The Higgs boson

—

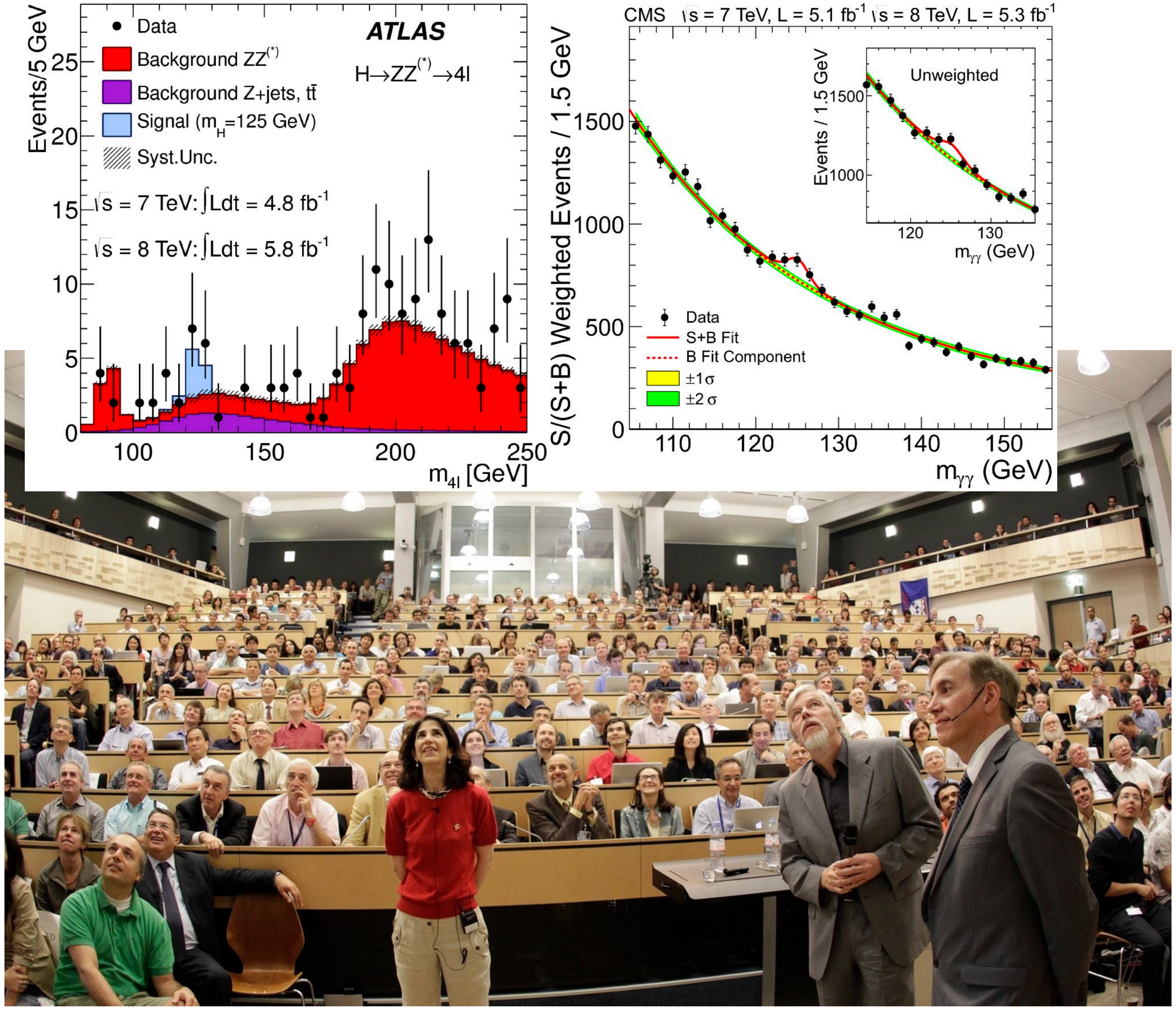
an endeavor towards precision

筑波大学
University of Tsukuba

Karsten Köneke
Universität Freiburg / CERN

11. 09. 2021

9 years ago: 4. Juli 2012



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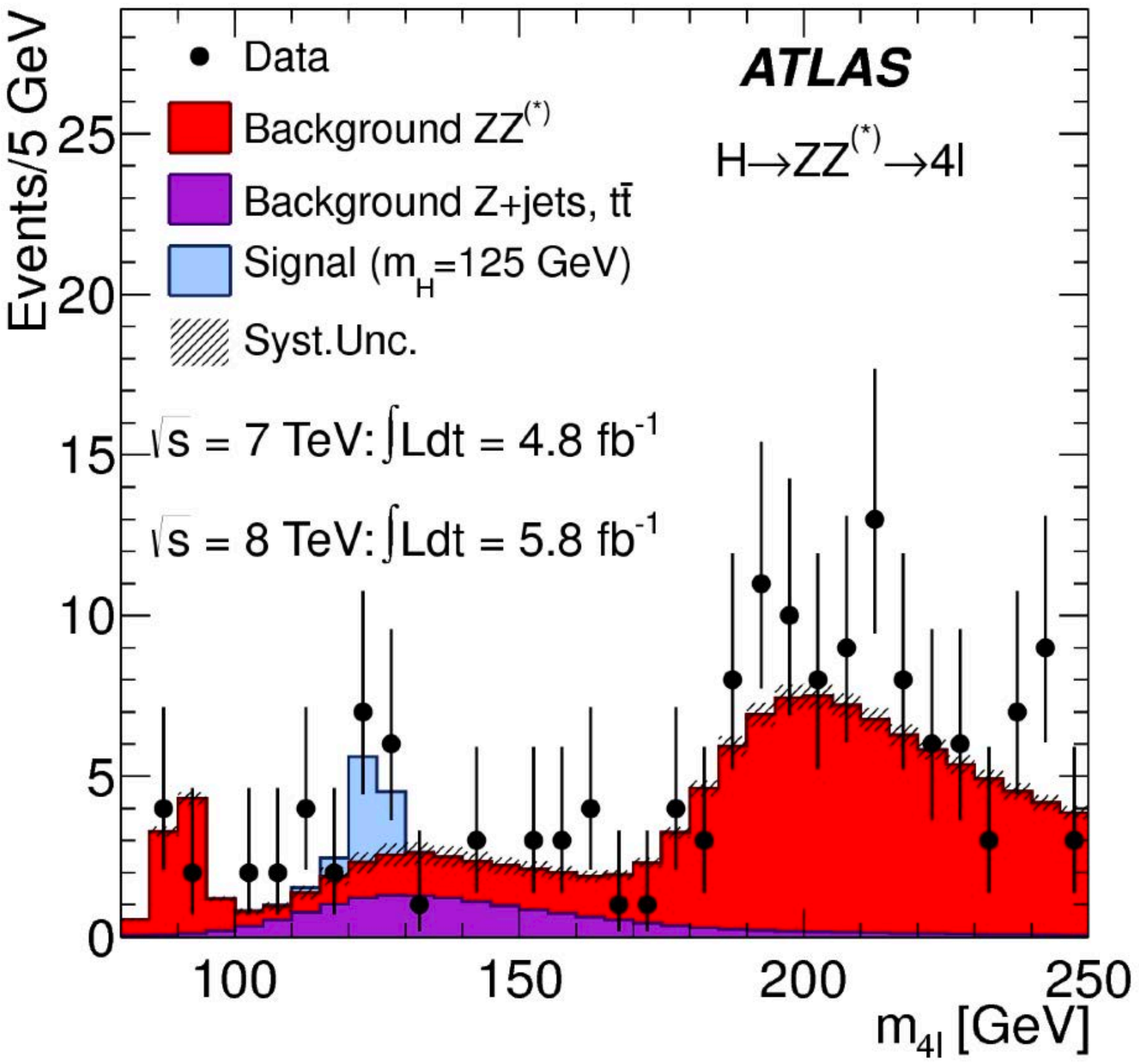

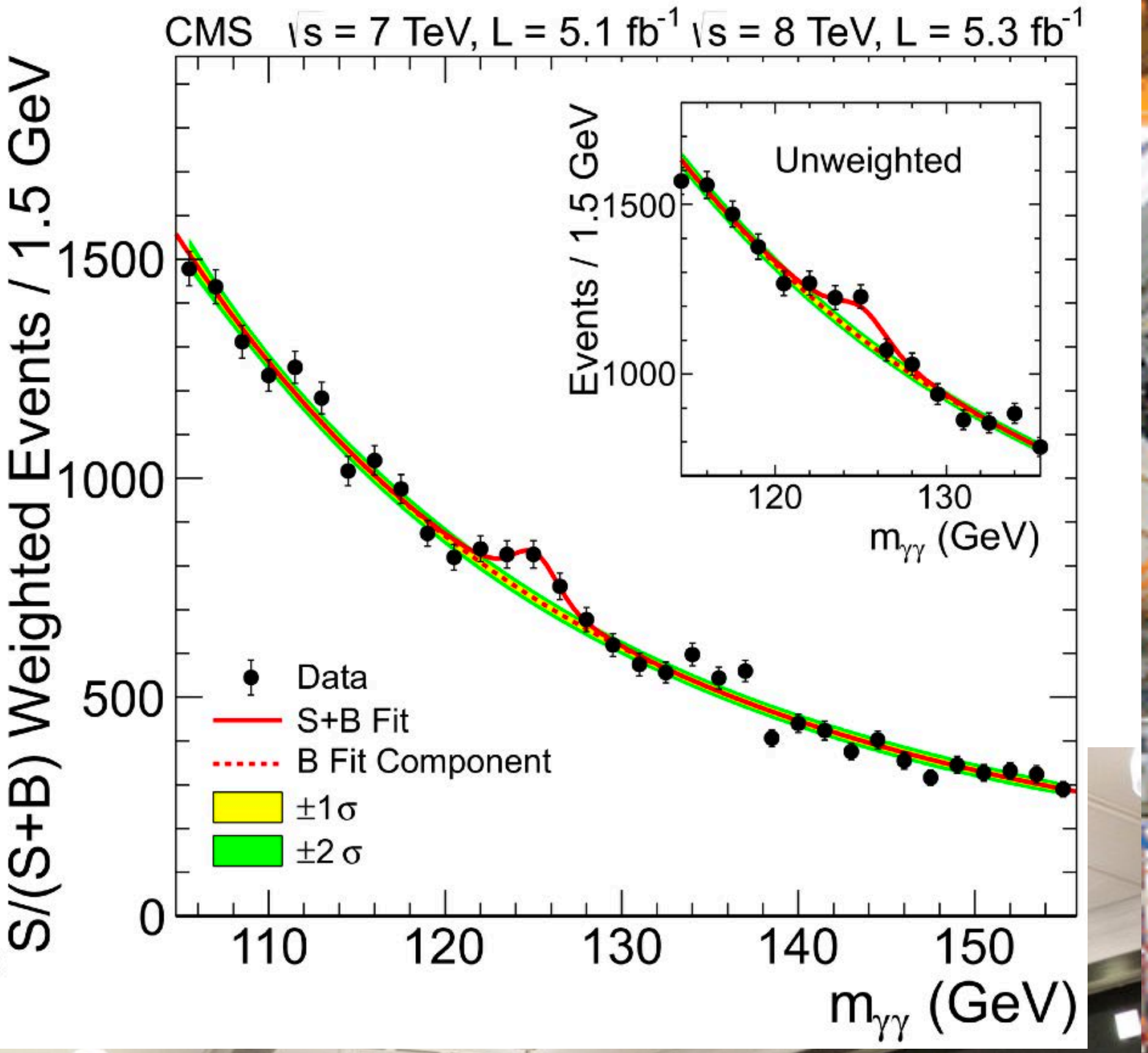

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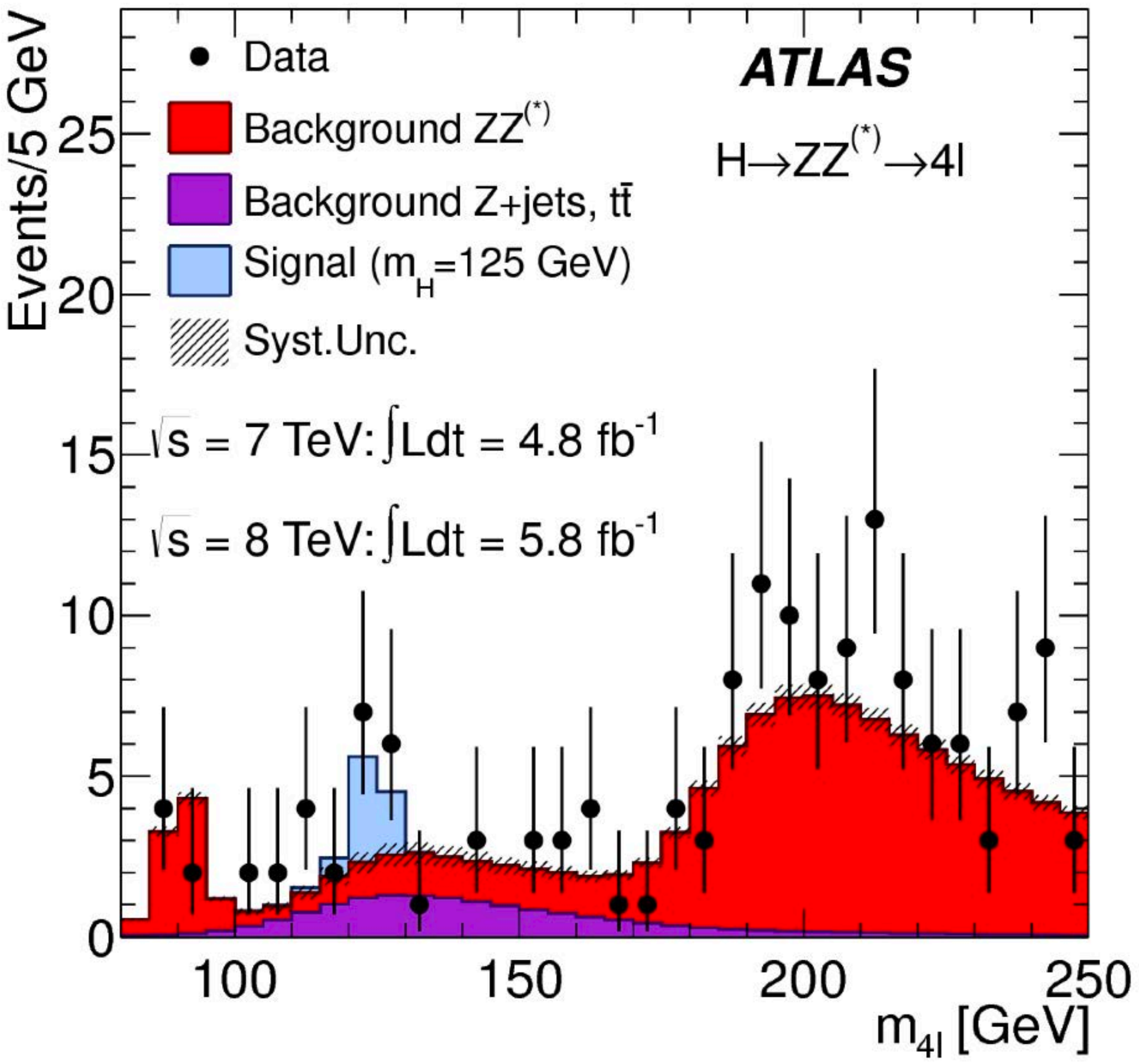

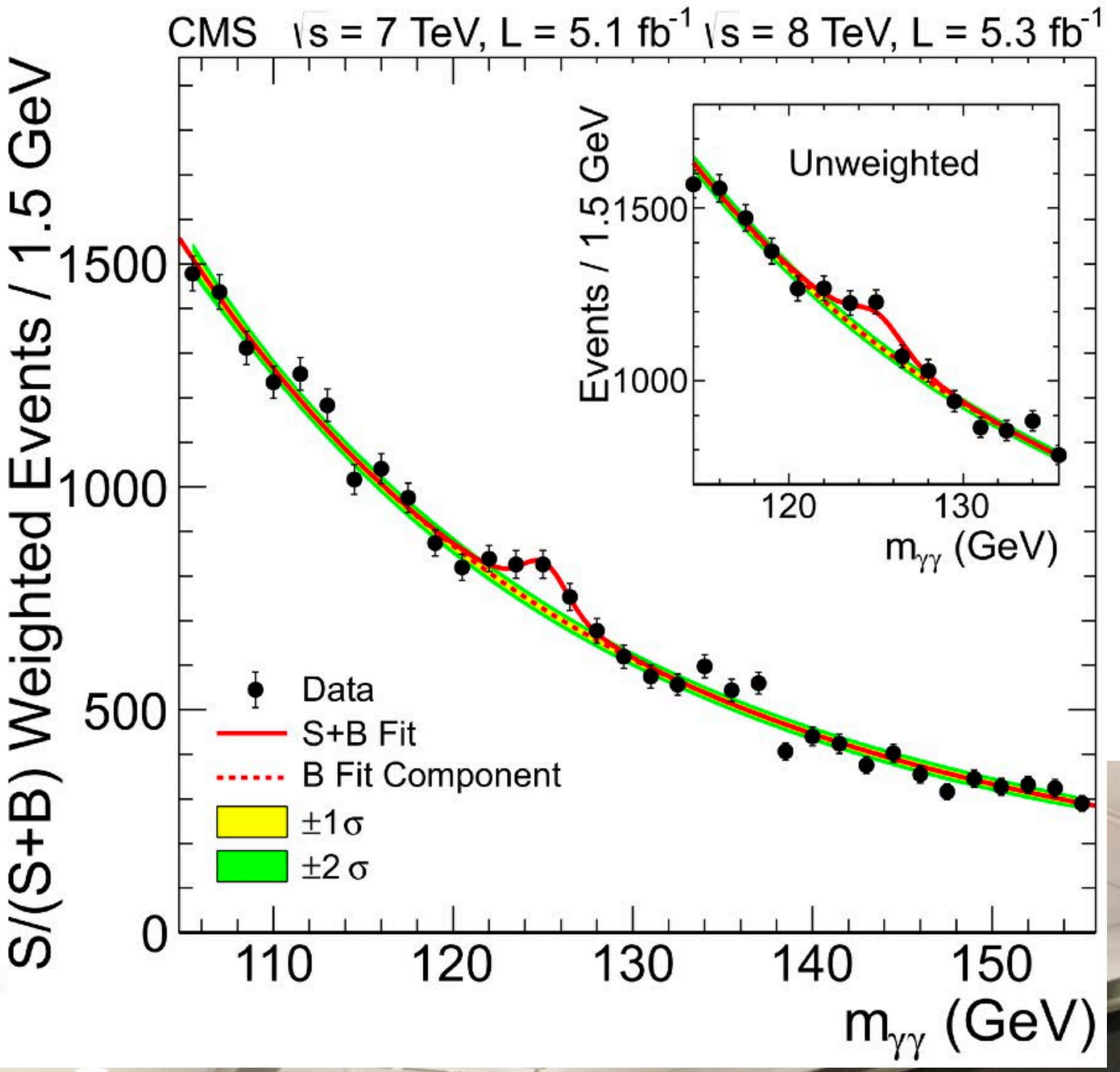

Why a Nobel prize?

Explanation of **Mass**…

Outline

Mass in “normal” Matter

- **Mass in atoms:**

  > 99.9% in the nucleus

- **Mass in nucleus:**

  ~95% binding energy of the Strong Force

$$E = mc^2$$

Brout-Englert-Higgs Mechanism

- **Problem**: *Mass of elementary particles*:
  - Mass terms in Lagrangian (boson:$-\frac{1}{2}m_A^2 A_\mu A^\mu$; fermion:$-m_f\bar{\psi}\psi$) violate invariance under gauge transformation!

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  (developed in 1960s by Brout, Englert, Higgs, and others)
  - Introduce complex scalar field $\boldsymbol{\phi(x)}$ with potential:

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

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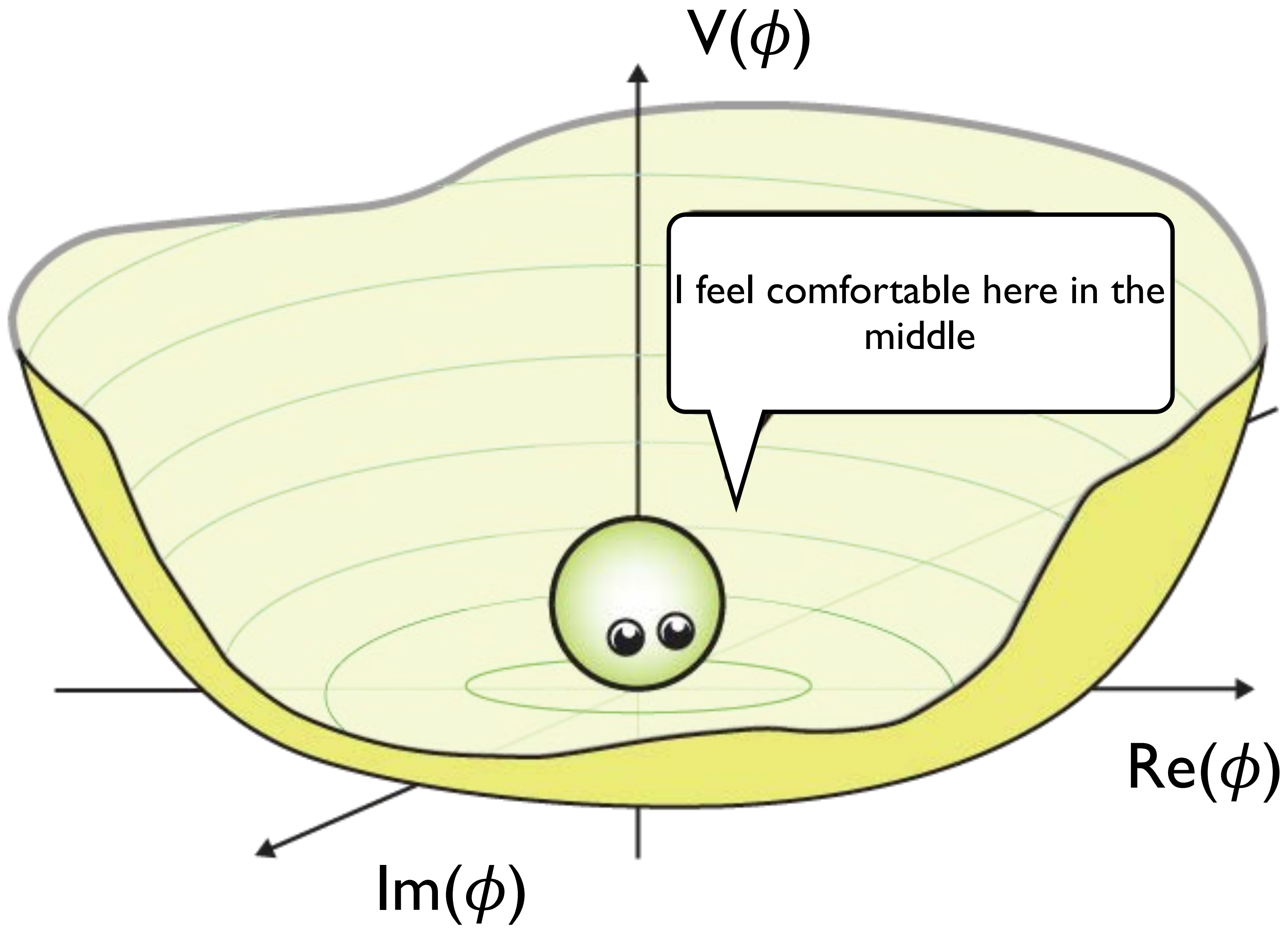

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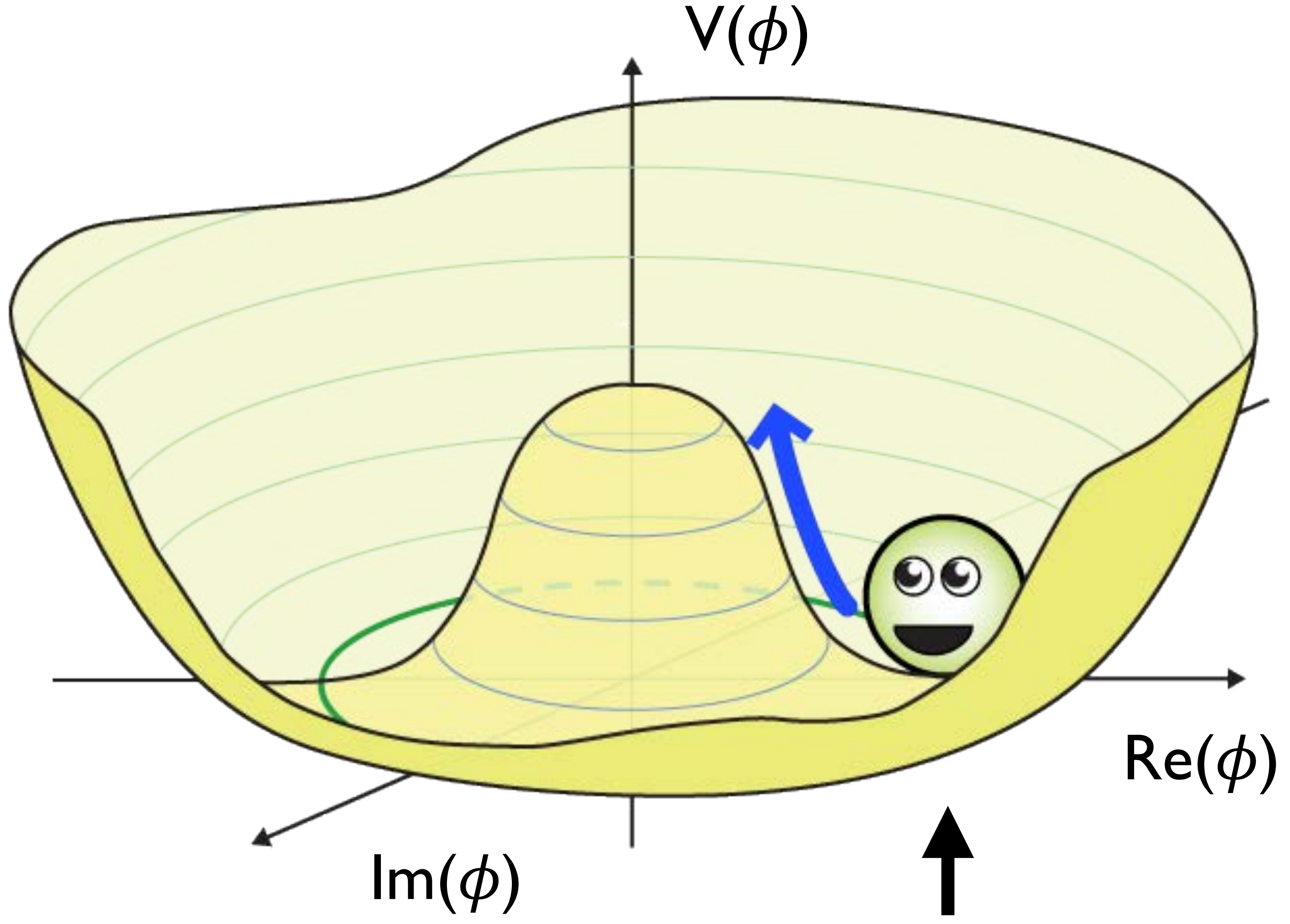
Spontaneous symmetry breaking



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

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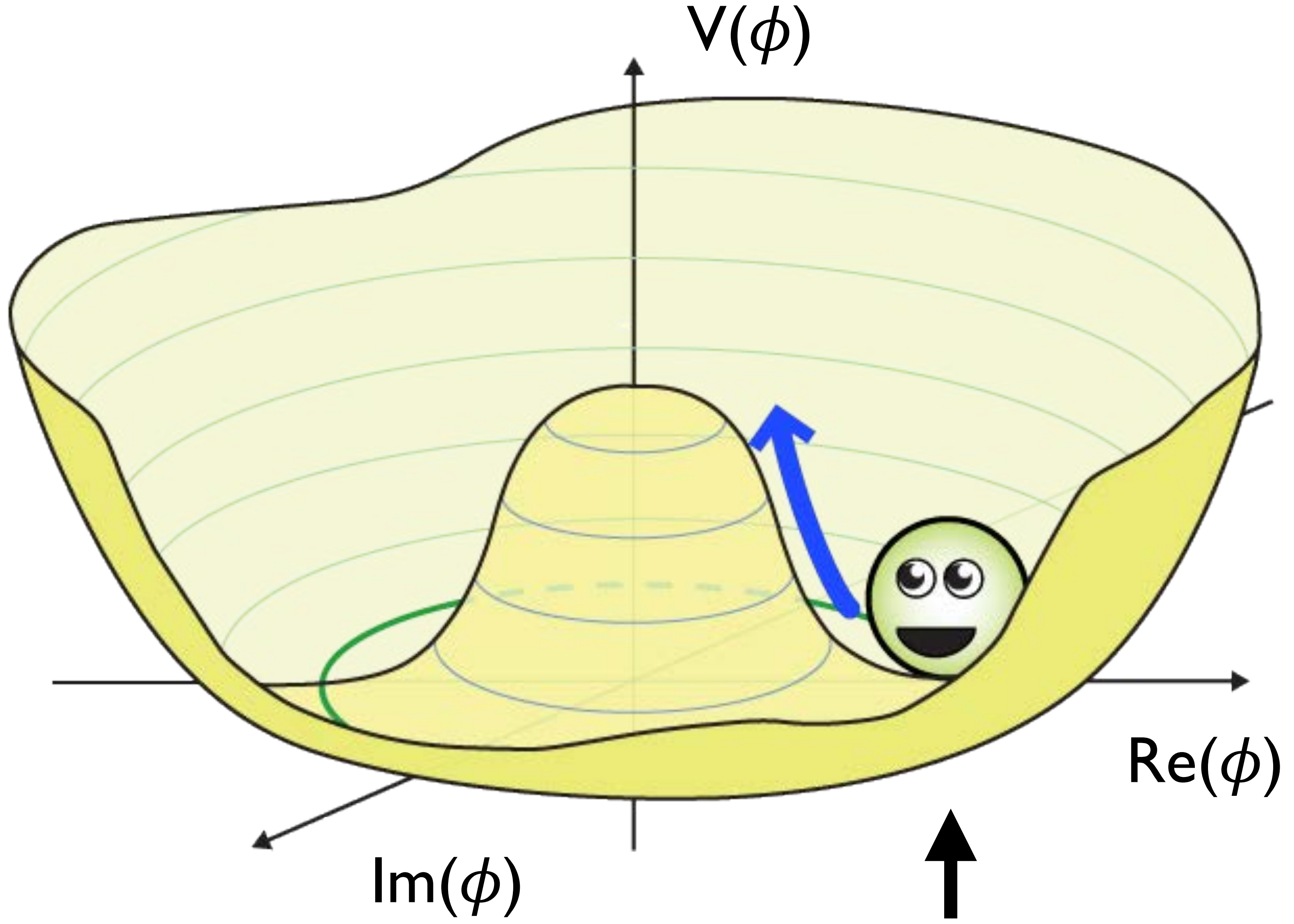

Expand $\phi(x)$ around new vacuum:

$$\phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

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Consequences

- Higgs boson with mass:

$$\boxed{m_{\mathrm{H}} = \sqrt{2\lambda}v}$$

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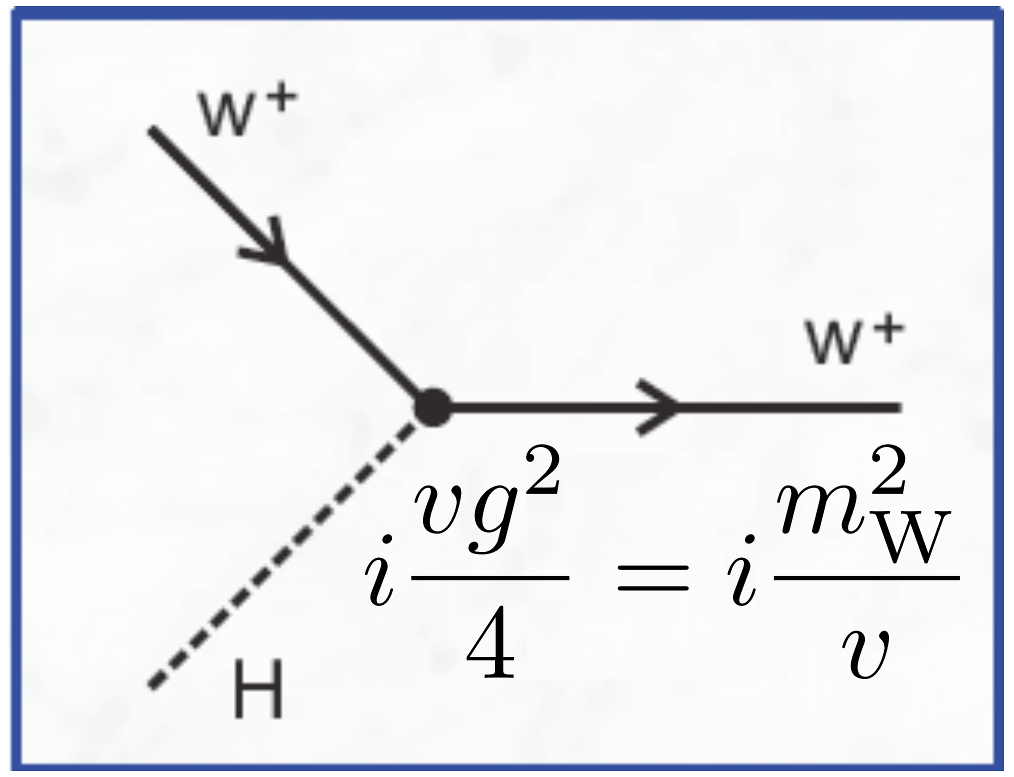
direct connection



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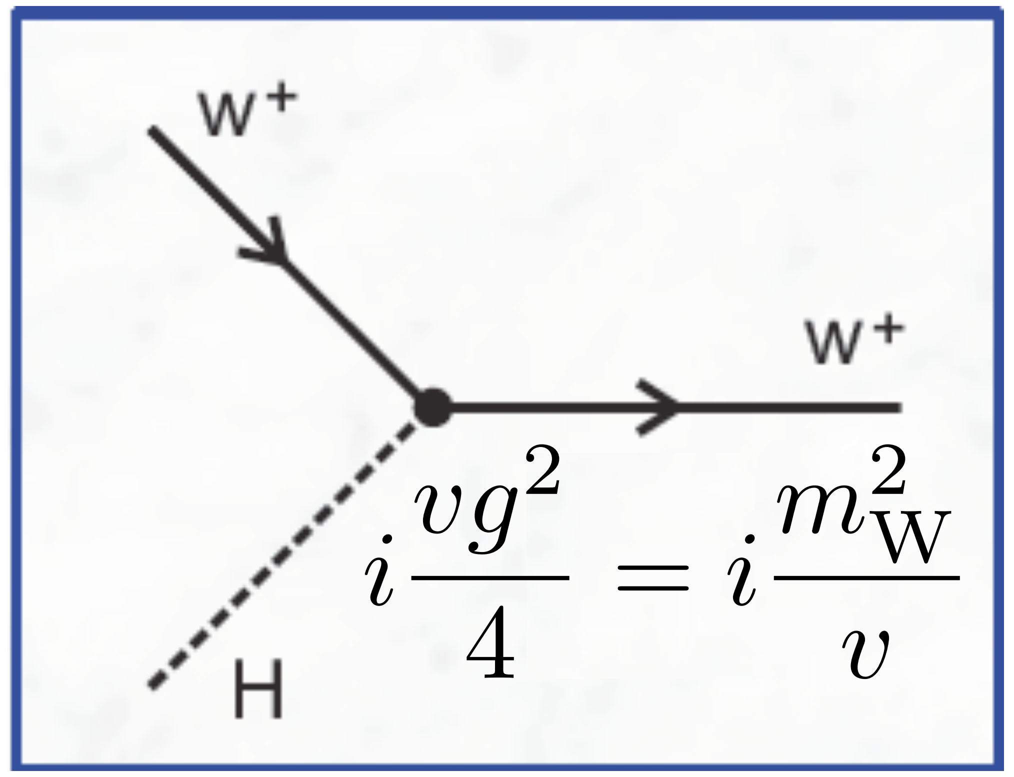
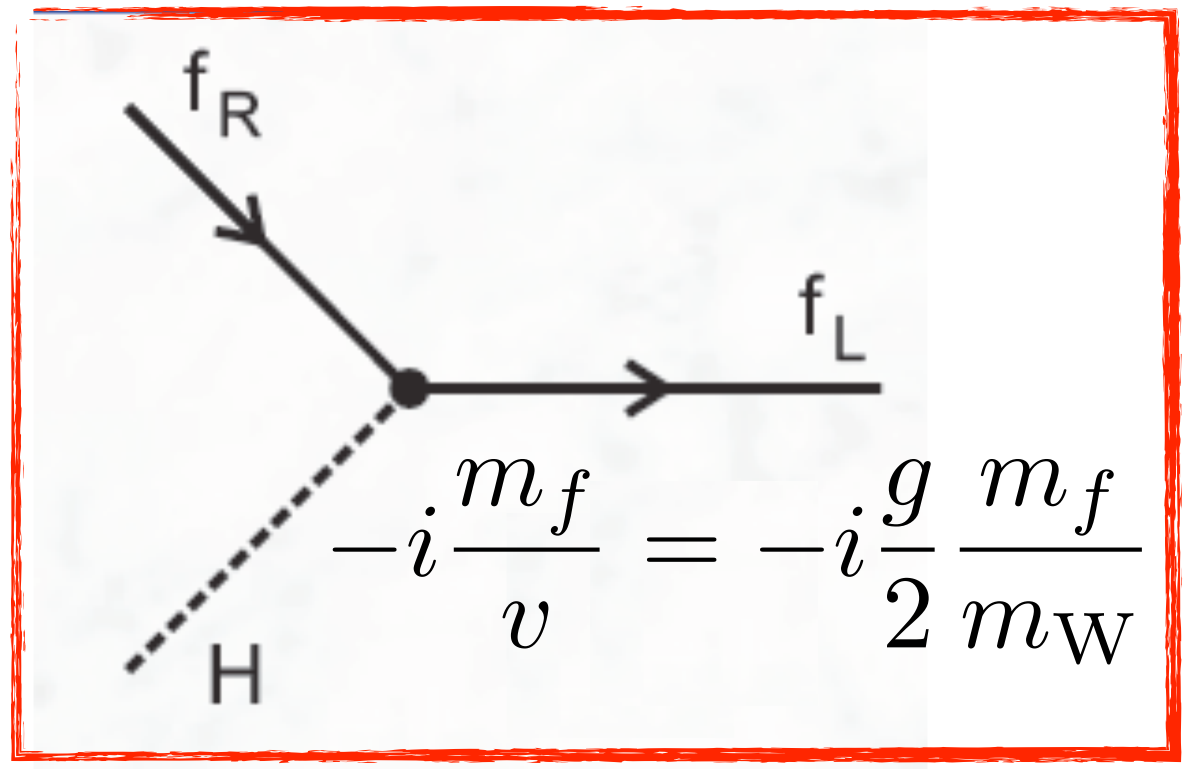


$$i\frac{vg^2}{4} = i\frac{m_{\mathrm{W}}^2}{v}$$

- Fermion masses and Yukawa interactions:

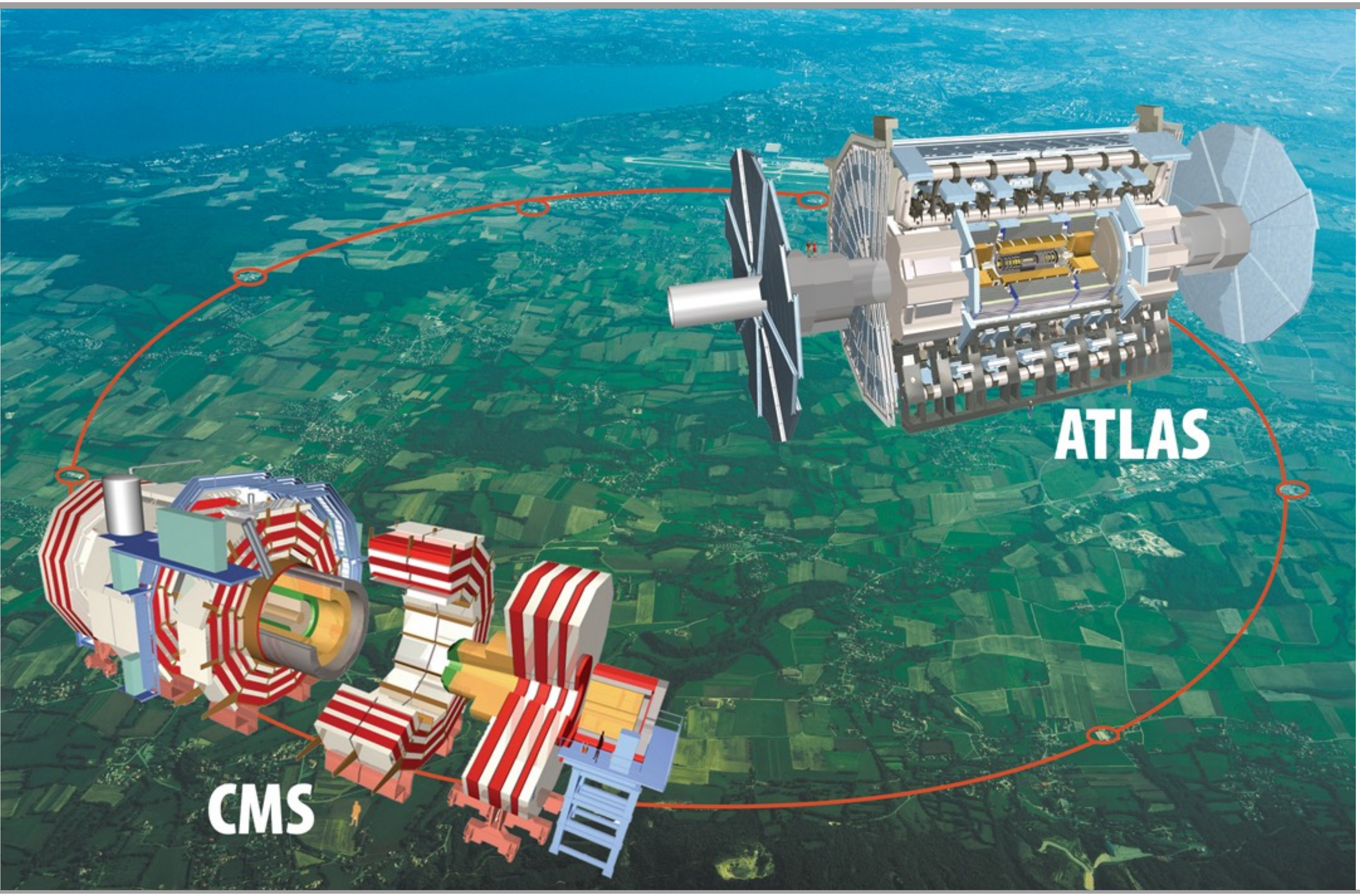
$$m_f = \frac{\lambda_f v}{\sqrt{2}}$$

direct connection ⟷



$$-i\frac{m_f}{v} = -i\frac{g}{2}\frac{m_f}{m_{\mathrm{W}}}$$

The LHC with ATLAS & CMS



LHC beam bunch crossing rate:
40 MHz

Up to ~70 pp collisions per bunch crossing

⇒ ~3 billion pp collisions per second

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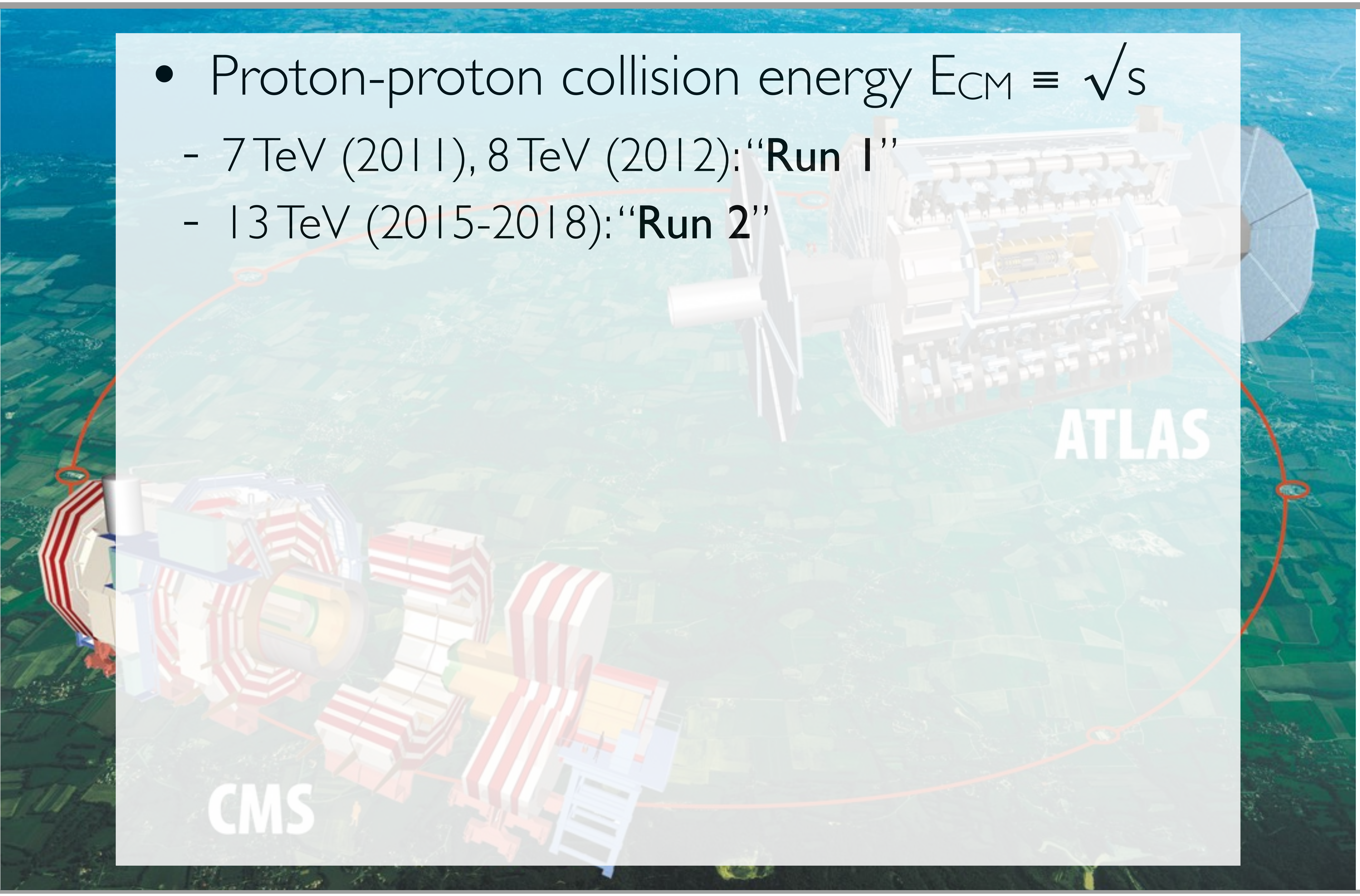

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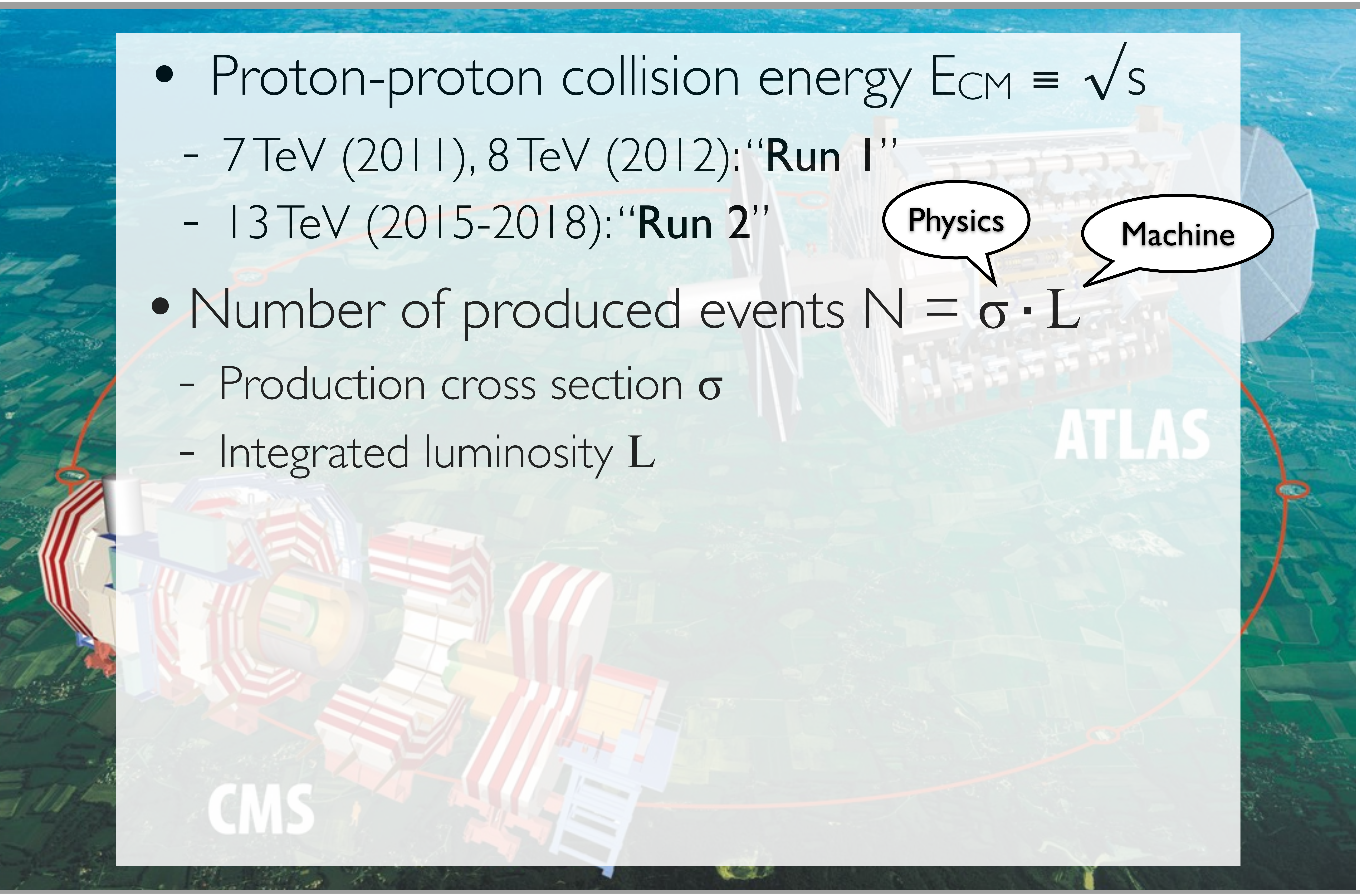

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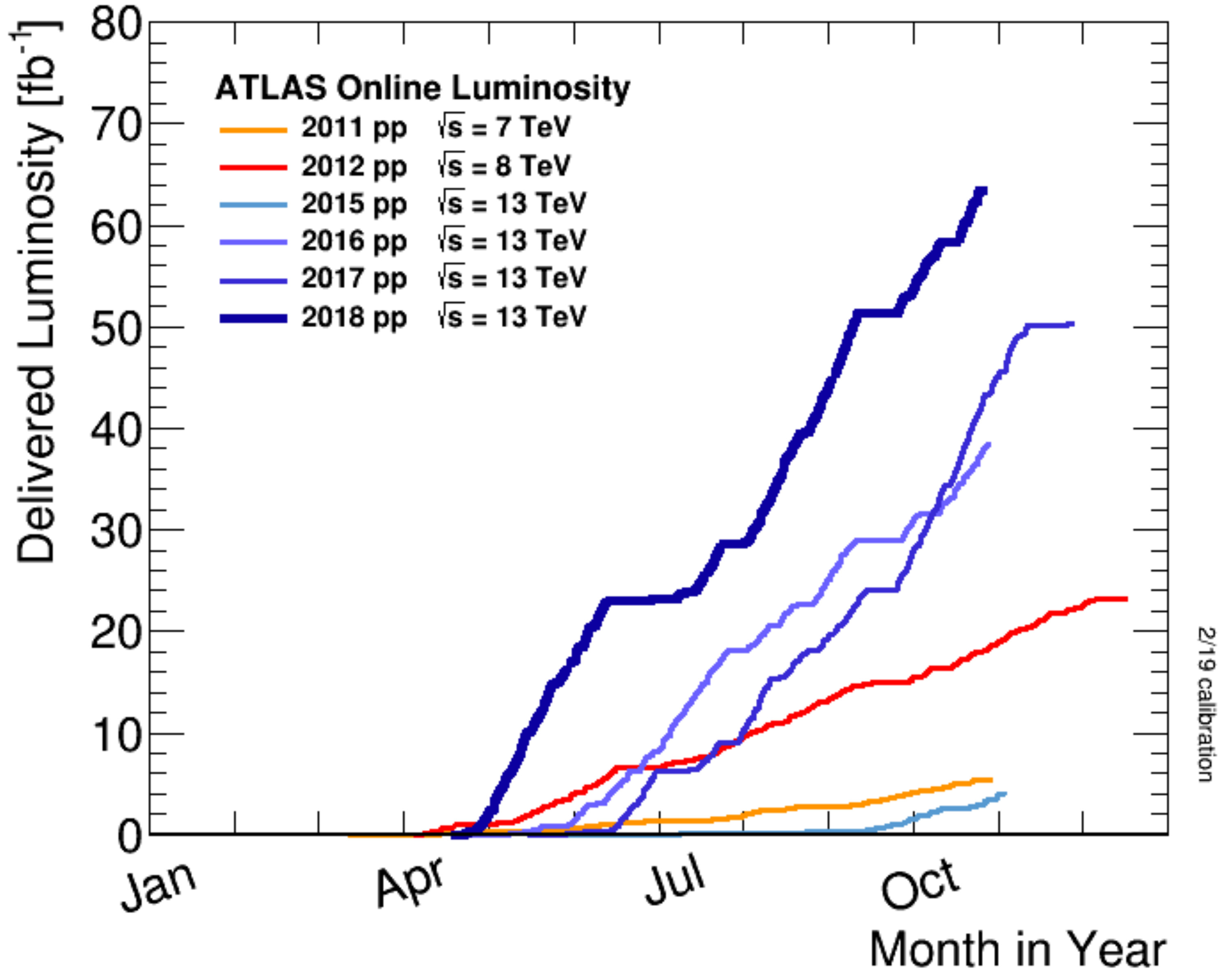

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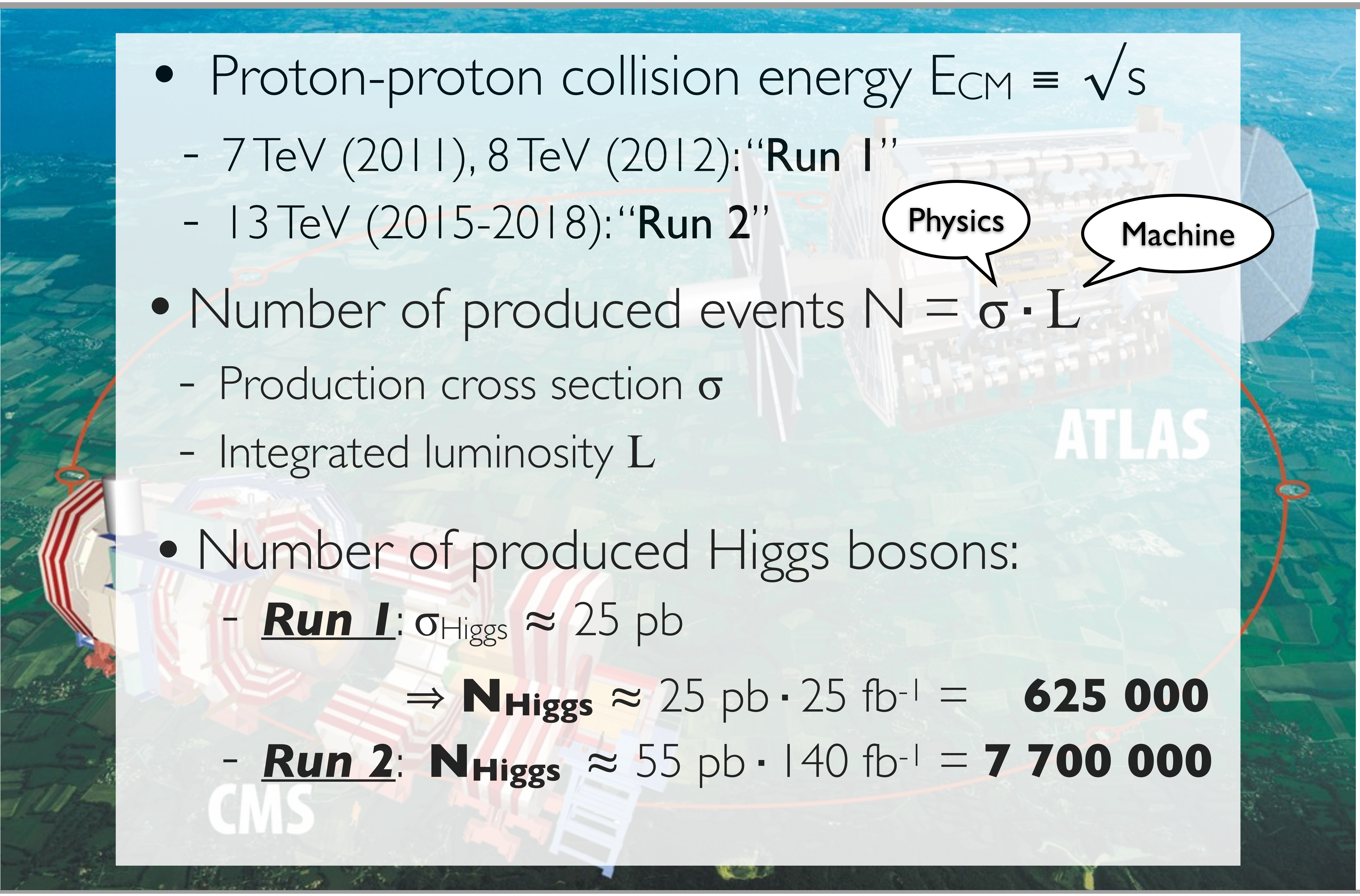

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  - ***Run 1***: $\sigma_{\text{Higgs}} \approx 25$ pb

    $\Rightarrow \mathbf{N_{Higgs}} \approx 25\ \text{pb} \cdot 25\ \text{fb}^{-1} =$ **625 000**
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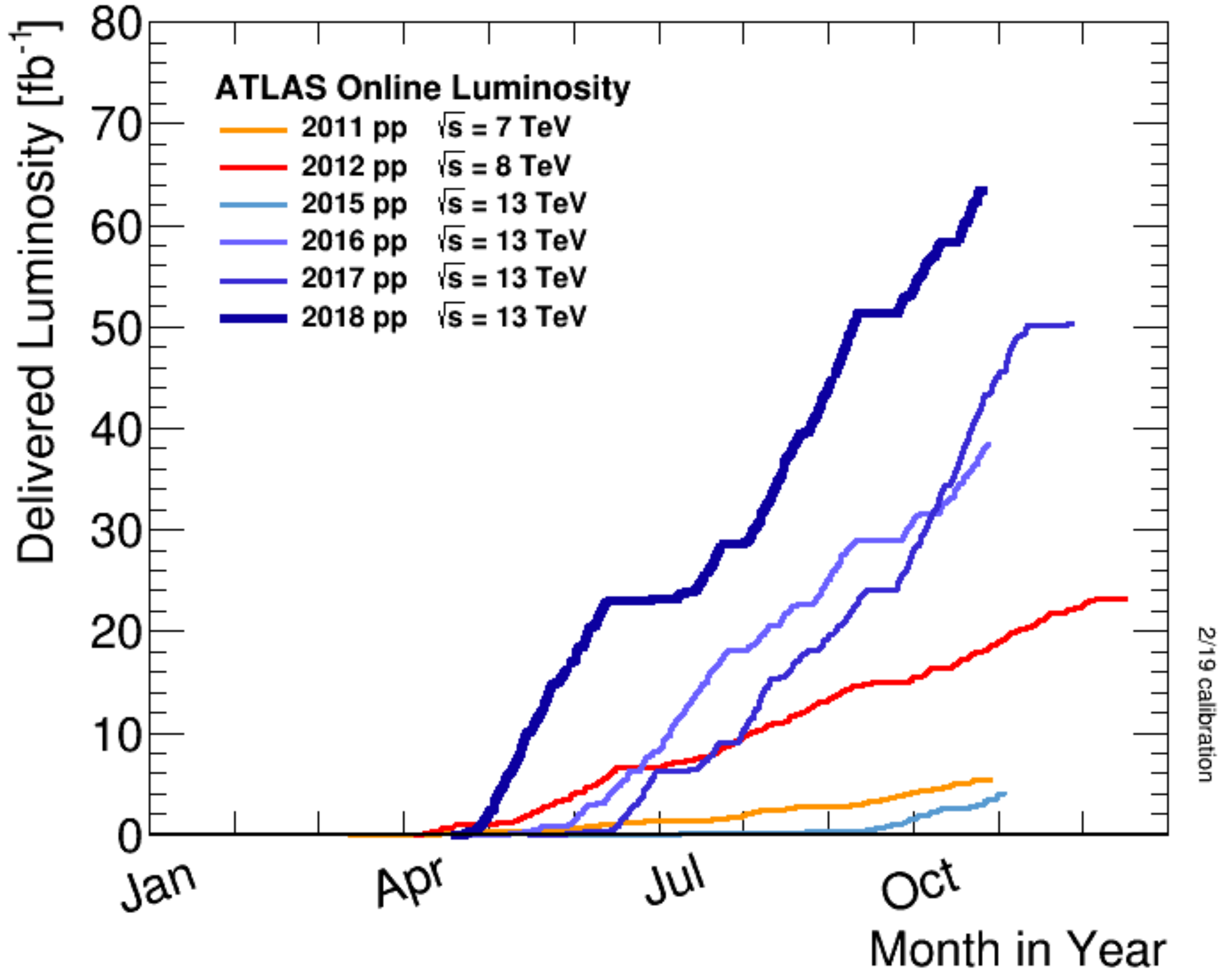

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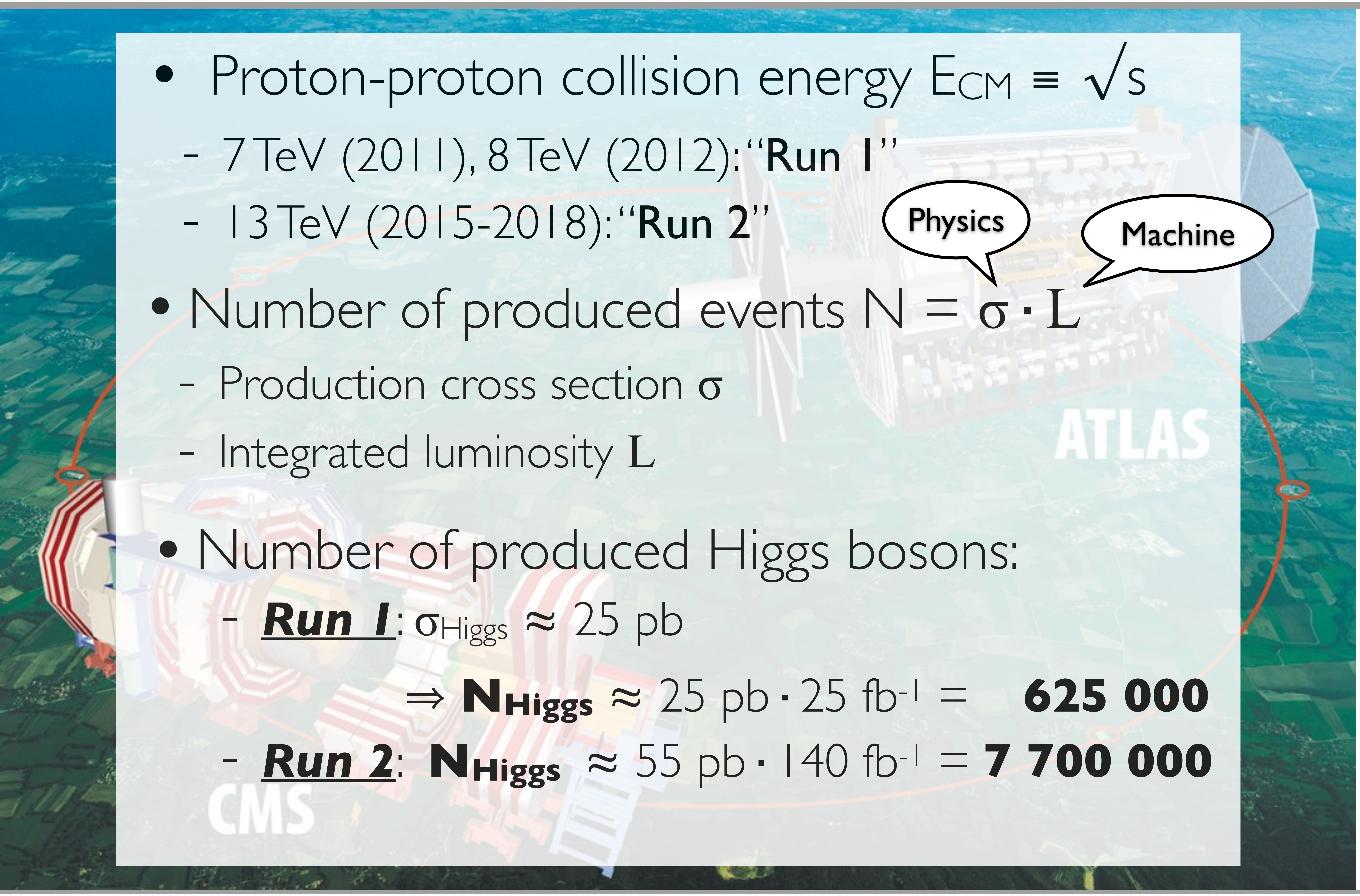

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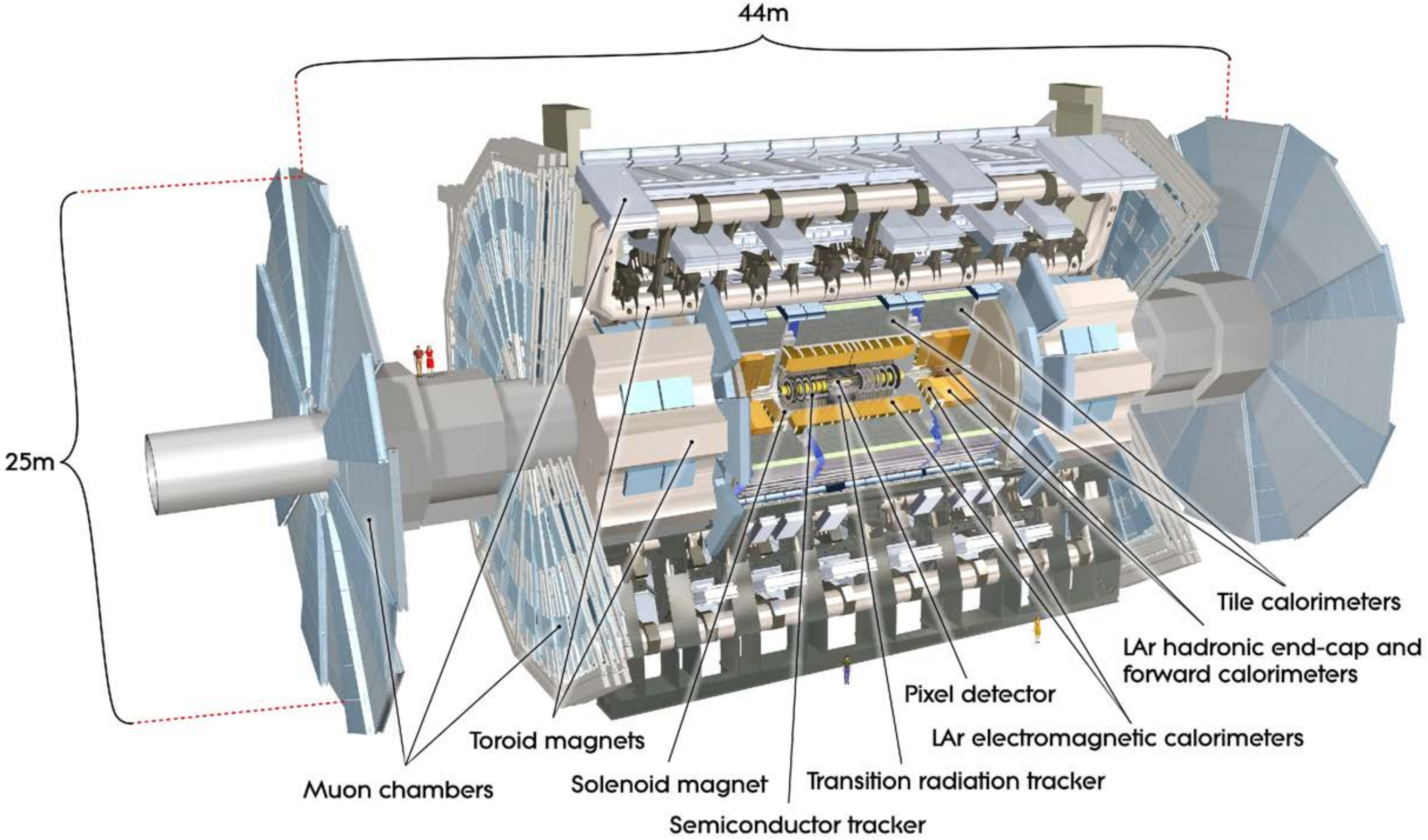
A Higgs boson is only produced in 1 out of 10^9 collisions

ATLAS Detektor



Higgs Boson Production at the LHC

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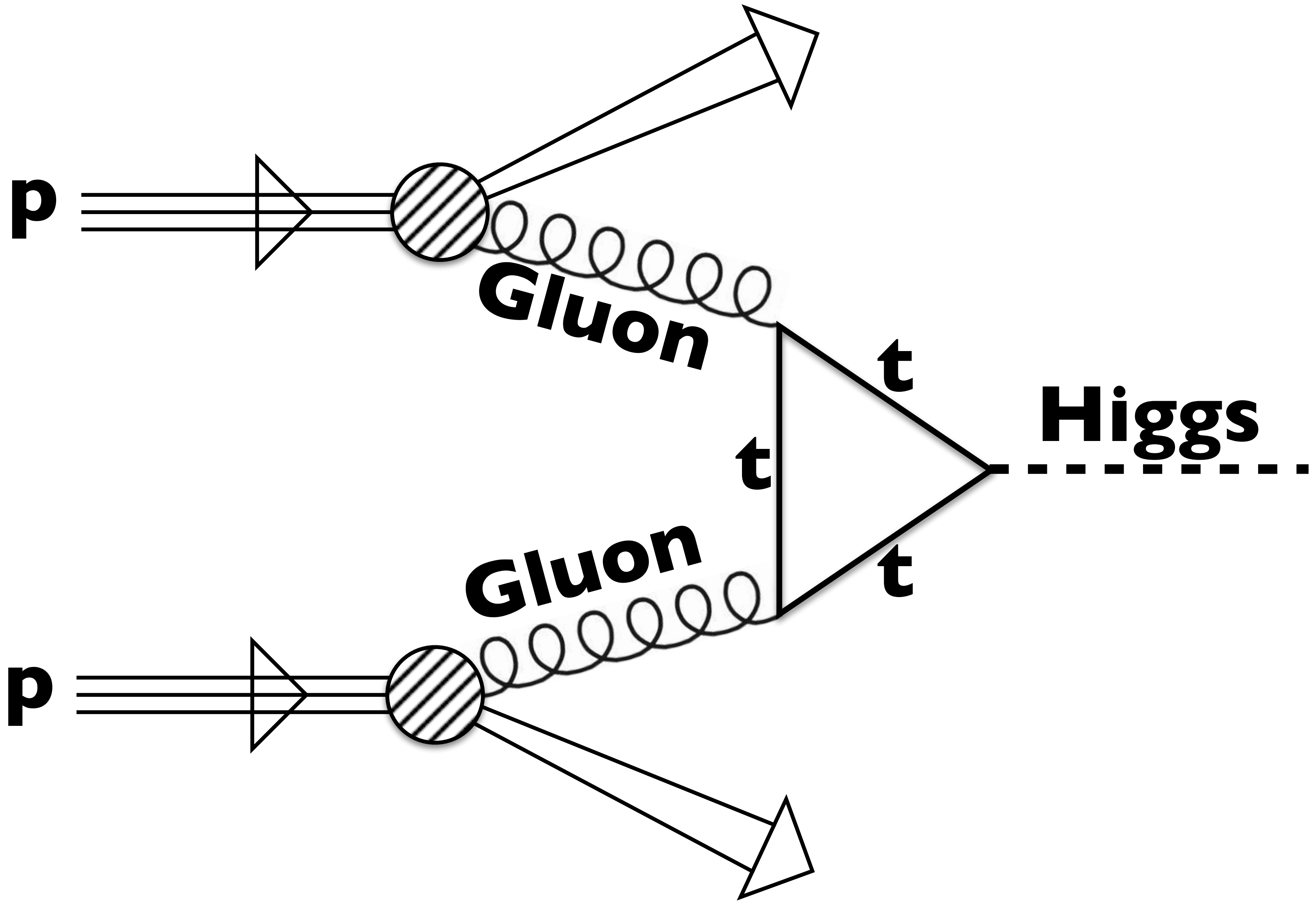

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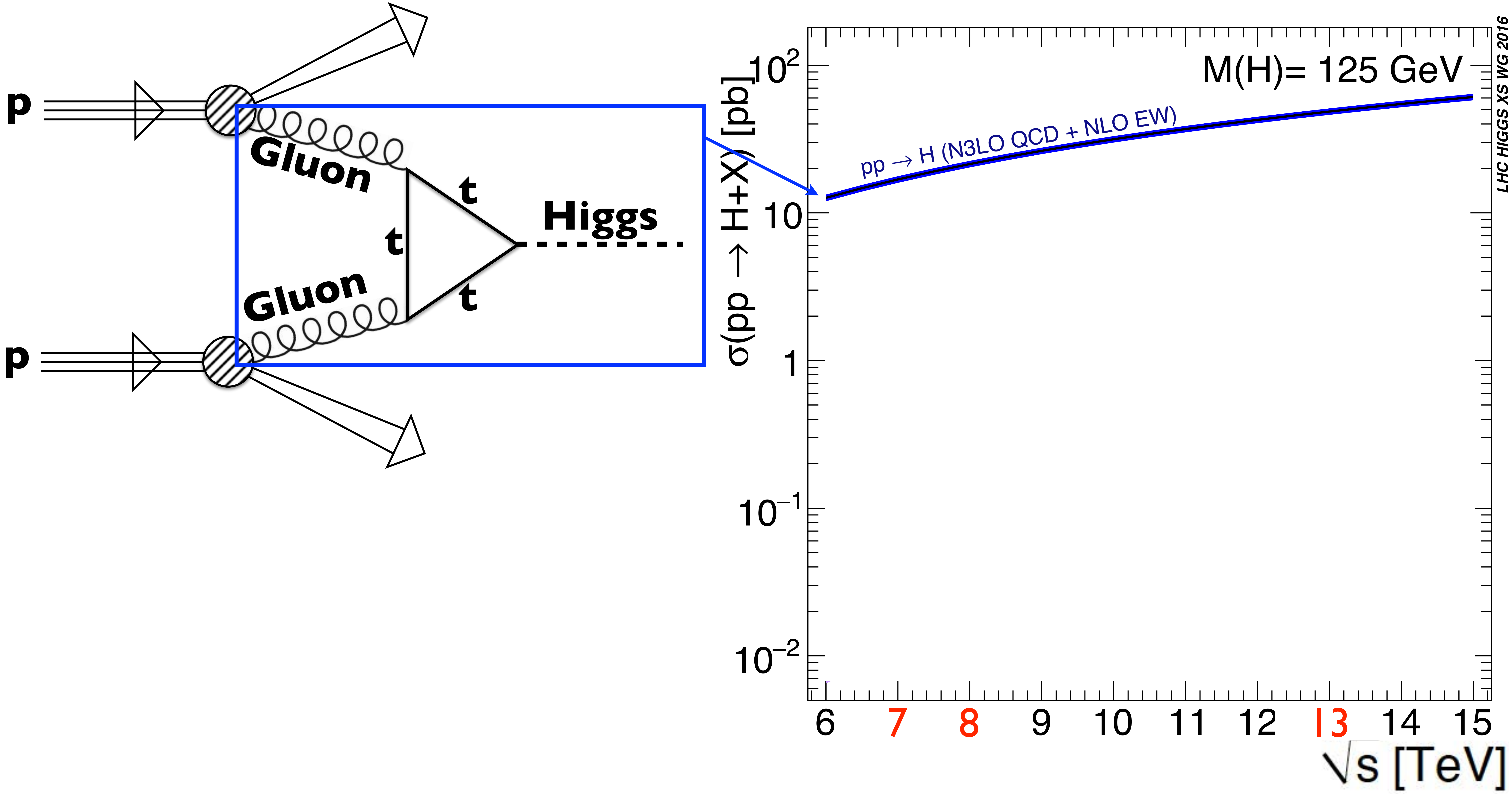

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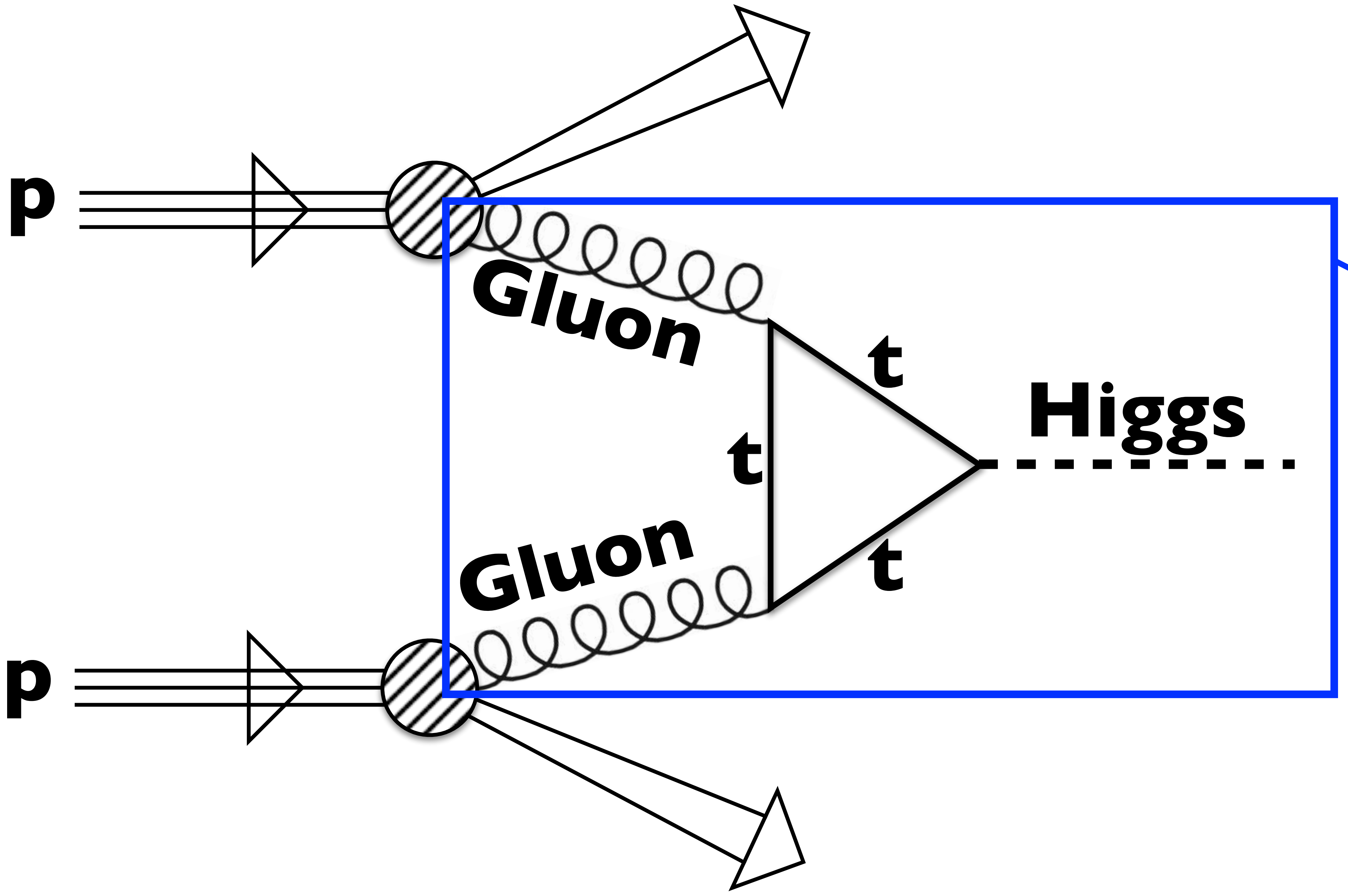
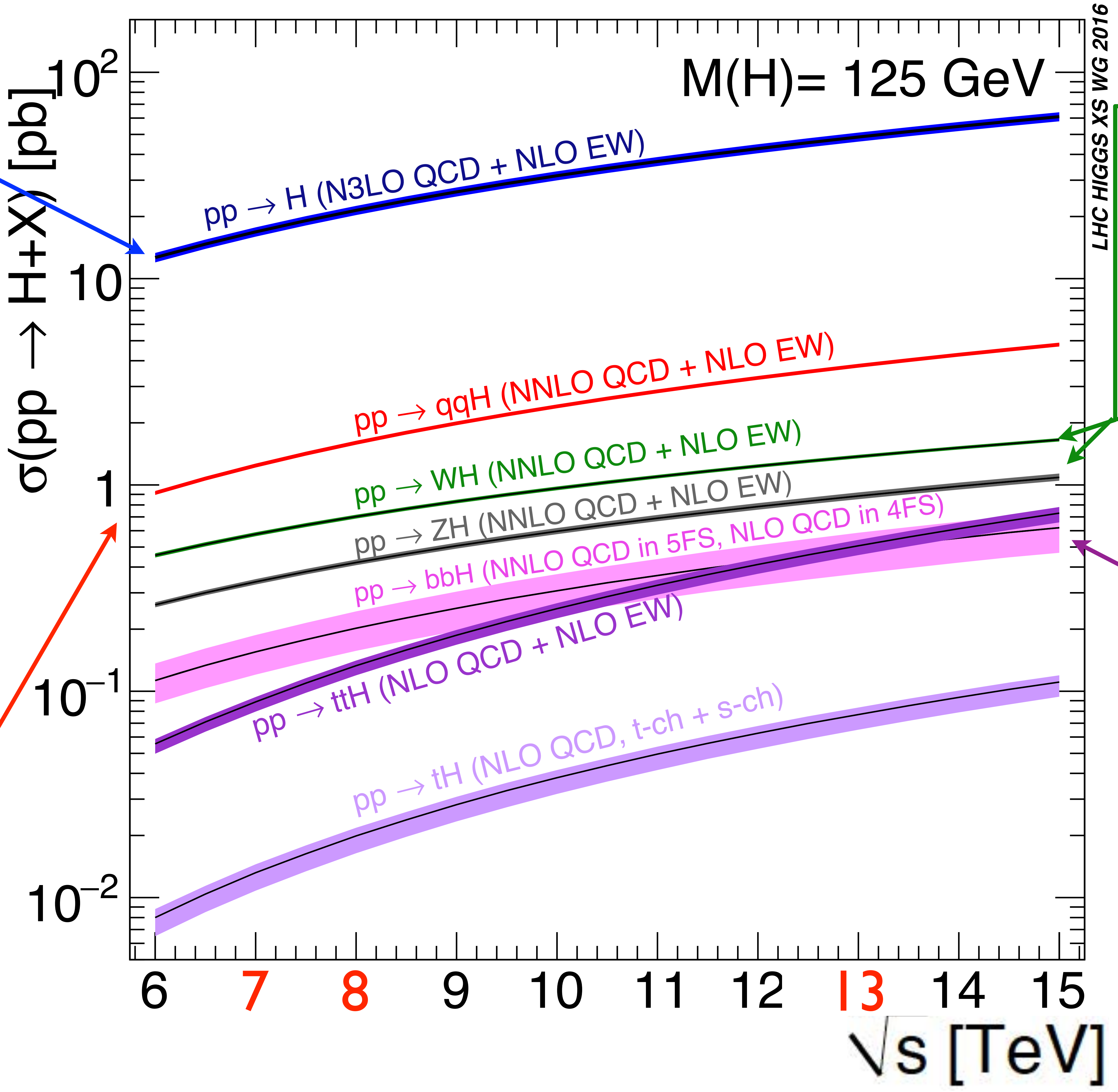
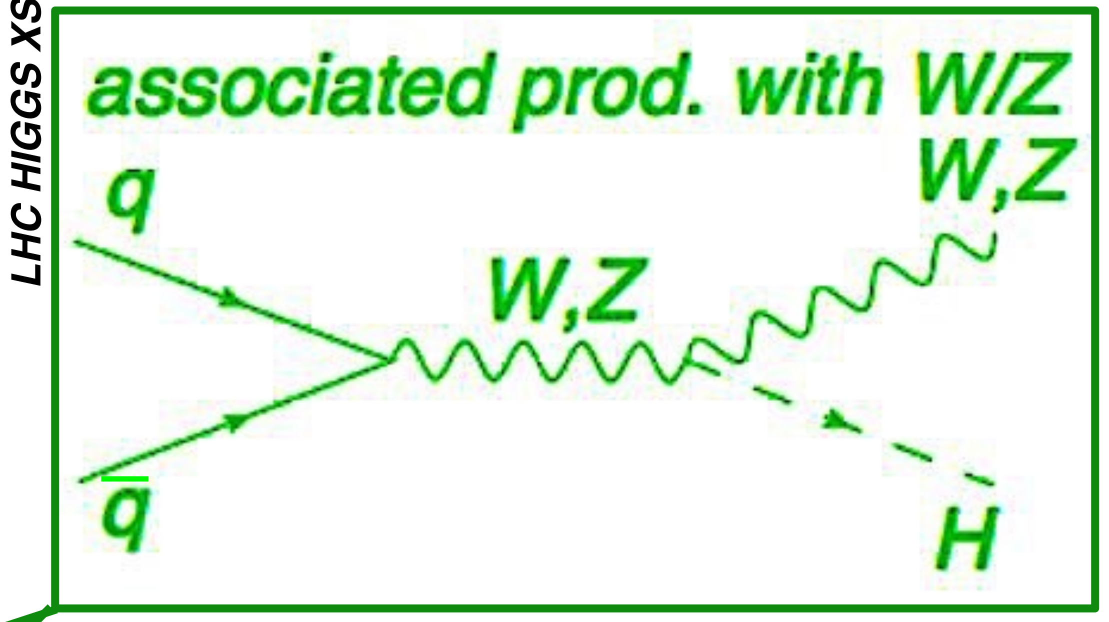
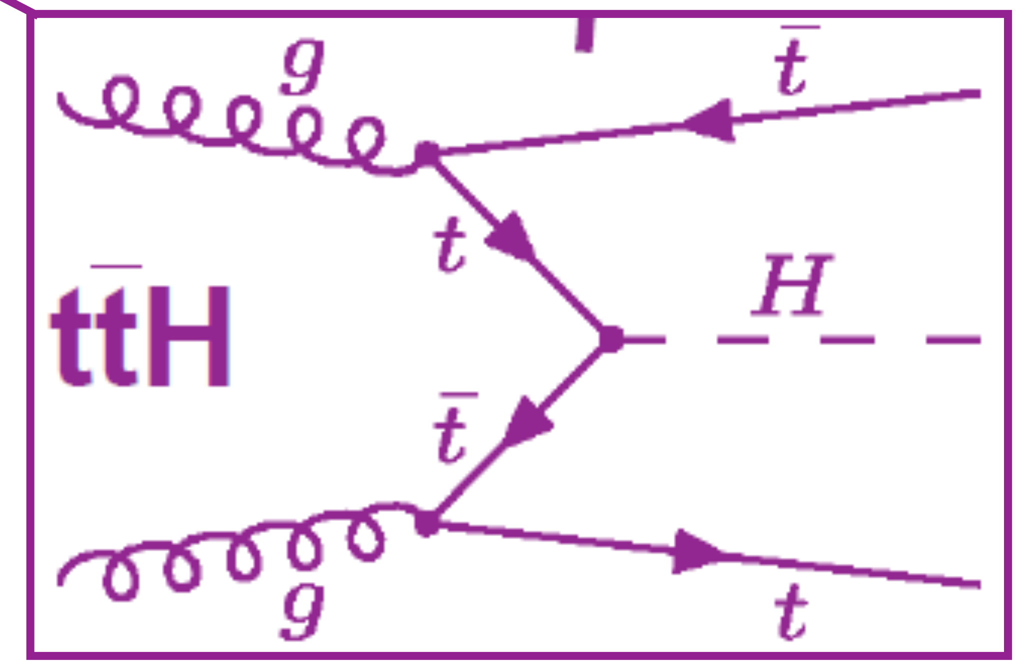
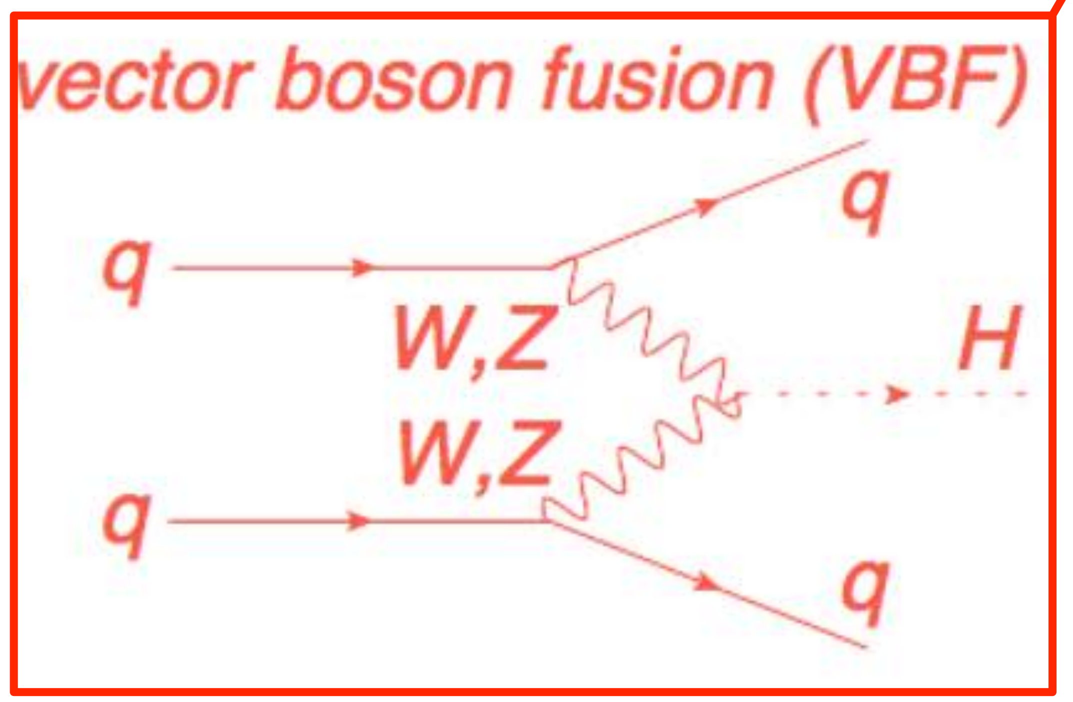


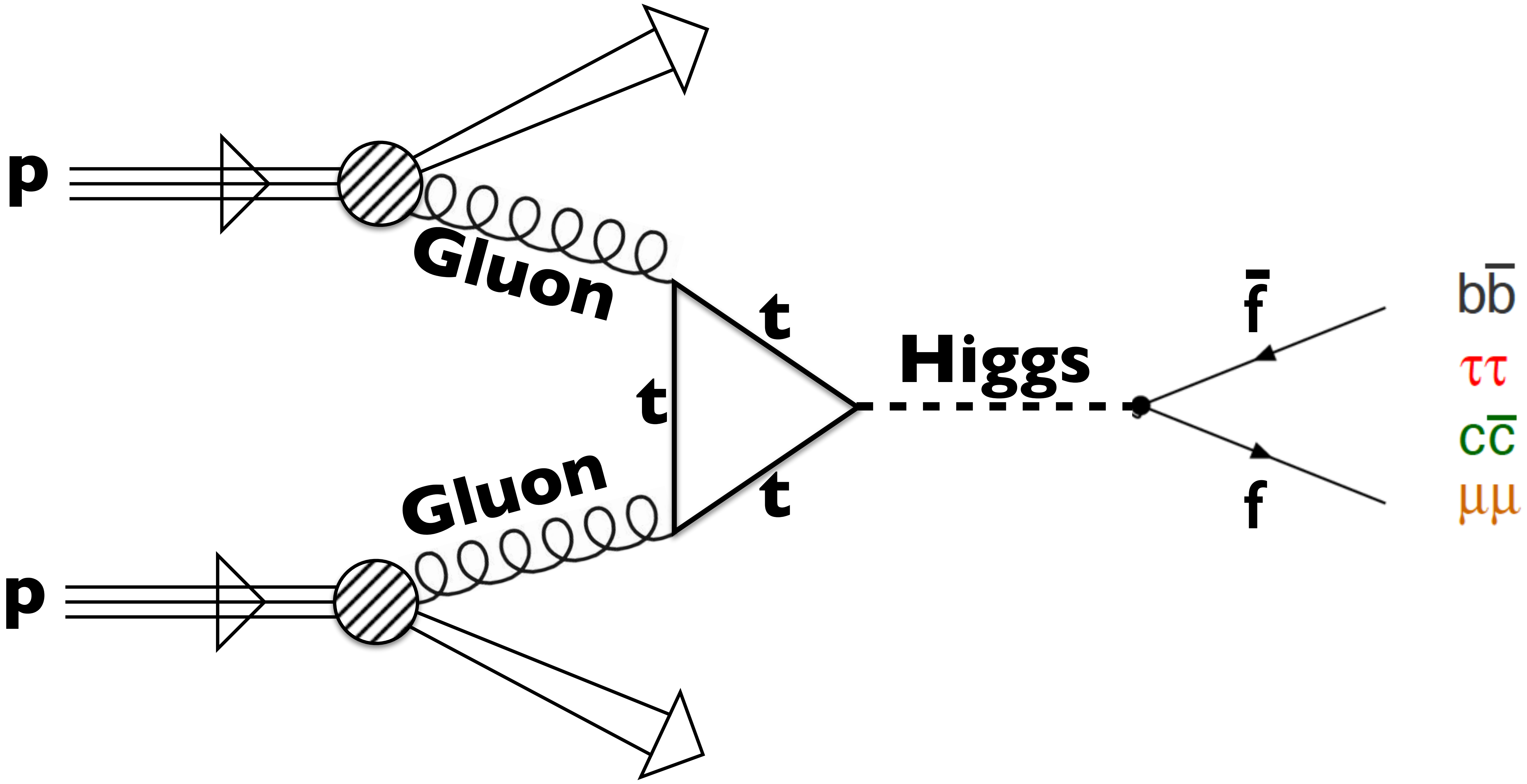


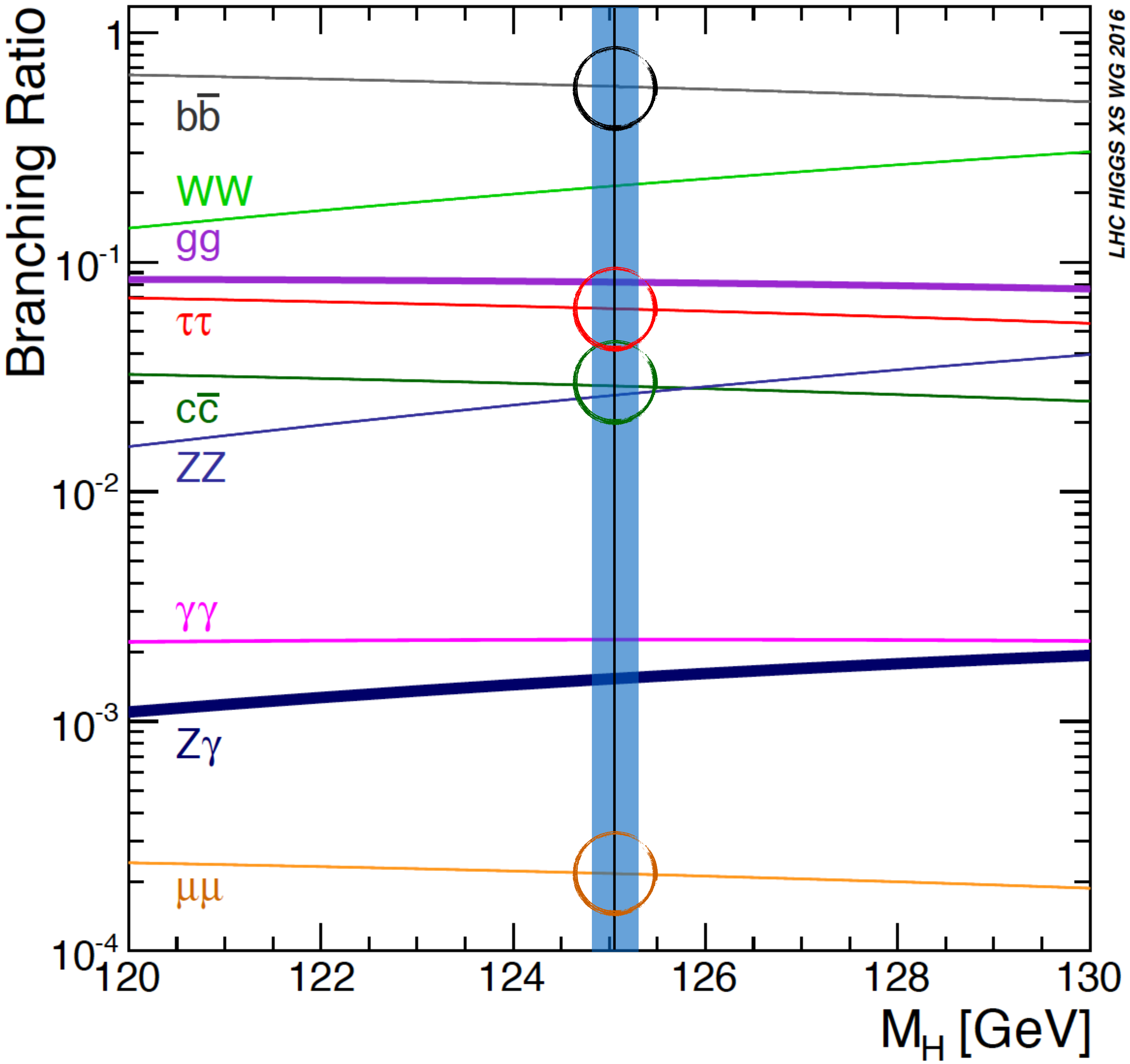






Higgs Boson Decay





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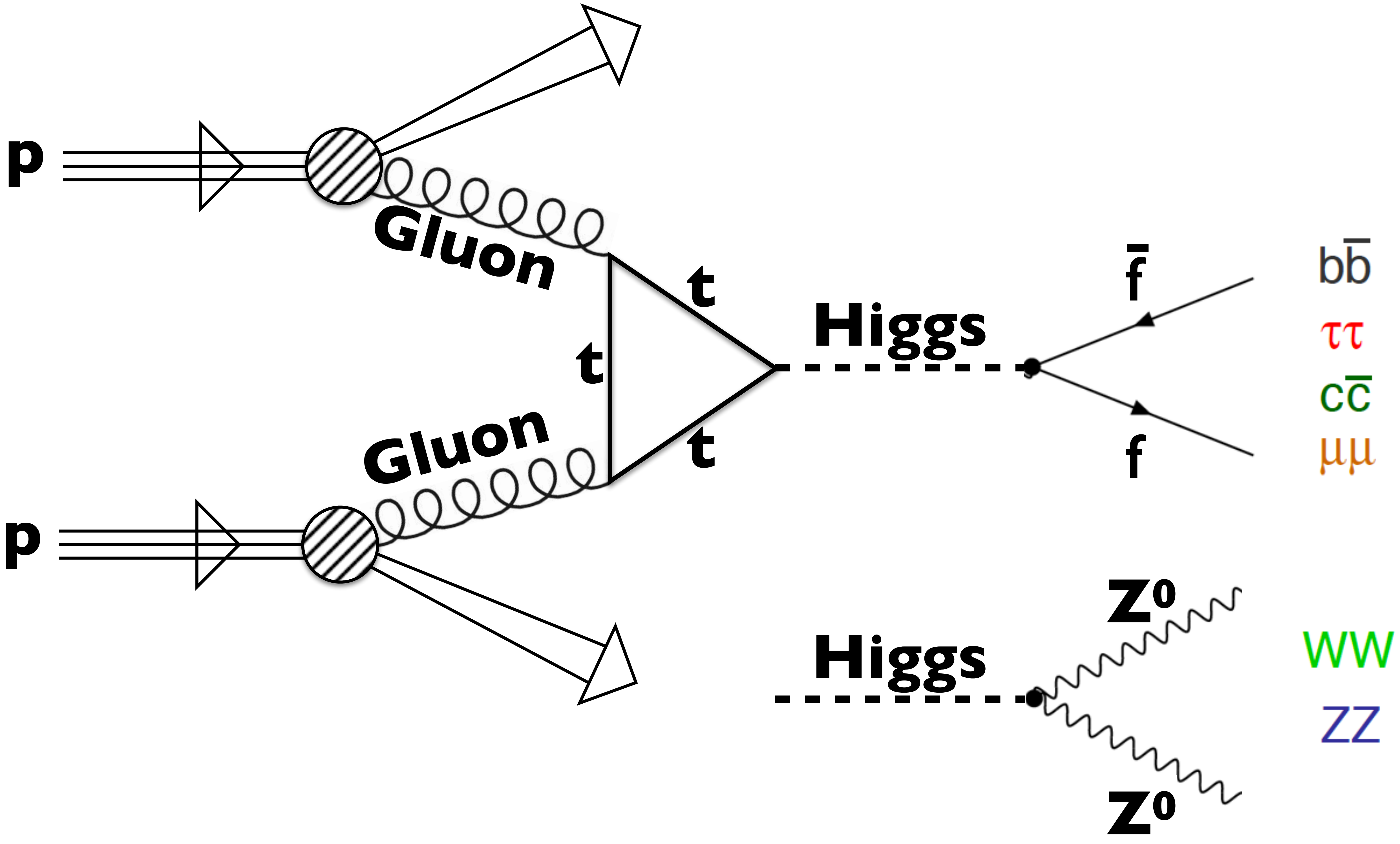

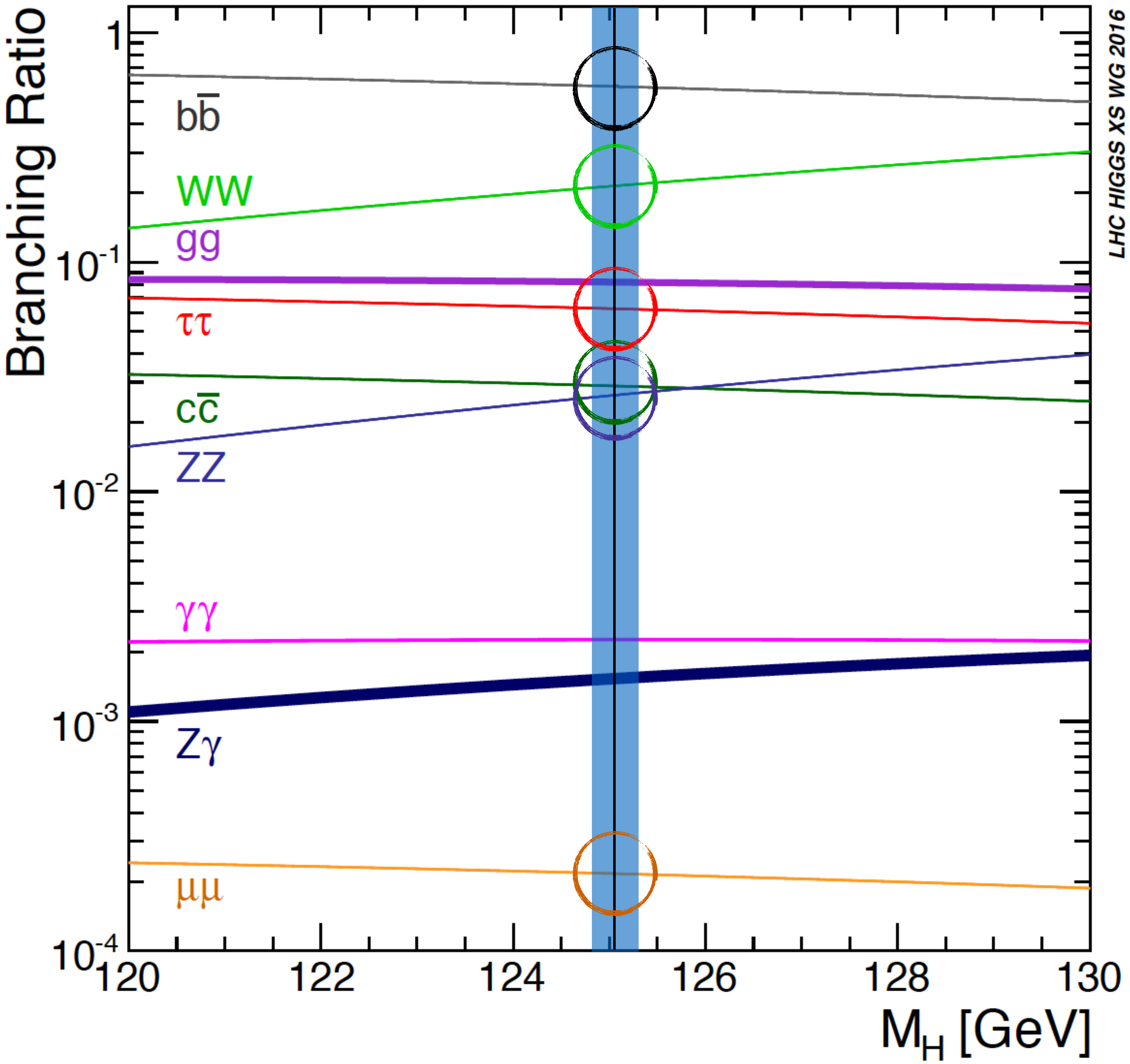

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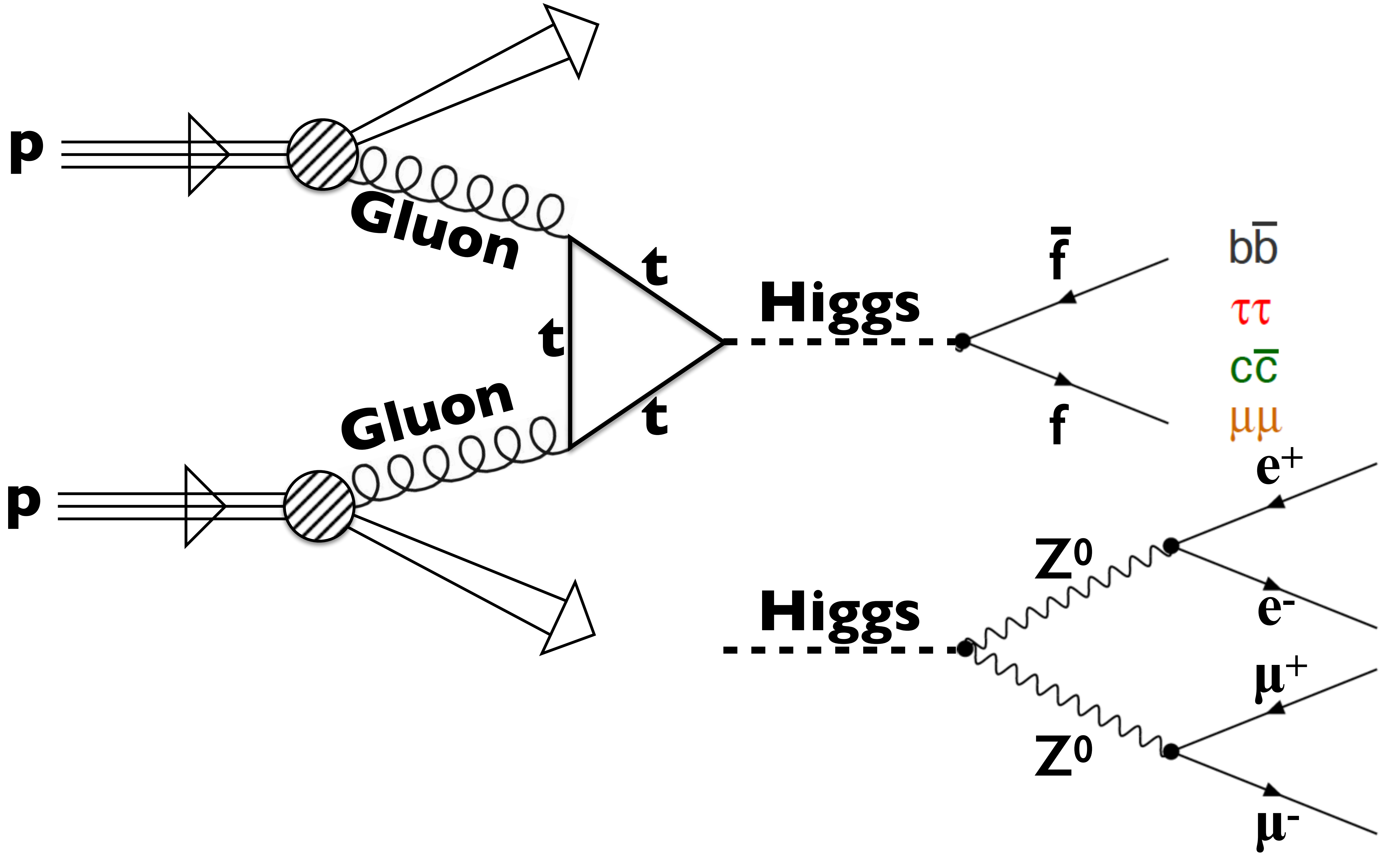

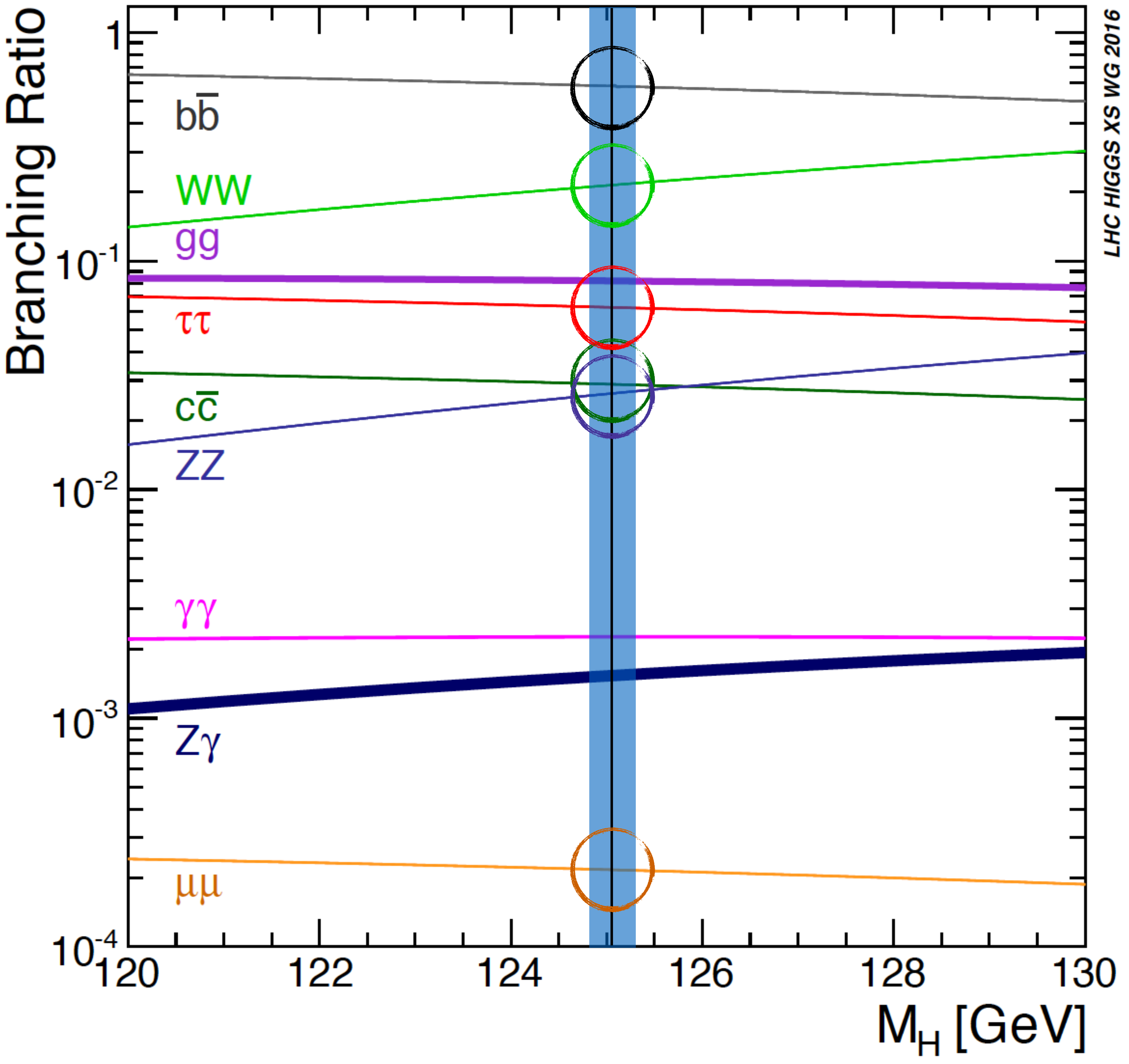

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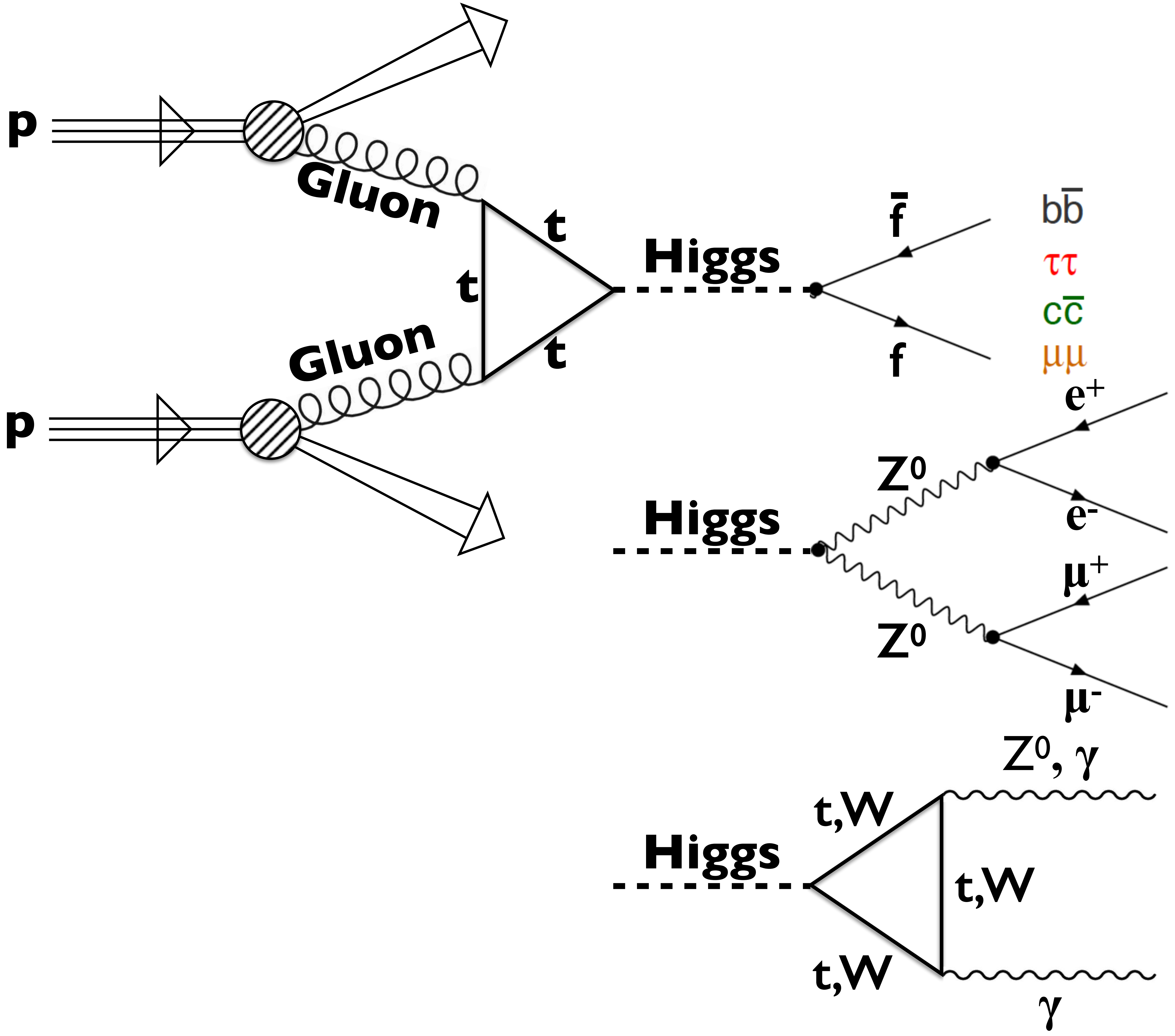

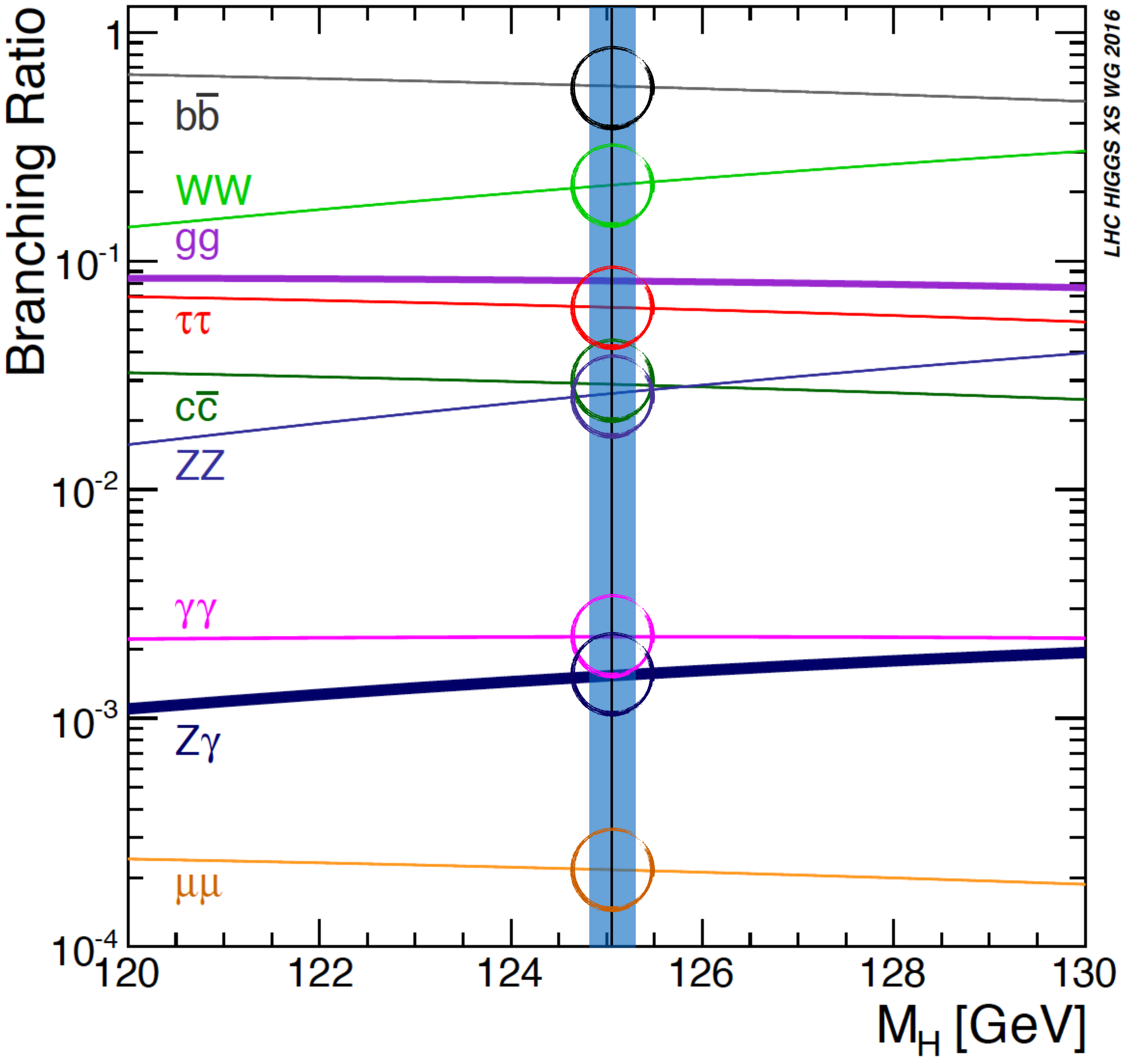

How do we “see” the Higgs boson?

- “Clean” Signatures: leptons or photons
- Calculate invariant mass from decay products:

$$m^2 = |\mathbf{p}_1 + \mathbf{p}_2|^2 = (E_1 + E_2)^2 - |\vec{p}_1 + \vec{p}_2|^2$$

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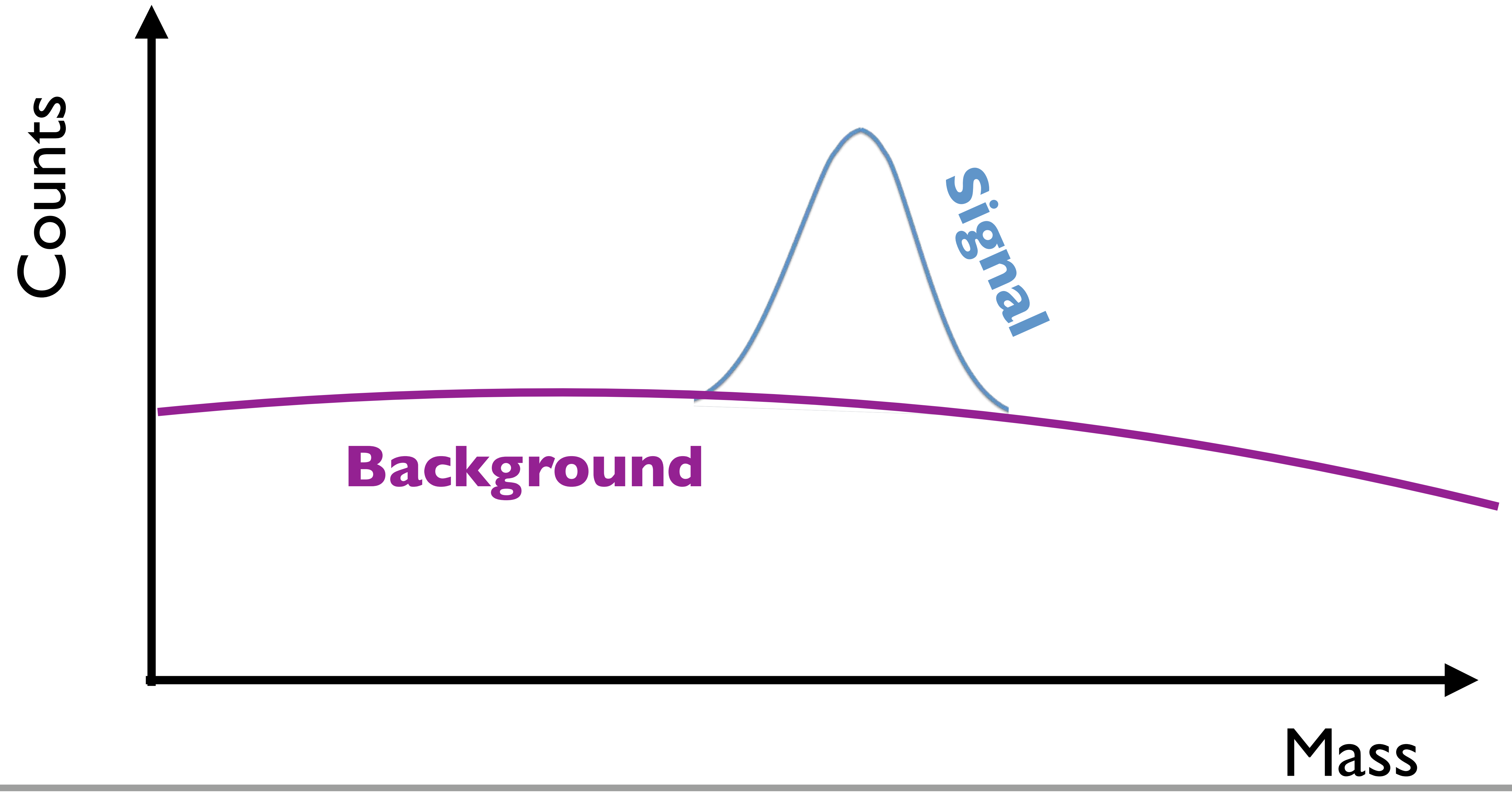
- Search for a signal peak over background:



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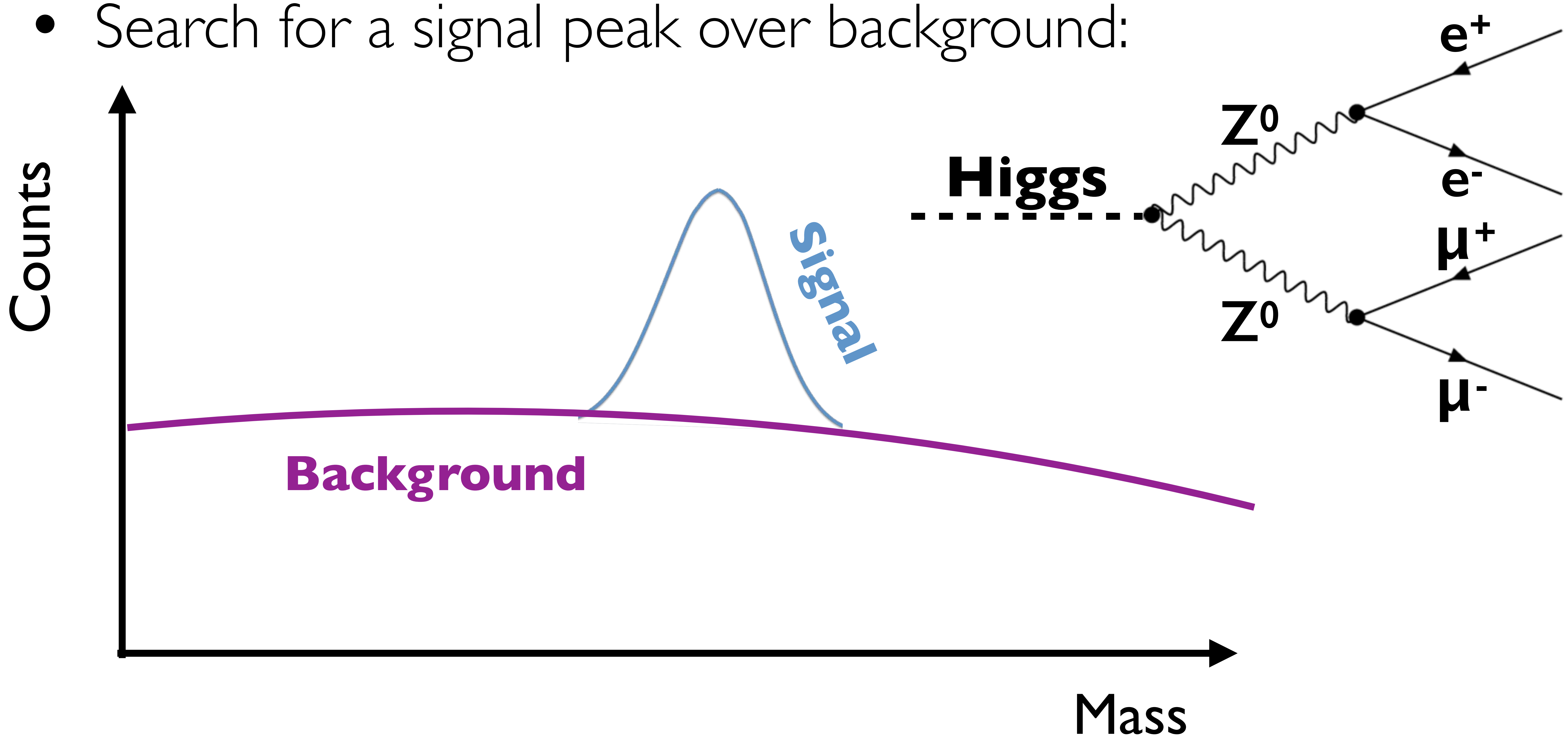
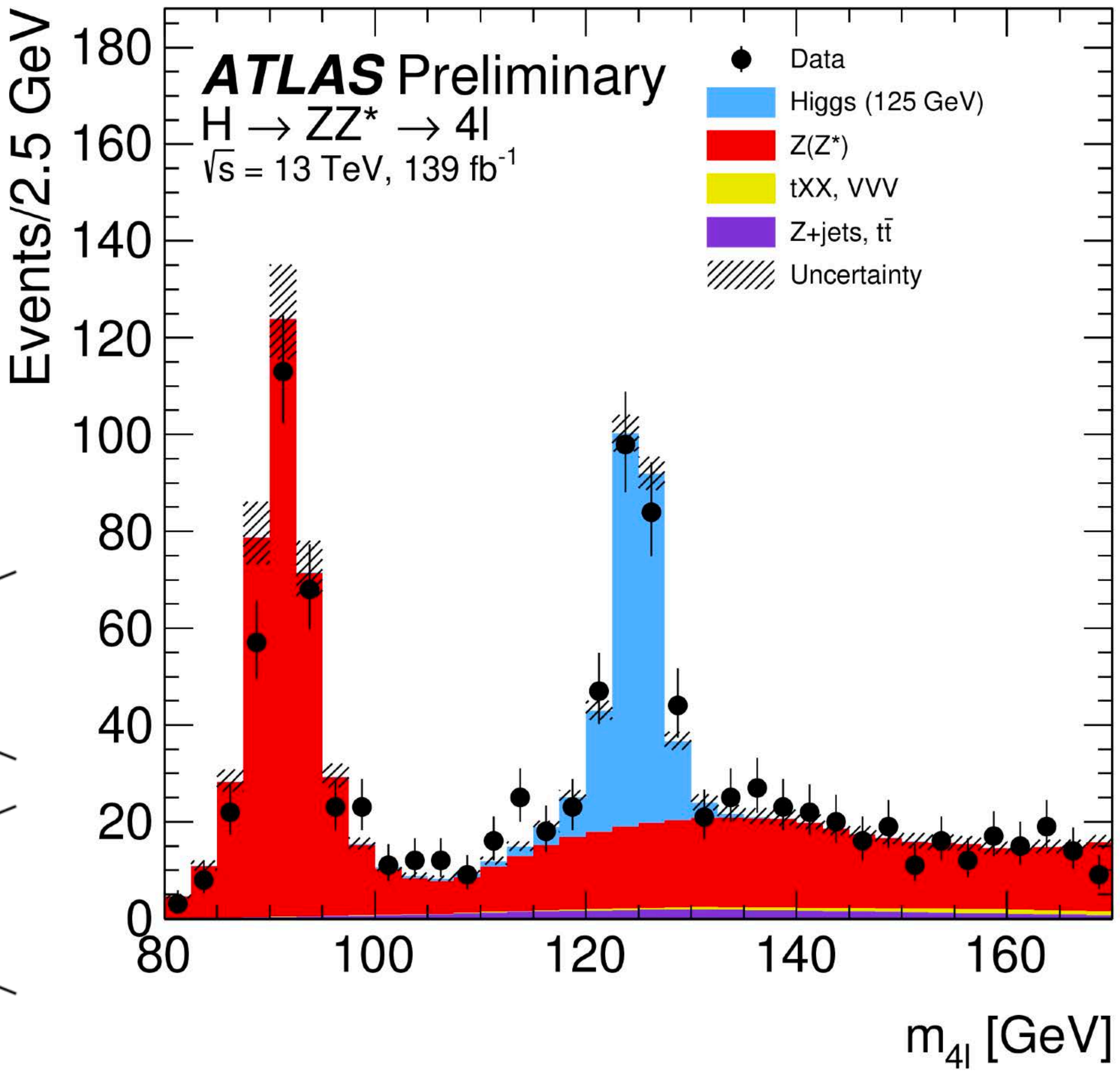
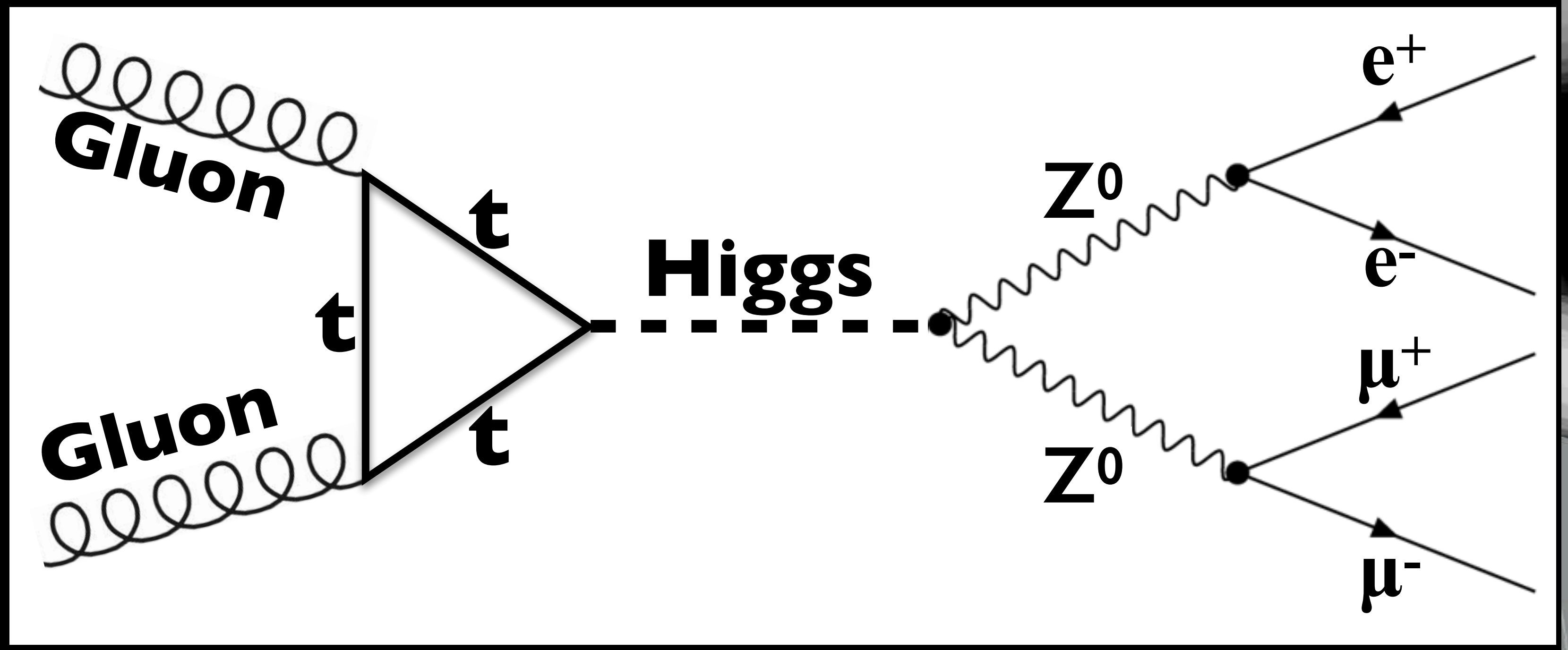
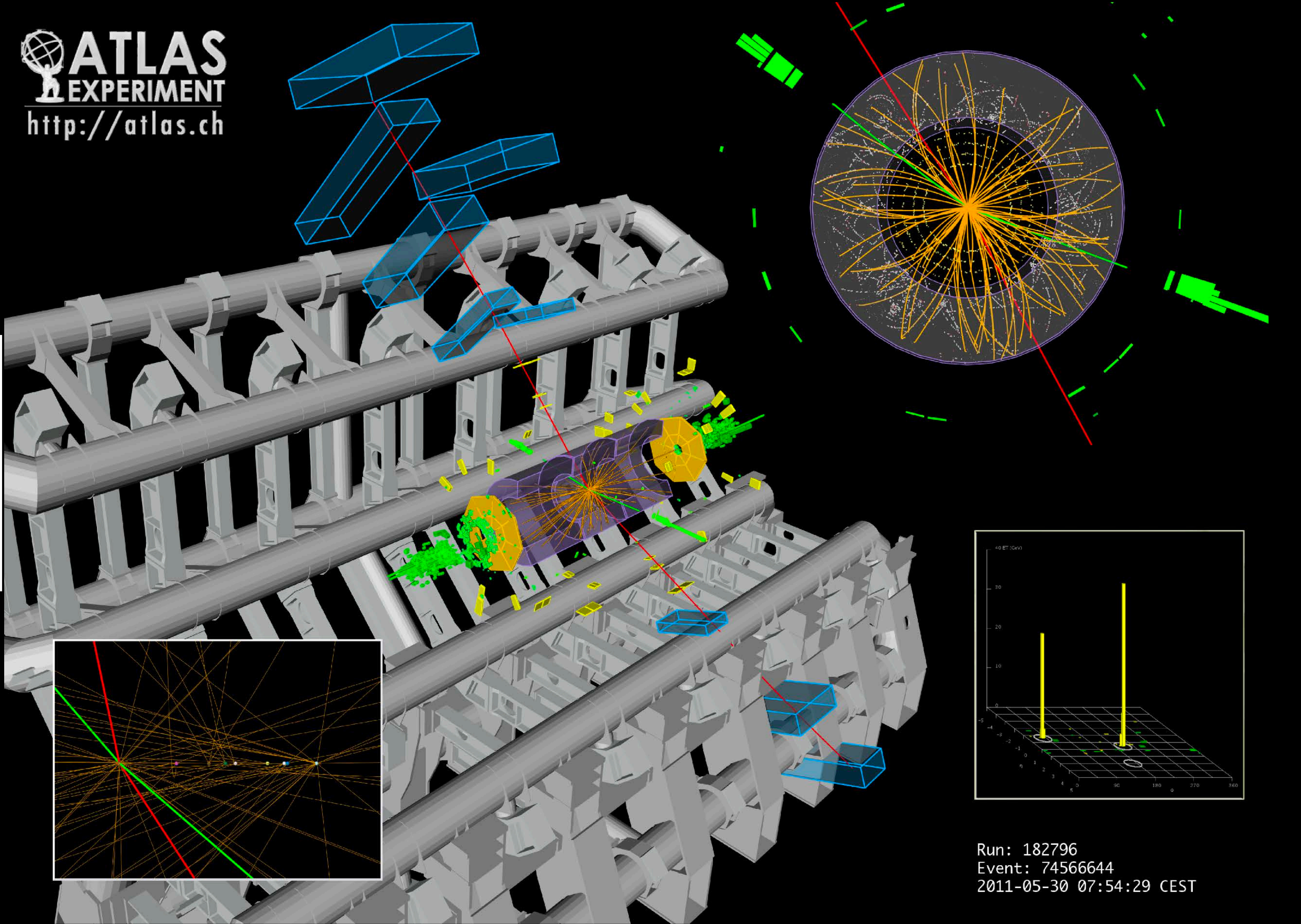




$H \rightarrow ZZ^* \rightarrow 4\ell$



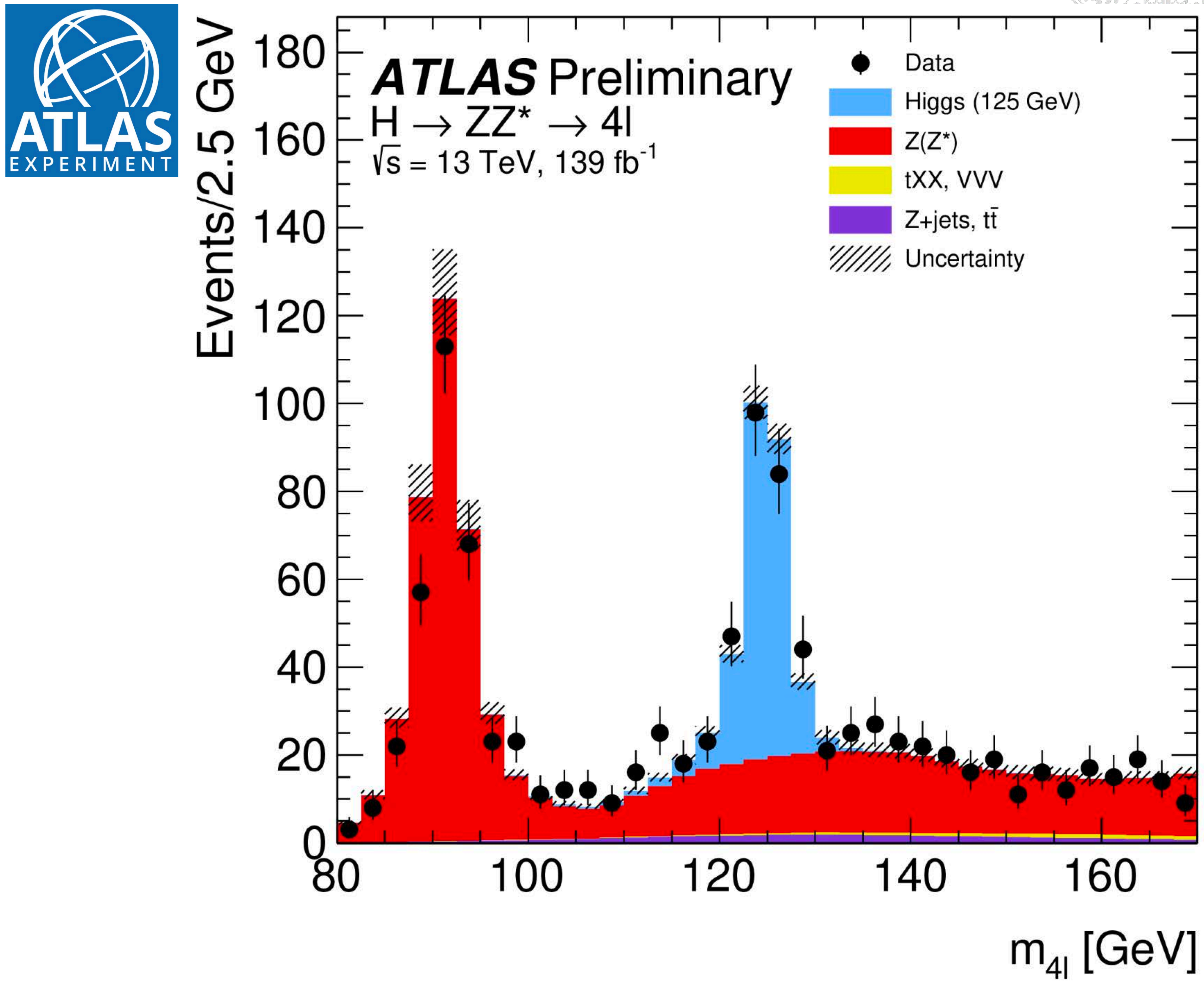


Run: 182796
Event: 74566644
2011-05-30 07:54:29 CEST

$m_{\mathrm{H}} = \sqrt{2\lambda}v$ not predicted!

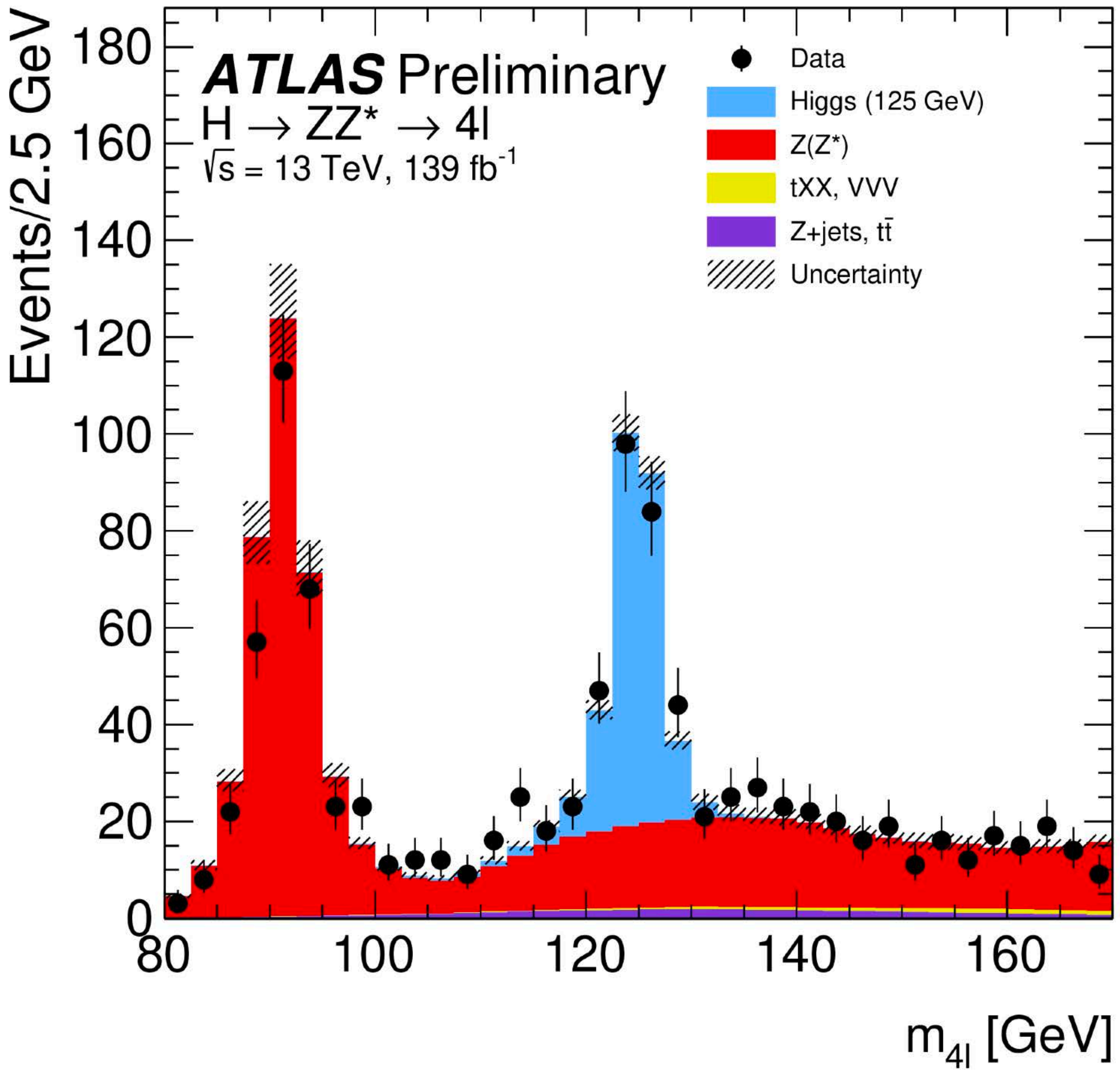
⇒ as soon as experimentally measured, everything else is calculable

Higgs Boson Mass



ATLAS-CONF-2020-005

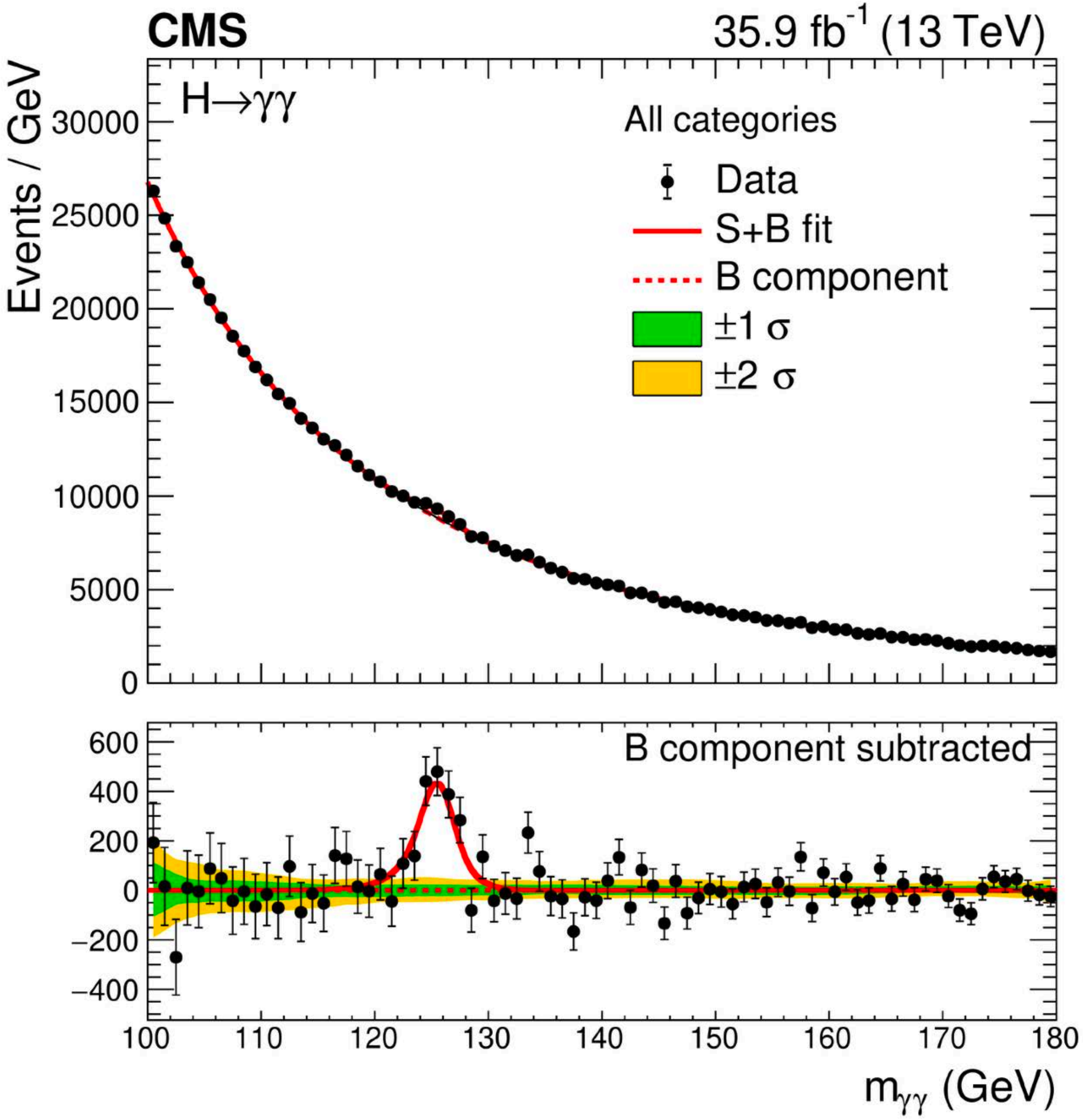
Higgs Boson Mass

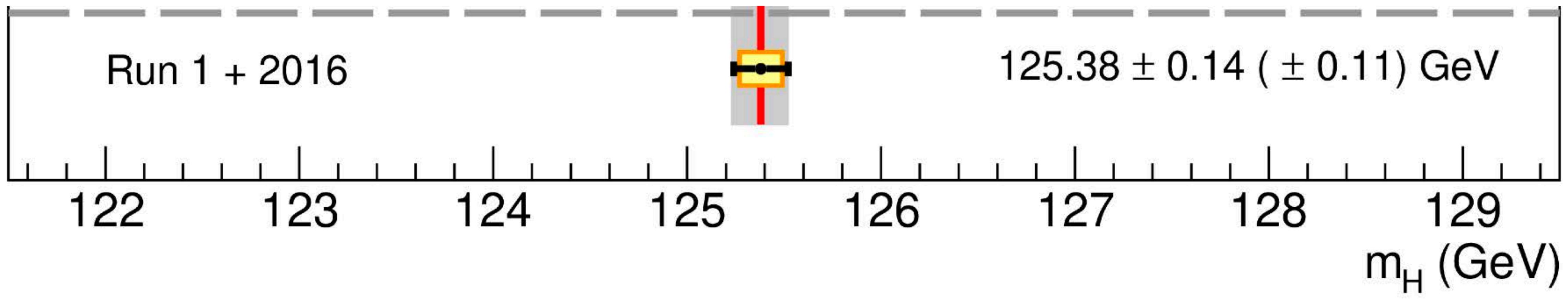


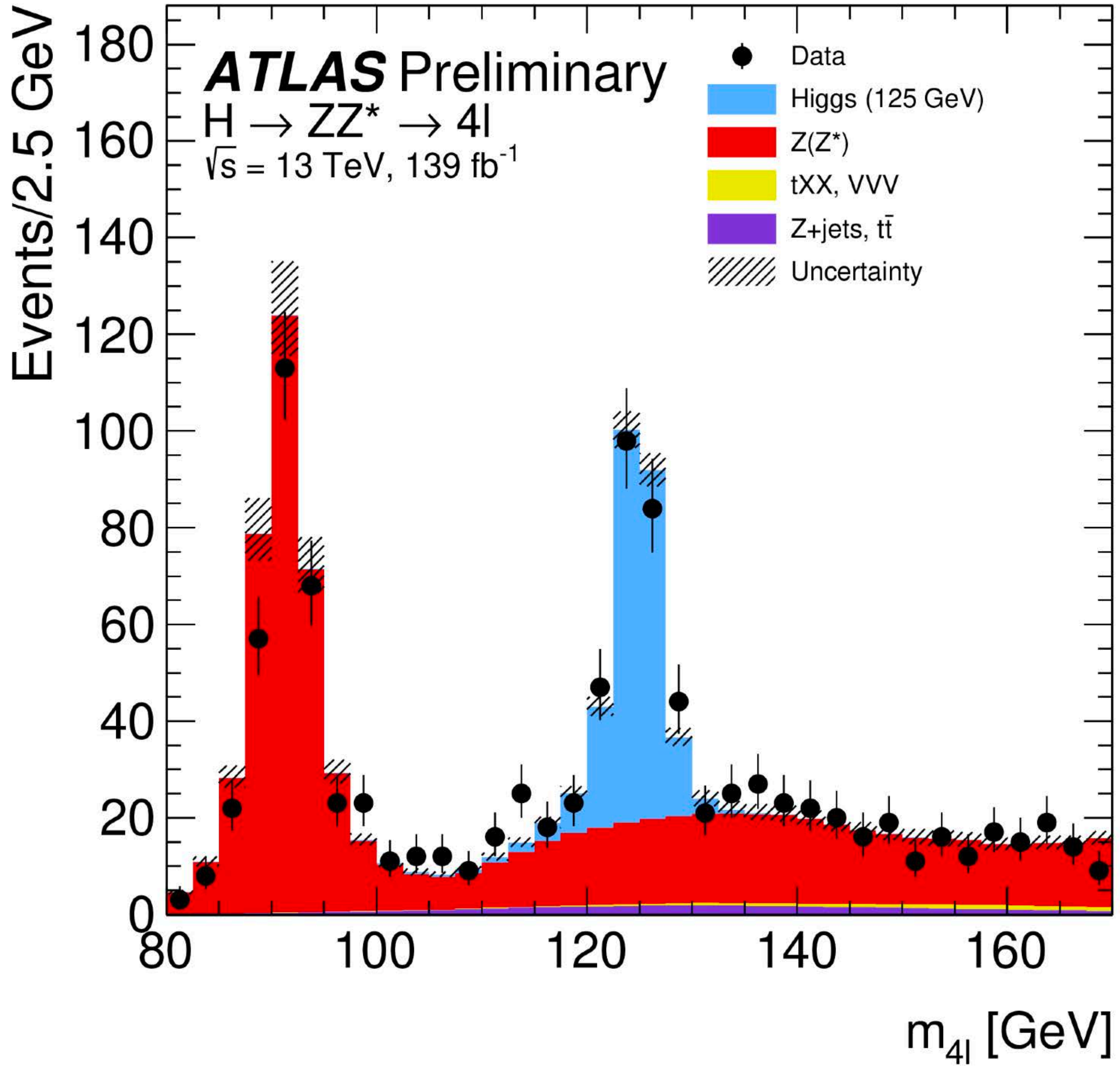
$$m_H = 124.92 \pm 0.19(\text{stat.})^{+0.09}_{-0.06}(\text{syst.})\ \text{GeV}$$

ATLAS-CONF-2020-005

Higgs Boson Mass







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Phys. Lett. B 805 (2020) 135425

ATLAS-CONF-2020-005

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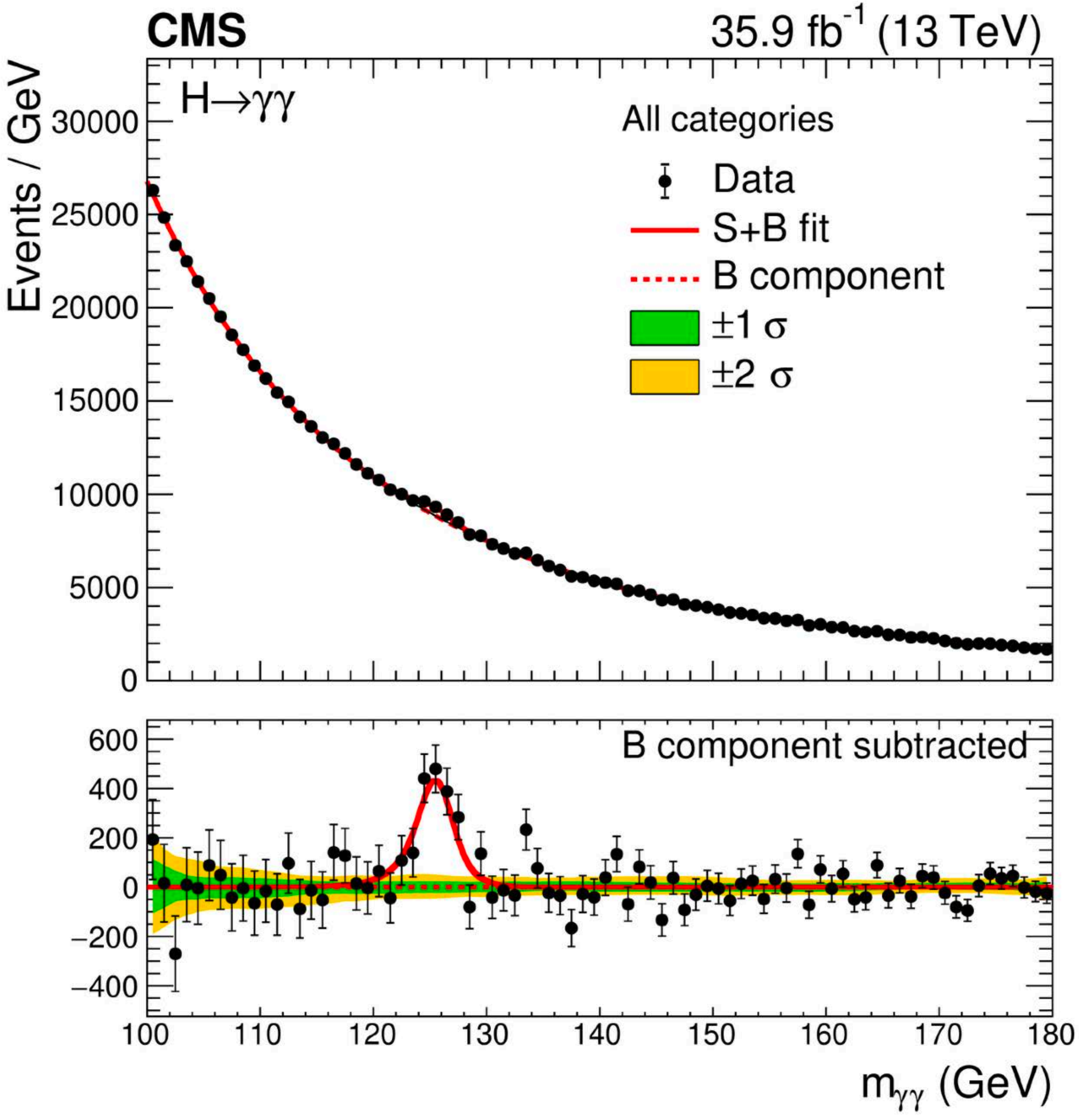

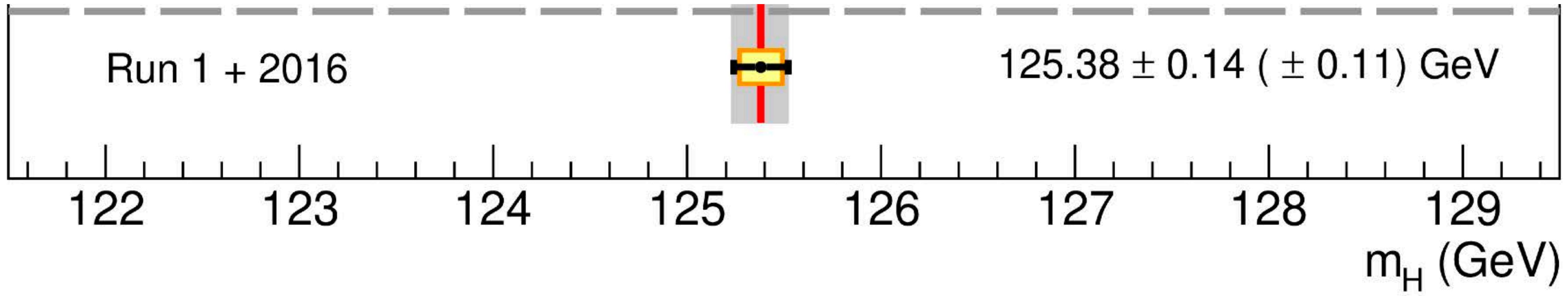

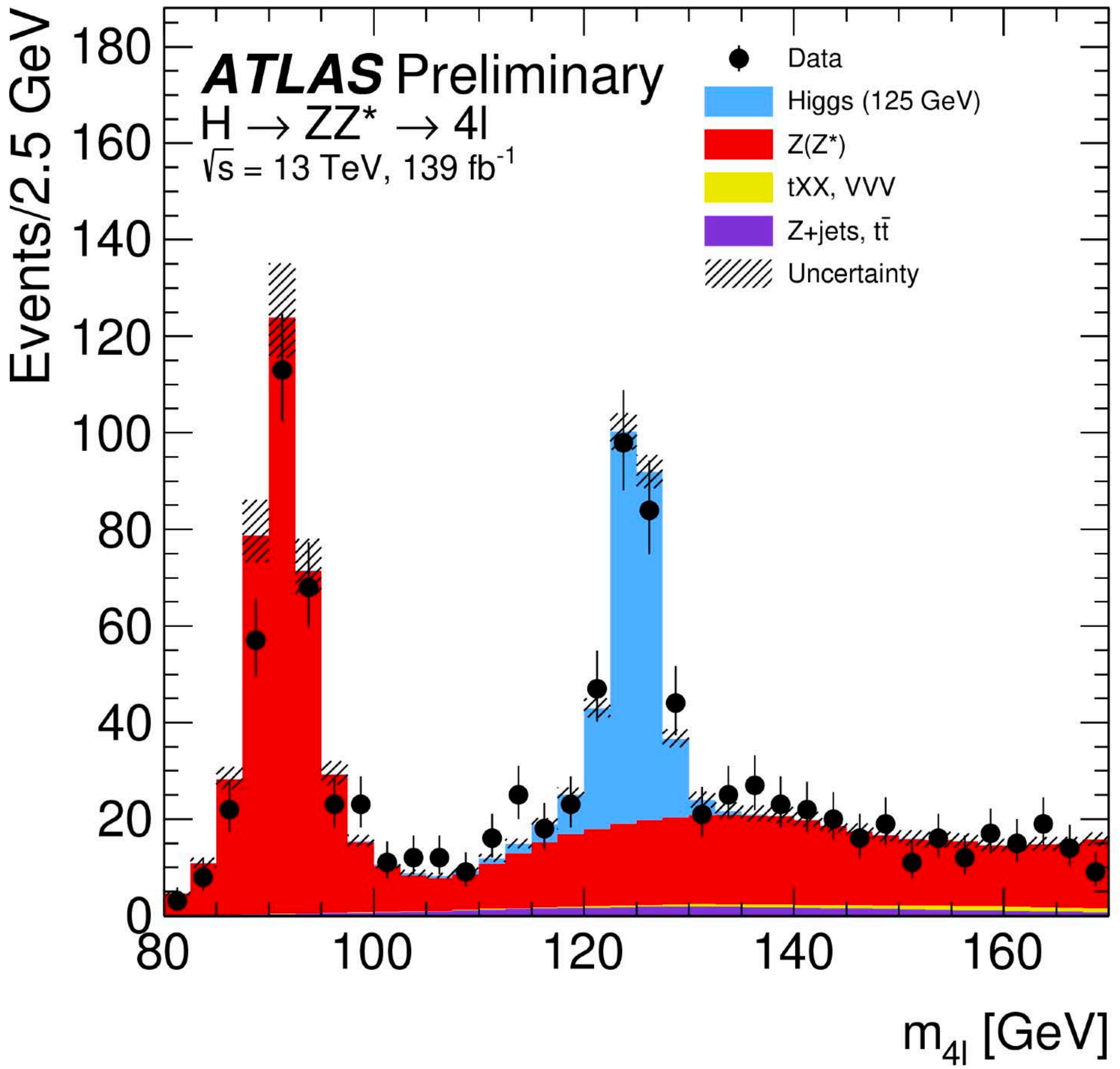

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Phys. Rev. Lett. 114 (2015) 191803

Consistent with ATLAS+CMS Run 1 result:

$m_H = 125.09 \pm 0.24$ GeV 2‰ uncertainty!

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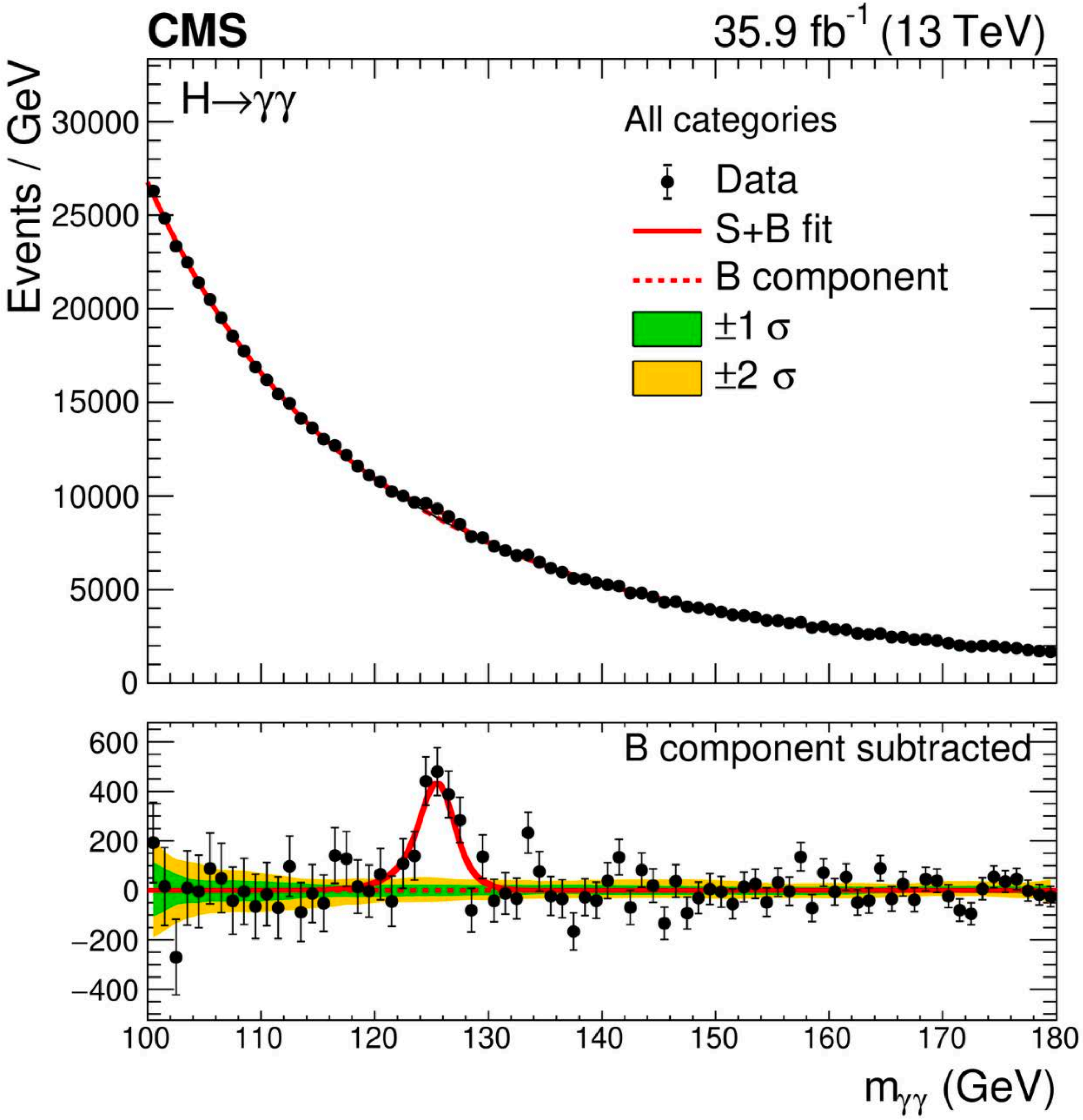
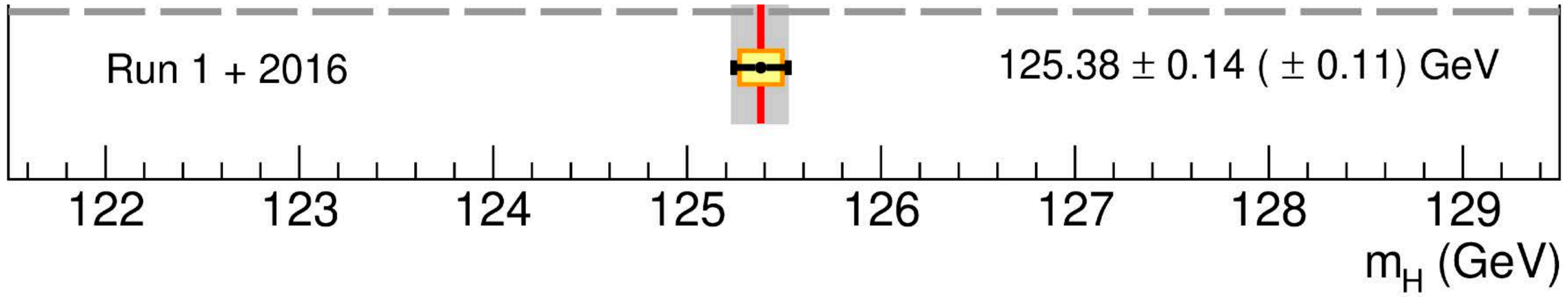
Higgs Boson Mass





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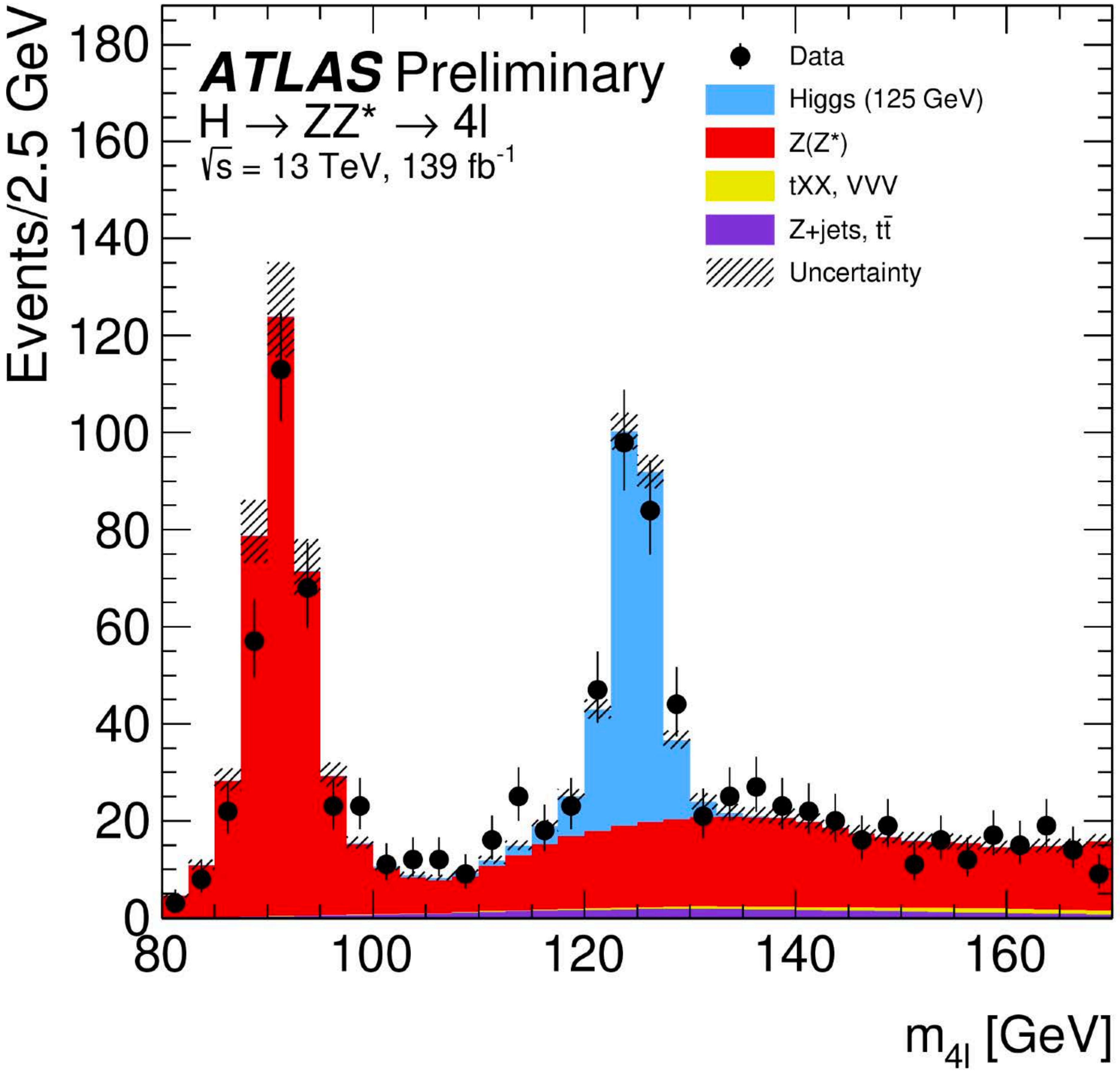
not predicted!



$$m_H = 124.92 \pm 0.19(\mathrm{stat.})^{+0.09}_{-0.06}(\mathrm{syst.})\ \mathrm{GeV}$$

Phys. Rev. Lett. 114 (2015) 191803

Consistent with ATLAS+CMS Run 1 result:

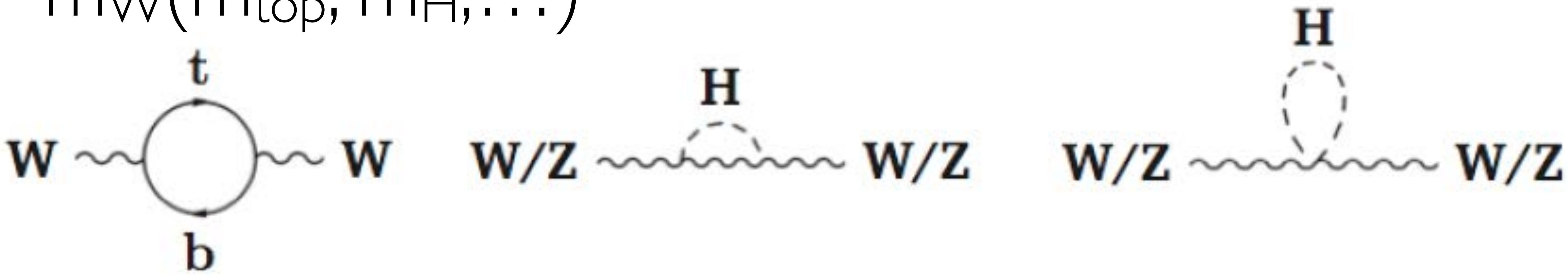
$m_H = 125.09 \pm 0.24$ GeV 2‰ uncertainty!

Phys. Lett. B 805 (2020) 135425

ATLAS-CONF-2020-005

Impact of m_H

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



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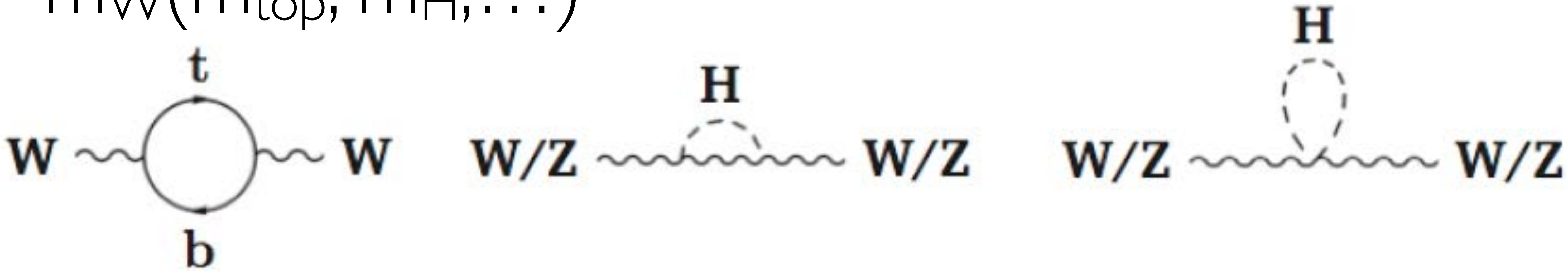

- Mesurement: $m_W = 80.379 \pm$ **0.013** GeV
- Impact on m_W in electroweak fit: $\Delta m_W(\text{Top})$ = **±2.7** MeV, **Δm_W(H) = ±0.1 MeV**

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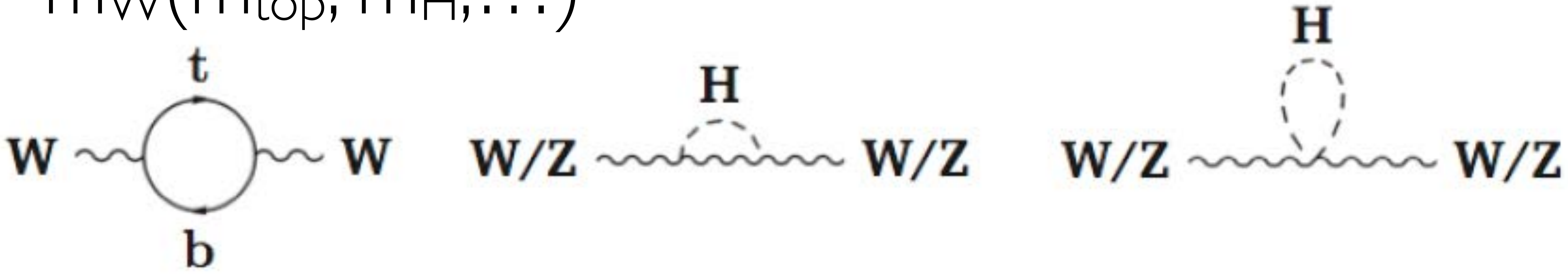

- Mesurement: m_W = 80.379 ± **0.013** GeV
- Impact on m_W in electroweak fit: Δm_W(Top) = **±2.7** MeV, **Δm_W(H) = ±0.1 MeV**

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

	Δ_{theo}	**Δ_{exp}**	**Δm_H**
BR(ZZ)	±1%	~10%	±2.5%
σ_{VBF}	±2%	~19%	±0.3%

Impact of m_H

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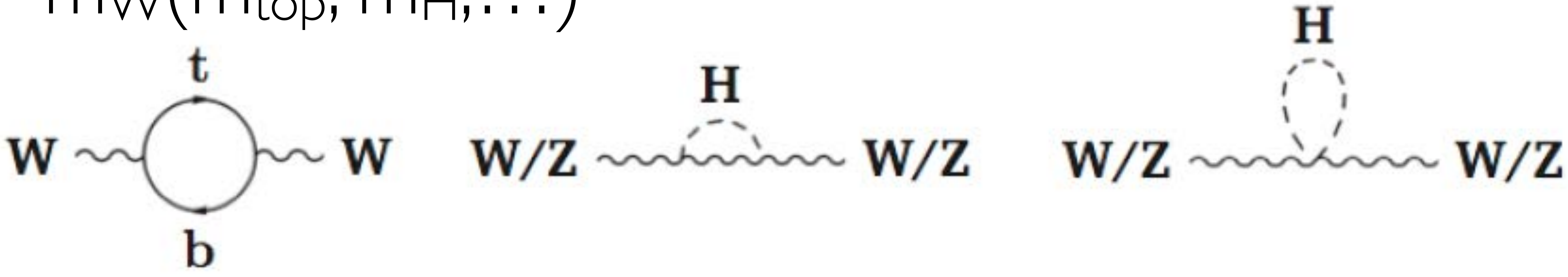

- Mesurement: $m_W = 80.379 \pm \mathbf{0.013}$ GeV
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	Δ_{theo}	Δ_{exp}	Δm_H
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⇒ Measurement precision of m_H good enough for this

- but precise measurement important!

1. Introduction
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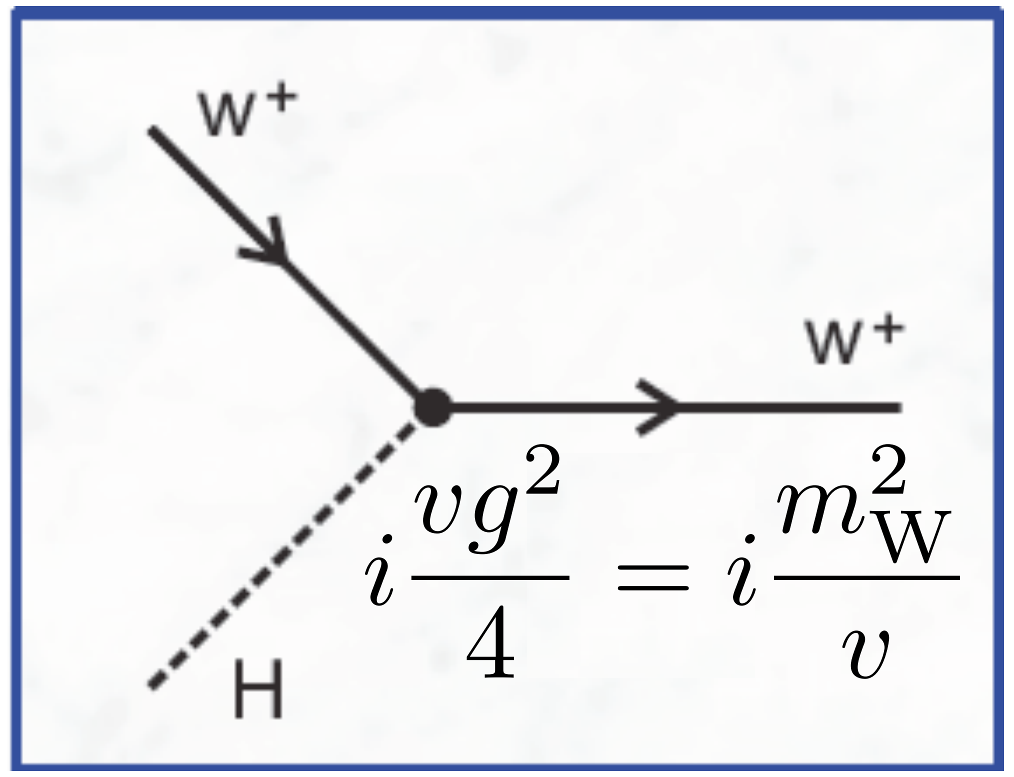


$$i\frac{vg^2}{4} = i\frac{m_{\mathrm{W}}^2}{v}$$

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

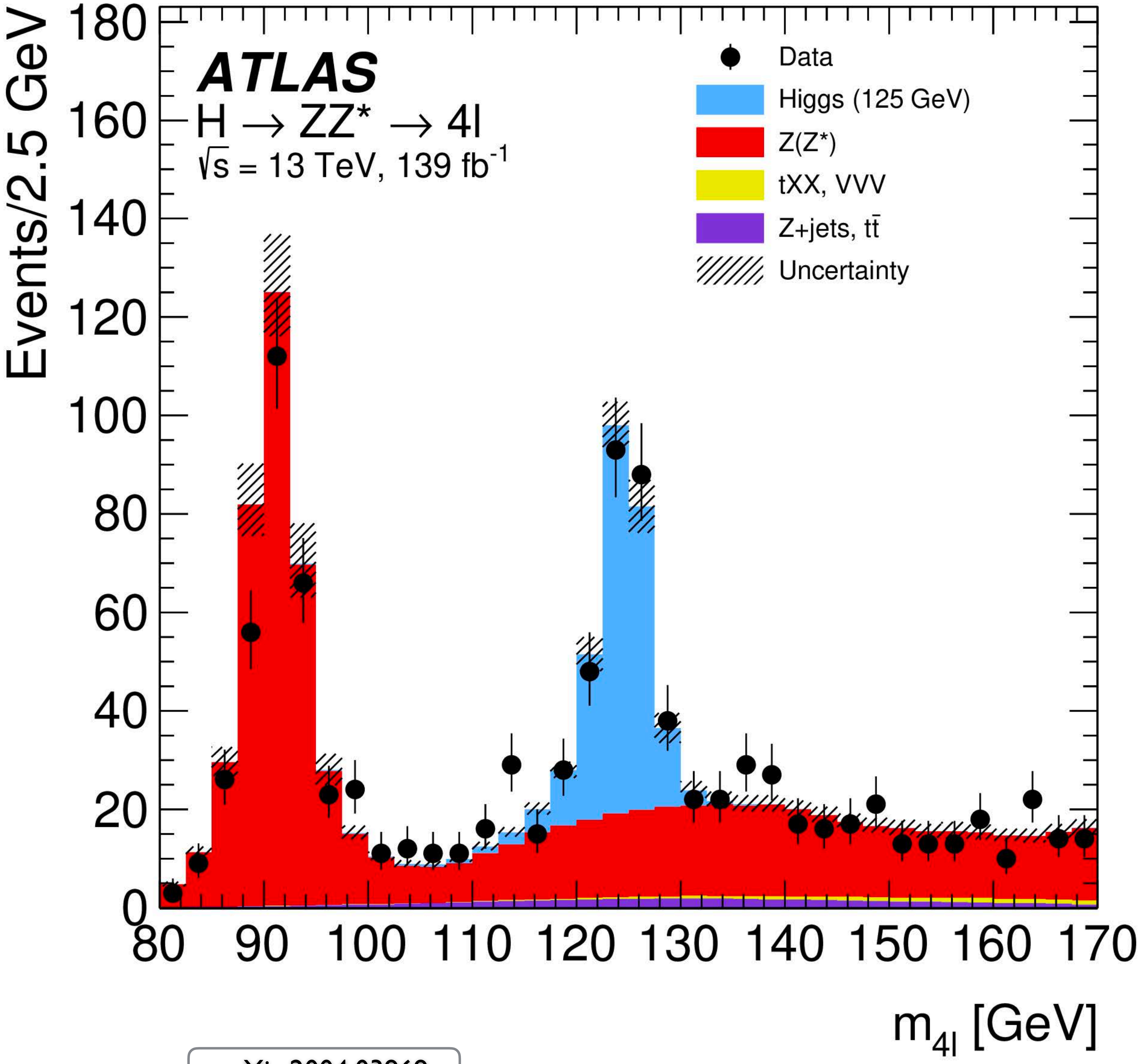
- **$BR_{SM}(H \rightarrow ZZ^*) \approx 2.6\%$**
  - $BR_{SM}(Z \rightarrow \ell\ell) \approx 3.4\%$

    $\Rightarrow BR_{SM}(\mathbf{H} \rightarrow \mathbf{ZZ^*} \rightarrow 4\ell) = 0.016\%$

$\Rightarrow$~1200 H → ZZ* → 4ℓ events in 139 fb^{-1}

- Expect to see **206 signal events** $(A \cdot \boldsymbol{\varepsilon})$
- Excellent signal reconstruction and S/B

- Fiducial cross-section measurement:
  - Observed: $\boldsymbol{\sigma}_{\text{fid}}(H \rightarrow ZZ^* \rightarrow 4\ell) = \mathbf{3.28 \pm 0.32\ fb}$
  - Expected: $\boldsymbol{\sigma}_{\text{fid,SM}}(H \rightarrow ZZ^* \rightarrow 4\ell) = \mathbf{3.41 \pm 0.18\ fb}$



arXiv:2004.03969

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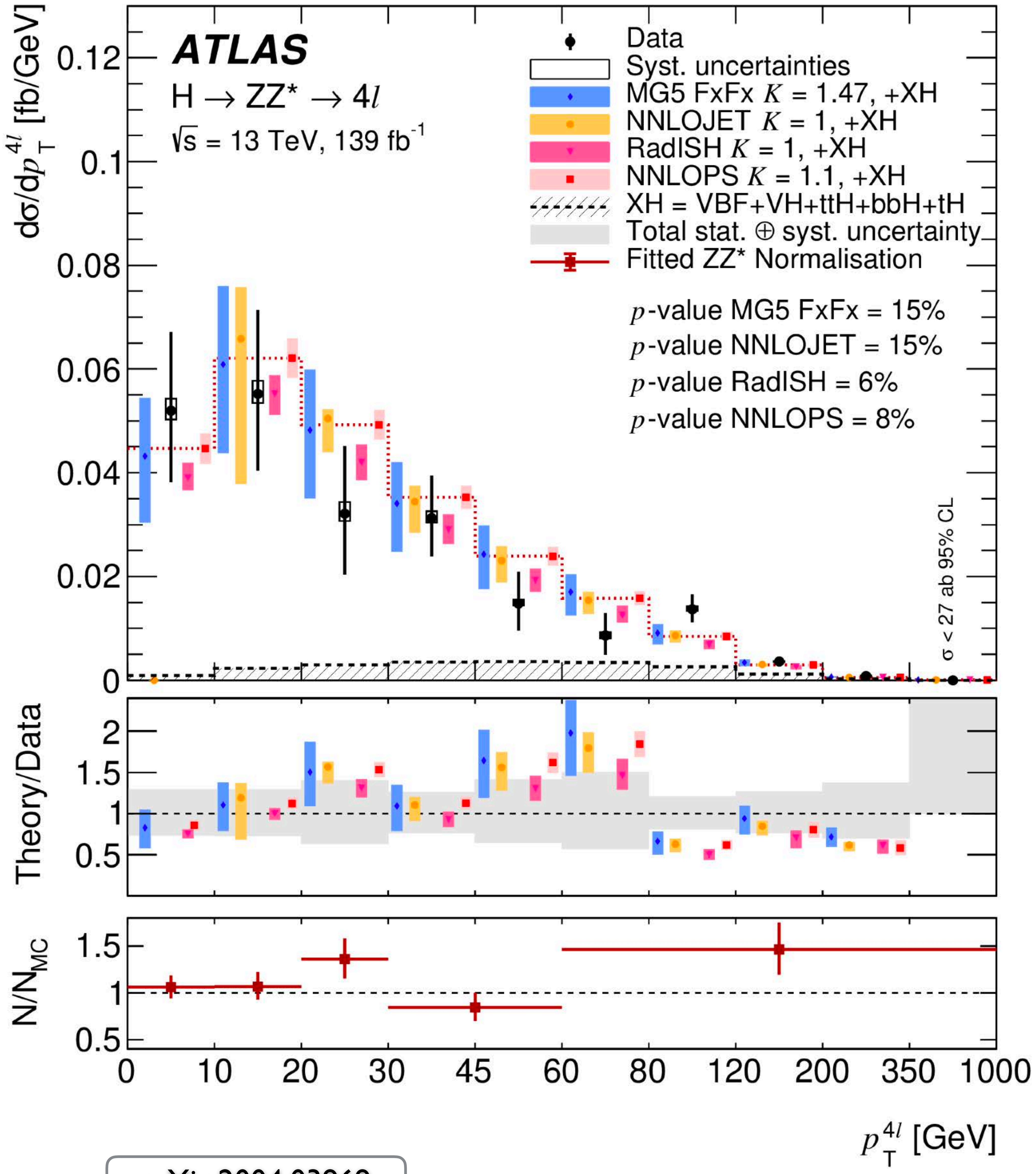
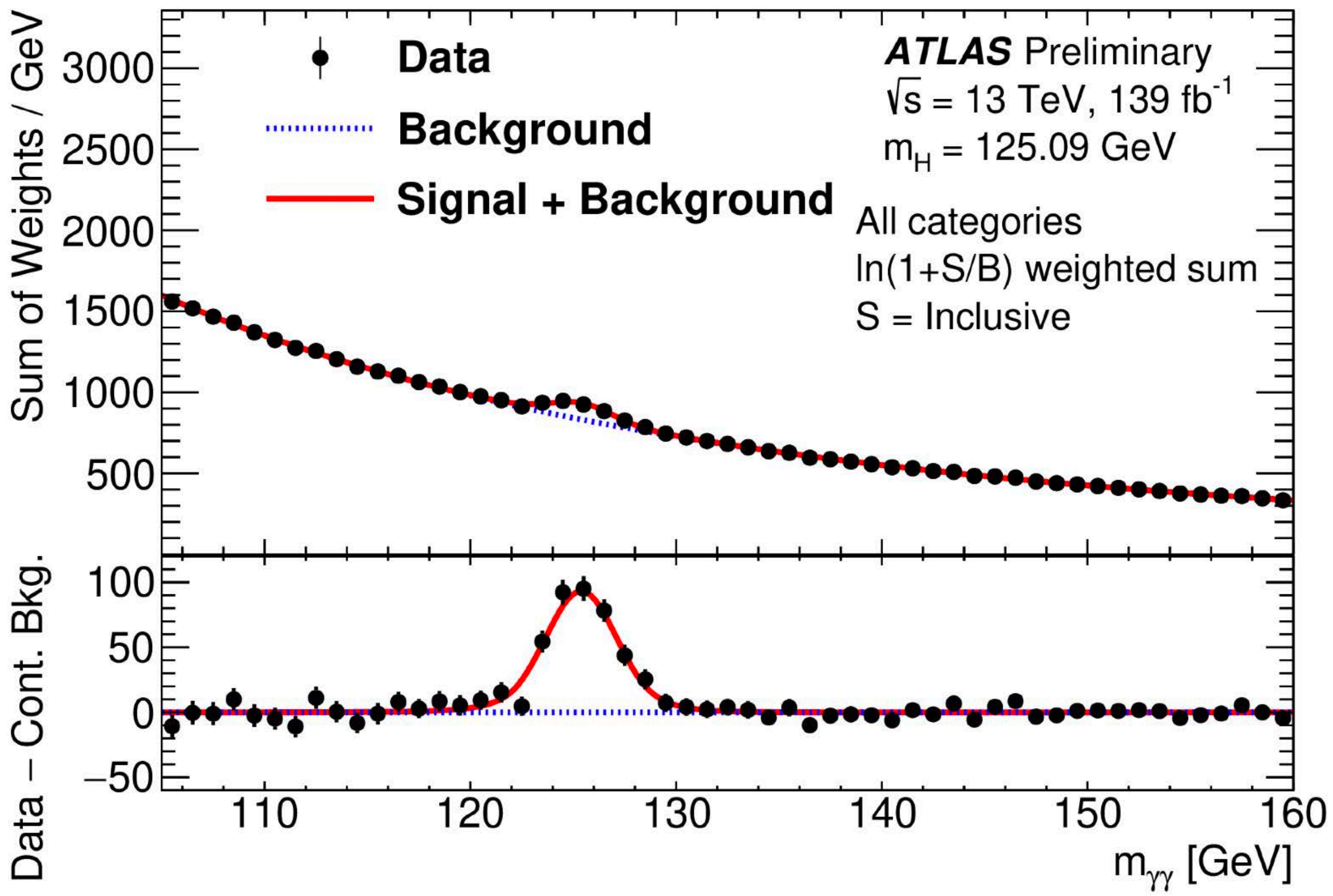
  $\Rightarrow$ Differential cross-section measurements; Comparison with theory predictions



arXiv:2004.03969

$H \rightarrow \gamma\gamma$

- **$BR_{SM}(H \rightarrow \gamma\gamma) \approx 0.23\%$**
- Expect: ~17500 signal events
  - Excellent signal reconstruction



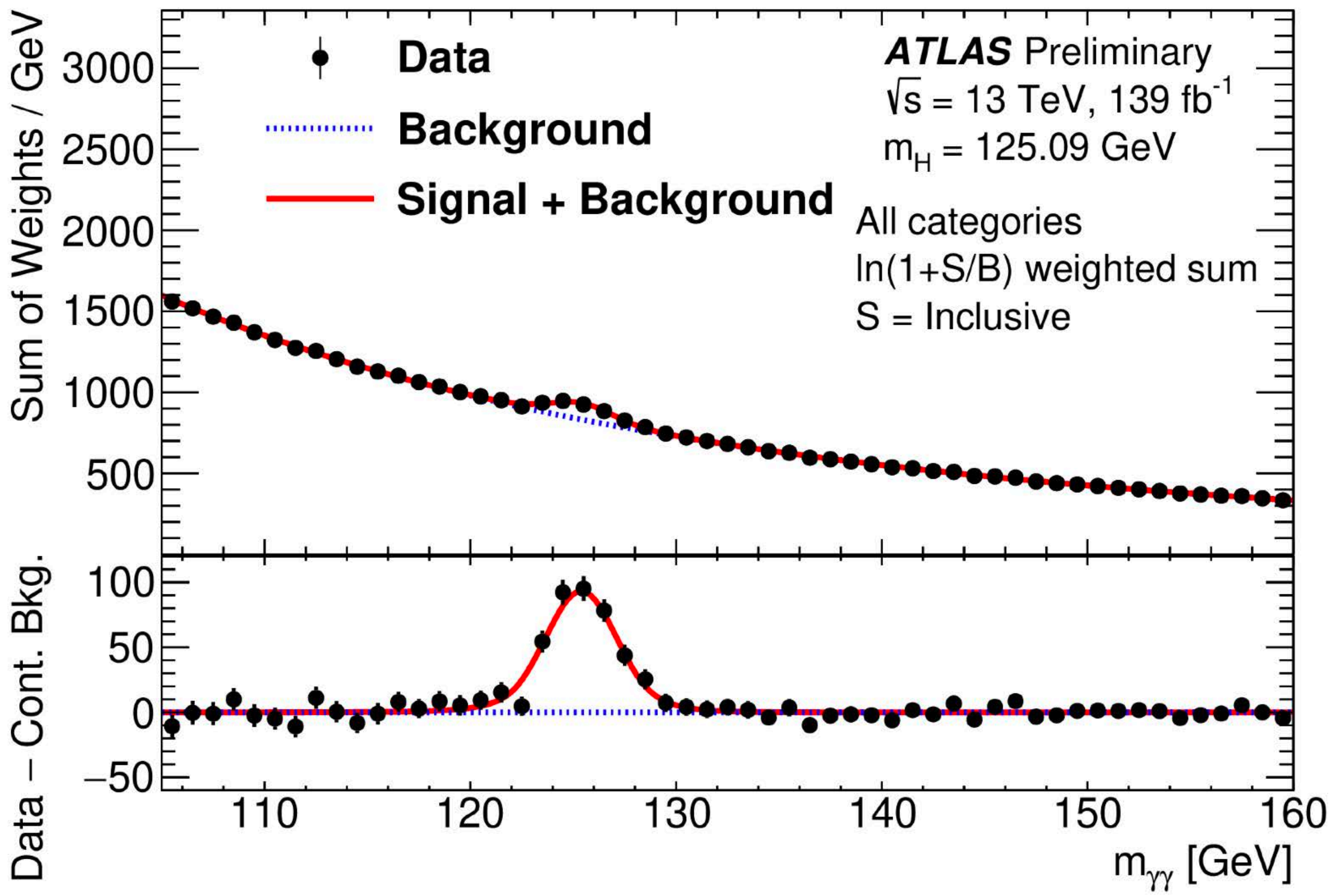
- Cross section measurement:

$$
\begin{aligned}
(\sigma \times B_{\gamma\gamma})_{\text{obs}} &= 127 \pm 10\,\text{fb} \\
&= 127 \pm 7\,(\text{stat.}) \pm 7\,(\text{syst.})\,\text{fb} \\
(\sigma \times B_{\gamma\gamma})_{\text{exp}} &= 116 \pm 5\,\text{fb}
\end{aligned}
$$

ATLAS-CONF-2020-026

$H \rightarrow \gamma\gamma$

- $\mathrm{BR_{SM}}(H \rightarrow \gamma\gamma) \approx 0.23\%$
- Expect: ~17 500 signal events
  - Excellent signal reconstruction



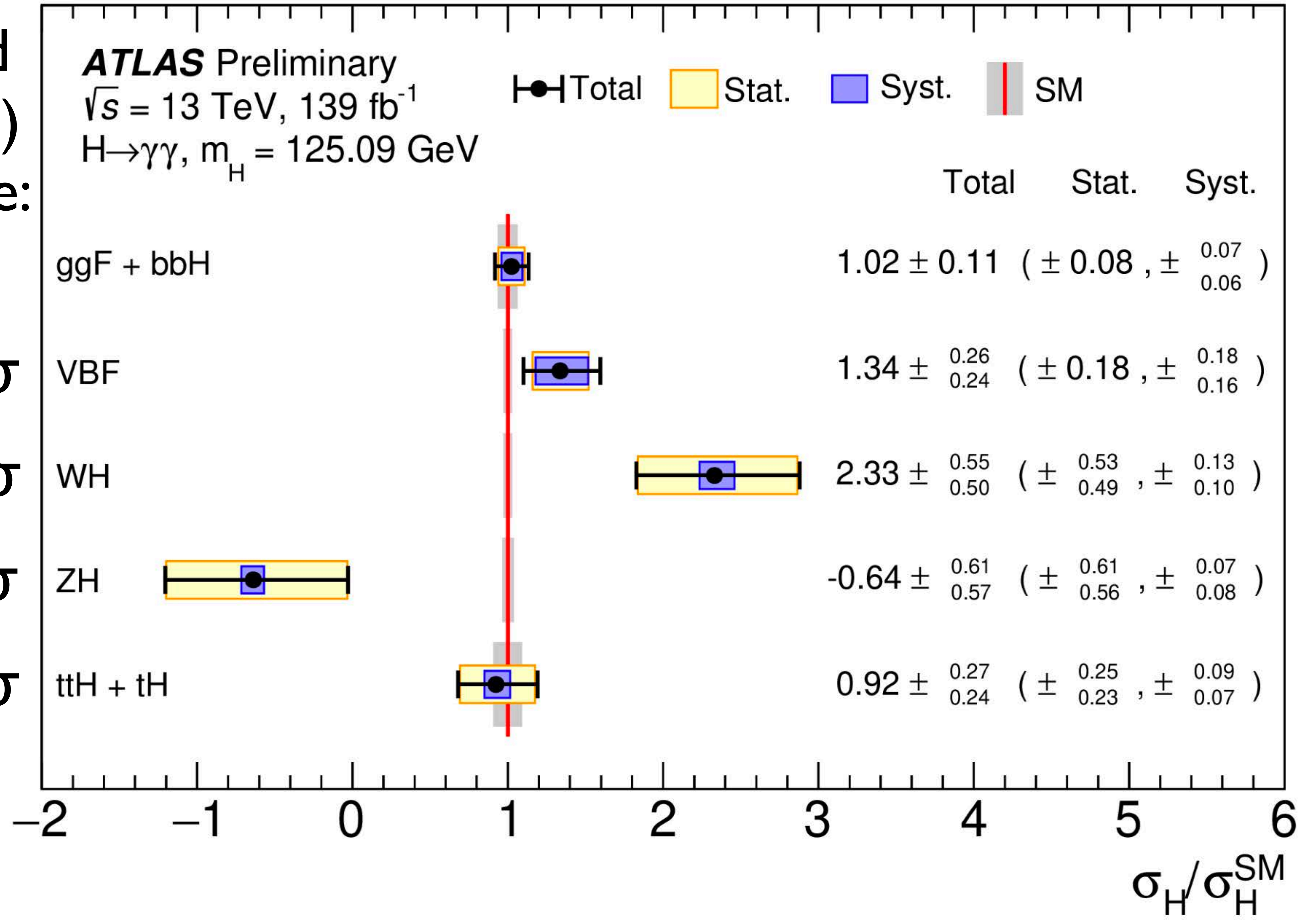
Observed
(expected)
significance:

7.5 (6.1) σ

5.6 (2.8) σ

(1.7) σ

4.7 (5.0) σ

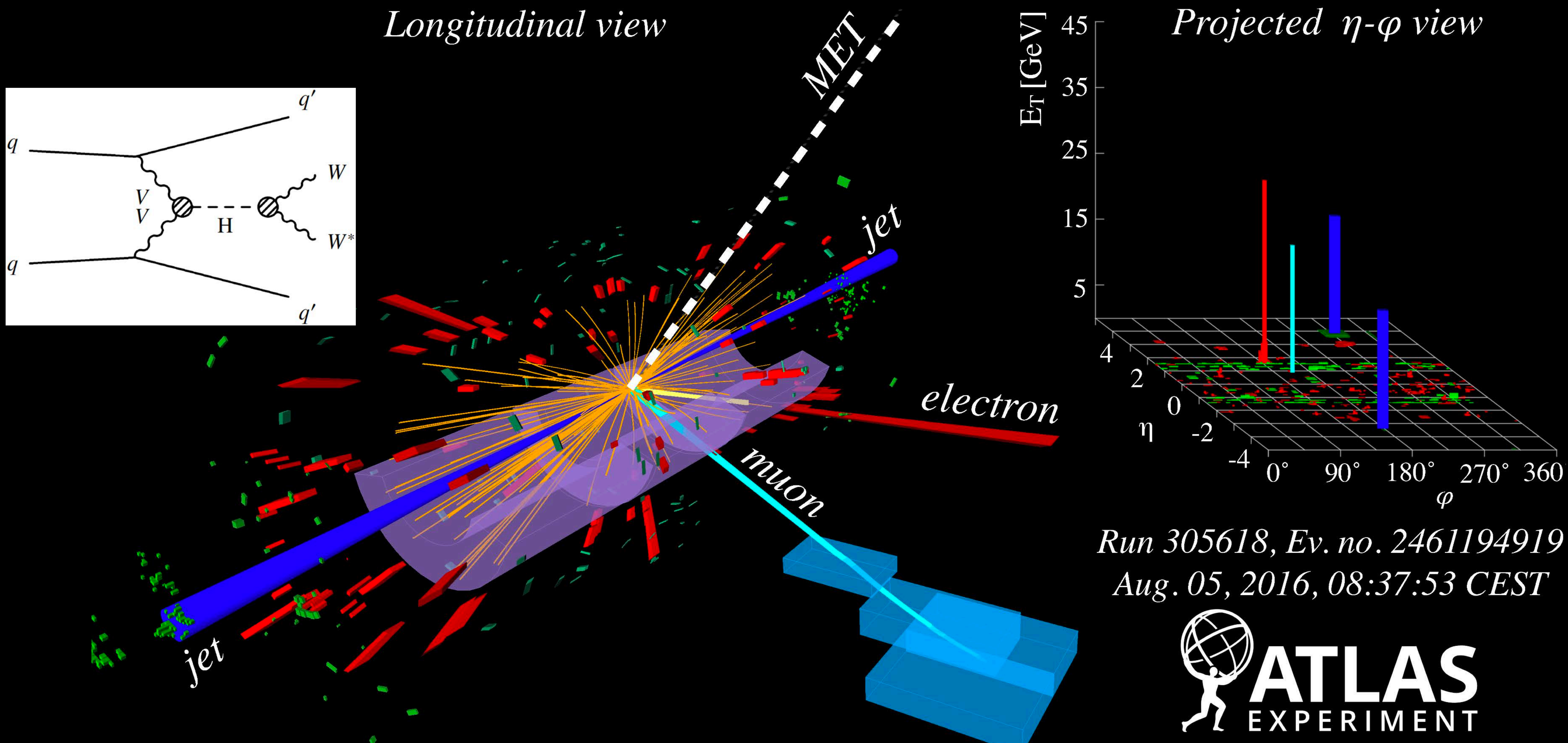


- σ(tH): < 8 times SM production rate
  - Best limit thus far!

ATLAS-CONF-2020-026

VBF H → WW* → eνμν

$H \rightarrow WW^* \rightarrow e\nu\mu\nu$ candidate and two jets with VBF topology



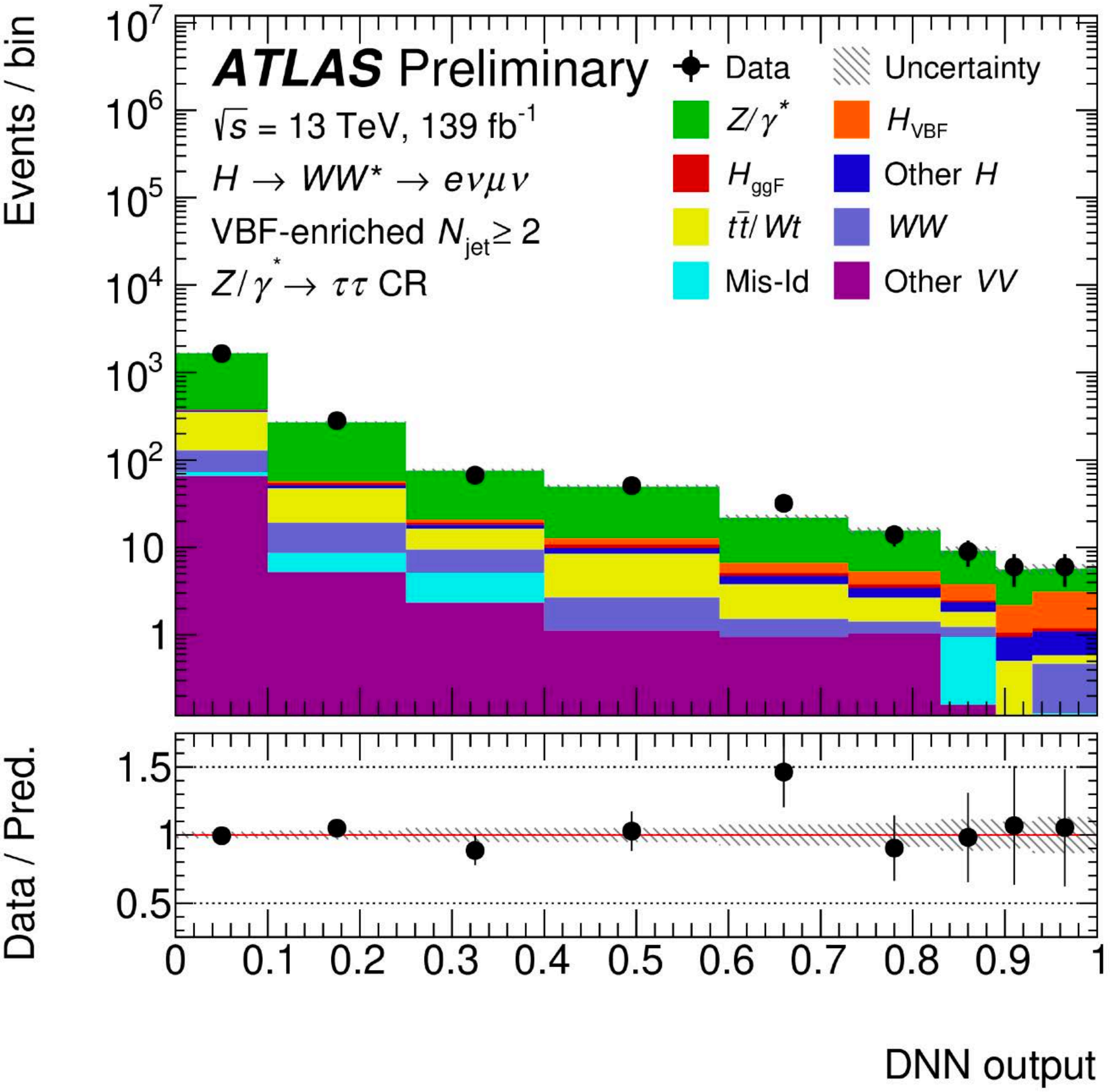
Run 305618, Ev. no. 2461194919
Aug. 05, 2016, 08:37:53 CEST

ATLAS EXPERIMENT

VBF H → WW^* → eνμν

- Large $BR_{SM}(H \to WW^*) \approx 22\%$
  - $BR_{SM}(W \to \ell\nu) \approx 10.8\% \Rightarrow BR_{SM}(H \to WW^* \to e\nu\mu\nu) = 0.25\%$

⇒ **~1300 VBF H → WW^* → eνμν events in 139 fb^{-1},**
but difficult backgrounds… employ deep neural network

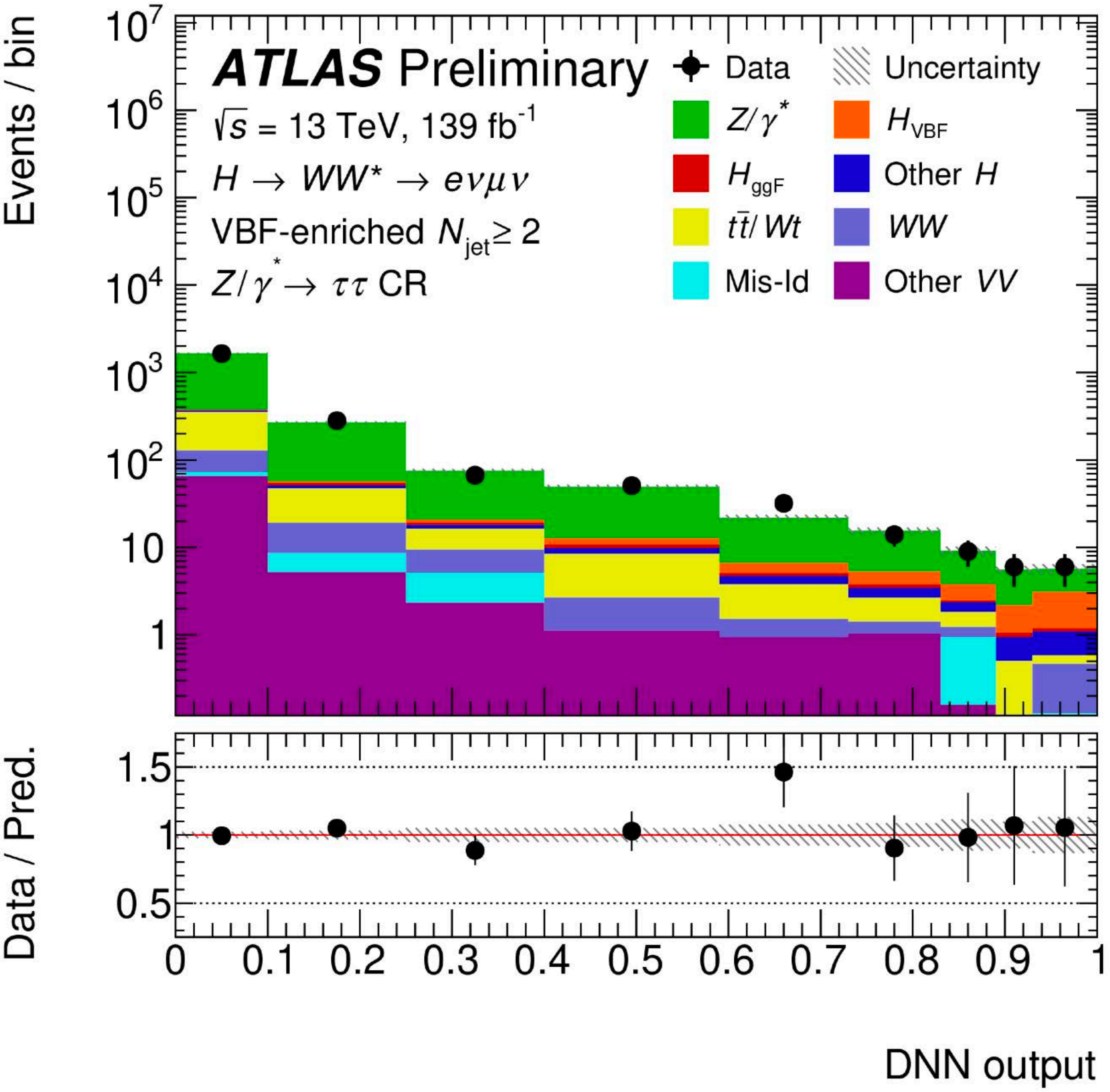


ATLAS-CONF-2021-014

VBF H → WW* → eνμν

- **Large $\mathrm{BR}_{\mathrm{SM}}(H \rightarrow WW^*) \approx 22\%$**
  - $\mathrm{BR}_{\mathrm{SM}}(W \rightarrow \ell\nu) \approx 10.8\% \Rightarrow \mathrm{BR}_{\mathrm{SM}}(\mathbf{H} \rightarrow WW^* \rightarrow e\nu\mu\nu) = 0.25\%$

⇒ **~1300 VBF H → WW* → eνμν events in 139 fb^{-1},**
but difficult backgrounds… employ deep neural network

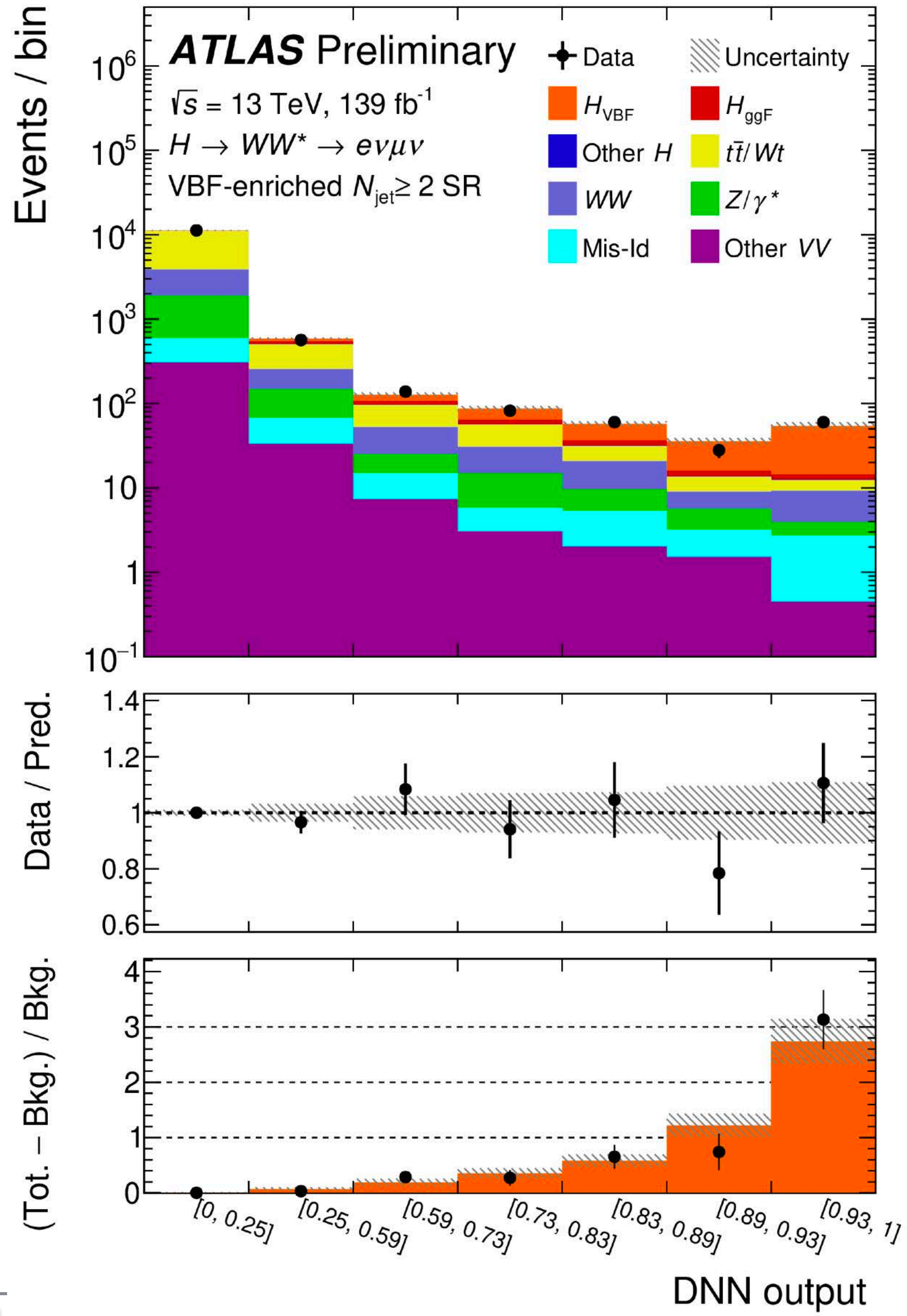


Signal strength:

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

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

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

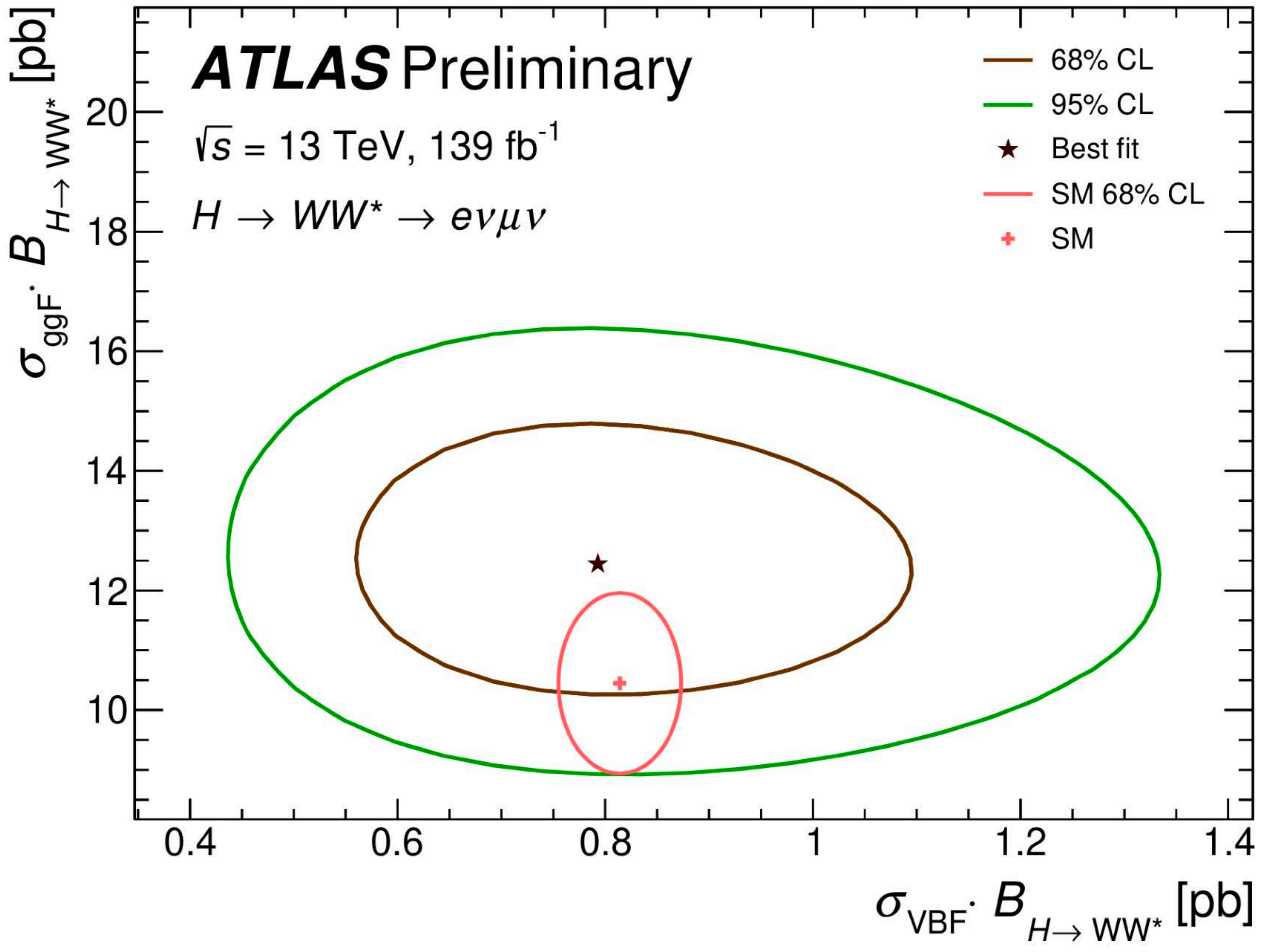


ATLAS-CONF-2021-014

H → WW* → eνμν

- **Large BR$_{SM}$(H → WW*) ≈ 22%**
    - BR$_{SM}$(W → $\ell\nu$) ≈ 10.8% ⇒ BR$_{SM}$(**H → WW*** → eνμν) = 0.25%

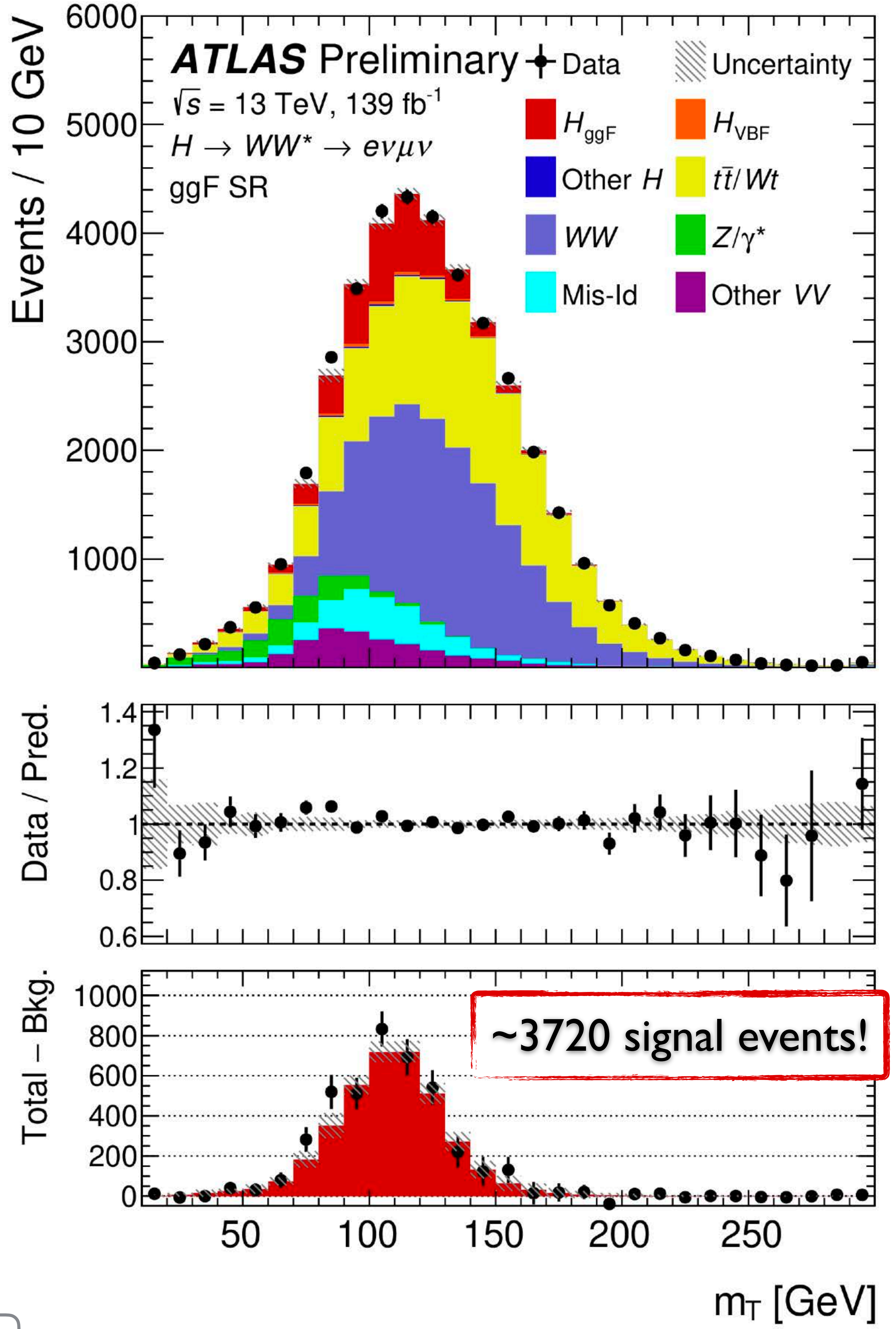
⇒ **~420 000 H → WW* → eνμν events in 139 fb^{-1}**, but difficult backgrounds…



Signal strength:

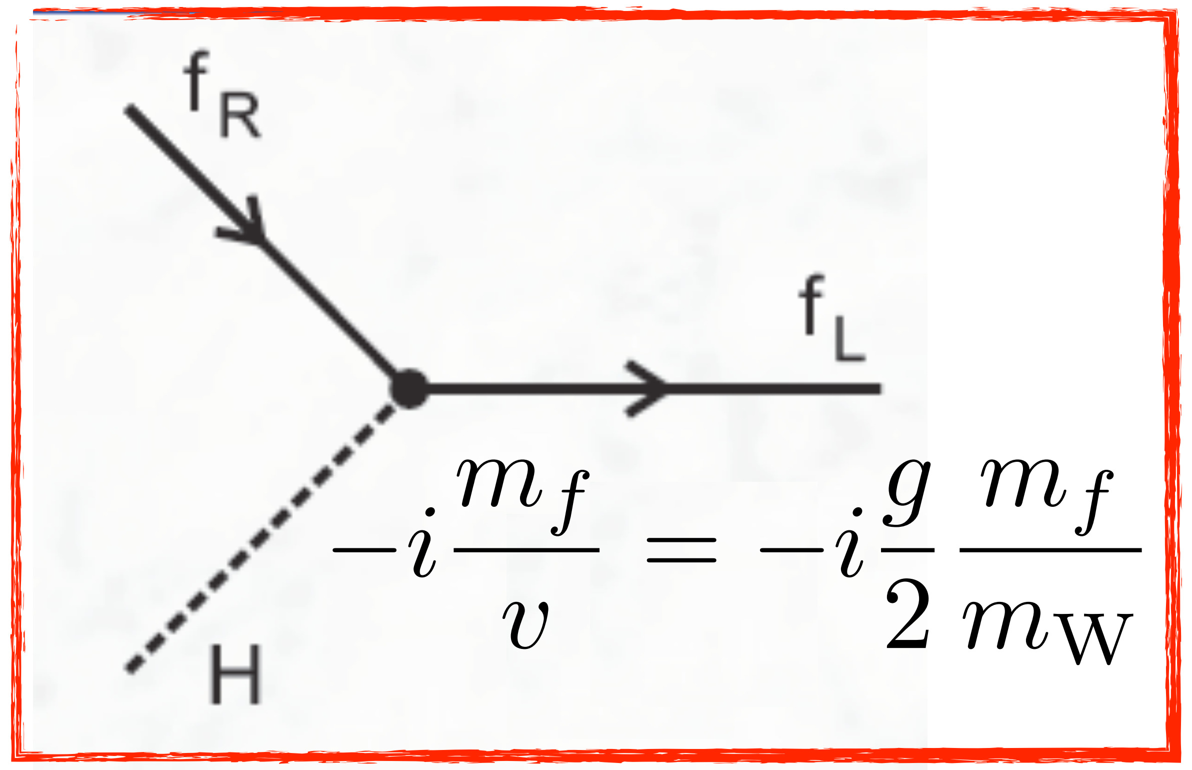
$$\mu := \frac{\sigma_i \cdot \mathcal{B}^f}{(\sigma_i \cdot \mathcal{B}^f)_{\mathrm{SM}}}$$

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



~3720 signal events!

ATLAS-CONF-2021-014



$$-i\frac{m_f}{v} = -i\frac{g}{2}\frac{m_f}{m_W}$$

Fermion Masses

- Also Fermion masses violate fundamental invariance under gauge transformations

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- Fermion mass via *Yukawa coupling* λ$_f$:

Fermion

$$\mathcal{L}_{\text{fermion}} = -\lambda_f \left[\bar{\psi}_L \phi \psi_R + \bar{\psi}_R \phi \psi_L\right]$$

Higgs field

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Higgs field

Expand $\boldsymbol{\phi}(\boldsymbol{x})$ around minimum:

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

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⇐

Fermion mass

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

Fermion Masses

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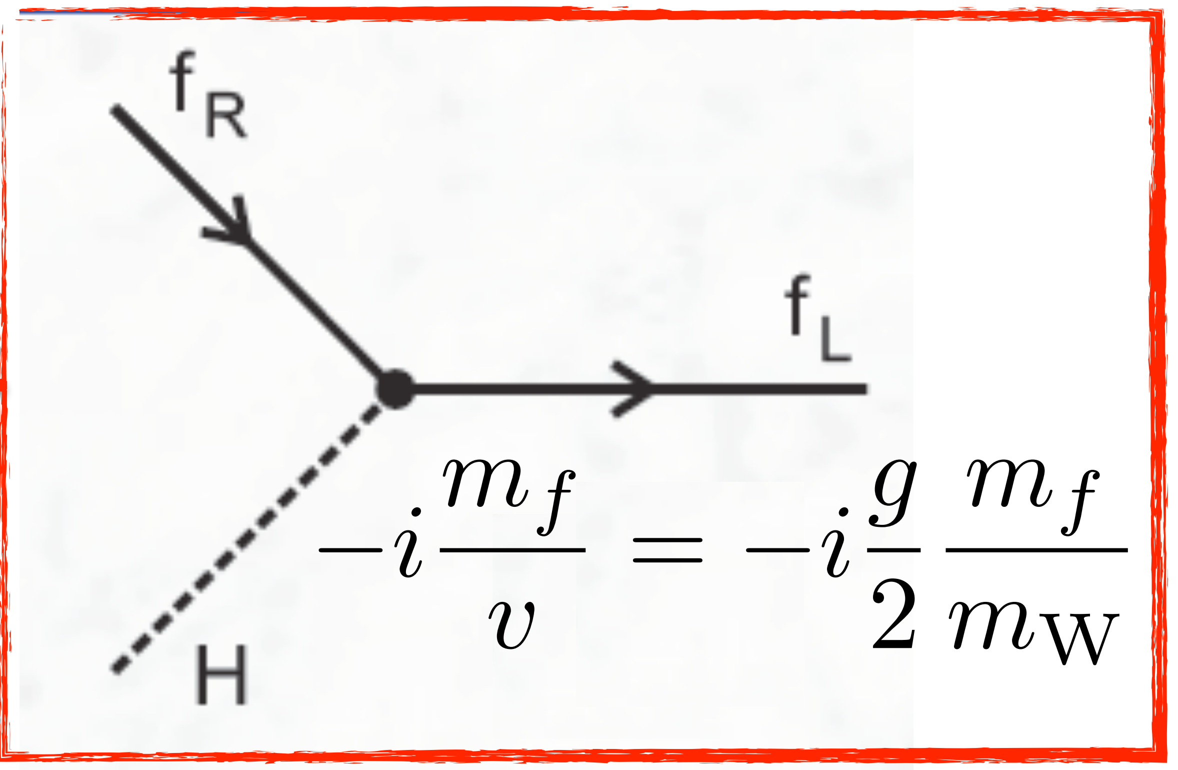

$$-i\frac{m_f}{v} = -i\frac{g}{2}\frac{m_f}{m_W}$$

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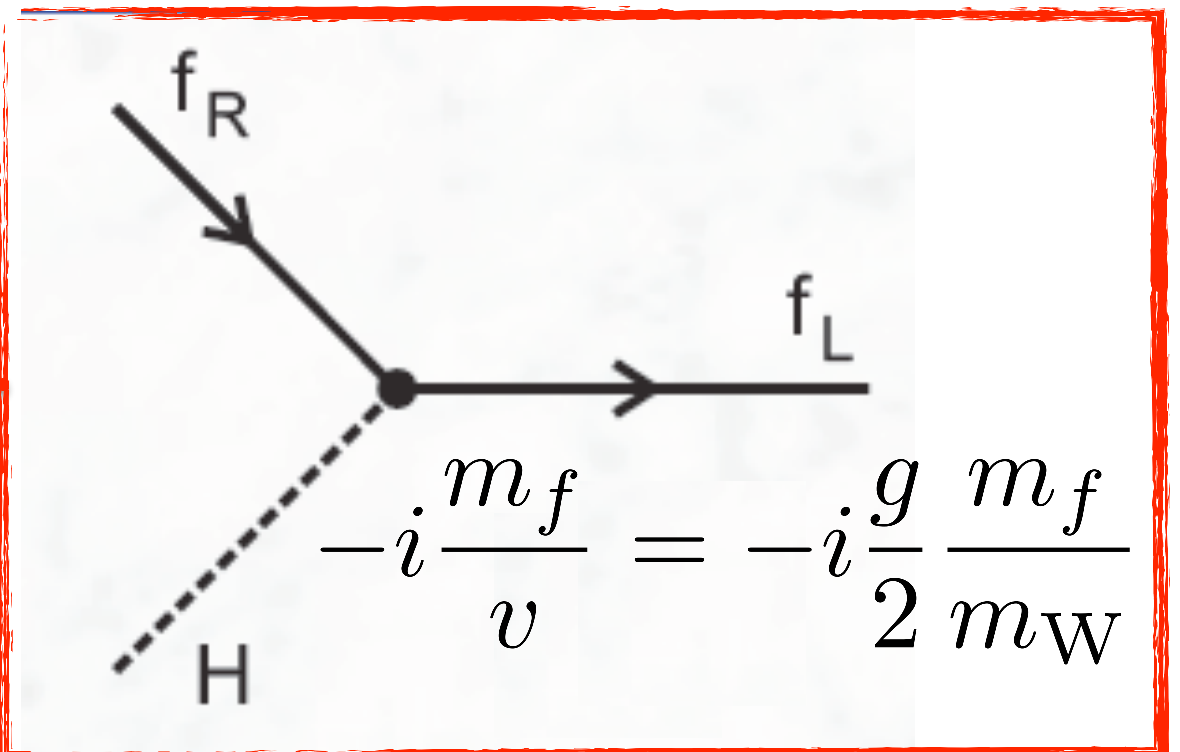


$$-i\frac{m_f}{v} = -i\frac{g}{2}\frac{m_f}{m_W}$$

Fermion mass

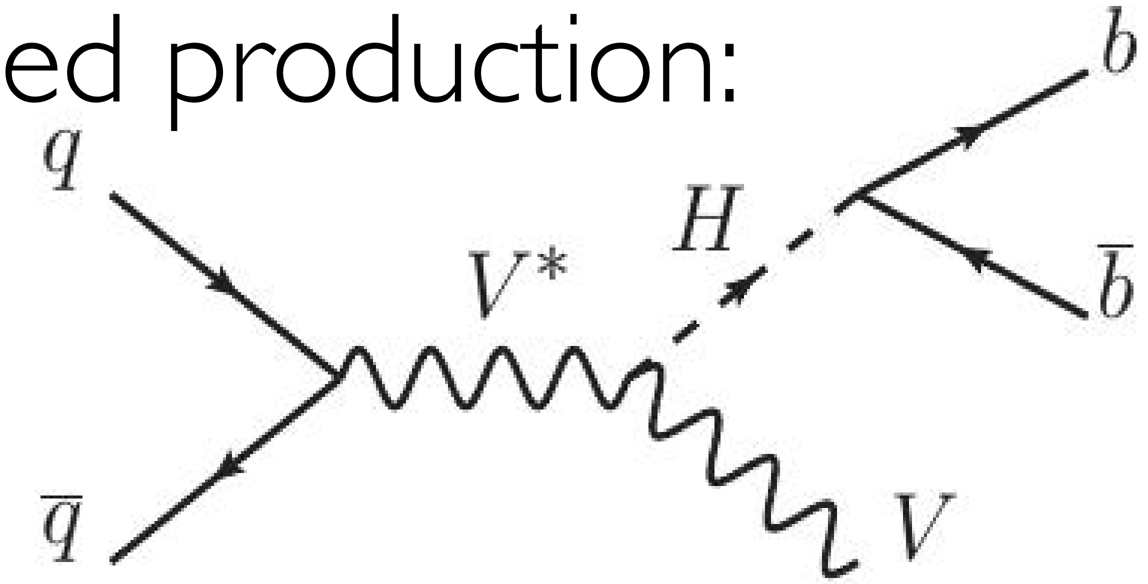
$$m_f = \frac{\lambda_f v}{\sqrt{2}}$$

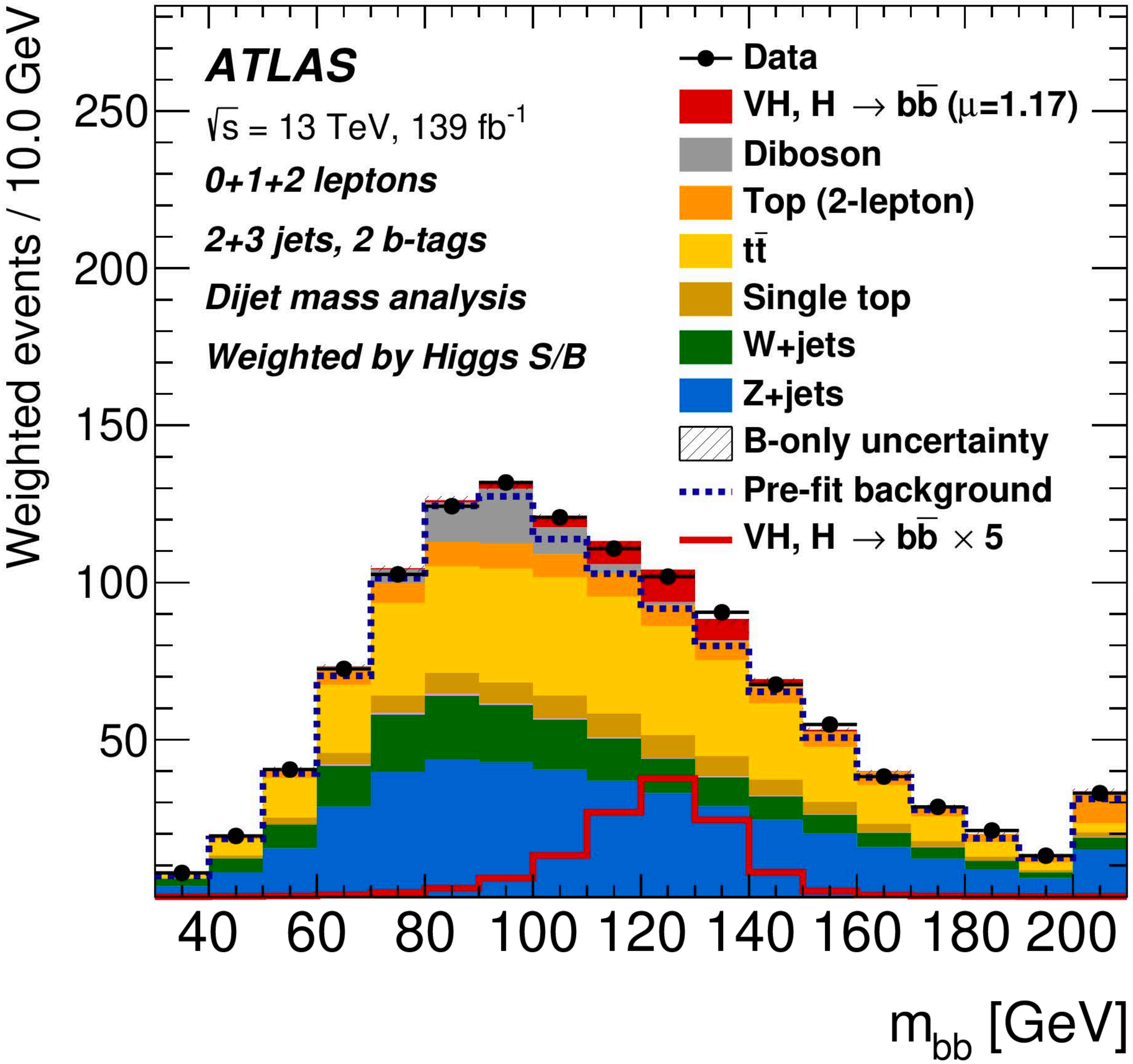
Fundamentally independent from masse generation for gauge bosons!

H → b$\bar{b}$

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

⇒ ~30 000 V(→leptons)H(→ bb) events in 139 fb^{-1}





arXiv:2007.02873

$H \rightarrow b\bar{b}$

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- VH (V=W or Z) associated production:
  - 0 lepton ($Z \rightarrow \nu\nu$)
  - 1 lepton ($W \rightarrow \ell\nu$)
  - 2 lepton ($Z \rightarrow \ell\ell$)

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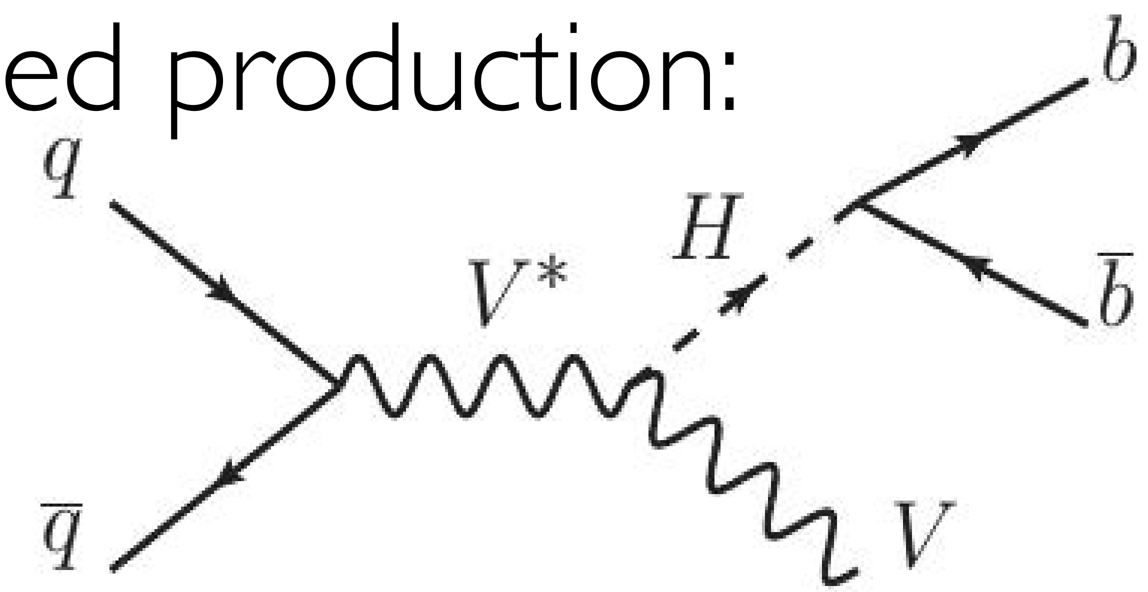

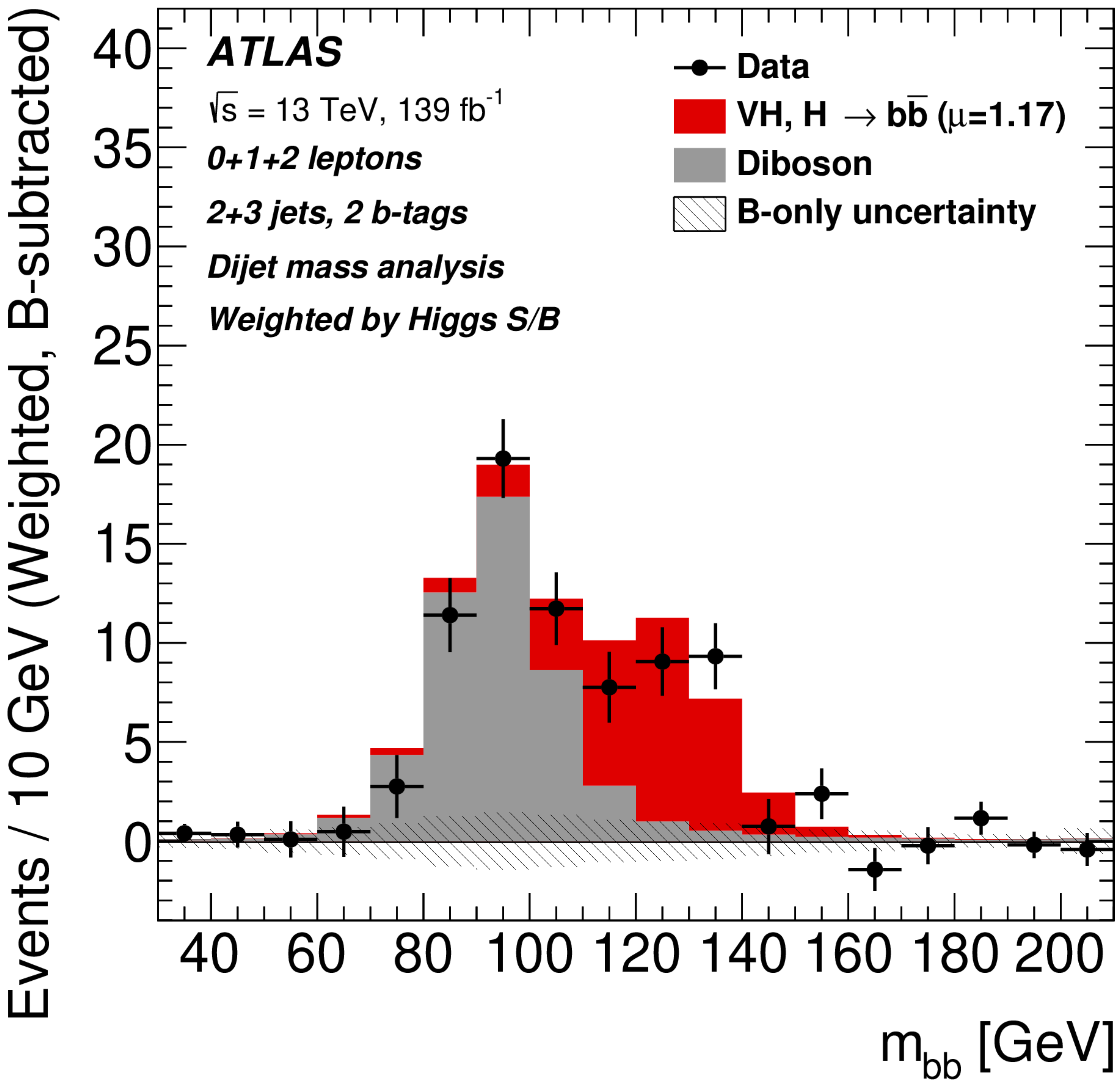

arXiv:2007.02873

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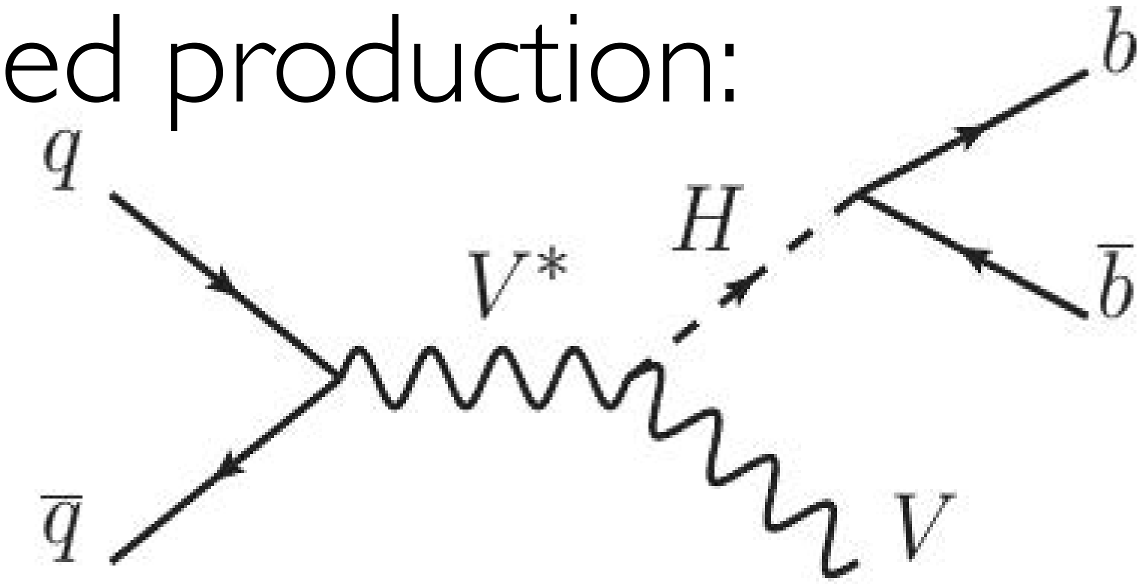
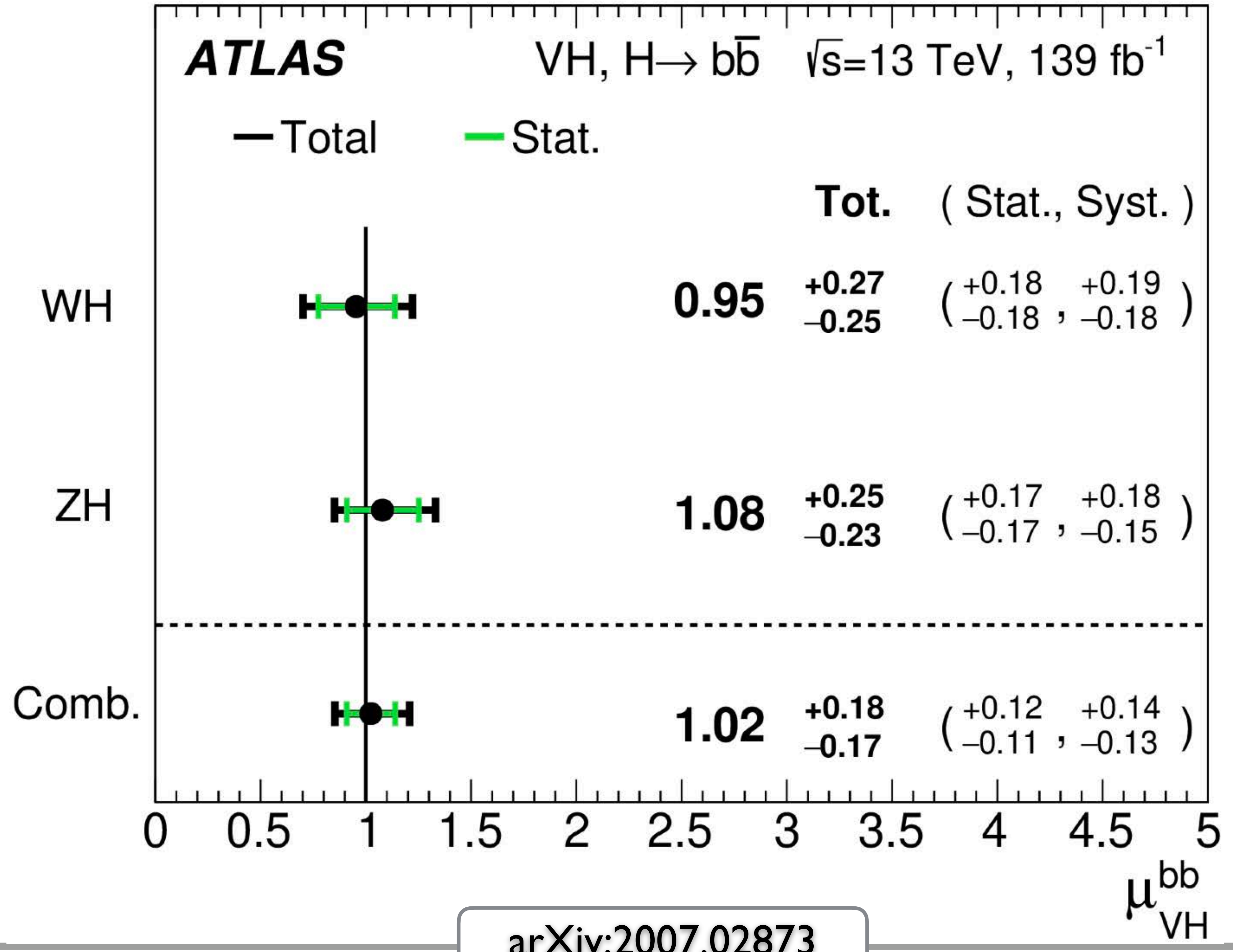


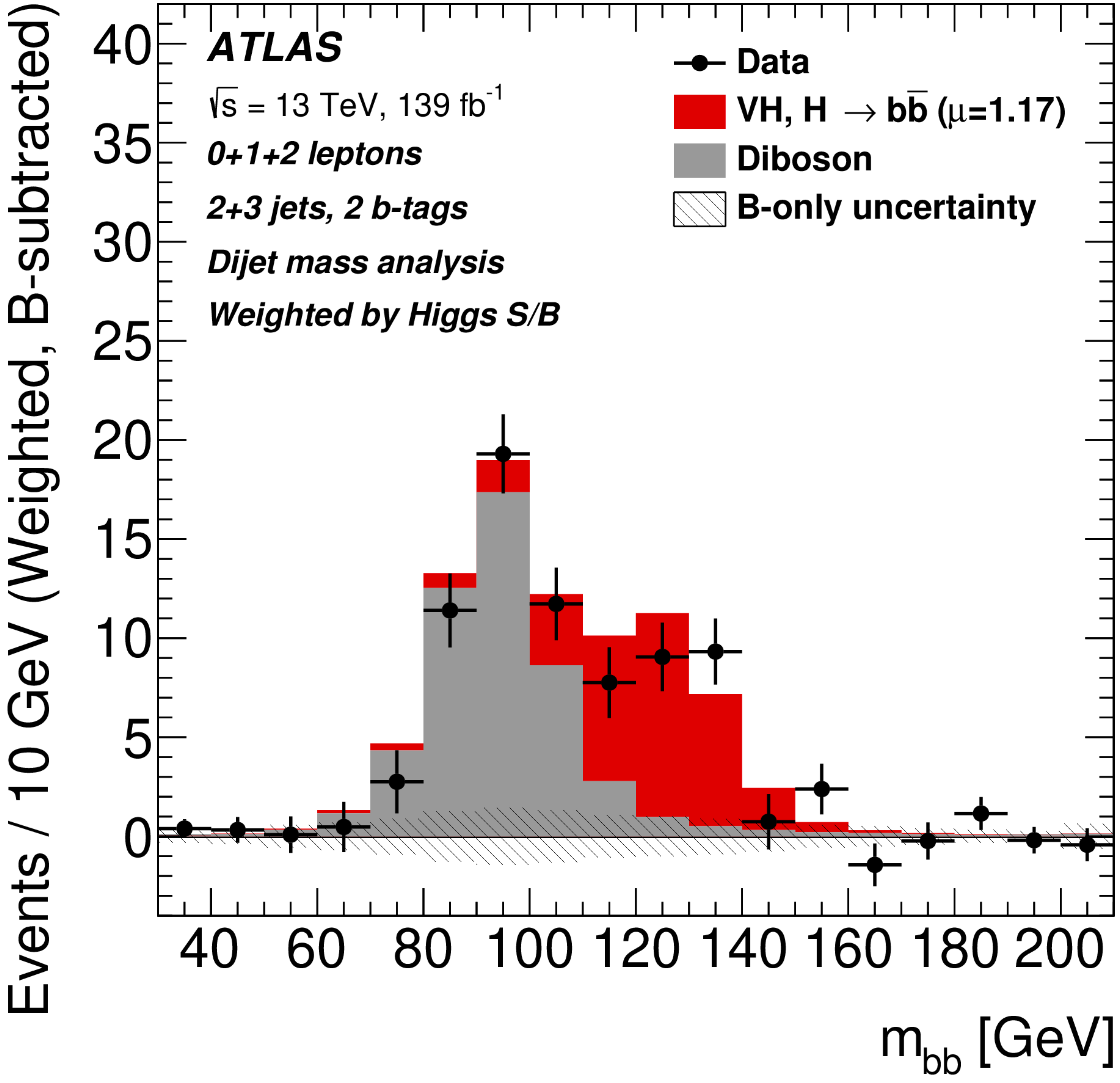
⇒ ~30 000 V(→leptons)H(→ bb) events in 139 fb^{-1}



4.0 σ

5.3 σ

6.7 σ

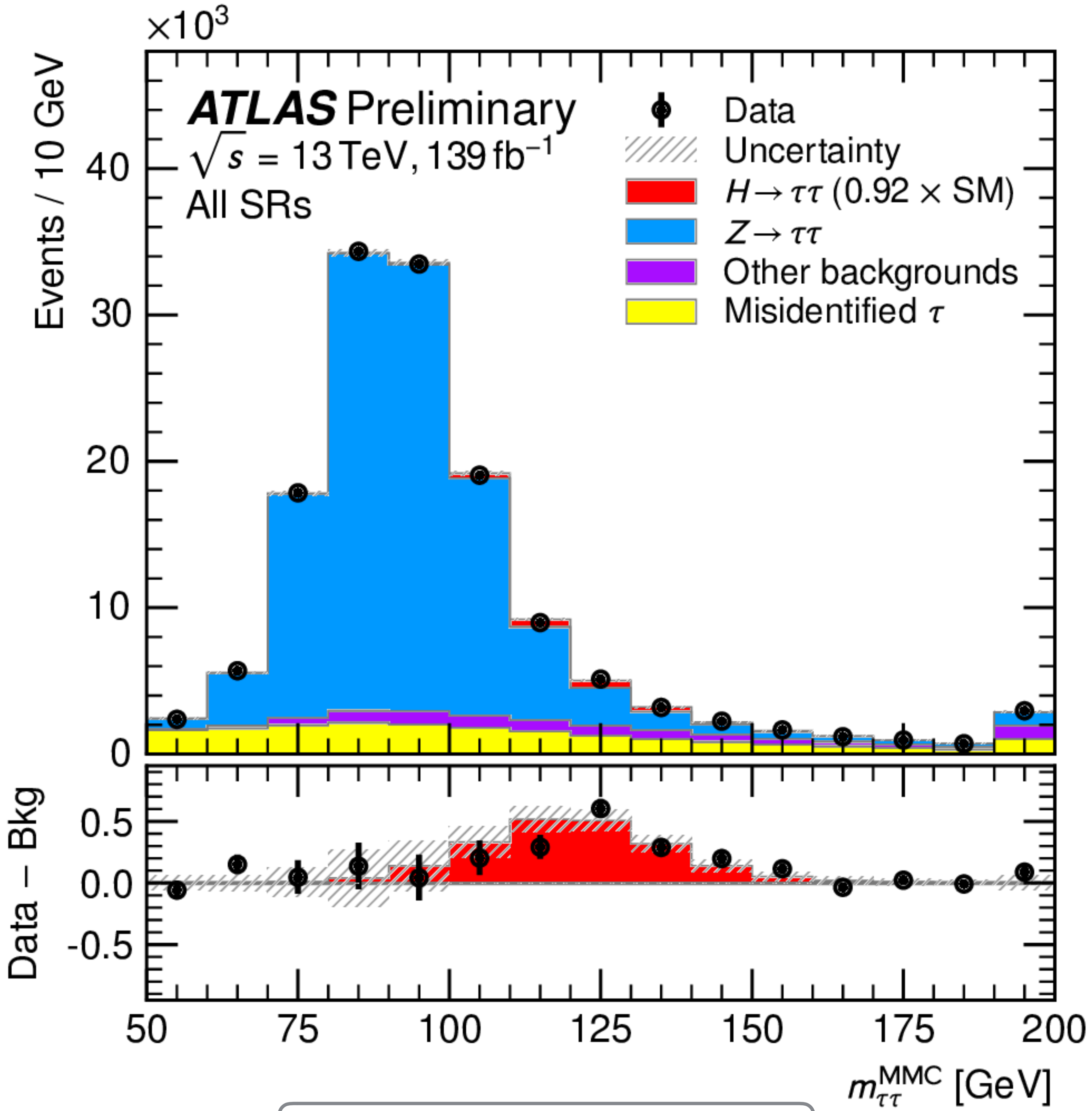


arXiv:2007.02873

H → ττ

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

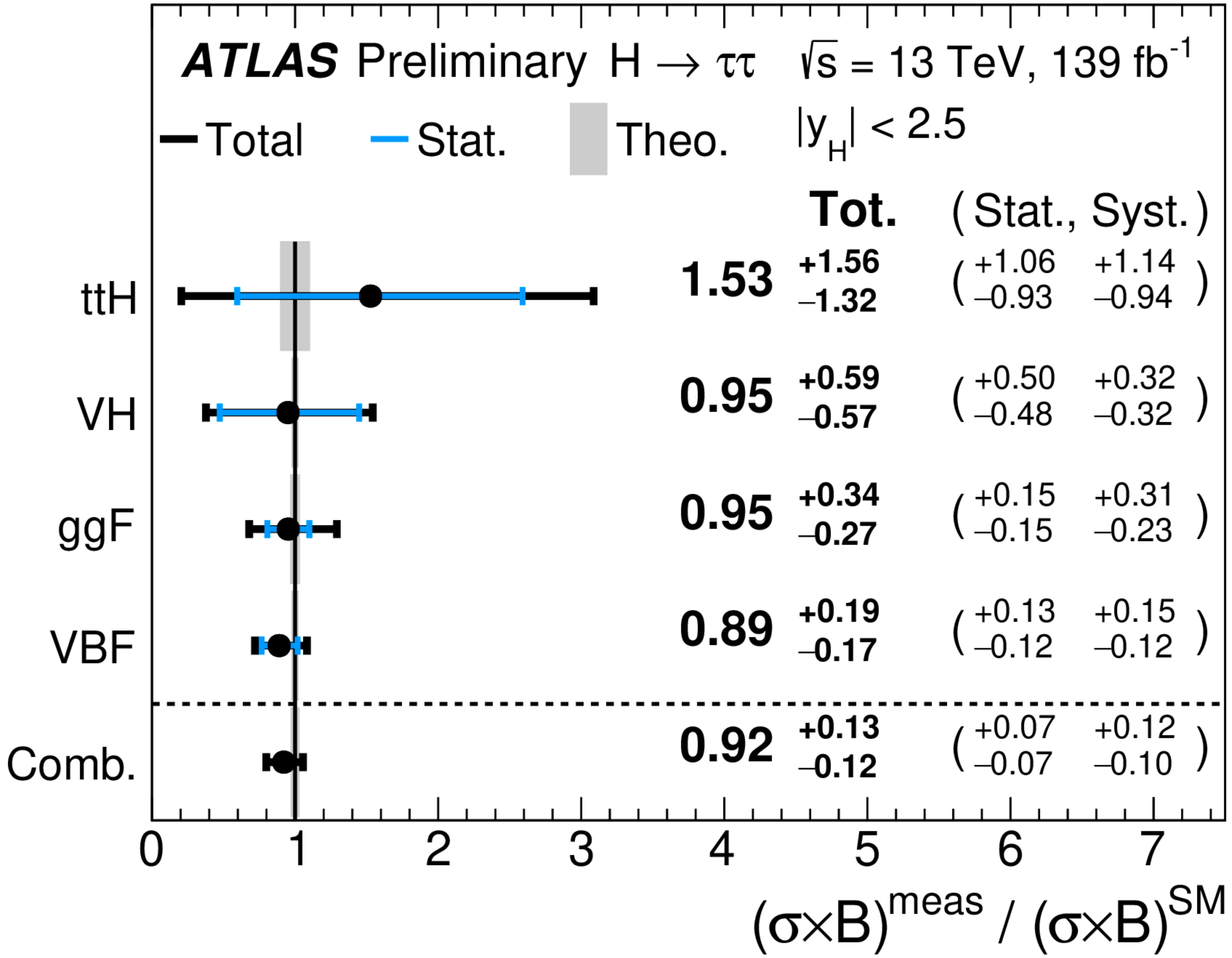
⇒ ~480 000 $H \rightarrow \tau\tau$ events in 139 fb^{-1}



Observed (expected) significance:

3.9 (4.6) σ

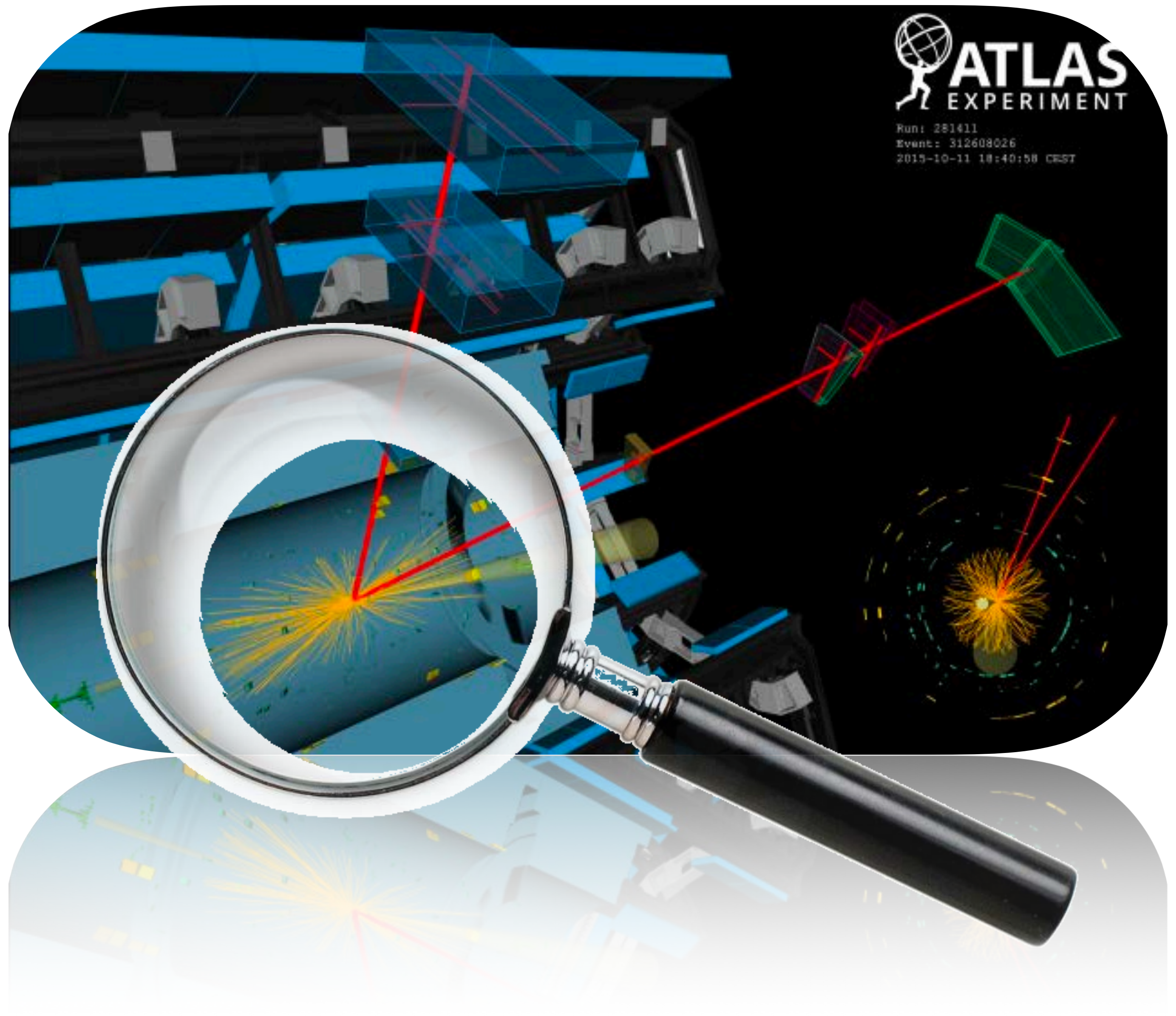
5.3 (6.2) σ



	Tot.		(Stat.,	Syst.)
ttH	1.53	$^{+1.56}_{-1.32}$	$^{+1.06}_{-0.93}$	$^{+1.14}_{-0.94}$
VH	0.95	$^{+0.59}_{-0.57}$	$^{+0.50}_{-0.48}$	$^{+0.32}_{-0.32}$
ggF	0.95	$^{+0.34}_{-0.27}$	$^{+0.15}_{-0.15}$	$^{+0.31}_{-0.23}$
VBF	0.89	$^{+0.19}_{-0.17}$	$^{+0.13}_{-0.12}$	$^{+0.15}_{-0.12}$
Comb.	0.92	$^{+0.13}_{-0.12}$	$^{+0.07}_{-0.07}$	$^{+0.12}_{-0.10}$

ATLAS-CONF-2021-044

1. Introduction
2. Mass measurement
3. Decays into Bosons
4. Decays into Fermions
5. **Rare processes**
6. Combinations and Interpretations
7. Future
8. Summary

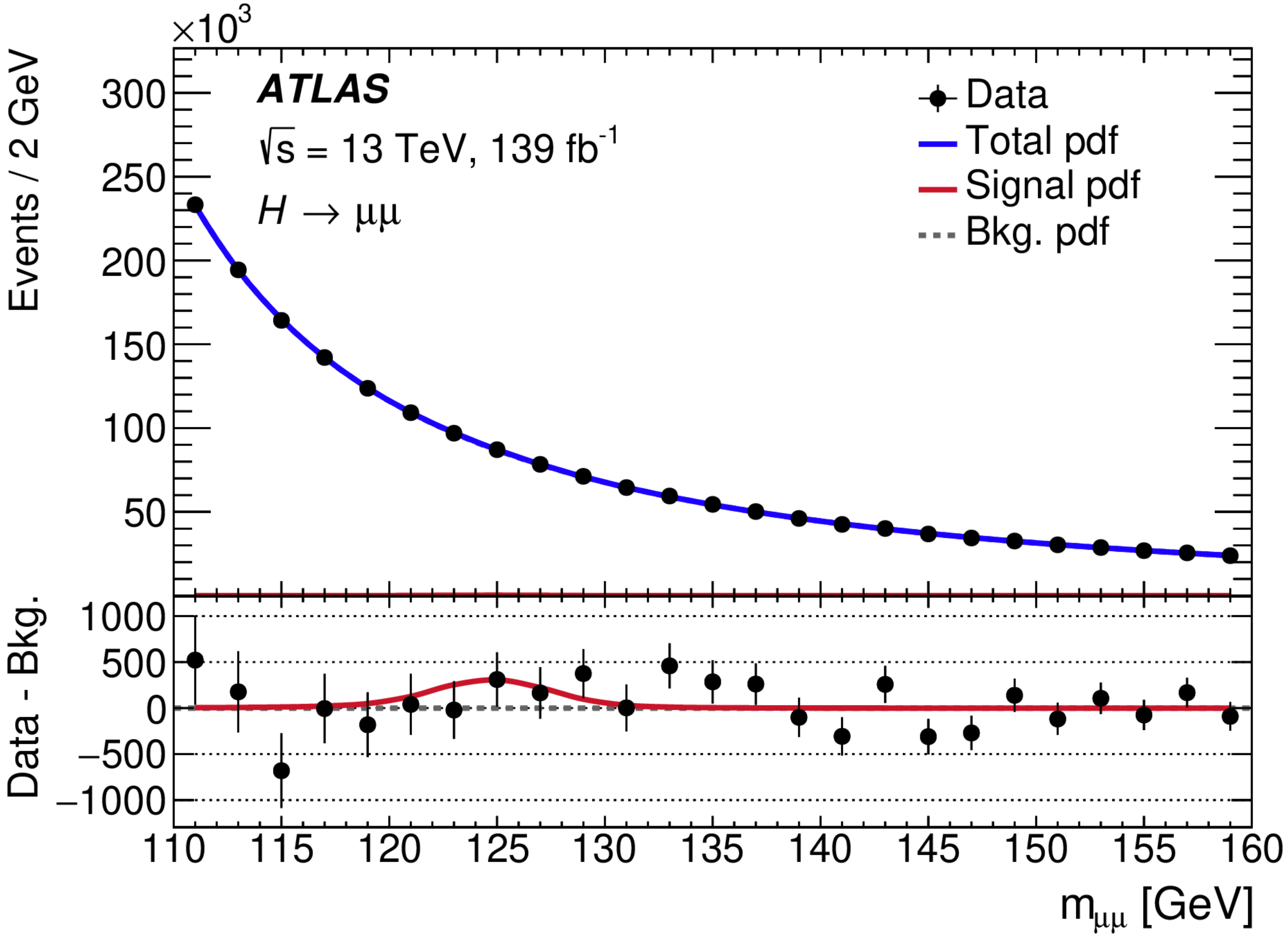


$H \rightarrow \mu\mu$

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

⇒ **~1700 $H \rightarrow \mu\mu$ events in 139 fb^{-1}**,
huge $Z/\gamma^* \rightarrow \mu\mu$ background

- Split events into 20 categories to maximize sensitivity
- Fit $m_{\mu\mu}$ spectrum
  - Determine background function with huge MCs
- Results:
  - Signal strength μ **=1.2 ± 0.6**
  - Observed (expected) significance: **2.0 (1.7) σ**
  - Observed (expected) upper limit on BR: **2.2 (1.1) × SM** (95% C.L.)



⇒ Non-universal coupling to leptons!

Phys. Lett. B 812 (2021) 135980

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

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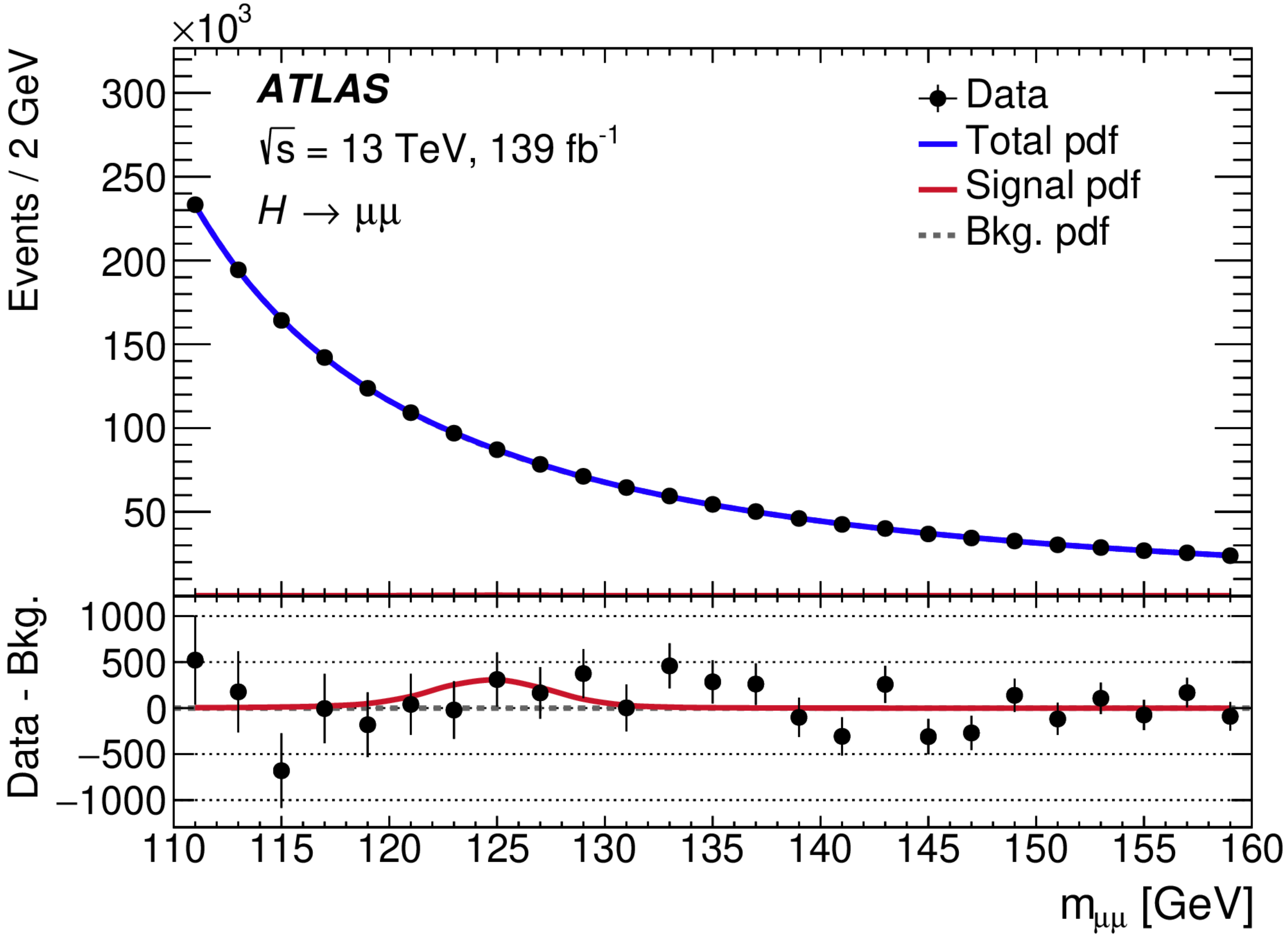
  - Observed (expected) upper limit on BR: **2.2 (1.1) × SM** (95% C.L.)

⇒ Non-universal coupling to leptons!



Recent CMS result:

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

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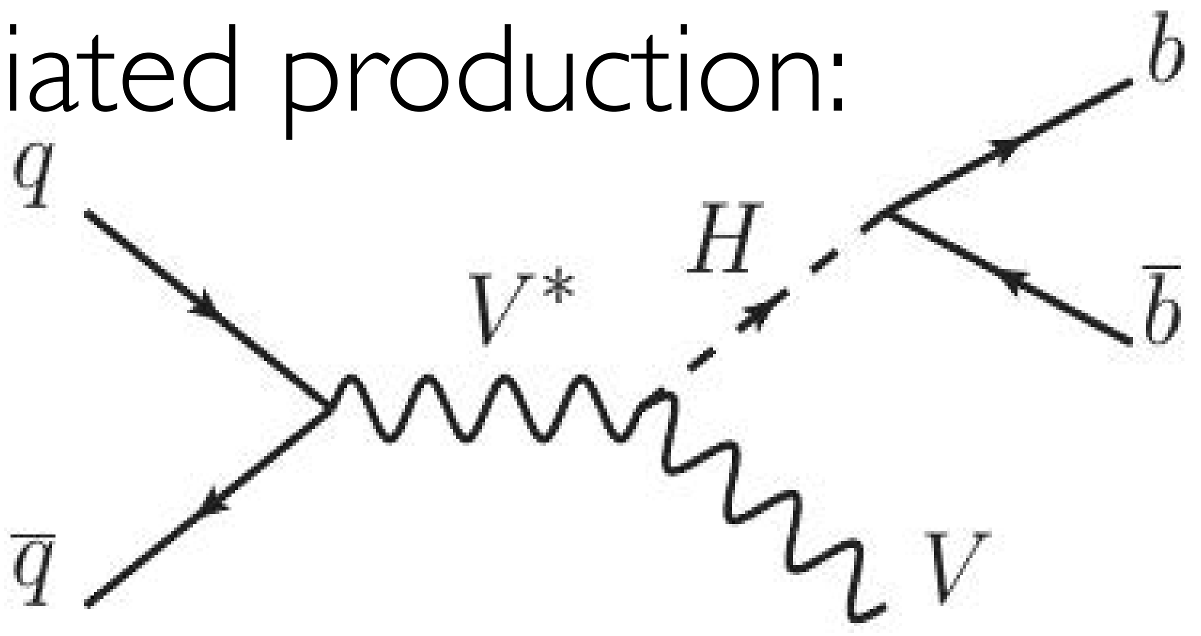
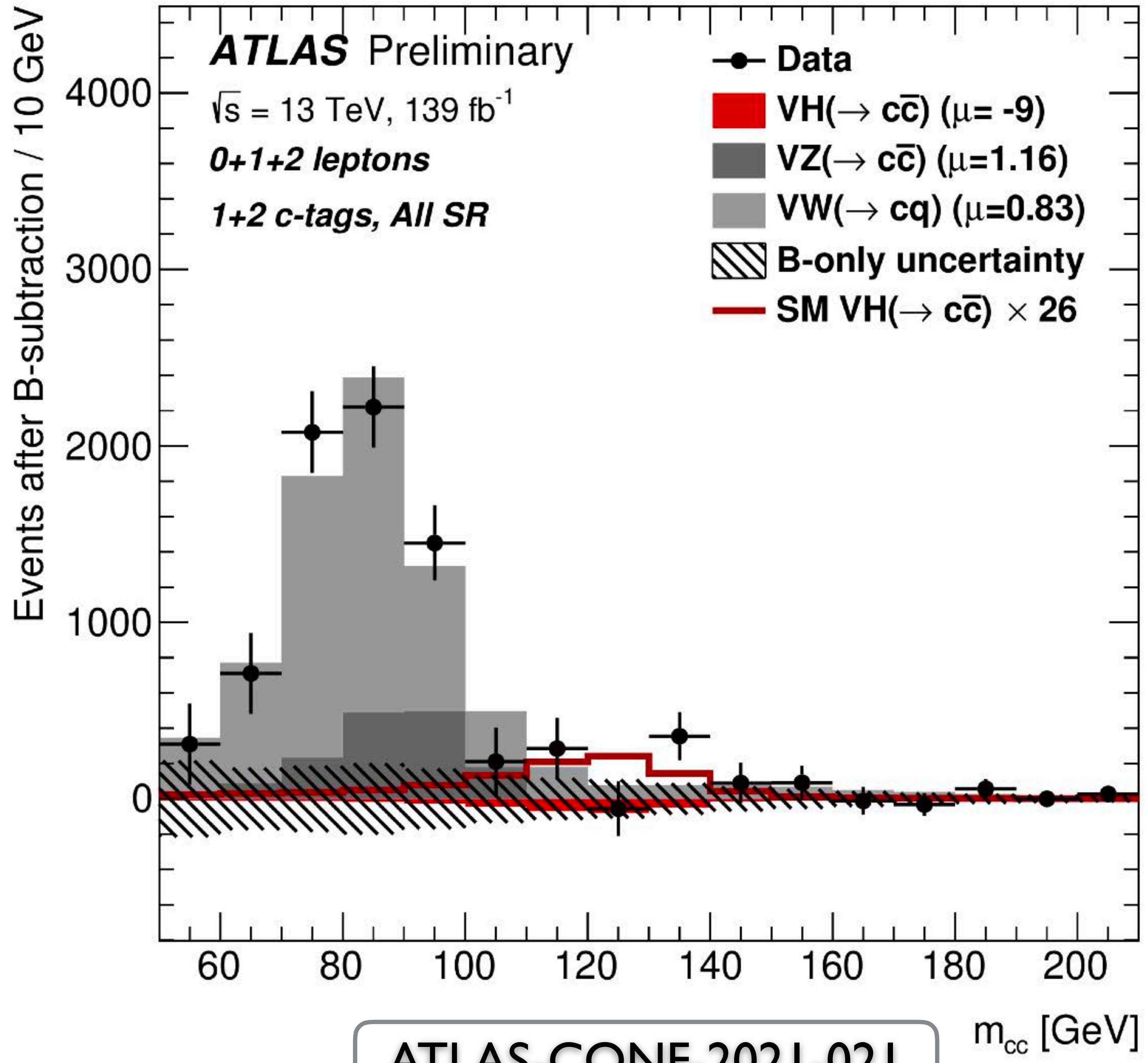
$H \to c\bar{c}$

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



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



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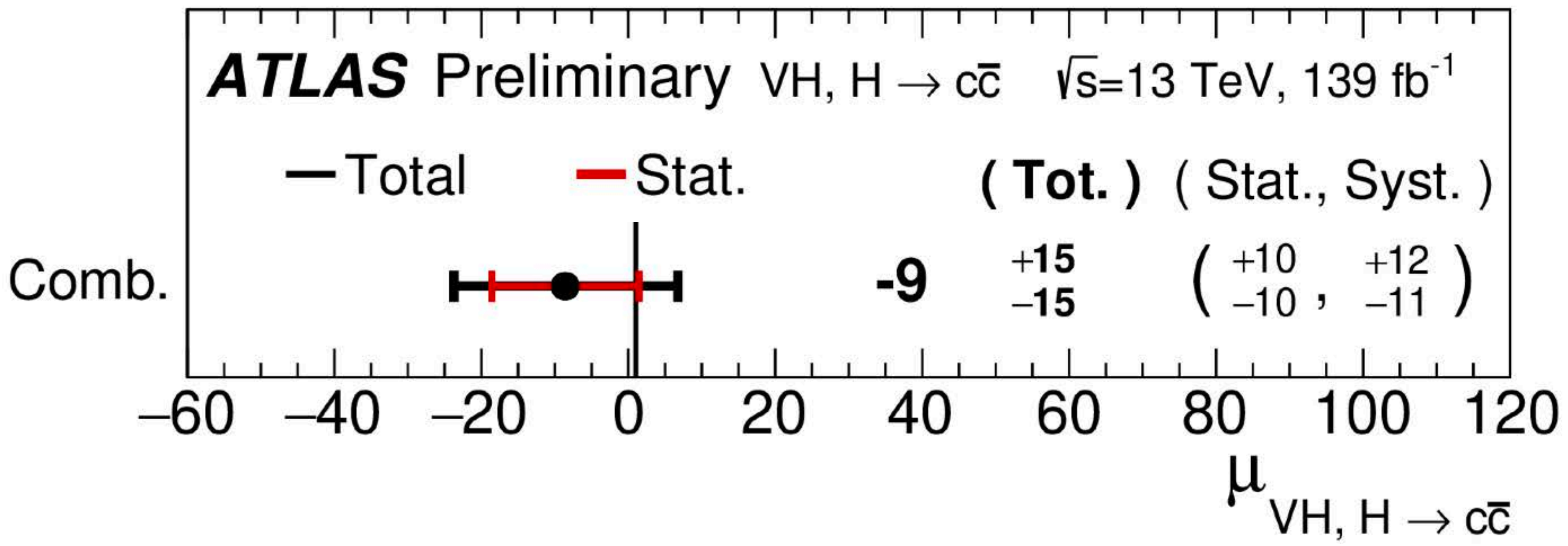
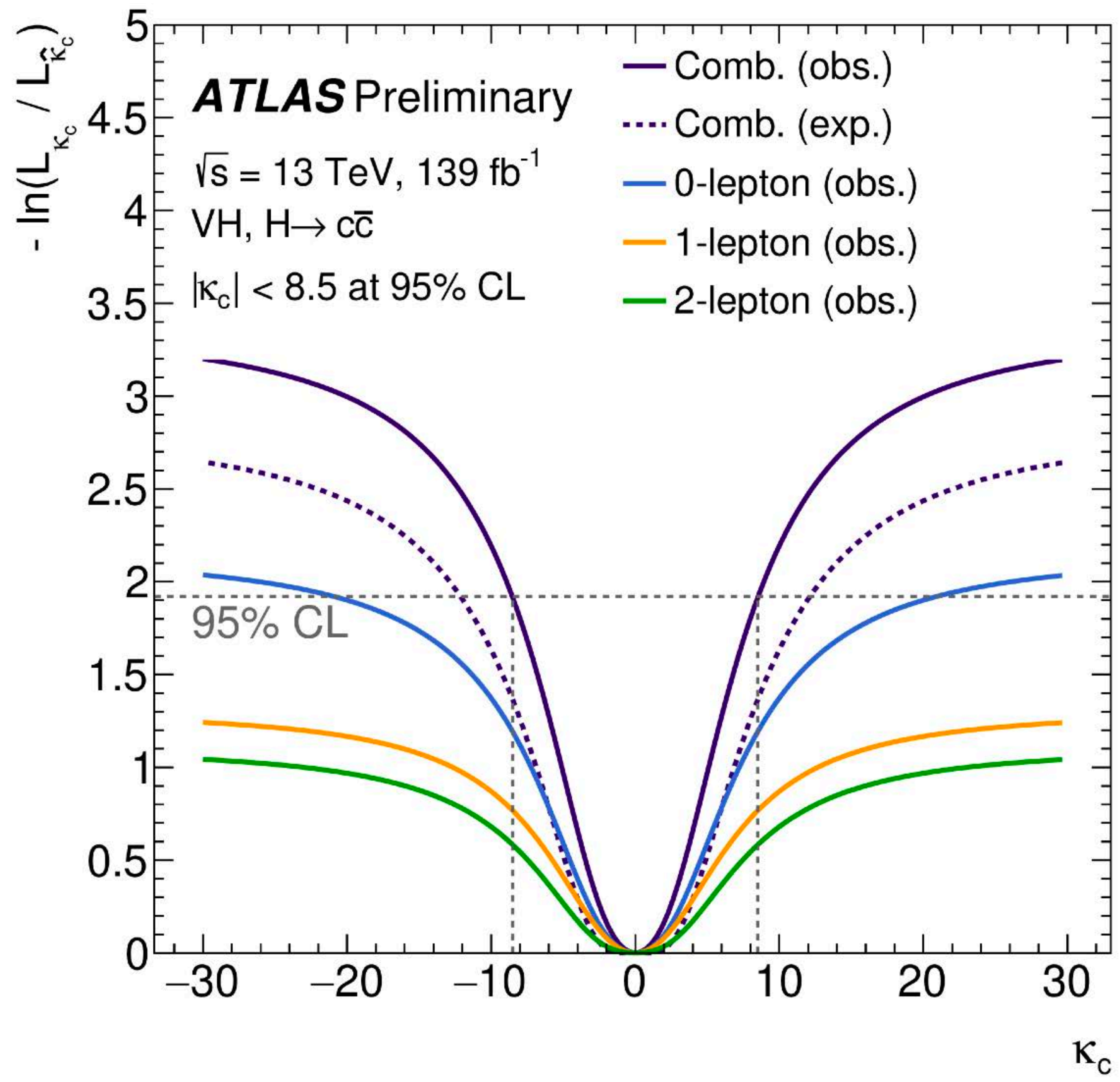


- Observed (expected) upper limit on $\sigma \cdot$BR **26 (31) × SM** (95% C.L.)

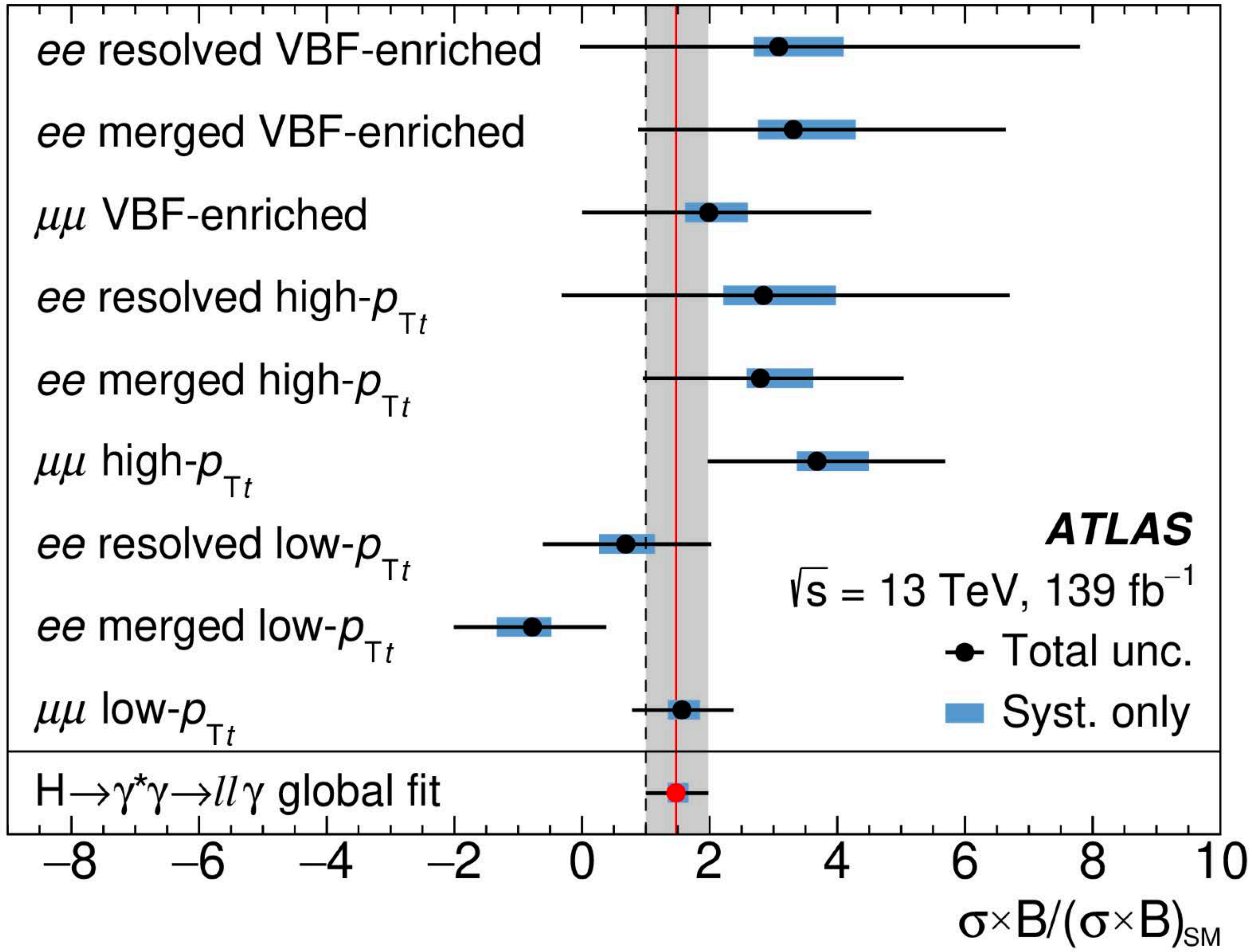


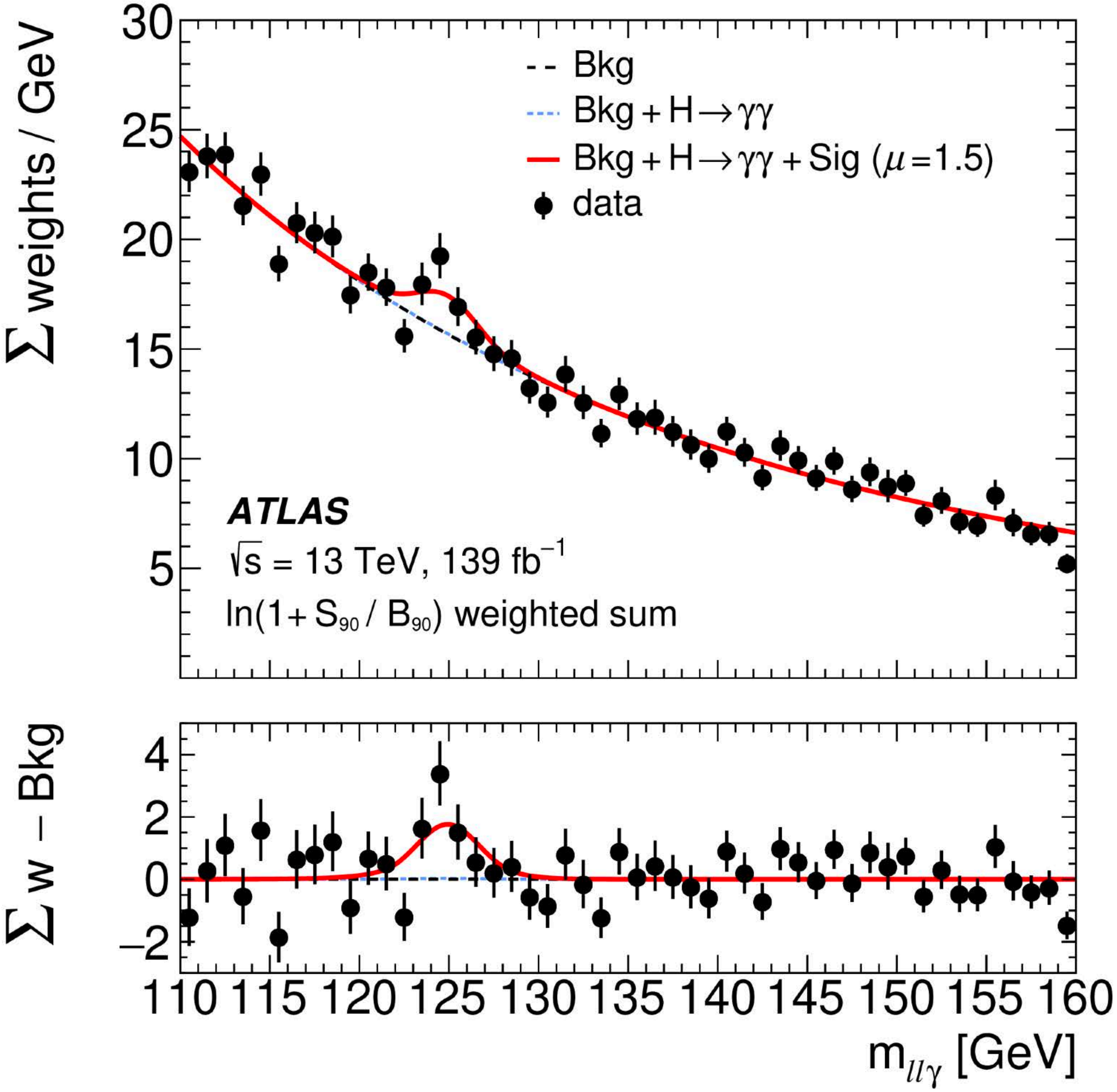
- Observed (expected) upper limit on Higgs-charm-coupling: **8.5 (12.4) × SM** (95% C.L.)

$H \rightarrow \mu\mu\gamma$

H → $\ell\ell\gamma$

- Tiny branching fractions:
  - $\mathrm{BR_{SM}}(H \rightarrow ee\gamma)|_{m_{\ell\ell}<30\ \mathrm{GeV}} = 7.20 \times 10^{-5}$
    $\mathrm{BR_{SM}}(H \rightarrow \mu\mu\gamma)|_{m_{\ell\ell}<30\ \mathrm{GeV}} = 3.42 \times 10^{-5}$
  - ~1200 H → $\ell\ell\gamma$ events in 139 fb^{-1}





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

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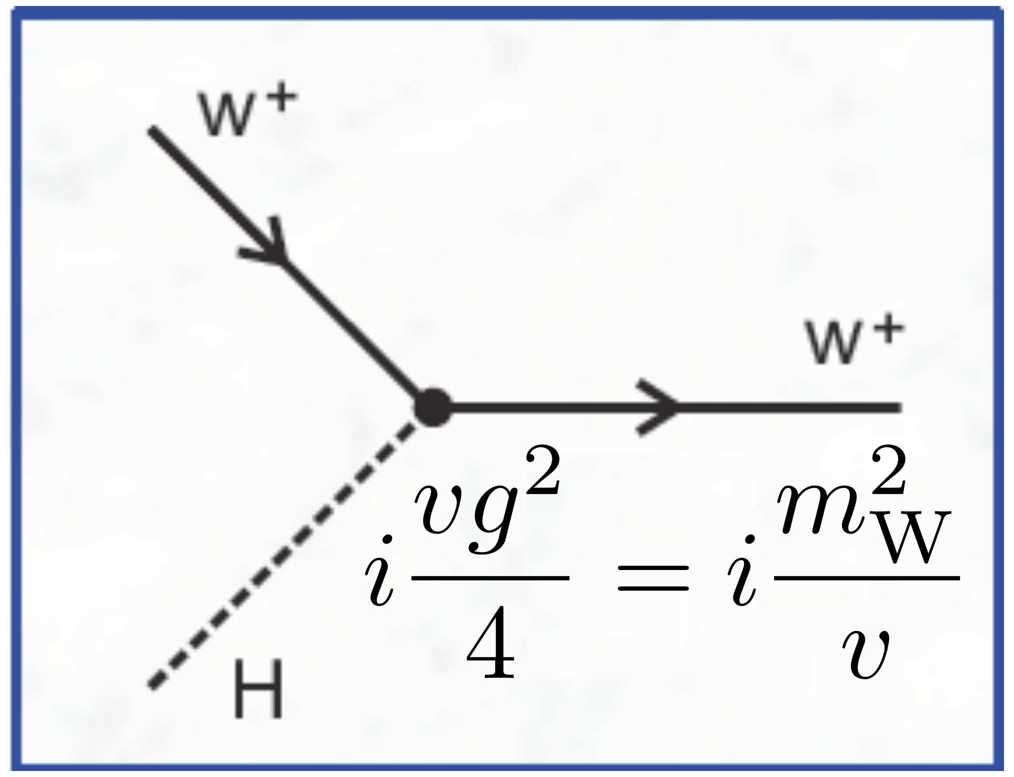
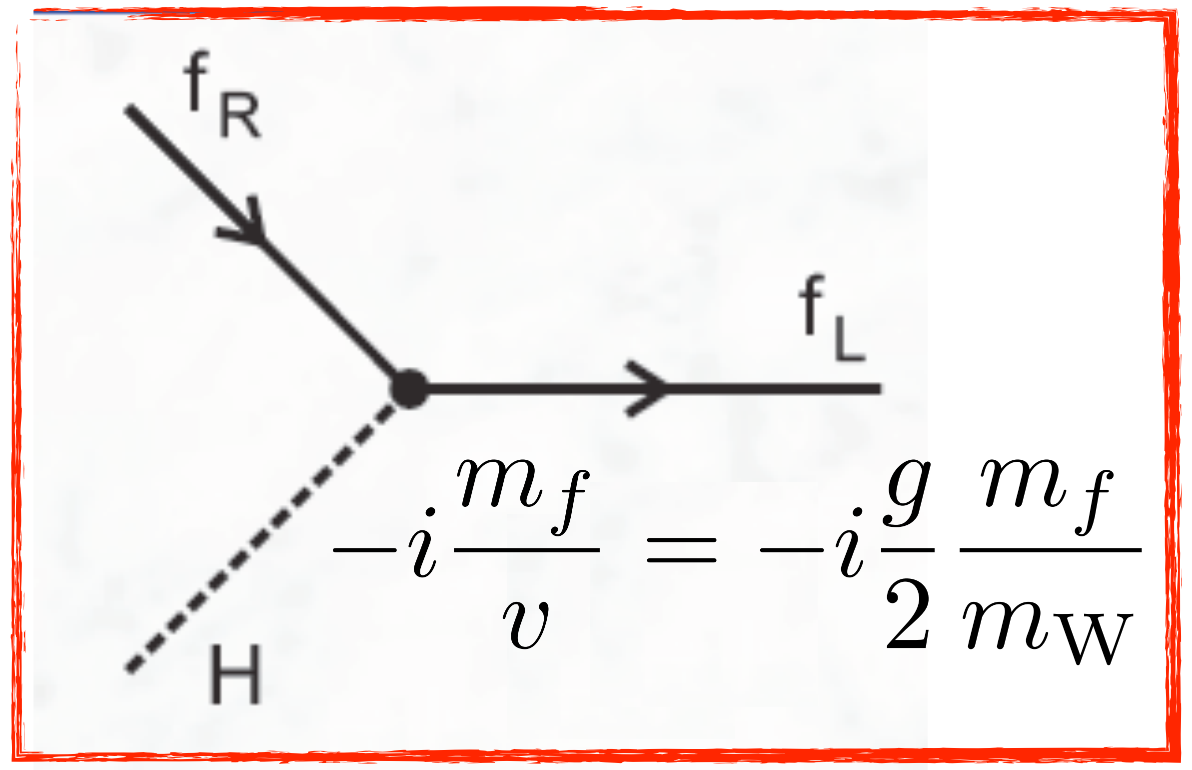
1. Introduction
2. Mass measurement
3. Decays into Bosons
4. Decays into Fermions
5. Rare processes
6. **Combinations and Interpretations**
7. Future
8. Summary

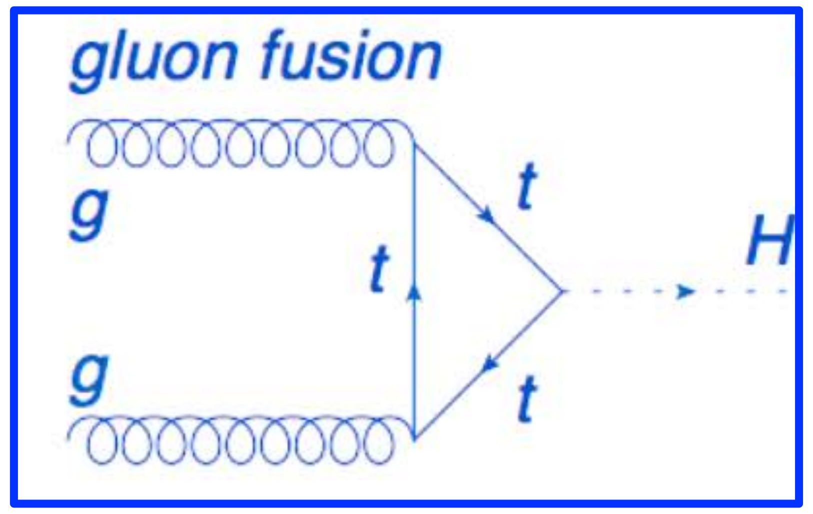


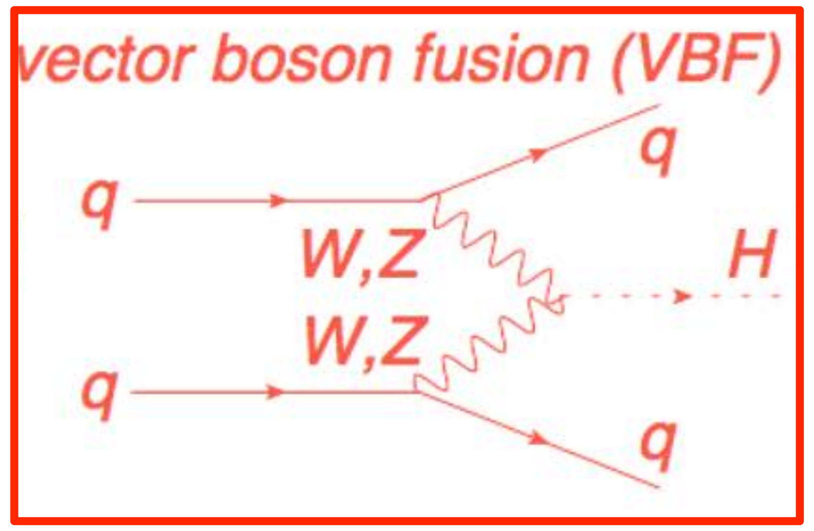
$$i\frac{vg^2}{4} = i\frac{m_W^2}{v}$$

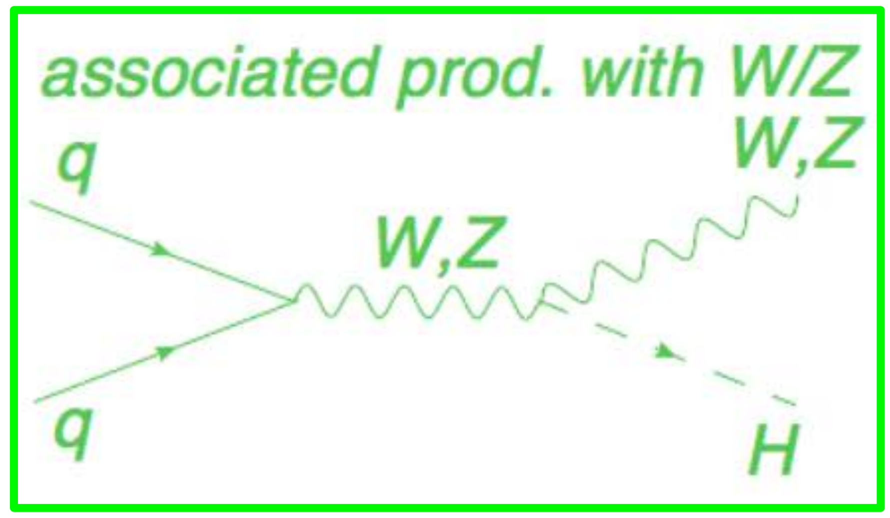


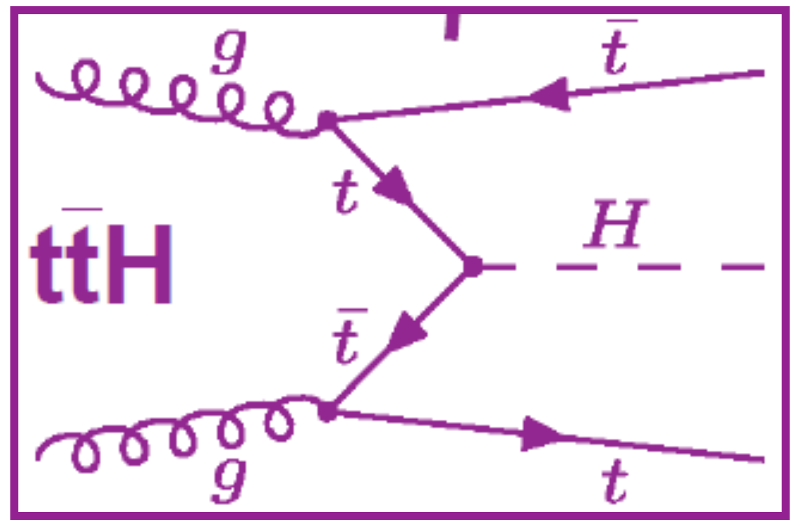
$$-i\frac{m_f}{v} = -i\frac{g}{2}\frac{m_f}{m_W}$$

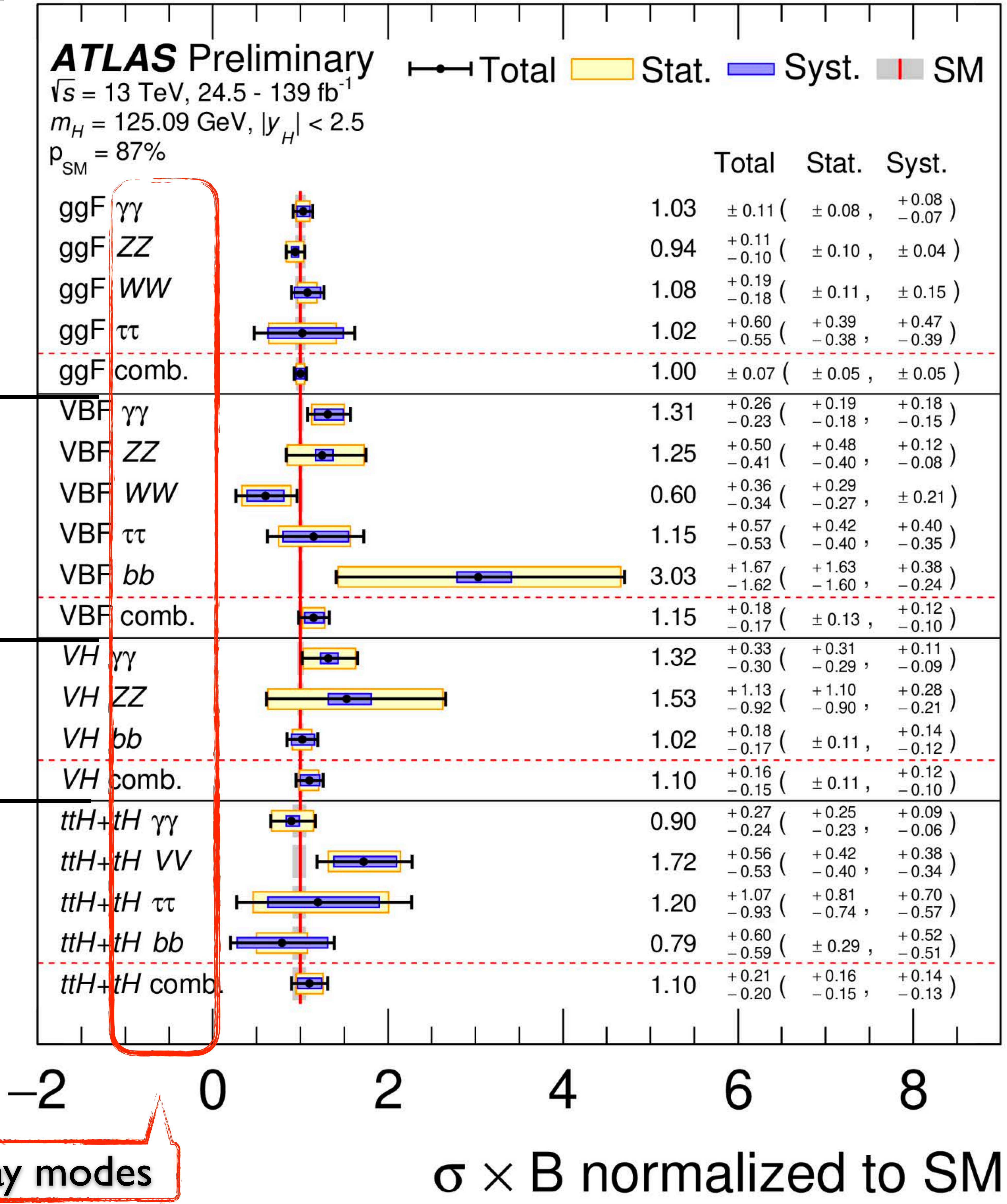
Production and Decay Modes











Decay modes

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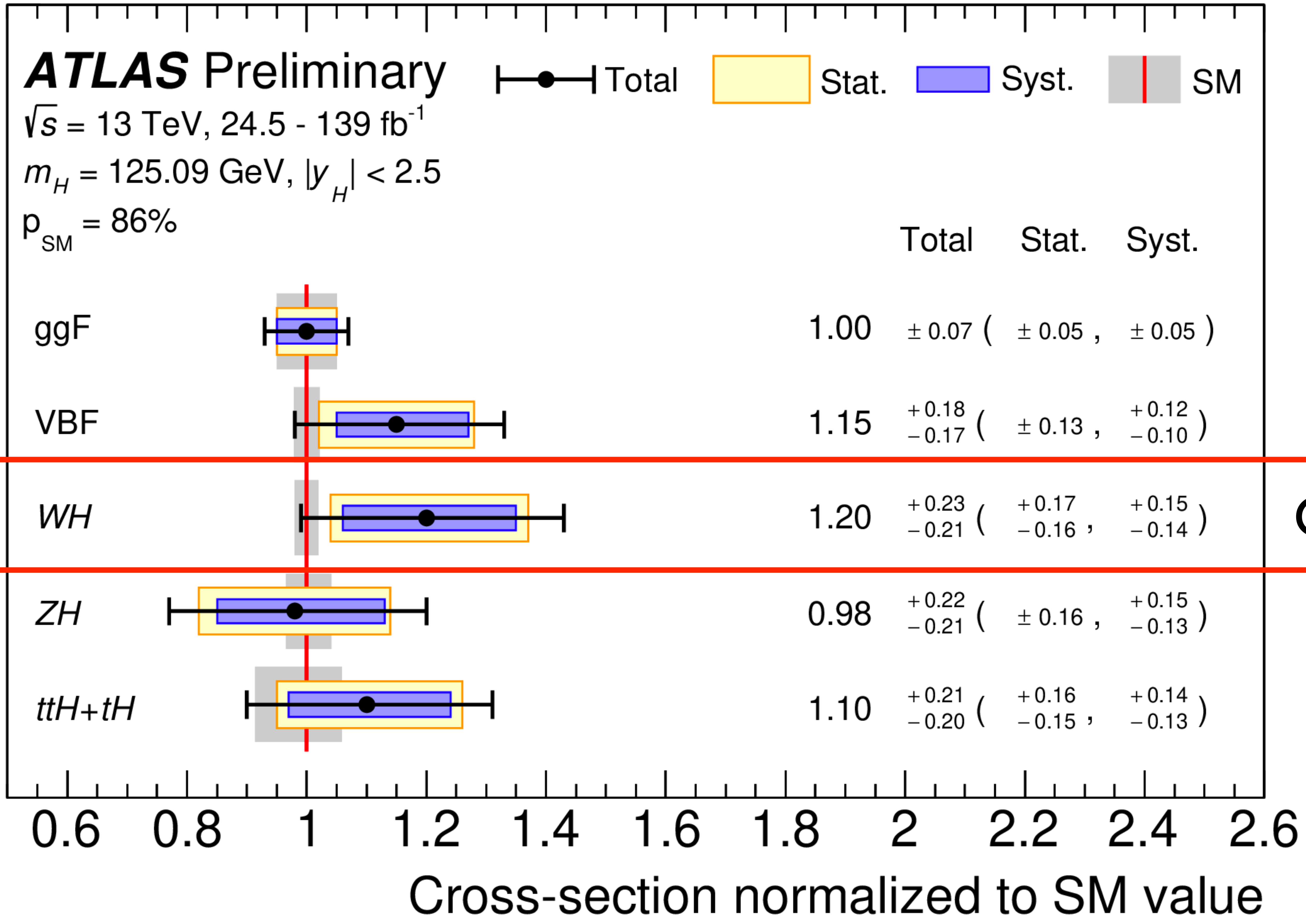
Production Modes

- Assume SM branching ratios



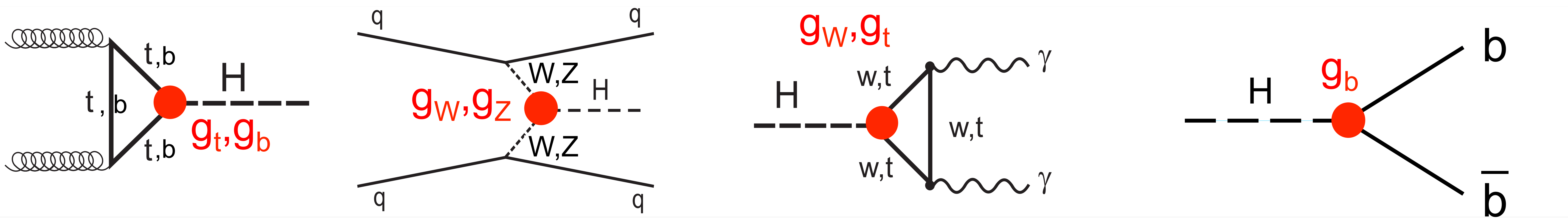
Observed (expected) significance: 6.3 (5.2) σ

$$\text{Global } \mu = 1.06 \pm 0.07 = 1.06 \pm 0.04\,(\text{stat.}) \;\pm 0.03\,(\text{exp.})\,^{+0.05}_{-0.04}\,(\text{sig. th.}) \;\pm 0.02\,(\text{bkg. th.})$$

ATLAS-CONF-2020-027

The κ Framework

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



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

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

Assumption:

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

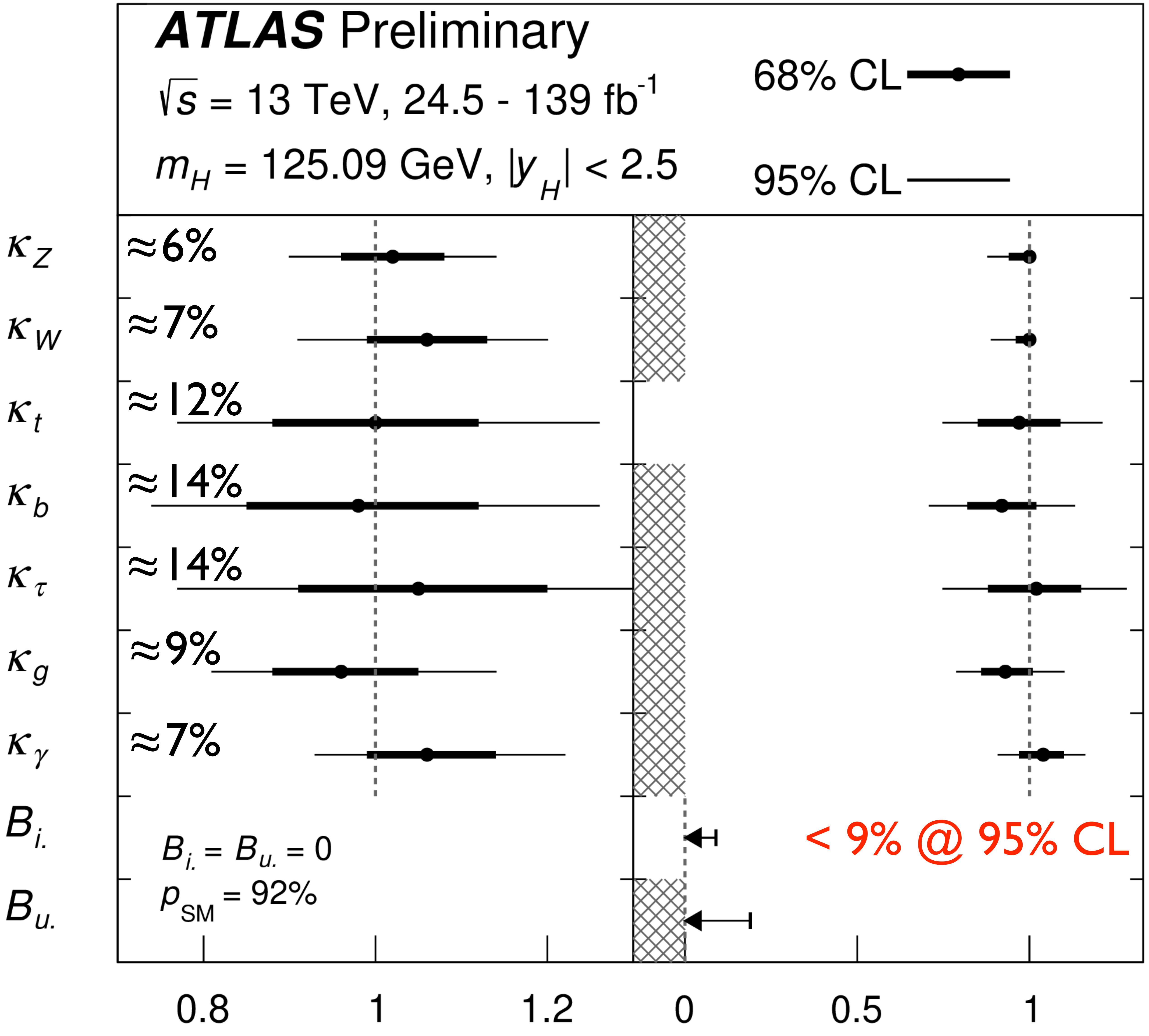
LHC Higgs XS WG (arxiv:1307.1347)

κ Coupling Modifiers

Assume:

No BSM contributions

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



< 9% @ 95% CL (< 11% expected)

Assume:

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

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

Add:

VBF H → invisible

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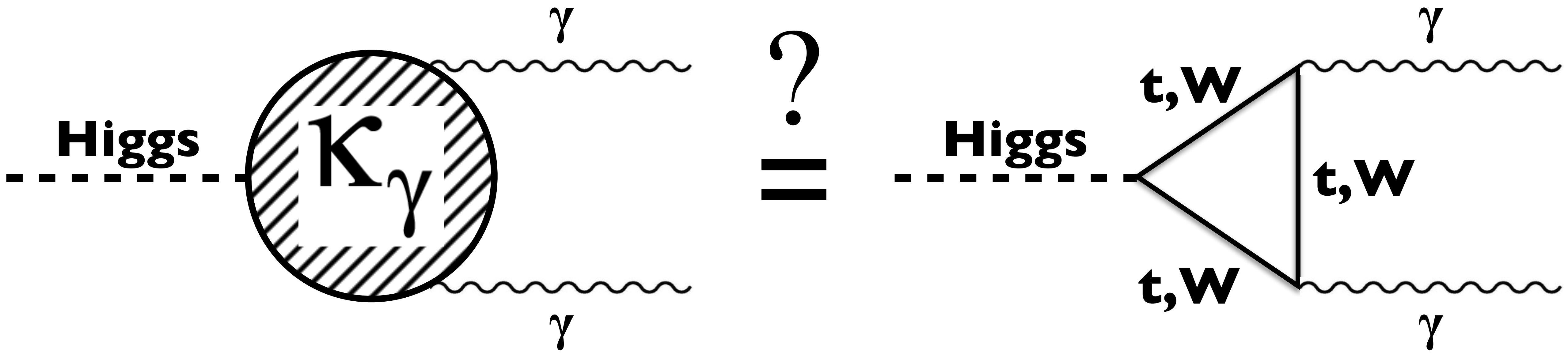
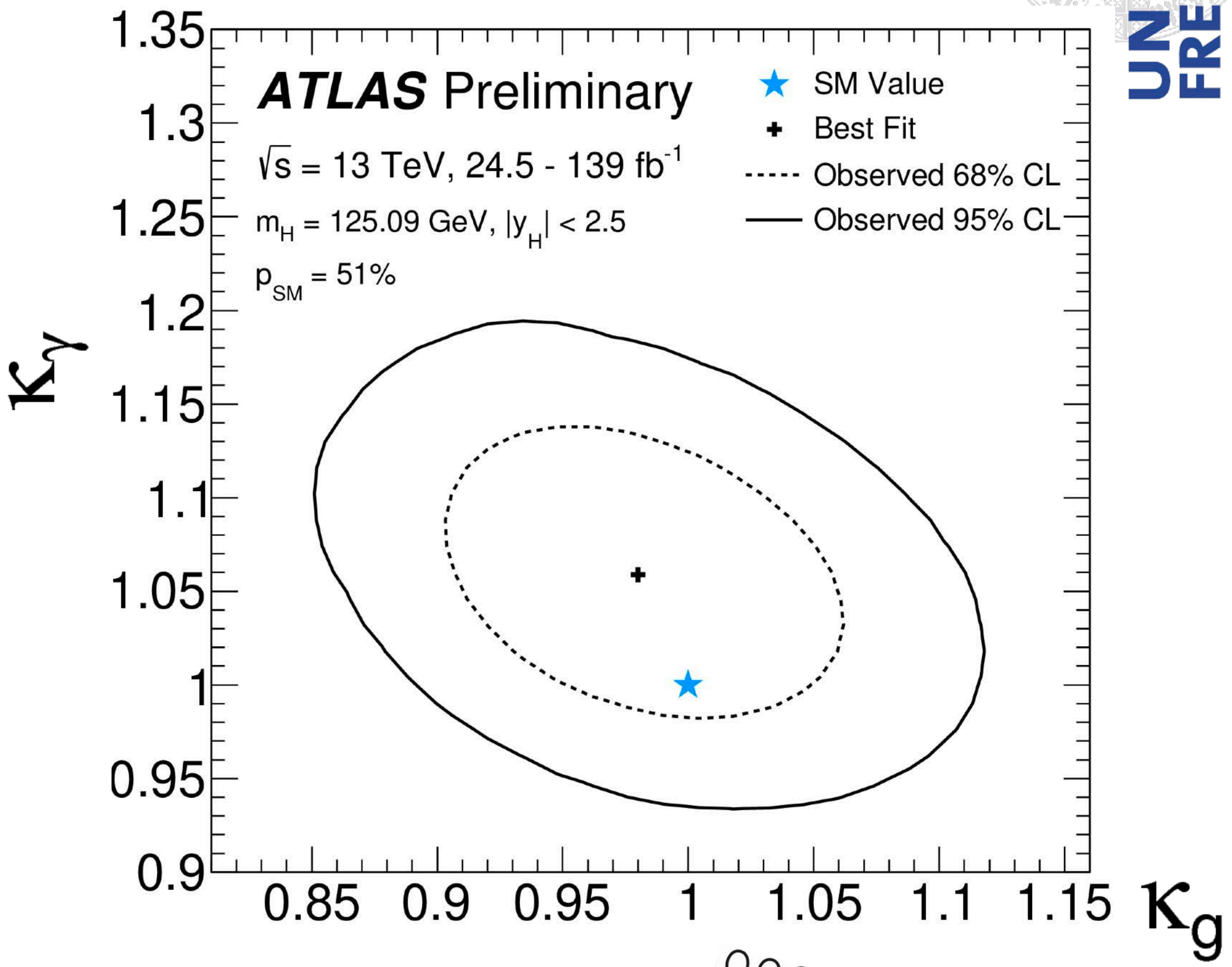
Loop-induced Couplings

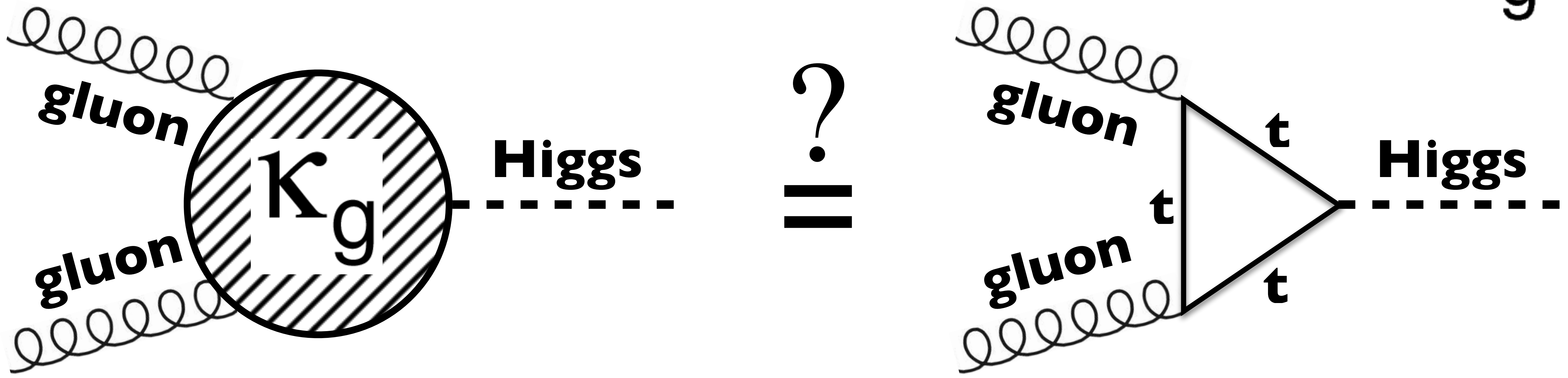
- SM: ggF and H → γγ are loop-induced
  - New particles could participate in the loop

⇒ Contributions of BSM?

⇒ Test effective coupling factors for photons (κ_γ) and gluons (κ_g)







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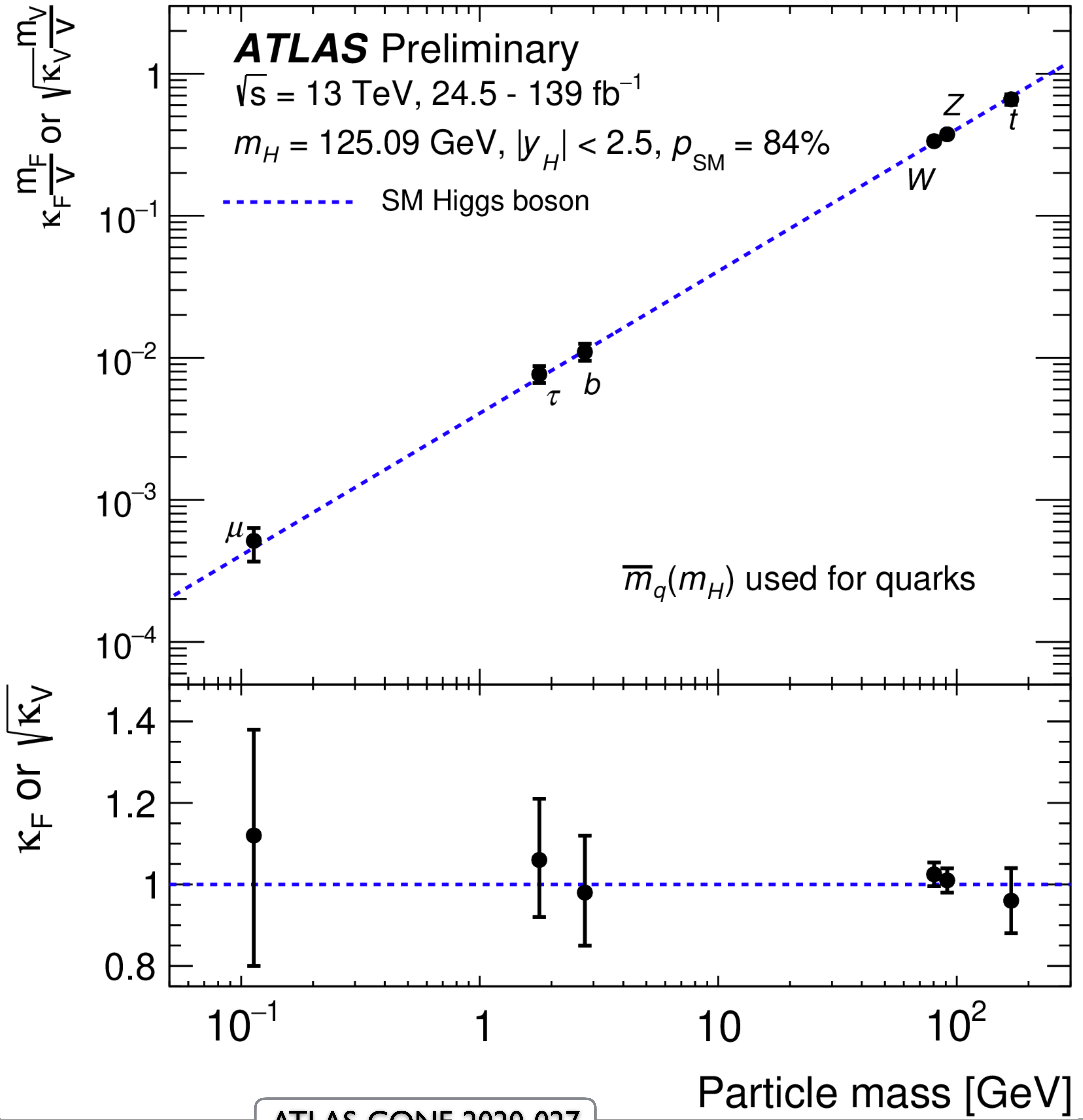
Mass ~ Coupling Strength?

Assumption:

SM Higgs boson coupled only to SM particles, i.e. no "beyond SM physics (BSM)

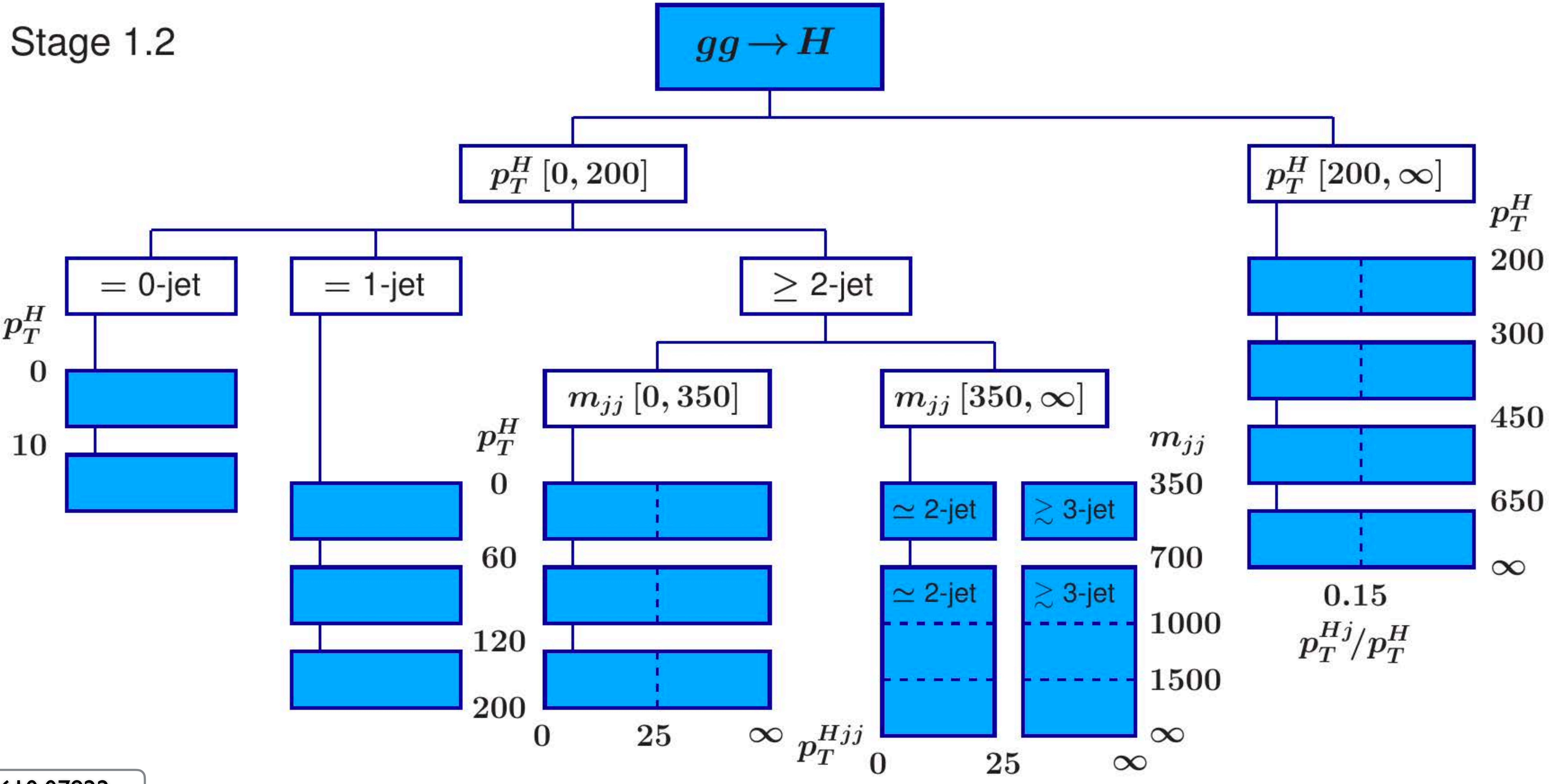
- effective couplings to photons and gluons, Higgs-boson width resolved using SM assumptions



ATLAS-CONF-2020-027

Simplified Template Cross Sections (STXS)

- Evolution of κ model
  - Measure cross section in exclusive kinematic regions



arxiv:1610.07922

Combined STXS Measurement

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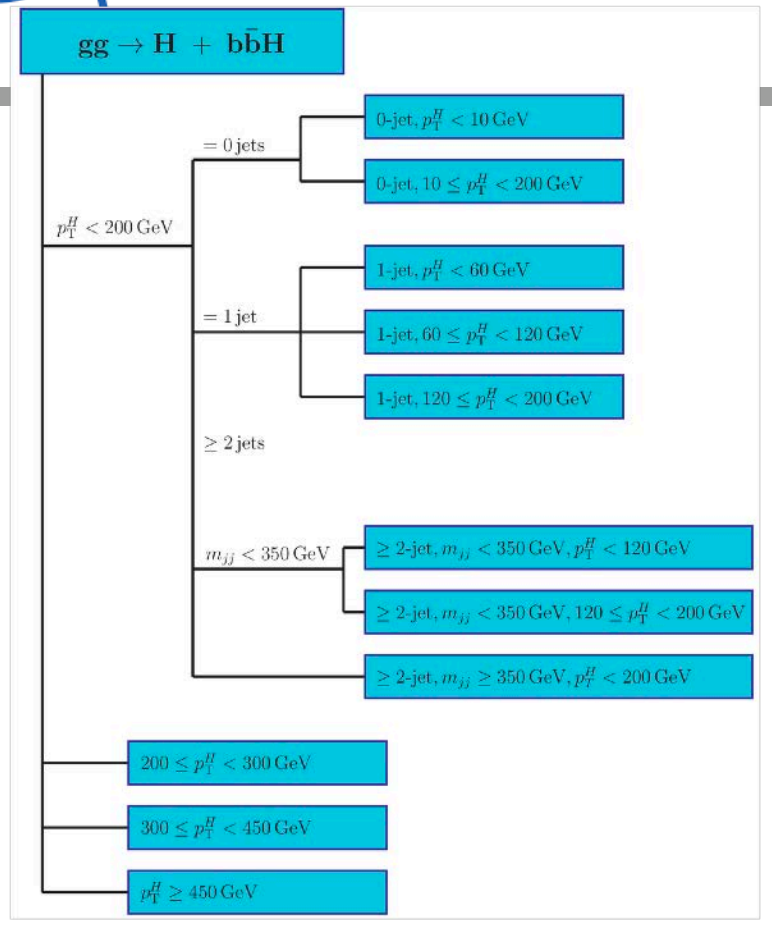
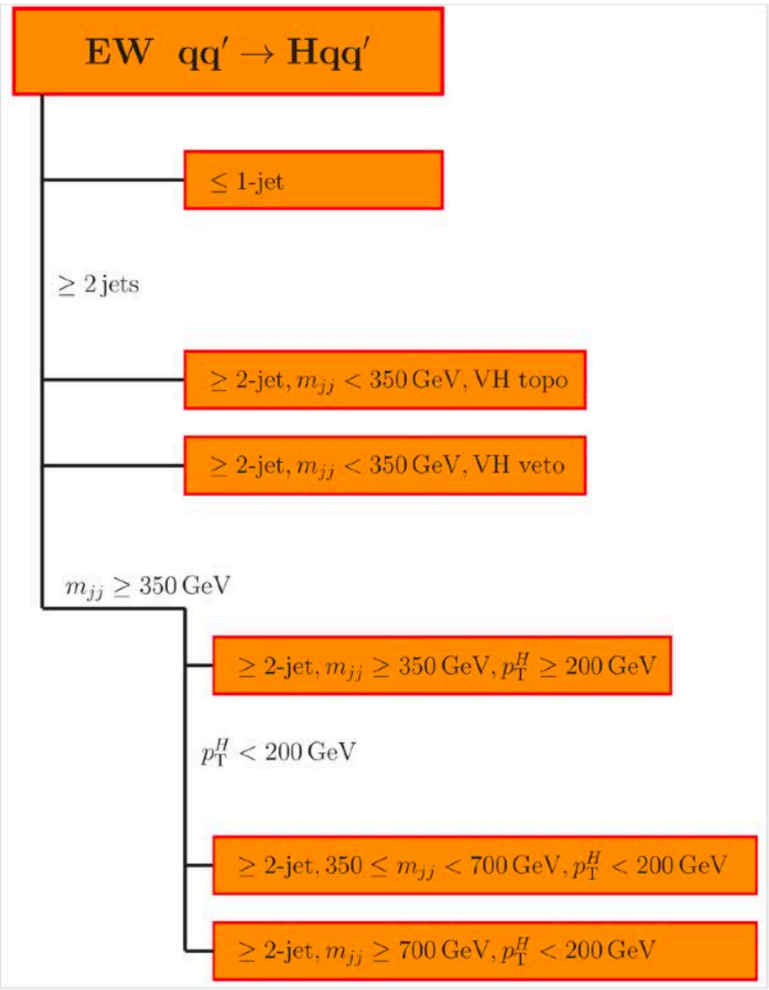
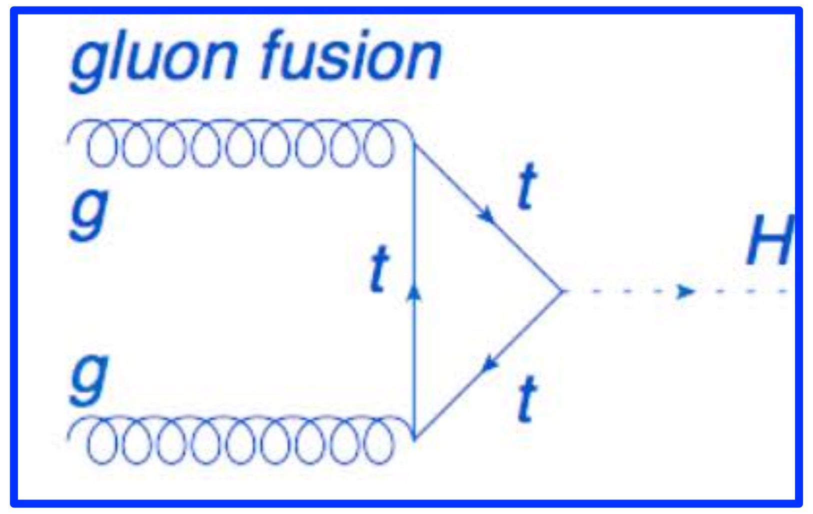
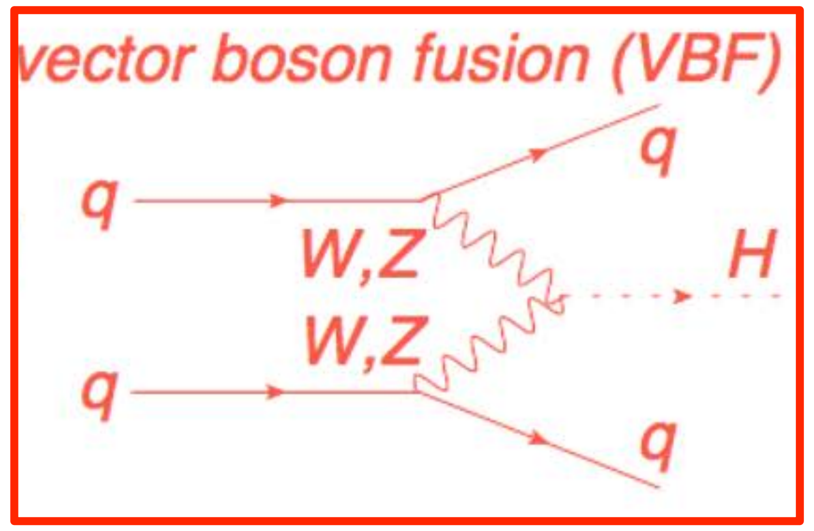
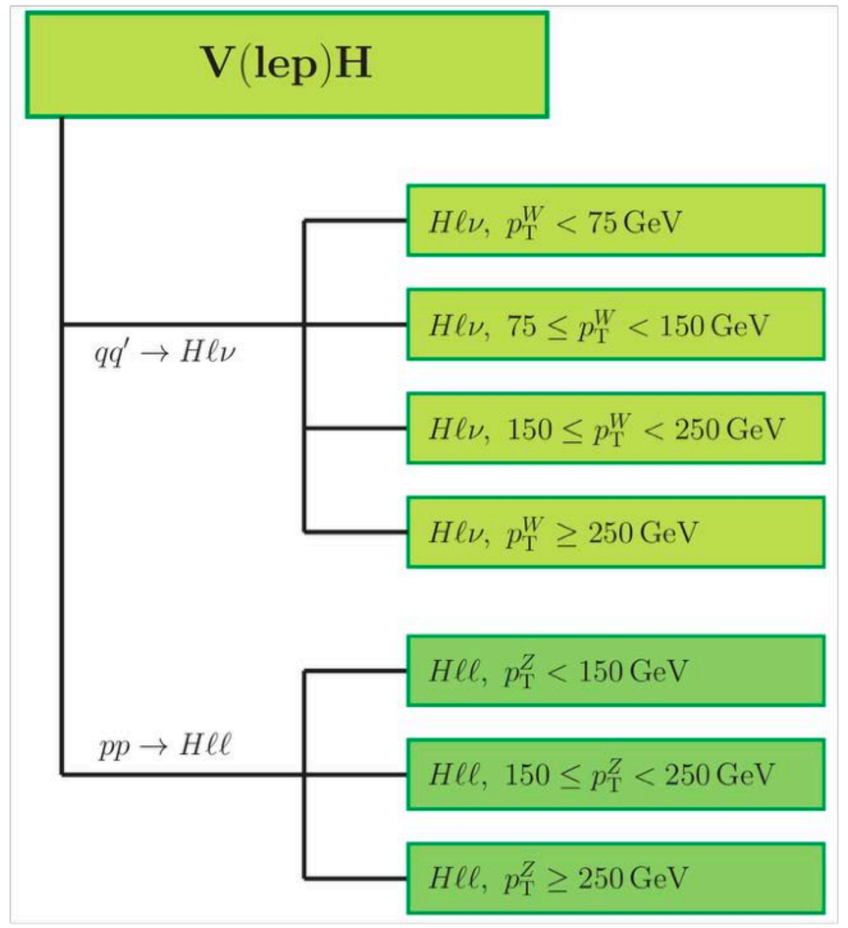
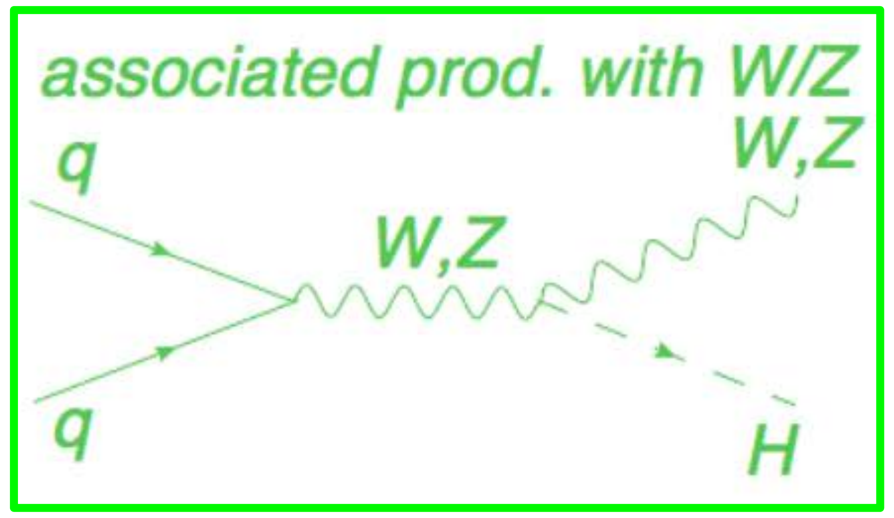


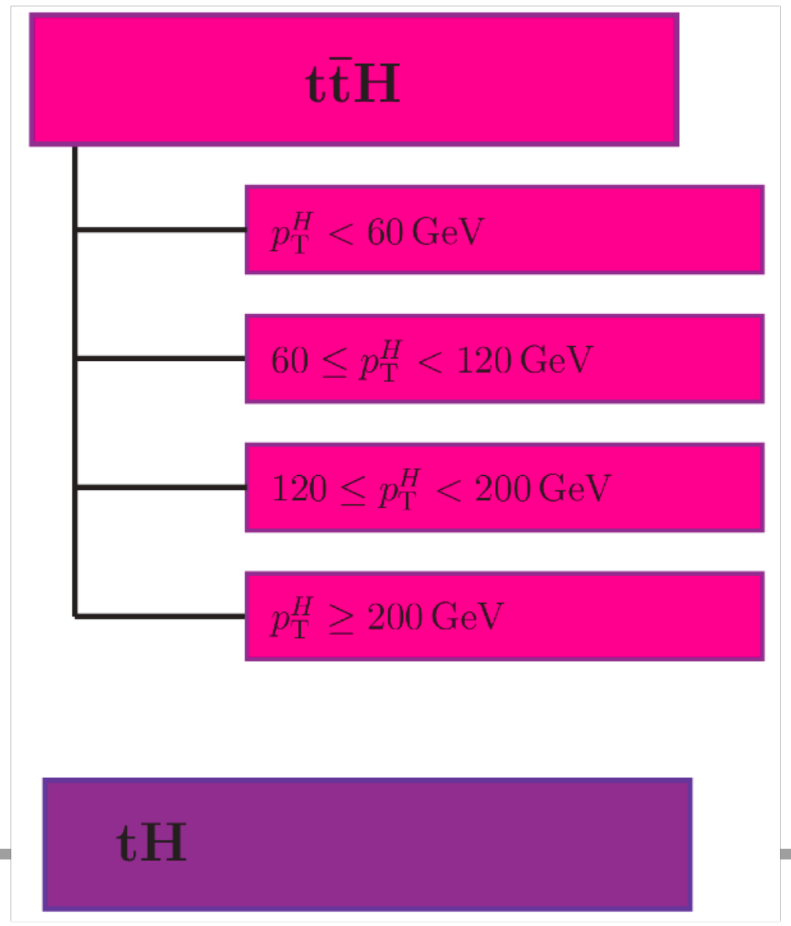


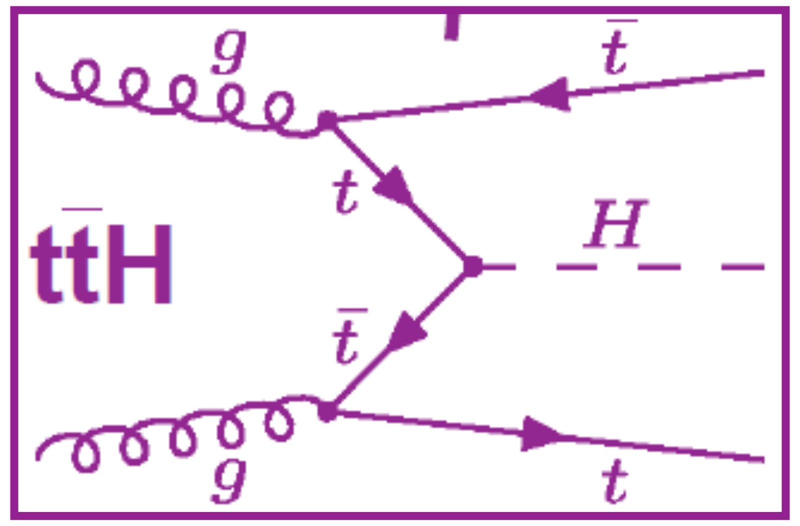




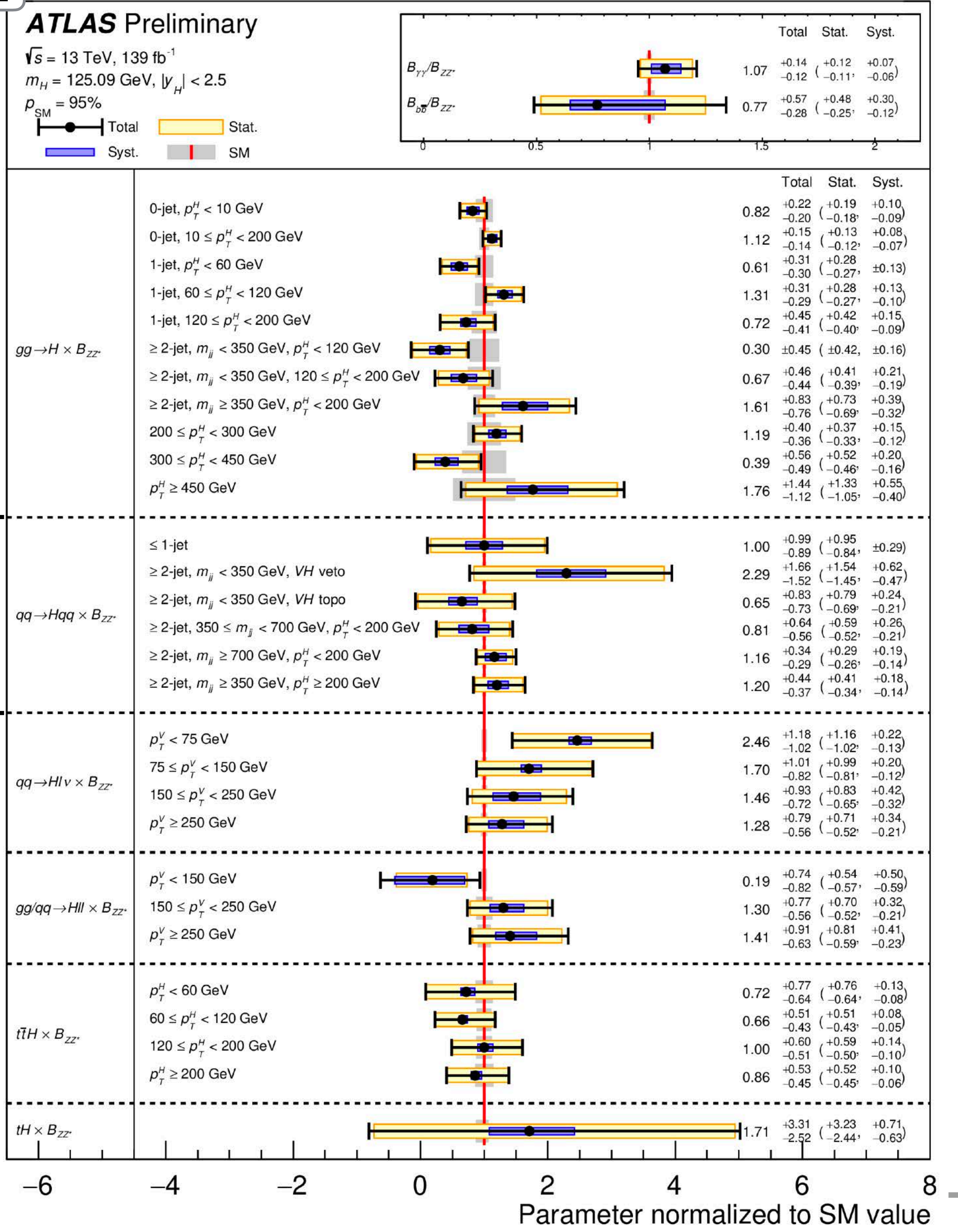








- Channels:
  - H → ZZ* → 4ℓ
  - H → γγ
  - VH, H → bb



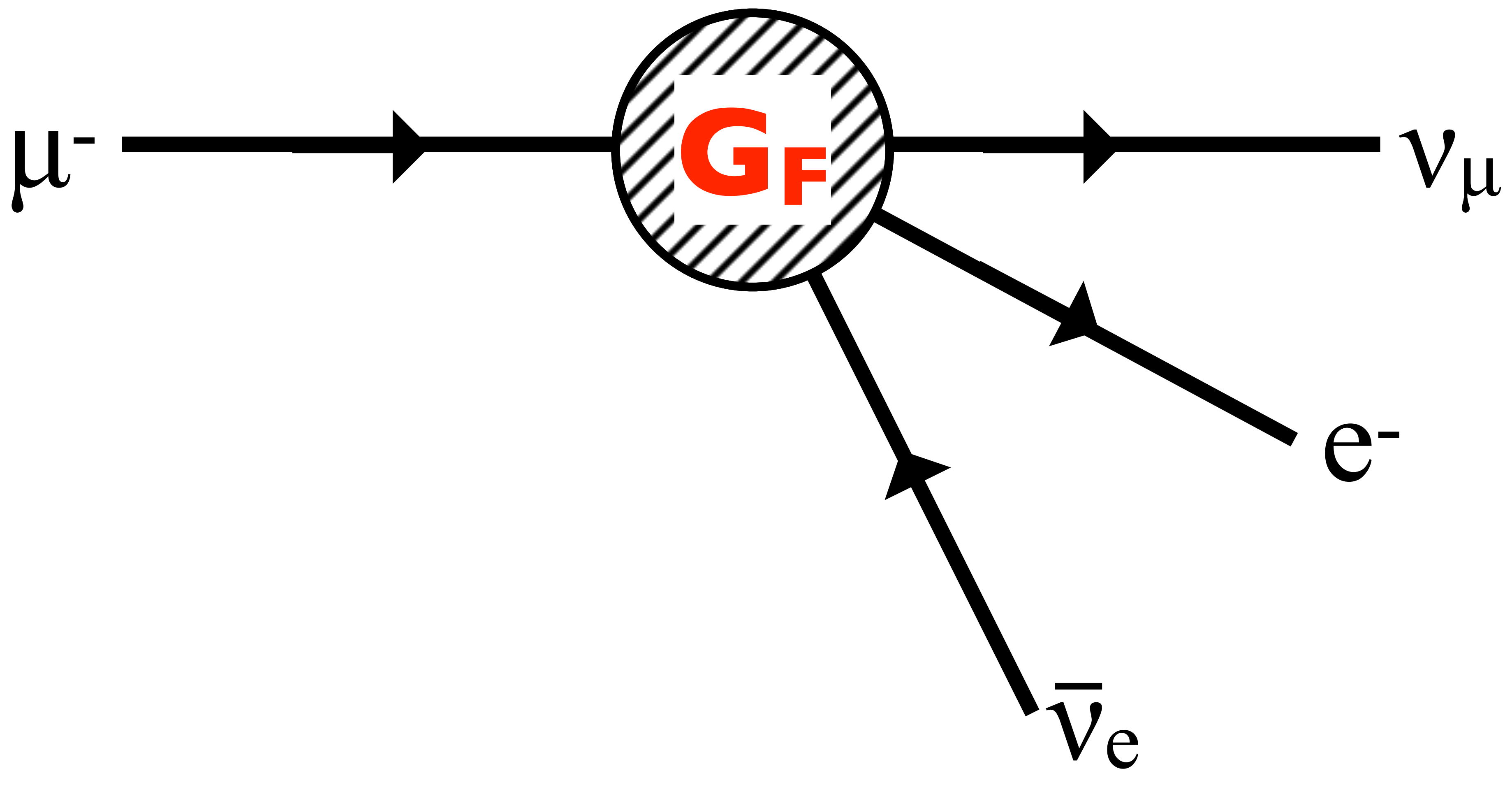
Effective Field Theories: Muon Decay

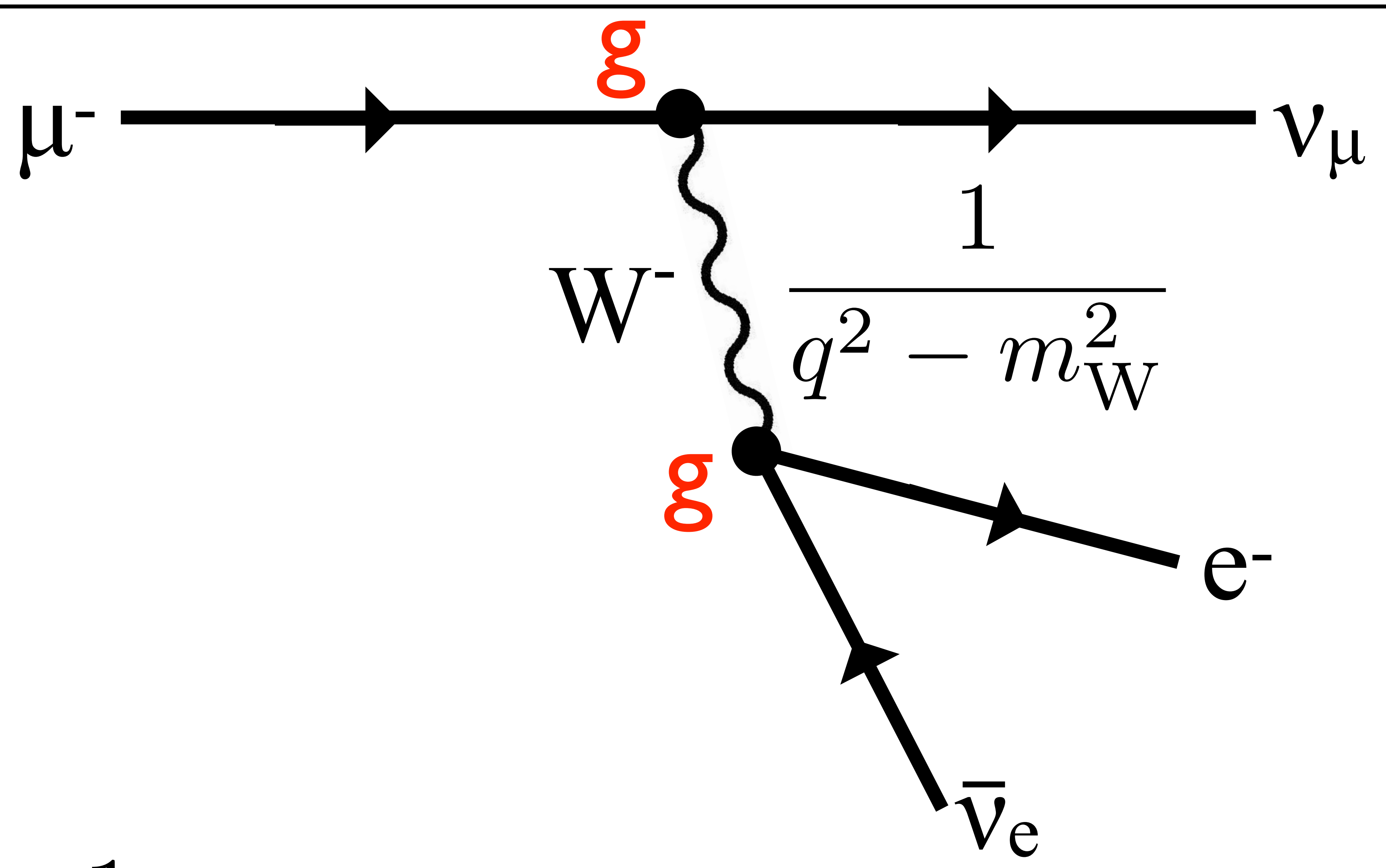
Fermi-Theory (1933)

Effective Field Theory

Theory of Weak Interaction

“Full" Field Theory





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

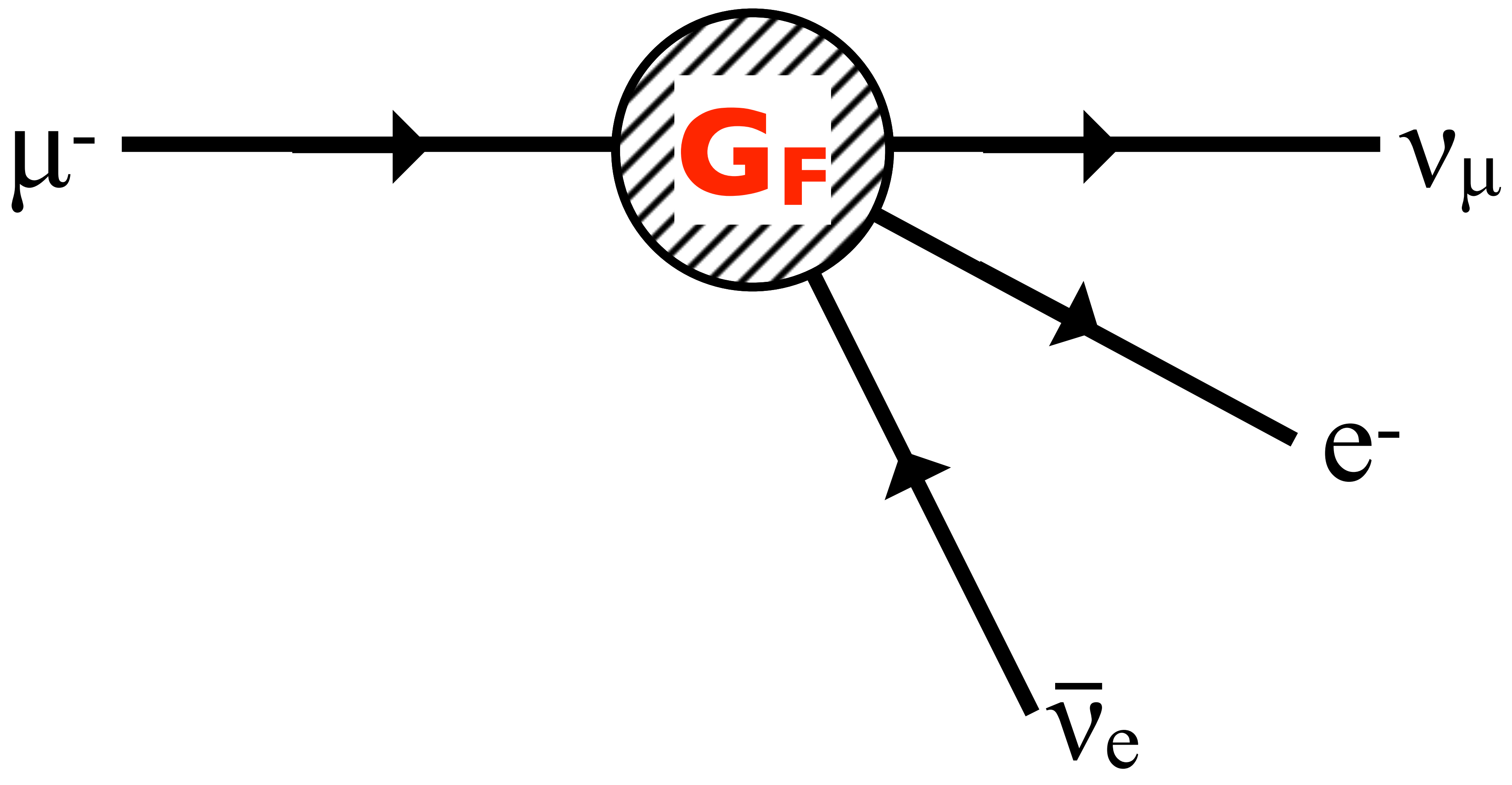
Effective Field Theories: Muon Decay

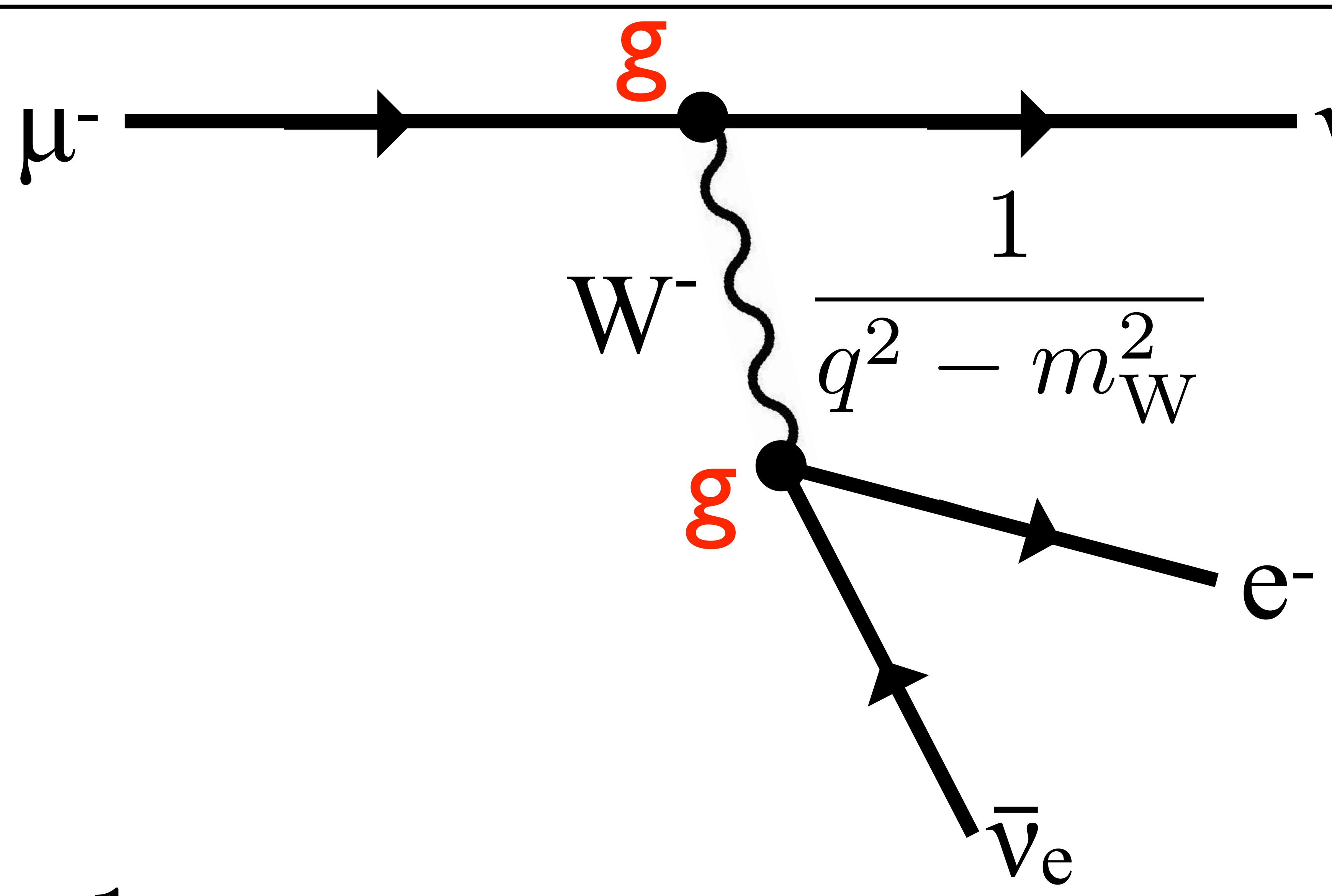
Fermi-Theory (1933)

Effective Field Theory

Theory of Weak Interaction

"Full" Field Theory



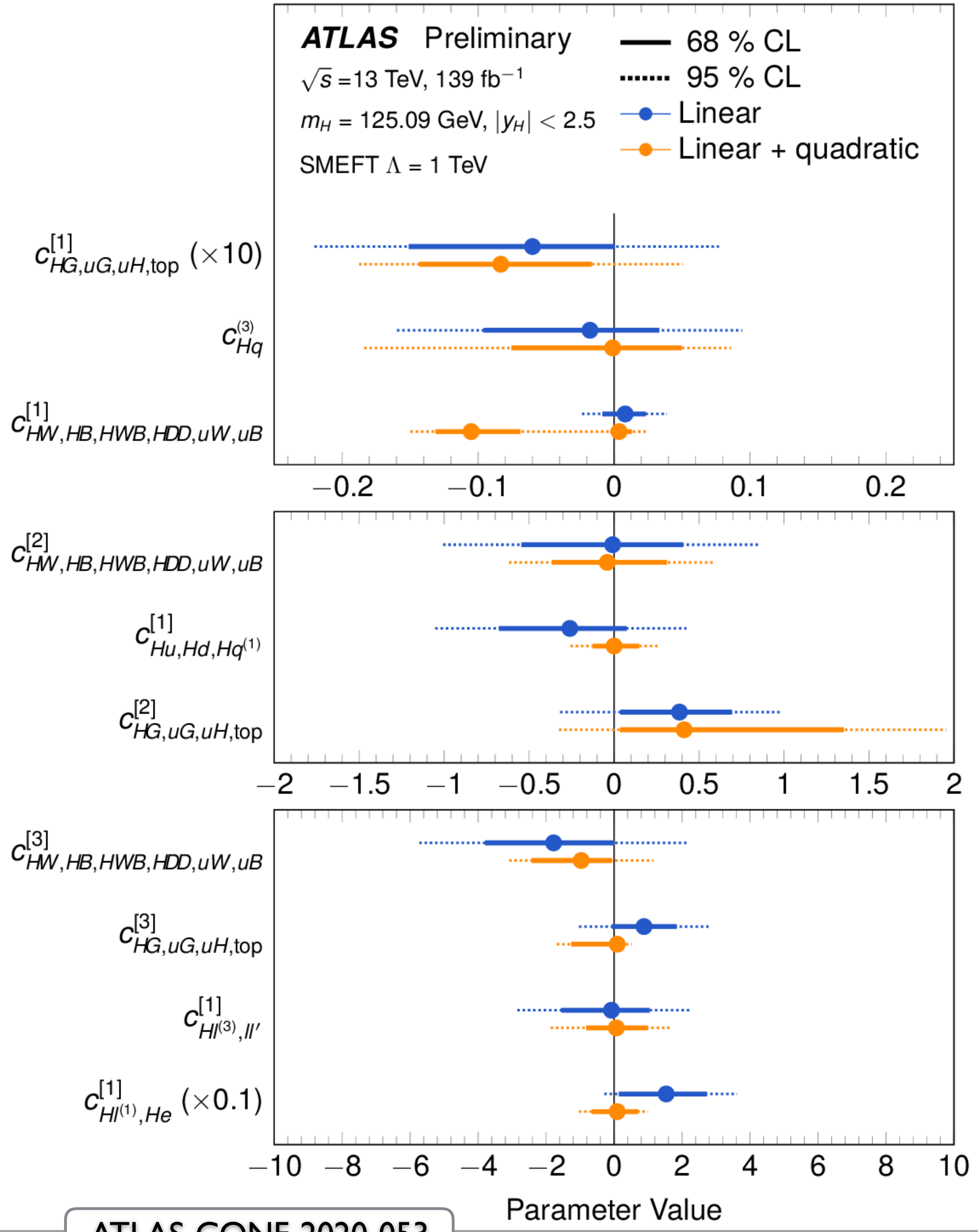


For $q^2 << m_W^2$ is $\frac{1}{q^2 - m_W^2} \rightarrow \frac{1}{-m_W^2}$ and $\frac{g^2}{8m_W^2} \rightarrow \frac{G_F}{\sqrt{2}}$

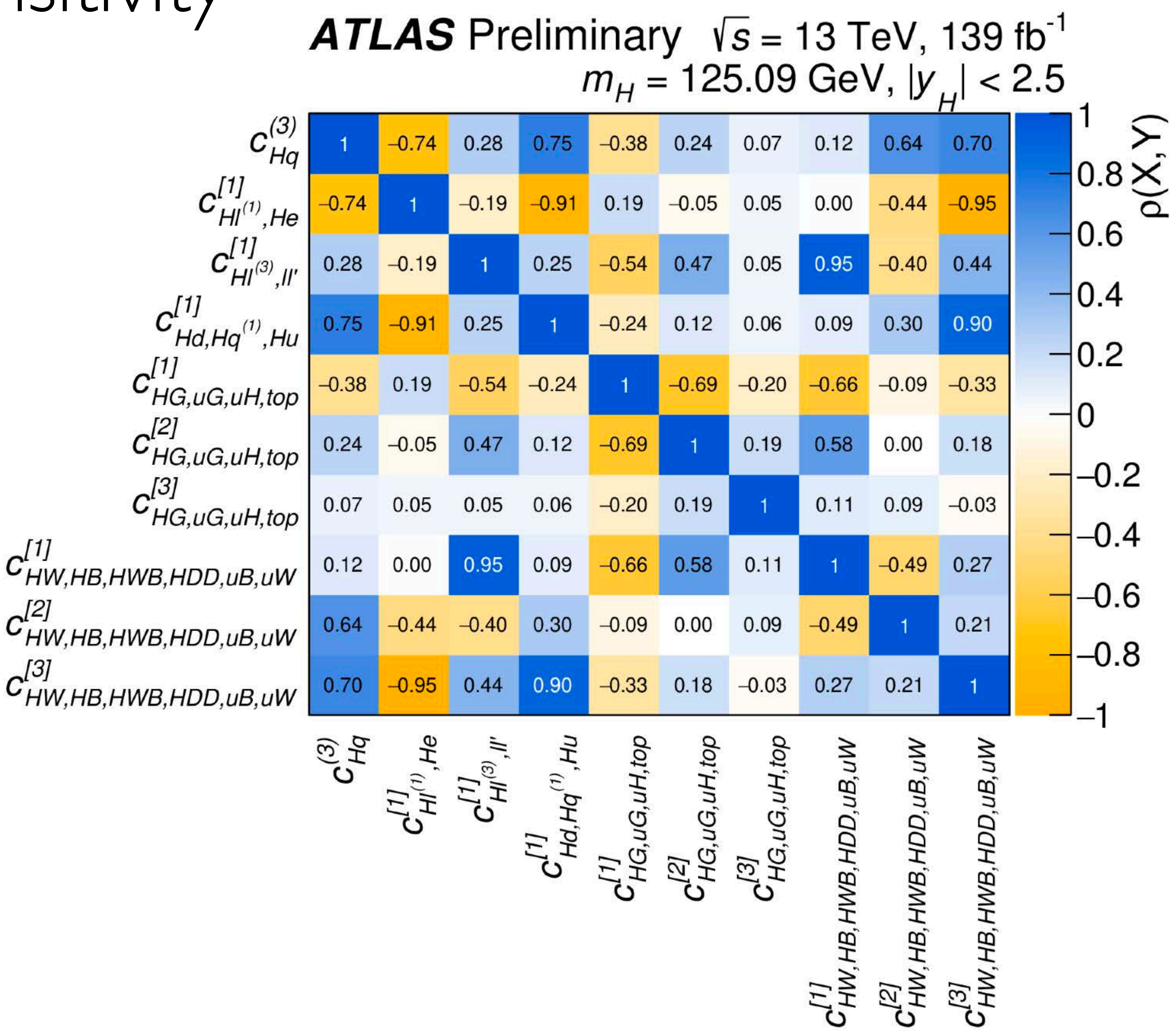
- Extend SM with new BSM operators:
  - Assume: No new particles below Λ = 1 TeV

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

EFT Fit Results



- 10 EFT parameters fitted simultaneously!
  - Excellent sensitivity


ATLAS Preliminary $\sqrt{s}$ = 13 TeV, 139 fb^{-1}
m_H = 125.09 GeV, $|y_H| < 2.5$

	$c^{(3)}_{Hq}$	$c^{[1]}_{Hl^{(1)},He}$	$c^{[1]}_{Hl^{(3)},ll'}$	$c^{[1]}_{Hd,Hq^{(1)},Hu}$	$c^{[1]}_{HG,uG,uH,top}$	$c^{[2]}_{HG,uG,uH,top}$	$c^{[3]}_{HG,uG,uH,top}$	$c^{[1]}_{HW,HB,HWB,HDD,uB,uW}$	$c^{[2]}_{HW,HB,HWB,HDD,uB,uW}$	$c^{[3]}_{HW,HB,HWB,HDD,uB,uW}$
$c^{(3)}_{Hq}$	1	−0.74	0.28	0.75	−0.38	0.24	0.07	0.12	0.64	0.70
$c^{[1]}_{Hl^{(1)},He}$	−0.74	1	−0.19	−0.91	0.19	−0.05	0.05	0.00	−0.44	−0.95
$c^{[1]}_{Hl^{(3)},ll'}$	0.28	−0.19	1	0.25	−0.54	0.47	0.05	0.95	−0.40	0.44
$c^{[1]}_{Hd,Hq^{(1)},Hu}$	0.75	−0.91	0.25	1	−0.24	0.12	0.06	0.09	0.30	0.90
$c^{[1]}_{HG,uG,uH,top}$	−0.38	0.19	−0.54	−0.24	1	−0.69	−0.20	−0.66	−0.09	−0.33
$c^{[2]}_{HG,uG,uH,top}$	0.24	−0.05	0.47	0.12	−0.69	1	0.19	0.58	0.00	0.18
$c^{[3]}_{HG,uG,uH,top}$	0.07	0.05	0.05	0.06	−0.20	0.19	1	0.11	0.09	−0.03
$c^{[1]}_{HW,HB,HWB,HDD,uB,uW}$	0.12	0.00	0.95	0.09	−0.66	0.58	0.11	1	−0.49	0.27
$c^{[2]}_{HW,HB,HWB,HDD,uB,uW}$	0.64	−0.44	−0.40	0.30	−0.09	0.00	0.09	−0.49	1	0.21
$c^{[3]}_{HW,HB,HWB,HDD,uB,uW}$	0.70	−0.95	0.44	0.90	−0.33	0.18	−0.03	0.27	0.21	1

Opens the window to global combined analyses!

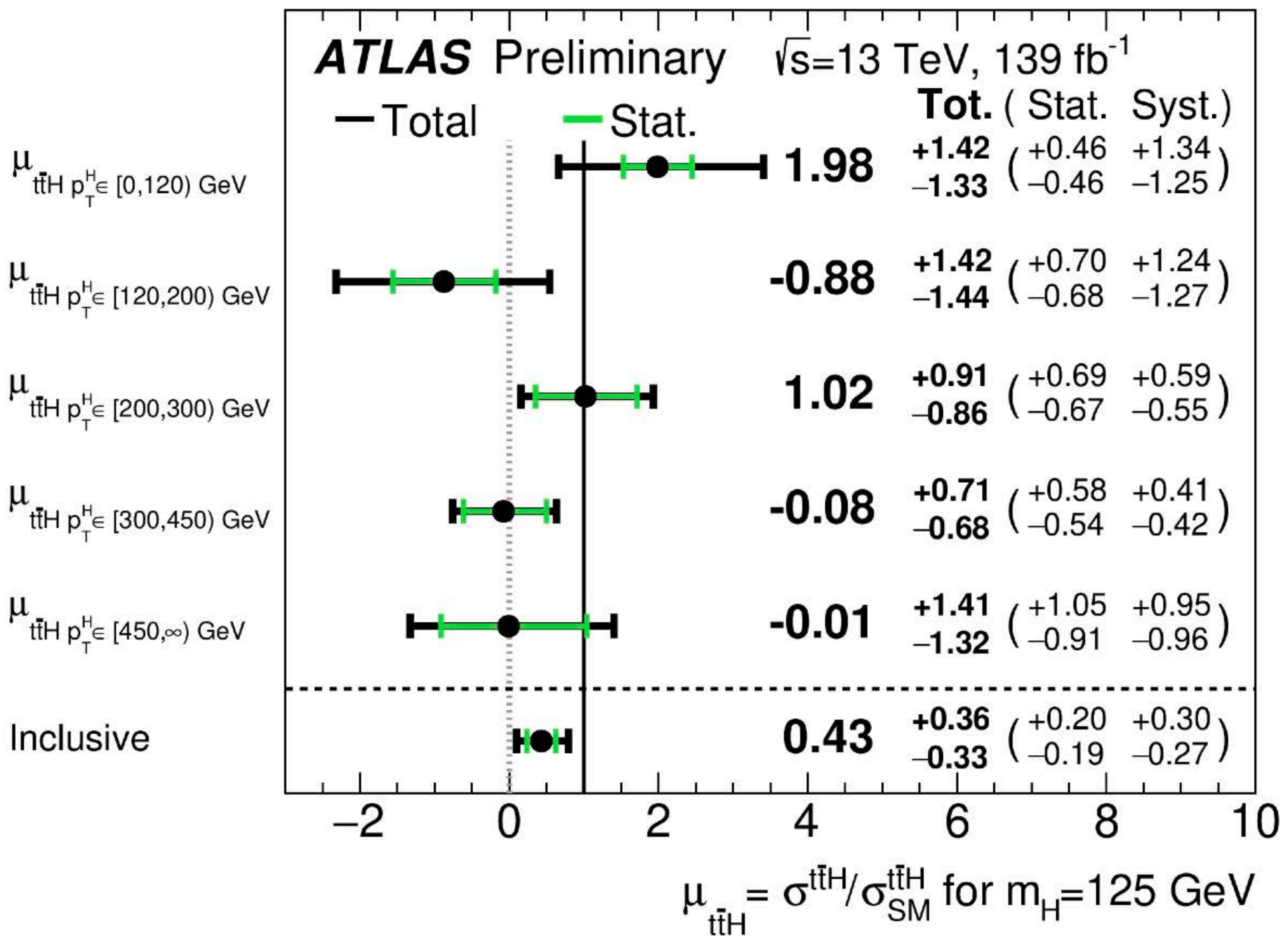
ATLAS-CONF-2020-053

1. Introduction
2. Mass measurement
3. Decays into Bosons
4. Decays into Fermions
5. Rare processes
6. Combinations and Interpretations
7. **Future**
8. Summary

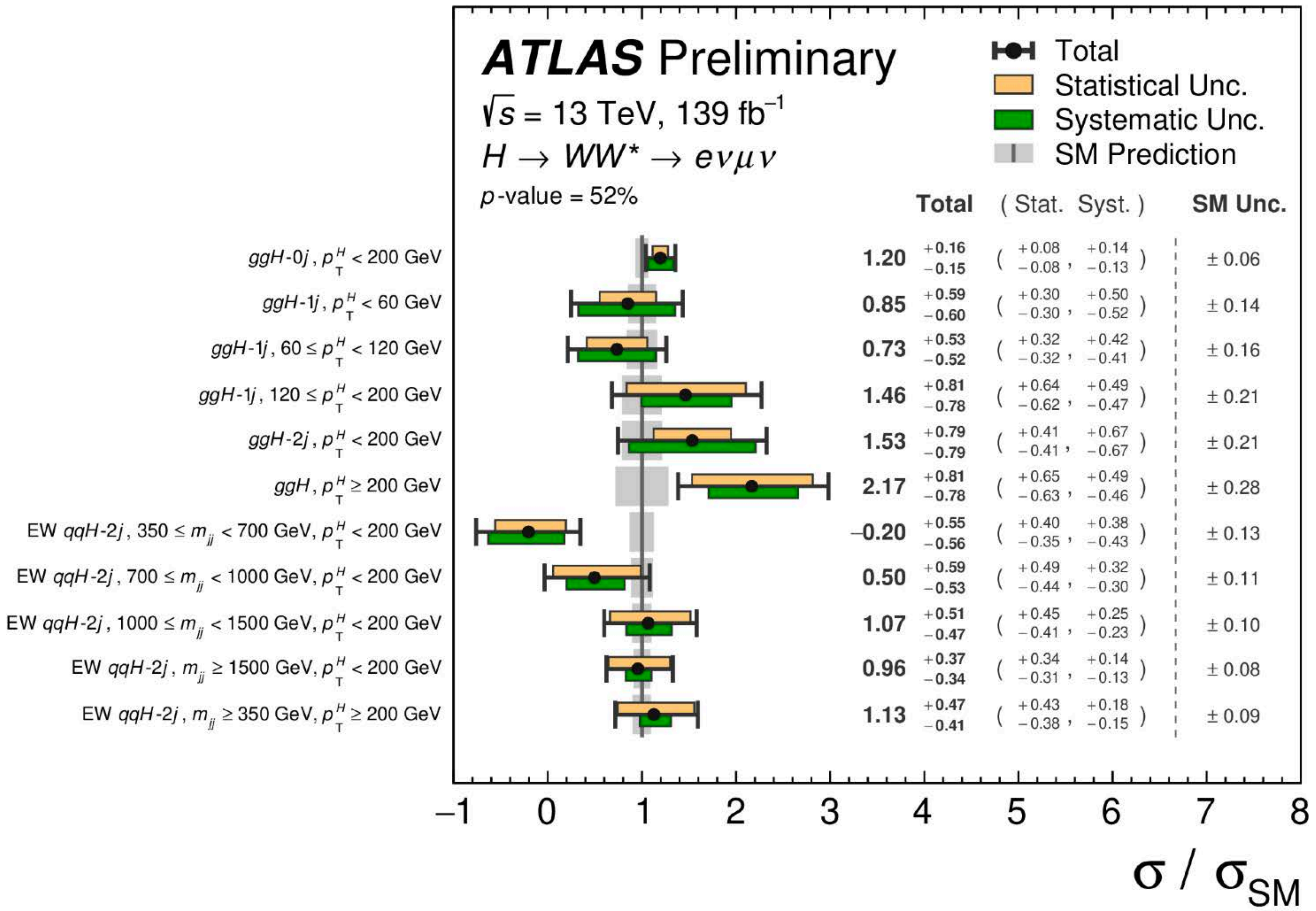
Imminent Future

- STXS from

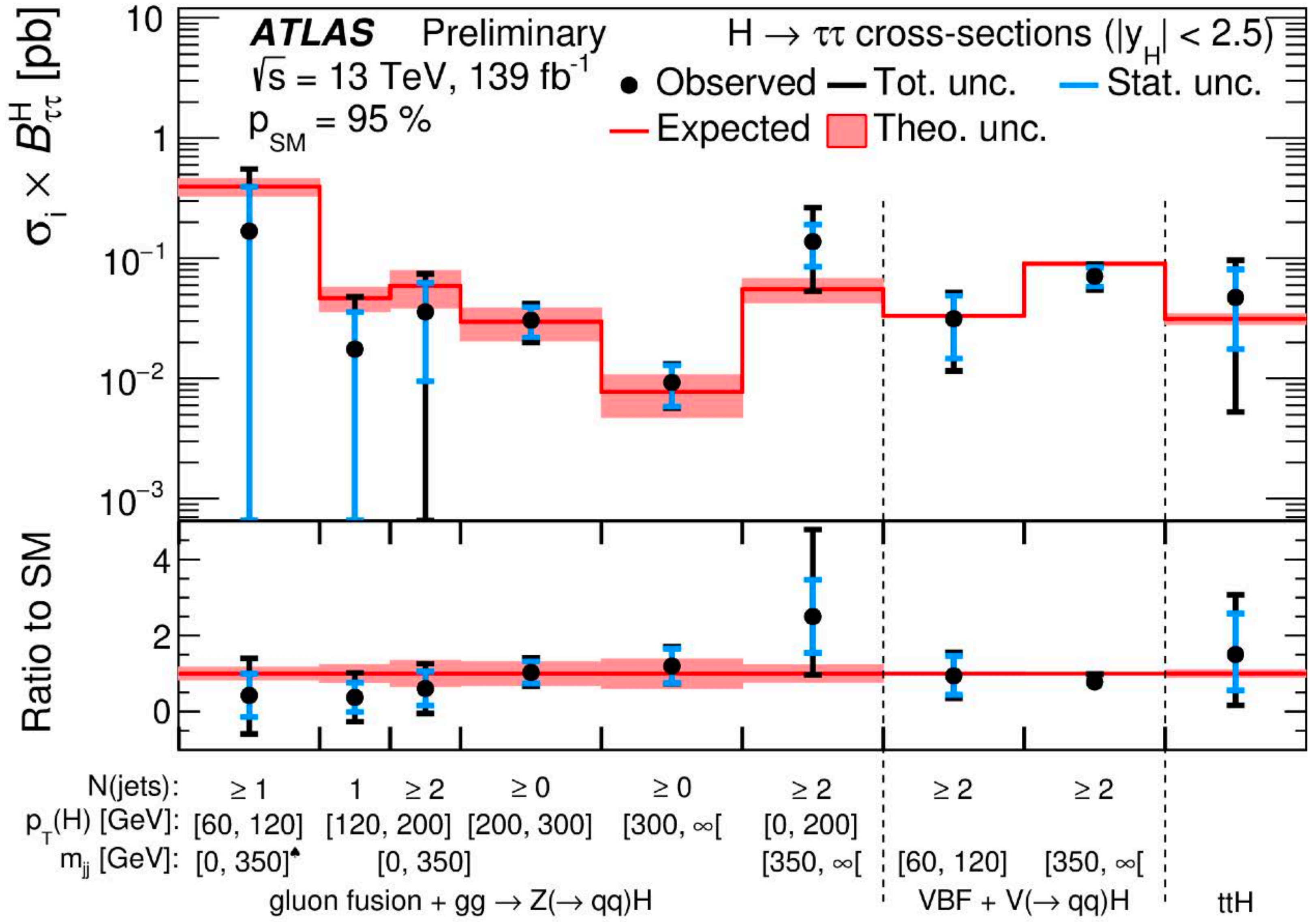
ttH, H → bb



H → WW*



H → ττ

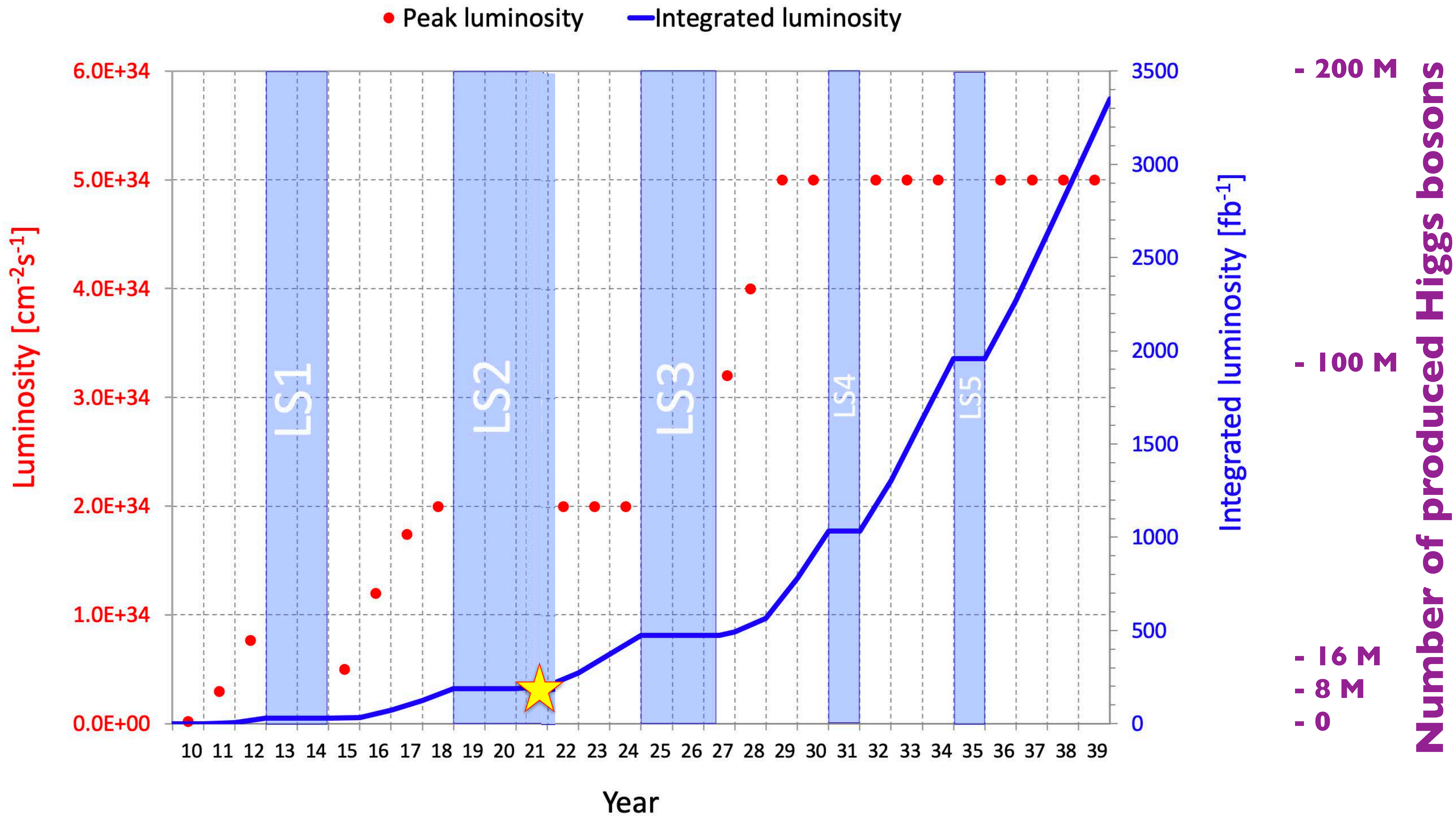


…and more available…

⇒ New addition to combination ⇒ more precise determination of EFT coefficients

… and combination with other diboson, top, etc. measurements…

High Luminosity LHC (HL-LHC)



Extrapolations

Summary

What we know about the Higgs boson

- <2‰ precision on **m_H**
- **All measured quantities are consistent with SM**
- Many more $\sqrt{s} = 13$ TeV results available and in the pipeline

Significant progress in theory, essential for precise measurements and interpretations

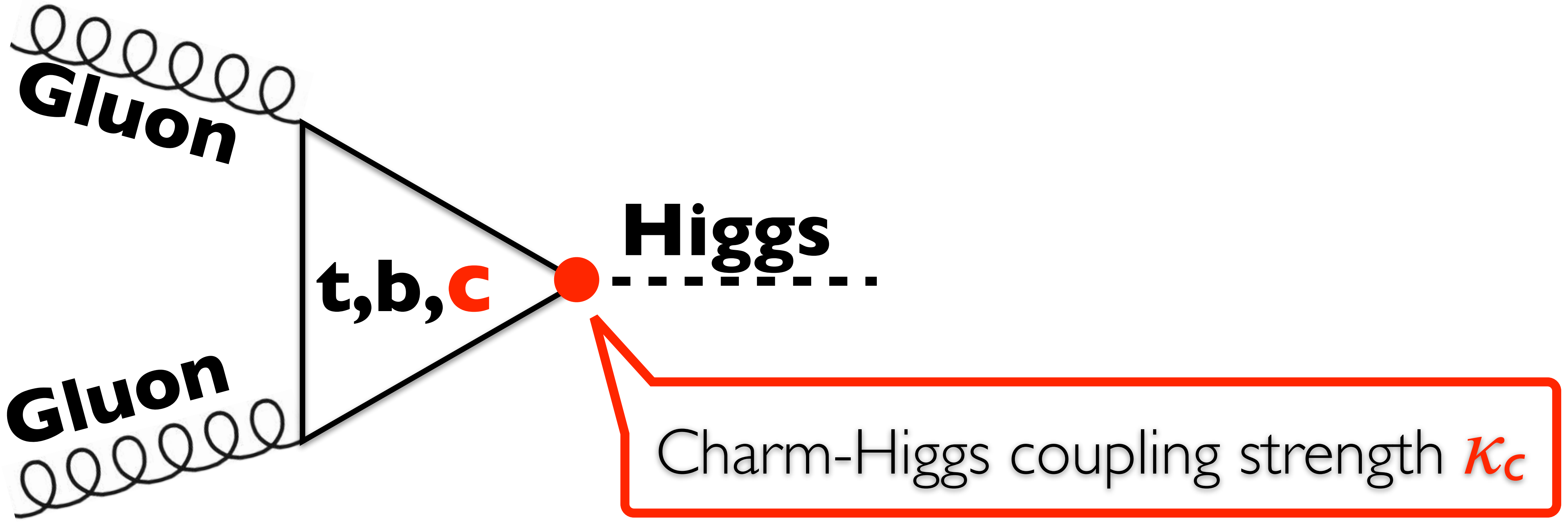
- e.g. improved calculation of ggF cross section (N^3LO QCD) ⇒ theory uncertainty: 8.5% ⟶ 5.0%

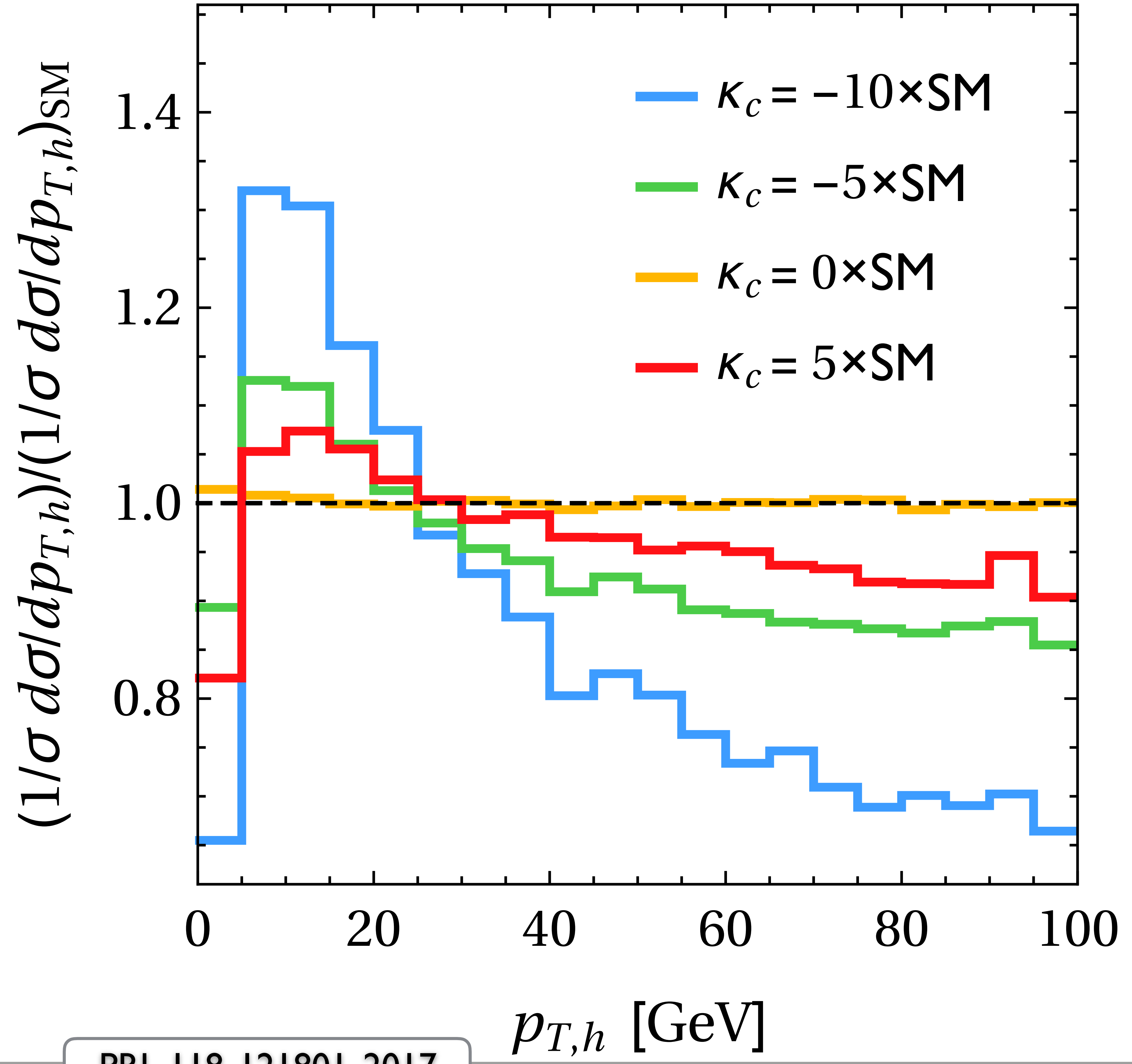
New era of precision and interpretation, access to rarer and rarer processes

- **~8 Million produced Higgs bosons in 139 fb^{-1} during LHC Run 2**
- Differential cross section measurements
- Simplified Template Cross Sections
- Effective Field Theory interpretations

Charm-Higgs Coupling from $p_T(H)$

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

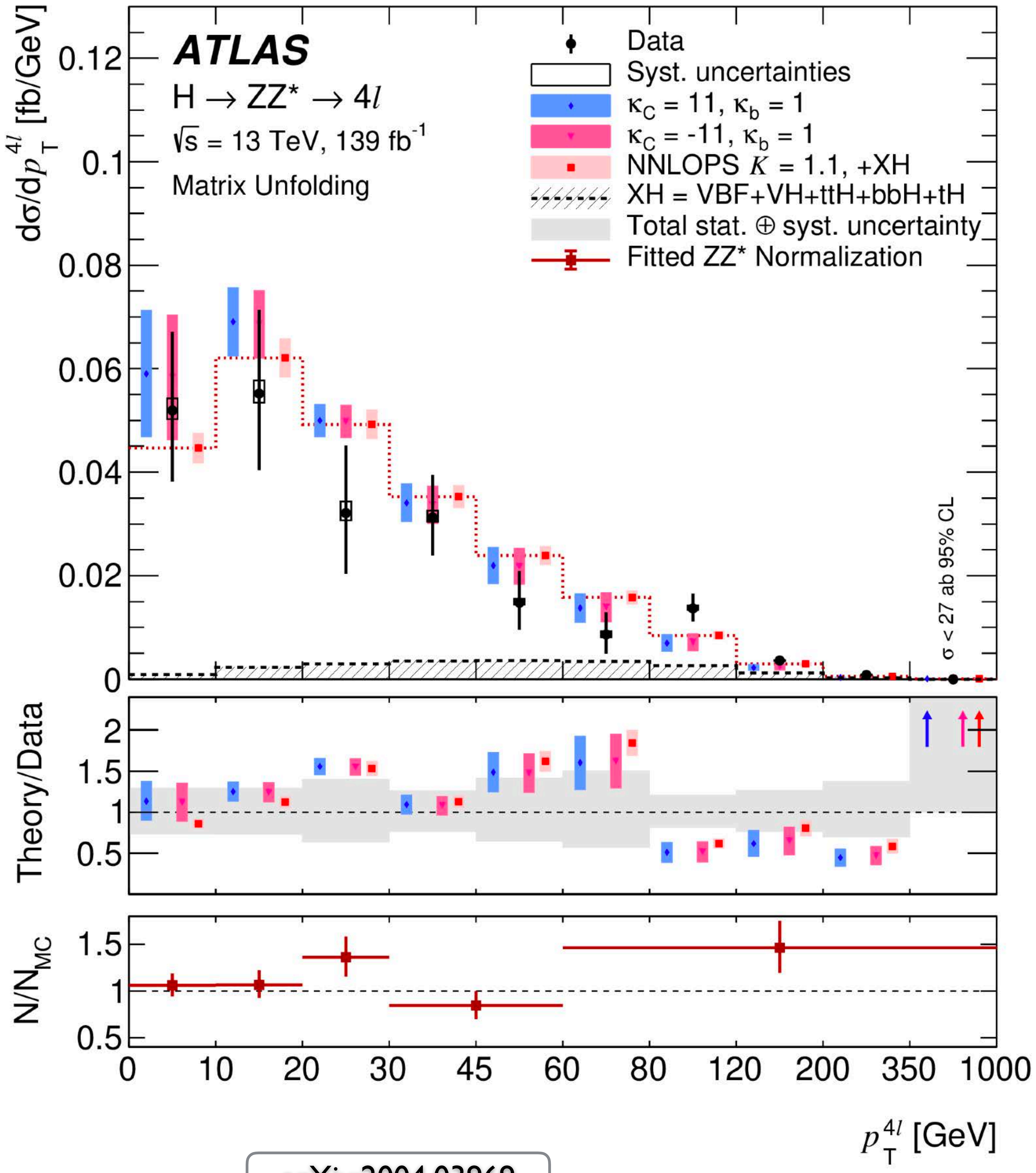




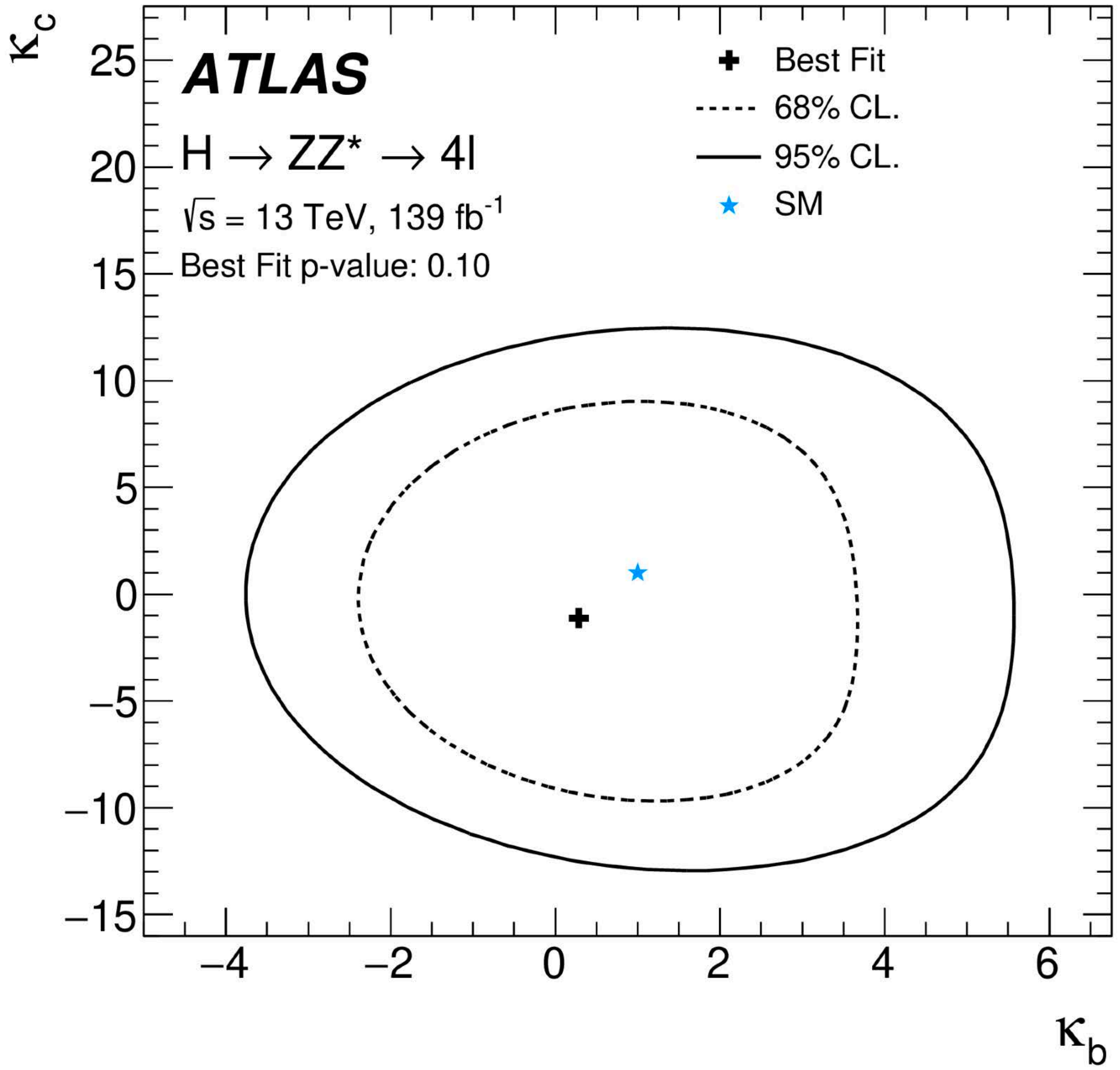
PRL 118, 121801, 2017

  - Direct cc → H production

Charm-Higgs Coupling from $p_T(H \to ZZ^* \to 4\ell)$

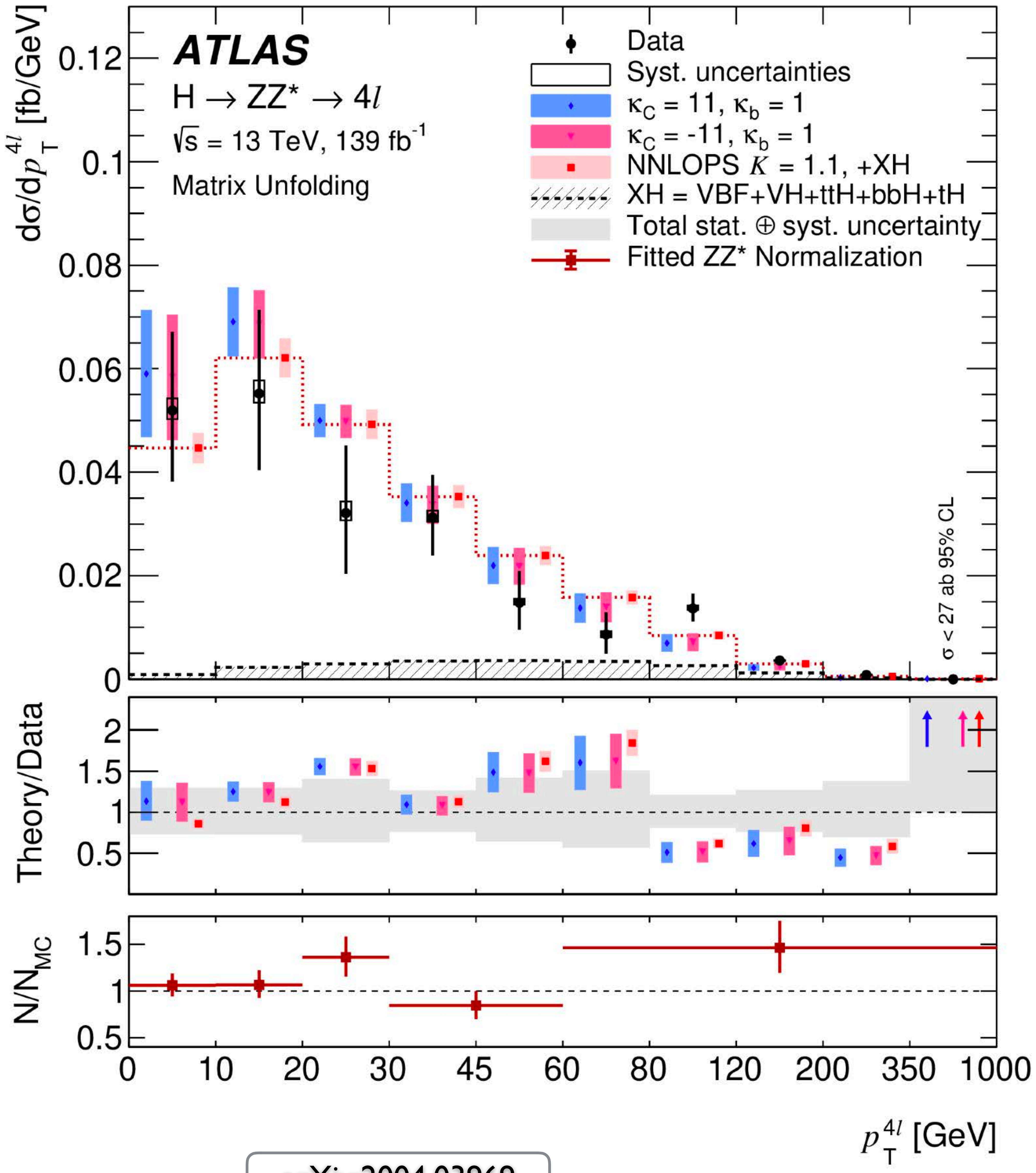


Use only the shape of $p_T(4\ell)$

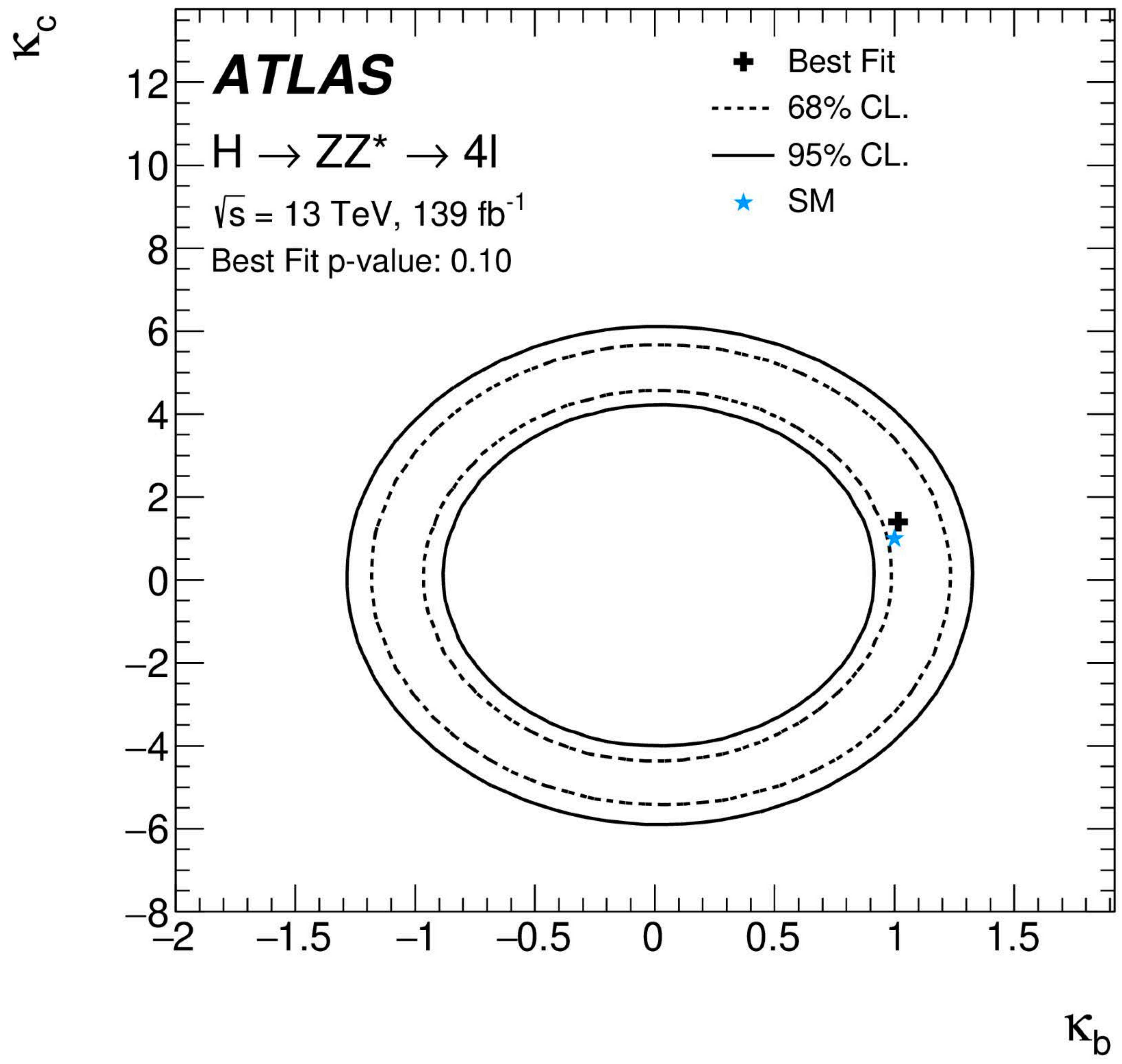


arXiv:2004.03969

Charm-Higgs Coupling from $p_T(H \rightarrow ZZ^* \rightarrow 4\ell)$



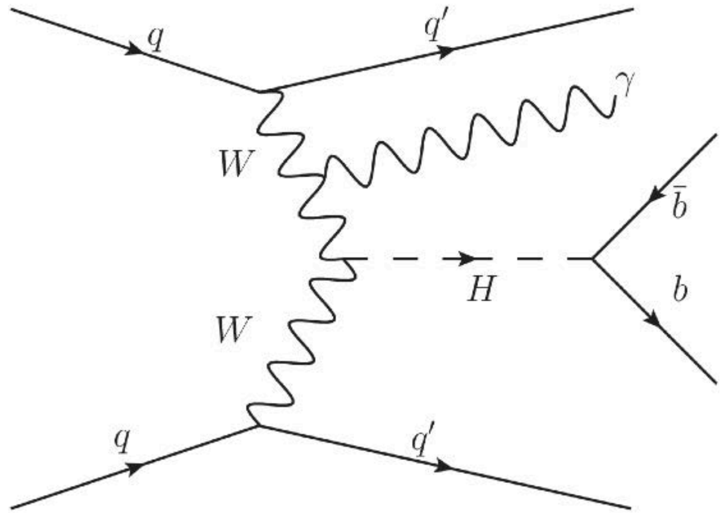
Use differential distribution and changes to total width

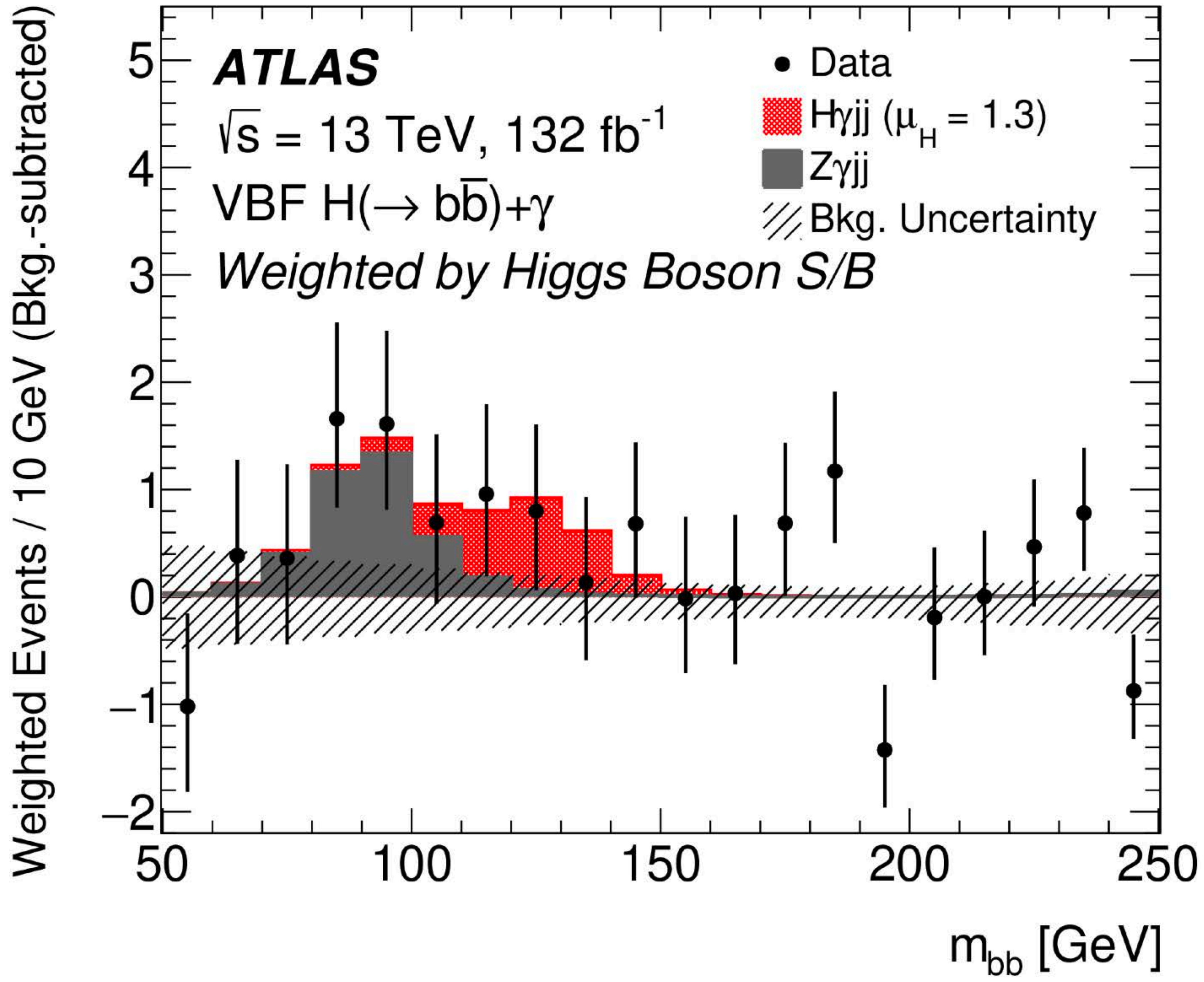


arXiv:2004.03969

VBF(γ) Production in $H \to b\bar{b}$ Decays

- Photon tagged





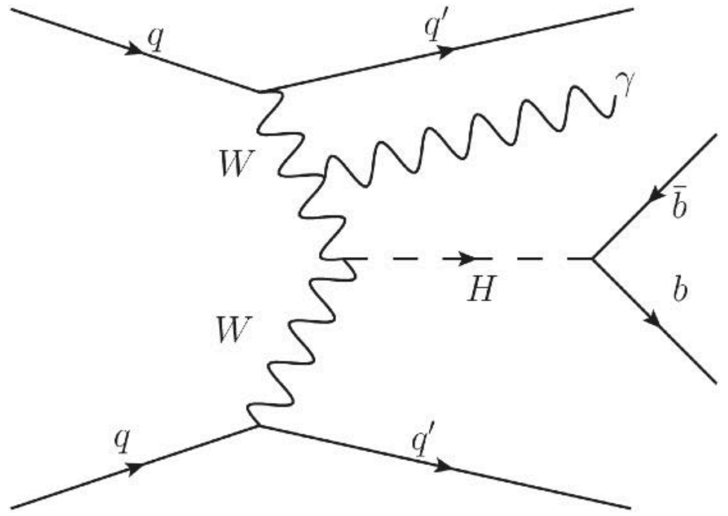
$\mu = 1.3 \pm 1.0$

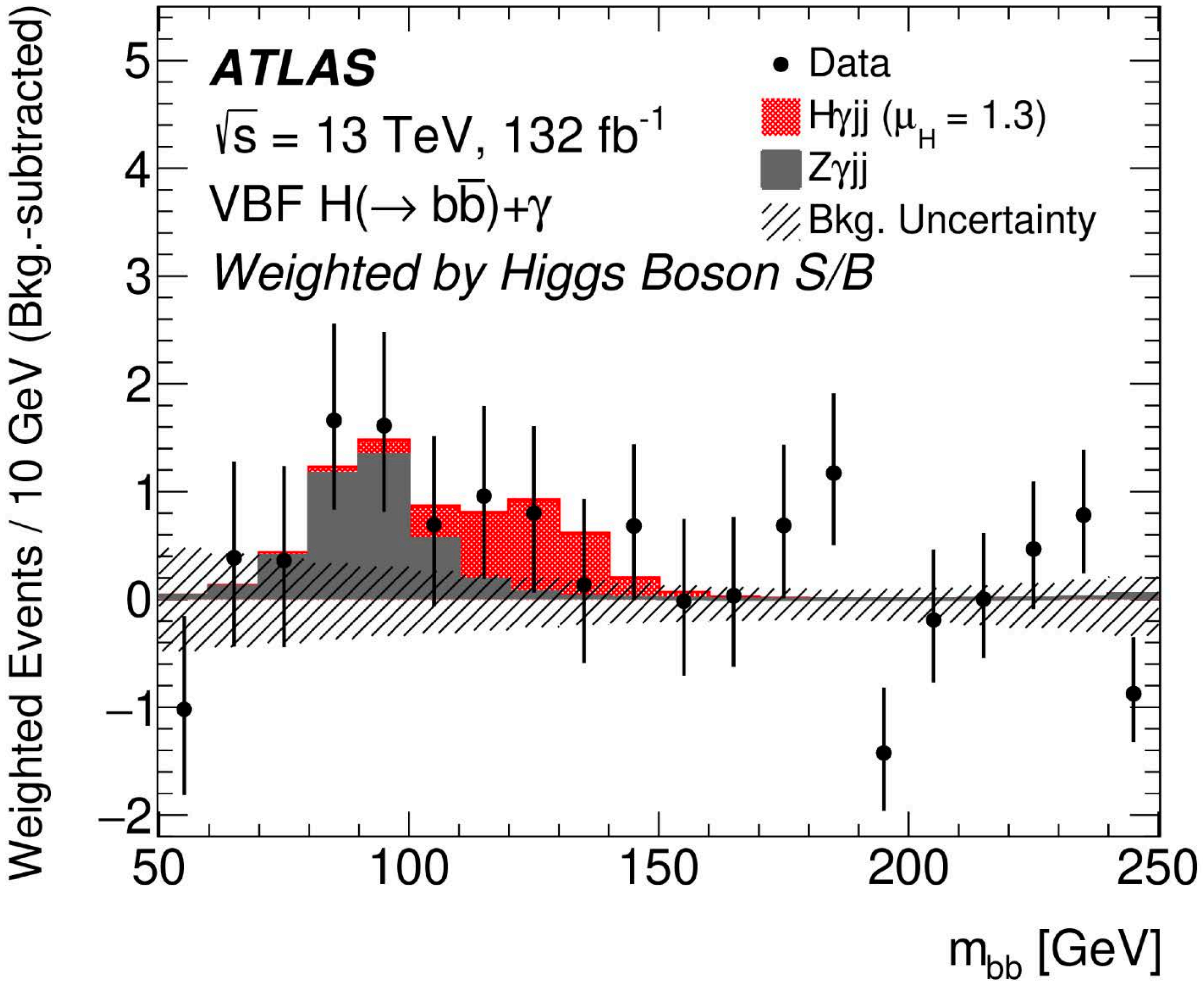
Observed (expected) significance: 1.3 (1.0) σ

arXiv:2010.13651

VBF(γ) Production in $H \rightarrow b\bar{b}$ Decays

- Photon tagged

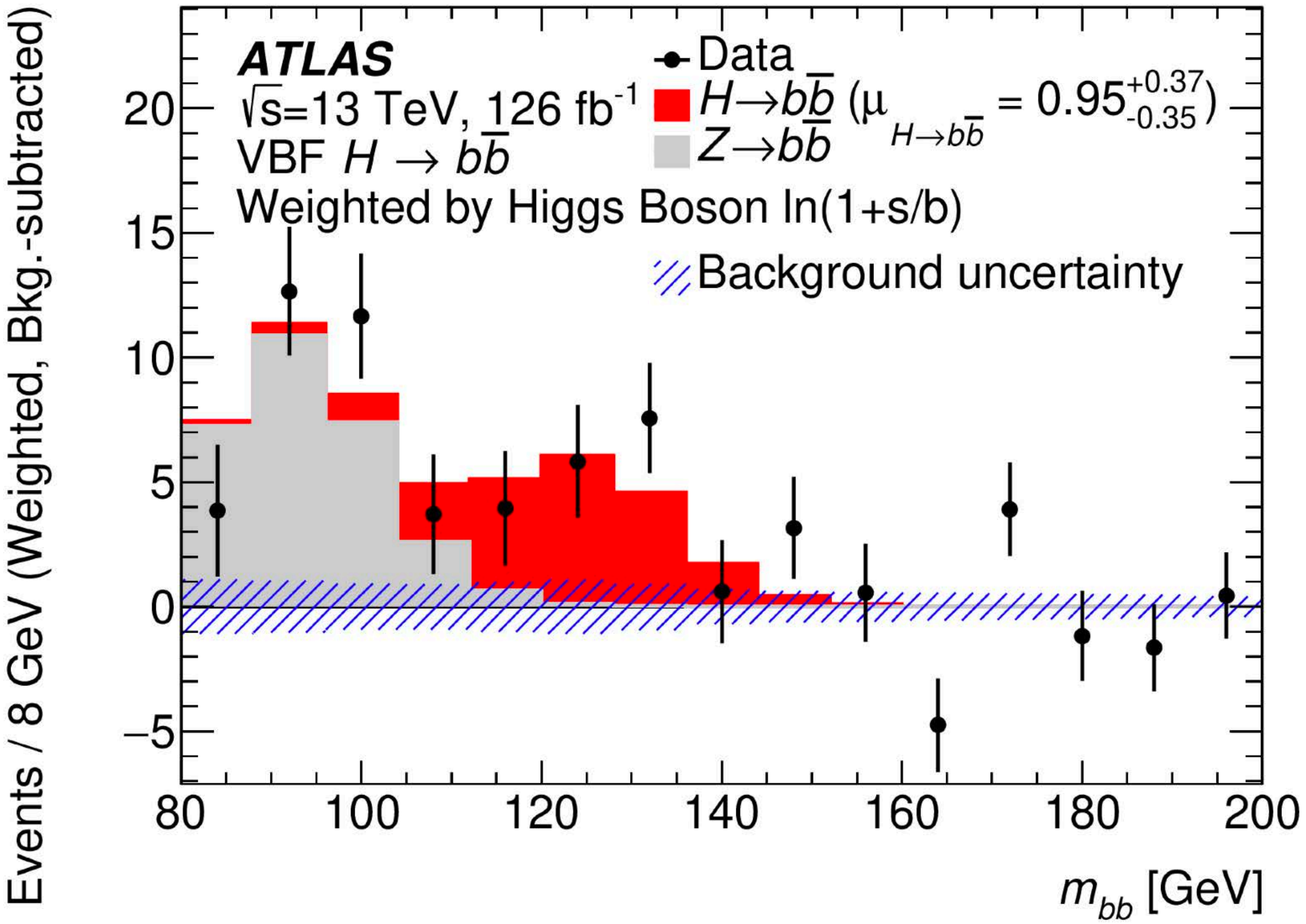




μ = 1.3 ± 1.0
Observed (expected) significance: 1.3 (1.0) σ

arXiv:2010.13651

- Inclusive (with photon veto):



Inclusive Production:

$\mu = 0.95 +0.37 -0.35$

Obs. (exp.) significance: 2.7 (2.9) σ

VBF Production:

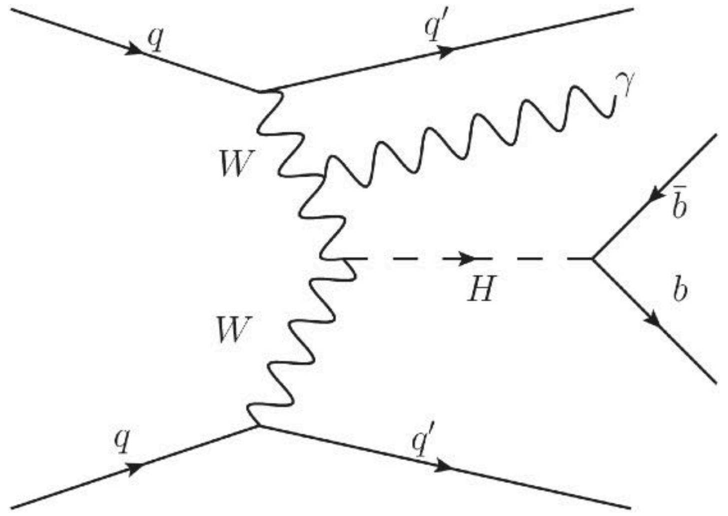
$\mu = 0.95 +0.38 -0.36$

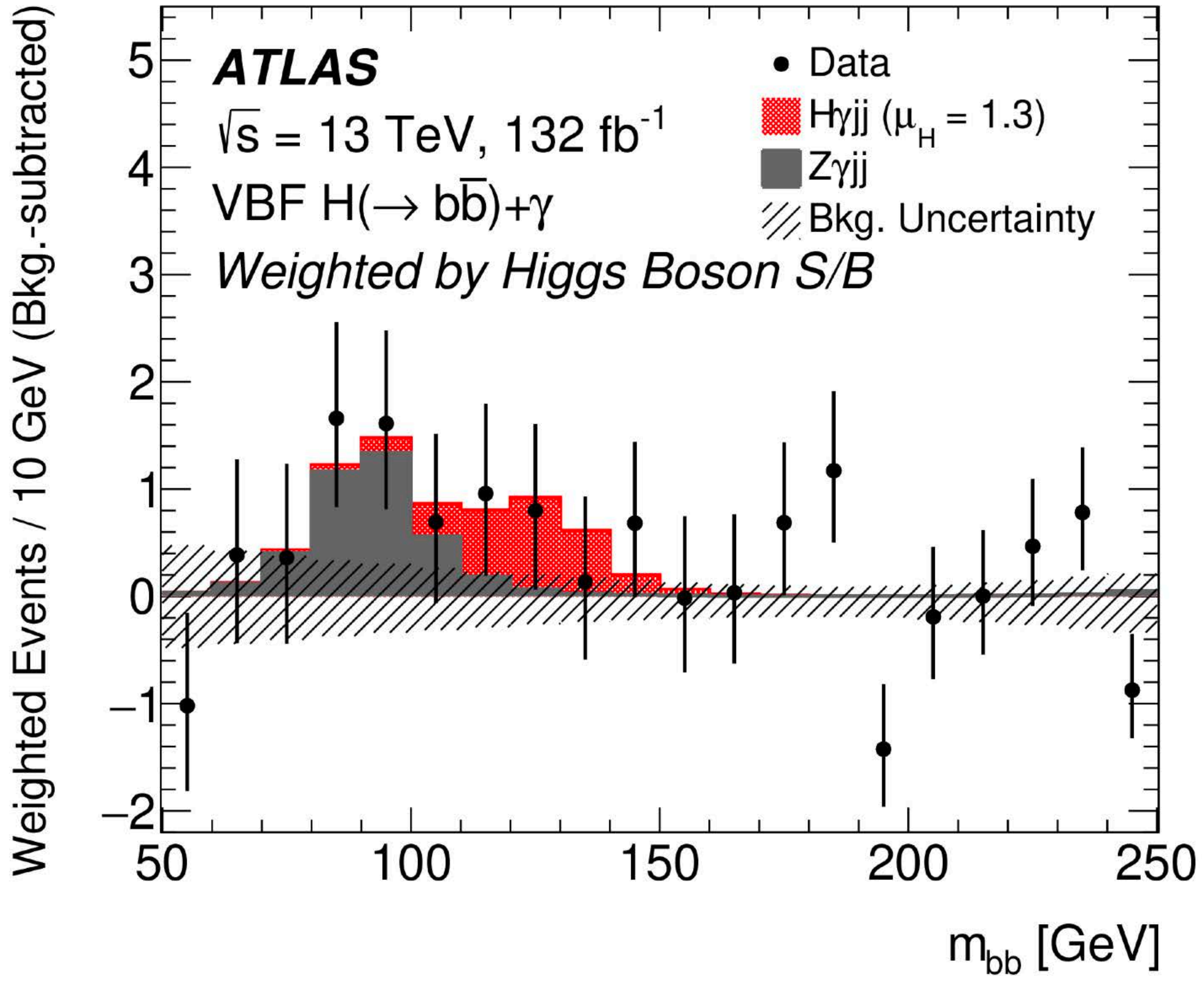
Obs. (exp.) significance: 2.6 (2.8) σ

arXiv:2011.08280

VBF(γ) Production in H → $b\bar{b}$ Decays

- Photon tagged

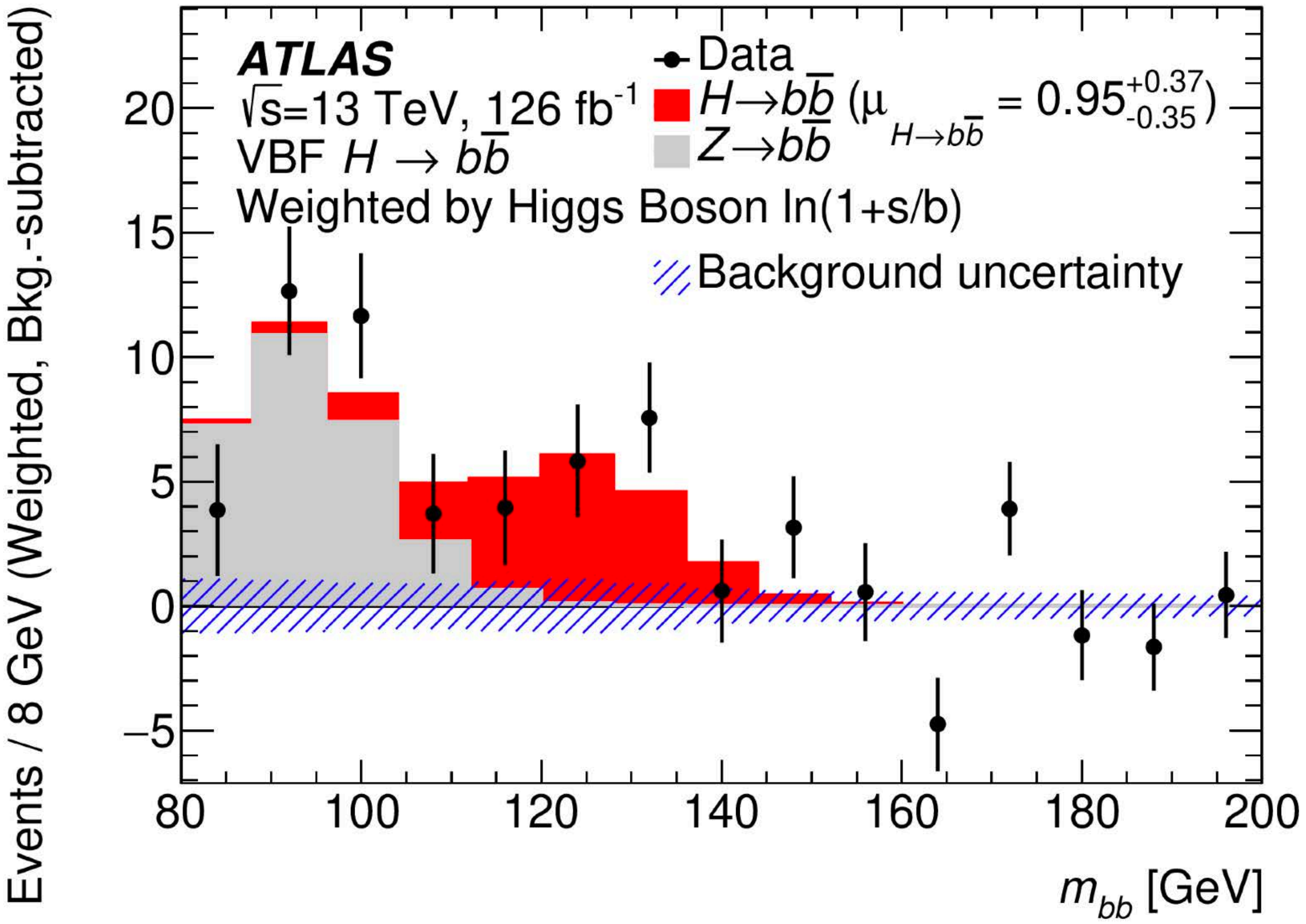




$\mu = 1.3 \pm 1.0$
Observed (expected) significance: 1.3 (1.0) σ

arXiv:2010.13651

- Inclusive (with photon veto):



Inclusive Production:

$\mu = 0.95 +0.37 -0.35$

Obs. (exp.) significance: 2.7 (2.9) σ

VBF Production:

$\mu = 0.95 +0.38 -0.36$

Obs. (exp.) significance: 2.6 (2.8) σ

- Combination:

Inclusive Production:

$\mu = 0.99 +0.35 -0.33$

Obs. (exp.) significance: 3.0 (3.0) σ

VBF Production:

$\mu = 0.99 +0.36 -0.34$

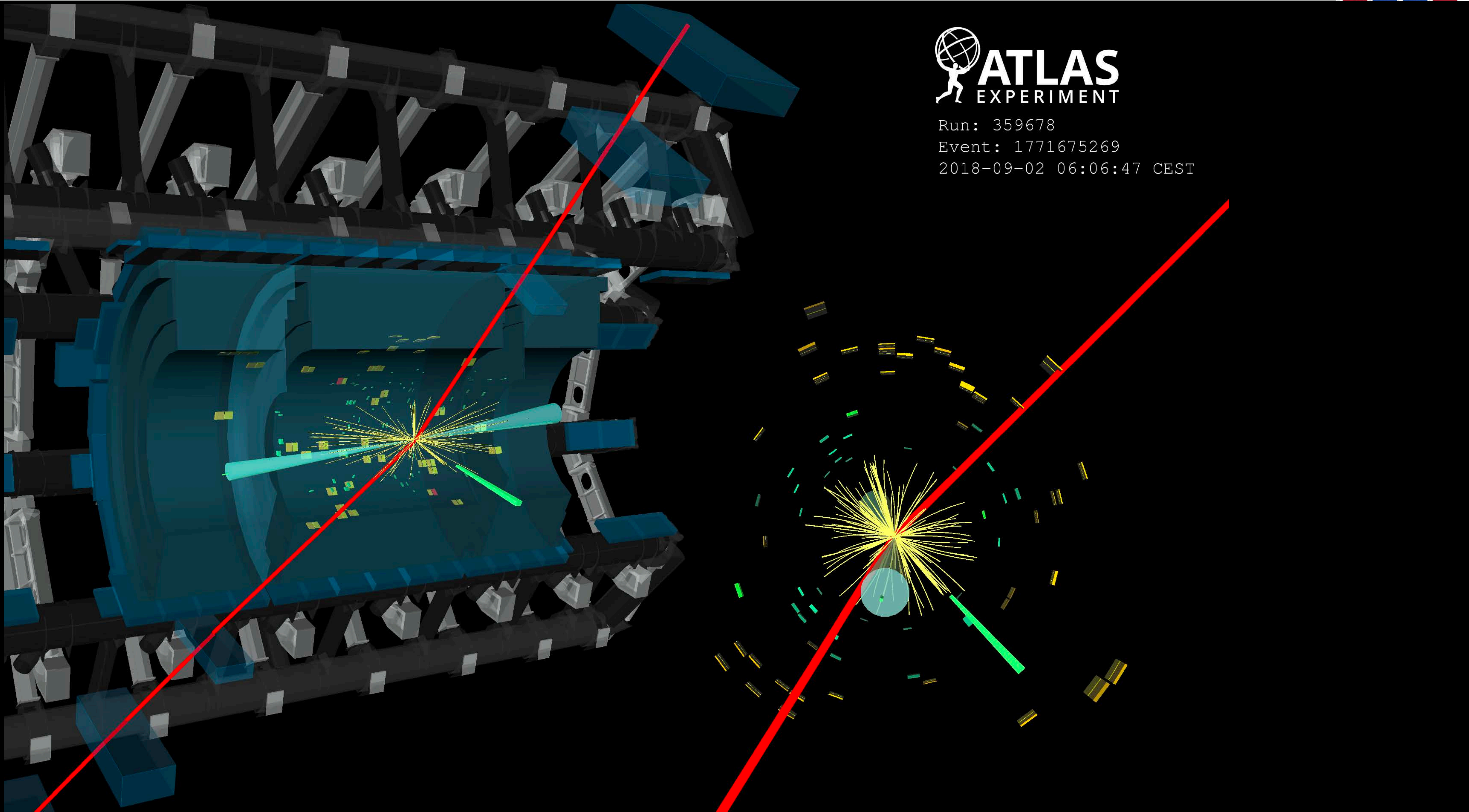
Obs. (exp.) significance: 2.9 (2.9) σ

arXiv:2011.08280

$H \rightarrow ee\gamma$

Run: 339387
Event: 812083095
2017-10-28 09:47:43 CEST

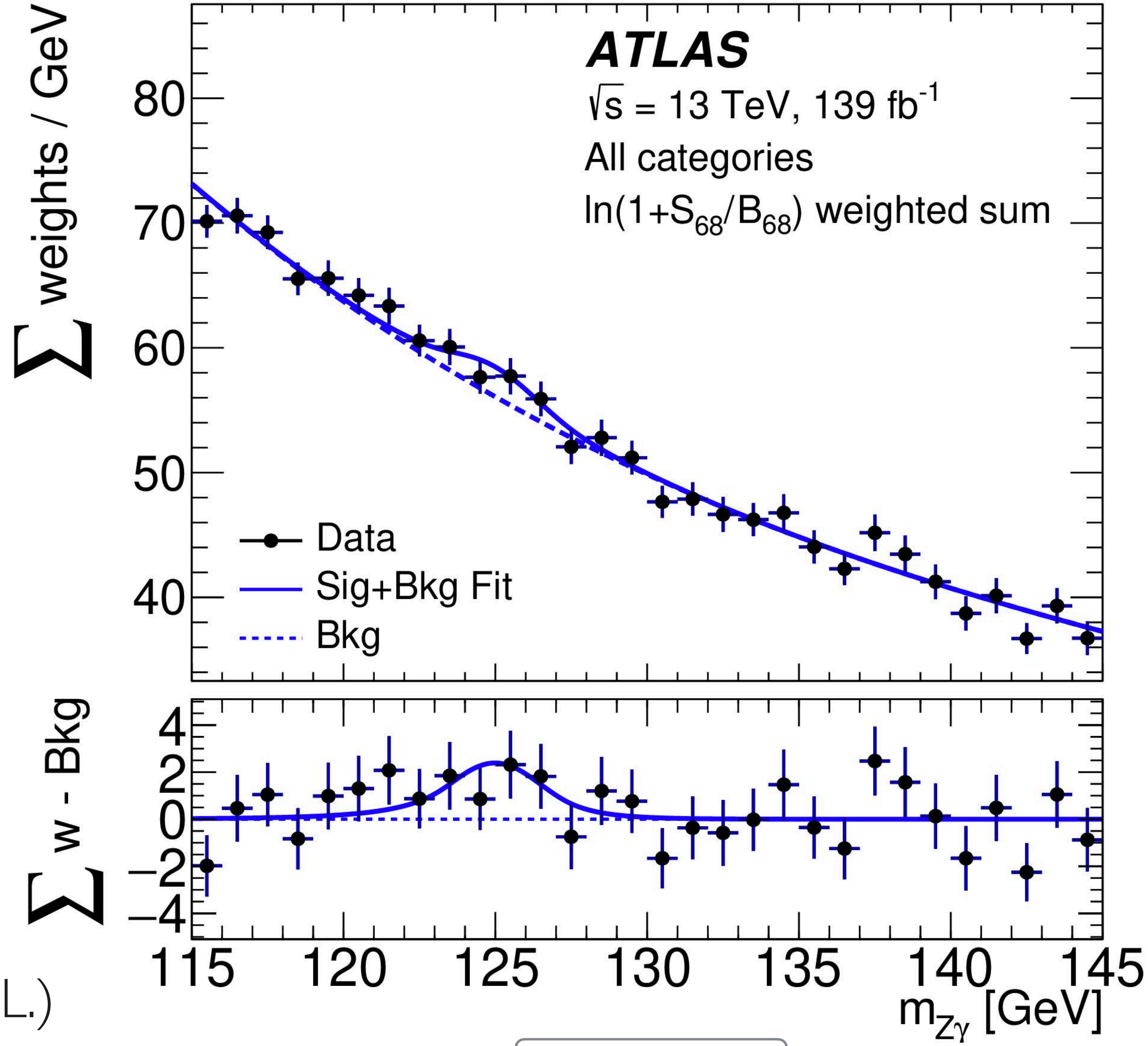
Rare Decay H → Zγ



$H \rightarrow Z\gamma$

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

$\Rightarrow$ **~765 $H \rightarrow Z\gamma \rightarrow \ell\ell\gamma$ events in 139 fb^{-1}**
but difficult kinematics



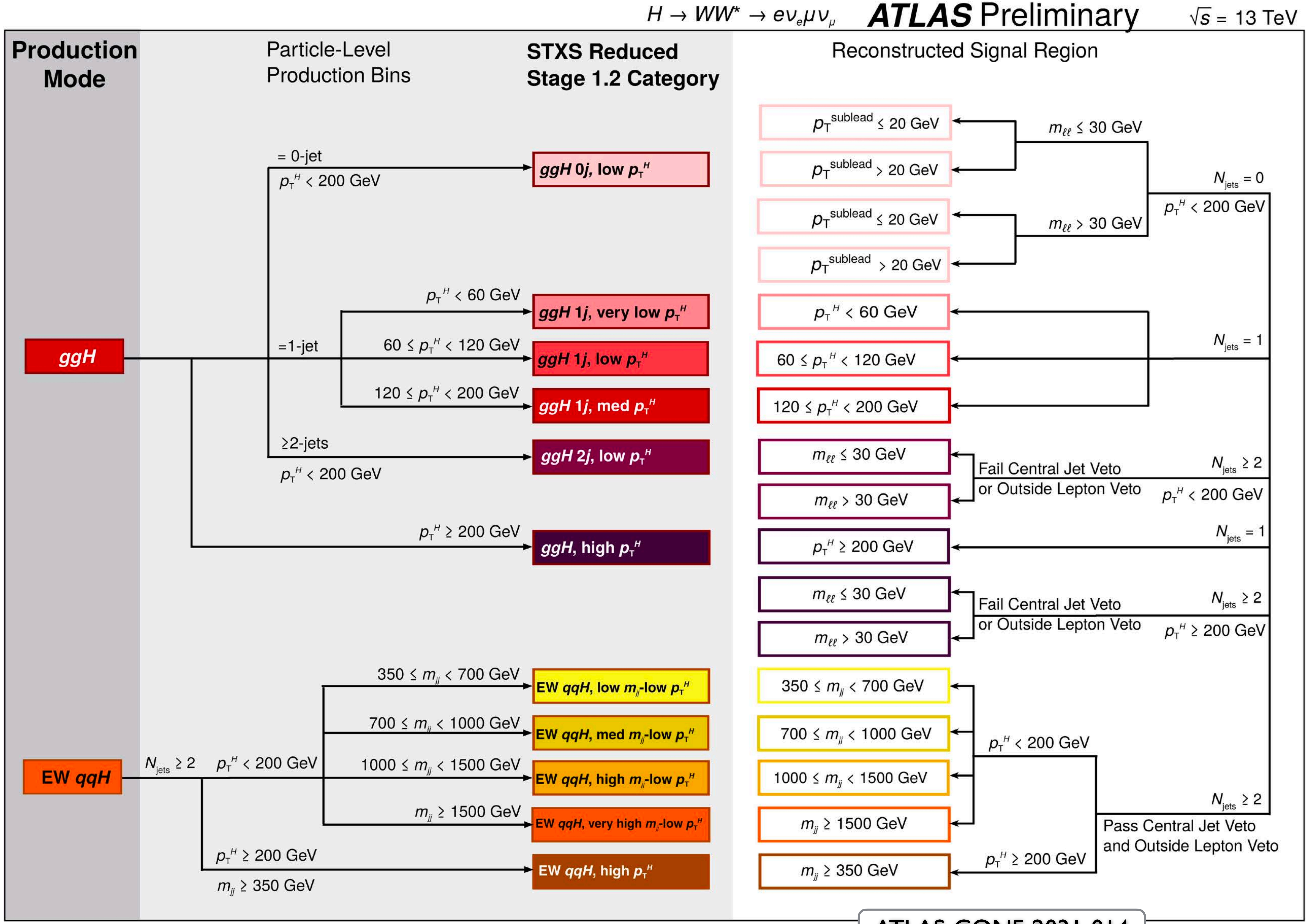
Category	μ	Significance
Combined	$2.0^{+1.0}_{-0.9}$ $(1.0^{+0.9}_{-0.9})$	2.2 (1.2)

- Upper limit:

- Observed (expected): <3.6 (2.6) × SM (95% C.L.)

arXiv:2005.05382

$H \rightarrow WW^* \rightarrow e\nu\mu\nu$



$H \rightarrow WW^* \rightarrow e\nu_e\mu\nu_\mu$ ***ATLAS*** Preliminary $\sqrt{s}$ = 13 TeV

Production Mode

Particle-Level Production Bins

STXS Reduced Stage 1.2 Category

Reconstructed Signal Region

ggH

= 0-jet, p_T^H < 200 GeV → ***ggH* 0j, low p_T^H**

=1-jet, p_T^H < 60 GeV → ***ggH* 1j, very low p_T^H**

=1-jet, 60 ≤ p_T^H < 120 GeV → ***ggH* 1j, low p_T^H**

=1-jet, 120 ≤ p_T^H < 200 GeV → ***ggH* 1j, med p_T^H**

≥2-jets, p_T^H < 200 GeV → ***ggH* 2j, low p_T^H**

p_T^H ≥ 200 GeV → ***ggH*, high p_T^H**

EW qqH

N_{jets} ≥ 2, p_T^H < 200 GeV, 350 ≤ m_{jj} < 700 GeV → **EW *qqH*, low m_{jj}-low p_T^H**

N_{jets} ≥ 2, p_T^H < 200 GeV, 700 ≤ m_{jj} < 1000 GeV → **EW *qqH*, med m_{jj}-low p_T^H**

N_{jets} ≥ 2, p_T^H < 200 GeV, 1000 ≤ m_{jj} < 1500 GeV → **EW *qqH*, high m_{jj}-low p_T^H**

N_{jets} ≥ 2, p_T^H < 200 GeV, m_{jj} ≥ 1500 GeV → **EW *qqH*, very high m_{jj}-low p_T^H**

N_{jets} ≥ 2, p_T^H ≥ 200 GeV, m_{jj} ≥ 350 GeV → **EW *qqH*, high p_T^H**

Reconstructed signal regions:

N_{jets} = 0, p_T^H < 200 GeV:
- $m_{\ell\ell}$ ≤ 30 GeV: $p_T^{sublead}$ ≤ 20 GeV; $p_T^{sublead}$ > 20 GeV
- $m_{\ell\ell}$ > 30 GeV: $p_T^{sublead}$ ≤ 20 GeV; $p_T^{sublead}$ > 20 GeV

N_{jets} = 1:
- p_T^H < 60 GeV
- 60 ≤ p_T^H < 120 GeV
- 120 ≤ p_T^H < 200 GeV

N_{jets} ≥ 2, p_T^H < 200 GeV, Fail Central Jet Veto or Outside Lepton Veto:
- $m_{\ell\ell}$ ≤ 30 GeV
- $m_{\ell\ell}$ > 30 GeV

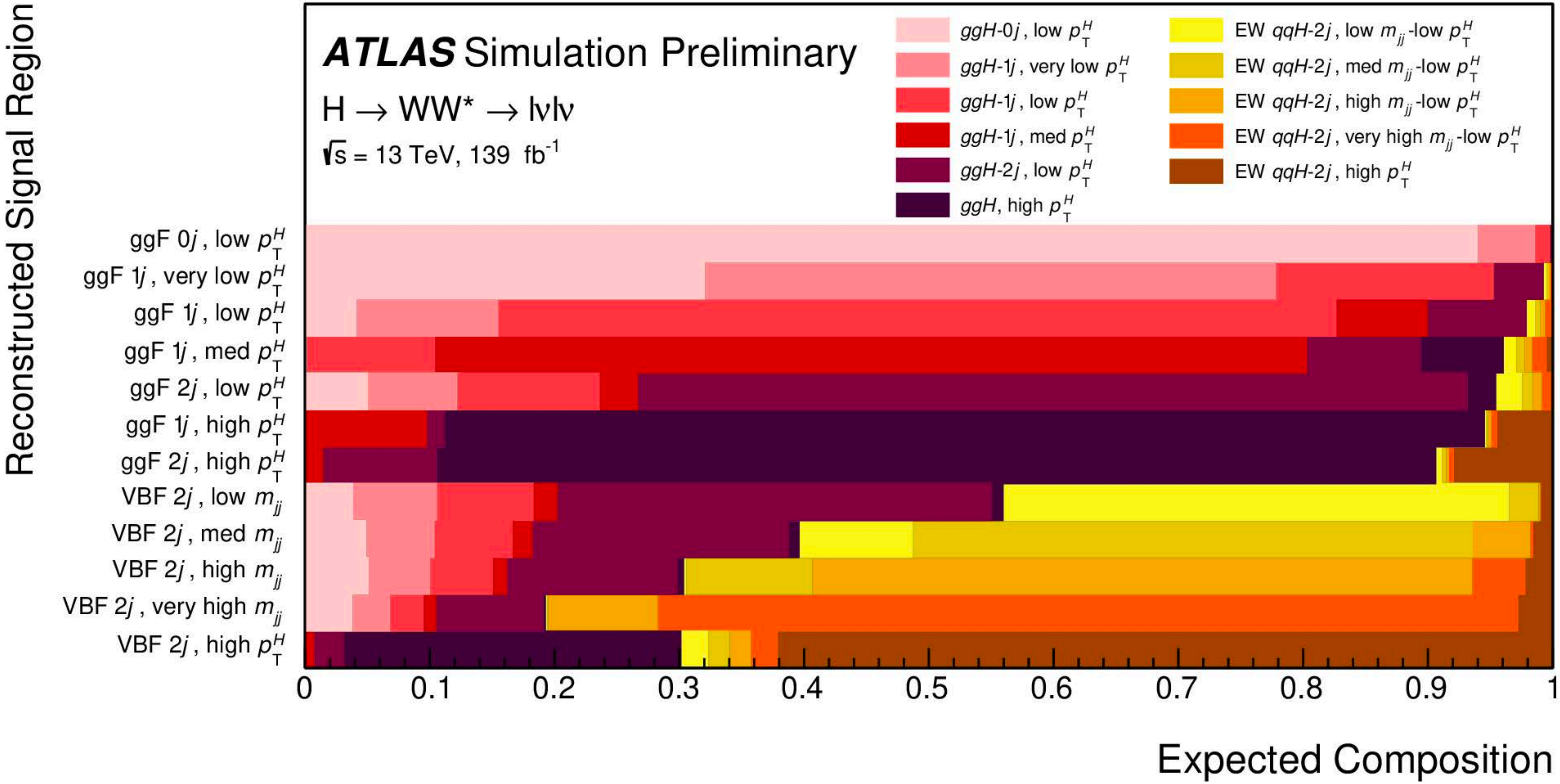
N_{jets} = 1:
- p_T^H ≥ 200 GeV

N_{jets} ≥ 2, p_T^H ≥ 200 GeV, Fail Central Jet Veto or Outside Lepton Veto:
- $m_{\ell\ell}$ ≤ 30 GeV
- $m_{\ell\ell}$ > 30 GeV

N_{jets} ≥ 2, Pass Central Jet Veto and Outside Lepton Veto:
- p_T^H < 200 GeV: 350 ≤ m_{jj} < 700 GeV; 700 ≤ m_{jj} < 1000 GeV; 1000 ≤ m_{jj} < 1500 GeV; m_{jj} ≥ 1500 GeV
- p_T^H ≥ 200 GeV: m_{jj} ≥ 350 GeV

ATLAS-CONF-2021-014

$H \rightarrow WW^* \rightarrow e\nu\mu\nu$

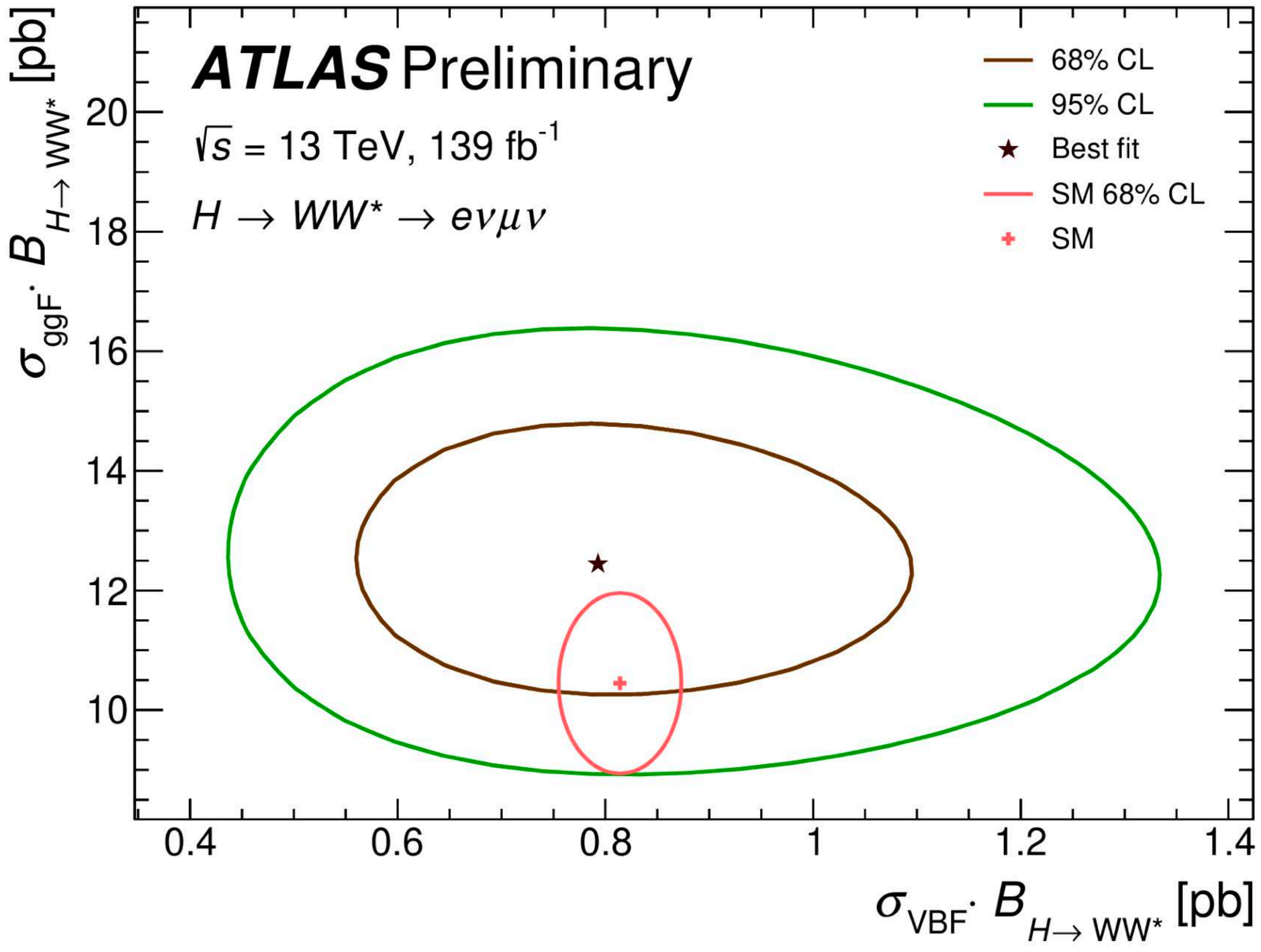


ATLAS-CONF-2021-014

H → WW* → eνμν

- **Large $\mathrm{BR_{SM}}(H \rightarrow WW^*) \approx 22\%$**
  - $\mathrm{BR_{SM}}(W \rightarrow \ell\nu) \approx 10.8\% \Rightarrow \mathrm{BR_{SM}}(H \rightarrow WW^* \rightarrow e\nu\mu\nu) = 0.25\%$

⇒ **~420 000 $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ events in 139 fb^{-1}**,
but difficult backgrounds…

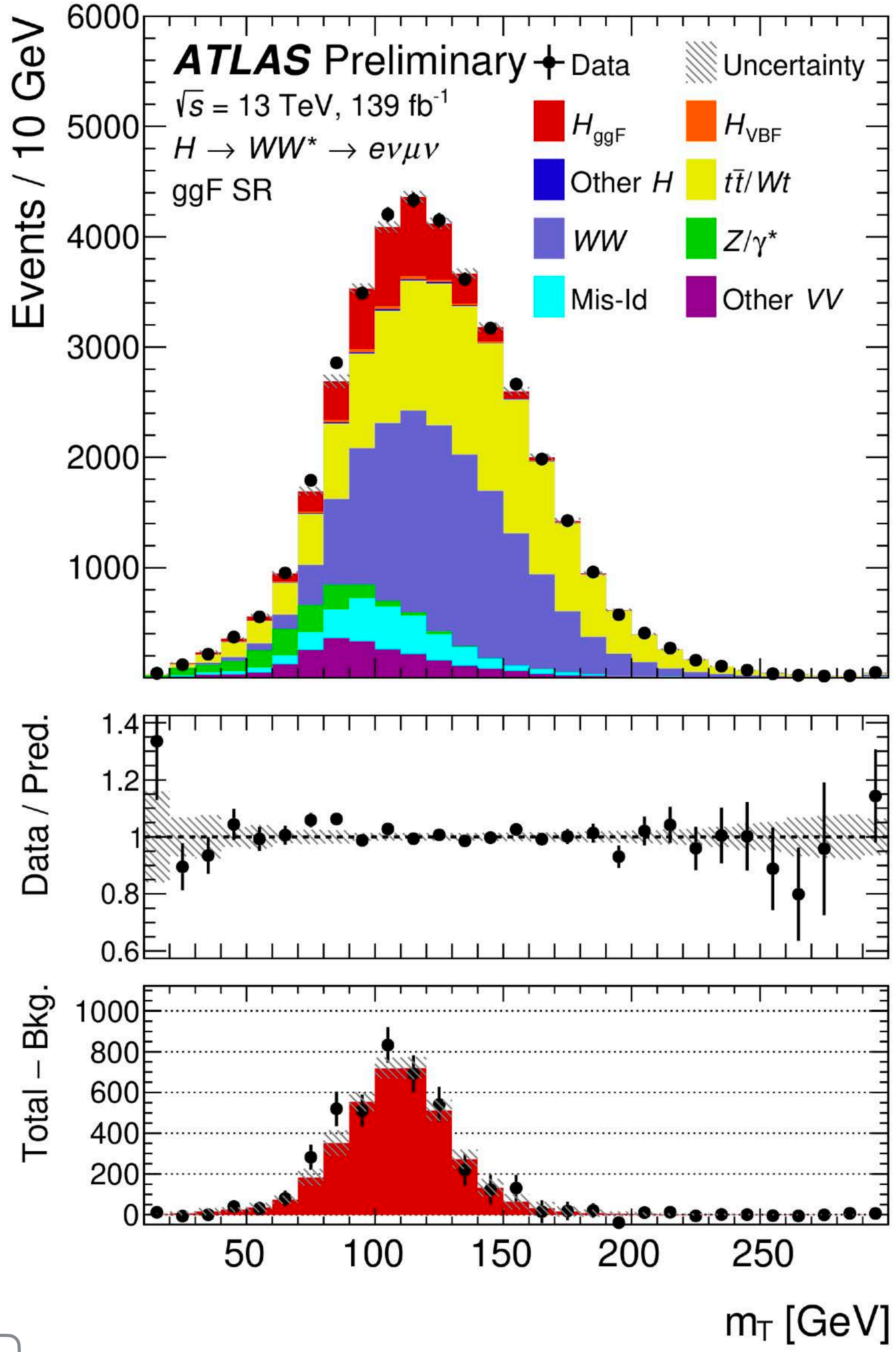


Signal strength:

$$\mu := \frac{\sigma_i \cdot \mathcal{B}^f}{(\sigma_i \cdot \mathcal{B}^f)_{\mathrm{SM}}}$$

$$\mu_{\mathrm{ggF}} = 1.20\,^{+0.16}_{-0.15}$$

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

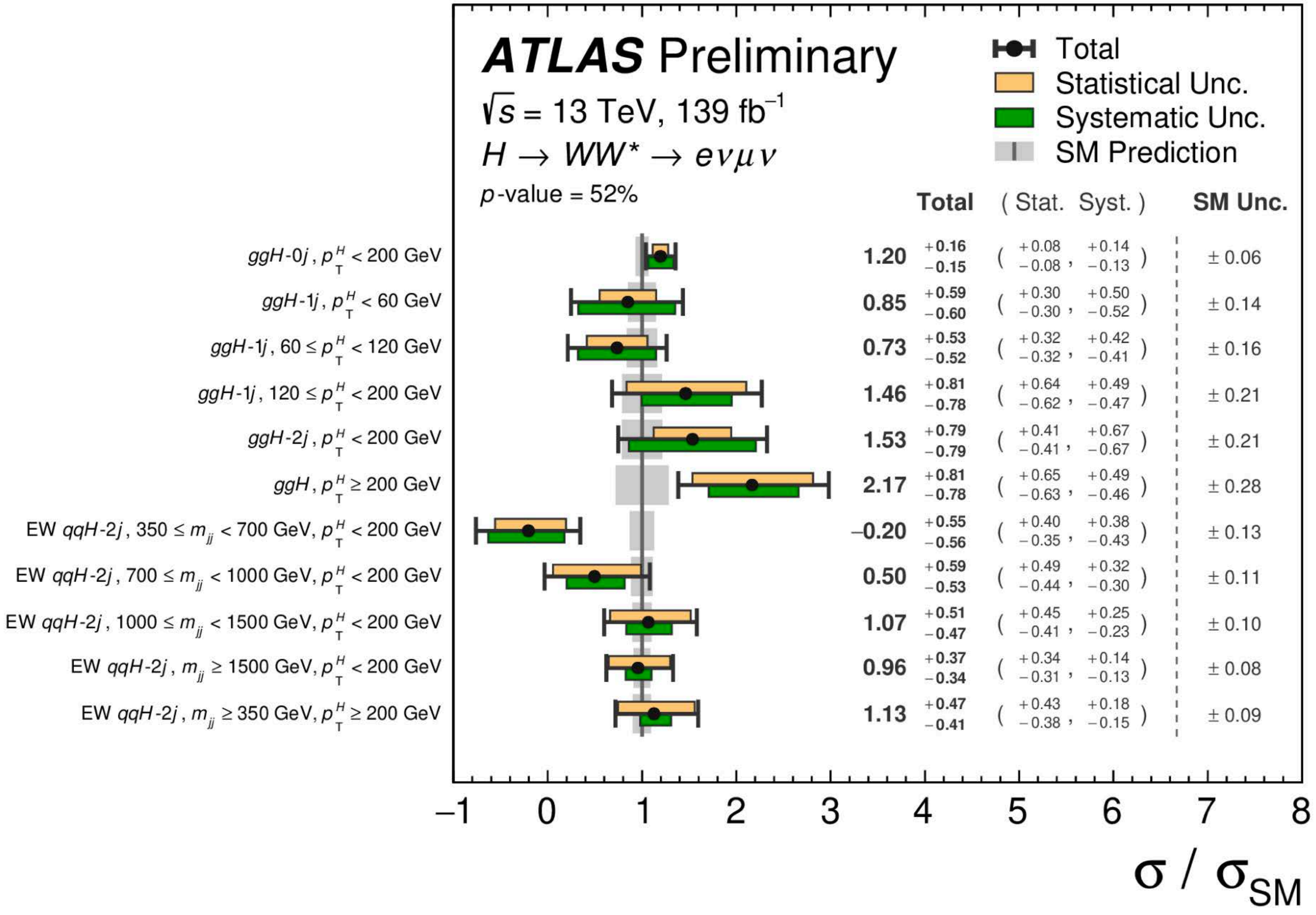


ATLAS-CONF-2021-014

$H \rightarrow WW^* \rightarrow e\nu\mu\nu$

- **Large $BR_{SM}(H \rightarrow WW^*) \approx 22\%$**
  - $BR_{SM}(W \rightarrow \ell\nu) \approx 10.8\% \Rightarrow BR_{SM}(H \rightarrow WW^* \rightarrow e\nu\mu\nu) = 0.25\%$

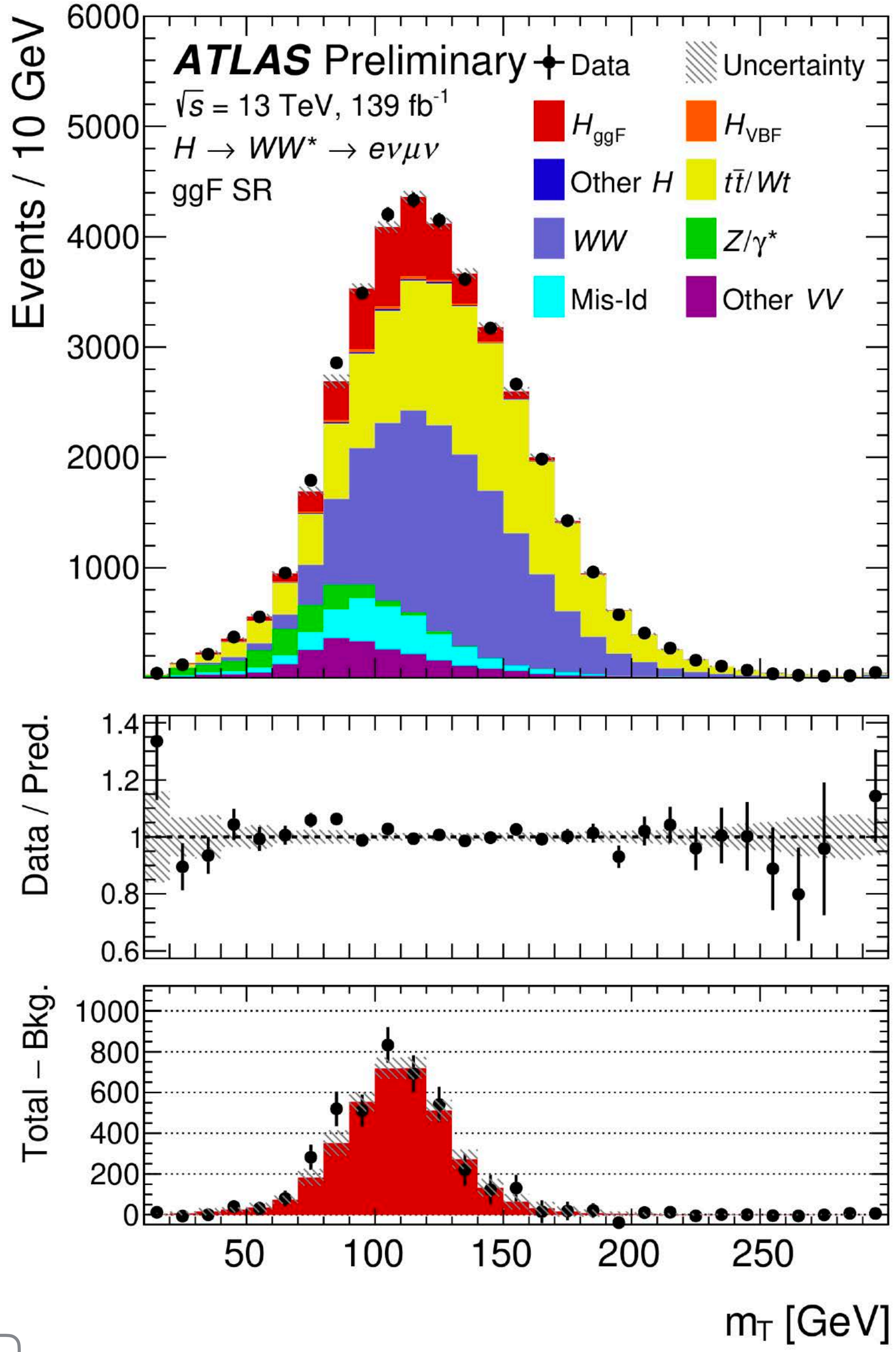
$\Rightarrow$ **~420 000 $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ events in 139 fb^{-1}**, but difficult backgrounds…



Signal strength:

$$\mu := \frac{\sigma_i \cdot \mathcal{B}^f}{(\sigma_i \cdot \mathcal{B}^f)_{\mathrm{SM}}}$$

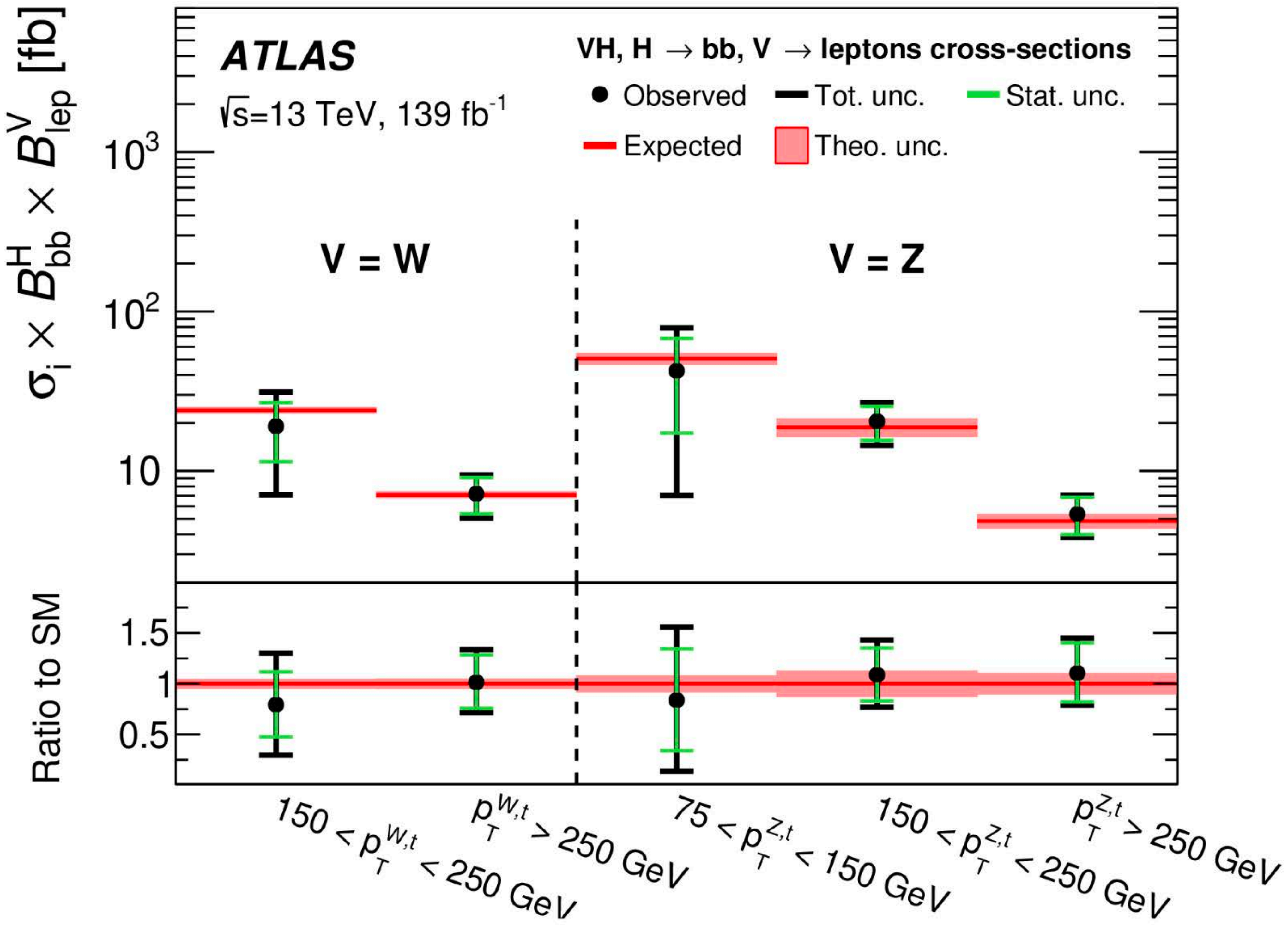
$$\begin{aligned}\mu_{\mathrm{ggF}} &= 1.20\,^{+0.16}_{-0.15} \\ &= 1.20 \pm 0.05\ (\mathrm{stat.}) \\ &\quad ^{+0.09}_{-0.08}\ (\mathrm{exp\ syst.}) \\ &\quad ^{+0.10}_{-0.08}\ (\mathrm{sig\ theo.}) \\ &\quad ^{+0.12}_{-0.11}\ (\mathrm{bkg\ theo.})\end{aligned}$$



ATLAS-CONF-2021-014

$H \rightarrow b\bar{b}$

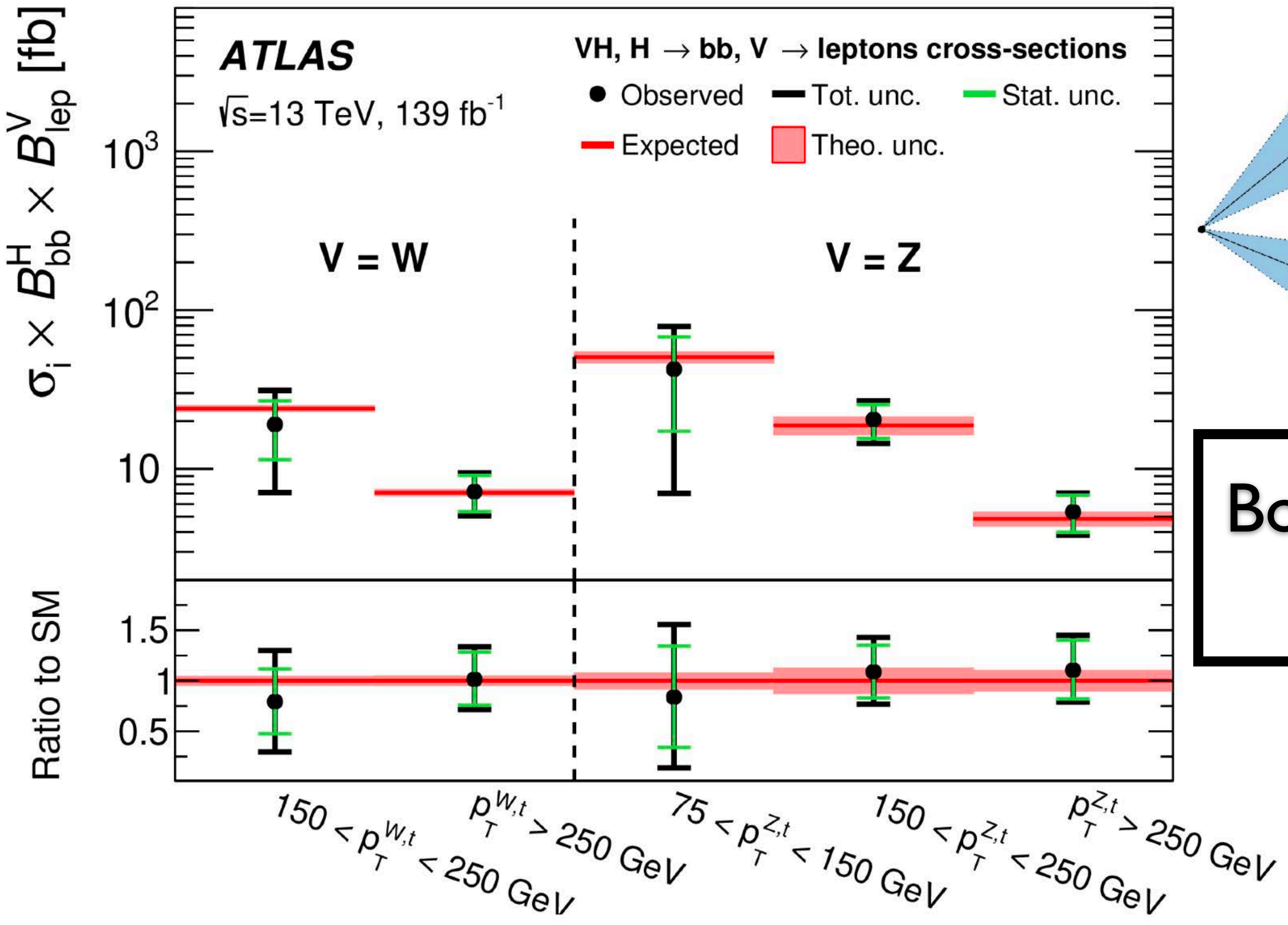
- Cross-section measurements as function of $p_T(V)$



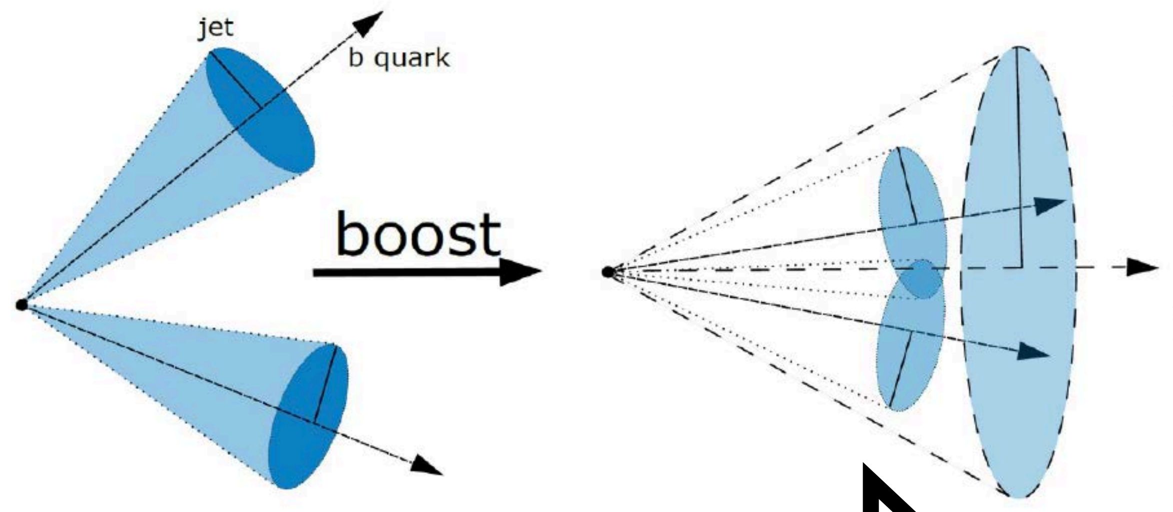
arXiv:2007.02873

$H \rightarrow b\bar{b}$

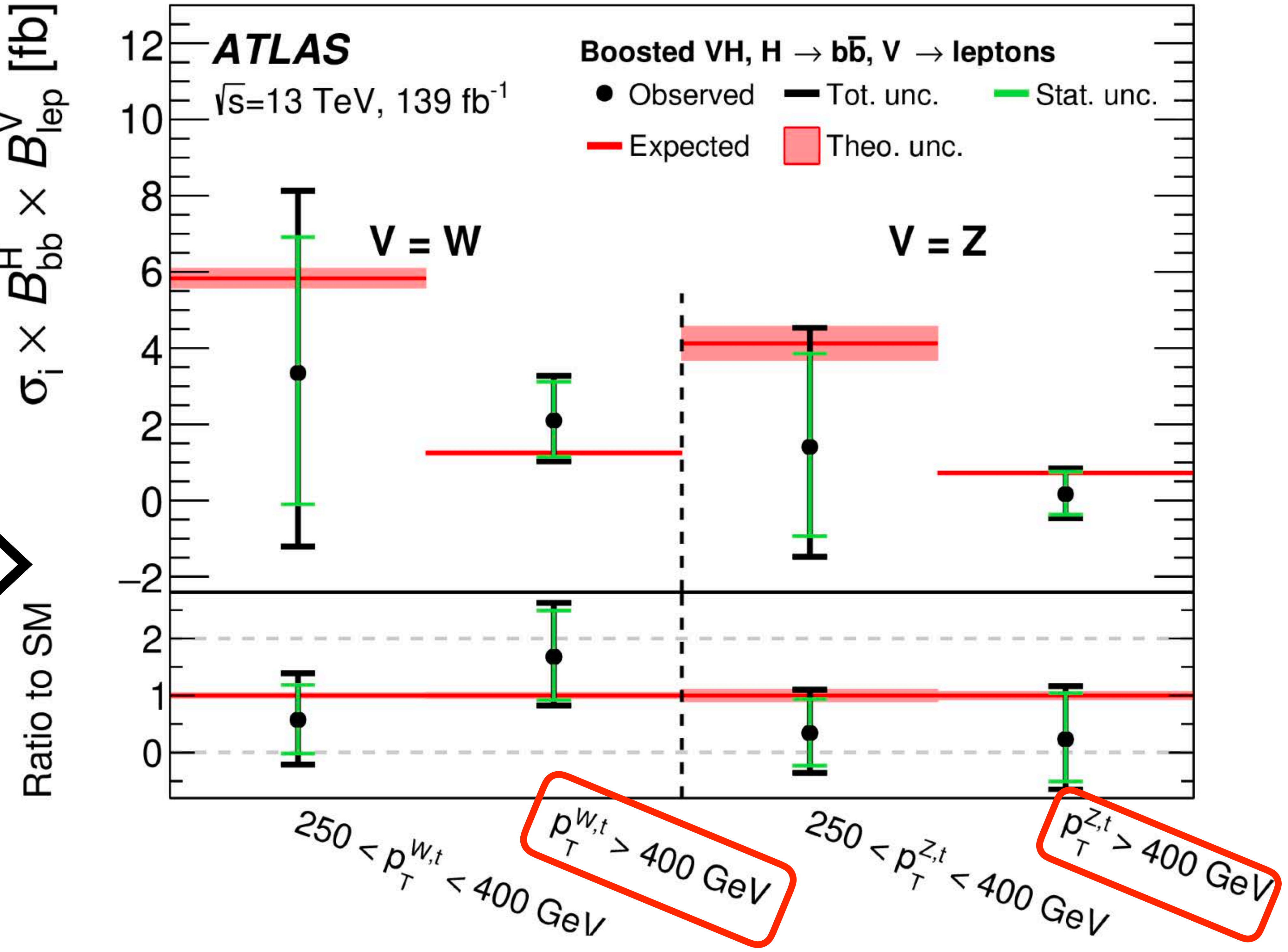
- Cross-section measurements as function of $p_T(V)$



arXiv:2007.02873



Boosted Higgs-boson decay topology



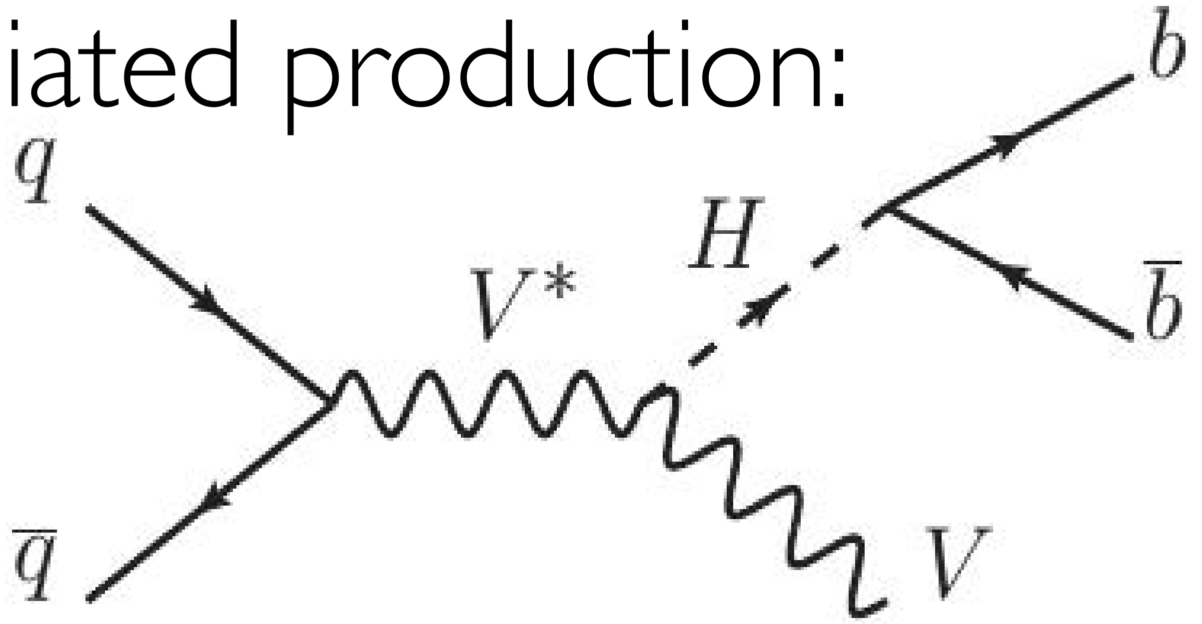
- Explores higher $p_T(V)$

$\Rightarrow$ Increase sensitivity to BSM

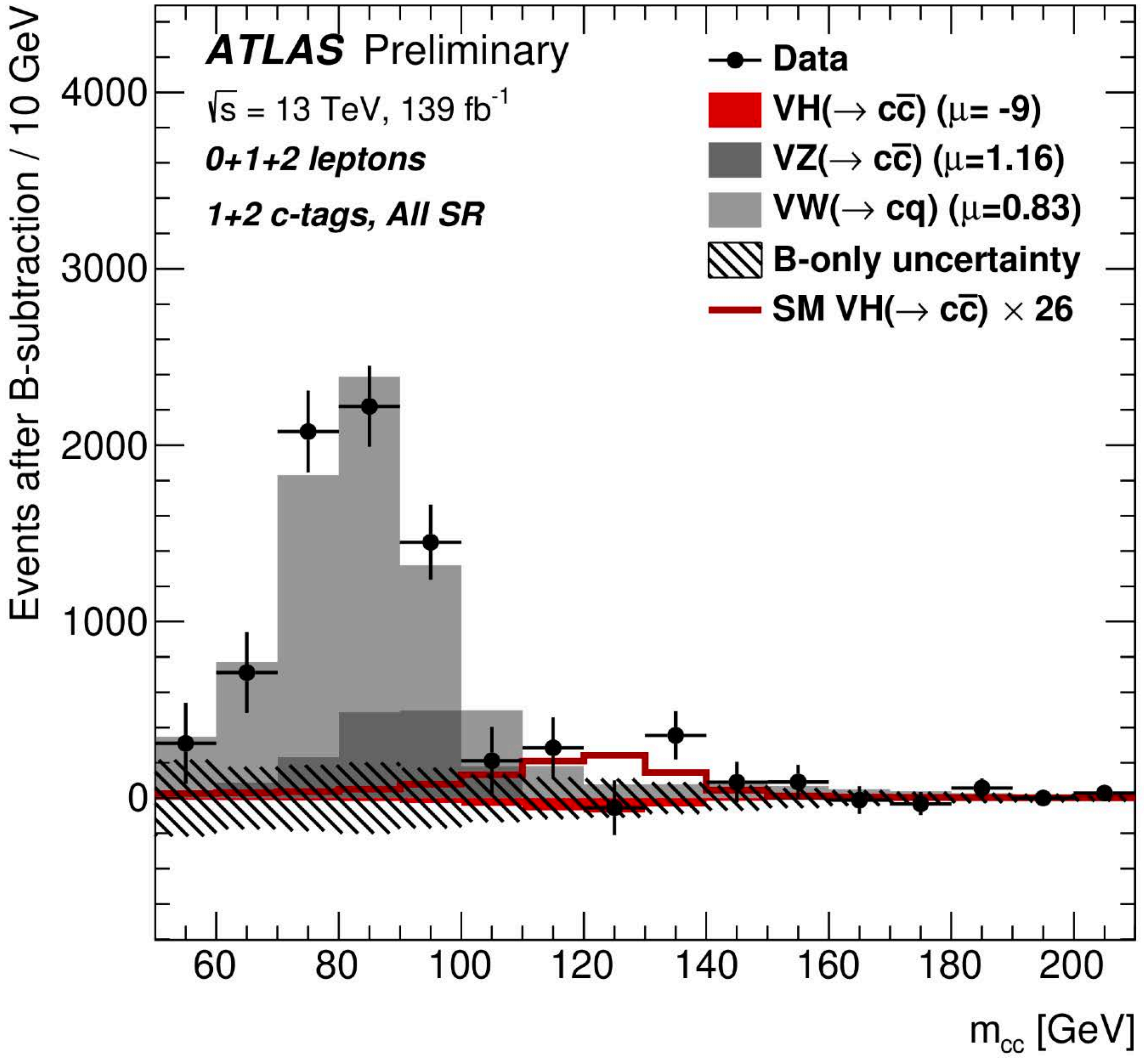
arXiv:2008.02508

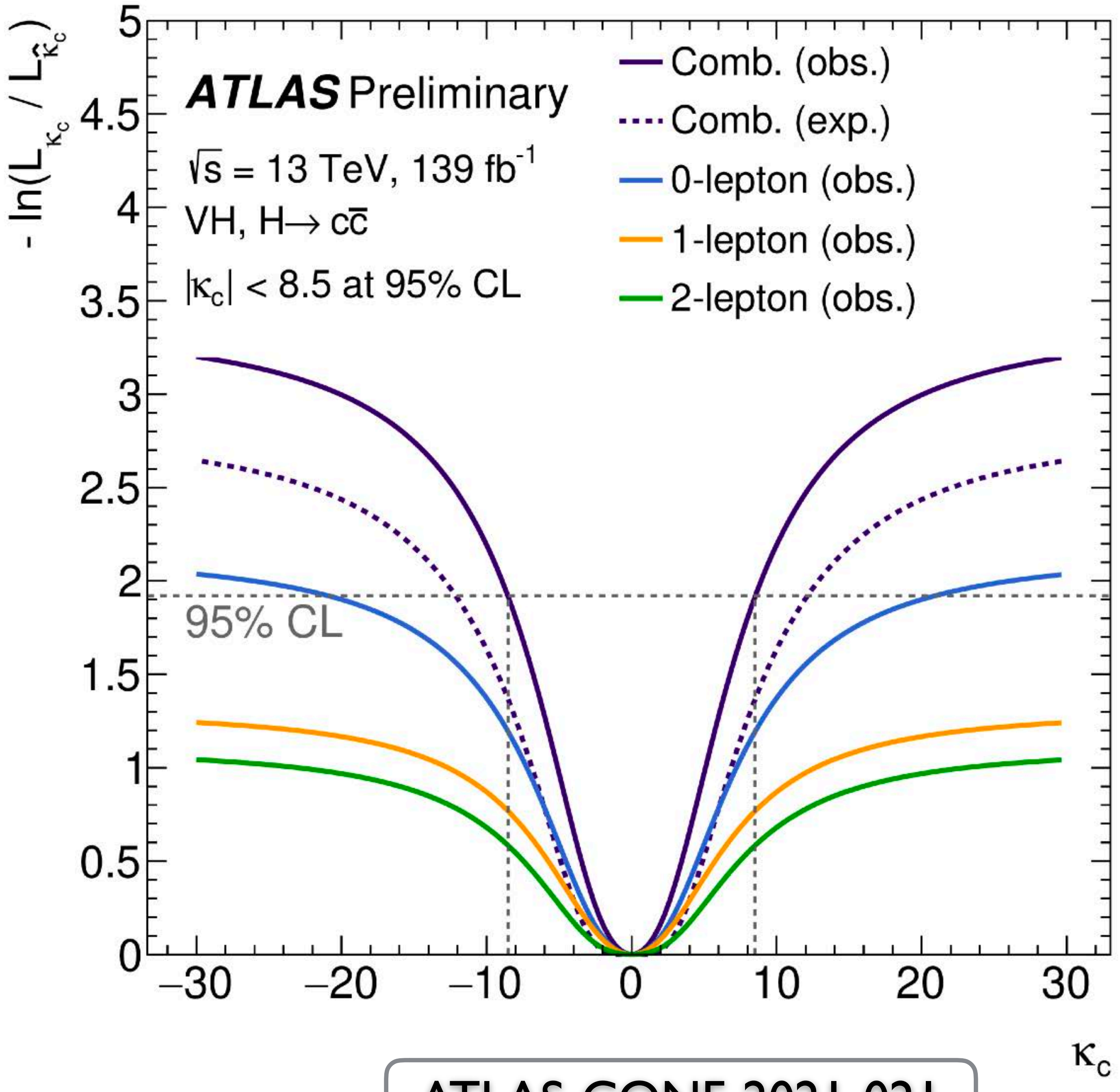
H → c$\bar{c}$

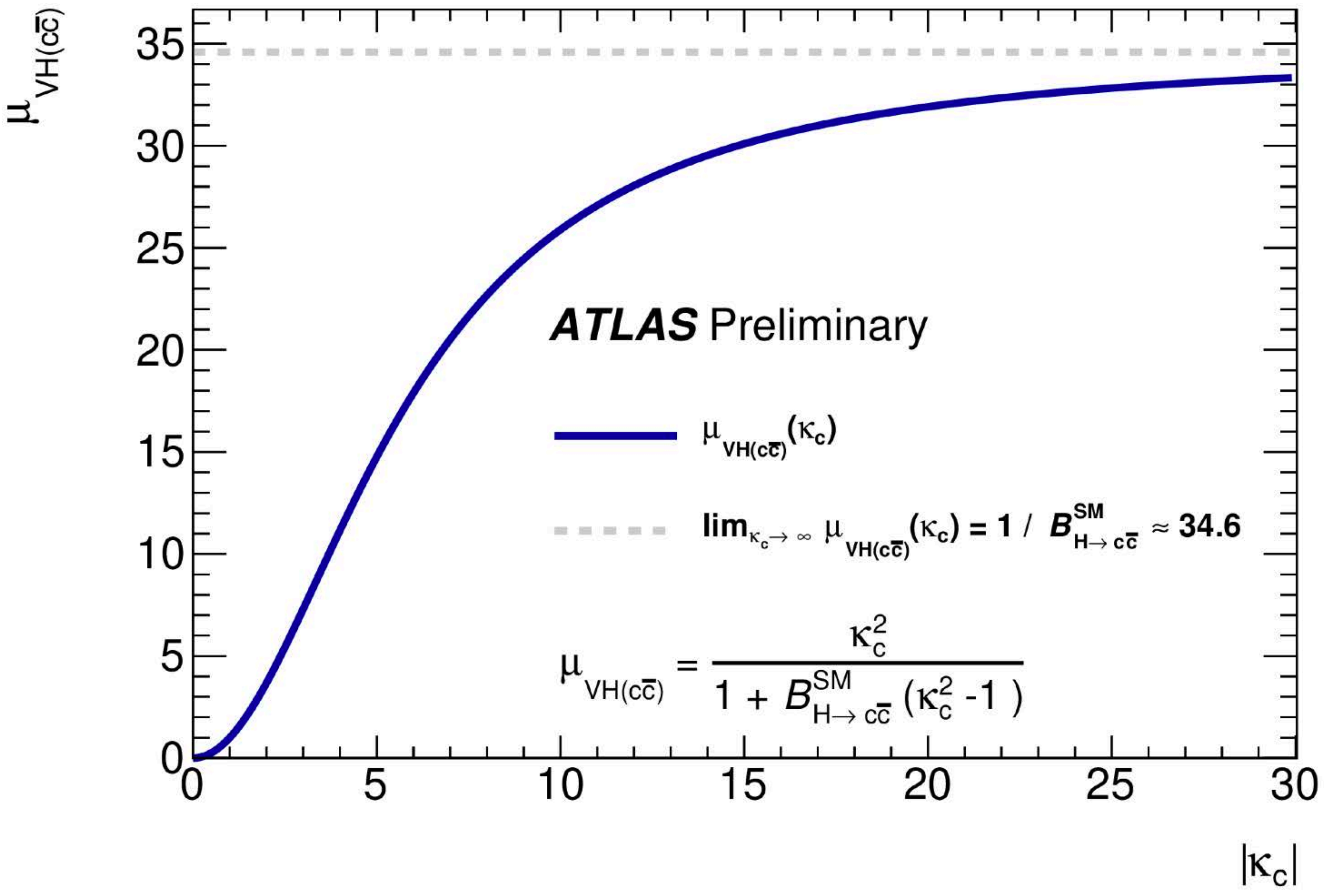
- H → cc 2nd generation decay channel (BR ~2.9%)
- VH (V=W or Z) associated production:
  - 0 lepton (Z → νν)
  - 1 lepton (W → ℓν)
  - 2 lepton (Z → ℓℓ)

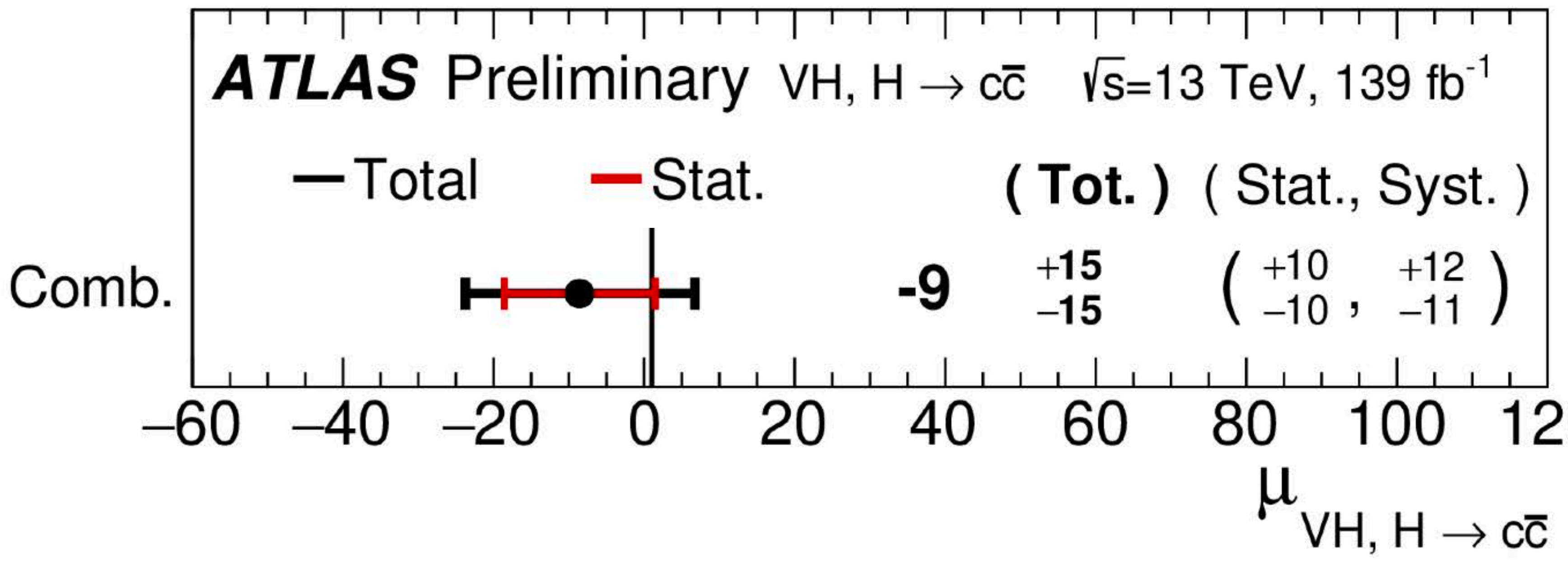


⇒ **~1500 V(→leptons)H → cc events in 139 fb^{-1}**



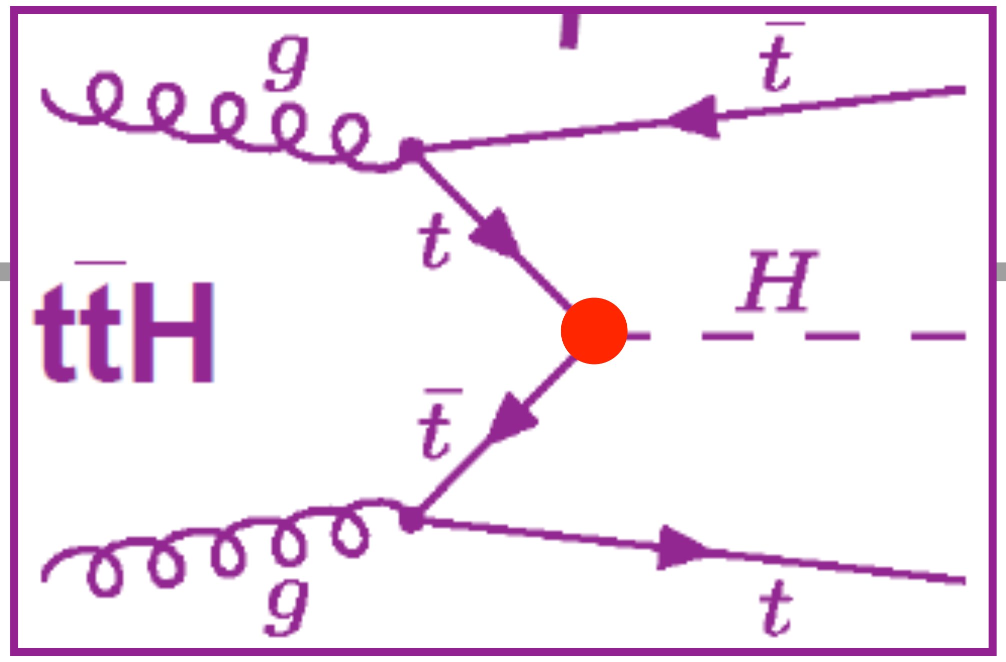




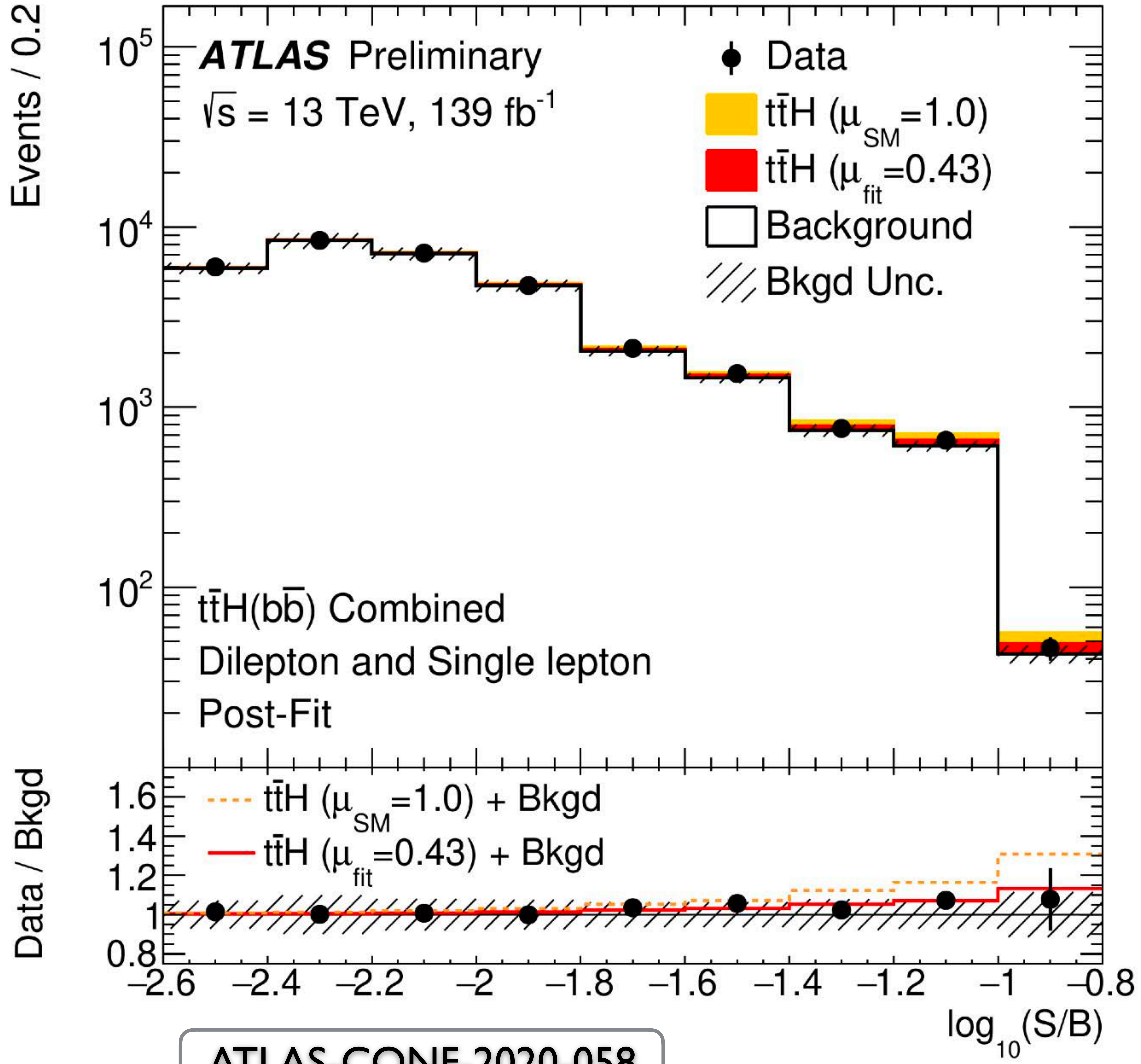


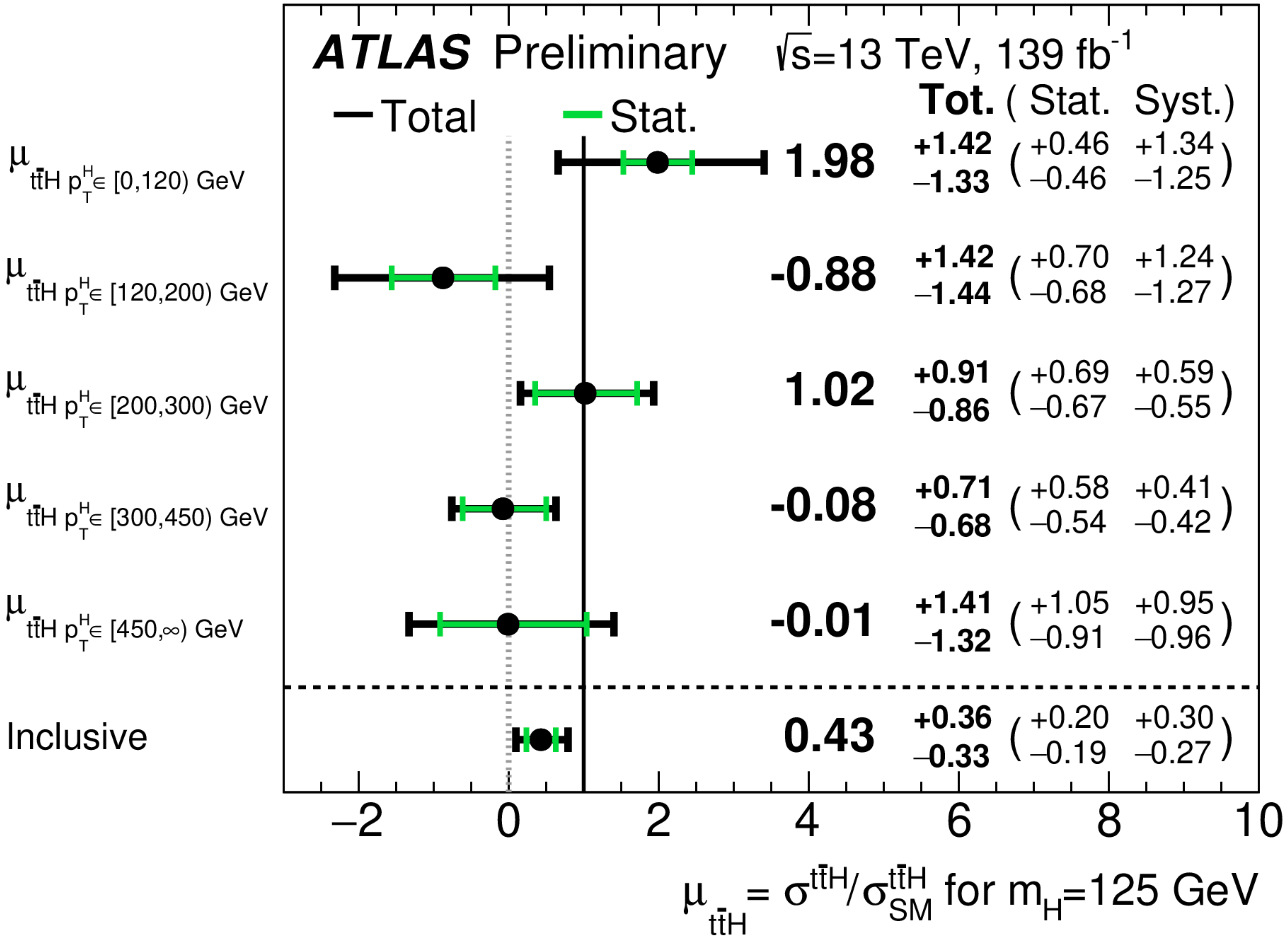
ATLAS-CONF-2021-021

ttH, H → b$\bar{b}$



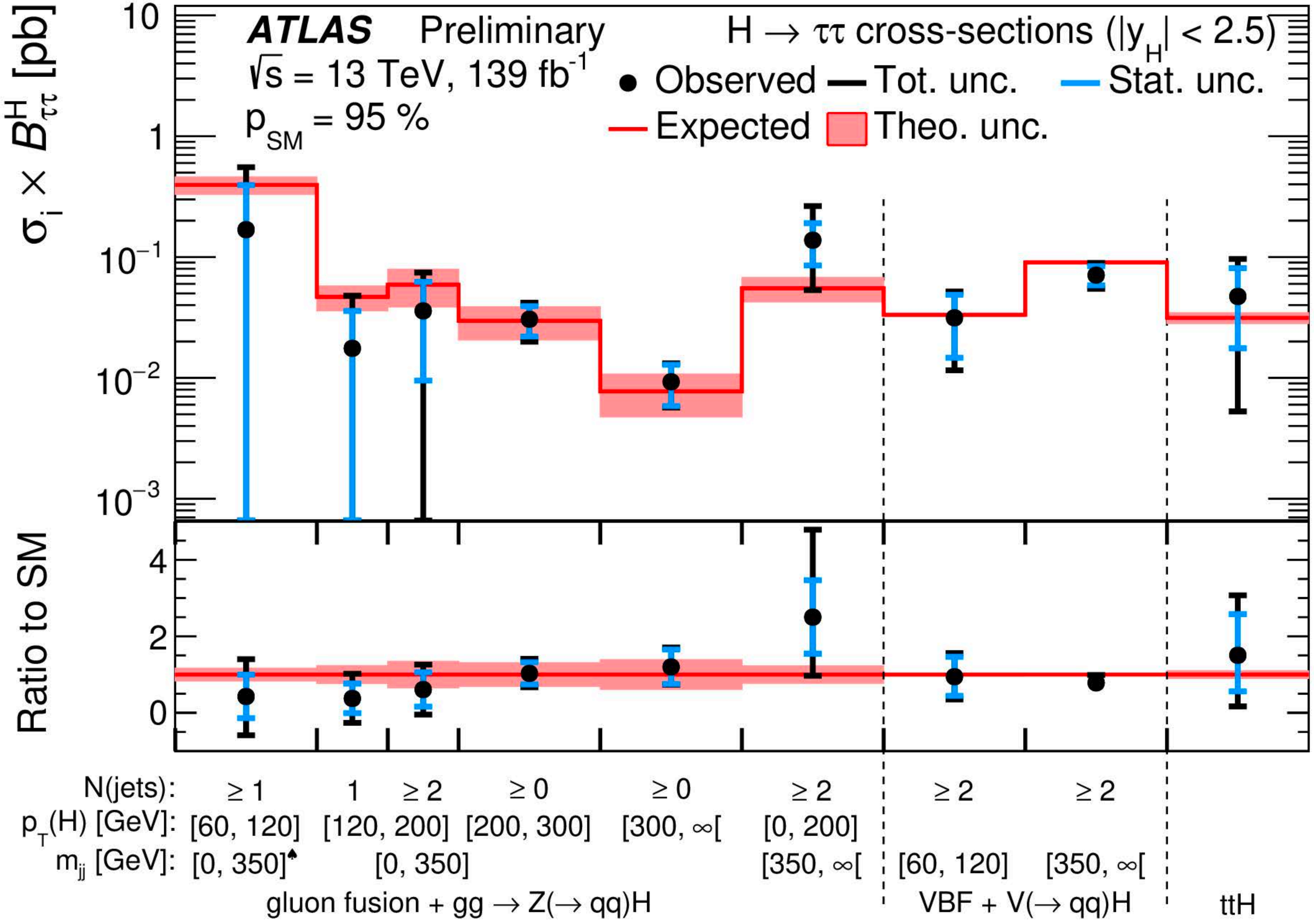
- Tree-level **top-Yukawa** measurement
  - Difficult topology, many objects in final state
  - Very difficult to predict and model dominant ttbb background
  - Employ machine learning; measure p_T(H)
  - Observed (expected) significance: **1.3 (3.0)** σ





ATLAS-CONF-2020-058

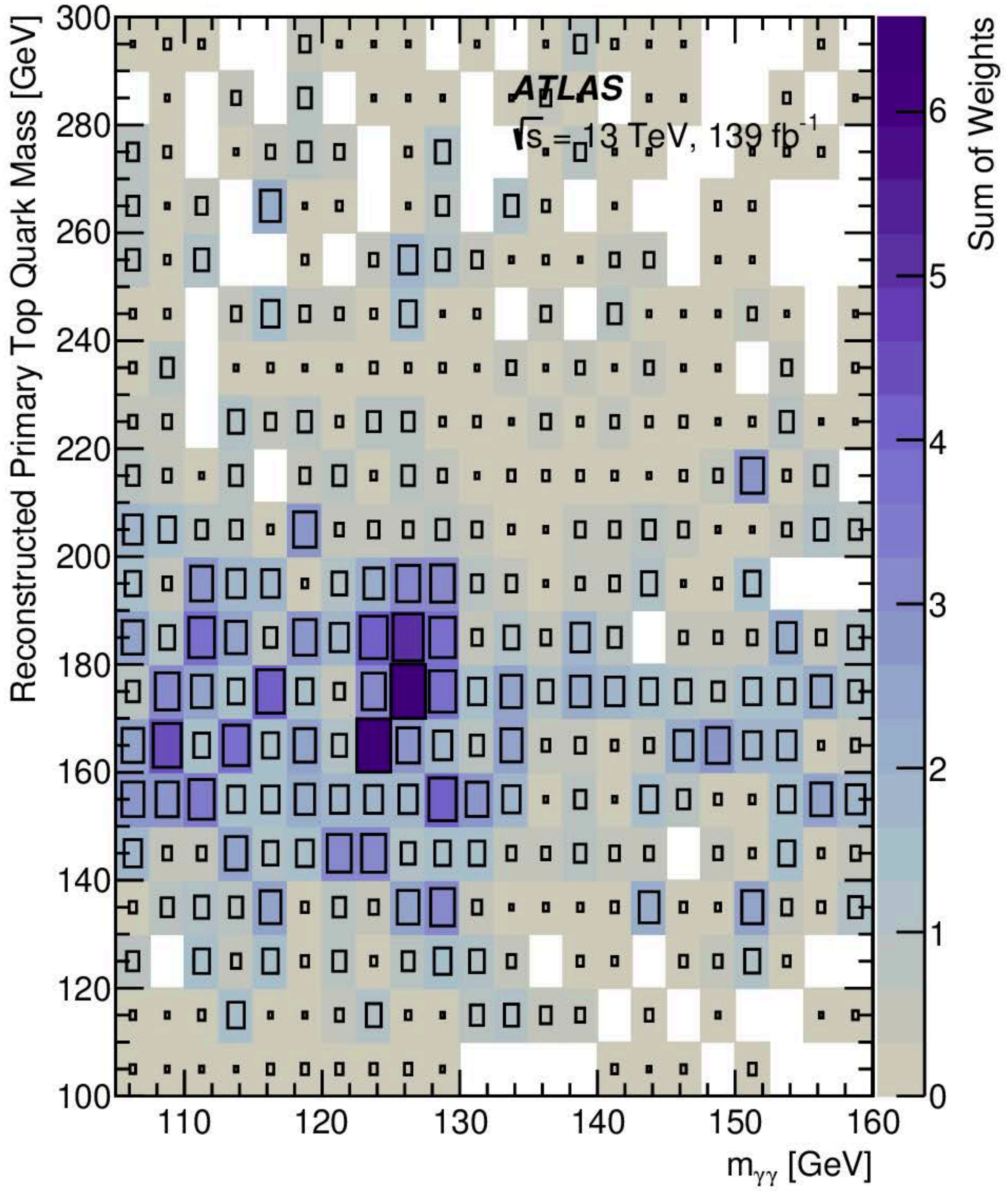
$H \to \tau\tau$

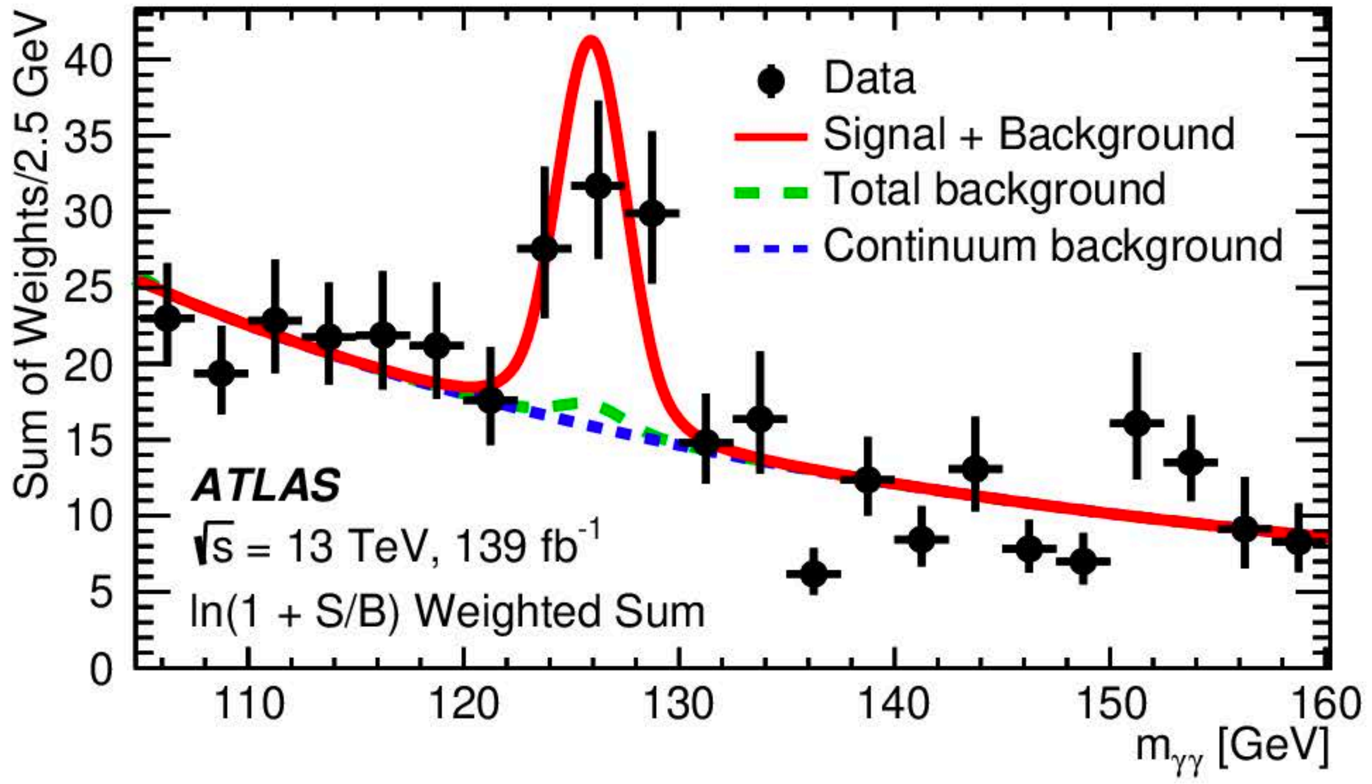


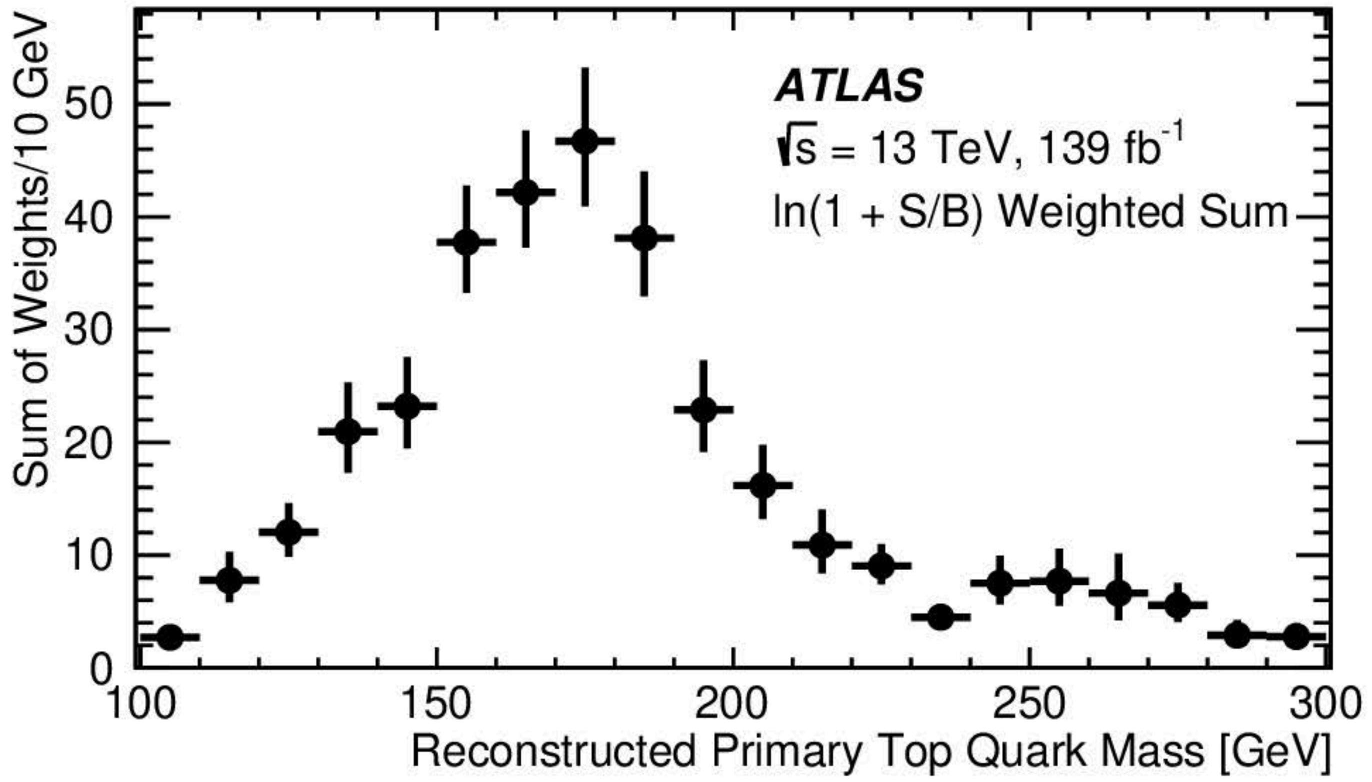
ATLAS-CONF-2021-044

CP Measurement in ttH Production with H → $\gamma\gamma$

- Expect ~**160 events** in 139 fb^{-1}
- Results:
  - Signal strength: $\mu = 1.4 \pm 0.4$ (stat.) $\pm$ 0.2 (sys.)
  - Significance: **5.2 σ**
  - **tH** rate < **12 × SM** @ 95% C.L.



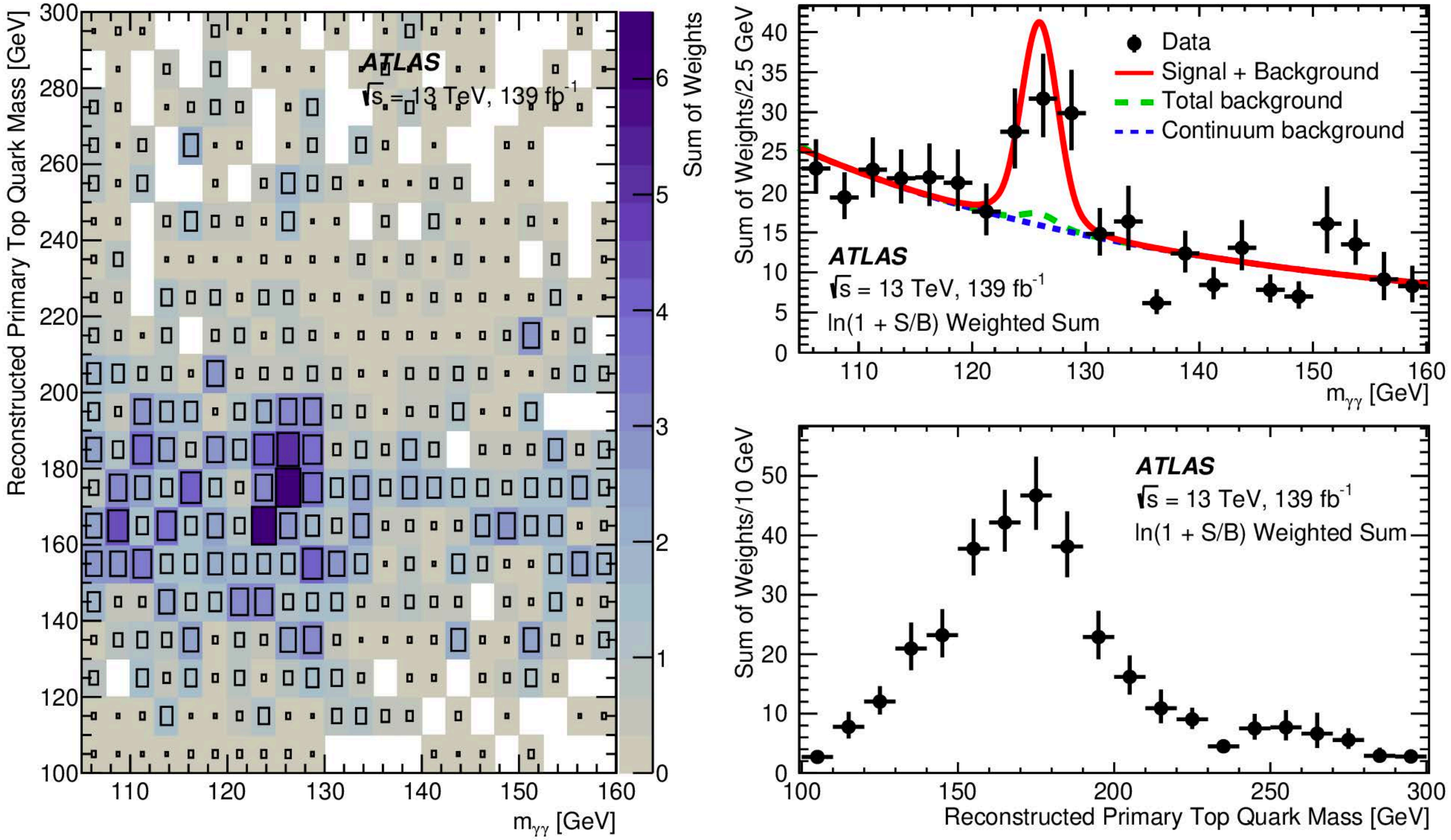




Phys. Rev. Lett. 125 (2020) 061802

CP Measurement in ttH Production with H → γγ

- Expect ~**160 events** in 139 fb^{-1}
- Results:
  - Signal strength:
    $\mu = 1.4 \pm 0.4\ \text{(stat.)} \pm 0.2\ \text{(sys.)}$
  - Significance: **5.2 σ**
  - **tH** rate < **12 × SM** @ 95% C.L.



- Parametrize ttH coupling:

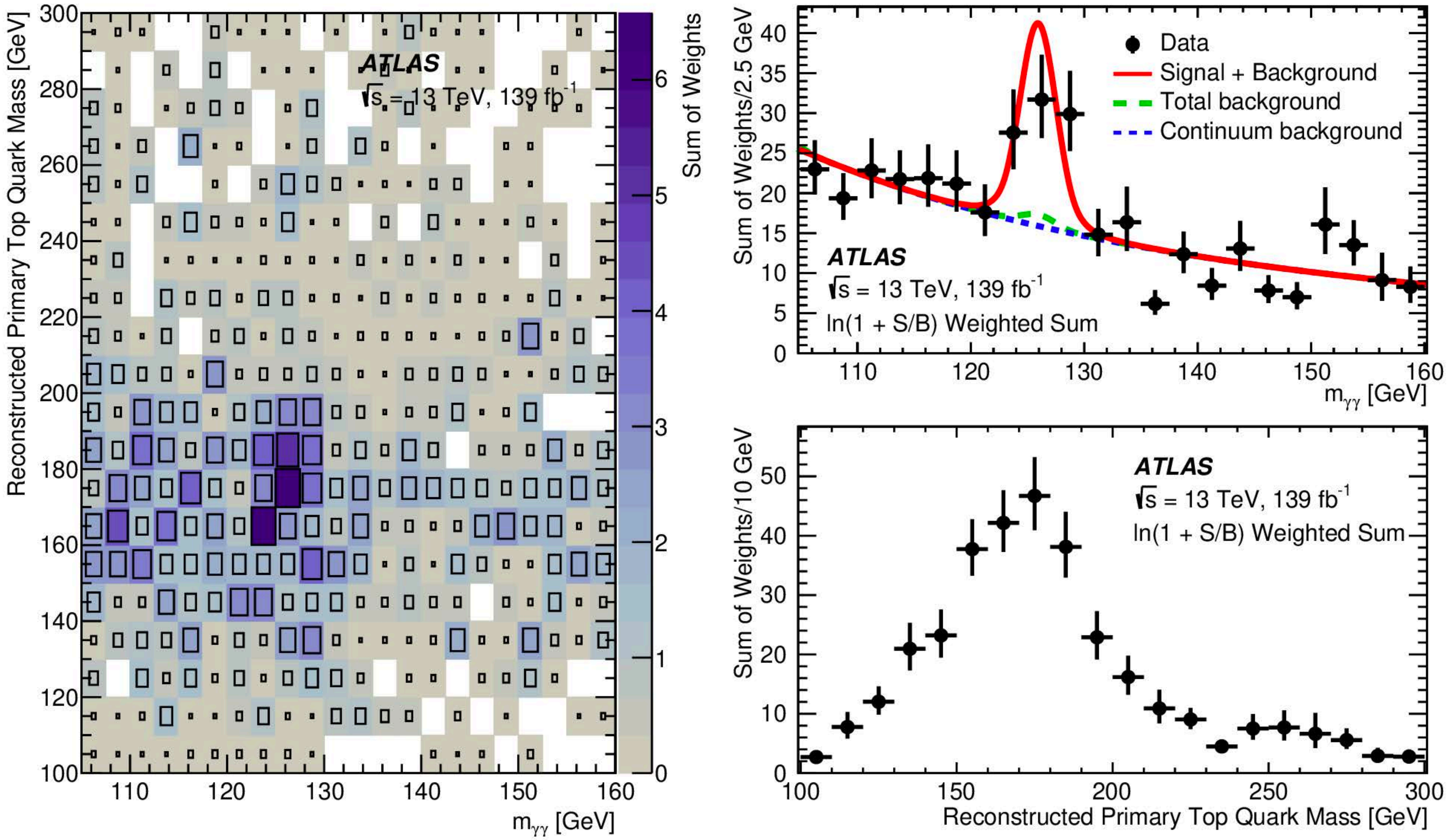
$$\mathcal{L} = -\frac{m_t}{v}\left\{\bar{\psi}_t \kappa_t \left[\cos(\alpha) + \mathrm{i}\sin(\alpha)\gamma_5\right]\psi_t\right\} H$$

- SM ttH coupling: CP-even (**α**=0)

Phys. Rev. Lett. 125 (2020) 061802

CP Measurement in ttH Production with H → γγ

- Expect ~**160 events** in 139 fb^{-1}
- Results:
  - Signal strength: $\mu = 1.4 \pm 0.4$ (stat.) $\pm$ 0.2 (sys.)
  - Significance: **5.2 σ**
  - **tH** rate < **12 × SM** @ 95% C.L.



- Parametrize ttH coupling:

$$\mathcal{L} = -\frac{m_t}{v}\left\{\bar{\psi}_t \kappa_t \left[\cos(\alpha) + \mathrm{i}\sin(\alpha)\gamma_5\right]\psi_t\right\} H$$

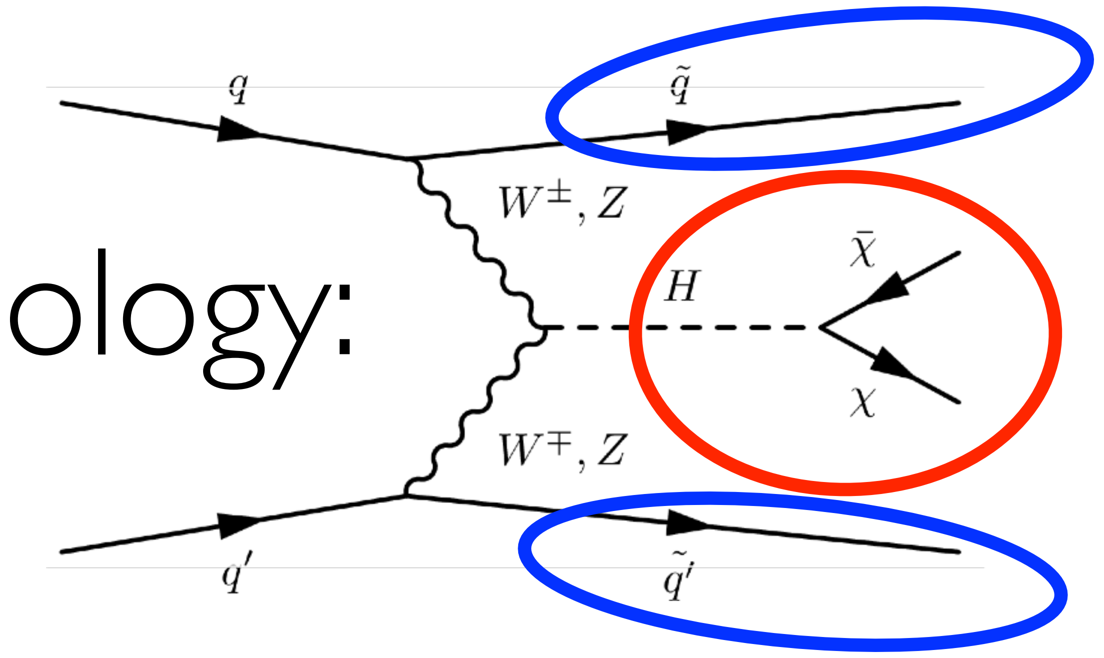
- SM ttH coupling: CP-even (**α**=0)

- Results:
  - **|α| > 43°** excluded (95% C.L.)
  - Pure CP-odd coupling excluded at **3.9 σ**

Phys. Rev. Lett. 125 (2020) 061802

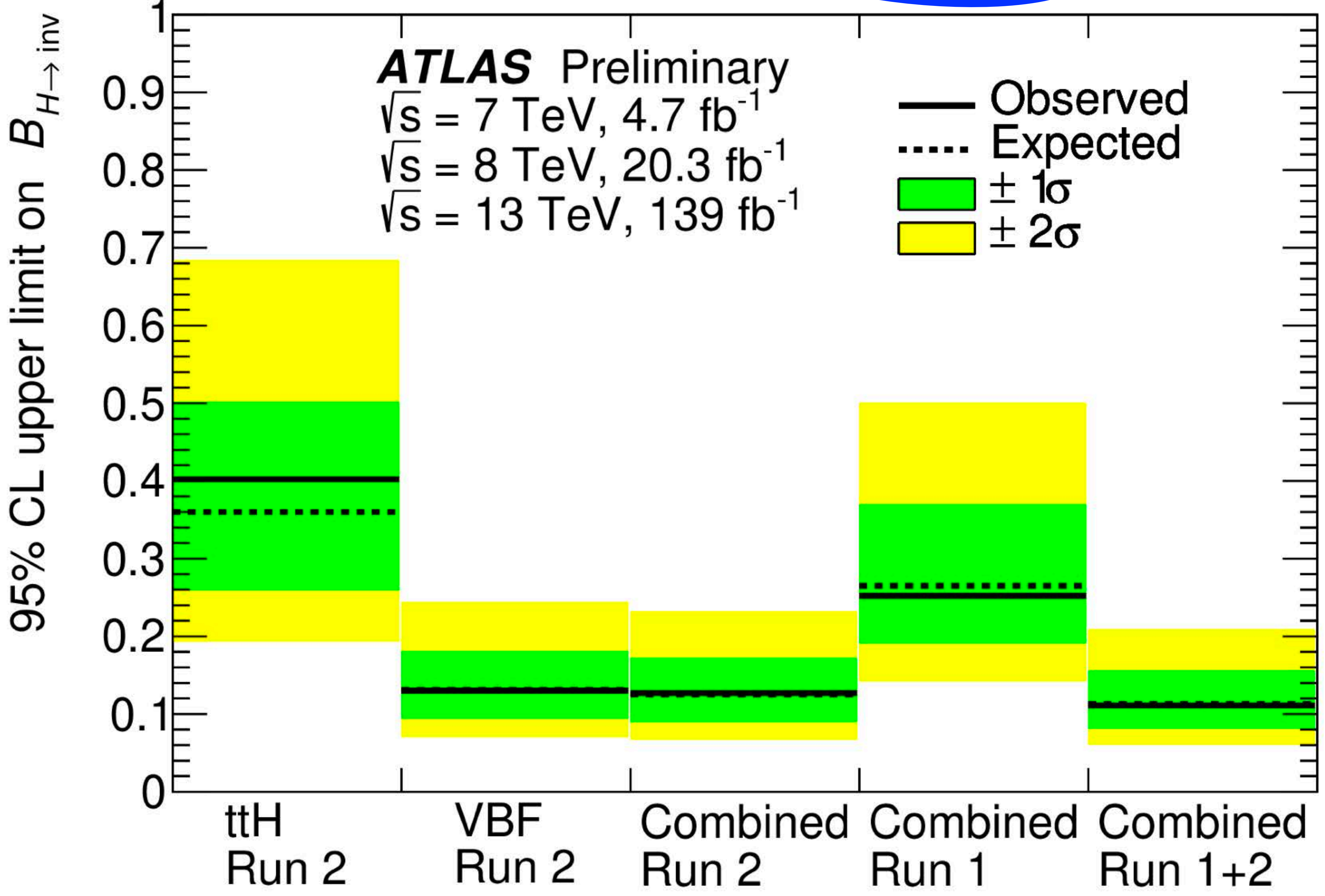
Invisible Decays of the Higgs Boson

- VBF topology:



2 jets with spatial separation

Missing transverse energy

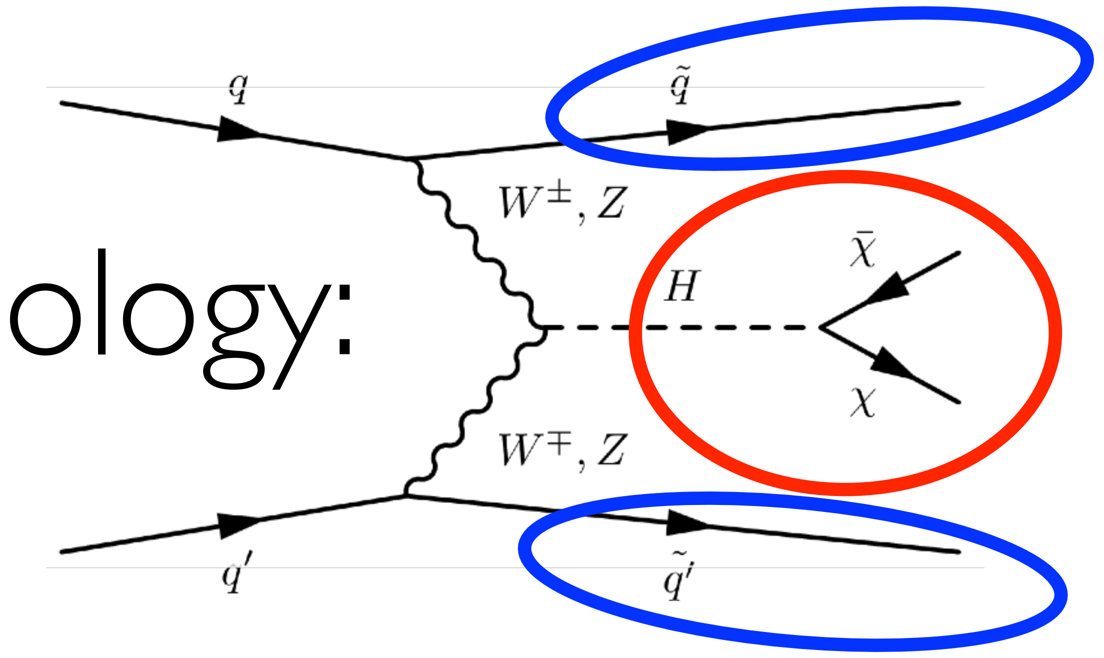


Upper limit BR(H → invisible): **<0.11** @ 95% C.L.

ATLAS-CONF-2020-052

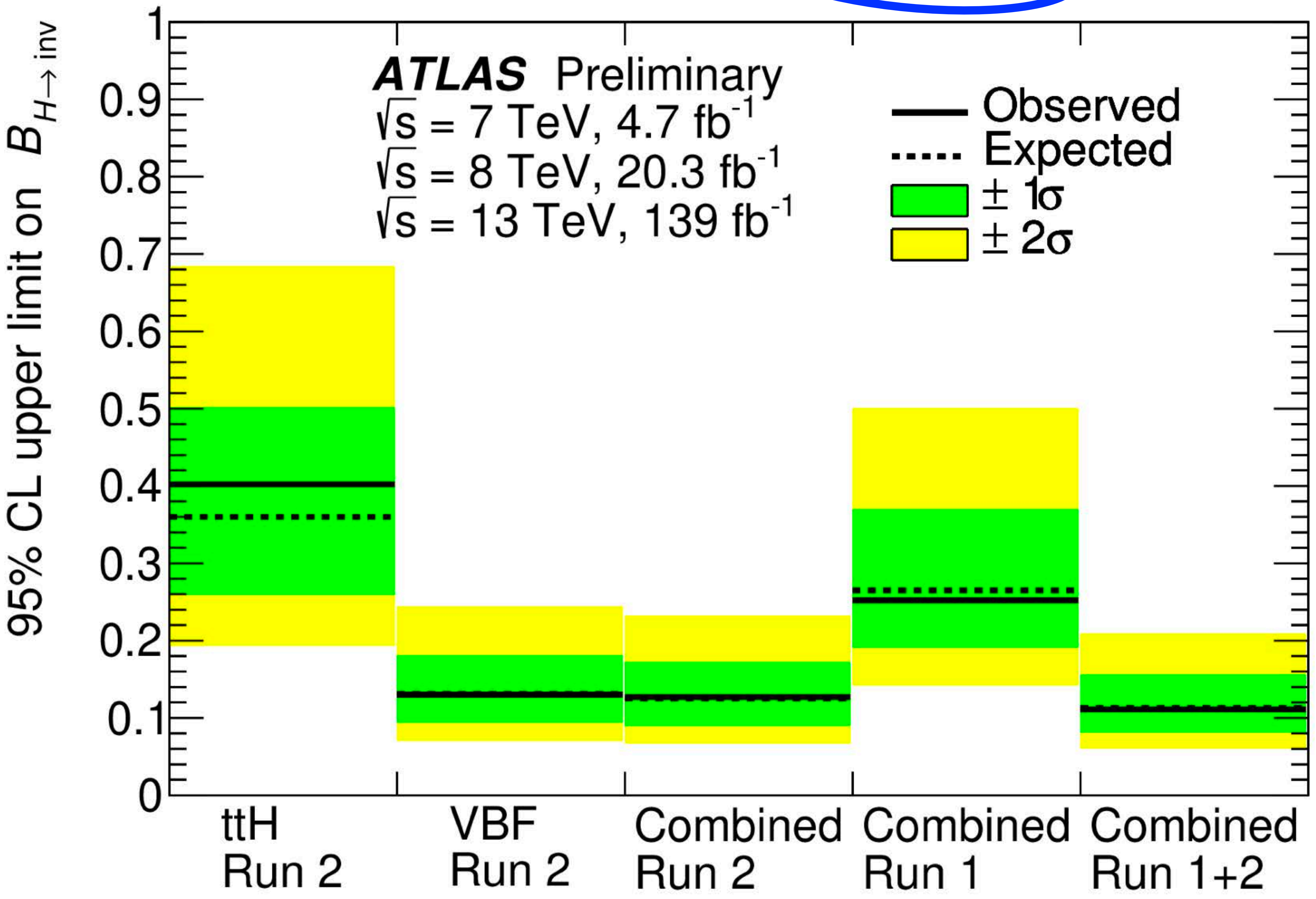
Invisible Decays of the Higgs Boson

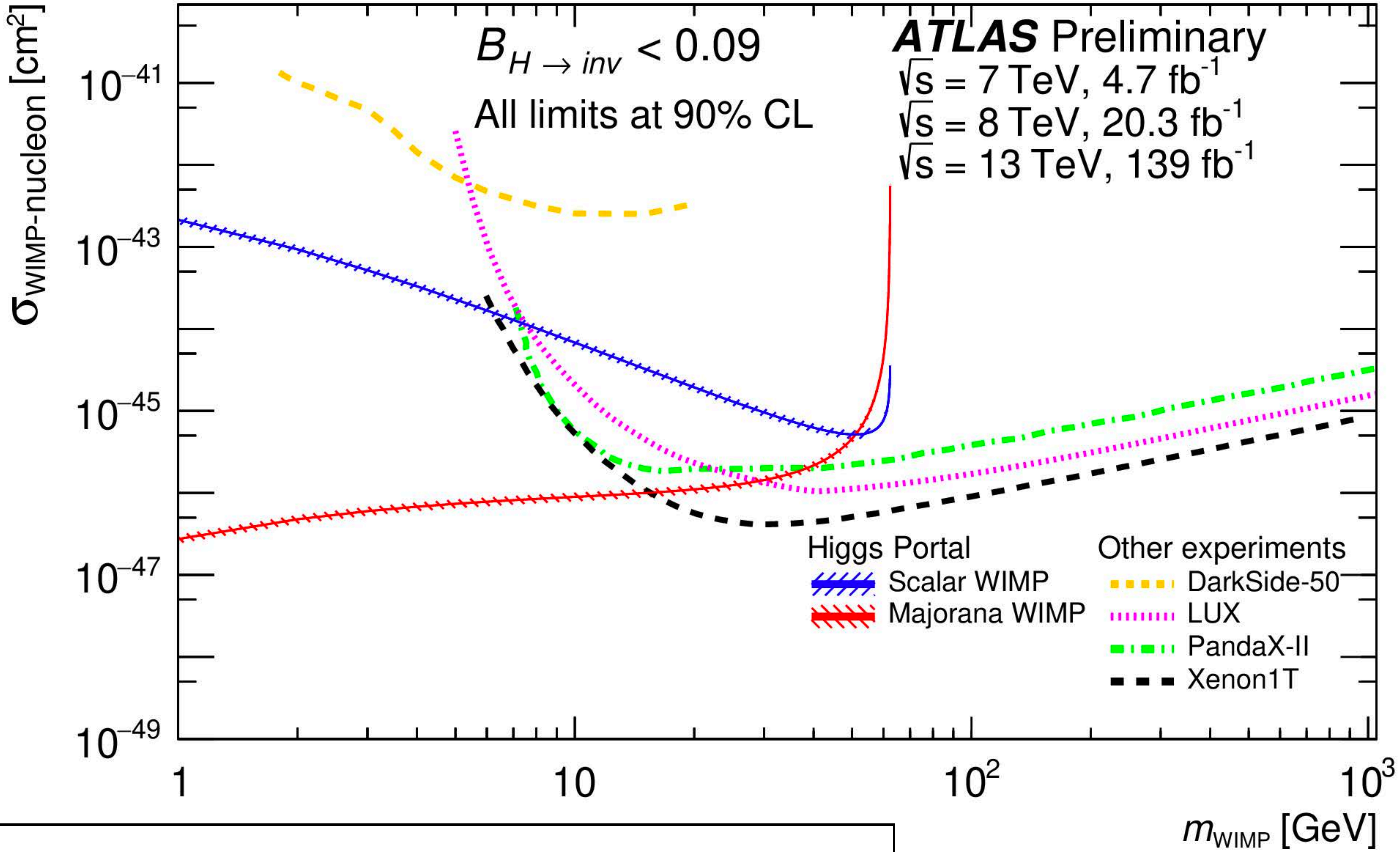
- VBF topology:



2 jets with spatial separation

Missing transverse energy



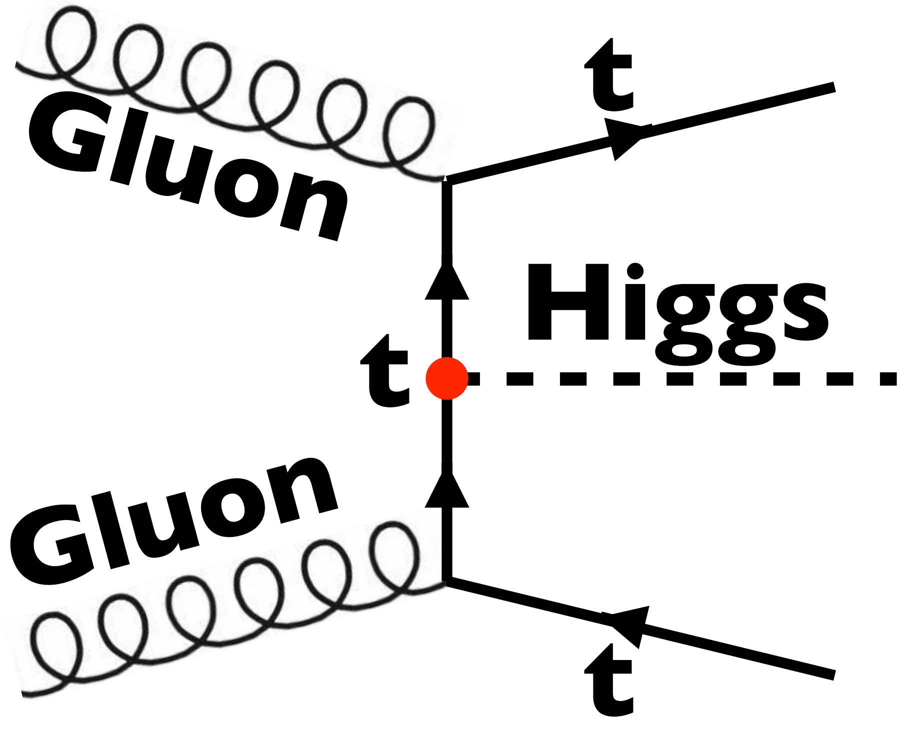


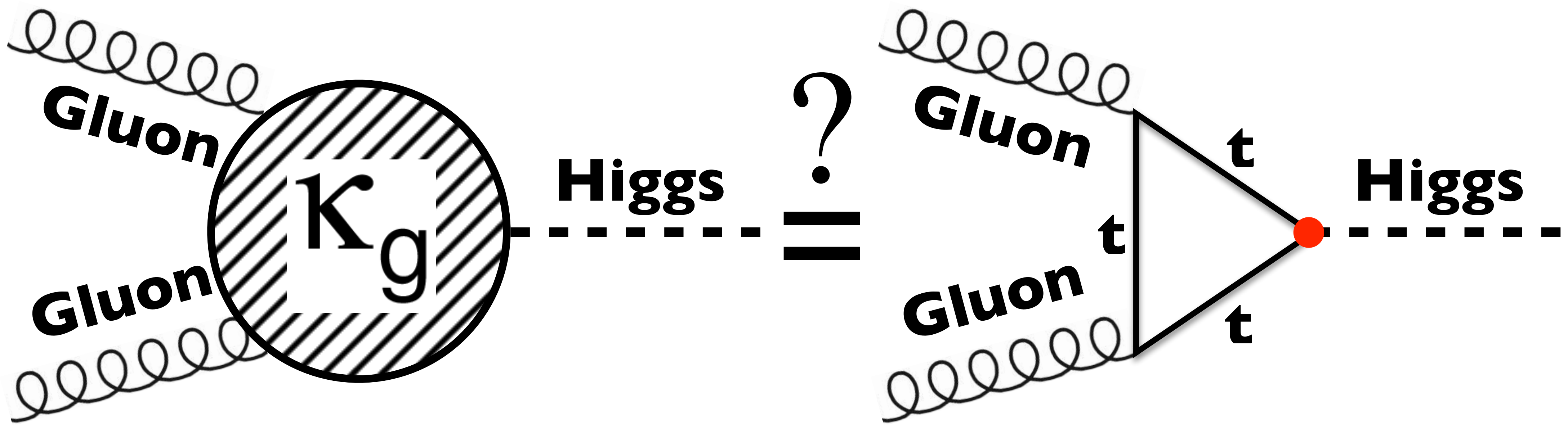
Upper limit BR(H → invisible): **<0.11** @ 95% C.L.

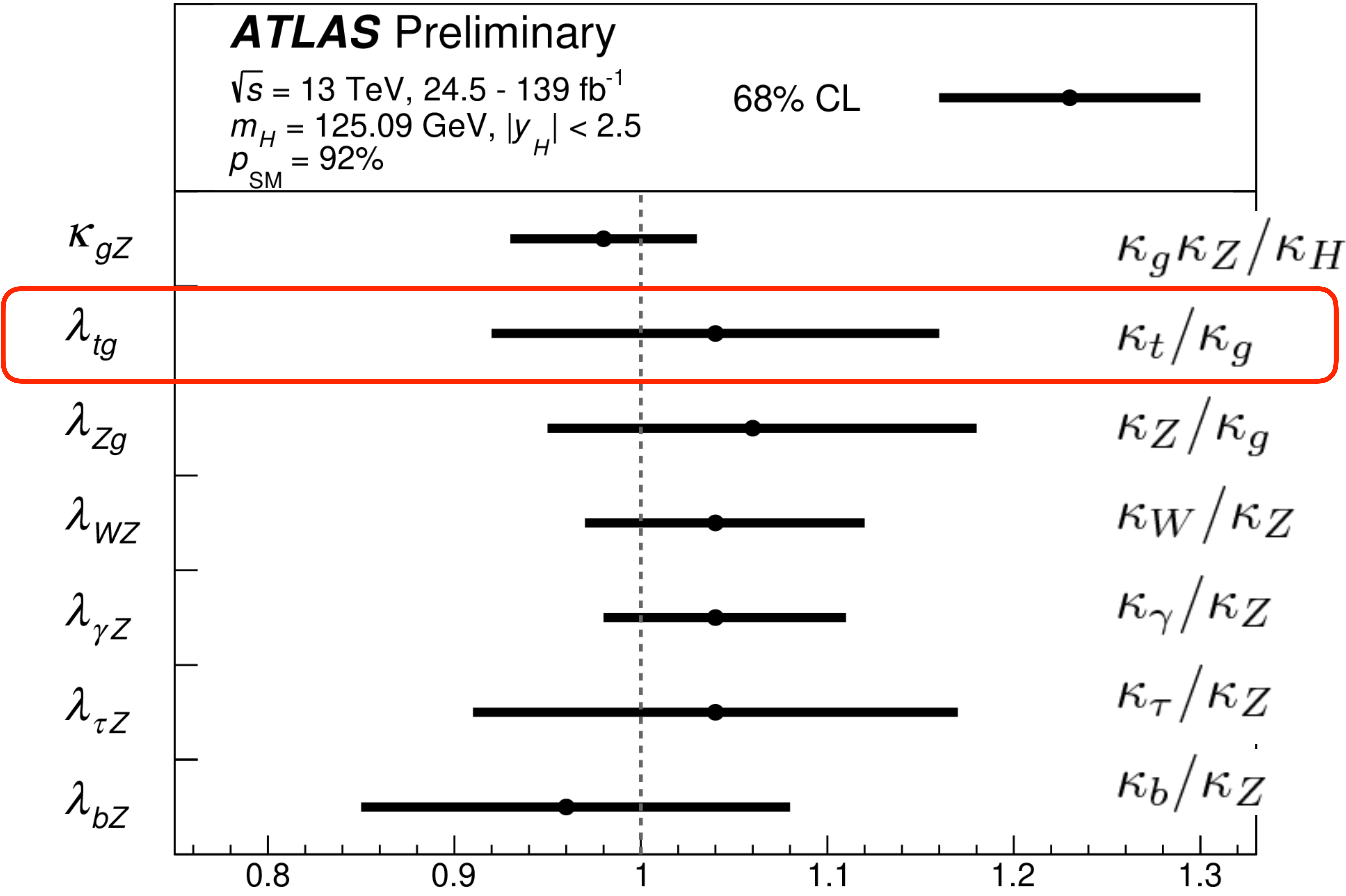
ATLAS-CONF-2020-052

Ratio of Coupling Modifiers

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







ATLAS-CONF-2020-027

Effective Field Theory

- Taylor expand SM in (E, vev)/Λ:

energy scale
of the process

energy scale of new physics

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda_i}\mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda_i^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(7)}}{\Lambda_i^3}\mathcal{O}_i^{(7)} + \sum_i \frac{c_i^{(8)}}{\Lambda_i^4}\mathcal{O}_i^{(8)} + \ldots$$

Wilson coefficients
= free parameters of the theory

operators from SM fields with higher mass dimension
(Lorentz invariance, gauge invariance, locality)

Graphics courtesy of Brian Moser at Higgs 2020

Effective Field Theory

- Taylor expand SM in (E, vev)/Λ:

violate L,
some violate B,
high suppression

further suppressed

19 parameters

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda_i} \mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda_i^2} \mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(7)}}{\Lambda_i^3} \mathcal{O}_i^{(7)} + \sum_i \frac{c_i^{(8)}}{\Lambda_i^4} \mathcal{O}_i^{(8)} + \ldots$$

1 operator type
(Weinberg operator)

Majorana ν masses
(m_ν small -> Λ_i high)

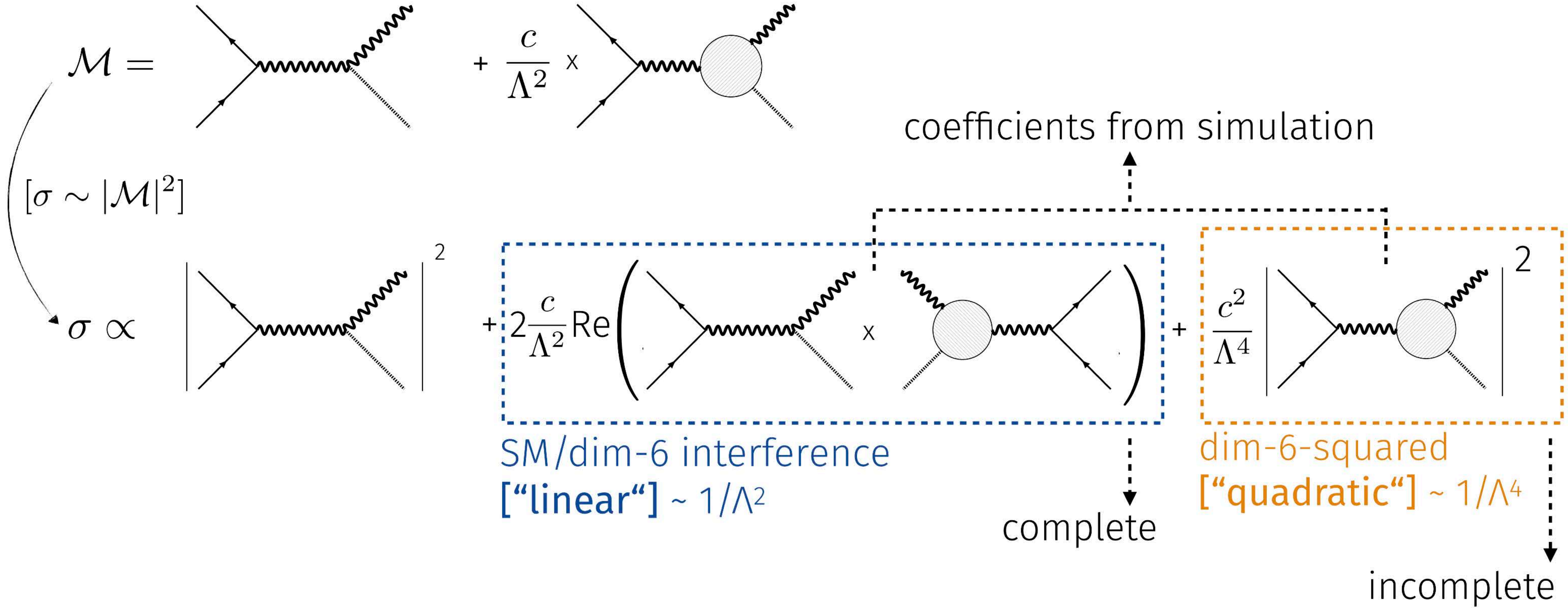
2499 parameters with ΔL=ΔB=0
+ O(300) with ΔL=ΔB=1 ⟶ proton decay -> Λ_i high

↓

76 assuming $U(3)^5$ flavor symmetry

Graphics courtesy of Brian Moser at Higgs 2020

From Lagrangian to Observables



coefficients from simulation

SM/dim-6 interference
[“linear“] ~ $1/\Lambda^2$

complete

dim-6-squared
[“quadratic“] ~ $1/\Lambda^4$

incomplete

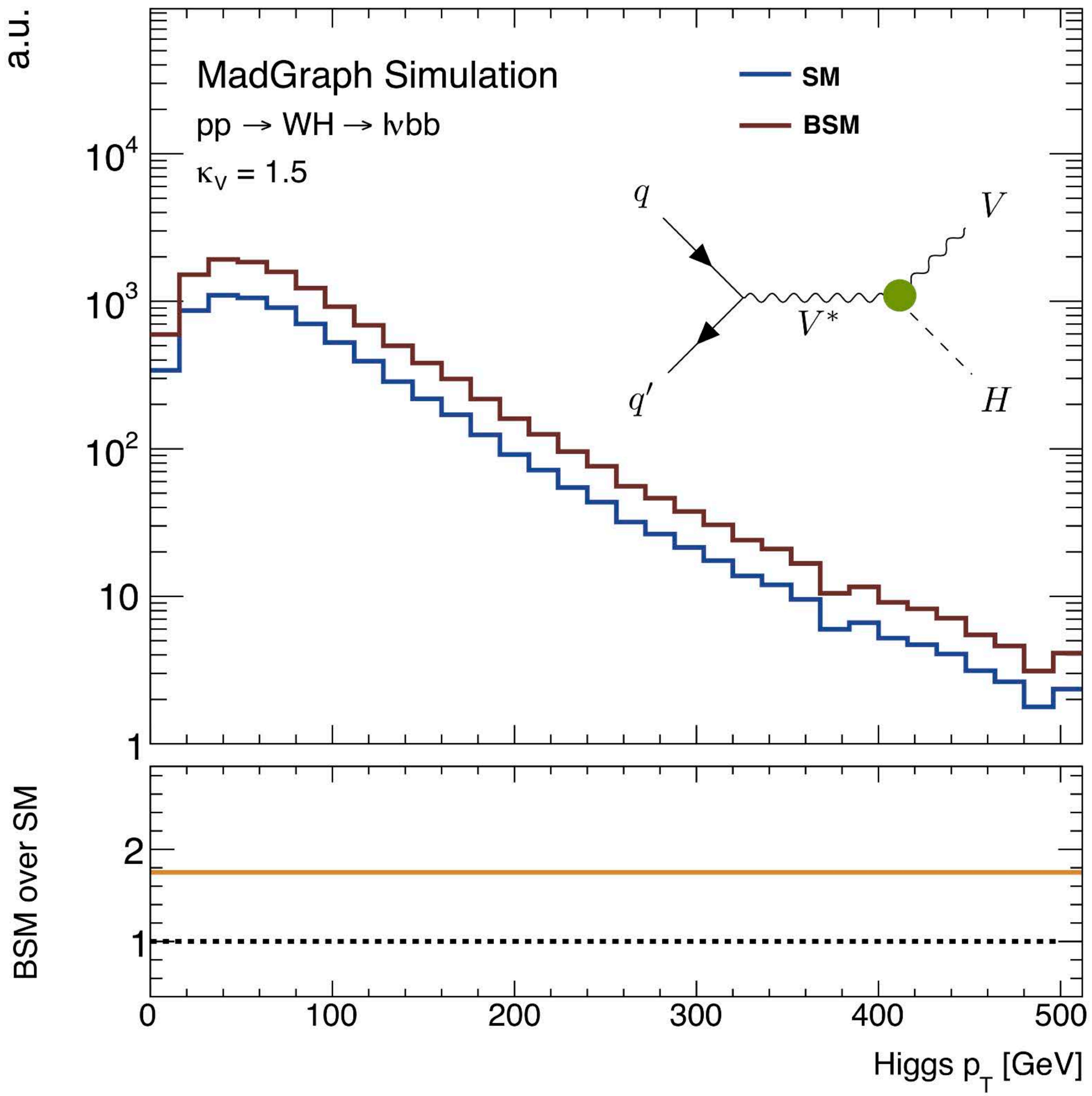
similar for
Higgs BR
(part. Γ / total Γ)
multiplicative
because of
narrow width

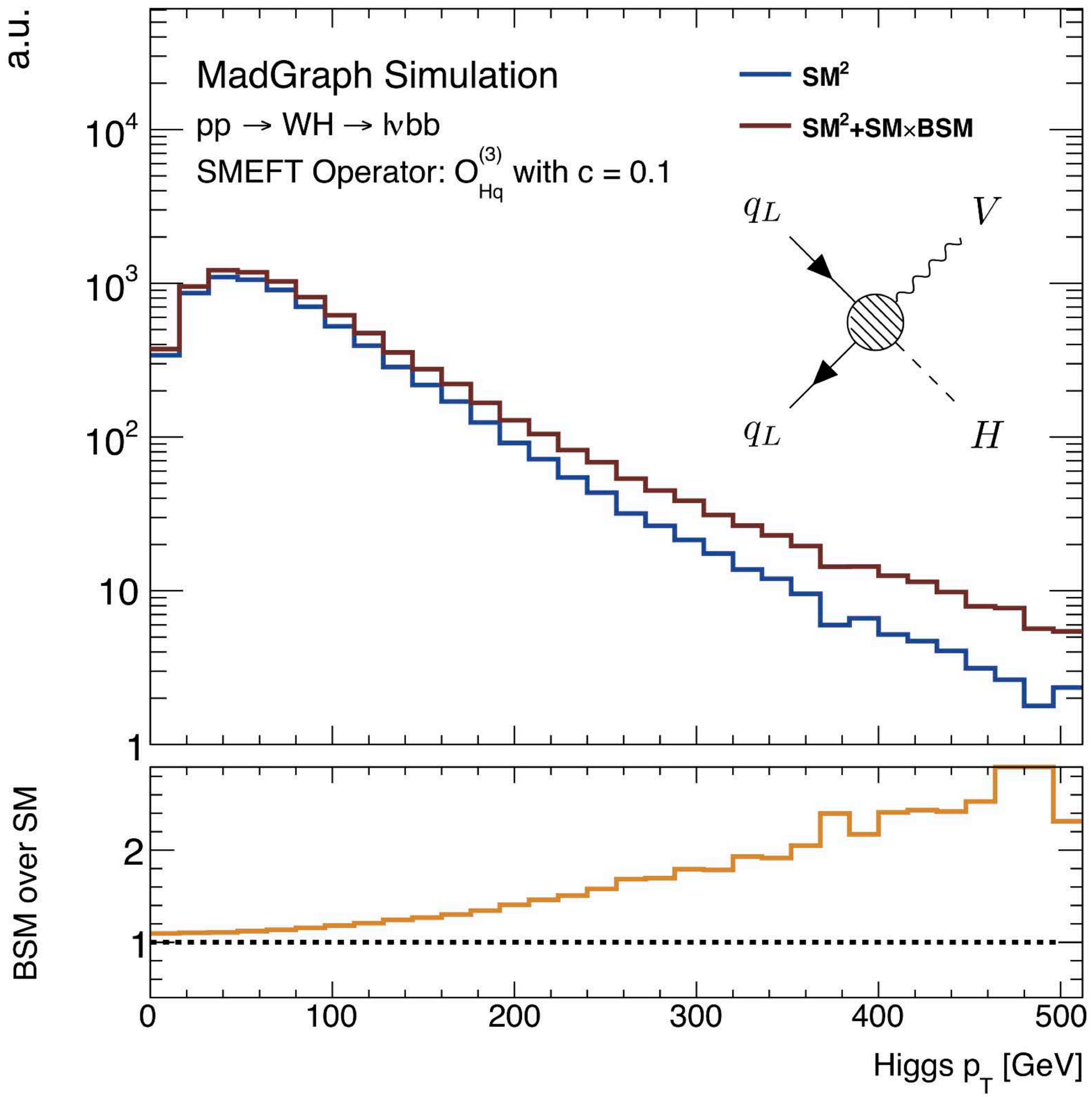
Graphics courtesy of Brian Moser at Higgs 2020

κ Framework vs. EFT Example

κ-framework: κ_V = 1.5

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

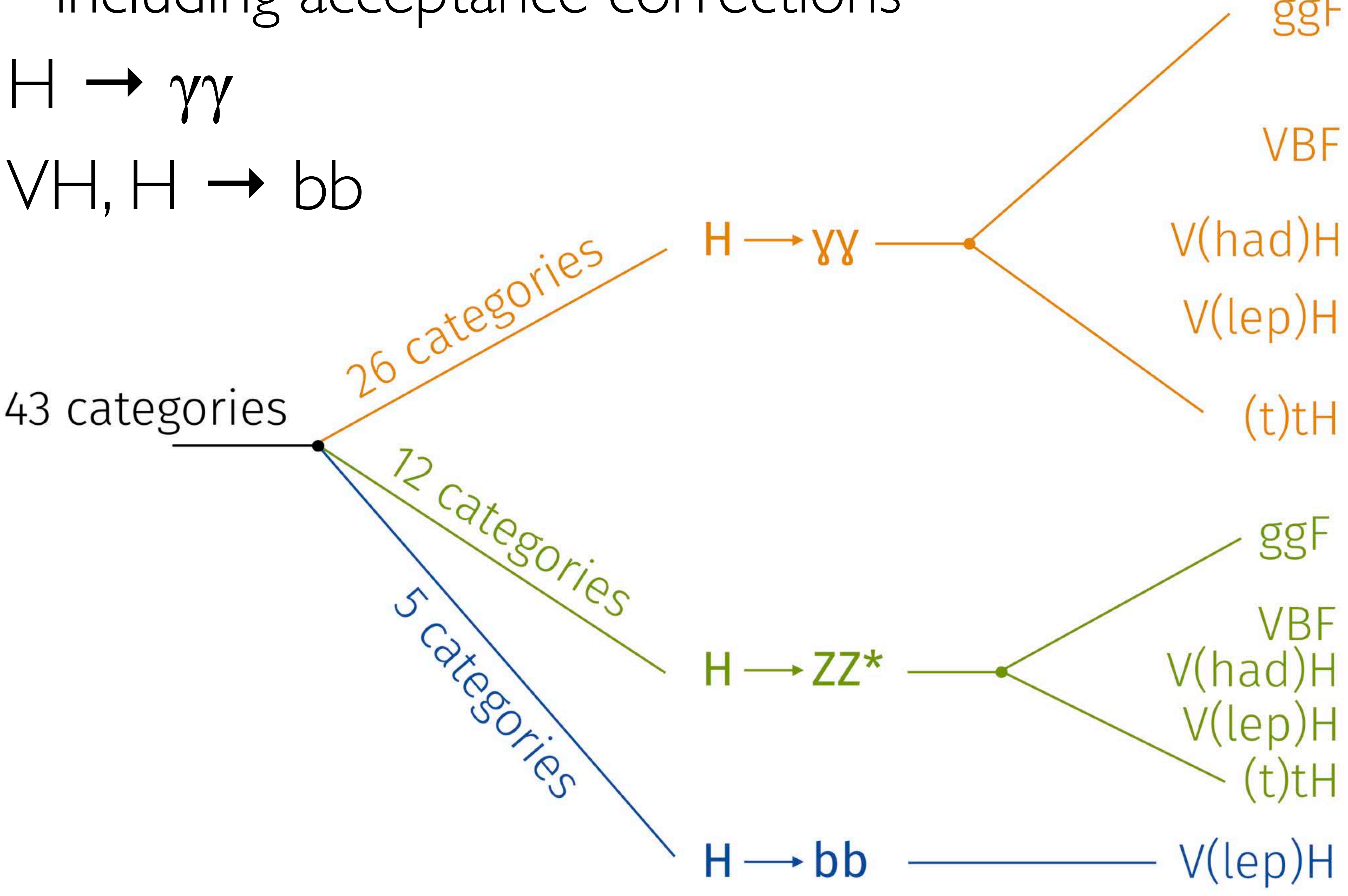




Graphics courtesy of Brian Moser at Higgs 2020

STXS for EFTs

- Use combined STXS measurement
  - $H \rightarrow ZZ^* \rightarrow 4\ell$
    - including acceptance corrections
  - $H \rightarrow \gamma\gamma$
  - VH, $H \rightarrow bb$



43 categories

26 categories

H → γγ

ggF

VBF

V(had)H

V(lep)H

(t)tH

12 categories

H → ZZ*

ggF

VBF

V(had)H

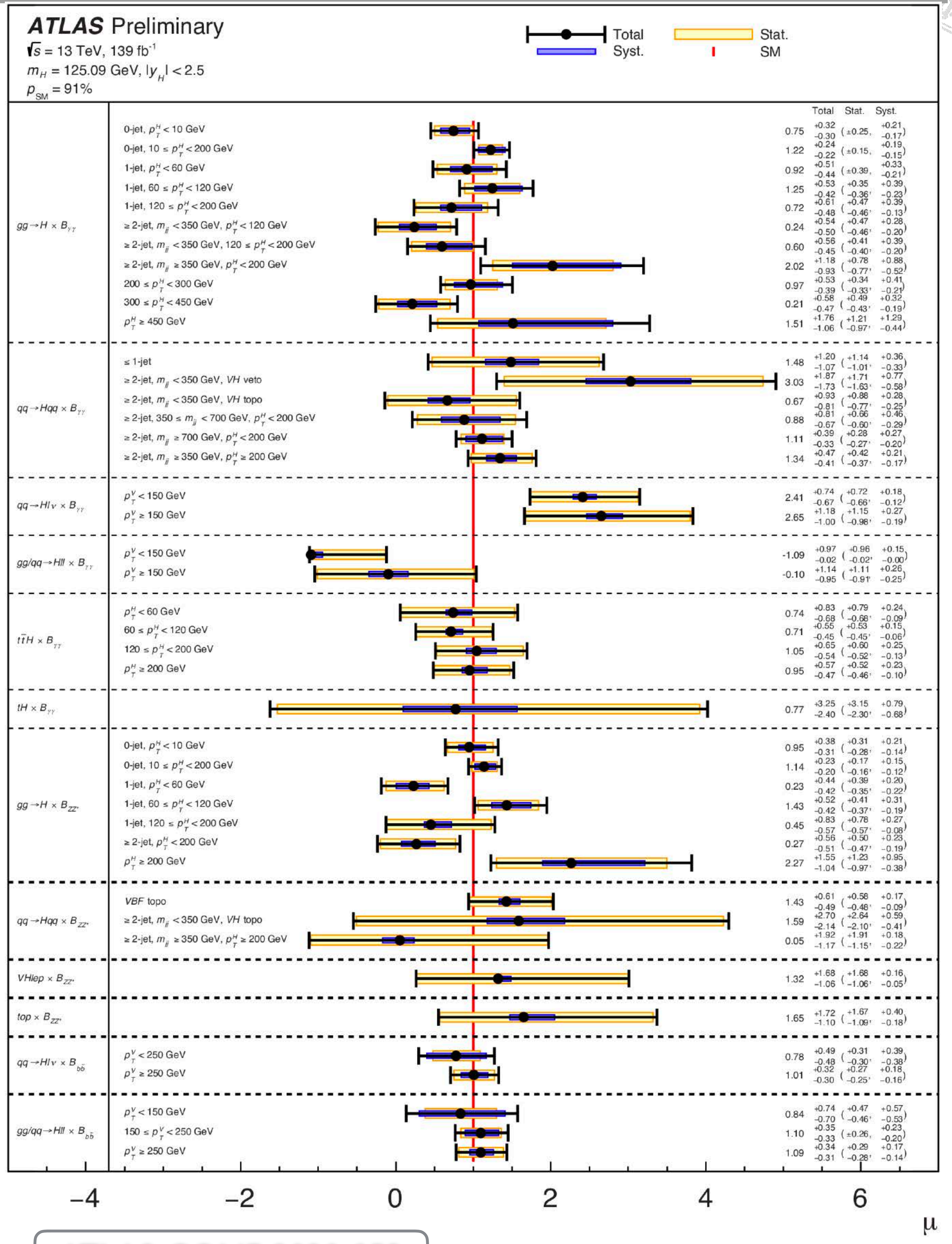
V(lep)H

(t)tH

5 categories

H → bb

V(lep)H



Graphics courtesy of Brian Moser at Higgs 2020

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Parametrizing STXS Measurements with EFTs

- Simulated with MadGraph using SMEFTSim package
  - Important loop contributions simulated with SMEFT@NLO

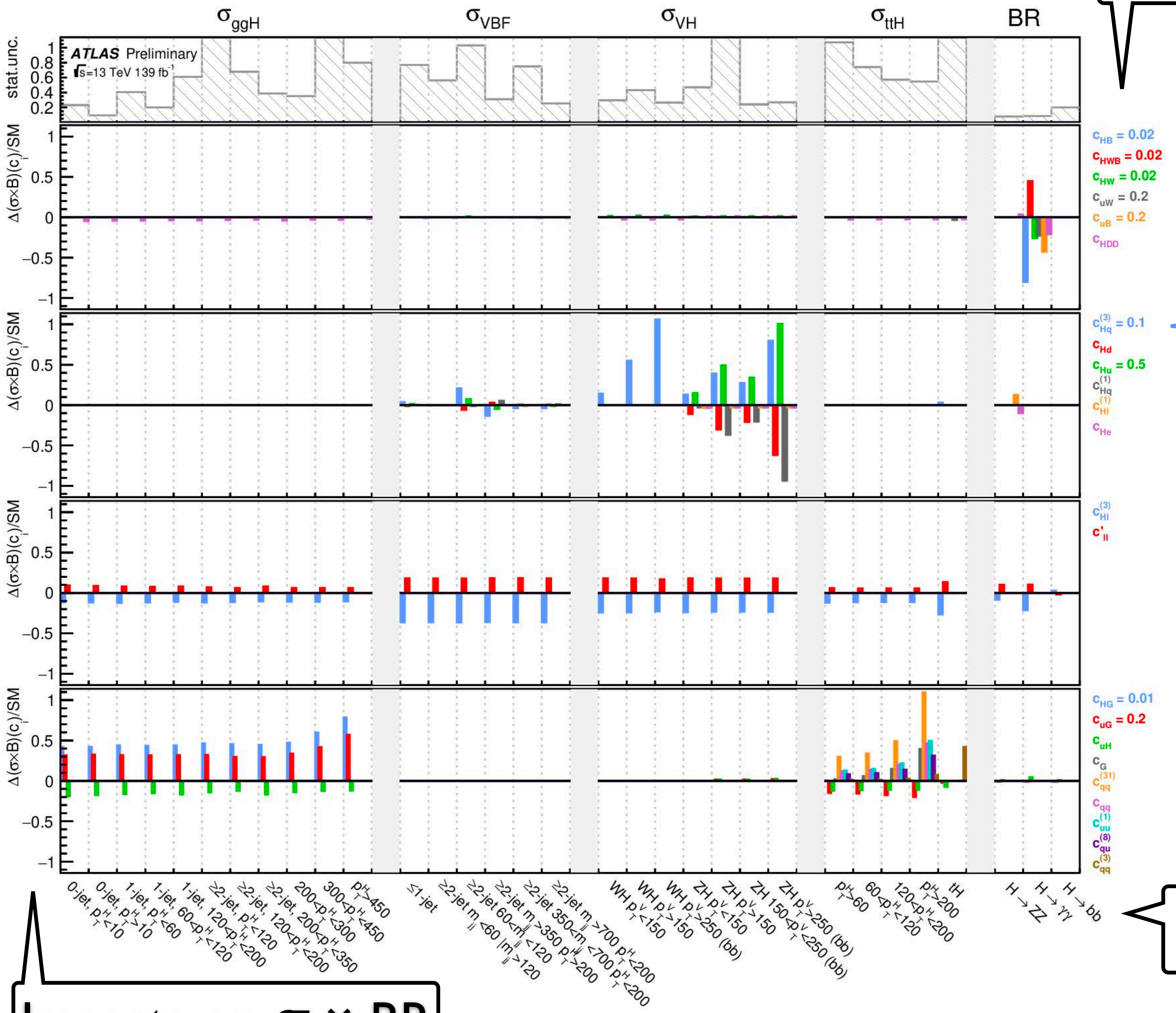
- Determine polynomials of Wilson coefficients for each process and STXS phase-space region
  - Obtain numerical values for a_i, b_{ij}, A_i, B_{ij},…

$$\mu = \frac{\sigma \times \mathrm{BR}(H \to ff)}{[\sigma \times \mathrm{BR}(H \to ff)]_{\mathrm{SM}}} = \overbrace{\frac{\sigma}{\sigma^{\mathrm{SM}}}}^{1 + a_i\ c_i + b_{ij}\ c_i c_j} \times \frac{\overbrace{\frac{\Gamma(H \to ff)}{[\Gamma(H \to ff)]_{\mathrm{SM}}}}^{1 + A_i^{ff}\ c_i + B_{ij}^{ff}\ c_i c_j}}{\underbrace{\frac{\Gamma(H)}{[\Gamma(H)]_{\mathrm{SM}}}}_{1 + A_i\ c_i + B_{ij}\ c_i c_j}}$$

Graphics courtesy of Brian Moser at Higgs 2020

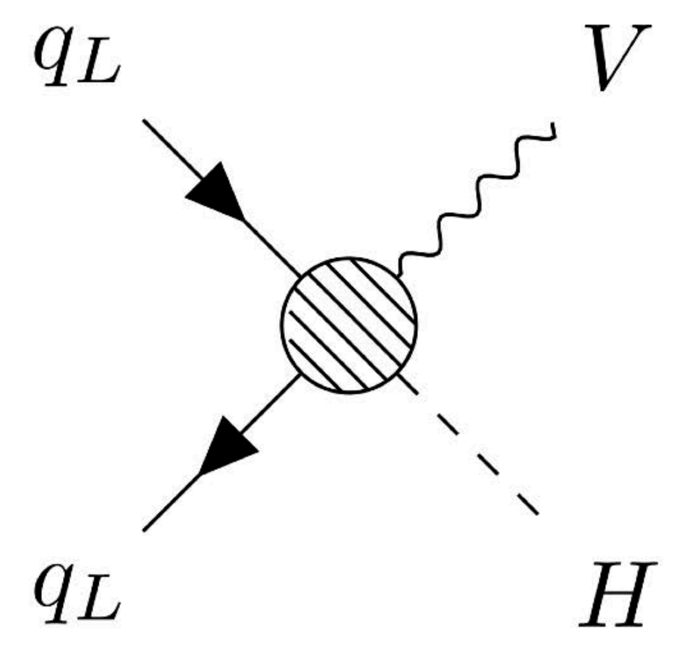
EFT Impact on Measurements

Wilson coefficients of “Warsaw” EFT basis



~STXS bins

Impacts on σ × BR



$$\mathcal{O}_{Hq}^{(3)} = (H^\dagger i \overset{\leftrightarrow}{D}{}^I{}_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$$

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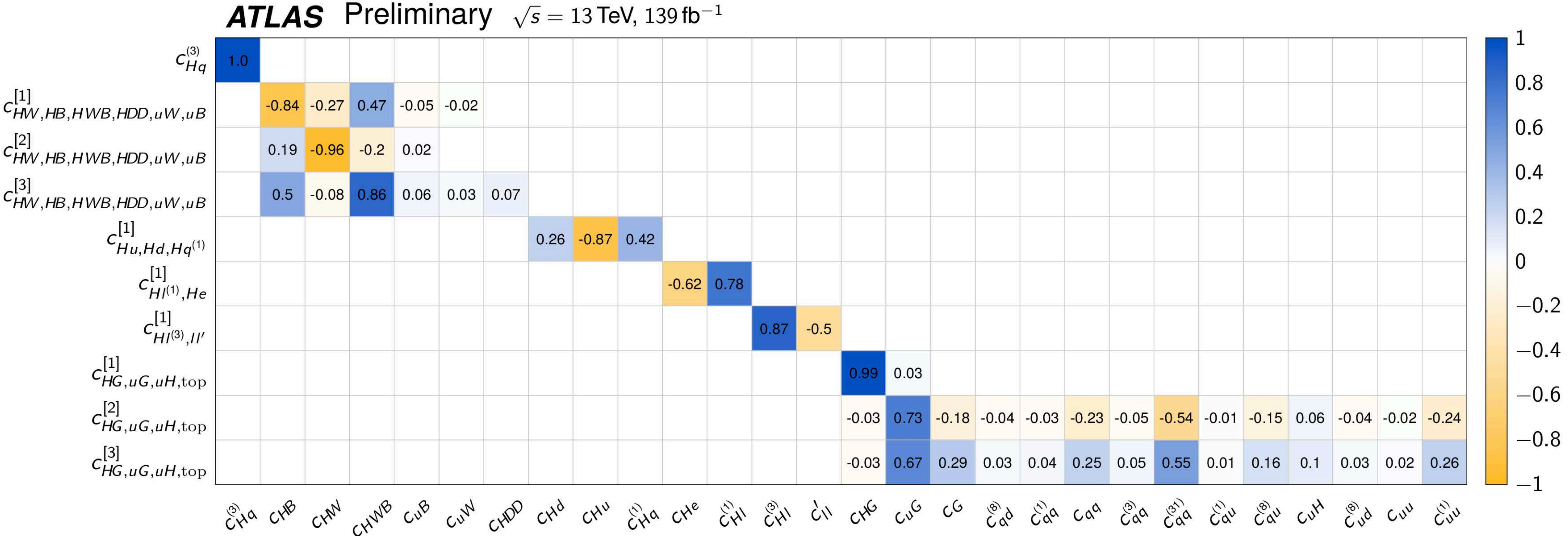
Reducing the Complexity

- Perform principal component analysis of covariance matrix
  - Group operators with similar effect; remove insensitive directions

⇒ Identify 10 most sensitive combinations to be fit simultaneously



	$c_{Hq}^{(3)}$	c_{HB}	c_{HW}	c_{HWB}	c_{uB}	c_{uW}	c_{HDD}	c_{Hd}	c_{Hu}	$c_{Hq}^{(1)}$	c_{He}	$c_{Hl}^{(1)}$	$c_{Hl}^{(3)}$	c'_{ll}	c_{HG}	c_{uG}	c_G	$c_{qd}^{(8)}$	$c_{qq}^{(1)}$	c_{qq}	$c_{qq}^{(3)}$	$c_{qq}^{(31)}$	$c_{qu}^{(1)}$	$c_{qu}^{(8)}$	c_{uH}	$c_{ud}^{(8)}$	c_{uu}	$c_{uu}^{(1)}$
$c_{Hq}^{(3)}$	1.0																											
$c_{HW,HB,HWB,HDD,uW,uB}^{[1]}$		-0.84	-0.27	0.47	-0.05	-0.02																						
$c_{HW,HB,HWB,HDD,uW,uB}^{[2]}$		0.19	-0.96	-0.2	0.02																							
$c_{HW,HB,HWB,HDD,uW,uB}^{[3]}$		0.5	-0.08	0.86	0.06	0.03	0.07																					
$c_{Hu,Hd,Hq^{(1)}}^{[1]}$								0.26	-0.87	0.42																		
$c_{Hl^{(1)},He}^{[1]}$											-0.62	0.78																
$c_{Hl^{(3)},ll'}^{[1]}$													0.87	-0.5														
$c_{HG,uG,uH,\mathrm{top}}^{[1]}$															0.99	0.03												
$c_{HG,uG,uH,\mathrm{top}}^{[2]}$															-0.03	0.73	-0.18	-0.04	-0.03	-0.23	-0.05	-0.54	-0.01	-0.15	0.06	-0.04	-0.02	-0.24
$c_{HG,uG,uH,\mathrm{top}}^{[3]}$															-0.03	0.67	0.29	0.03	0.04	0.25	0.05	0.55	0.01	0.16	0.1	0.03	0.02	0.26

Rotated fit basis

Warsaw basis

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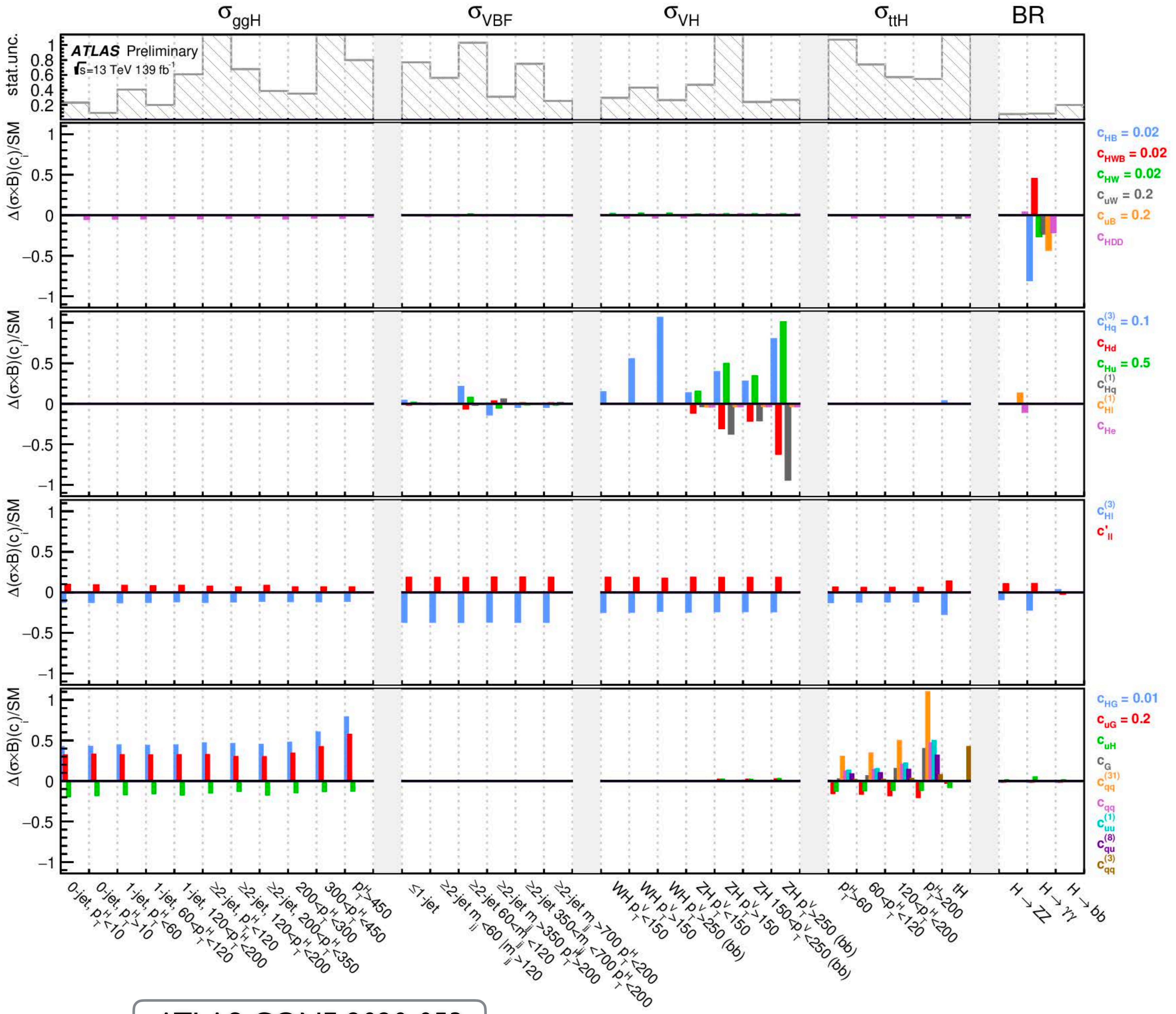
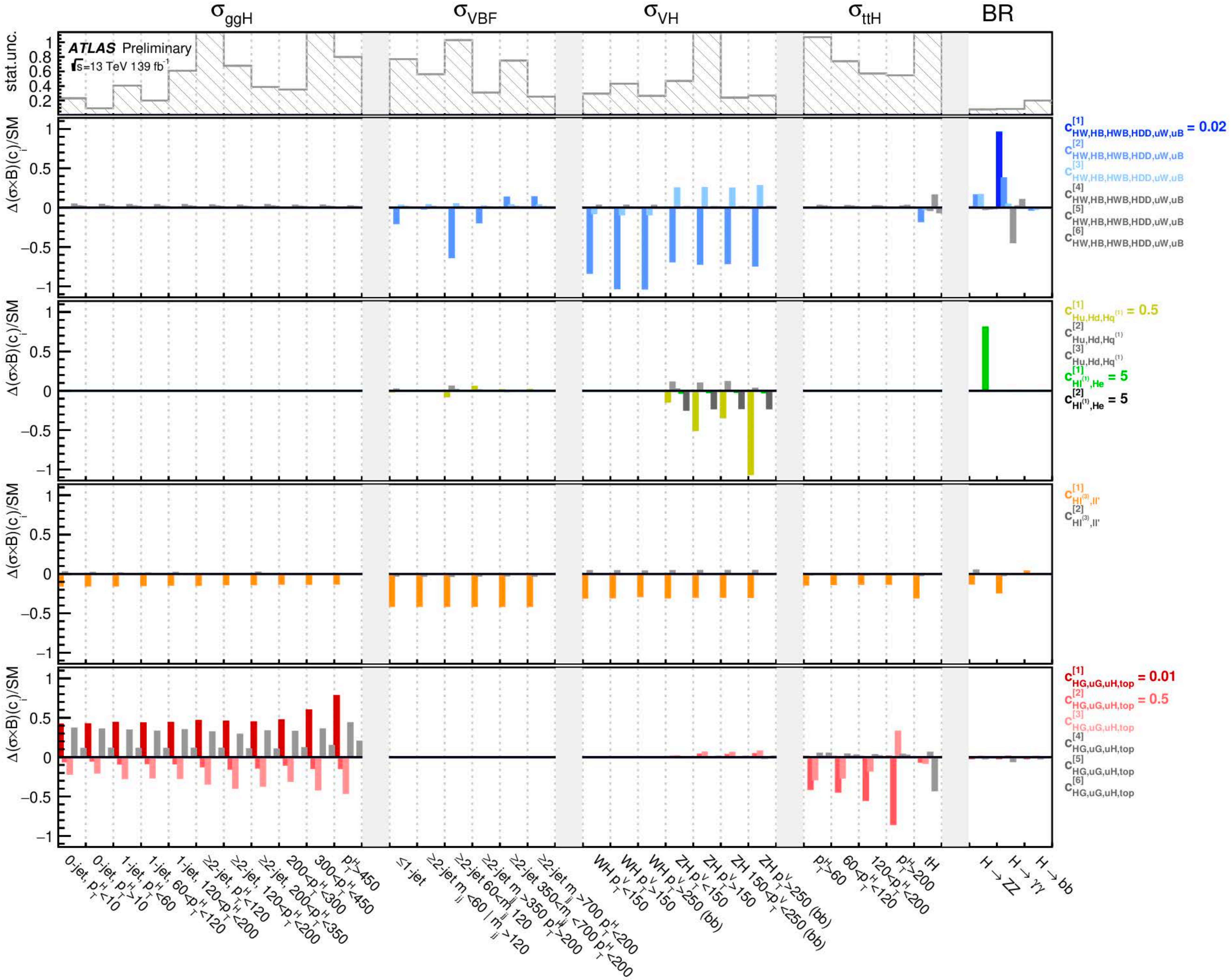
EFT impact on Measurements

Warsaw basis



Rotated fit basis



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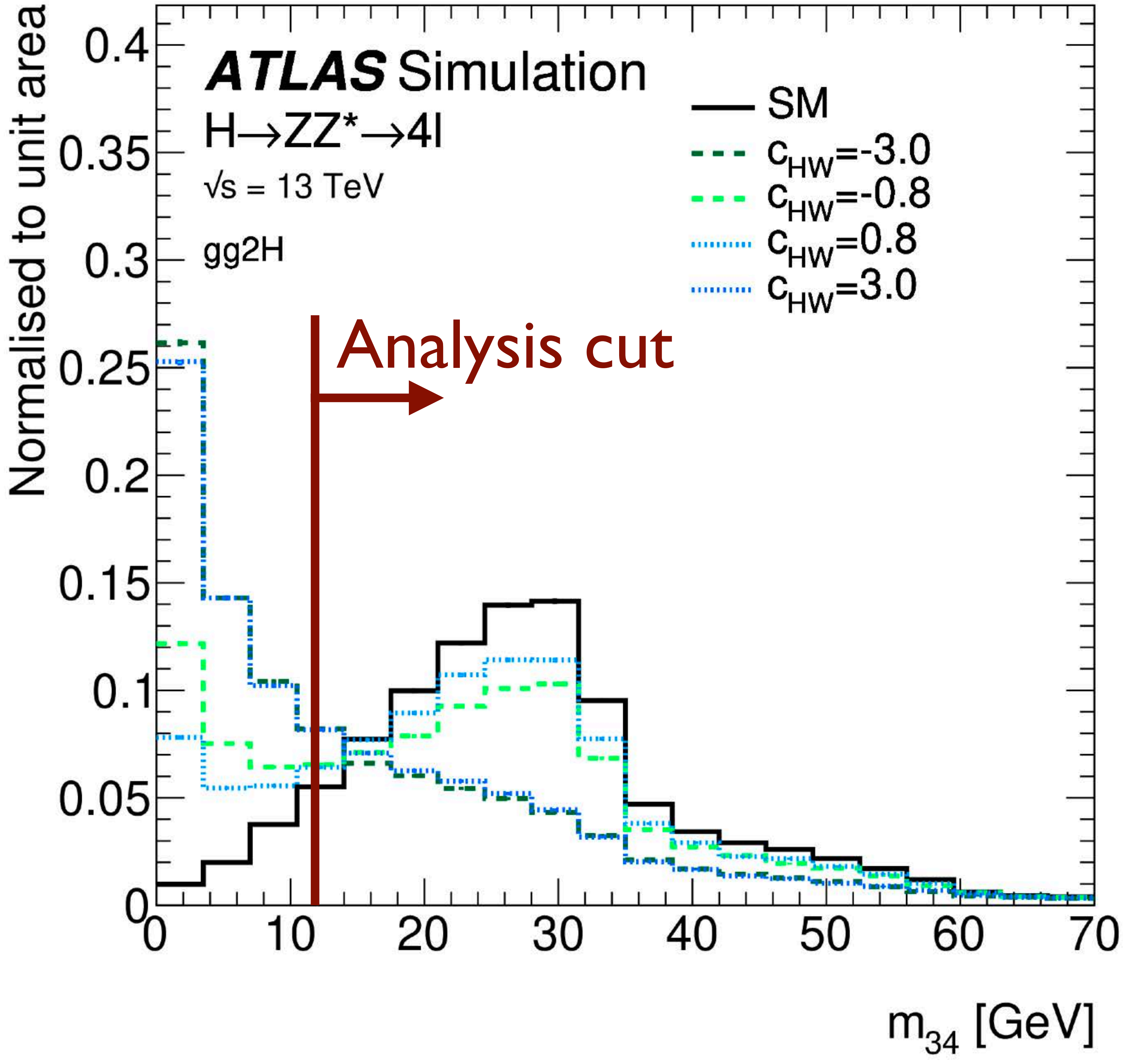
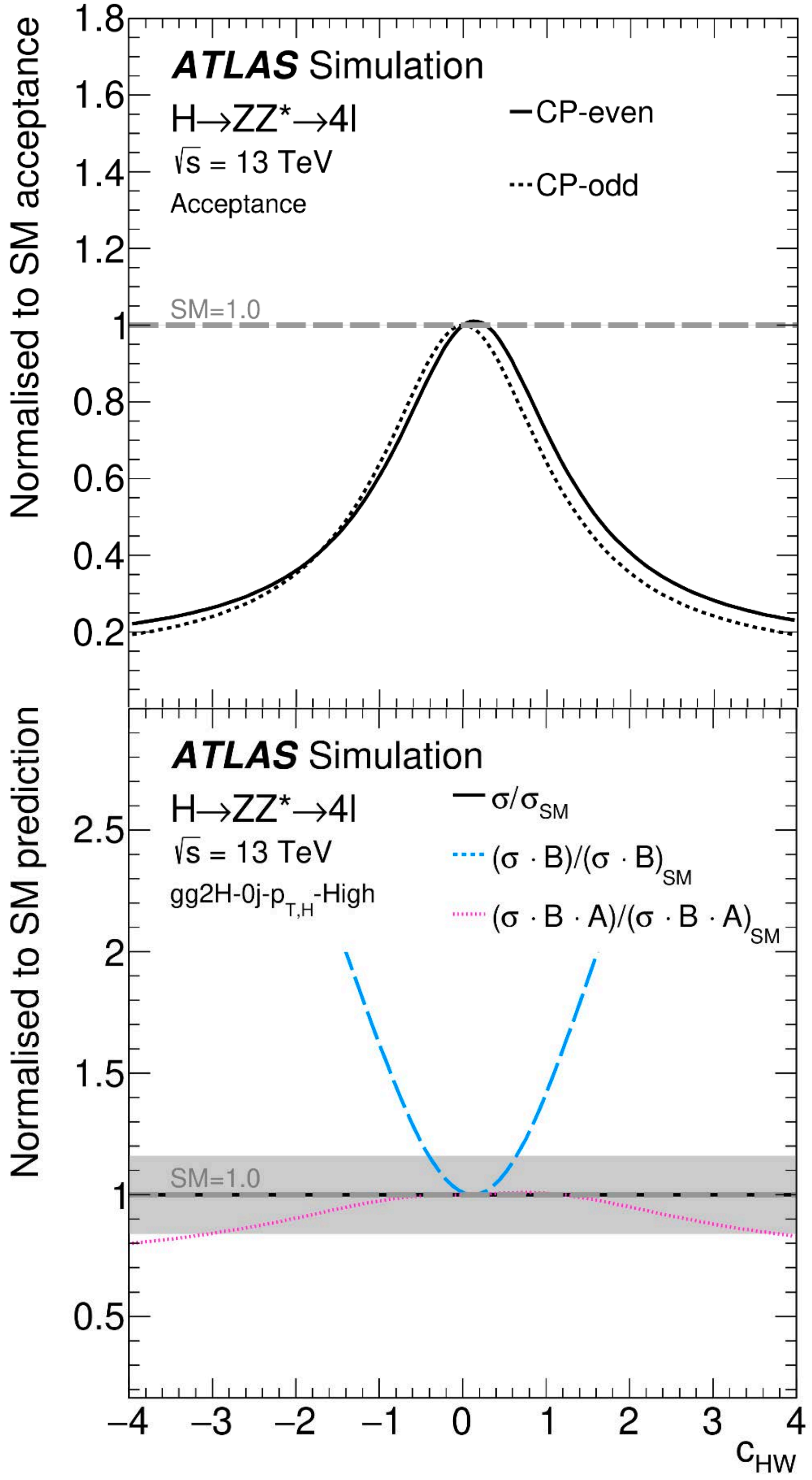
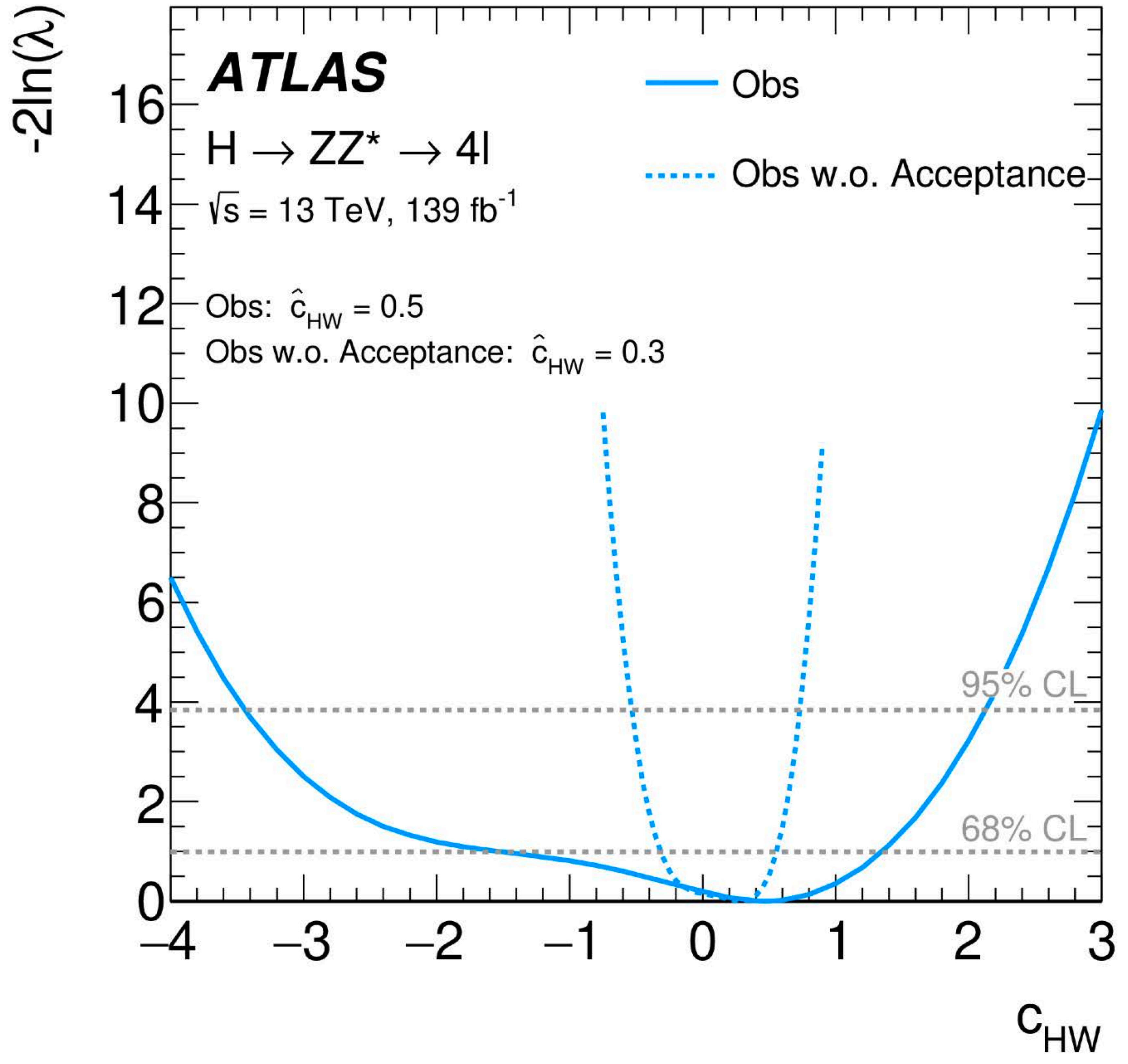
EFT with H → ZZ* → 4ℓ

- **Acceptance corrections**
  as a function of BSM operator

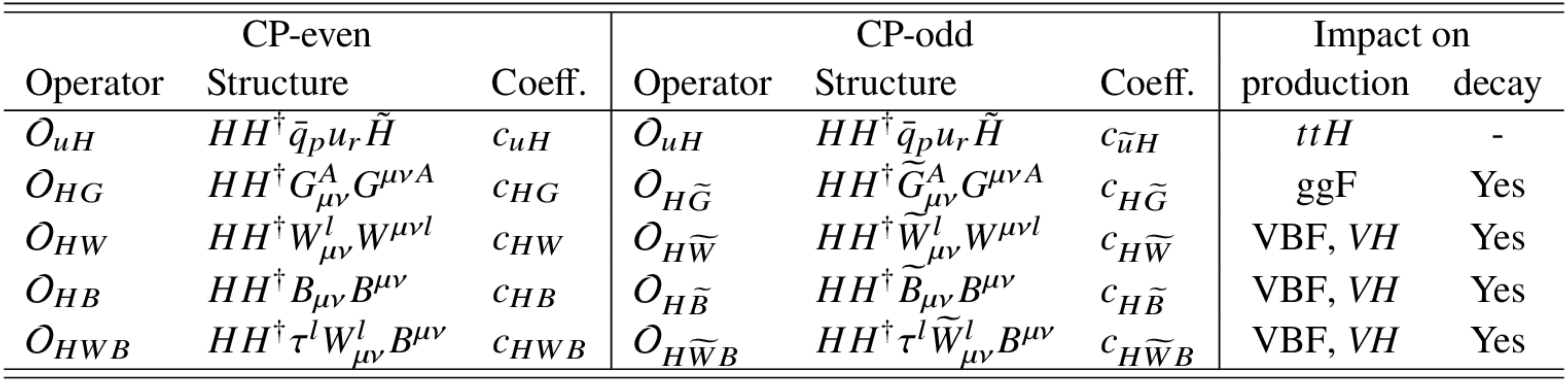






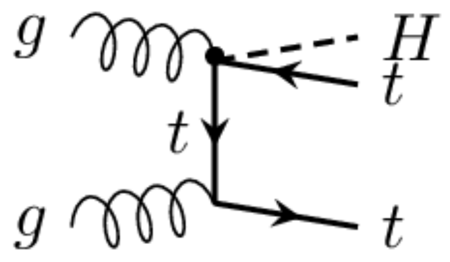
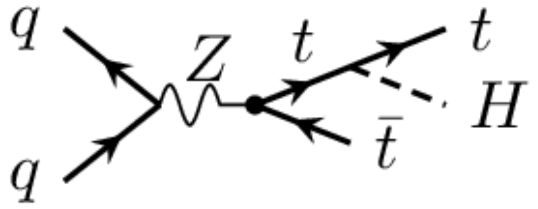
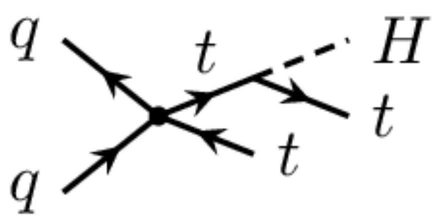
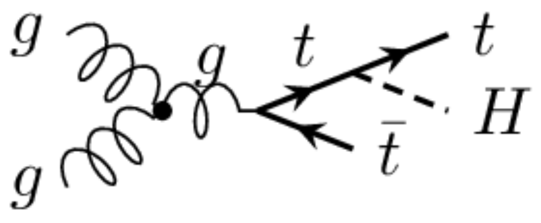
SMEFT

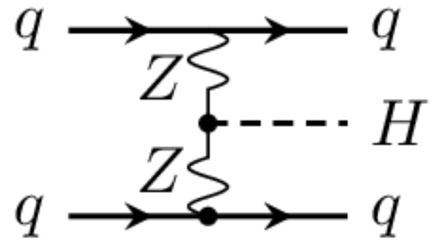
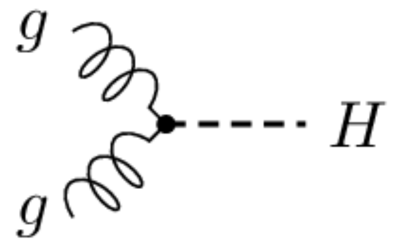
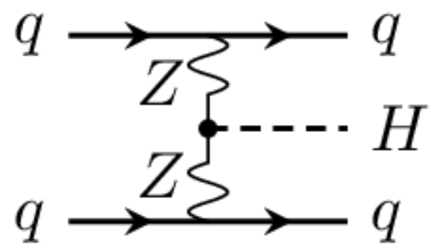
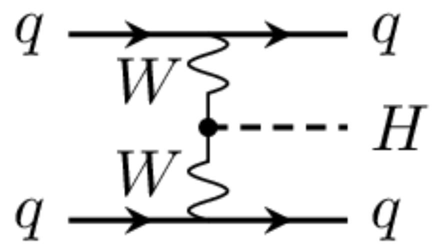
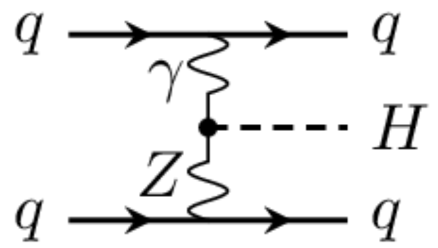
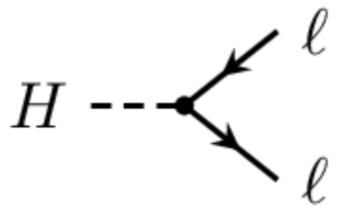
arXiv:2004.03447

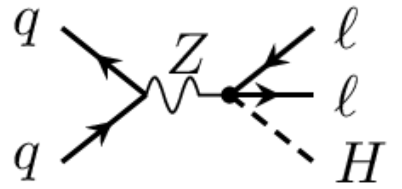
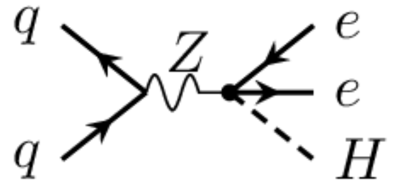


CP-even			CP-odd			Impact on	
Operator	Structure	Coeff.	Operator	Structure	Coeff.	production	decay
$\mathcal{O}_{uH}$	$HH^\dagger\bar{q}_p u_r \tilde{H}$	c_{uH}	$\mathcal{O}_{uH}$	$HH^\dagger\bar{q}_p u_r \tilde{H}$	$c_{\tilde{u}H}$	ttH	-
$\mathcal{O}_{HG}$	$HH^\dagger G^A_{\mu\nu}G^{\mu\nu A}$	c_{HG}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

SMEFT

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

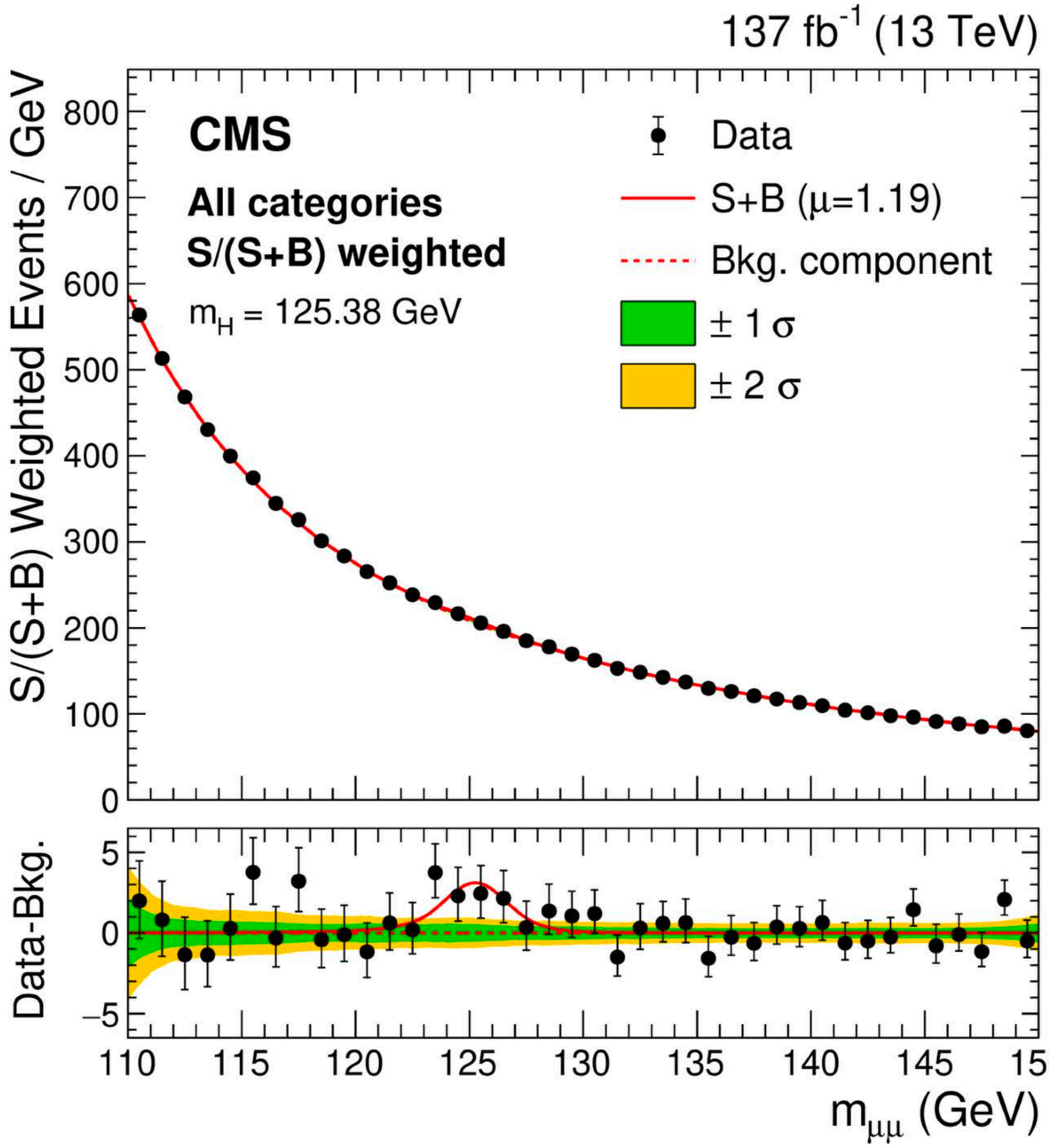
Coefficient	Operator	Example process
c_{HDD}	$(H^\dagger D^\mu H)^*(H^\dagger D_\mu H)$	
c_{HG}	$H^\dagger H\,G^A_{\mu\nu}G^{A\mu\nu}$	
c_{HB}	$H^\dagger H\,B_{\mu\nu}B^{\mu\nu}$	
c_{HW}	$H^\dagger H\,W^I_{\mu\nu}W^{I\mu\nu}$	
c_{HWB}	$H^\dagger\tau^I H\,W^I_{\mu\nu}B^{\mu\nu}$	
c_{eH}	$(H^\dagger H)(\bar{l}_p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

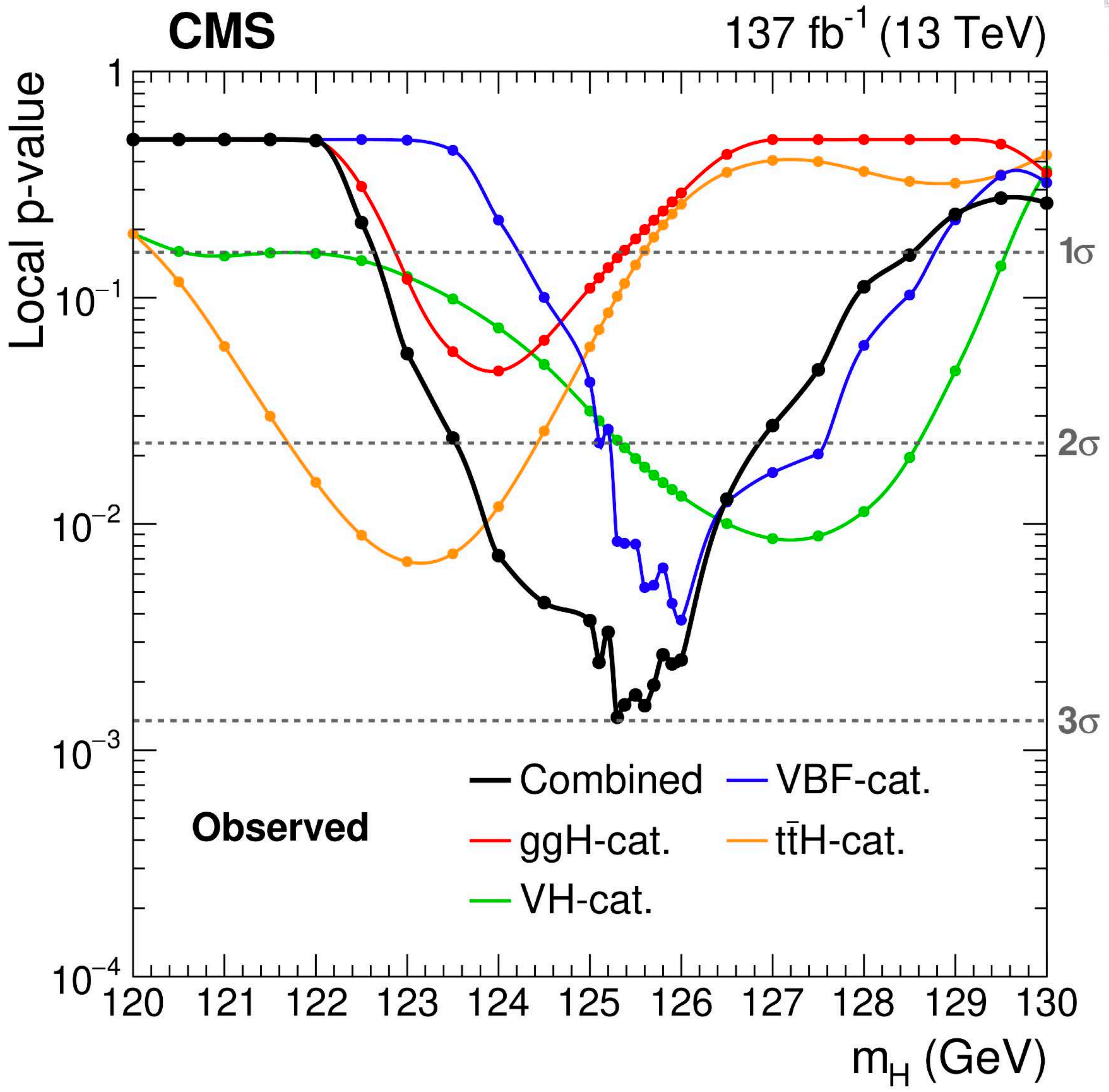
Coefficient	Operator	Example process
$c^{(1)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$	
$c^{(3)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p\tau^I\gamma^\mu l_r)$	
c_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$	
$c^{(1)}_{Hq}$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

$H \rightarrow \mu\mu$

Recent CMS result:

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





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HH Prospects

Gluon fusion

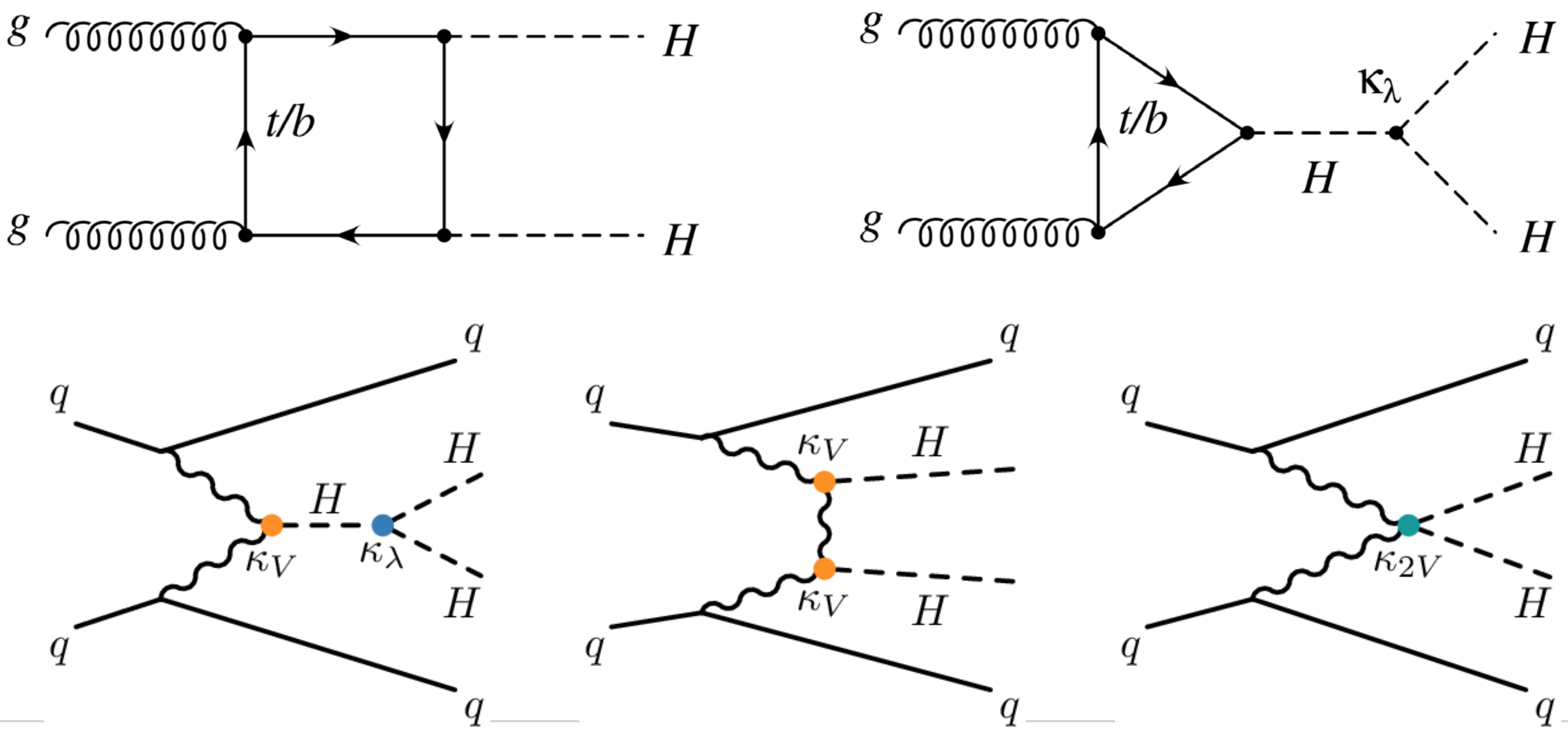
σ = 31.05 fb

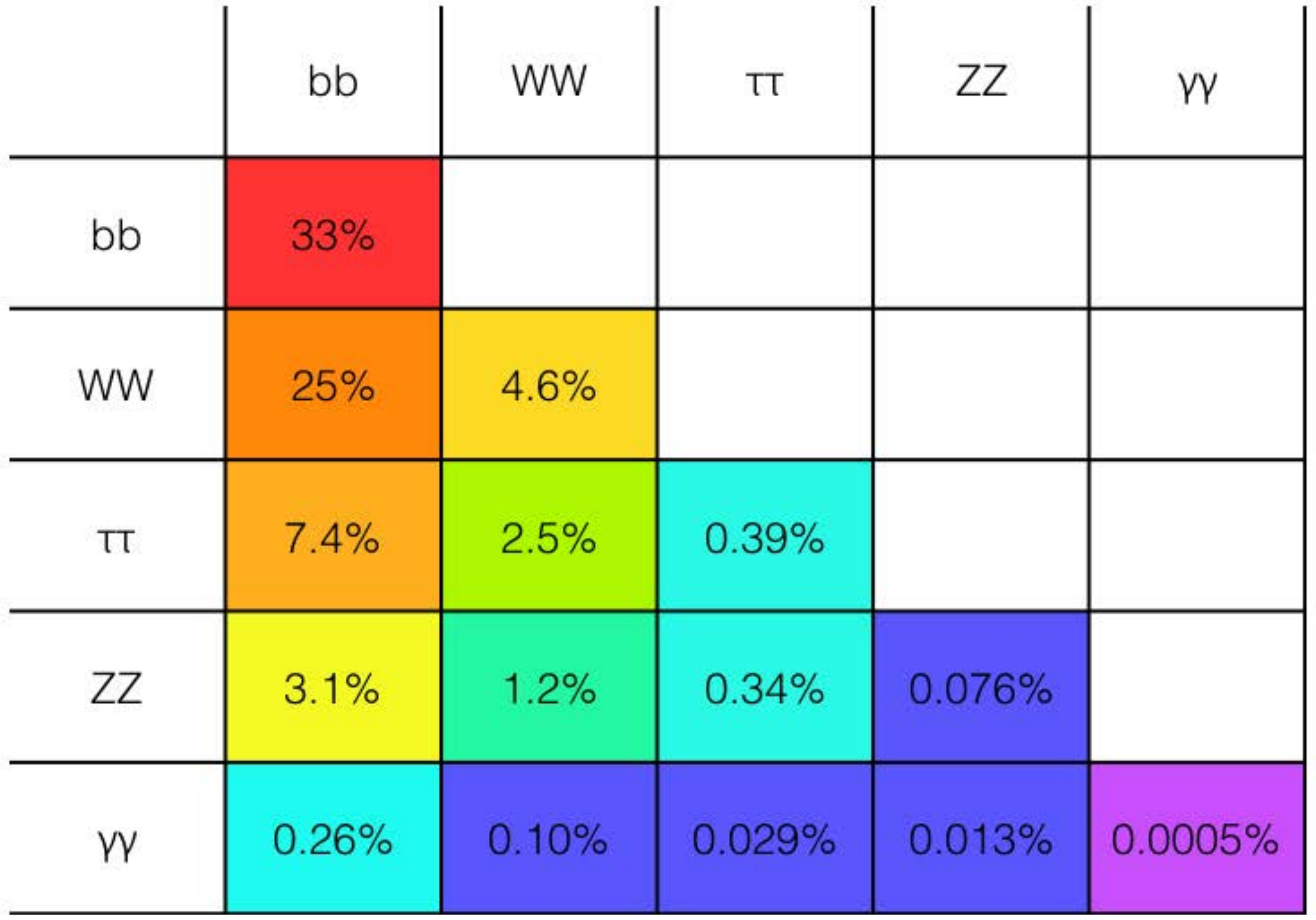
Self-coupling, λ

VBF

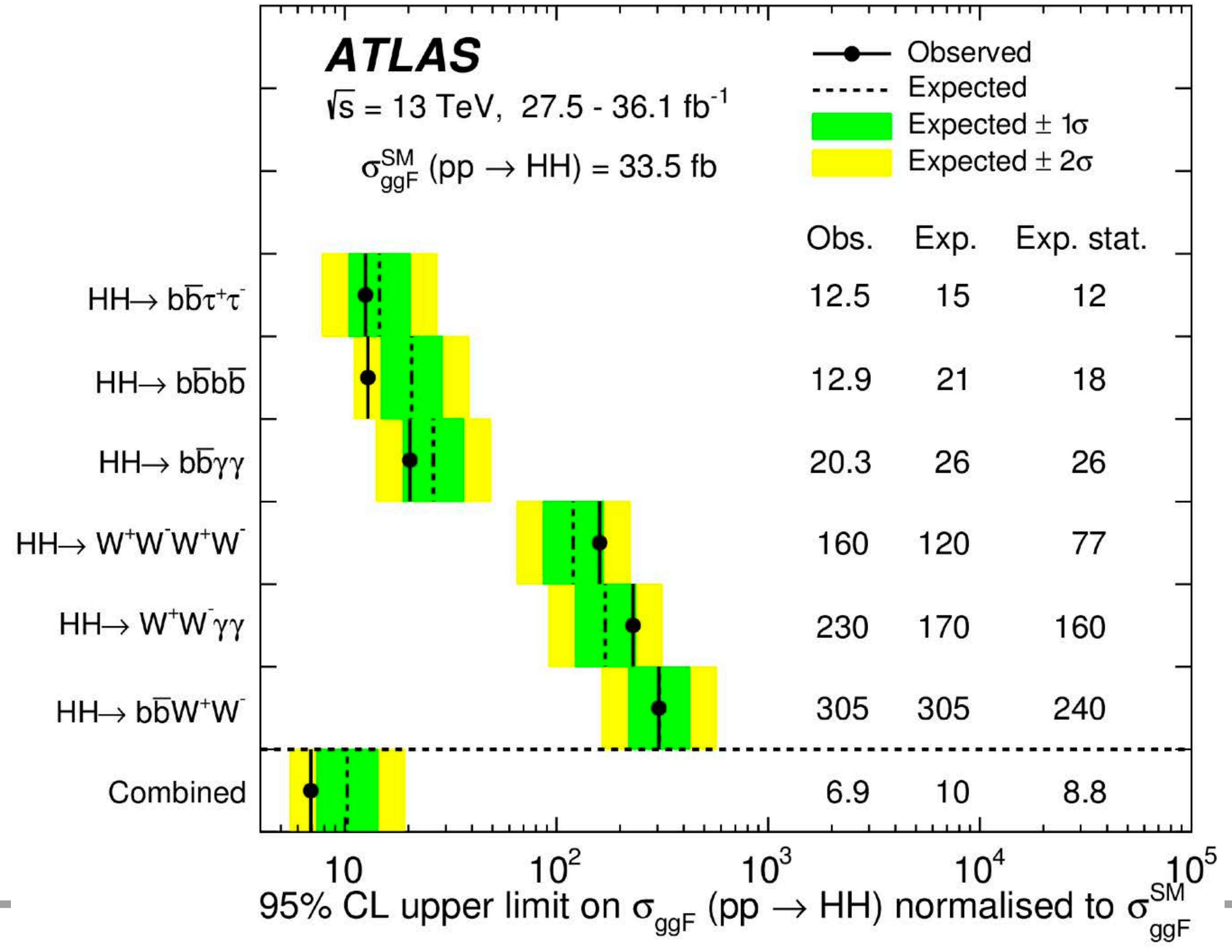
σ = 1.726 fb

VVHH coupling, c2V

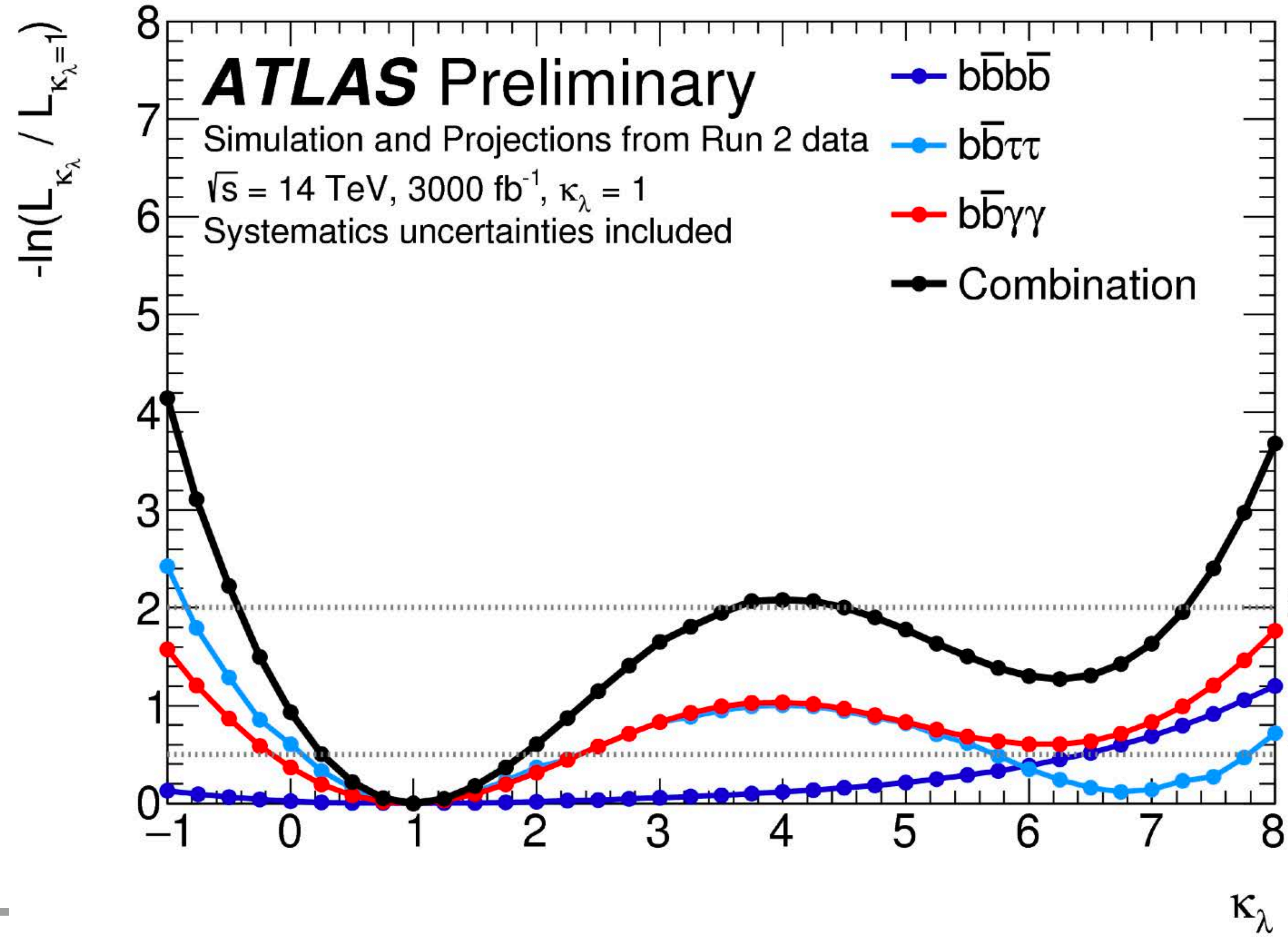




	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

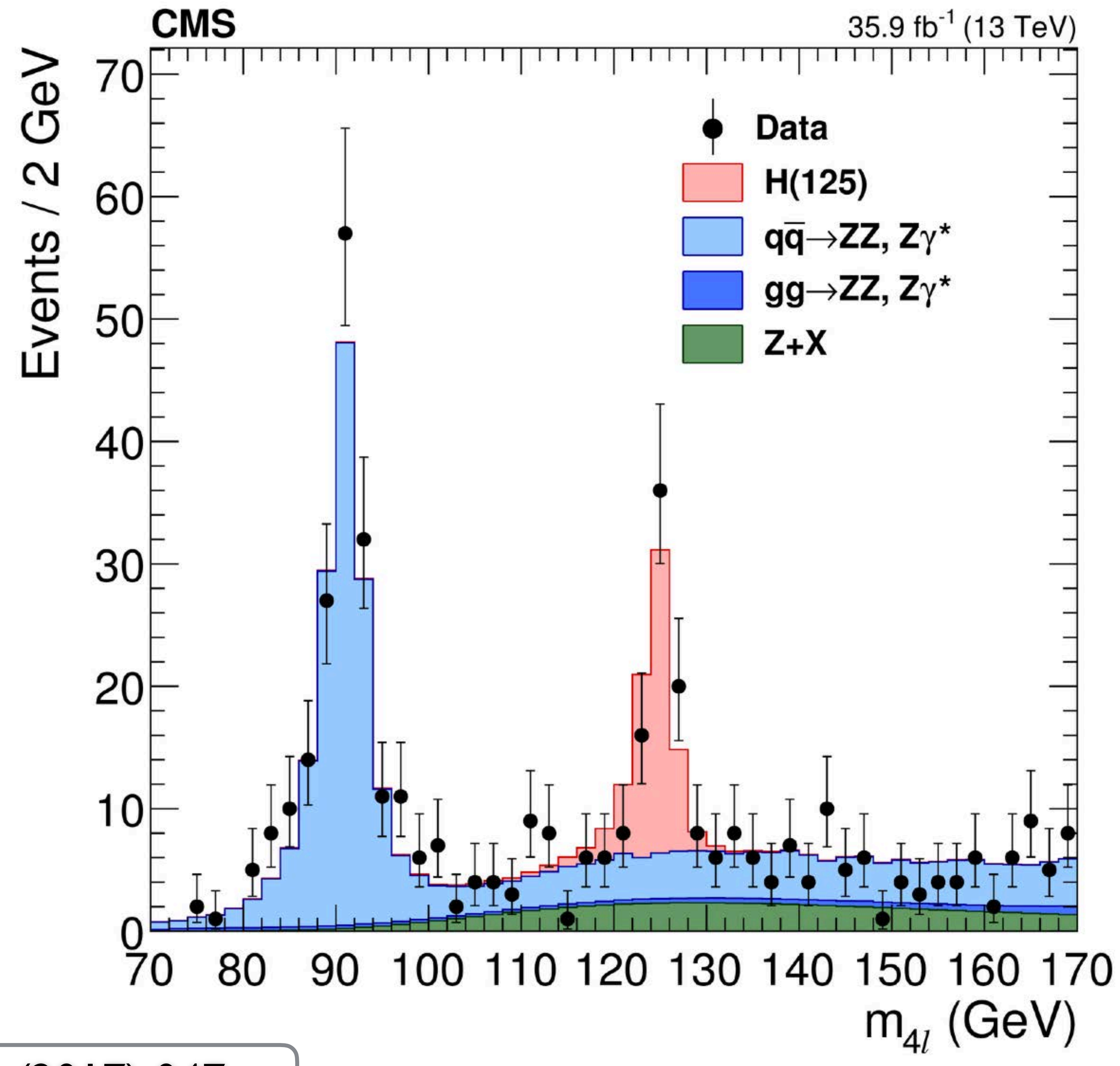


$\Longrightarrow$



Higgs Boson Width

- Expected width: $\Gamma_{H,SM} = 4.07$ MeV
  - Too small to measure
    (exp. resolution: 1-2 GeV)
  - Direct limits: $\Gamma_H < 1.1$ GeV (~$260 \times \Gamma_{H,SM}$)



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Higgs Boson Width

- Expected width: $\Gamma_{H,SM} = 4.07$ MeV
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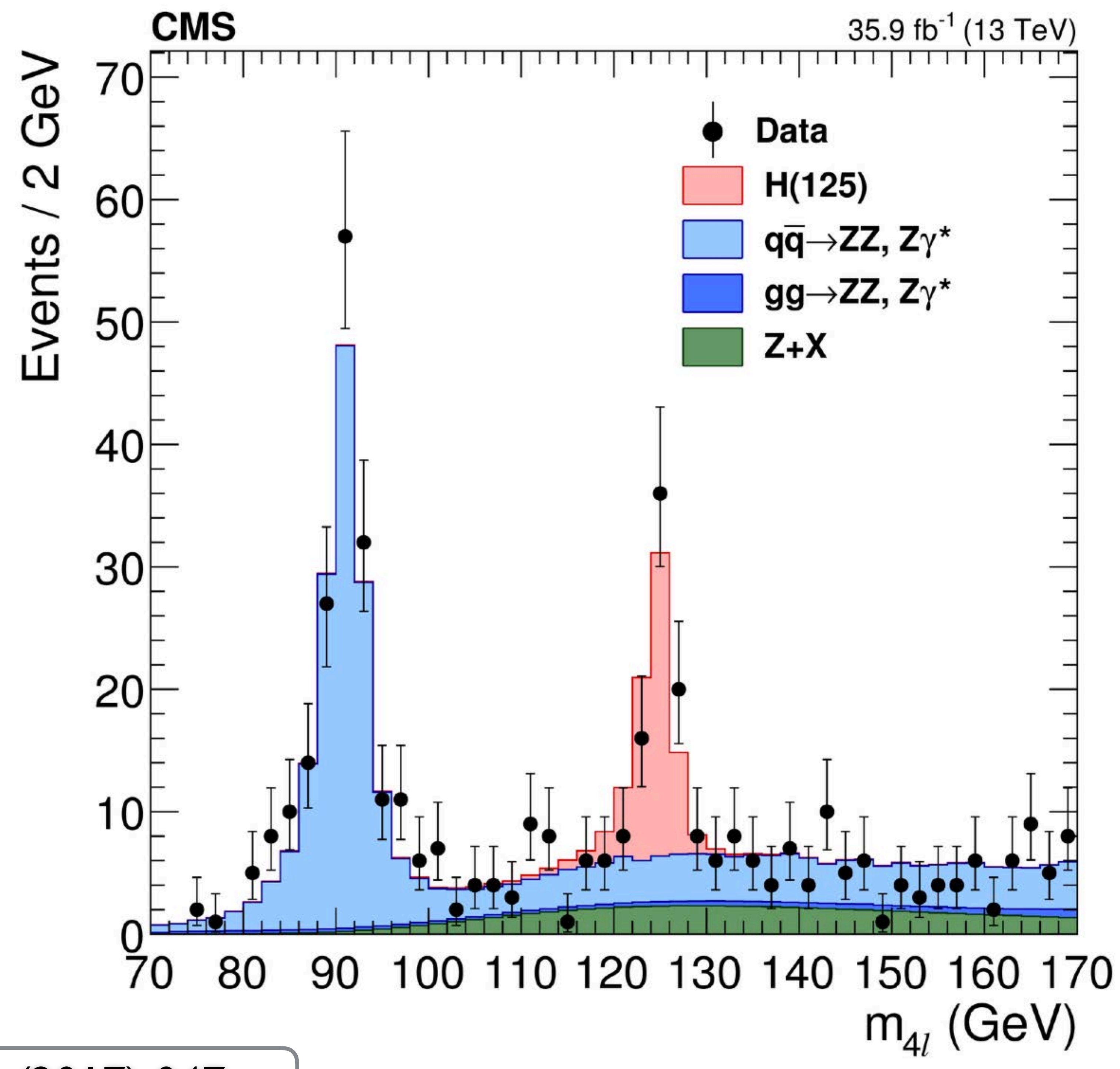

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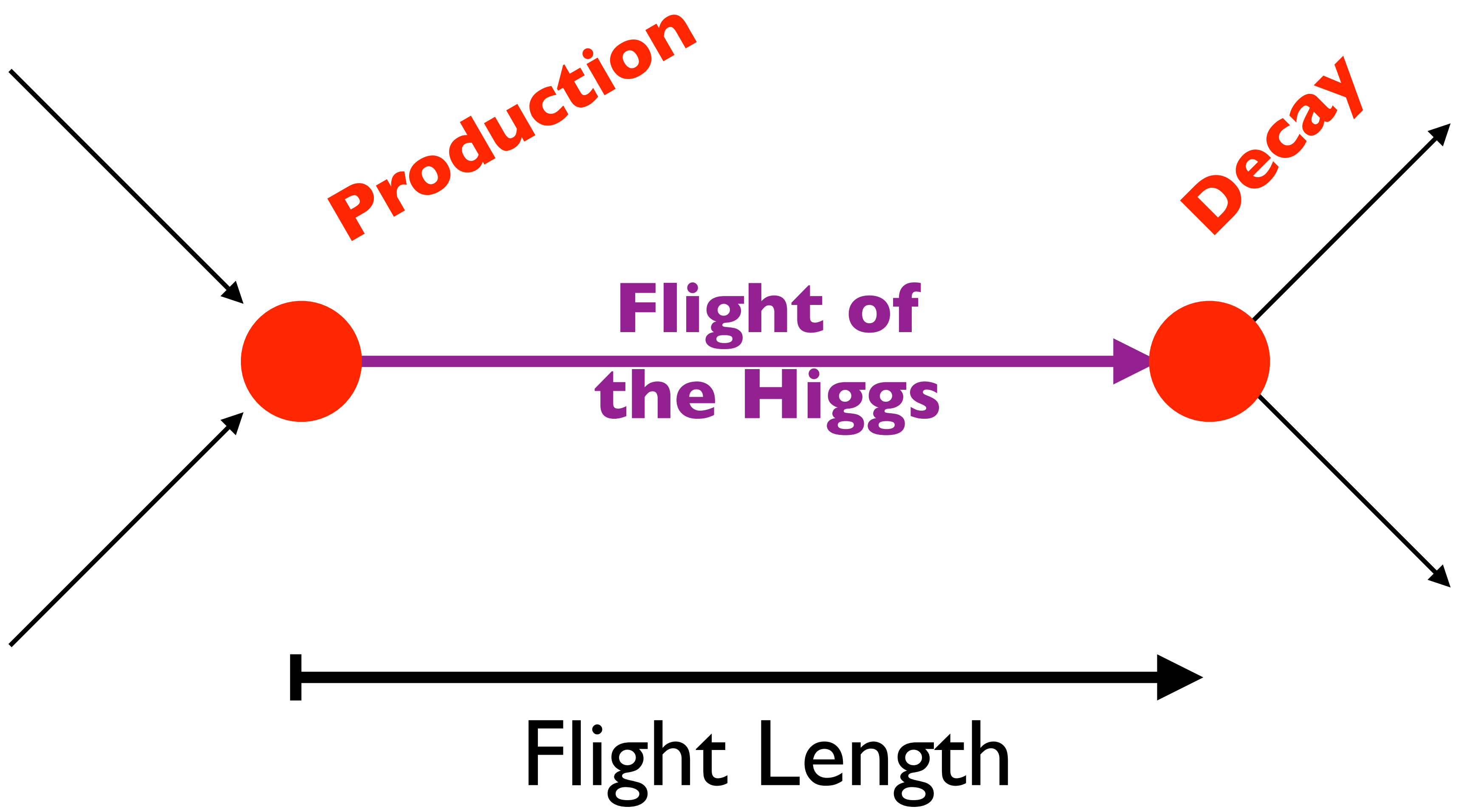
- Maybe via lifetime, *i.e.*, if it flies far enough?
  - $\tau = \hbar/\Gamma \approx 1.6 \times 10^{-22}$ s
    $\Rightarrow c\,\tau \approx 5 \times 10^{-14}$ m

    $\Rightarrow$ too short to measure; put limit:

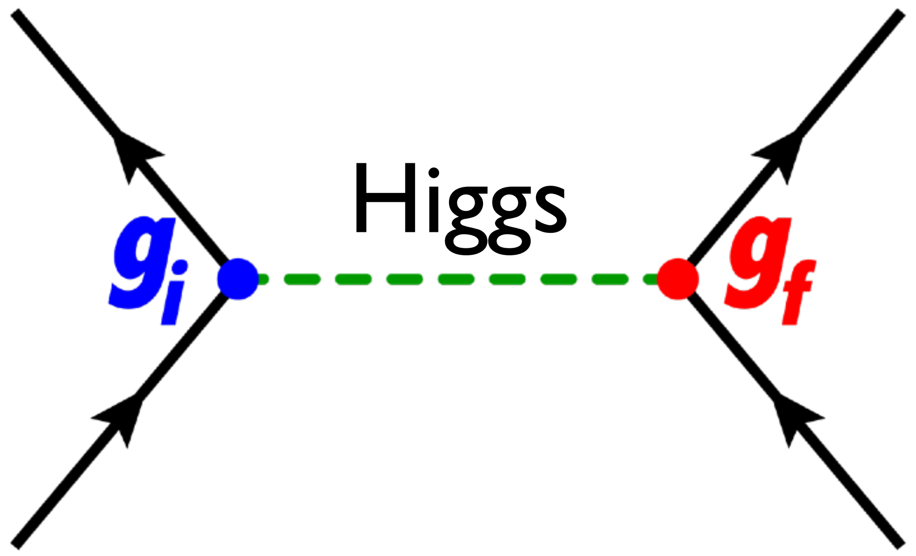
    $\Gamma_H > 3.5 \times 10^{-9}$ MeV @ 95% CL



Phys. Rev. D 92, 072010 (2015)

Indirect Contraints on Higgs Boson Width

- Idea:



  - Cross-section on-resonance:

$$\sigma^{\text{on}}_{i\to H\to f} = \int \frac{g_{\text{i}}^2 g_{\text{f}}^2}{(s-m_{\text{H}}^2)^2 + \boxed{\Gamma_{\text{H}}^2 m_{\text{H}}^2}} ds$$

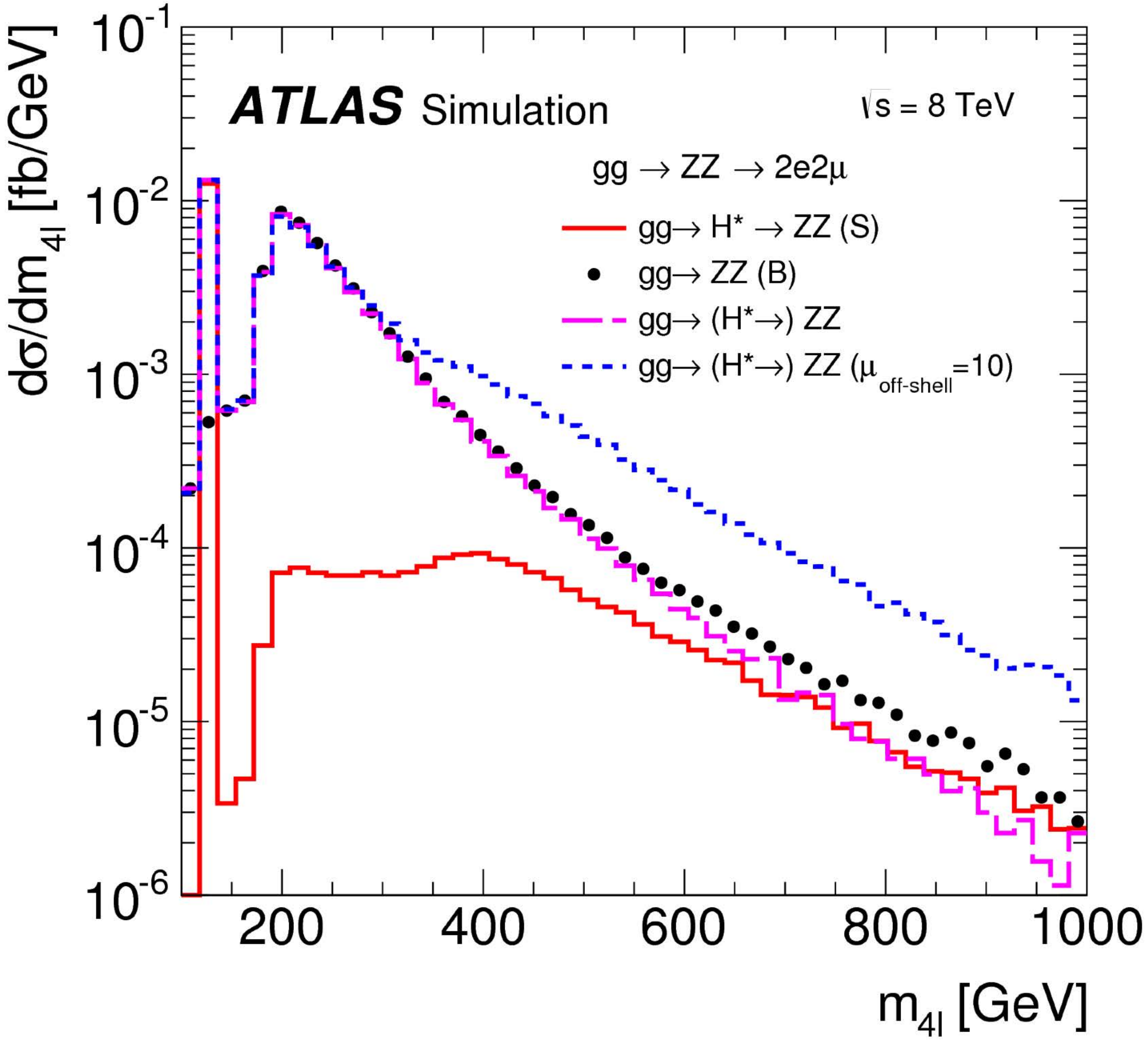
$$\propto \frac{g_{\text{i}}^2 g_{\text{f}}^2}{\Gamma_{\text{H}}}$$

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

$$\sigma^{\text{off}}_{i\to H\to f} = \int \frac{g_{\text{i}}^2 g_{\text{f}}^2}{\boxed{(s-m_{\text{H}}^2)^2} + \Gamma_{\text{H}}^2 m_{\text{H}}^2} ds$$

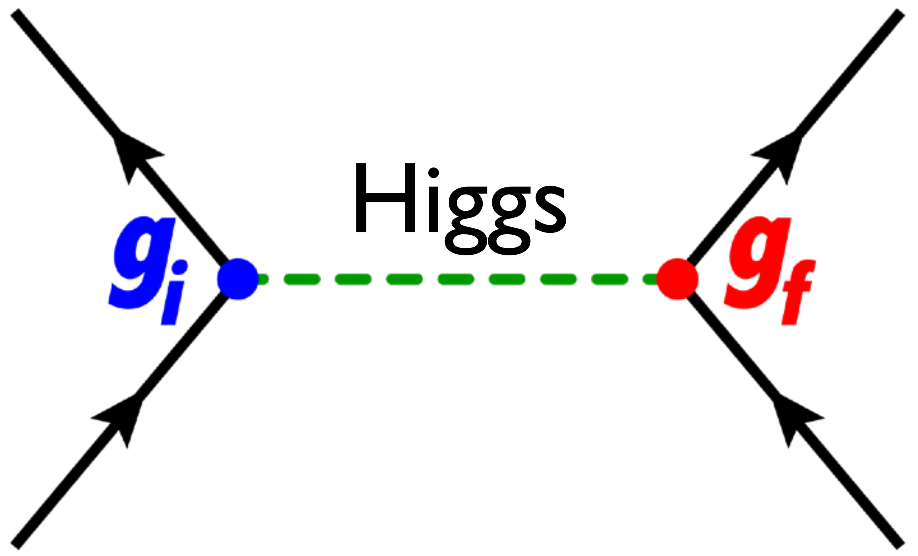
$$\propto g_{\text{i}}^2 g_{\text{f}}^2$$

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



Indirect Contraints on Higgs Boson Width

- Idea:



- Cross-section on-resonance:

$$\sigma^{\mathrm{on}}_{i\to H\to f} = \int \frac{g_{\mathrm{i}}^2 g_{\mathrm{f}}^2}{(s-m_{\mathrm{H}}^2)^2 + \boxed{\Gamma_{\mathrm{H}}^2 m_{\mathrm{H}}^2}} ds$$

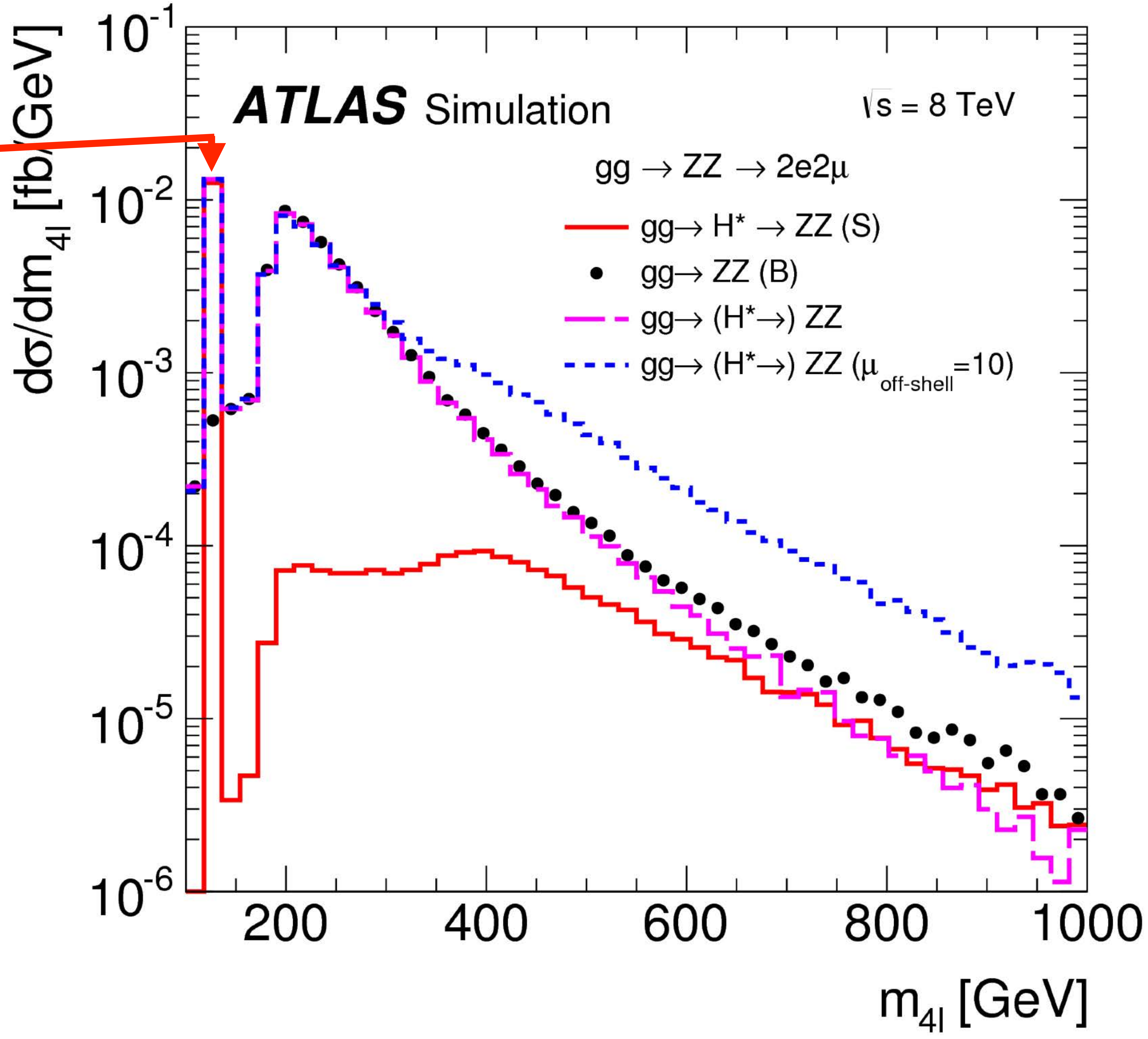
$$\propto \frac{g_{\mathrm{i}}^2 g_{\mathrm{f}}^2}{\Gamma_{\mathrm{H}}}$$

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

$$\sigma^{\mathrm{off}}_{i\to H\to f} = \int \frac{g_{\mathrm{i}}^2 g_{\mathrm{f}}^2}{\boxed{(s-m_{\mathrm{H}}^2)^2} + \Gamma_{\mathrm{H}}^2 m_{\mathrm{H}}^2} ds$$

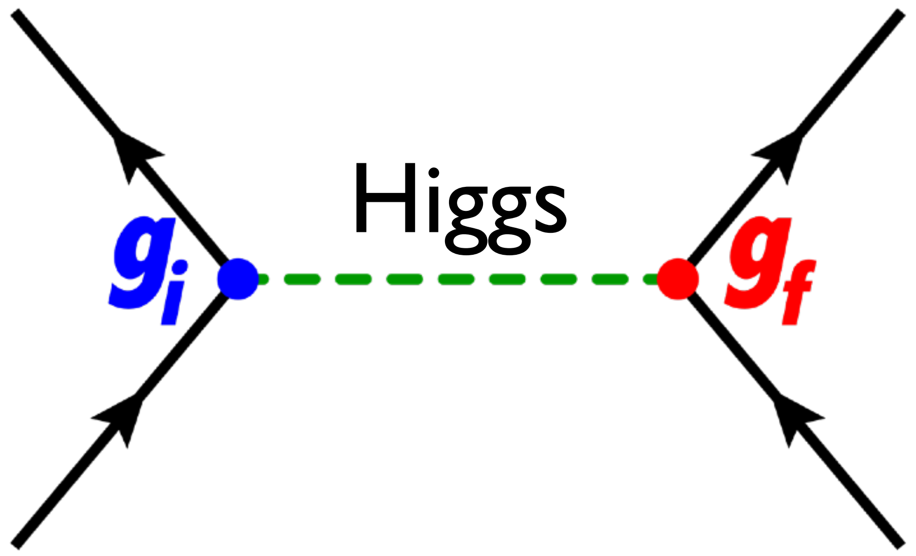
$$\propto g_{\mathrm{i}}^2 g_{\mathrm{f}}^2$$

- Measure ratio of both: $\Gamma_{\mathrm{H}} \propto \frac{\sigma_{\mathrm{off}}}{\sigma_{\mathrm{on}}}$



Indirect Contraints on Higgs Boson Width

- Idea:



  - Cross-section on-resonance:

$$\sigma^{\text{on}}_{i\to H\to f} = \int \frac{g_{\text{i}}^2 g_{\text{f}}^2}{(s-m_{\text{H}}^2)^2 + \boxed{\Gamma_{\text{H}}^2 m_{\text{H}}^2}} ds$$

$$\propto \frac{g_{\text{i}}^2 g_{\text{f}}^2}{\Gamma_{\text{H}}}$$

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

$$\sigma^{\text{off}}_{i\to H\to f} = \int \frac{g_{\text{i}}^2 g_{\text{f}}^2}{\boxed{(s-m_{\text{H}}^2)^2} + \Gamma_{\text{H}}^2 m_{\text{H}}^2} ds$$

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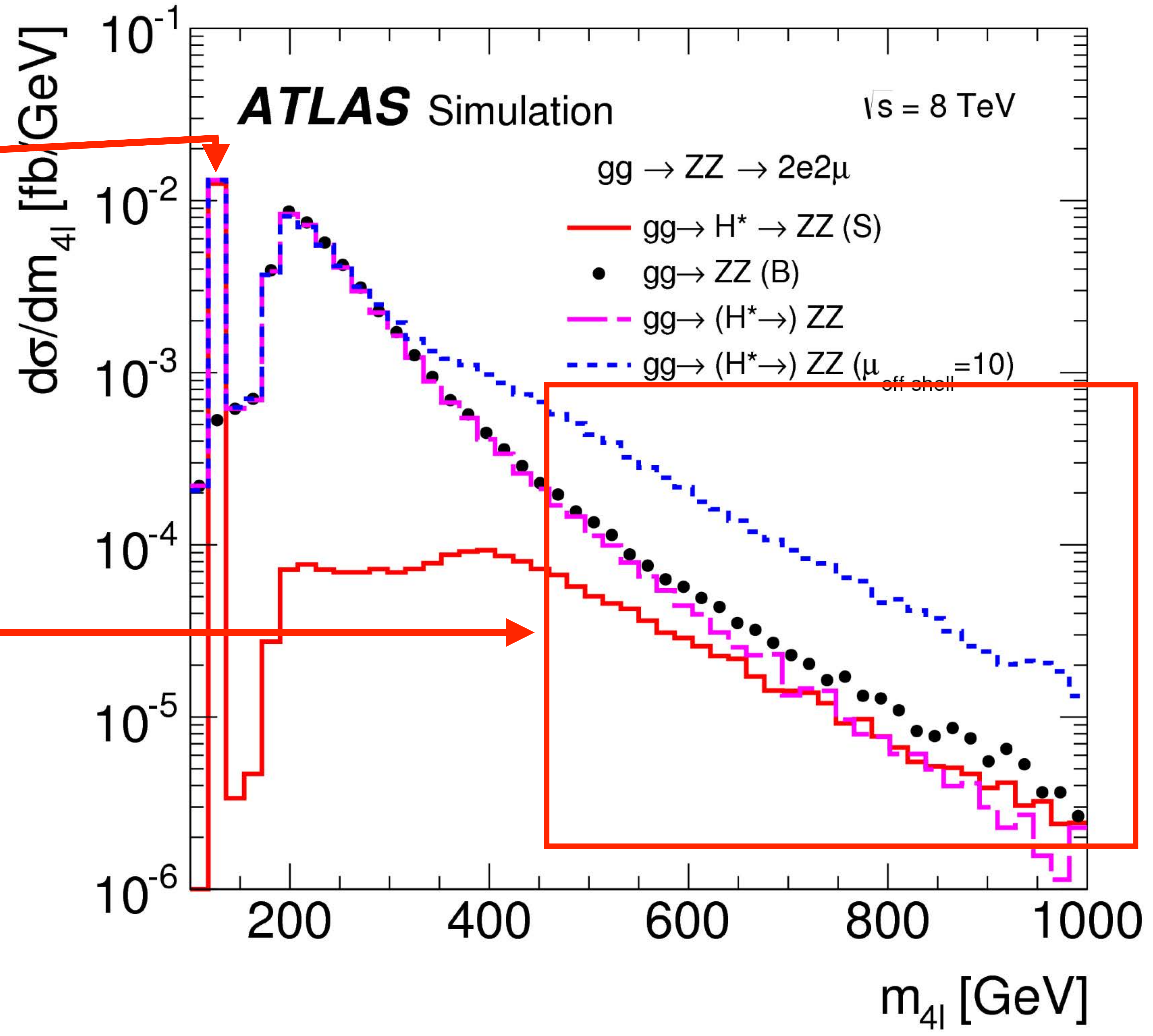
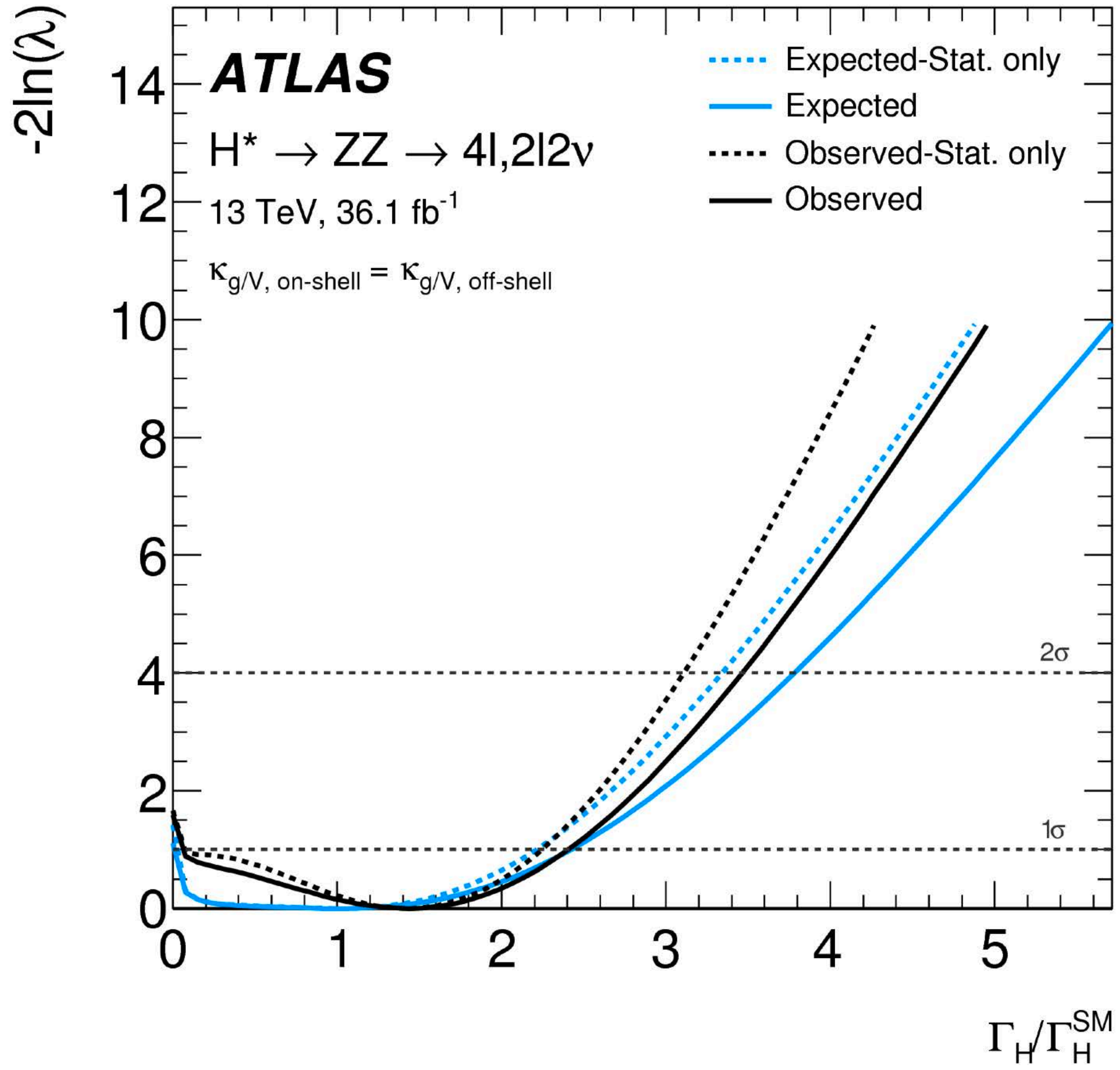


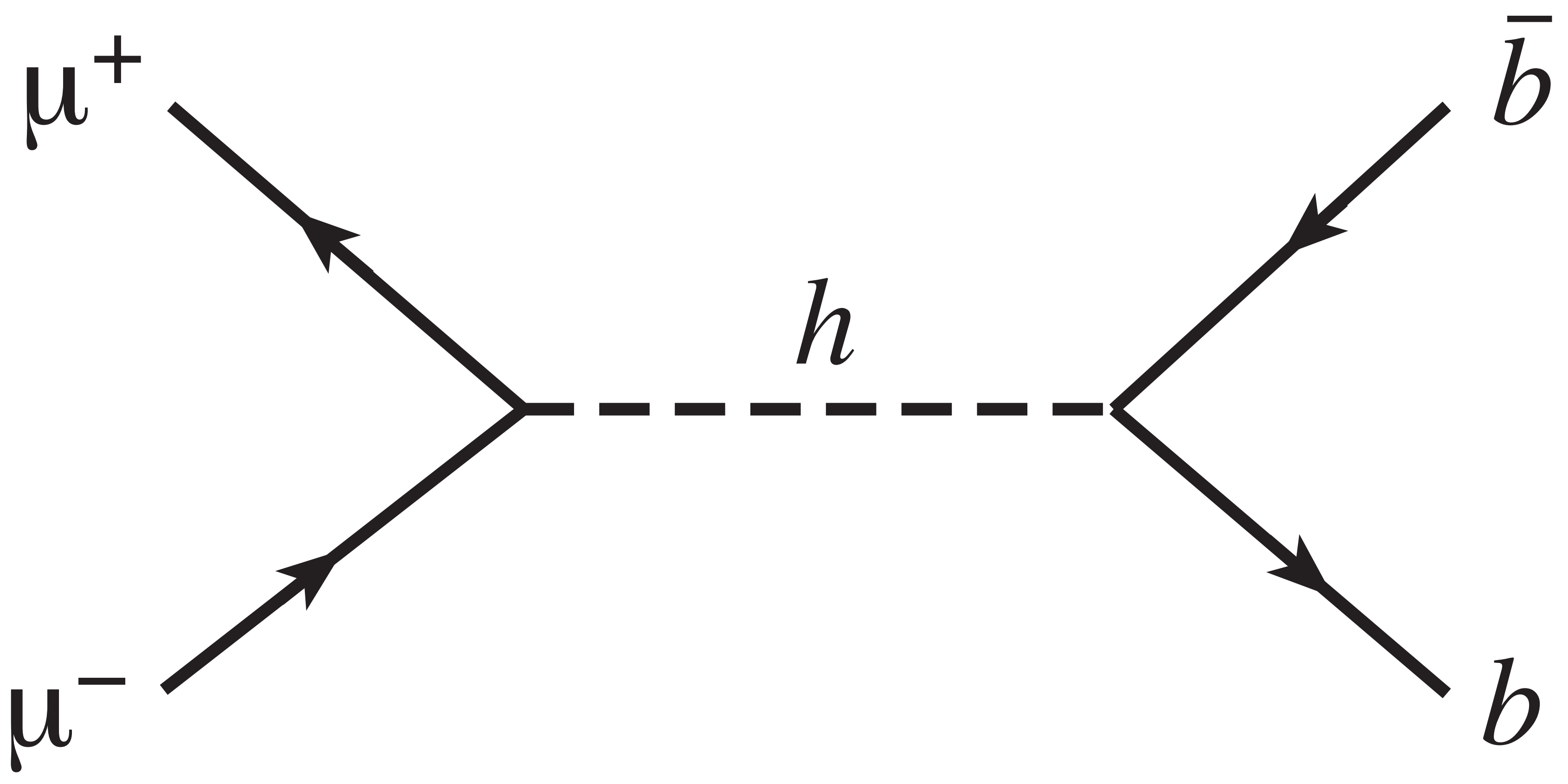
Indirect Contraints on Higgs Boson Width

- Use H ➞ $ZZ^{(*)}$
- ATLAS result: $\mathbf{\Gamma_H}$ **< 14.4 MeV** @ 95% CL (3.5 × $\Gamma_{H,SM}$)
- Caveats:
  - gg ➞ ZZ cross sections not well known
  - New physics effects could change high-mass behavior
  - Assuming on-shell coupling is same as off-shell coupling
    - Discussed assumption

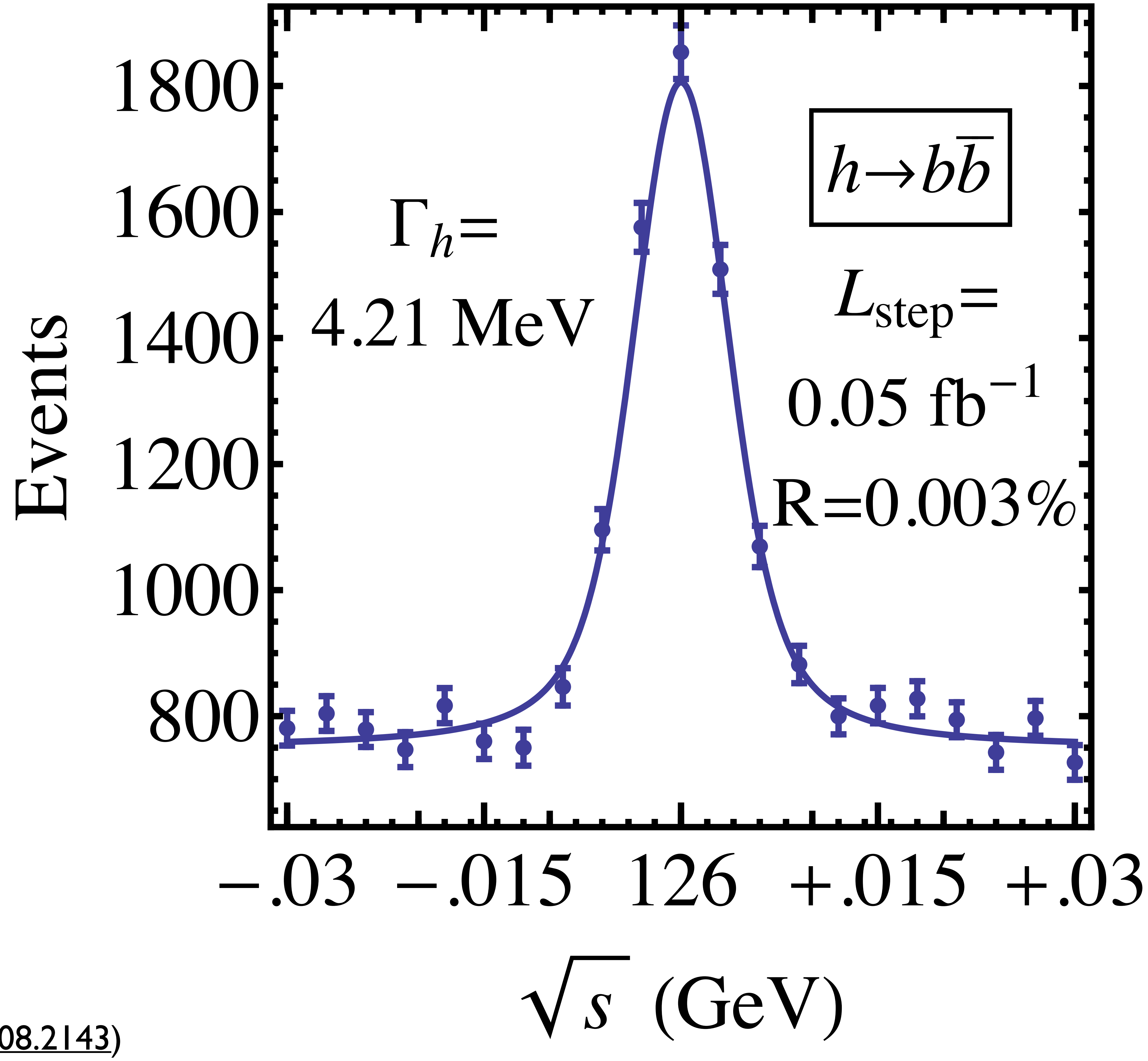


Only direct Width Measurement

- s-channel production at future muon collider:



- Precision ~5%

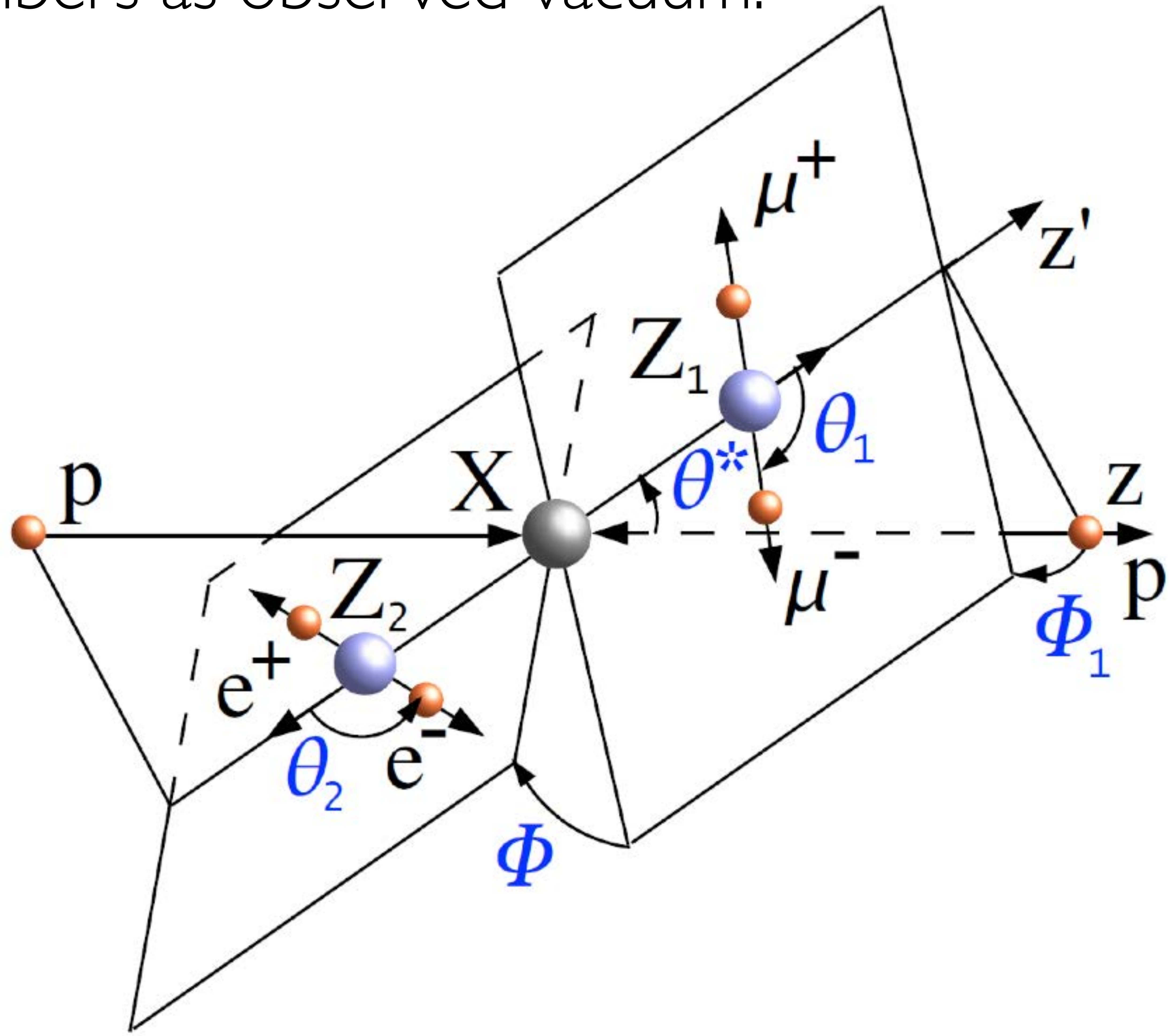


(arxiv:1308.2143)

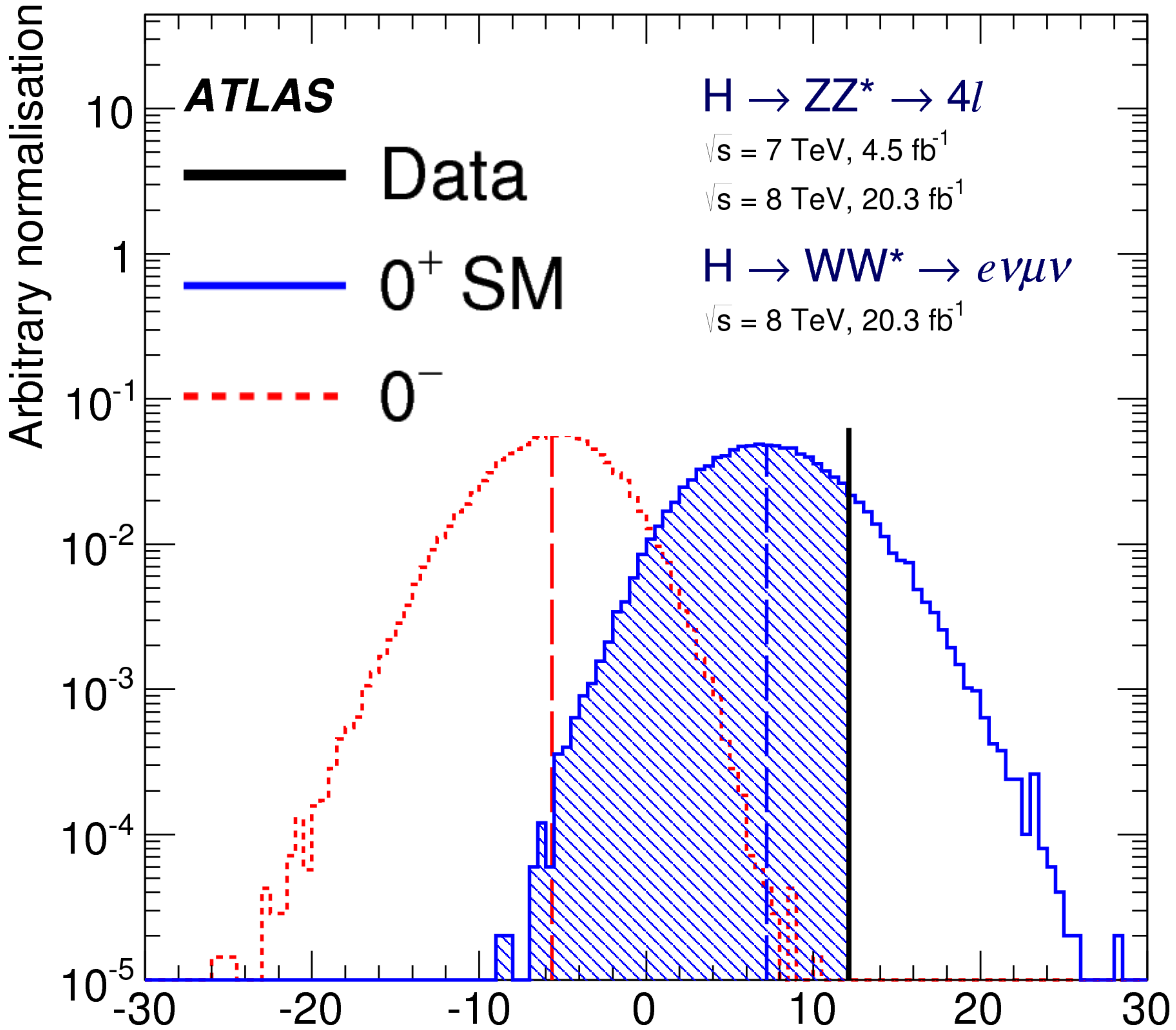
Spin and Parity

Why Spin 0?

- Higgs boson should have same quantum numbers as observed vacuum:
  - No charge: 👍
  - Mass cannot depend on direction ⇒ **Spin 0**
- Standard Model Higgs boson: $\mathbf{J^P = 0^+}$
  - **P**arity (“mirror”) transformation”: $\hat{P}\,\vec{x} \longrightarrow -\vec{x}$
  - Strategy: *falsify other hypotheses* $(0^-, 1^+, 1^-, 2^+, 2^-)$, *demonstrate consistency with* 0^+ *hypothesis*
  - Spin-1 excluded by observed H → $\gamma\gamma$
  - Use angular variables
  - Calculate likelihood ratio between alternative hypothesis and standard $J^P = 0^+$ hypothesis

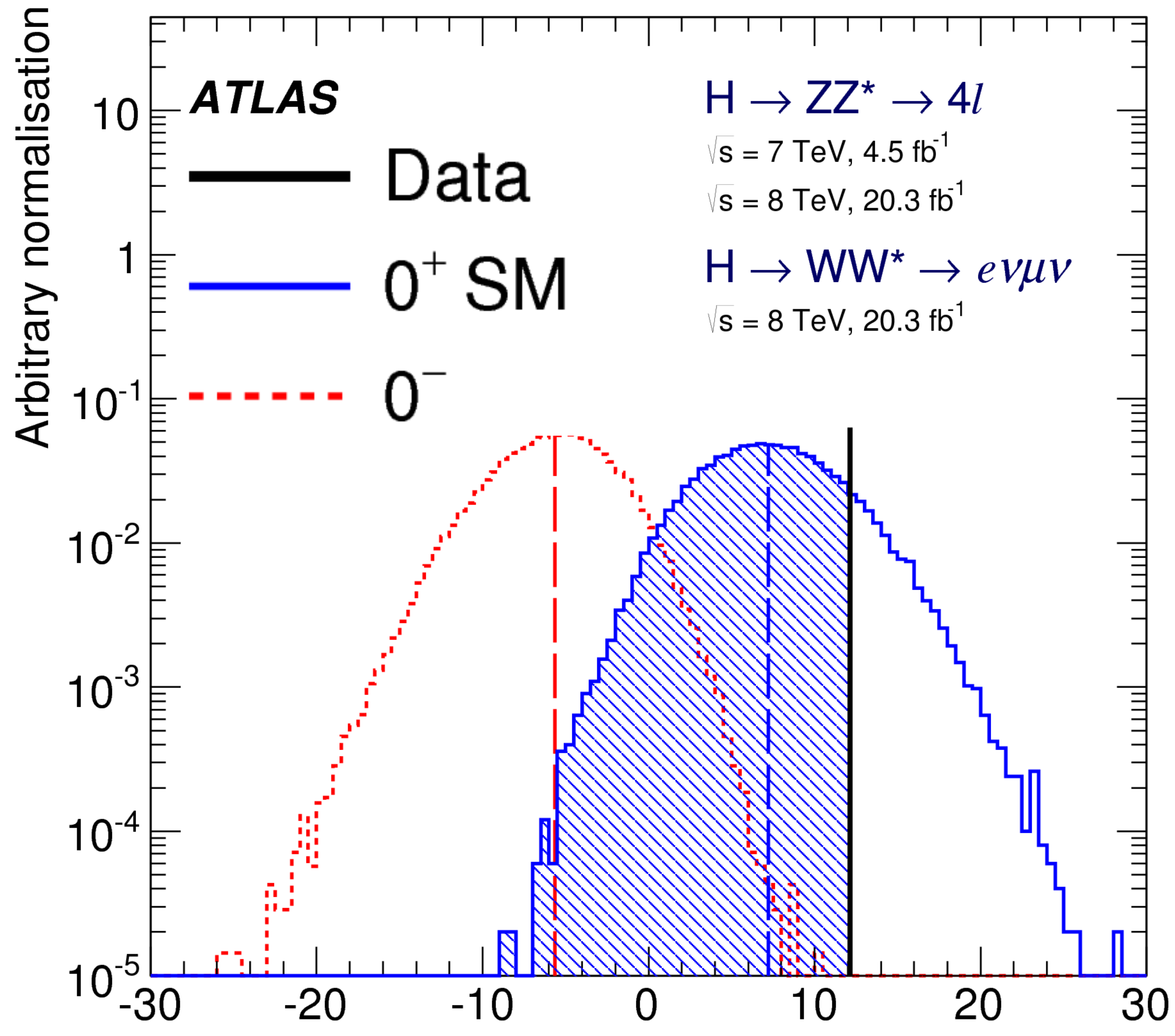


Spin and Parity



$$\tilde{q} = -2 \cdot \ln\left(L_{\mathrm{J^P}} / L_{0^+}\right)$$

Spin and Parity



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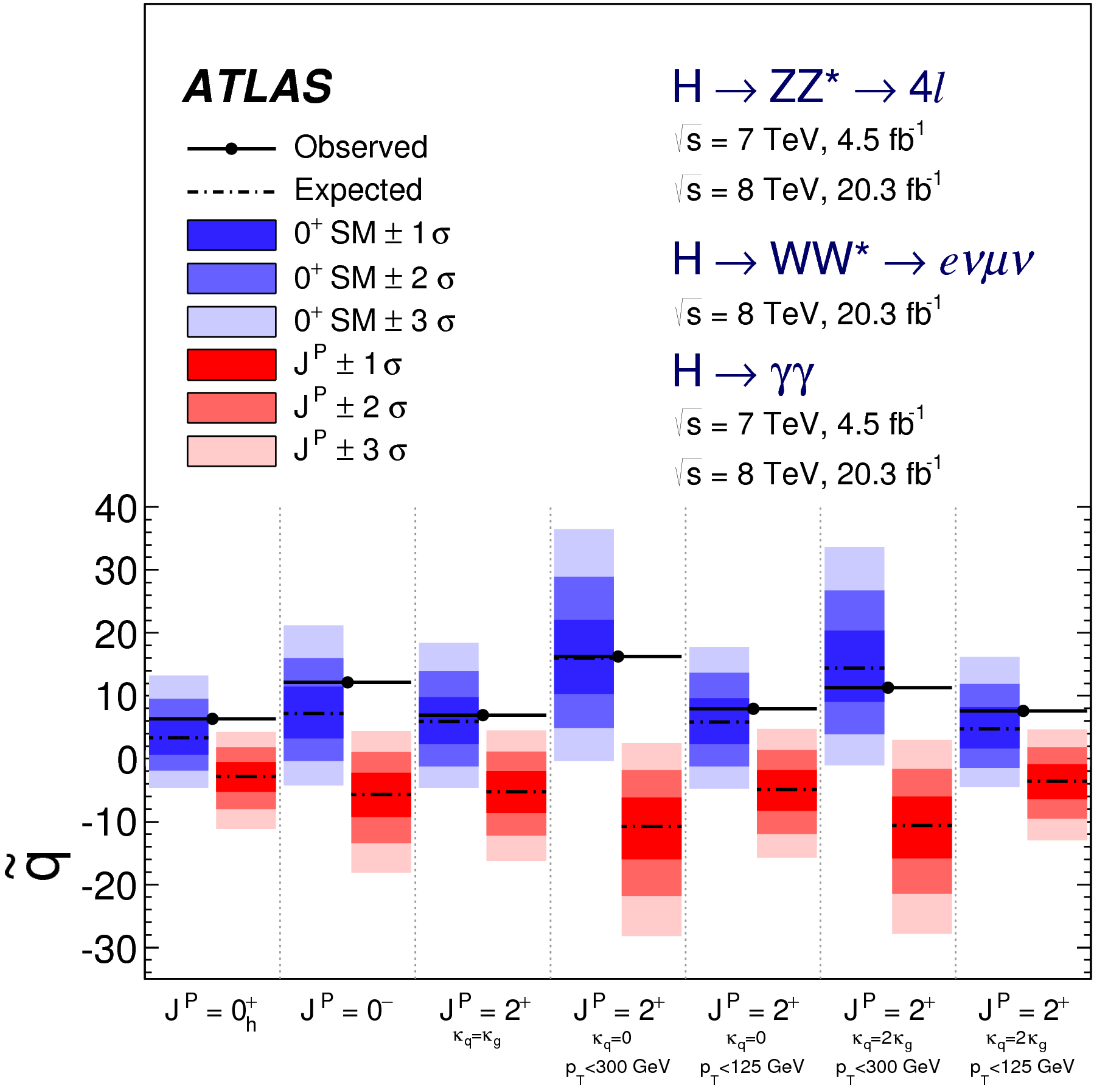
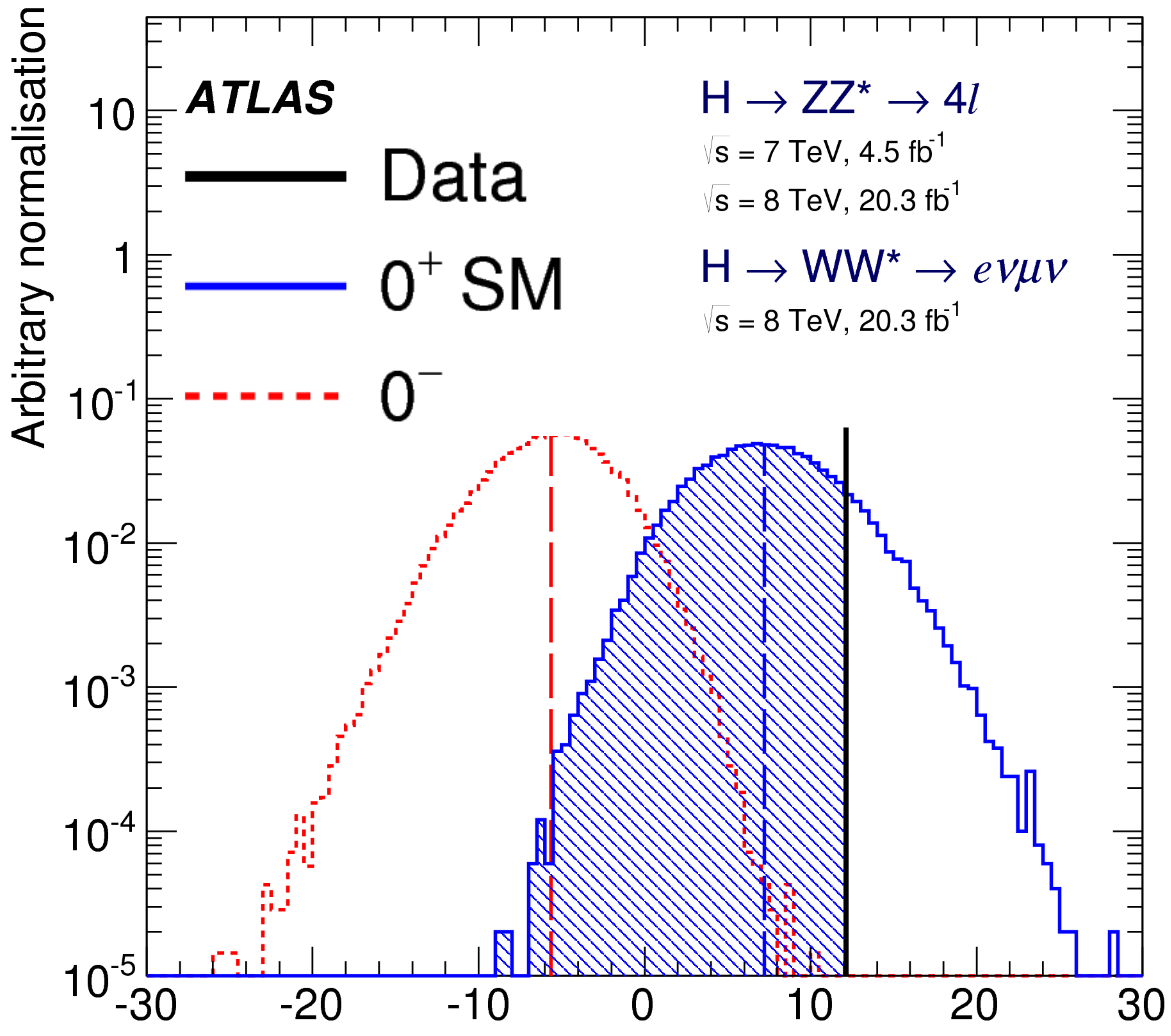
projection



Spin and Parity



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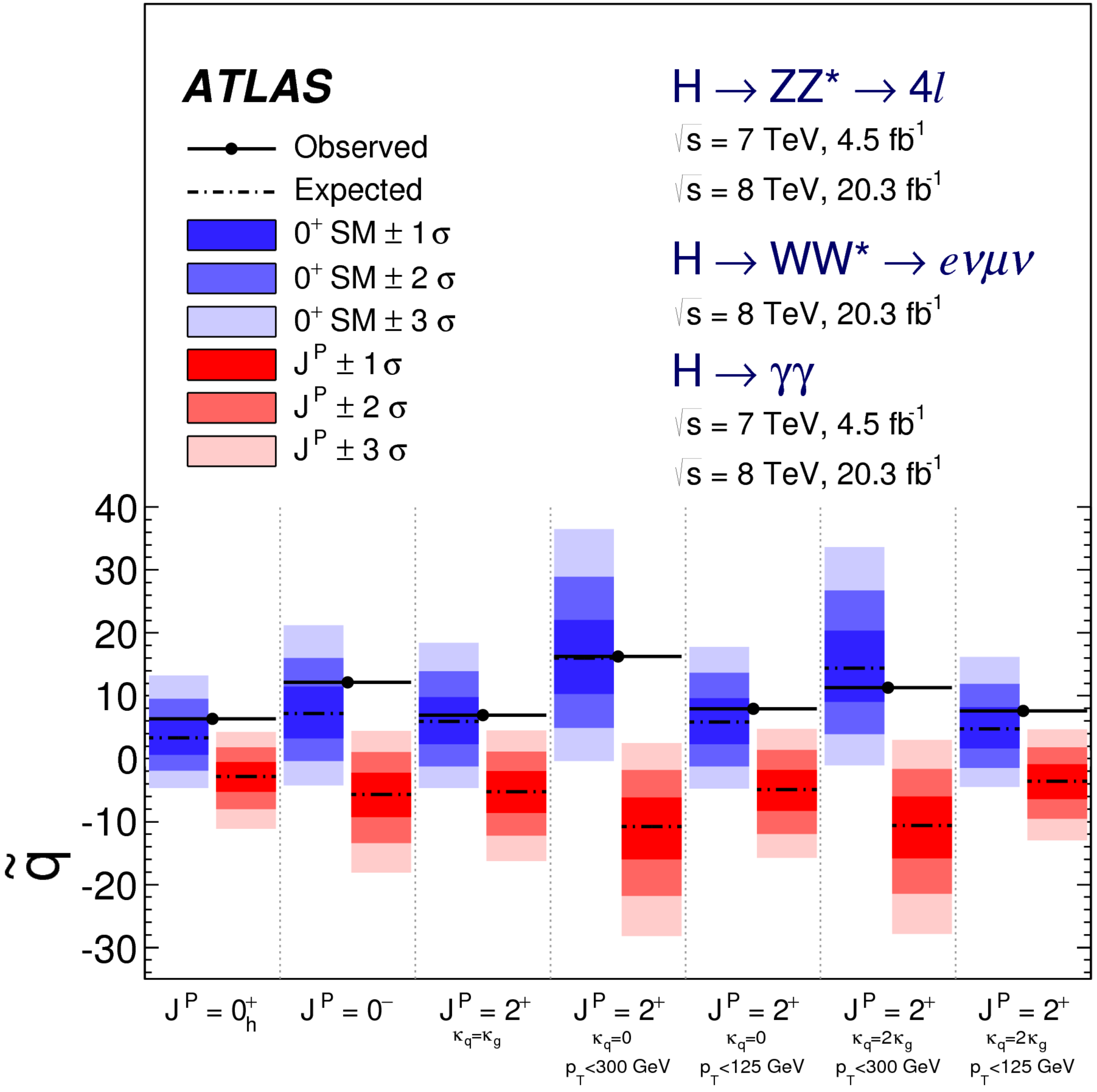


- SM $J^P = 0^+$ favored
- Other models disfavored at >99%
- CMS tested many more alternative models negatively

How sure are we?

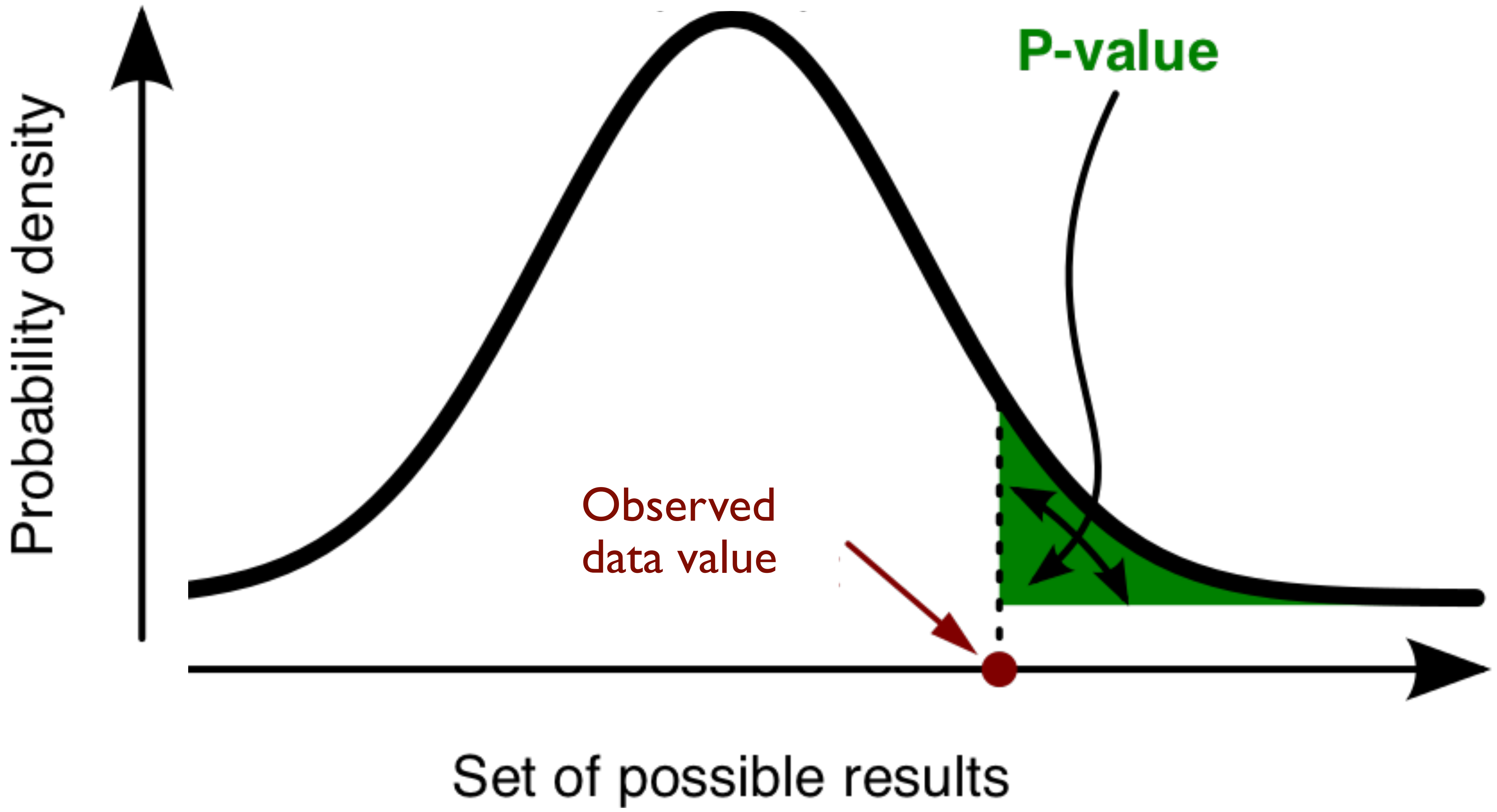
- Calculate the "p-value":

1. Build probability density distribution *f* for background-only hypothesis H_0: $f(x|H_0)$
2. Probability to obtain result x_{obs} or less likely, given $f(x|H_0)$:

$$p = \int_{x_{\mathrm{obs}}}^{\infty} f\left(x|H_0\right)dx$$

- Map p-value to Gaussian standard deviations N_σ:

$$p = \int_{N_\sigma}^{\infty} \frac{e^{-2y^2/2}}{\sqrt{2\pi}}dy$$



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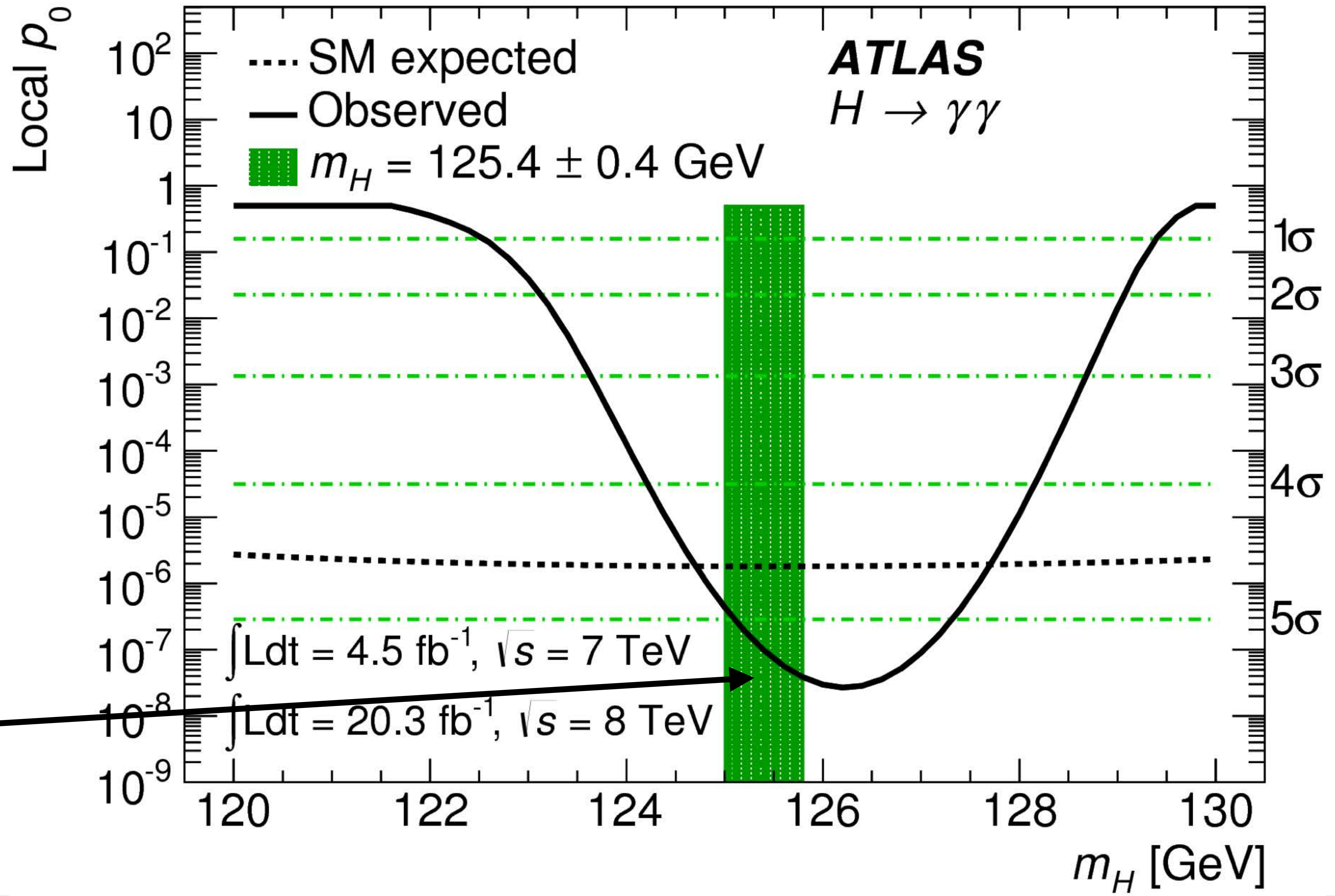
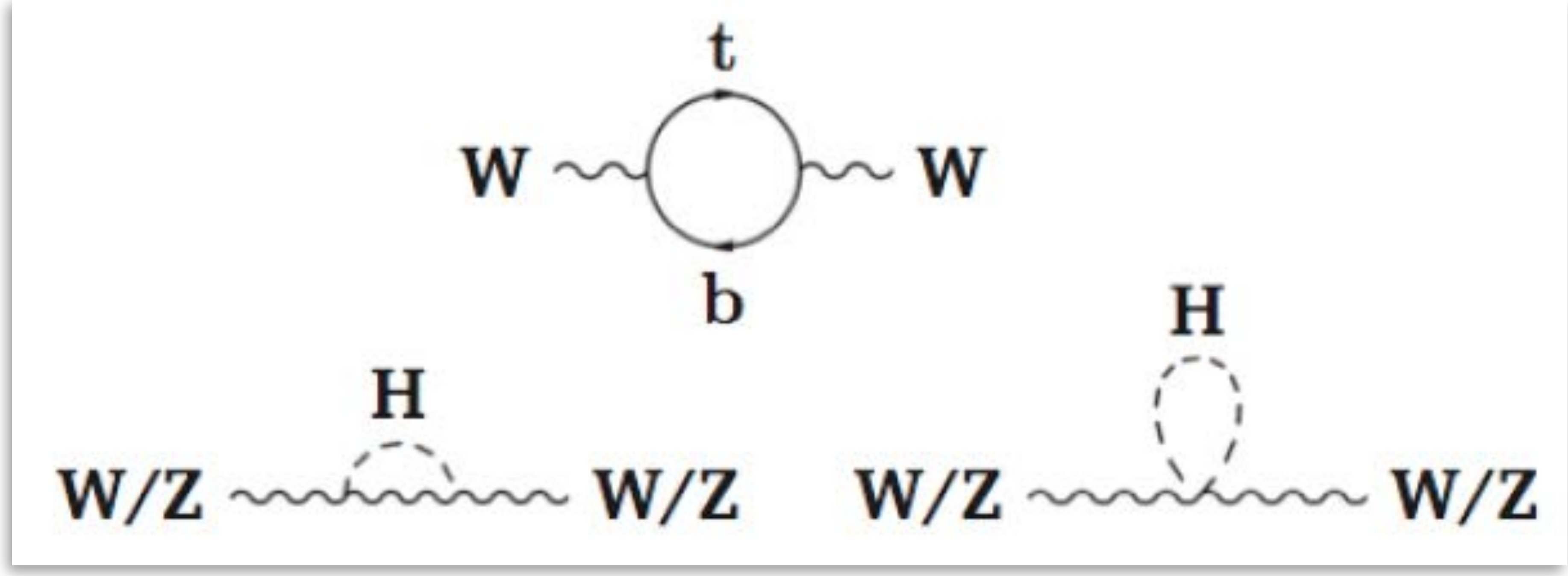
- Significance: **5.2σ**

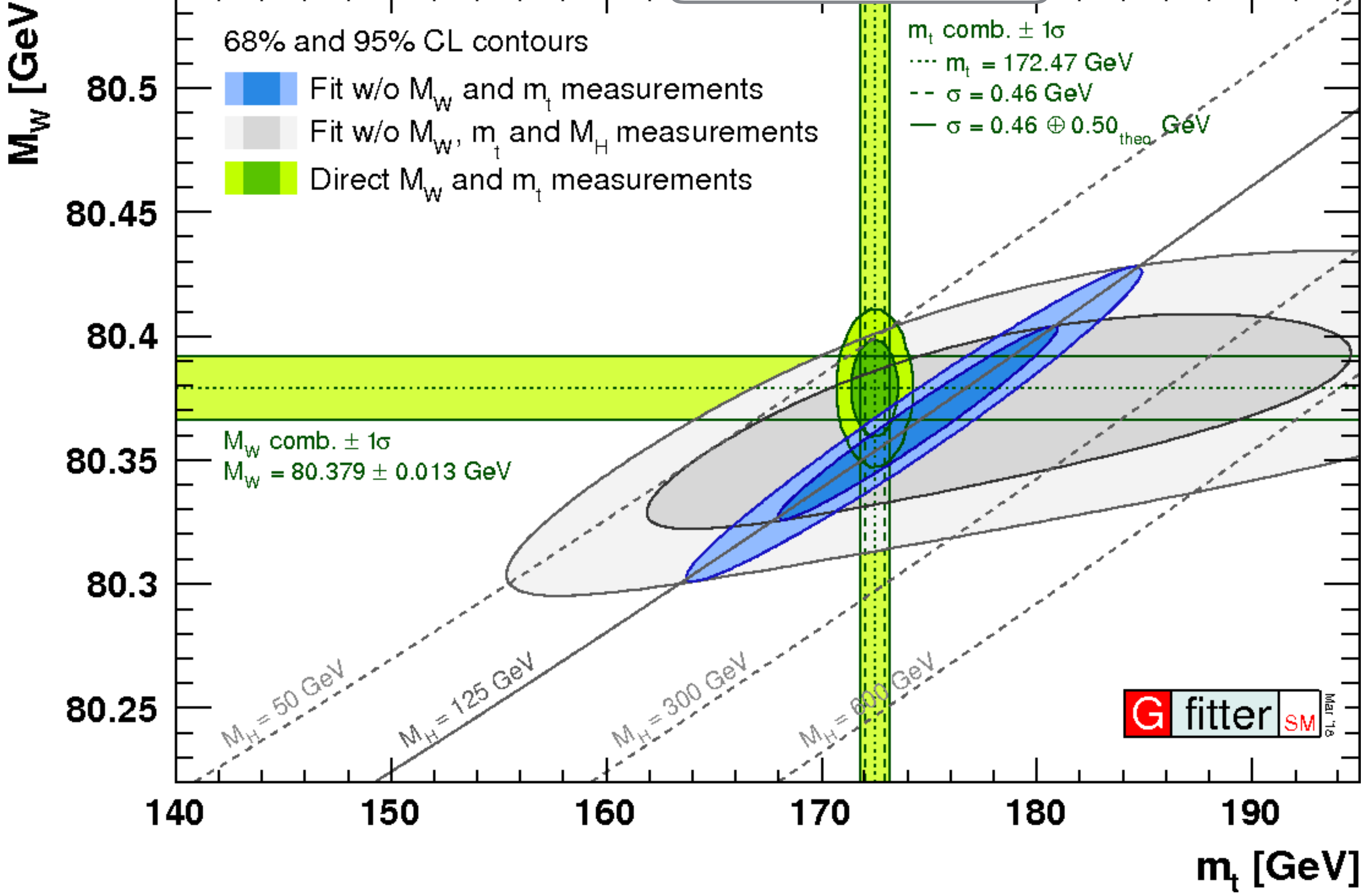


Impact of m_H

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



arXiv:1803.01853



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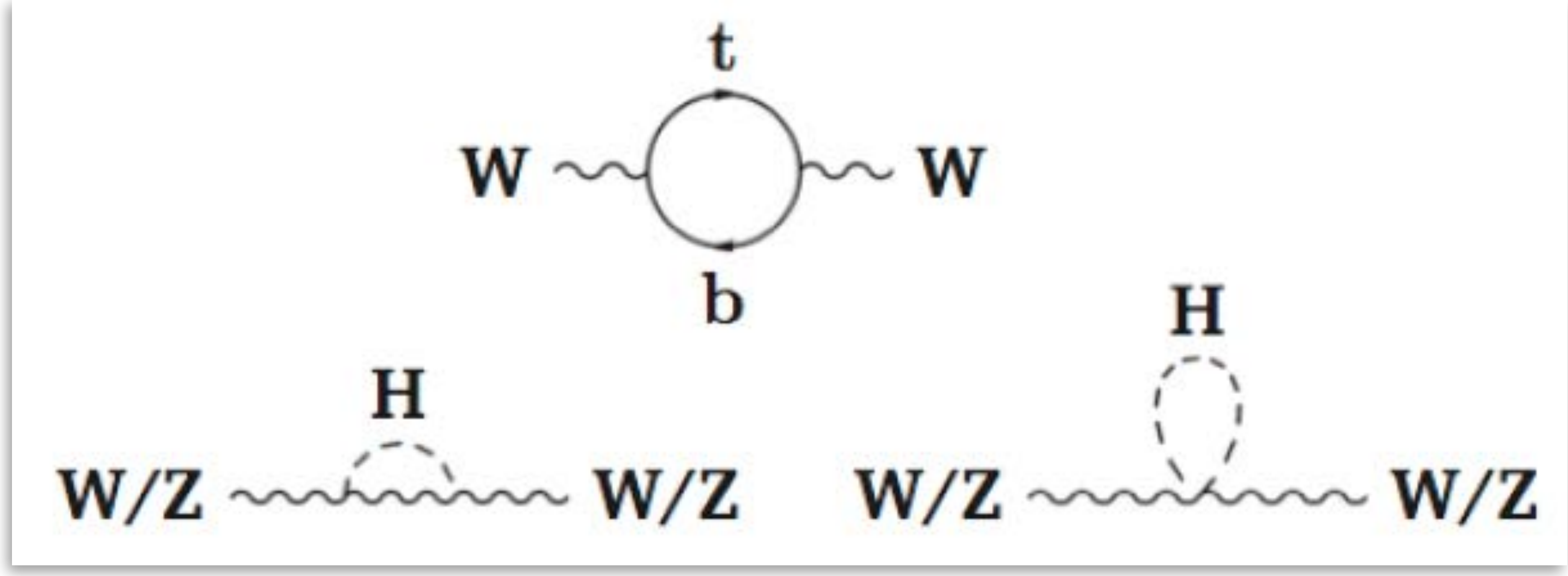

- Mesurement: $m_W = 80.379 \pm 0.013$ GeV
- Impact on m_W in electroweak fit:
  Δm_W(Top) = ±2.7 MeV, **Δm_W(H) = ±0.1 MeV**

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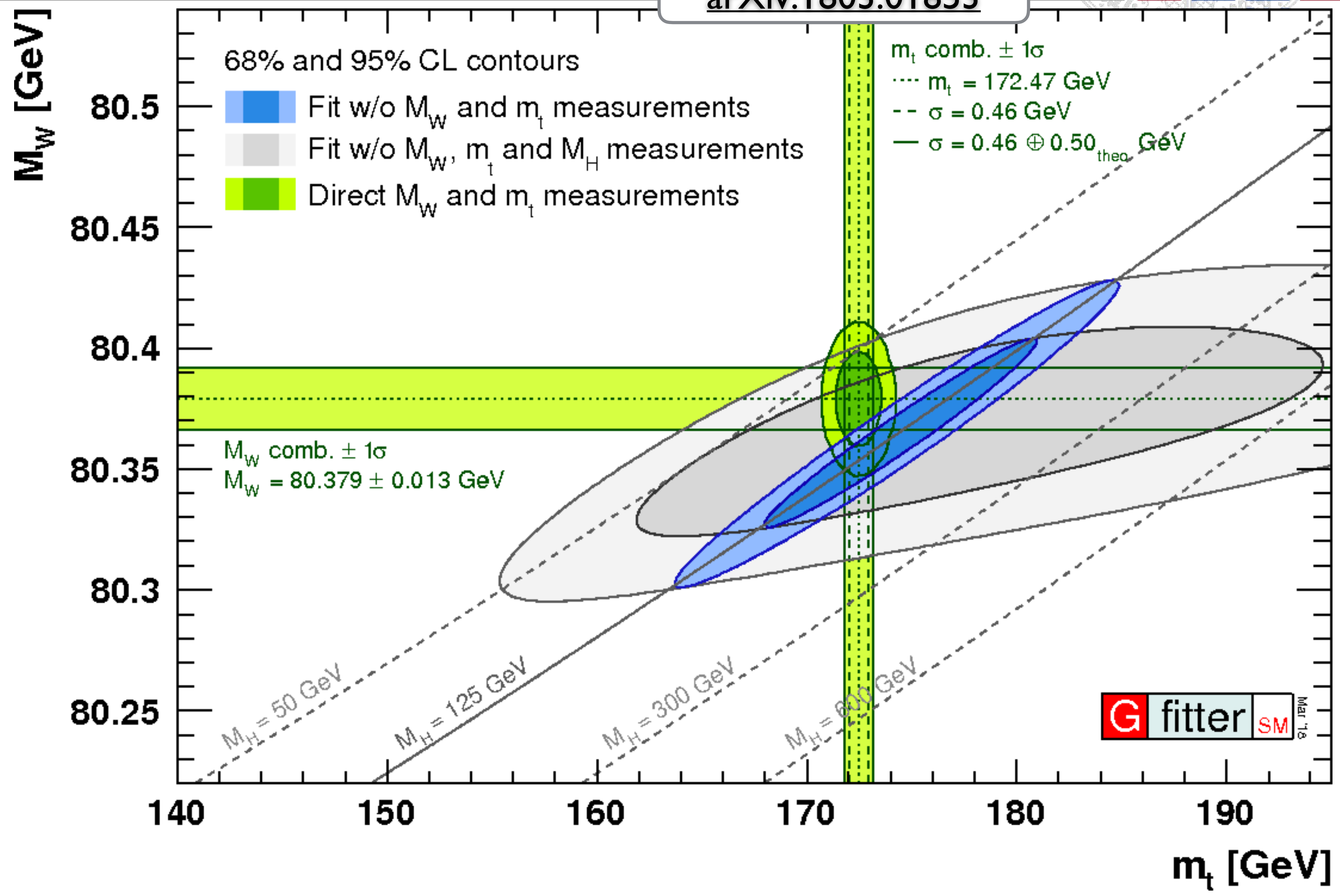

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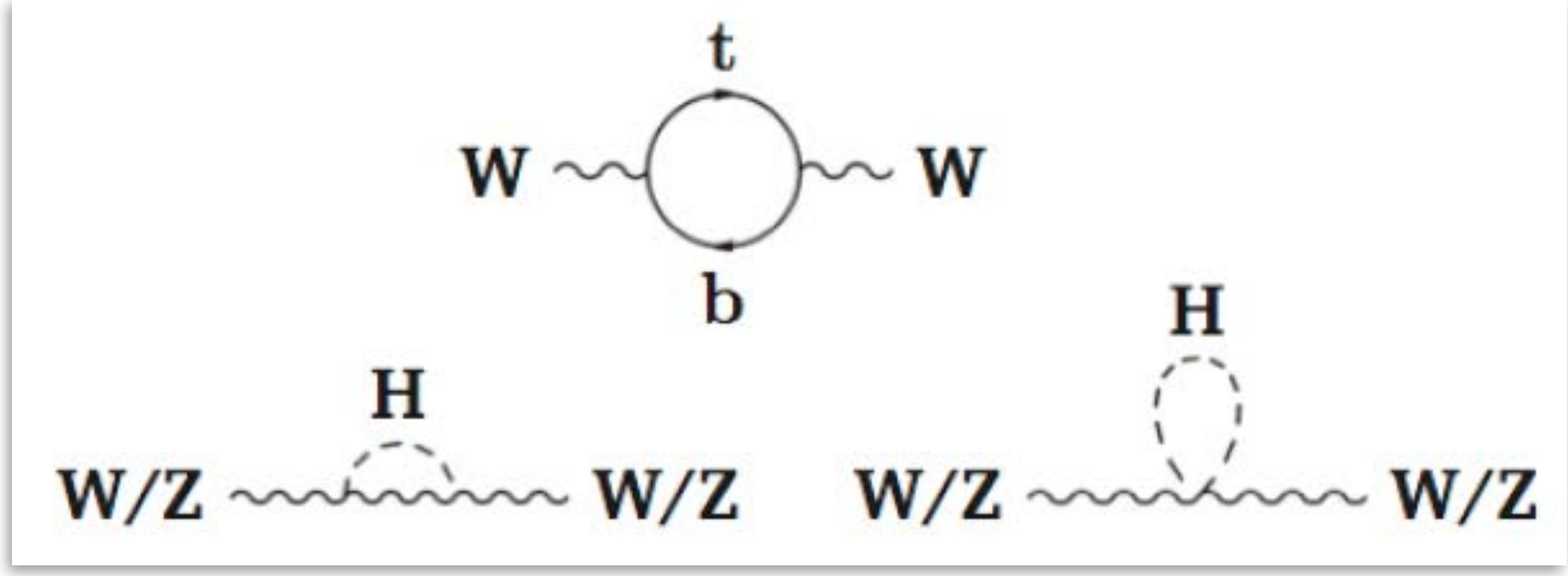

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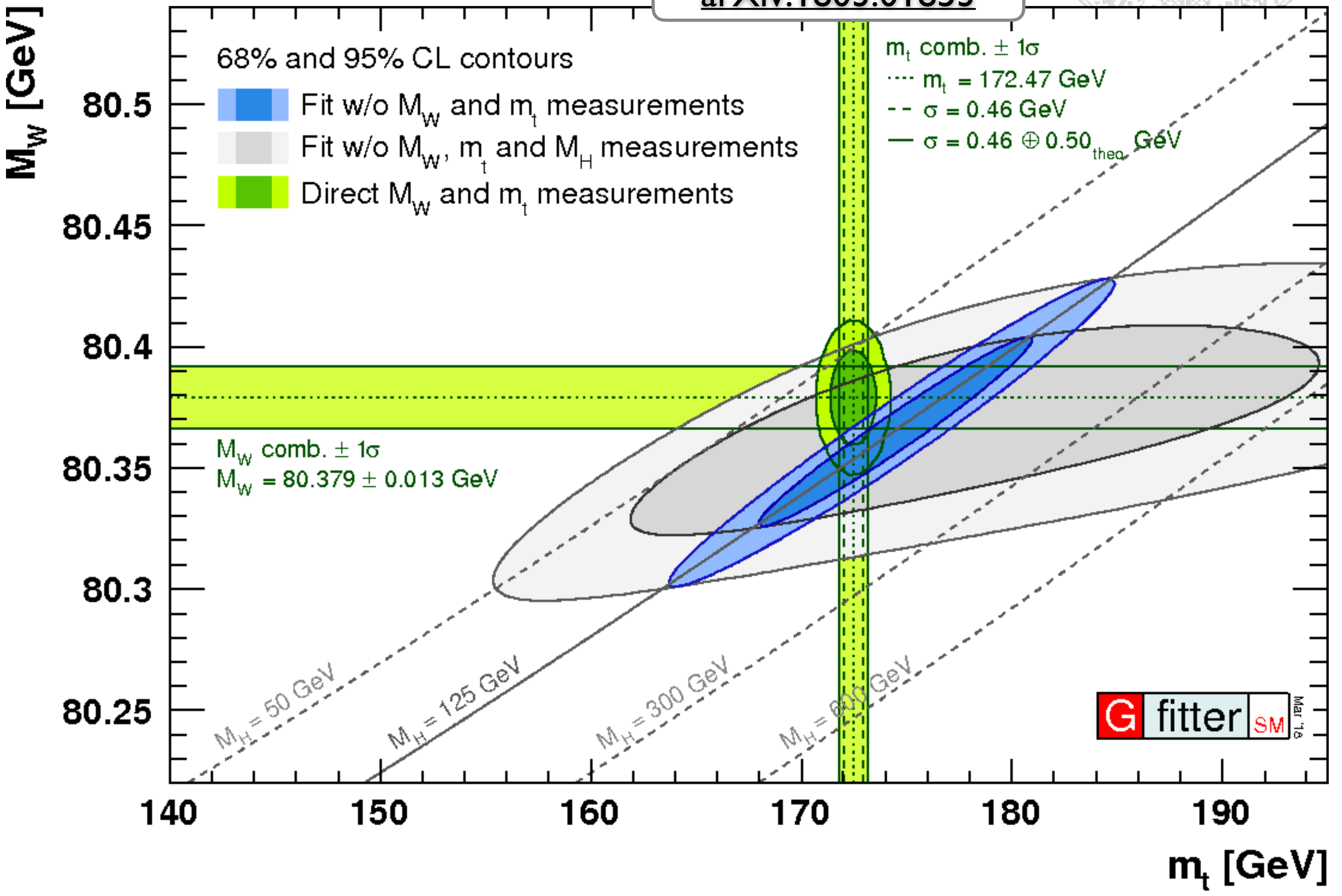
  $\Delta m_W(\text{Top}) = \pm 2.7$ MeV, **$\Delta m_W(H) = \pm 0.1$ MeV**

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

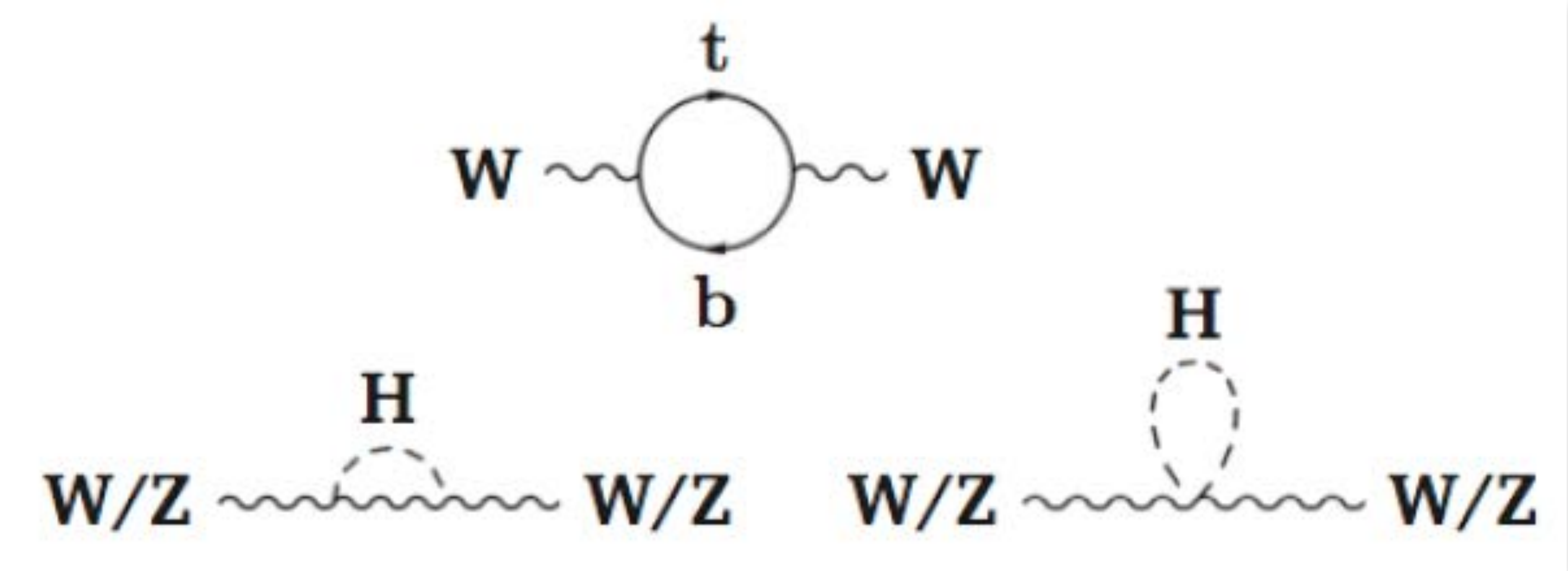
arXiv:1803.01853



	Δ_{theo}	Δ_{exp}	Δm_H
BR(ZZ)	±1%	~10%	±2.5%
σ_{VBF}	±2%	~19%	±0.3%

Impact of m_H

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



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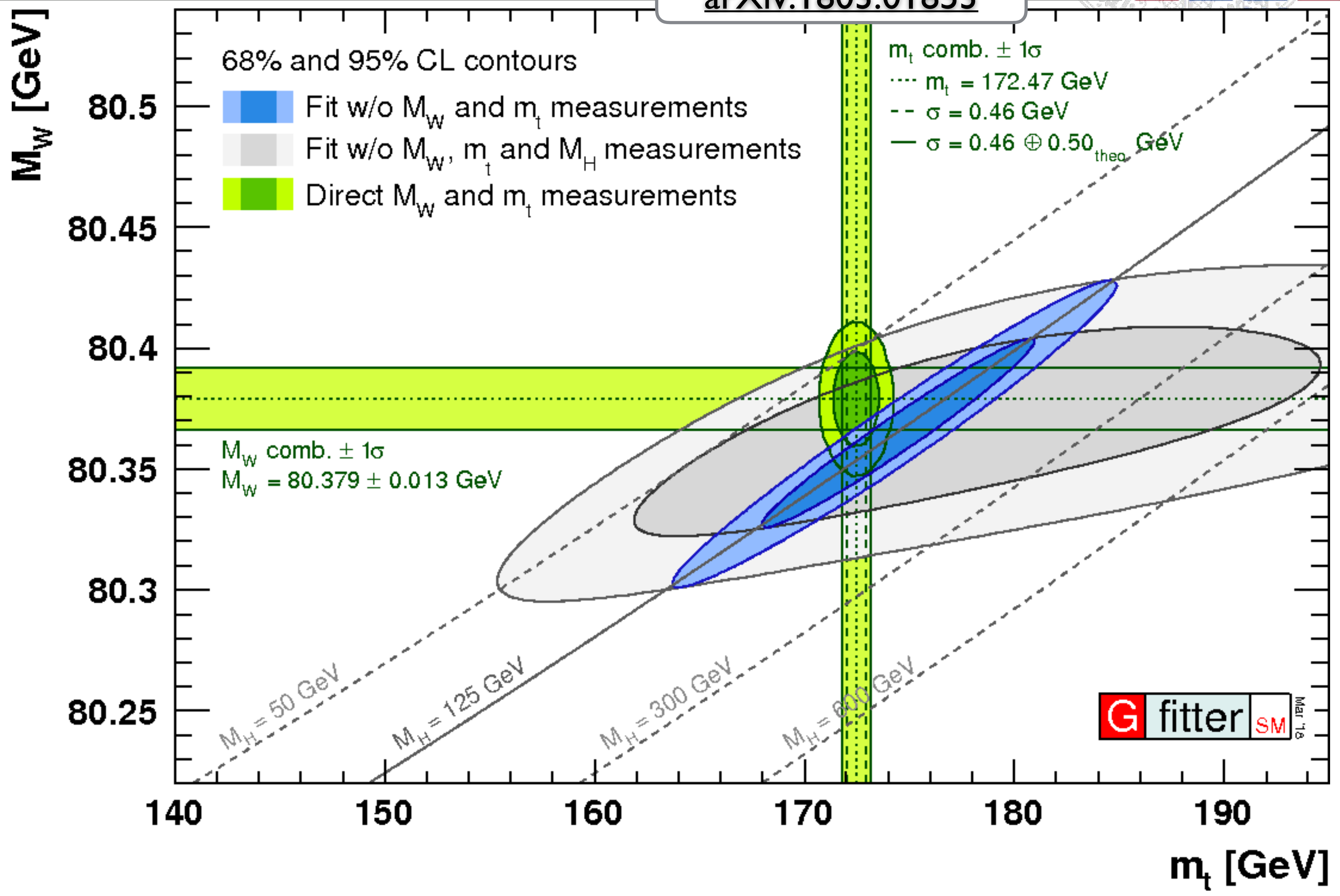

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	Δ_{theo}	Δ_{exp}	Δm_H
BR(ZZ)	±1%	~10%	±2.5%
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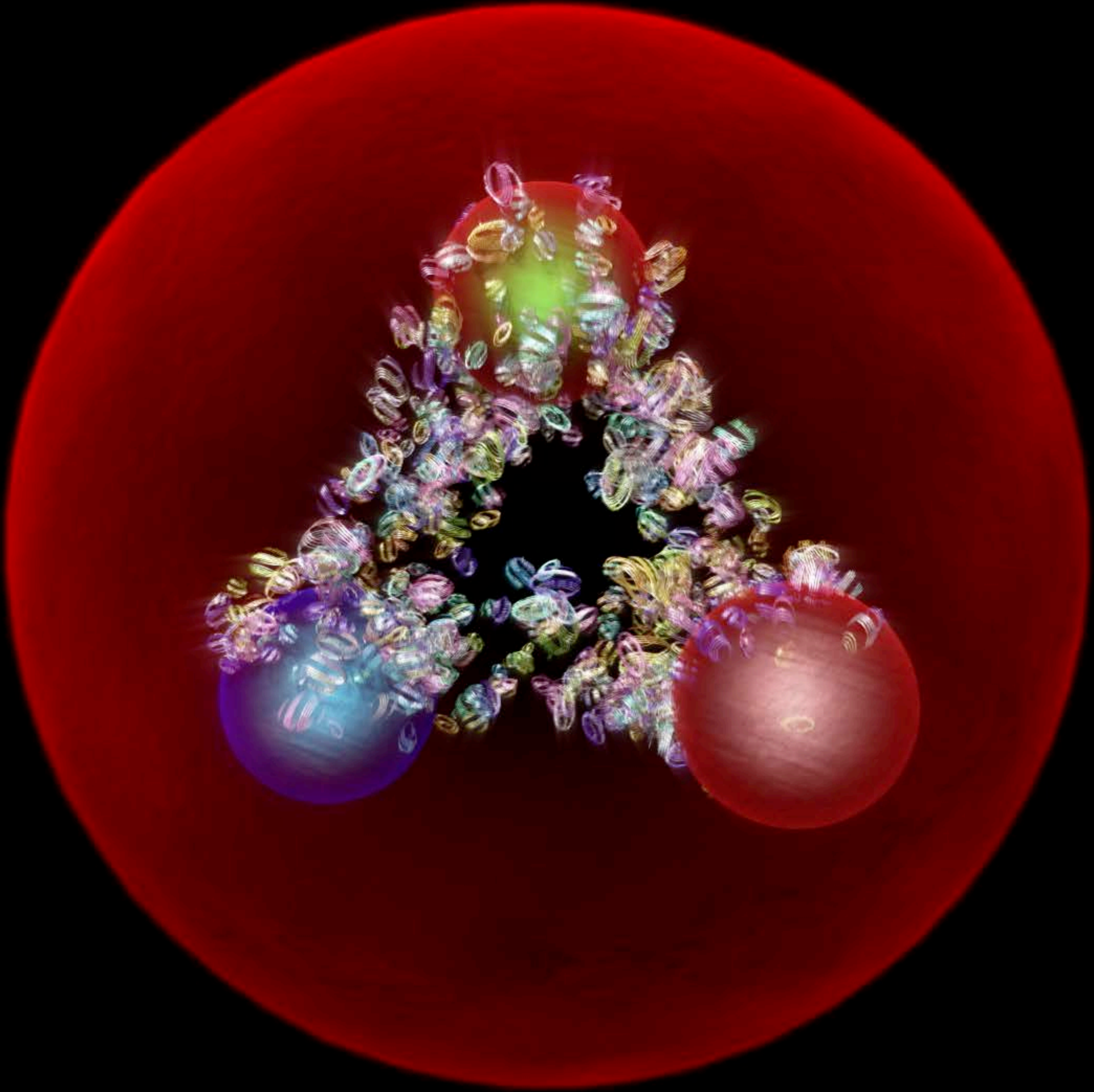
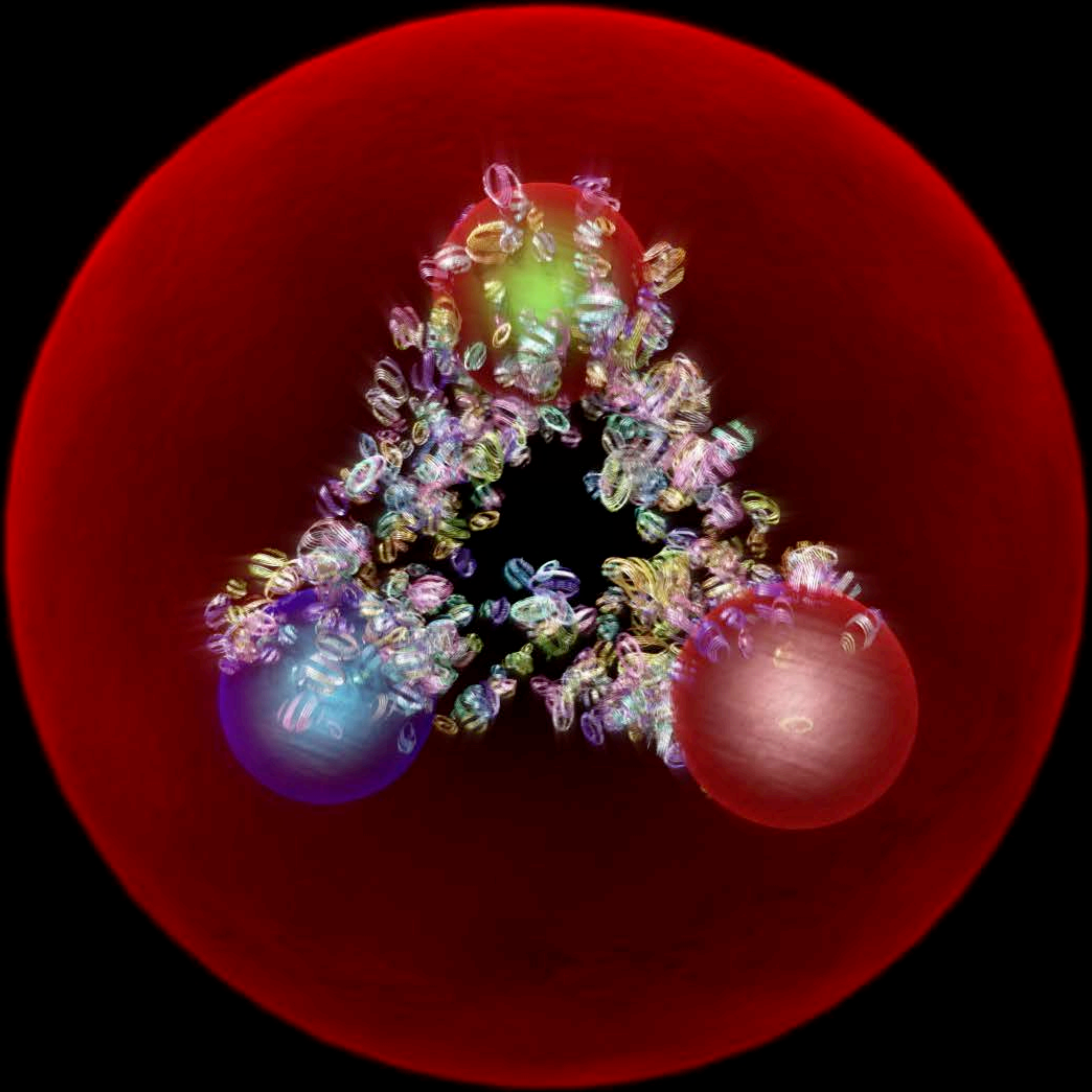
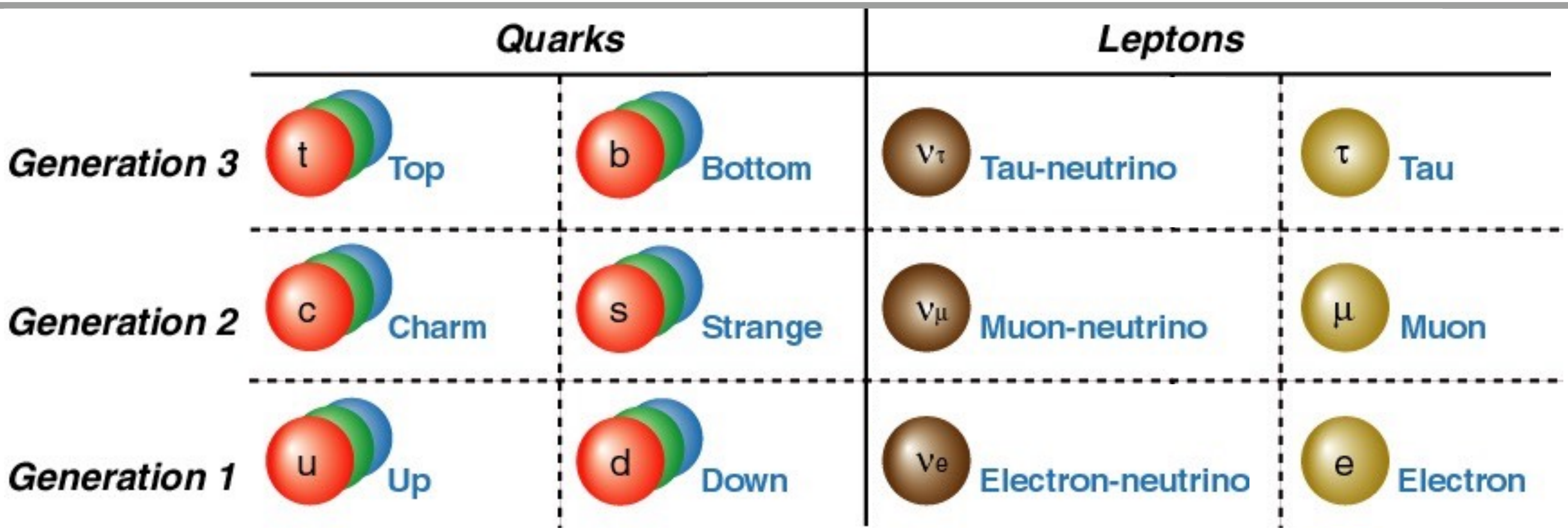
⇒ Measurement precision of m_H good enough for this

  - but precise measurement important!





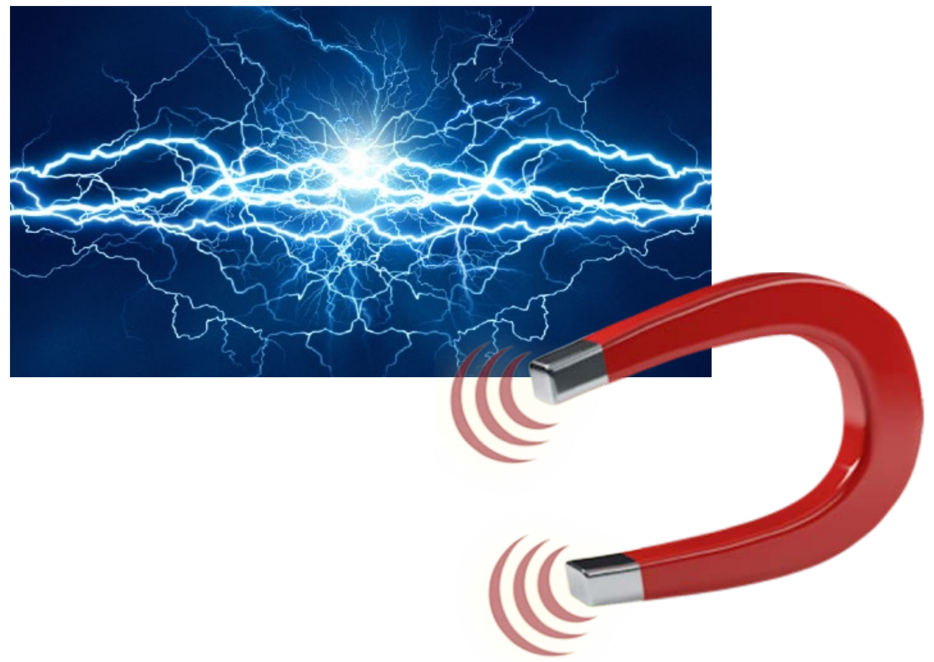
Matter

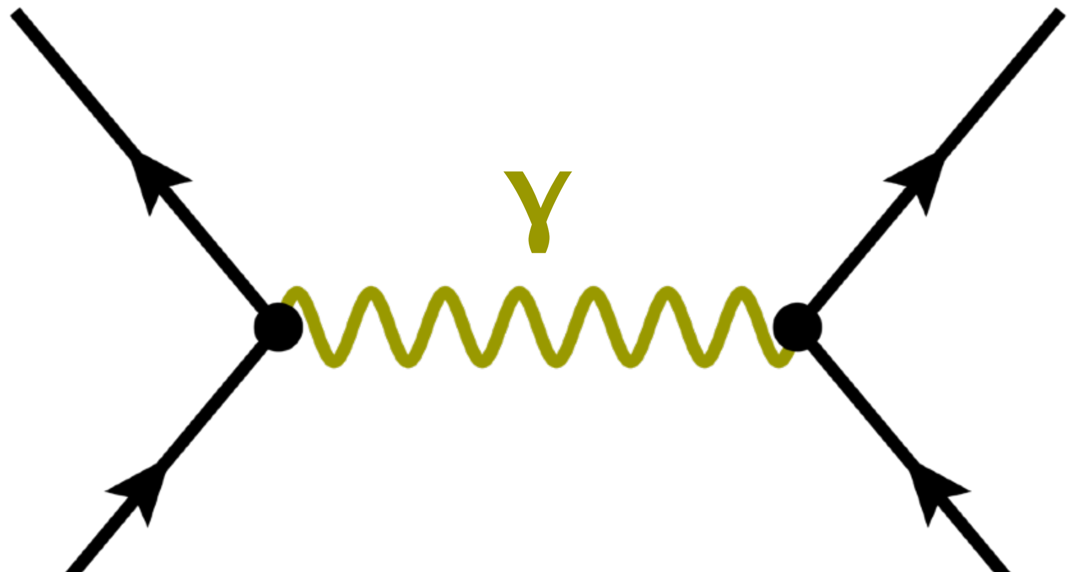


	Quarks		Leptons	
Generation 3	t Top	b Bottom	ν_τ Tau-neutrino	τ Tau
Generation 2	c Charm	s Strange	ν_μ Muon-neutrino	μ Muon
Generation 1	u Up	d Down	ν_e Electron-neutrino	e Electron

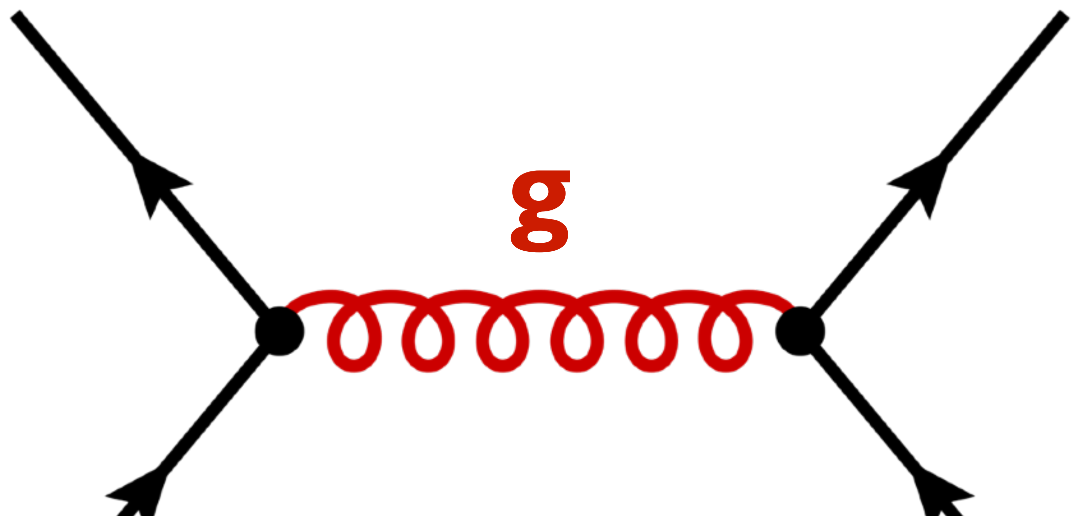
- Masses increase with every “generation”
  - $m_e \approx 0.5$ MeV
  - $m_\mu \approx 106$ MeV
  - $m_{top} \approx 173000$ MeV = 173 GeV ($\approx m_{Gold}$)

Forces

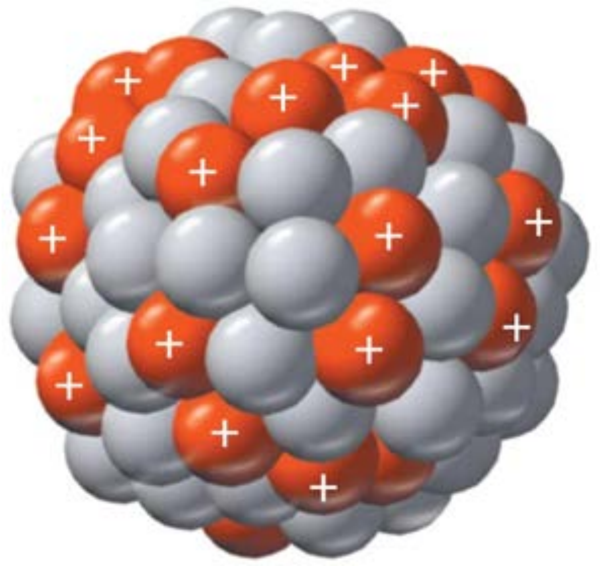


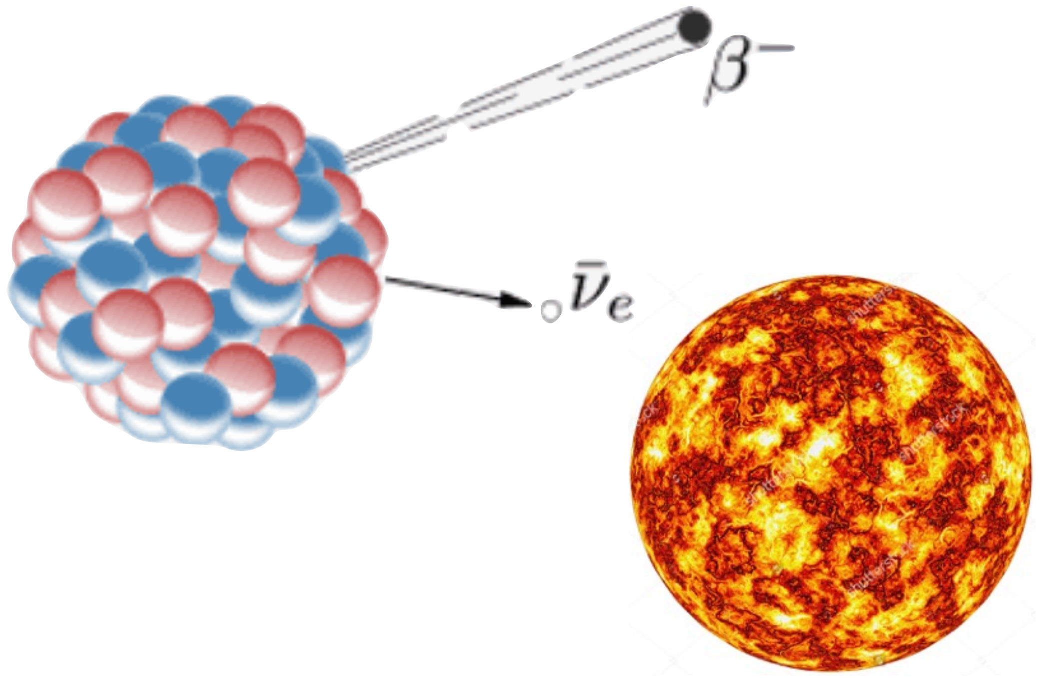


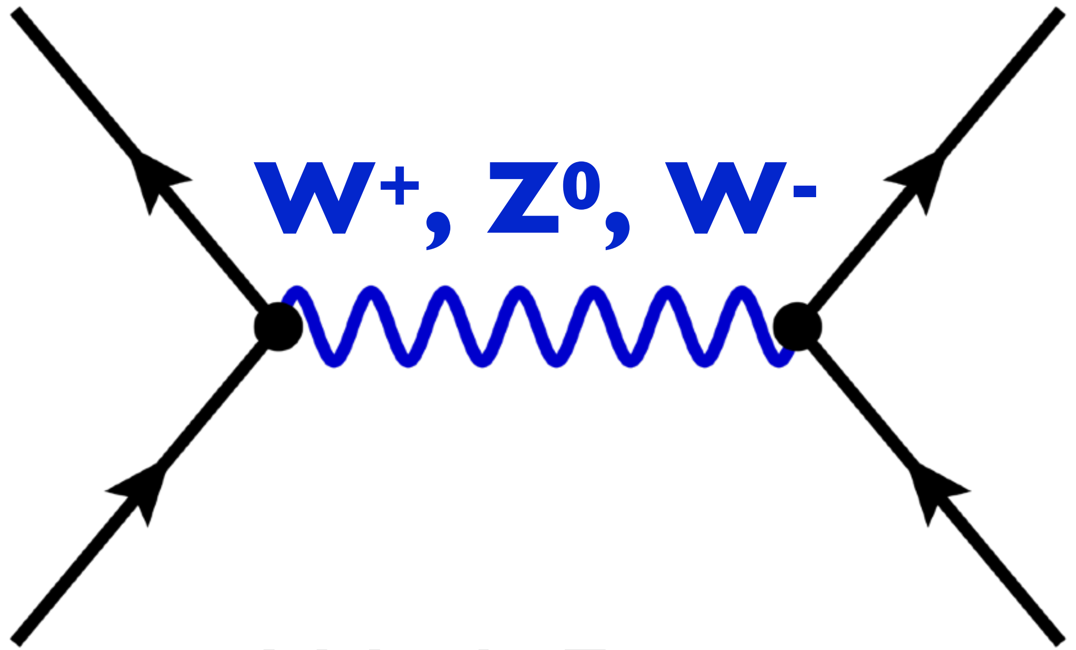
Elektromagnetism



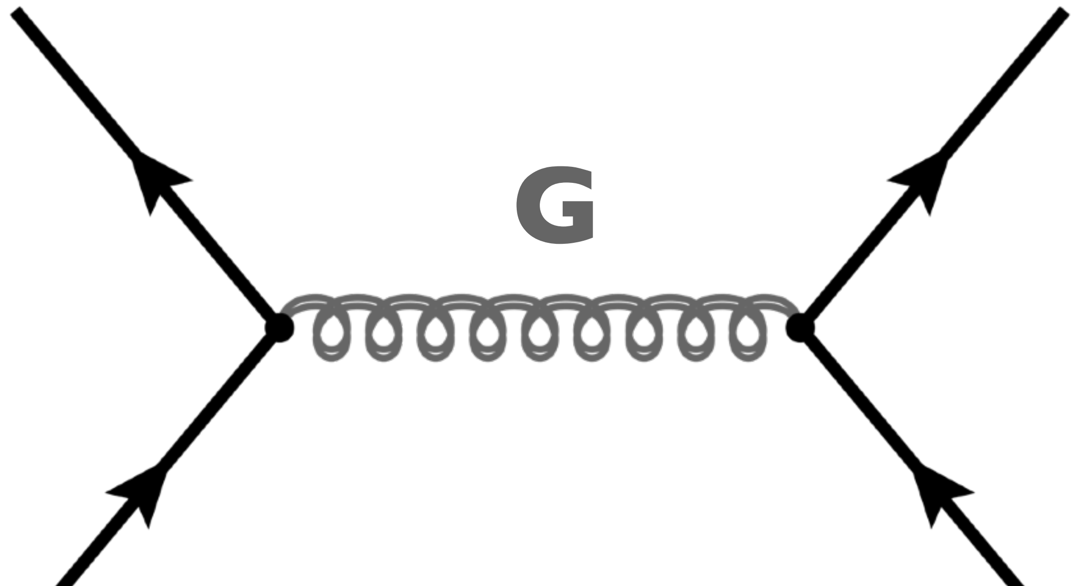
Strong Force







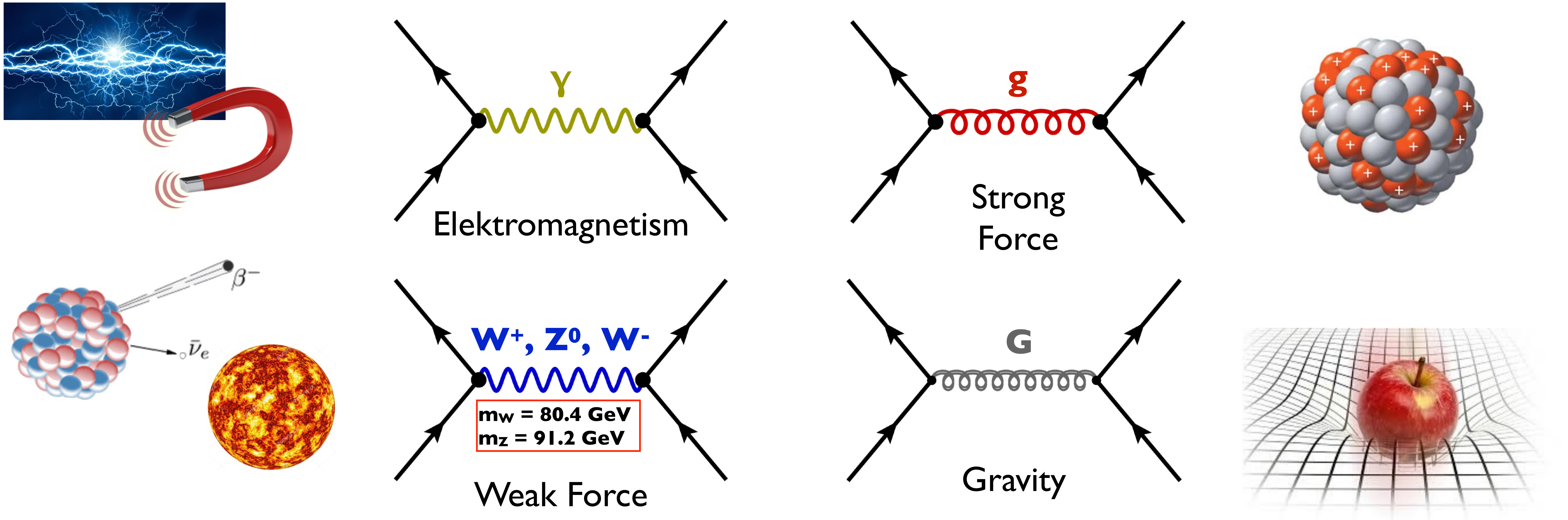
Weak Force



Gravity

- Carriers of forces:
  - Photon (γ), Gluons (g), $W^{\pm}$ and Z^0 Bosons
  - should be massless…

Forces



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