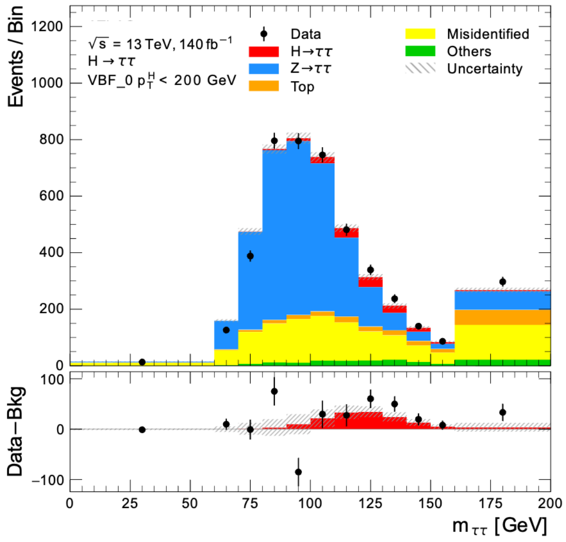

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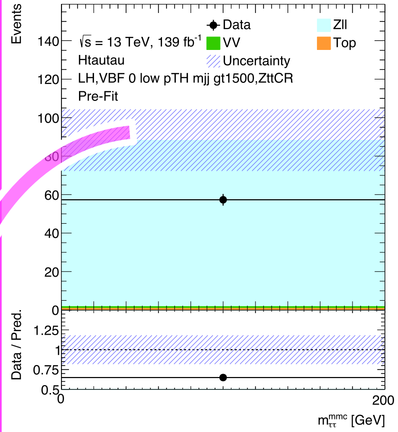
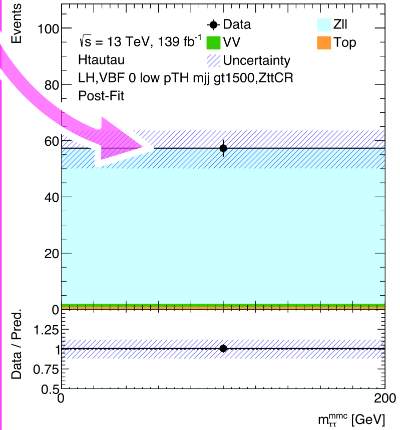
CONTROL REGION

FIT





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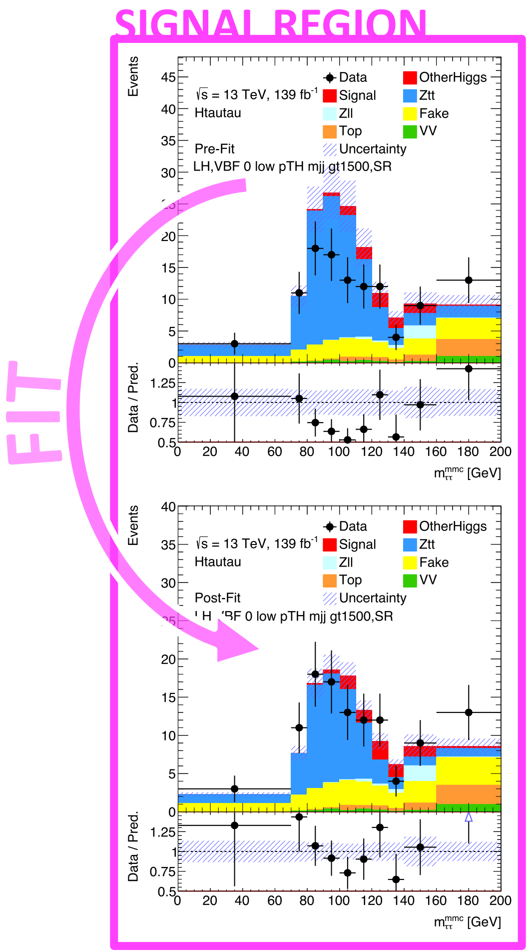

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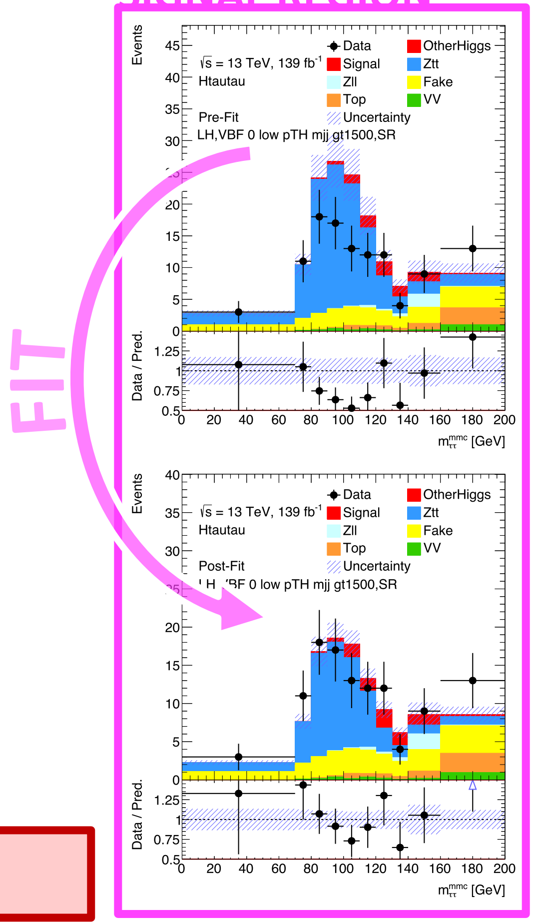
→ **Fit finds set of parameters (μ, θ, k) that maximize likelihood**

SIGNAL REGION



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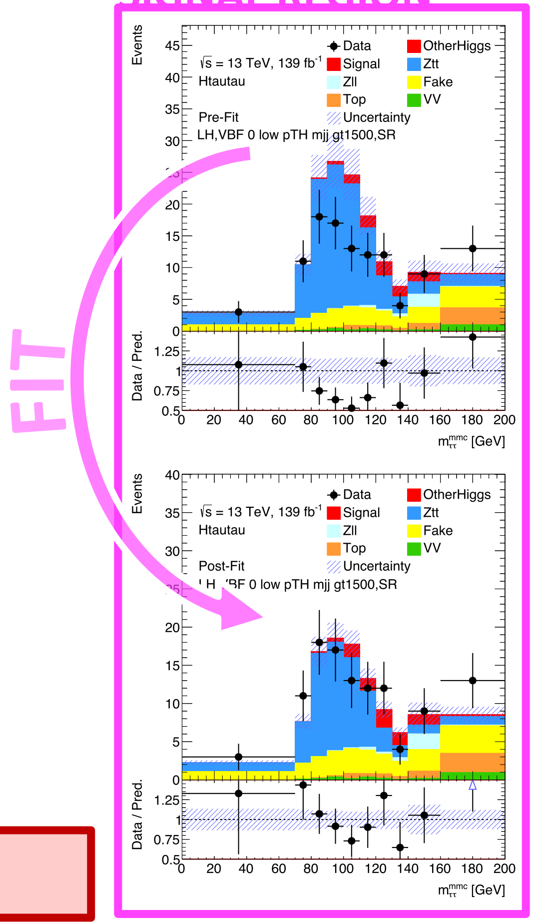
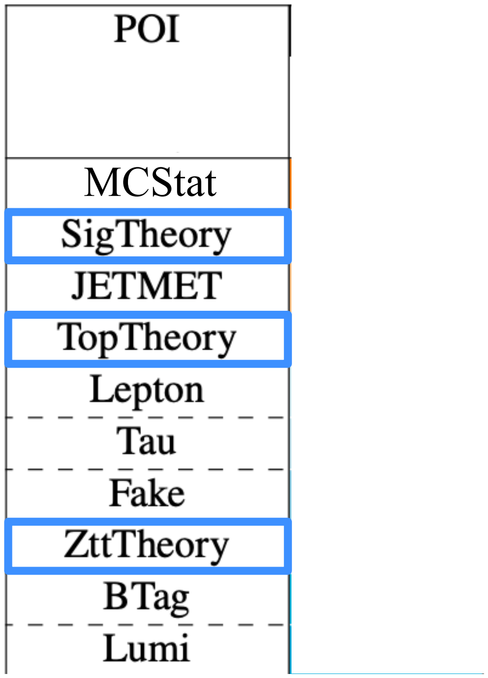


GROUPED IMPACT

→ Systematic uncertainties categorized in groups

- Theory Uncertainty on signal & background



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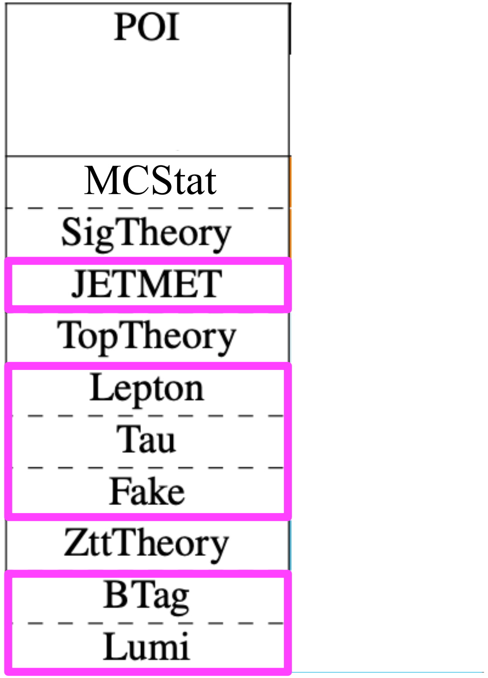

GROUPED IMPACT

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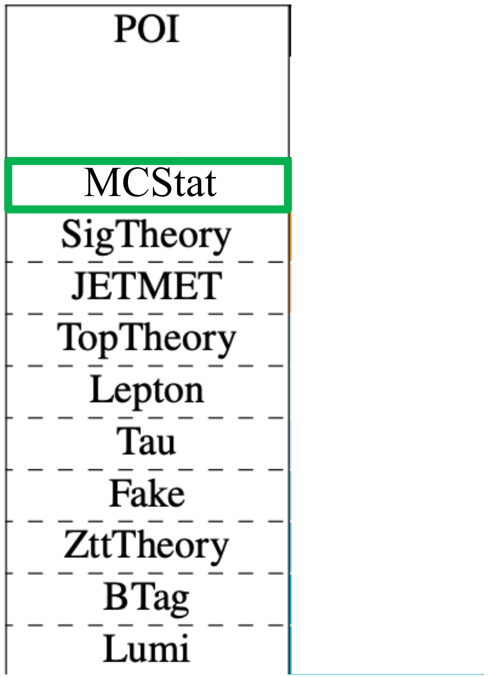
- Statistical uncertainty on Monte-Carlo Sample



GROUPED IMPACT

→ Systematic uncertainties categorized in groups

- Theory Uncertainty on signal & background
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→ **Share** of uncertainty group to total uncertainty

$$\textbf{impact} = \sqrt{(\Delta\mu)^2 - (\Delta\mu')^2}$$

Uncertainty … … on **Parameter of Interest** … **excluding** a **given group**

POI	mjj_350700_ptH_0_200
MCStat	0.376
SigTheory	0.191
JETMET	0.147
TopTheory	0.086
Lepton	0.086
Tau	0.079
Fake	0.06
ZttTheory	0.042
BTag	0.031
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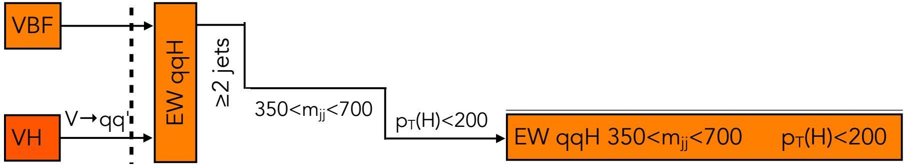

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→ **Dominant Contribution:**

Statistical uncertainty on MC Sample

POI	mjj_350700_ptH_0_200
MCStat	0.376
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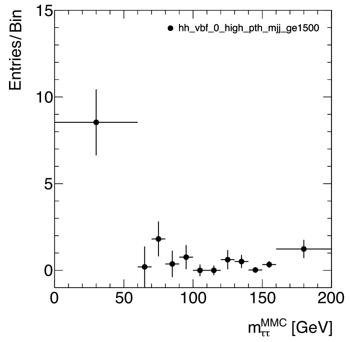
→ **Dominant Contribution:**

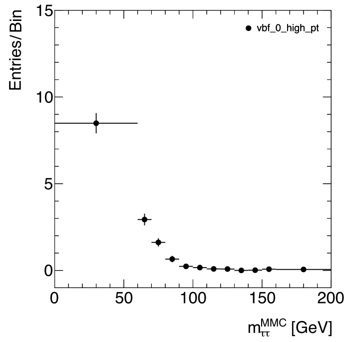
Statistical uncertainty on MC Sample

POI	mjj_350700_ptH_0_200	
Fake Template	Reference	Combined
MCStat	0.376	0.335
SigTheory	0.191	0.191
JETMET	0.147	0.148

… with **original** fake **template**



… with **combined** fake **template**



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Uncertainty … … on Parameter of Interest … excluding a given group

→ **Dominant Contribution:**

Statistical uncertainty on MC Sample

→ **Fake Templates Combination reduce impact of MC Stat**

POI	mjj_350700_ptH_0_200	
Fake Template	Reference	Combined
MCStat	0.376	0.335
SigTheory	0.191	0.191
JETMET	0.147	0.148
TopTheory	0.086	0.081
Lepton	0.086	0.078
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Fake	0.06	0.105
ZttTheory	0.042	0.041
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Uncertainty … | **… on Parameter of Interest** ($\Delta\mu$) | **… excluding a given group** ($\Delta\mu'$)

→ **Dominant Contribution:**

Statistical uncertainty on MC Sample

→ **Fake Templates Combination reduce impact of MC Stat + increases impact of Fake systematics**

POI Fake Template	mjj_350700_ptH_0_200 Reference	 Combined
MCStat	0.376	0.335
SigTheory	0.191	0.191
JETMET	0.147	0.148
TopTheory	0.086	0.081
Lepton	0.086	0.078
Tau	0.079	0.071
Fake	0.06	0.105
ZttTheory	0.042	0.041
BTag	0.031	0.031
Lumi	0.017	0.017

GROUPED IMPACT

→ Systematic uncertainties categorized in groups

- Theory Uncertainty on signal & background
- Experimental uncertainties
- Statistical uncertainty on Monte-Carlo Sample

→ **Share** of uncertainty group to total uncertainty

$$\textbf{impact} = \sqrt{(\Delta\mu)^2 - (\Delta\mu')^2}$$

Uncertainty … | … on Parameter of Interest ($\Delta\mu$) | … excluding a given group ($\Delta\mu'$)

→ **Dominant Contribution:**

Statistical uncertainty on MC Sample

→ **Fake Templates Combination reduce impact of MC Stat + increases impact of Fake systematics**

POI	mjj_350700_ptH_0_200	
Fake Template	Reference	Combined
Full Syst	0.535	0.513
MCStat	0.376	0.335
SigTheory	0.191	0.191
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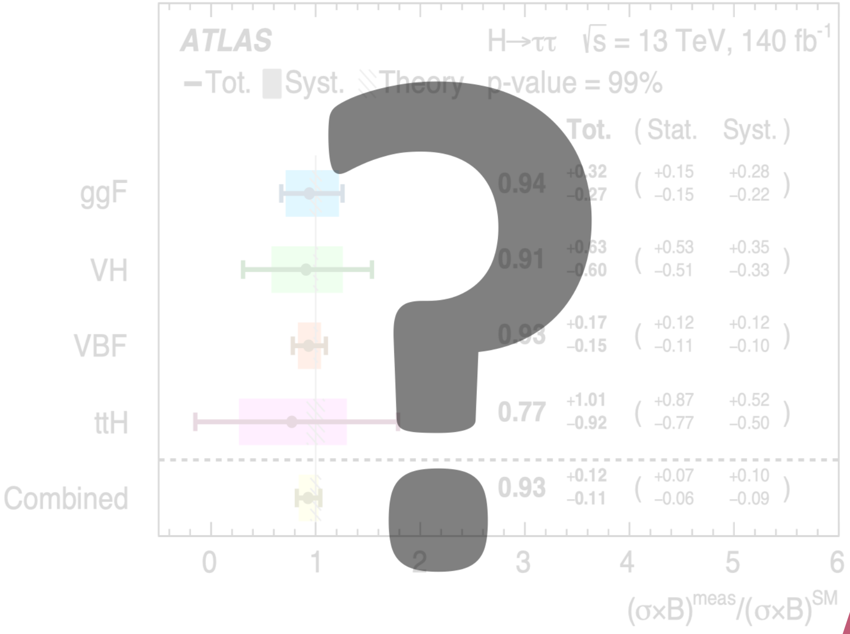
→ Positive Impact of Combined Fake Templates!

RECENT FINDINGS FROM THE ATLAS COLLABORATION

2024 Analysis: arxiv 2407.16320



STANDARD MODEL REAFFIRMED ???

Two-Track Strategy

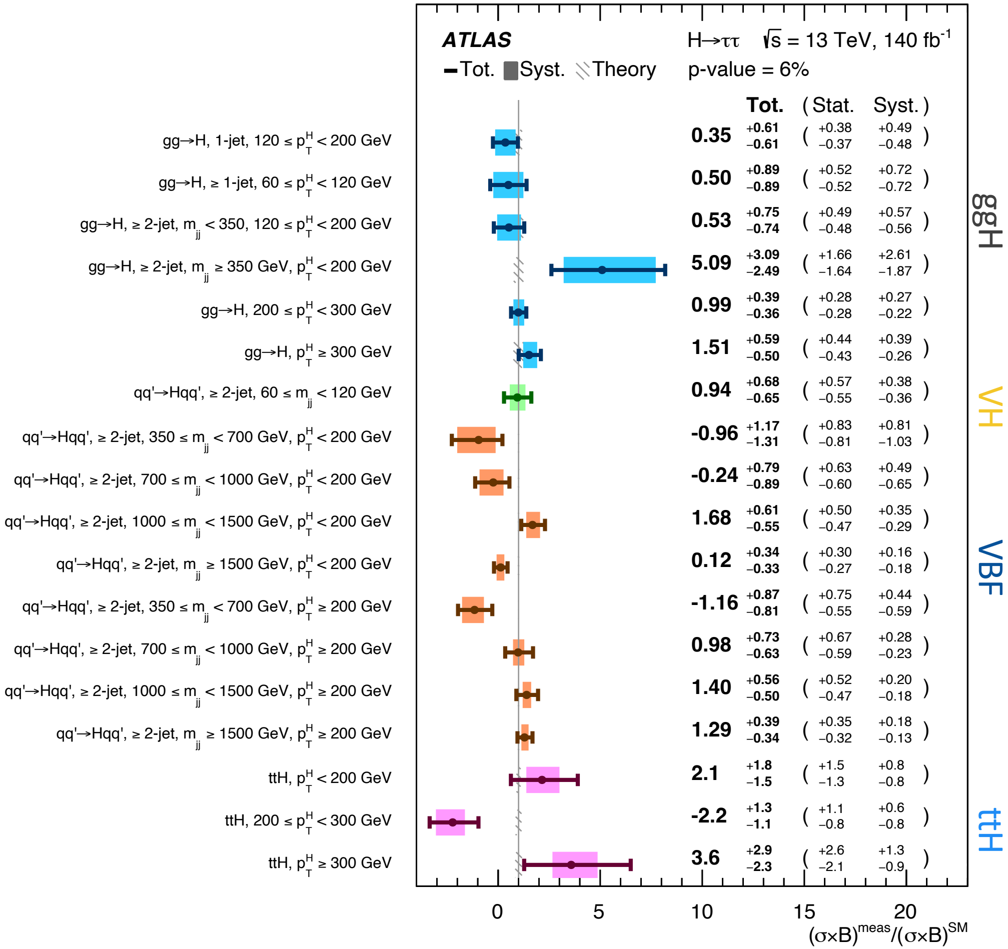
→ Investigate BSM-sensitive phase-space

→ Improve precision

- Background contamination
- Sources of uncertainty

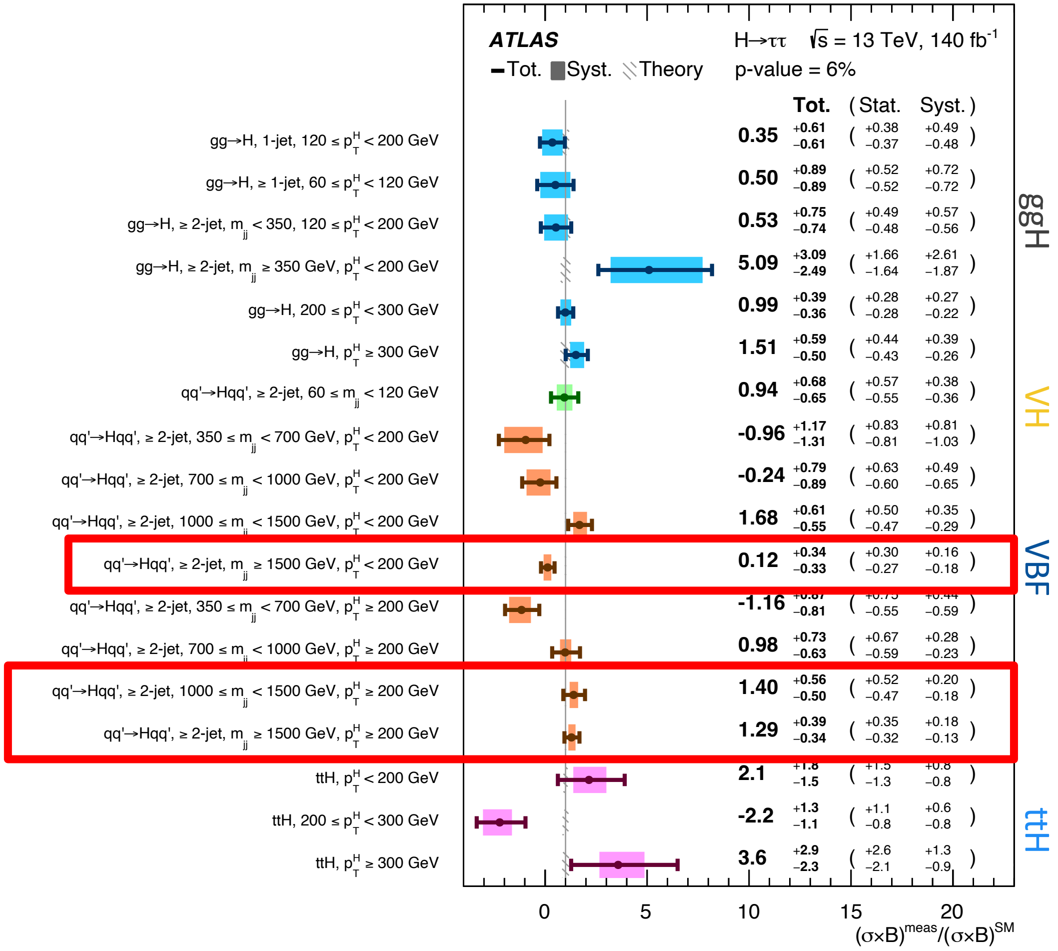
STXS MEASUREMENT

arxiv 2407.16320



STXS MEASUREMENT

→ Remarkable precision in high p_T^H / m_{jj}



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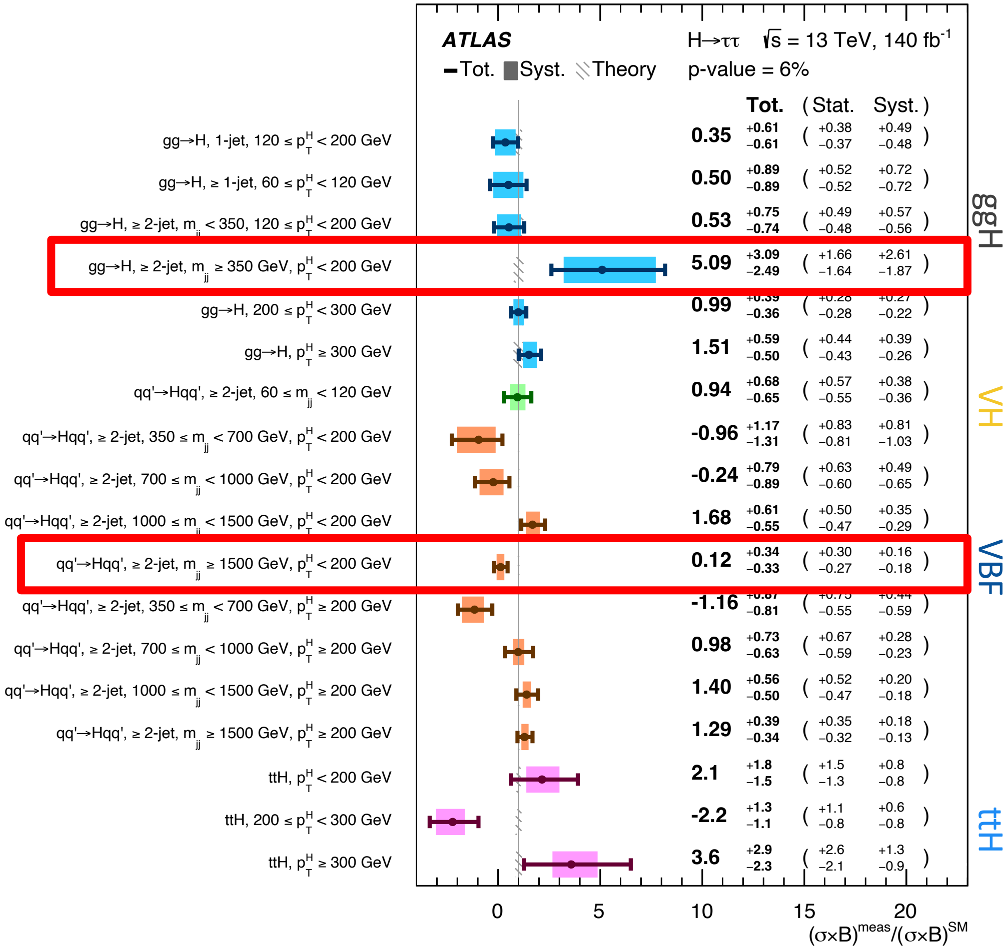
→ **Relative precision** $(\mu = 1)$:
$\mathbf{35\% \ - 300\%}$



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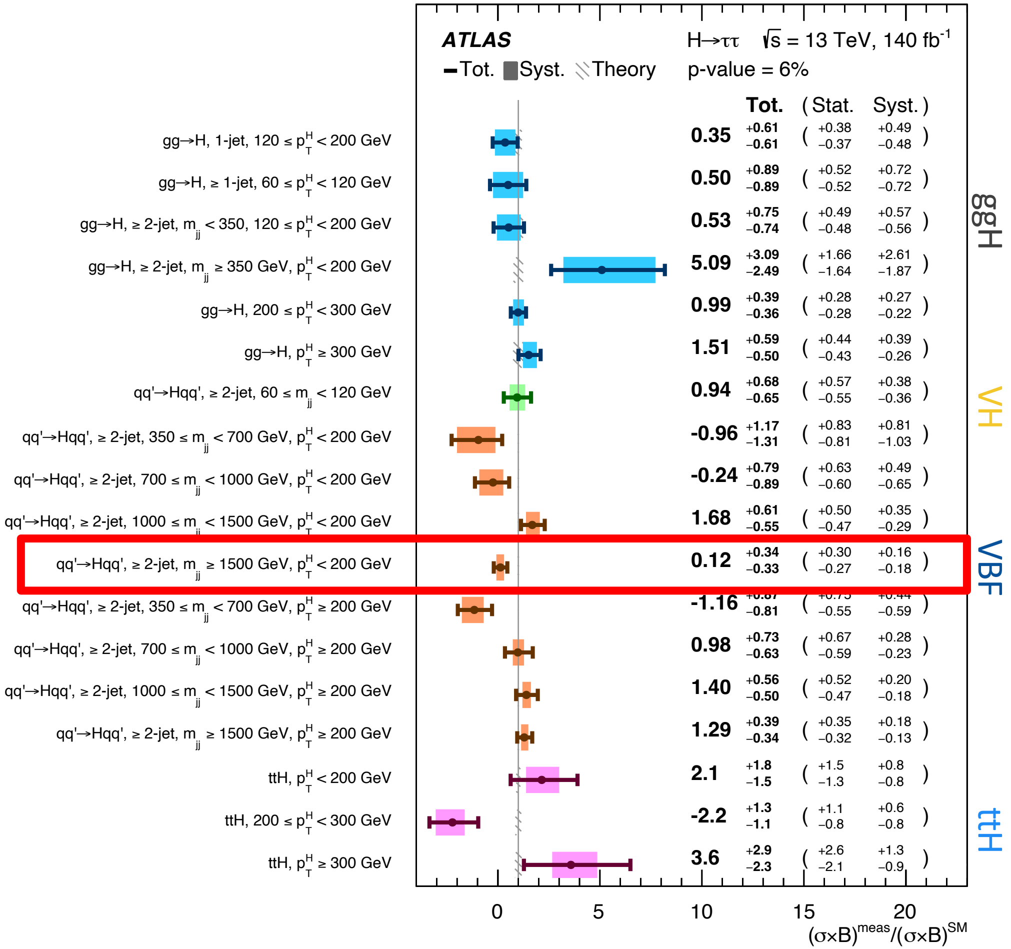
→ Observations of **strong pulls**

Extreme cases up to 3σ

$$pull = \frac{\hat{\theta} - \theta_0}{\Delta\theta}$$



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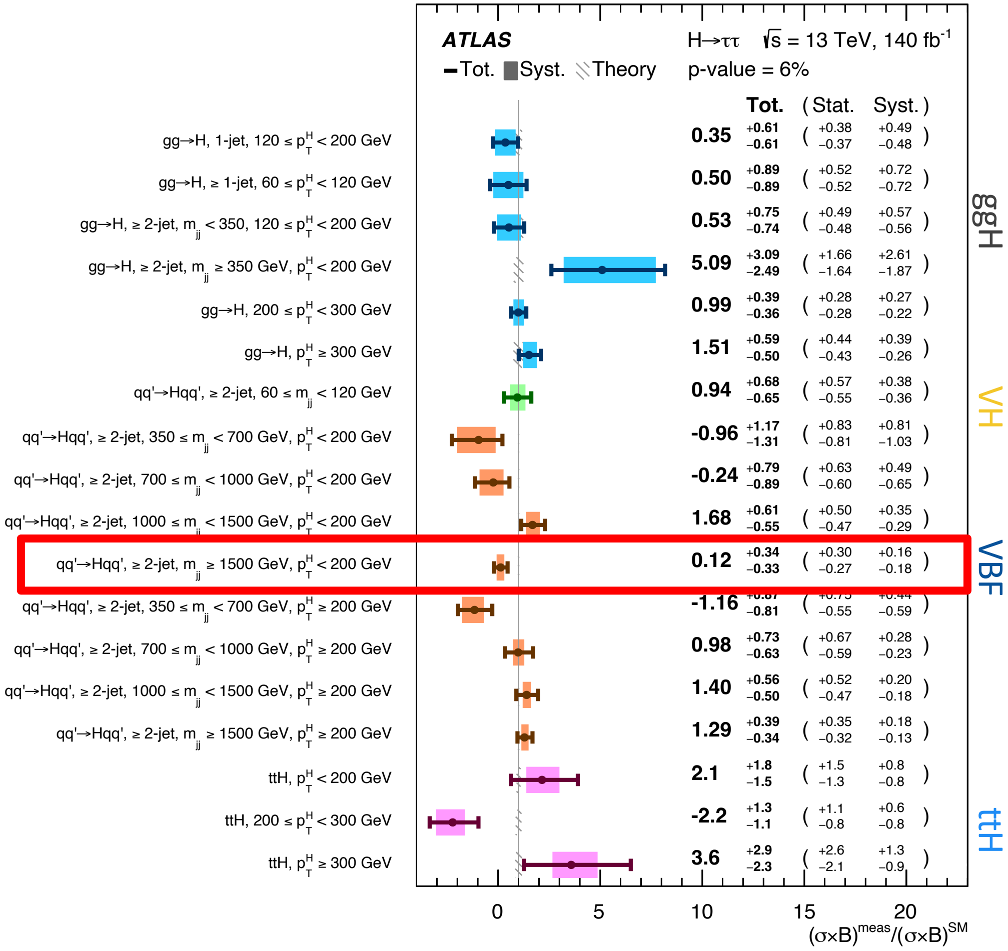
BUT: measurements strongly correlated

→ Relative movement understood and validated in dedicated studies

Statistical Fluctuation



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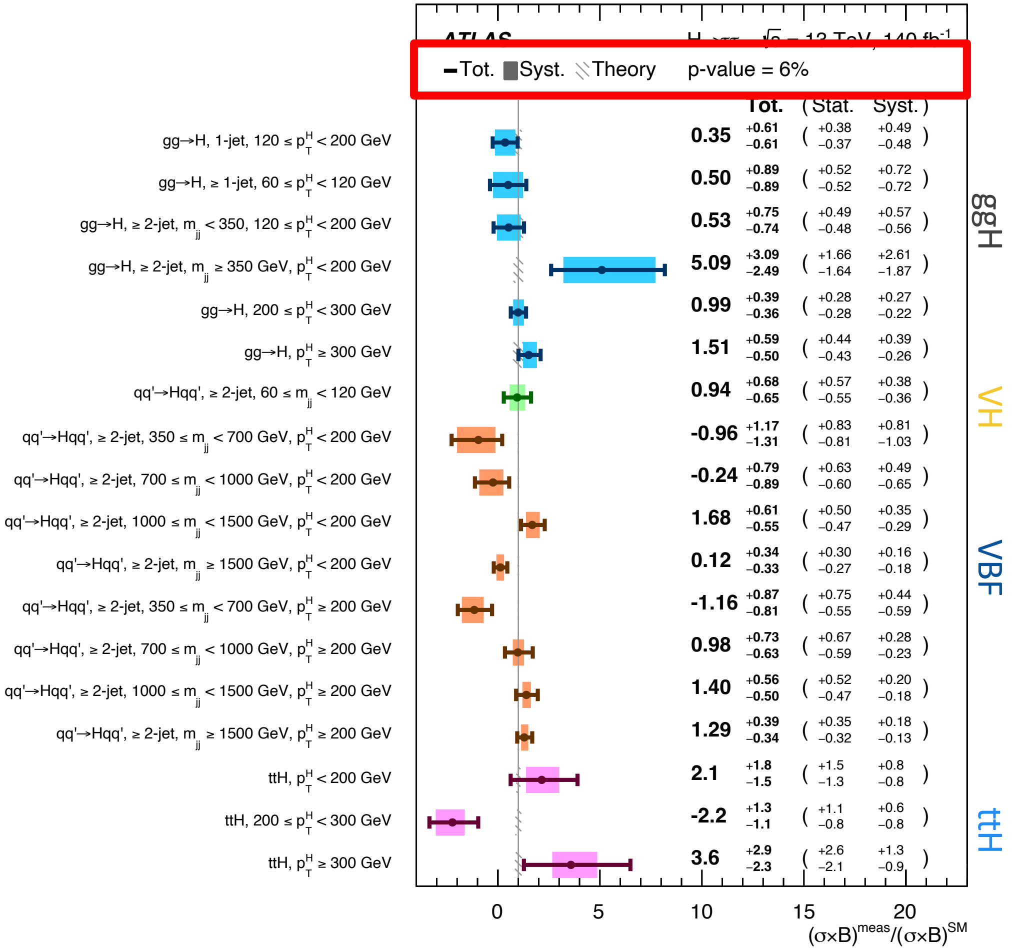

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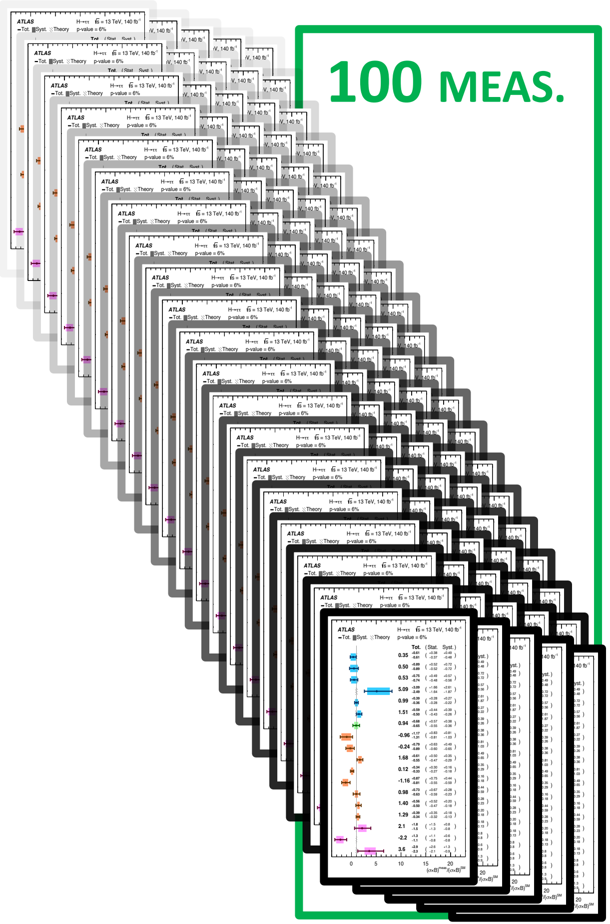
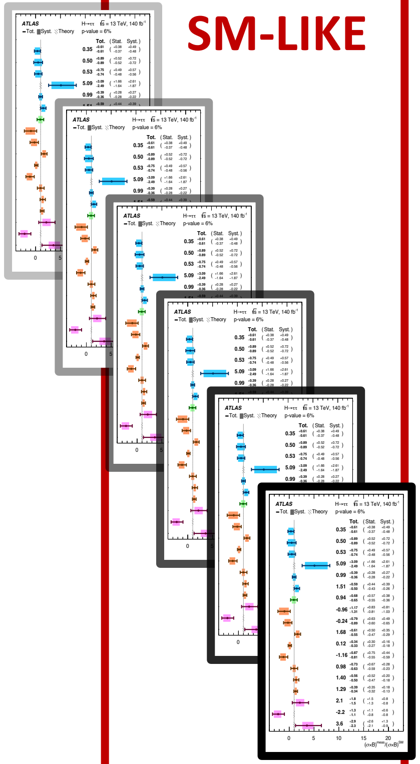
100 MEAS.



6 × less

SM-LIKE



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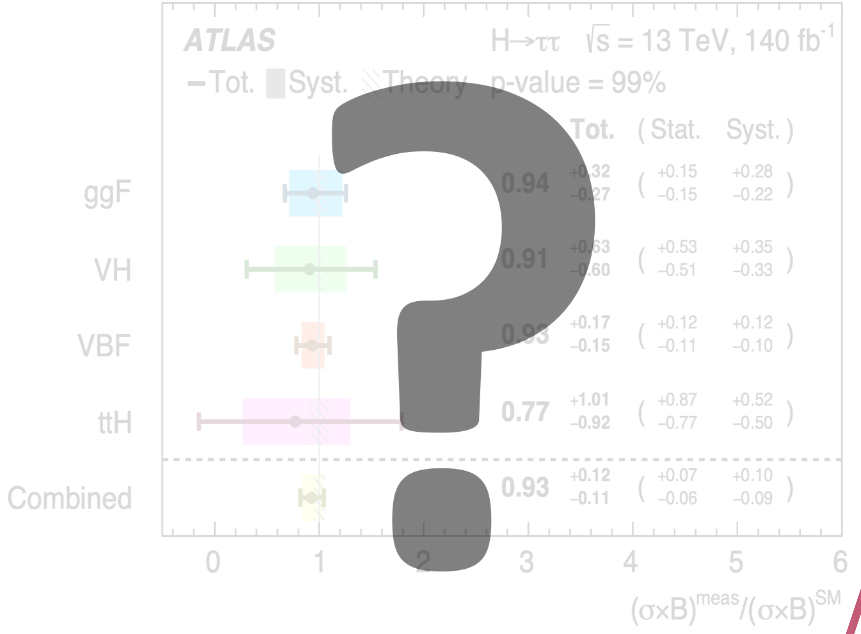

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  - Background contamination
  - ☑ Sources of uncertainty

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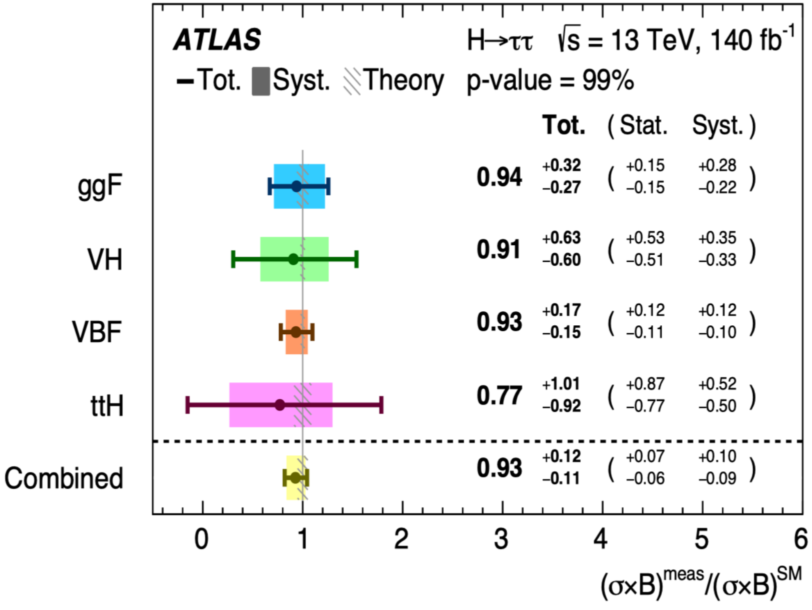

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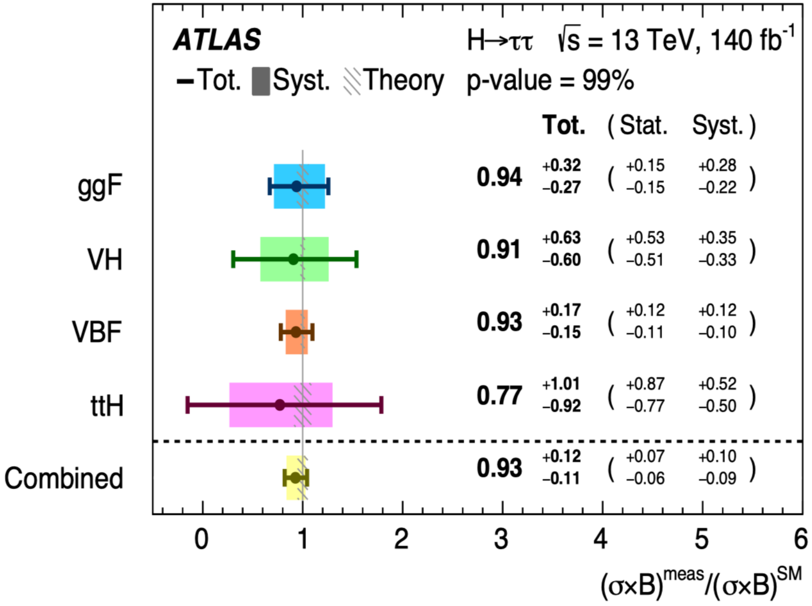


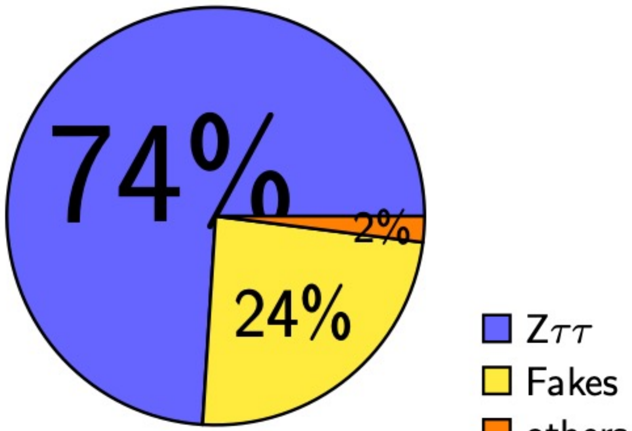
STANDARD MODEL REAFFIRMED

Two-Track Strategy

- ✓ Investigate BSM-sensitive phase-space
- → Improve precision
  - **Background contamination**
  - ✓ Sources of uncertainty

DECAY-MODE DEPENDENT BACKGROUND COMPOSITION

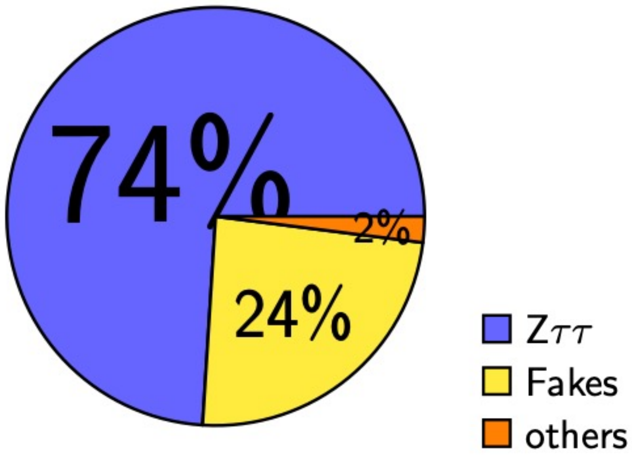
Composition of background not constant across full phase-space

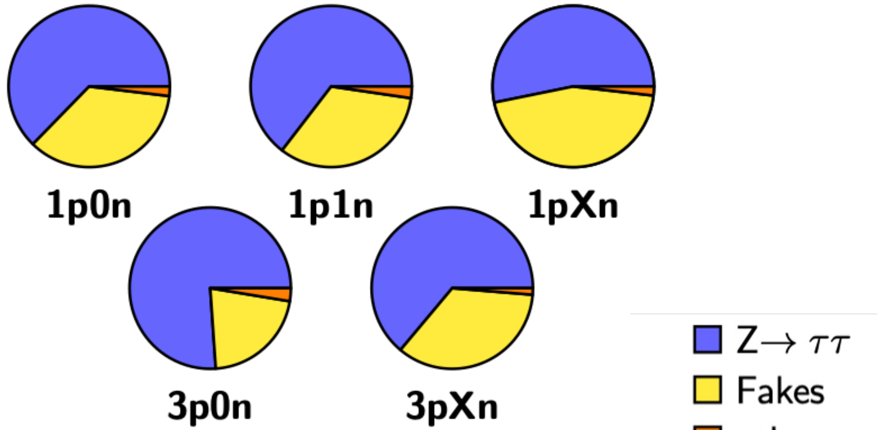


DECAY-MODE DEPENDENT BACKGROUND COMPOSITION

Composition of background not constant across full phase-space

Fake contribution increases with number of neutral pions



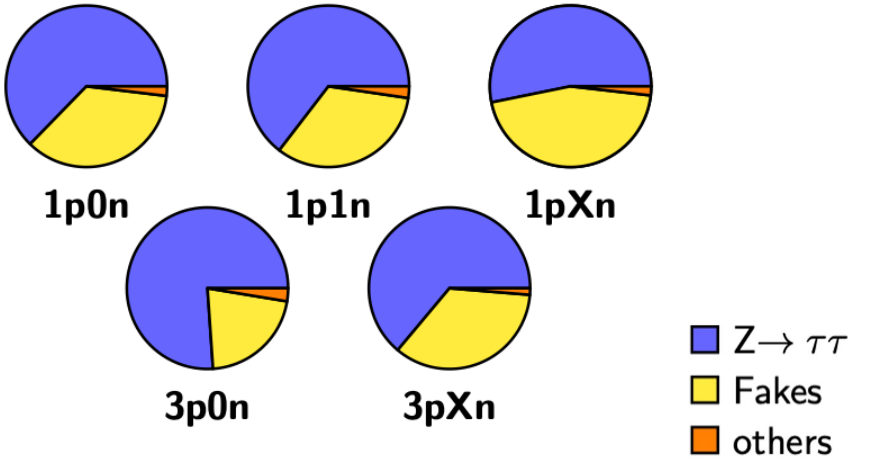


DECAY-MODE DEPENDENT BACKGROUND COMPOSITION

Incorporate the dependency in the Fake estimation ⇐ **Fake contribution increases with number of neutral pions**

- More-detailed description
- Identify signal regions with good signal to background ration
  ⇢ Prospect to loosen τ-ID working point

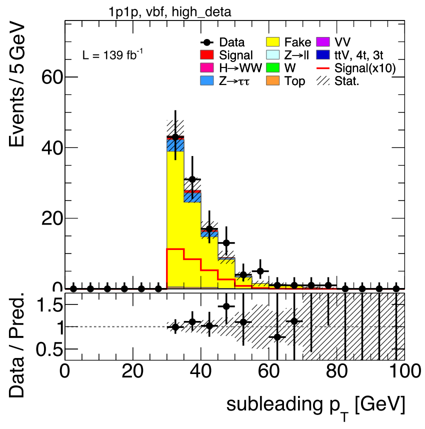
τ \ τ	1p0n	1p1n	1pXn	3p0n	3pXn
1p0n	3.3%	14.8%	6%	5.6%	3%
1p1n		16.8%	14%	12.6%	6.8%
1pXn			2.9%	5.2%	2.8%
3p0n				2.4%	2.6%
3pXn					0.7%

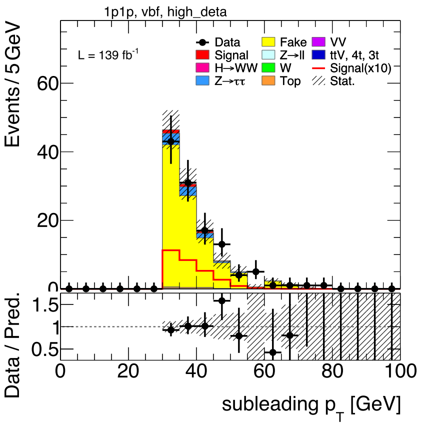


DECAY-MODE DEPENDENT FAKE ESTIMATION IN NEWLY DEFINED SIGNAL REGIONS

Decay-mode dependent **Fake Factors determined** and **validated**

CONVENTIONAL





Fake enriched phase-space

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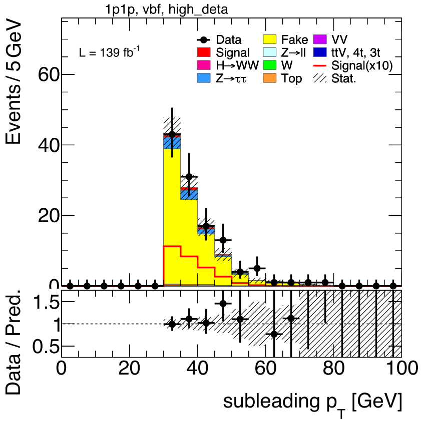
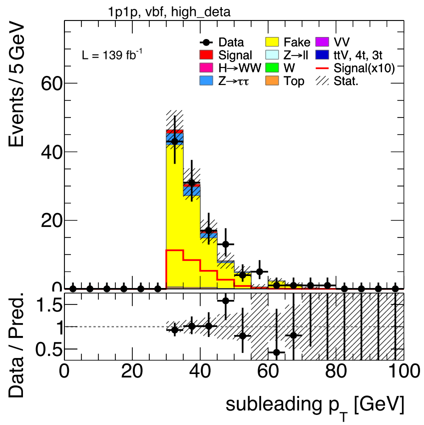


DECAY-MODE DEPENDENT



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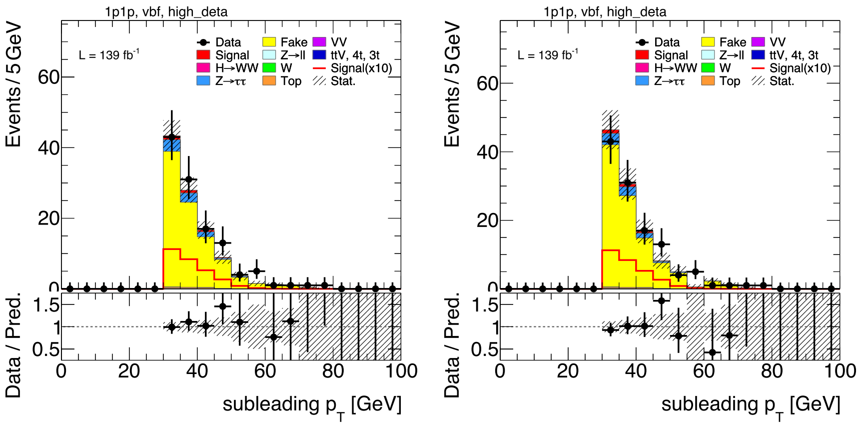

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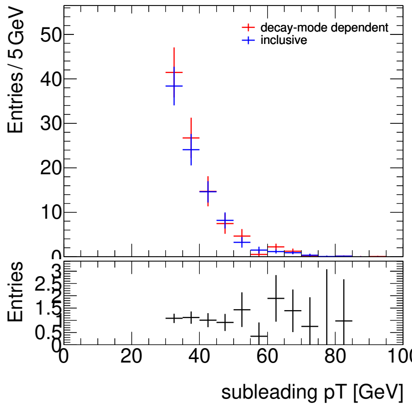

COMPATIBLE

DECAY-MODE DEPENDENT FAKE ESTIMATION IN NEWLY DEFINED SIGNAL REGIONS

- ✅ Decay-mode dependent **Fake Factors determined** and **validated**
- ✅ Low-background signal regions identified

τ \ τ	1p0n	1p1n	1pXn	3p0n	3pXn
1p0n	3.3%	14.8%	6%	5.6%	3%
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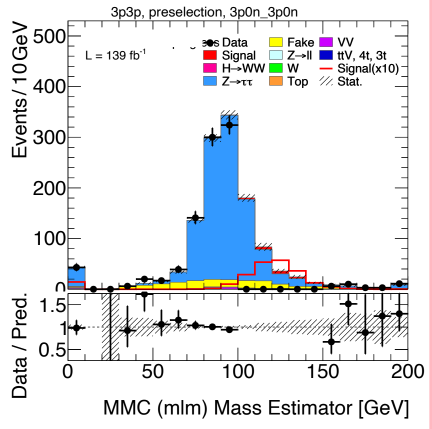

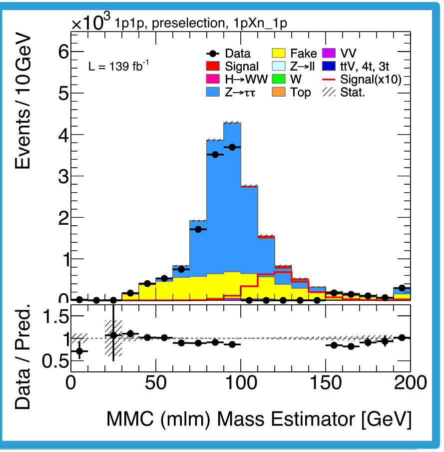

DECAY-MODE DEPENDENT FAKE ESTIMATION IN NEWLY DEFINED SIGNAL REGIONS

- Decay-mode dependent **Fake Factors determined** and **validated**
- Low-background signal regions identified

Promising approach for future setups

TO DO: Study interplay of

– fit stability

– statistical uncertainties

– signal purity

τ \ τ	1p0n	1p1n	1pXn	3p0n	3pXn
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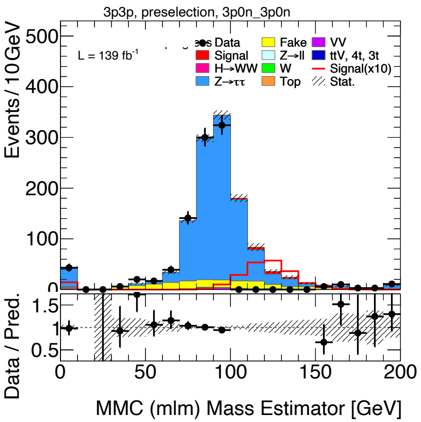
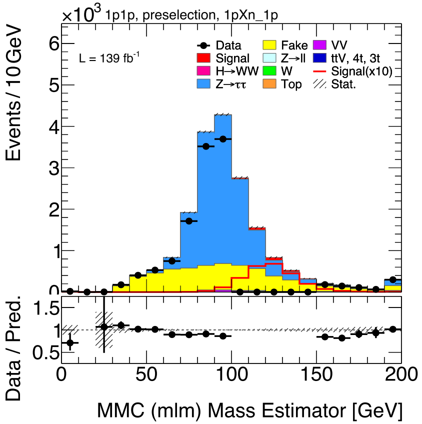




arxiv 2407.16320

CONCLUSION

→ $H \rightarrow \tau\tau$: **Good agreement** with SM at current level of precision

→ **STXS** cross-section measurements yield **increased level of detail**

→ **Fake Background** promises **precision gain**

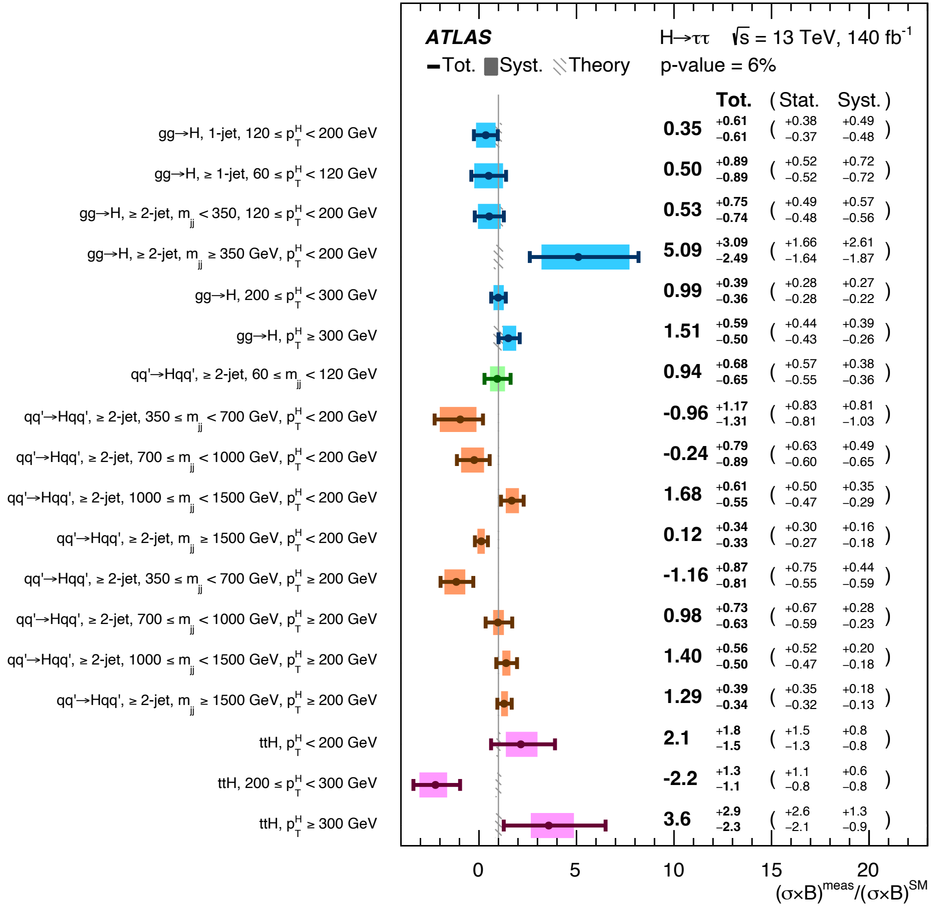
OUTLOOK

→ **Increase in statistics:**

– **factor 2 in Run 3**

– **factor 10** over the HL-LHC era

→ **Complex analysis strategies continuously refined**



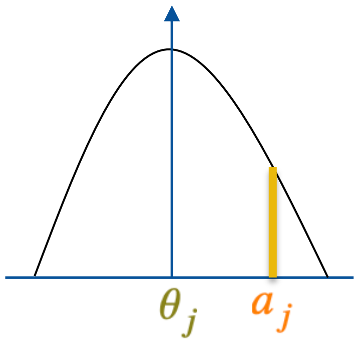
UNIVERSITÄT BONN

ATLAS EXPERIMENT

THE ANALYSIS: BINNED PROFILE LIKELIHOOD FIT

- **Likelihood fit** → find parameter set that optimizes modeling of data
- **Validation** of model **crucial** → investigate parameter dependencies

$$\mathcal{L}\left(\vec{n},\vec{a}|\vec{\theta},\vec{k}\right) = \prod_{i\in\text{bins}} \text{Pois}\left(n_i|\mu\times S_i(\vec{\theta}) + B_i(\vec{k},\vec{\theta})\right) \times \prod_{j\in\text{sys}} c_j\left(a_j|\theta_j\right)$$



- ATLAS performance groups determine auxiliary measurements

Gaussian constraint to deviate from prior knowledge

i.e.: $\mathrm{L} = (140 \pm 21)\mathrm{fb}^{-1}$
a → 140
θ → 132

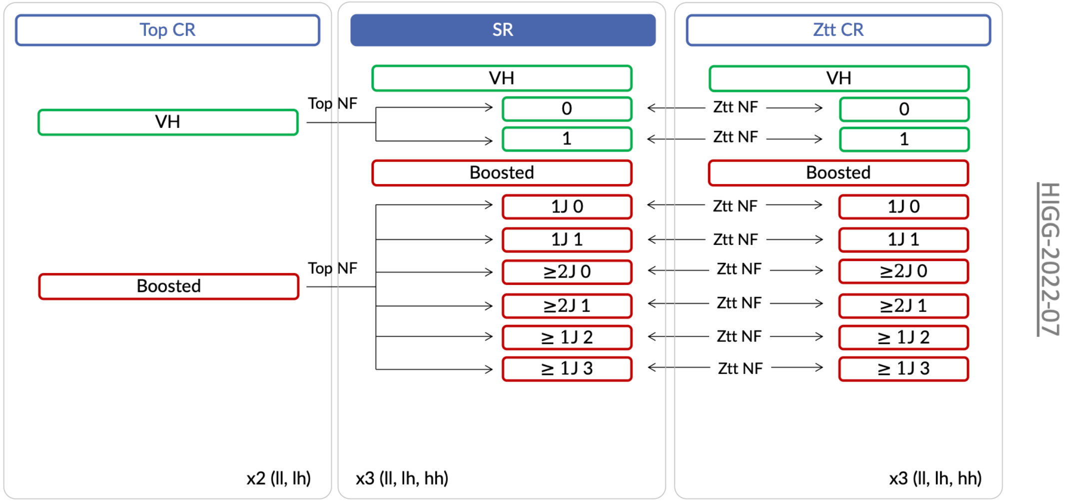
SELECTION

	$\tau_e\tau_\mu$	$\tau_{lep}\tau_{had}$: $e\tau_{had}$	$\tau_{lep}\tau_{had}$: $\mu\tau_{had}$	$\tau_{had}\tau_{had}$
Preselection Object counting	# of e = 1, # of μ = 1, # of $\tau_{had,vis}$ = 0	# of e/μ = 1, # of $\tau_{had,vis}$ = 1		# of e/μ = 0, # of $\tau_{had,vis}$ = 2
p_T cut	e/μ : p_T cut 10 to 27.3 GeV	e/μ : p_T cut 21 to 27.3 GeV, $\tau_{had,vis}$: $p_T > 30$ GeV		$\tau_{had,vis}$: $p_T > 40$,30 GeV
ID, Isolation, and eveto	e/μ: Medium e: FCLoose, μ: FCTightTrackOnly	e/μ: Medium, $\tau_{had,vis}$: RNN Medium e: FCLoose, μ: FCTightTrackOnly 1-prong $\tau_{had,vis}$: eleBDT e-veto		$\tau_{had,vis}$: RNN Medium
Charge product	Opposite charge	Opposite charge		Opposite charge
Kinematics	$m_{\tau\tau}^{coll} > m_Z - 25$ GeV $30 < m_{e\mu} < 100$ GeV	$m_T < 70$ GeV		
b-veto	# of b-jets = 0 wp: DL1r_FixedCutBEff_85	# of b-jets = 0 wp: DL1r_FixedCutBEff_85		# of b-jets = 0 wp: DL1r_FixedCutBEff_70 not applied in tt(0L)$H \to \tau_{had}\tau_{had}$
E_T^{miss}	$E_T^{miss} > 20$ GeV	$E_T^{miss} > 20$ GeV		$E_T^{miss} > 20$ GeV
Leading jet	$p_T > 40$ GeV	$p_T > 40$ GeV		$p_T > 70$ GeV, $\|\eta\| < 3.2$
Angular	$\Delta R_{e\mu} < 2.0$, $\|\Delta\eta_{e\mu}\| < 1.5$	$\Delta R_{l\tau_{\text{had, vis}}} < 2.5$, $\|\Delta\eta_{l\tau_{\text{had, vis}}}\| < 1.5$		$0.6 < \Delta R_{\tau_{\text{had, vis}}\tau_{\text{had, vis}}} < 2.5$ $\|\Delta\eta_{\tau_{\text{had, vis}}\tau_{\text{had, vis}}}\| < 1.5$
Coll. app. x_1/x_2	$0.1 < x_1 < 1.0$, $0.1 < x_2 < 1.0$	$0.1 < x_1 < 1.4$, $0.1 < x_2 < 1.2$		$0.1 < x_1 < 1.4$, $0.1 < x_2 < 1.4$

VBF inclusive	sub-leading jet $p_T > 30$ GeV $m_{jj} > 350$ GeV, $\|\Delta\eta_{jj}\| > 3$ $\eta(j_0) \times \eta(j_1) < 0$ lepton centrality: visible decay products of the τ leptons between VBF jets
VH inclusive	$60 \text{ GeV} < m_{jj} < 120$ GeV sub-leading jet $p_T > 30$ GeV
tt(0L)$H \to \tau_{had}\tau_{had}$	# of jets ≥ 6 and # of b-jets ≥ 1 or # of jets ≥ 5 and # of b-jets ≥ 2
Boost inclusive	Not VBF inclusive Not VH inclusive $p_T(H) > 100$ GeV

arxiv 2407.16320

ANALYSIS DESIGN



added to CONF note appendix

- 78 signal regions targeting 18 stage 1.2 STXS bins
  - boost: 3 x 6
  - VH: 3 x (1+1)
  - VBF: 3 x (8+8)
  - $t\bar{t}H$: 3 + 3
- 80 control regions to normalize top and Ztt backgrounds
  - boost: 3 x 6 Ztt, 2 x 1 $t\bar{t}$
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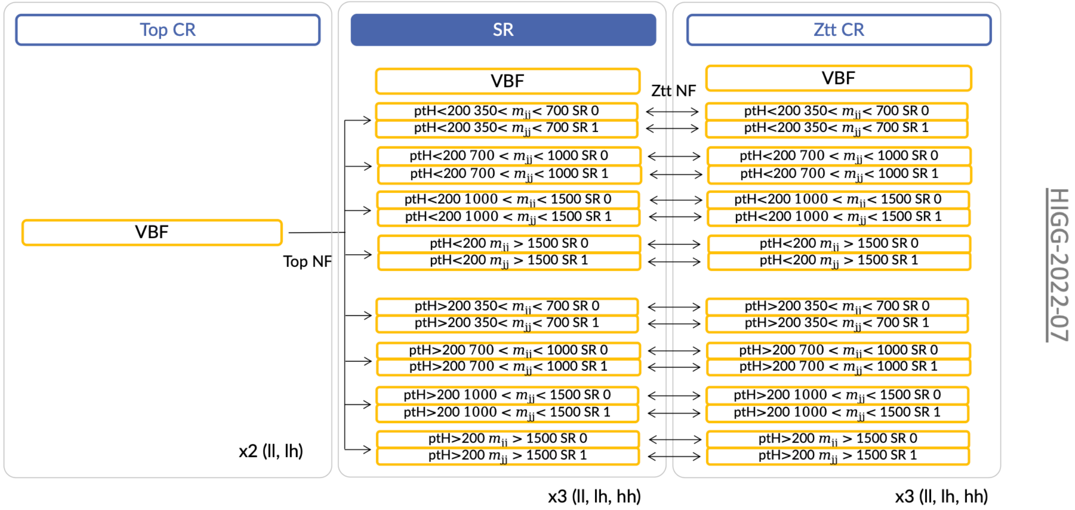

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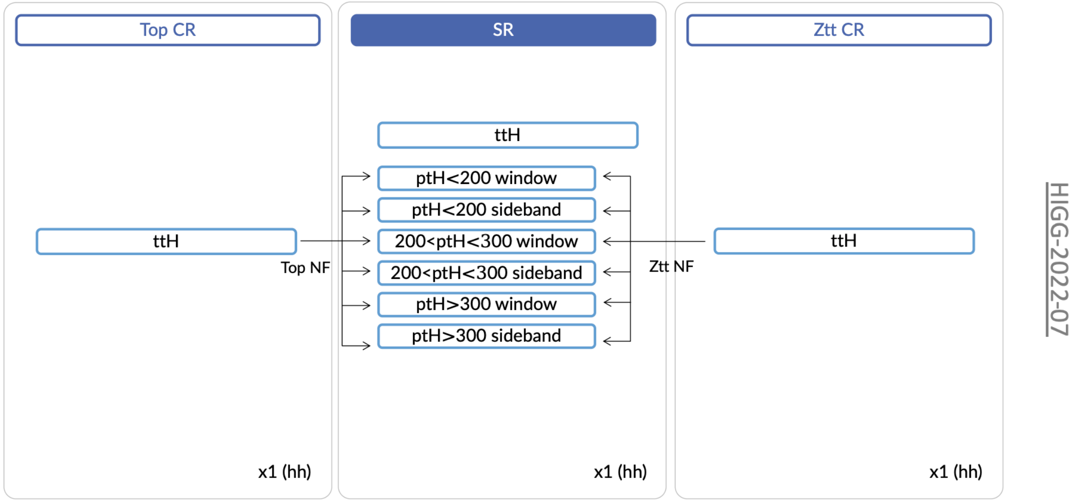

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  - $t\bar{t}H$: 1 x Ztt, 1 x $t\bar{t}$

TAGGER

- **VBF tagger:** differentiate ggH and $Z \rightarrow \tau\tau$
  - VBF 0 enhanced in bkg, VBF 1 in signal
  - Per region choose threshold to maximize

$$\sigma = \sqrt{\frac{S_0^2}{S_0 + B_0} + \frac{S_1^2}{S_1 + B_1}}$$

- **ttH:** multiclass BDT with 3 output nodes: differentiate signal $Z \rightarrow \tau\tau$, $t\bar{t}$
  - Separate training for low, high p_T^H
  - Score used to define regions

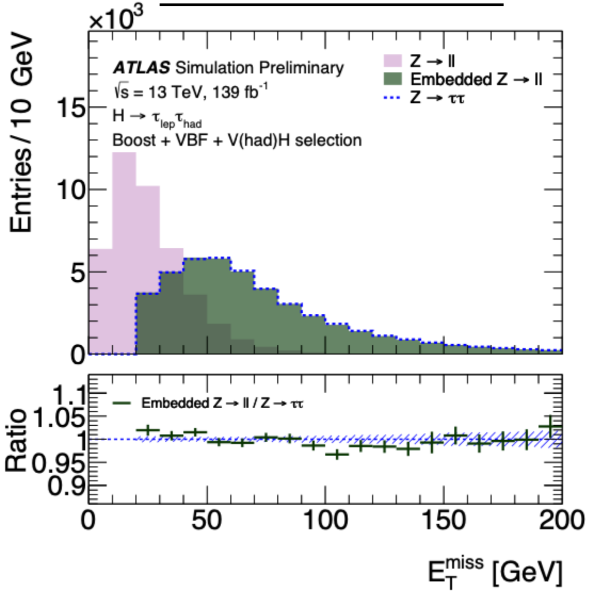
	Variable	VBF	ttH multiclass
Jet properties	Invariant mass of the two leading jets	•	
	$p_T(jj)$	•	
	Product of η of the two leading jets	•	
	Sub-leading jet p_T	•	
	η of the 5 leading jets		•
	Scalar sum of all jets p_T		•
	Scalar sum of all b-tagged jets p_T		•
	Best W-candidate dijet invariant mass		•
	Best t-quark-candidate three-jet invariant mass		•
Angular distances	$\Delta\phi$ between the two leading jets	•	
	$\Delta\eta$ between the two leading jets	•	
	Minimum ΔR between two jets		•
	Minimum ΔR between a b-tagged and a τ		•
	$\lvert\Delta\eta(\tau,\tau)\rvert$		•
	$\Delta R(\tau,\tau)$		•
τ prop.	$p_T(\tau\tau)$		•
	Sub-leading τ p_T		•
	Leading τ η		•
H cand.	$p_T(Hjj)$	•	
$\vec{E}_T^{miss}$	Missing transverse momentum E_T^{miss}		•
	Smallest $\Delta\phi$ $(\tau, \vec{E}_T^{miss})$		•

HIGG-2022-07

$Z \rightarrow \tau\tau$

- Shortcomings in modelling of Z+jets events
  $\rightarrow$ uncertainties folded with uncertainties from tau decay
- Can not study background in SR
- Determine normalization for MC from embedded $Z \rightarrow ll$ in control regions
- Embedding :
  1. Select $Z \rightarrow ll$
  2. Unfold effects from lepton reconstruction, isolation, identification
  3. Parametrize tau decay from visible pt and total truth p_T
  4. Scale lepton p accordingly
  5. Consider efficiencies by reweighting
  6. Apply τ SR selection

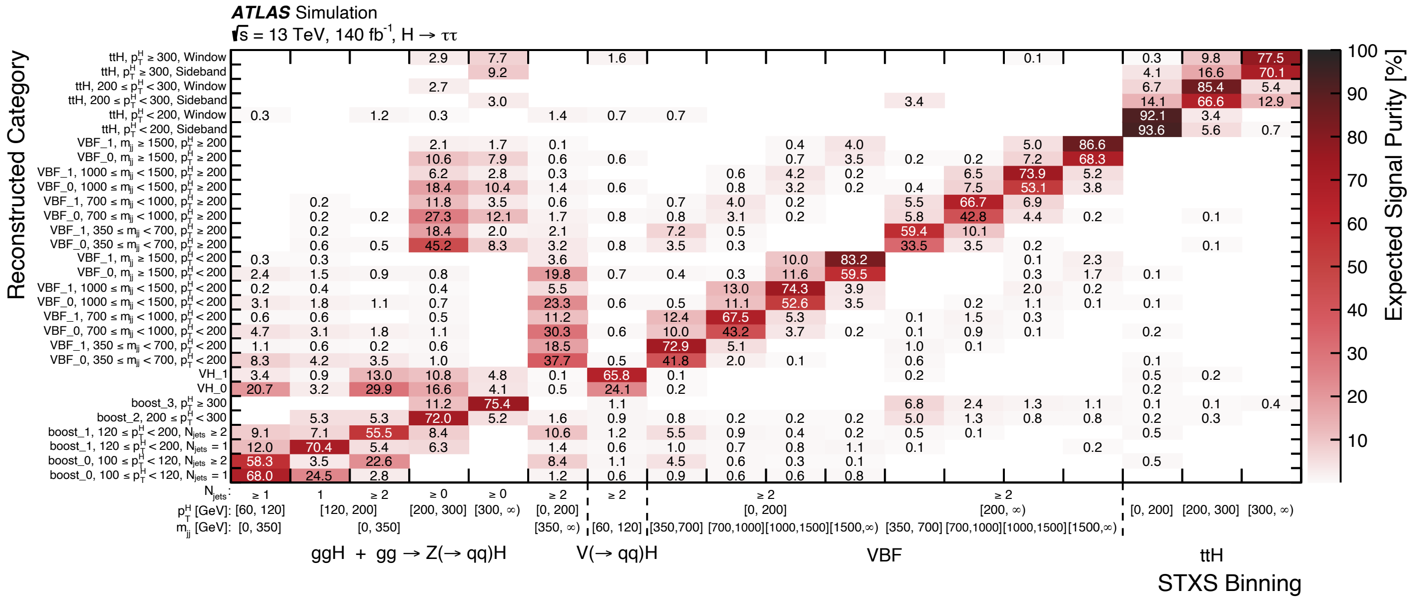
ATLAS-CONF-2021-044



SIGNAL PURITY

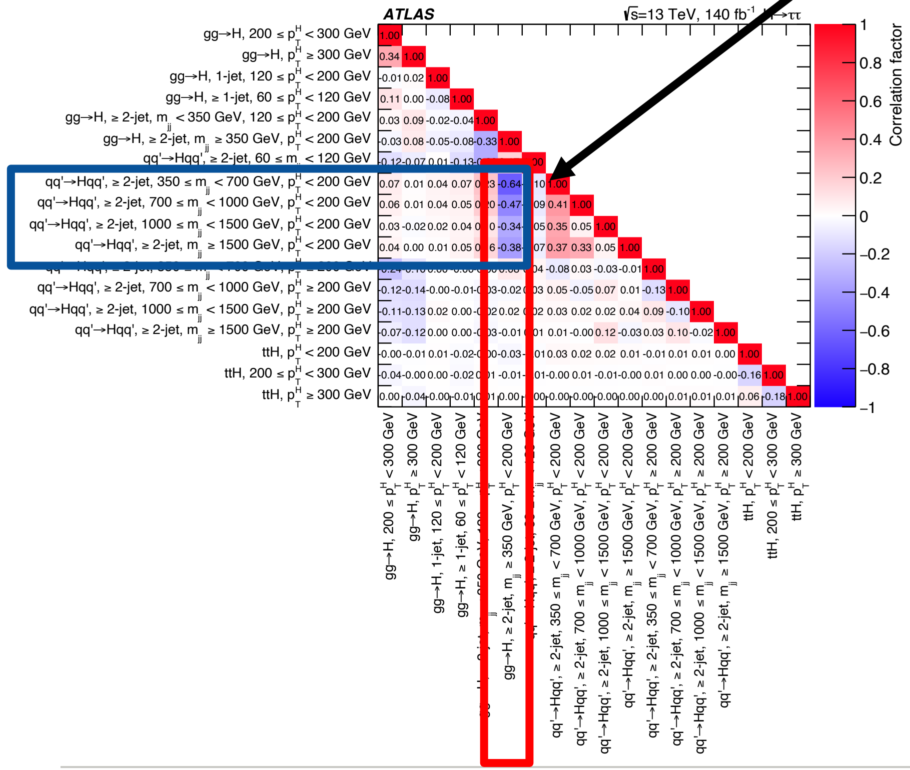
- **VBF 0:** background enriched, **VBF 1:** signal enriched
- **VBF-like ggH** events contribute strongly in VBF 0

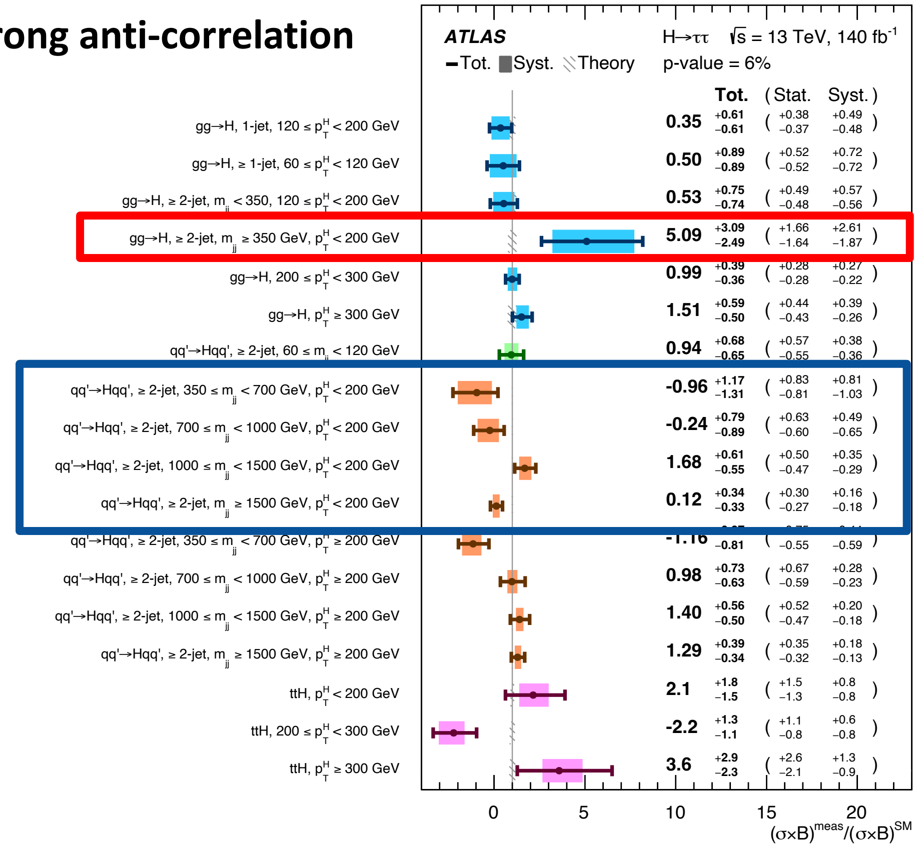
arxiv 2407.16320



CORRELATIONS

strong anti-correlation





arxiv 2407.16320

CONSEQUENCES FOR FUTURE MEASUREMENTS

Signal separation:

- Profit from MVA techniques to ensure better separation (VBF vs ggH)
- Neural network observable instead of MMC to differentiate higgs processes
- Optimize STXS binning

$Z \rightarrow \tau\tau$:

- Modelling in extreme phase-space not satisfactory
- Can also extract shape from embedding
- Binned normalization factors

Fakes:

- Signal region split in decay-mode dependent reconstruction

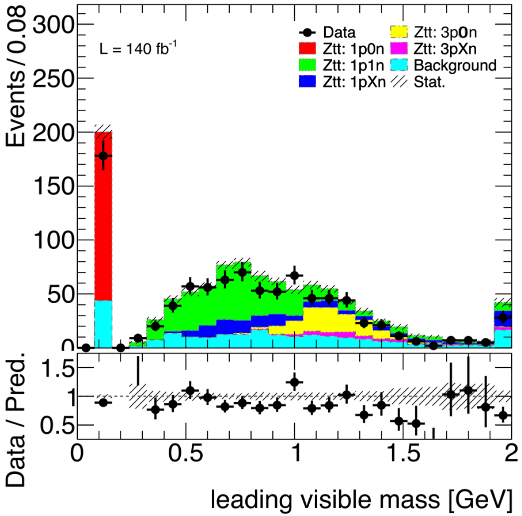
Tau reconstruction:

- End-to-end in particle flow

DECAY-MODE EFFICIENCY CORRECTION FACTORS

APPROACH: Account for decreasing classification efficiency by correction factors in the fit

$$m(\tau_{\text{had-vis},0}) = \sqrt{(E_{0,c} + E_{0,n})^2 - (Px_{0,c} + Px_{0,n})^2 - (Py_{0,c} + Py_{0,n})^2 - (Pz_{0,c} + Pz_{0,n})^2}$$



→ **Define new CR**

region	general	additionally
tau_m_vis_CR	pre-selection	30 GeV< $pT(j_1)$ <40 GeV & 60 GeV< MMC(mlm)<95 GeV
tau_m_vis_VAL	pre-selection	$pT(j_1)$ < 40 GeV & MMC(mlm)<60 GeV
vbf_new	VBF	$pT(j_1)$ > 40 GeV or ($pT(j_1)$ < 40 GeV & MMC(mlm) >95 GeV)

MATRIX METHOD FOR LEP FAKES

- Applied in leplep channel

$$\begin{bmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{bmatrix} = \begin{bmatrix} \epsilon_r \epsilon_r & \epsilon_r \epsilon_f & \epsilon_f \epsilon_r & \epsilon_f \epsilon_f \\ \epsilon_r (1-\epsilon_r) & \epsilon_r (1-\epsilon_f) & (1-\epsilon_f)\epsilon_r & \epsilon_f (1-\epsilon_f) \\ (1-\epsilon_r)\epsilon_r & (1-\epsilon_r)\epsilon_f & (1-\epsilon_f)\epsilon_r & (1-\epsilon_f)\epsilon_f \\ (1-\epsilon_r)(1-\epsilon_r) & (1-\epsilon_r)(1-\epsilon_f) & (1-\epsilon_f)(1-\epsilon_r) & (1-\epsilon_f)(1-\epsilon_f) \end{bmatrix} \begin{bmatrix} N_{rr} \\ N_{rf} \\ N_{fr} \\ N_{ff} \end{bmatrix}$$

- Differentiate real and fake leptons
- Determine efficiencies of real or fake leptons passing tight selection
- Determine number of tight and loose leptons

FAKE ESTIMATION HADHAD CHANNEL

- Both τs failing loose excluded in n-tuples
- W+jet CR of the lephad selection includes failing loose
- If both τs fake, need additional FF

$$FF_{\text{nm}} = \frac{\left(N^{\tau}_{\text{Data}} - N^{\tau}_{\text{MC, genuine }\tau}\right)^{\text{WCR}}_{\text{medium }\tau}}{\left(N^{\text{anti}-\tau}_{\text{Data}} - N^{\text{anti}-\tau}_{\text{MC, genuine }\tau}\right)^{\text{WCR}}_{\text{not medium }\tau}}$$

$$FF_{\text{lnm}} = \frac{\left(N^{\tau}_{\text{Data}} - N^{\tau}_{\text{MC, genuine }\tau}\right)^{\text{WCR}}_{\text{medium }\tau}}{\left(N^{\text{anti}-\tau}_{\text{Data}} - N^{\text{anti}-\tau}_{\text{MC, genuine }\tau}\right)^{\text{WCR}}_{\text{loose not medium }\tau}}$$

- τs selected in the SR:

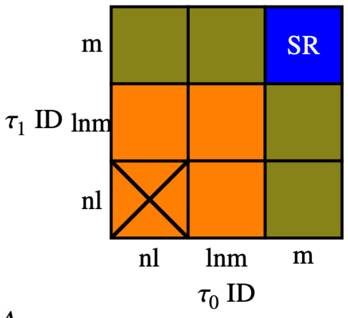
$$\tau_0^P \tau_1^P = \tau_0^T \tau_1^T + FF^0 \tau_0^A \tau_1^P + FF^1 \tau_0^P \tau_1^A - FF^0 FF^1 \tau_0^A \tau_1^A .$$

Application:

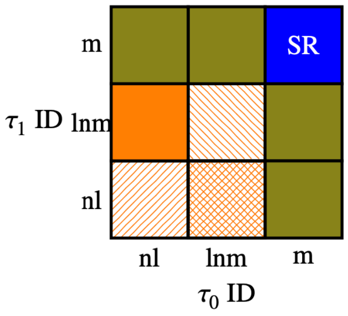
- Single-fake → exclusively nm FF
- Double-fake → …

1. τ_0-ID: lnm, τ_1-ID: nl: $w = -\frac{1}{2}\left(FF_{lnm}(\tau_0) \cdot FF_{nm}(\tau_1)\right)$

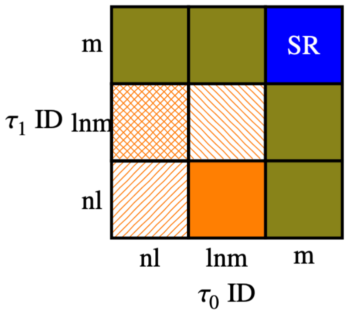
3. τ_1-ID: lnm, τ_0-ID: lnm: $w = -\frac{1}{2}\left(FF_{lnm}(\tau_0) \cdot FF_{nm}(\tau_1) + FF_{nm}(\tau_0) \cdot FF_{lnm}(\tau_1)\right)$



(a) τ-ID combinations



(b) τ_0-ID: lnm,τ_1-ID: nm



(c) τ_1-ID: lnm,τ_0-ID: nm

FAKE UNCERTAINTIES

1. Statistical:

Cause: W+jet CR with limited statistics

→ Vary FF by 1σ of statistical uncertainty originating from CR

2. Parametrization:

Cause: closure of method not guaranteed

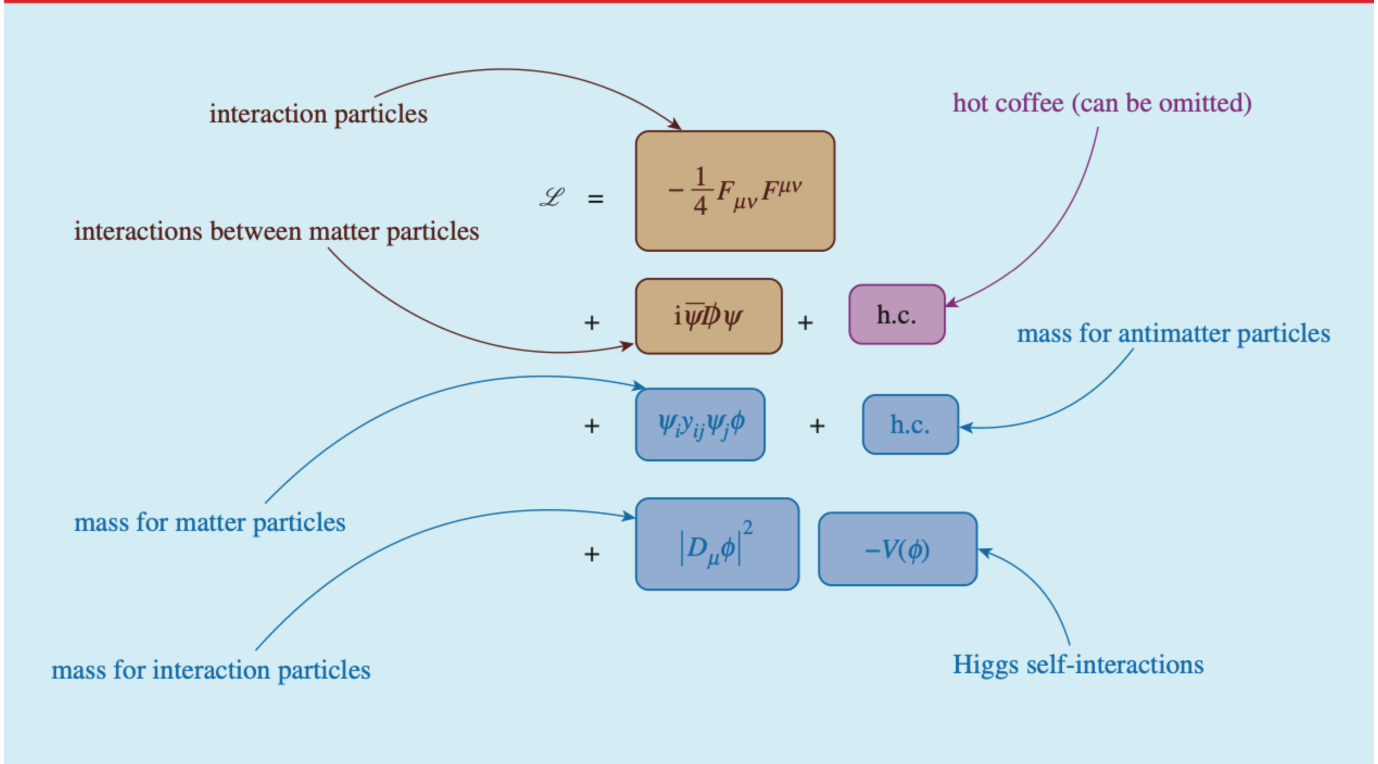
→ Derive FF for a SS region + determine deviation between data and background as measure of non-closure (test application strategy)

3. Background composition

Cause: different background composition in SR and CR

→ Determine FFs in different fake enriched regions + consider deviations

THE STANDARD MODEL LAGRANGIAN



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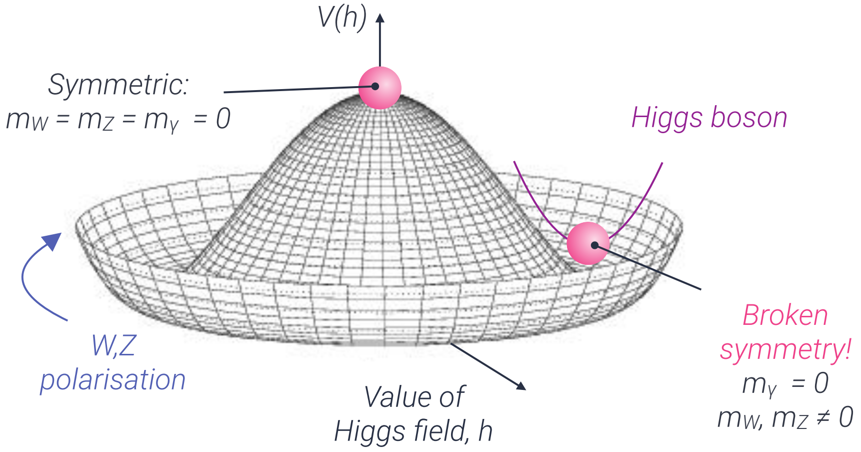
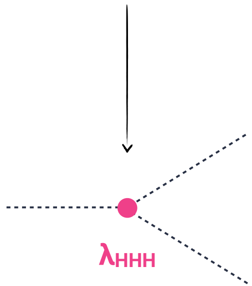
ELECTROWEAK SYMMETRY BREAKING



$$V(h) \simeq \frac{1}{2} m_H^2 h^2 + \lambda v h^3 + \frac{1}{4} \lambda h^4 + \ldots$$



Directly measure λ_{HHH} via HH production

Strength of λ_{HHH} relative to SM prediction ($\lambda_{HHH}/\lambda_{SM}$) = κ_λ

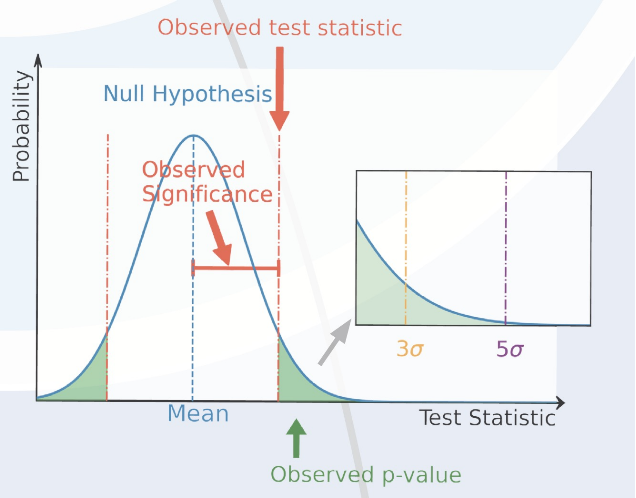
Katharine Leney: [1]

P-VALUE FOR STXS

- Describe compatibility with SM
- Test statistic:

  $\mathrm{D} = 2 \cdot ||\mathrm{NLL} - \mathrm{NLL_{SM}}||$

  NLL_SM → negative log-likelihood value for setting "all POIs = 1"
- D follows χ^2 with #dof $-$ #POI
- P-value $= 1 - \mathrm{CDF}$



[1]