Precision Higgs experiment

The 10th Annual
Large Hadron Collider Physics Conference
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2022 LHCP TAIPEI Online

Karsten Köneke

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UNI FREIBURG

on behalf of the ATLAS & CMS Collaborations

18. 5. 2022

Outline

1. Introduction
2. Mass and width measurements
3. CP coupling structure
4. Fiducial and differential cross sections
5. Simplified Template Cross Sections (STXS)
6. HH
7. Summary

Motivation

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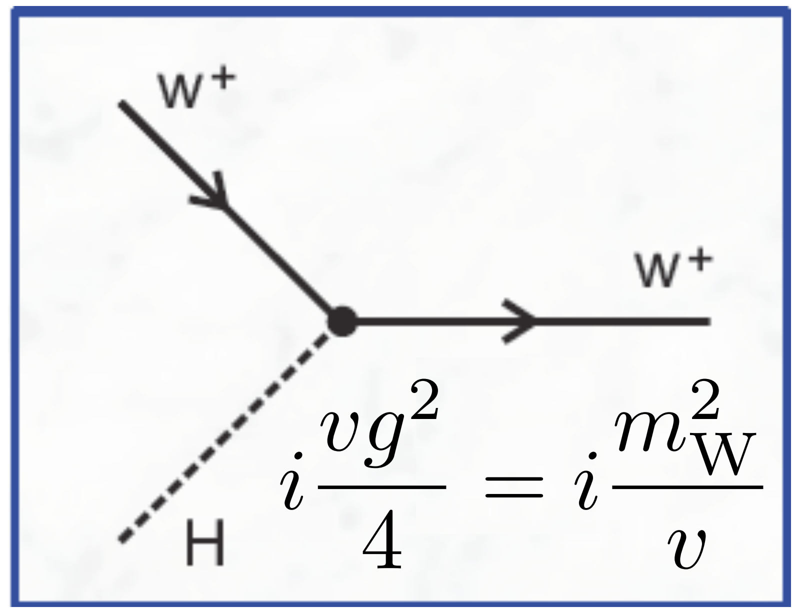
- W boson mass and interaction:

$$\boxed{m_{\mathrm{W}} = \frac{vg}{2}}$$

direct connection



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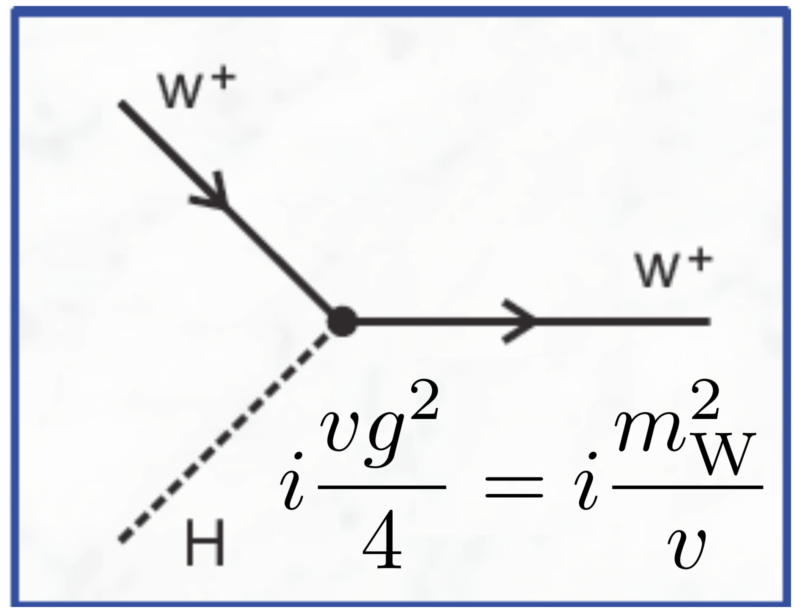
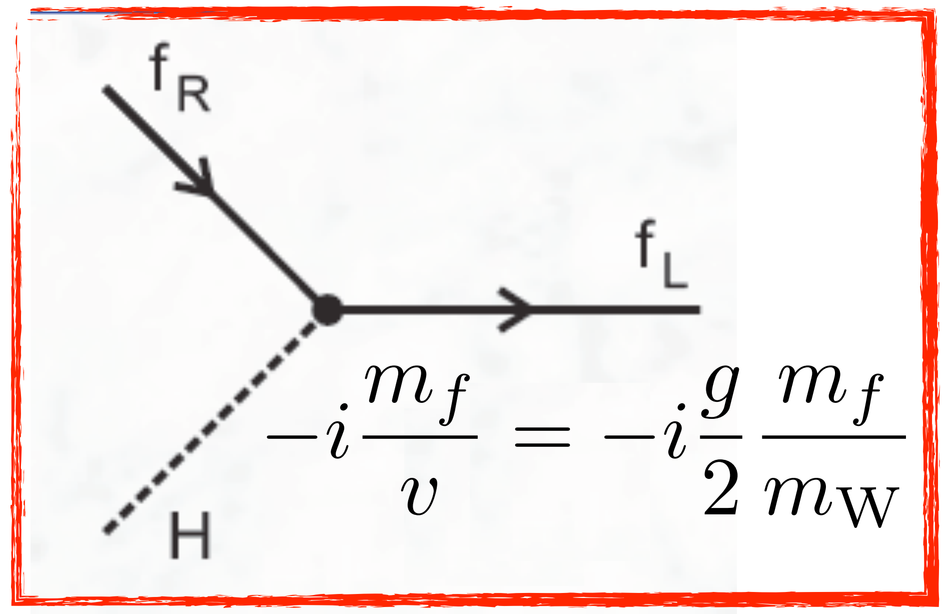


- Fermion masses and Yukawa interactions:

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

direct connection



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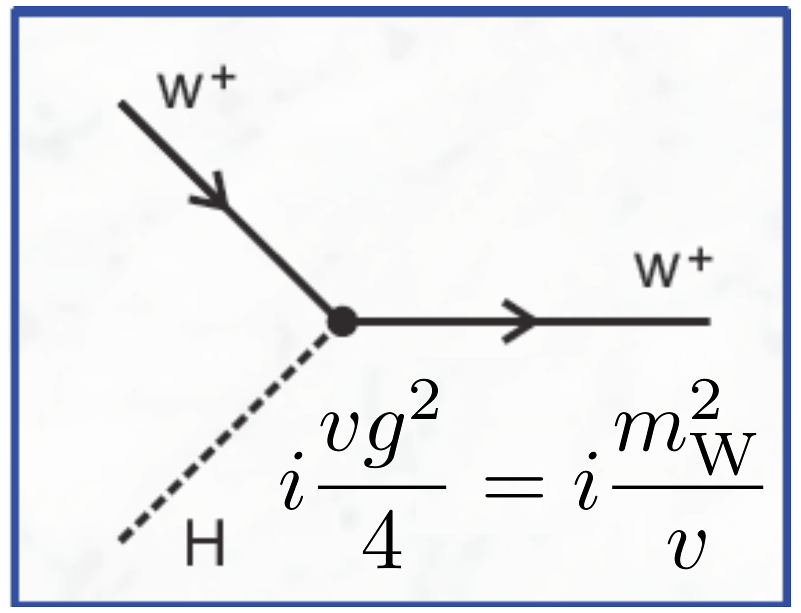

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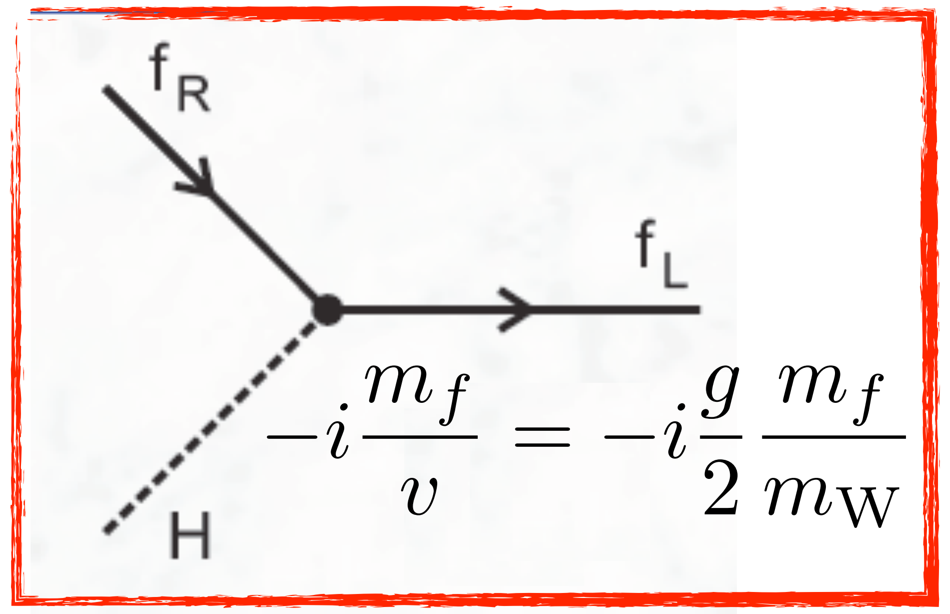
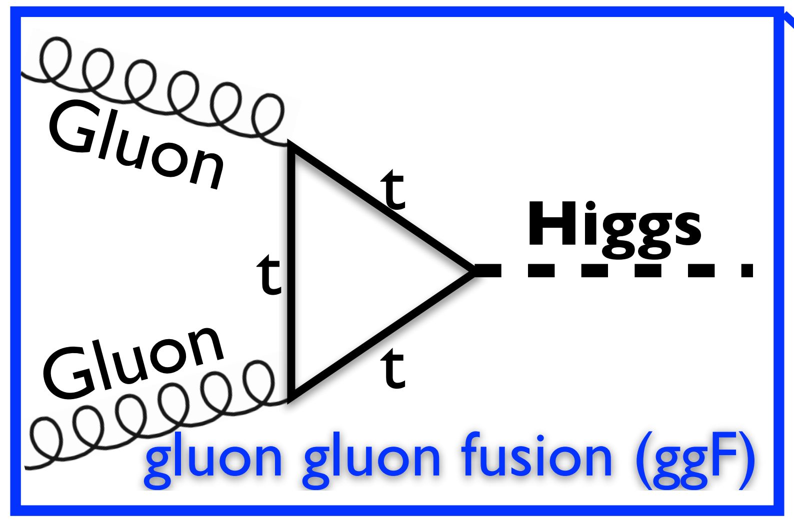


- Higgs potential:

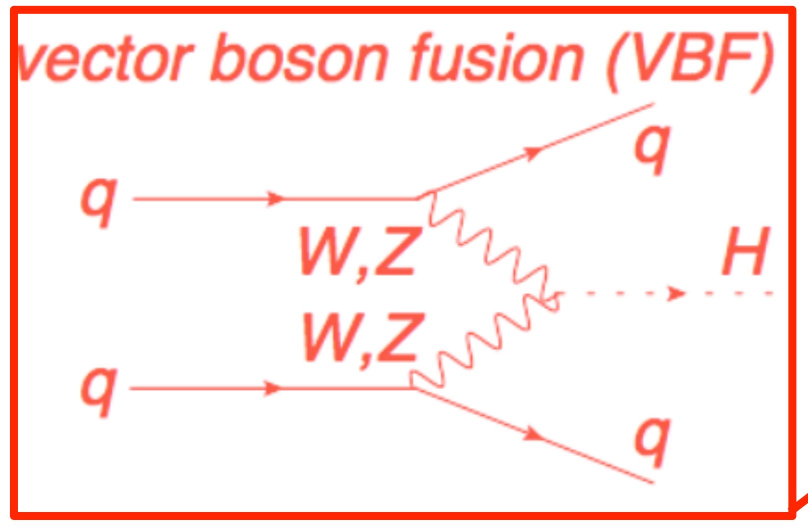
Does HH production exist? ⟷ **In SM:** $\lambda = \frac{1}{2} m_{\mathrm{H}}^2 / v^2$ ⟷ $\mu^2 \left(\phi^\dagger \phi\right) + \lambda \left(\phi^\dagger \phi\right)^2$ H potential as in SM?

Higgs Boson at the LHC

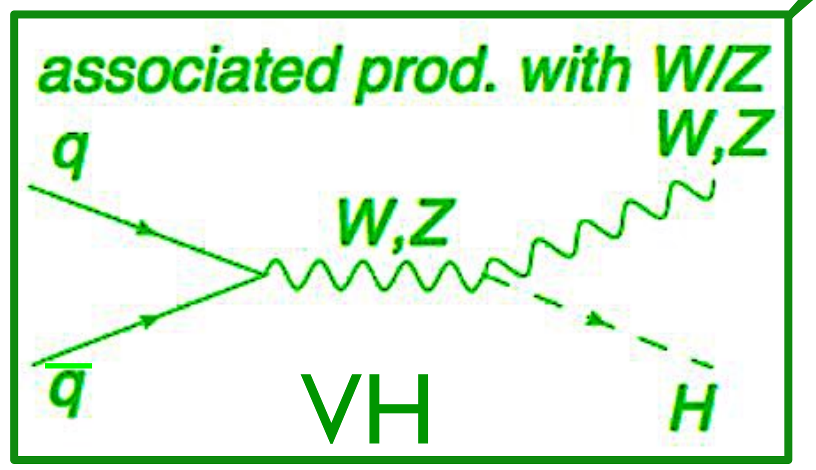
Production



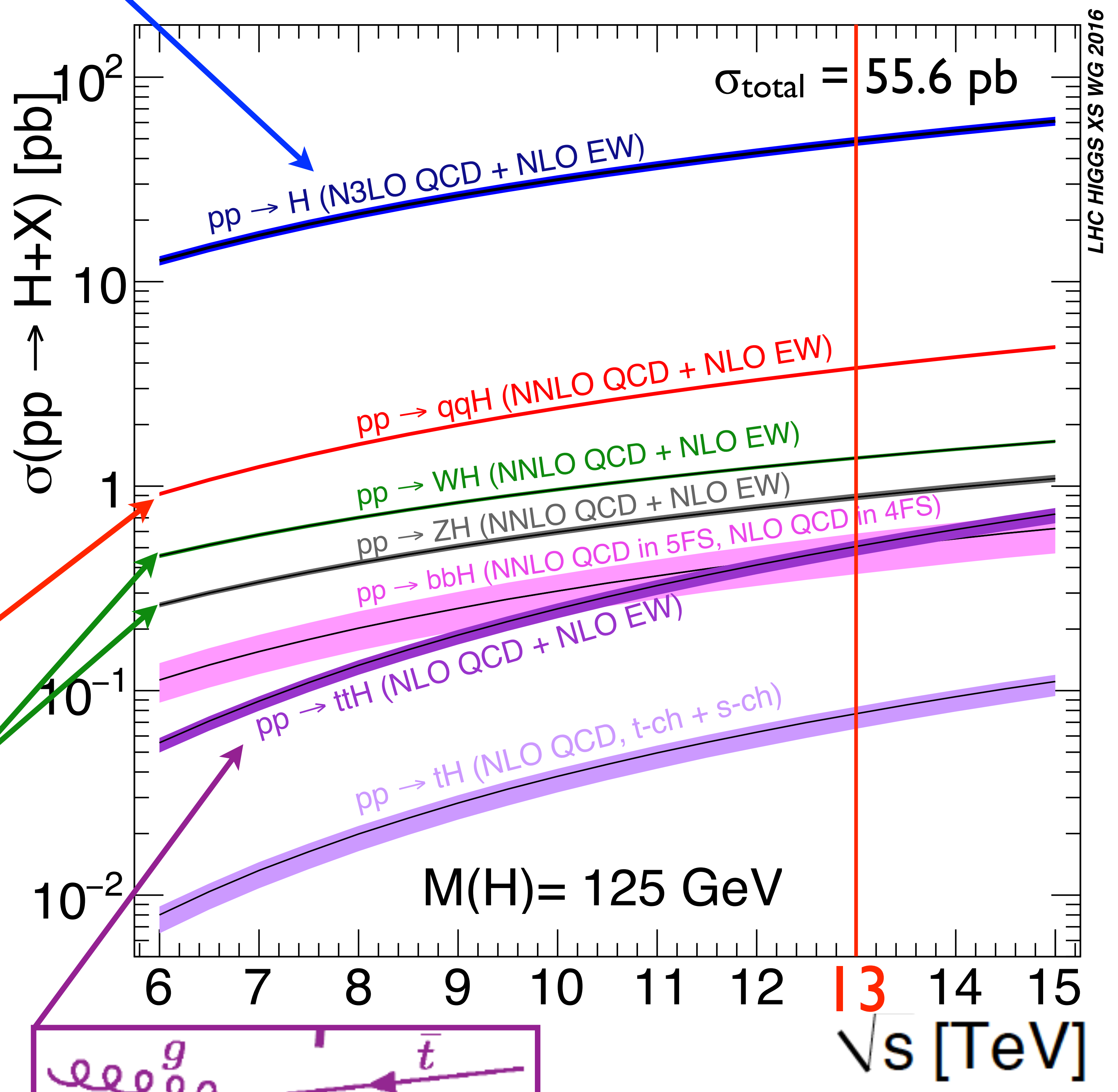
σ_{ggF} = 48.5 pb (87 %)

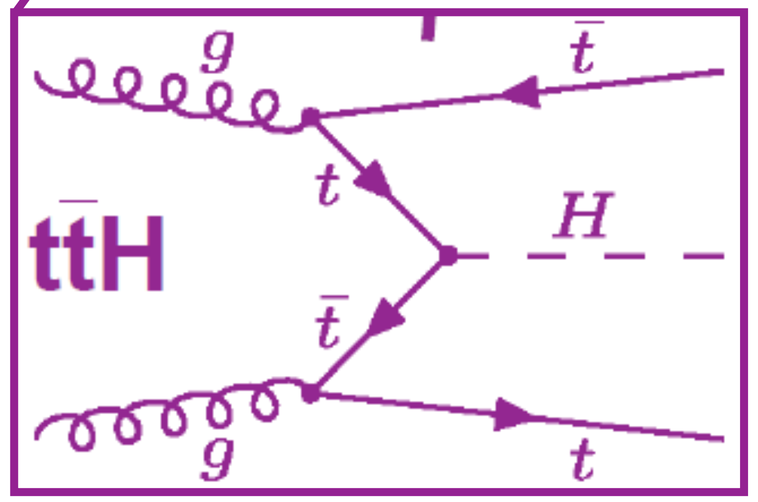


σ_{VBF} = 3.78 pb (7 %)



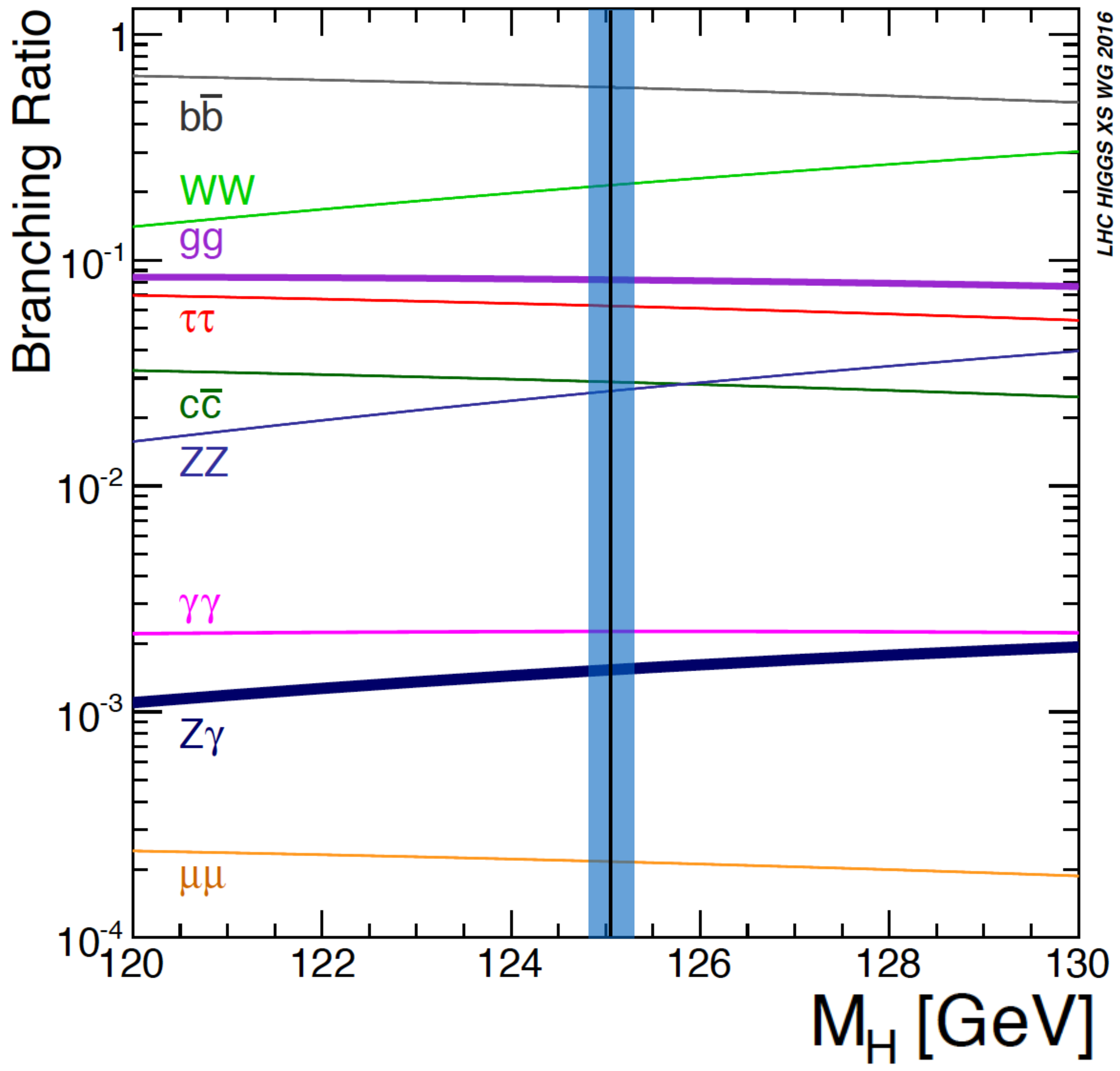
σ_{VH} = 2.3 pb (4 %)

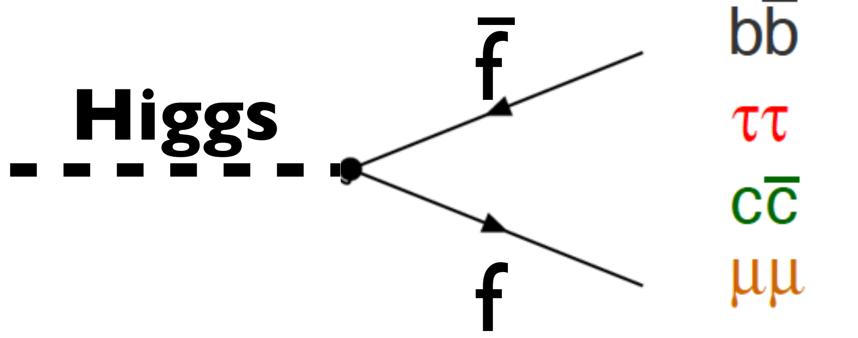


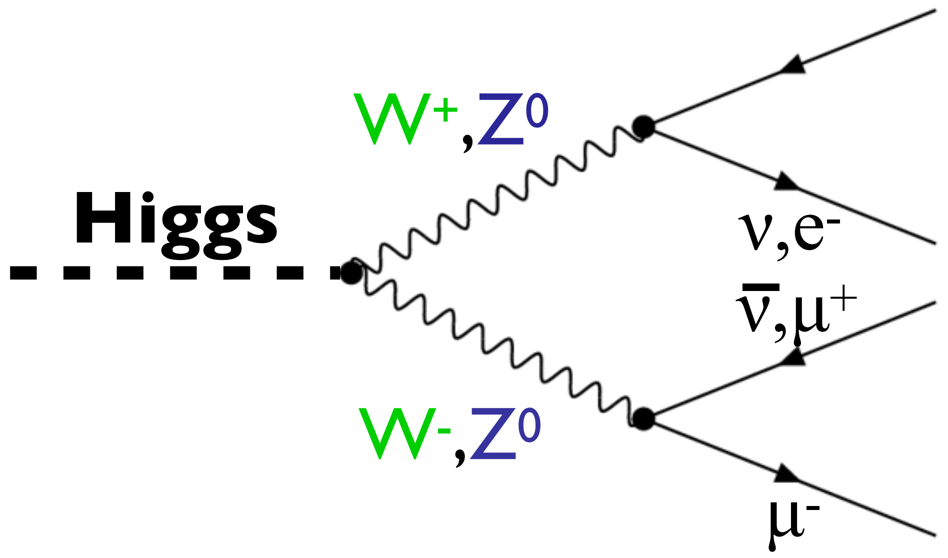


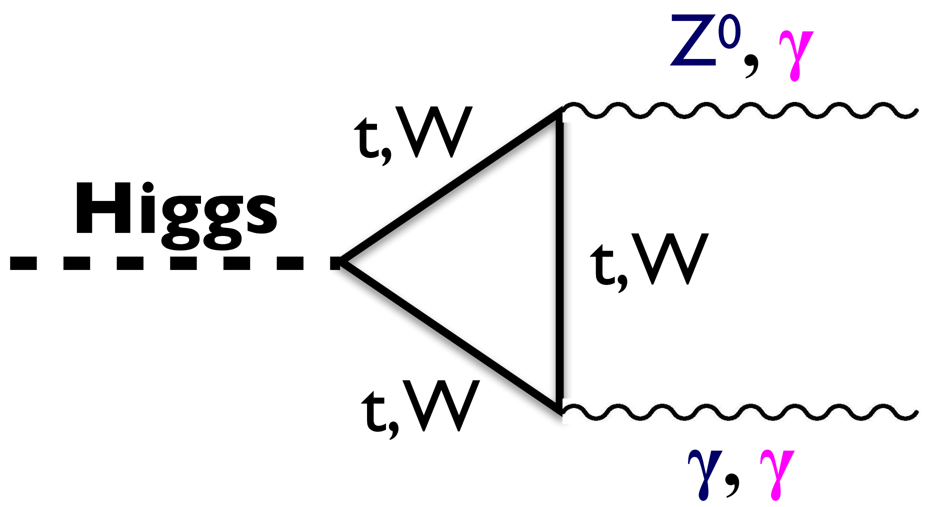
σ_{ttH} = 0.5 pb (0.9 %)

Decay









Karsten Köneke

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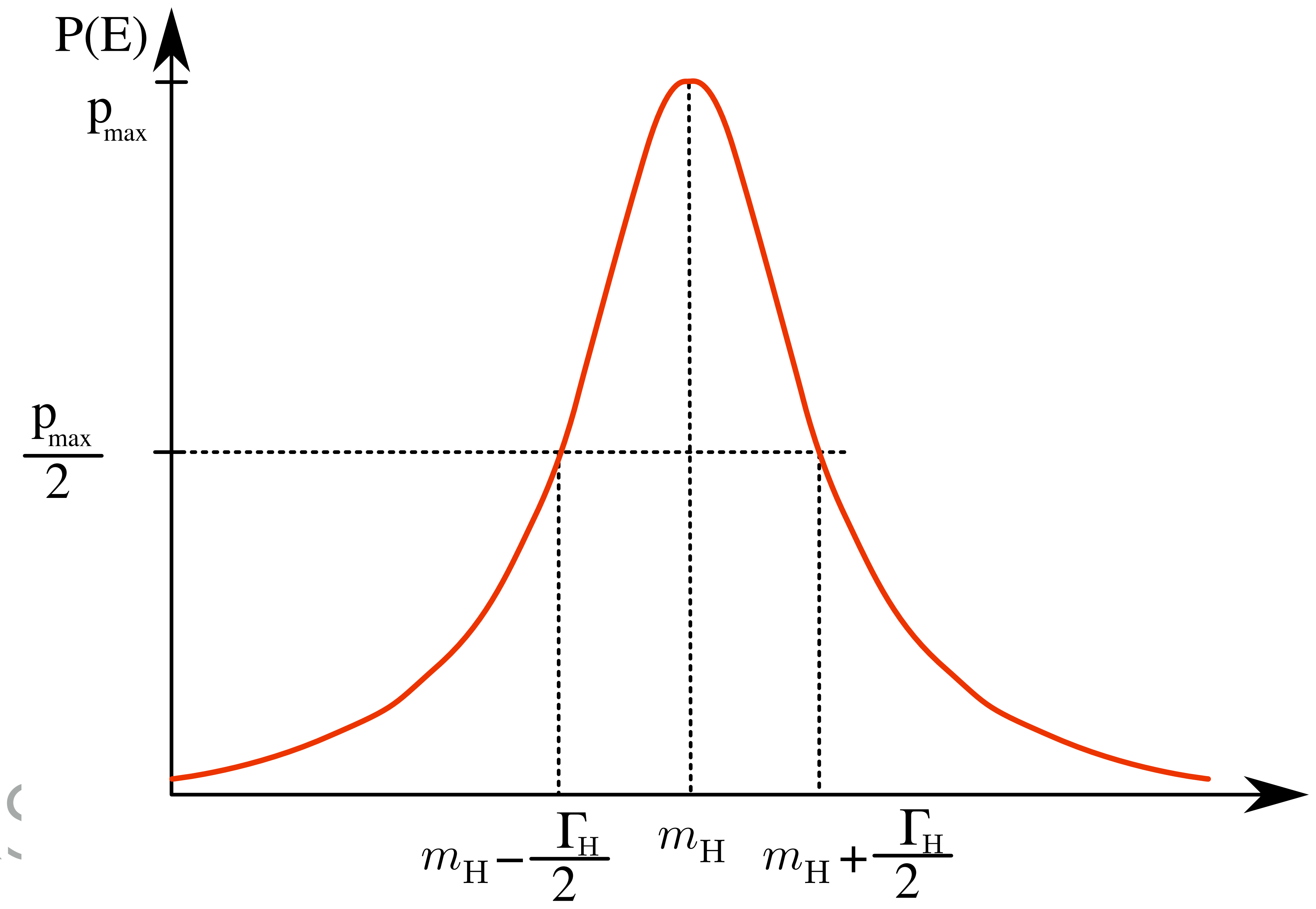
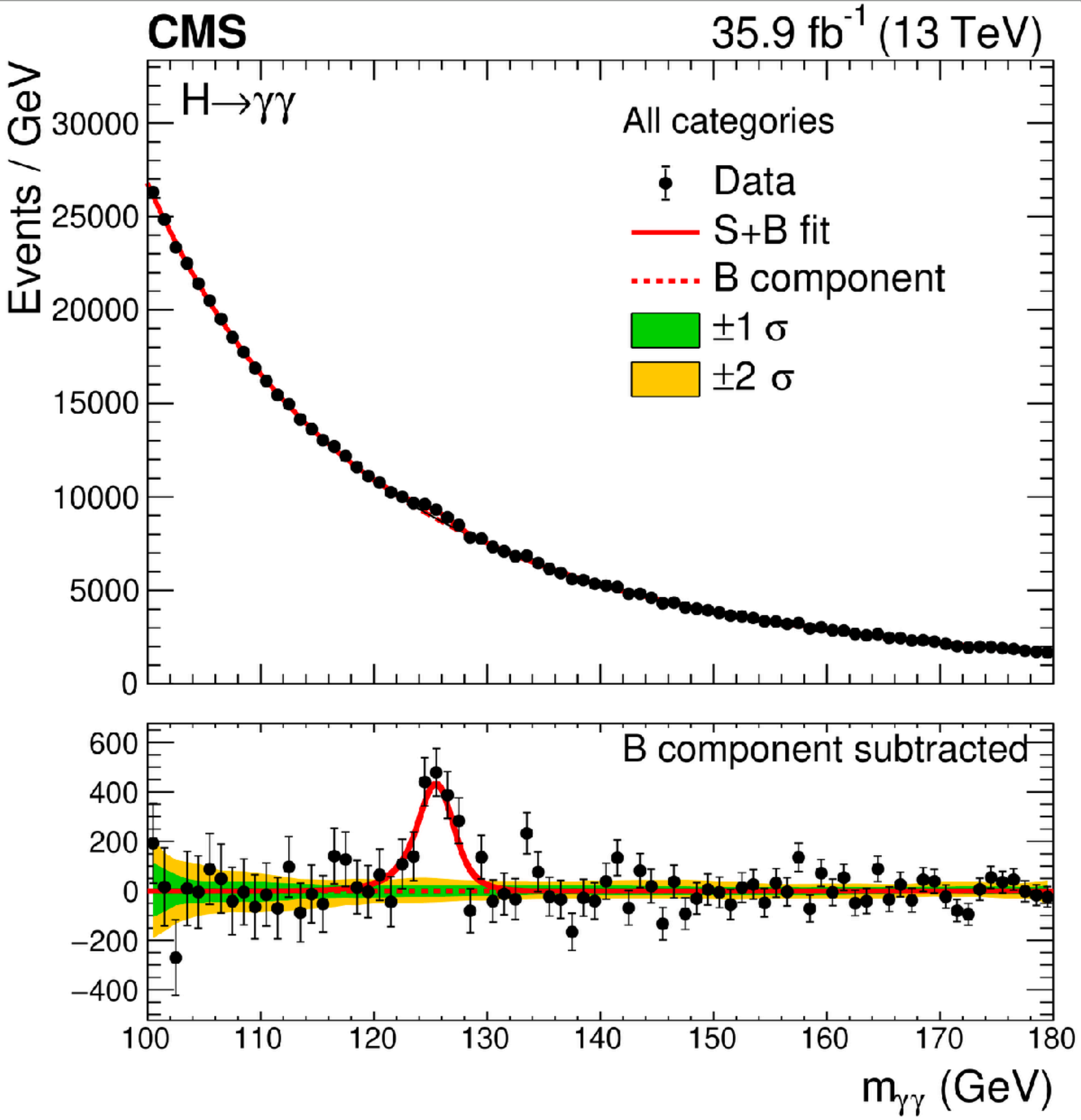
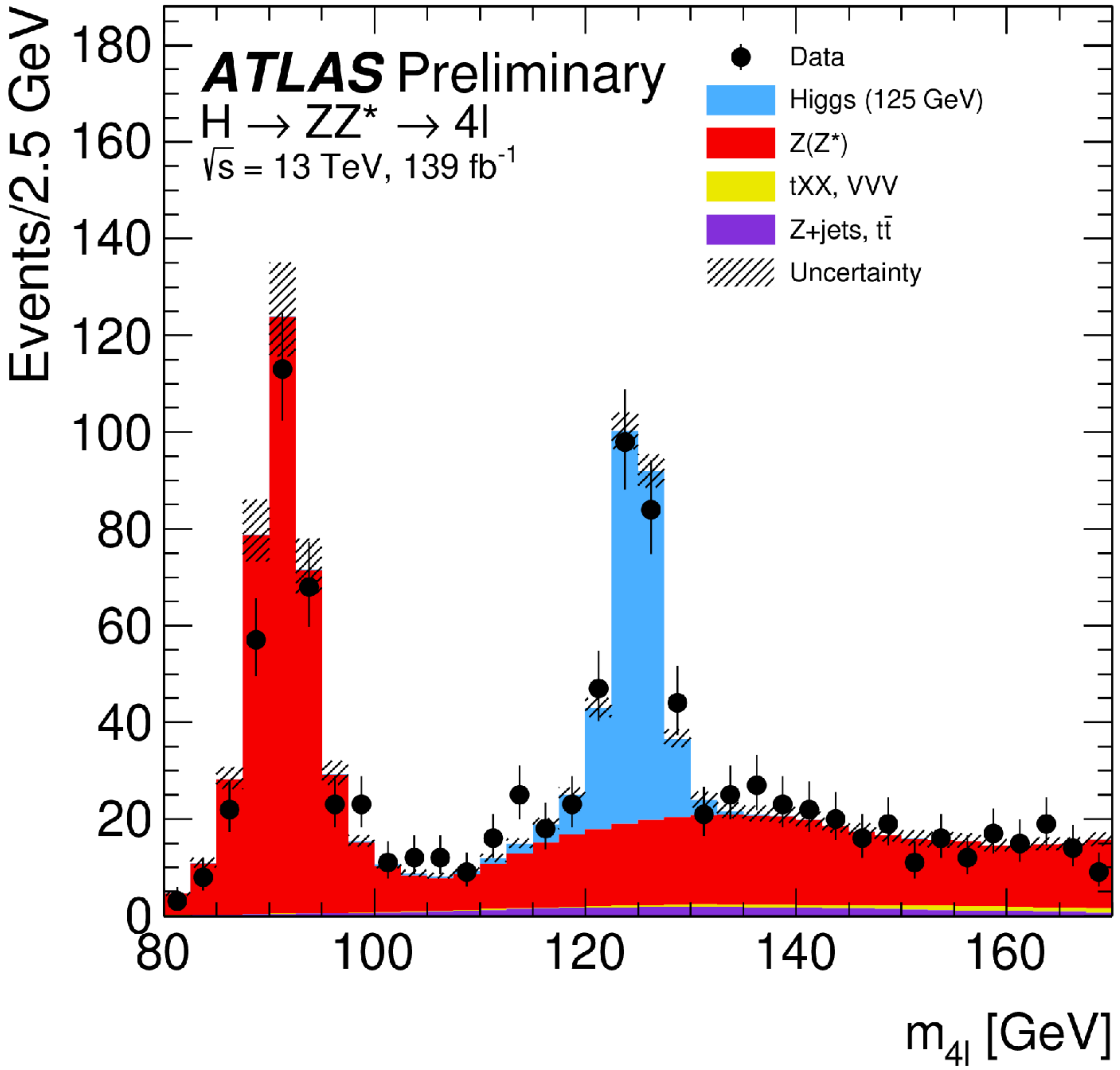


Higgs Boson Mass





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

$$m_H = 125.38 \pm 0.11(\text{stat}) \pm 0.08\ (\text{syst})\ \text{GeV} \pm 0.14\ (\text{total})$$

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

Phys. Lett. B 805 (2020) 135425

ATLAS-CONF-2020-005

Higgs Boson Width

- Expected width: $\Gamma_{H,SM} = 4.1$ MeV
  - Direct limit: $\Gamma_H < 1.1$ GeV ($\sim 260 \times \Gamma_{H,SM}$) JHEP 11 (2017) 047
  - Lifetime too short to measure:
    $\Gamma_H > 3.5 \times 10^{-9}$ MeV @ 95% CL Phys. Rev. D 92, 072010 (2015)

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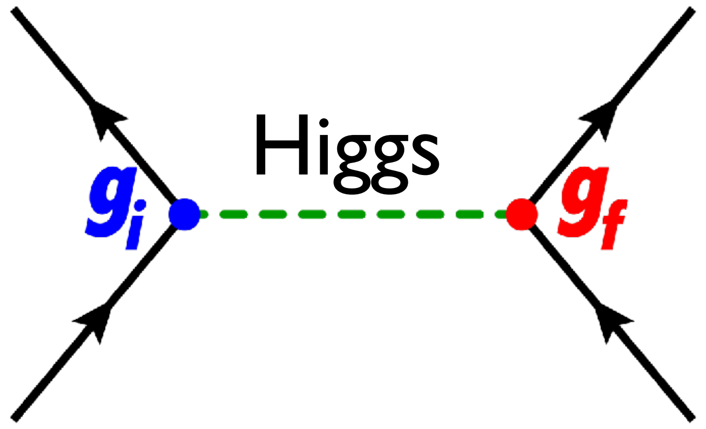
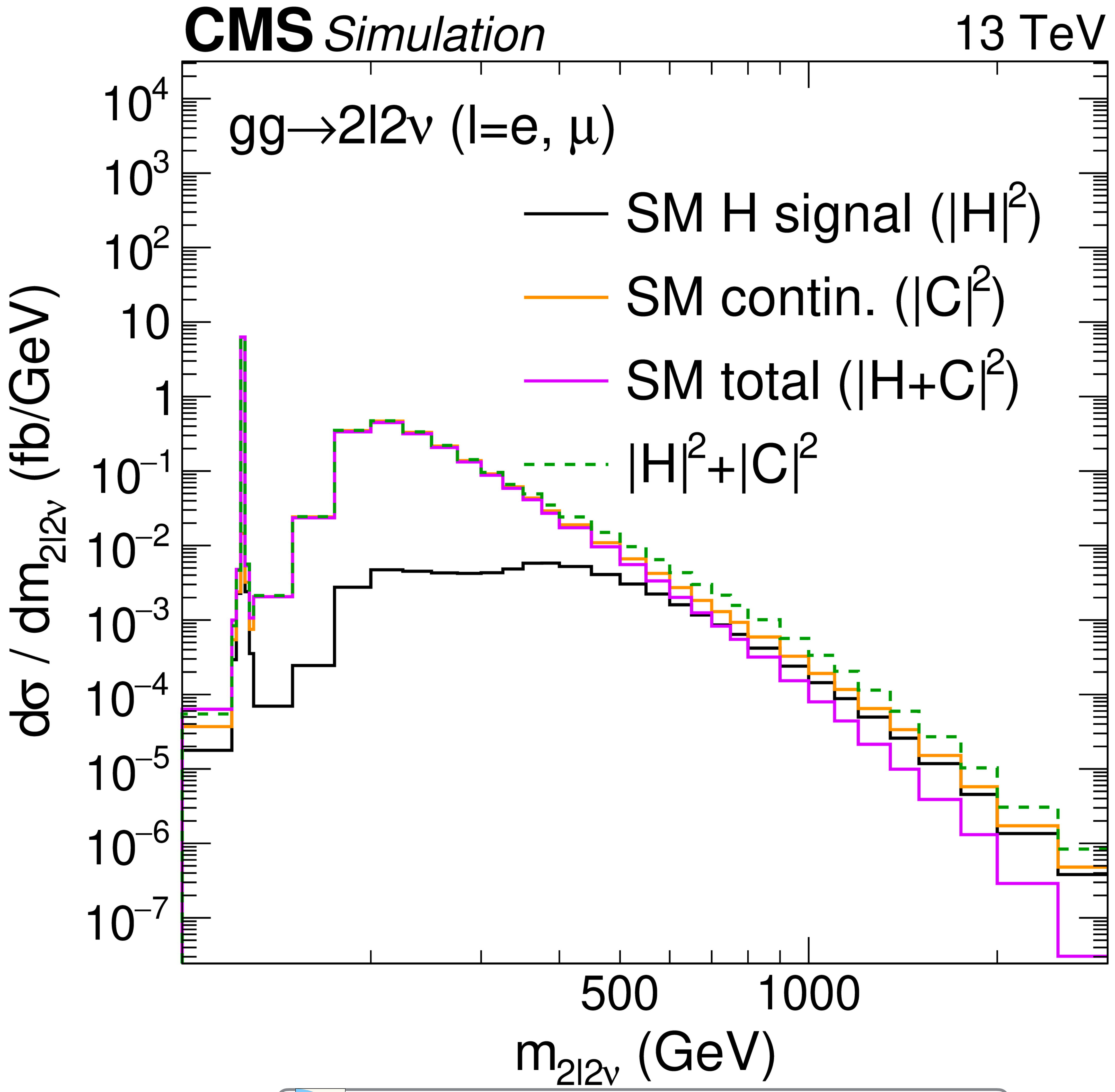
- Idea:



  - Cross-section

$$\sigma_{i\to H\to f} = \int \frac{g_{\rm i}^2 g_{\rm f}^2}{(s-m_{\rm H}^2)^2+\Gamma_{\rm H}^2 m_{\rm H}^2} ds$$



CMS-HIG-21-013 (submitted to Nature Physics)

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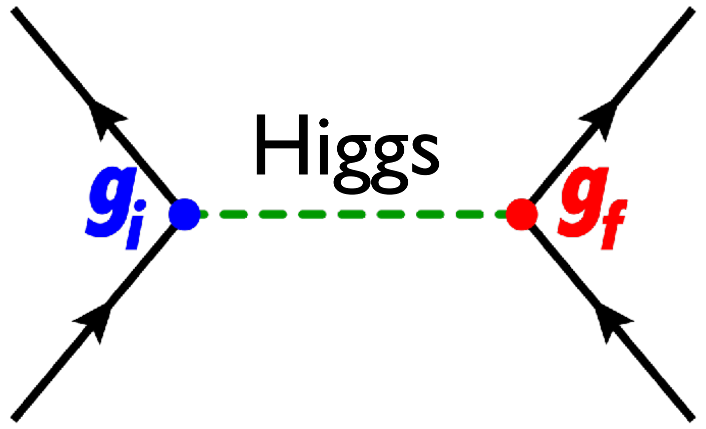
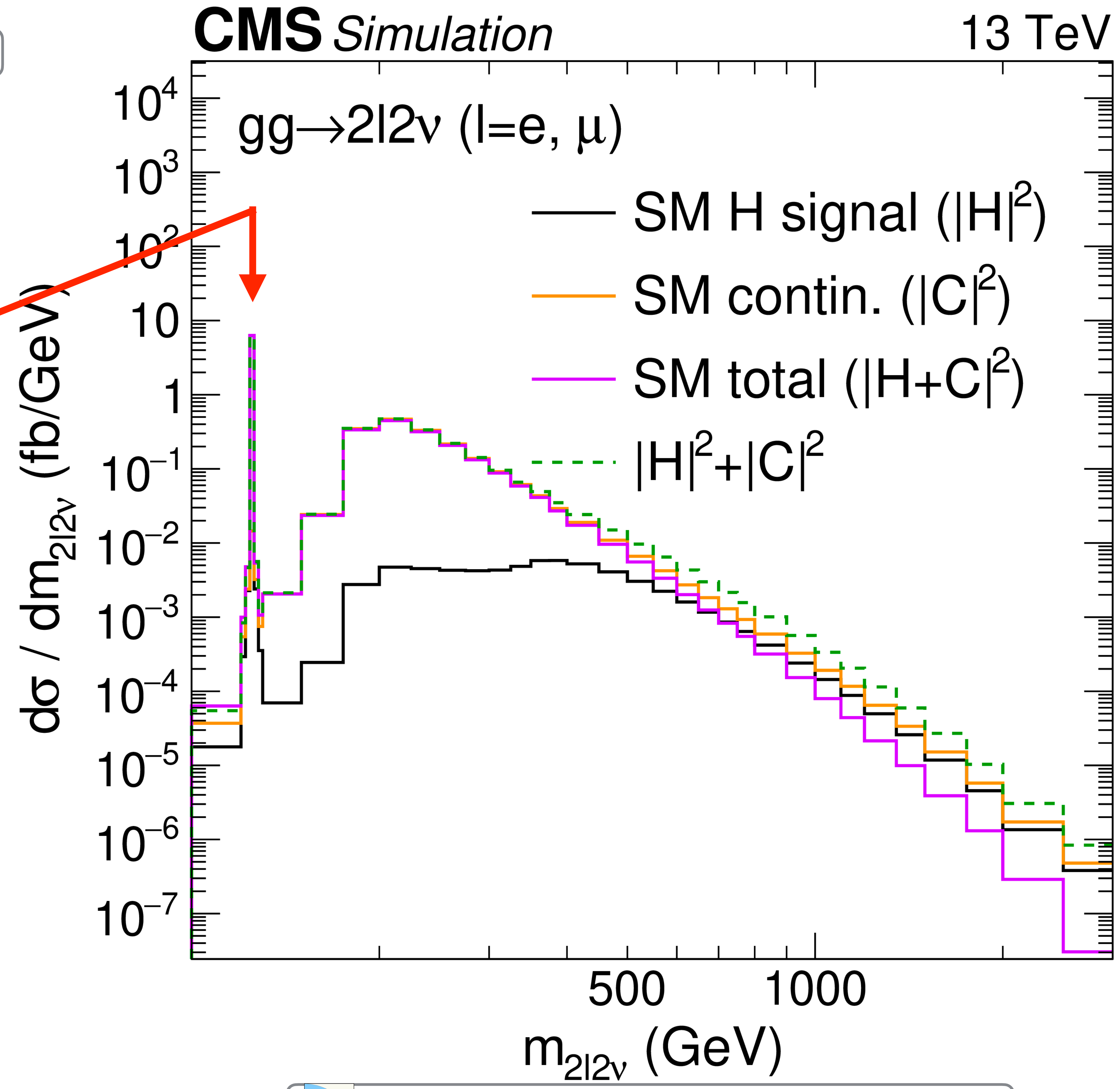


  - Cross-section on-resonance:

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



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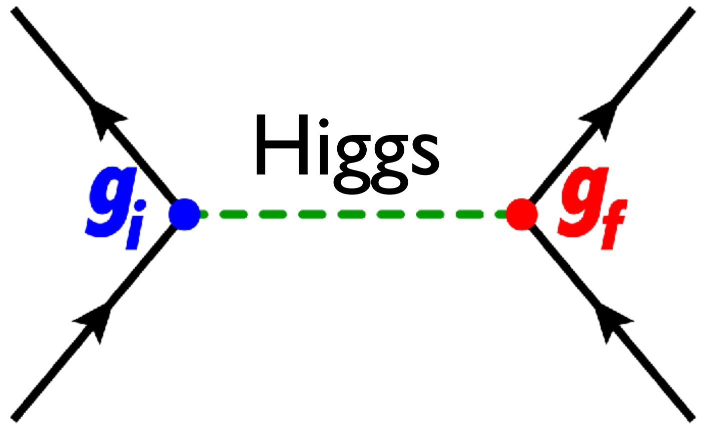

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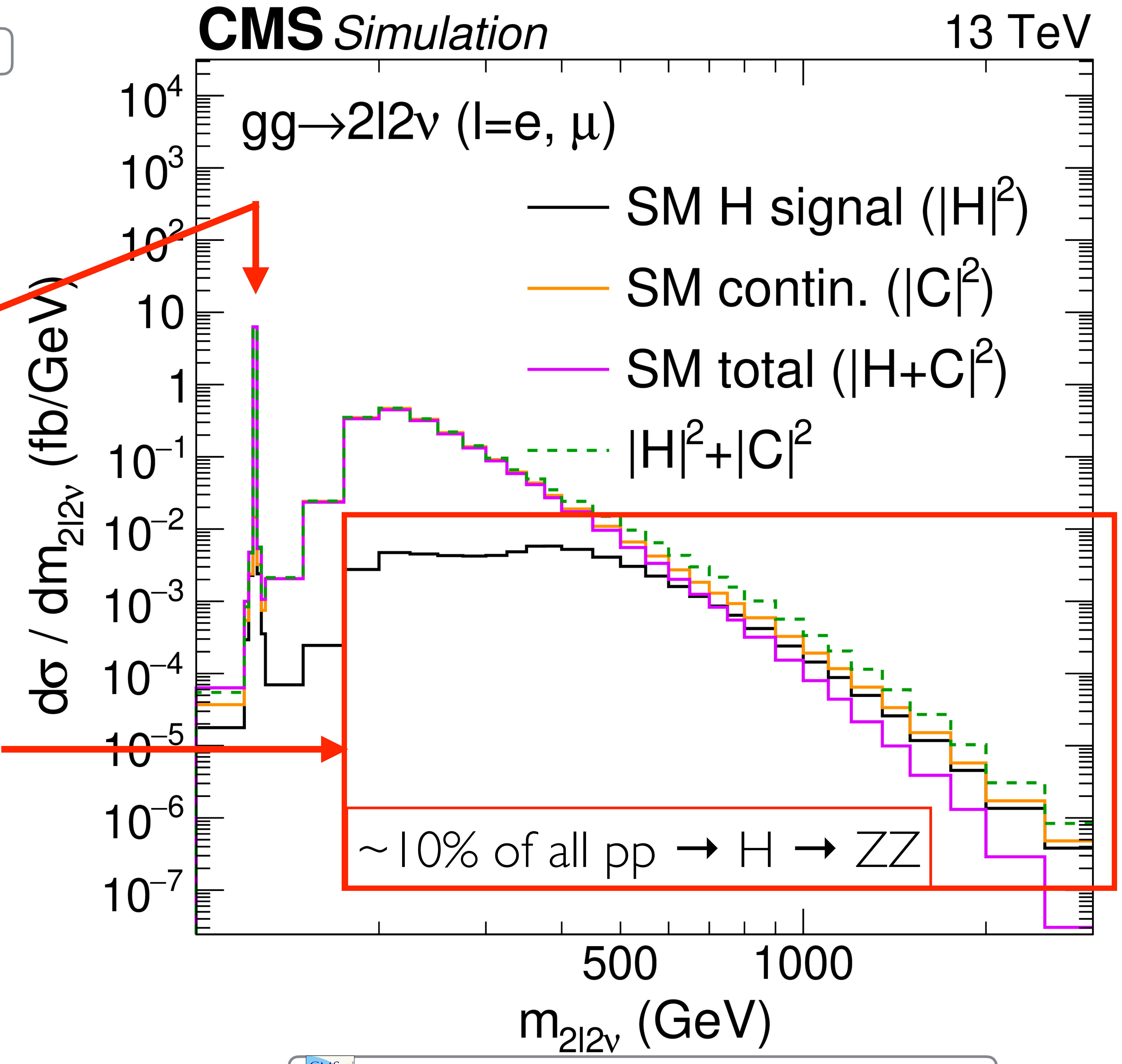
  - Cross section far above resonance ("off-shell"):

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



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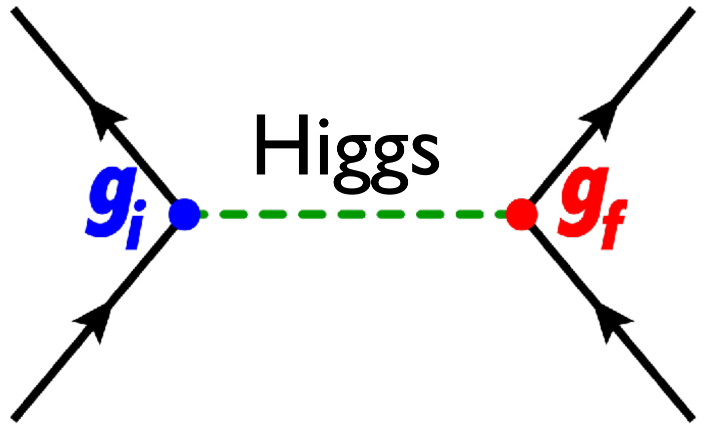

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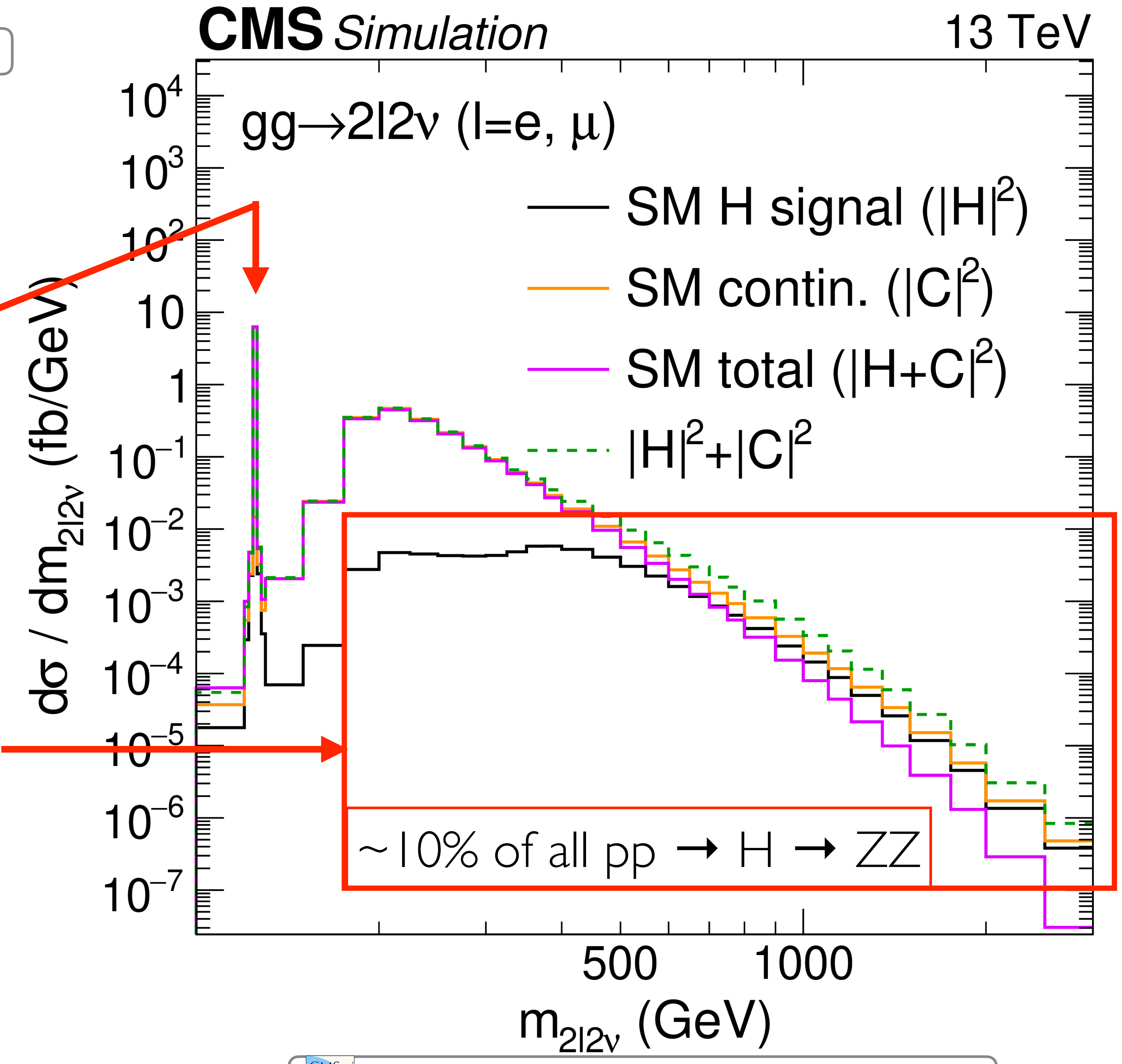
  - Measure ratio of both: $\boxed{\Gamma_H \propto \frac{\sigma_{\text{off}}}{\sigma_{\text{on}}}}$



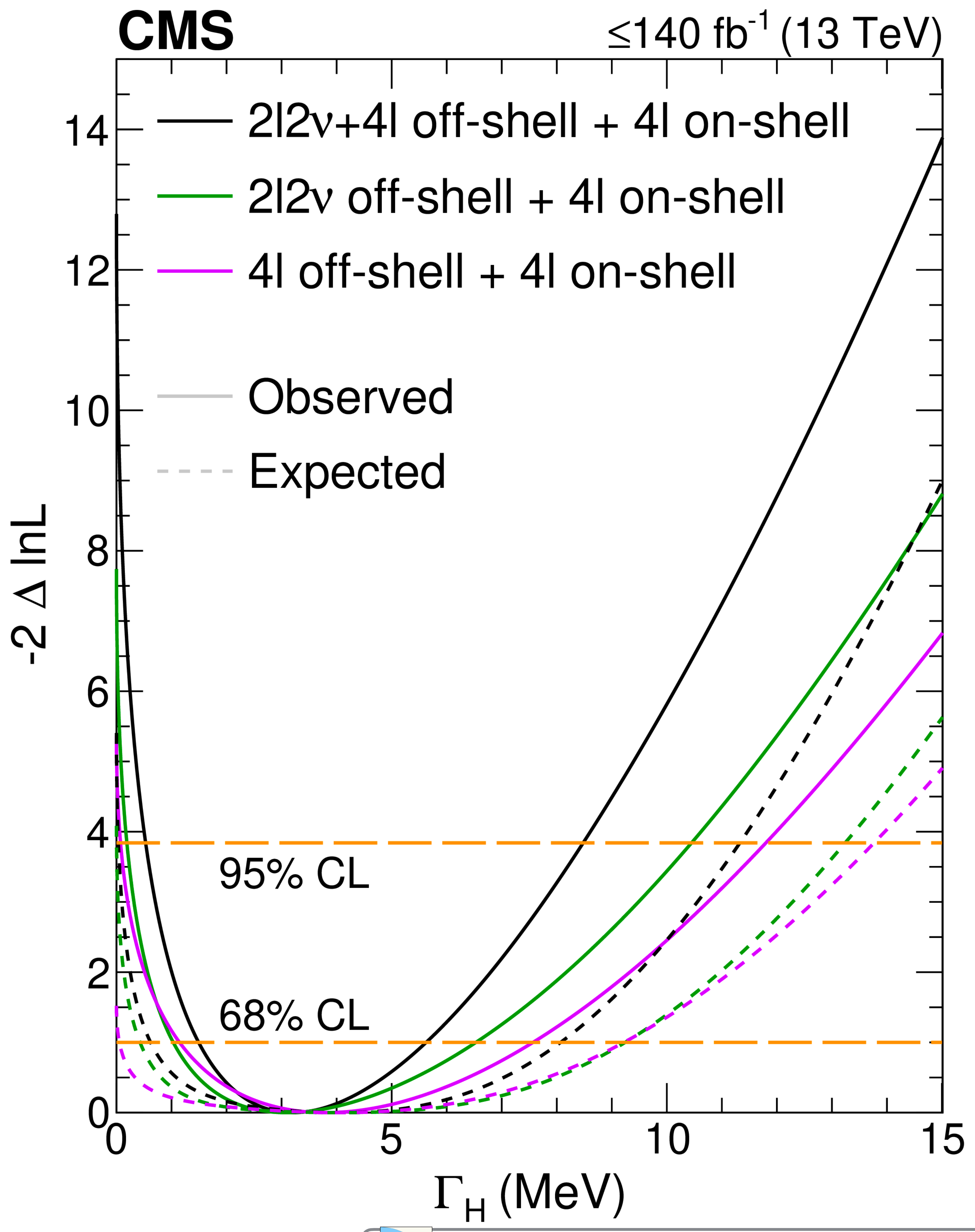
CMS-HIG-21-013 (submitted to Nature Physics)

Indirect Contraints on Higgs Boson Width

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

- Results:
  - Evidence for off-shell production: **3.6 σ**
  - $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV

Feb 2022



CMS-HIG-21-013 (submitted to Nature Physics)

Outline

CP Measurement in t(t)H Production

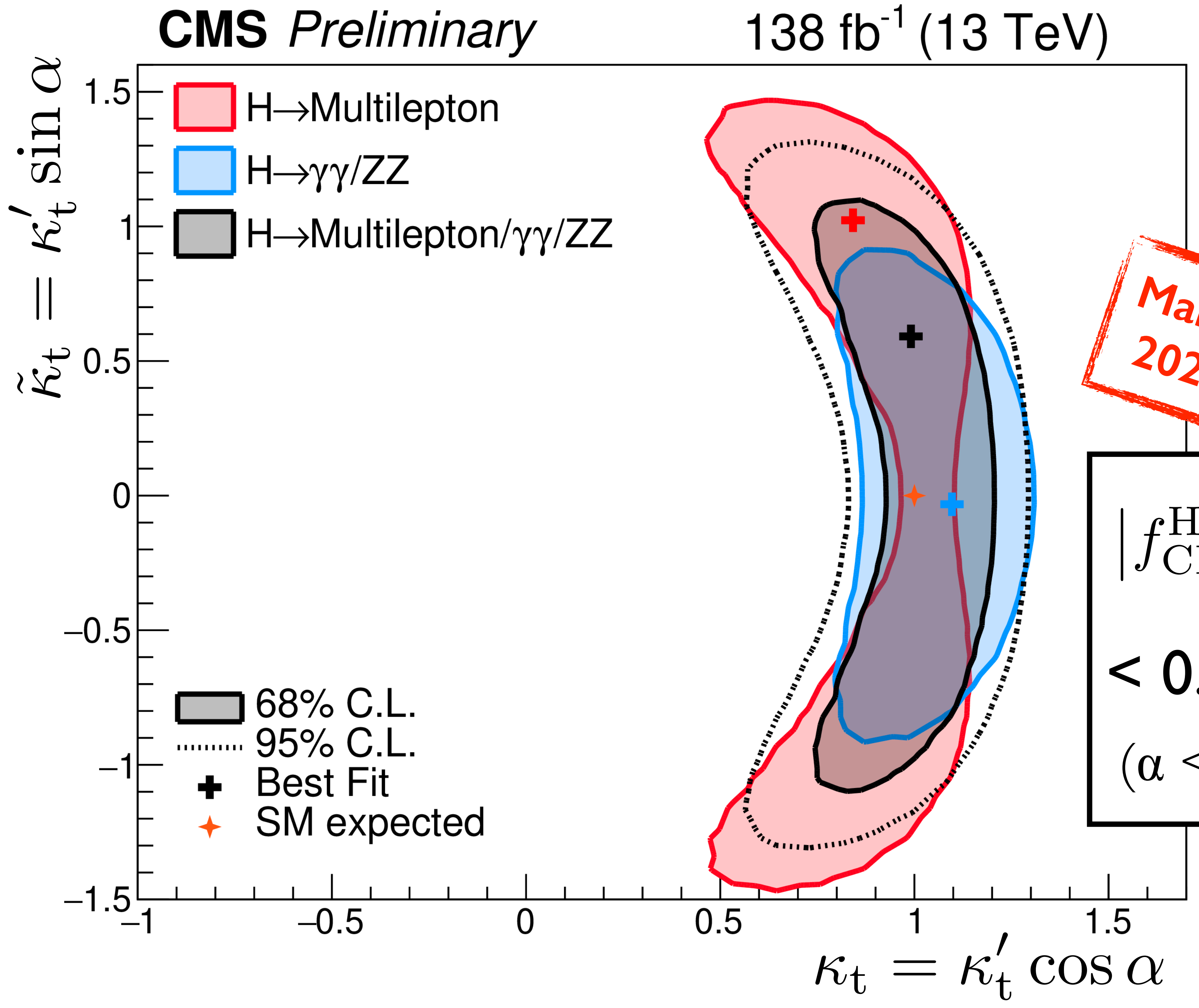
- CP-odd in Higgs-Gauge interactions need higher-order operators
- CP-odd in **top-Yukawa** can be **tree-level**

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

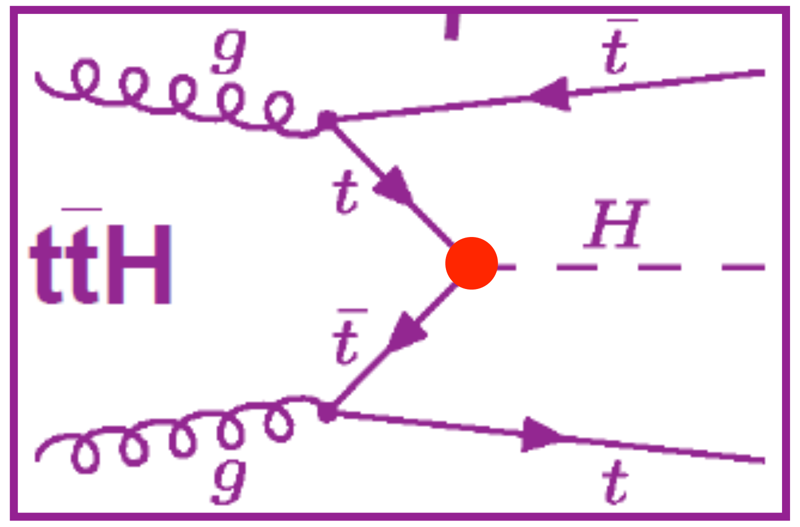
"**multilepton**" topology
Combine with $\gamma\gamma$ and ZZ*

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

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



March 2022



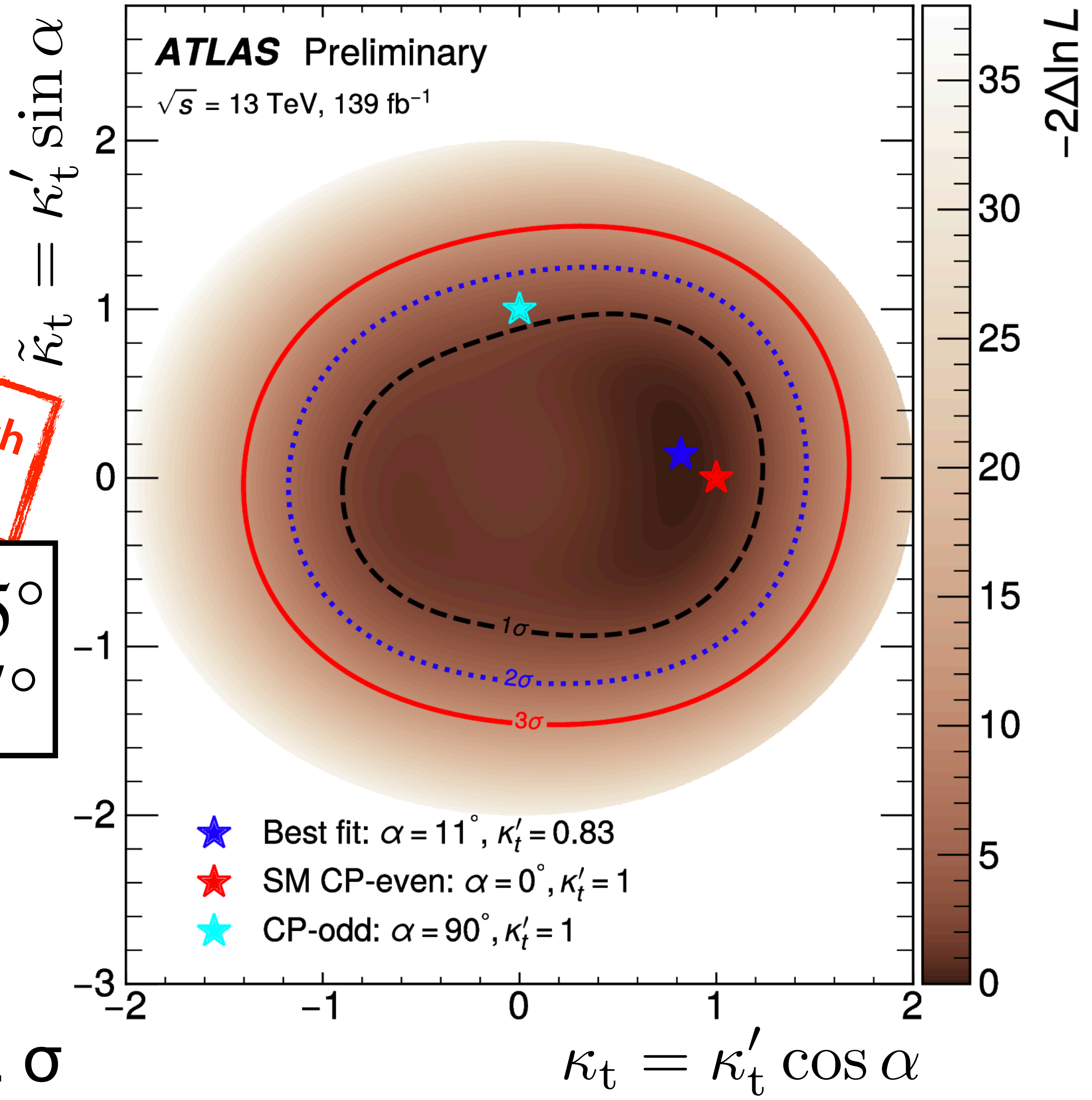
$$\left|f_{CP}^{Htt}\right| = \left|\frac{\tilde{\kappa}_t^2}{\tilde{\kappa}_t^2 + \kappa_t^2}\right|$$

< 0.55 @ 68% C.L.

(α < 48° @ 68% C.L.)

$$\alpha = 11^{\circ}{}^{+55^{\circ}}_{-77^{\circ}}$$

March 2022



- Pure CP-odd coupling excluded at **3.7 σ** … …at **1.2 σ**

CMS-PAS-HIG-21-006 ⇒ More

ATLAS-CONF-2022-016 ⇒ More

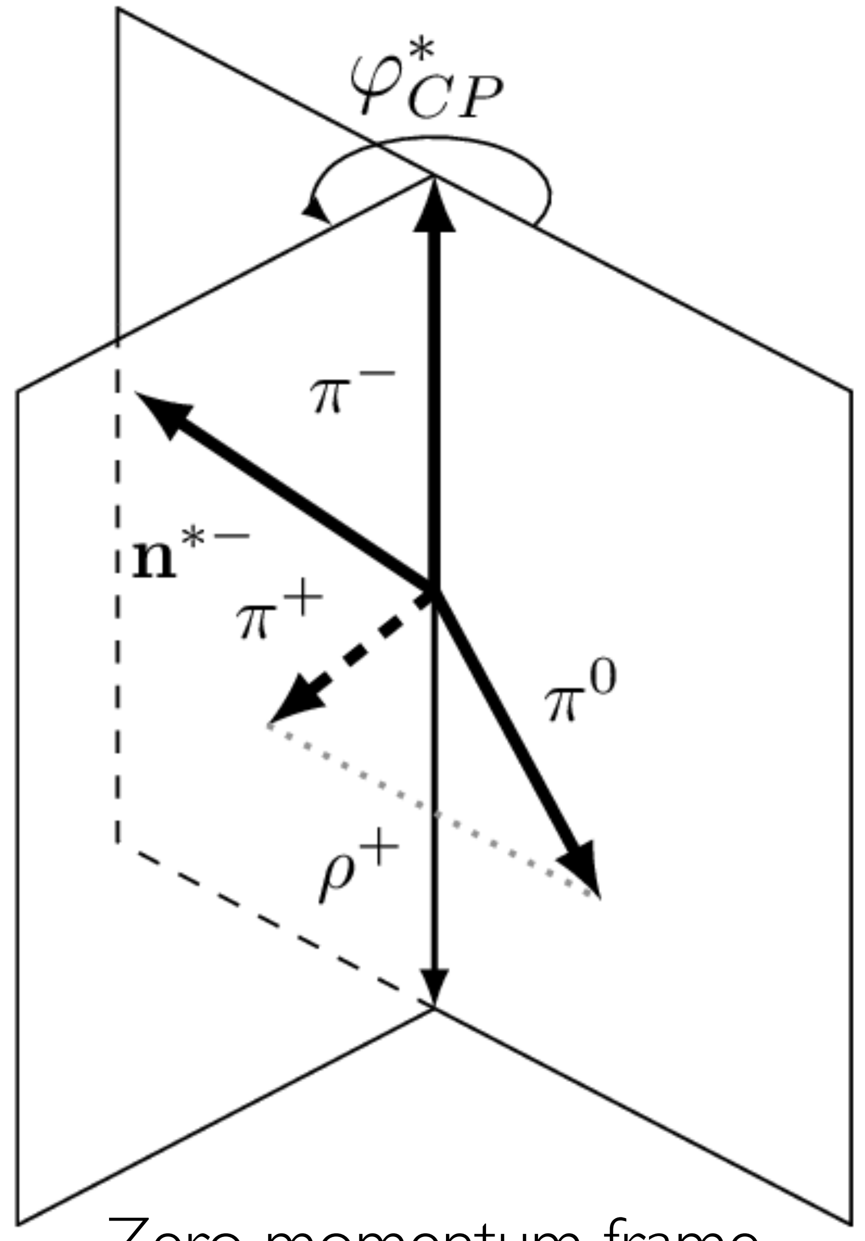
CP Measurement in H → ττ Decay

ATLAS-CONF-2022-032

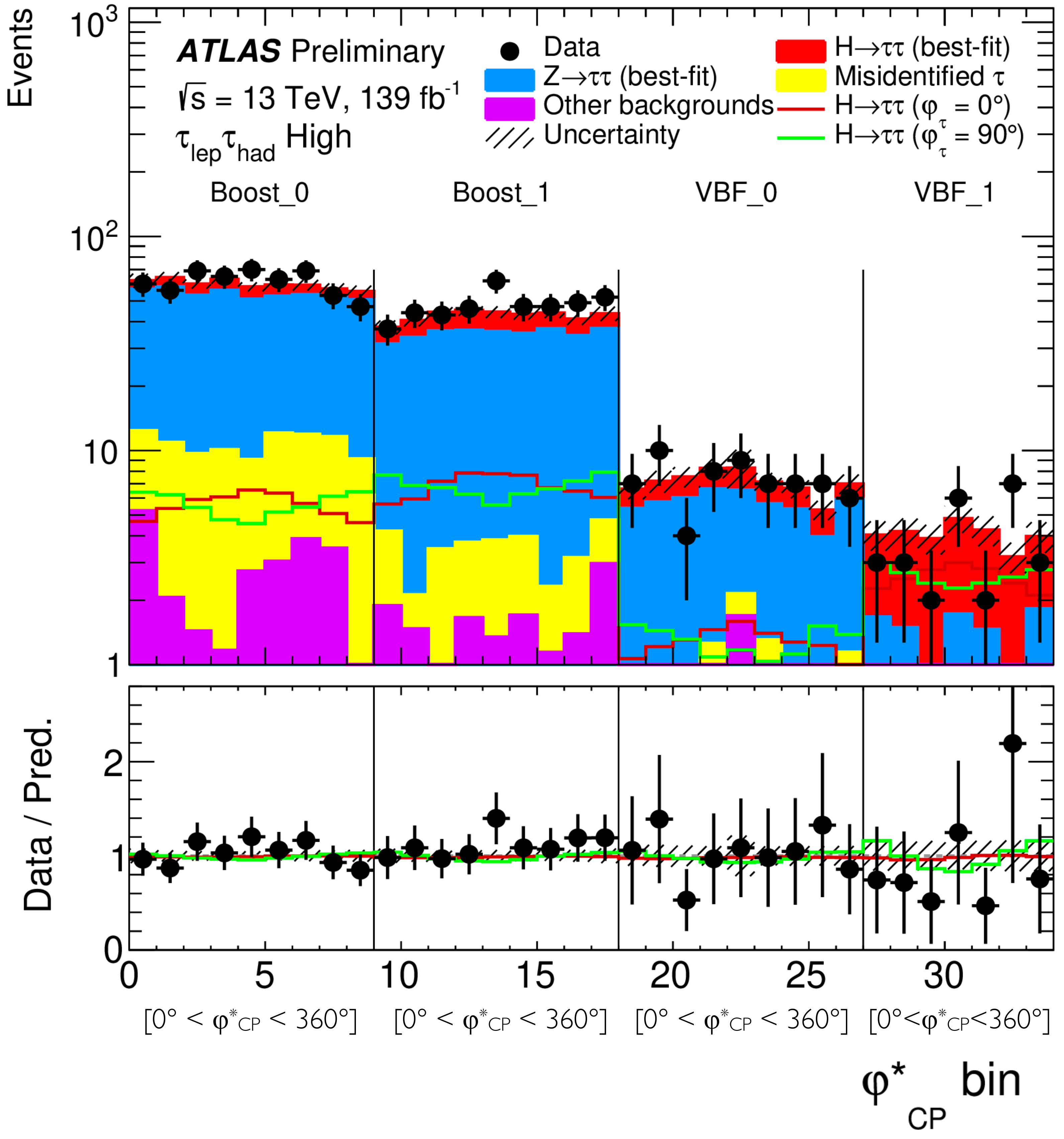
Parametrize **τ-Yukawa** coupling: $\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)H$ SM Hττ coupling: CP-even ($\phi_\tau = 0°$)

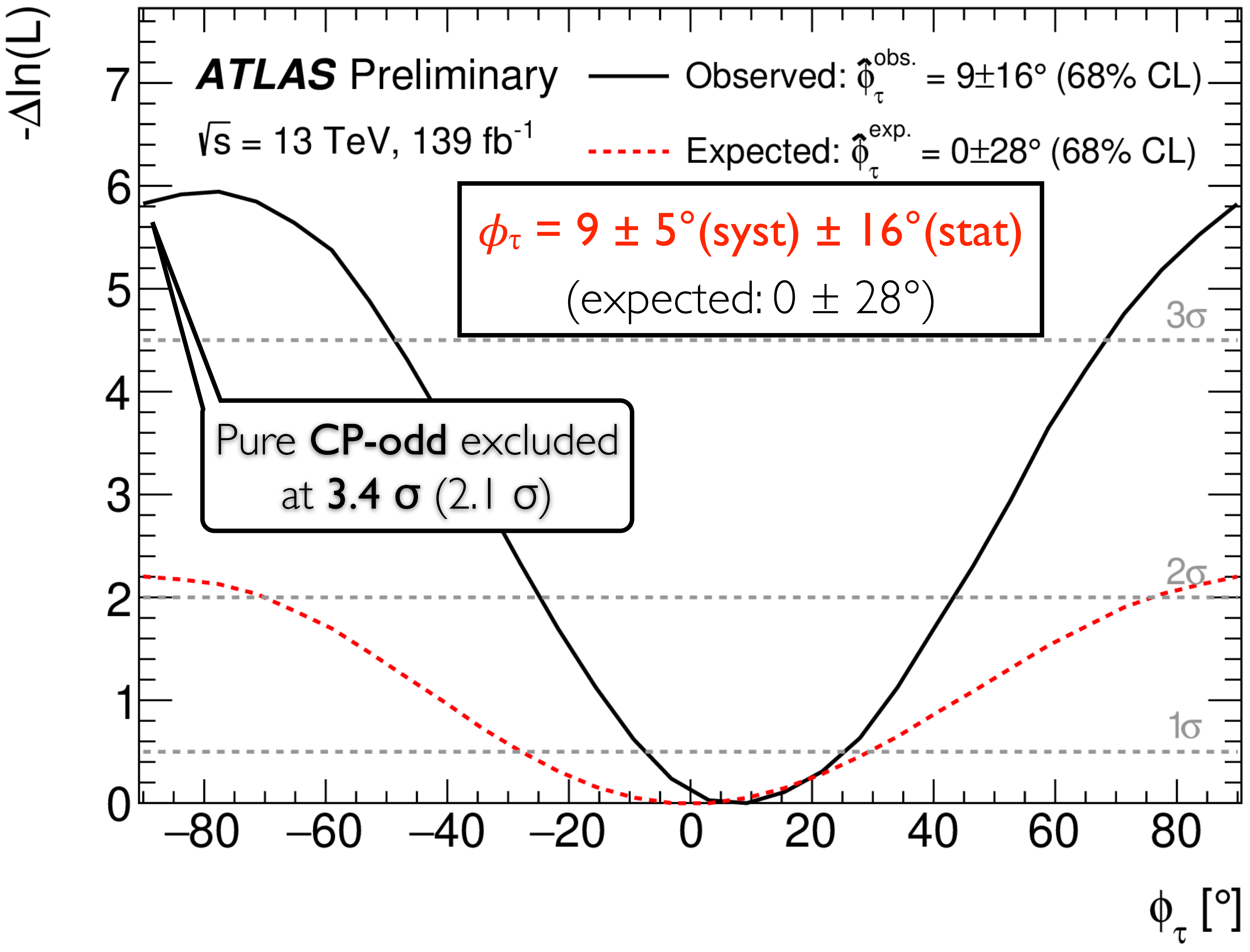
- Reconstruct τ decay modes
- Observable: signed acoplanarity angle between τ decay planes
  - spanned by impact parameter and/or decay products ($\pi^\pm, \pi^0$)

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



Zero momentum frame





$\phi_\tau = 9 \pm 5°(\text{syst}) \pm 16°(\text{stat})$
(expected: $0 \pm 28°$)

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

⇒ More

⇒ CMS ϕ_τ **= -1 ± 19°** (0 ± 21°) [arXiv:2110.04836]

Karsten Köneke

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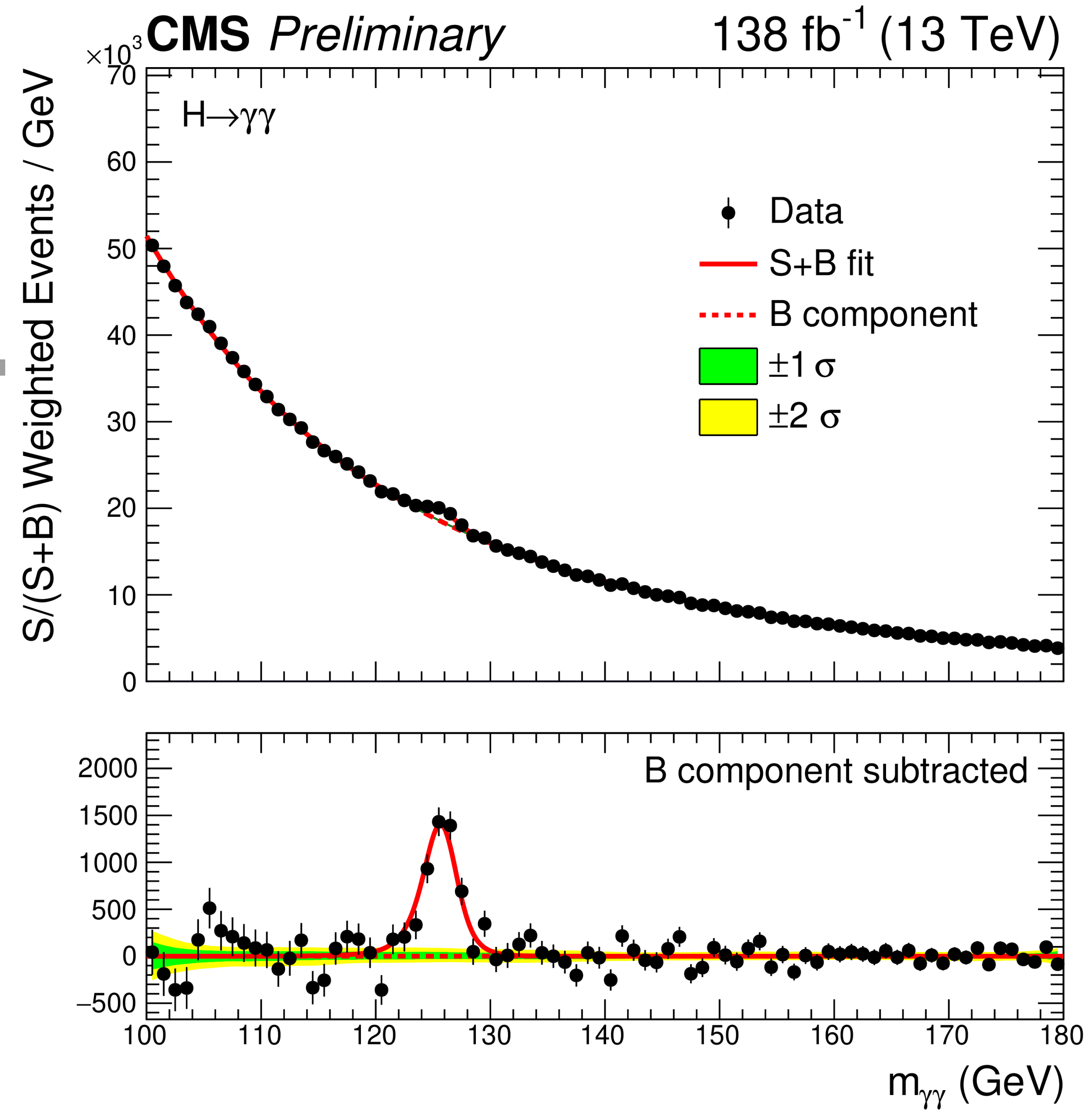
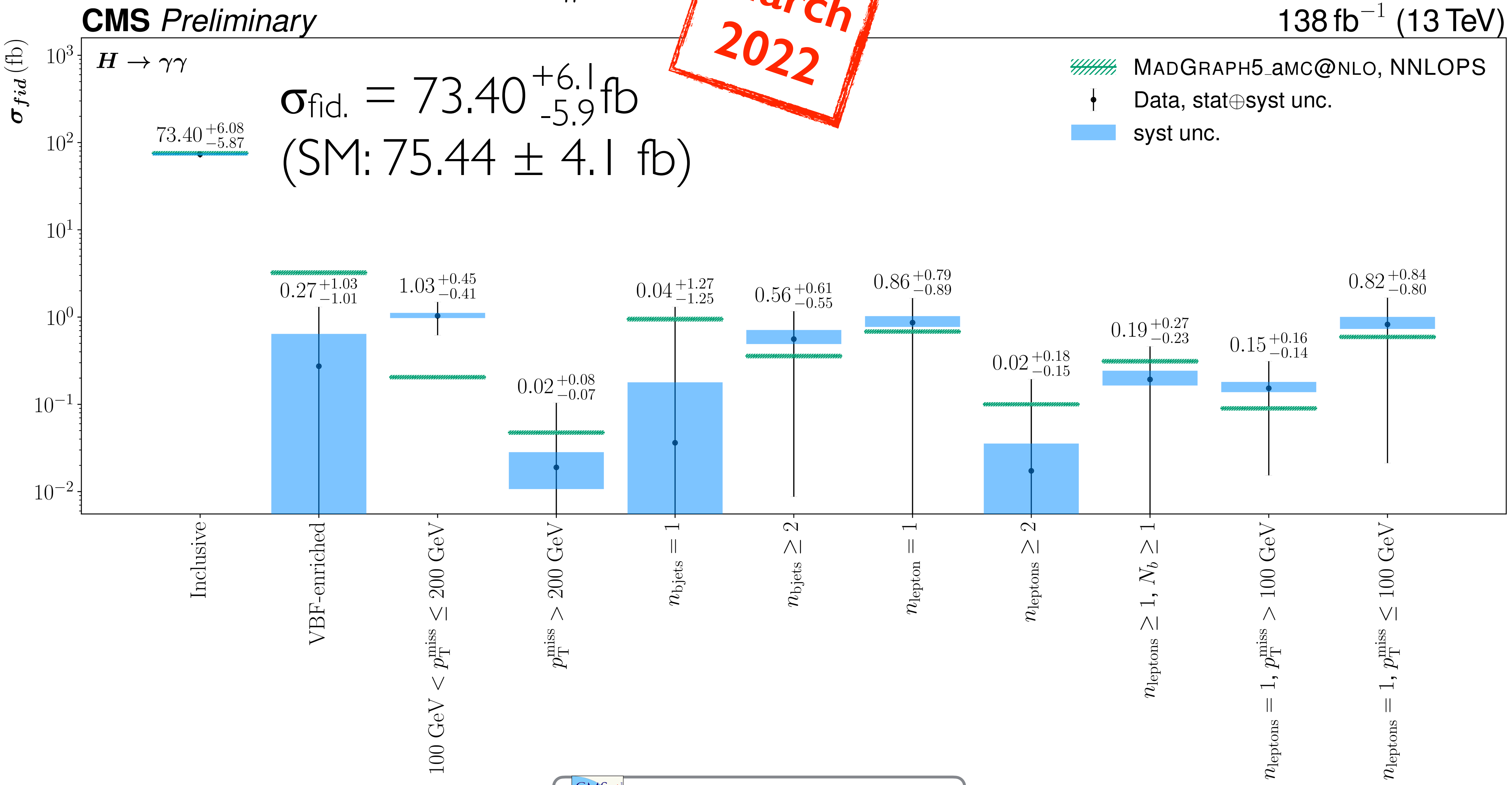


H → γγ fiducial Measurements

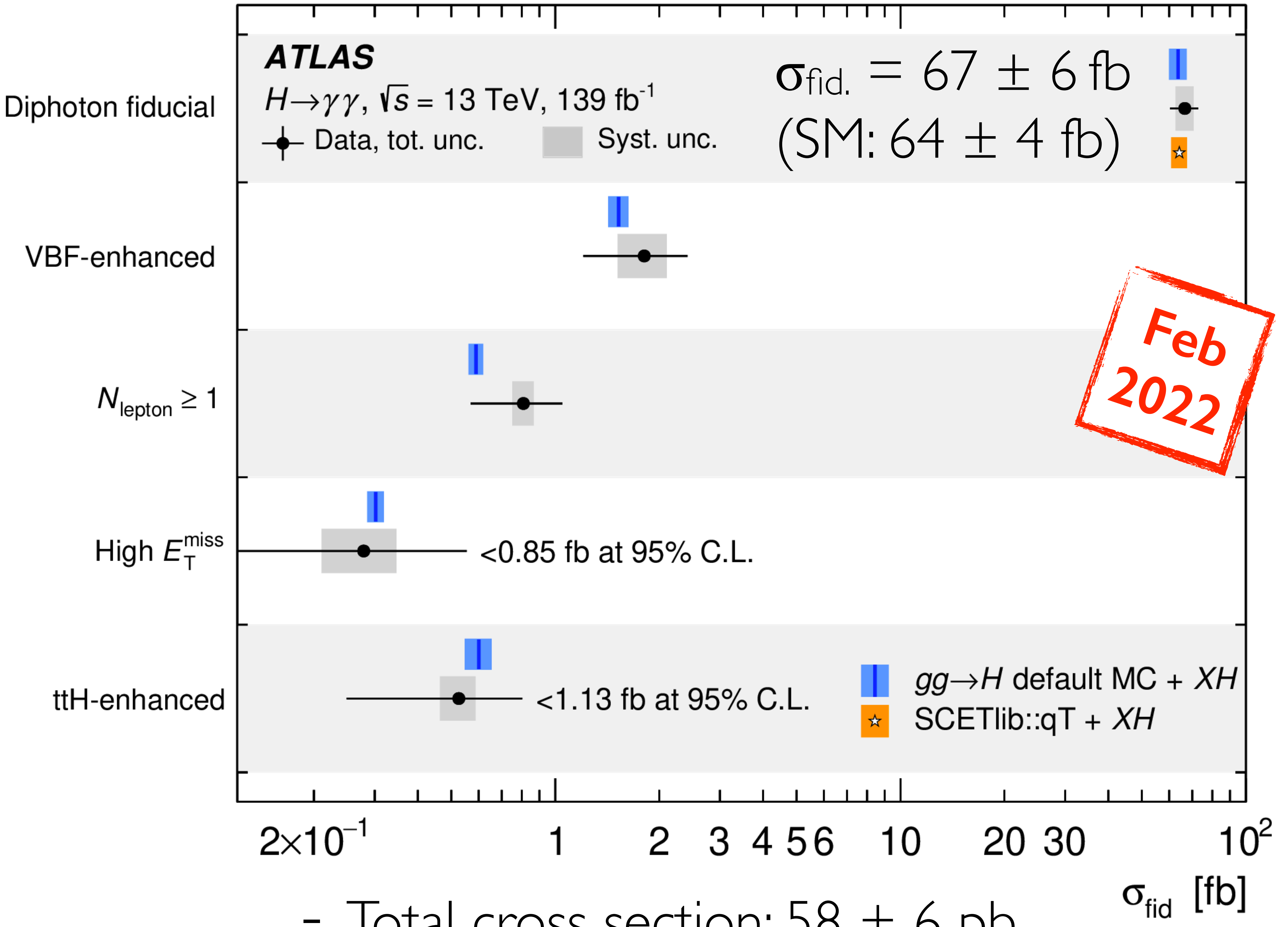
- $BR_{SM}(H \to \gamma\gamma)$ = **0.23%** ⇒ Expect: ~17 500 signal events
  - Excellent signal reconstruction
- O(20) 1-d and O(5) 2-d differential cross-sections in different phase spaces

⇒ More ATLAS and CMS results

March 2022



CMS CMS-PAS-HIG-19-016



Feb 2022

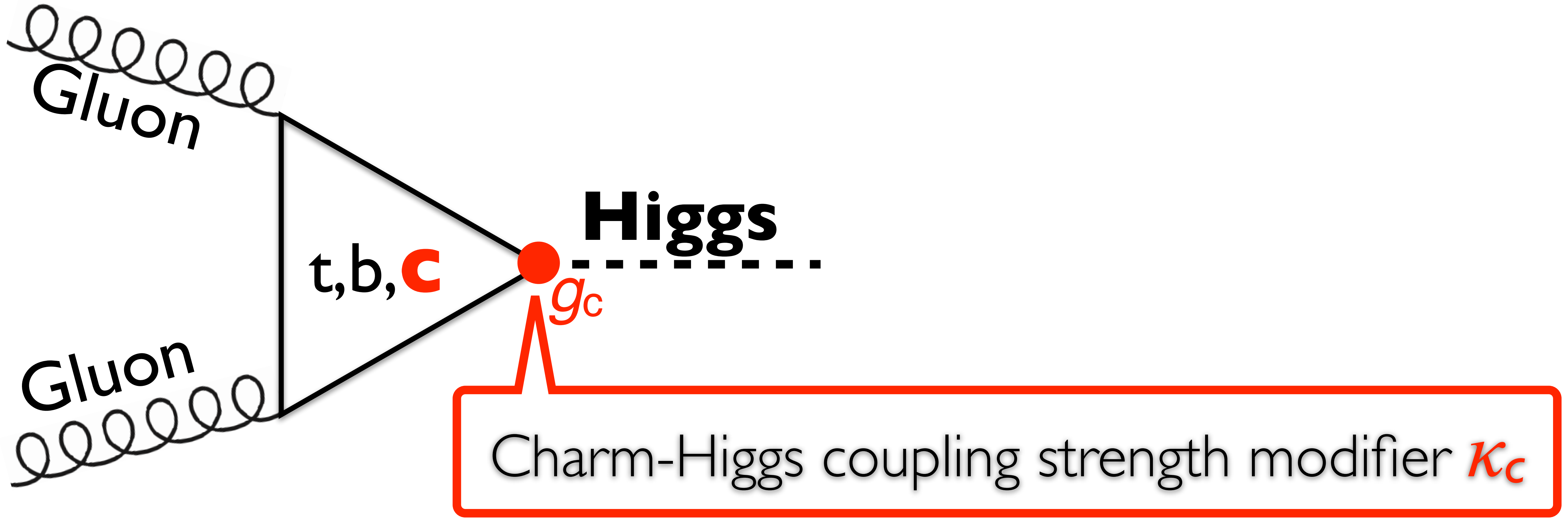
- Total cross section: 58 ± 6 pb

ATLAS arXiv:2202.00487 (submitted to JHEP)

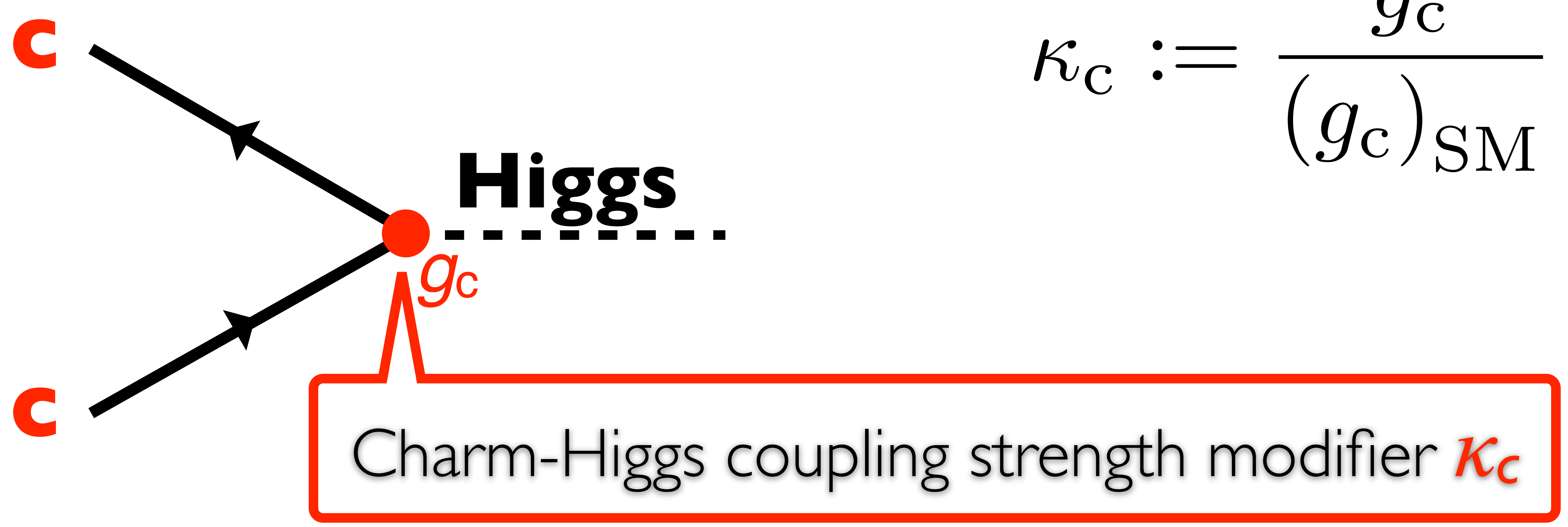
⇒ SMEFT interpretations ATLAS

Charm-Higgs Coupling from $p_T(H)$

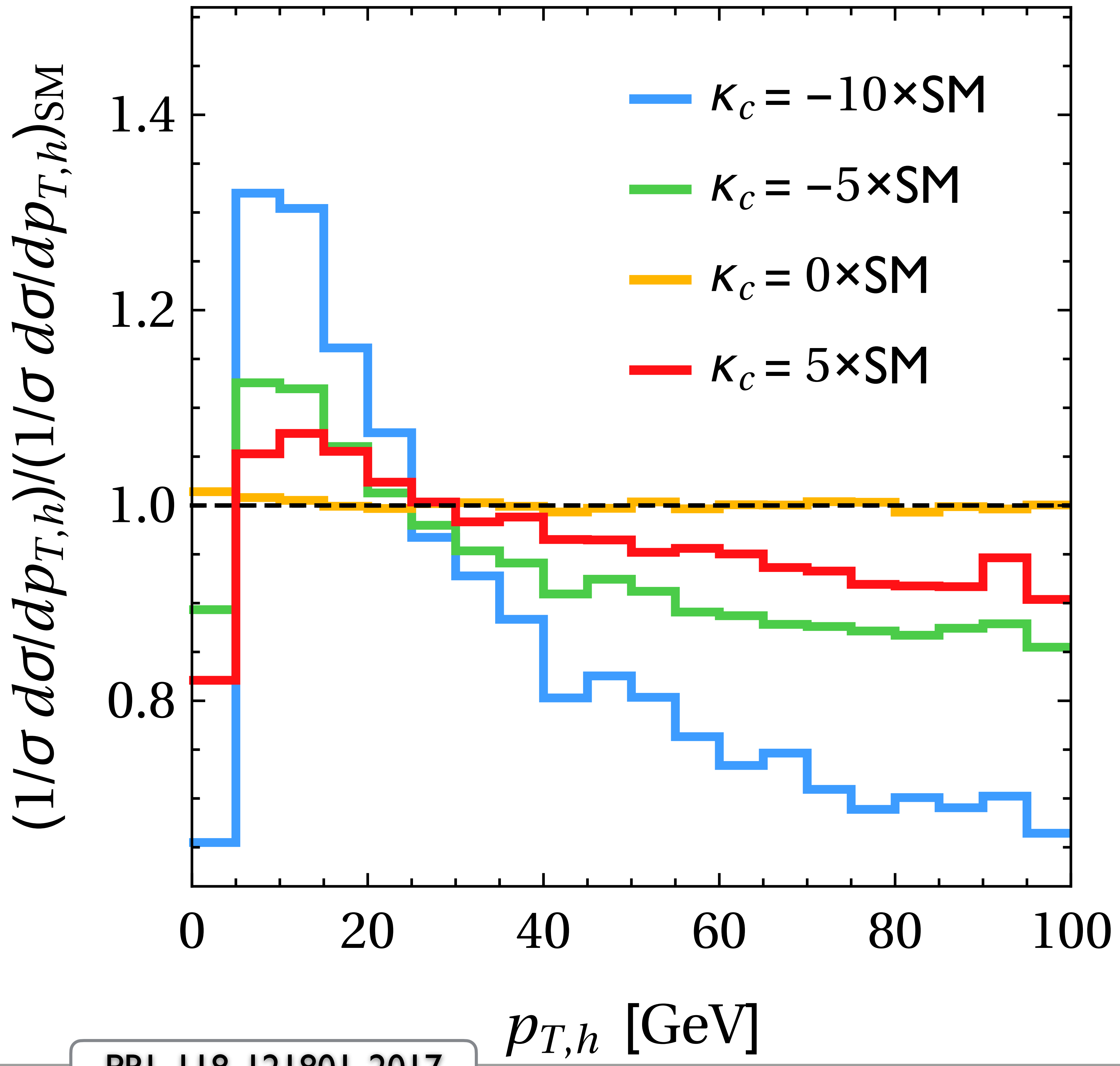
- **Idea**: $p_T(H)$ sensitiv to Charm-Yukawa coupling:
  - Interference between Charm-, Bottom-, and Top-quark loop in ggF



  - Direct cc → H production



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

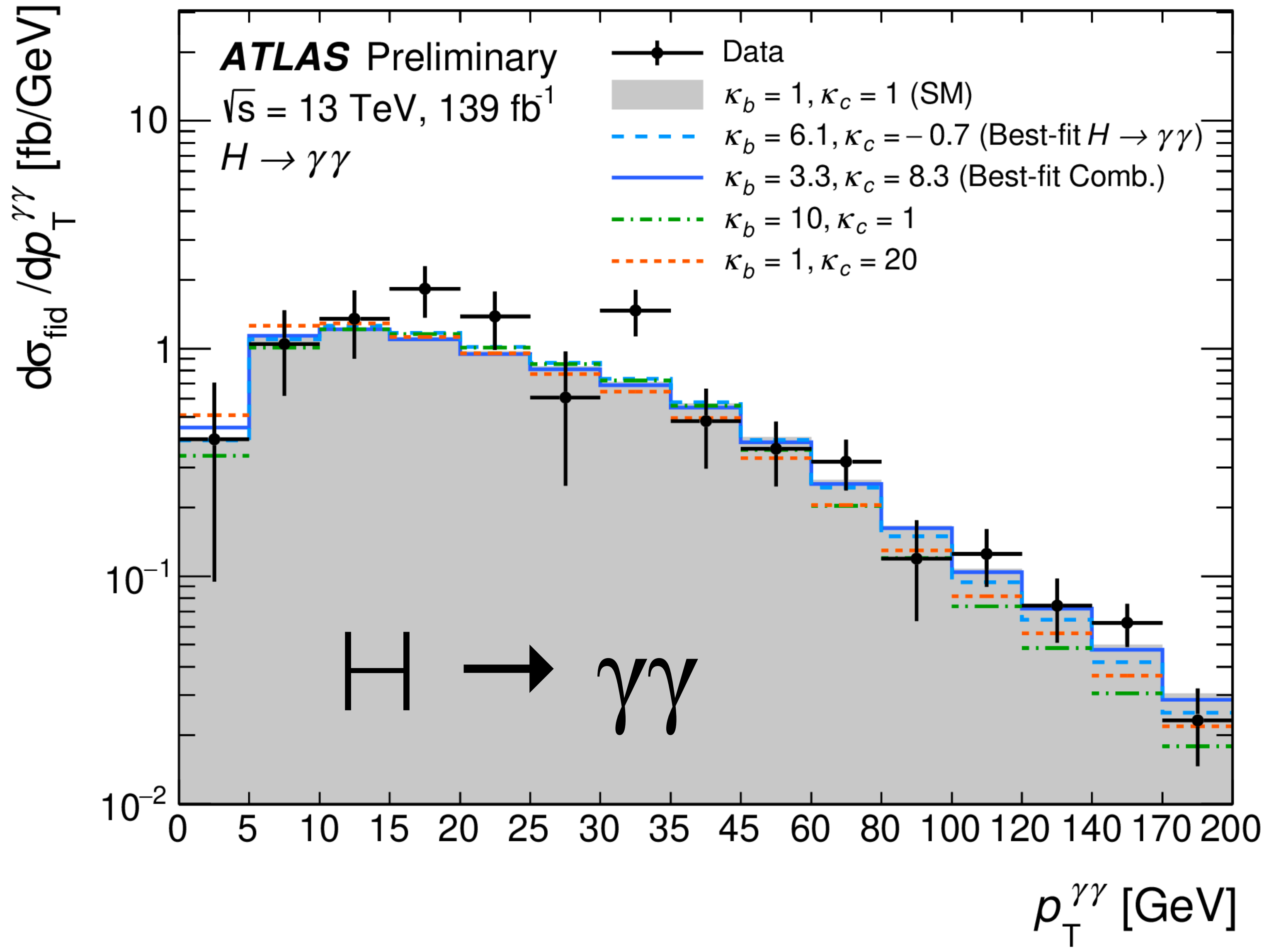


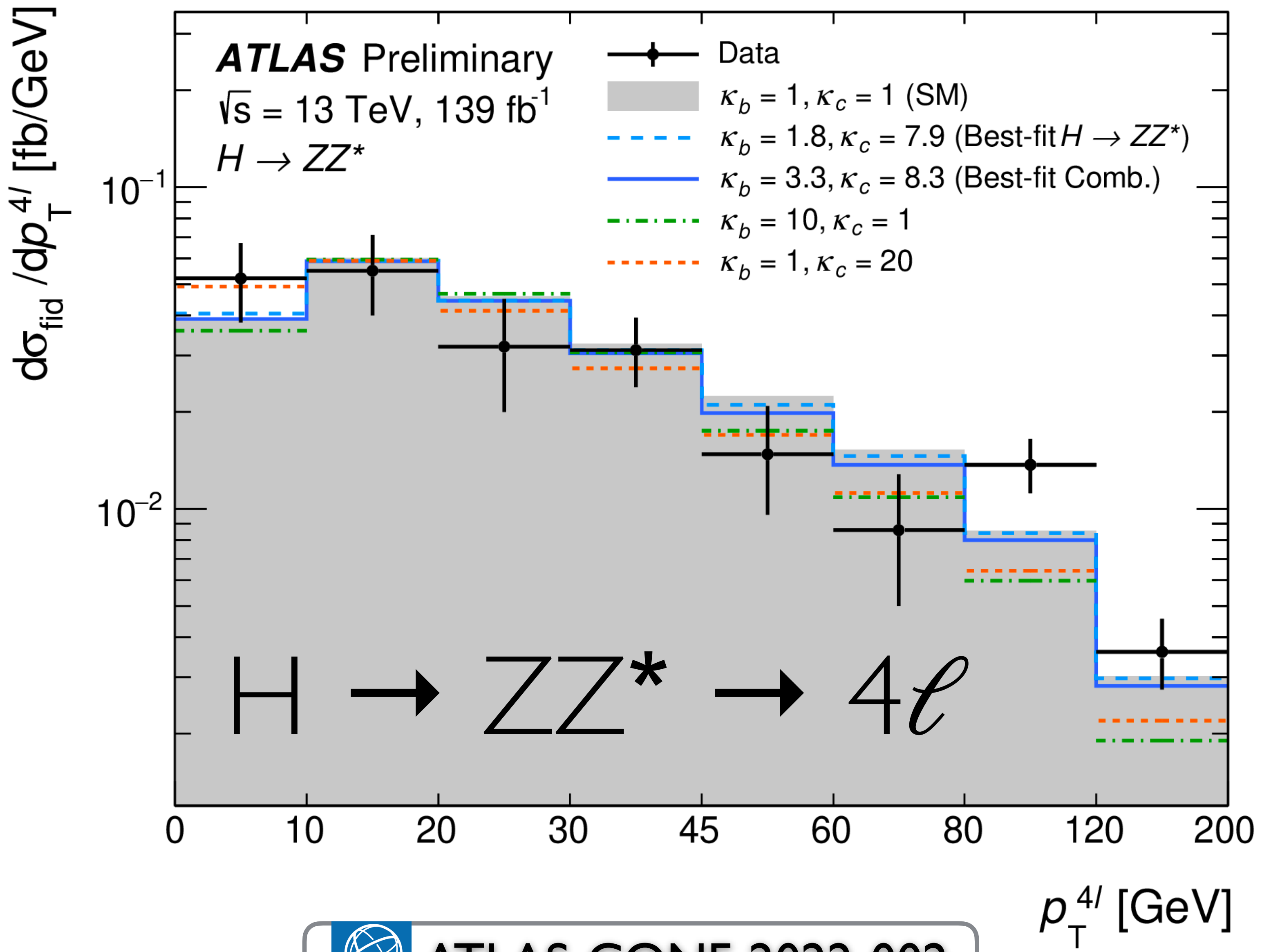
PRL 118, 121801, 2017

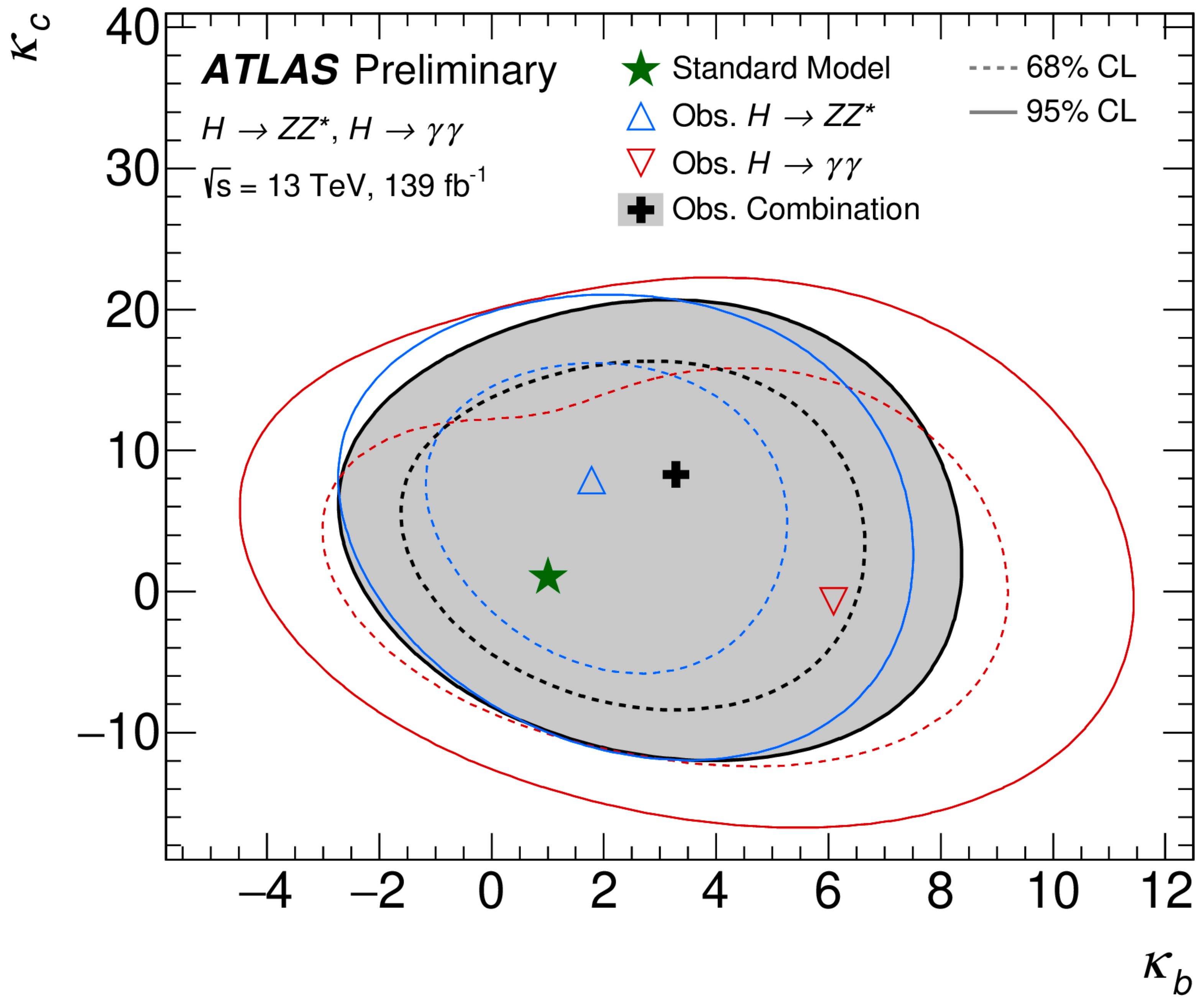
Combination: H → γγ and H → ZZ* → 4ℓ

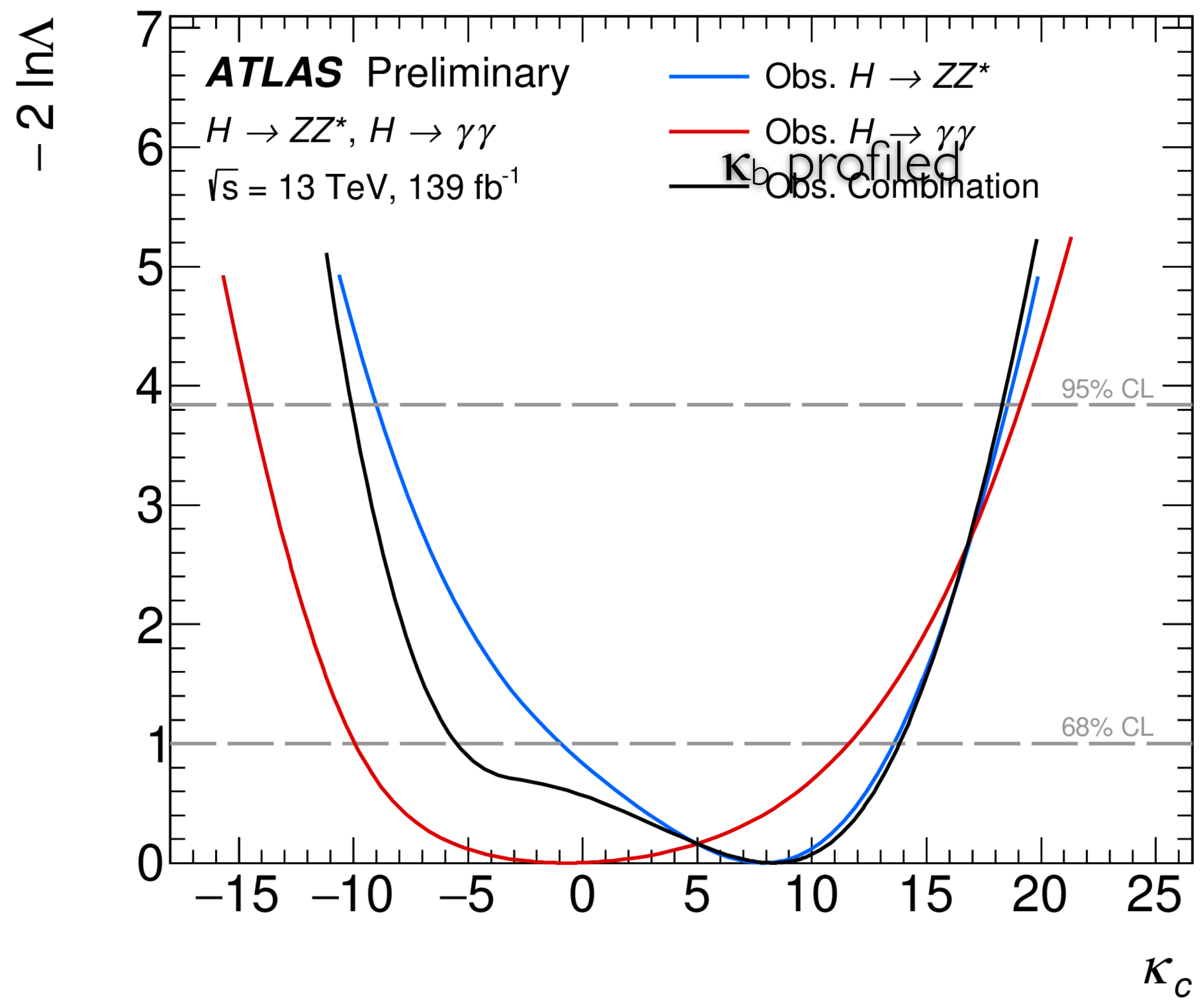
Jan 2022

- Measure σ_{tot}, y_H, N_{jet}, p_T(jet 1), p_T(H) ⇒ More
- Combined interpretation from separate **p_T(H)** distributions
  - Only modifications to p_T(H) shape are considered for these results









Parameter best-fit	Observed 95% confidence interval	Expected 95% confidence interval
$\kappa_b = 3.3^{+2.4}_{-4.1}$	$[-2.1,\ 7.4]$	$[-2.2,\ 7.4]$
$\kappa_c = 8.3^{+5.5}_{-13.8}$	$[-10.1,\ 18.3]$	$[-10.3,\ 16.6]$

⇒ For direct κ_c measurements, see: "*Rare & BSM Higgs experiment*", Andrzej Novak, **Thu 16:40**

ATLAS-CONF-2022-002

⇒New H → bb fiducial measurement at large E_T^{miss}

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   - Measure production-mode specific cross sections in exclusive kinematic phase spaces
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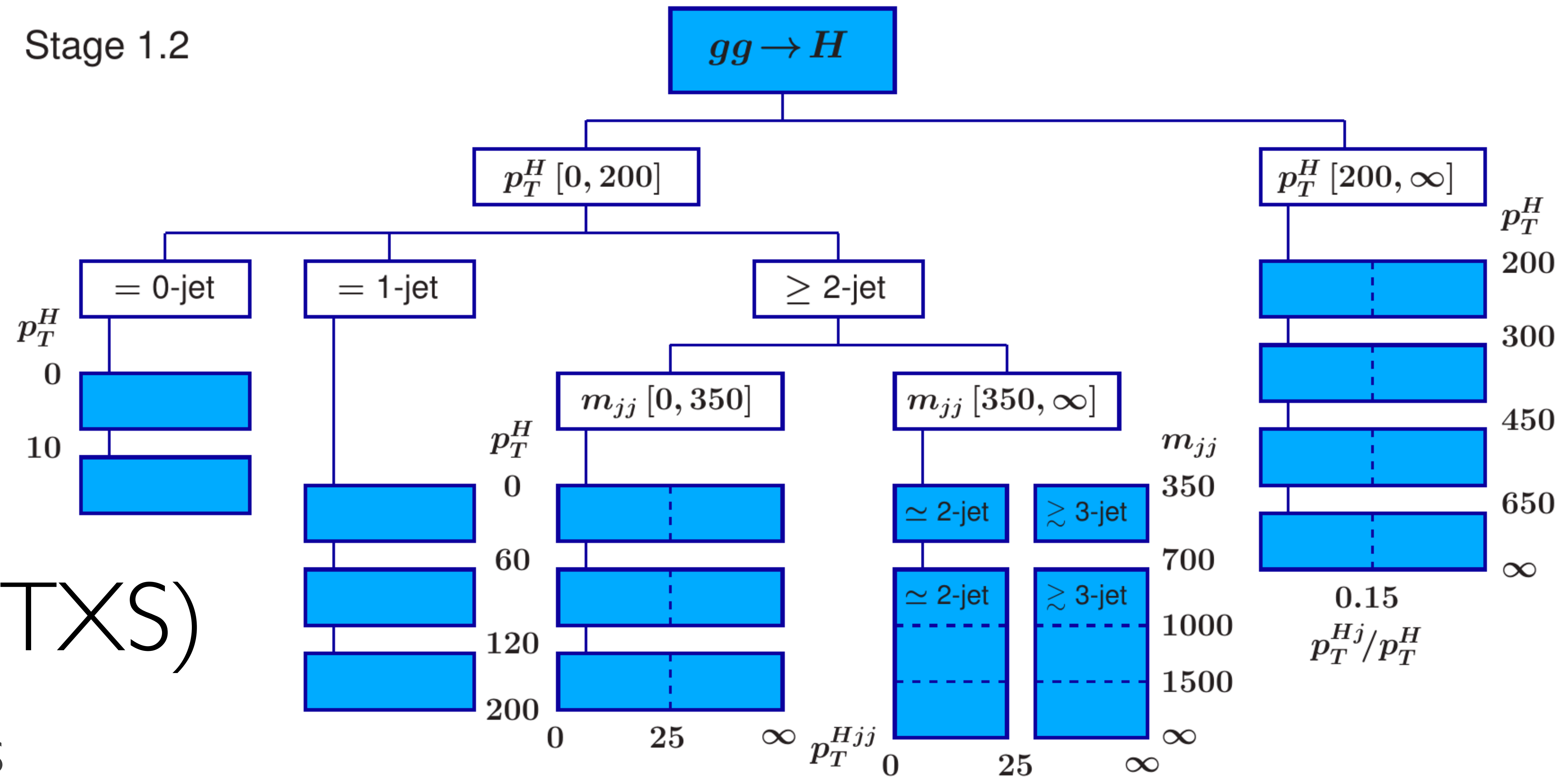


$H \to WW^* \to \ell\nu\ell\nu$

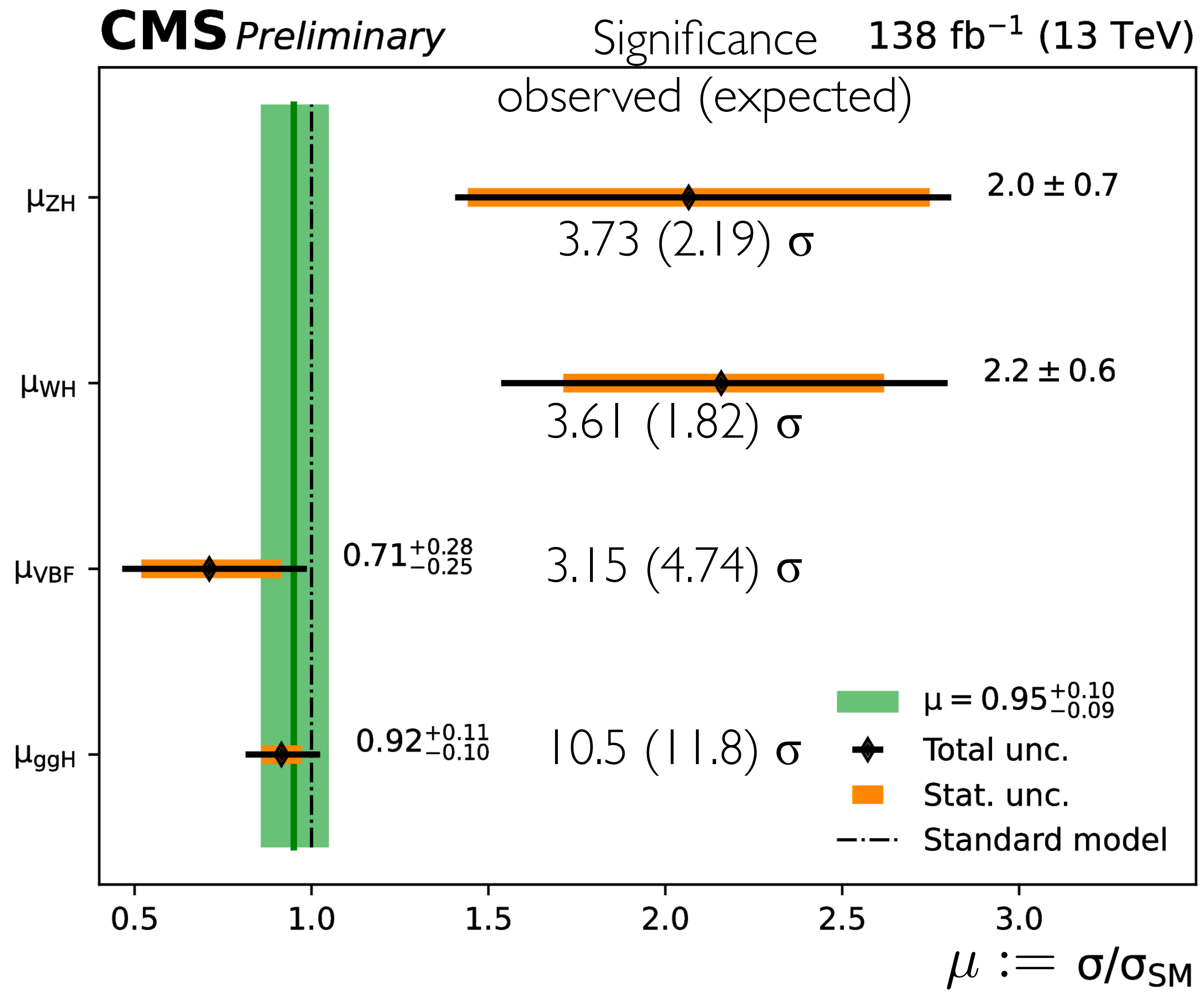
March 2022

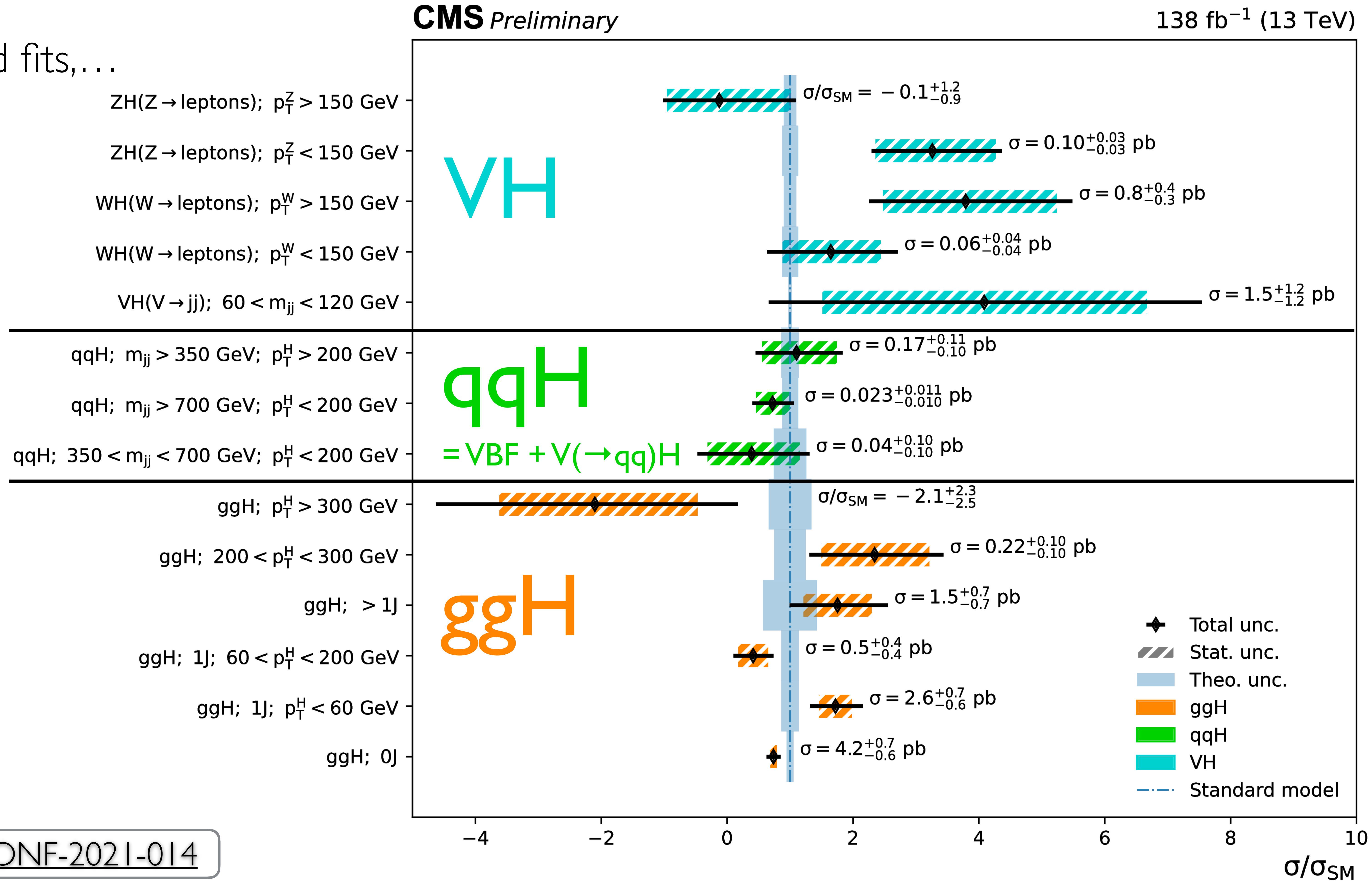
CMS-PAS-HIG-20-013

- Large $BR_{SM}(H \to WW^*) \approx 22\%$
  - $BR_{SM}(H \to WW^* \to \ell\nu\ell\nu) = 1\%$

$\Rightarrow$ **~80 000 $H \to WW^* \to \ell\nu\ell\nu$ events,**

but difficult backgrounds… MVAs, categories, 2-d fits,…



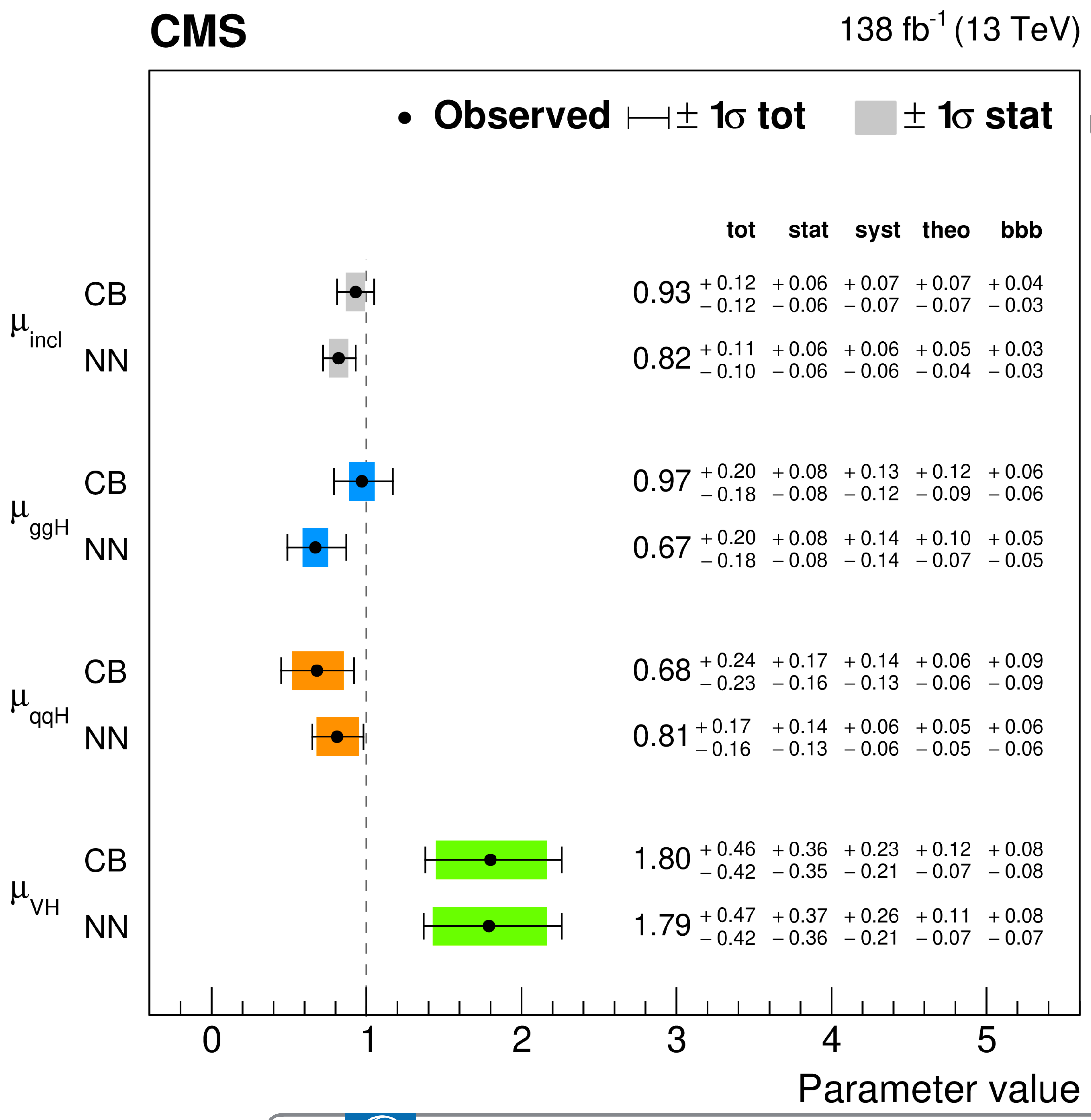


$\Rightarrow$ ATLAS $H \to WW^* \to e\nu\mu\nu$ results from March 2021: ATLAS-CONF-2021-014

$H \to \tau\tau$

arXiv:2204.12957 (submitted to Eur. Phys. J. C)

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



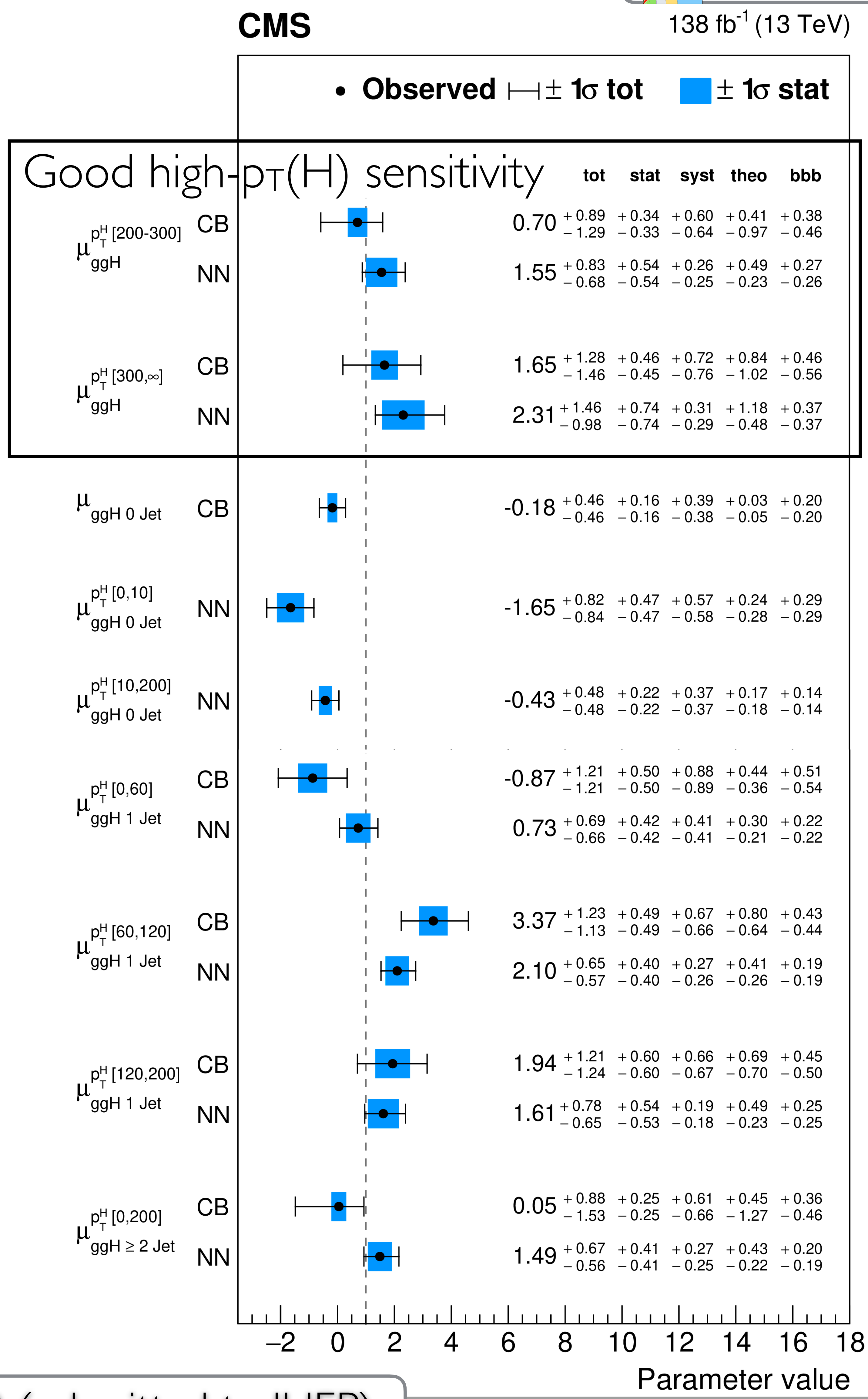
Expected uncertainty NN (CB) [symmetrized]

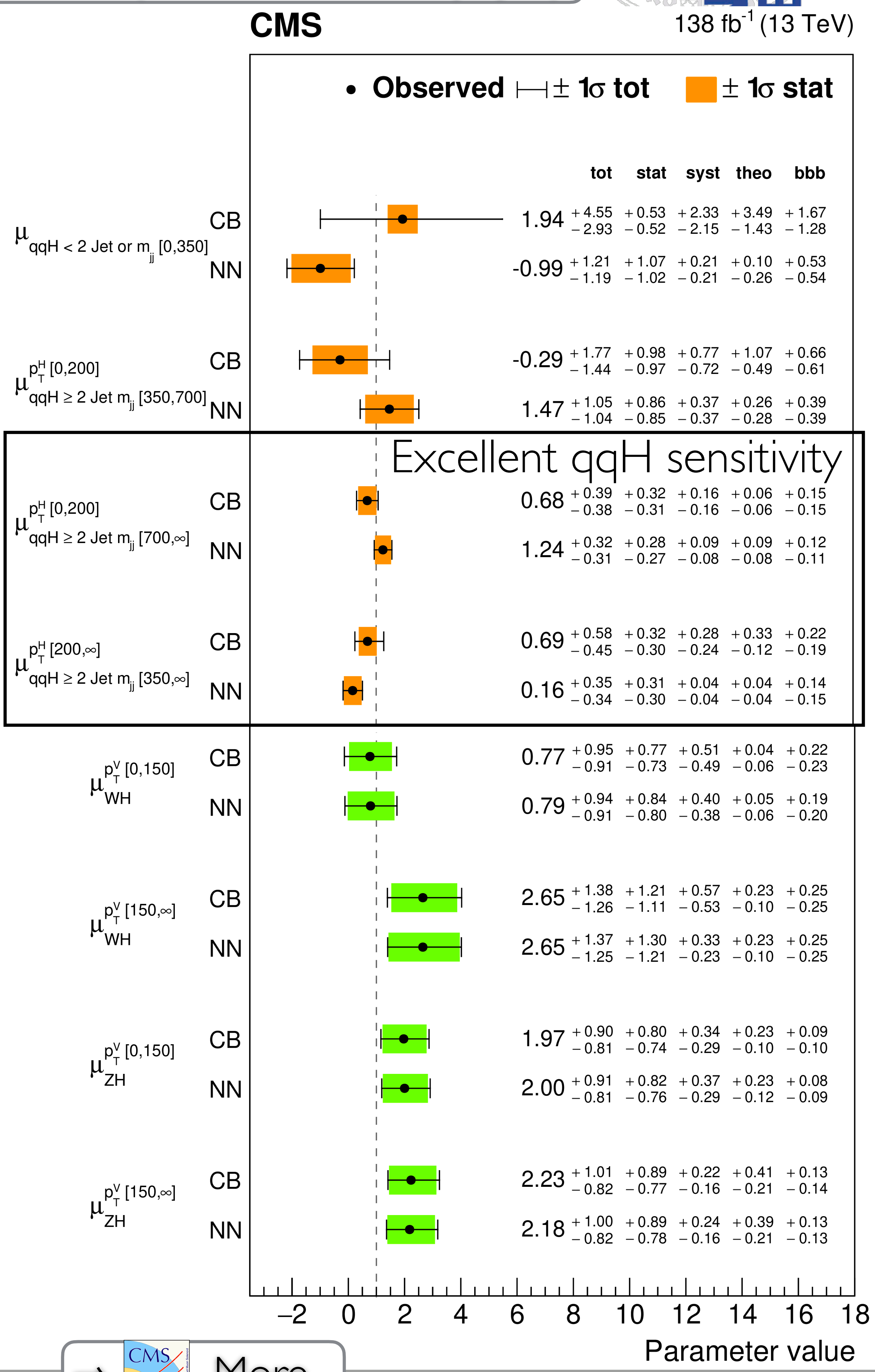
12% (13%)

25% (23%)

17% (24%)

39% (39%)



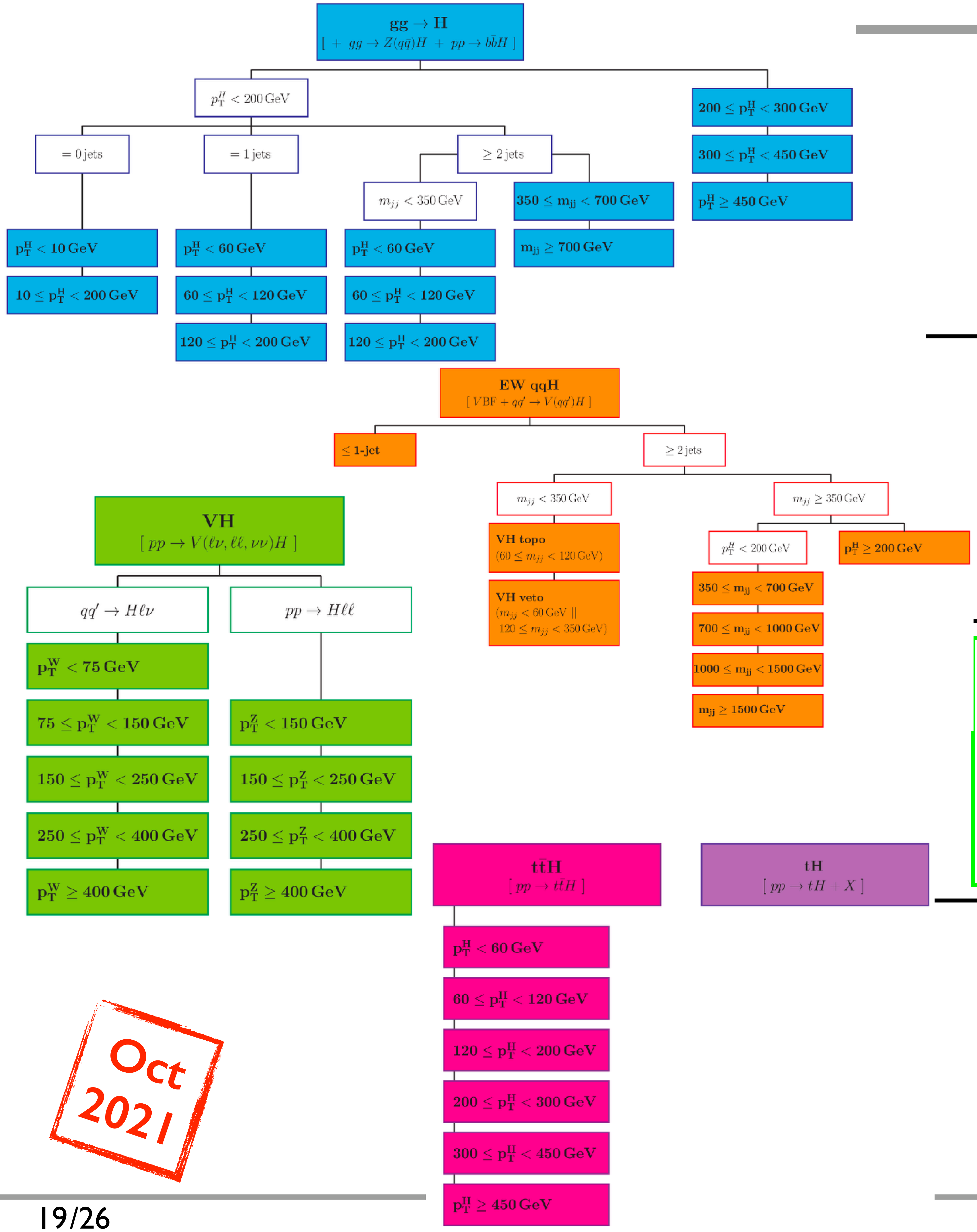


⇒ H → ττ results from January 2022: arXiv:2201.08269 (submitted to JHEP)

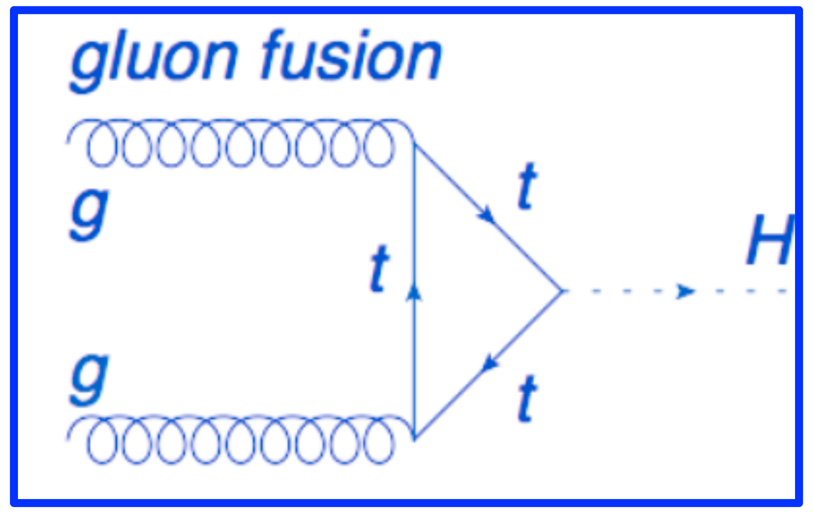
⇒ More

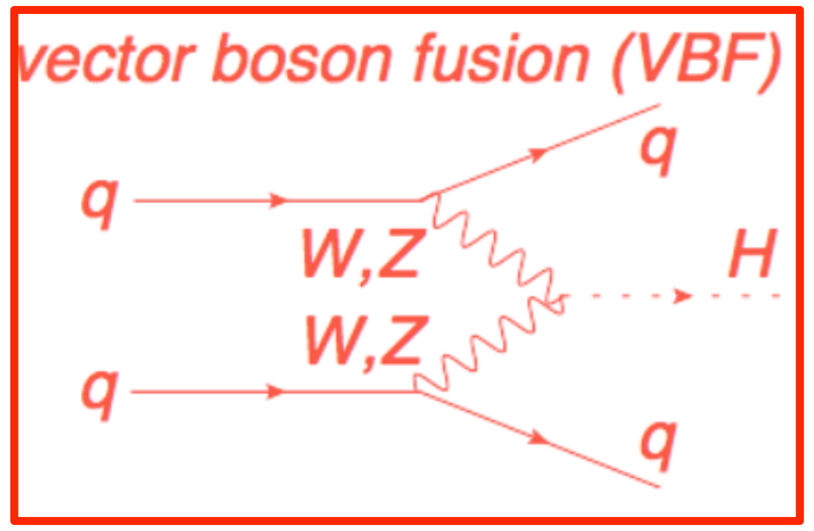
Combined STXS Measurement

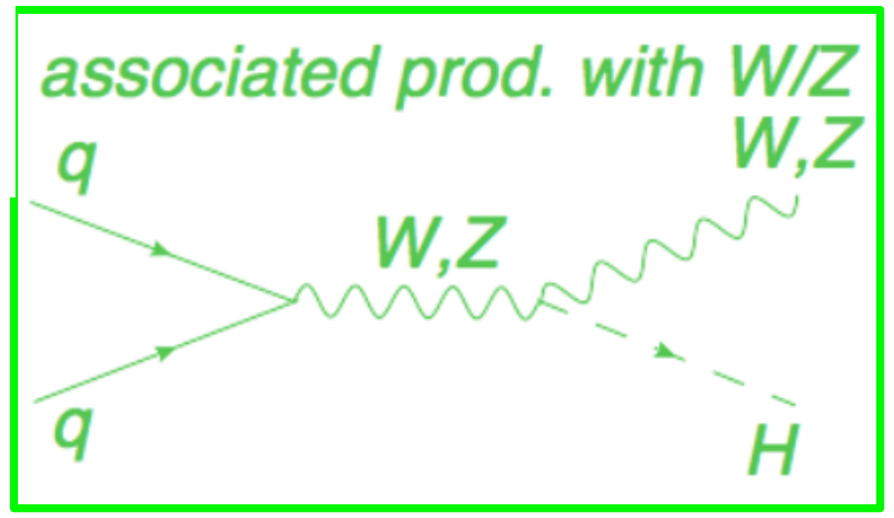
ATLAS-CONF-2021-053 ⇒ More

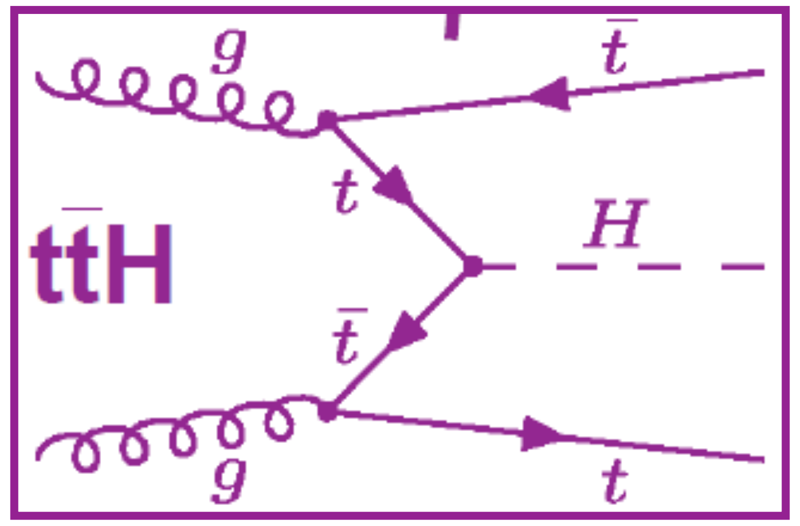


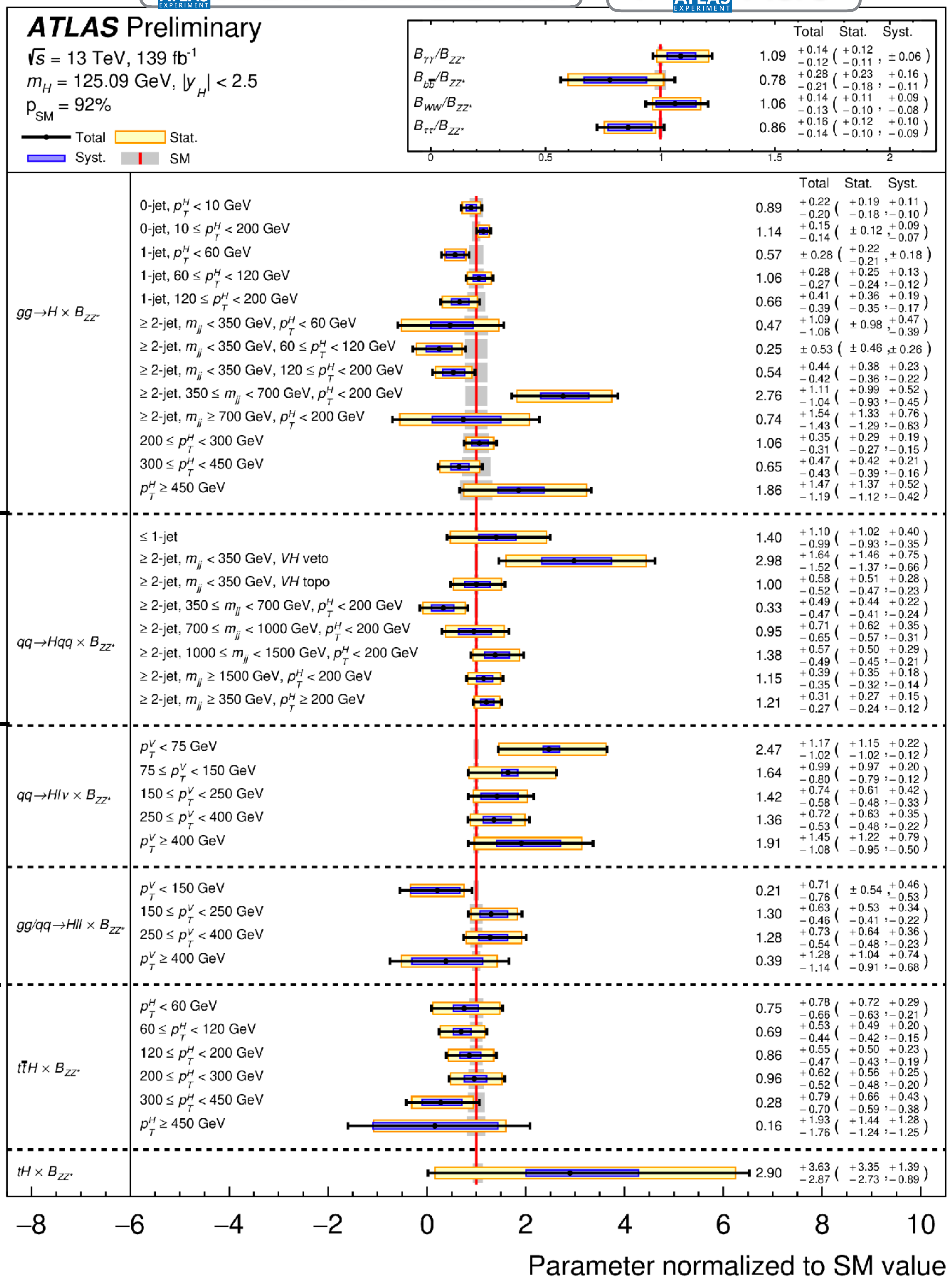
Oct 2021





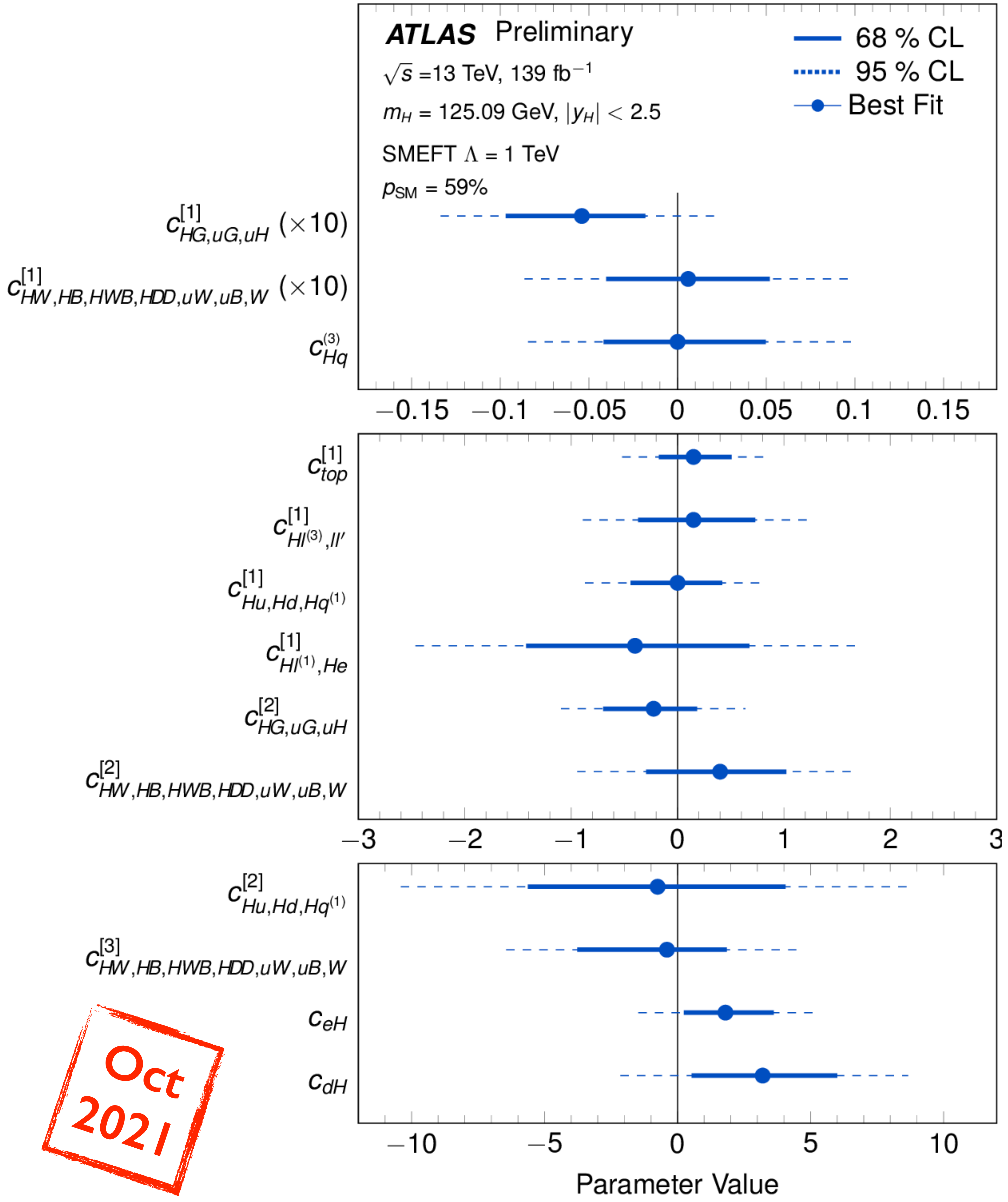




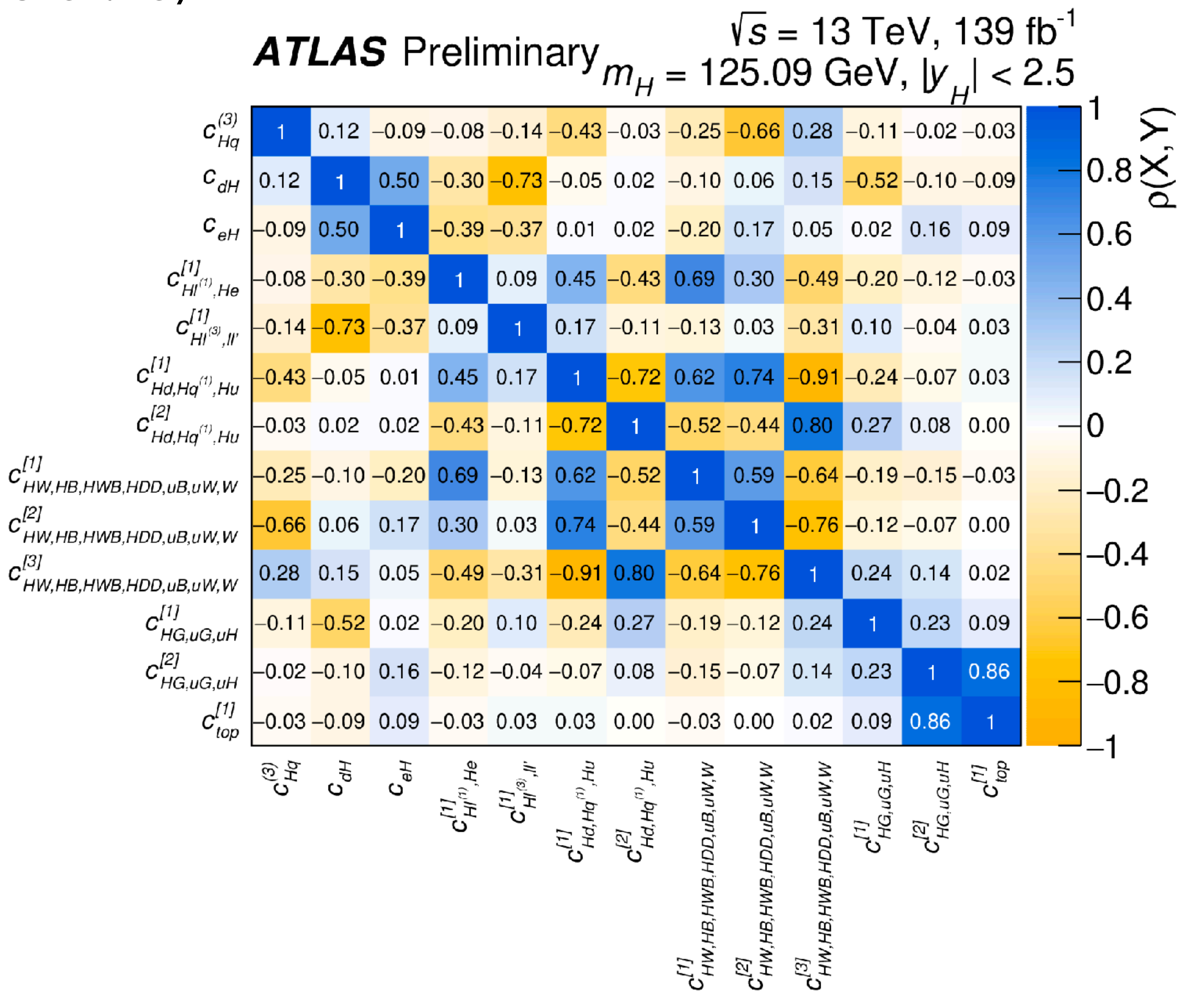


EFT Fit Results

ATLAS-CONF-2021-053



- 13 EFT parameters fitted simultaneously!
  - Excellent sensitivity



Opens the window to global combined analyses!

Oct 2021

Outline

1. Introduction
2. Mass and width measurements
3. CP coupling structure
4. Fiducial and differential cross sections
5. Simplified Template Cross Sections (STXS)
6. HH
7. Summary

Does HH production exist?

direct connection $\longleftrightarrow$

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

H potential as in SM?

HH: Twice the Higgs, twice the fun

<u>Gluon fusion</u>

σ = 31.05 fb

Self-coupling modifier:

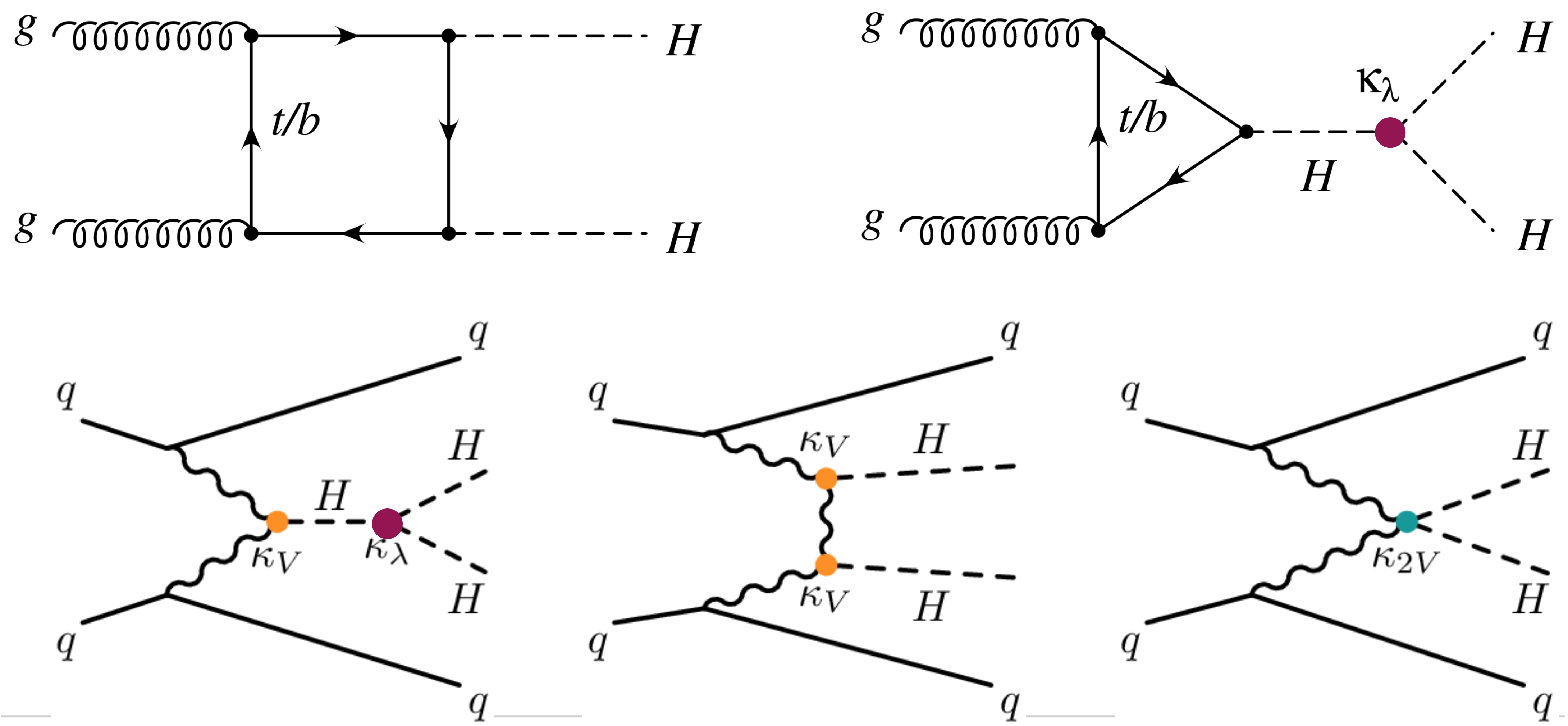
$\kappa_\lambda = \lambda_{HHH} / \lambda_{HHH}^{SM}$

<u>VBF</u>

σ = 1.726 fb

Self-coupling modifier: κ_λ

VVHH coupling modifier: κ_{2V}



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

	bb4l	WWγγ	Multilepton	bbγγ	bbττ	bbll	WWWW	bbWW	bbbb	bbbb boosted
BR_{SM}	0.01%	0.1%	0.39 - 4.6%	0.26%	7.3%	0.1 - 1.6%	4.6%	25 %	33 %	
ATLAS EXPERIMENT	-	230 (160)	-	4.2 (5.7)	4.7 (3.9)	40 (29)	160 (120)	300 (300)	12.9 (20.7)	
				⇒ Comb. 3.1 (3.1)	⇒ HEFT					
CMS	30 (37)	-	21.8 (19.6)	7.7 (5.2)	3.33 (5.22)	-	-	79 (89)	3.9 (7.8)	9.9 (5.1)

March 2022

March 2022

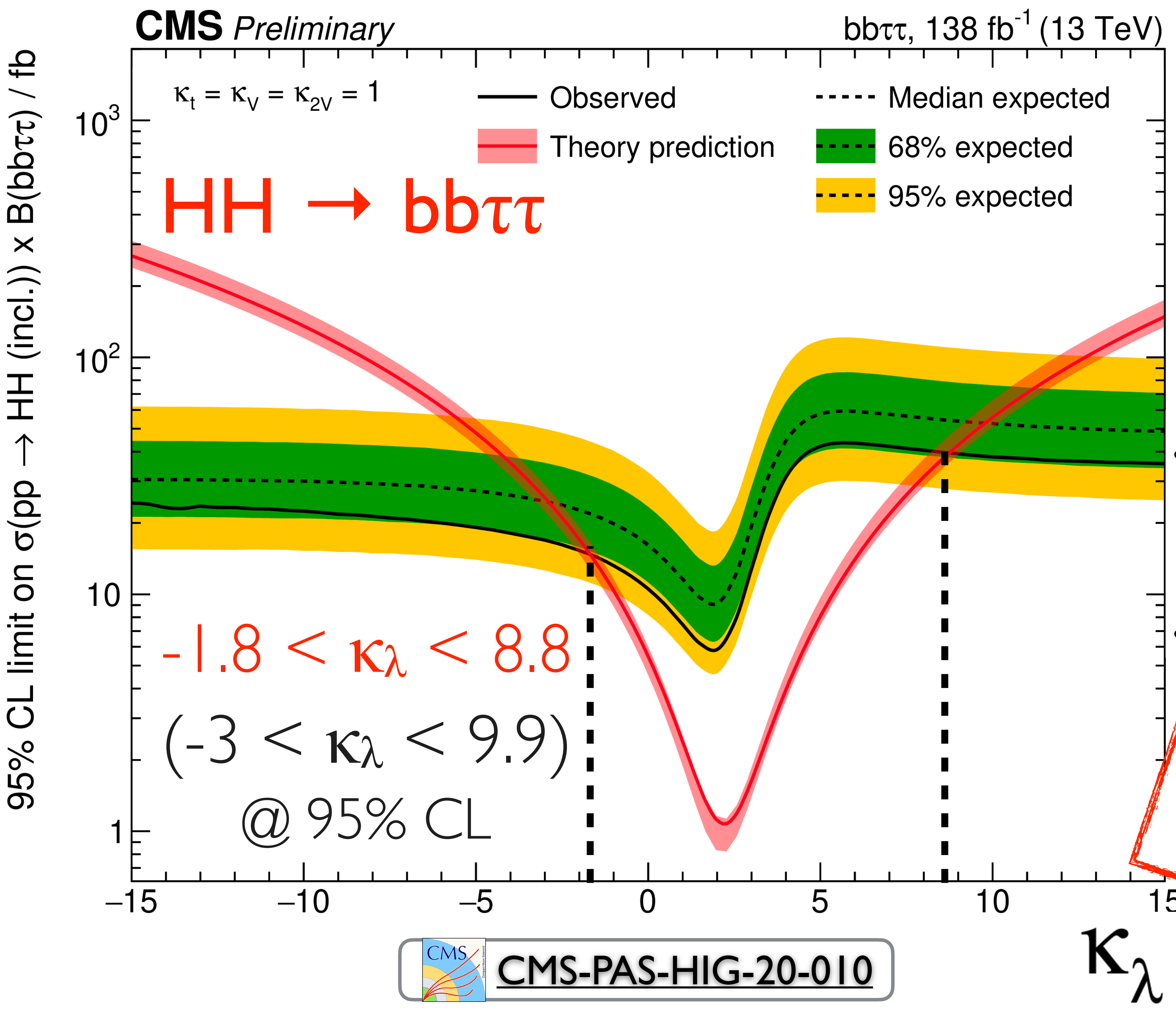
Full and **partial** Run 2 observed (expected) 95% CL upper limits on μ or σ/σ_{SM} ($\sigma_{SM} = \sigma_{ggF}$ or $\sigma_{ggF+VBF}$)

CMS-PAS-HIG-20-010

CMS-B2G-22-003 (submitted to PRL)

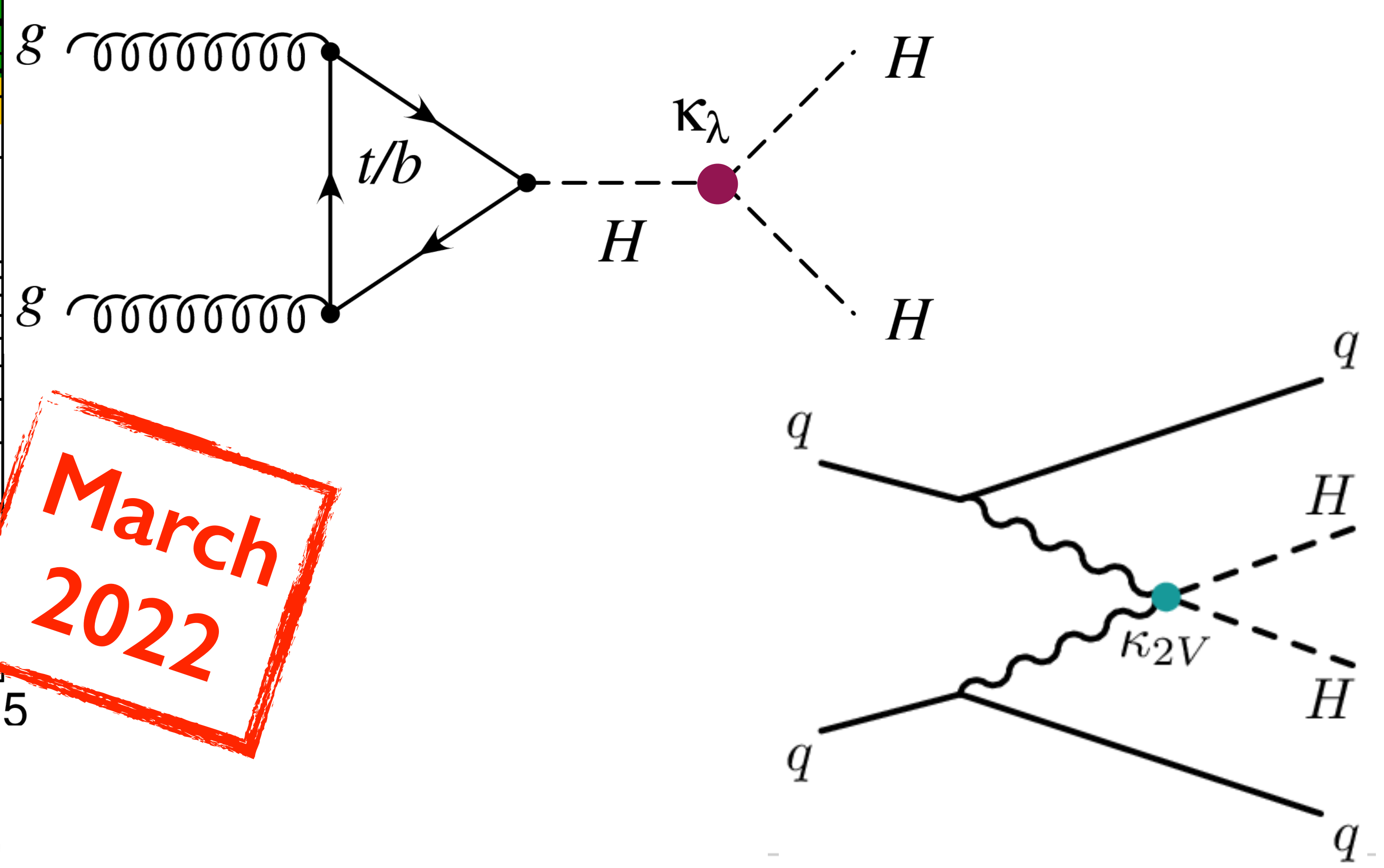
HH → bbττ and HH → bbbb

- Combine large BR & good signatures
  - BR_{SM}(HH → bbττ) = 7.4% ⇒ ~320 events in 138 fb^{-1}
  - BR_{SM}(HH → bbbb) = 33% ⇒ ~1400 events in 138 fb^{-1}



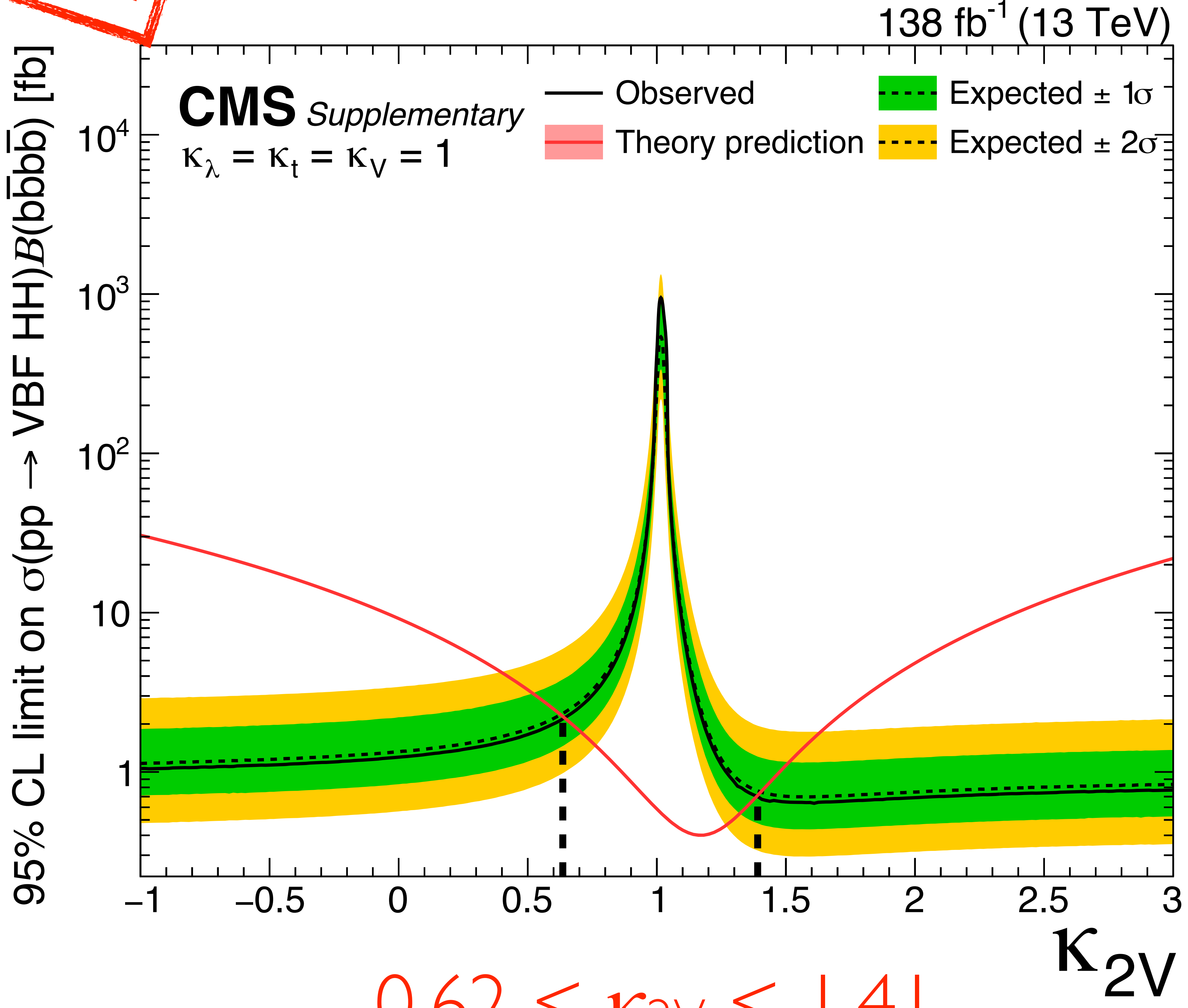
CMS-PAS-HIG-20-010

	bbττ	bbbb boosted
$\sigma_{ggF+VBF}/\sigma_{SM}$	<3.3 (5.2)	<9.9 (5.1)
σ_{VBF}/σ_{SM}	<124 (154)	<728 (409)



May 2022

HH → bbbb boosted



$0.62 < \kappa_{2V} < 1.41$

($0.66 < \kappa_{2V} < 1.37$) @ 95% CL

(all other couplings fixed to SM)

CMS-B2G-22-003 (submitted to PRL)

⇒ bbγγ observed (expected) κ_λ limits: $-3.3 < \kappa_\lambda < 8.5$ ($-2.5 < \kappa_\lambda < 8.2$) [JHEP 03 (2021) 257]

⇒ Currently best observed (expected) κ_λ limits from ATLAS bbττ+bbγγ combination: $-1.0 < \kappa_\lambda < 6.6$ ($-1.2 < \kappa_\lambda < 7.2$)

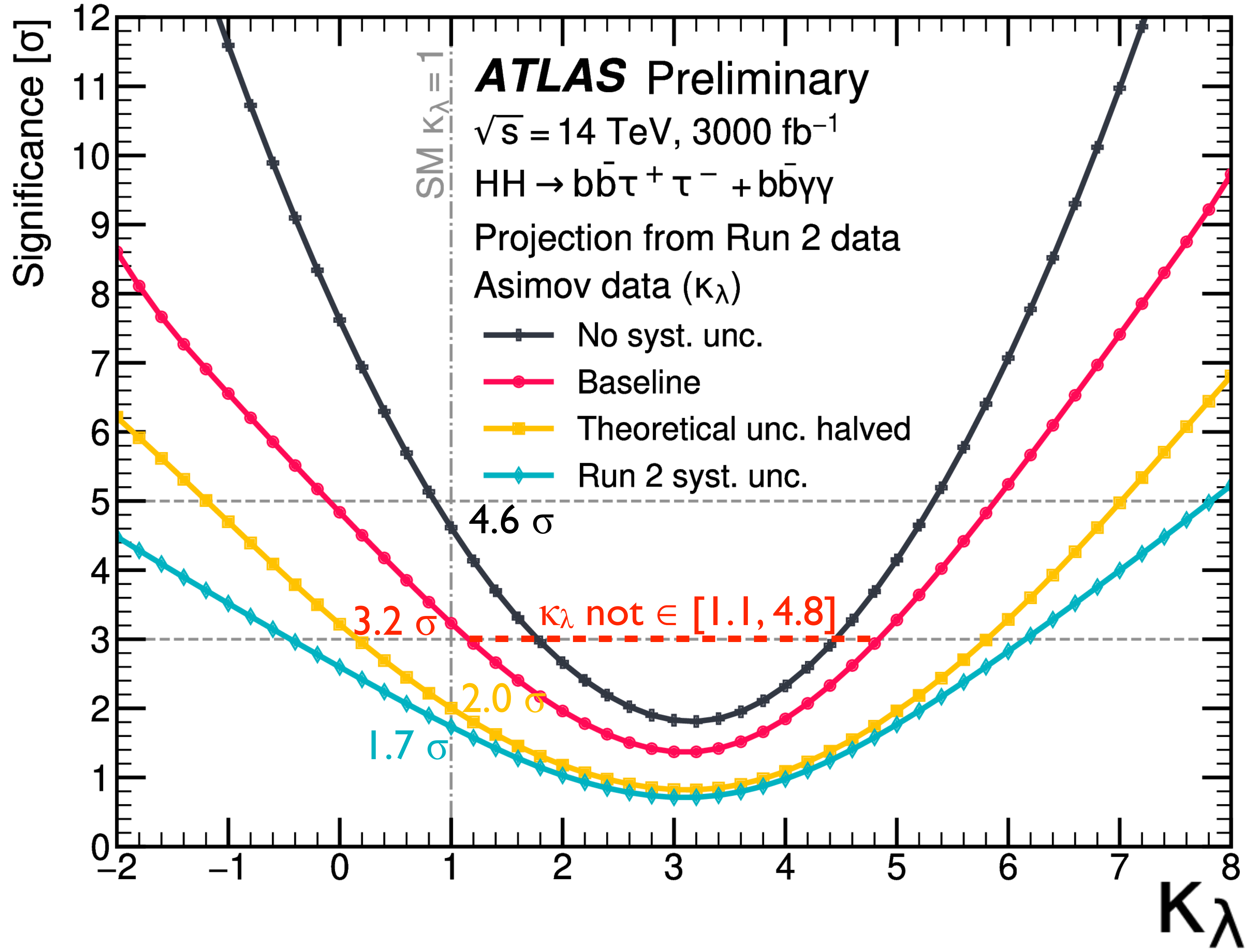
HH: Future fun

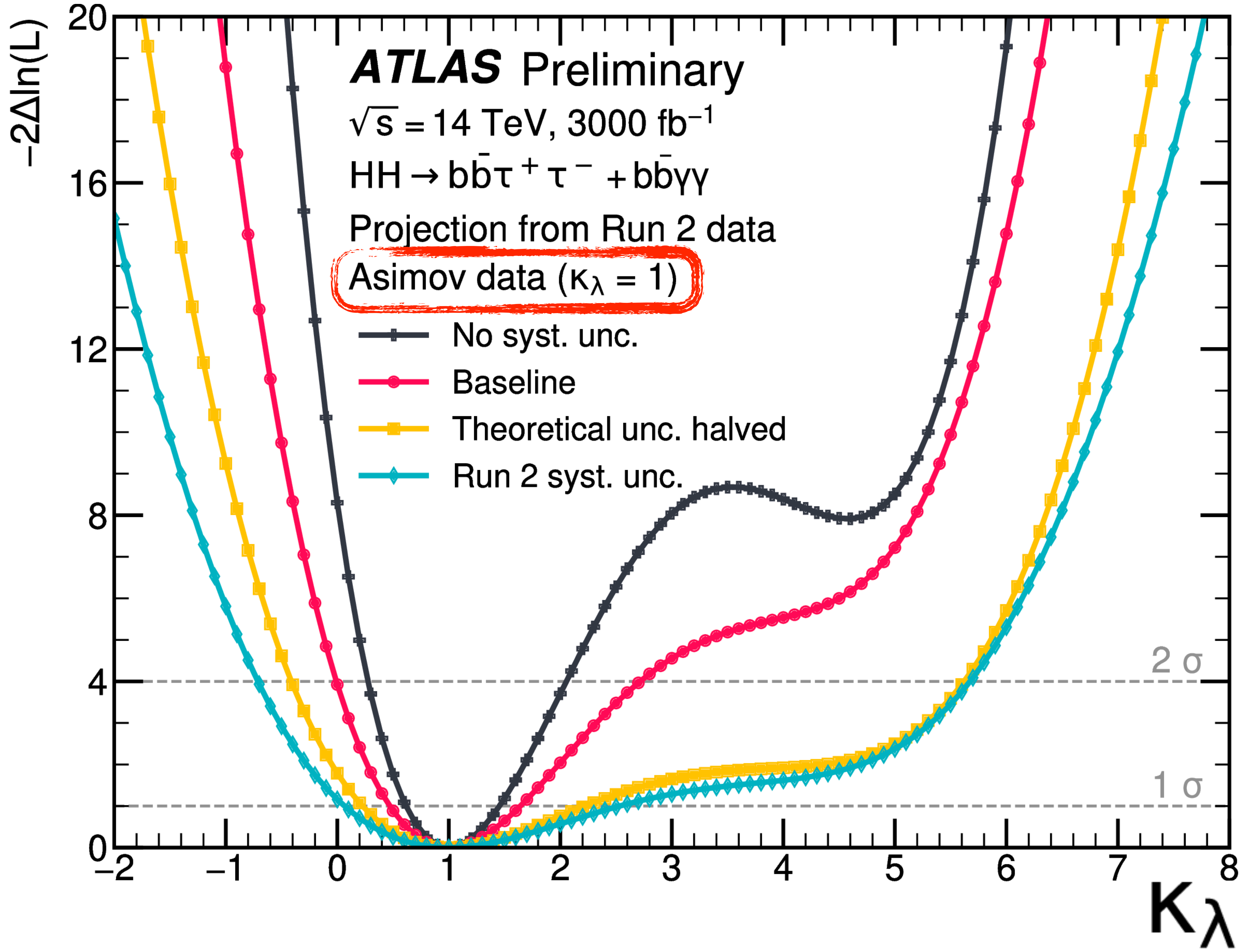
February 2022

ATL-PHYS-PUB-2022-005

- HL-LHC extrapolation from full Run 2 combination of:
  - $BR_{SM}(HH \to bb\tau\tau) = 7.4\% \Rightarrow$ ~6900 events in 3000 fb^{-1}
  - $BR_{SM}(HH \to bb\gamma\gamma) = 0.26\% \Rightarrow$ ~240 events in 3000 fb^{-1}

Uncertainty scenario	Likelihood scan 1σ CI	Likelihood scan 2σ CI
No syst. unc.	[0.6, 1.5]	[0.3, 2.1]
Baseline	[0.5, 1.6]	[0.0, 2.7]
Theoretical unc. halved	[0.2, 2.2]	[−0.4, 5.6]
Run 2 syst. unc.	[0.1, 2.5]	[−0.7, 5.7]





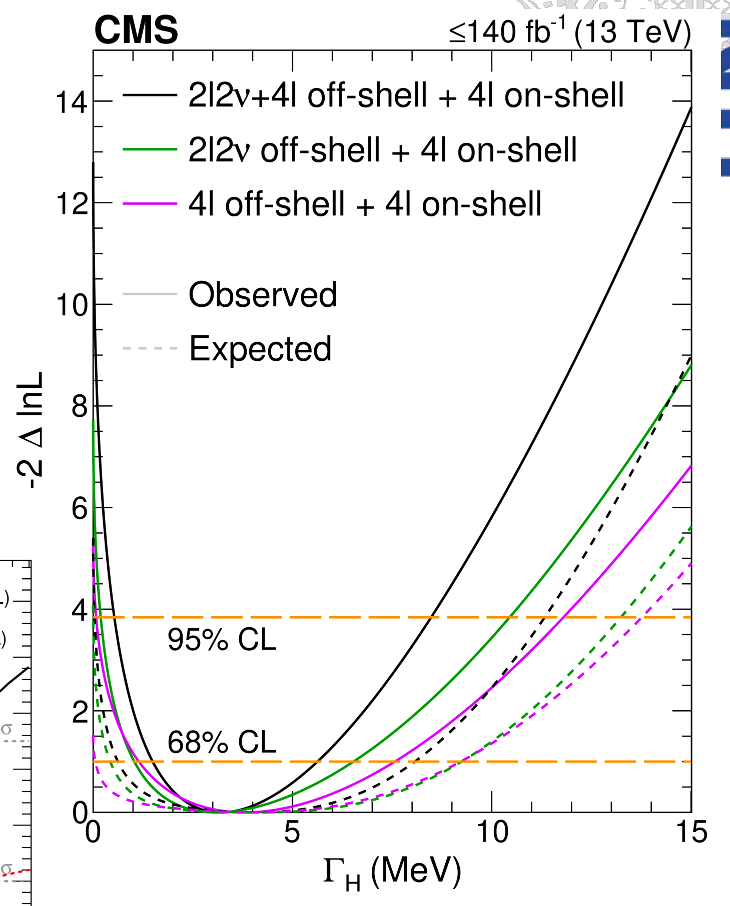
⇒ CMS $bb\gamma\gamma$ expected significance at 3000 fb^{-1}: **2.16 σ** [CMS-PAS-FTR-21-004]

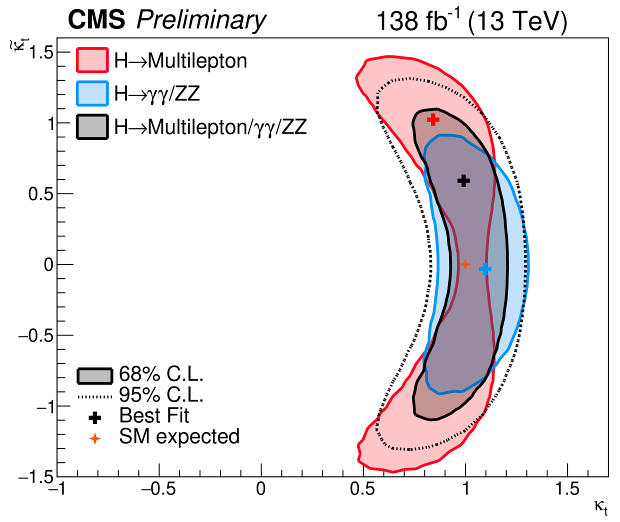
⇒ ATLAS + CMS (3+3 ab^{-1}, all channels) from CERN HL-LHC Yellow Report (w/ systematics): HH significance: **4.0 σ** and **$0.52 < \kappa_\lambda < 1.5$** @ 68% C.L.

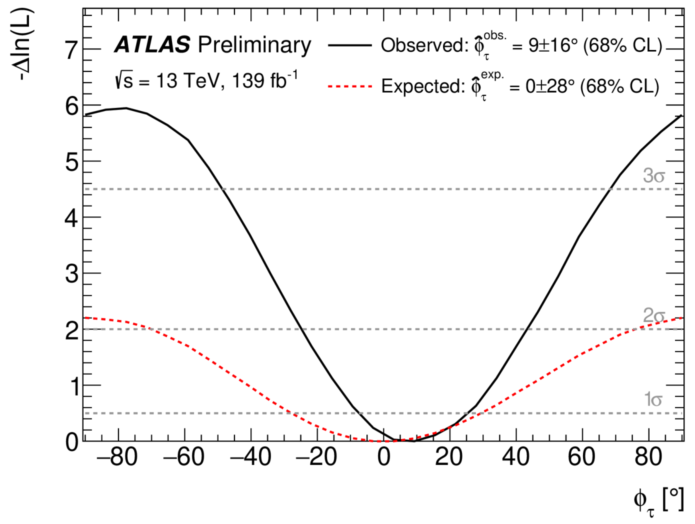
Summary

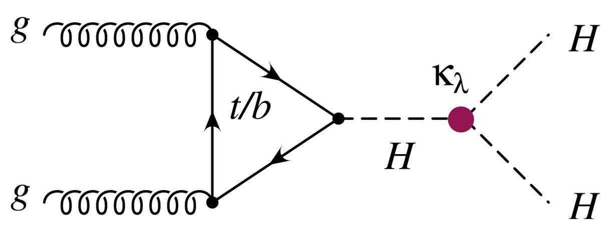
We learned so much in the last 10 years!

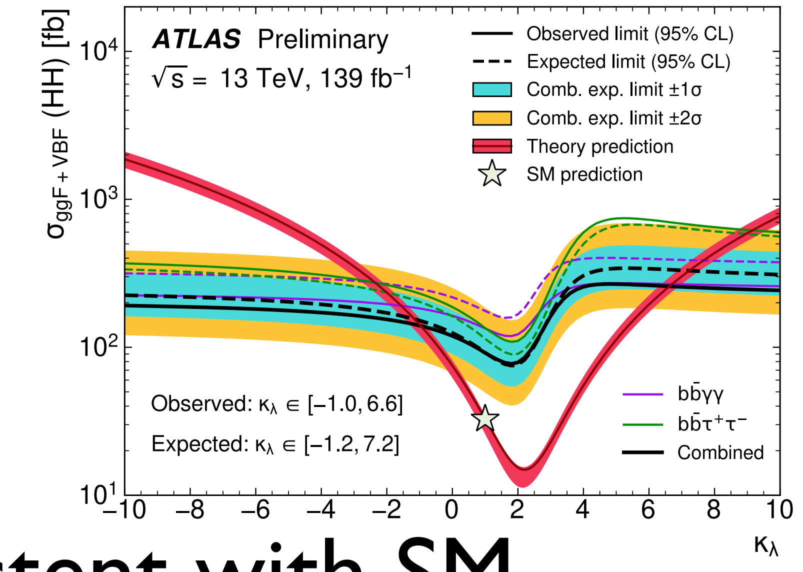
- And have **~8 Million produced Higgs bosons thus far**
- **1‰ precision** on **m$_H$** and first (indirect) measurement of $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV
- Probing **CP** structure of Higgs couplings in Yukawa couplings
- Measuring **total, fiducial**, **differential**, and **STXS** cross sections
- Various interpretations:
  - κ coupling modifiers: precision **6%** (κ_Z, κ_W, κ_γ) - **25%** (κ_μ, $\kappa_{Z\gamma}$),
  - EFTs, etc.
- Improving **HH** beyond lumi-scaling:
  - σ_{HH} **< 2.8 × SM**
  - **-1.0 <** κ_λ **< 6.6**
  - $\kappa_{2V} \in$ **[0.62, 1.41]**
- **All measured quantities are consistent with SM**

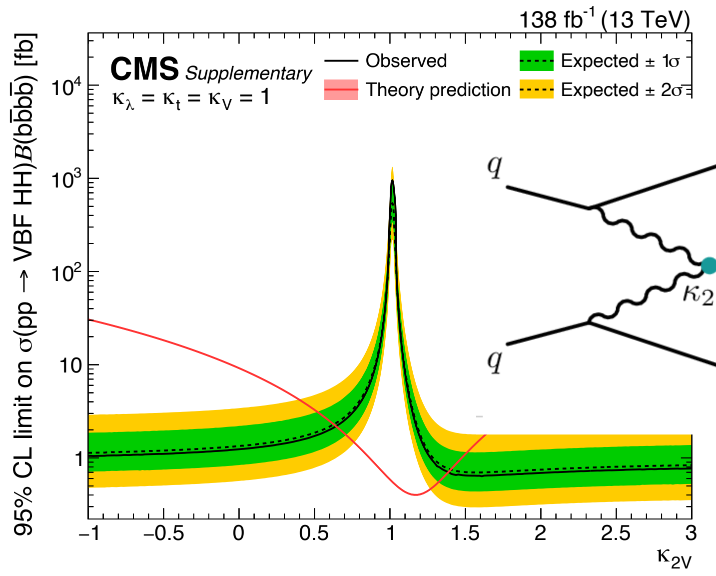


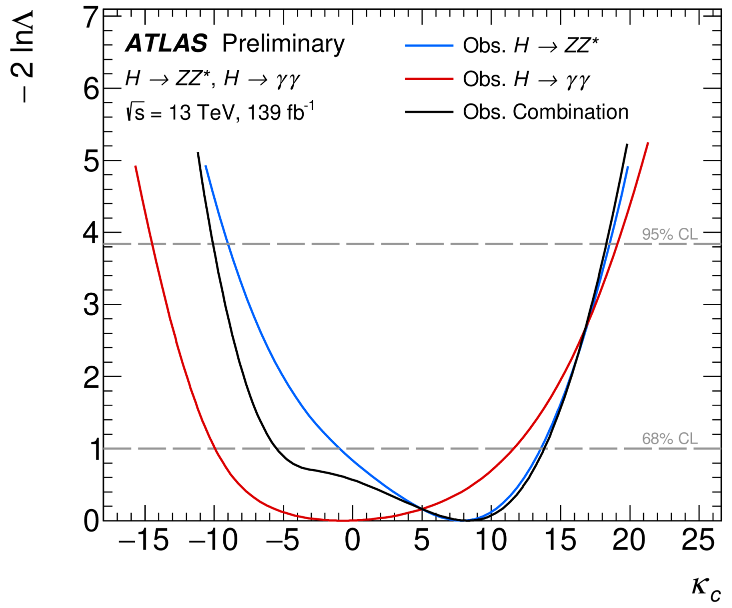


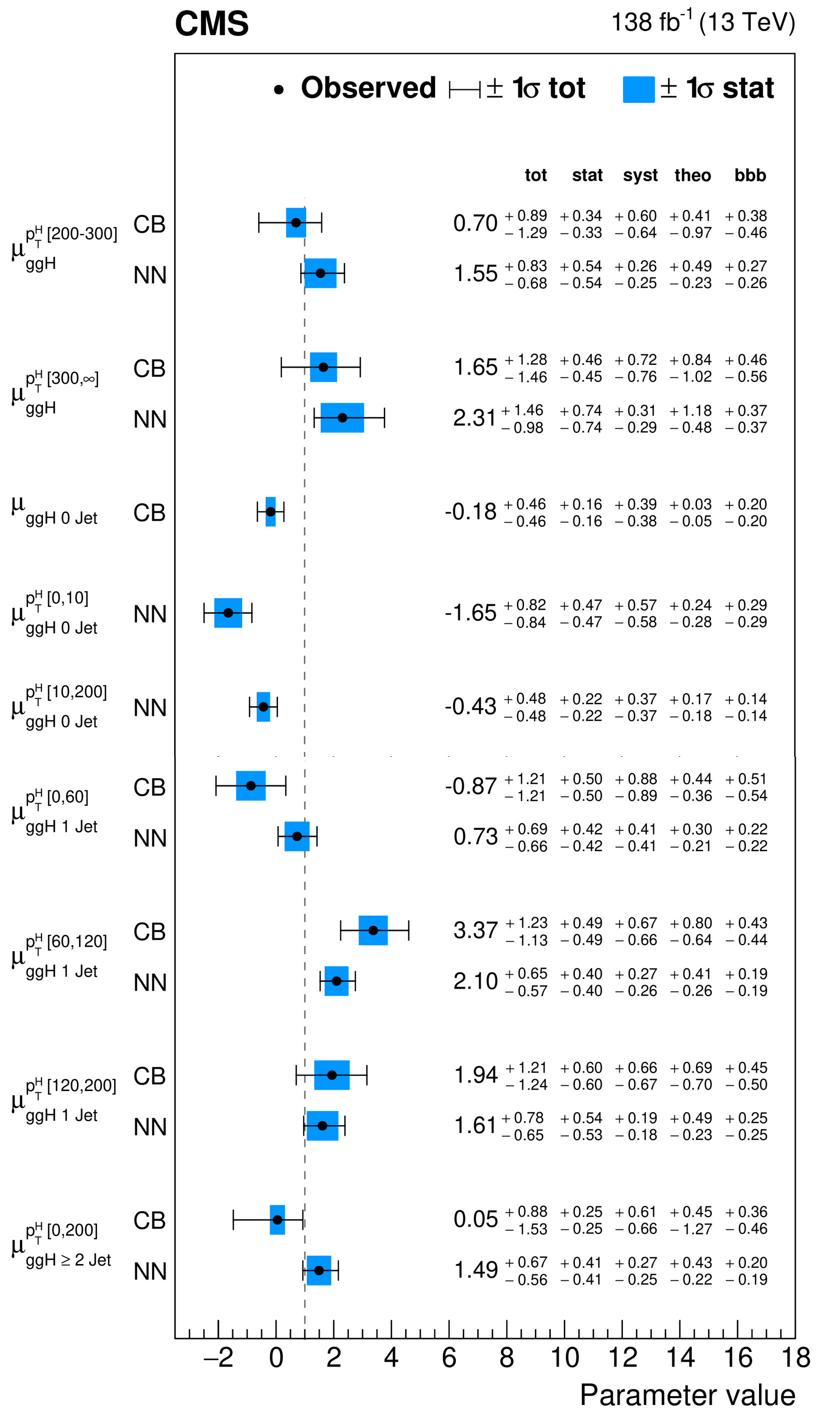










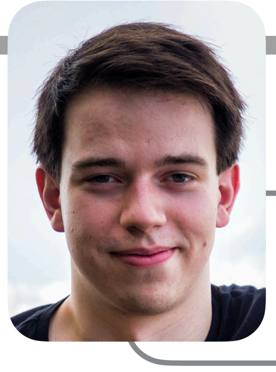


LHC Run 3 will give us another boost in our understanding

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

More about precision Higgs experiment…

Plenary talk:



Thu 16:40, _Rare & BSM Higgs experiment_, Andrzej Novak

Parallel talks:

Mo 15:51, _ttH/tH production ATLAS_, Ana Luisa Carvalho

Mo 16:09, _ttH/tH production CMS_, Angela Giraldi

Mo 16:27, _ttbb modeling for ttH ATLAS+CMS_, Nihal Brahimi

Tu 14:15, _Higgs decays to bosons at ATLAS and CMS_, Matthew Basso

Tu 14:35, _Higgs decays to 3rd generation fermions at ATLAS and CMS_, Soumya Mukherjee

Tu 14:55, _Higgs rare decays at ATLAS and CMS_, Milos Dordevic

Tu 15:55, _Higgs properties (CP, mass, width,..) at ATLAS and CMS_, Jeffrey Davis

We 14:15, _Higgs fiducial and differential measurements at ATLAS and CMS_, Fábio Lucio Alves

We 14:35, _Higgs-charm coupling constraints at ATLAS and CMS_, Tristan Arnoldus Du Pree

We 14:55, _Higgs coupling combination at ATLAS and CMS_, Angela Taliercio

Thu 14:35, _Higgs EFT results at ATLAS and CMS_, Andrea Sciandra

Thu 15:15, _Higgs self-coupling at ATLAS_, Louis D'Eramo

Thu 15:33, _Higgs self-coupling at CMS_, Davide Zuolo

Posters (Tu at 19:00 and We at 10:00):

Measurement prospects for di-Higgs production in the HH to bbyy channel with the ATLAS experiment at the HL-LHC, Alex Wang

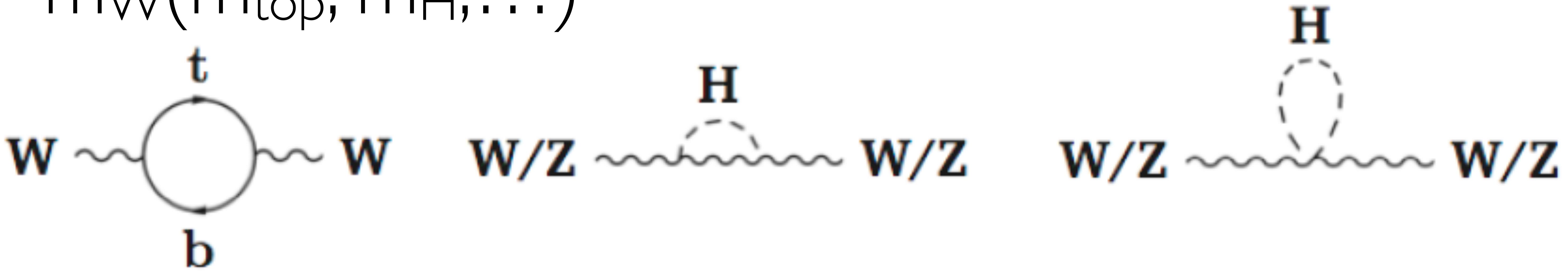
Probing the CP nature of the top-Higgs Yukawa coupling in ttH and tH events with H→bb using the ATLAS detector, Zak Lawrence

Projected sensitivity of Higgs boson pair production combining the bbyy and bbtautau decay channels at the HL-LHC with the ATLAS detector, Alkaid Cheng

Search for the Higgs boson decaying to a pair of muons in pp collisions at 13 TeV with the ATLAS detector, Jay Chan

Impact of m_H

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



- Measurement: $m_W = 80.379 \pm \mathbf{0.013}$ GeV
- Impact on m_W in electroweak fit: $\Delta m_W(\mathrm{Top}) = \pm\mathbf{2.7}$ MeV, $\boldsymbol{\Delta m_W(H) = \pm 0.1}$ **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%	~11%	±0.3%

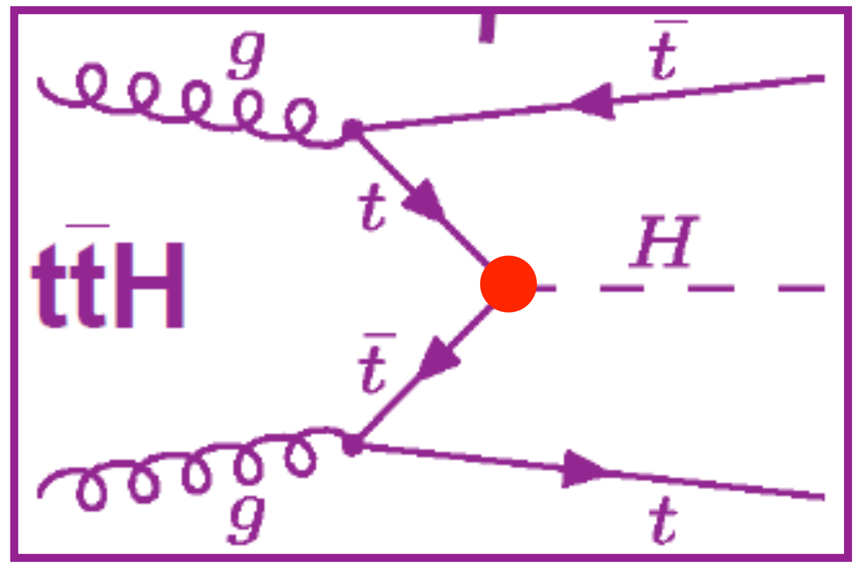
⇒ Measurement precision of m_H good enough for this

- but precise measurement important!

CP Measurement in t(t)H Production

CMS-PAS-HIG-21-006

- Tree-level **top-Yukawa** measurement
  - Difficult "**multilepton**" topology, many objects in final state
    - Use $2\ell SS + 1\tau_h$, $3\ell + 0\tau_h$ and $2\ell SS + 0\tau_h$ categories
    - Multiclass neural network to categorize ttH, tHq, (ttW) and background
    - BDT to separate CP-even from CP-odd
  - Combine with γγ and ZZ* decays



March 2022

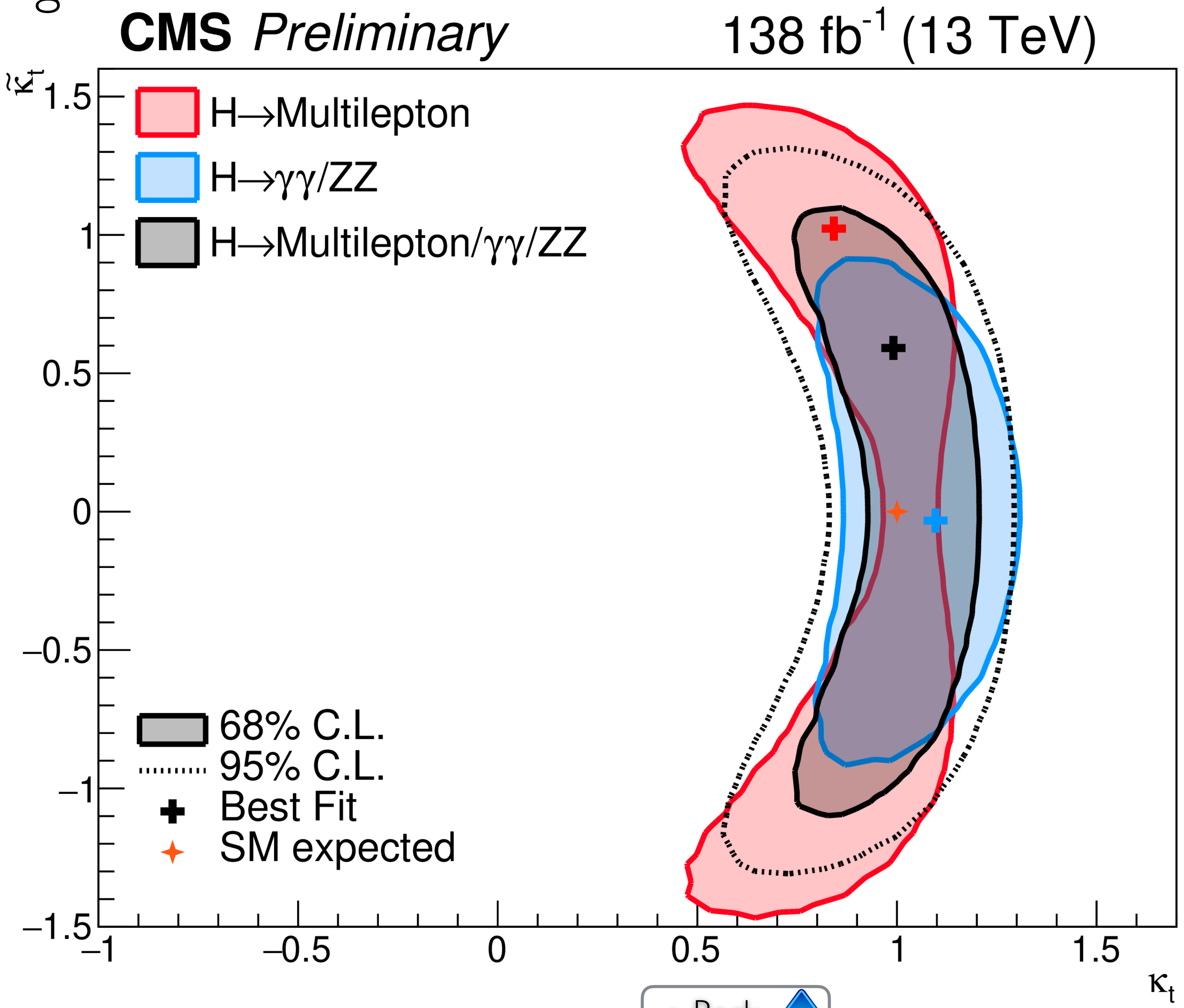
- Parametrize ttH coupling:

$$\mathcal{L}_{t\bar{t}H} = \frac{-y_t}{2}\bar{\psi}_t(\kappa_t + i\gamma_5\tilde{\kappa}_t)\psi_t H$$

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

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

- Results:
  - $|f_{CP}^{Htt}| < 0.55$ at 68%
  - Pure CP-odd coupling excluded at **3.7 σ**



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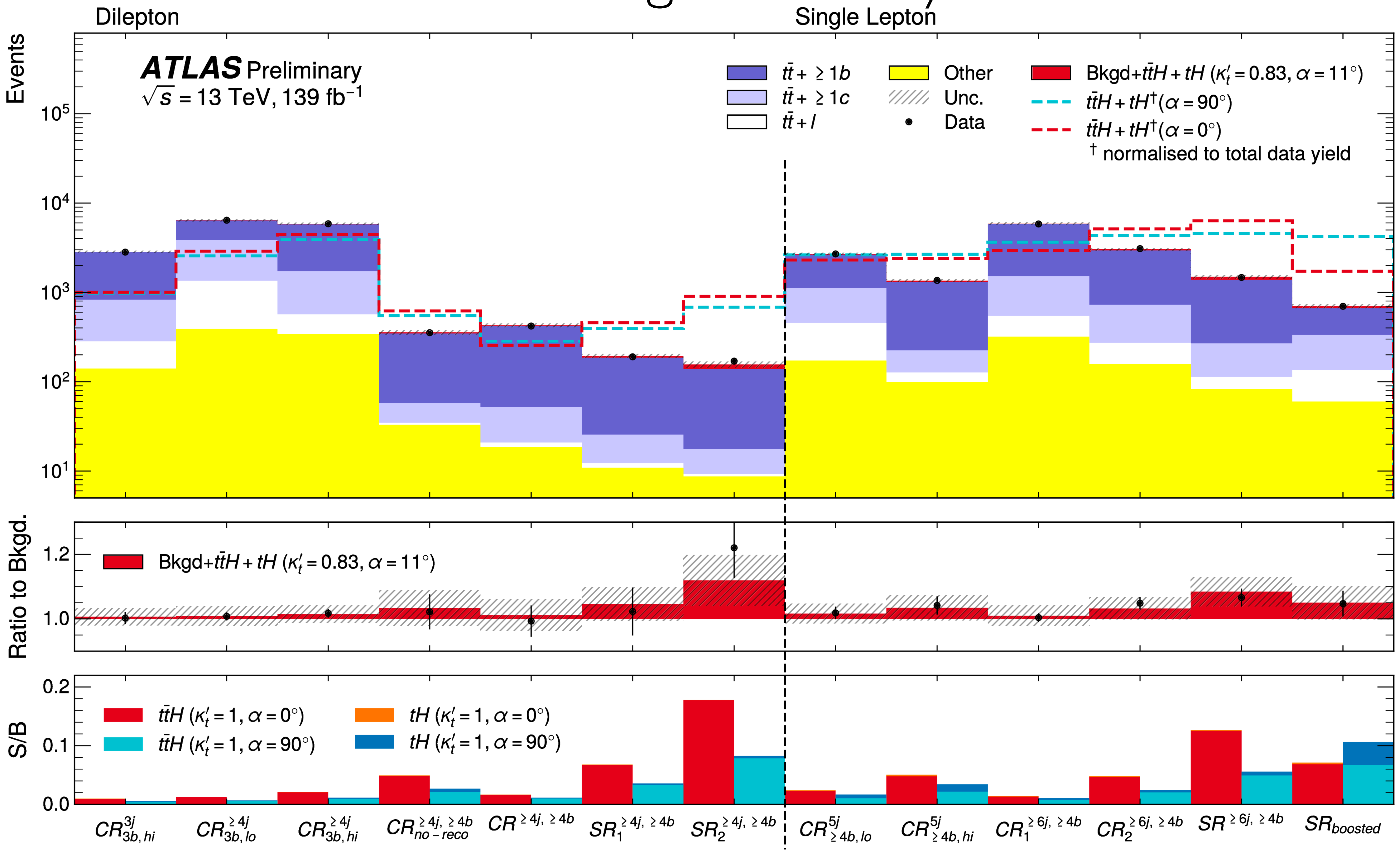
CP Measurement in t(t)H Production

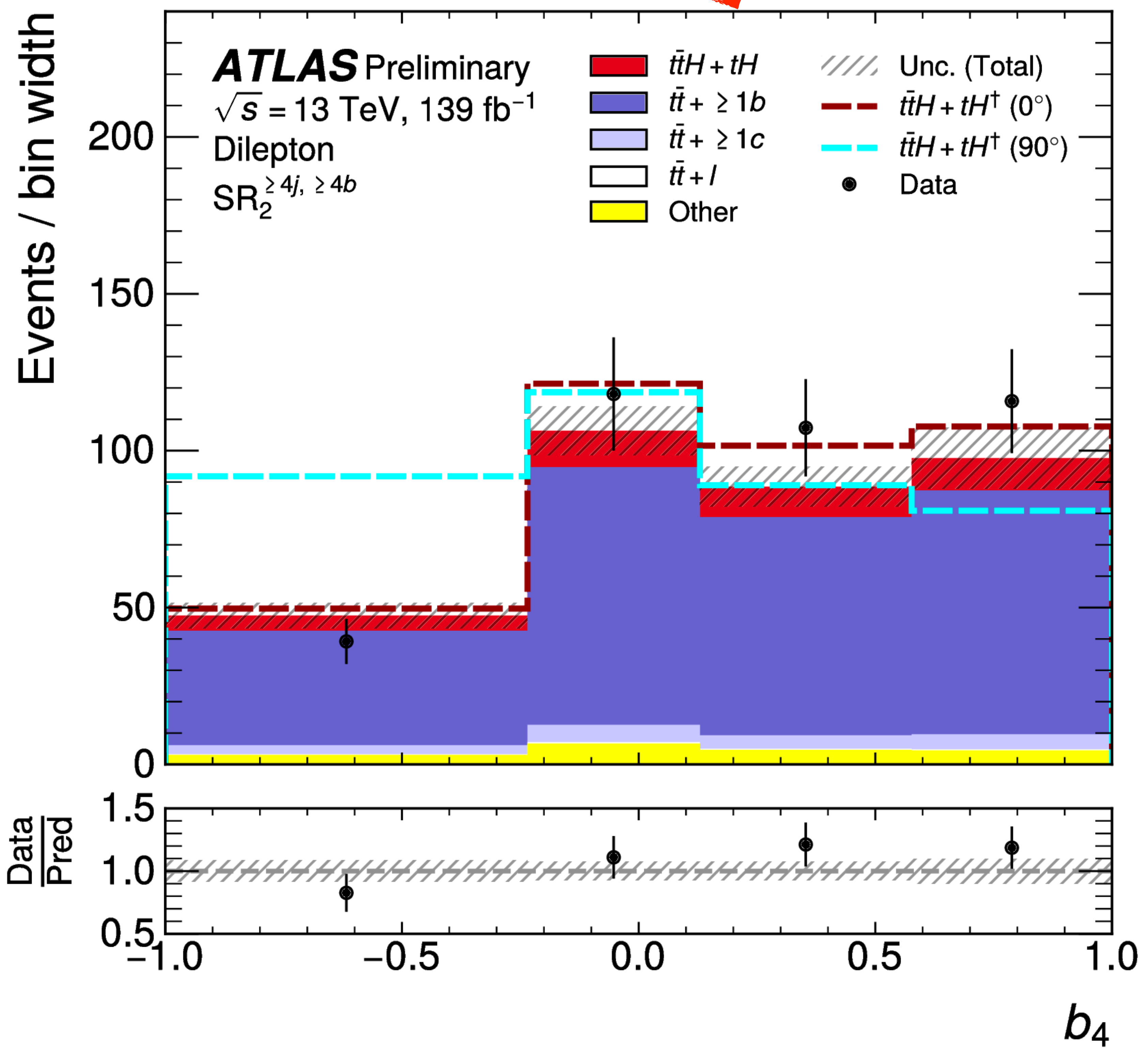
ATLAS-CONF-2022-016

March 2022

- Tree-level **top-Yukawa** measurement
  - Difficult **ttH, H → bb** topology, many objects in final state
  - Dominant ttbb background very difficult to model



† normalised to data yield



CP-sensitive angular variables calculated between the top quarks:

$$b_2 = \frac{(\vec{p}_1 \times \hat{n}) \cdot (\vec{p}_2 \times \hat{n})}{|\vec{p}_1||\vec{p}_2|}$$

Single-lepton

$$b_4 = \frac{p_1^z p_2^z}{|\vec{p}_1||\vec{p}_2|}$$

Dilepton

$\hat{n}$ = z-axis

Phys. Rev. Lett. 76, 4468

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CP Measurement in H → ττ Decay

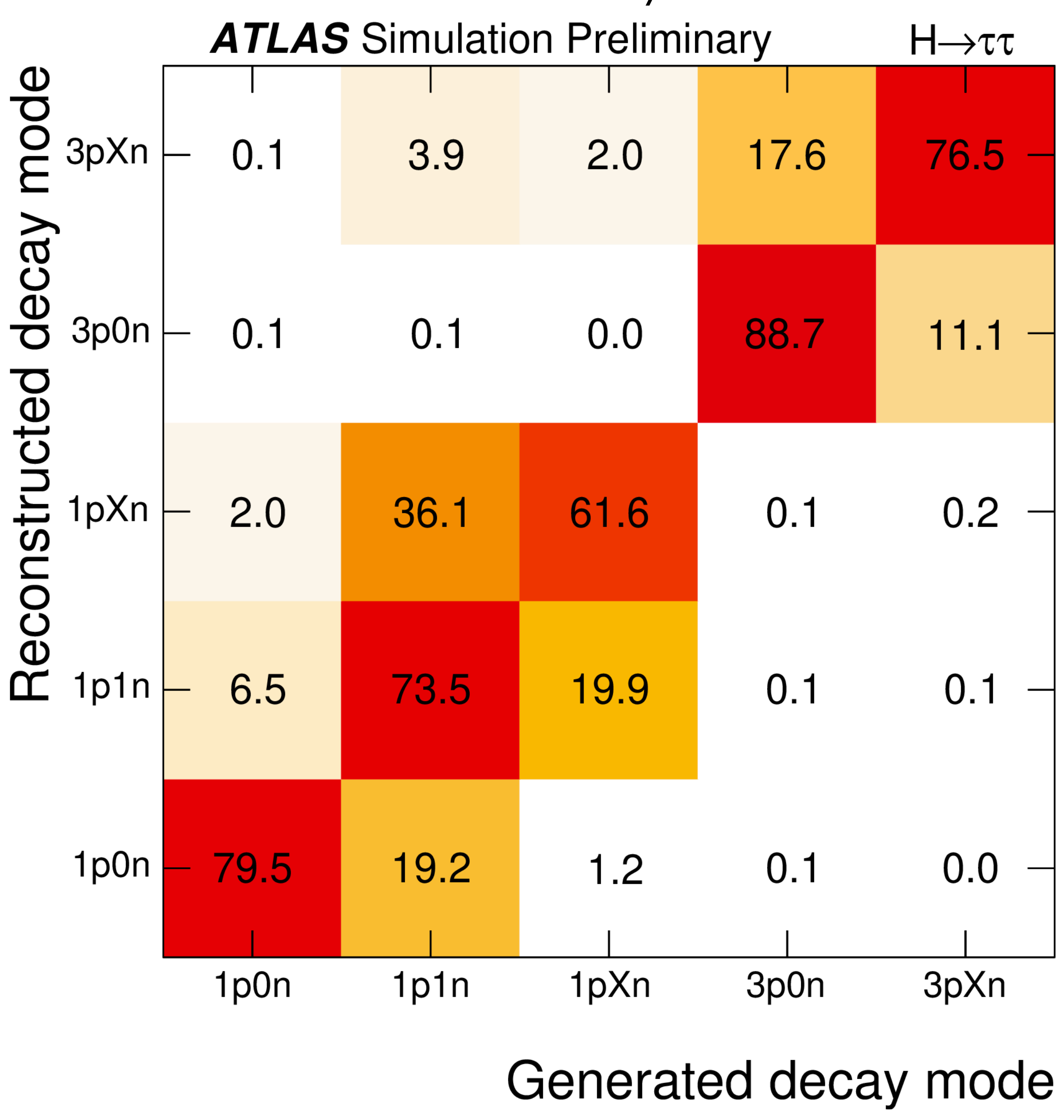
ATLAS-CONF-2022-032

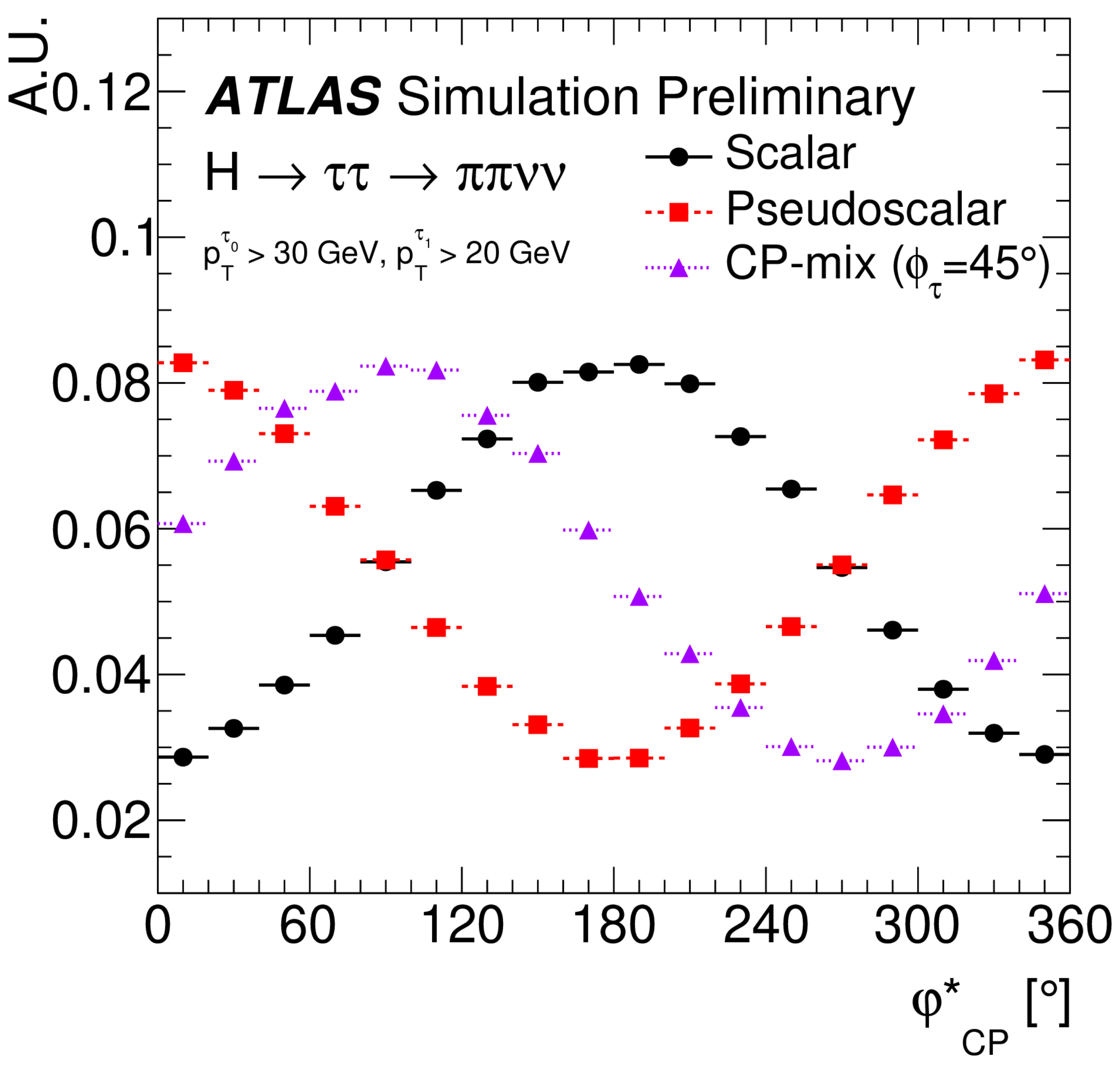
May 2022

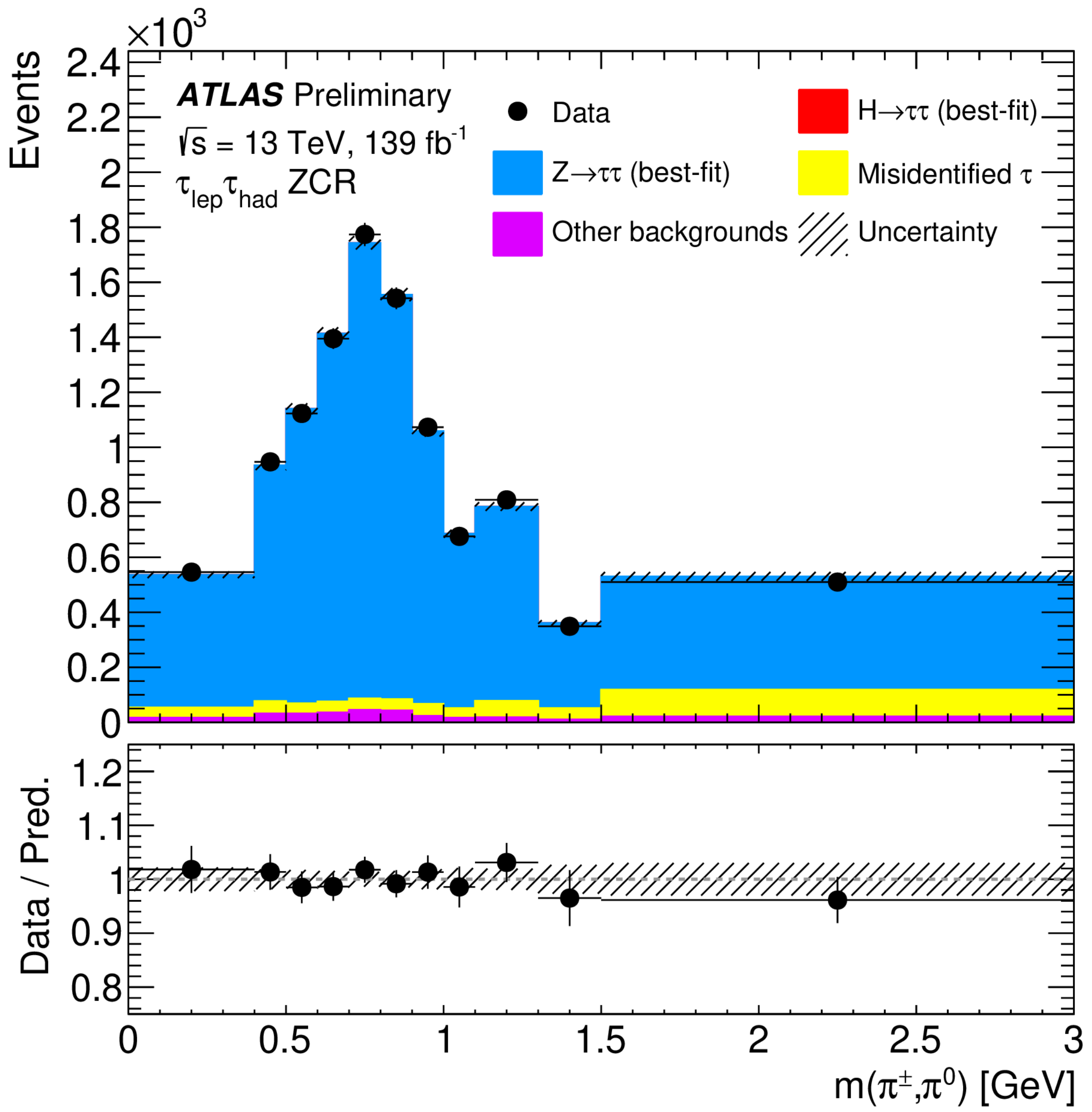
Parametrize **τ-Yukawa** coupling: $\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau \bar{\tau}\tau + \sin\phi_\tau \bar{\tau} i\gamma_5 \tau)H$

- Reconstruct τ decay modes
- Observable: signed acoplanarity angle between τ decay planes
  - spanned by impact parameter and/or decay products ($\pi^\pm, \pi^0$)

Purity







Region	Expected CP-odd exclusion (σ)
$\tau_{had}\tau_{had}$ High	1.38
$\tau_{had}\tau_{had}$ VBF 1 High	0.83
$\tau_{had}\tau_{had}$ VBF 0 High	0.38
$\tau_{had}\tau_{had}$ Boost 1 High	0.88
$\tau_{had}\tau_{had}$ Boost 0 High	0.49
$\tau_{had}\tau_{had}$ Medium	0.68
$\tau_{had}\tau_{had}$ VBF 1 Medium	0.38
$\tau_{had}\tau_{had}$ VBF 0 Medium	0.18
$\tau_{had}\tau_{had}$ Boost 1 Medium	0.44
$\tau_{had}\tau_{had}$ Boost 0 Medium	0.27
$\tau_{had}\tau_{had}$ Low	0.59
$\tau_{had}\tau_{had}$ VBF 1 Low	0.33
$\tau_{had}\tau_{had}$ VBF 0 Low	0.14
$\tau_{had}\tau_{had}$ Boosted 1 Low	0.38
$\tau_{had}\tau_{had}$ Boosted 0 Low	0.25
$\tau_{lep}\tau_{had}$ High	0.97
$\tau_{lep}\tau_{had}$ VBF 1 High	0.63
$\tau_{lep}\tau_{had}$ VBF 0 High	0.32
$\tau_{lep}\tau_{had}$ Boost 1 High	0.49
$\tau_{lep}\tau_{had}$ Boost 0 High	0.42
$\tau_{lep}\tau_{had}$ Medium	0.37
$\tau_{lep}\tau_{had}$ VBF 1 Medium	0.24
$\tau_{lep}\tau_{had}$ VBF 0 Medium	0.13
$\tau_{lep}\tau_{had}$ Boost 1 Medium	0.19
$\tau_{lep}\tau_{had}$ Boost 0 Medium	0.16
$\tau_{lep}\tau_{had}$ Low	0.41
$\tau_{lep}\tau_{had}$ VBF 1 Low	0.26
$\tau_{lep}\tau_{had}$ VBF 0 Low	0.12
$\tau_{lep}\tau_{had}$ Boost 1 Low	0.23
$\tau_{lep}\tau_{had}$ Boost 0 Low	0.18
$\tau_{had}\tau_{had}$	1.71
$\tau_{lep}\tau_{had}$	1.14
Combined	2.1

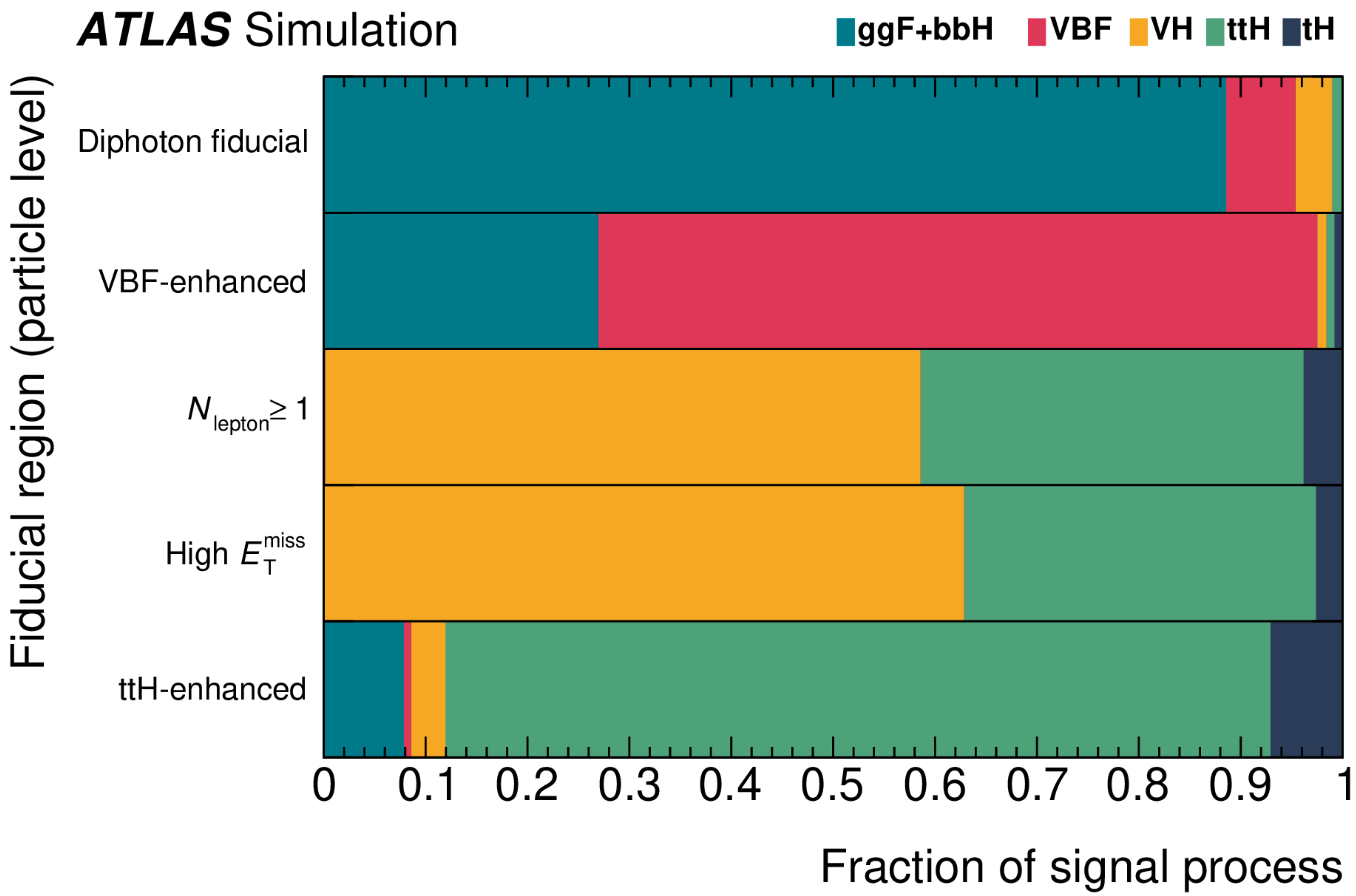
⇒ Back

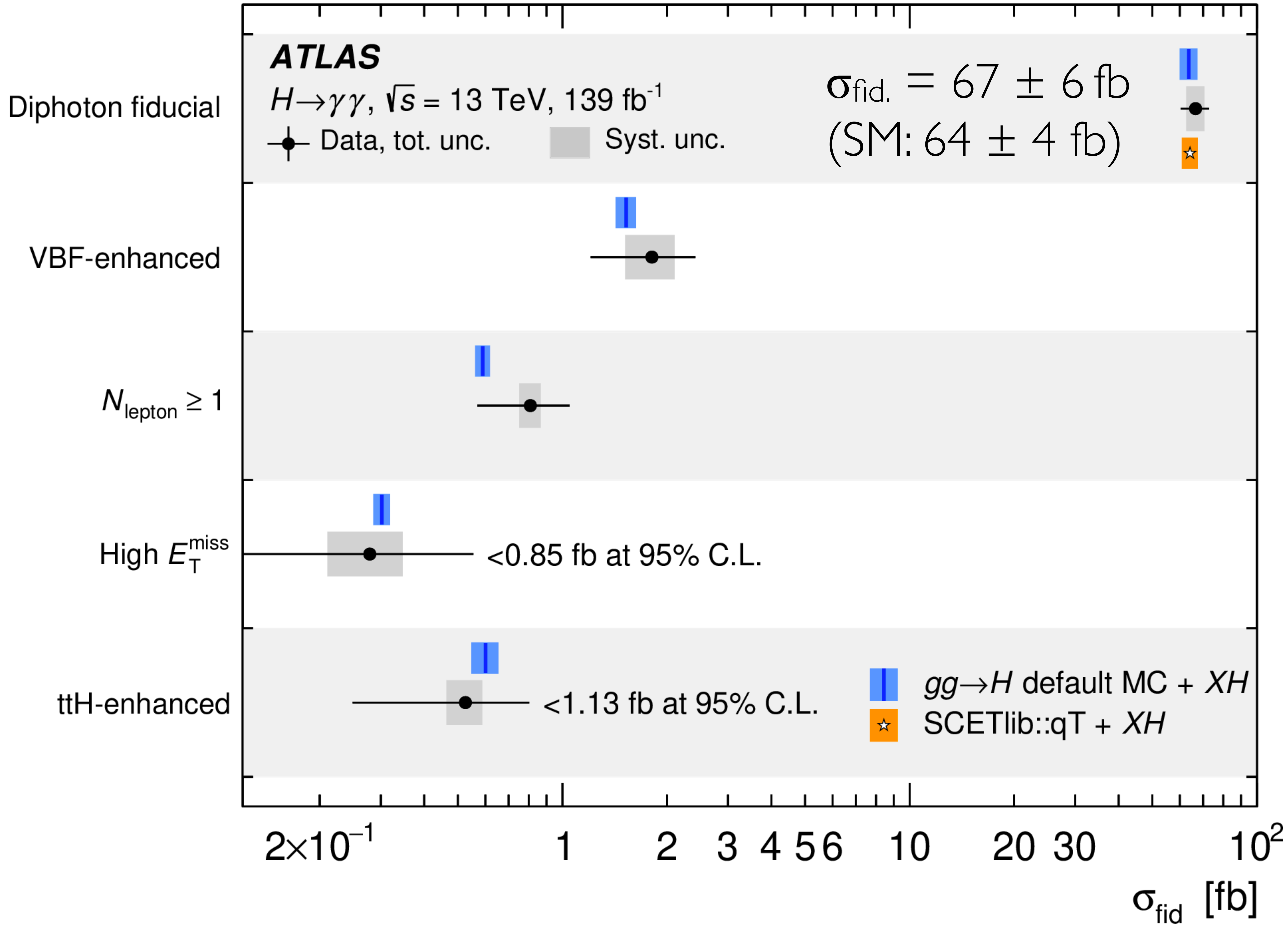
Feb 2022

$H \to \gamma\gamma$

arXiv:2202.00487 (submitted to JHEP)

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





- Total cross section: 58 ± 6 pb

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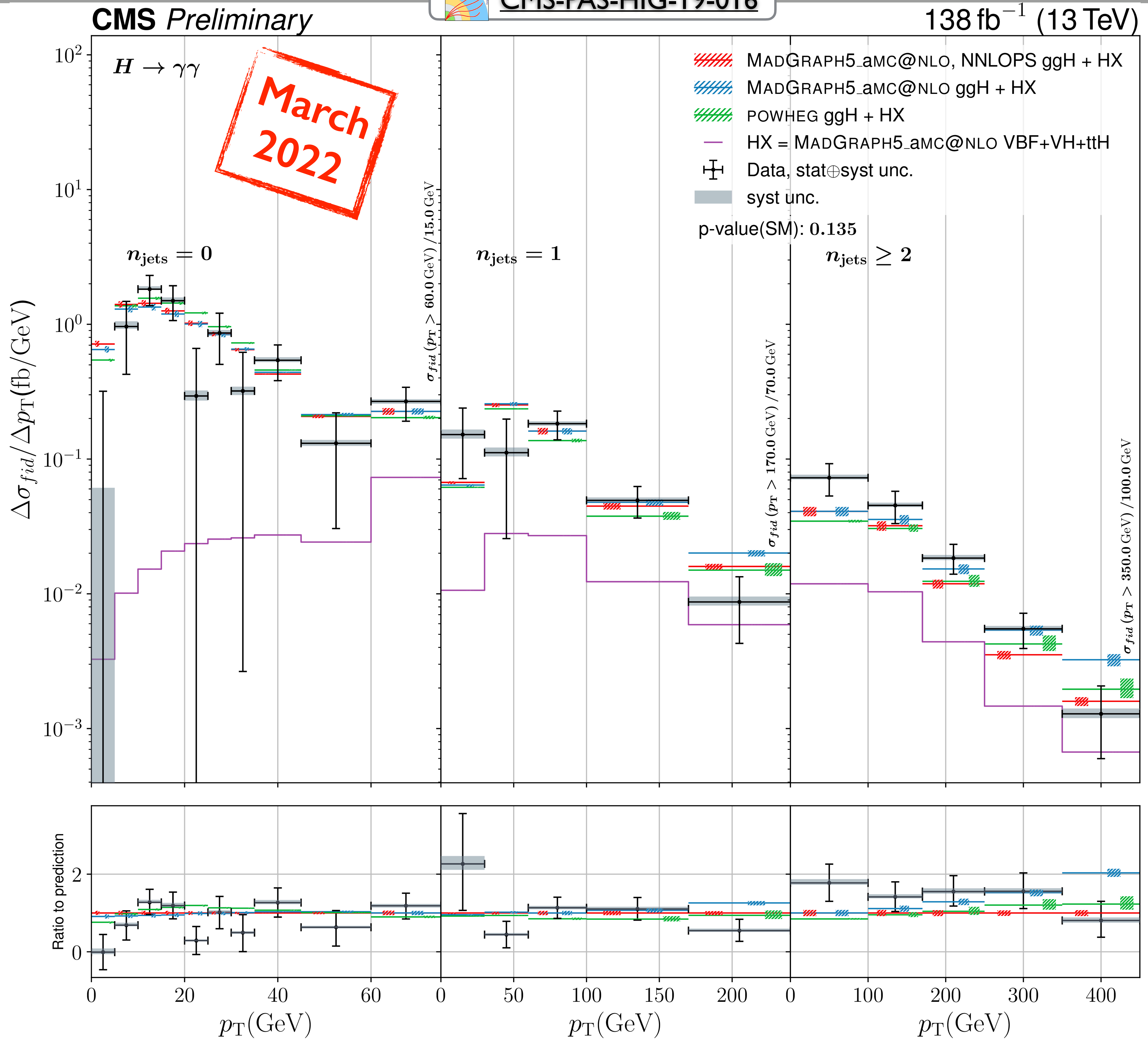
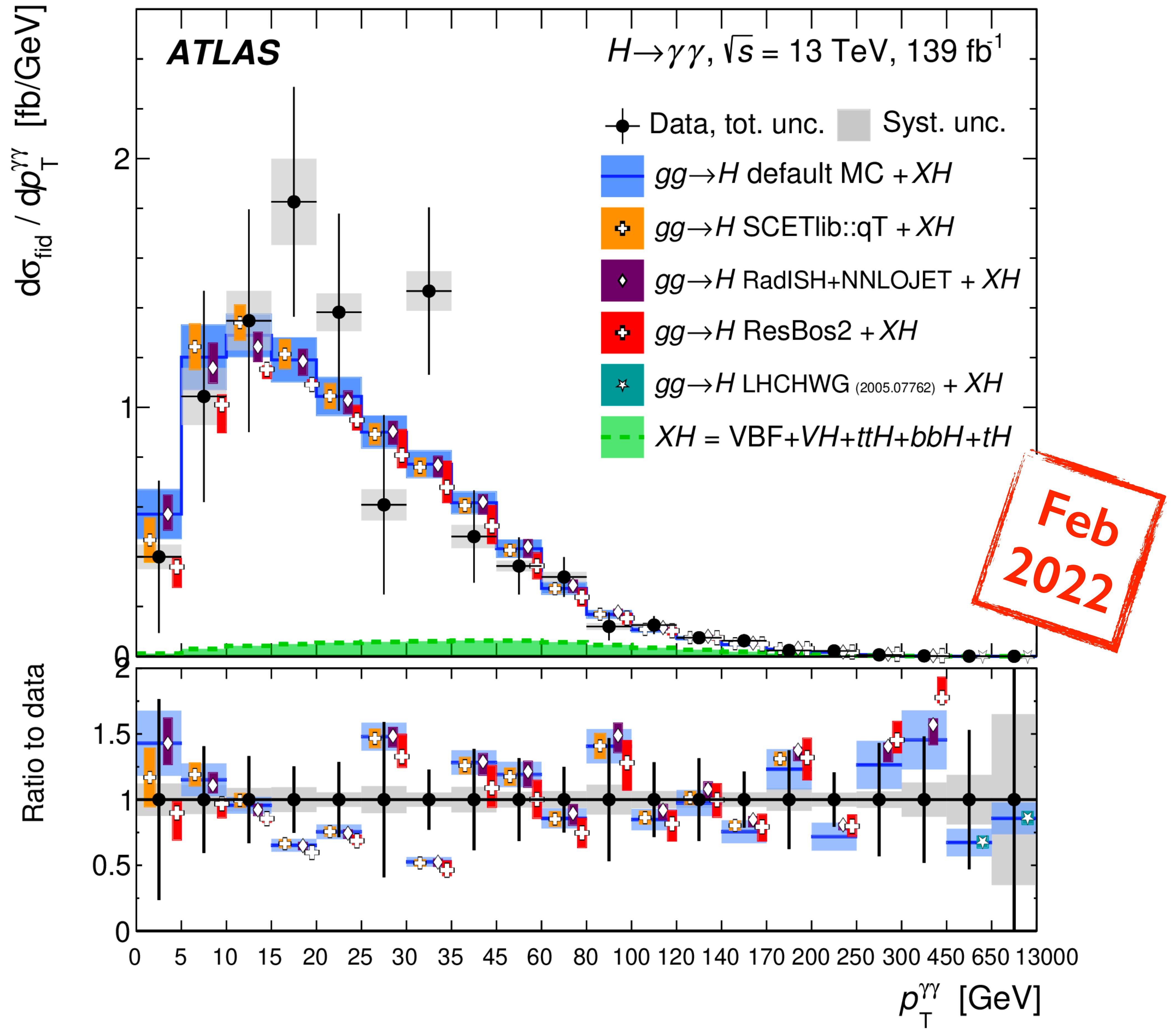
$H \to \gamma\gamma$ differential Measurements

CMS-PAS-HIG-19-016

arXiv:2202.00487 (submitted to JHEP)



- O(20) 1-d and O(5) 2-d distributions in different phase spaces



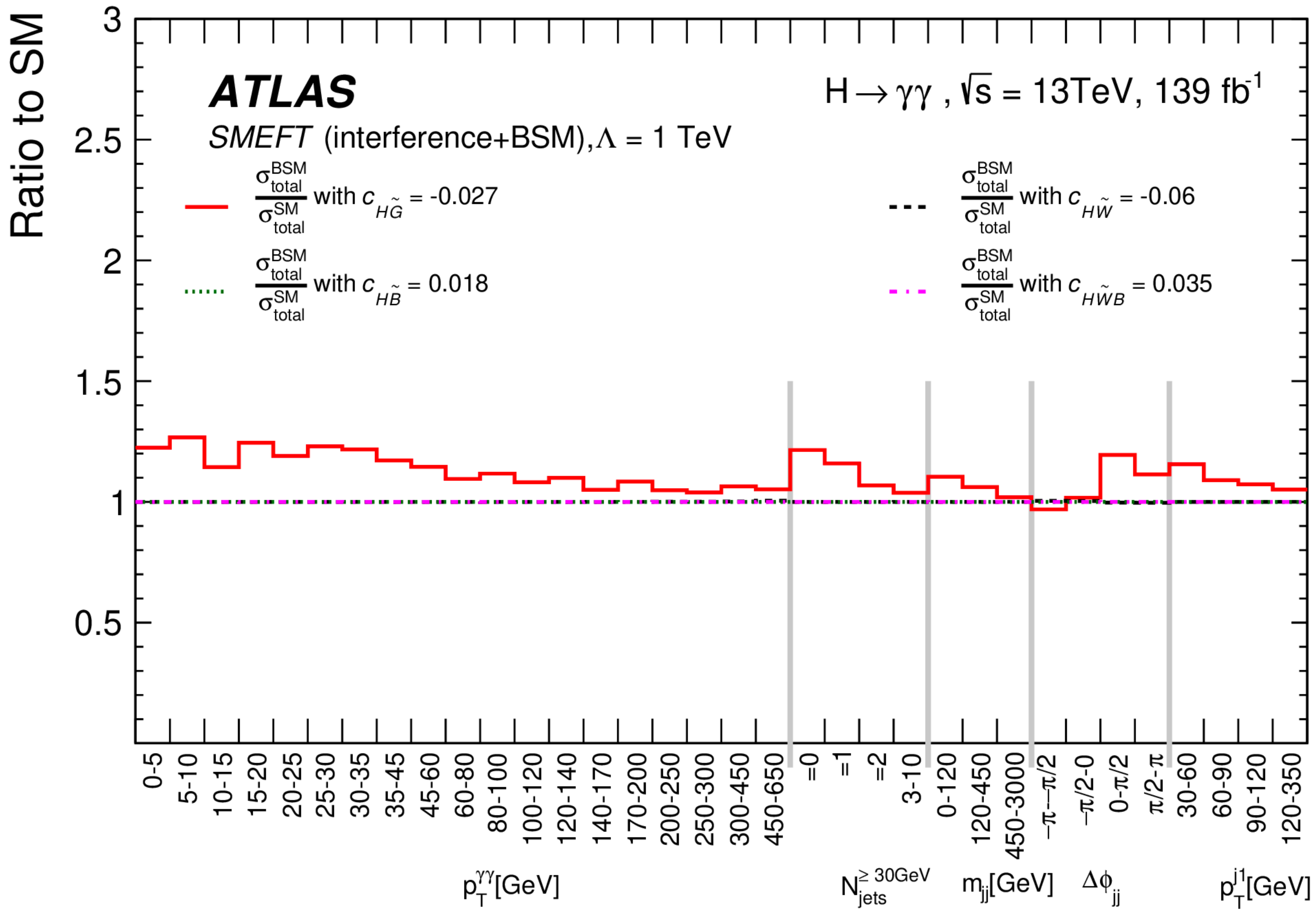
⇒ SMEFT interpretations

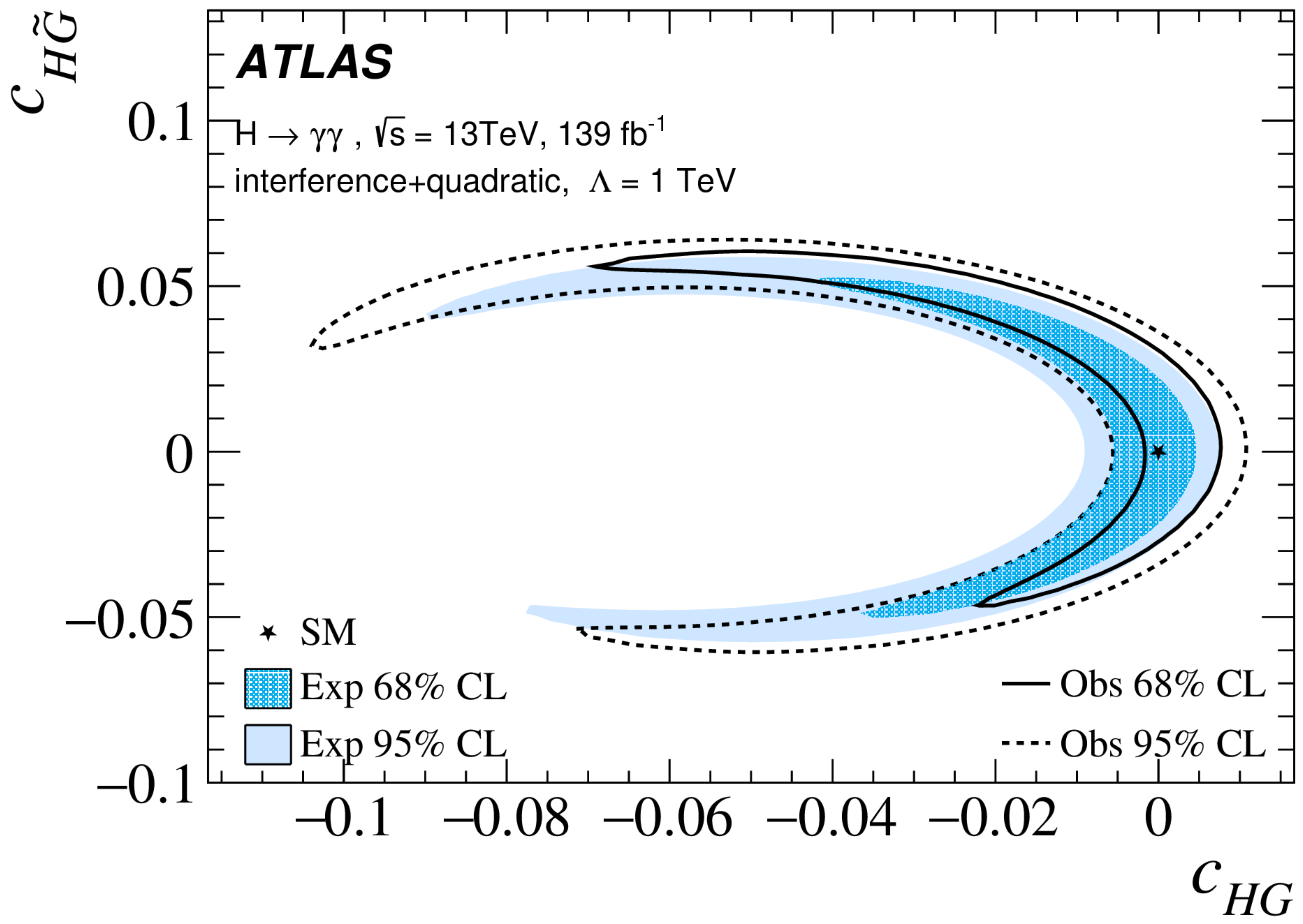
⇒ Back

$H \to \gamma\gamma$ SMEFT Interpretations

Feb 2022

- Simultaneous fit to p_{T}, N_{jet}, m_{jj}, $\Delta\phi_{\mathrm{jj}}$ and p_{T}(jet 1), incl. correlations
- Limits on 4 CP-even and 4 CP-odd Wilson coefficients





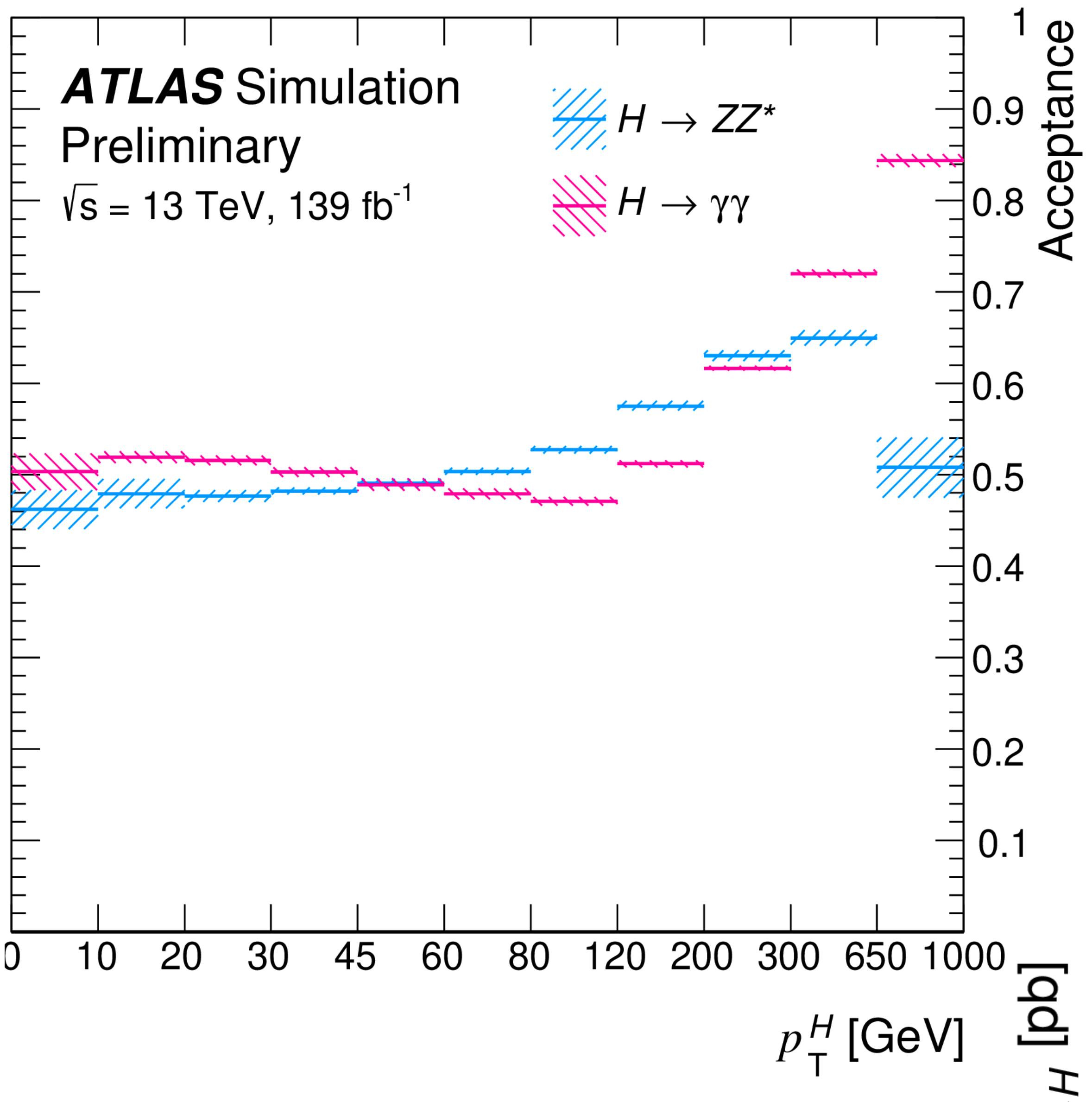
arXiv:2202.00487 (submitted to JHEP)

⇒ Back

Combination: H → γγ and H → ZZ* → 4ℓ

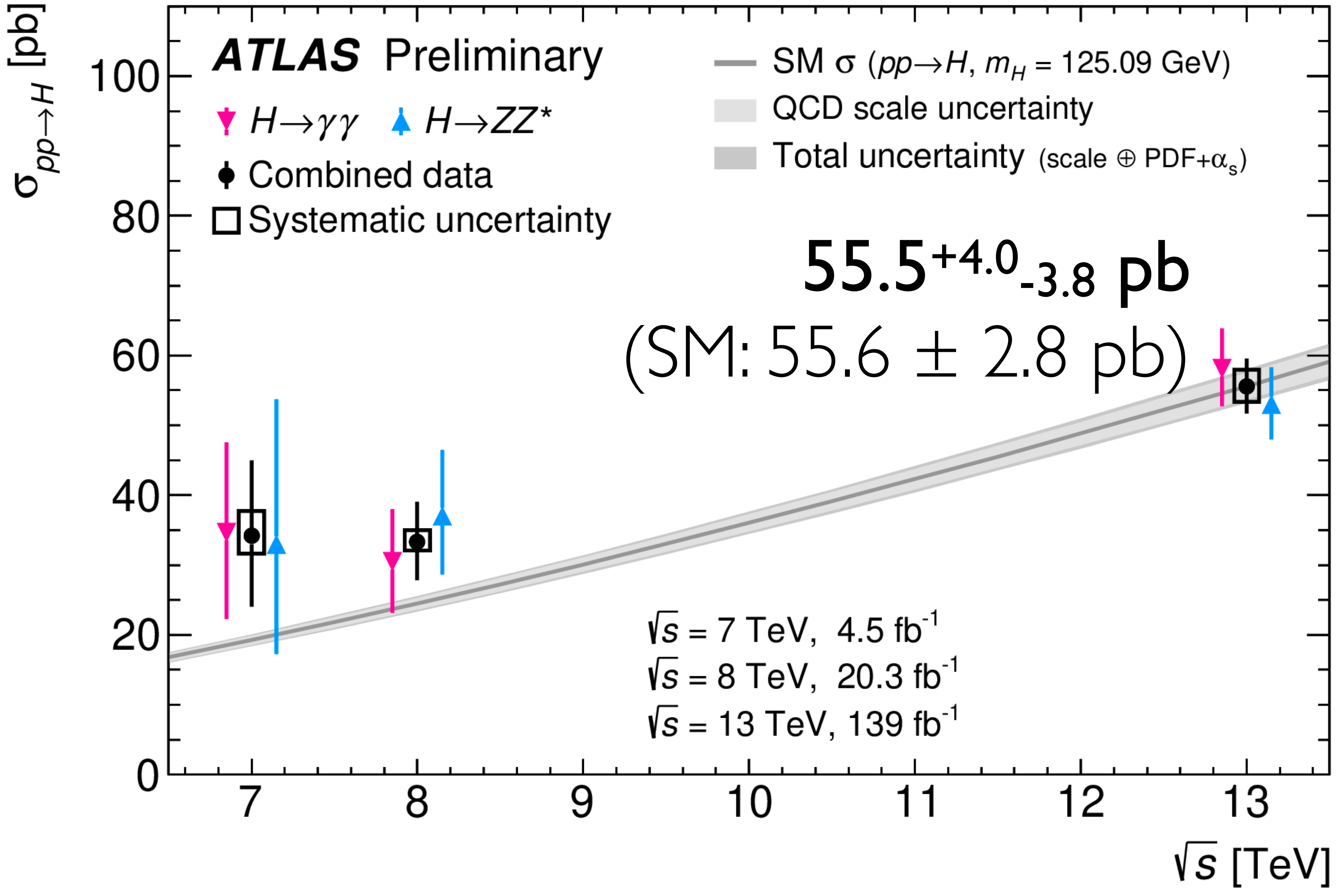
Jan 2022

ATLAS-CONF-2022-002

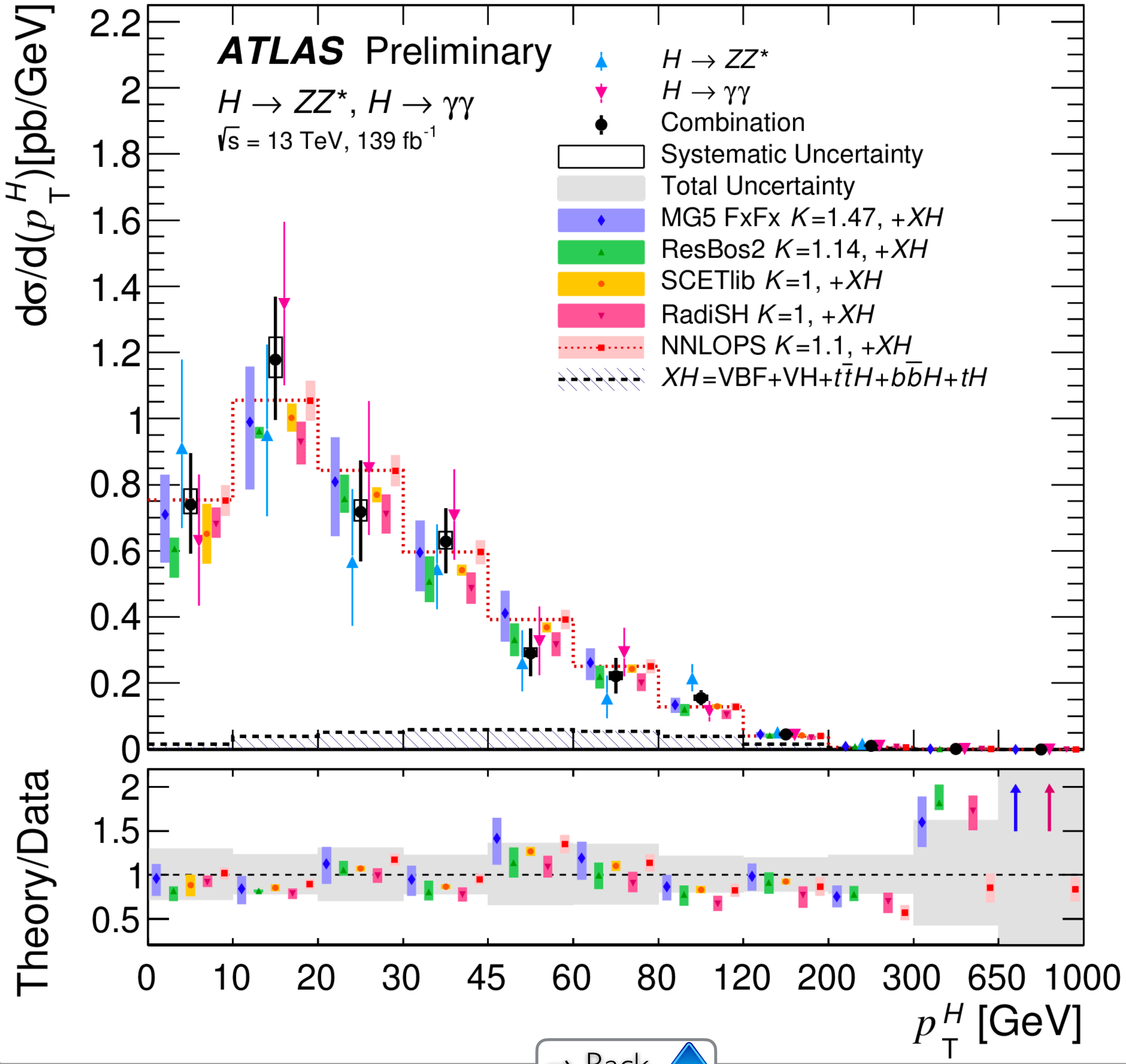


Extrapolate to full phase space

Total cross section:



Measure y(H), N_{jet}, p_T(jet 1), and $\mathbf{p_T(H)}$

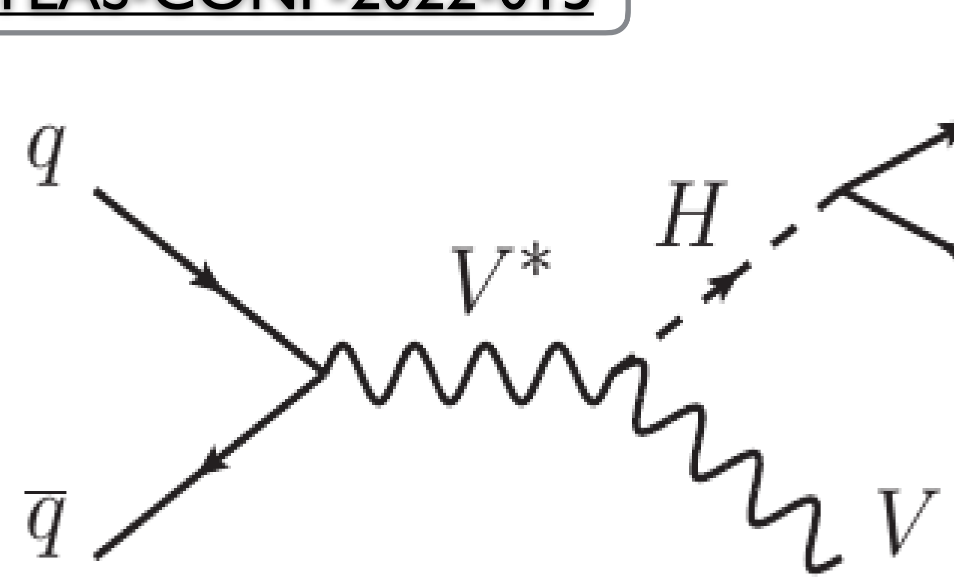


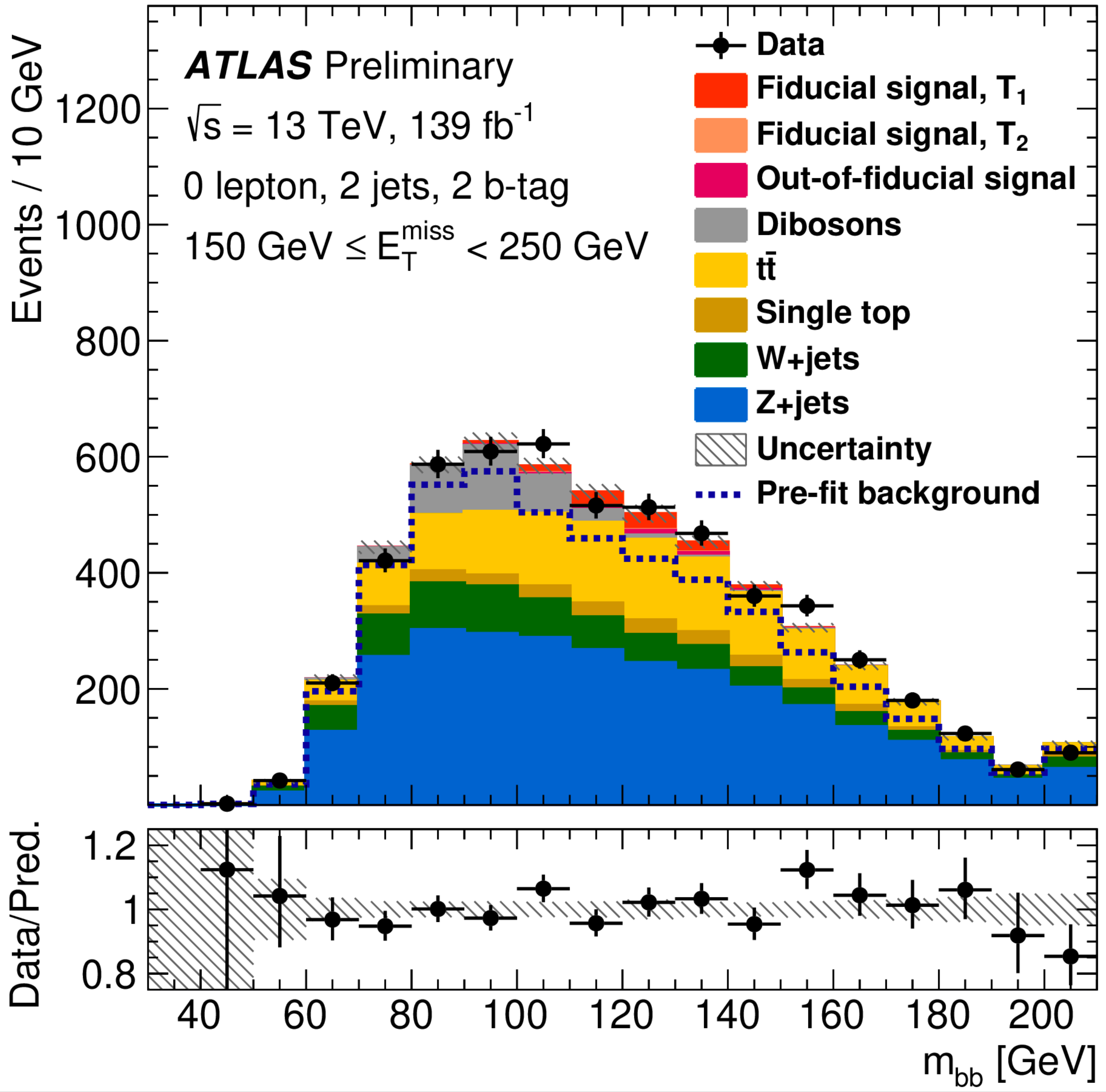
⇒ Back

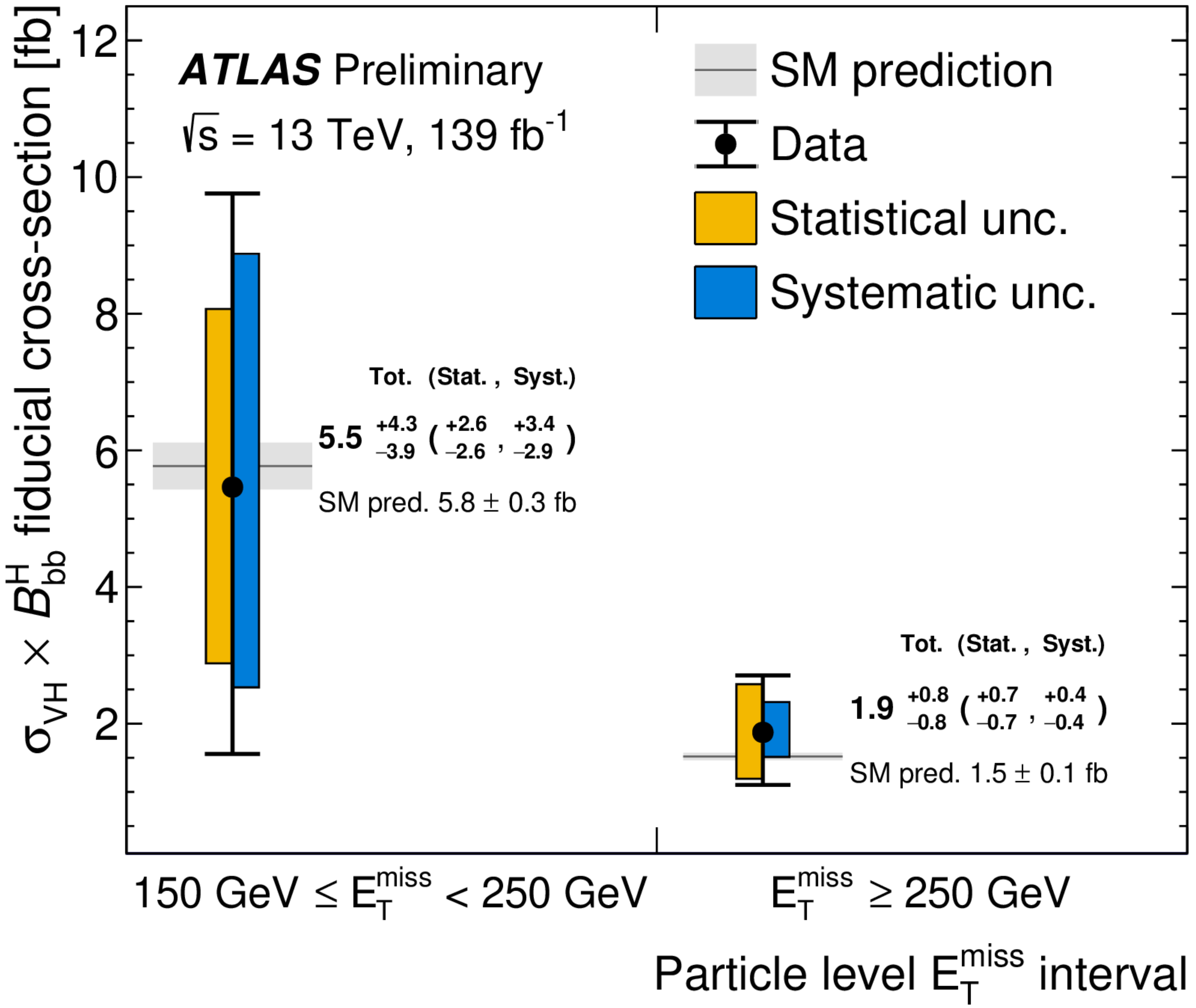
$H \rightarrow b\bar{b}$ fiducial measurement at large E_T^{miss}

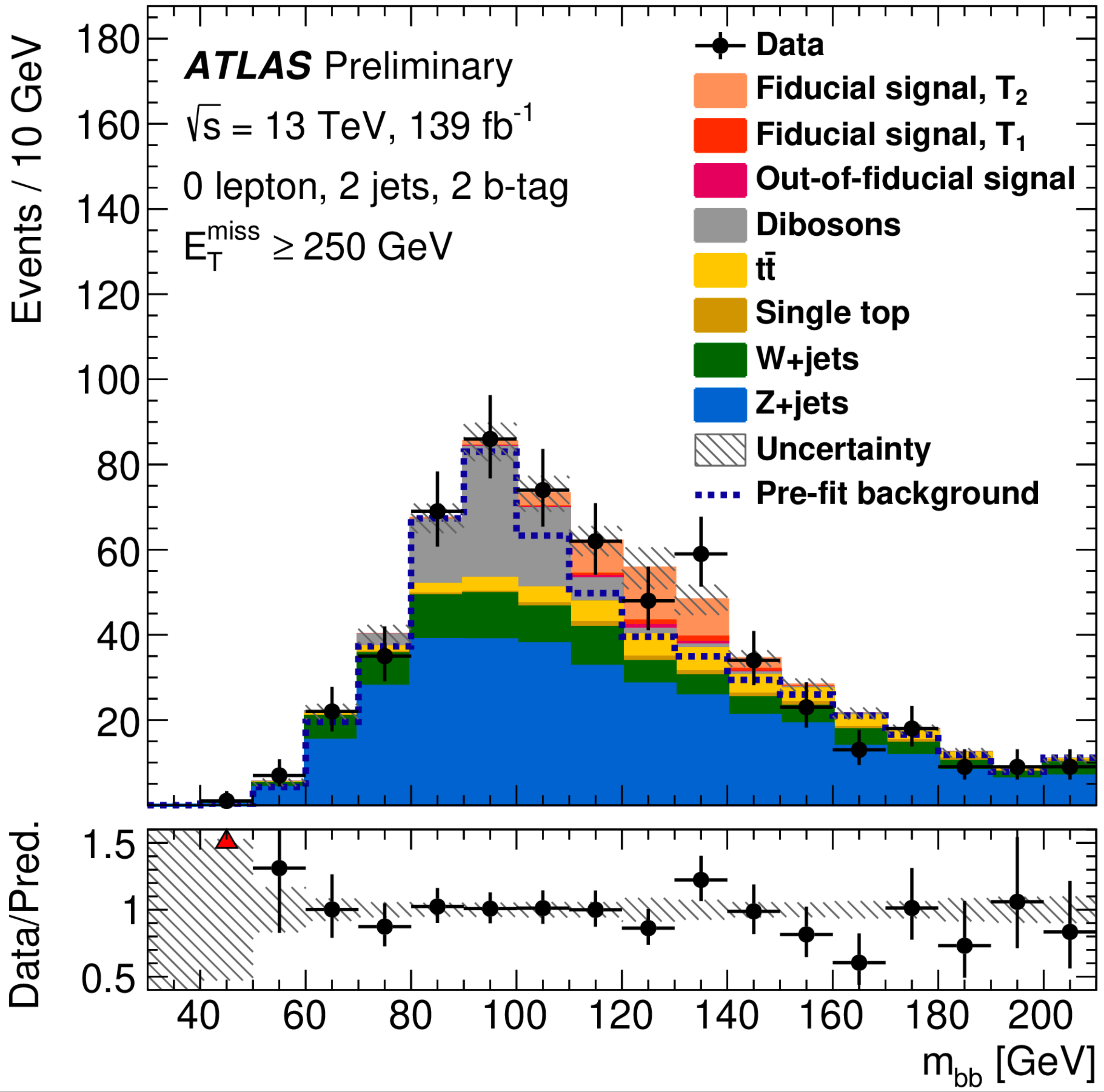
ATLAS-CONF-2022-015

- $H \rightarrow bb$ dominant decay channel (**BR = 58%**)
- VH (V=W or Z) associated production:
  - 0 lepton ($Z \rightarrow \nu\nu$) and 1 lepton ($W \rightarrow \ell\nu$)
- Based on VH, $H \rightarrow bb$ analysis
  - Eur. Phys. J. C 81 (2021) 178
- Veto electrons/muons
- Fit m_{bb}
- In-likelihood unfolding



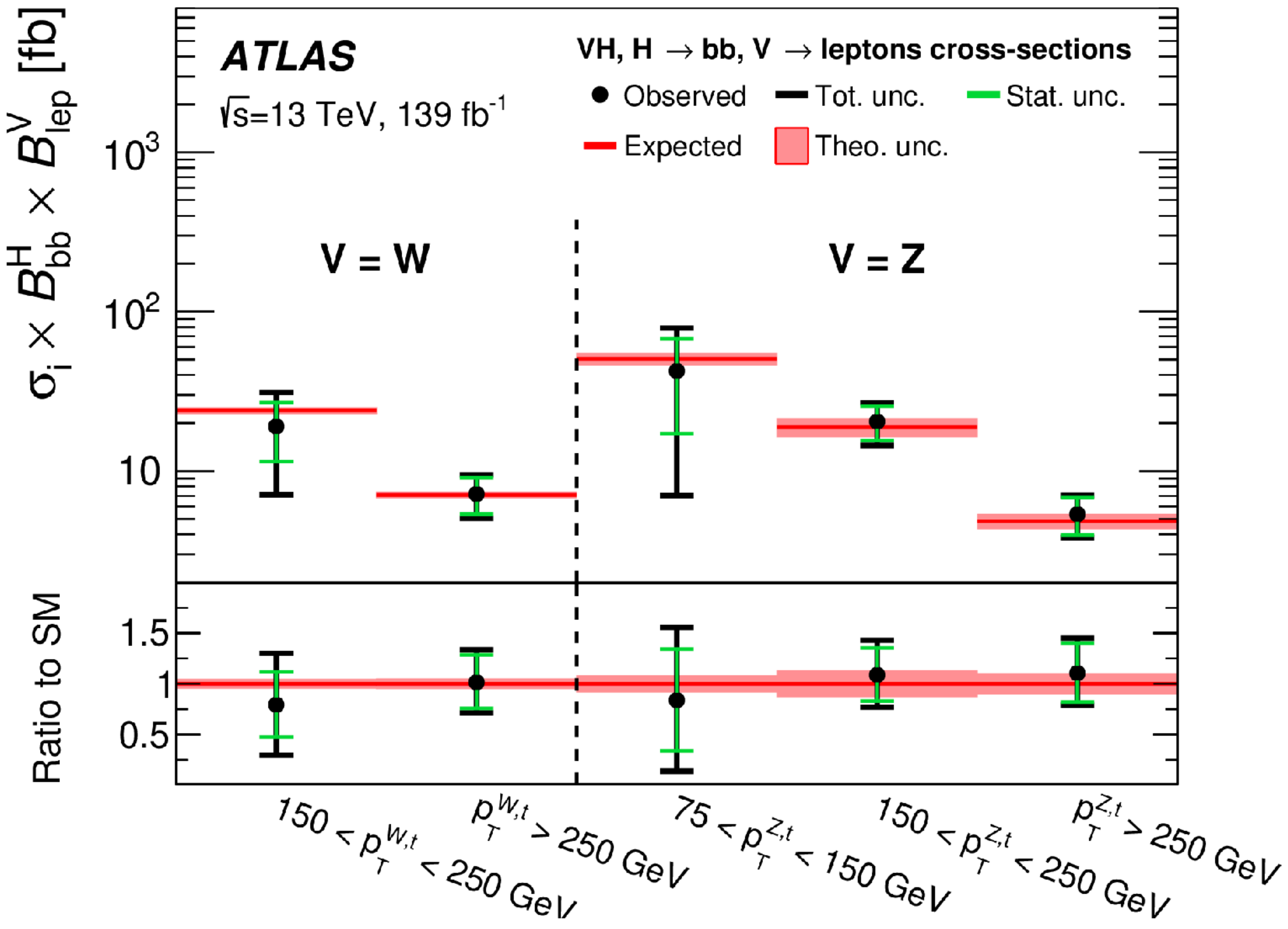






H → b$\bar{b}$

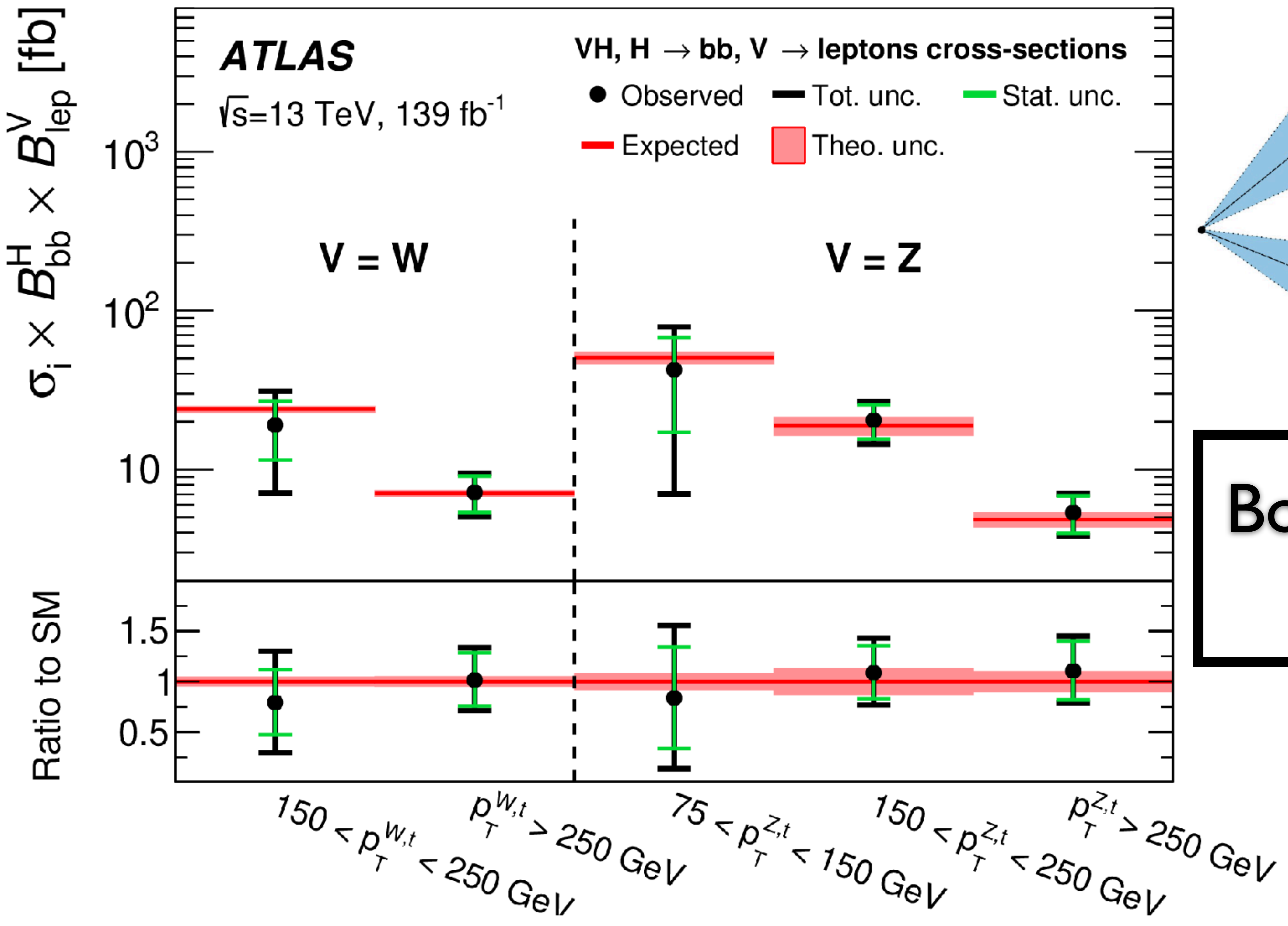
- Cross-section measurements as function of $p_T(V)$

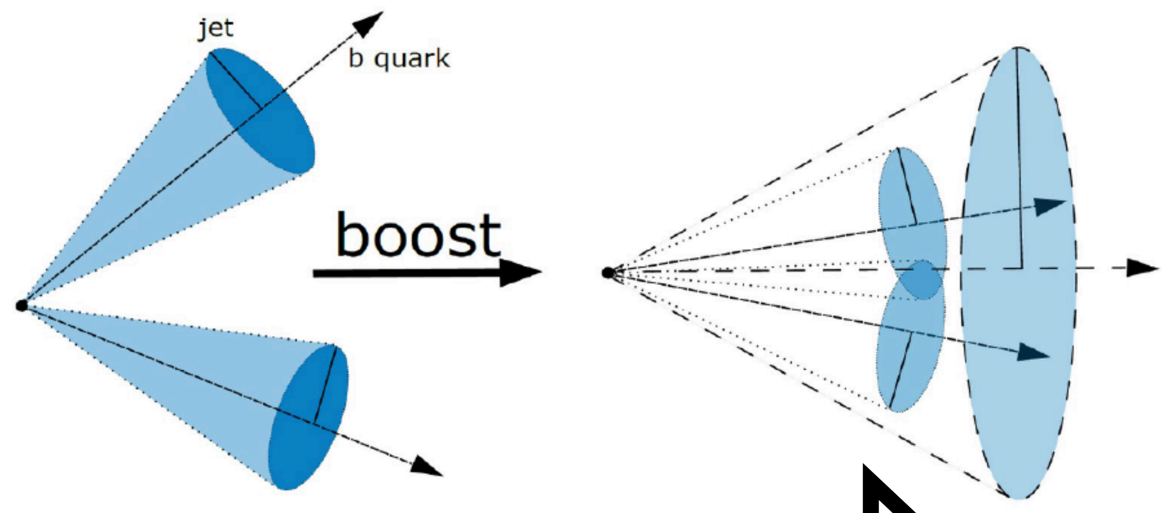


arXiv:2007.02873

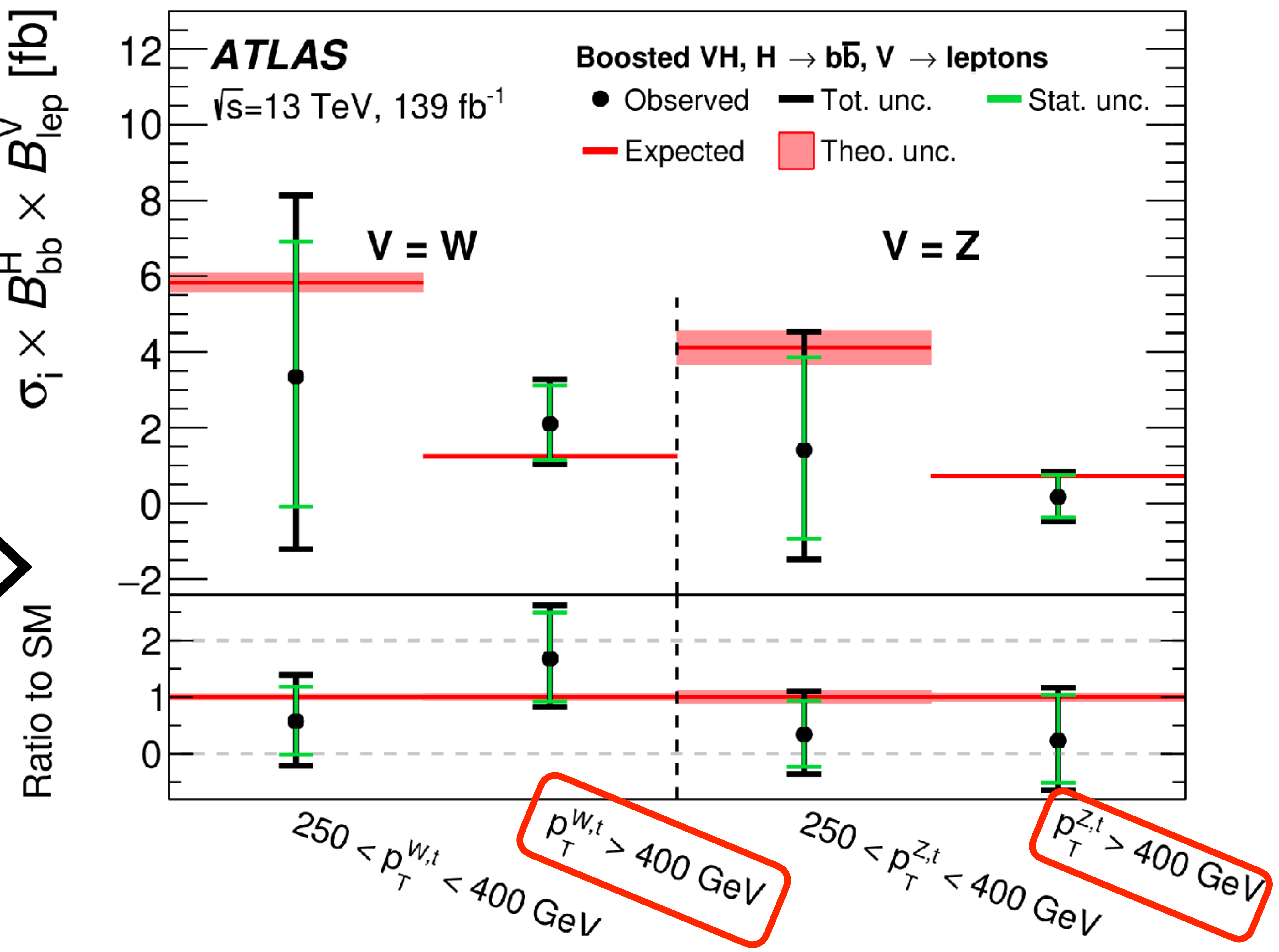
$H \rightarrow b\bar{b}$

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





Boosted Higgs-boson decay topology



- Explores higher $p_T(V)$

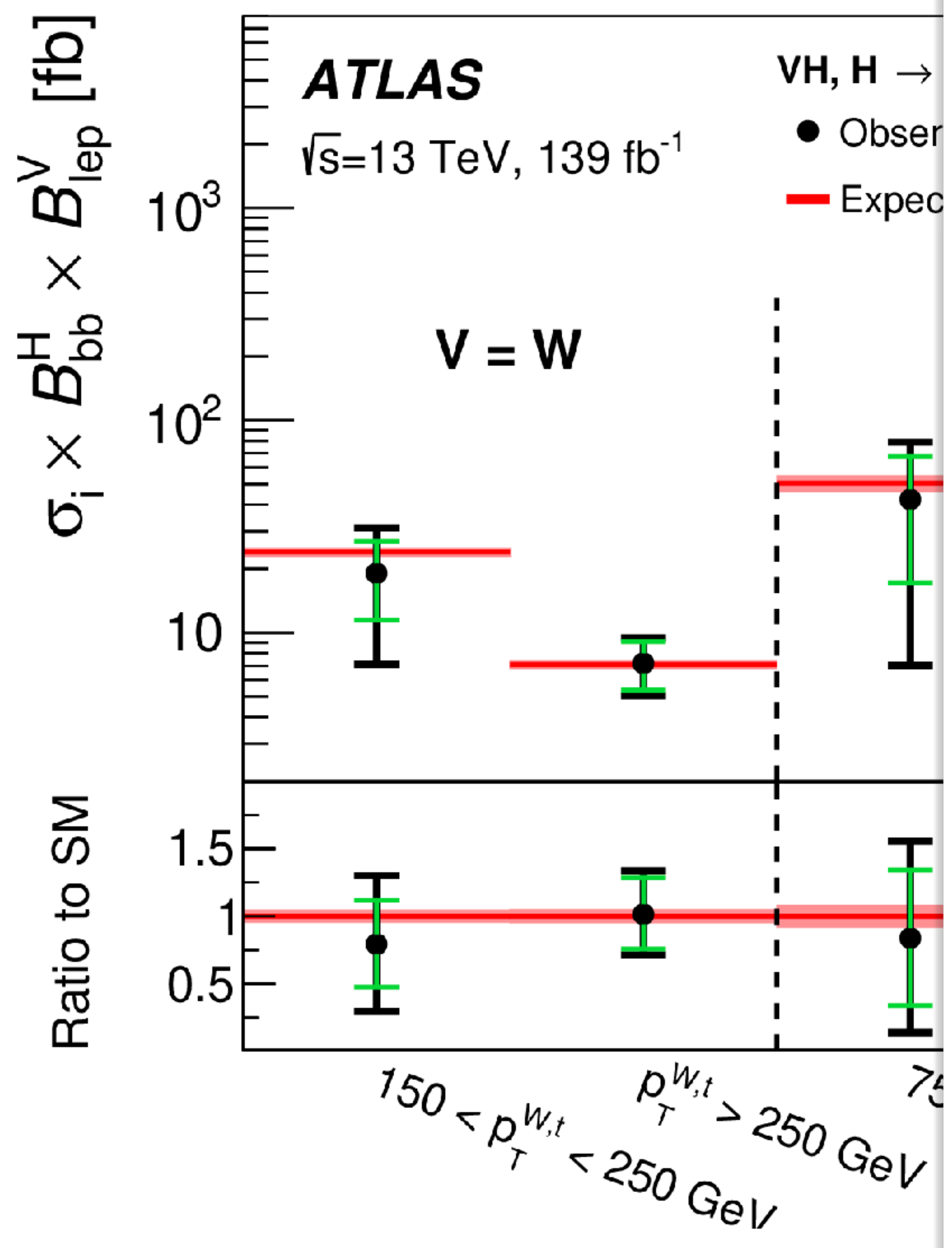
$\Rightarrow$ Increase sensitivity to BSM

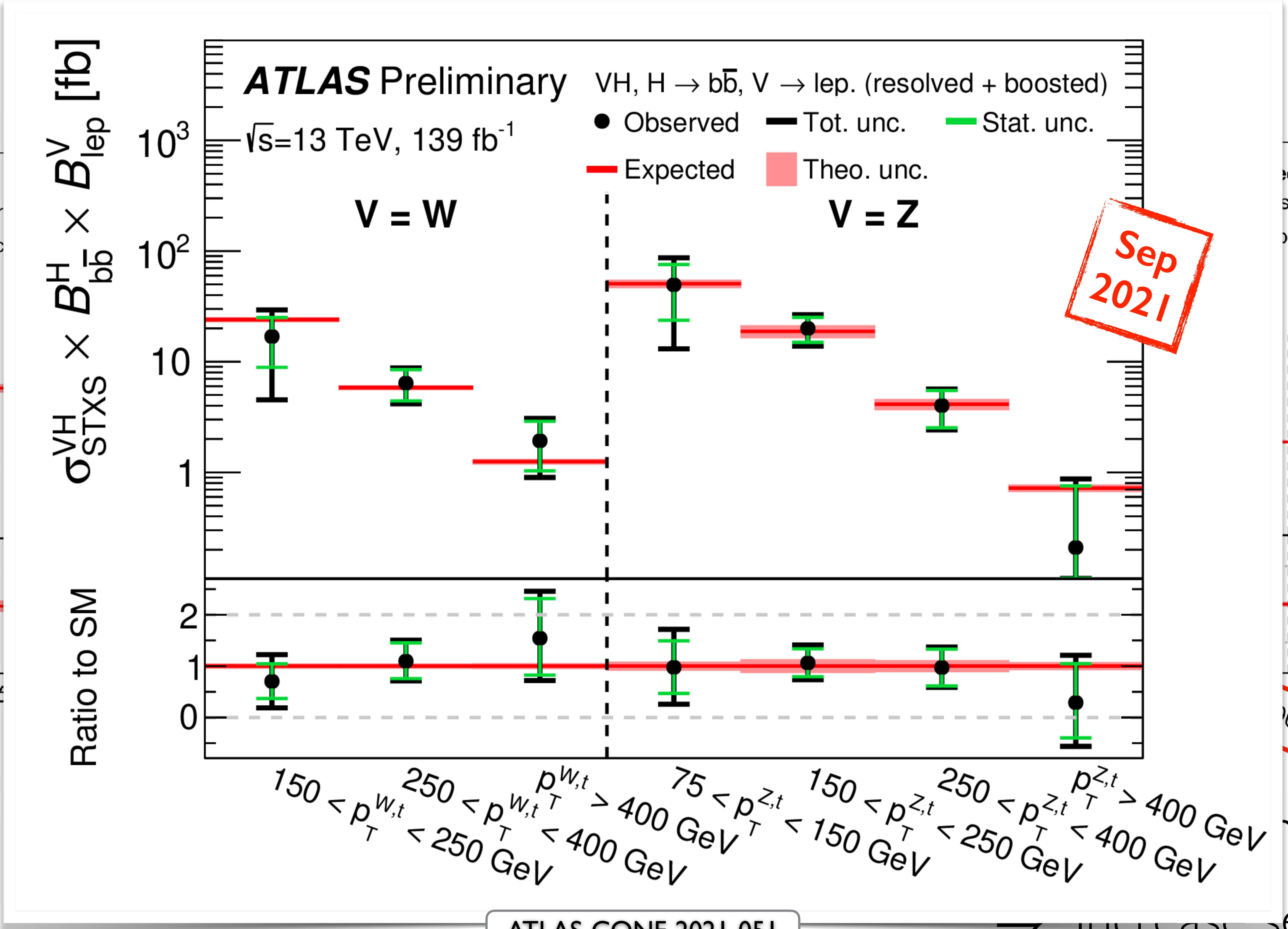
arXiv:2007.02873

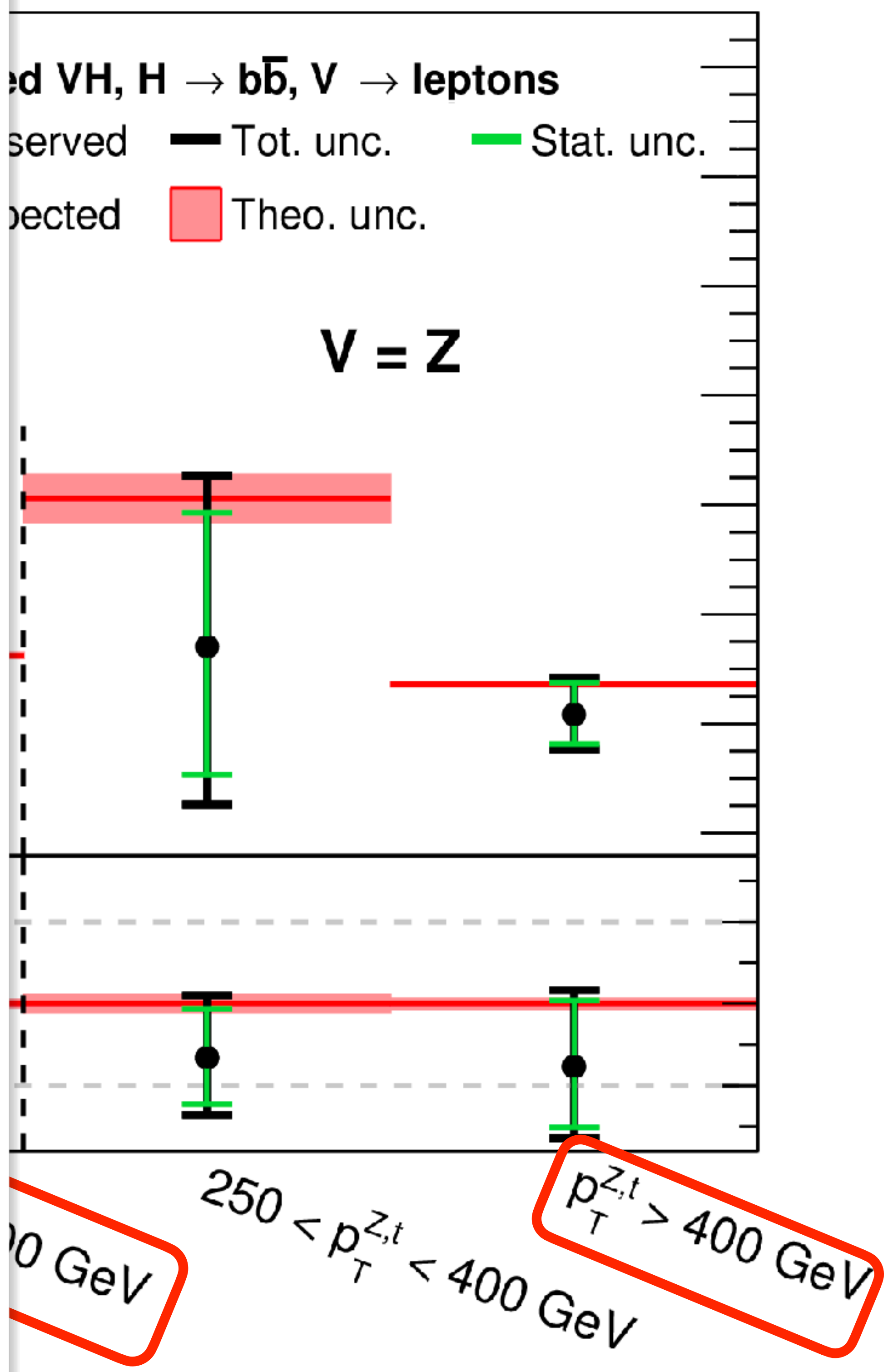
arXiv:2008.02508

$H \rightarrow b\bar{b}$

- Cross-section







her pT(V)

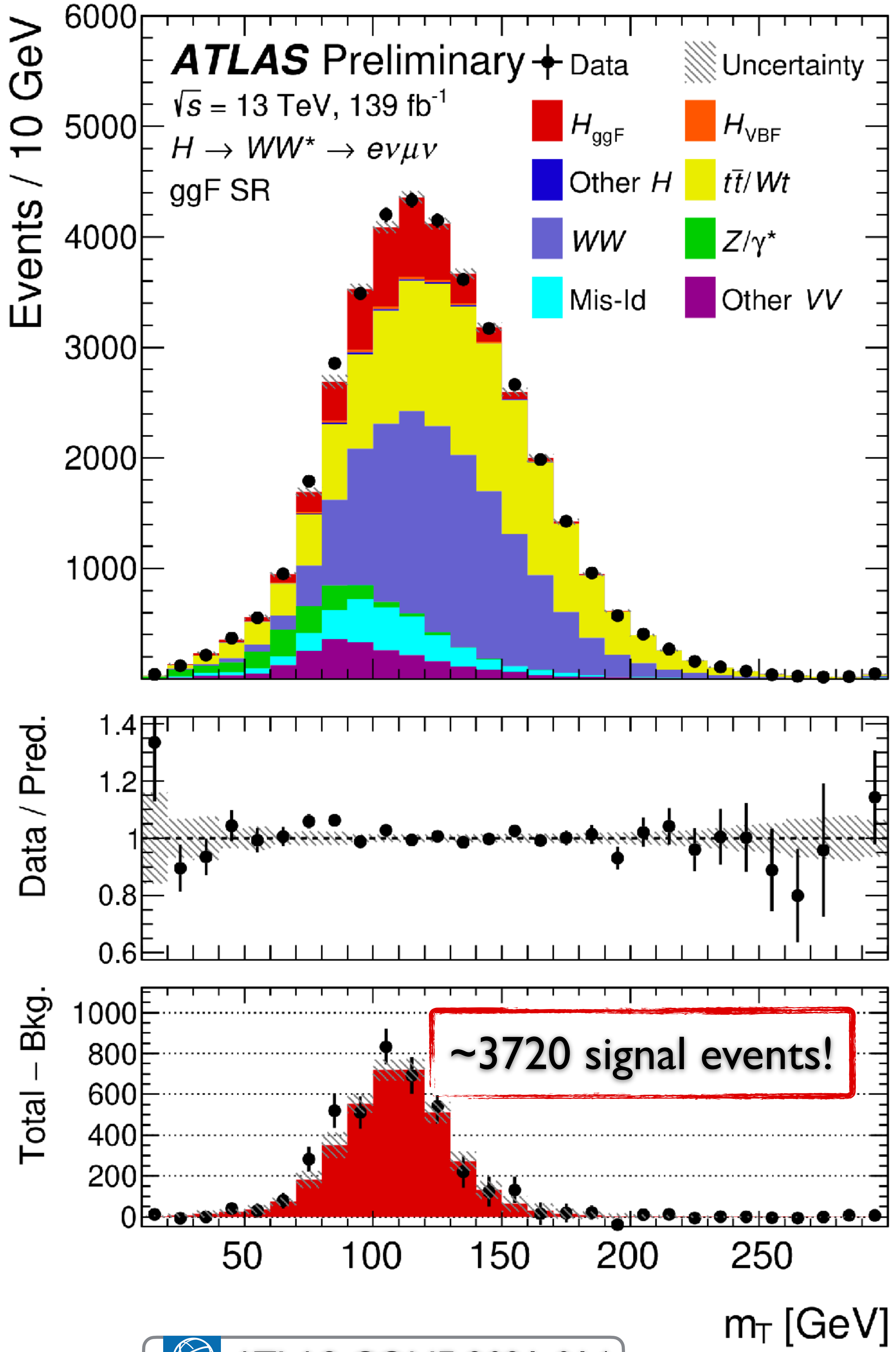
→ increase sensitivity to BSM

ATLAS-CONF-2021-051

arXiv:2007.02873

arXiv:2008.02508

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



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

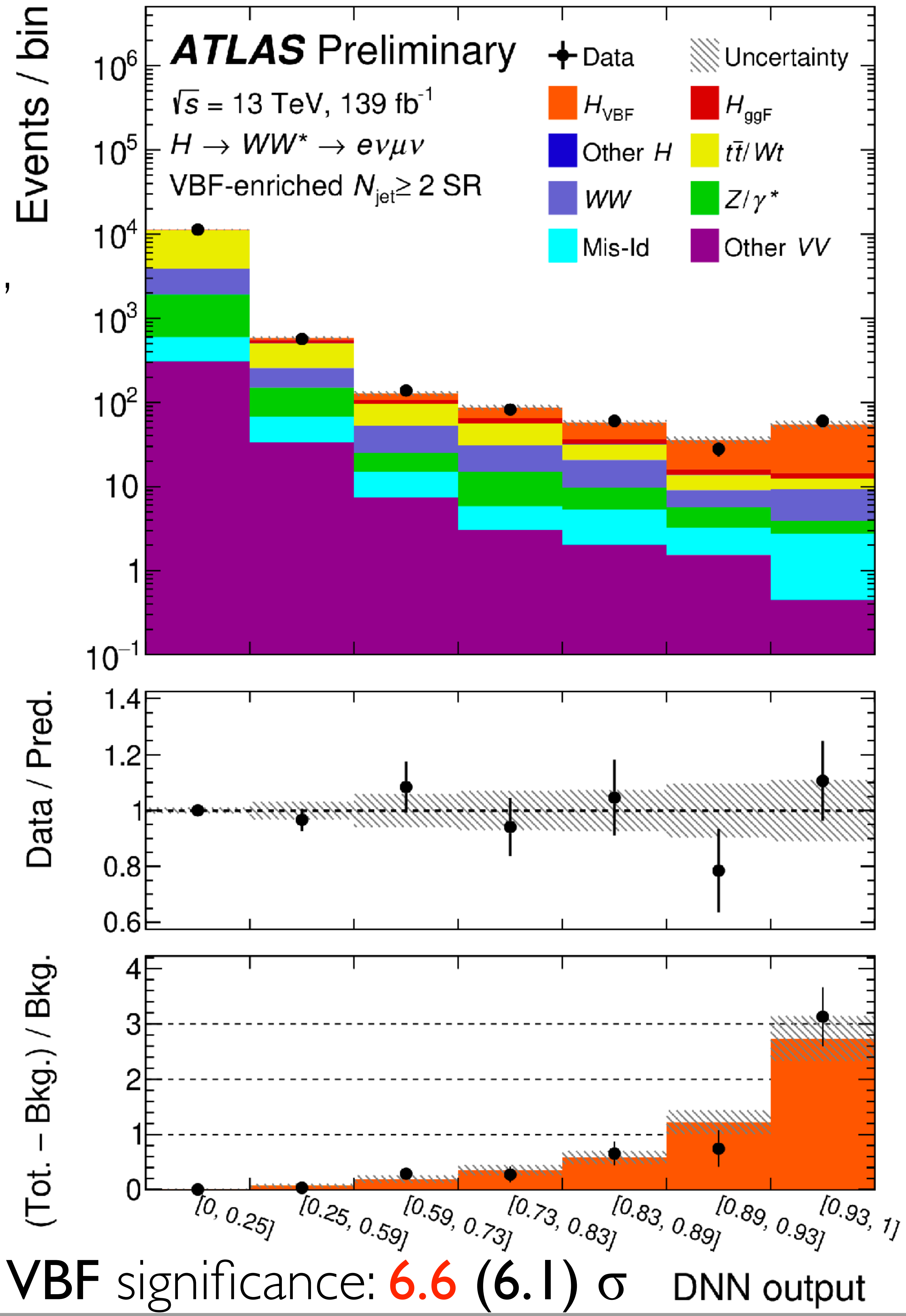
$\Rightarrow$ **~40 000 $H \to WW^* \to e\nu\mu\nu$ events in 139 fb^{-1}**, but difficult backgrounds…

Signal strength:

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

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

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



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

ATLAS-CONF-2021-014

⇒ Back

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

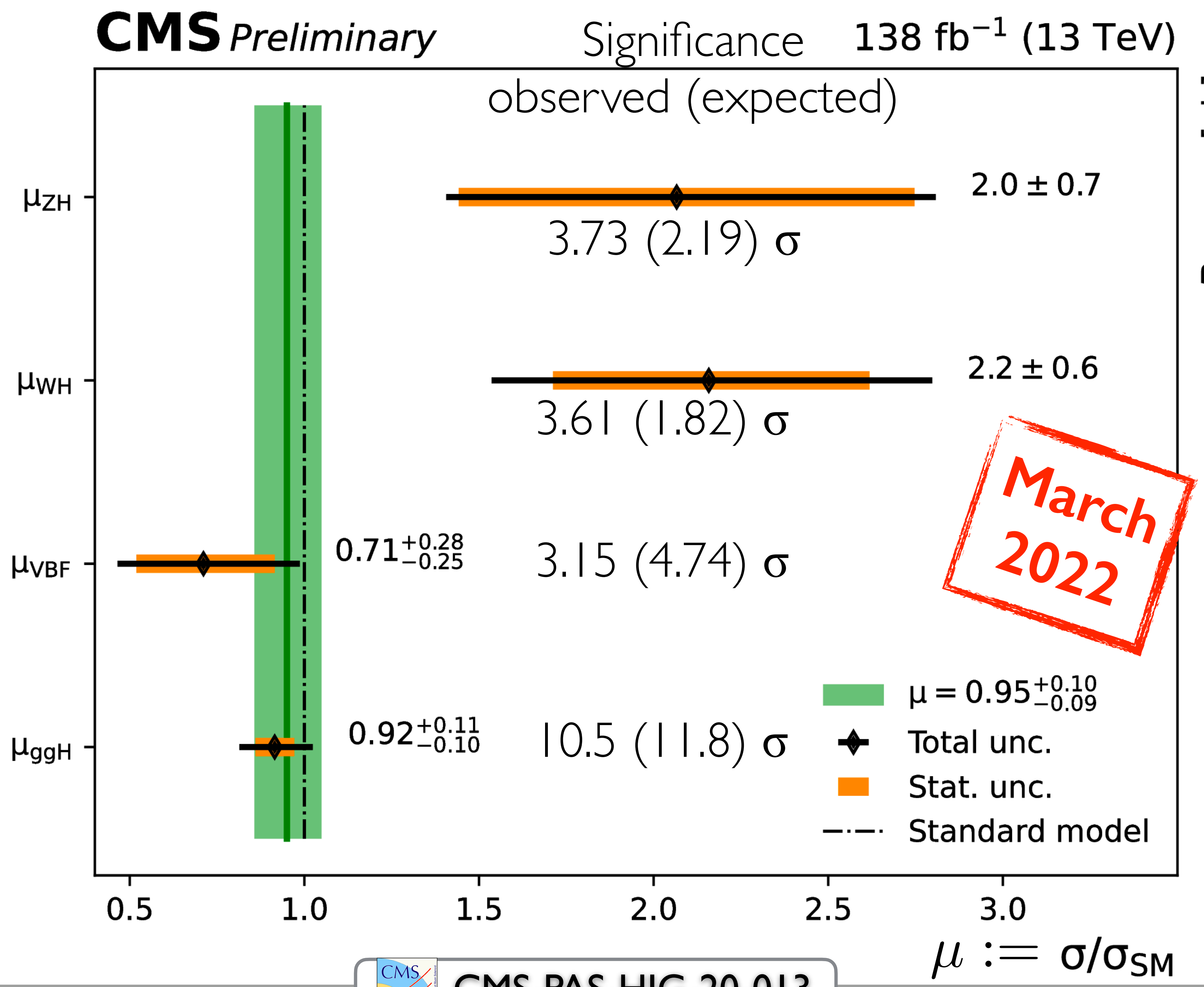
m_T [GeV]

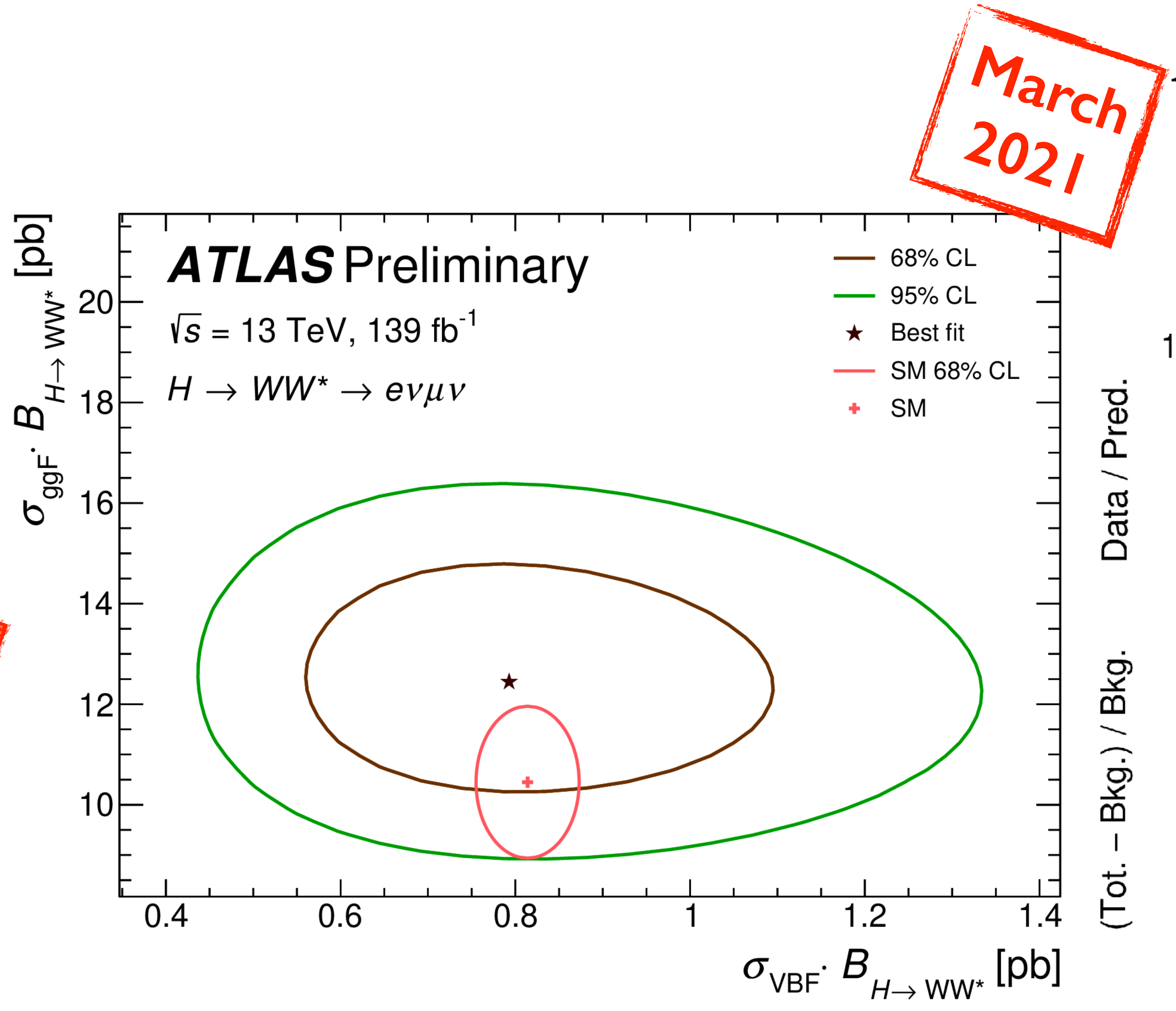
Observed (expected) **VBF** significance: 6.6 (6.1) σ   DNN output

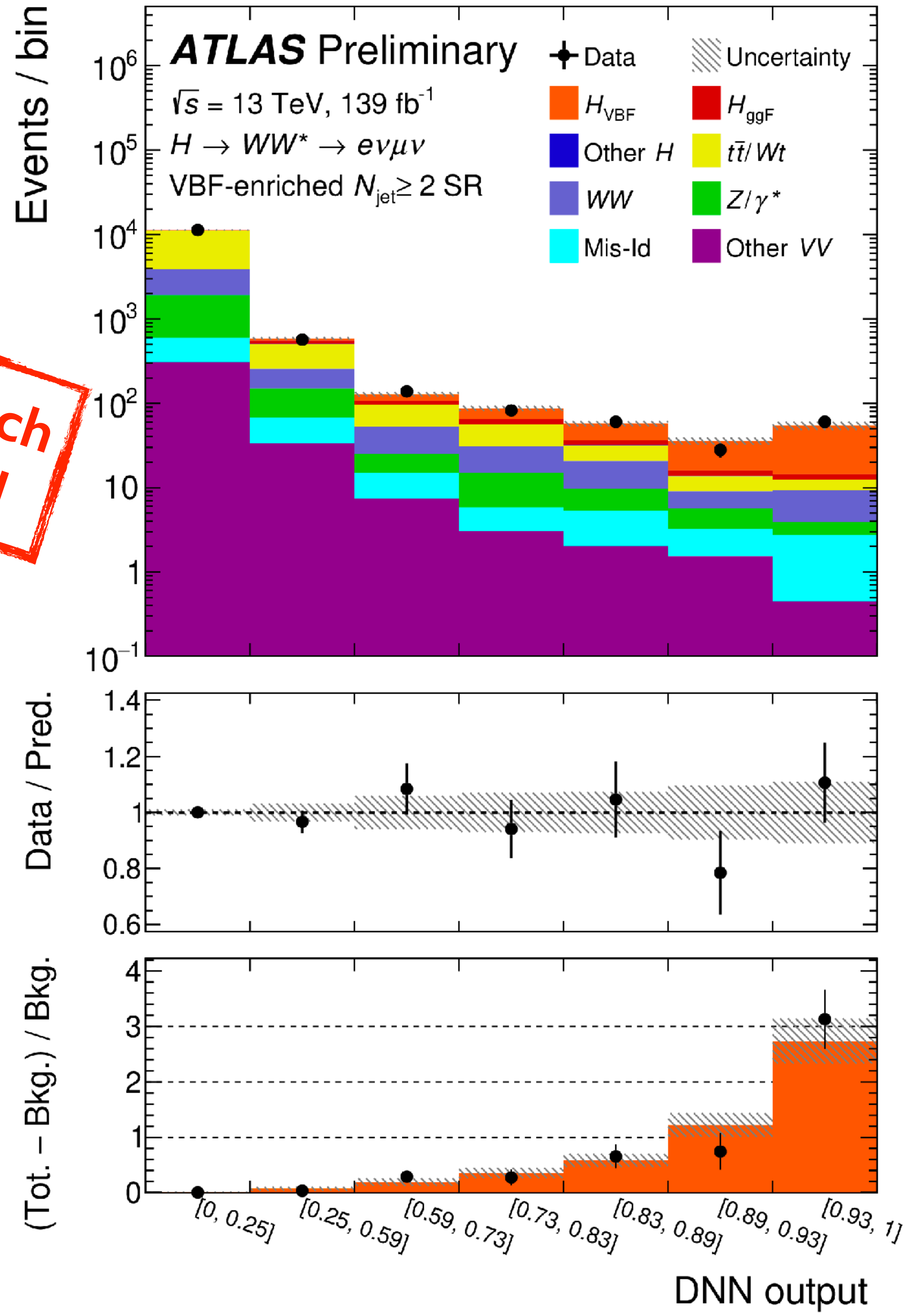
$H \to WW^* \to \ell\nu\ell\nu$

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

$\Rightarrow$ **~80 000 $H \to WW^* \to \ell\nu\ell\nu$ events,** but difficult backgrounds…







Obs. (exp.) **VBF** significance: **6.6 (6.1)** σ

CMS-PAS-HIG-20-013

ATLAS-CONF-2021-014

⇒ Back

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

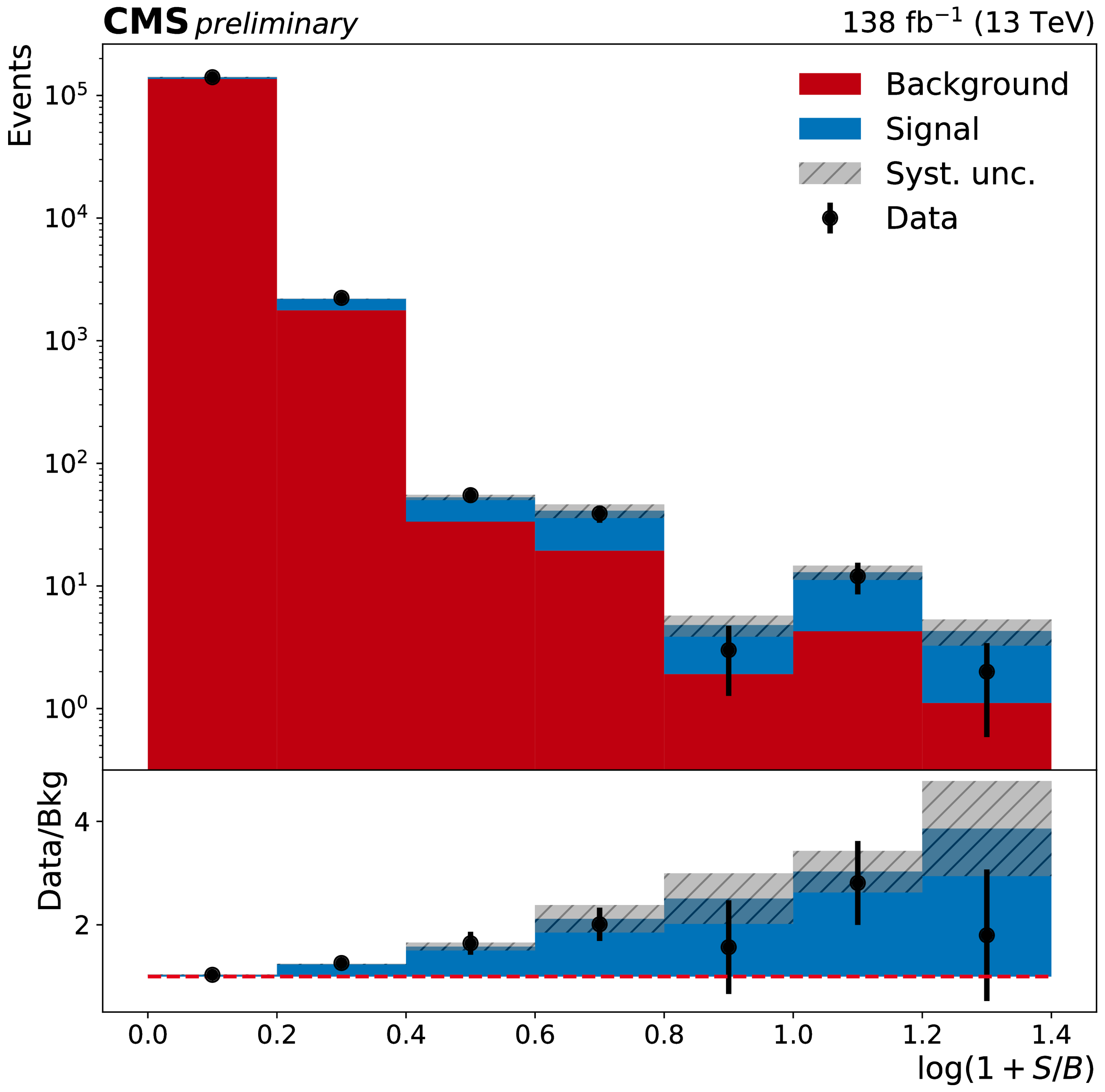
March 2022

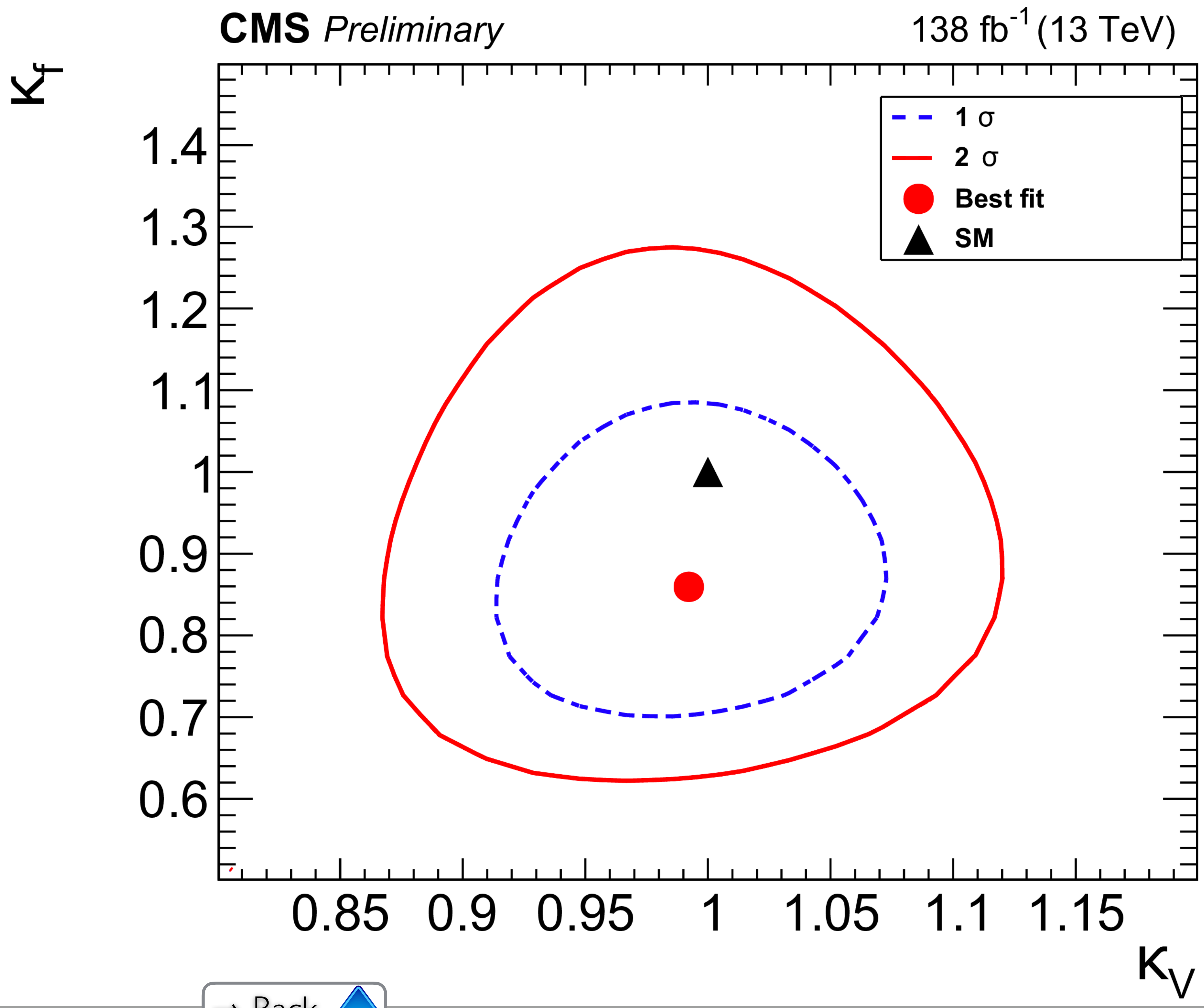
CMS-PAS-HIG-20-013

- Large $BR_{SM}(H \to WW^*) \approx 22\%$
  - $BR_{SM}(H \to WW^* \to \ell\nu\ell\nu) = 1\%$

$\Rightarrow$ **~80 000 $H \to WW^* \to \ell\nu\ell\nu$ events,**

but difficult backgrounds… MVAs, categories, 2-d fits,…

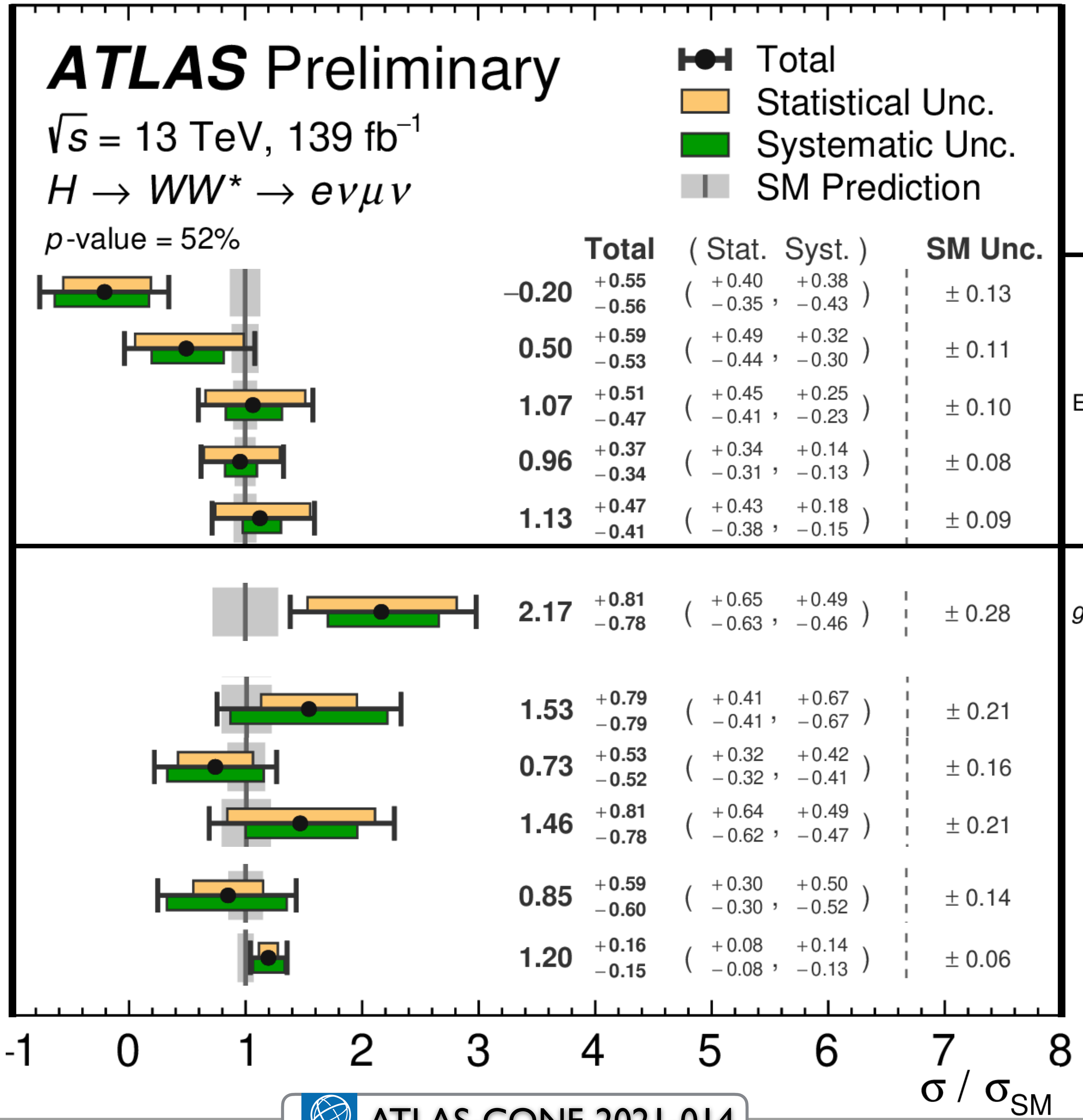


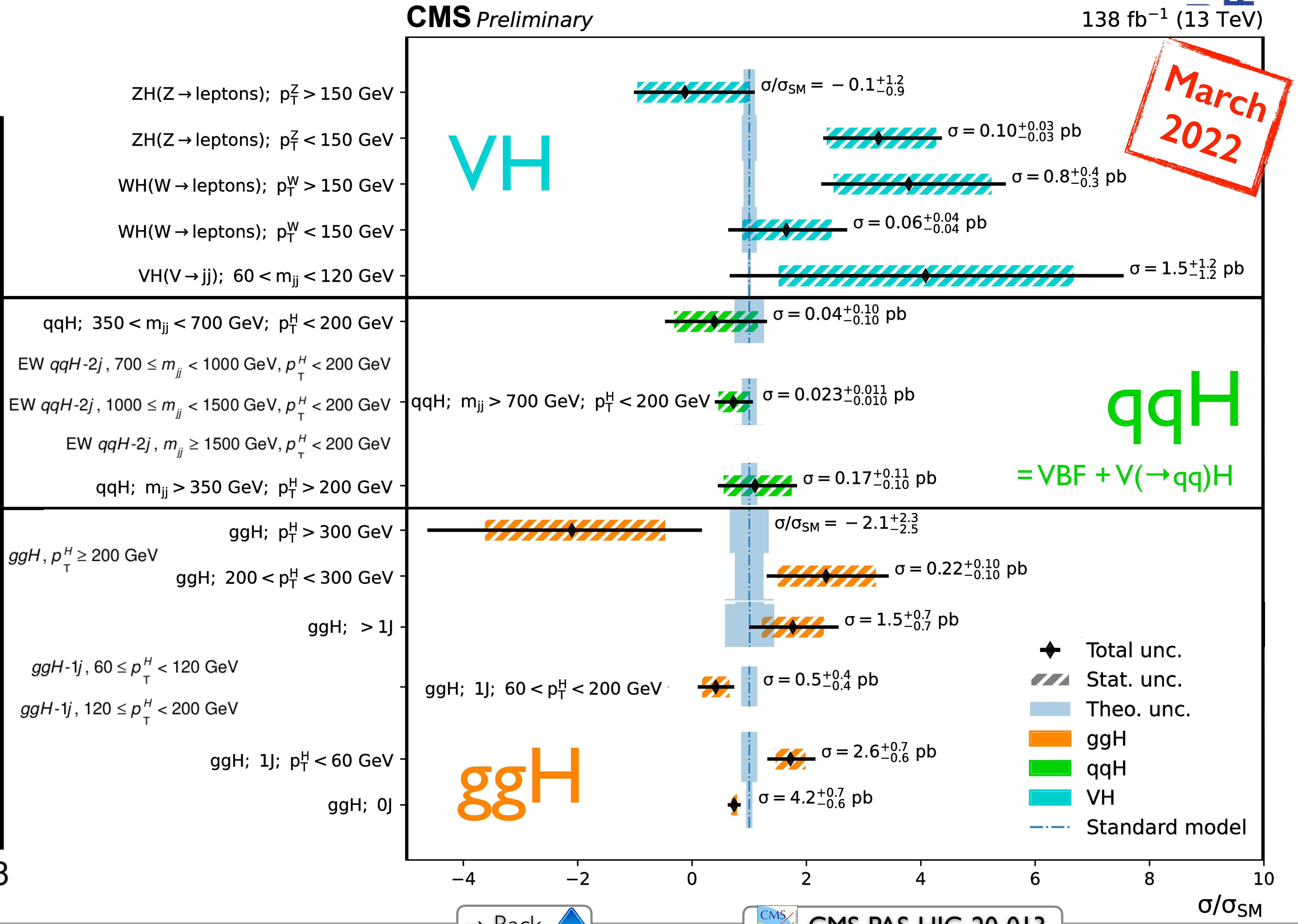


⇒ Back

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

- STXS comparison





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

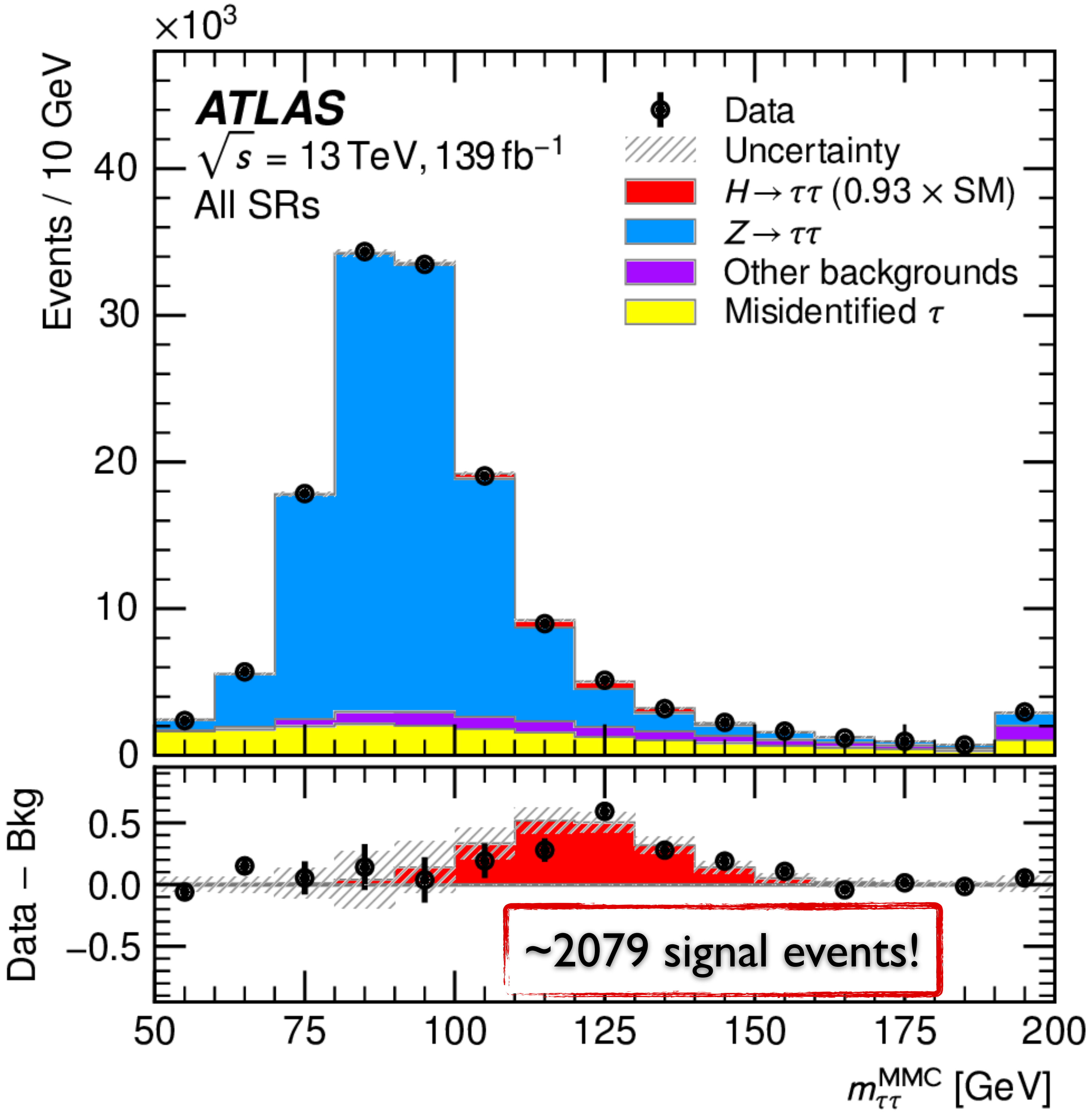
$H \to \tau\tau$

Jan 2022

arXiv:2201.08269 (submitted to JHEP)

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

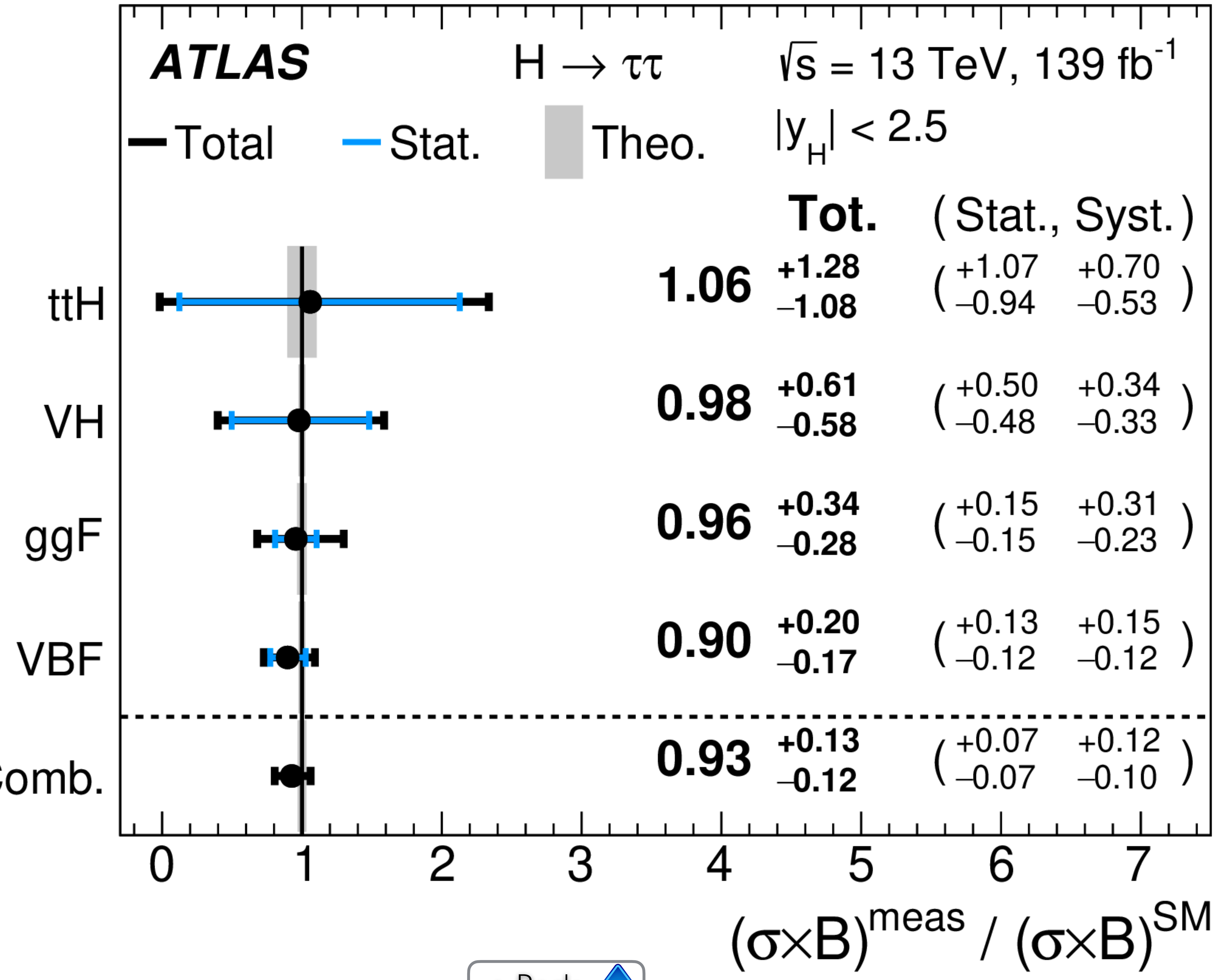
$\Rightarrow$ ~485 000 $H \to \tau\tau$ events



Observed (expected) significance:

3.9 (4.6) σ ggF

5.3 (6.2) σ VBF



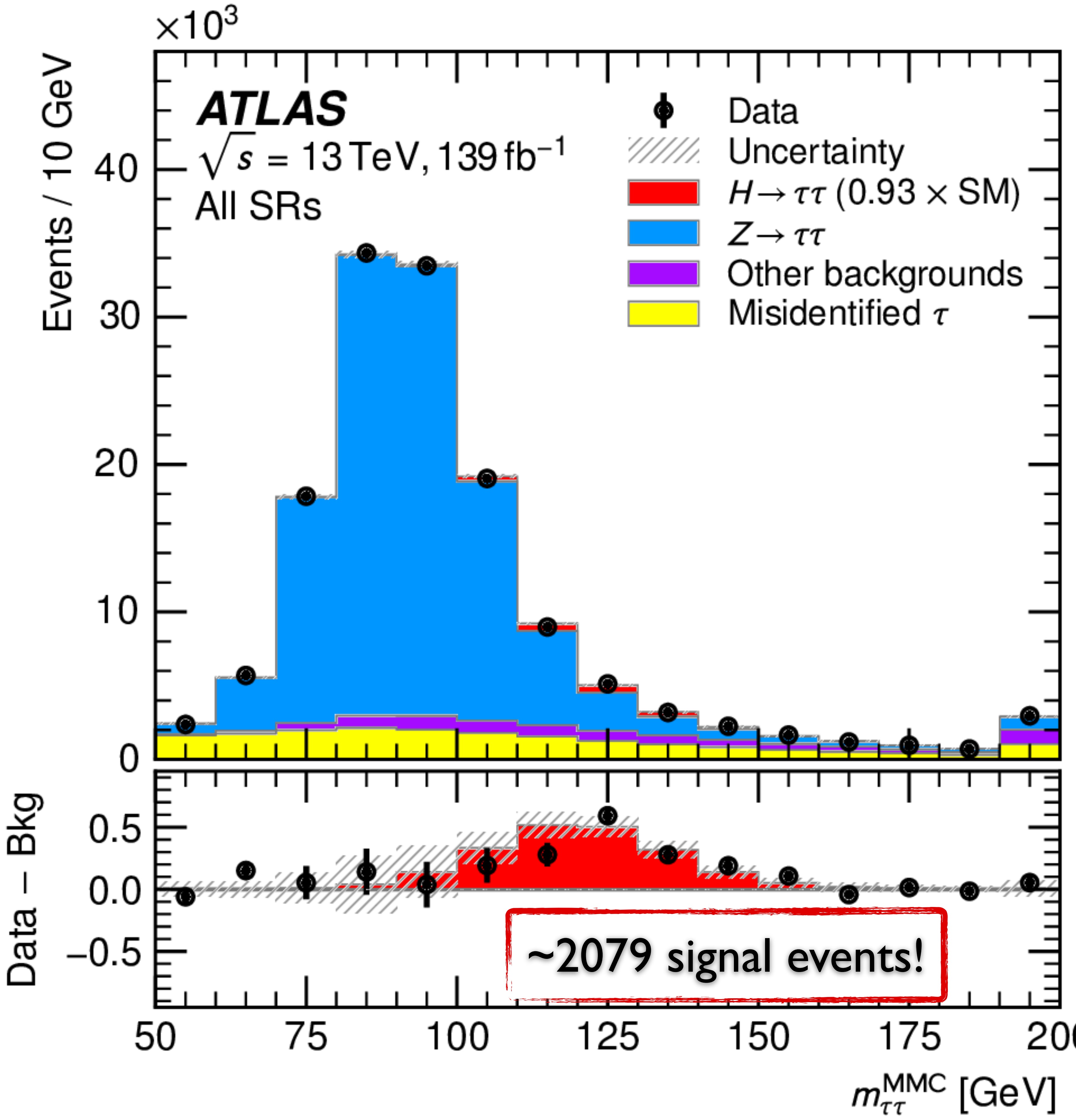
H → ττ

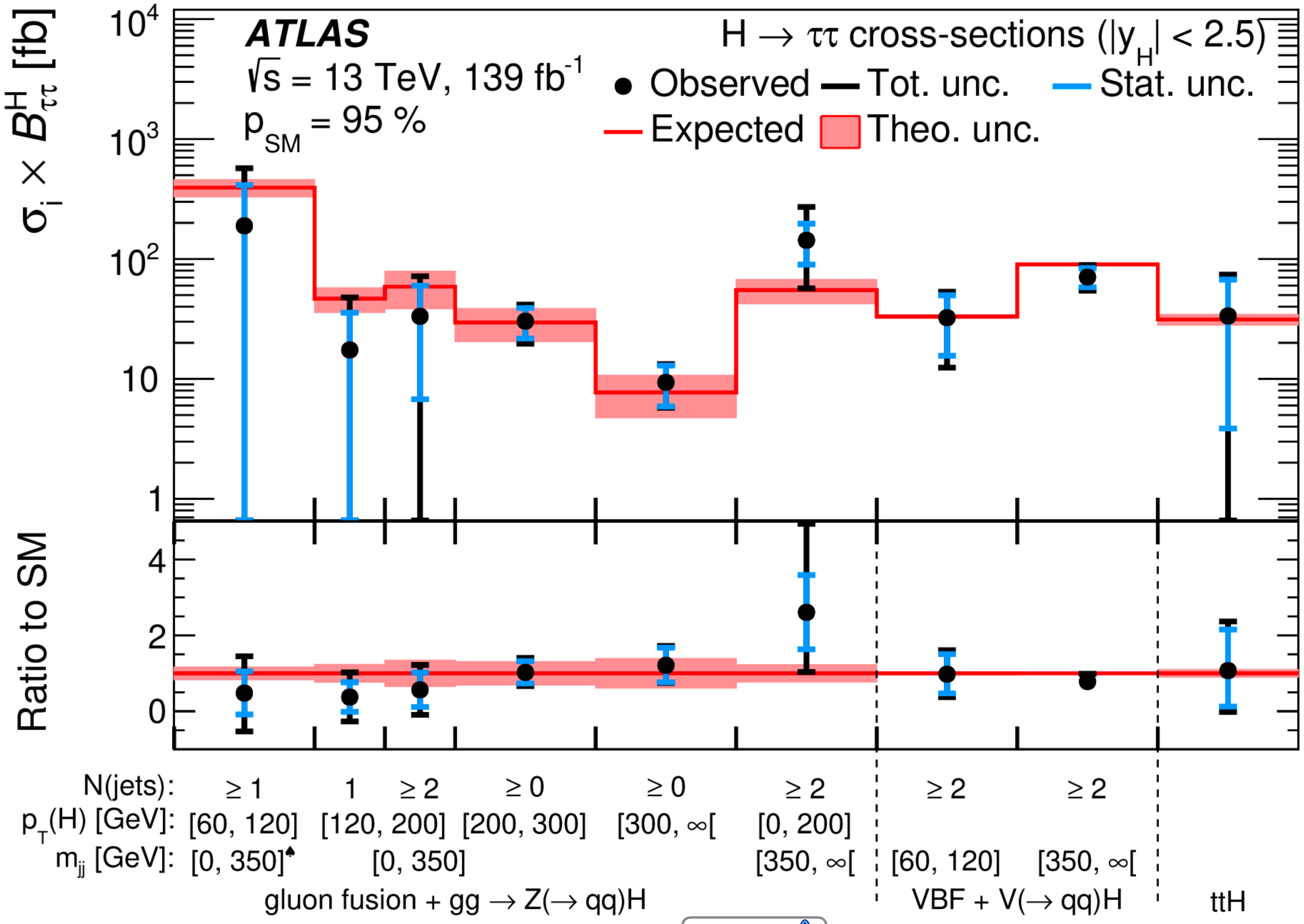
arXiv:2201.08269 (submitted to JHEP)

Jan 2022

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

⇒ **~485 000 H → ττ events**





⇒ Back

H → ττ

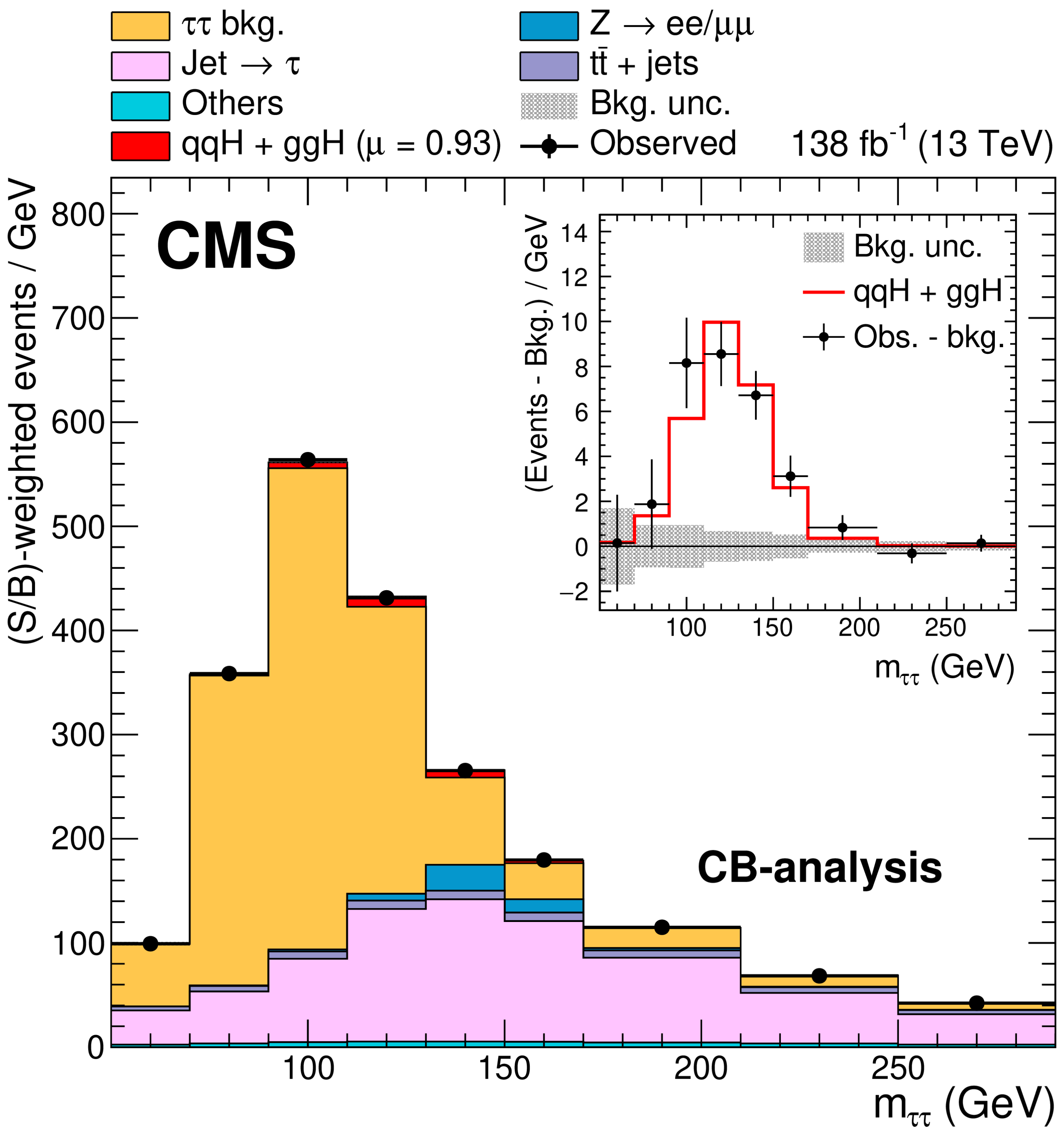
April 2022

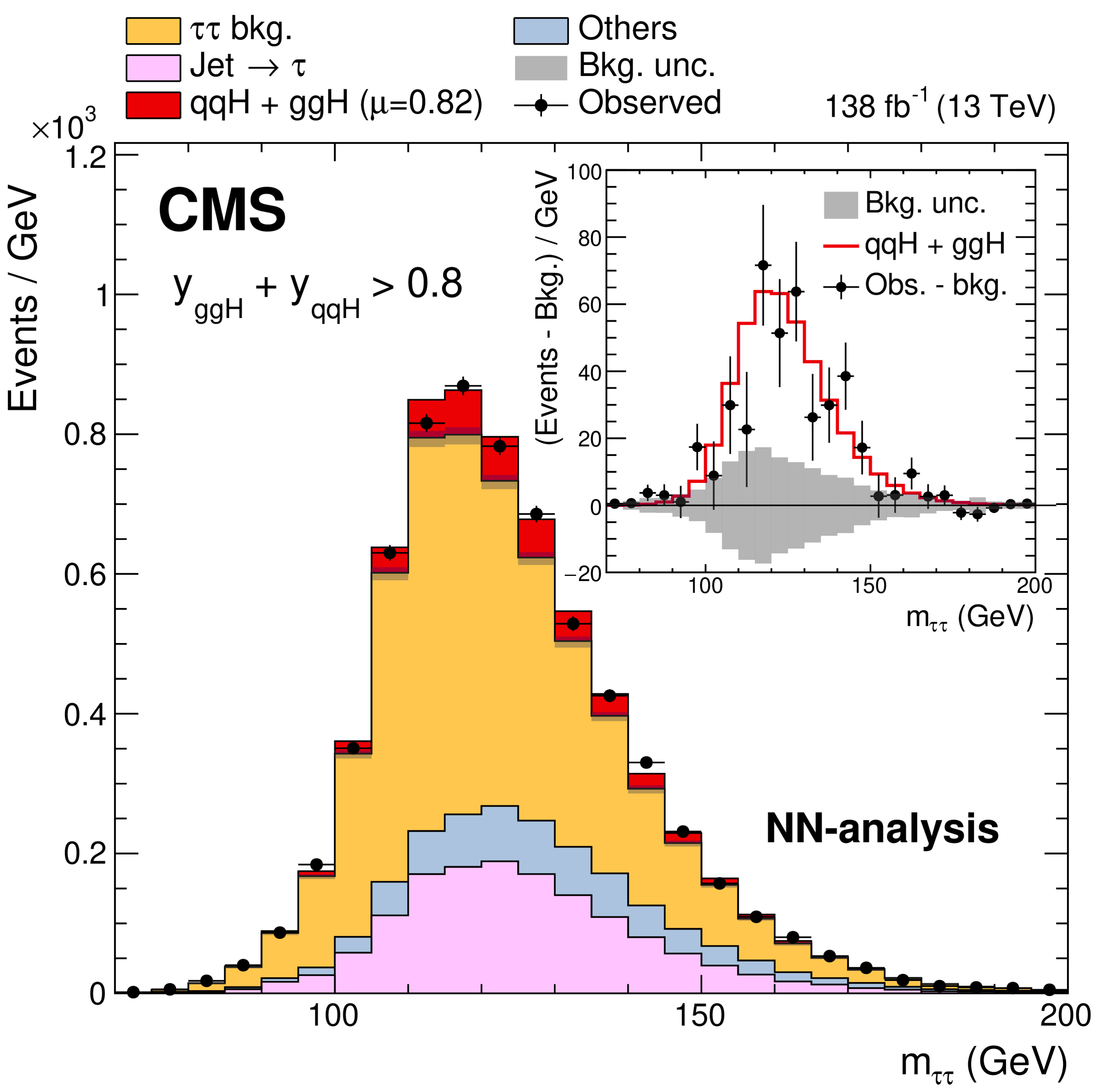
arXiv:2204.12957 (submitted to Eur. Phys. J. C)

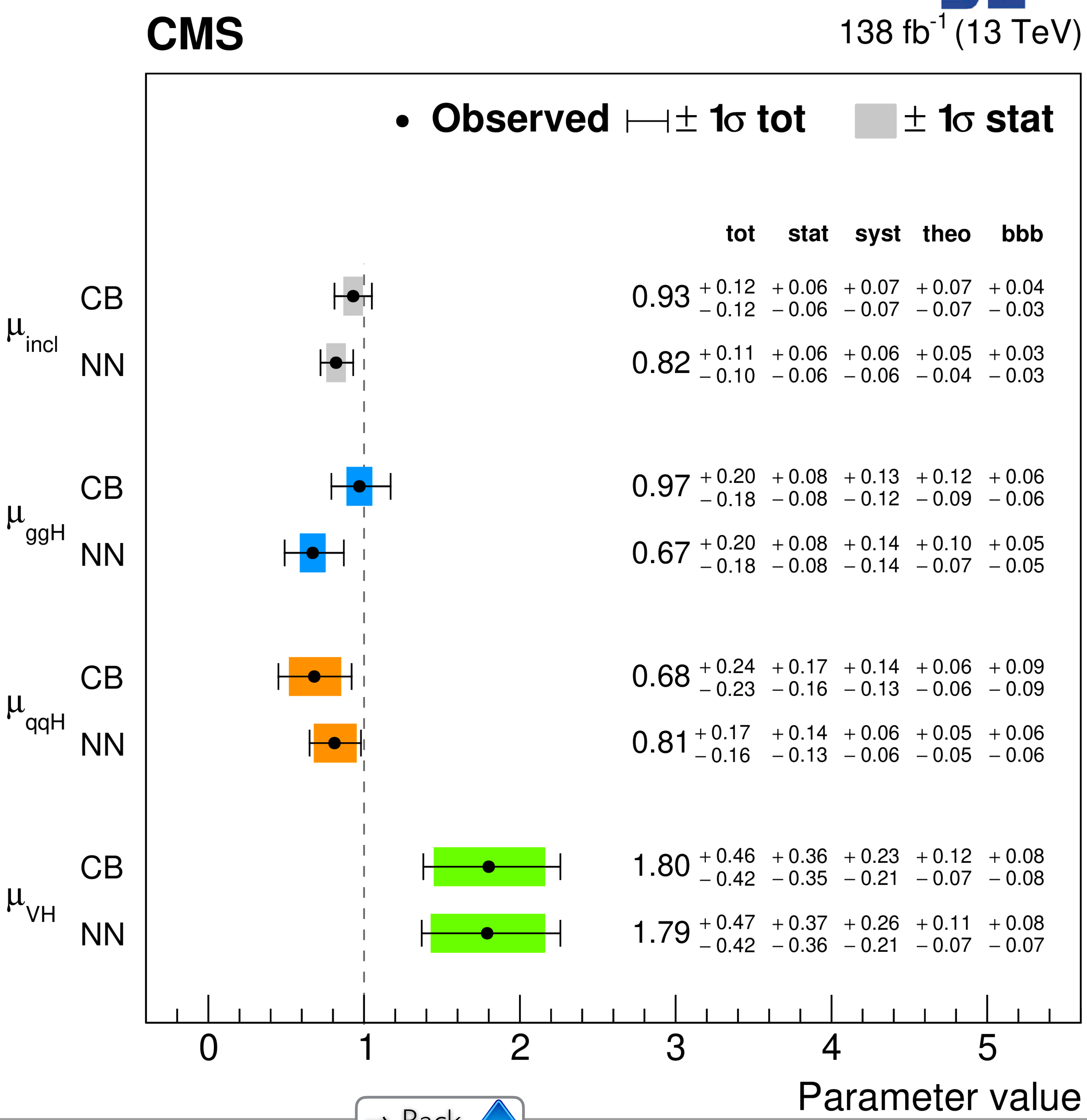
- Strongest coupling to leptons
  - $BR_{SM}(H \rightarrow \tau\tau) = 6.3\%$

⇒ **~485 000 H → ττ events**

  - Cut-based and **multi-class neural-network** analyses







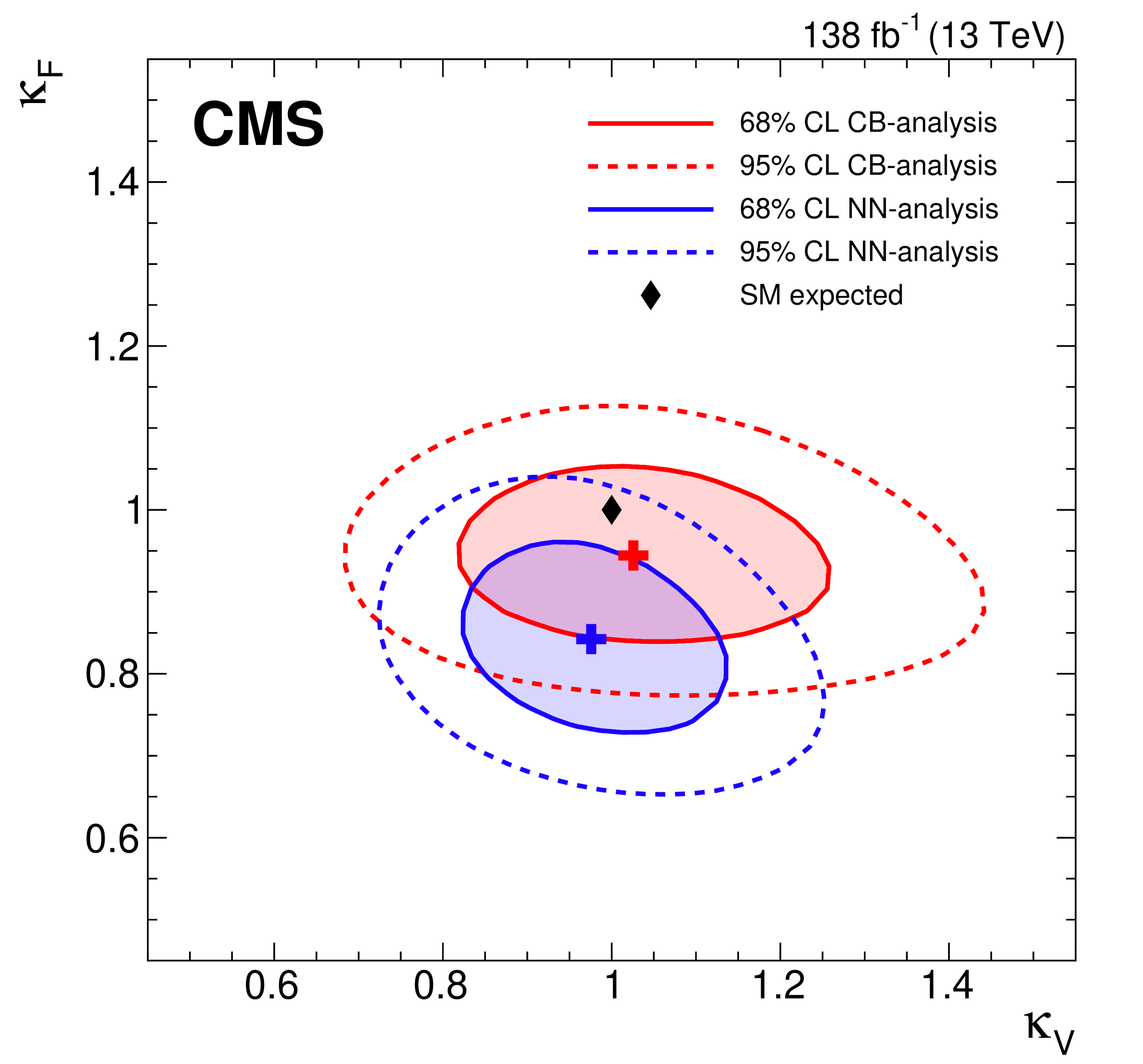
⇒ Back

$H \to \tau\tau$

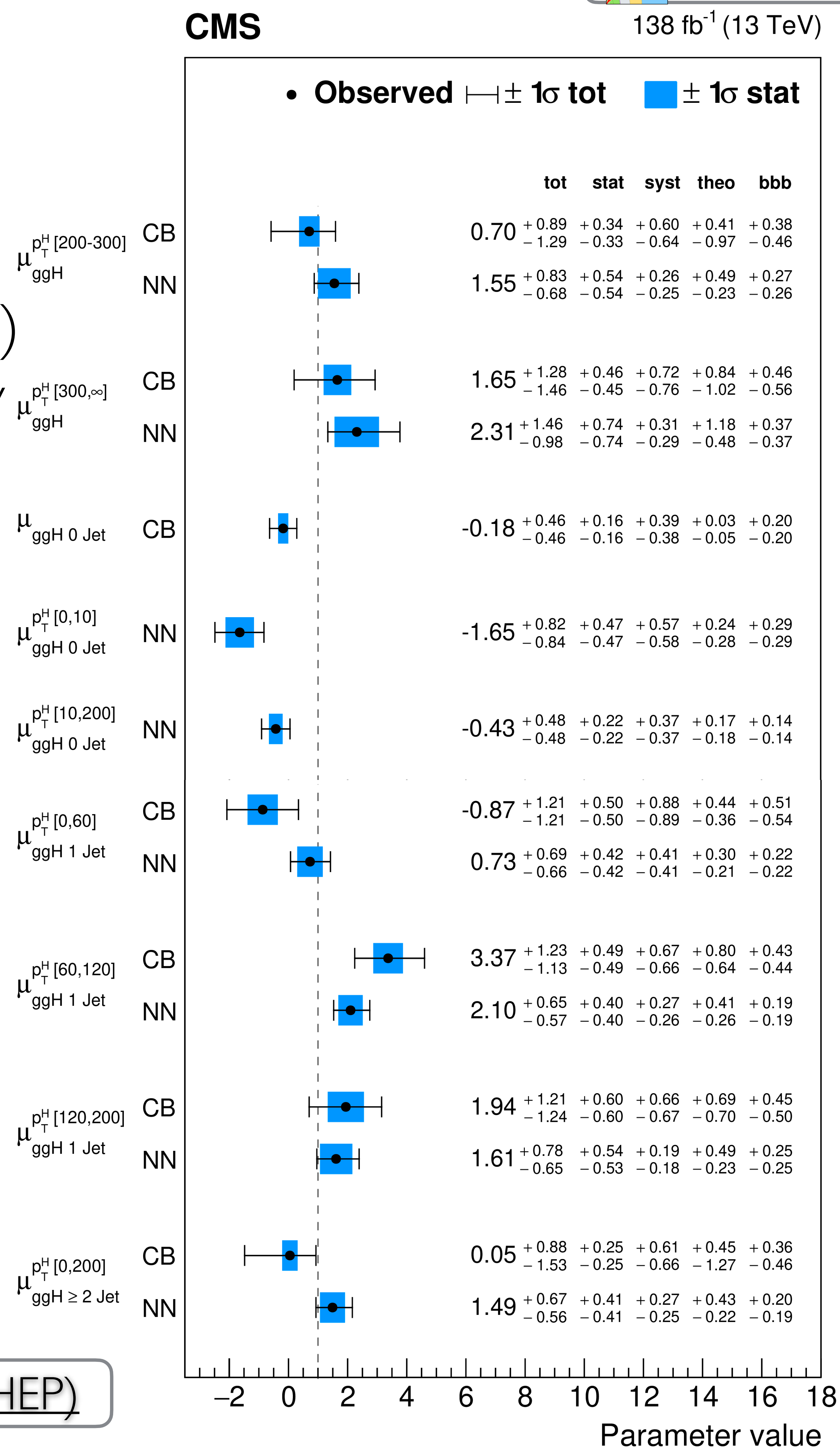
arXiv:2204.12957 (submitted to Eur. Phys. J. C)

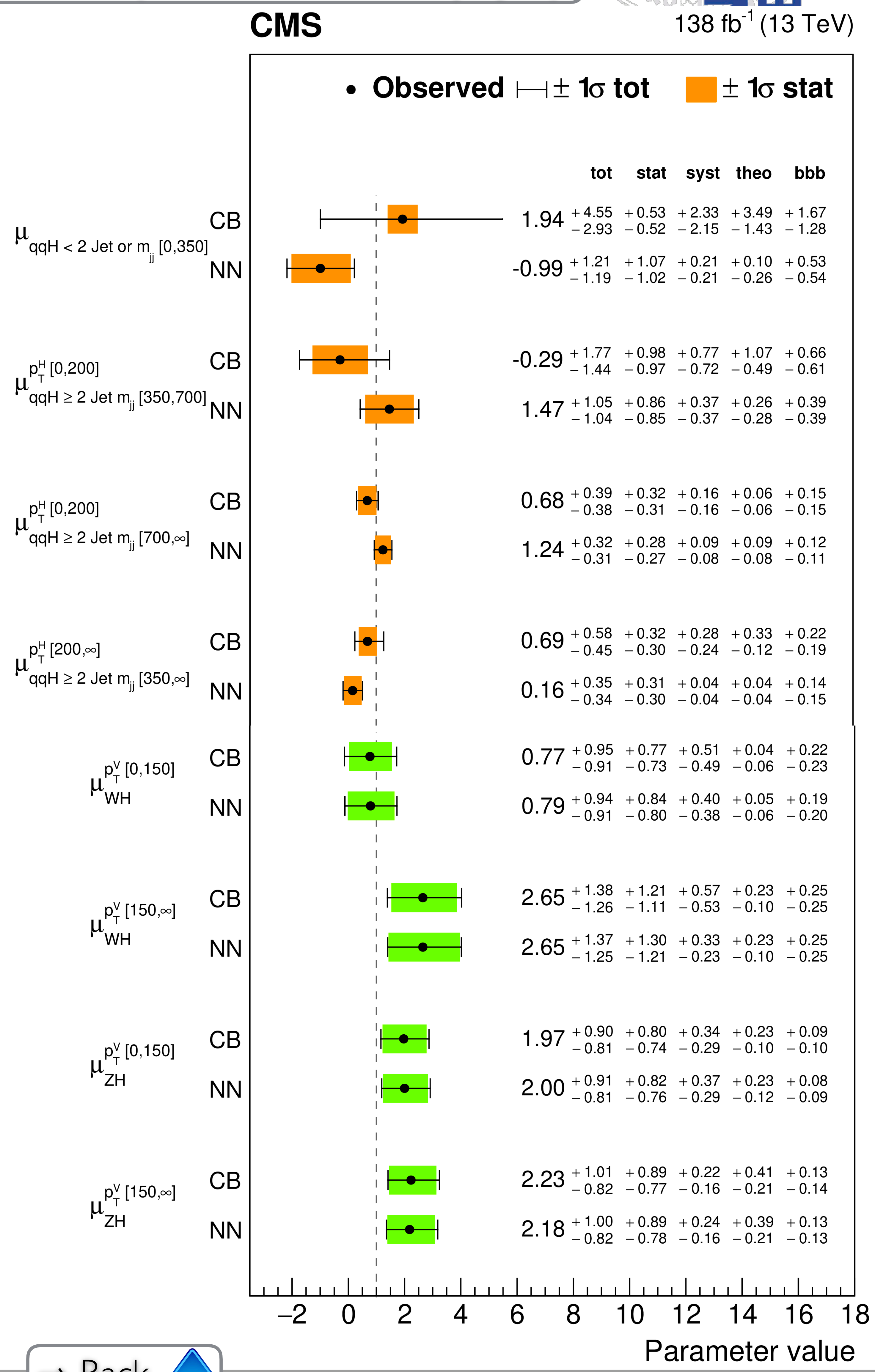
April 2022

- 16 (15) Stage 1.2 STXS bins in NN (cut based) analysis



Good high-p_T(H) sensitivity





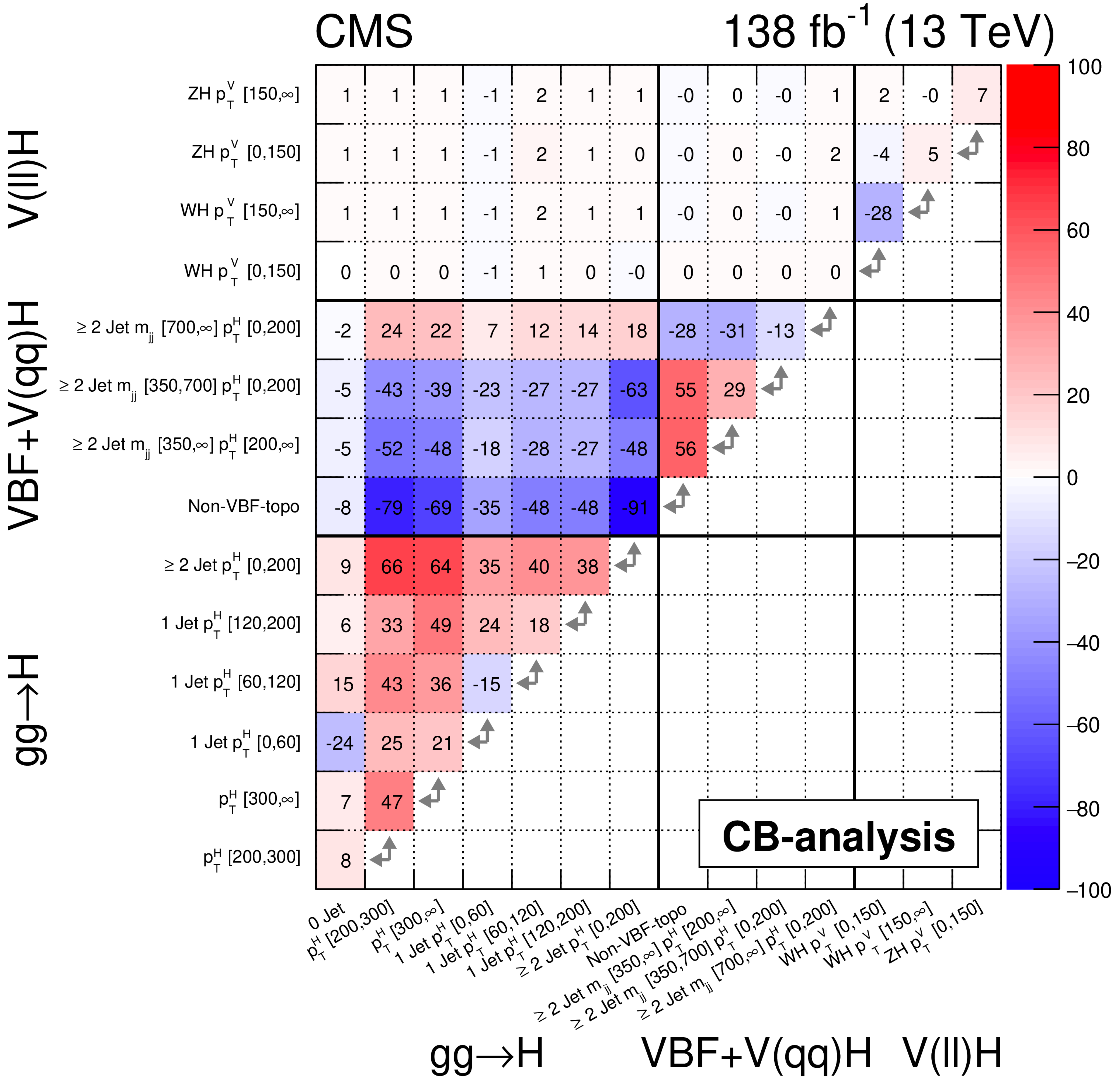
⇒ $H \to \tau\tau$ results from January 2022: arXiv:2201.08269 (submitted to JHEP)

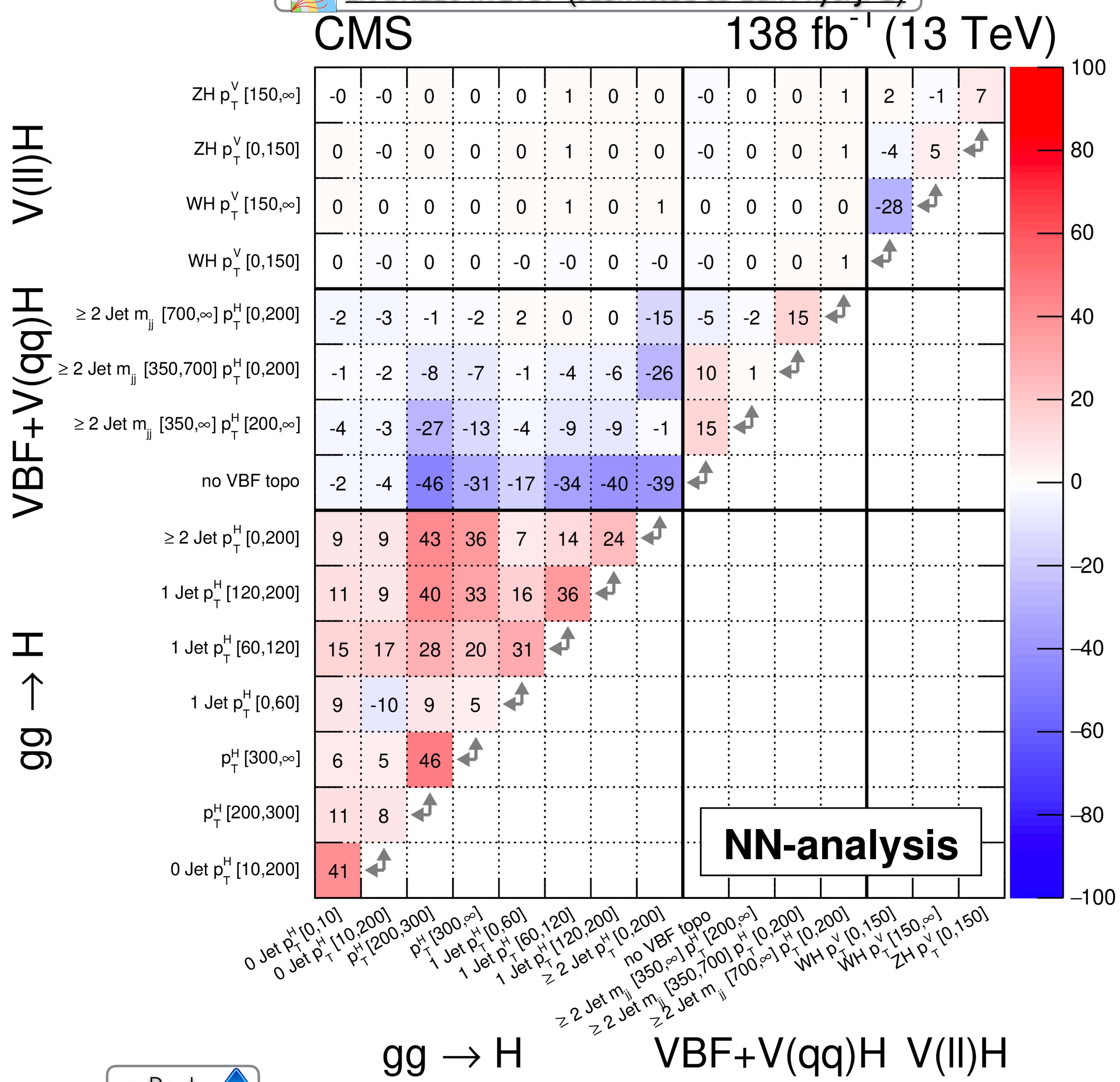
⇒ Back

H → ττ STXS correlations

April 2022

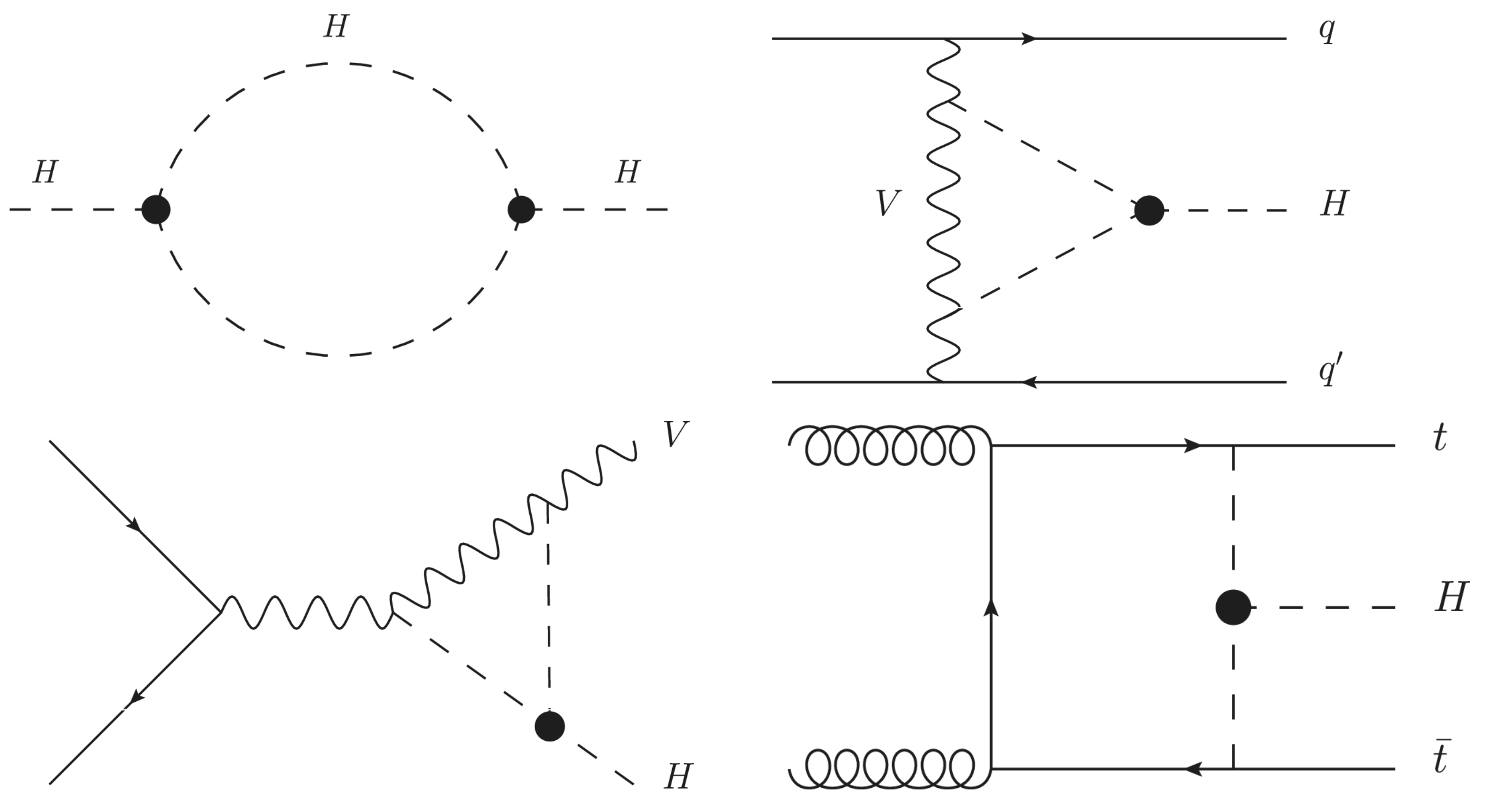
arXiv:2204.12957 (submitted to Eur. Phys. J. C)



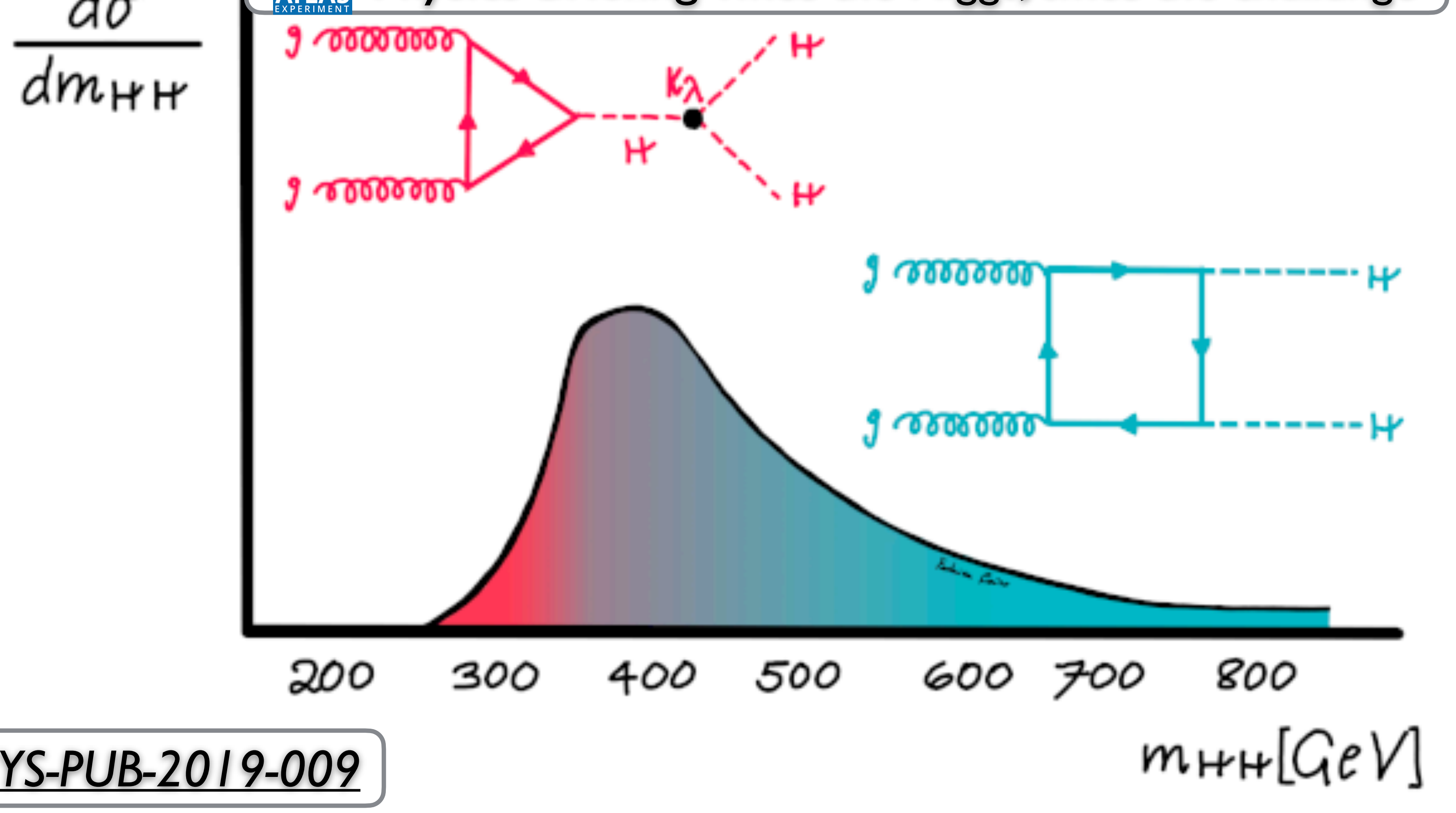


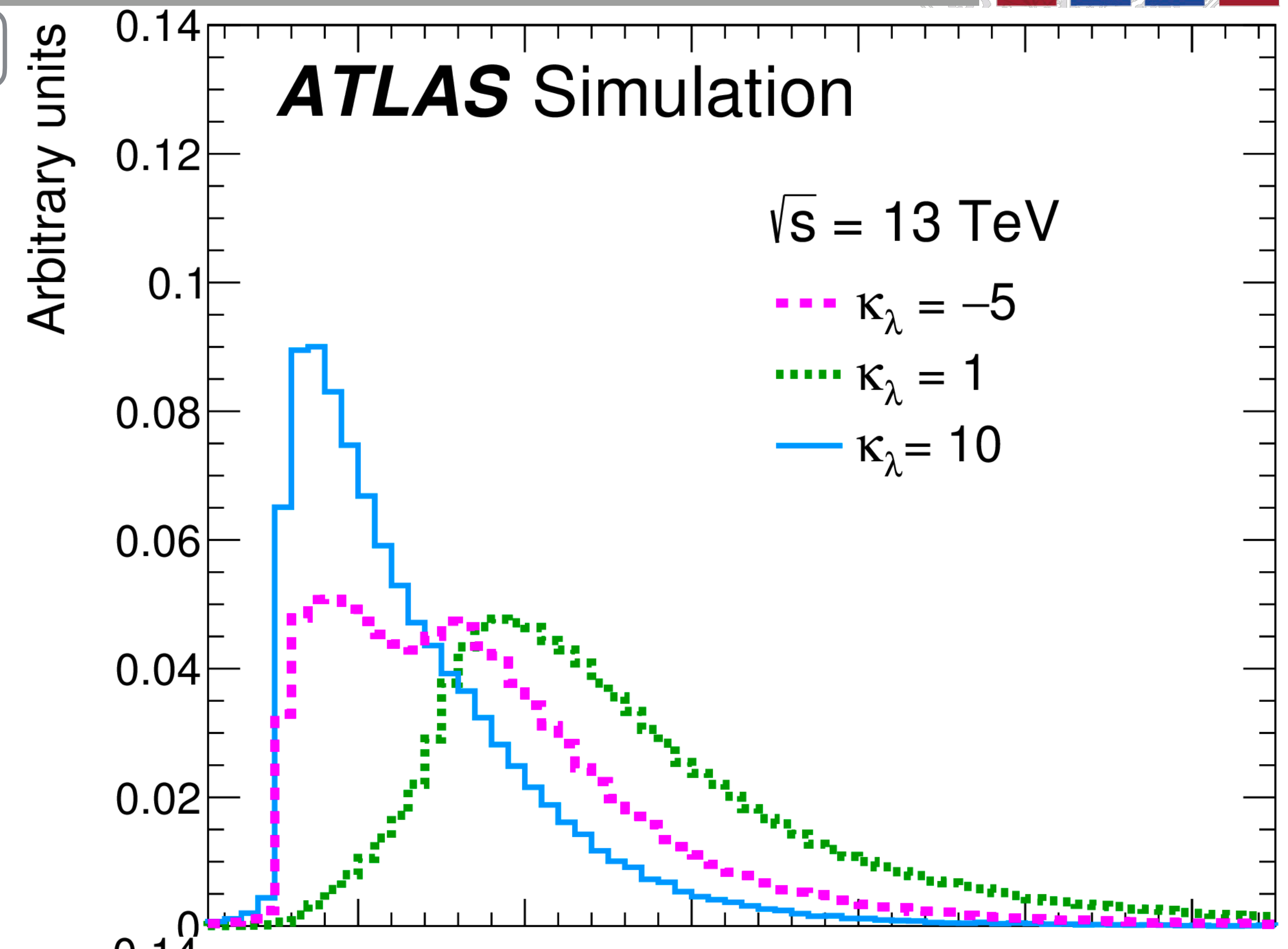
⇒ Back

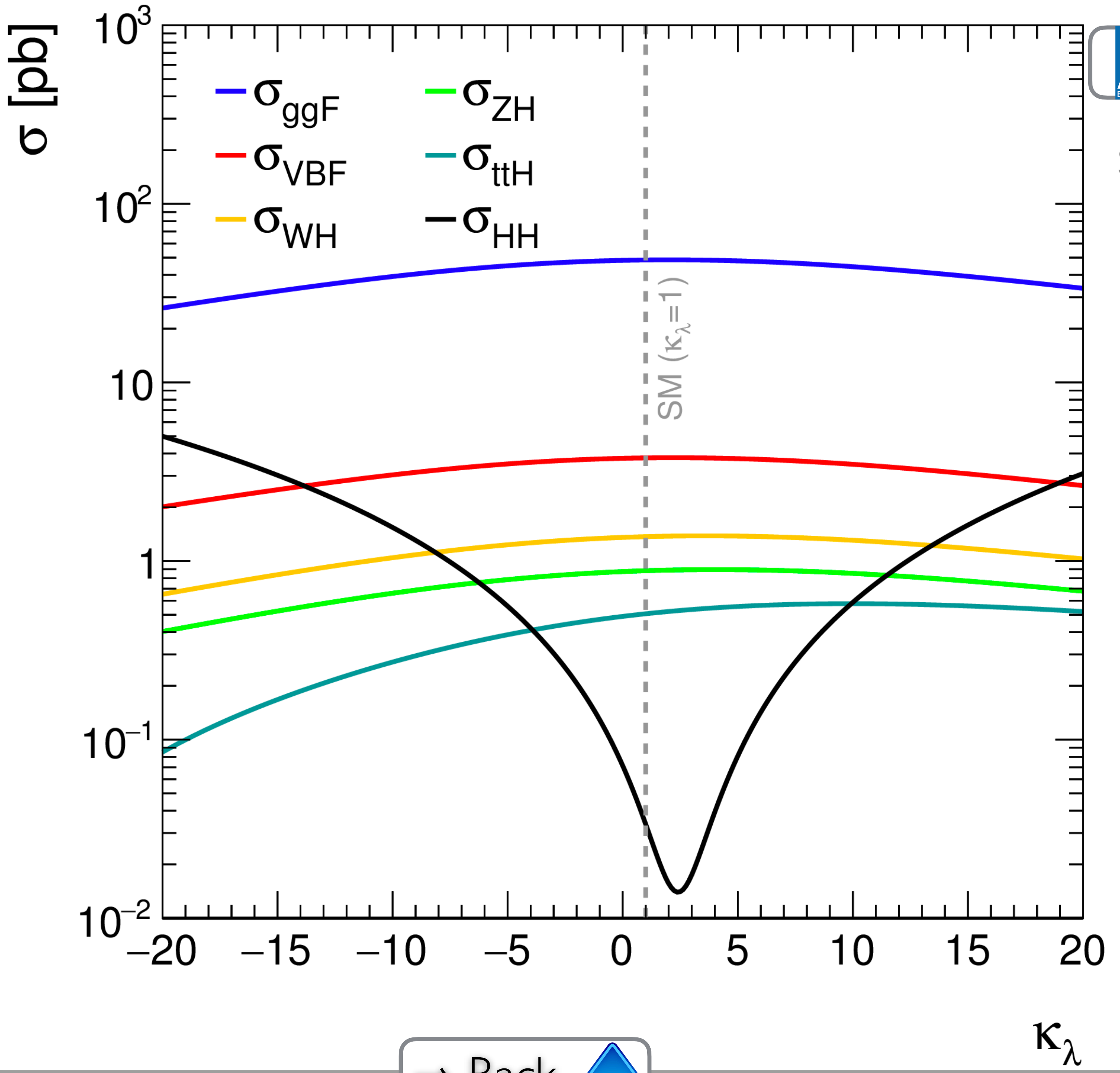
Extracting κλ



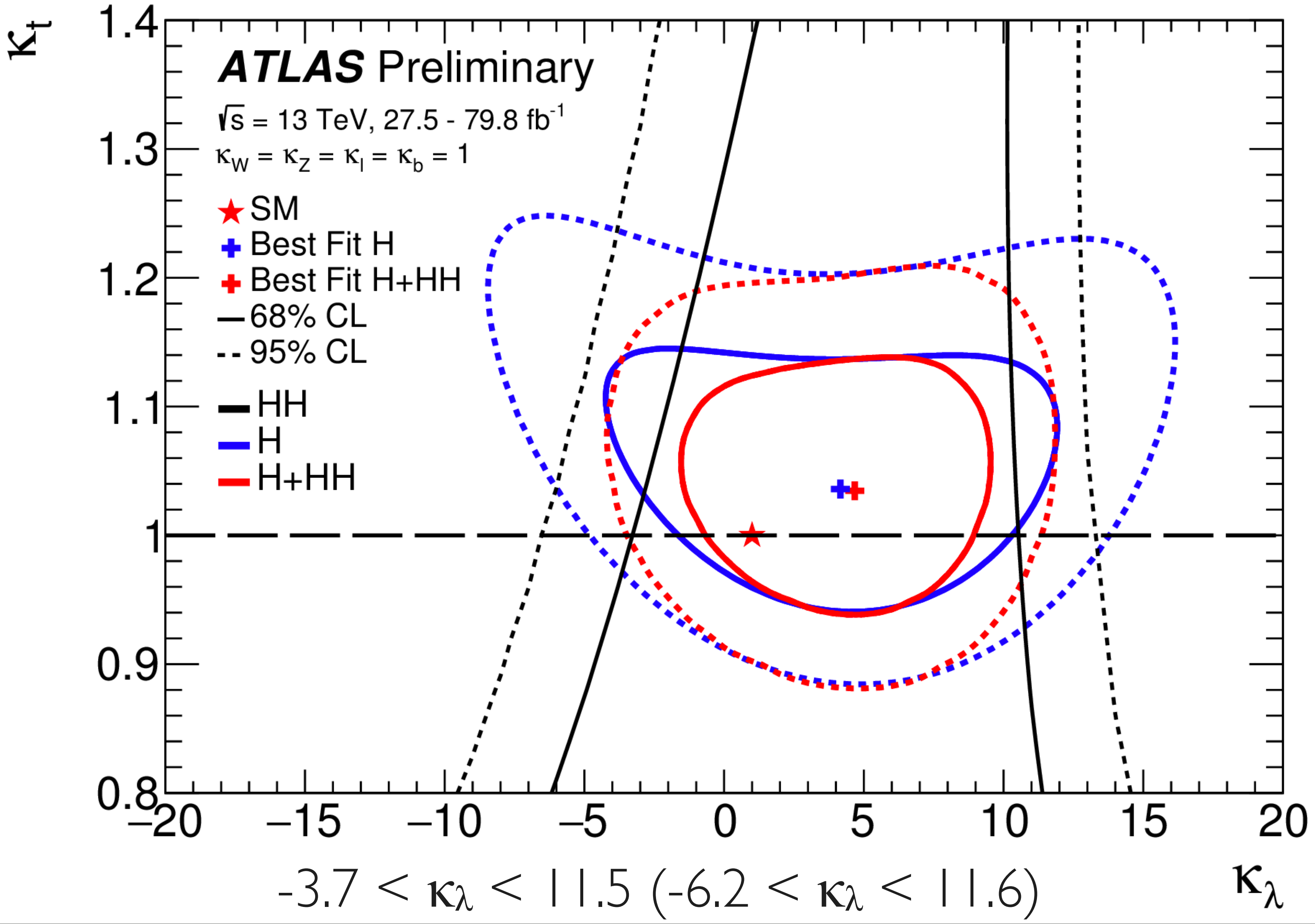
Physics Briefing *Twice the Higgs, twice the challange*



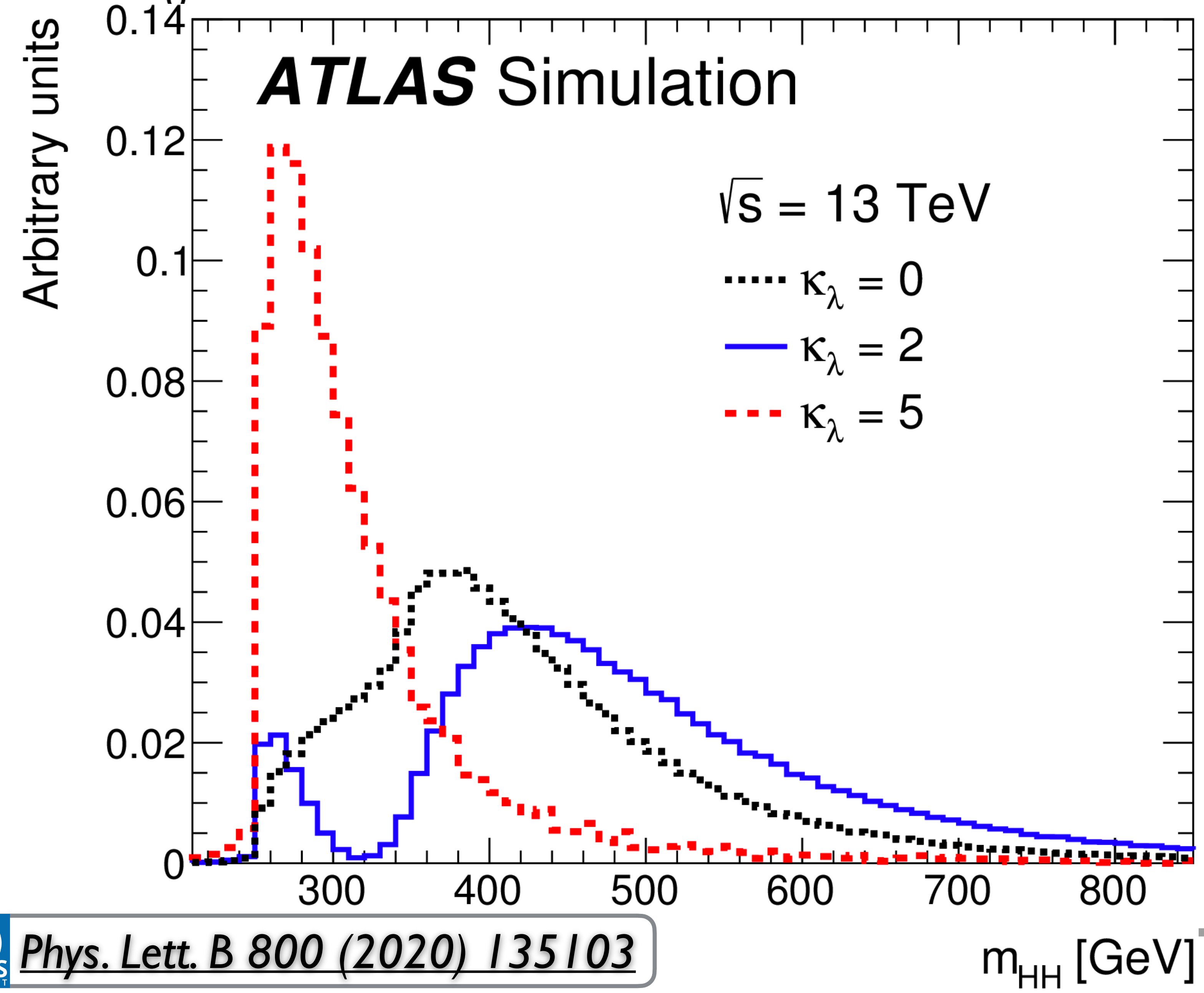




ATL-PHYS-PUB-2019-009



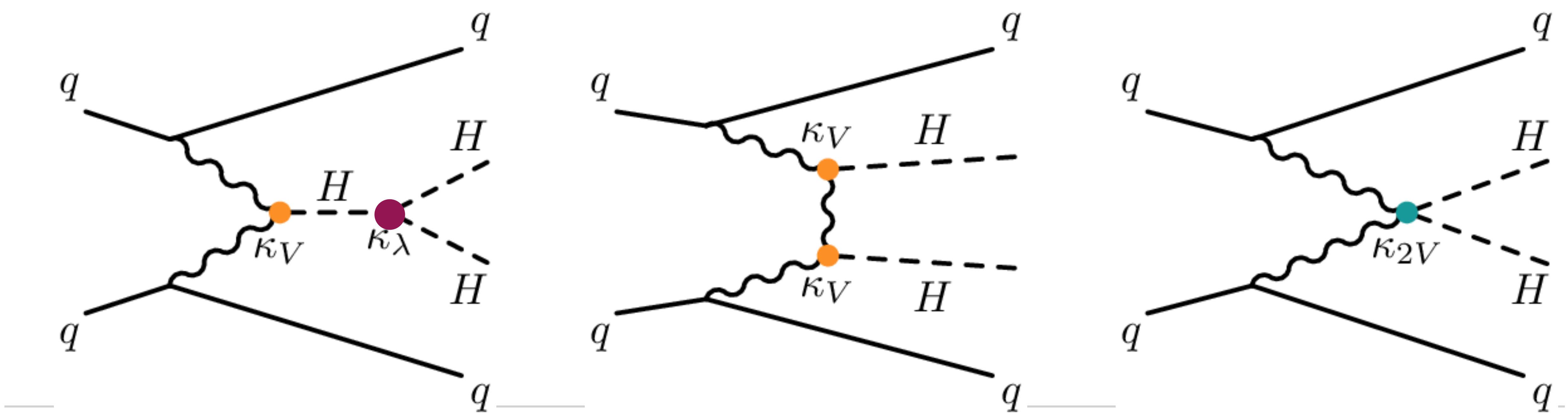
$-3.7 < \kappa_\lambda < 11.5$ ($-6.2 < \kappa_\lambda < 11.6$)



⇒ Back

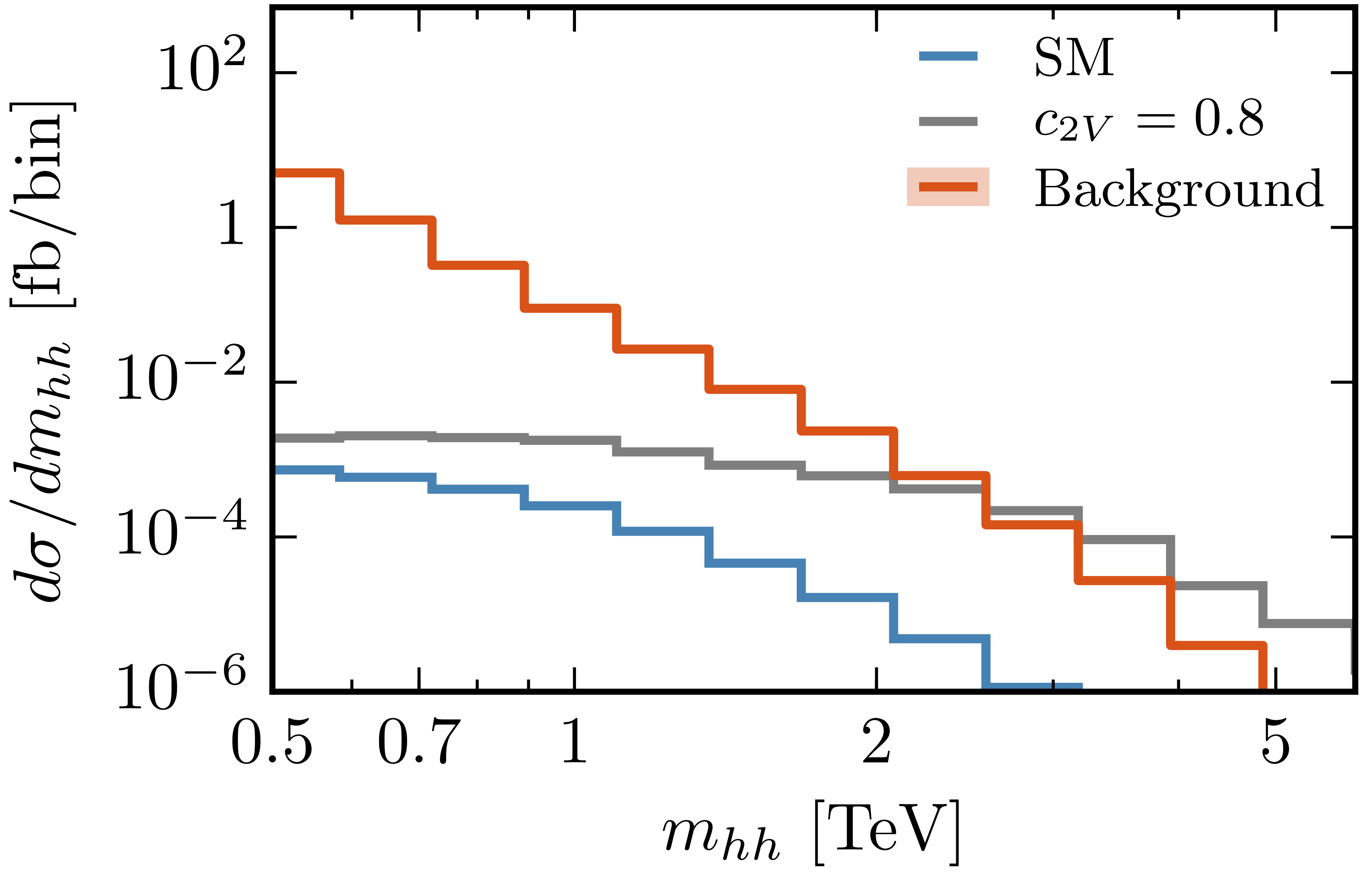
Phys. Lett. B 800 (2020) 135103

Extracting κ_{2V}



- In SM: $\mathscr{A}(V_L V_L \to hh) \simeq \frac{\hat{s}}{v^2}(c_{2V} - c_V^2)$

LHC 14 TeV arXiv:1611.03860



Karsten Köneke

⇒ Back

CMS HH Summary

CMS Higgs Summary Plots

bb ZZ
Expected: 40
Observed: 32

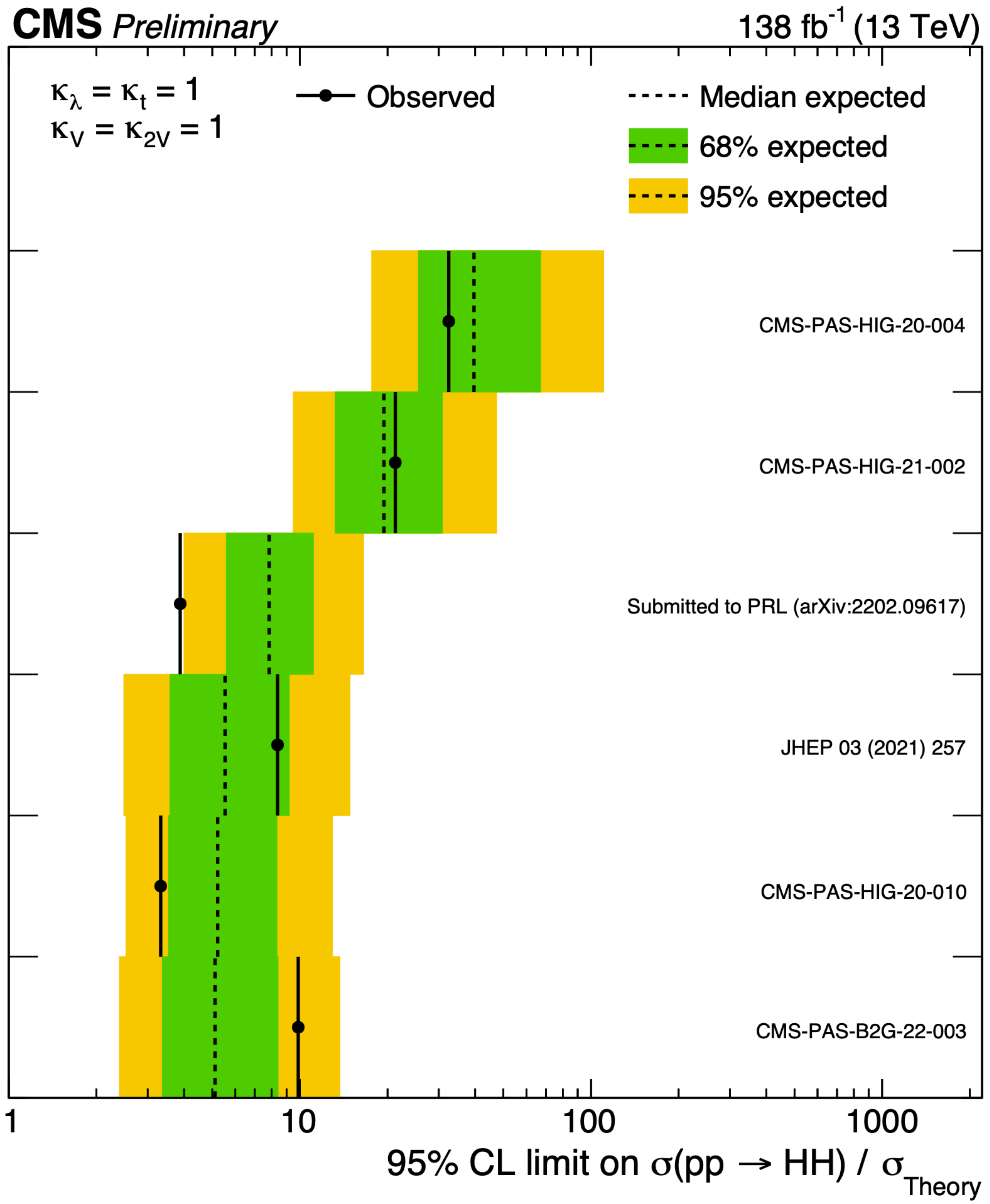
Multilepton
Expected: 19
Observed: 21

bb bb, resolved
Expected: 7.8
Observed: 3.9

bb $\gamma\gamma$
Expected: 5.5
Observed: 8.4

bb $\tau\tau$
Expected: 5.2
Observed: 3.3

bb bb, merged jet
Expected: 5.1
Observed: 9.9



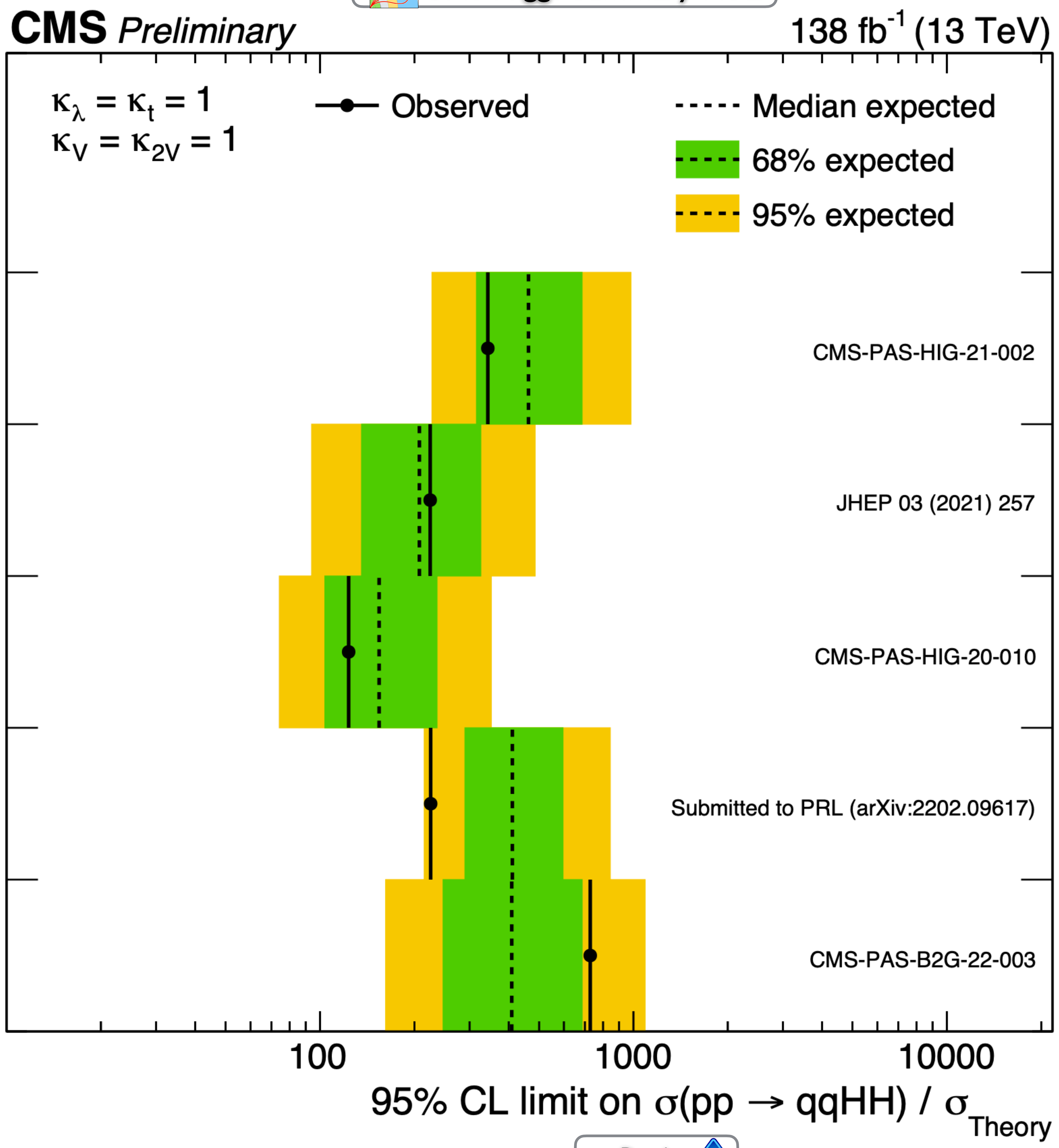
Multilepton
Expected: 462
Observed: 343

bb $\gamma\gamma$
Expected: 208
Observed: 225

bb $\tau\tau$
Expected: 154
Observed: 123

bb bb, resolved
Expected: 411
Observed: 225

bb bb, merged jet
Expected: 409
Observed: 728



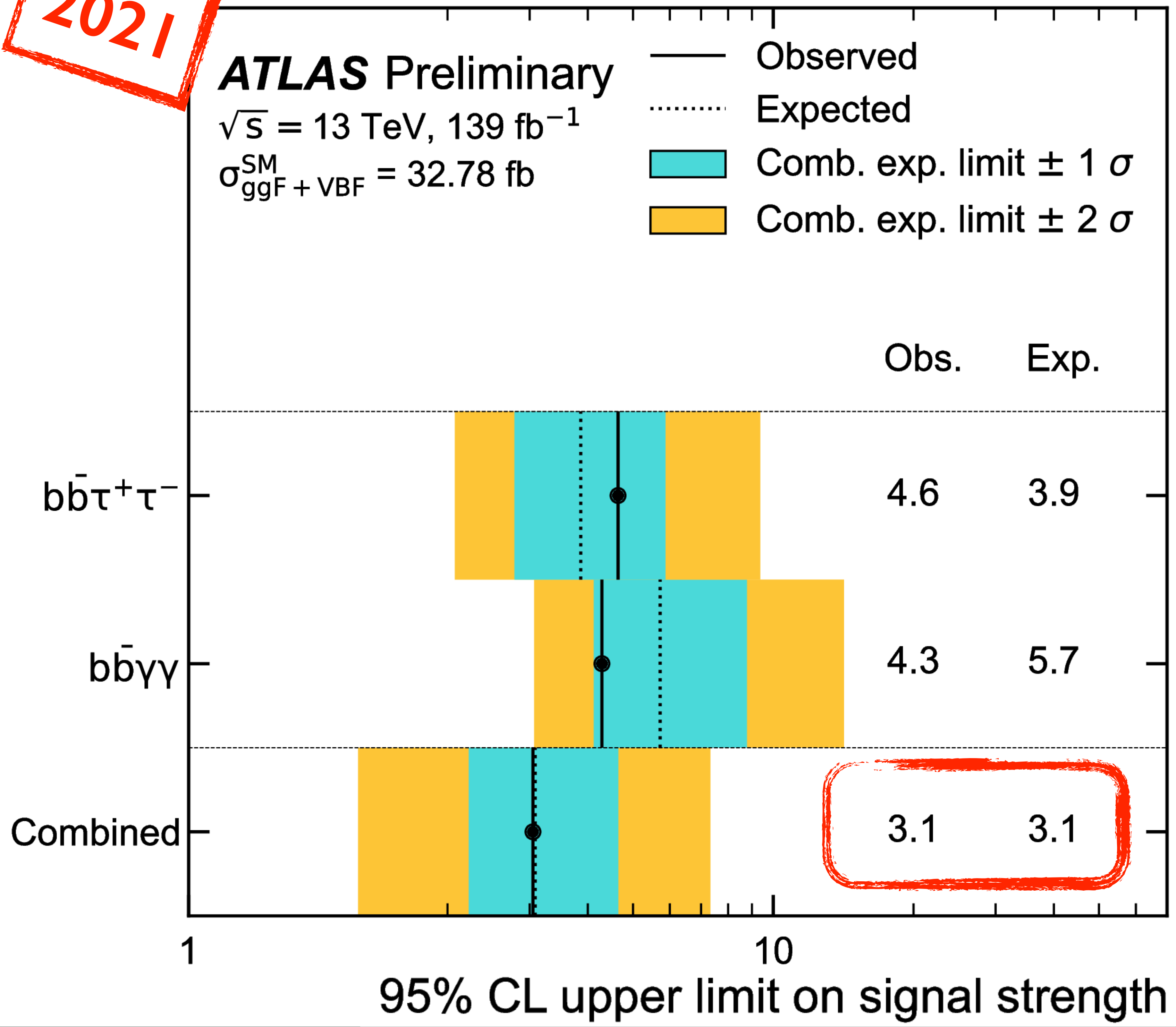
⇒ Back

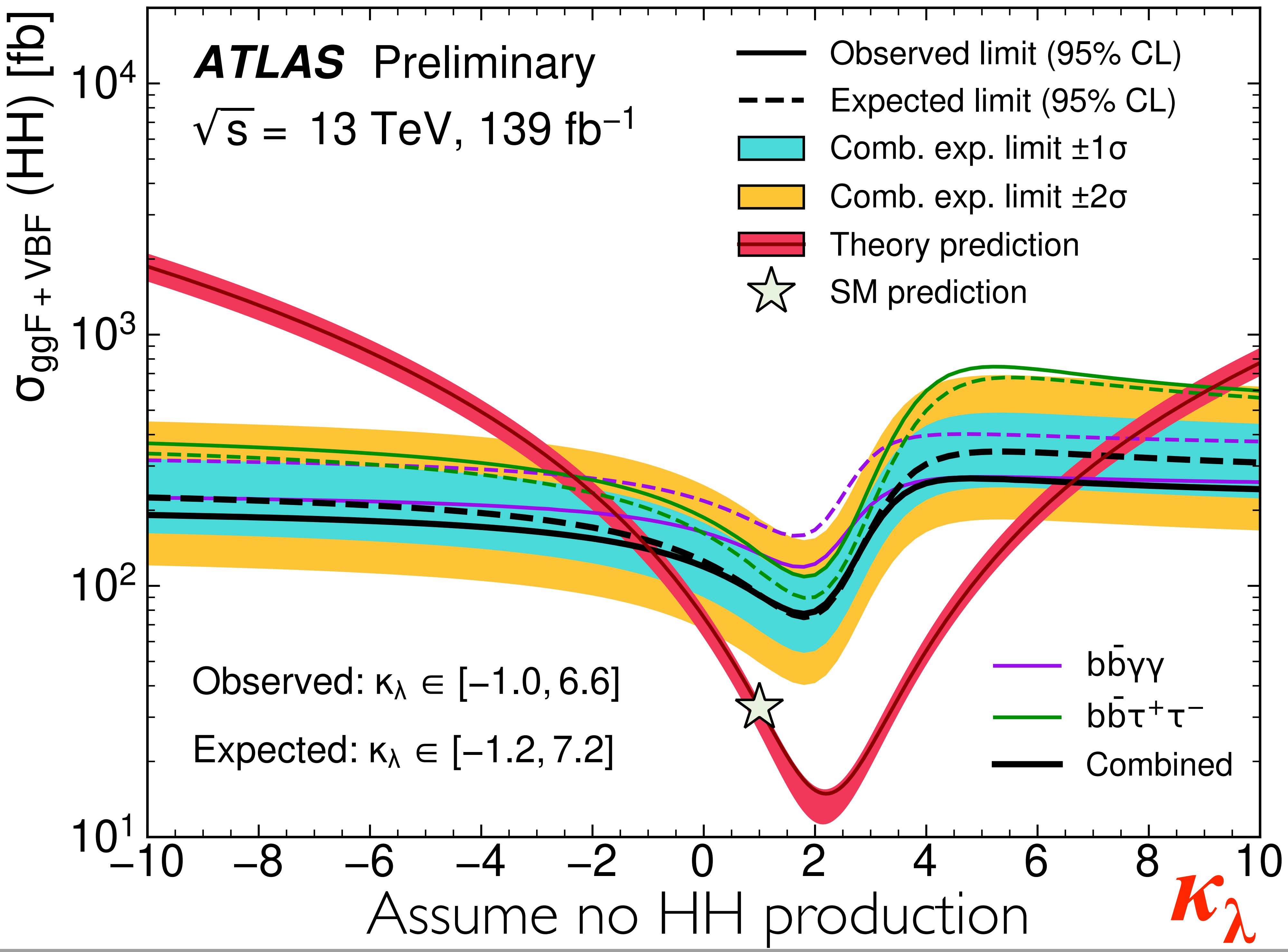
Combination of HH → bbττ and HH → bbγγ

ATLAS-CONF-2021-052

- Combine large BR & clean signatures
  - $BR_{SM}(HH \to bb\tau\tau) = 7.4\% \Rightarrow$ ~320 events in 139 fb^{-1}
  - $BR_{SM}(HH \to bb\gamma\gamma) = 0.26\% \Rightarrow$ ~11 events in 139 fb^{-1}

Oct 2021





ATLAS Combination of $b\bar{b}\tau\tau$ **and** $b\bar{b}\gamma\gamma$

Observed constraint on trilinear coupling at 95% CL:

$$-1.0 < \kappa_\lambda < 6.6$$

Expected range:

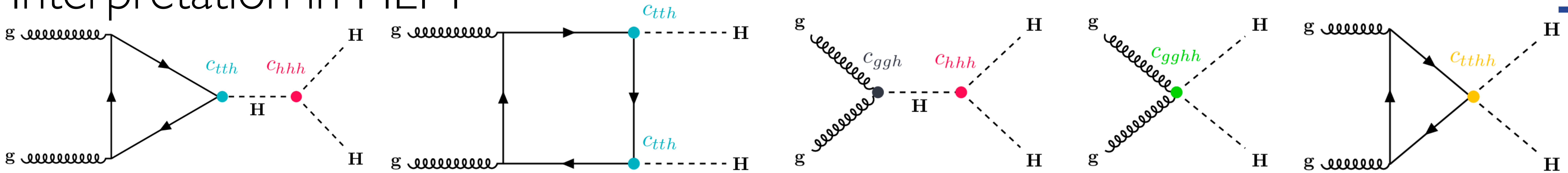
$$-1.2 < \kappa_\lambda < 7.2$$

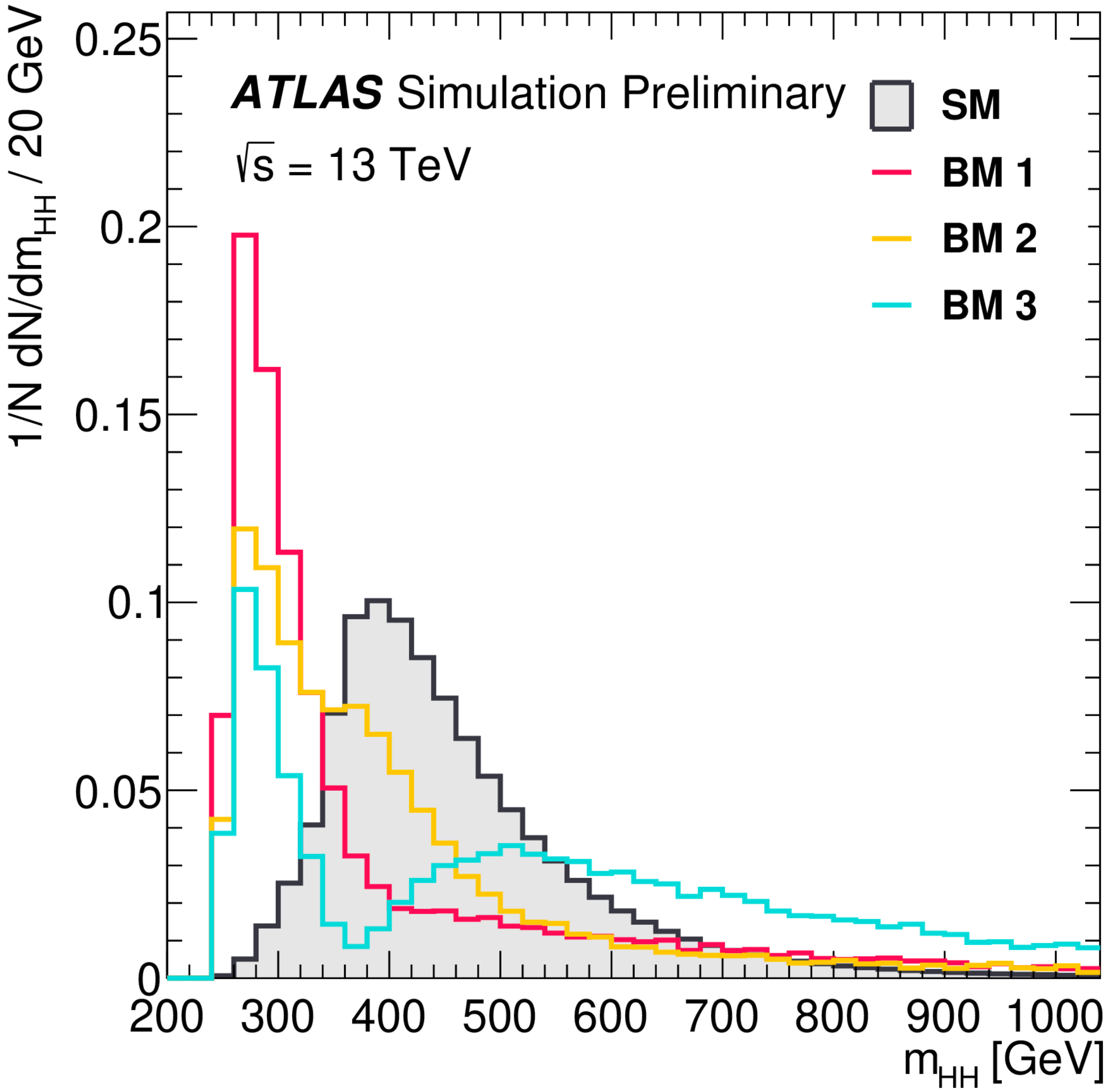
⇒ Back

HH: HEFT fun with $bb\gamma\gamma$ + $bb\tau\tau$

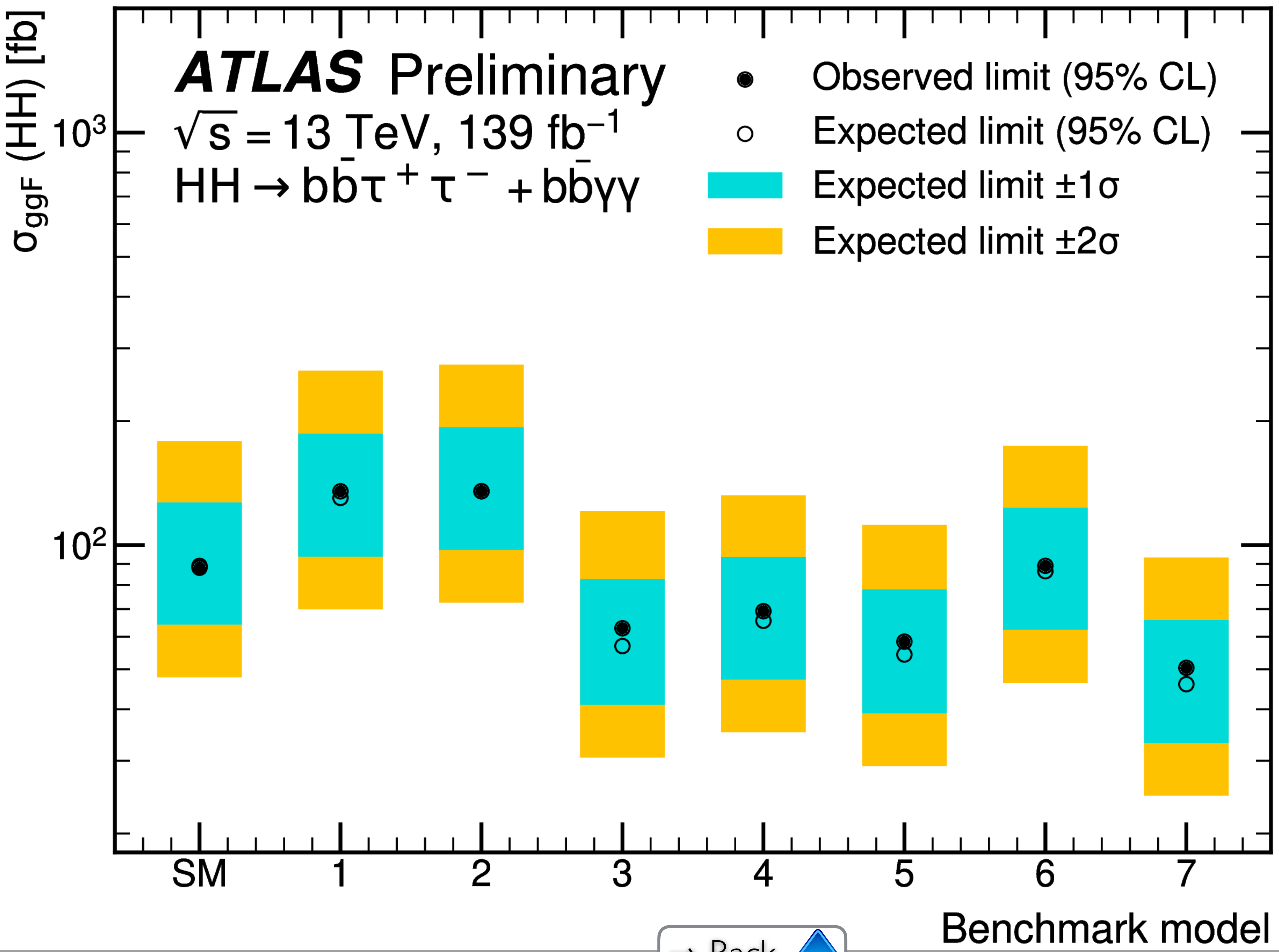
ATL-PHYS-PUB-2022-019

- Interpretation in HEFT





March 2022



⇒ Back

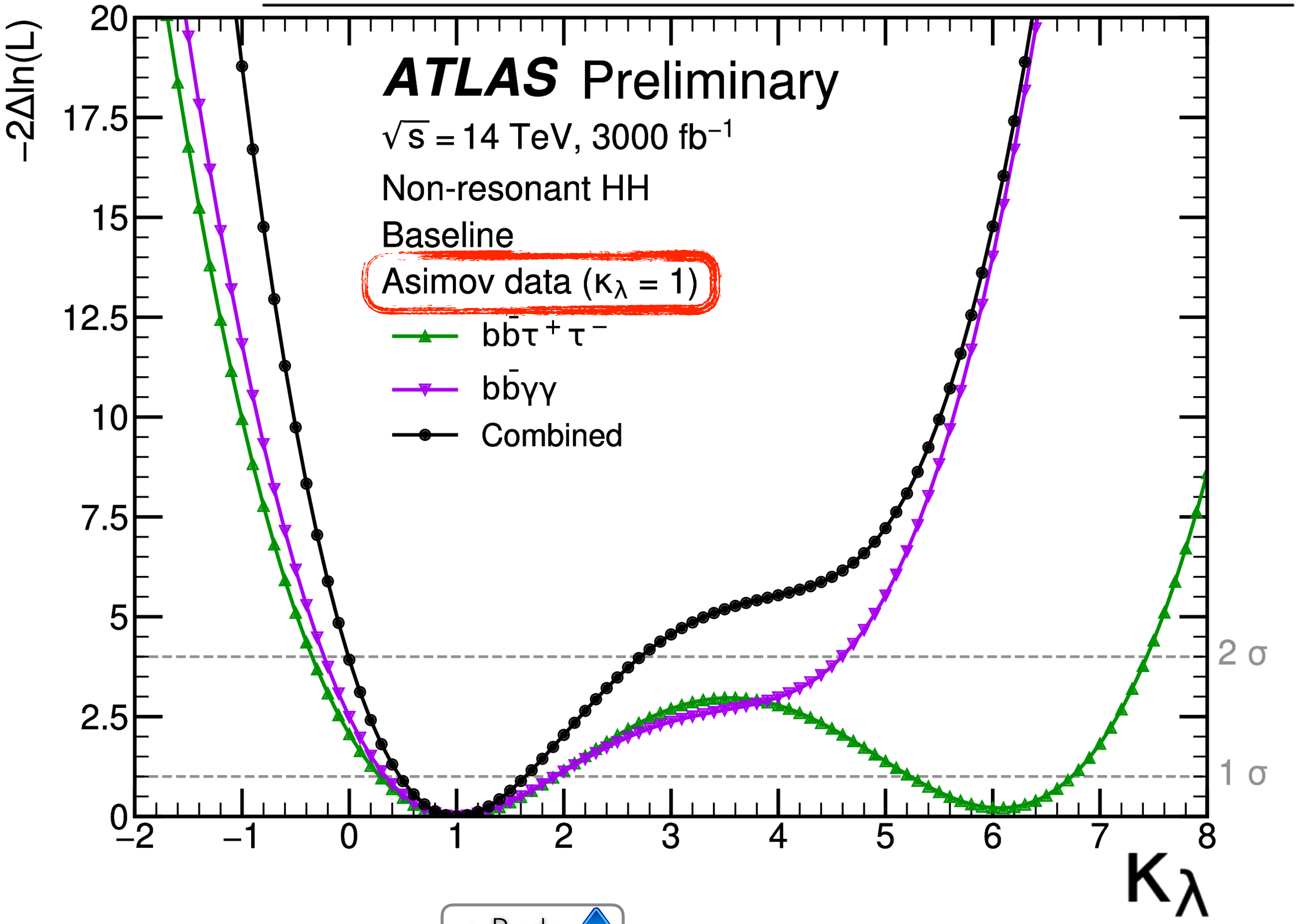
HH: Future fun

ATL-PHYS-PUB-2022-005

- Extrapolation to HL-LHC from full Run 2 combination of:
  - $BR_{SM}(HH \to bb\tau\tau) = 7.4\% \Rightarrow$ ~6900 events in 3000 fb^{-1}
  - $BR_{SM}(HH \to bb\gamma\gamma) = 0.26\% \Rightarrow$ ~240 events in 3000 fb^{-1}

Uncertainty scenario	Likelihood scan 1σ CI	Likelihood scan 2σ CI
No syst. unc.	$[0.6, 1.5]$	$[0.3, 2.1]$
Baseline	$[0.5, 1.6]$	$[0.0, 2.7]$
Theoretical unc. halved	$[0.2, 2.2]$	$[-0.4, 5.6]$
Run 2 syst. unc.	$[0.1, 2.5]$	$[-0.7, 5.7]$

Source	Scale factor	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$
Experimental Uncertainties			
Luminosity	0.6	*	*
b-jet tagging efficiency	0.5	*	*
c-jet tagging efficiency	0.5	*	*
Light-jet tagging efficiency	1.0	*	*
Jet energy scale and resolution, E_T^{miss}	1.0	*	*
κ_λ reweighting	0.0	*	*
Photon efficiency (ID, trigger, isolation efficiency)	0.8	*	
Photon energy scale and resolution	1.0	*	
Spurious signal	0.0	*	
Value of m_H	0.08	*	
τ_{had} efficiency (statistical)	0.0		*
τ_{had} efficiency (systematic)	1.0		*
τ_{had} energy scale	1.0		*
Fake-τ_{had} estimation	1.0		*
MC statistical uncertainties	0.0		*
Theoretical Uncertainties	0.5	*	*



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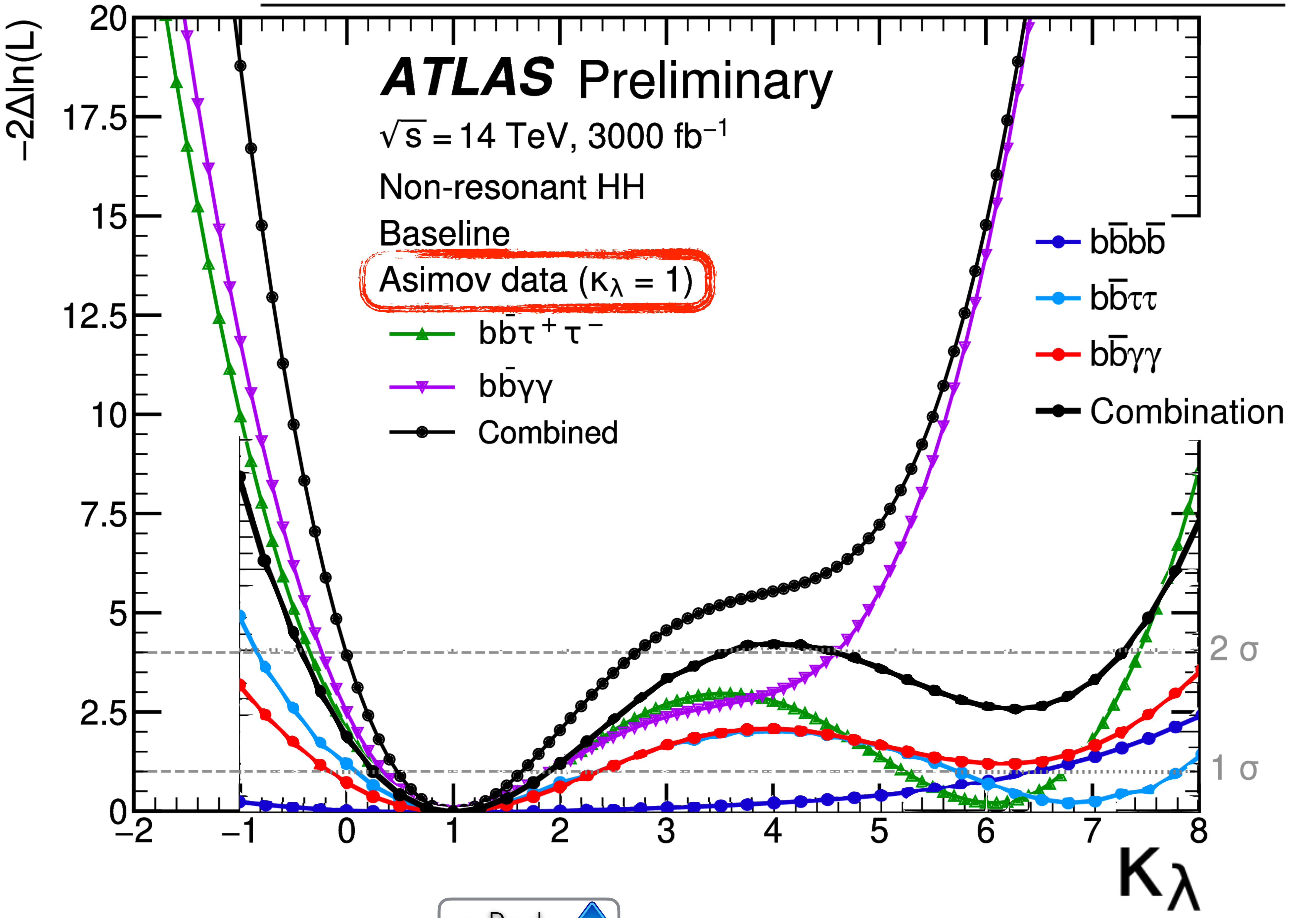
HH: Future fun

ATL-PHYS-PUB-2022-005

- Extrapolation to HL-LHC from full Run 2 combination of:
  - $BR_{SM}(HH \rightarrow bb\tau\tau) = 7.4\% \Rightarrow$ ~6900 events in 3000 fb^{-1}
  - $BR_{SM}(HH \rightarrow bb\gamma\gamma) = 0.26\% \Rightarrow$ ~240 events in 3000 fb^{-1}

Uncertainty scenario	Likelihood scan 1σ CI	Likelihood scan 2σ CI
No syst. unc.	$[0.6, 1.5]$	$[0.3, 2.1]$
Baseline	$[0.5, 1.6]$	$[0.0, 2.7]$
Theoretical unc. halved	$[0.2, 2.2]$	$[-0.4, 5.6]$
Run 2 syst. unc.	$[0.1, 2.5]$	$[-0.7, 5.7]$

Source	Scale factor	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$
Experimental Uncertainties			
Luminosity	0.6	*	*
b-jet tagging efficiency	0.5	*	*
c-jet tagging efficiency	0.5	*	*
Light-jet tagging efficiency	1.0	*	*
Jet energy scale and resolution, E_T^{miss}	1.0	*	*
κ_λ reweighting	0.0	*	*
Photon efficiency (ID, trigger, isolation efficiency)	0.8	*	
Photon energy scale and resolution	1.0	*	
Spurious signal	0.0	*	
Value of m_H	0.08	*	
τ_{had} efficiency (statistical)	0.0		*
τ_{had} efficiency (systematic)	1.0		*
τ_{had} energy scale	1.0		*
Fake-τ_{had} estimation	1.0		*
MC statistical uncertainties	0.0		*
Theoretical Uncertainties	0.5	*	*



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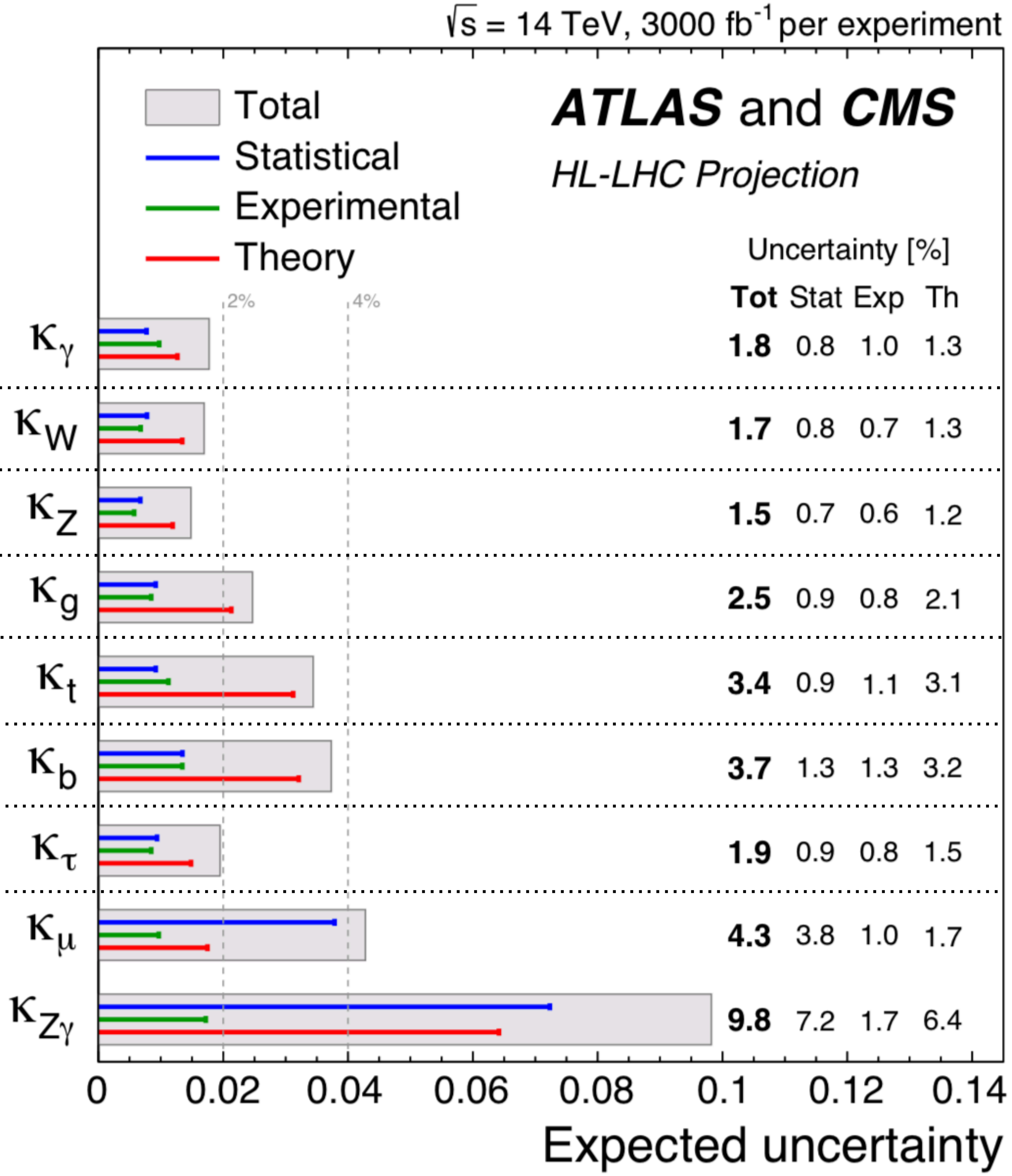
Higgs Couplings at HL-LHC

Higgs couplings strength with respective particles

	ATLAS - CMS Run 1 combination	Current precision
κ_γ	13%	6%
κ_W	11%	6%
κ_Z	11%	6%
κ_g	14%	7%
κ_t	30%	11%
κ_b	26%	11%
κ_τ	15%	8%
	JHEP 08 (2016) 045	ATLAS-CONF-2021-53 CMS-PAS-HIG-19-005



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

Measurements here assume no BSM in Higgs width

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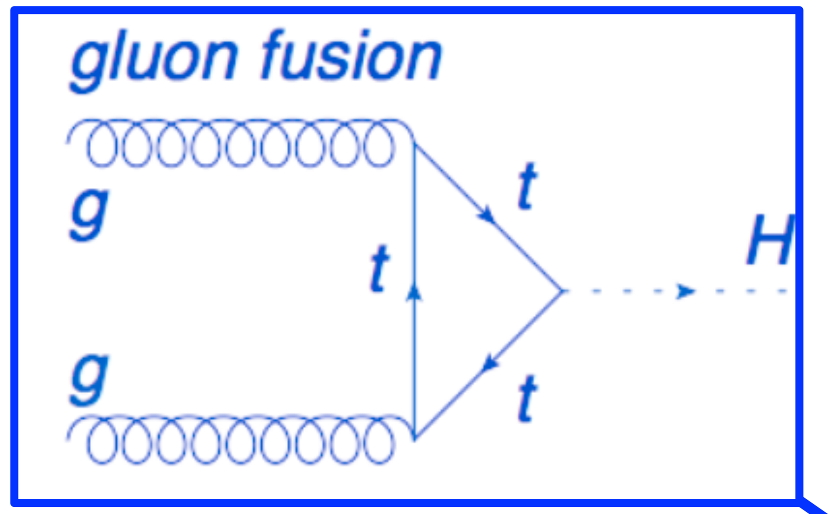
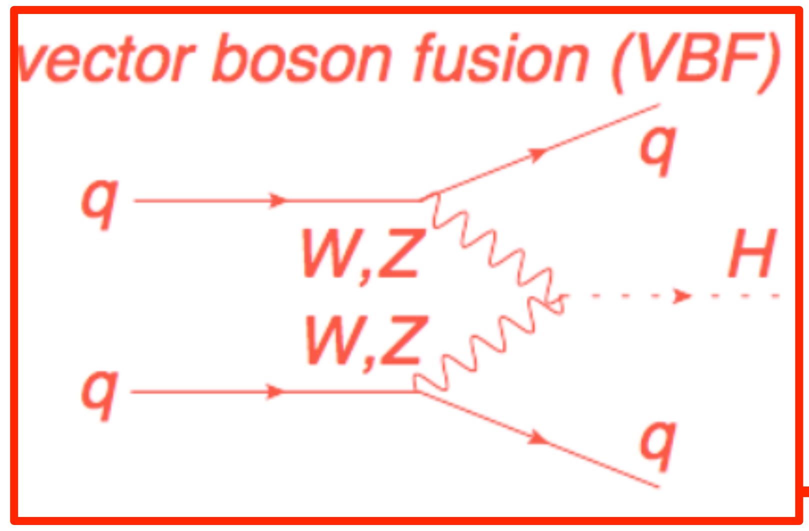
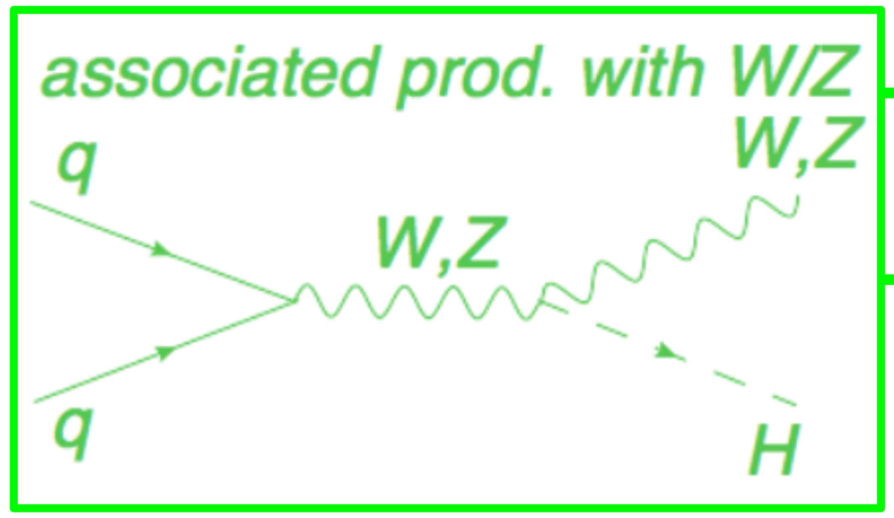
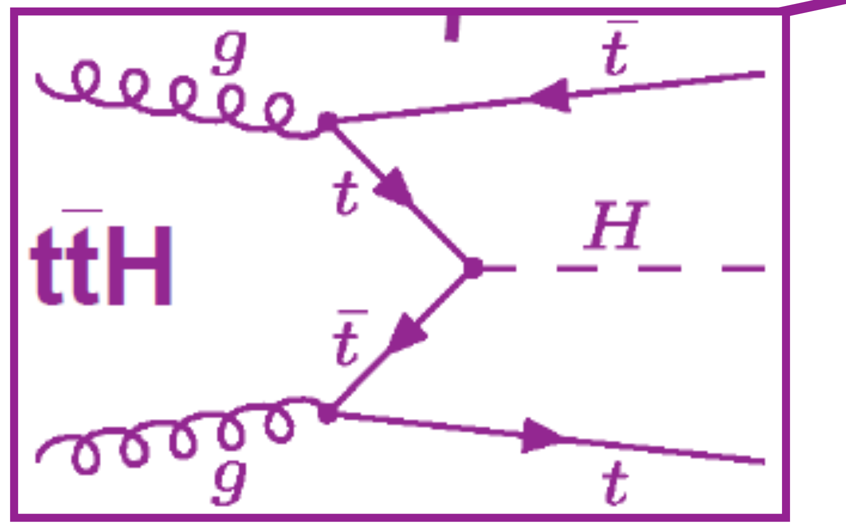
Production Modes

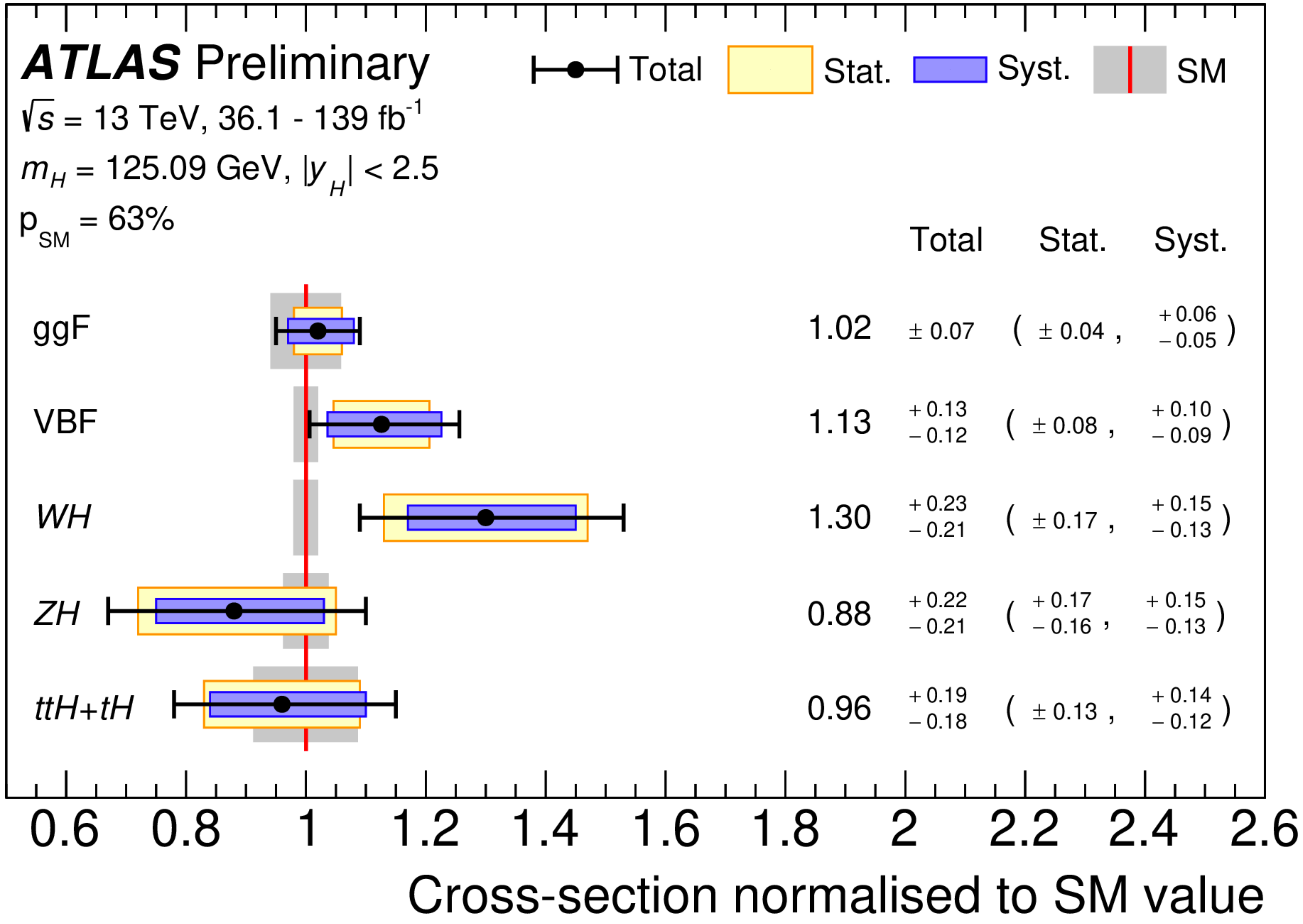
Main production modes observed (assume SM branching ratios)











Global $\mu = 1.06 \pm 0.06 = 1.06 \pm 0.03\,(\text{stat.}) \pm 0.03\,(\text{exp.}) \pm 0.04\,(\text{sig. th.}) \pm 0.02\,(\text{bkg. th.})$

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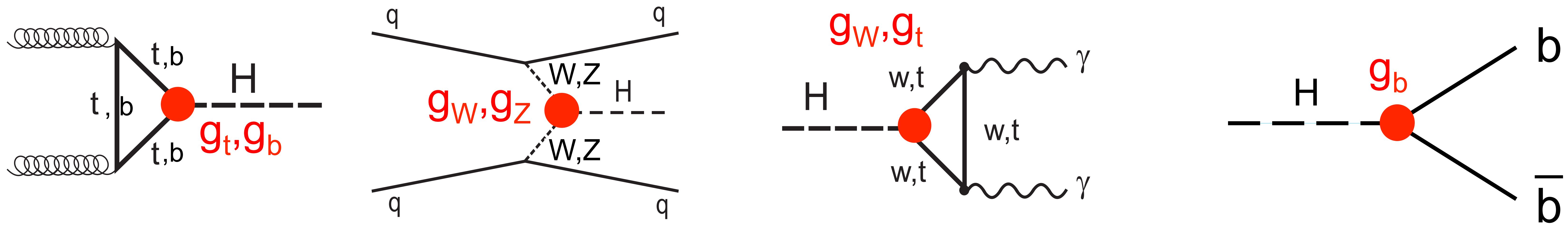
The κ Framework

- 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:



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

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

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

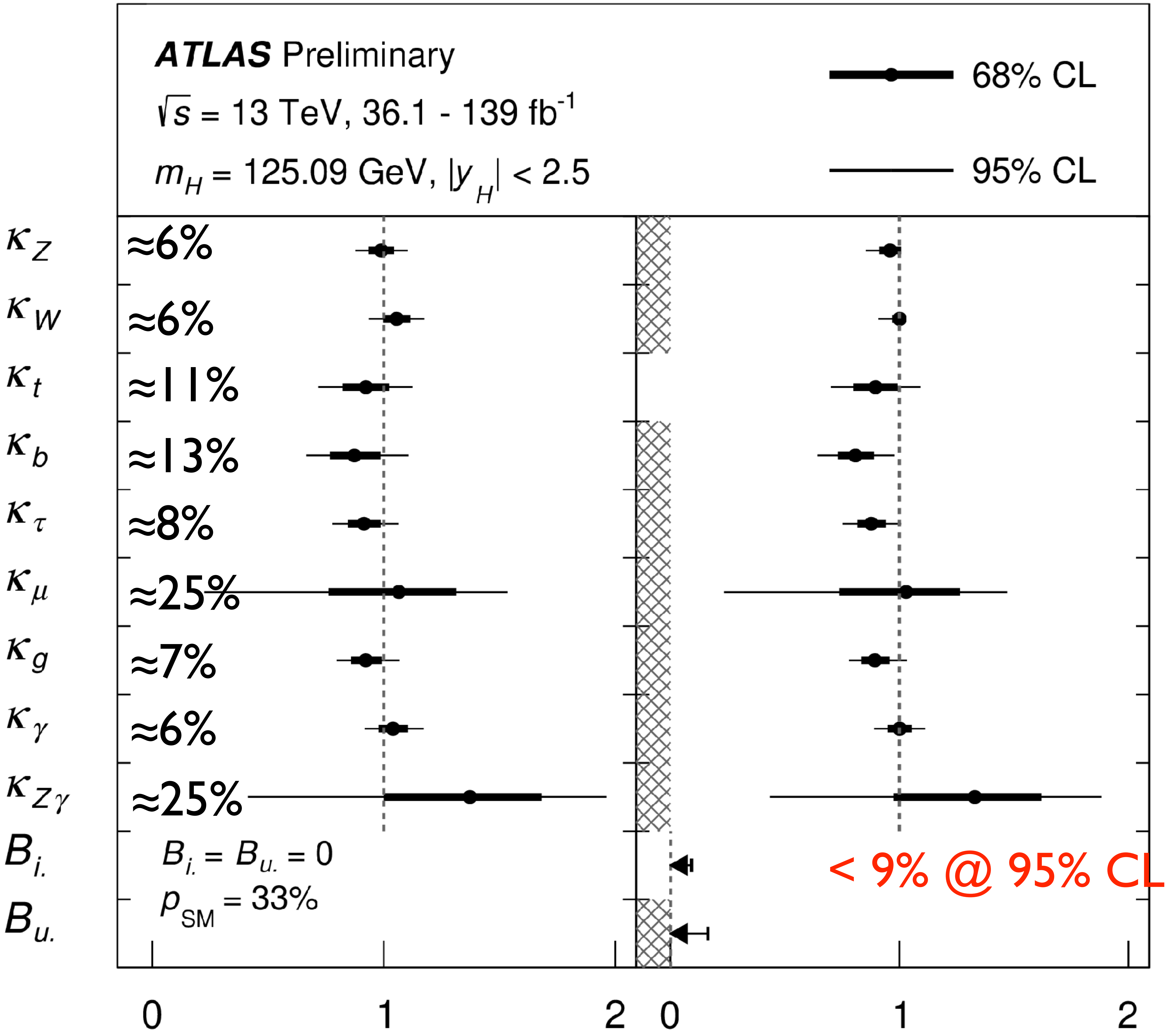
Assumption:

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



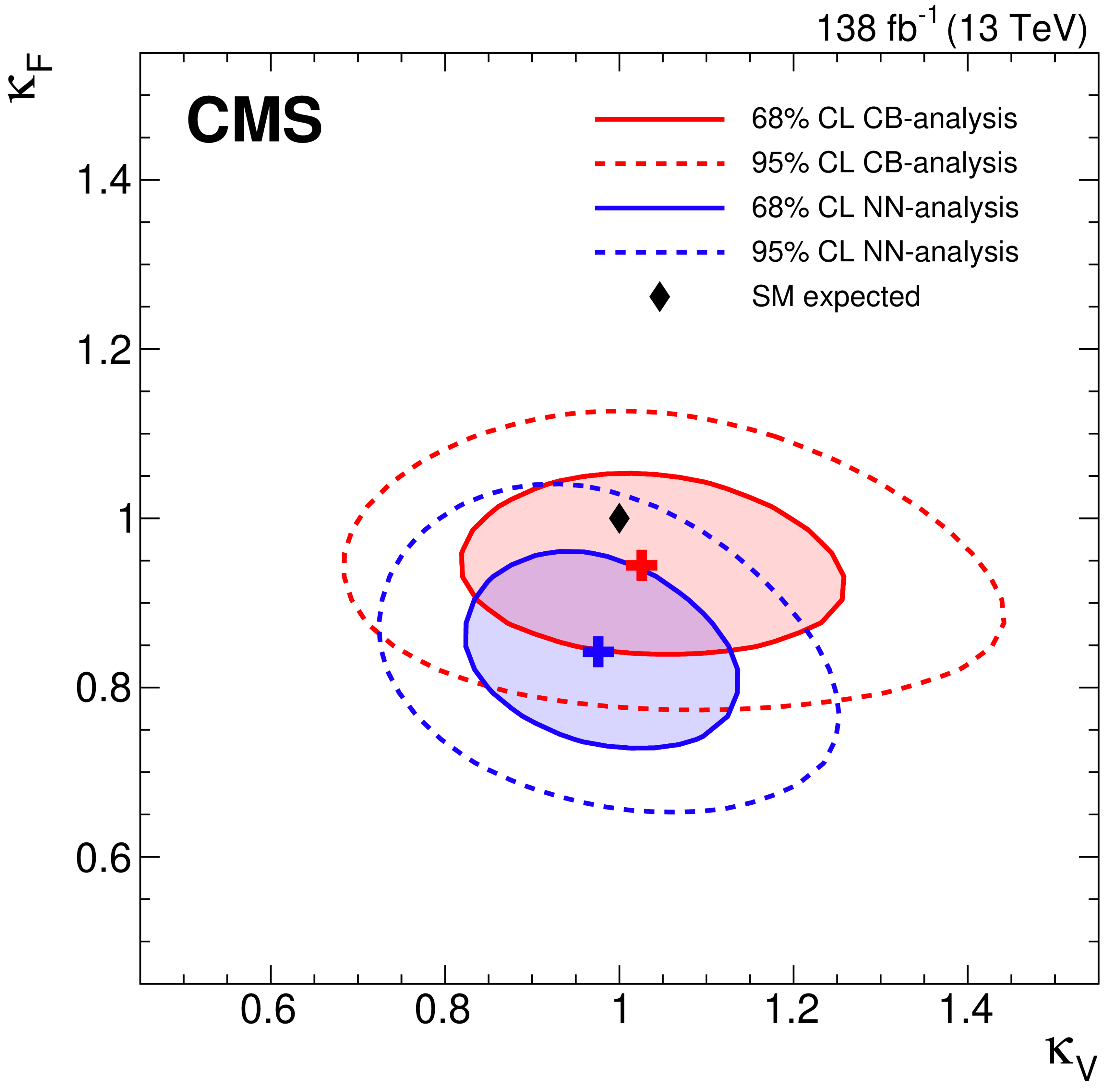
< 9% @ 95% CL (< 11% expected)

Assume:
B_{inv} and B_{undet} are free parameters.
Constrain $\kappa_W \leq 1$ and $\kappa_Z \leq 1$

Add:
VBF H → invisible

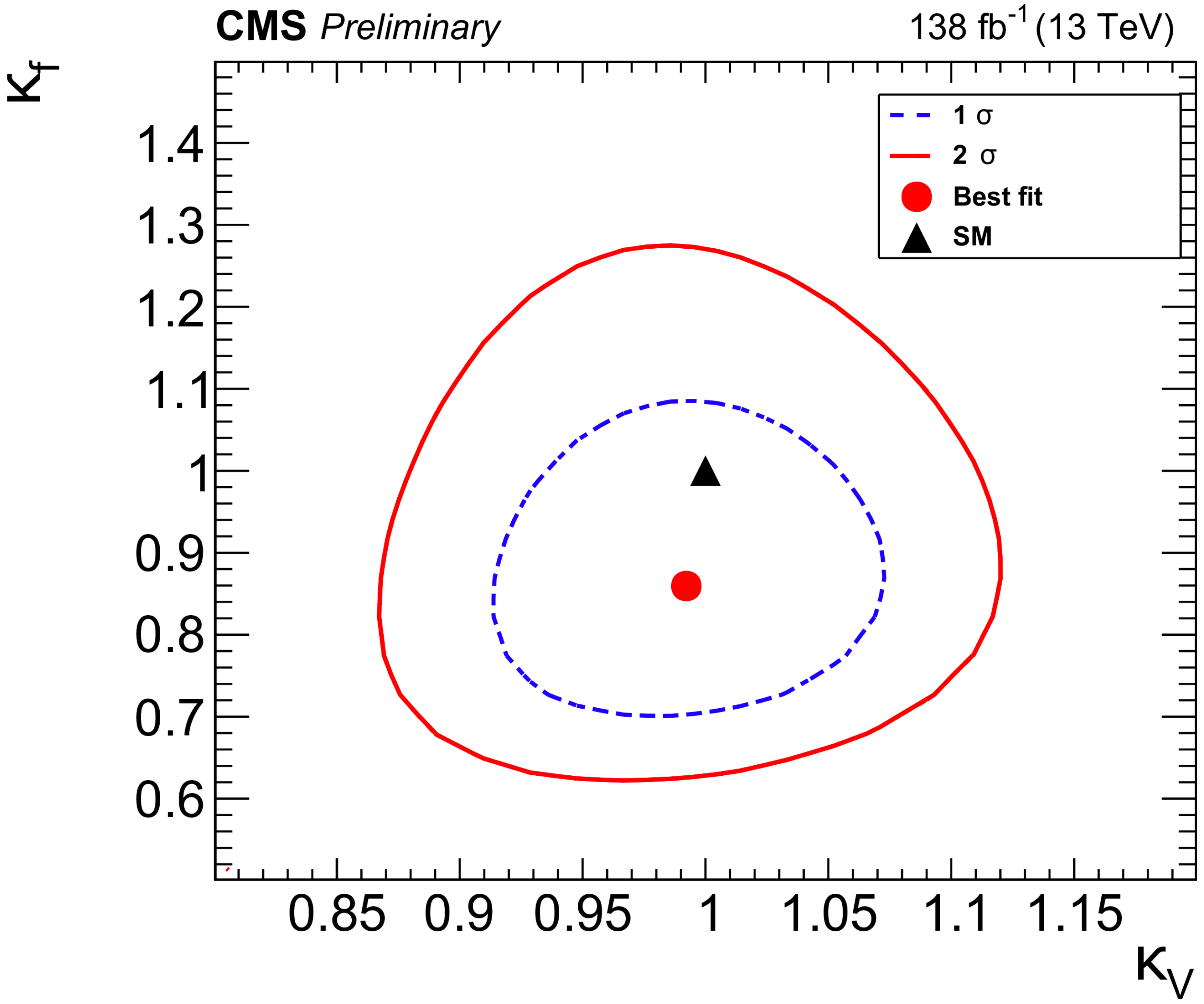
κ Coupling Modifiers: Fermions *vs.* Vector Bosons

CMS $H \to \tau\tau$



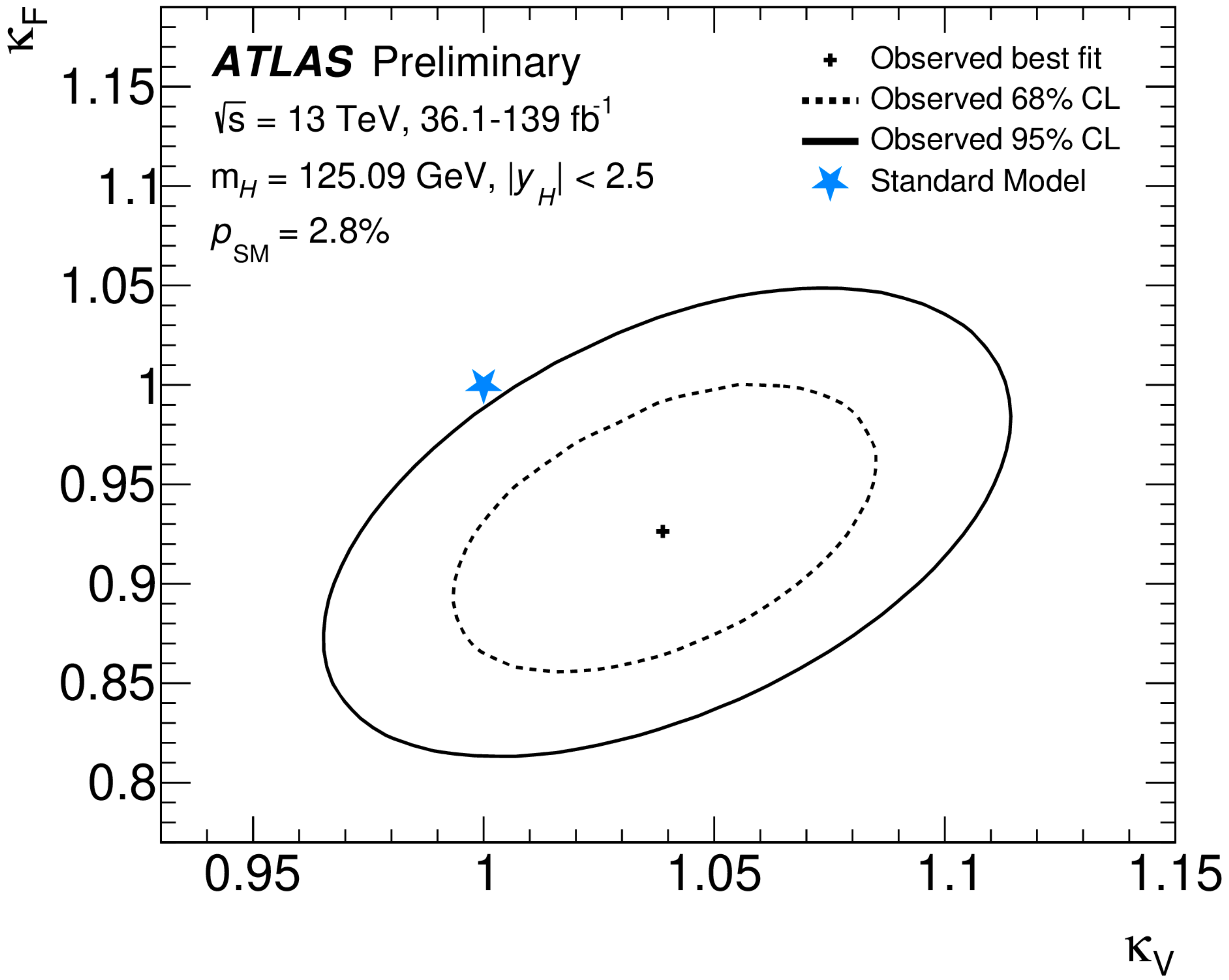
[arXiv:2204.12957 (submitted to Eur. Phys. J. C)]

CMS $H \to WW^* \to \ell\nu\ell\nu$



[CMS-PAS-HIG-20-013]

ATLAS Combination



[ATLAS-CONF-2021-053]

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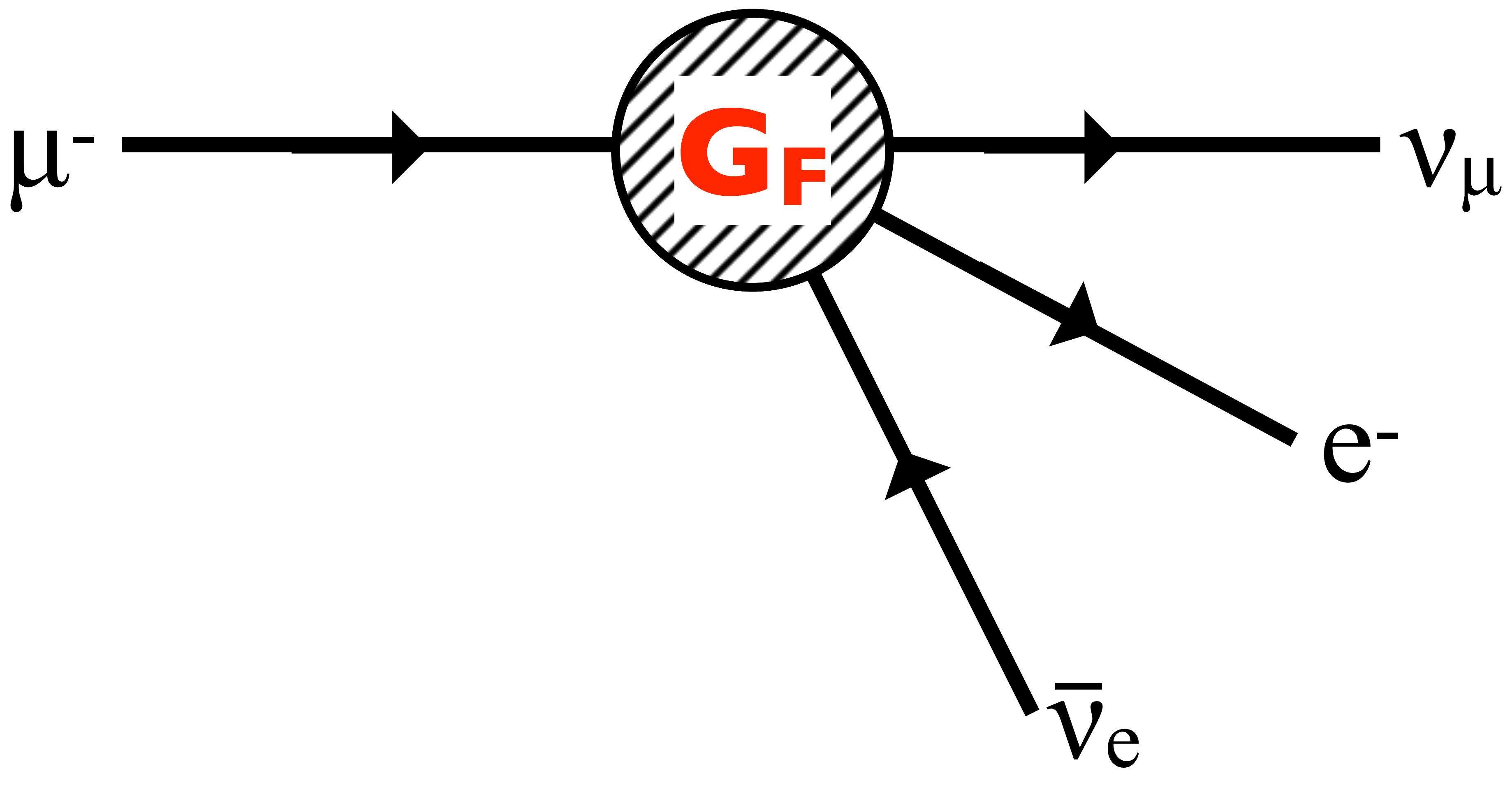
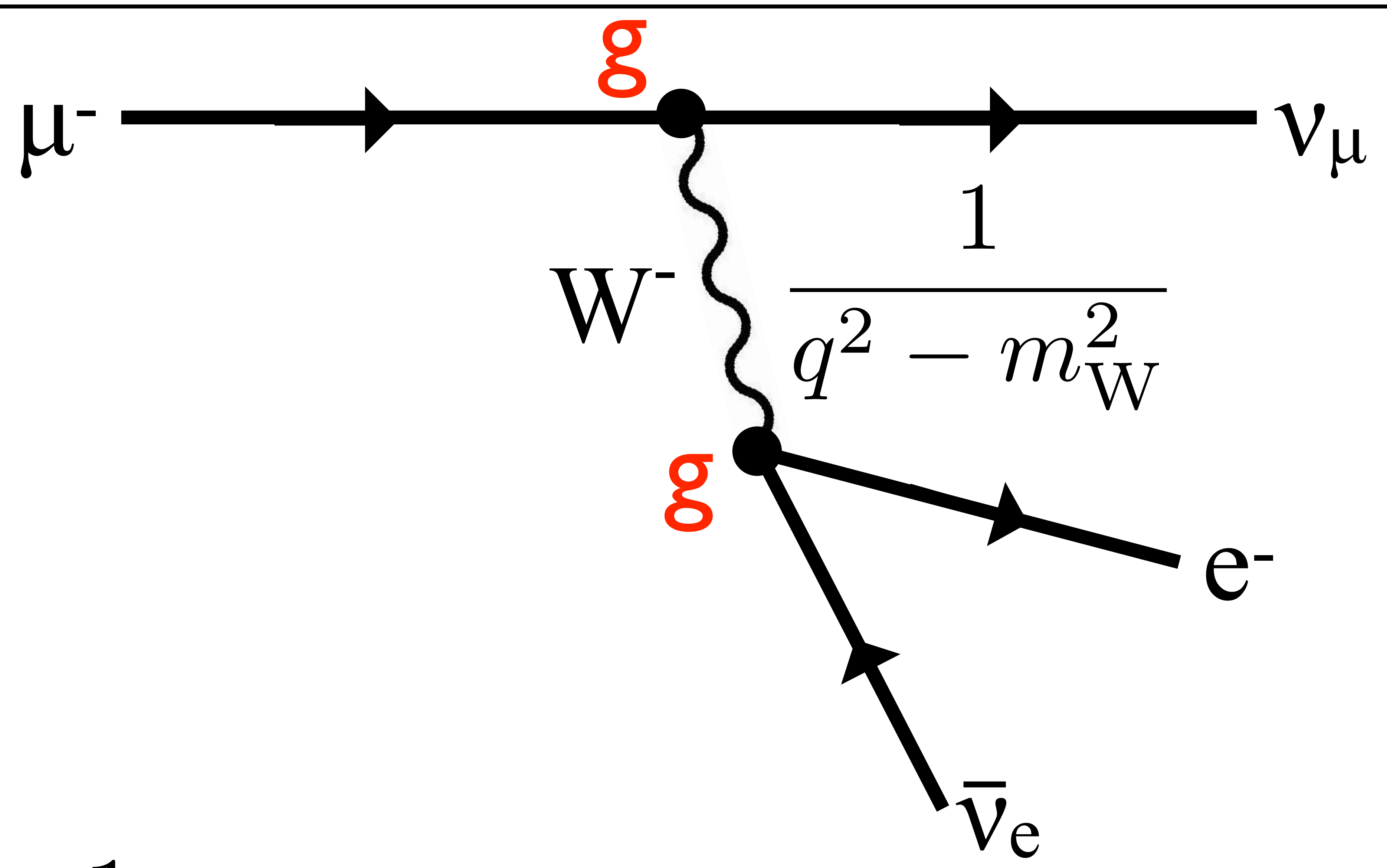
Effective Field Theories: Muon Decay

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: $\mathcal{L} = \mathcal{L}_{SM} + \sum_i c_i^{(6)} O_i^{(6)} / \Lambda^2$
  - Assume: No new particles below Λ = 1 TeV

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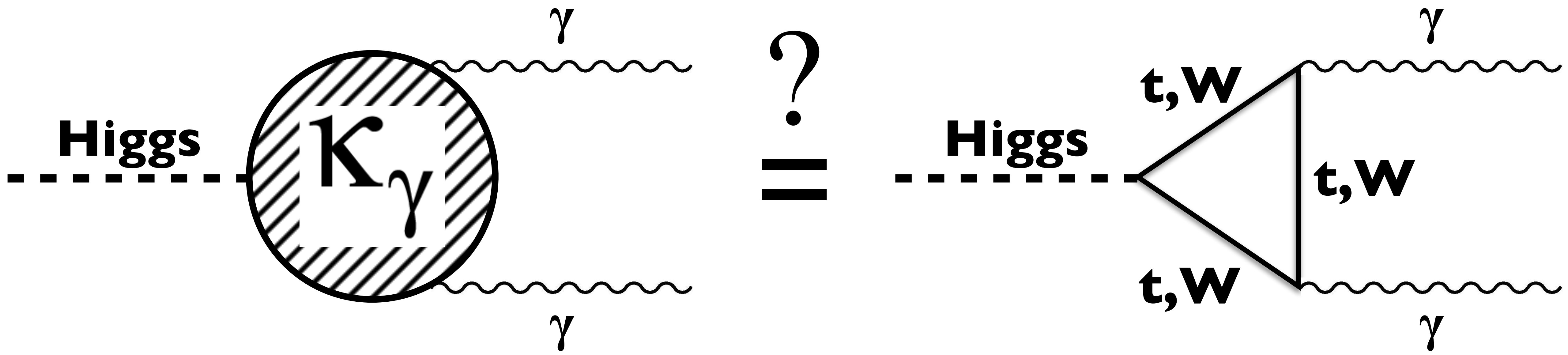
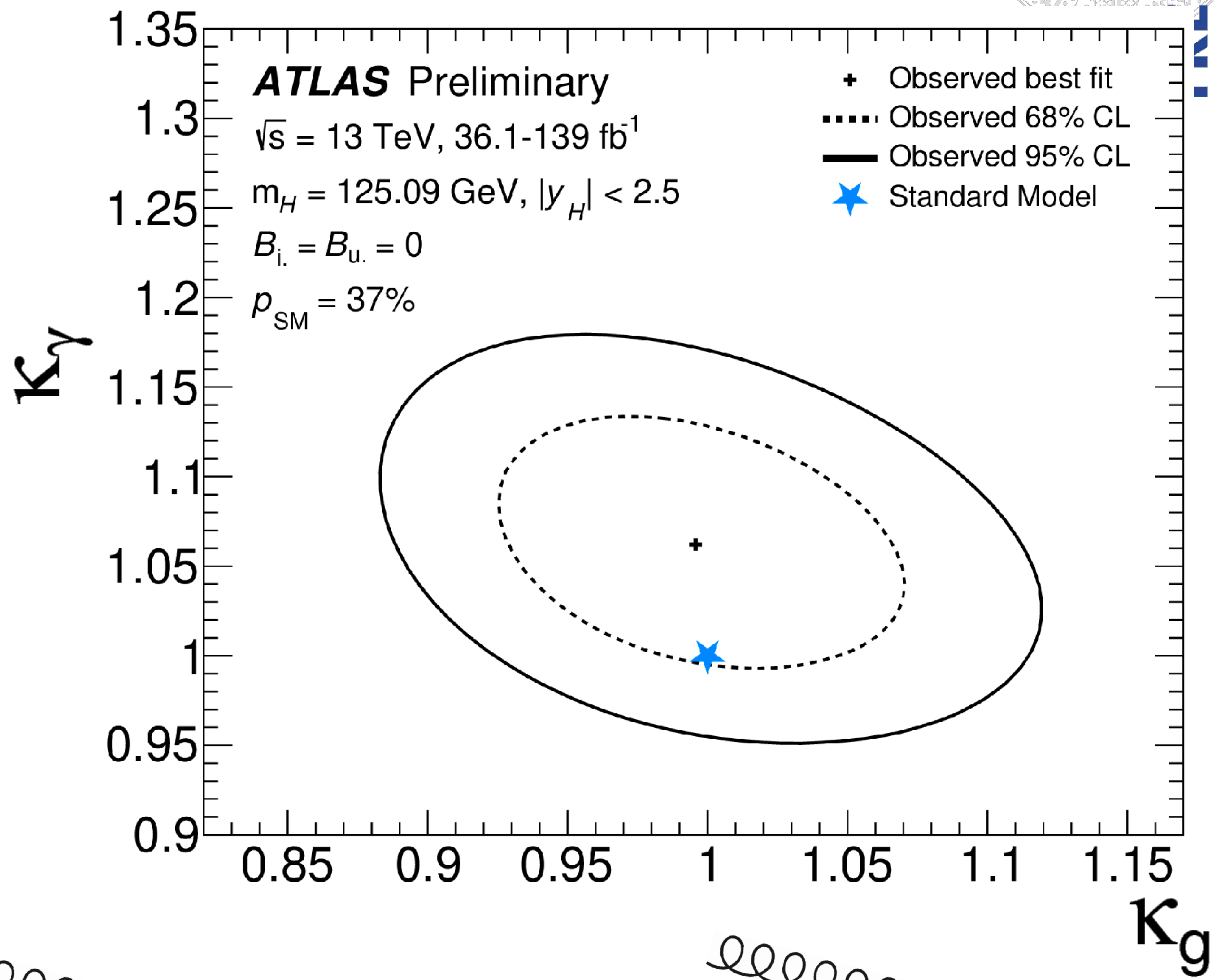
Loop-induced Couplings

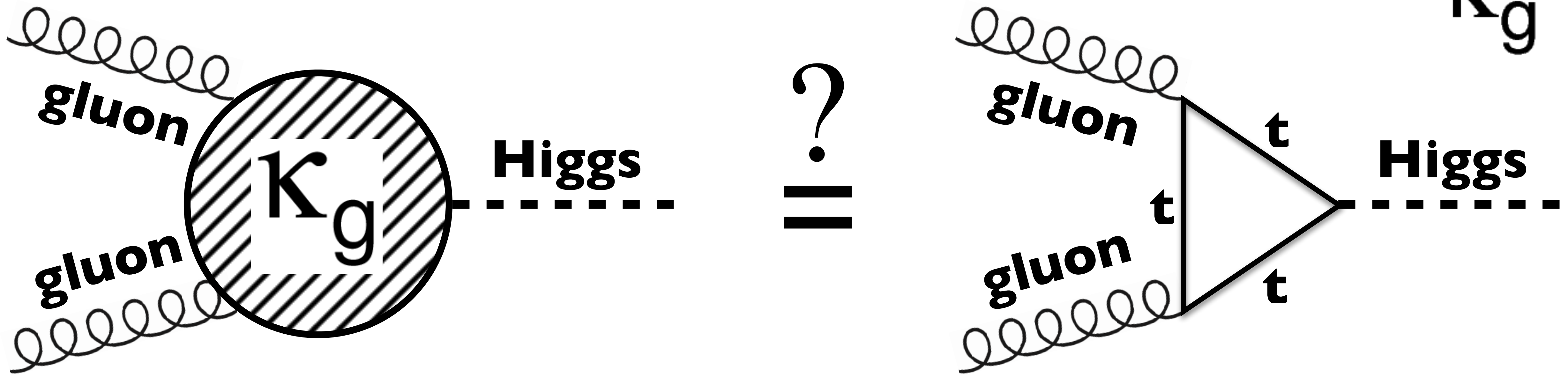
- SM: ggF and H → γγ are loop-induced
  - New particles could participate in the loop

⇒ Contributions of BSM?

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







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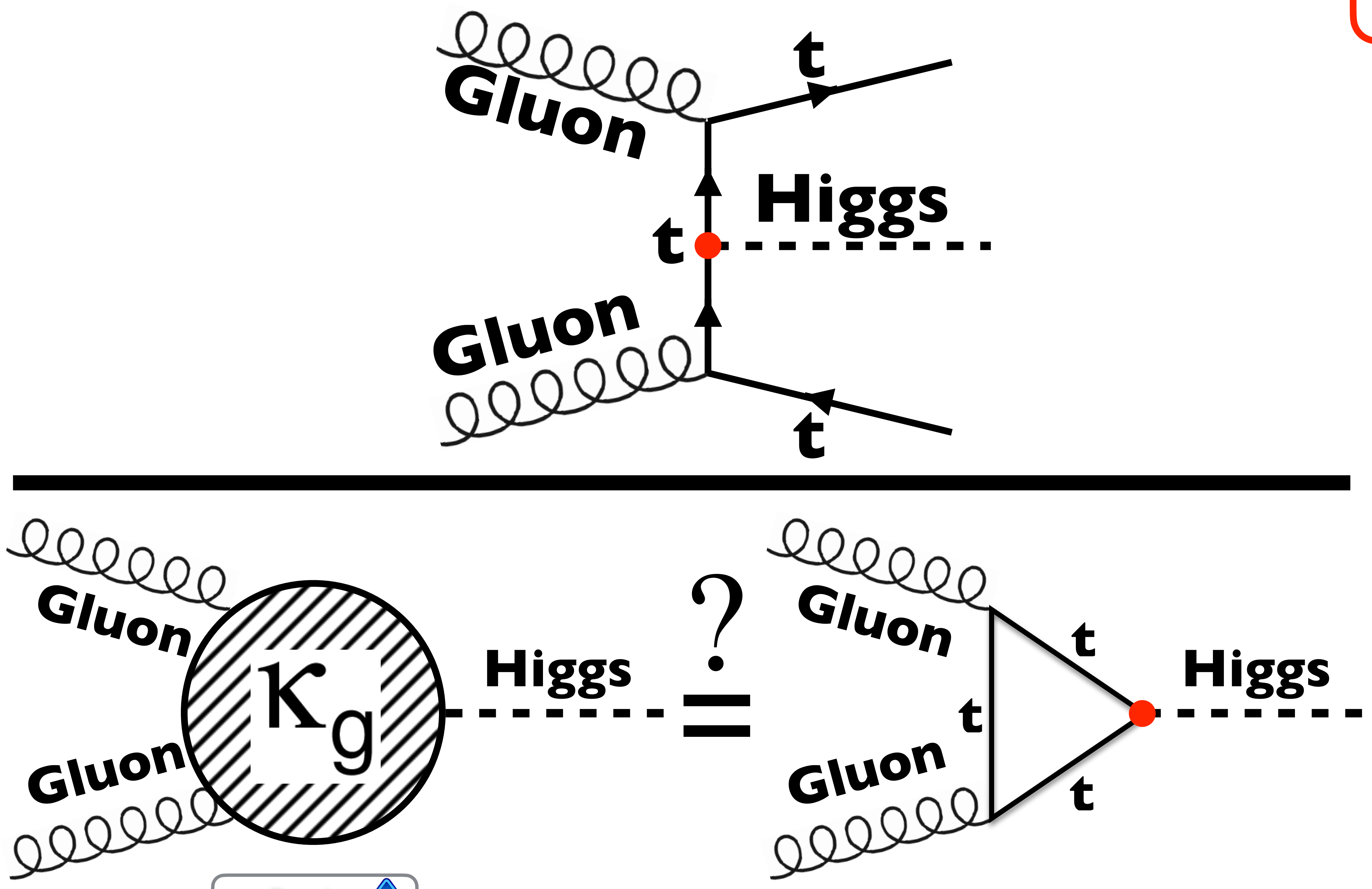
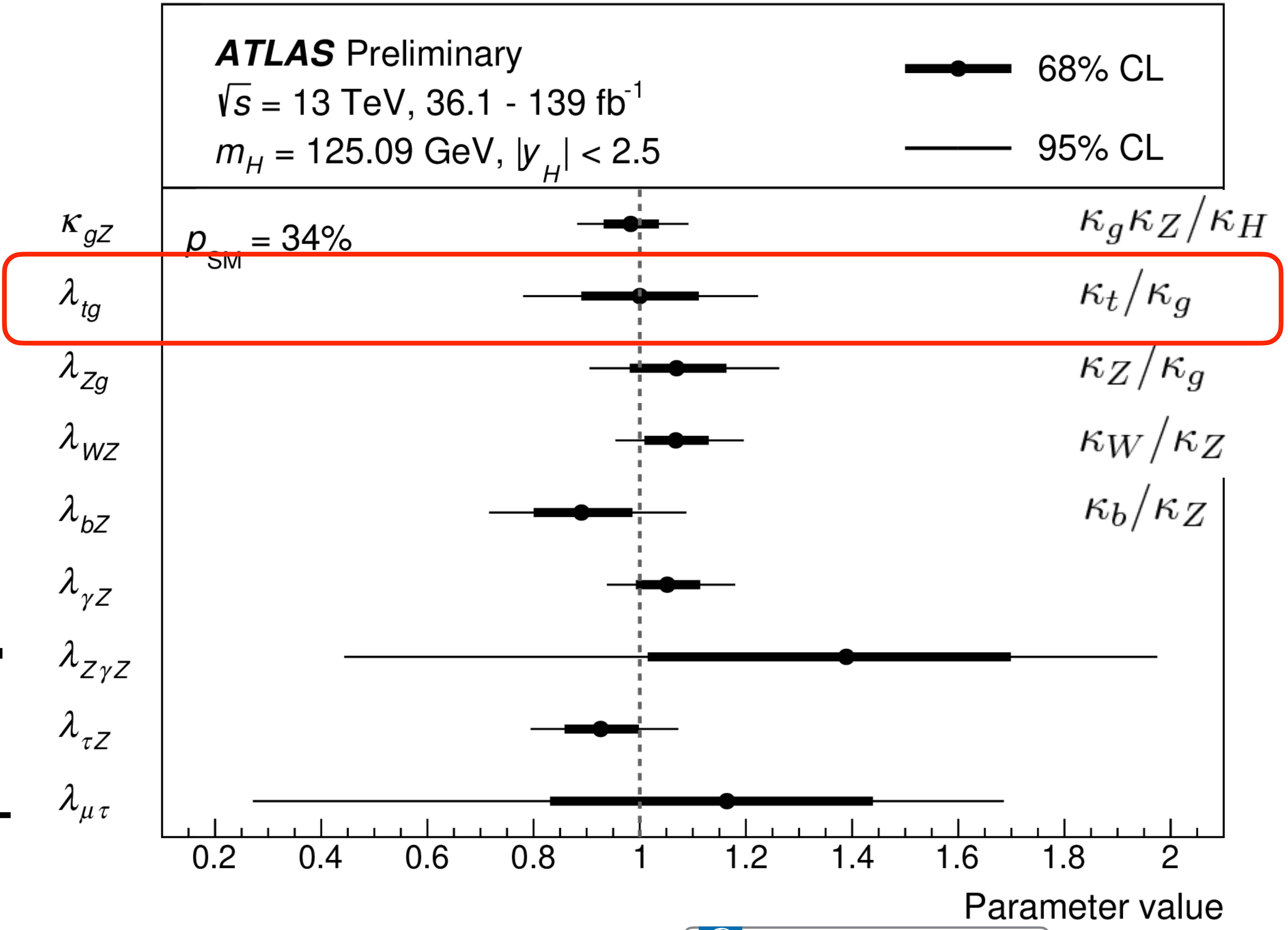
Ratio of Coupling Modifiers

- 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)





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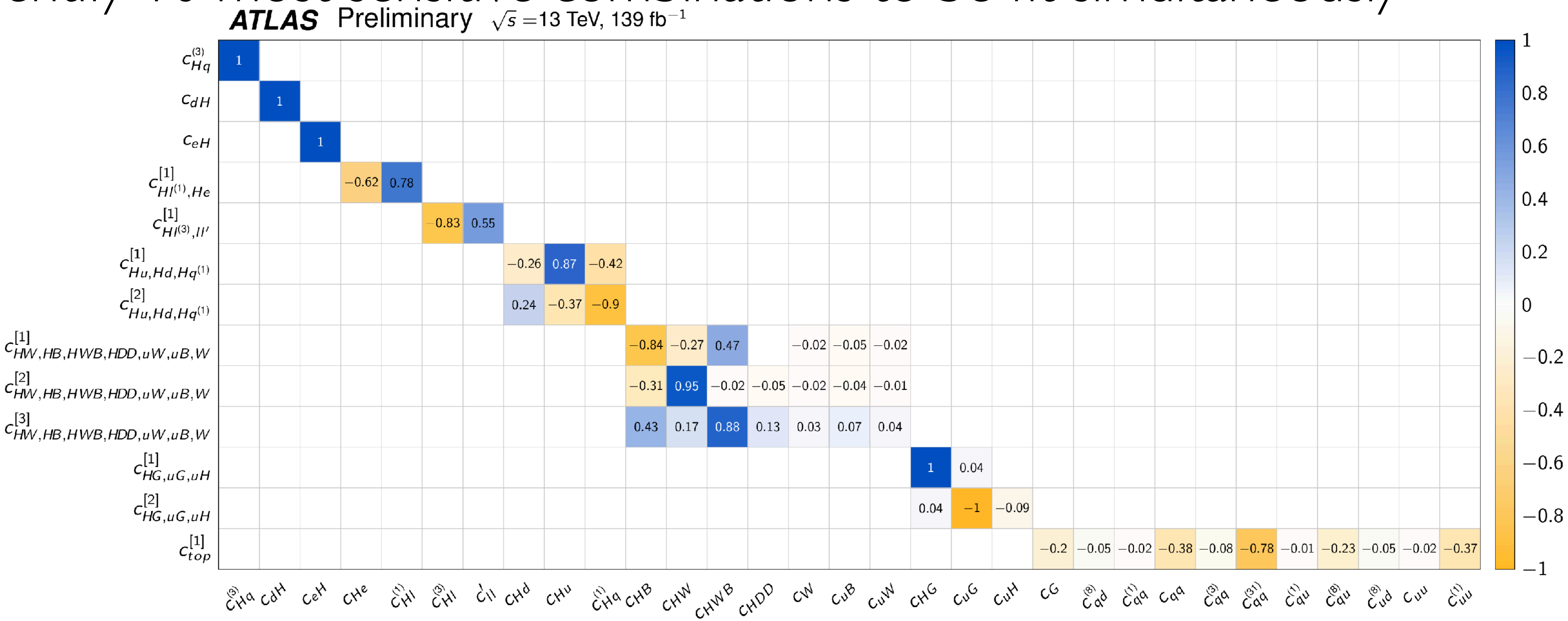
Reducing the Complexity

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

$\Rightarrow$ Identify 10 most sensitive combinations to be fit simultaneously

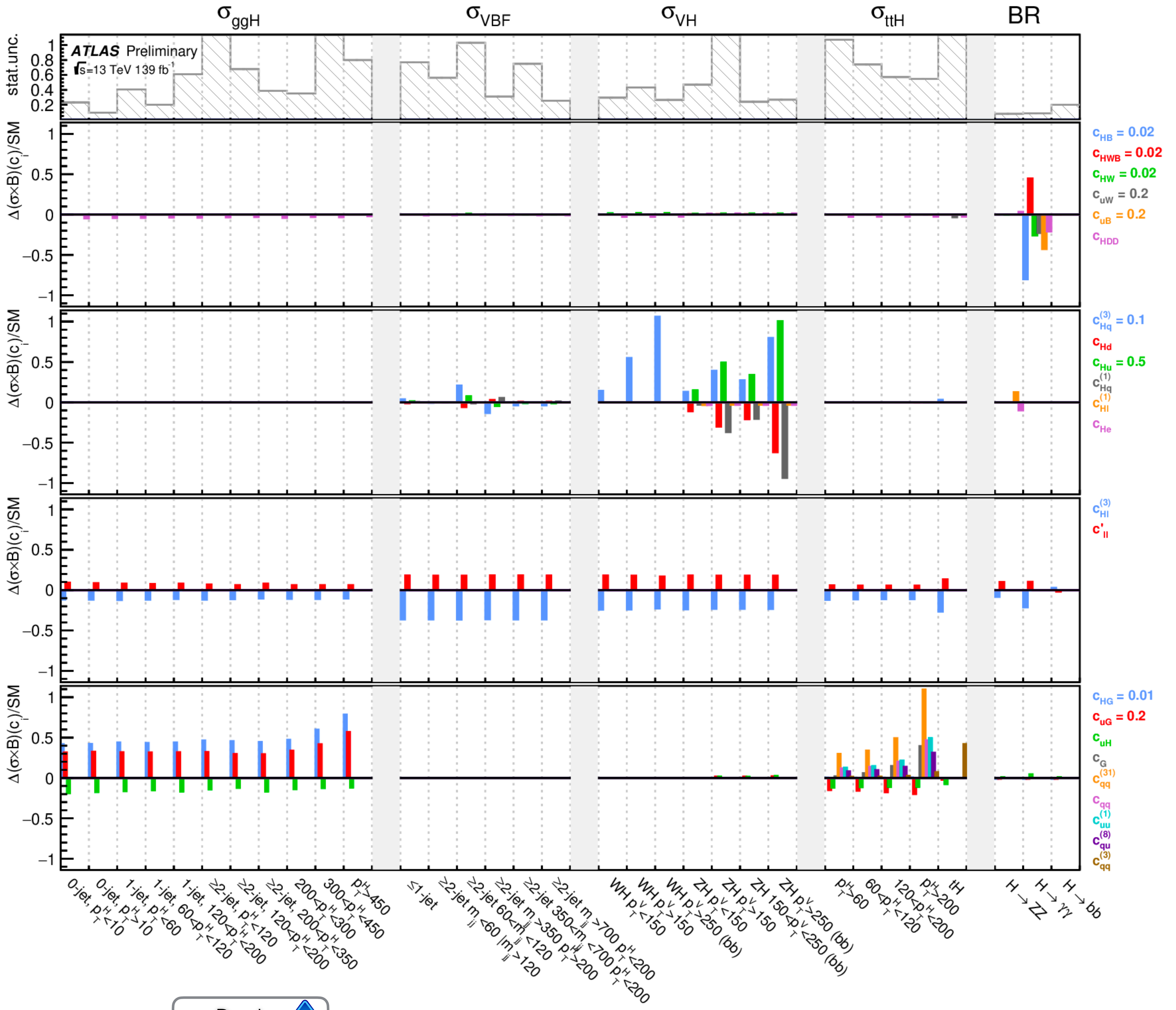


Rotated fit basis

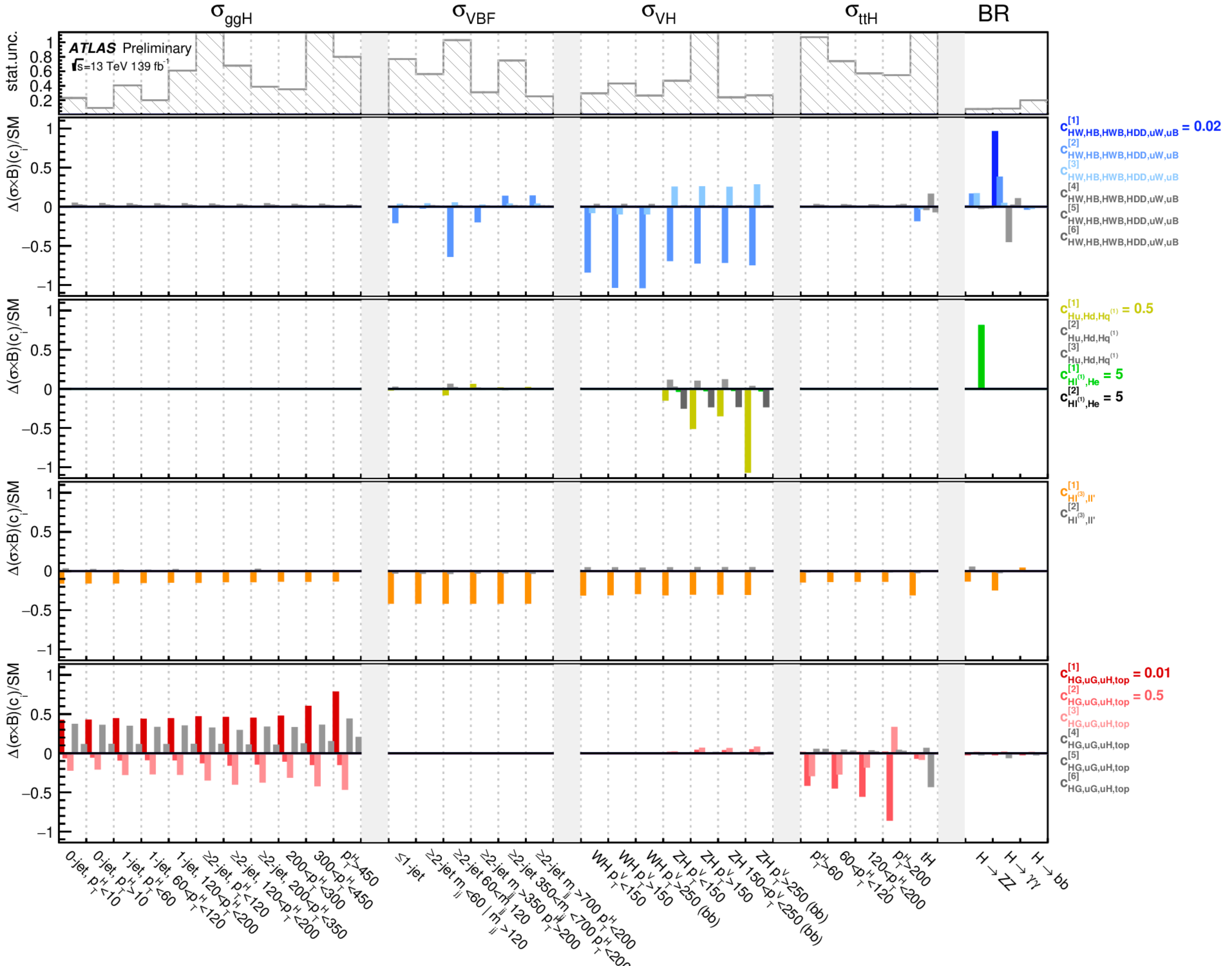
Warsaw basis

EFT impact on Measurements

Warsaw basis



Rotated fit basis



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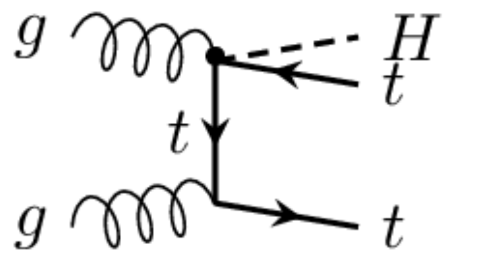
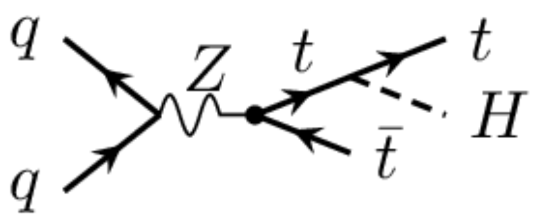
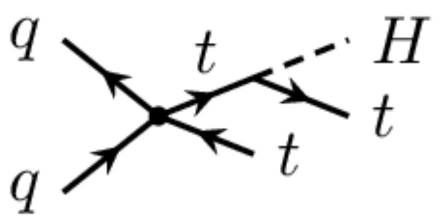
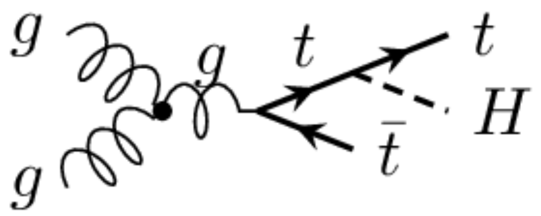
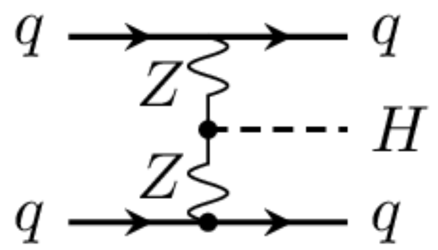
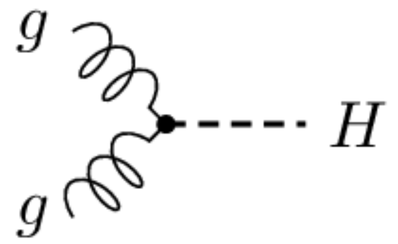
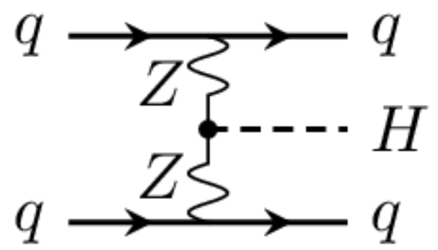
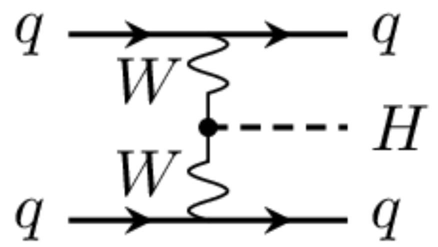
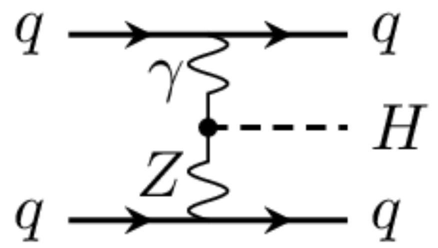
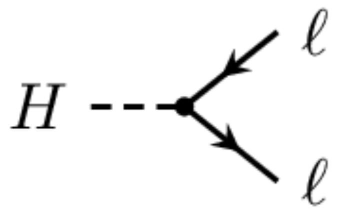
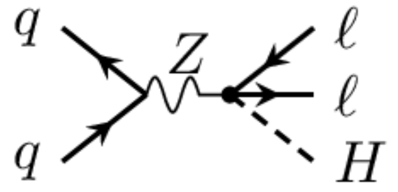
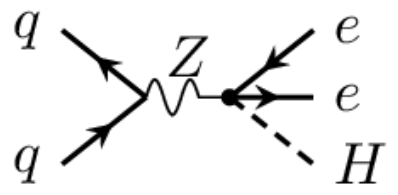
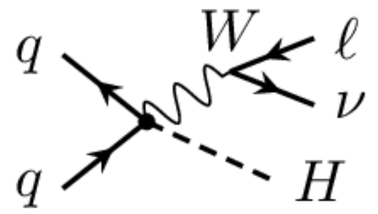
SMEFT

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}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$	

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!

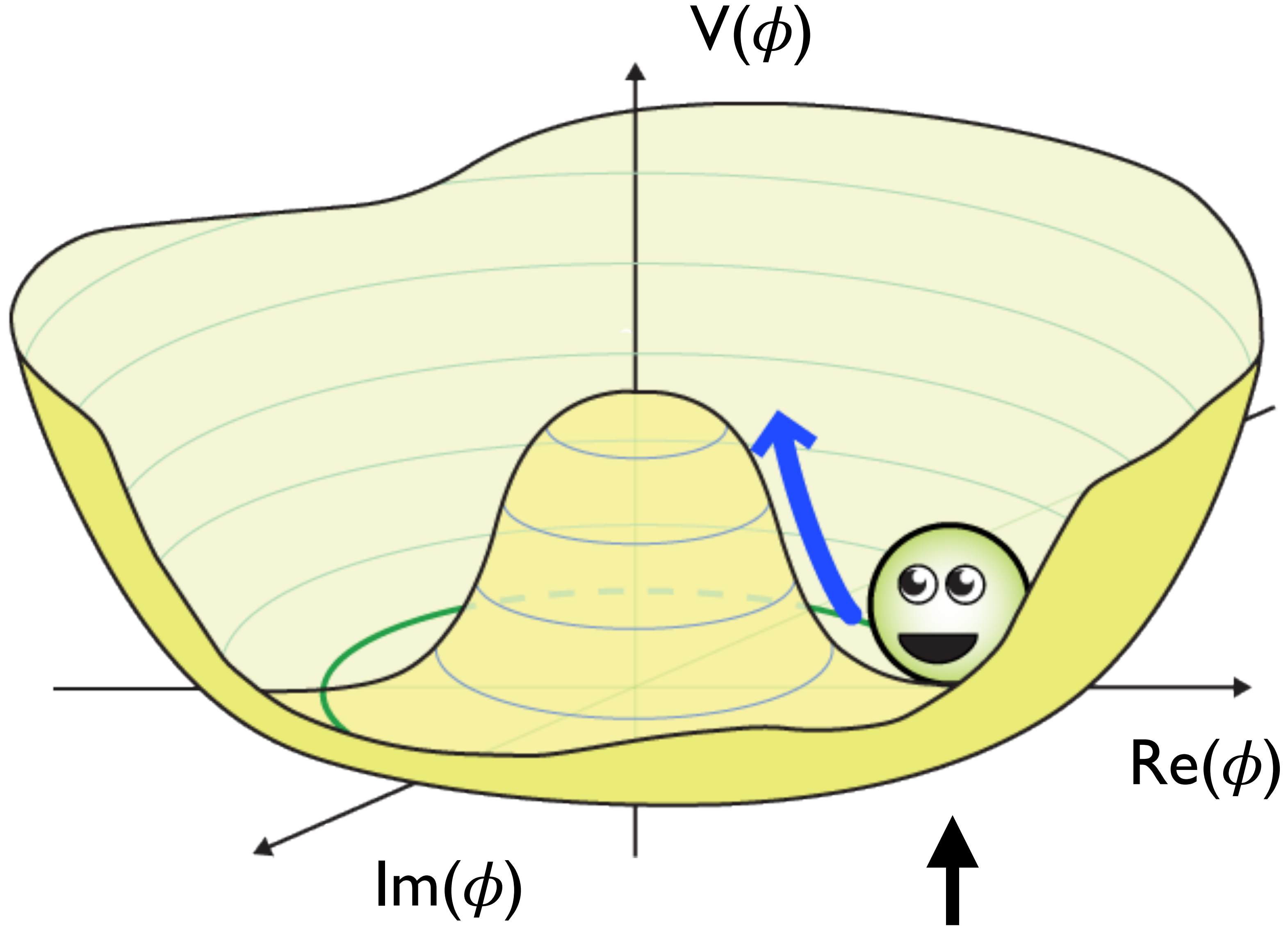
- **Solution:**
  (developed in 1960s by Brout, Englert, Higgs, and others)
  - Introduce complex scalar field $\boldsymbol{\phi}(\boldsymbol{x})$ with potential:

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

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

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

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



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

Lagrangian after electroweak Symmetry Breaking

- Resulting Higgs-boson Lagrangian:

Expand $\phi(x)$ around vacuum:

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

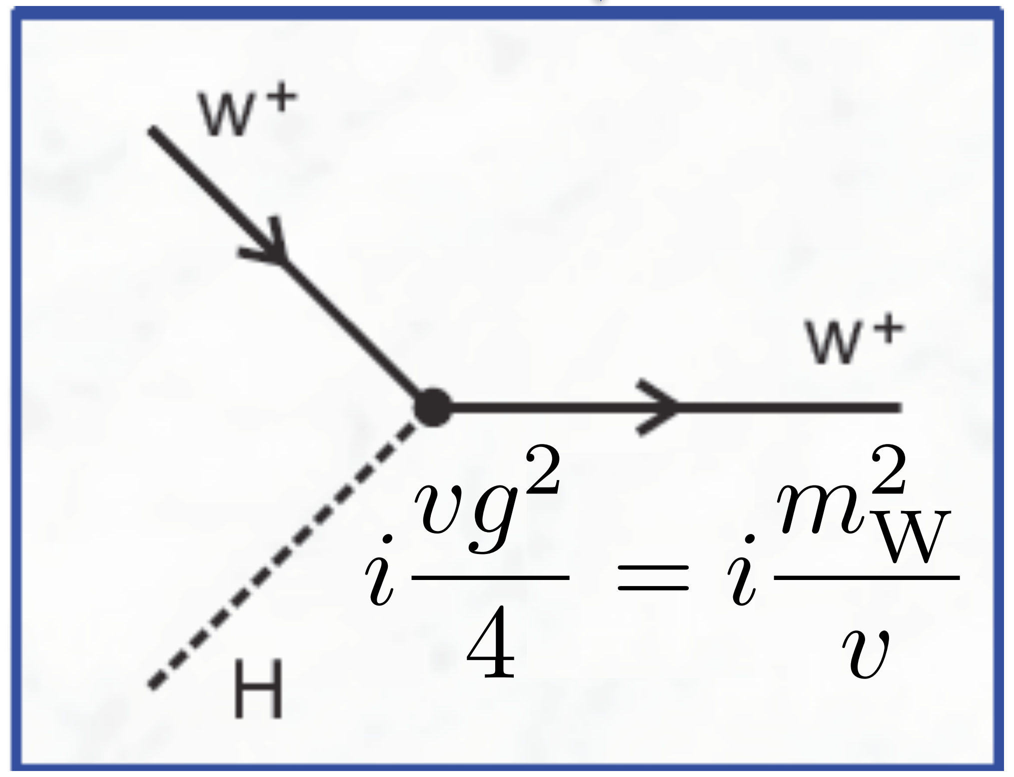
$$\mathcal{L}_H \ni \phi^2 \left(\frac{g^2}{4} W_\mu^\dagger W^\mu \right) - \mu^2 \phi^2 - \lambda \phi^4$$

$$\mathcal{L}_H \ni \frac{1}{2} (v + H)^2 \left(\frac{g^2}{4} W_\mu^\dagger W^\mu \right) - \frac{1}{2} \mu^2 (v + H)^2 - \frac{1}{4} \lambda (v + H)^4$$

$$\mathcal{L}_H \ni \frac{v^2 g^2}{8} W_\mu^\dagger W^\mu + \frac{v g^2}{4} H W_\mu^\dagger W^\mu + \frac{g^2}{8} H^2 W_\mu^\dagger W^\mu - \lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4} H^4$$

$\Downarrow$

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



$\Downarrow$

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

not predicted!

H self interactions

Fermion Masses

- Also Fermion masses violate fundamental invariance under gauge transformations
- Fermion mass via *Yukawa coupling* λ_f:

Fermion

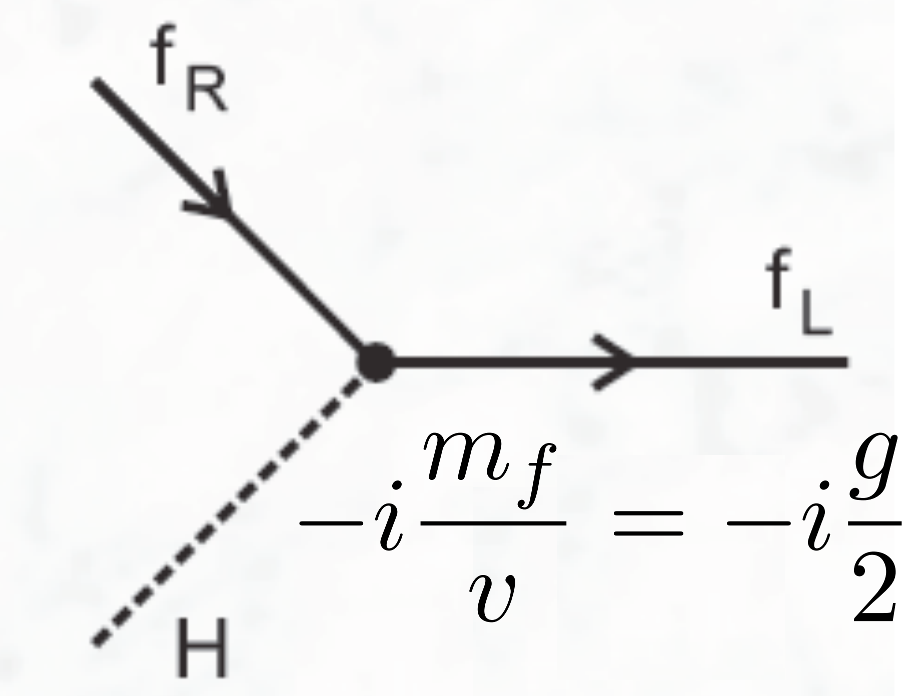
$$\mathcal{L}_{\text{fermion}} = -\lambda_f \left[\bar{\psi}_L \phi \psi_R + \bar{\psi}_R \phi \psi_L \right]$$

Higgs field

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

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

$$= -\frac{\lambda_f v}{\sqrt{2}} \bar{\psi}\psi \quad \boxed{-\frac{\lambda_f}{\sqrt{2}} H \bar{\psi}\psi}$$



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

Fermion mass

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

Fundamentally independent from masse generation for gauge bosons!

HH: Twice the Higgs, twice the fun

- Probing the Higgs potential via HHH coupling:

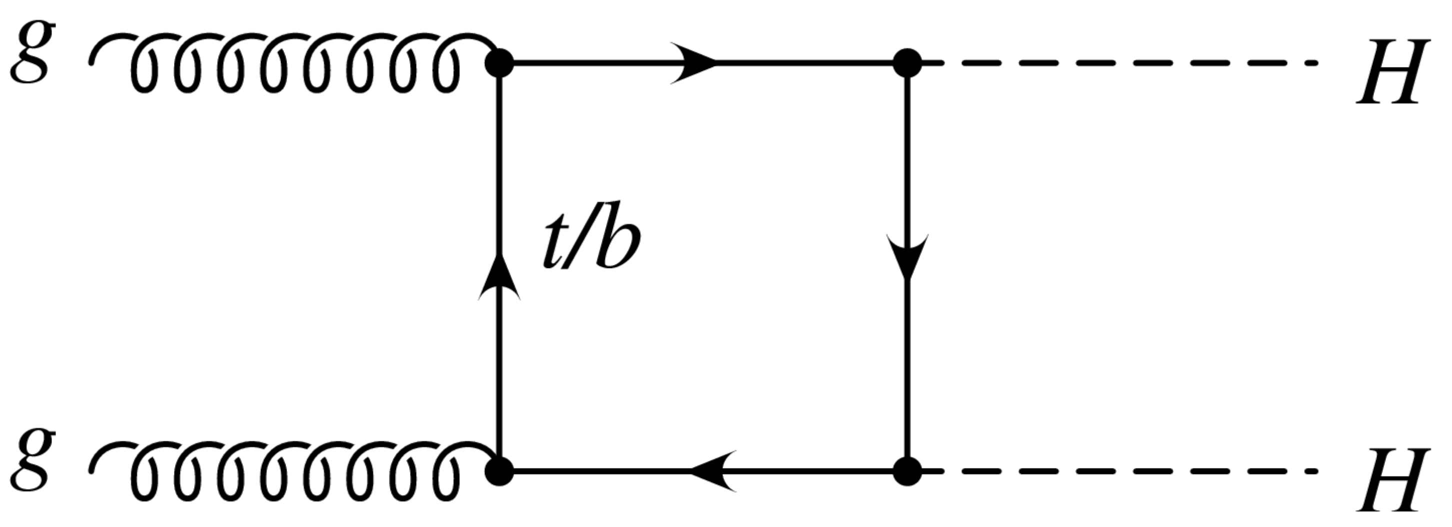
$$\mathcal{L}_H \ni -\mu^2\phi^2 - \lambda\phi^4$$

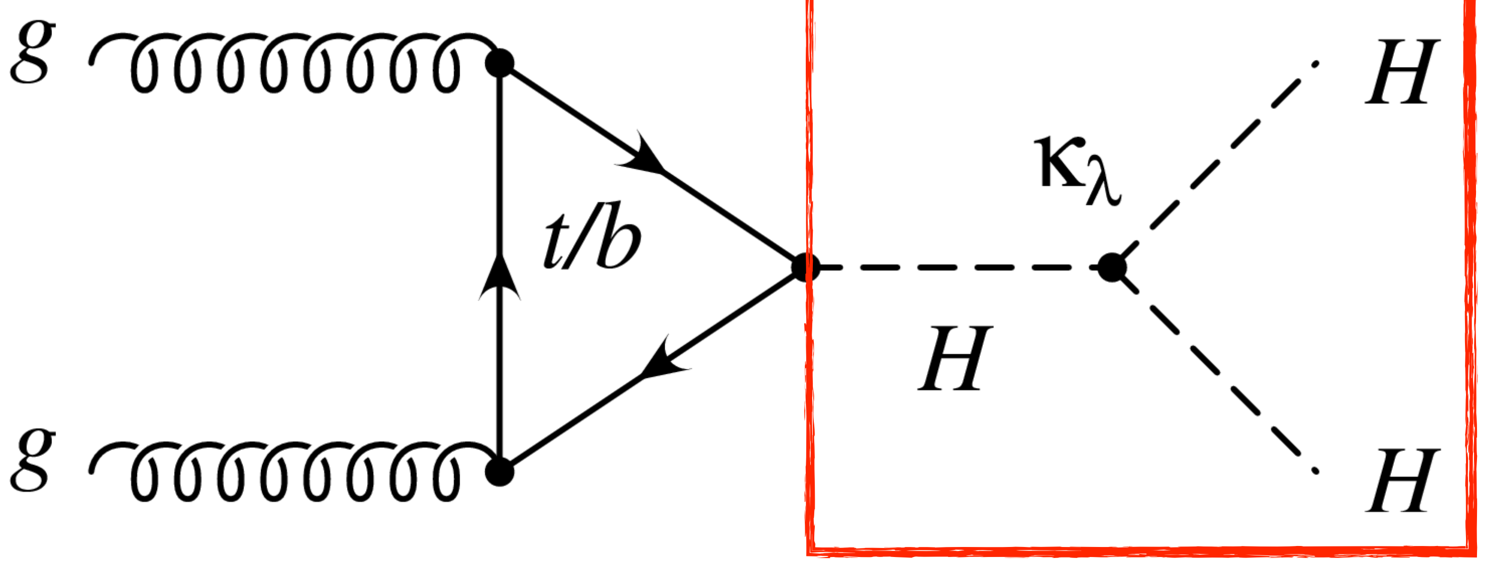
Expand $\phi(x)$ around vacuum:

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

$$\mathcal{L}_H \ni -\lambda v^2 H^2 \boxed{-\lambda v H^3 - \frac{\lambda}{4} H^4}$$

H self interactions





Destructive interference!

- Gluon fusion: **σ = 31.05 fb ⇒ ~4300 events in 139 fb^{-1}**