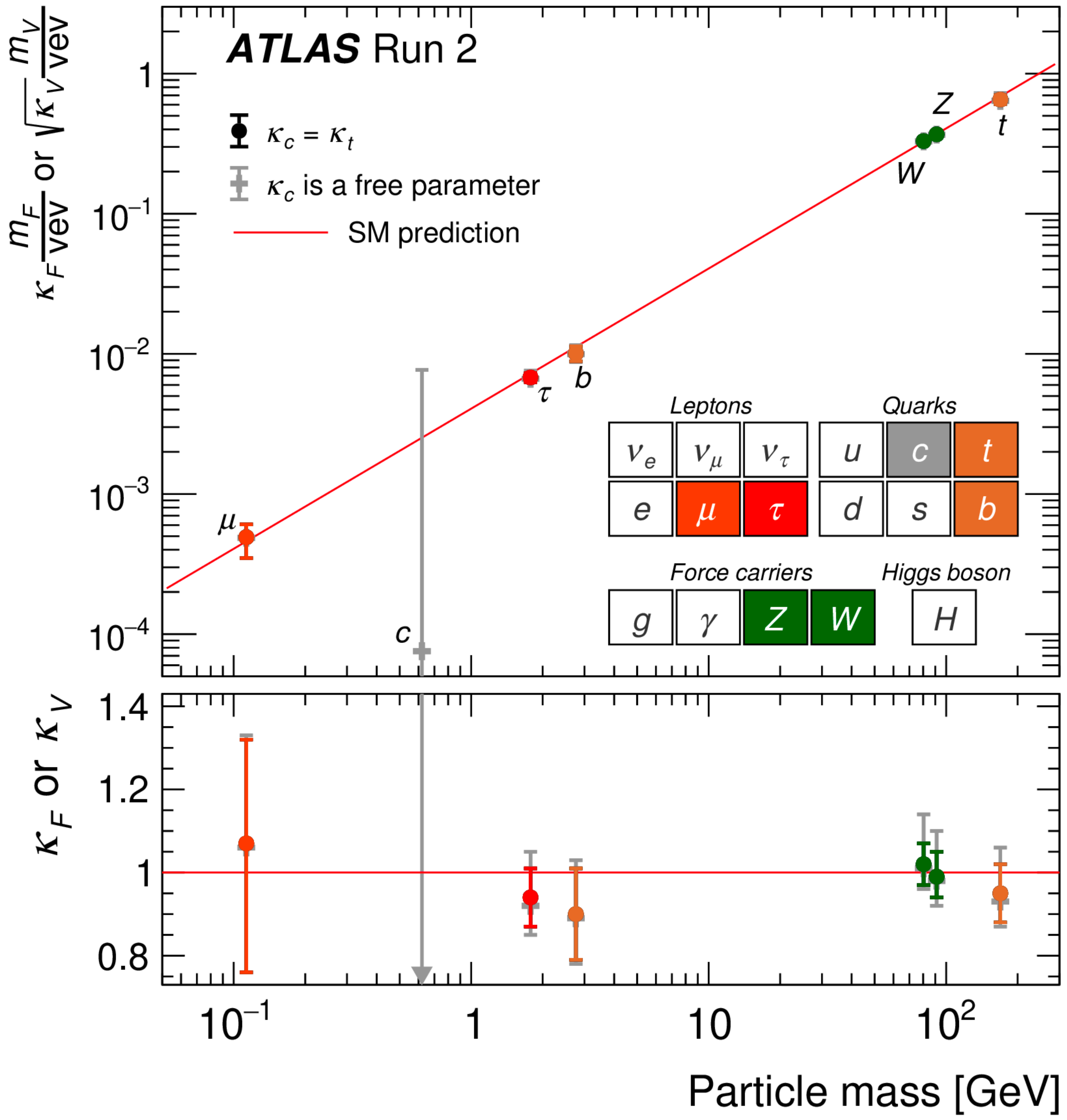
The Higgs Boson

(HL-)LHC

Current and Future



Karsten Köneke

karsten.koeneke@cern.ch

29. 2. 2024

Outline

1. Motivation
2. Mass and width
3. CP coupling structure
4. Decays into Bosons
   & fiducial and differential cross sections
5. Decays into Fermions
   & Simplified Template Cross Sections (STXS)
6. HH
7. Combinations and Interpretations
8. Another angle
9. Future
10. Summary

Motivation

- Higgs boson with mass: $m_\mathrm{H} = \sqrt{2\lambda}v$ not predicted!

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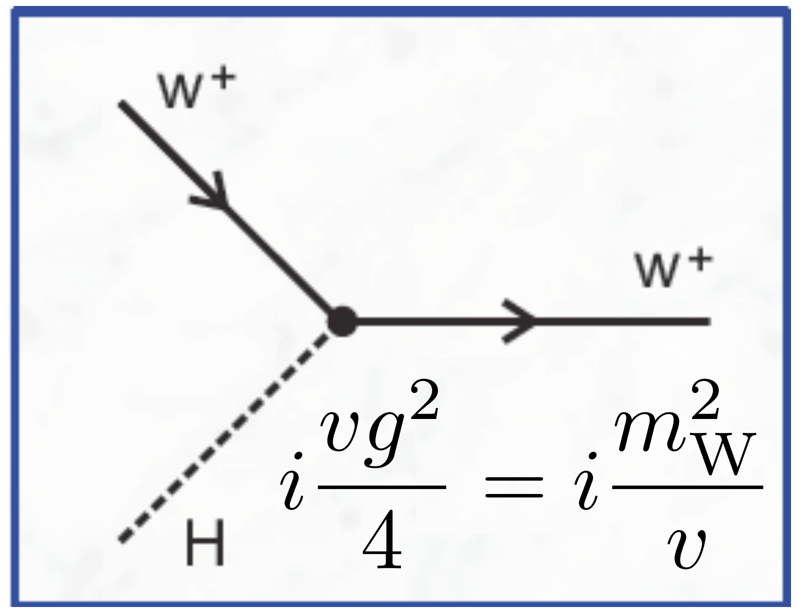
not predicted!

- W boson mass and interaction:

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

direct connection



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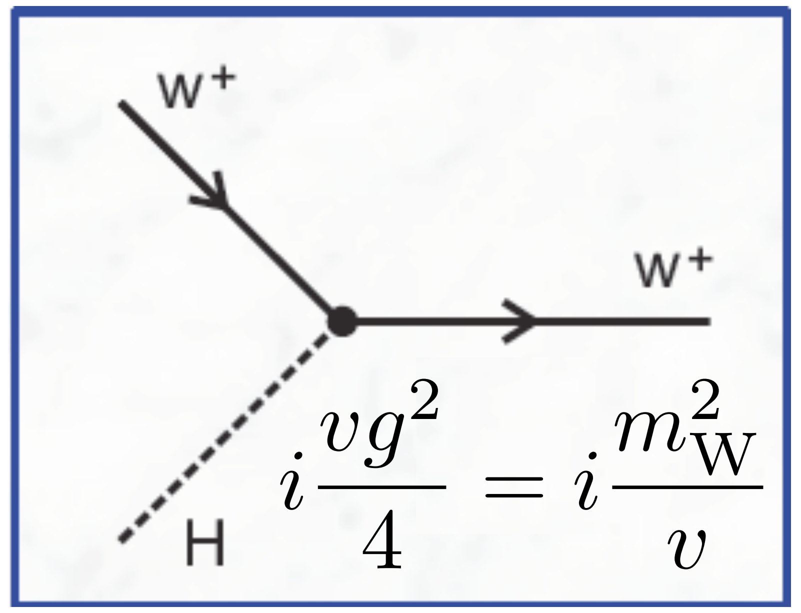
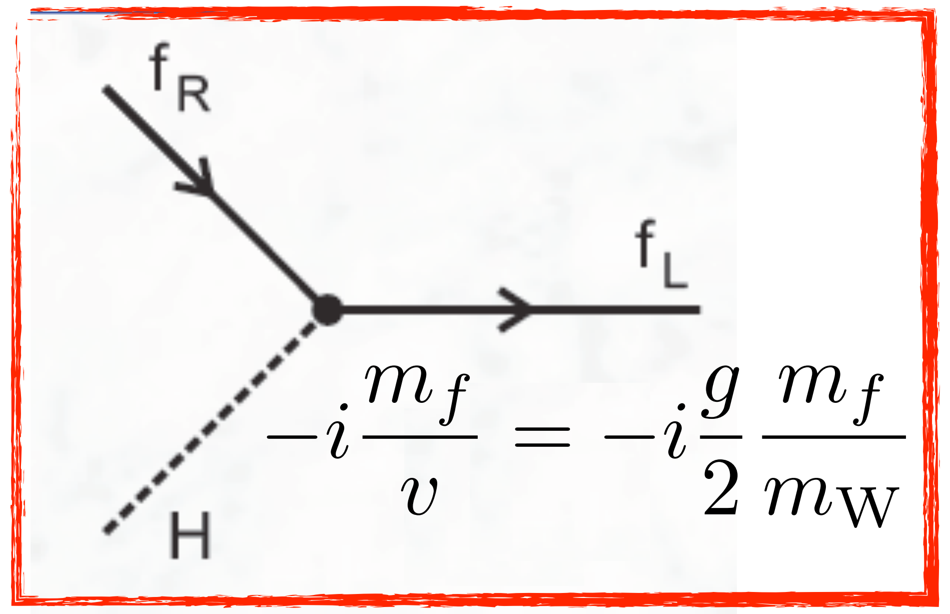


- Fermion masses and Yukawa interactions:

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

direct connection



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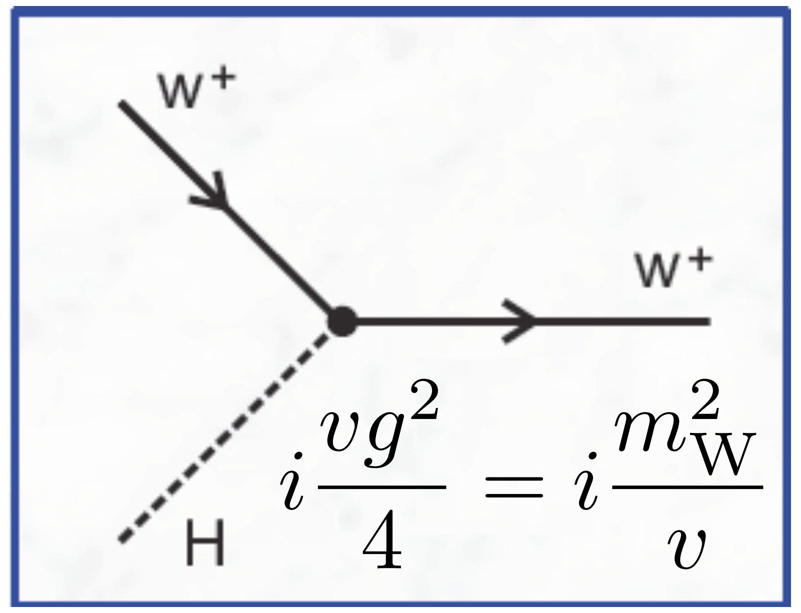

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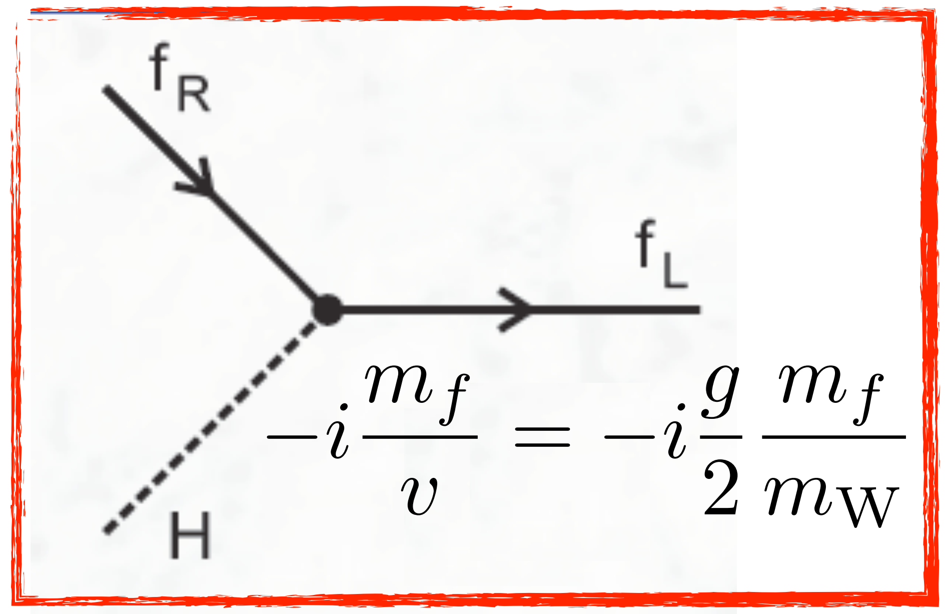


- Higgs potential:

Does HH production exist?

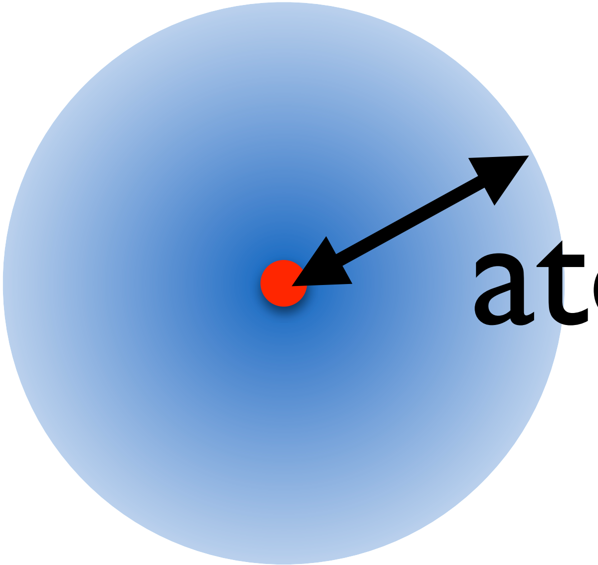
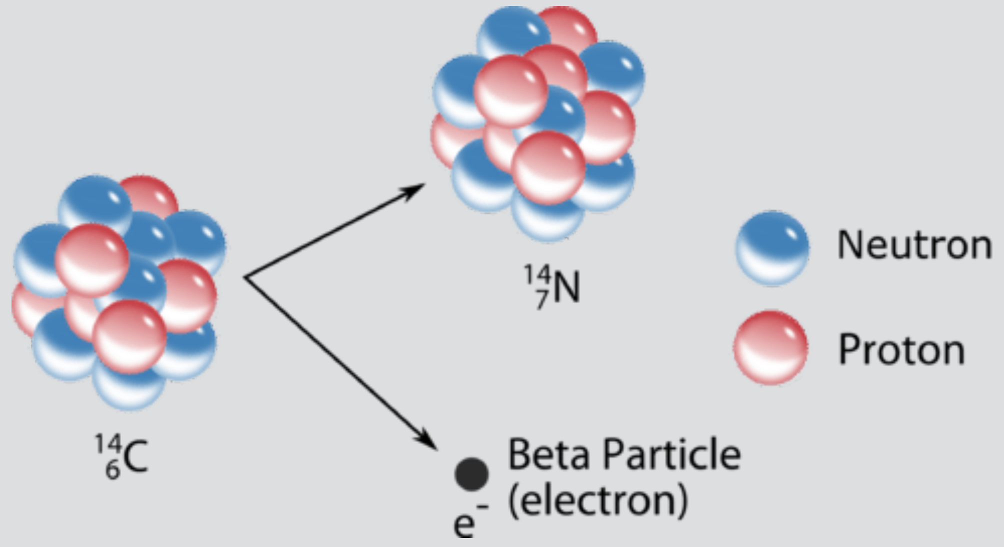
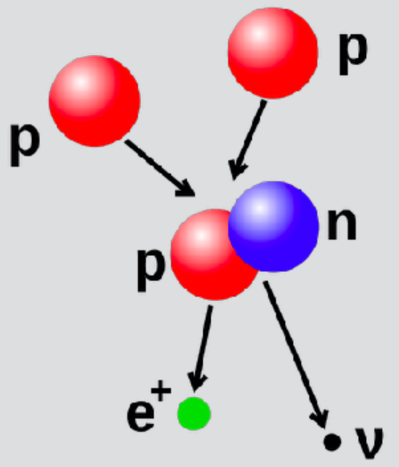
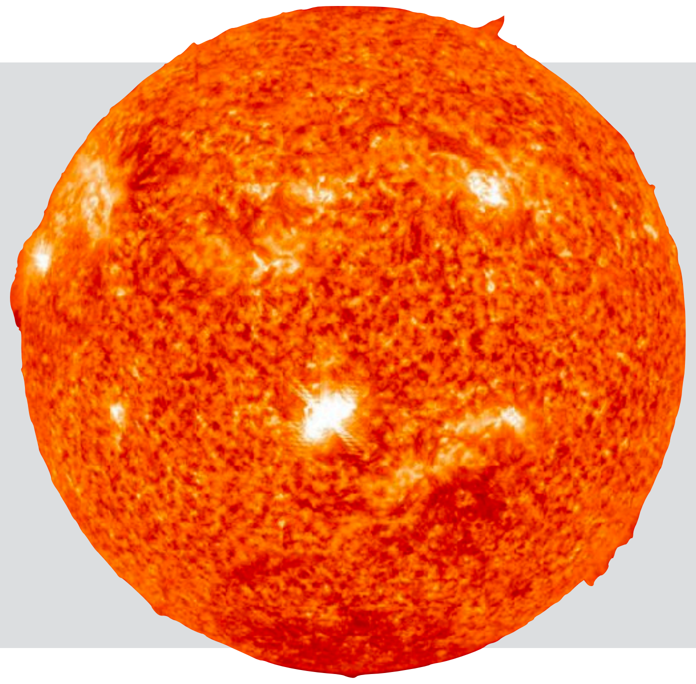
In SM: $\lambda = \frac{1}{2}m_{\mathrm{H}}^2/v^2$ ⟷

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

H potential as in SM?

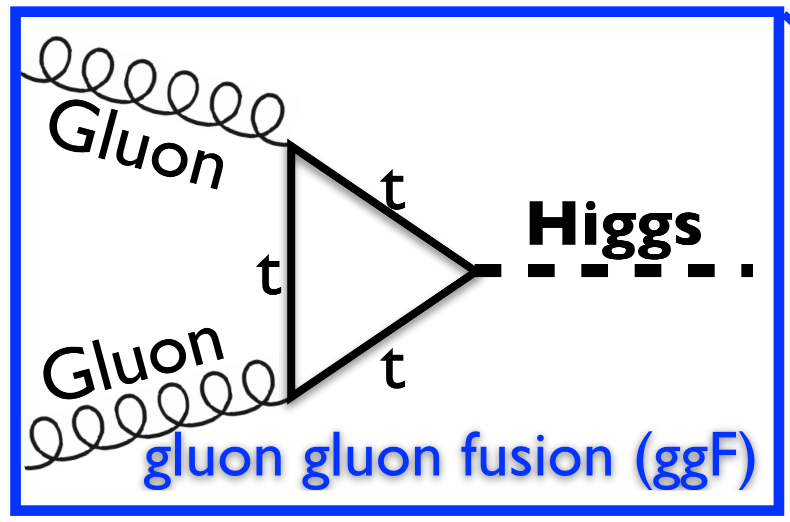
Higgs and our Universe

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

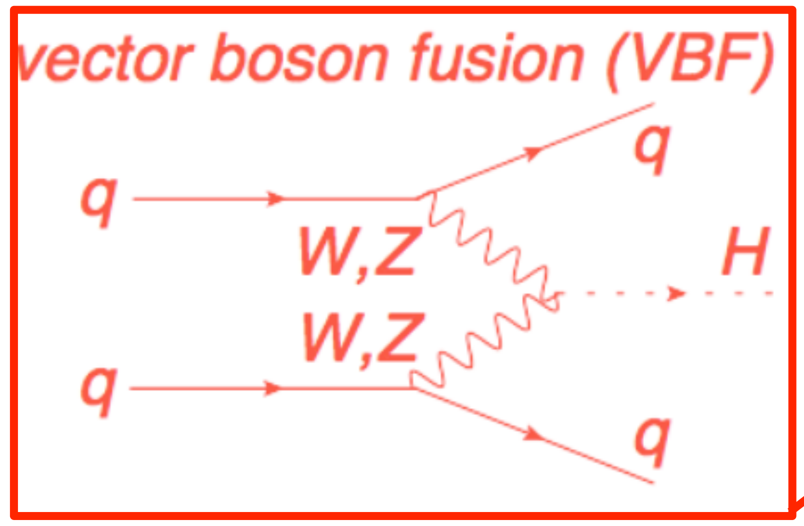
Role of elementary particle masses	Consequence	Higgs role established?
Up quarks (mass ~2.2 MeV) ***lighter than*** **down quarks (mass ~ 4.7 MeV)** **Proton** (up|**up**|down): 2.2 + **2.2** + 4.7 MeV + EM+strong force = **938.3 MeV** **Neutron** (up|**down**|down): 2.2 + **4.7** + 4.7 MeV + EM+strong force = **939.6 MeV**	**Proton lighter than Neutron** **⇒ Protons are stable** **⇒ Hydrogen atom**	**No**
 atomic radius $\propto \frac{1}{m_e}$	**Electron mass (m_e) sets size of atoms & energy levels of chemical reactions**	**No**
 rate $\propto \frac{1}{m_W^4}$  	**W-boson mass (m_W) sets rate of radioactive β-decay and burning of the sun**	**Yes**

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

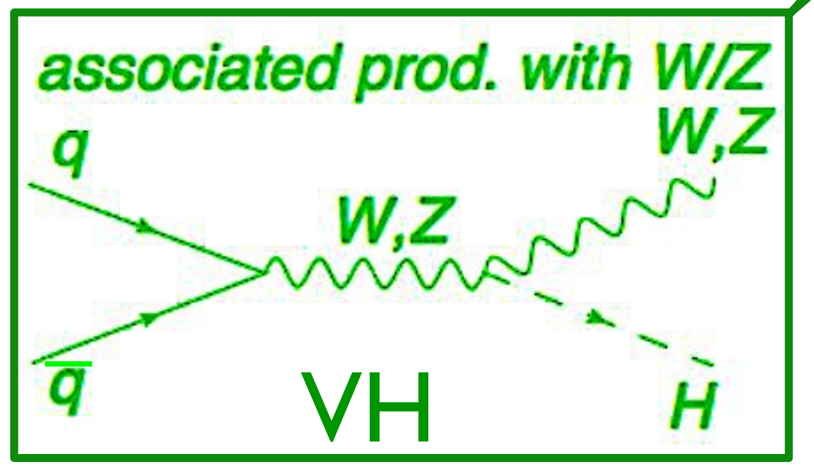
Higgs Boson at the LHC



σ_{ggF} = 48.5 pb (87 %)

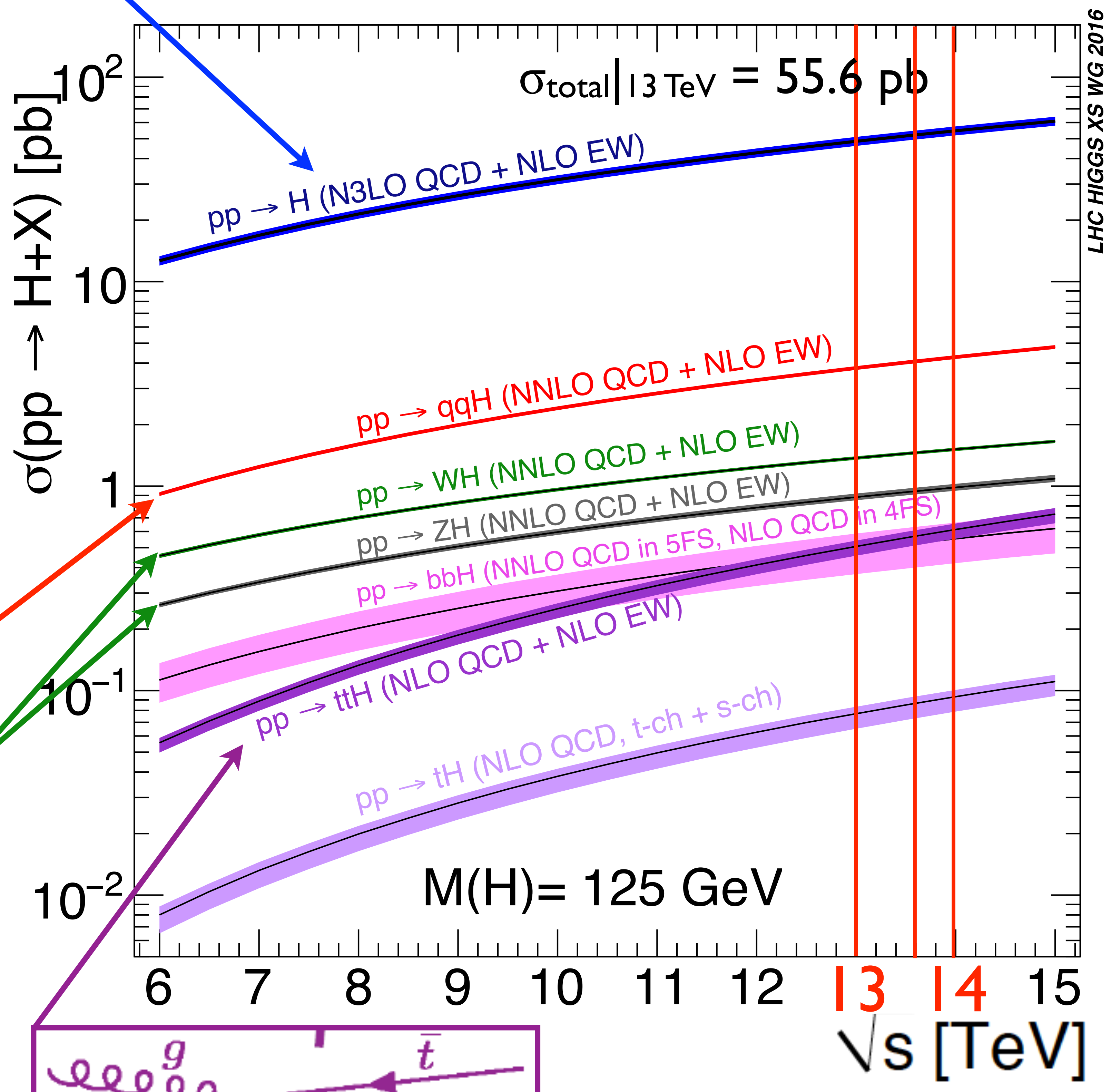


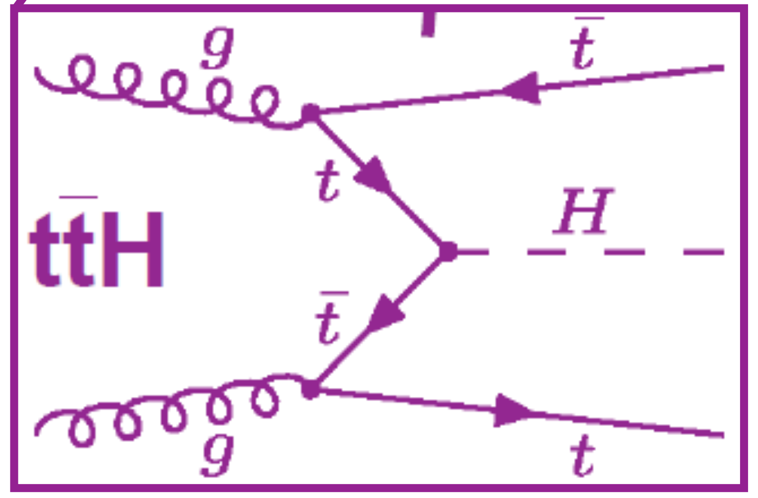
σ_{VBF} = 3.78 pb (7 %)



σ_{VH} = 2.3 pb (4 %)

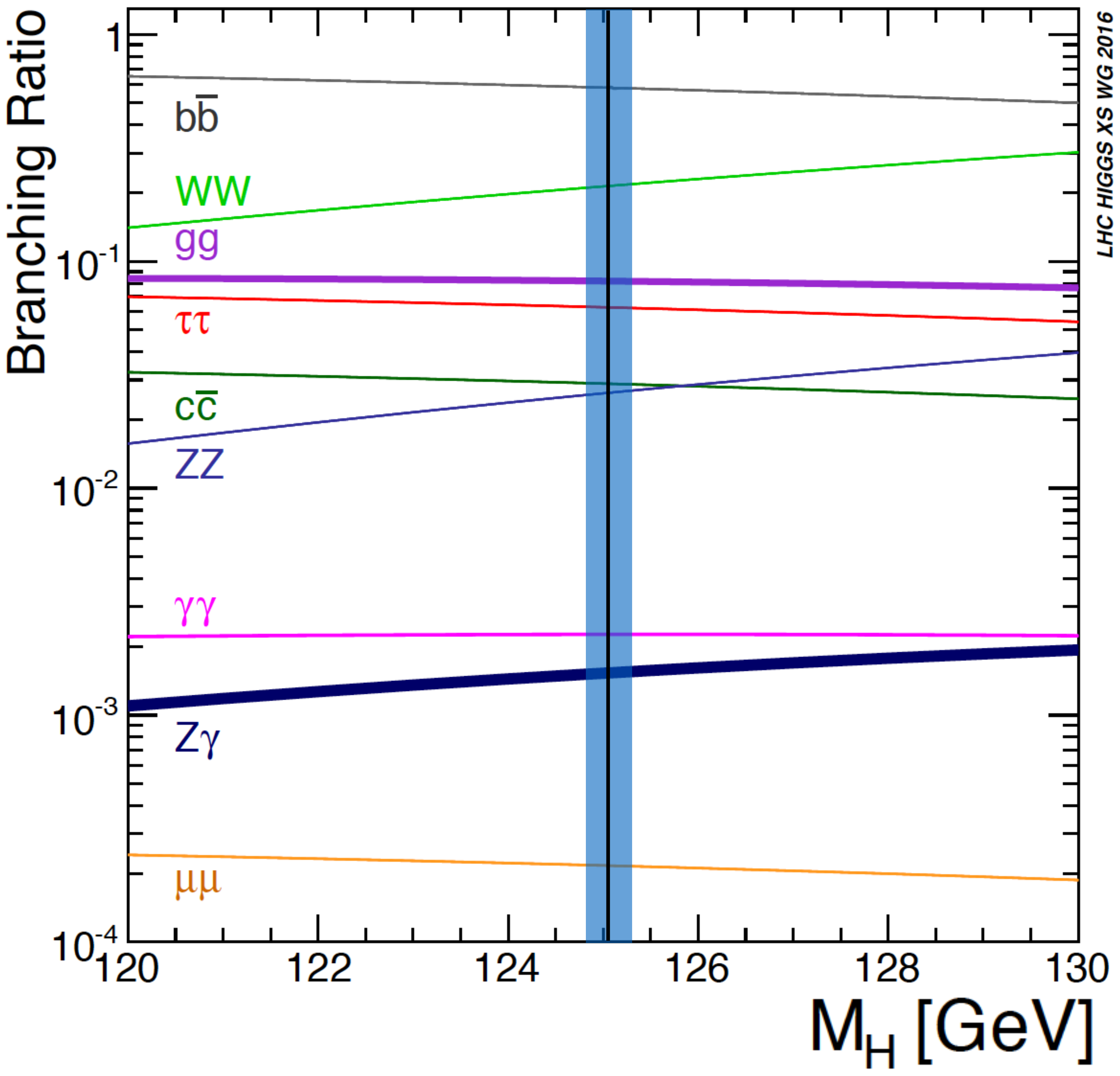
Production

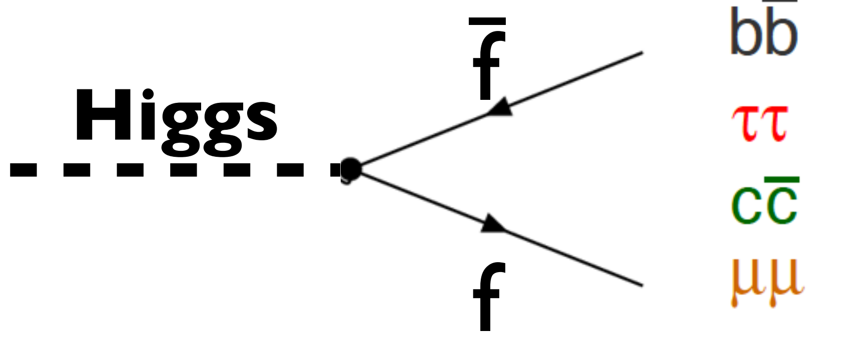


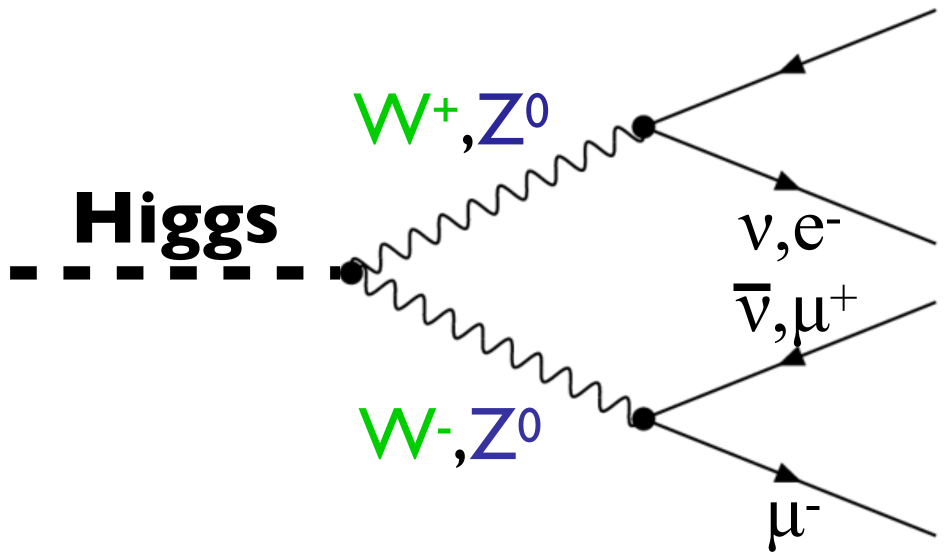


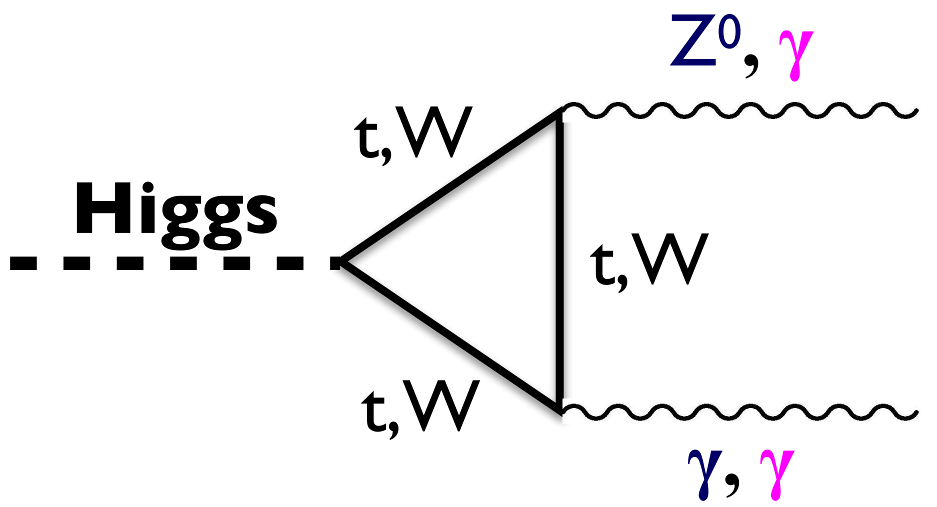
σ_{ttH} = 0.5 pb (0.9 %)

Decay









Karsten Köneke

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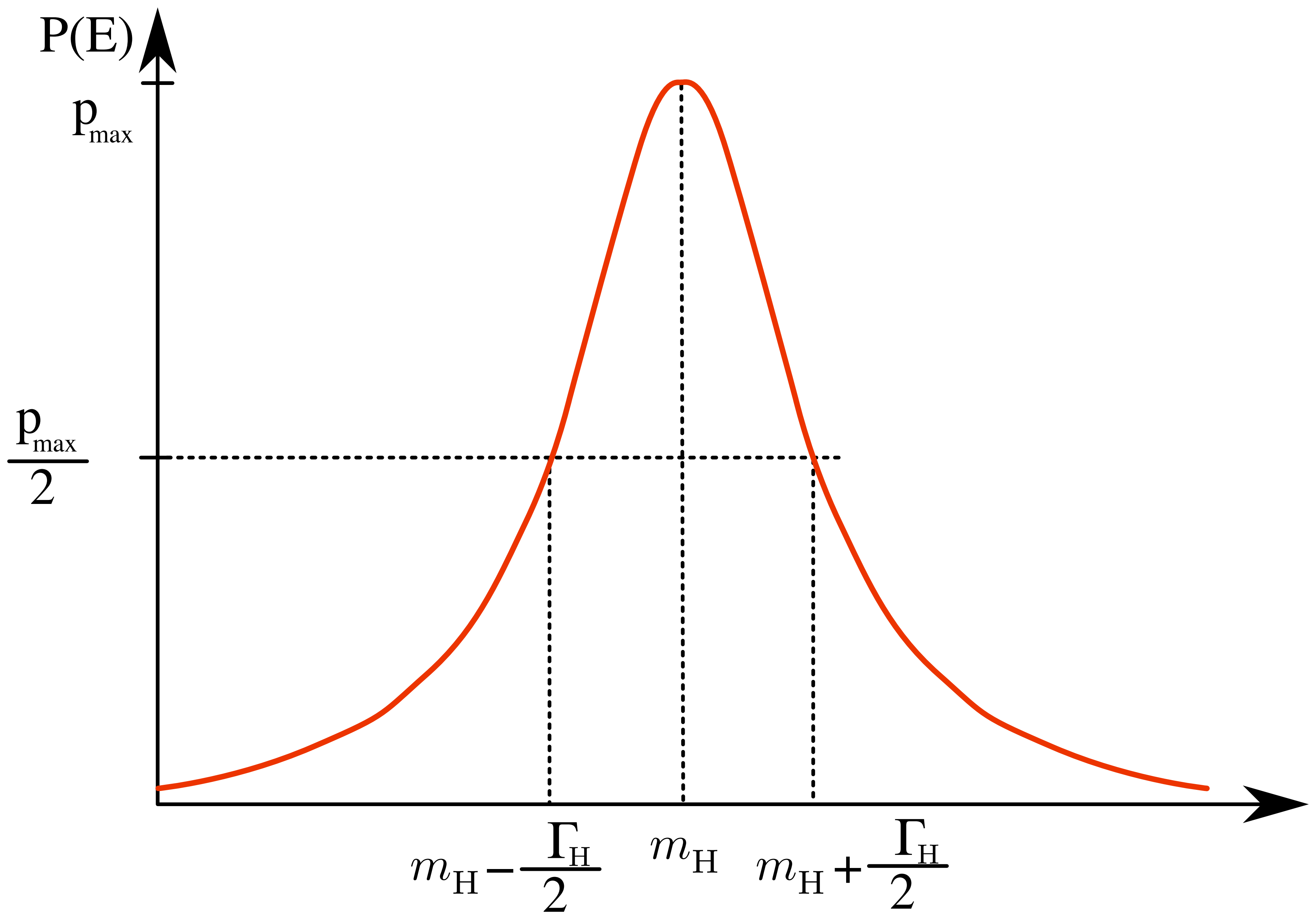
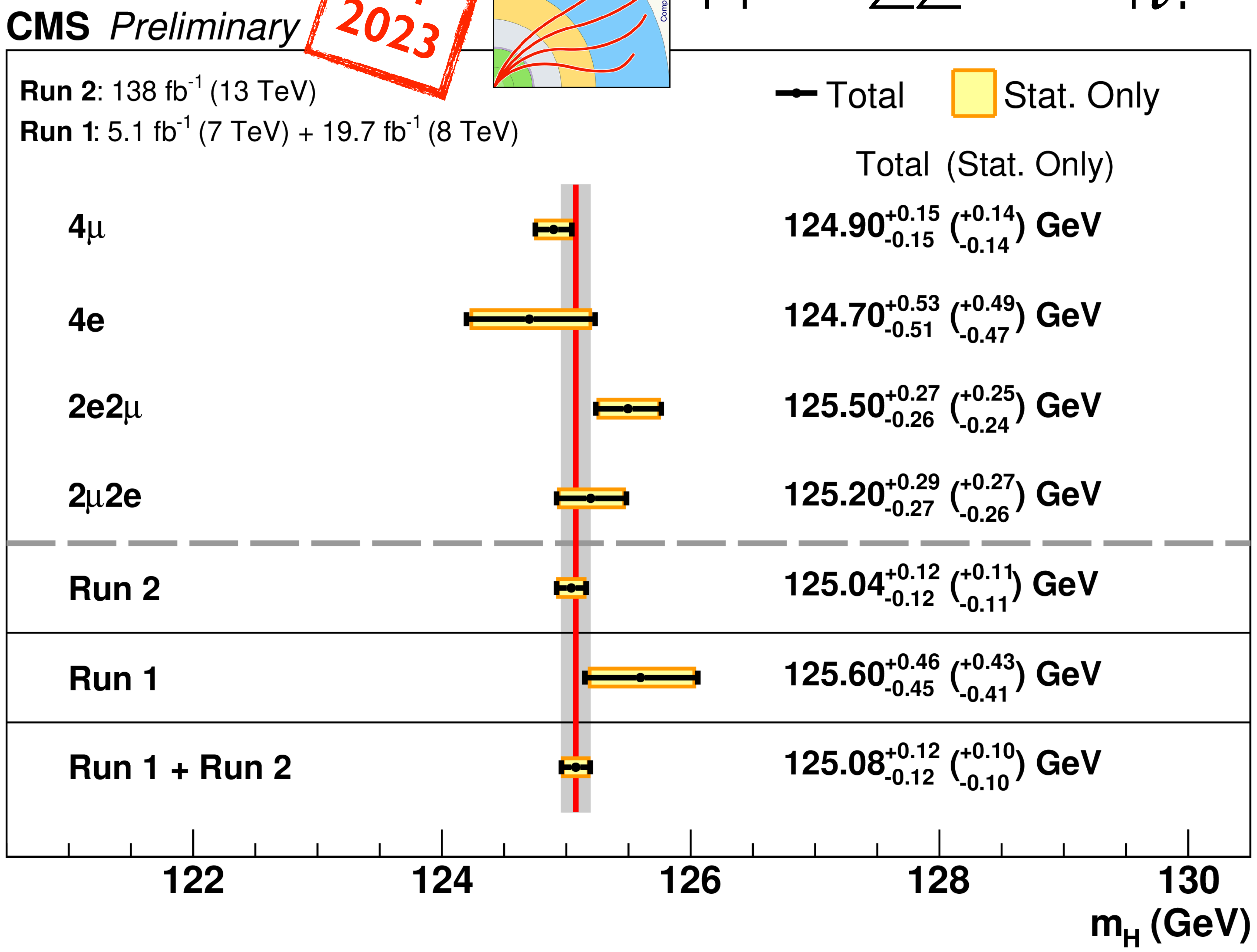


Higgs Boson Mass

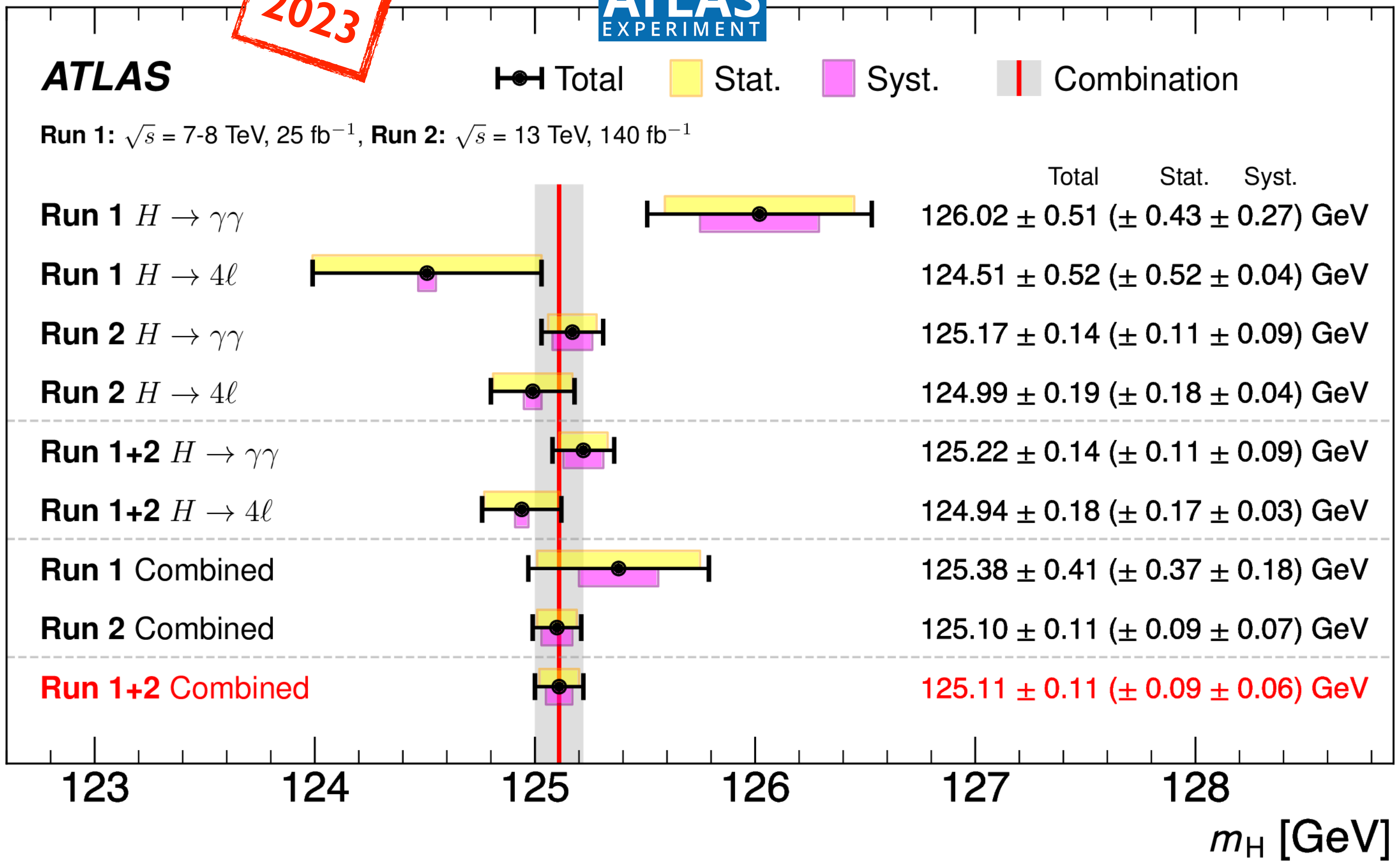
Sep 2023

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



$m_{\mathrm{H}} = 125.08 \pm 0.11(\mathrm{stat}) \pm 0.05\ (\mathrm{syst})\ \mathrm{GeV}$

Aug 2023



$m_{\mathrm{H}} = 125.08 \pm 0.11(\mathrm{stat}) \pm 0.05\ (\mathrm{syst})\ \mathrm{GeV}$

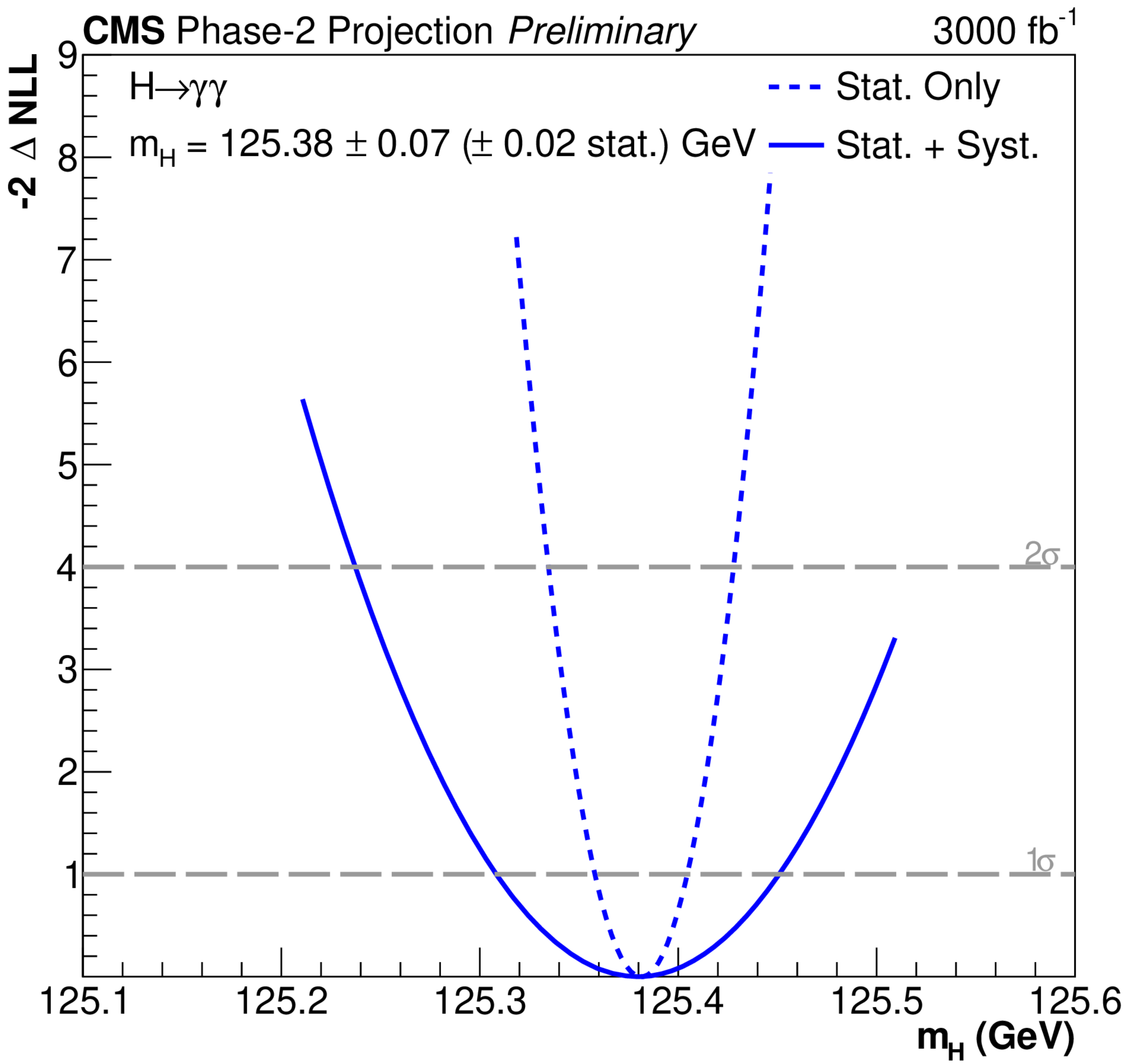
$\Gamma_{\mathrm{H}} < 60$ MeV @ **68 % C.L.** (≲320 MeV @ 95 % C.L.)

CMS-PAS-HIG-21-019

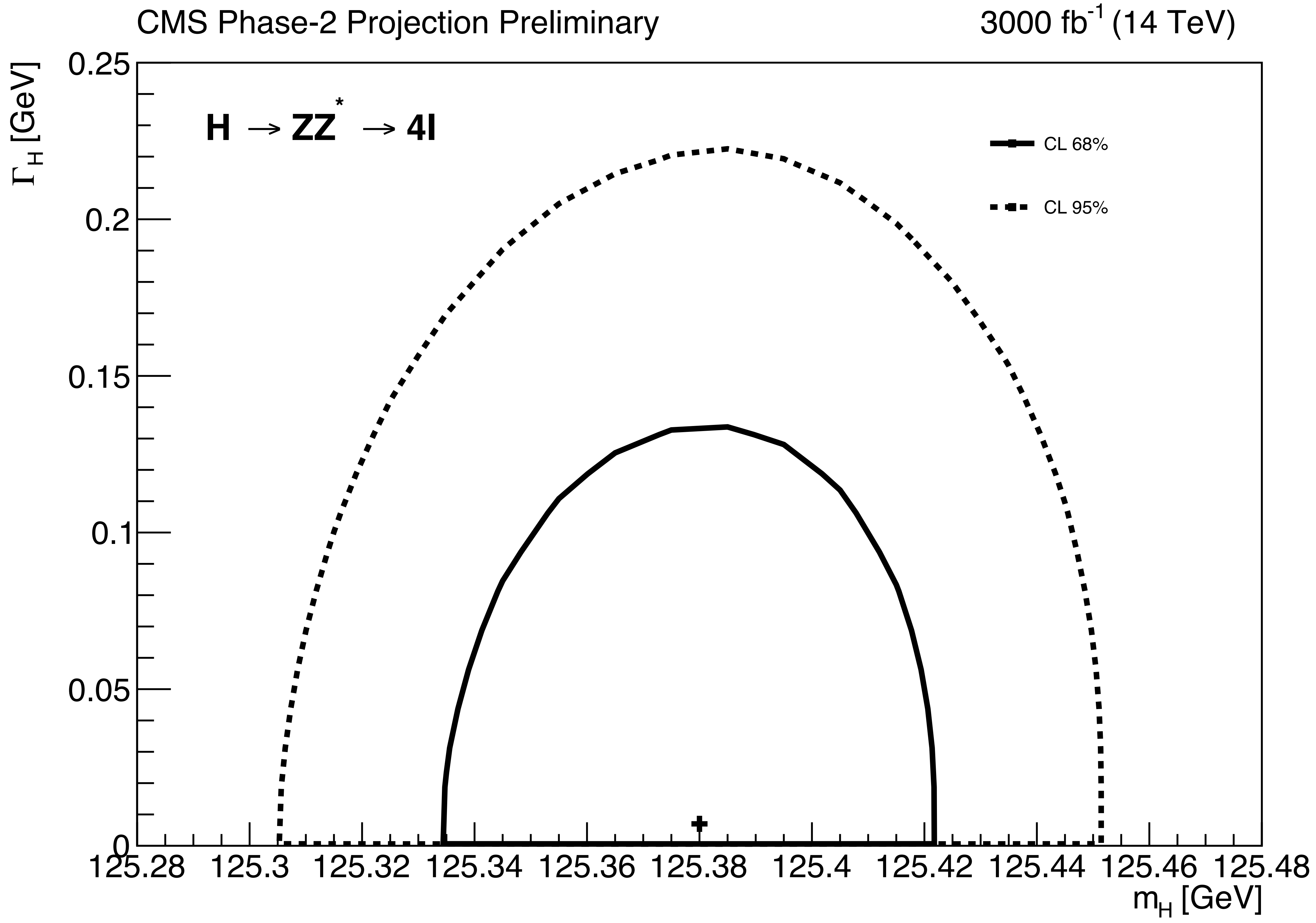
Phys. Rev. Lett. 131 (2023) 251802

HL-LHC Higgs Boson Mass

$H \rightarrow \gamma\gamma$



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



	Mass uncertainty (MeV)					Width upper limit at 95 % CL (MeV)
	Combined	4μ	4e	$2e2\mu$	$2\mu2e$	Combined
Stat. uncertainty	22	28	83	51	59	94
Syst. uncertainty	20	15	189	94	95	150
Total	30	32	206	107	112	177

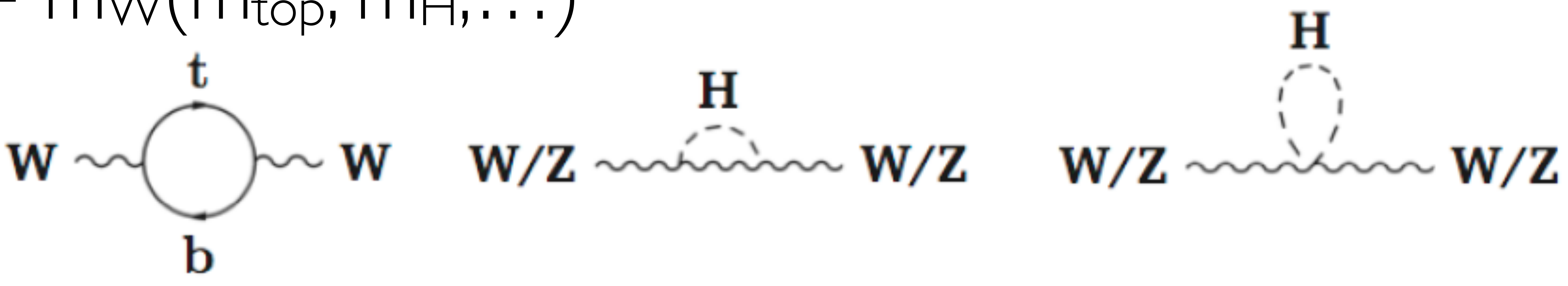
Mar 2022

CMS-PAS-FTR-21-008

CMS-PAS-FTR-21-007

Impact of m_H

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



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

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

	Δ_{theo}	Δ_{exp}	Δm_H
BR(ZZ)	±1%	~10%	±2.5%
σ_{VBF}	±2%	~11%	±0.3%

⇒ Measurement precision of m_H good enough for this

- but precise measurement important!

Indirect Contraints on Higgs Boson Width

- Use $H \to ZZ^{(*)} \to 4\ell$ and $2\ell 2\nu$
- Results:

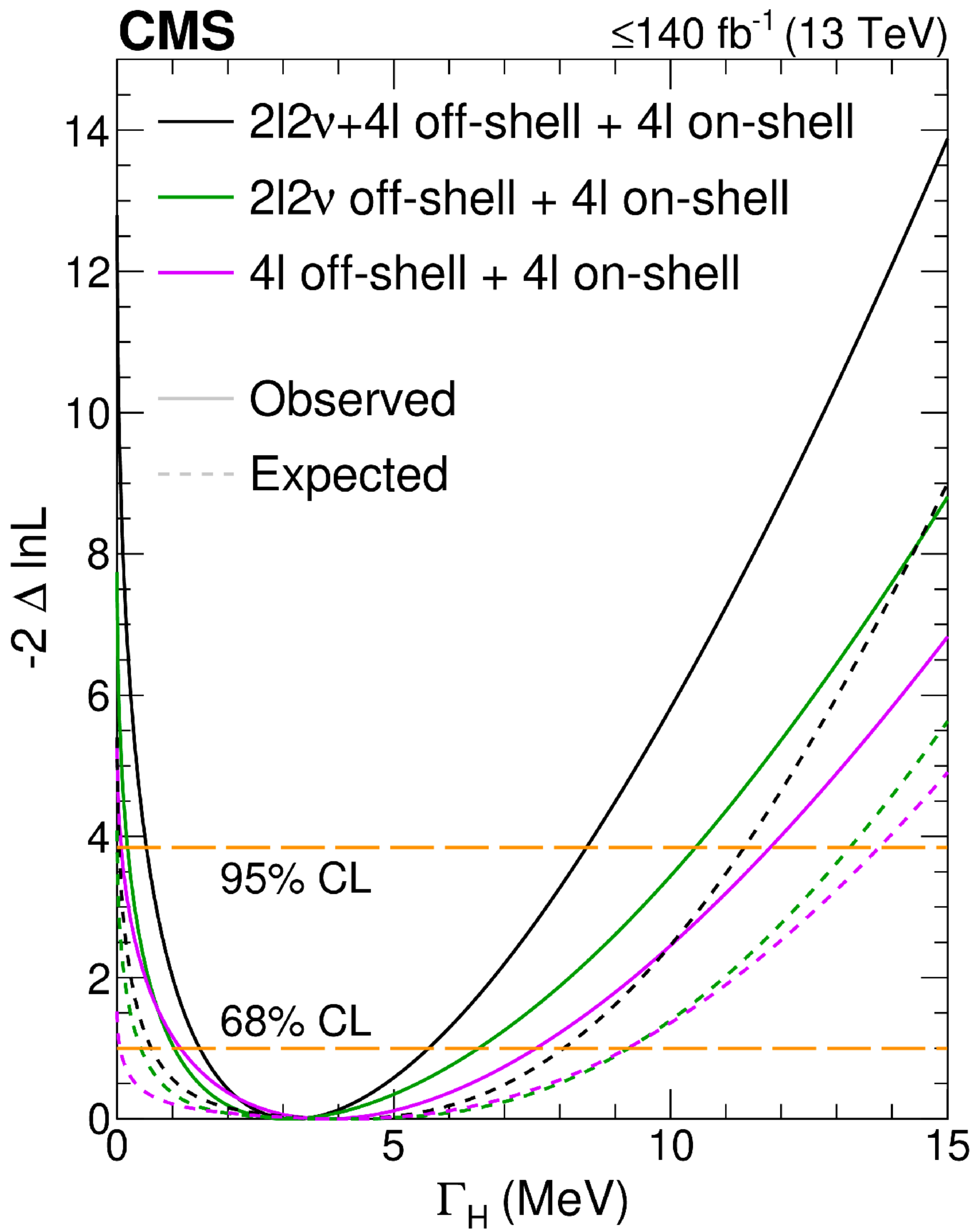
CMS
- Evidence for off-shell production: **3.6 σ**
- $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV

Feb 2022

ATLAS EXPERIMENT
- Evidence for off-shell production: **3.3 σ**
- $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV

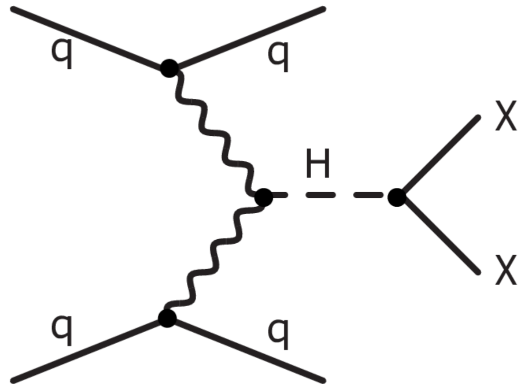
Apr 2023

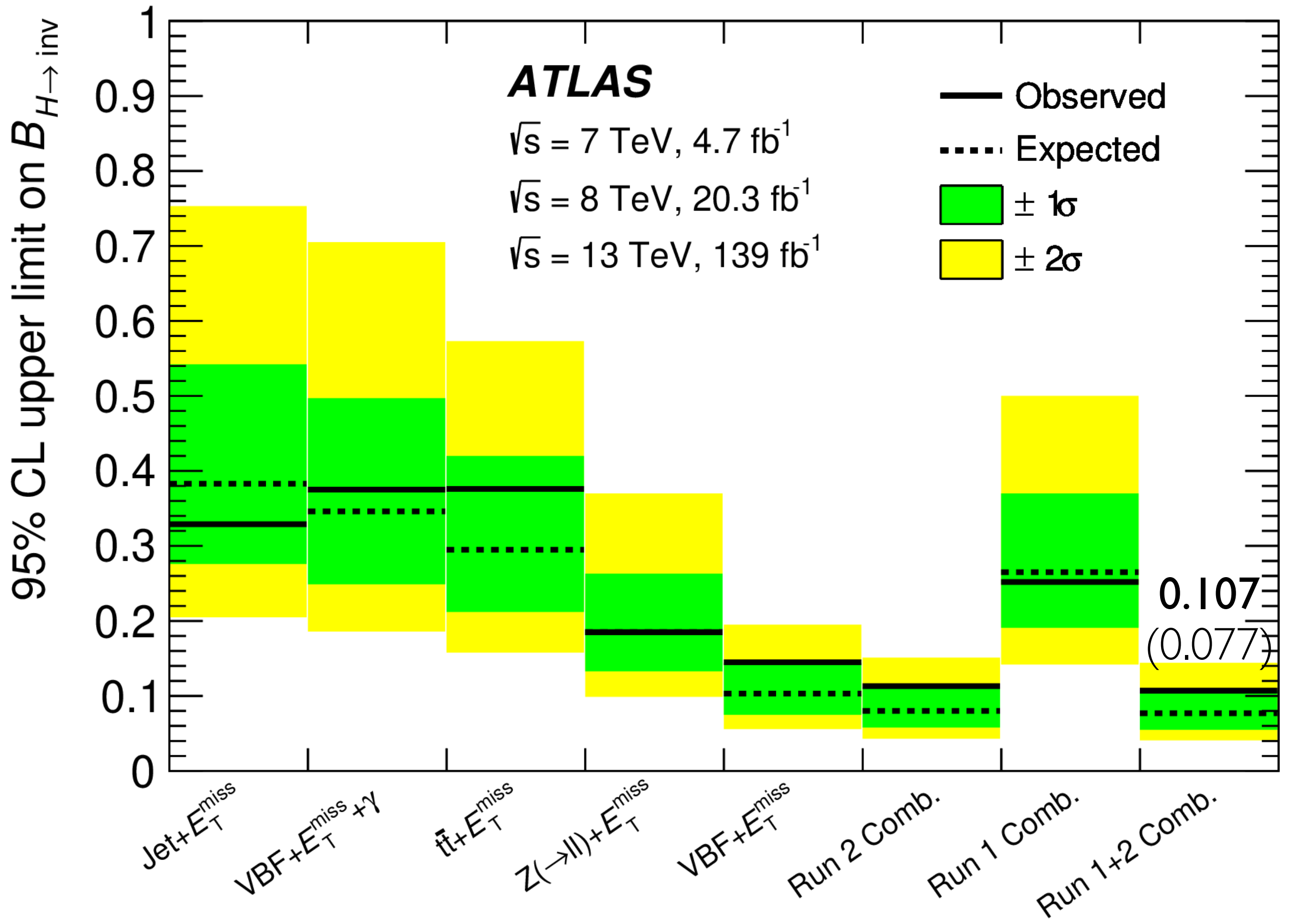
Phys. Lett. B 846 (2023) 138223

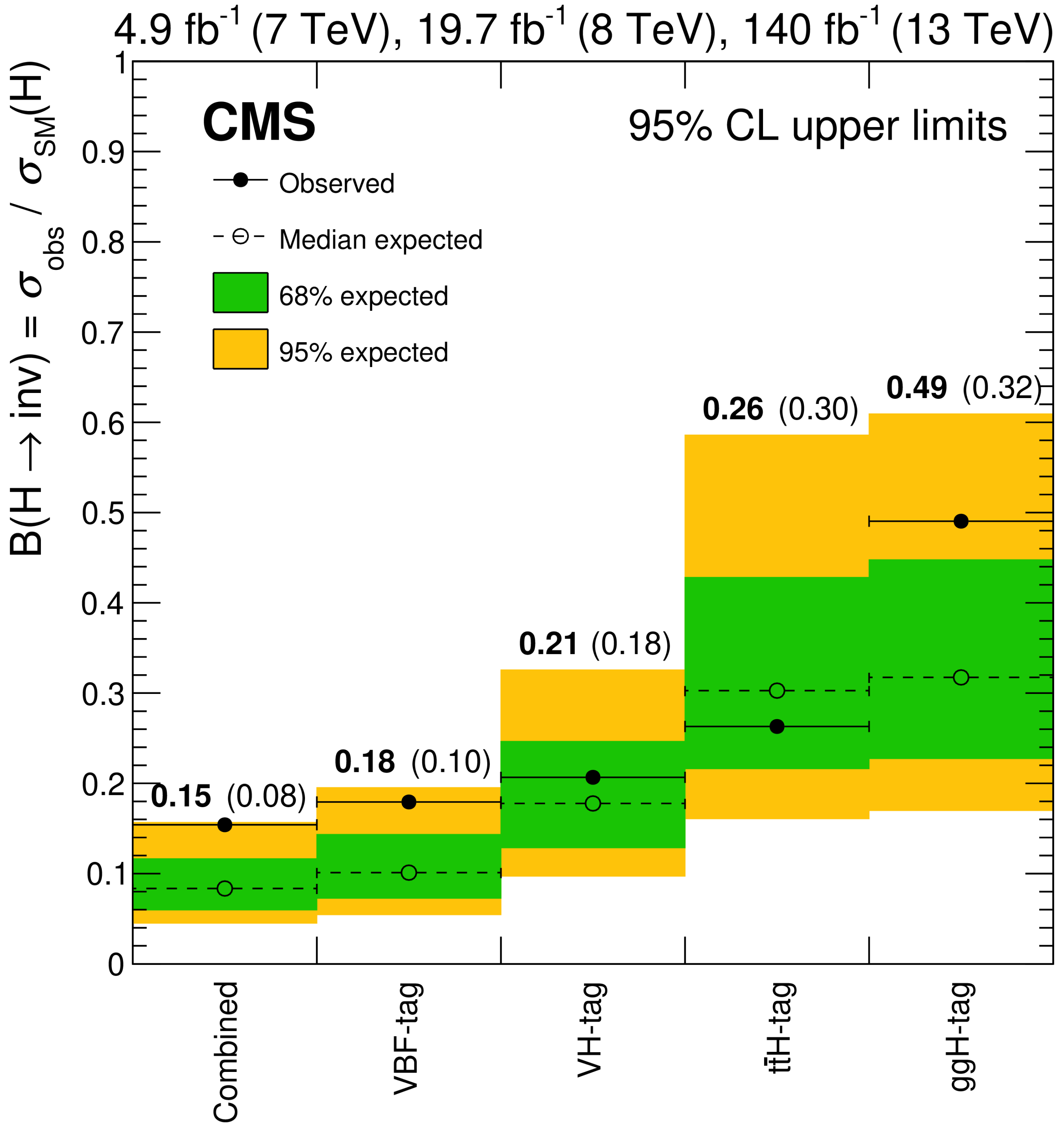


Nat. Phys. 18 (2022) 1329

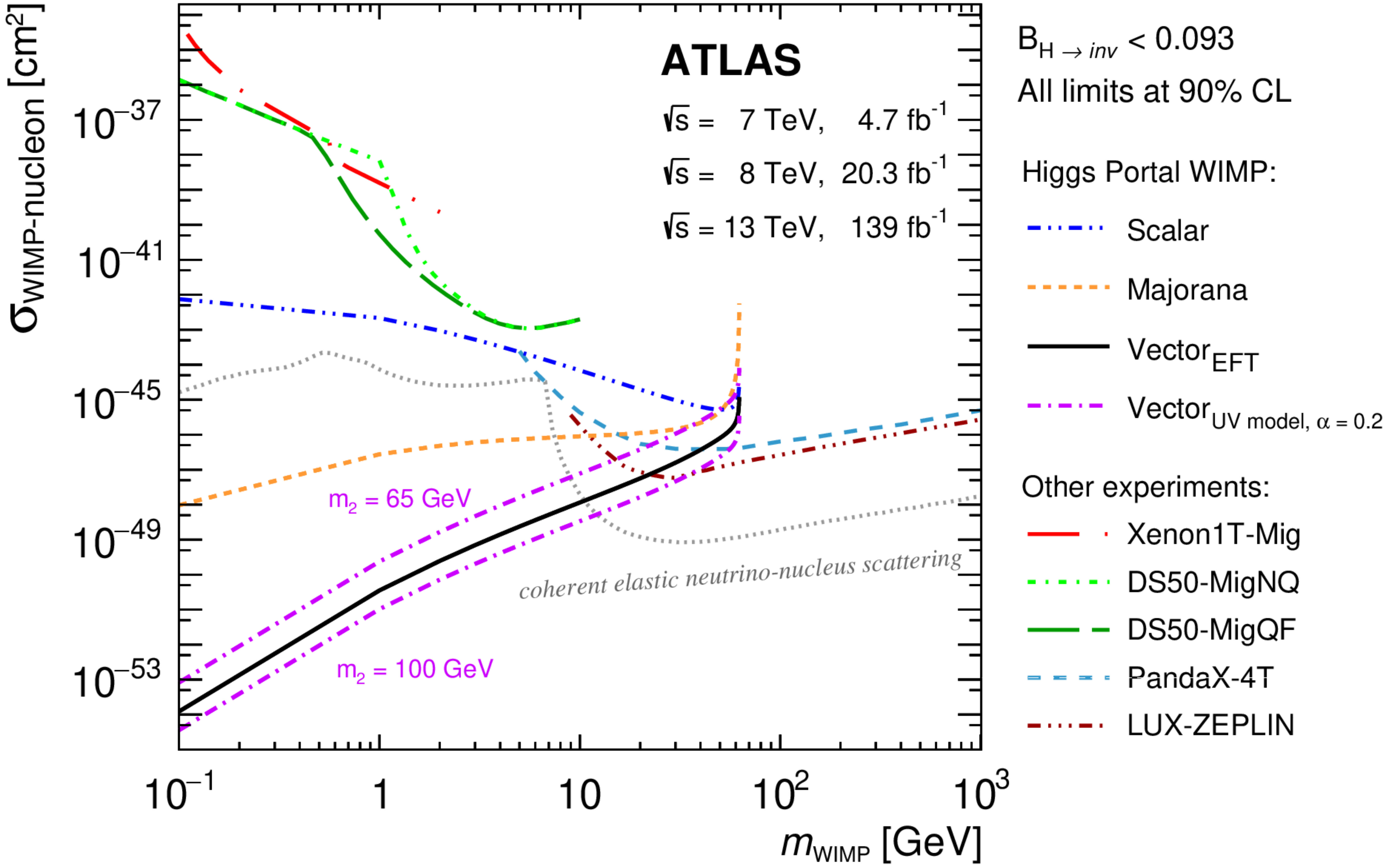
Invisible Higgs Boson Decays







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



⇒ DELPHES VBF analysis for 3000 fb^{-1}: BR(H → inv.) < 3.8 % @ 95% C.L. [CMS-PAS-FTR-18-016]

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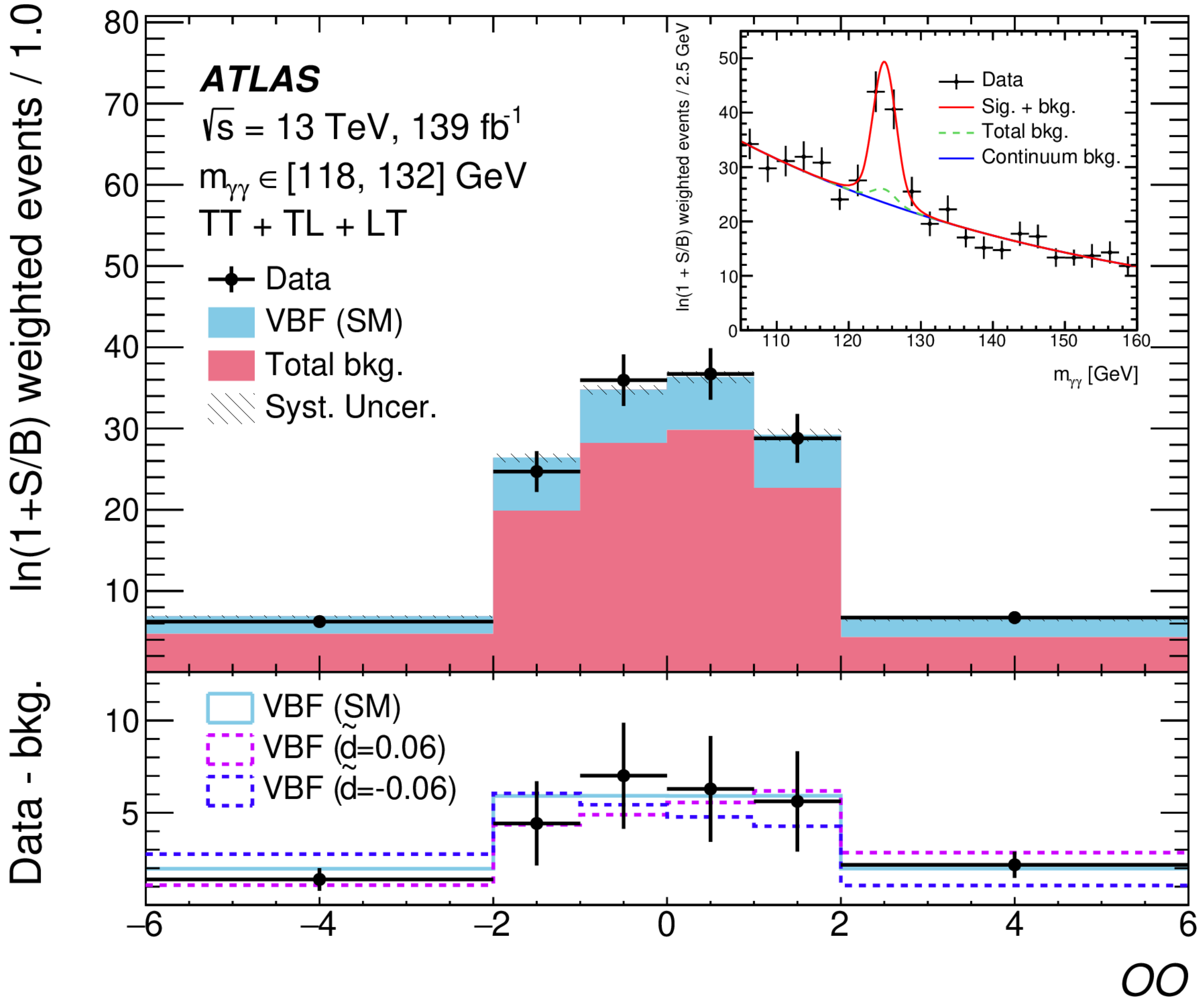
CP Measurement in HVV Coupling

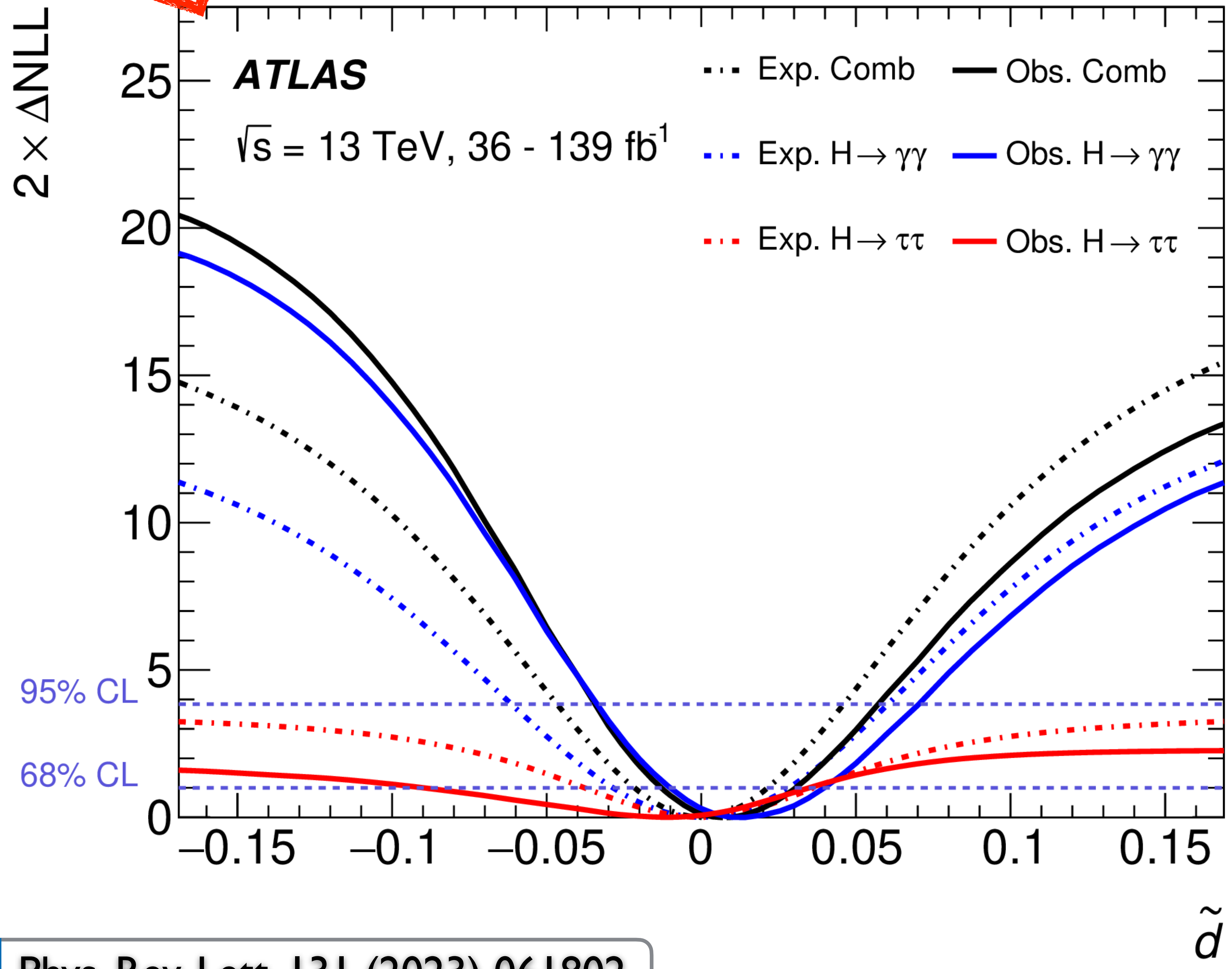
CP-odd through interference of SM with dim-6 CP-odd: $|\mathcal{M}|^2 = |\mathcal{M}_{\rm SM}|^2 + 2c_i \mathrm{Re}(\mathcal{M}^*_{\rm SM}\mathcal{M}_{CP\text{-odd}}) + c_i^2|\mathcal{M}_{CP\text{-odd}}|^2.$

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



Aug 2022

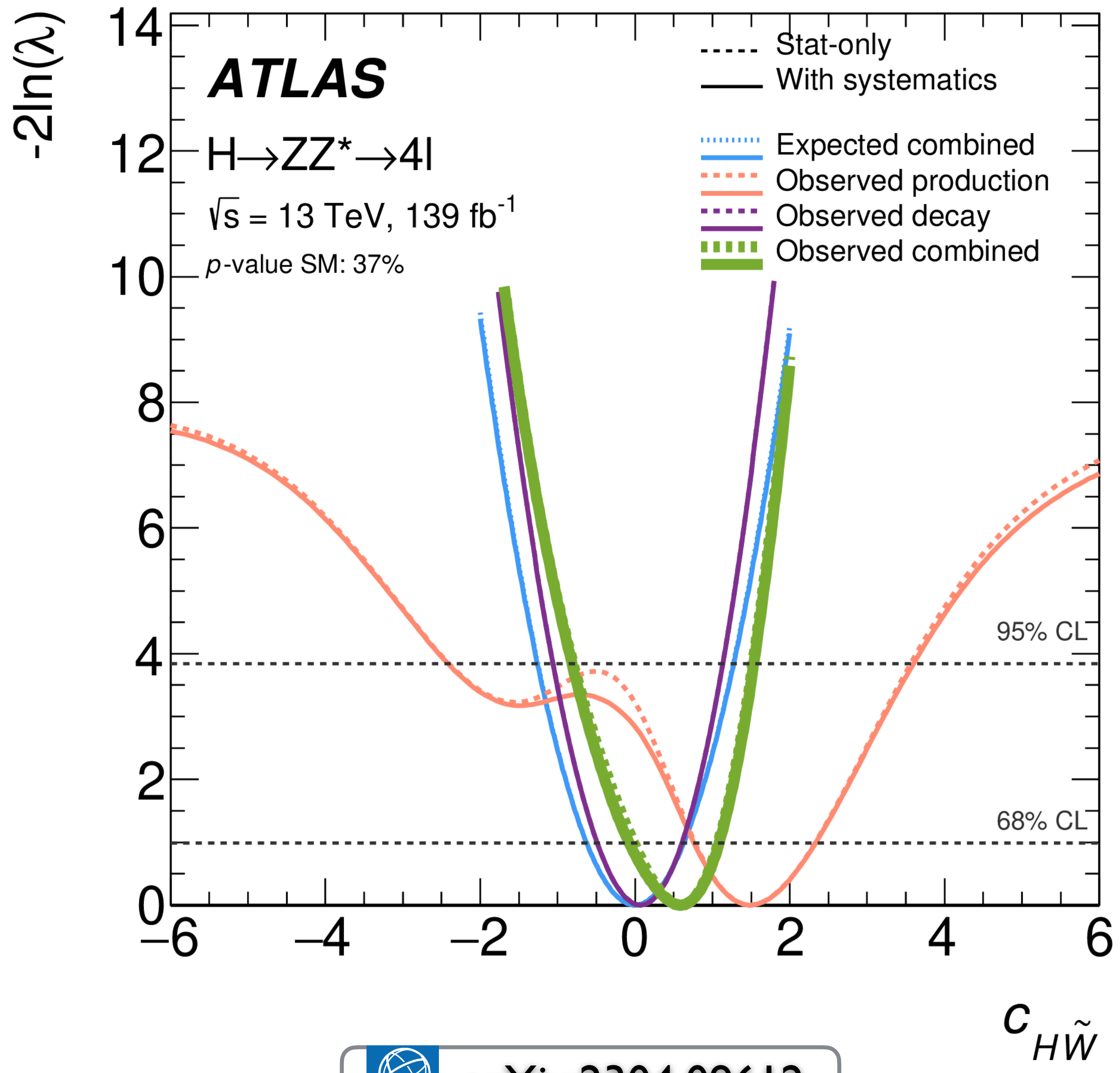
VBF production ($H \rightarrow \gamma\gamma$)



Phys. Rev. Lett. 131 (2023) 061802

April 2023

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



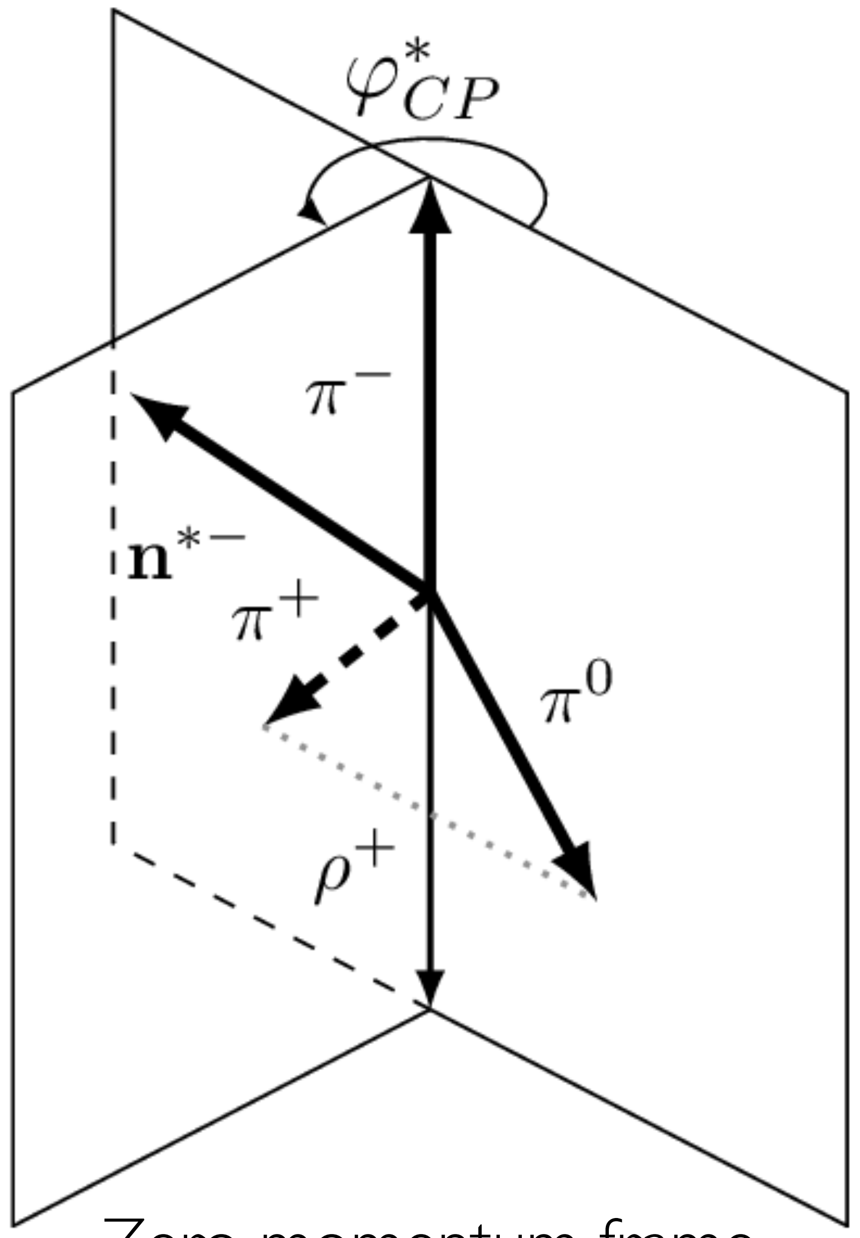
arXiv:2304.09612

CP Measurement in H → ττ Decay

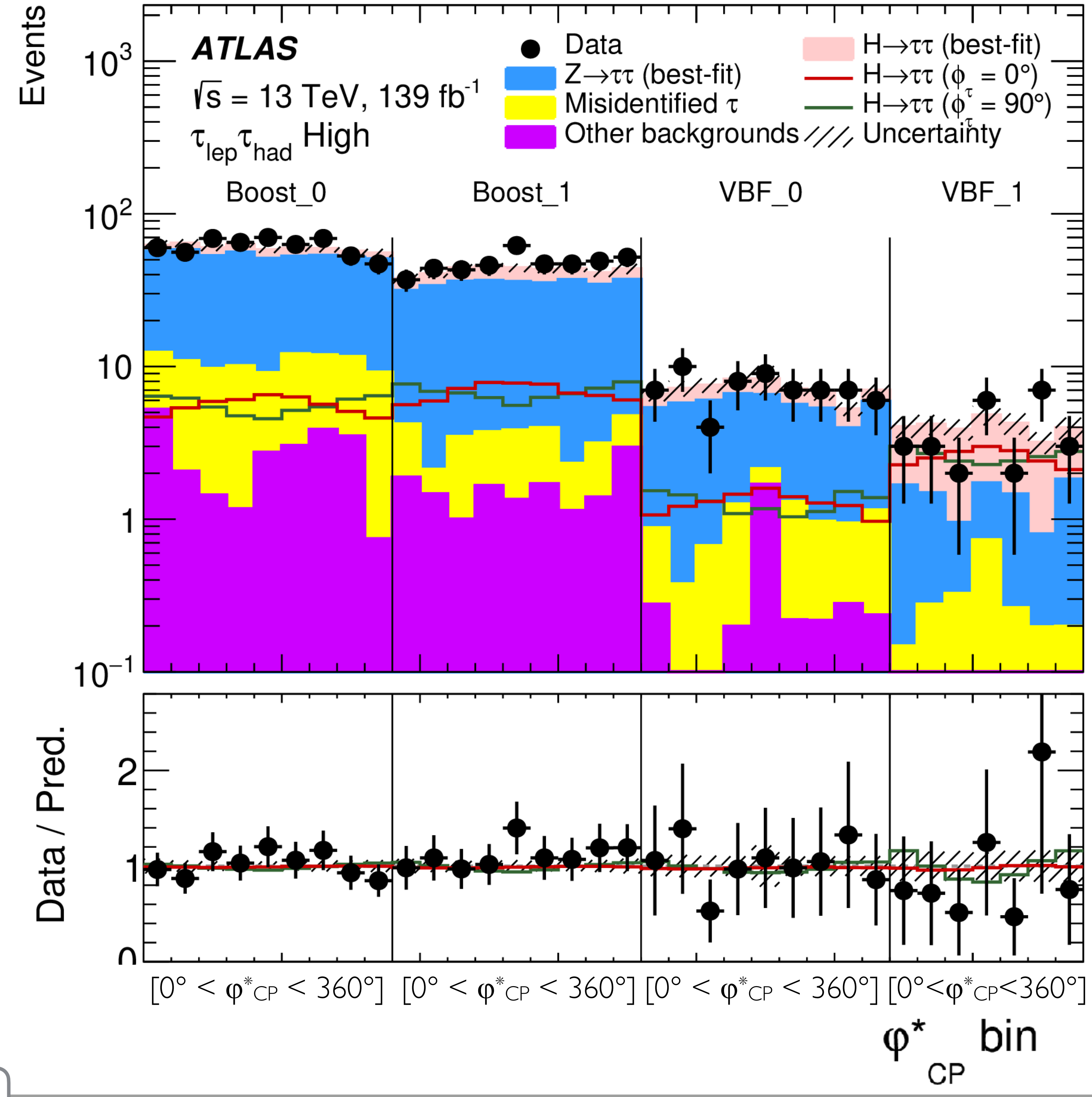
Parametrize **τ-Yukawa** coupling: $\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)H$ SM Hττ coupling: CP-even ($\phi_\tau = 0°$)

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

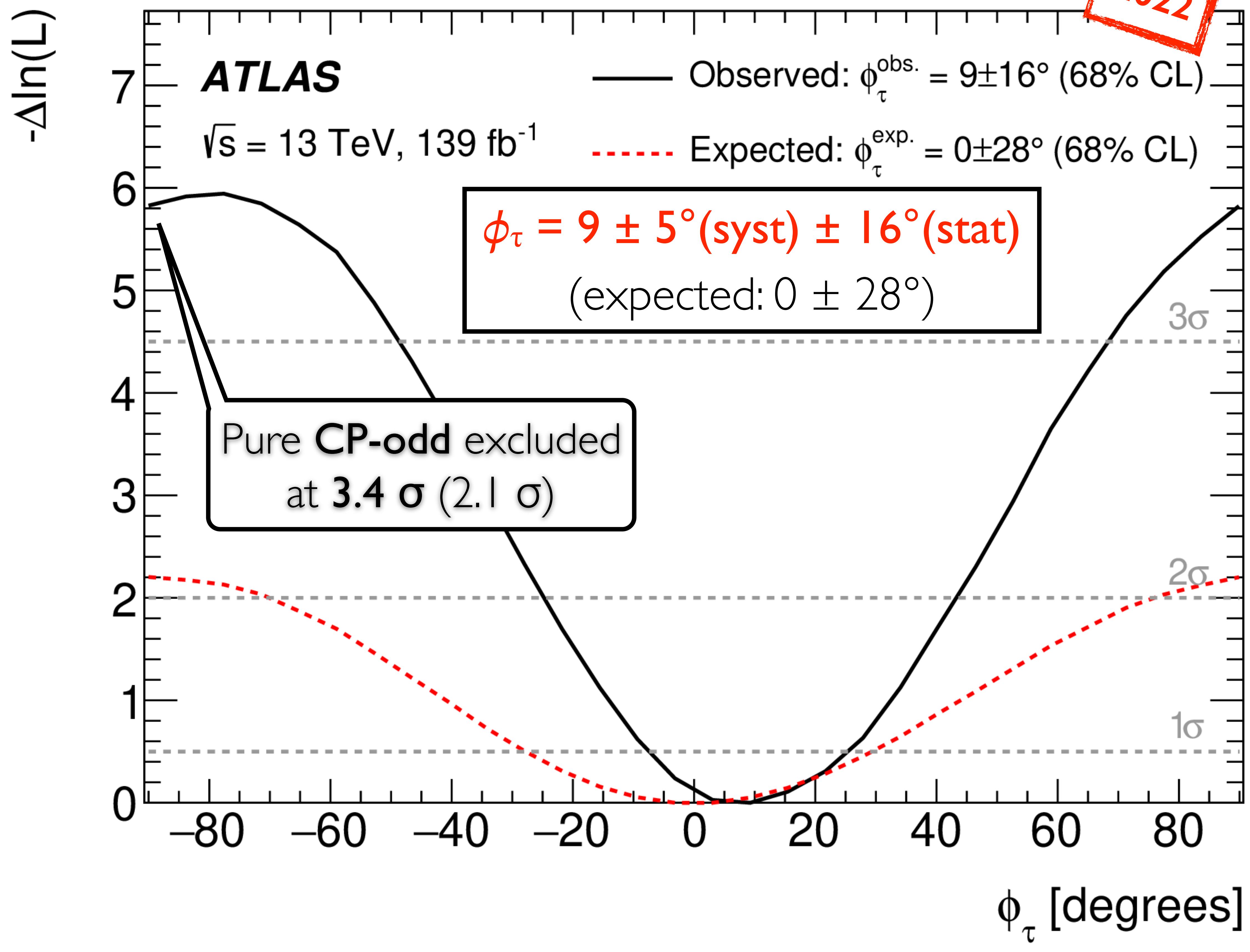
$H \to \tau^+\tau^- \to \pi^+\pi^0\nu\ \pi^-\nu$



Zero momentum frame



Dec 2022

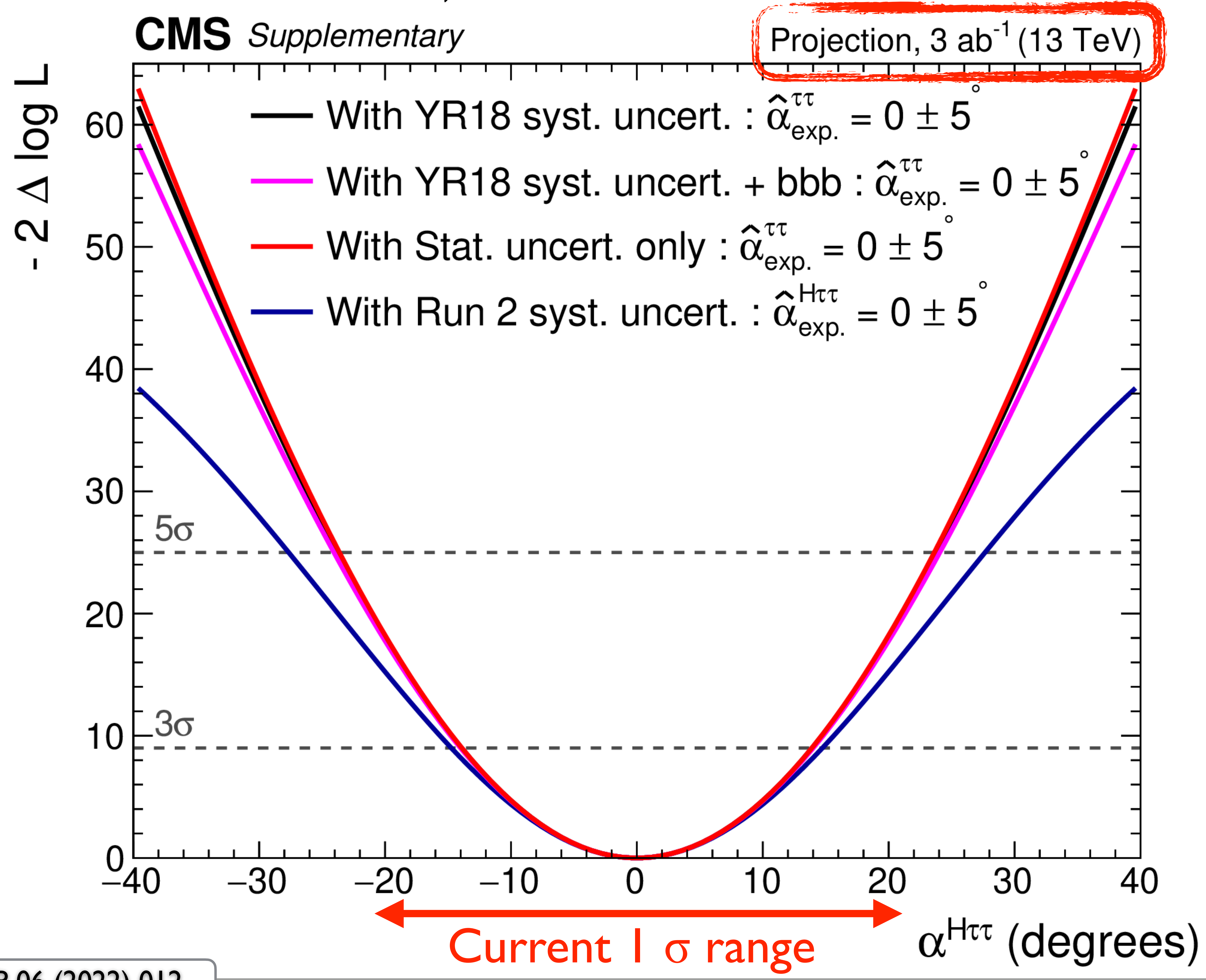


Eur. Phys. J. C 83 (2023) 563

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

HL-LHC CP Measurement in H → ττ Decay

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



JHEP 06 (2022) 012

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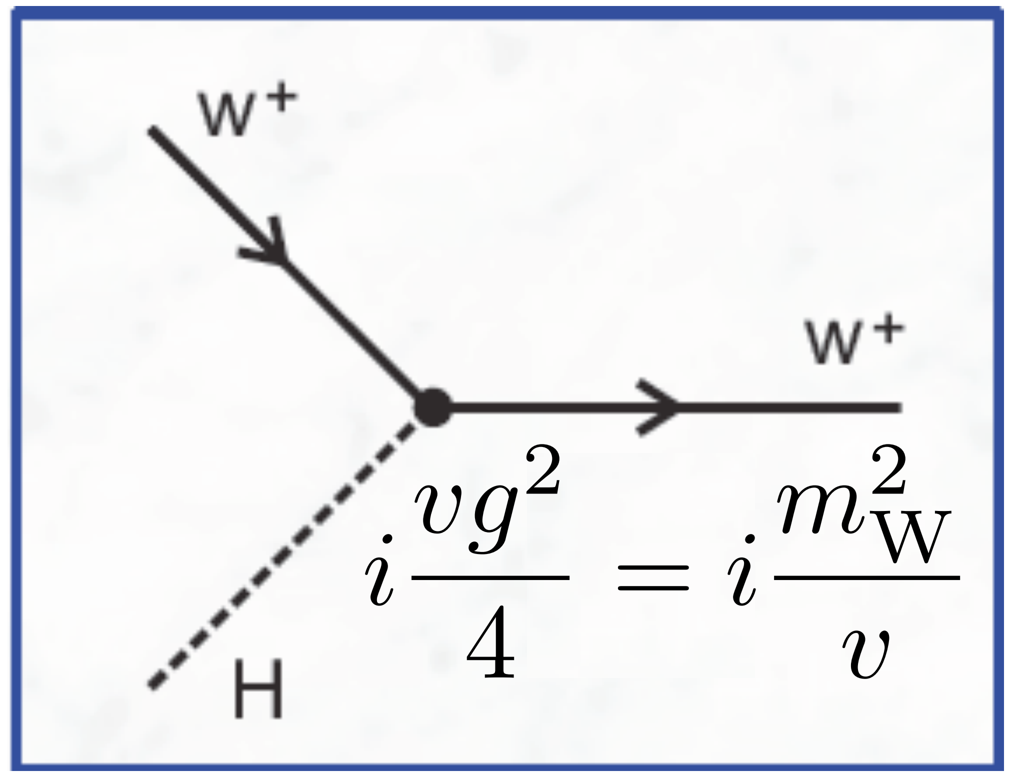
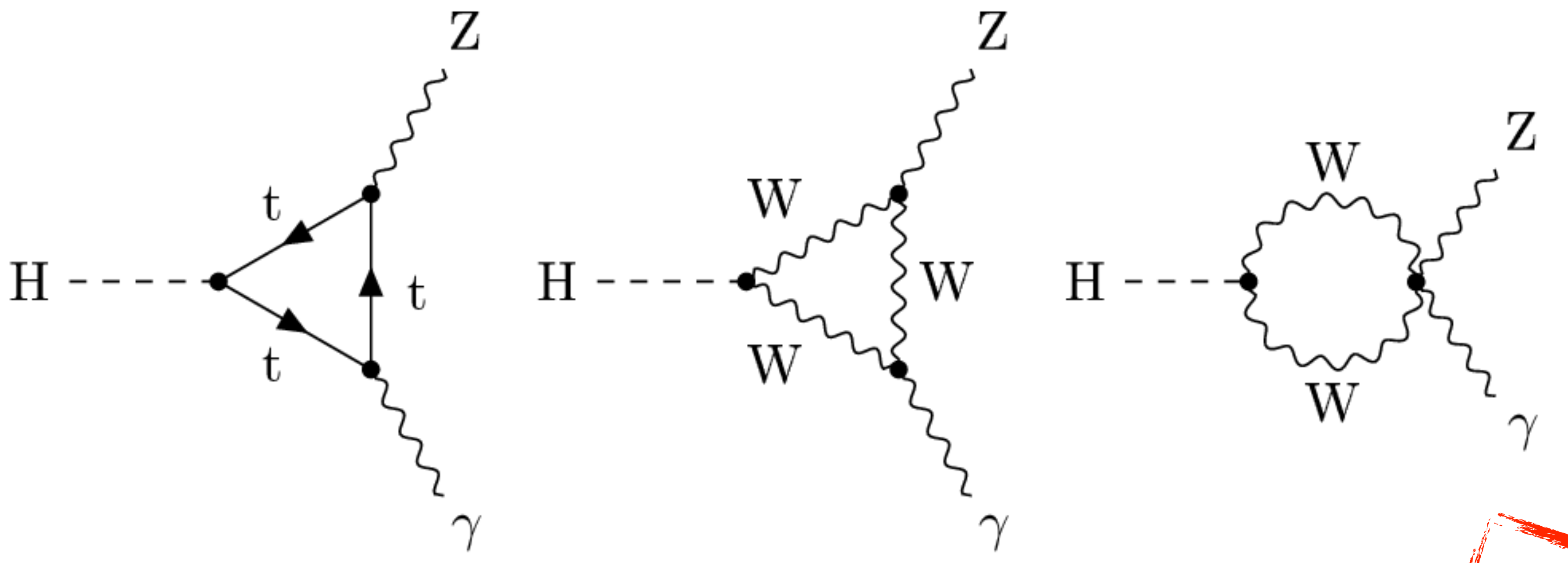


H → Zγ

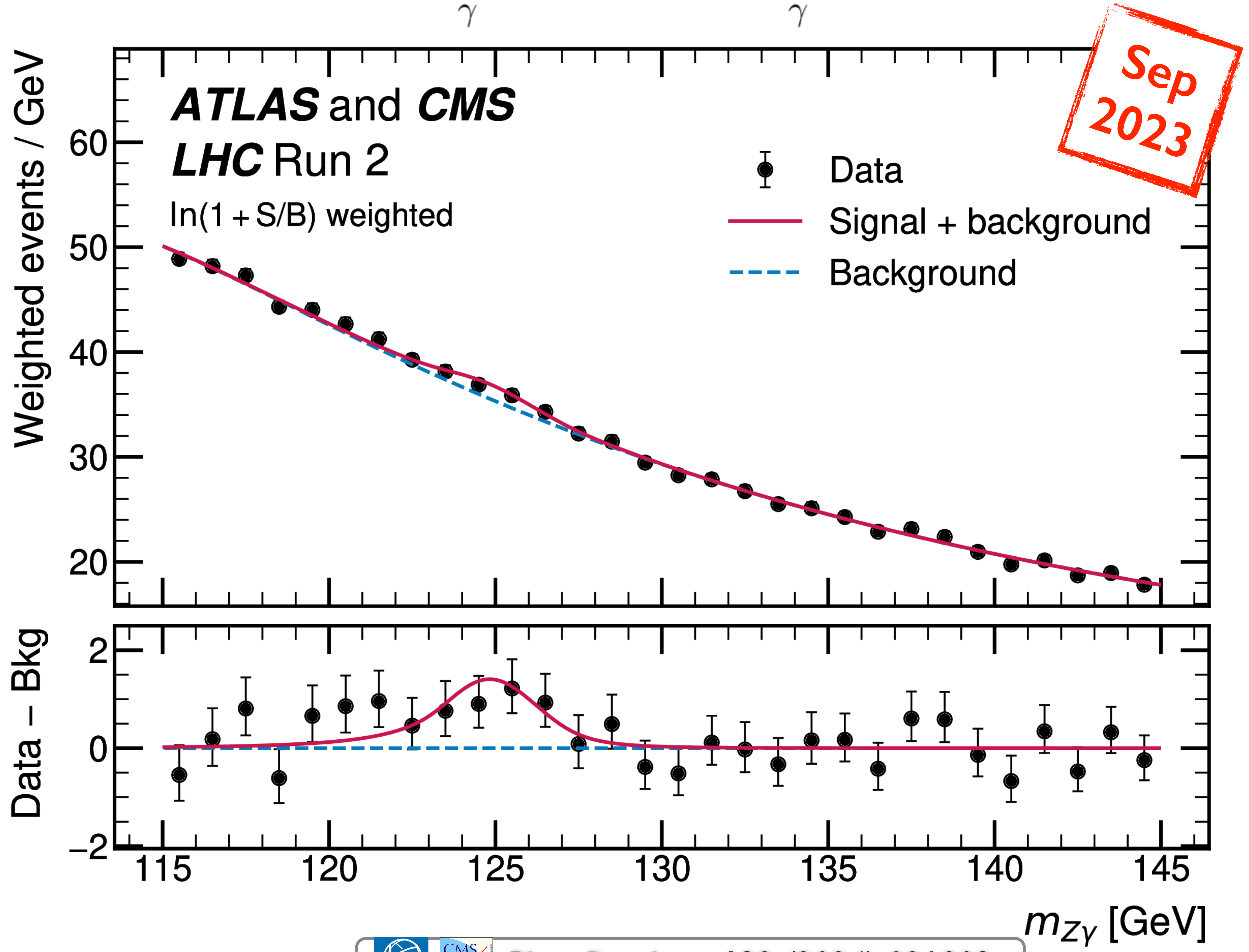
- **Small BR$_{SM}$(H → Zγ) ≈ 0.15%**
  - BR$_{SM}$(Z → ℓℓ) ≈ 3.4%

    ⇒ BR$_{SM}$(**H** → Zγ → ℓℓγ) = **0.01%**

⇒ **~765 H → Zγ → ℓℓγ events in 139 fb^{-1}**
  and difficult kinematics



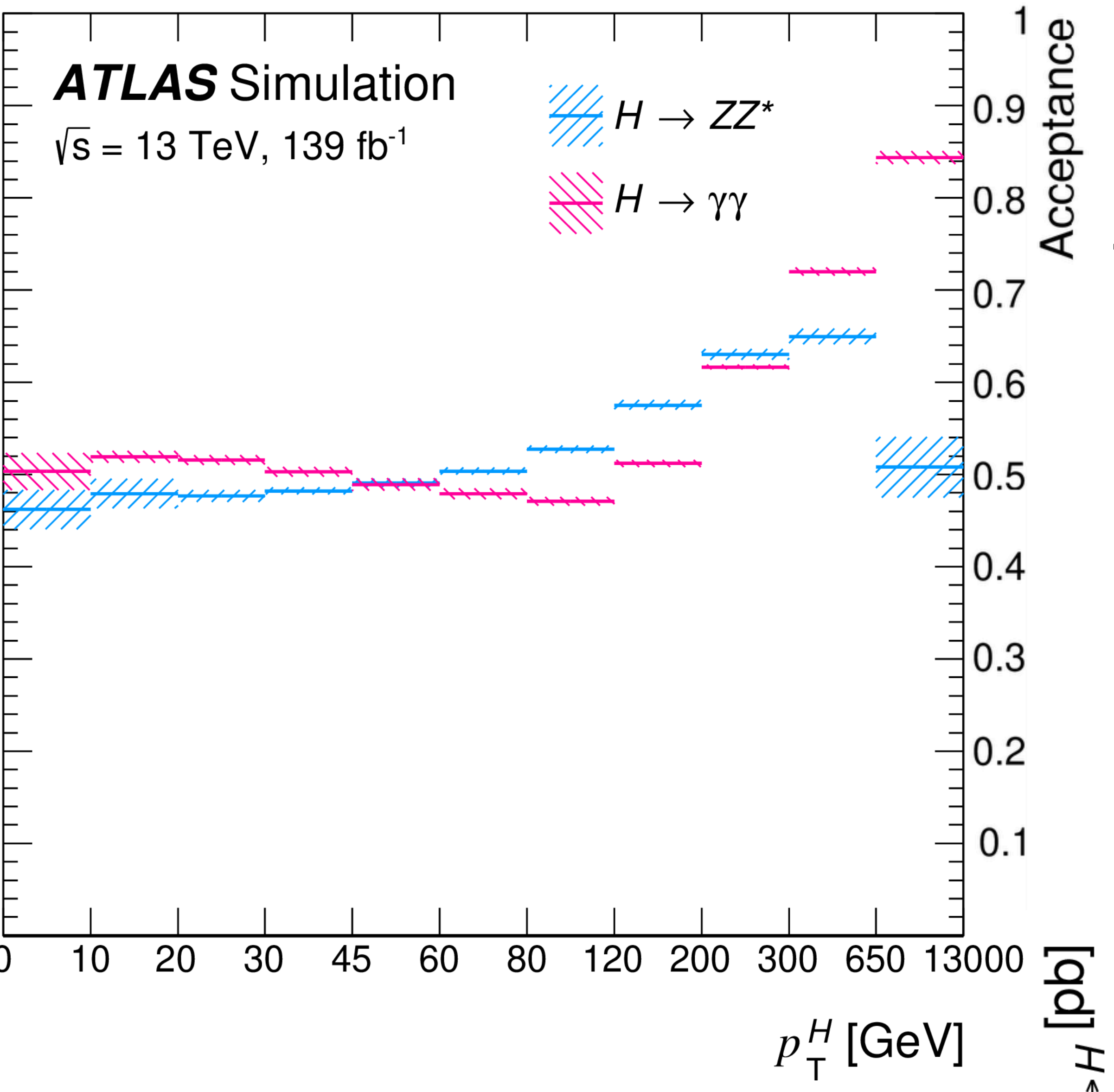
- First evidence from ATLAS+CMS combination:
  - Observed signal yield = **2.2 ± 0.7 × SM**
  - Observed (expected) significance: **3.4 σ** (1.6 σ)



Phys. Rev. Lett. 132 (2024) 021803

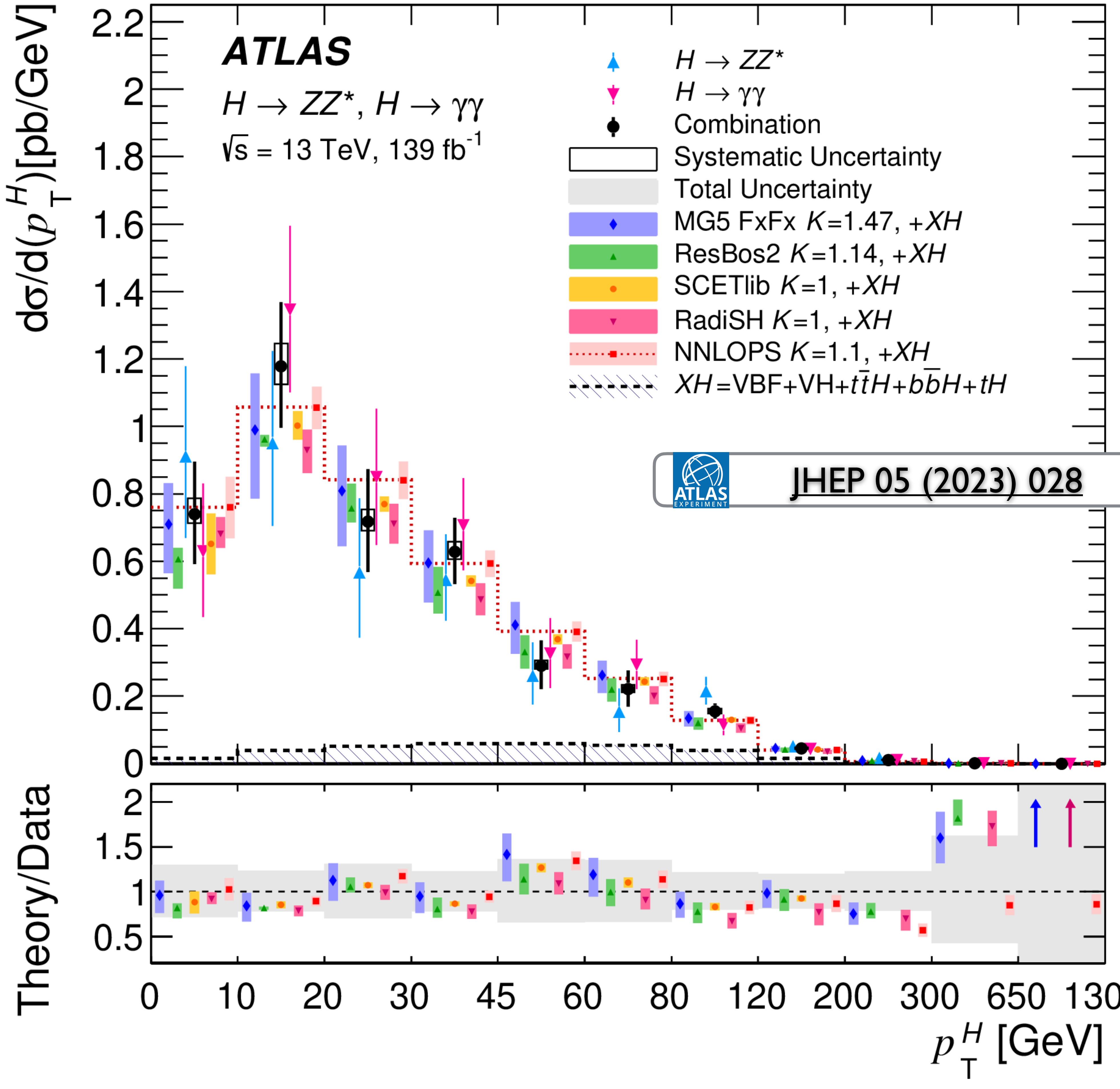
Combination: H → γγ and H → ZZ* → 4ℓ

Jan 2022



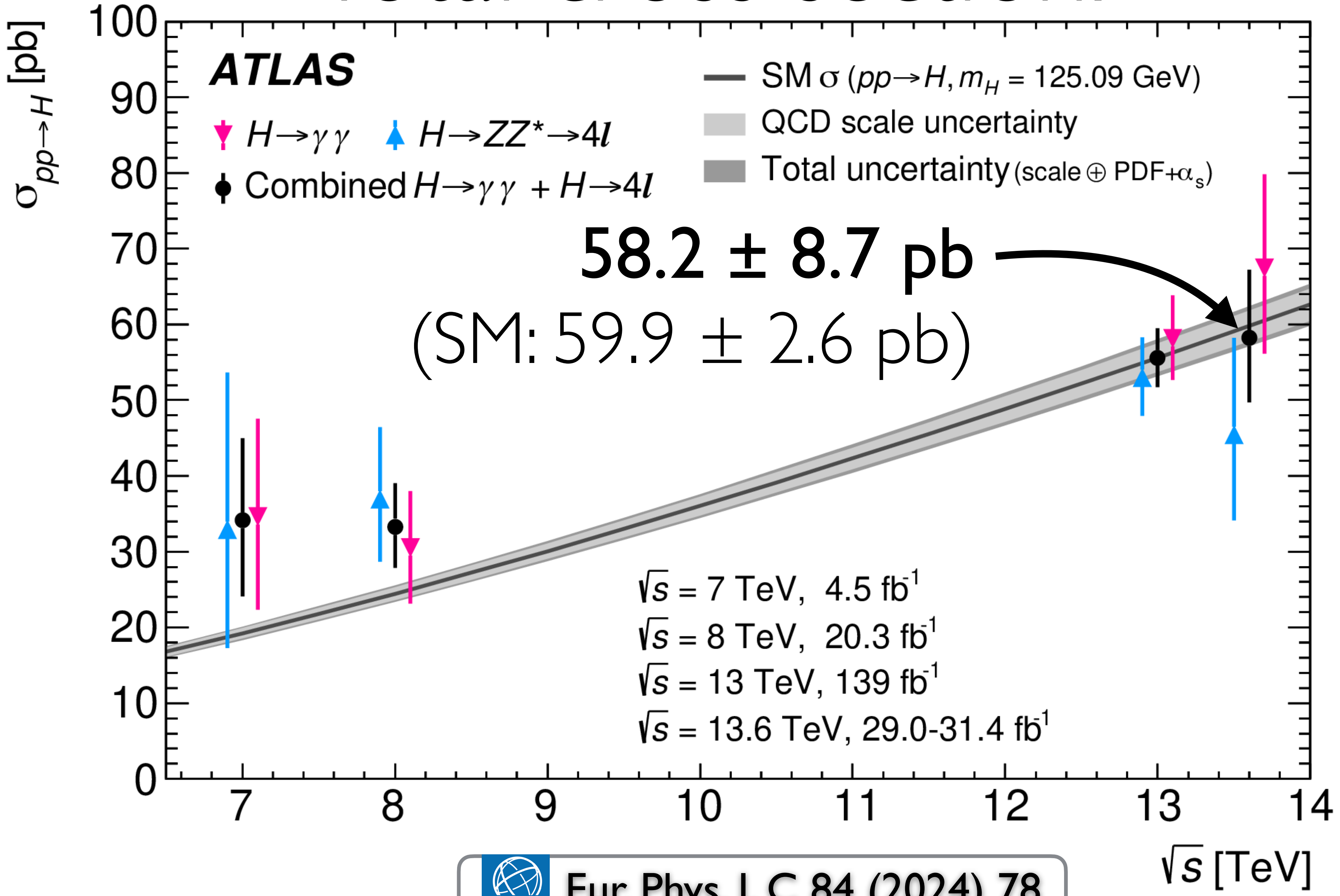
Extrapolate to full phase space

Measure y(H), N_{jet}, p_T(jet 1), and **p_T(H)**



JHEP 05 (2023) 028

Total cross section:



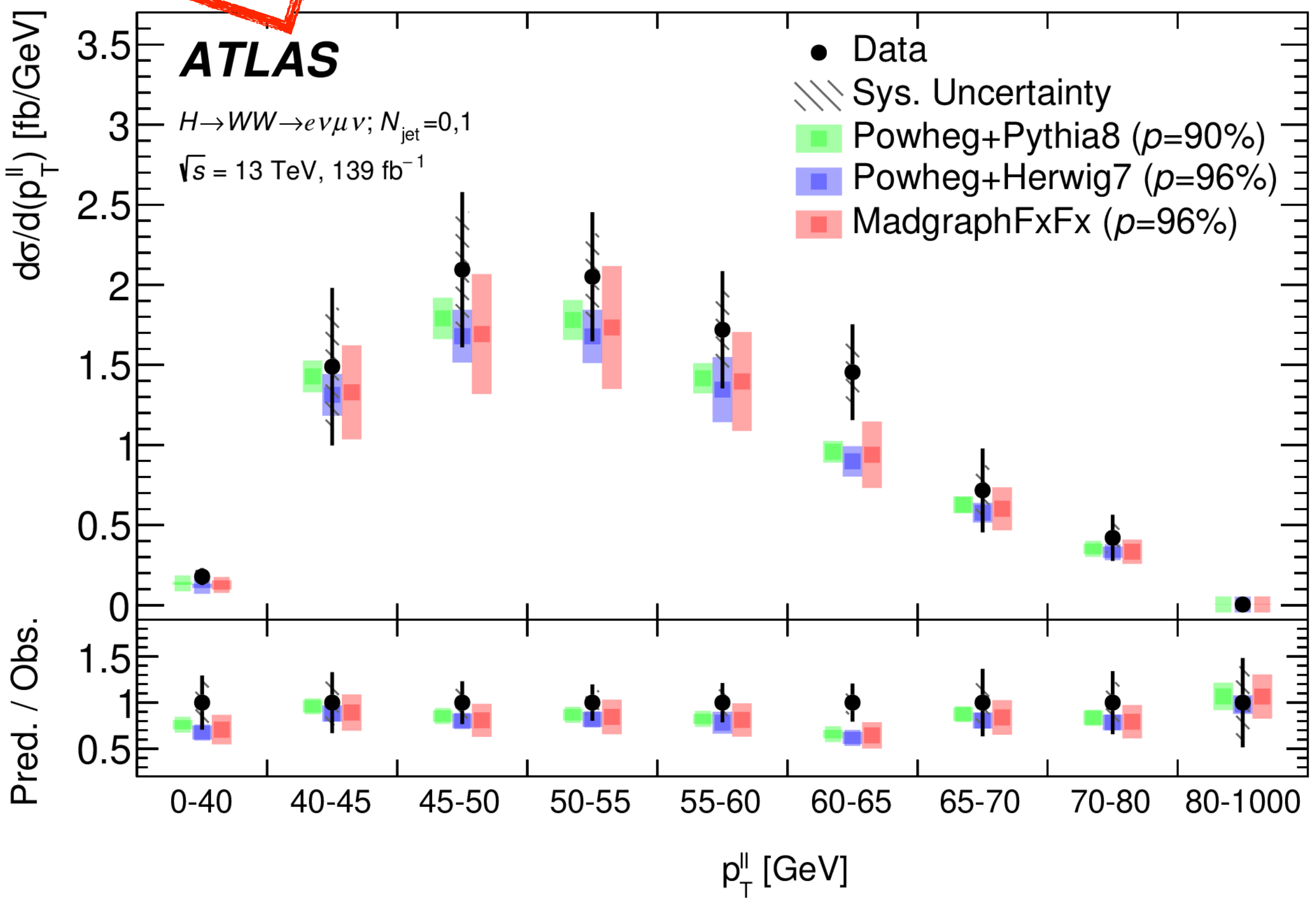
Eur. Phys. J. C 84 (2024) 78

H → WW* → ℓνℓν

- Differential cross sections

Jan 2023

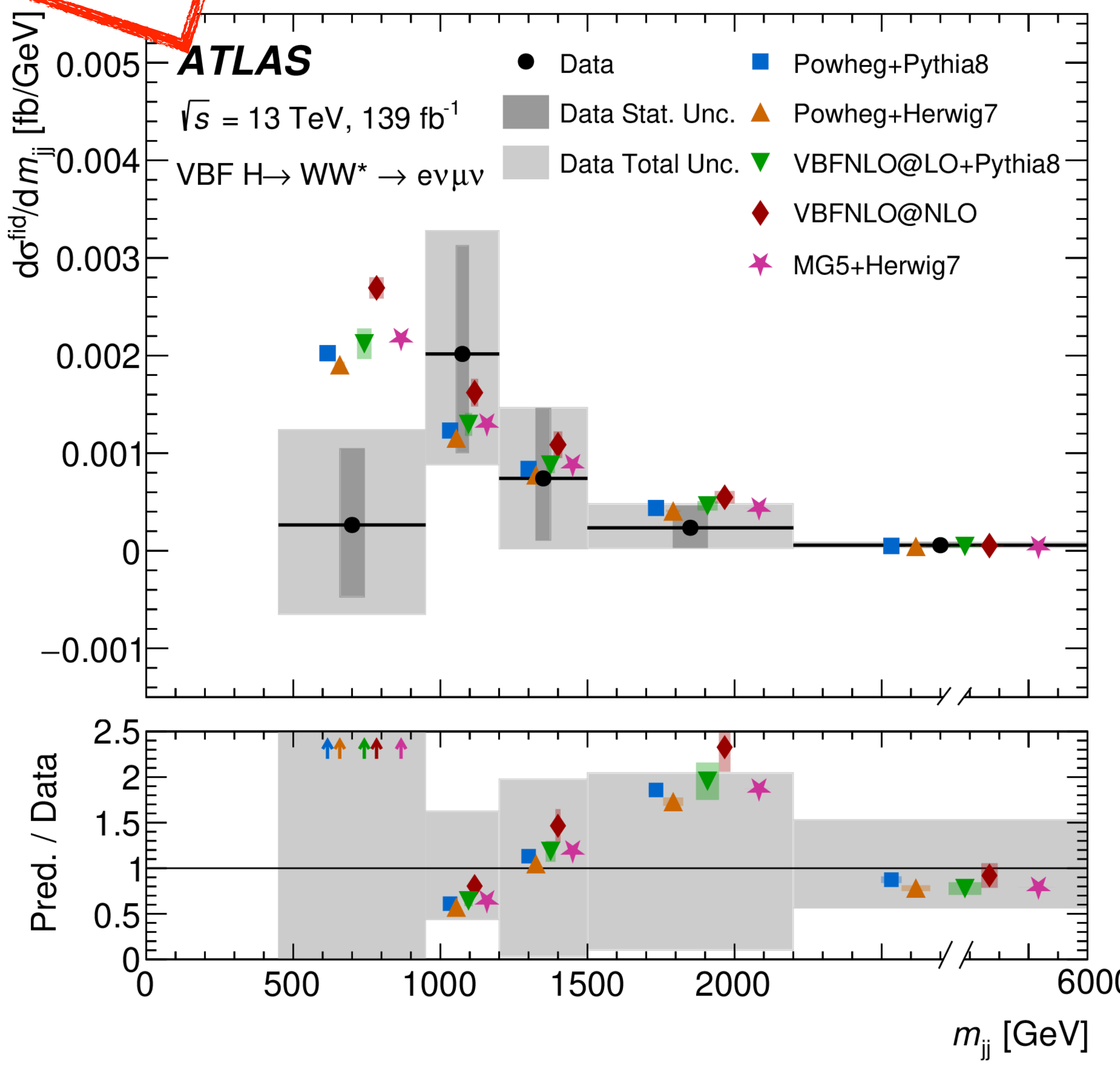
ggF production



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

April 2023

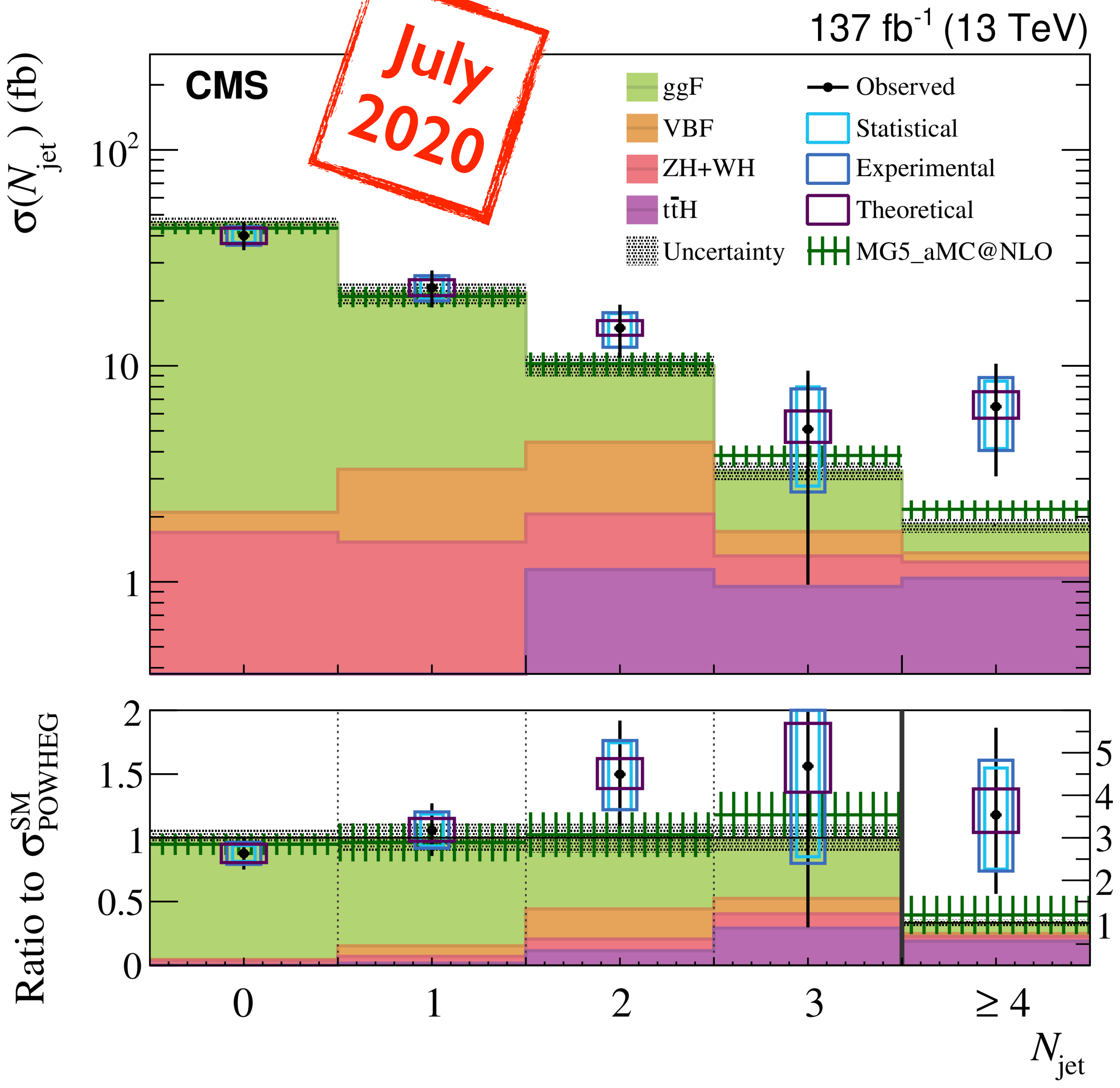
VBF phase space



Phys. Rev. D 108 (2023) 072003

All H → WW* → ℓνℓν

July 2020

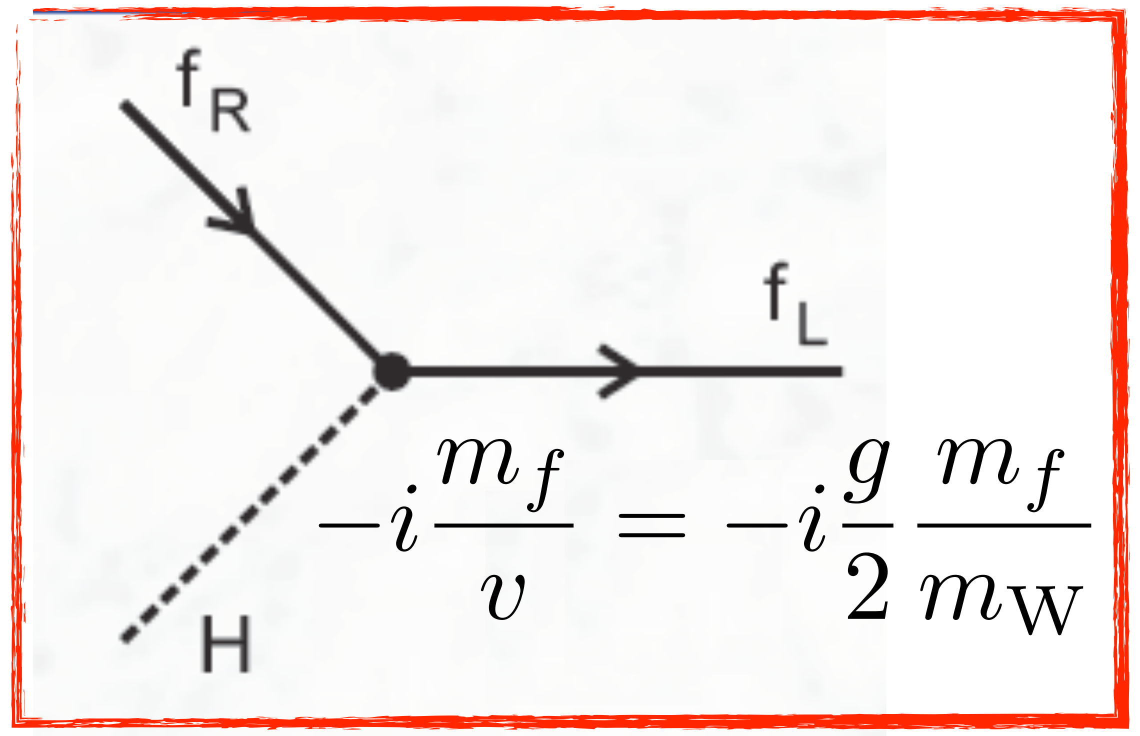


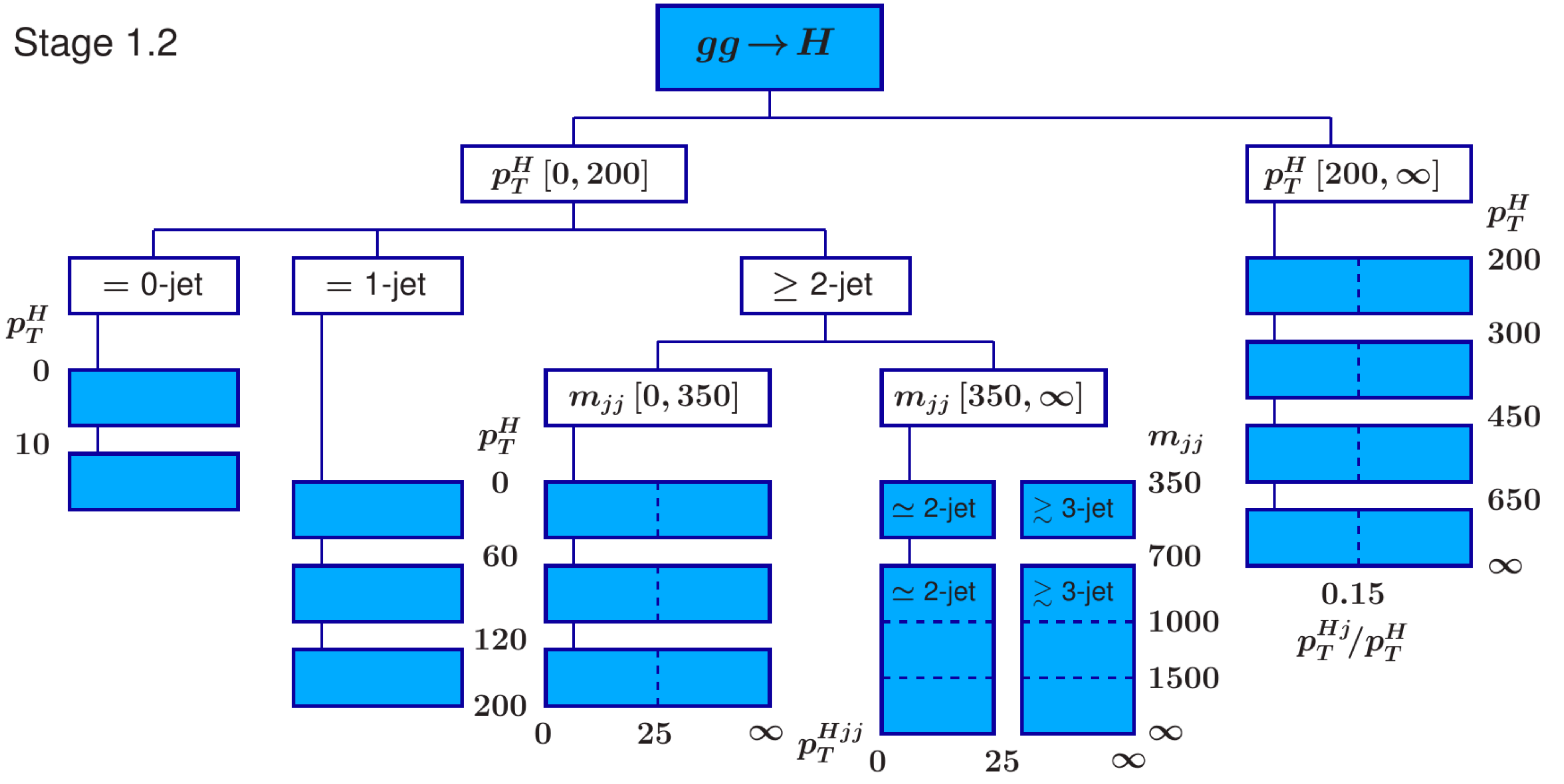
JHEP 03 (2021) 003

Outline

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

direct connection ⟷



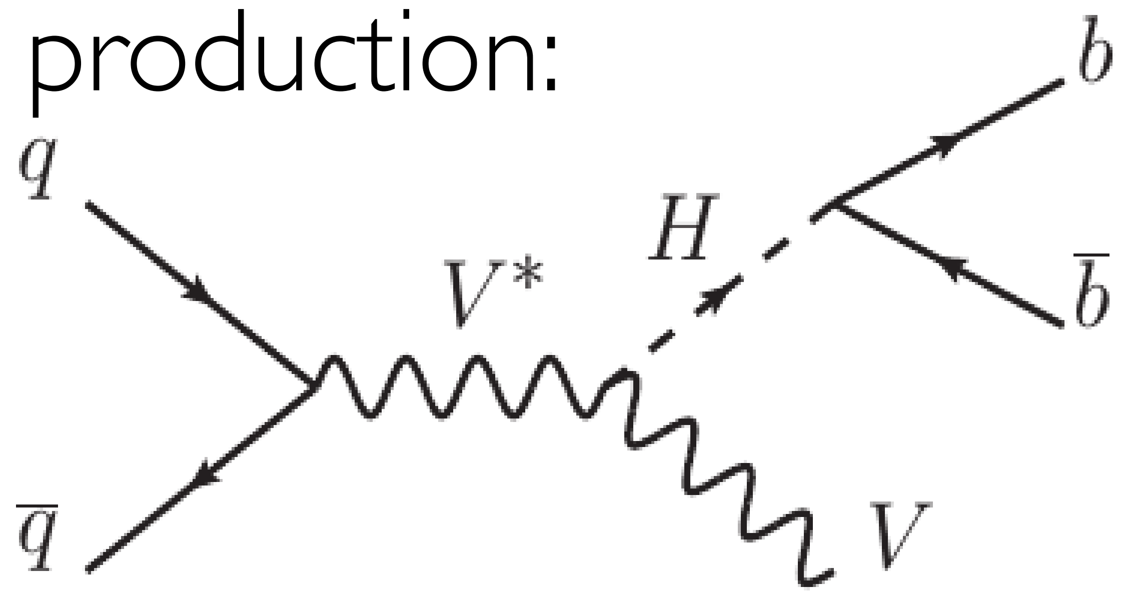


Karsten Köneke

$H \to b\bar{b}$

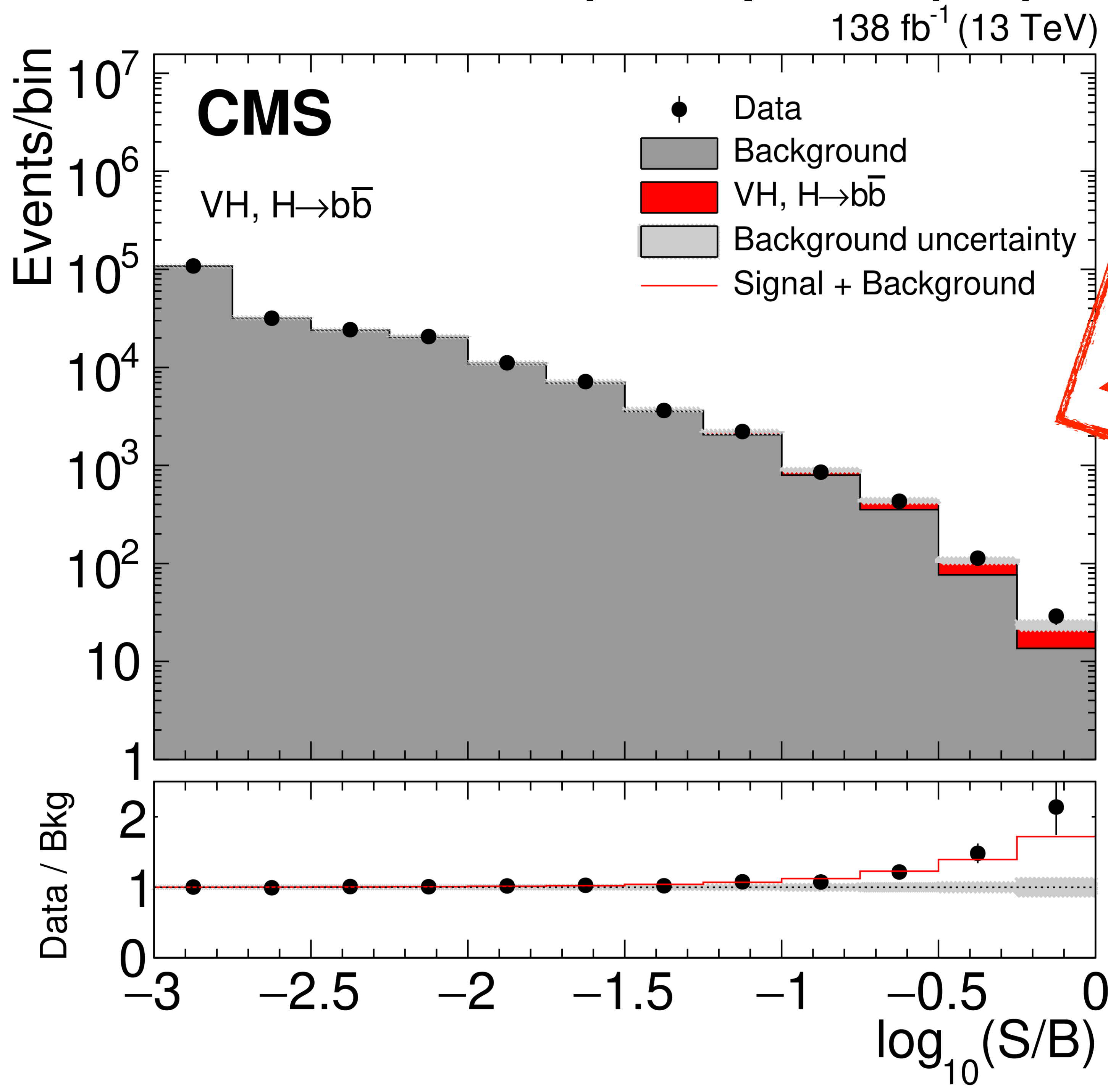
arXiv:2312.07562

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

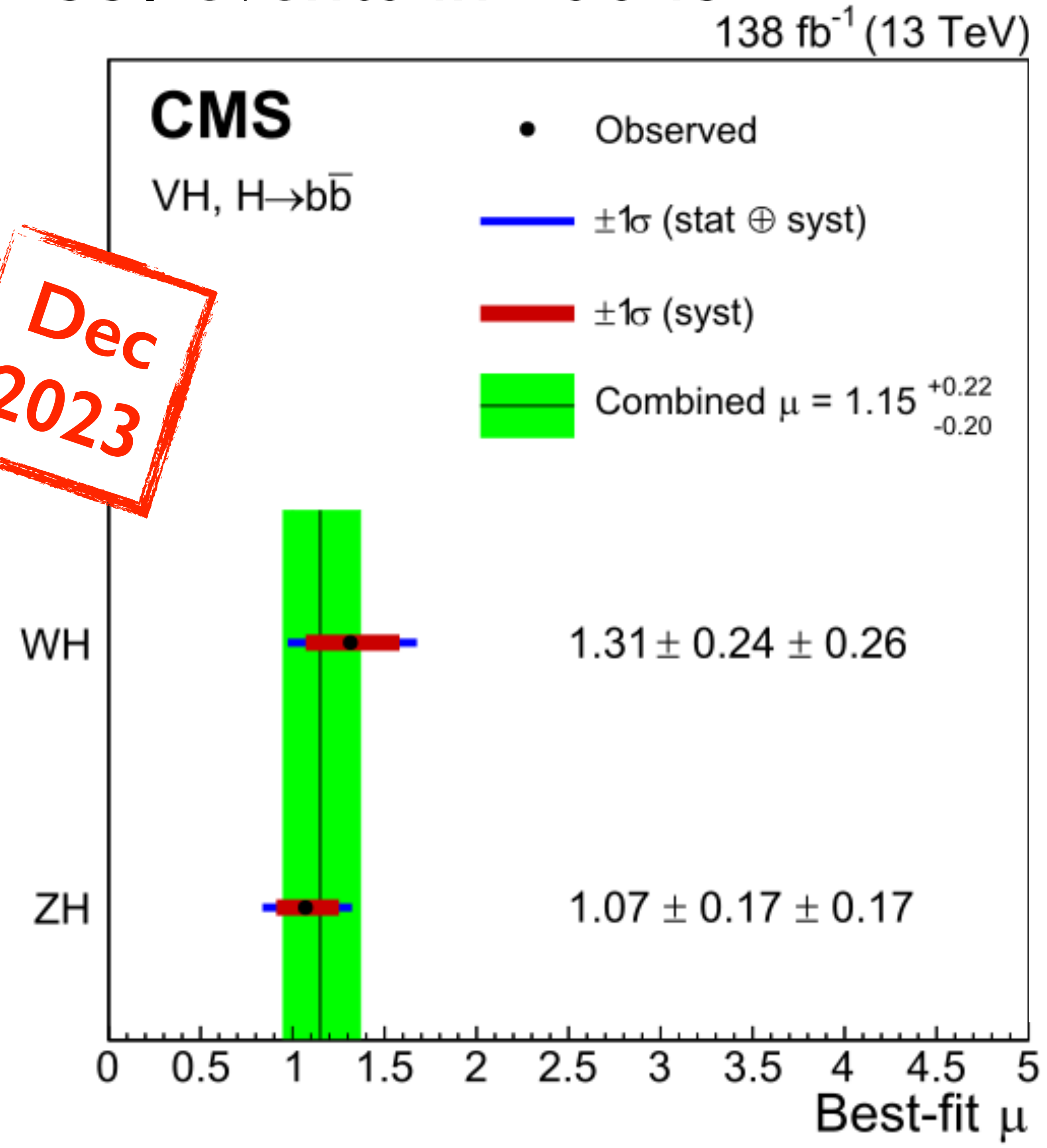


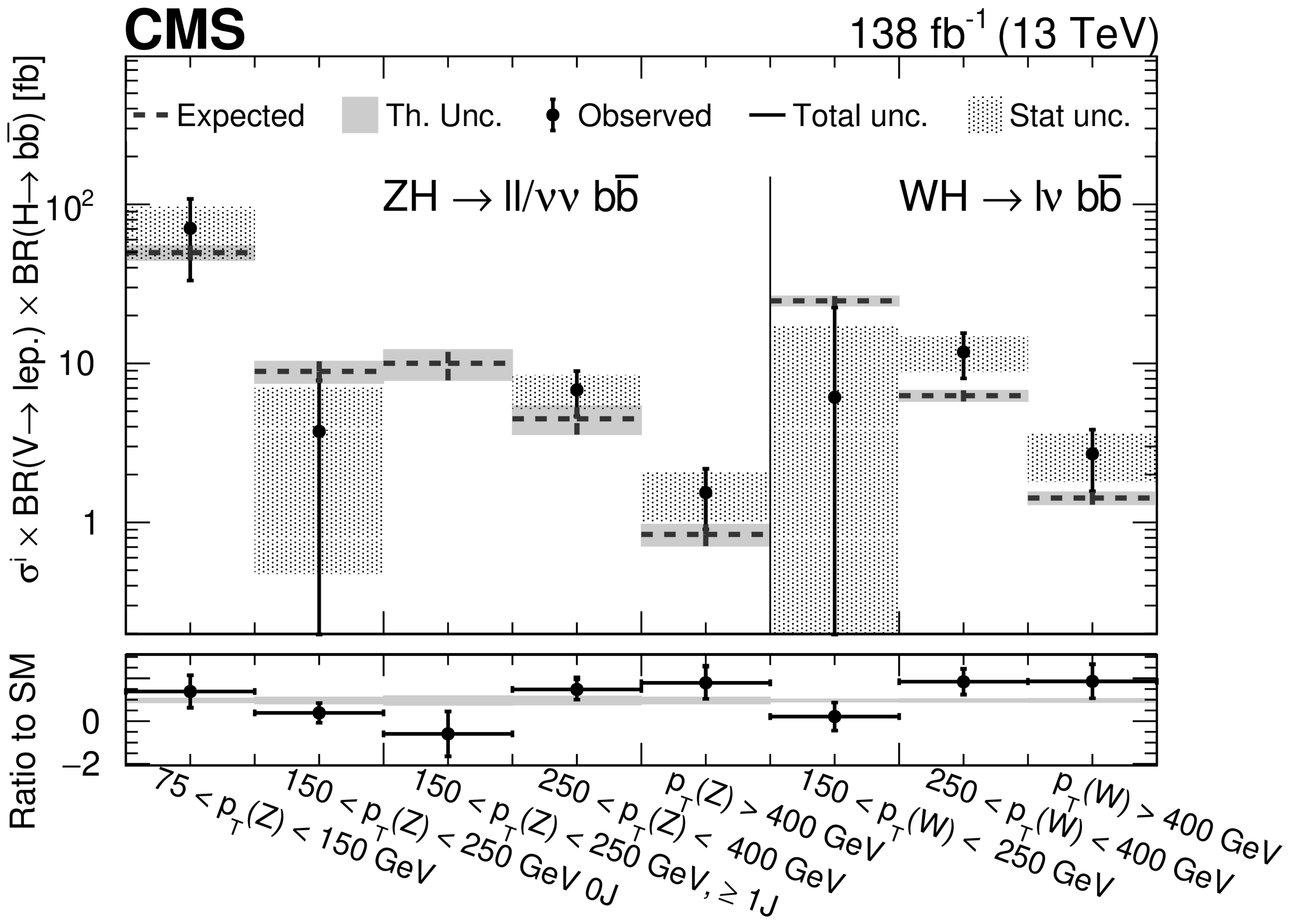
$\Rightarrow$ **~30000 V($\to$leptons)H($\to$ bb) events in 138 fb^{-1}**

- Resolved & boosted channels
- DNNs & BDTs for signal extraction
  - $\mu = 1.15^{+0.22}_{-0.20}$



Dec 2023



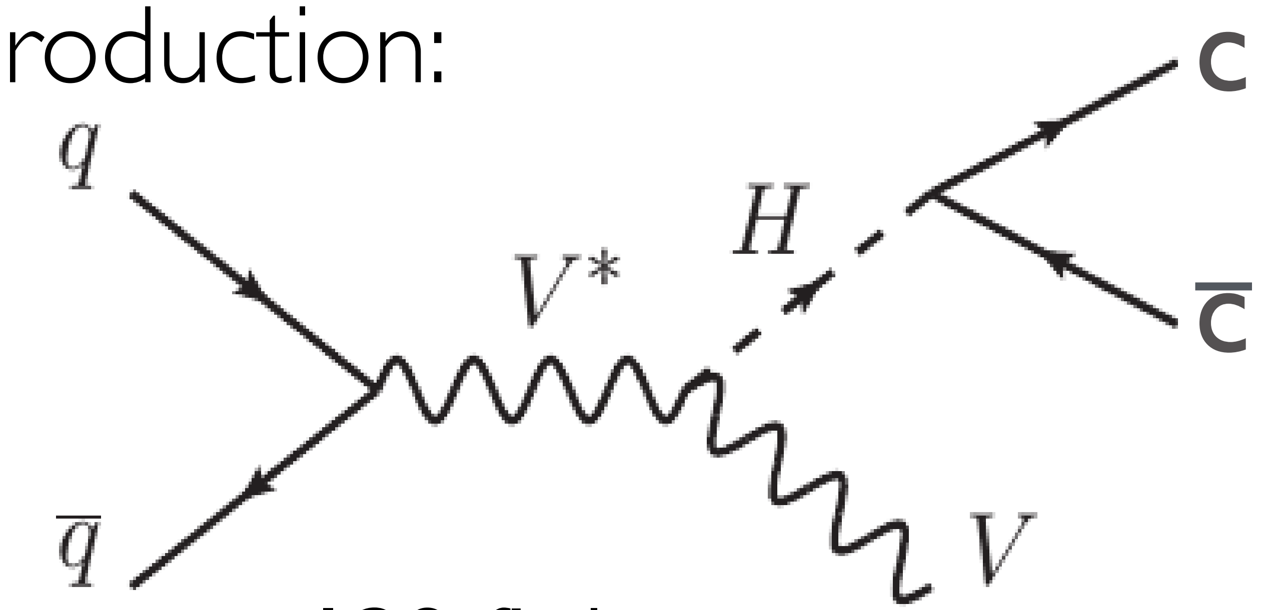


$\Rightarrow$ New ATLAS V(qq)H(bb) boosted result

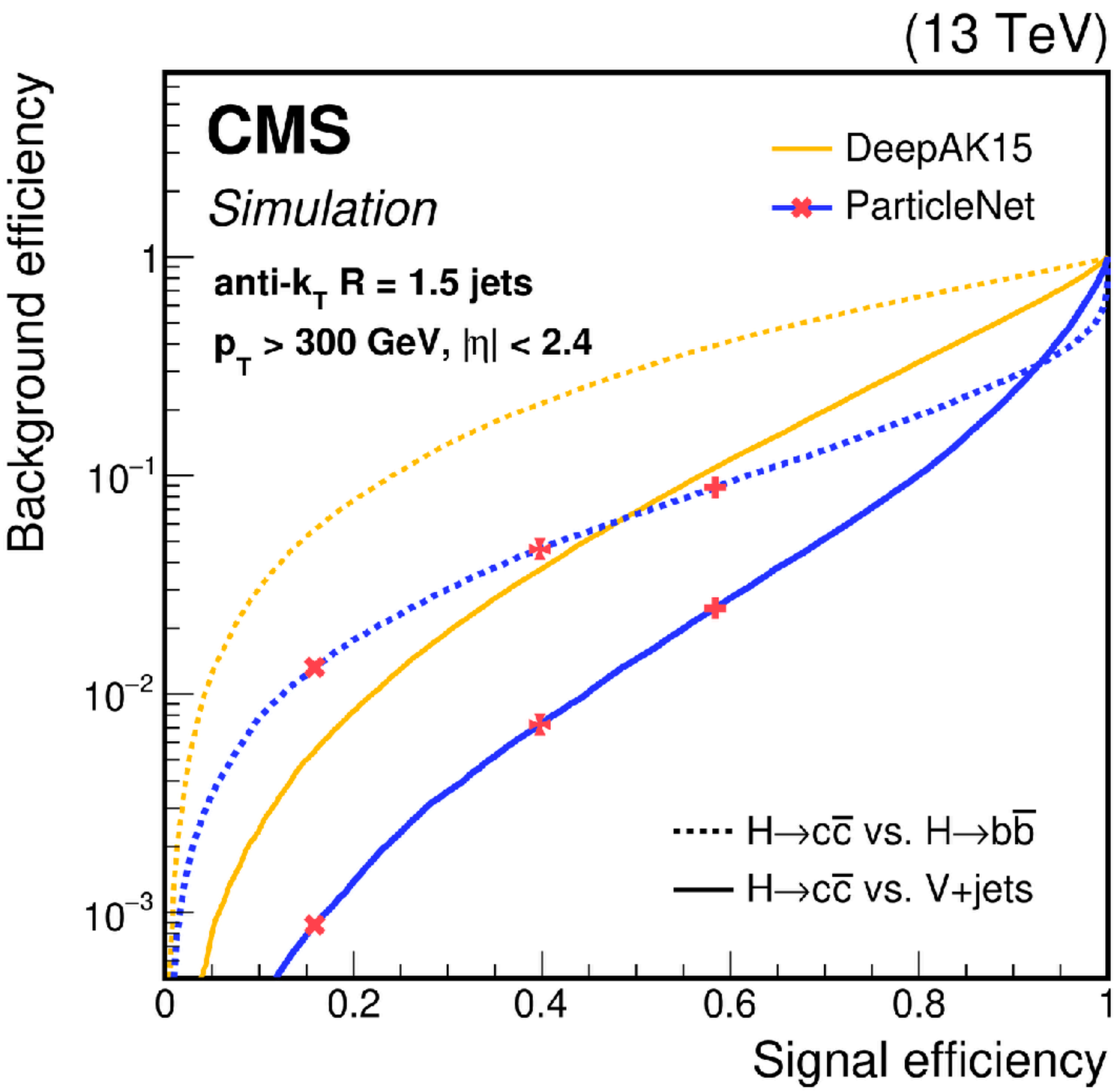
H → $c\bar{c}$

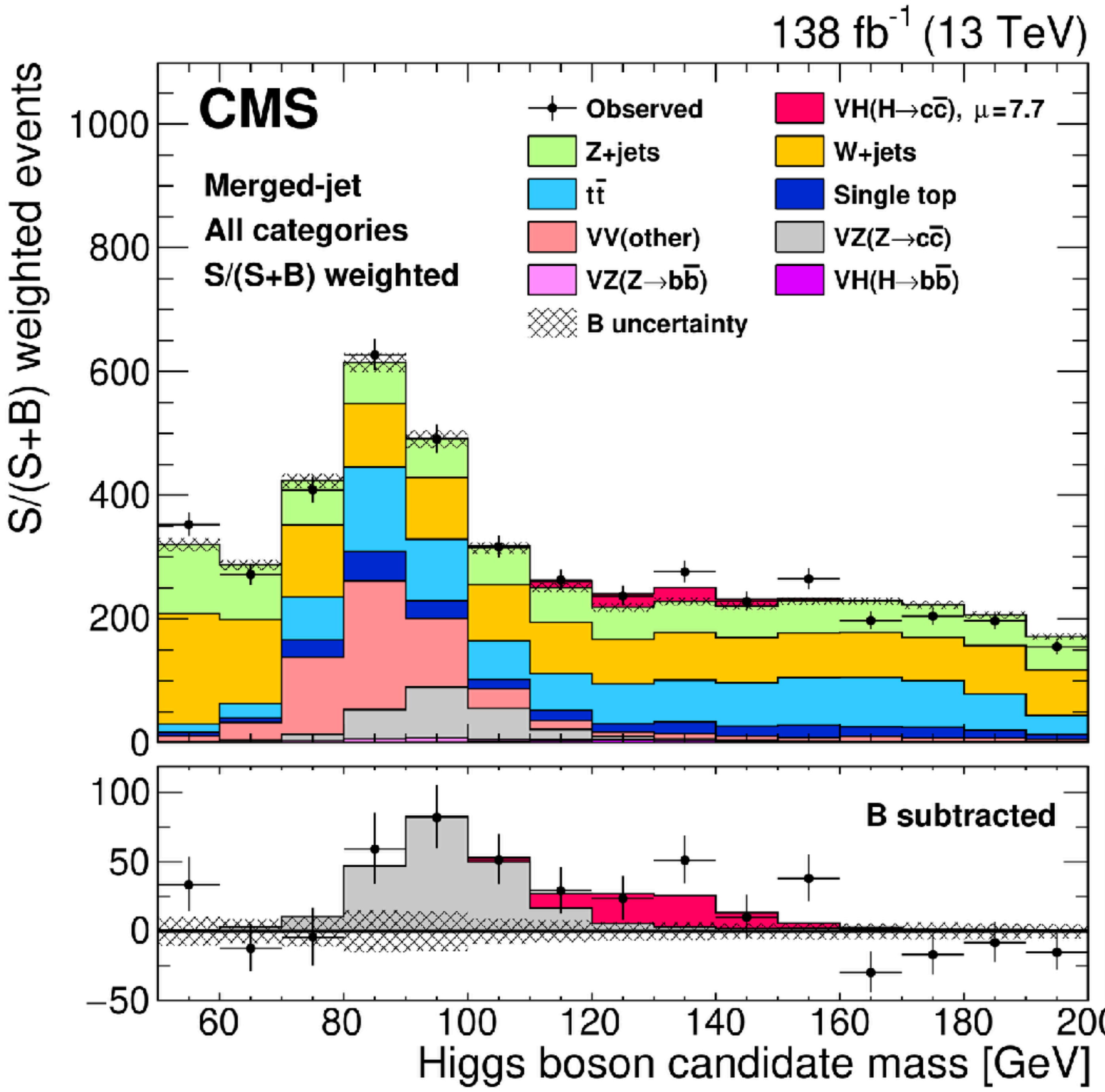
Phys. Rev. Lett. 131 (2023) 061801

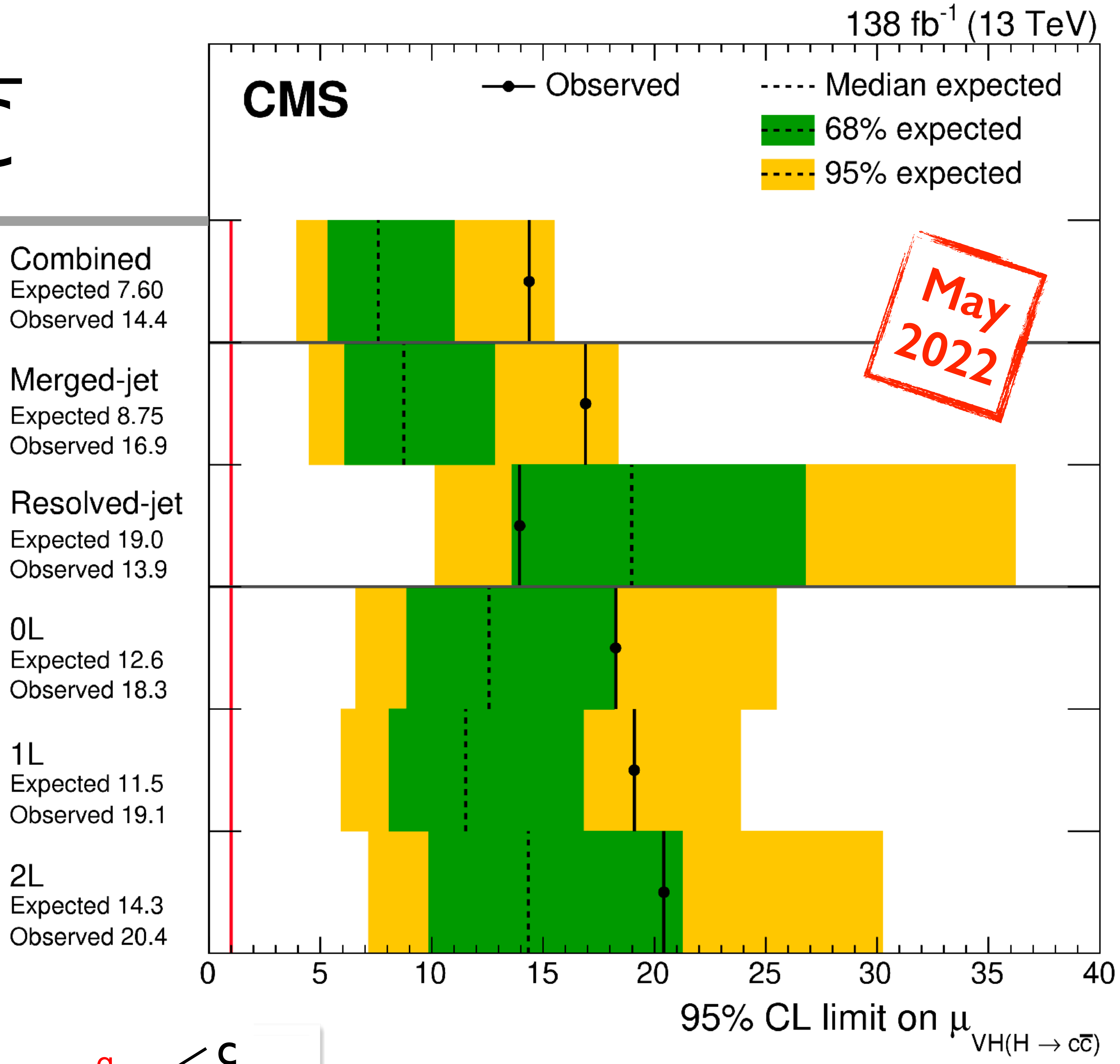
- H → cc 2nd generation decay channel (**BR ~2.9%**)
- VH (V=W or Z) associated production:
  - 0 lepton (Z → νν)
  - 1 lepton (W → ℓν)
  - 2 lepton (Z → ℓℓ)

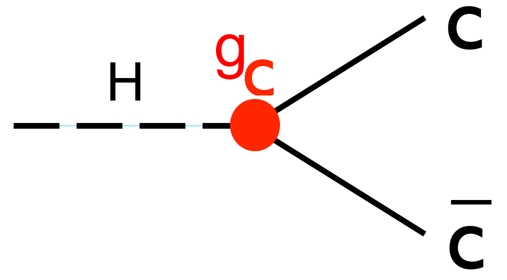


⇒ **~1500 V(→leptons)H(→cc) events in 139 fb⁻¹**









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

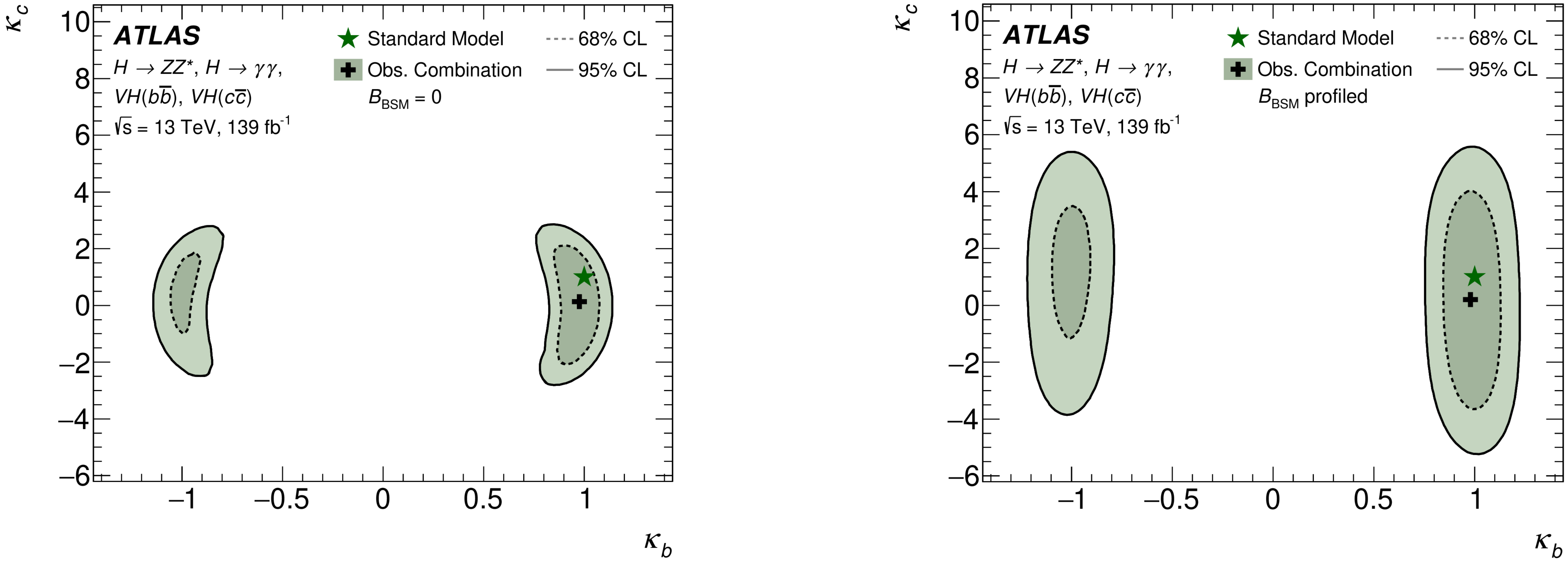
$$\mu := \frac{\sigma_i \cdot \mathcal{B}^f}{(\sigma_i \cdot \mathcal{B}^f)_{SM}} = \frac{\text{observed rate}}{\text{expected rate}}$$

Observed (expected) limit on Higgs-charm coupling modifier:
1.1 < |κc| < 5.5 (|κc| < 3.4) (95% C.L.)

⇒ ATLAS result

Combined κ_b and κ_c extraction

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



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

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HL-LHC Combination: H → bb and H → cc

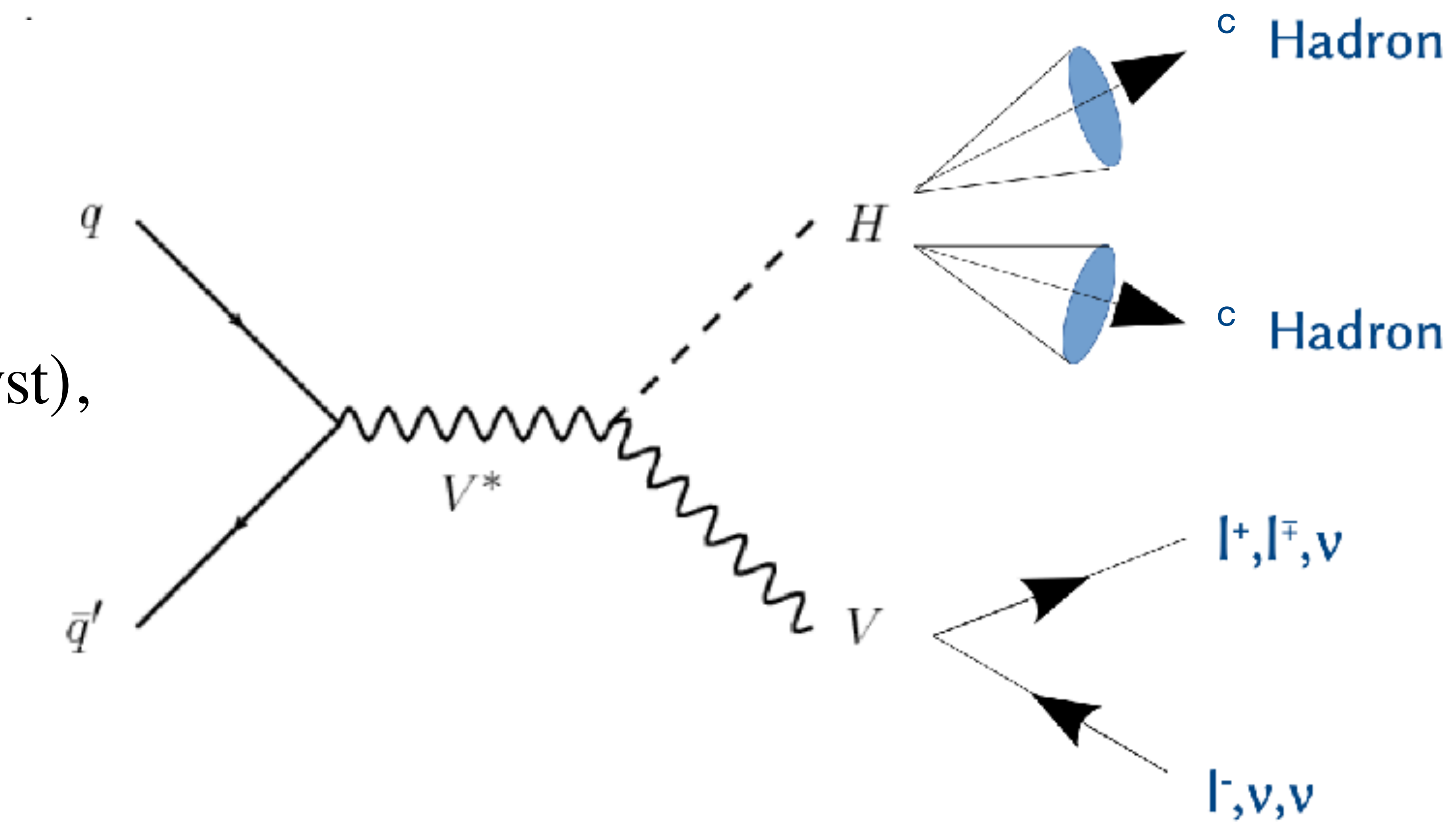
CMS-PAS-FTR-22-001

ATL-PHYS-PUB-2021-039

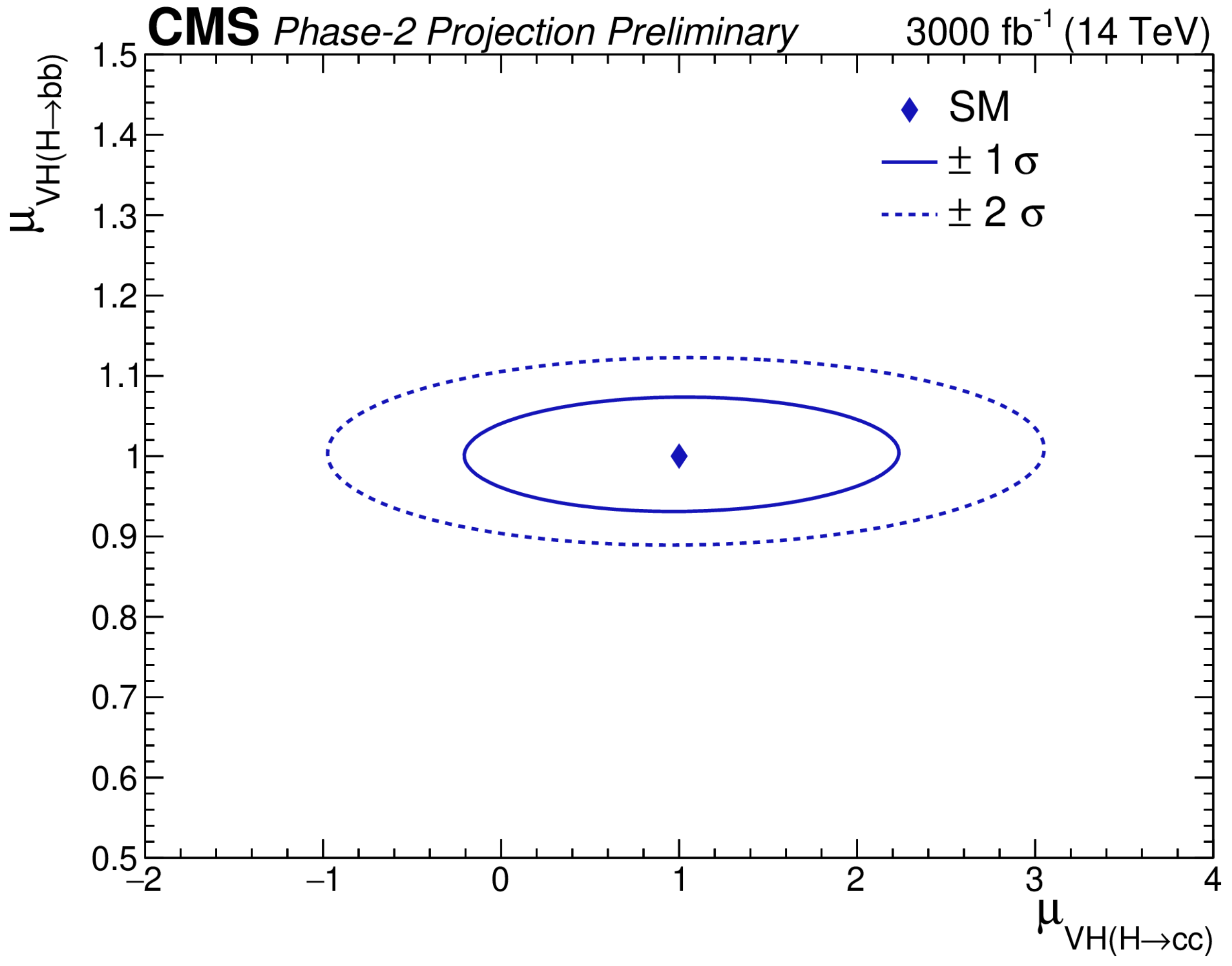
Aug 2022

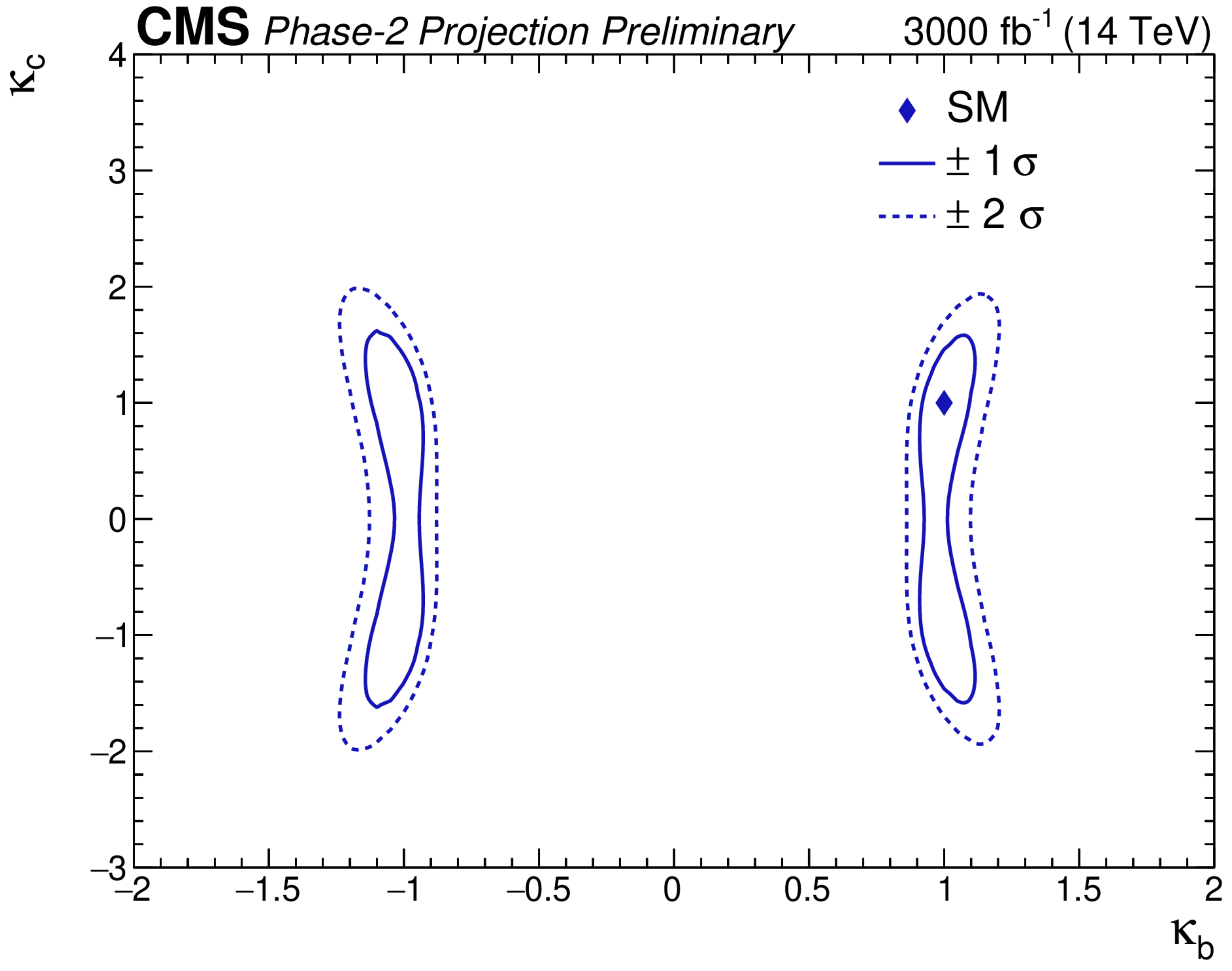
Nov 2021

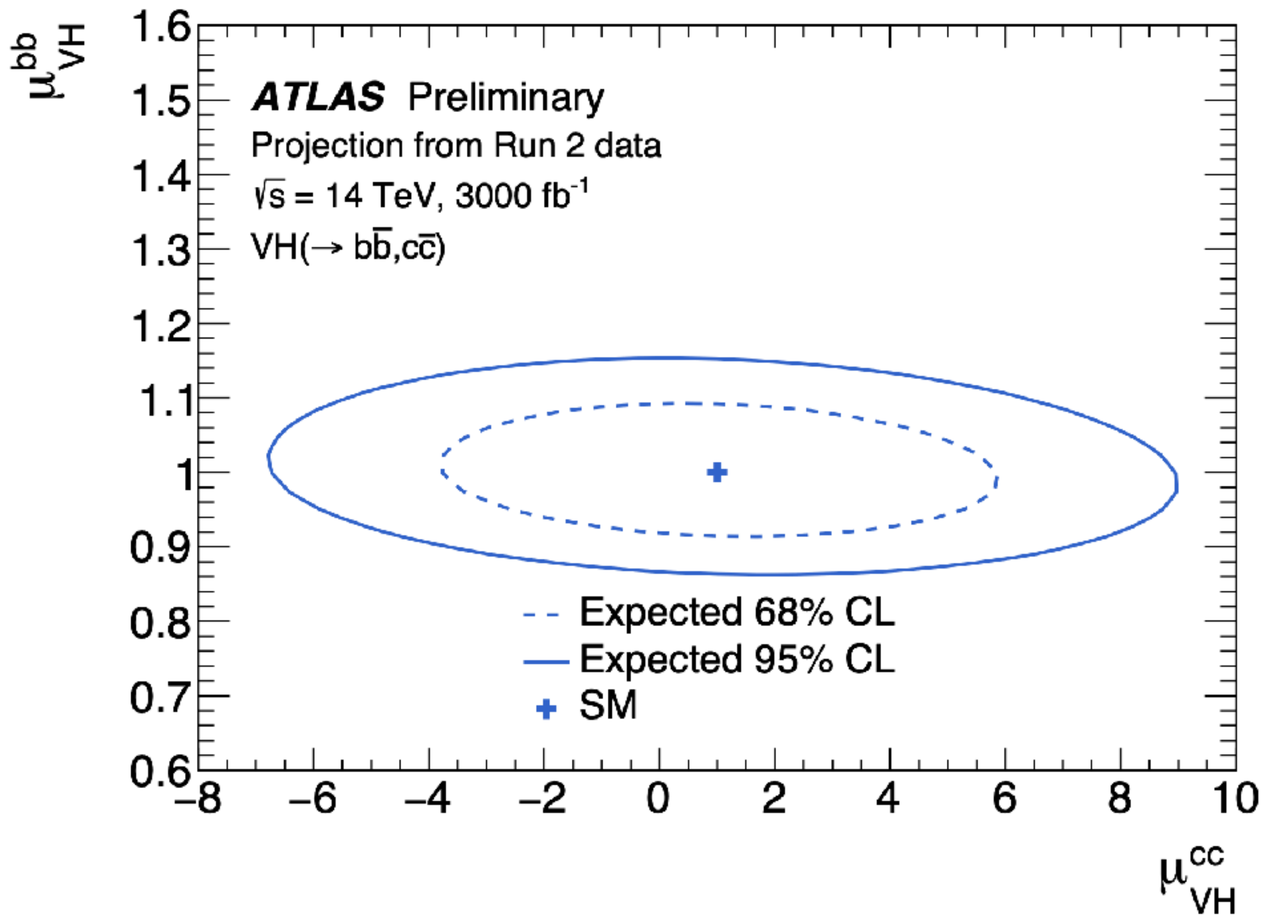
$$\mu_{VH(H\to b\bar{b})} = 1.00 \pm 0.03(\text{stat}) \pm 0.04(\text{syst}),$$
$$\mu_{VH(H\to c\bar{c})} = 1.0 \pm 0.6(\text{stat}) \pm 0.5(\text{syst}).$$



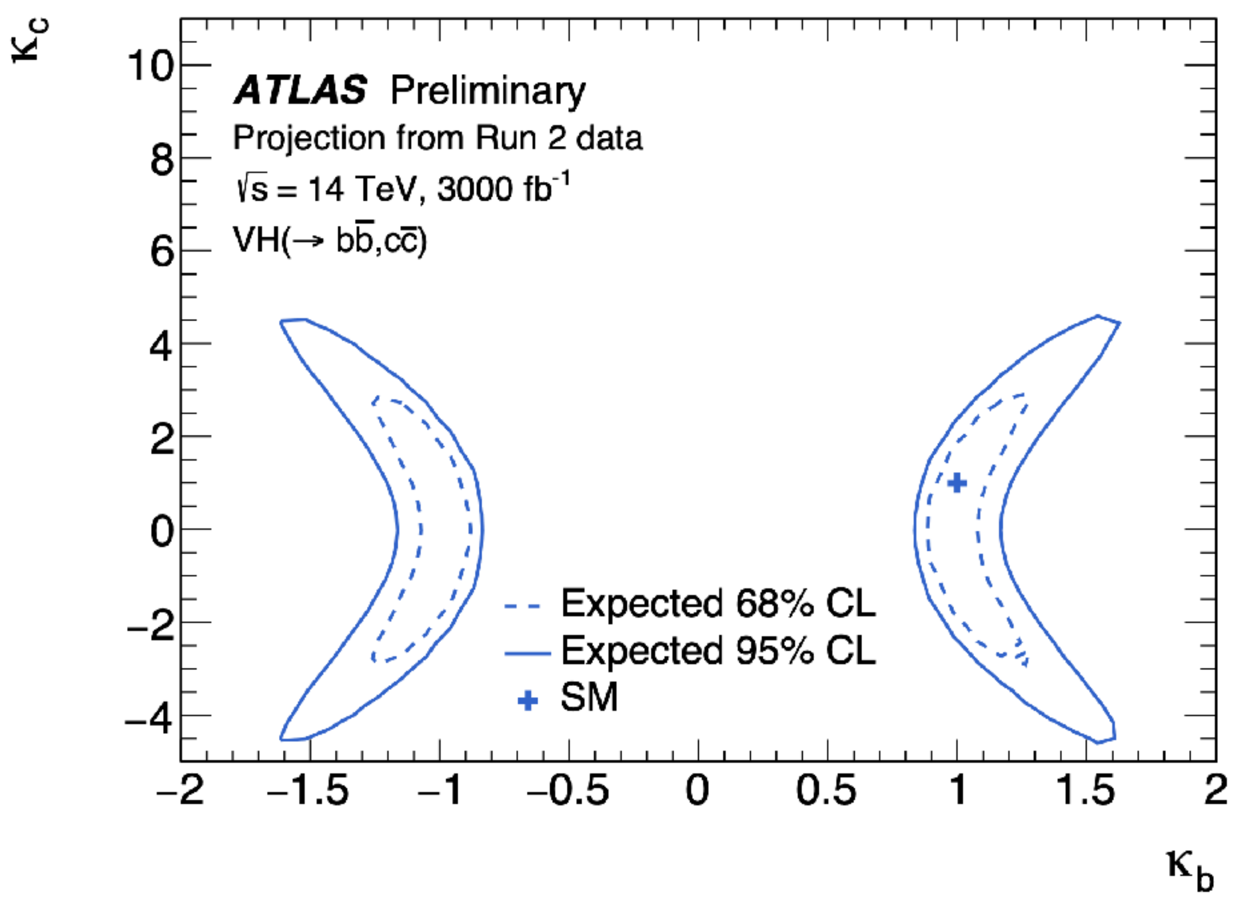
$$\mu_{VH}^{b\bar{b}} = 1.00 \pm 0.06,$$
$$\mu_{VH}^{c\bar{c}} = 1.00 \pm 3.20$$







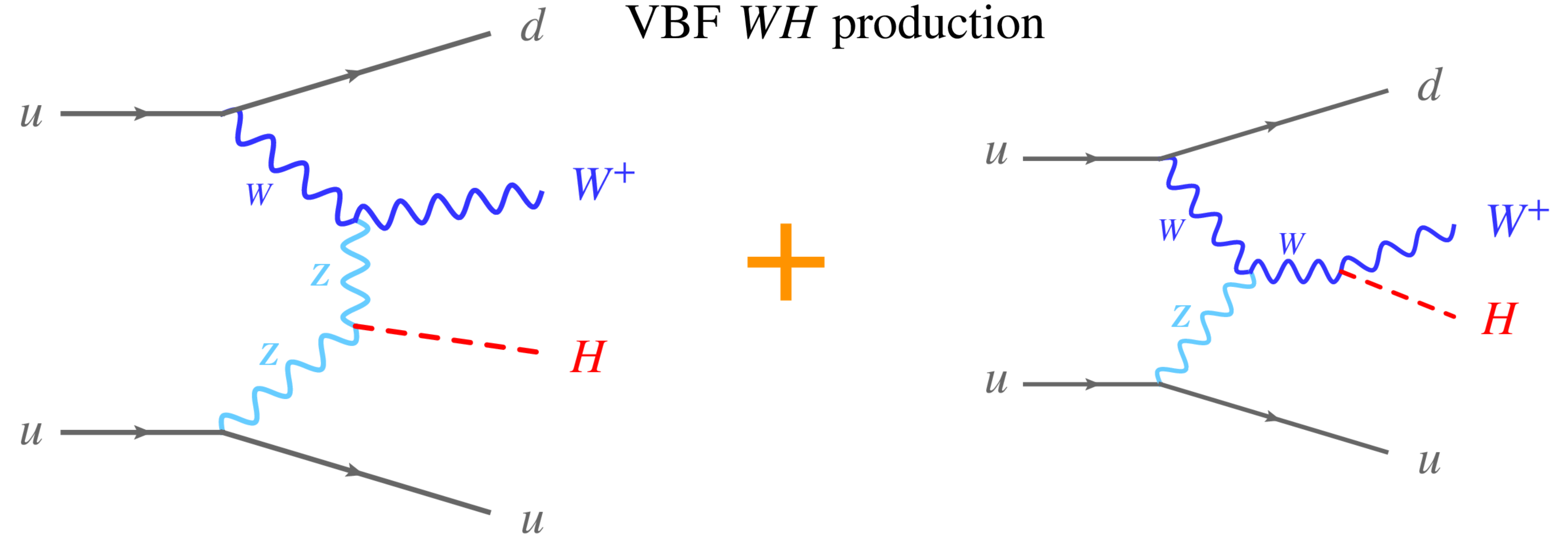
Moderate correlation of **-11%**



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

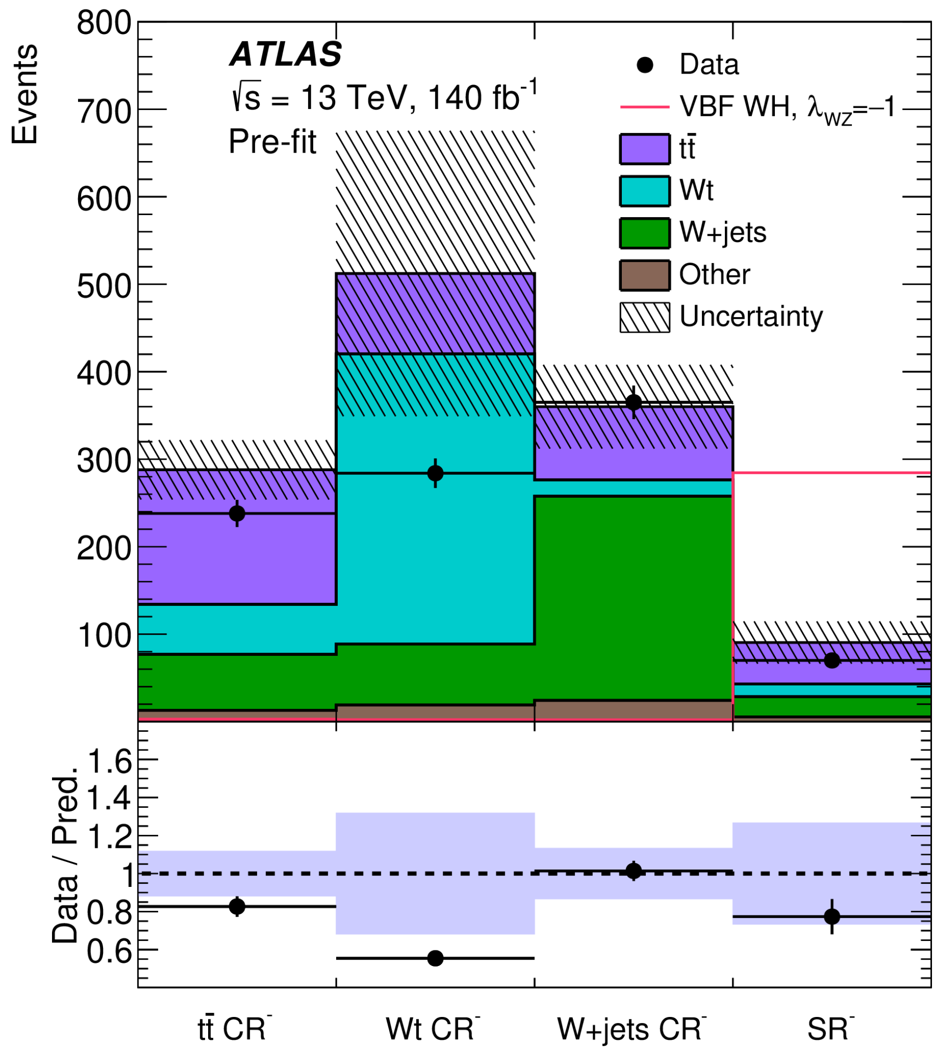
Relative sign between HZZ and HWW coupling

VBF WH production

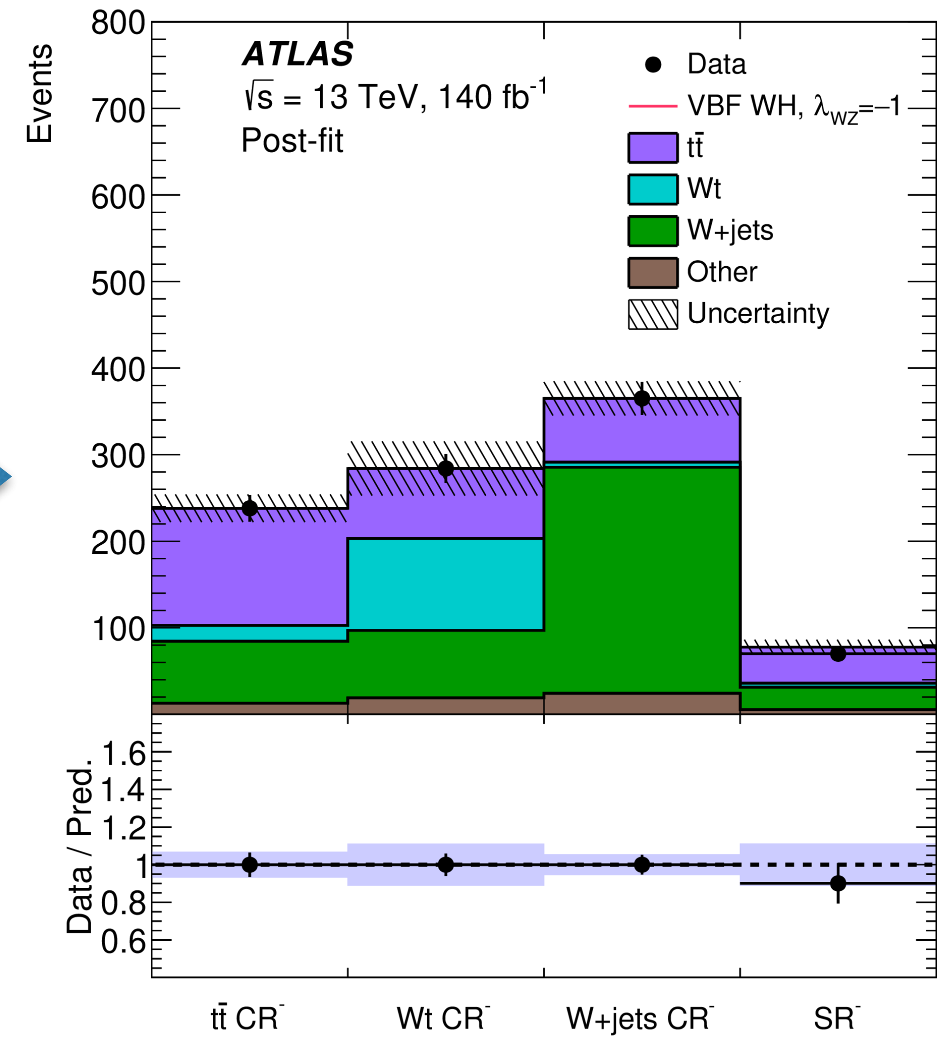


$\sim \kappa_Z^2$ Interference $\sim \kappa_W \kappa_Z$ $\sim \kappa_W^2$

$$\sigma_{\mathrm{VBF},WH} \propto \kappa_Z^2 |\mathcal{M}_Z|^2 + \kappa_W^2 |\mathcal{M}_W|^2 - 2\kappa_Z \kappa_W \Re[\mathcal{M}_Z^\dagger \mathcal{M}_W]$$
$$= \kappa_Z^2 |\mathcal{M}_Z|^2 + \kappa_W^2 |\mathcal{M}_W|^2 - 2\kappa_Z^2 \lambda_{WZ} \Re[\mathcal{M}_Z^\dagger \mathcal{M}_W]$$

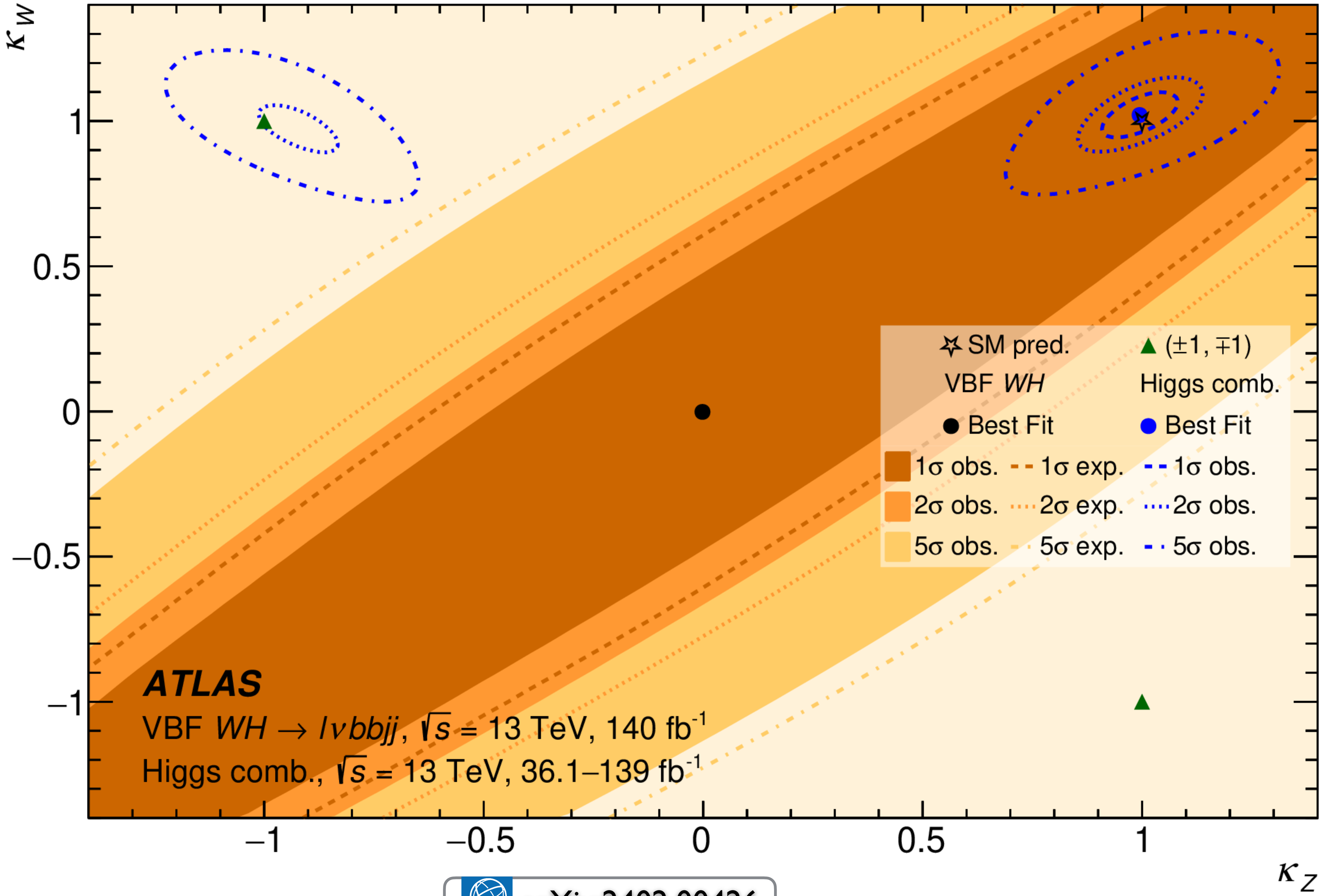


FIT



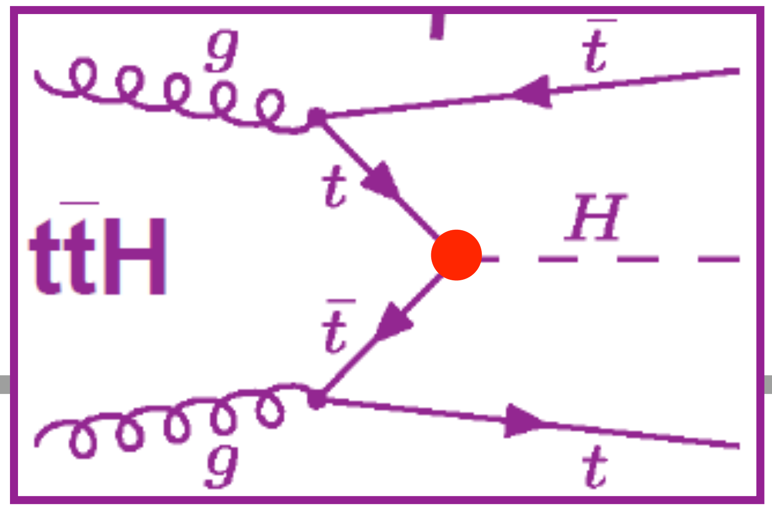
- Use interference in VBF WH production
  - H → bb and W → ℓν
  - Observed (expected) σ(VBF WH) < **9.0 (8.7)** × SM
  - Opposite-sign coupling rejected ≫ **5 σ**

Feb 2024



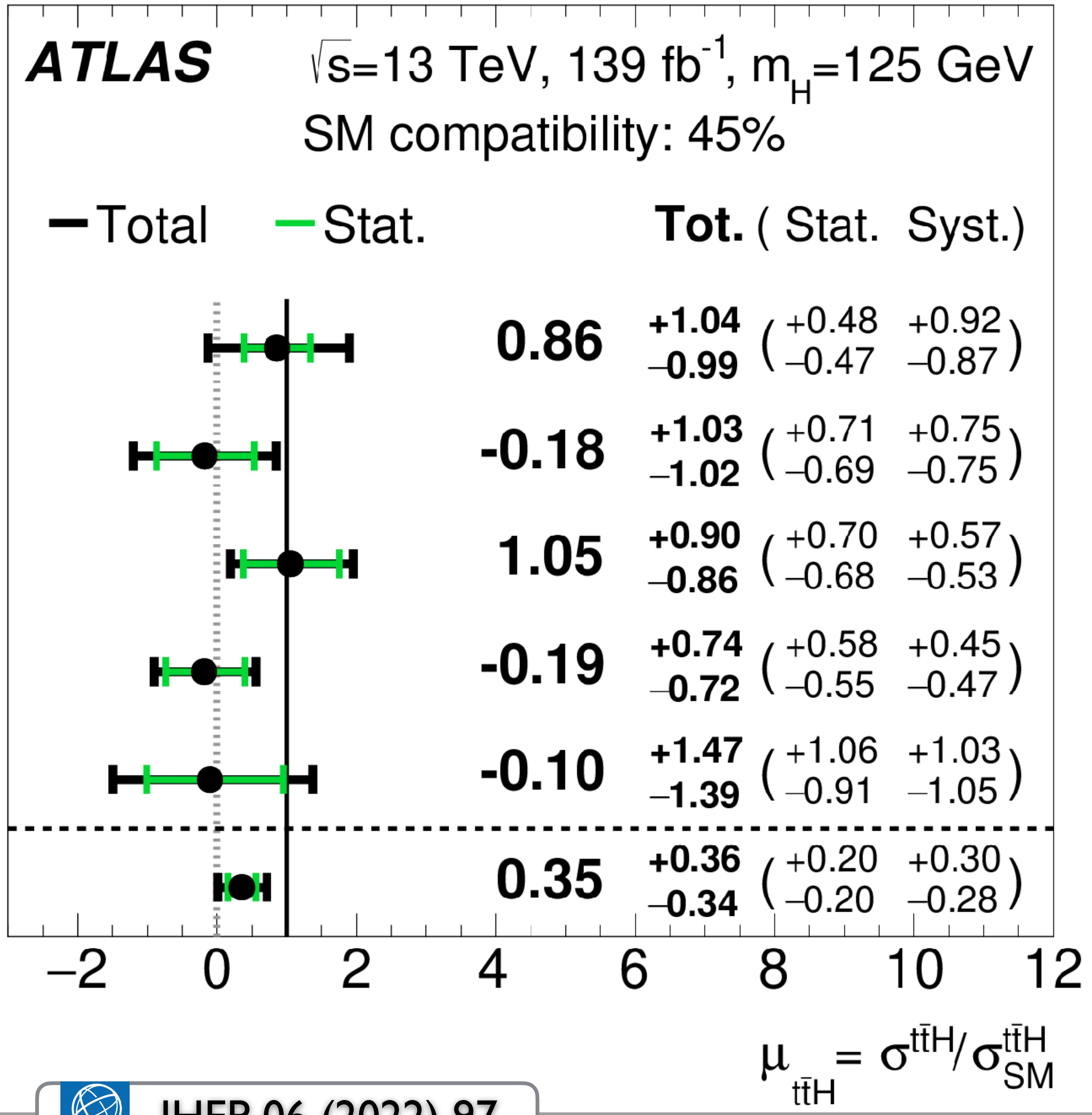
arXiv:2402.00426

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 $p_T(H)$
  - **ATLAS** obs. (exp.) significance: **1.0 (2.7)** σ
  - **CMS** obs. (exp.) significance: **1.3 (4.1)** σ

Nov 2021



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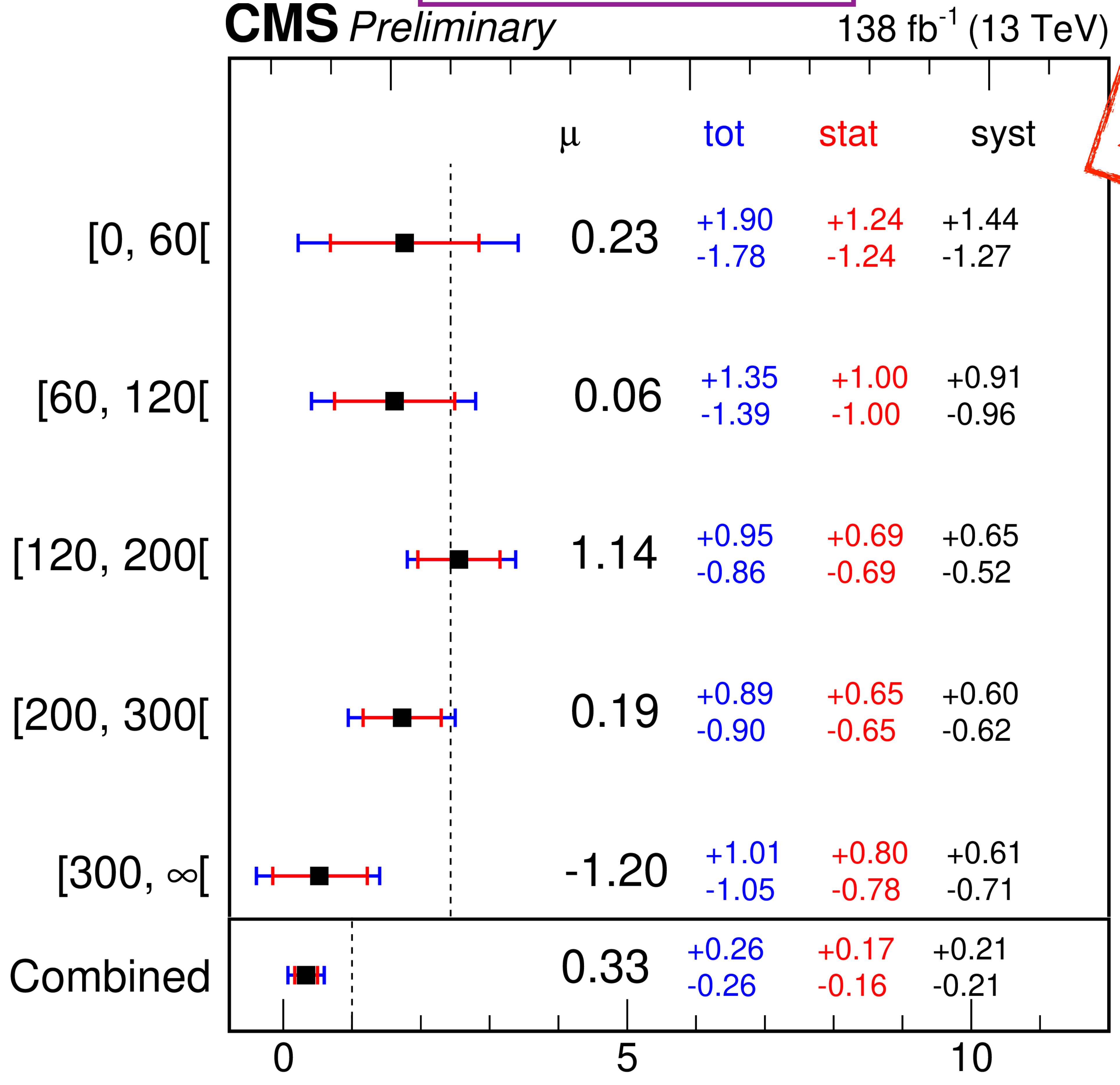
Aug 2023



CMS-PAS-HIG-19-011

$\hat{\mu} = \hat{\sigma}/\sigma_{SM}$

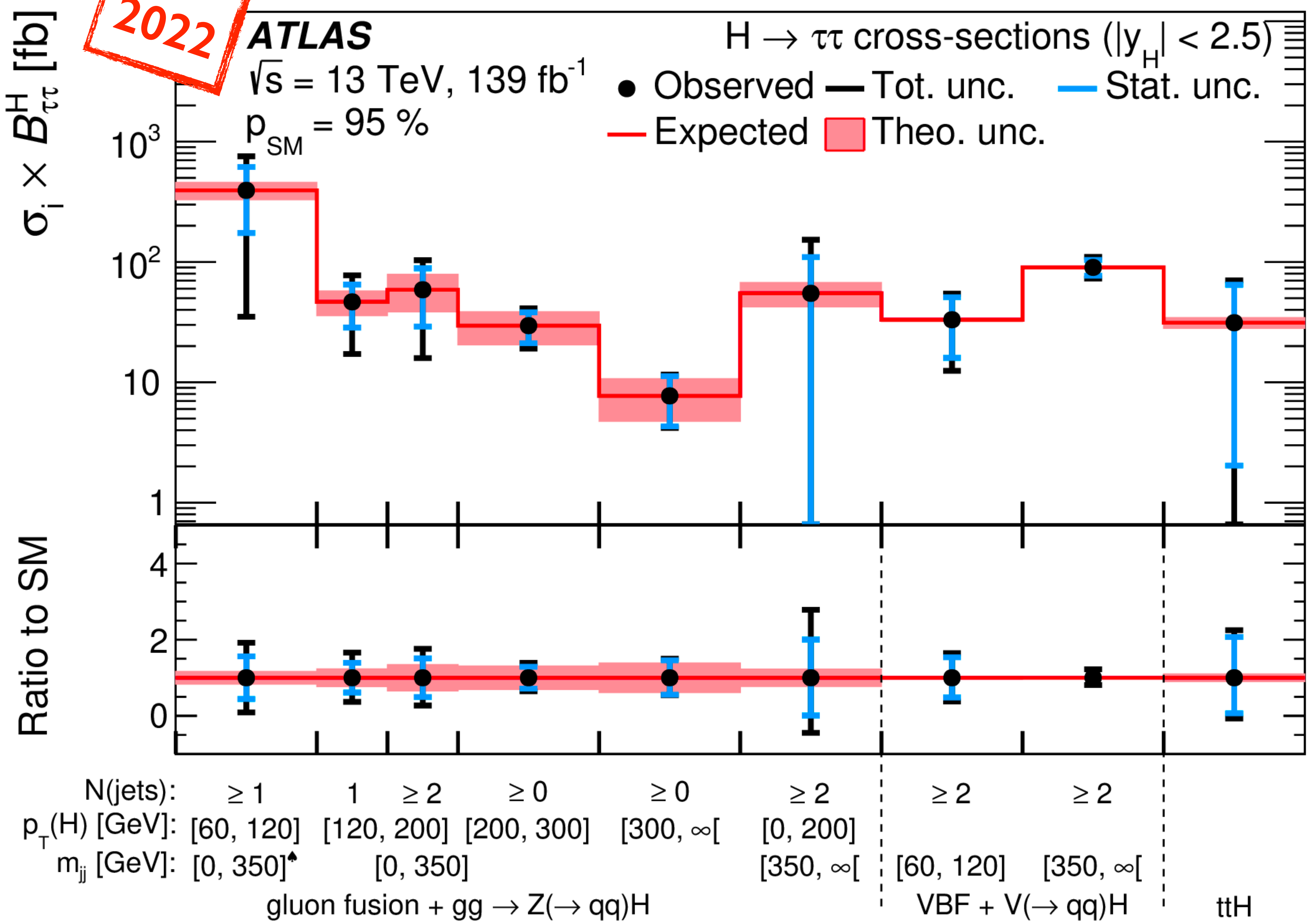
⇒ Projection from analysis of 2016+2017 data in the opposite-sign di-leptonic channel

$H \to \tau\tau$ and HL-LHC

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

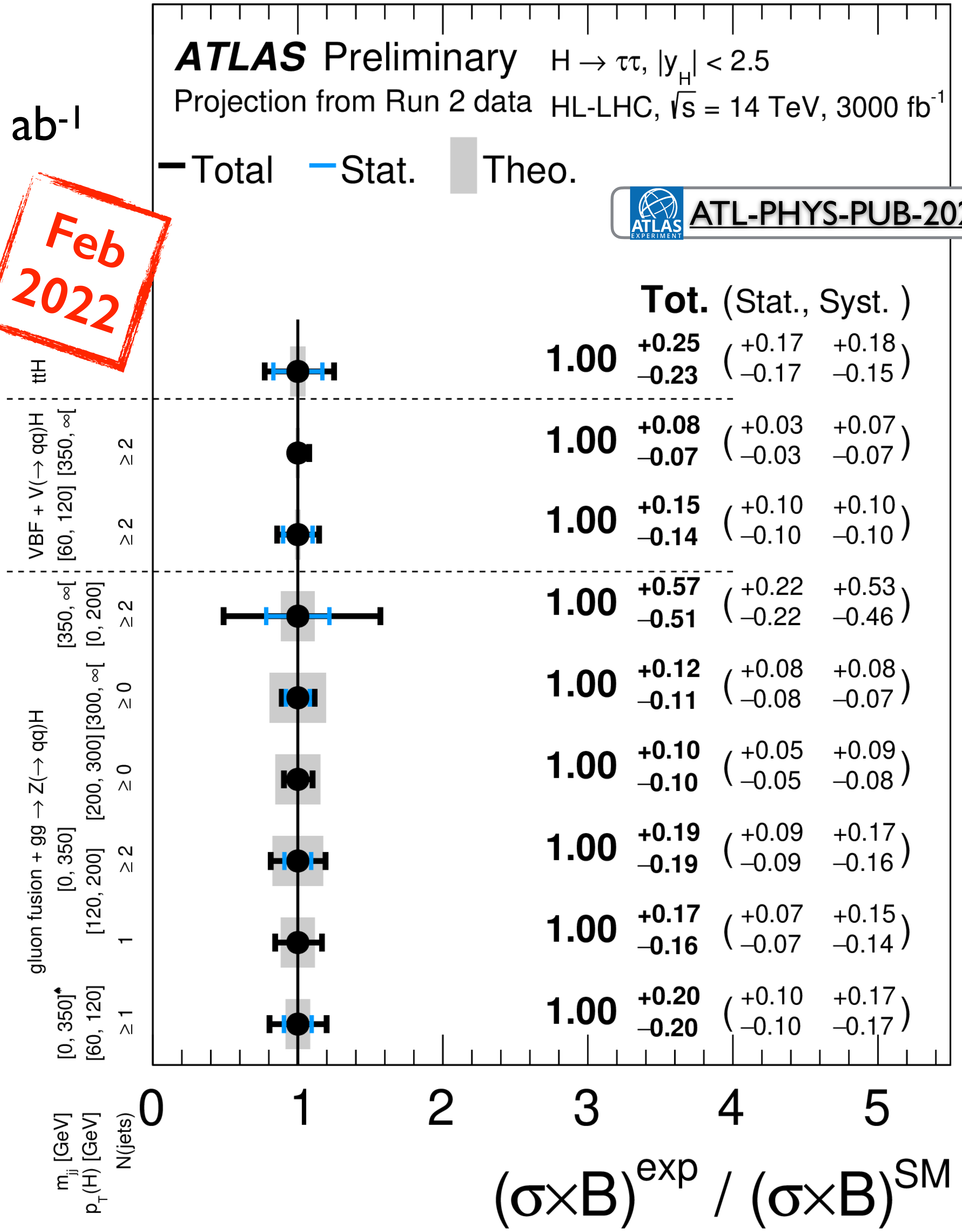
Jan 2022

JHEP 08 (2022) 175



Feb 2022

ATL-PHYS-PUB-2022-003



⇒ More

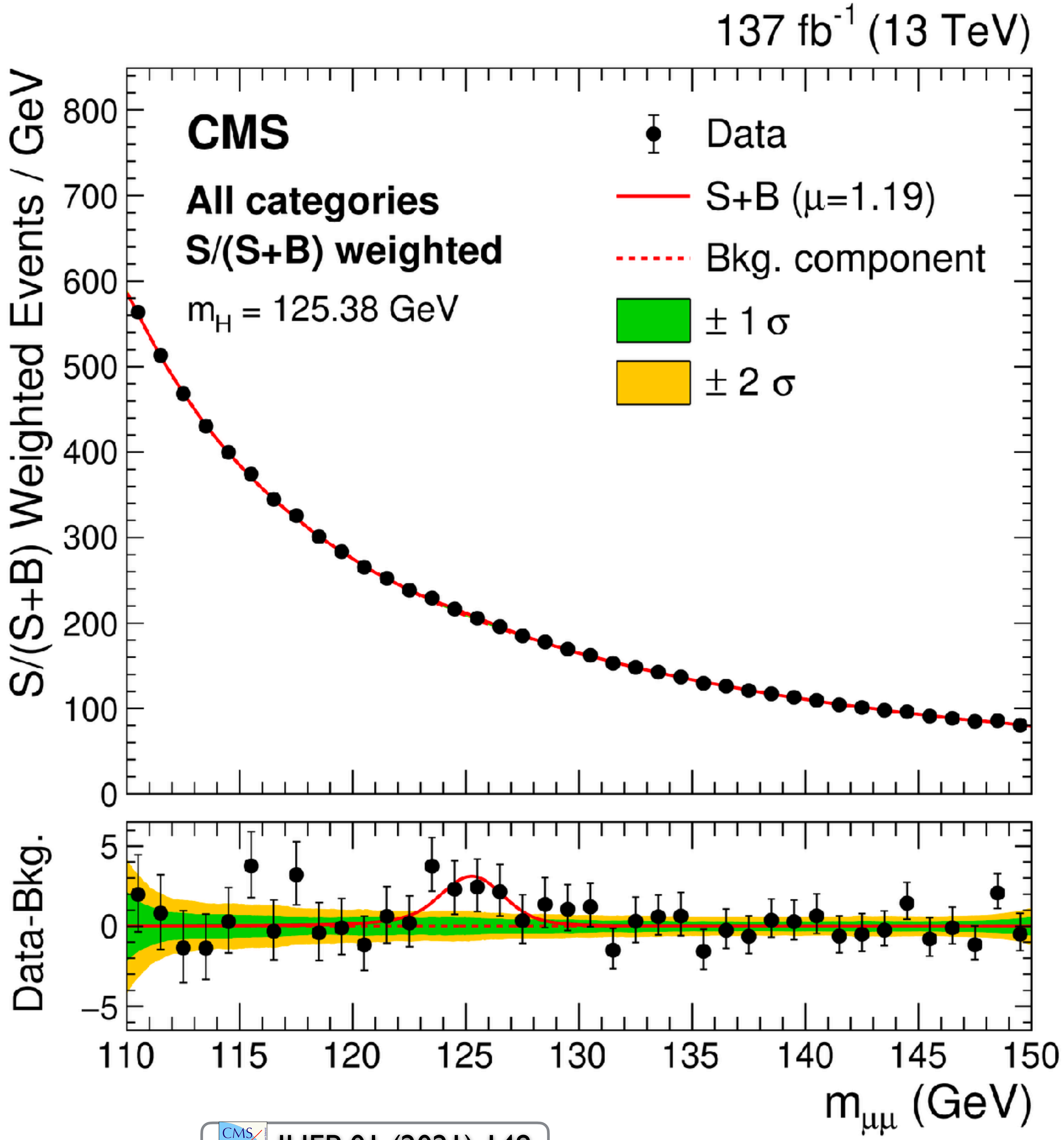
⇒ Boosted $H \to \tau\tau$ result

$H \to \mu\mu$

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

$\Rightarrow$ **~1700 $H \to \mu\mu$ events in 137 fb^{-1}**,
huge $Z/\gamma^* \to \mu\mu$ background

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



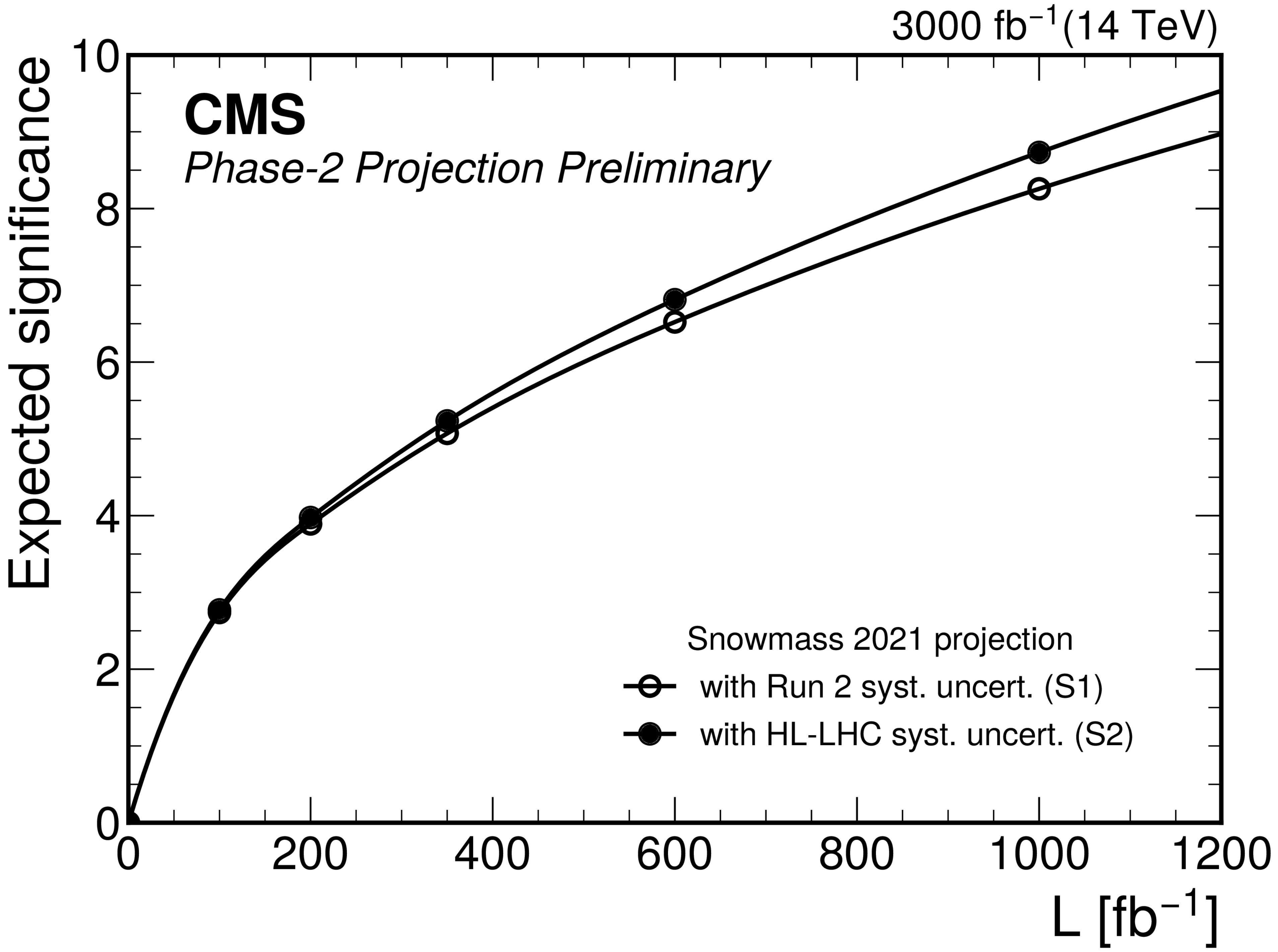
JHEP 01 (2021) 148

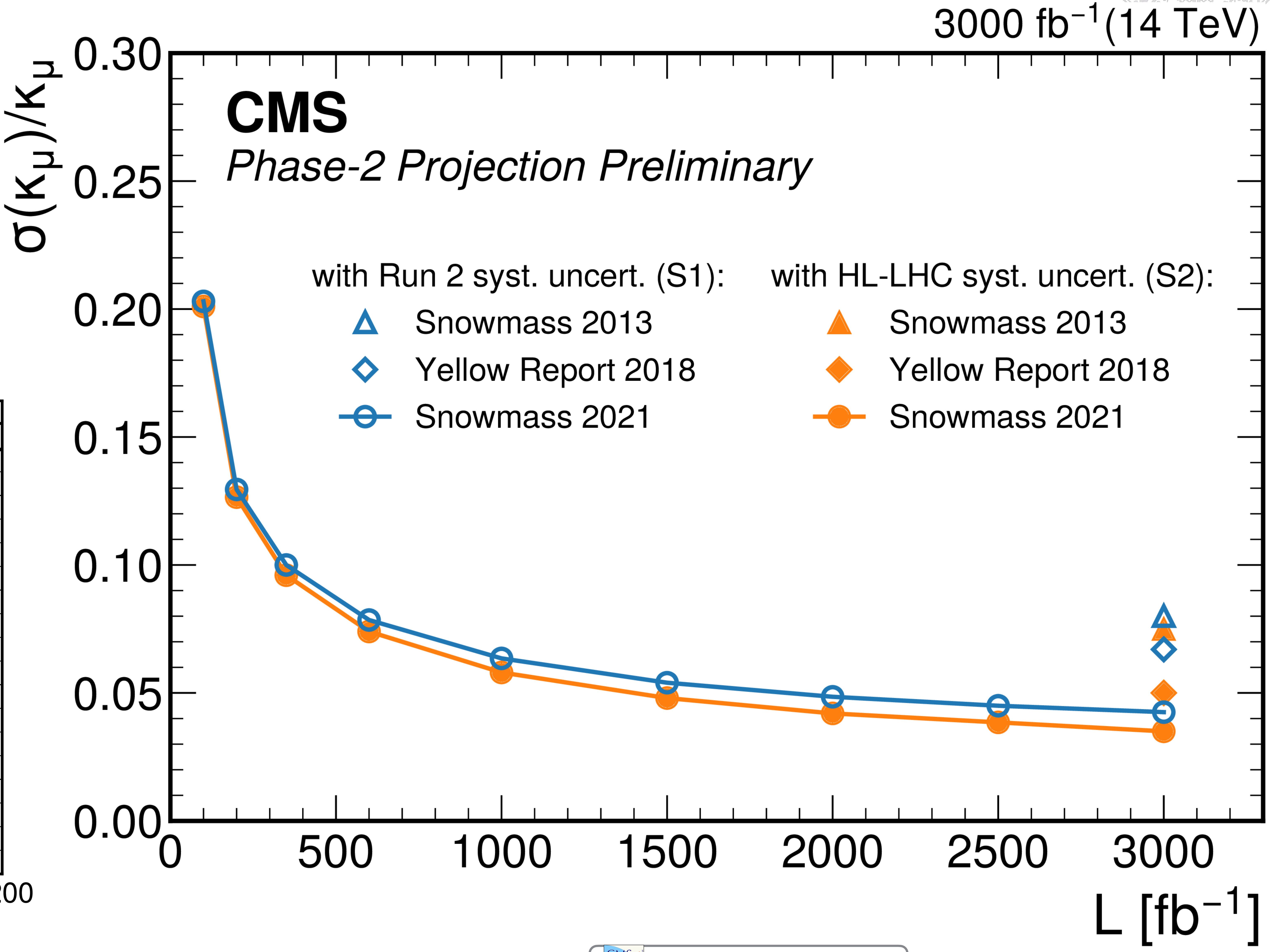
Phys. Lett. B 812 (2021) 135980

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

HL-LHC H → μμ

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





CMS-PAS-FTR-21-006

Outline

1. Introduction
2. Mass and width measurements
3. CP coupling structure
4. Decays into Bosons
   & fiducial and differential cross sections
5. Decays into Fermions
   & Simplified Template Cross Sections (STXS)
6. **HH**
7. Combinations and Interpretations
8. Another angle
9. Future
10. Summary

Does HH production exist?

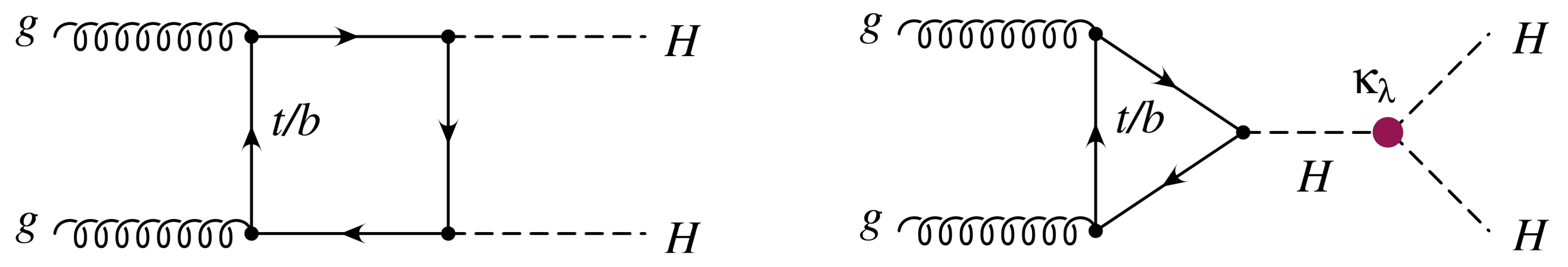
direct connection

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

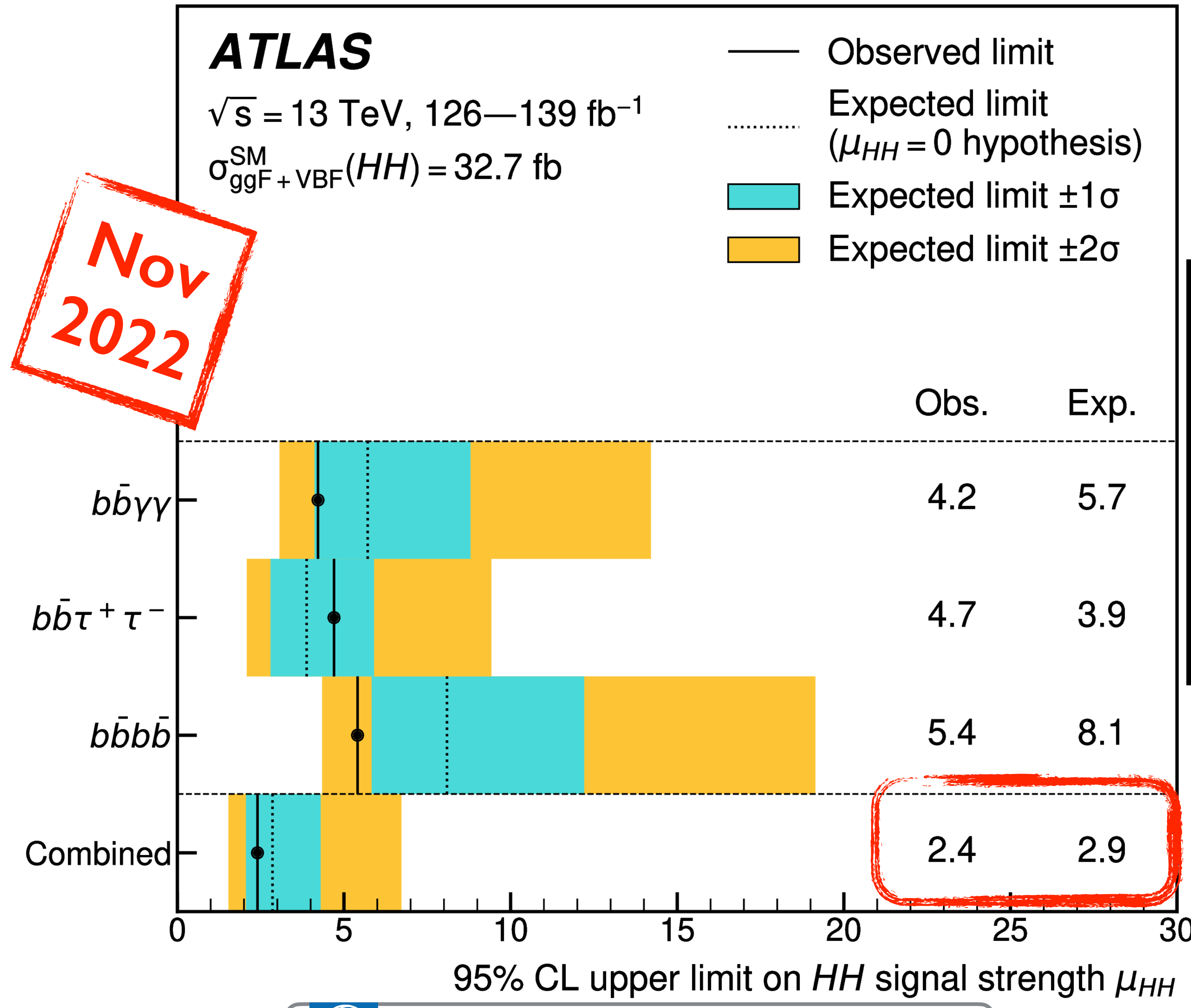
H potential as in SM?

Di-Higgs Production

- $\sigma(gg \to HH)$ = 31.05 fb
  $\Rightarrow$ ~4300 events in 139 fb^{-1}
- "Large" BR & clean signatures:
  - BR_{SM}(HH → bbbb) = 33% ⇒ ~1430 events in 139 fb^{-1}
  - BR_{SM}(HH → bbττ) = 7.4% ⇒ ~320 events in 139 fb^{-1}
  - BR_{SM}(HH → bbγγ) = 0.26% ⇒ ~11 events in 139 fb^{-1}

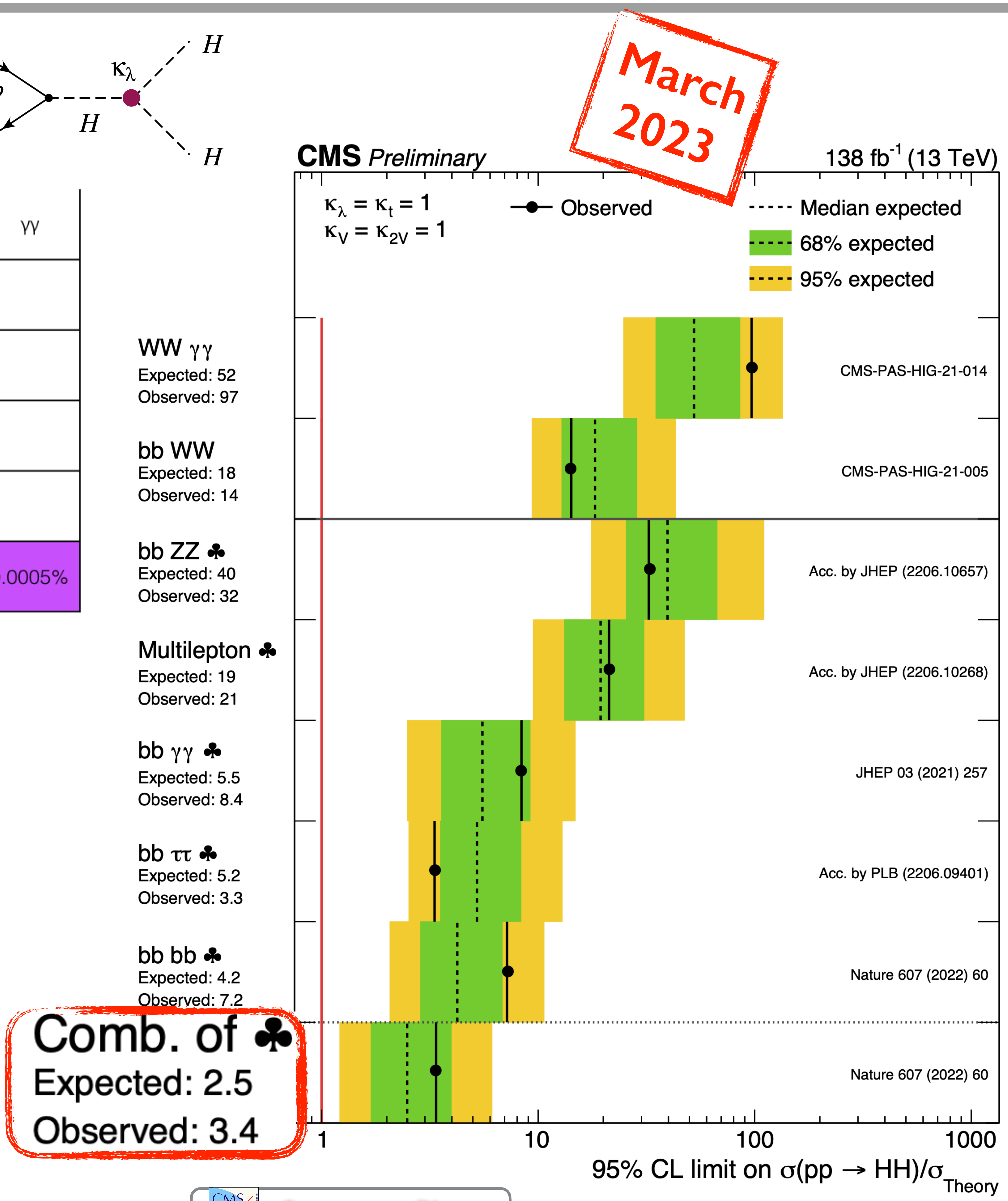


	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.3%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%



Improved results:

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



Phys. Lett. B 843 (2023) 137745

Summary Plots

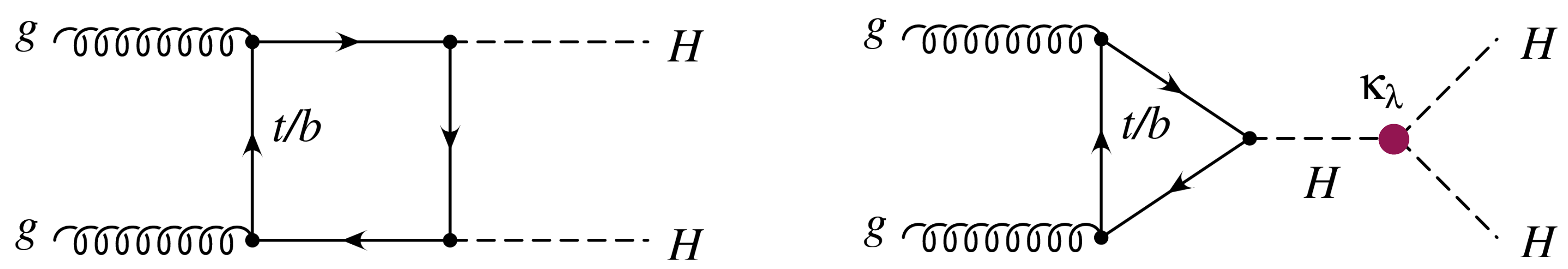
Extracting Trilinear Higgs Coupling λ_{HHH}

Gluon fusion

σ = 31.05 fb

Self-coupling modifier:

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

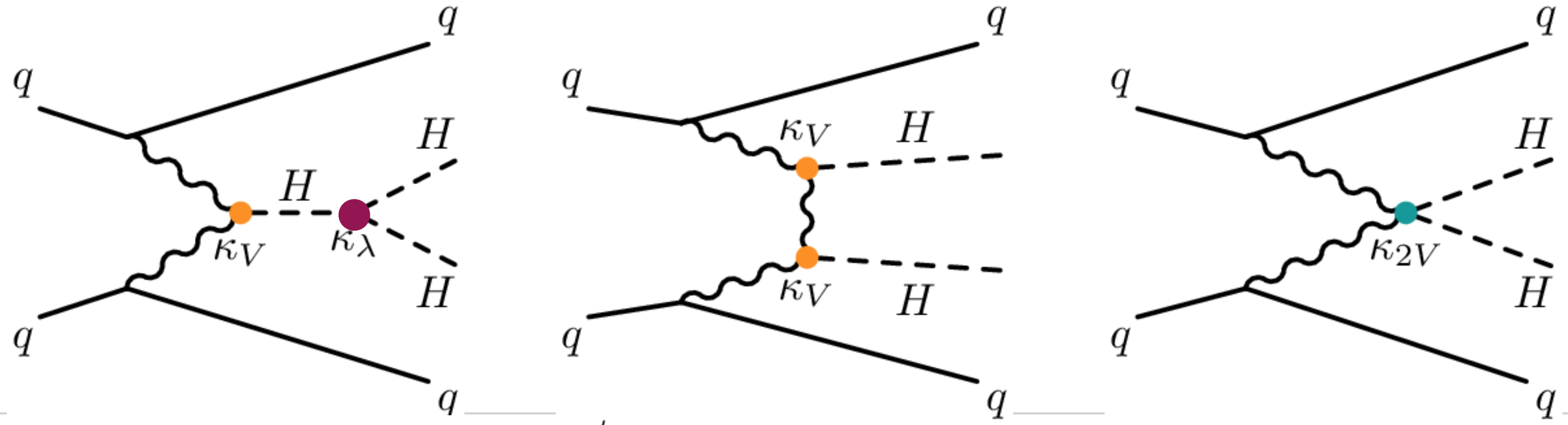


VBF

σ = 1.726 fb

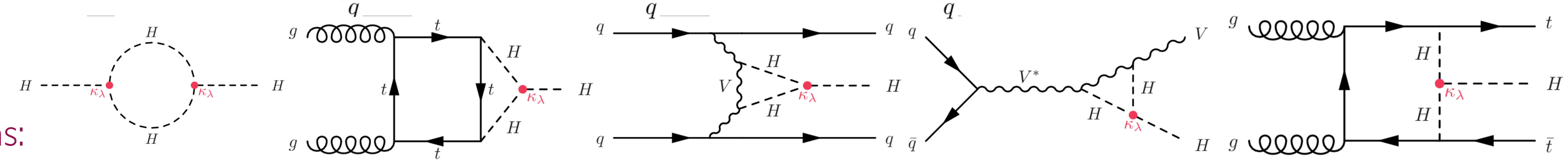
Self-coupling modifier: κ_λ

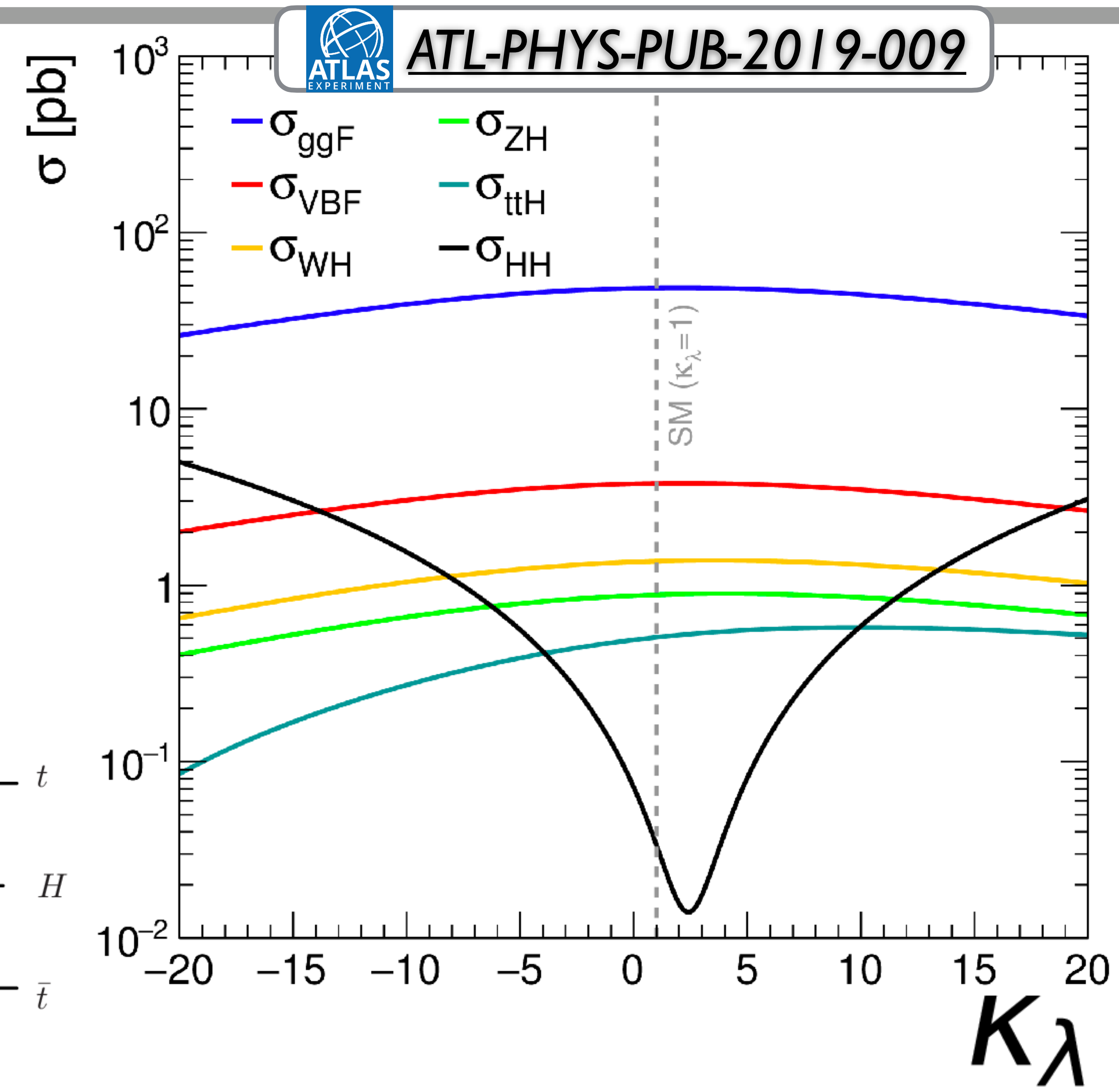
VVHH coupling modifier: κ_{2V}



Single-Higgs

Sensitivity to κ_λ via higher-order corrections:





Extracting Trilinear Higgs Coupling λ_{HHH}

Gluon fusion

σ = 31.05 fb

Self-coupling modifier:

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

VBF

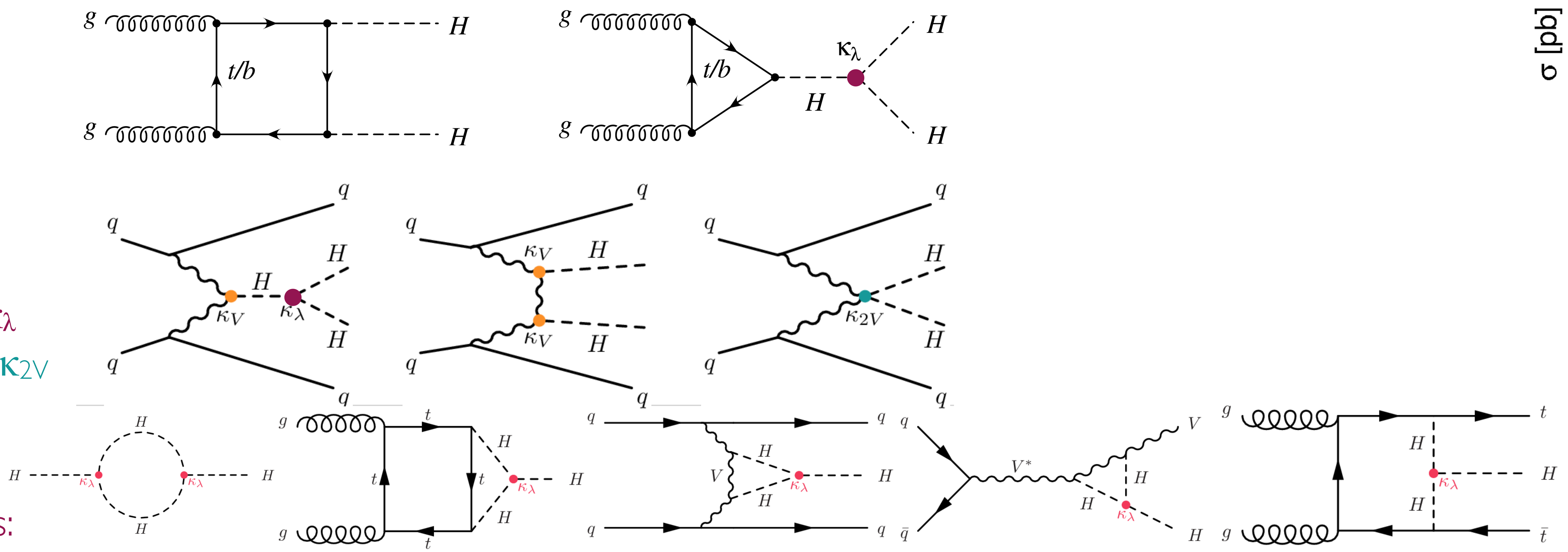
σ = 1.726 fb

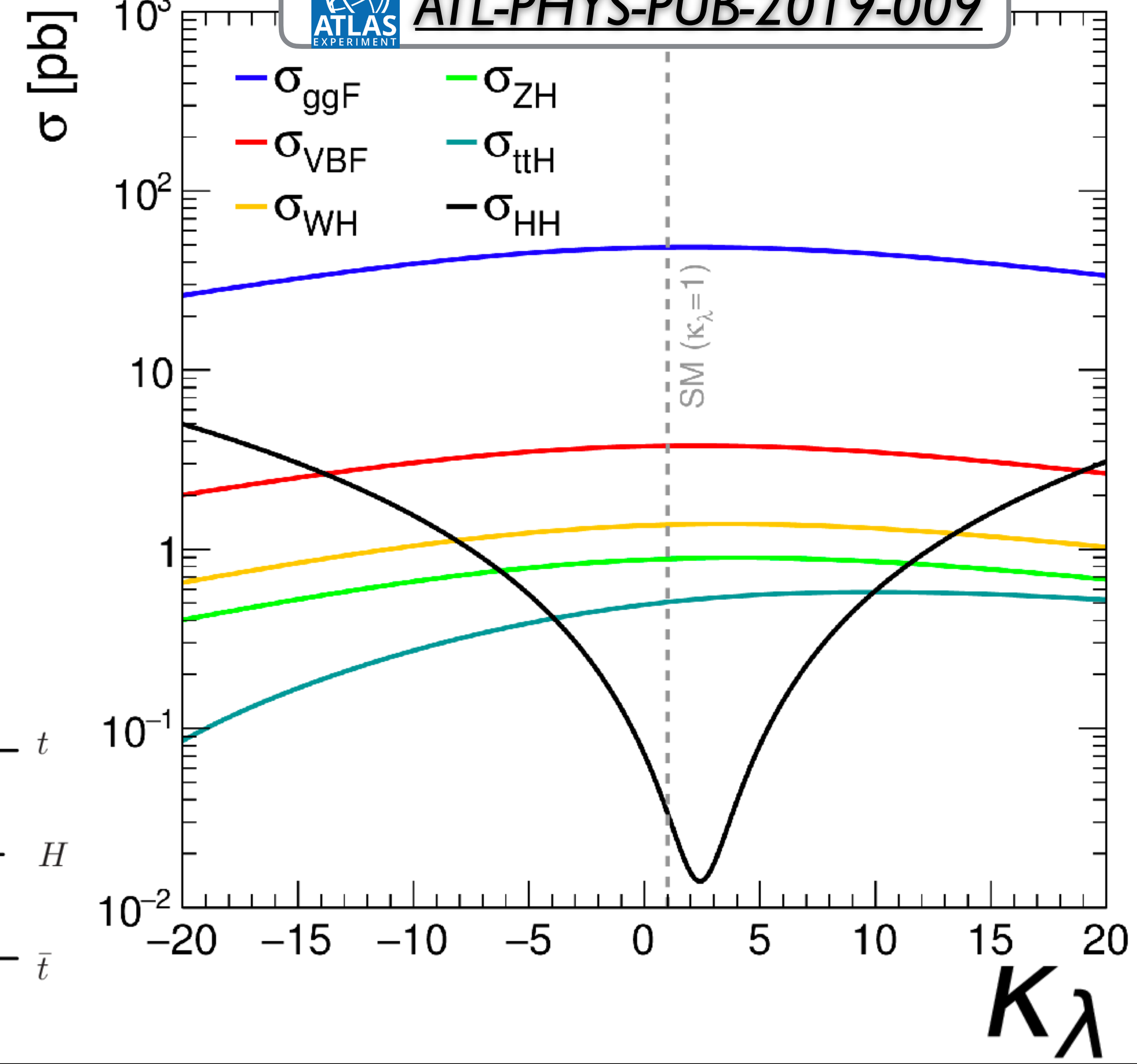
Self-coupling modifier: κ_λ

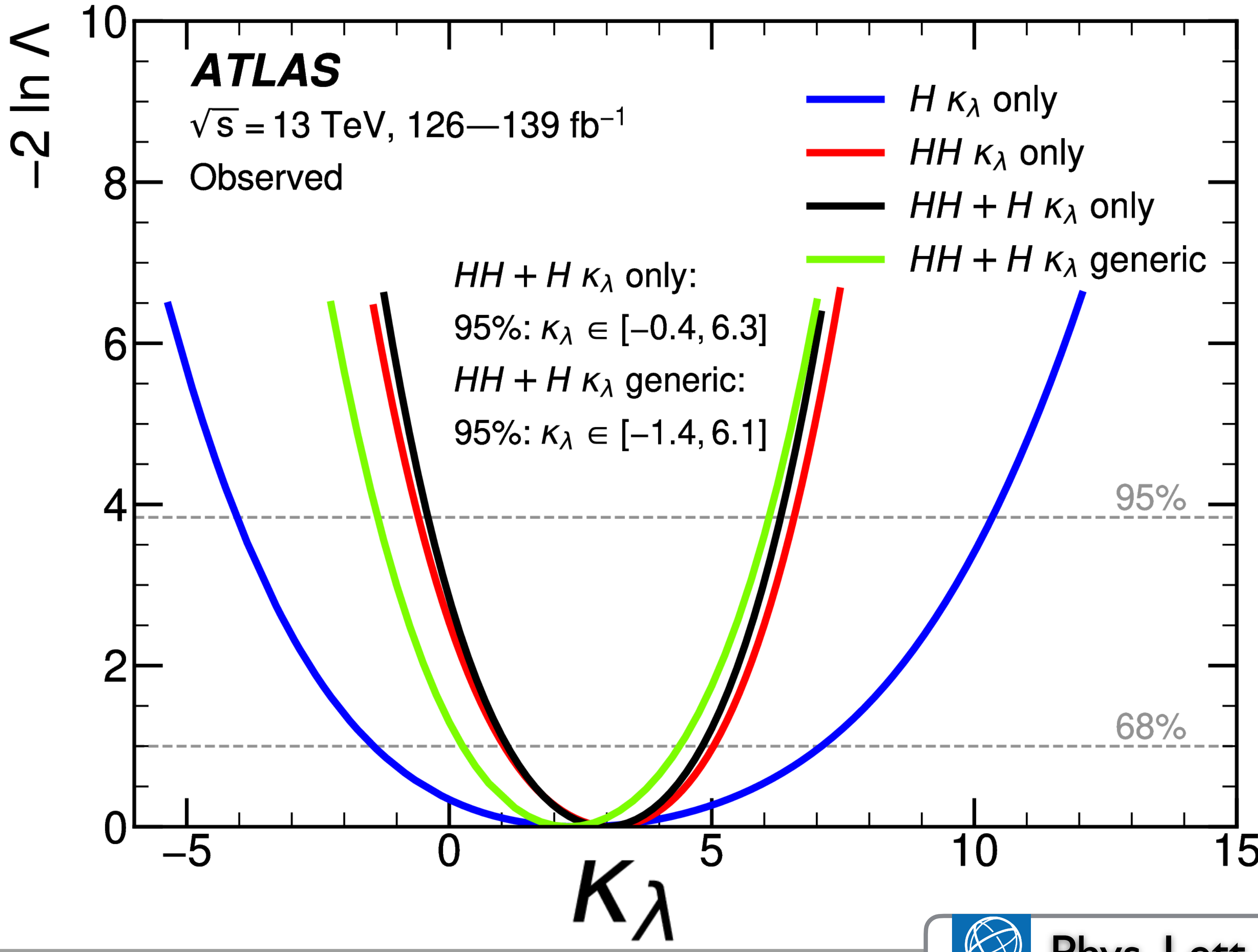
VVHH coupling modifier: κ_{2V}

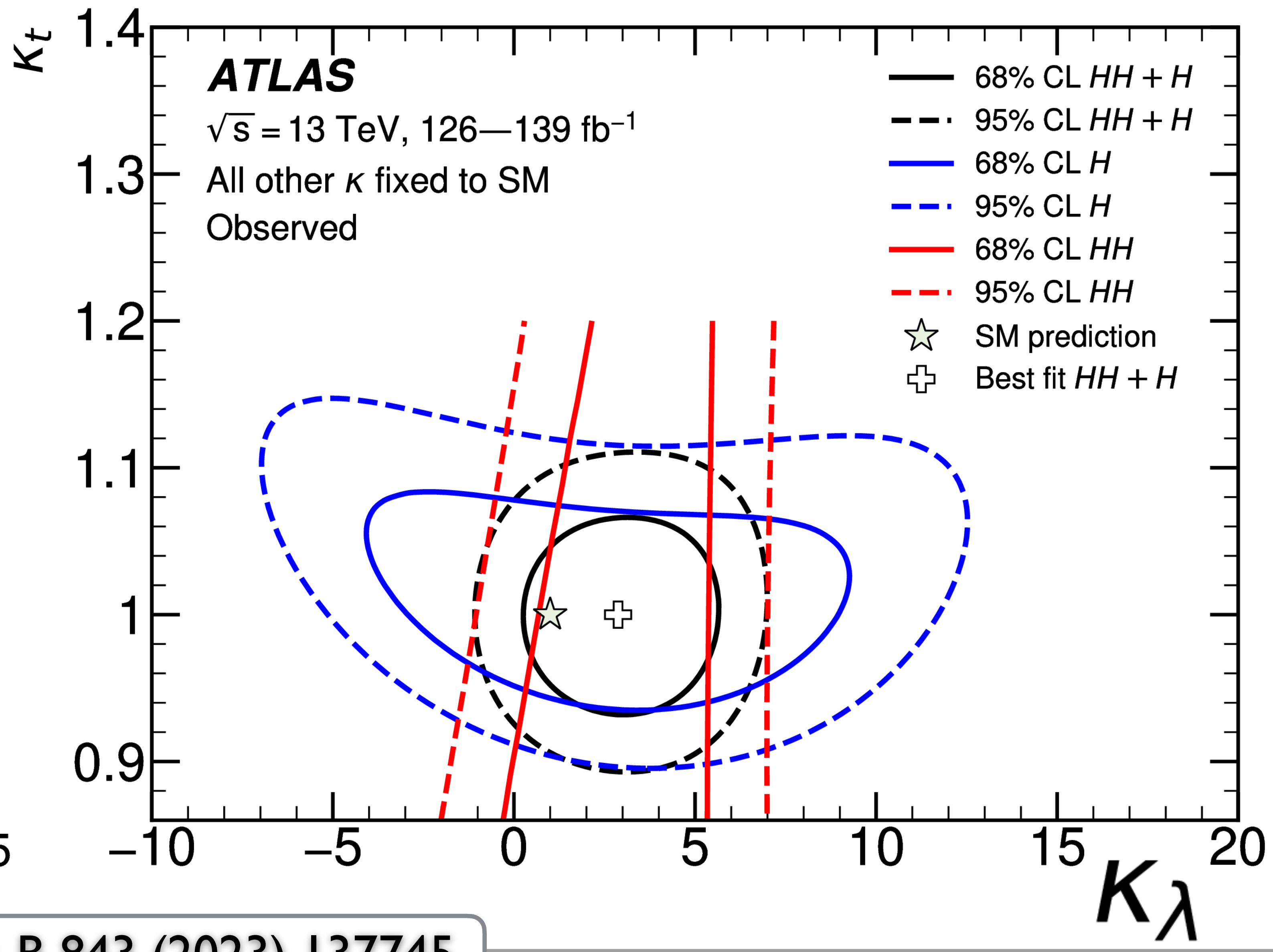
Single-Higgs

Sensitivity to κ_λ via higher-order corrections:









Phys. Lett. B 843 (2023) 137745

95% C.L. constraints on κ_λ observed (expected):

ATLAS (Nov 2022):

$-0.4 < \kappa_\lambda < 6.3$

$(-1.3 < \kappa_\lambda < 6.1)$

CMS (Nov 2023):

$-1.2 < \kappa_\lambda < 7.5$

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

CMS-PAS-HIG-23-006

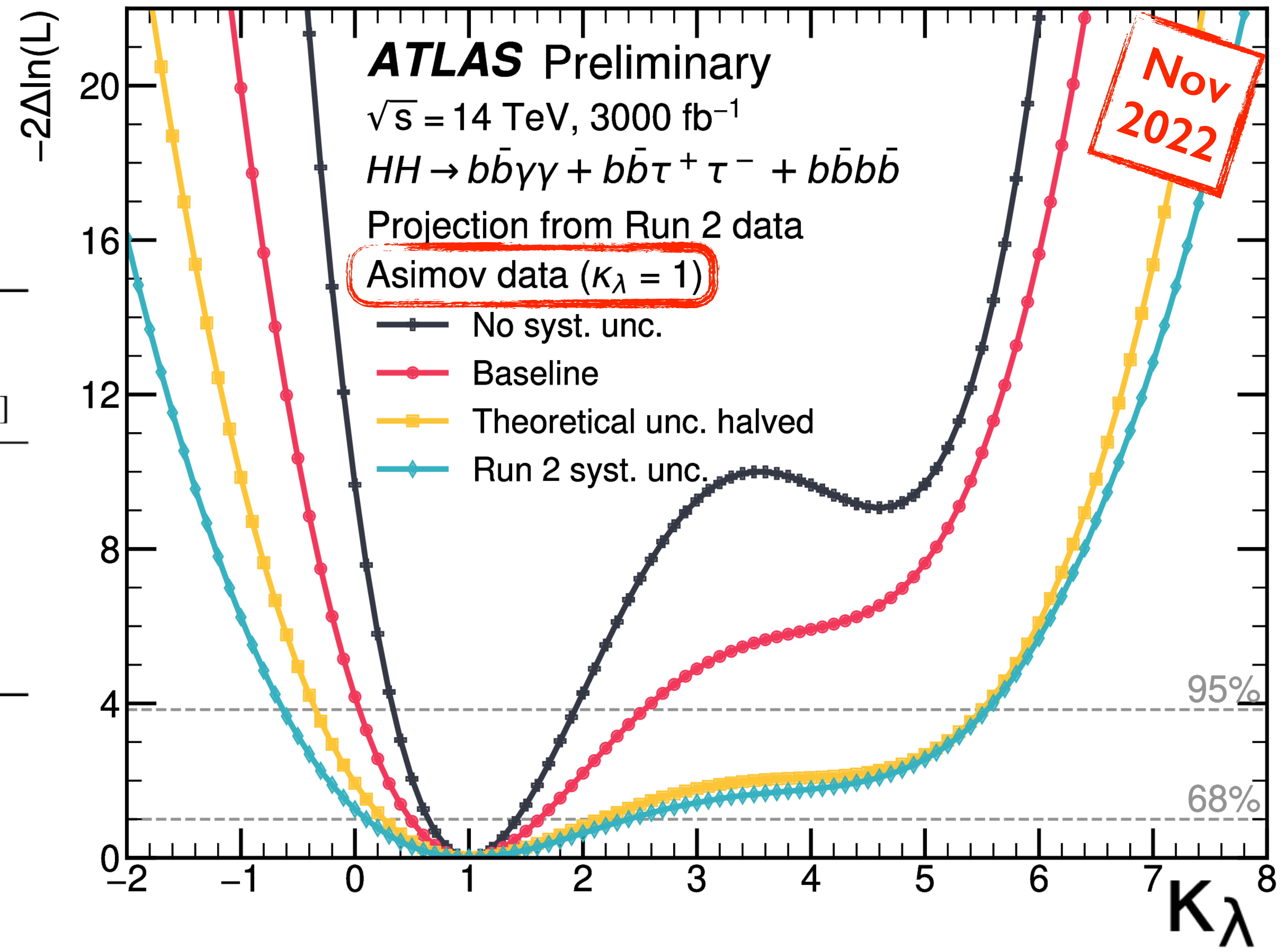
HH at HL-LHC

- HL-LHC extrapolation from full Run 2 combination of:
  - BR_{SM}(HH → bbbb) = 33% ⇒ ~38400 events in 3000 fb^{-1}
  - BR_{SM}(HH → bbττ) = 7.4% ⇒ ~6900 events in 3000 fb^{-1}
  - BR_{SM}(HH → bbγγ) = 0.26% ⇒ ~240 events in 3000 fb^{-1}

Uncertainty scenario	Significance [σ] $b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	$b\bar{b}b\bar{b}$	Combination	Combined signal strength precision [%]
No syst. unc.	2.3	4.0	1.8	4.9	−21/+22
Baseline	2.2	2.8	0.99	3.4	−30/+33
Theoretical unc. halved	1.1	1.7	0.65	2.1	−47/+48
Run 2 syst. unc.	1.1	1.5	0.65	1.9	−53/+65

Uncertainty scenario	κ_λ 68% CI	κ_λ 95% CI
No syst. unc.	[0.1, 2.6]	[-0.5, 6.4]
Baseline	[-0.5, 6.1]	[-1.6, 7.5]
Theoretical unc. halved	[-1.2, 6.9]	[-2.6, 8.5]
Run 2 syst. unc.	[-1.2, 6.9]	[-2.8, 8.5]

ATL-PHYS-PUB-2022-053



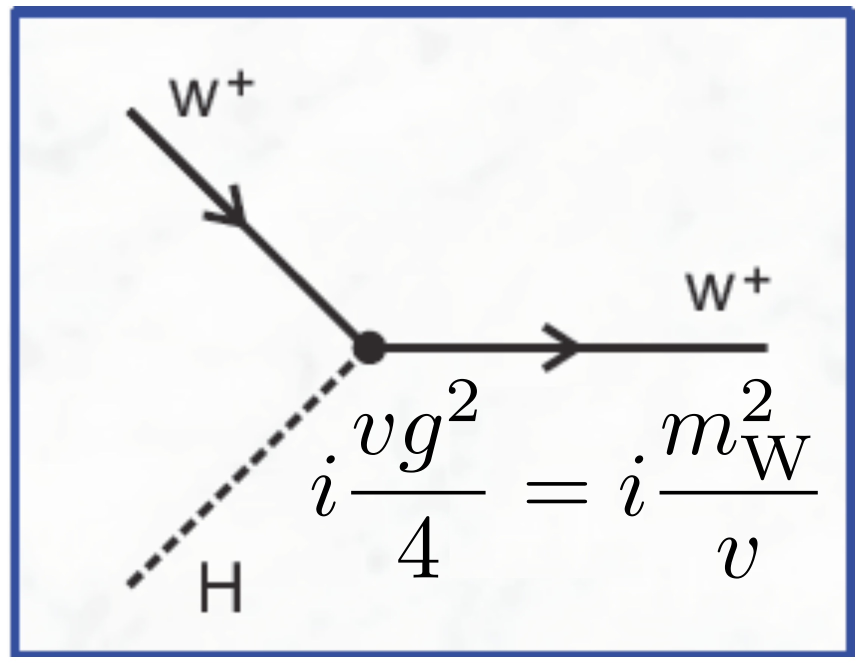
⇒ bbγγ expected significance at 3000 fb^{-1}: 2.16 σ [CMS-PAS-FTR-21-004]

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

Outline

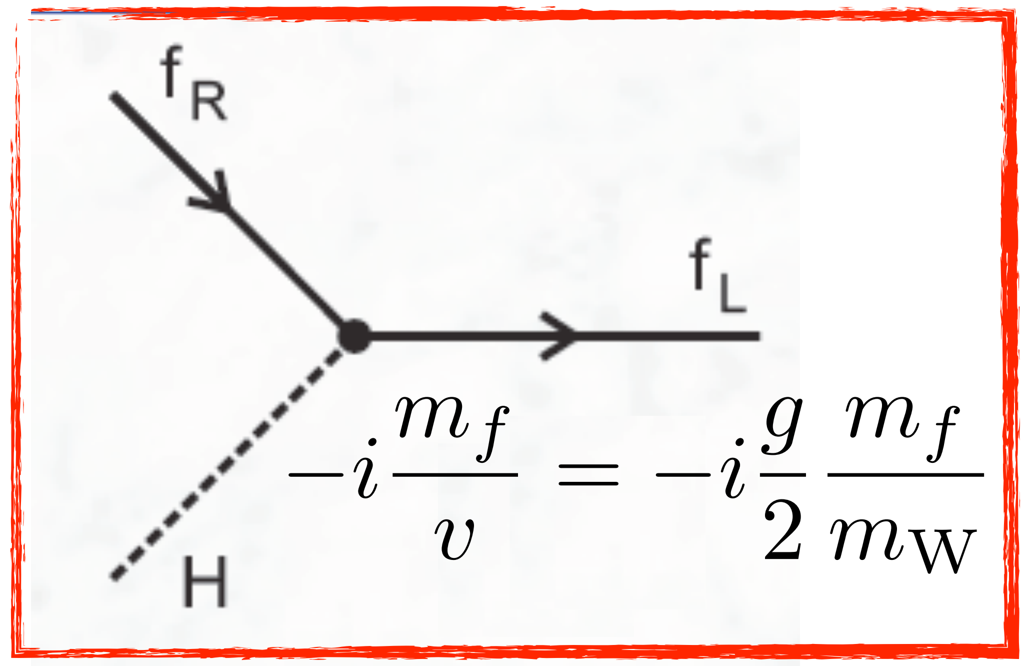
$$m_W = \frac{vg}{2}$$

direct connection



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

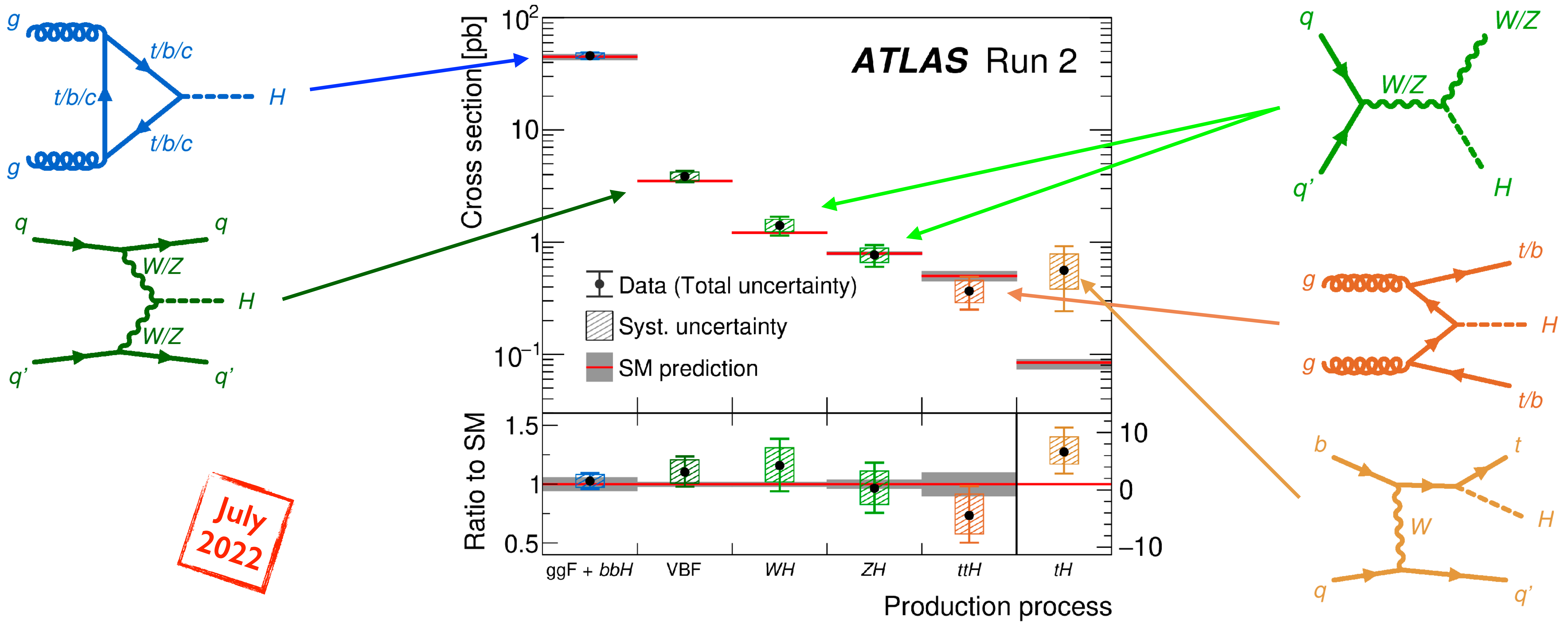
direct connection



Production Modes

Nature 607, 52–59 (2022)

Main production modes observed (assume SM branching ratios)



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

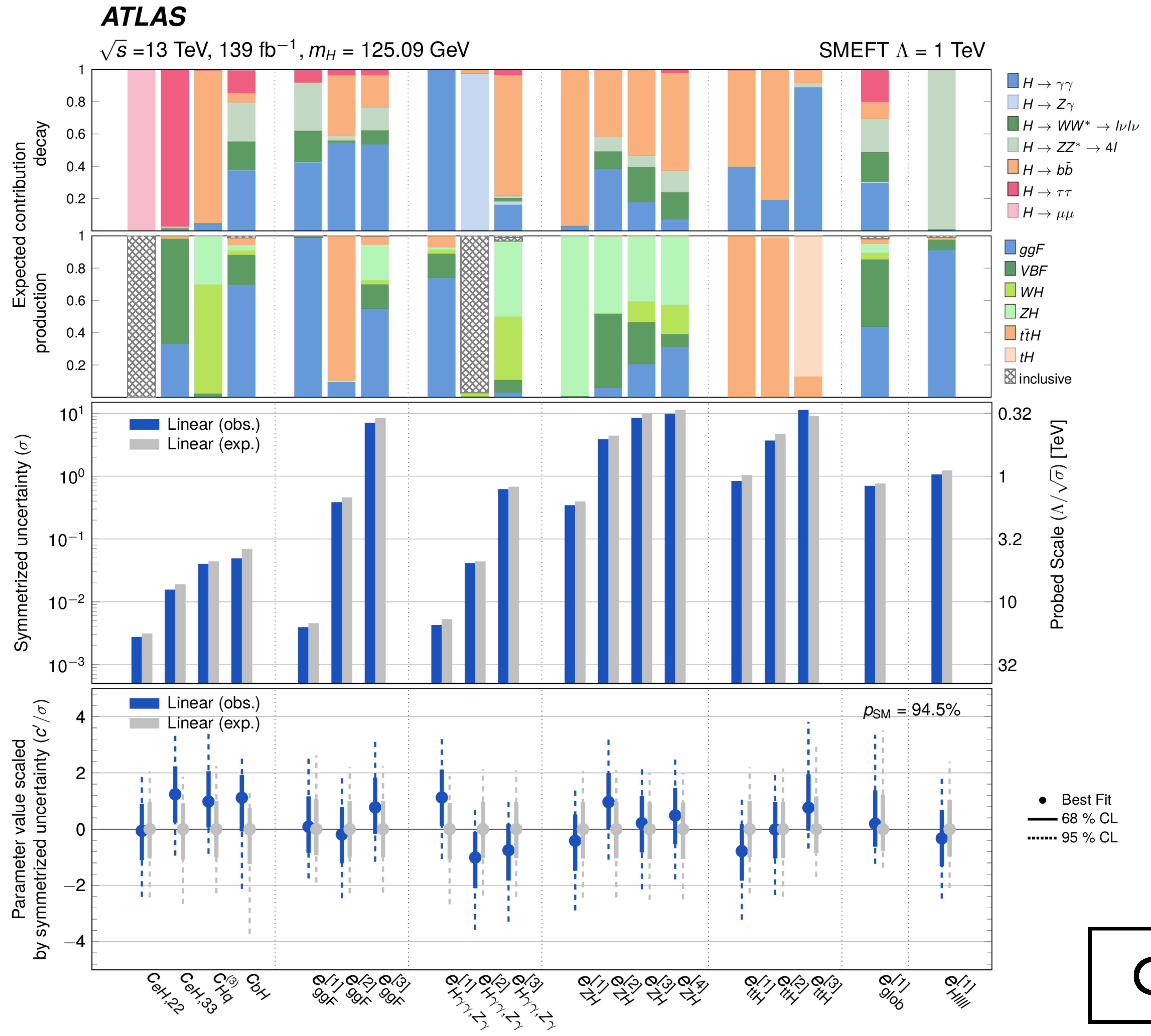
Combined STXS Measurement

Nature 607, 52–59 (2022)

- Measurements in many kinematic regions

Effective Field Theory Interpretations

arXiv:2402.05742



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

Feb 2024

Opens the window to global combined analyses!

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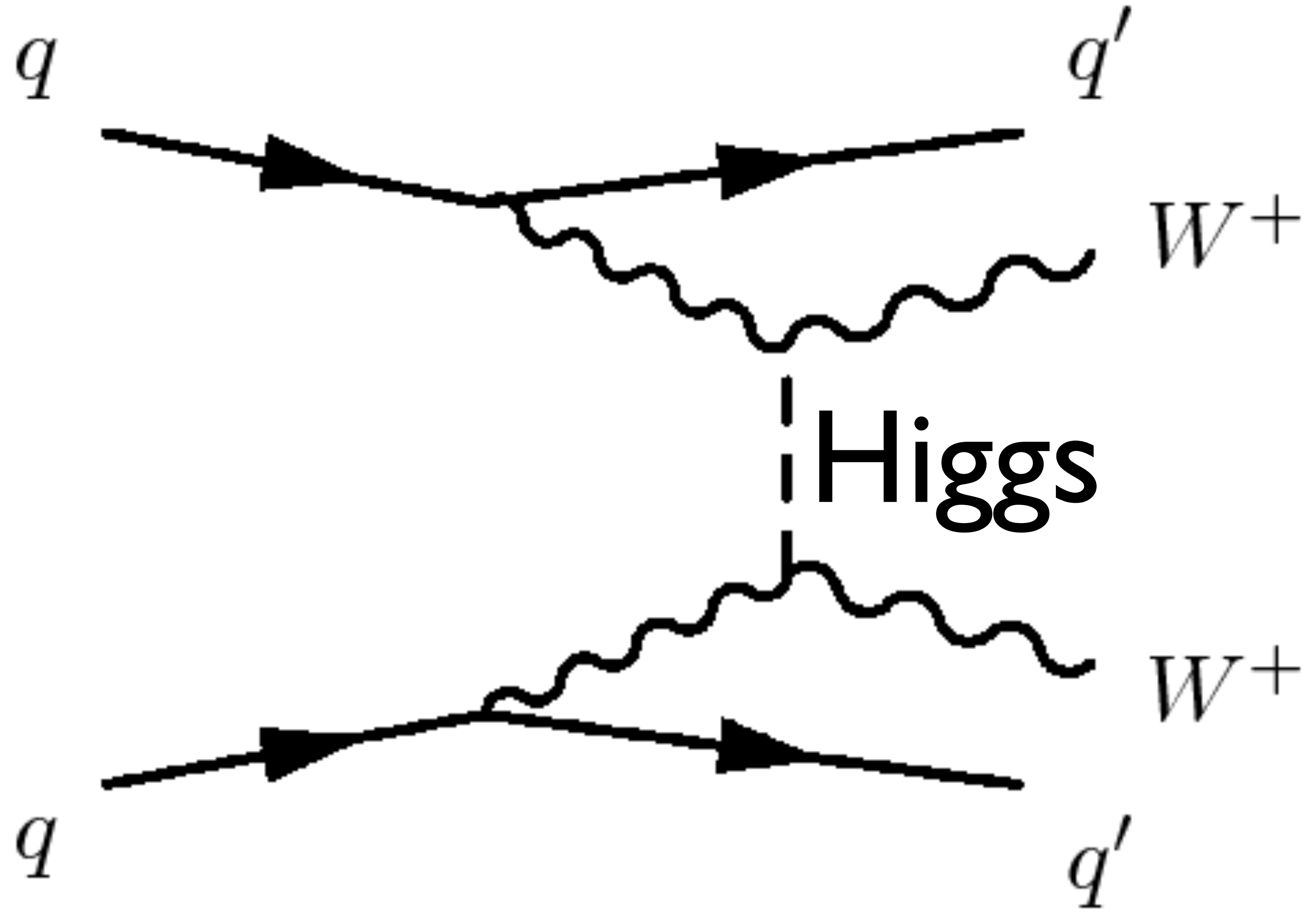
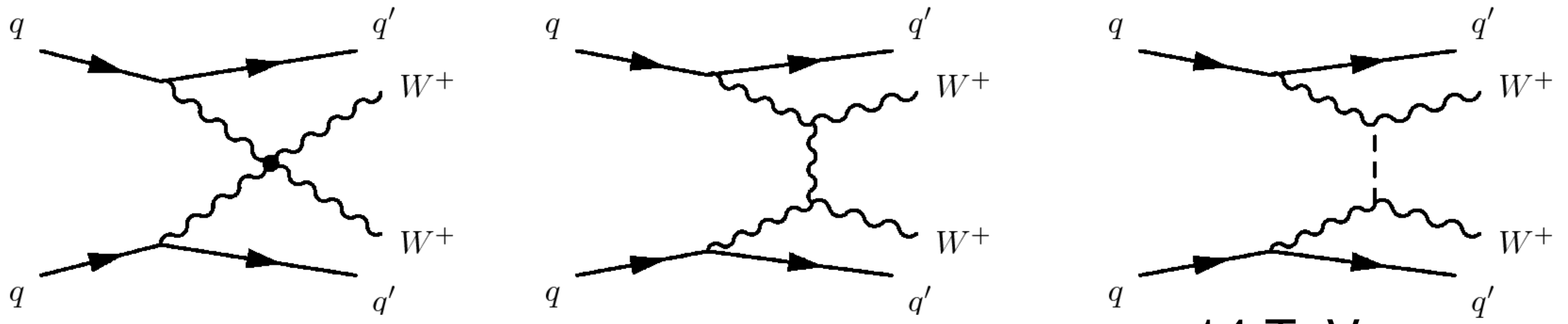
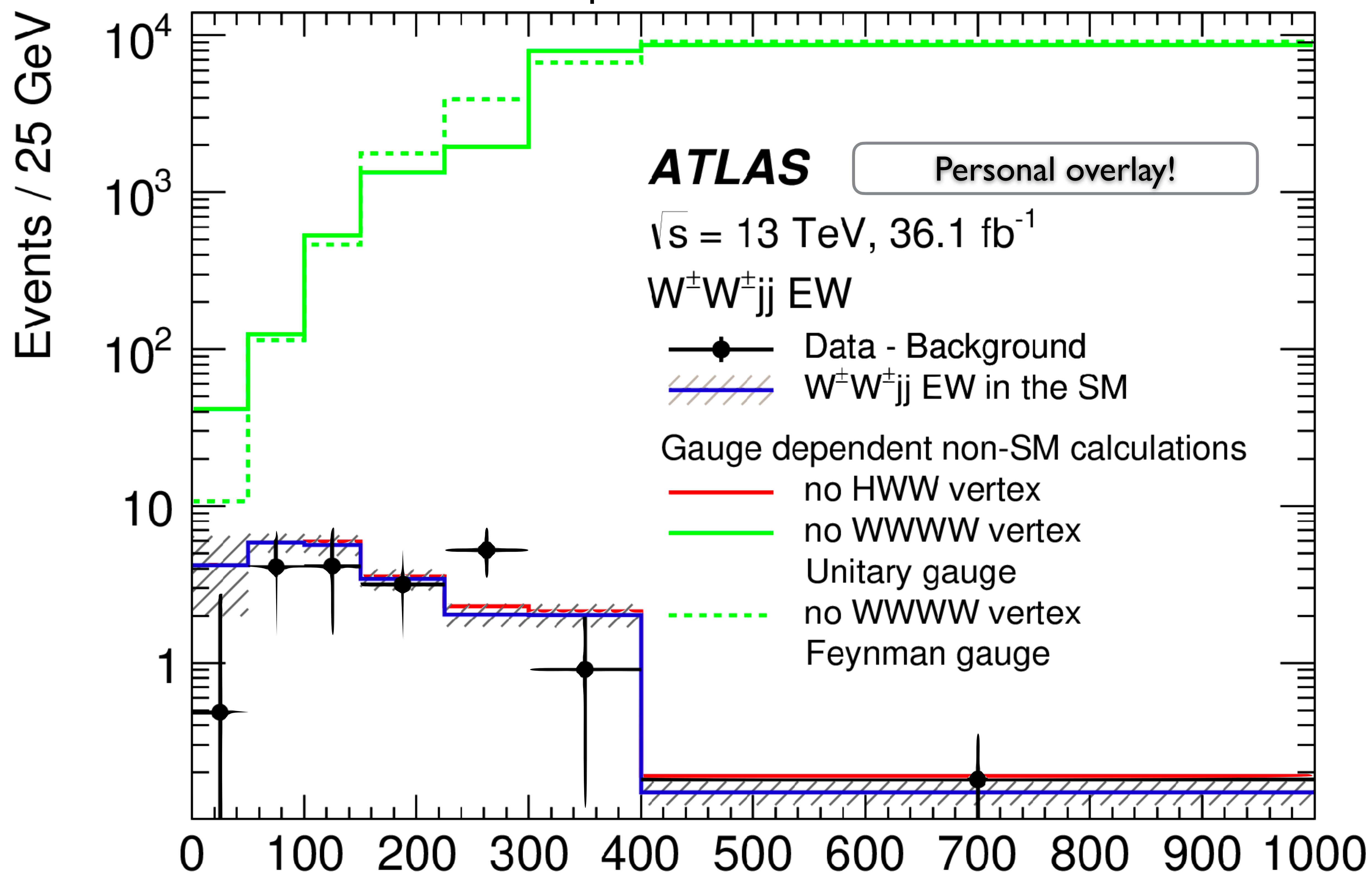


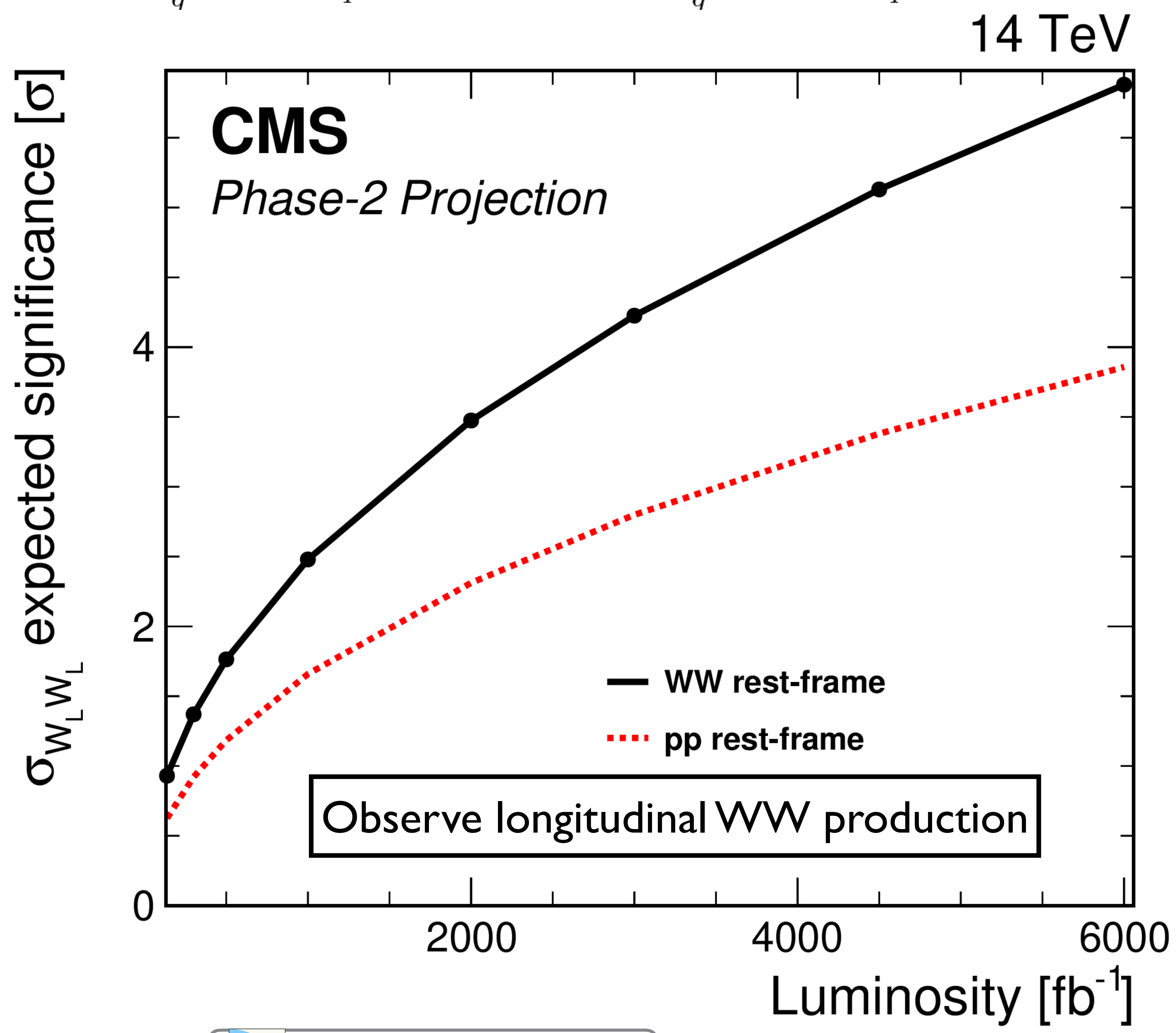
Vector Boson Scattering

- Brout-Englert-Higgs mechanism:
  - ⇒ Mass to W boson: adds longitudinal W-boson polarization mode





Observe electroweak production of $W^{\pm}W^{\pm}$ +2-jets with 6.5 σ



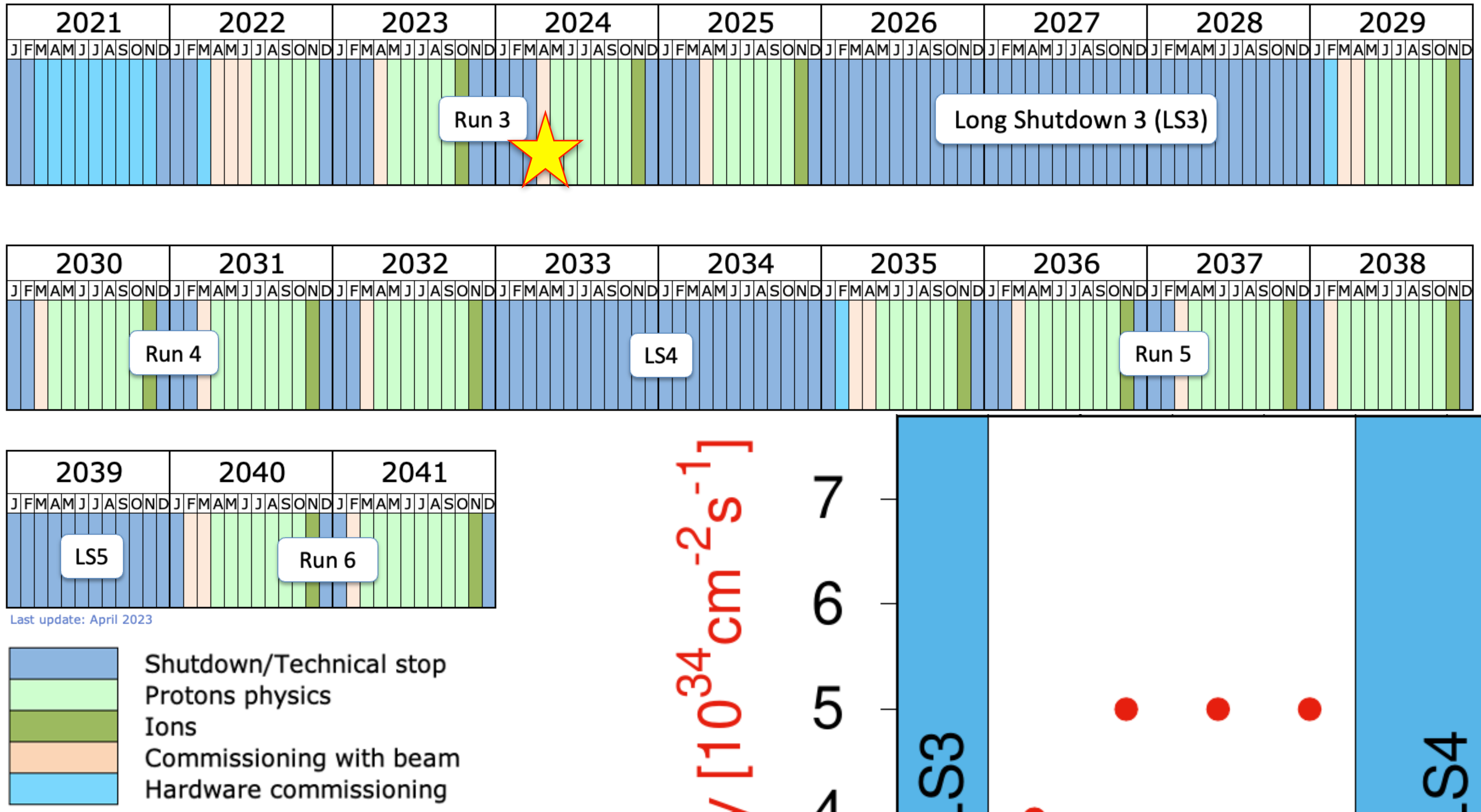
PRL 123 (2019) 161801

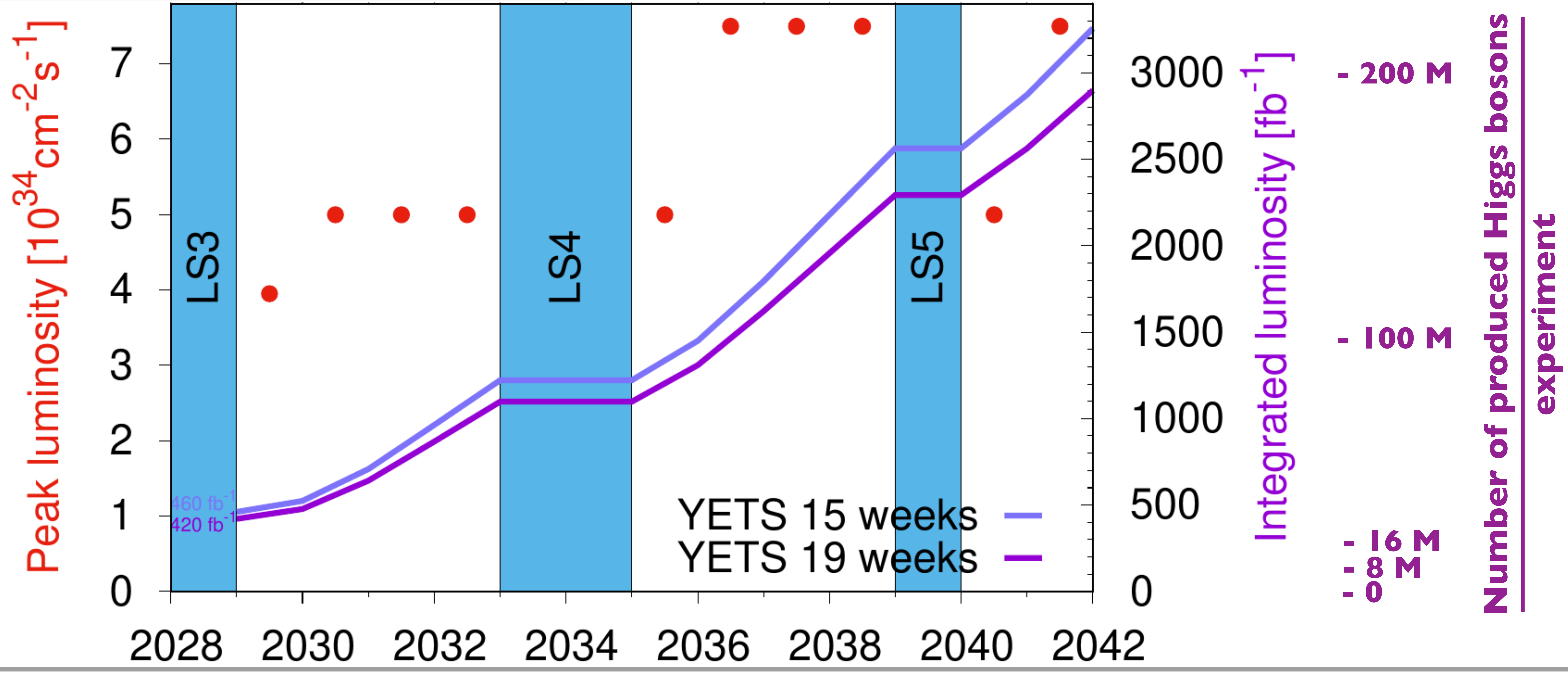
CMS PAS FTR-22-001

Outline

1. Introduction
2. Mass and width measurements
3. CP coupling structure
4. Decays into Bosons
   & fiducial and differential cross sections
5. Decays into Fermions
   & Simplified Template Cross Sections (STXS)
6. HH
7. Combinations and Interpretations
8. Another angle
9. **Future**
10. Summary

High Luminosity LHC (HL-LHC)





Karsten Köneke

Progress in TH Prediction (in a tiny nutshell)

Gavin Salam

the master formula

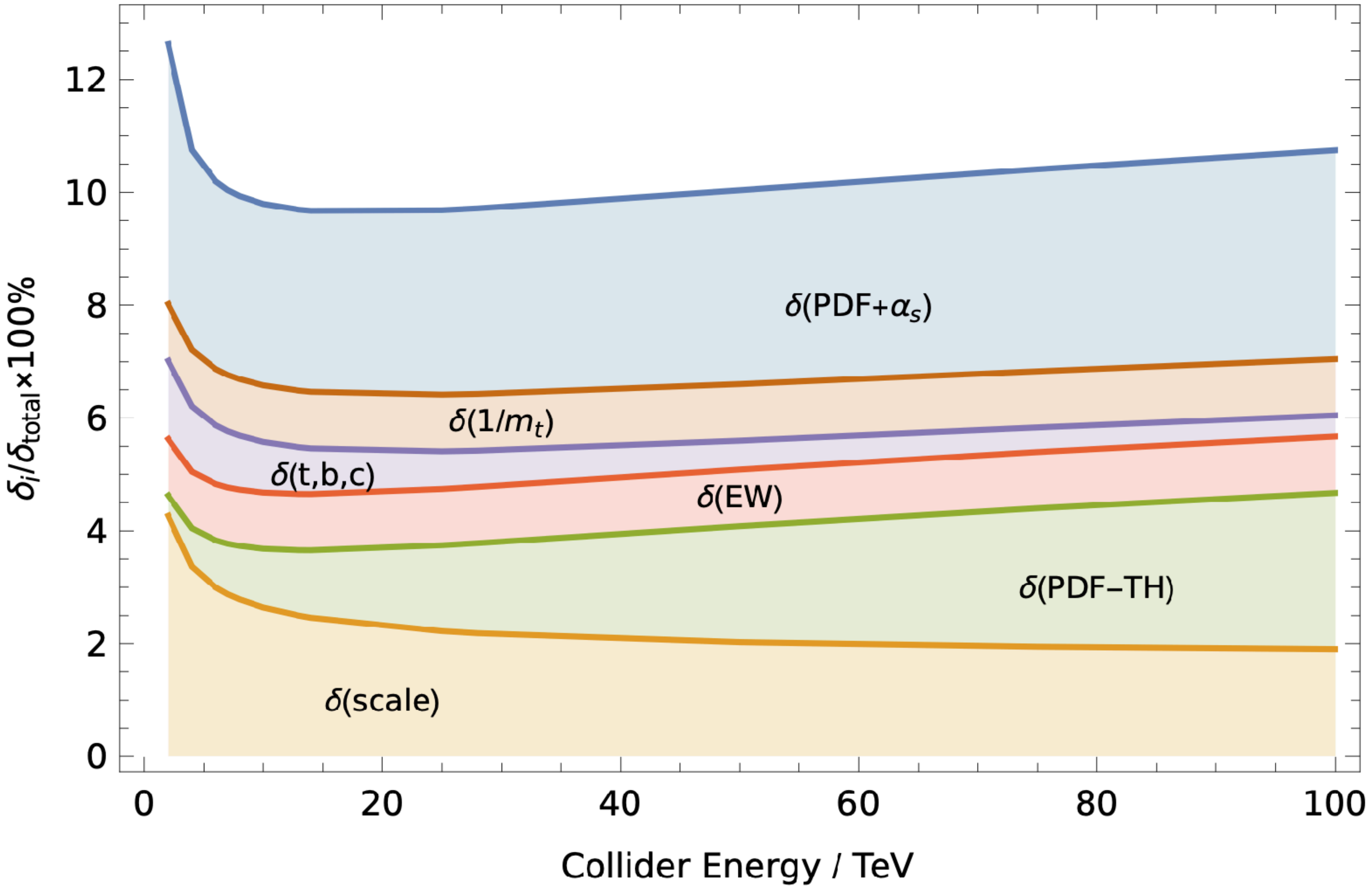
$$\sigma = \sum_{i,j} \int dx_1 dx_2\, f_{i/p}(x_1) f_{j/p}(x_2)\, \hat{\sigma}(x_1 x_2 s) \times \left[1 + \mathcal{O}(\Lambda/M)^p\right]$$

α_S Improvements in precision from the Lattice (until FCC-ee Z hadronic)

$$\sigma_{ggF} = 48.68 \pm 3.9\ (\text{scales}) \ \pm 1.9\ (\text{PDF}) \ \pm 2.6\ (\alpha_S) \ \ \text{Pb}$$

PDFs already at 1% (CT18 - NNPDF)
Discussions ongoing

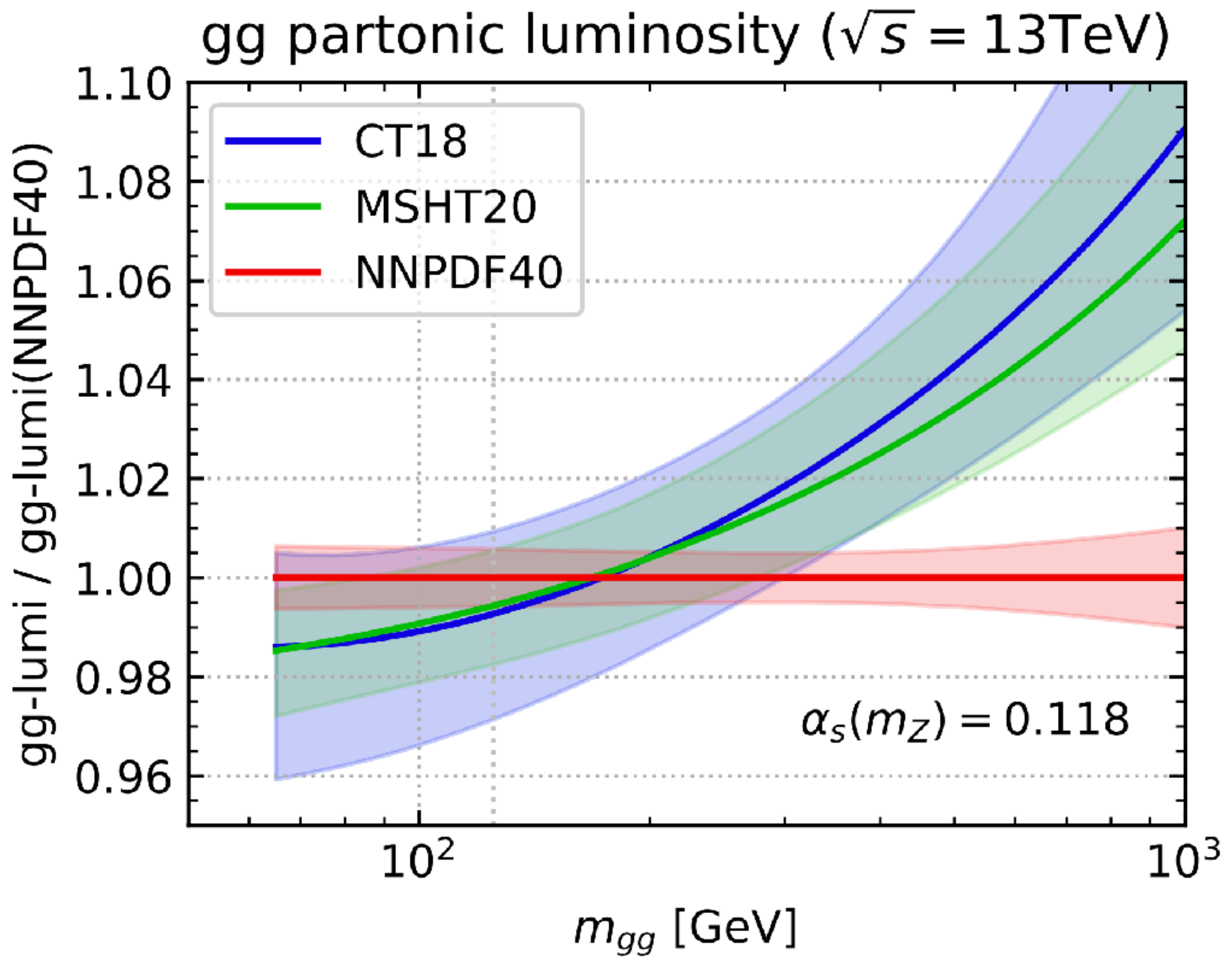
Gavin Salam



Alexander Huss

- PDF and α_S
- Finite quark masses effects
- Missing EW and mixed EW-QCD corrections
- Mismatch in the PDF (NNLO) and perturbative order N3LO
- Missing HO beyond N3LO

Many more signal processes!



Modelling of signal and background key!

- NLO QCD and EW predictions matched to PS
- NNLO PS matching
- CPU time challenge

Simon Plätzer
Frank Siegert

Marumi Kado at Higgs2021

Higgs Couplings at HL-LHC

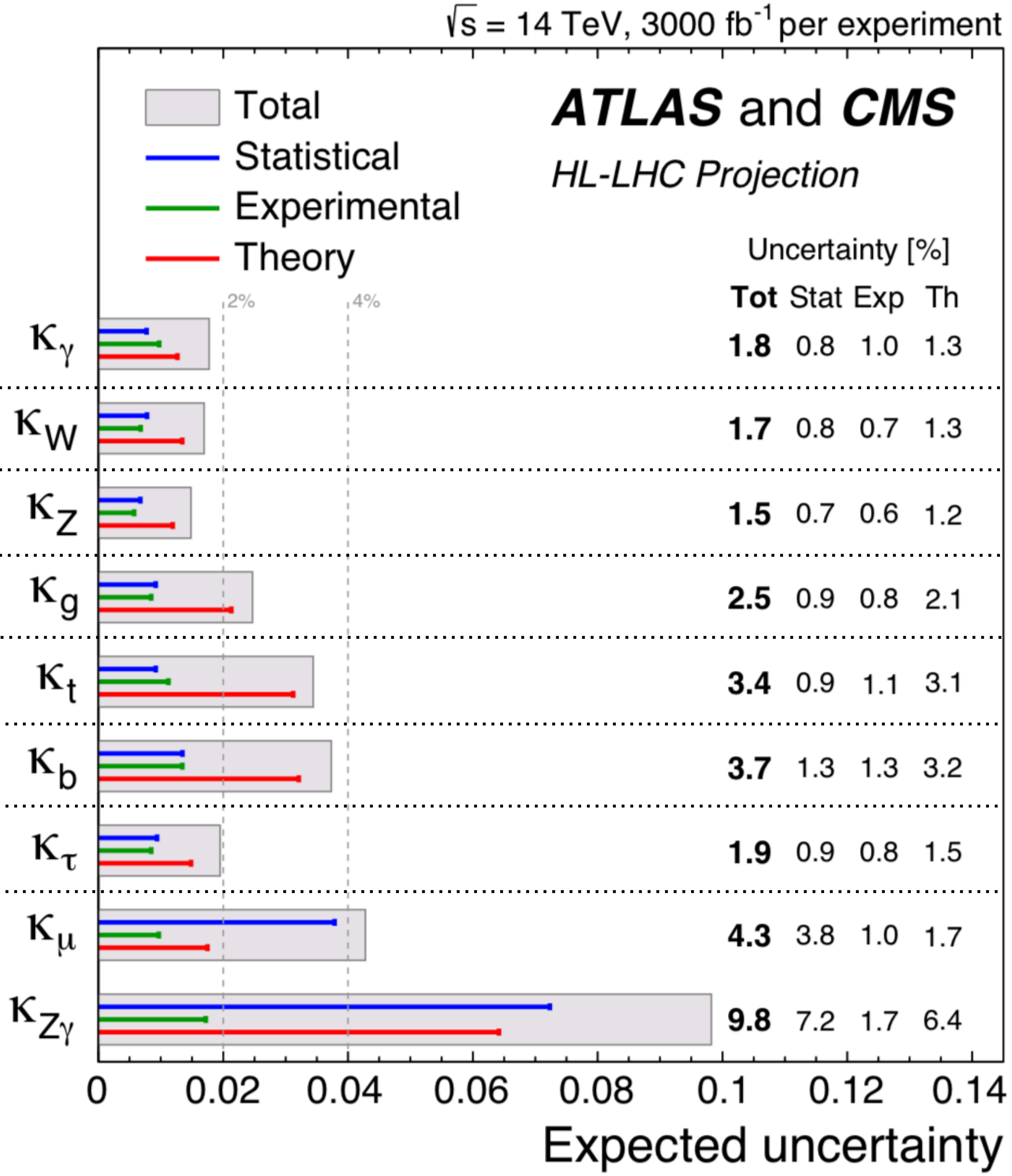
Higgs couplings strength with respective particles

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

JHEP 08 (2016) 045

Nature 607, 52–59 (2022)

Nature 607 (2022) 60-68



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

Measurements here assume no BSM in Higgs width

A bright Future…

arXiv:1905.03764

A bright Future…

arXiv:1905.03764

Summary

What we know about the Higgs boson

- **All measured quantities are consistent with SM**

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%, more improvements ongoing…

New era of precision and interpretation

- More and more "boosted" analyses and other things that were not possible before

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**!

Future upgrades and accelerators will dramatically improve our understanding of the mass generating mechanism

Higgs Boson Width

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

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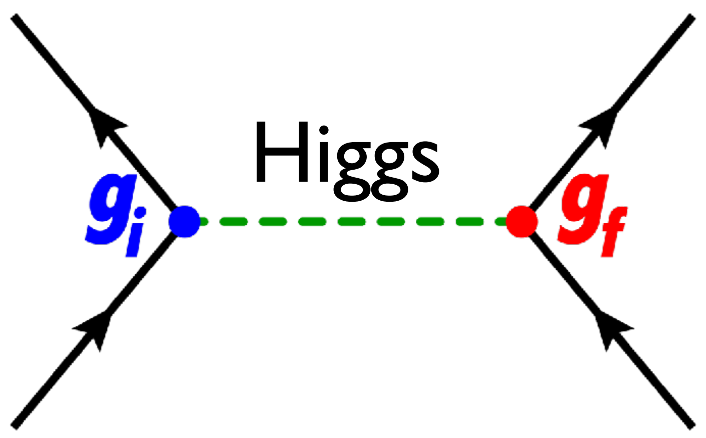
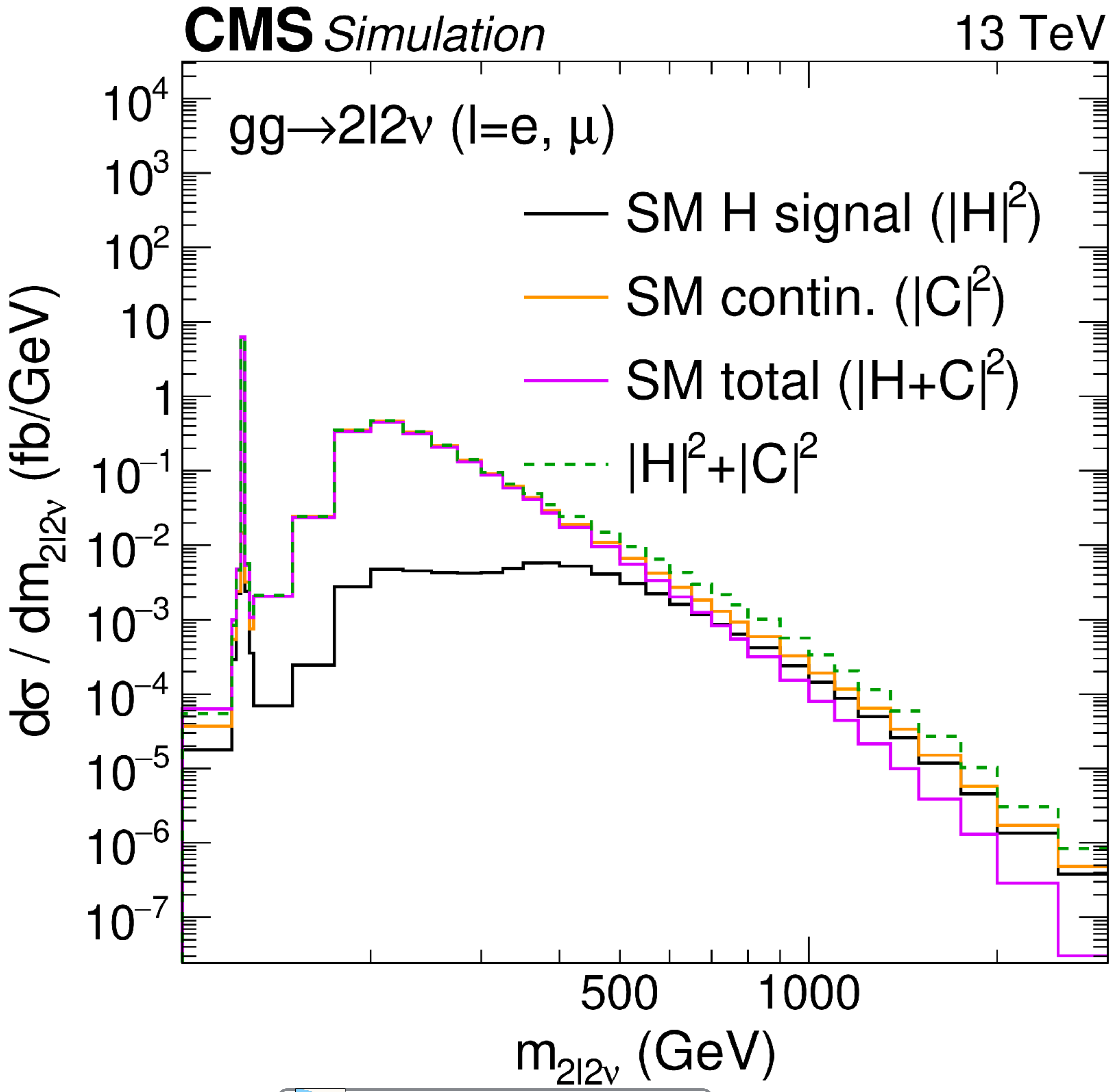
- Idea:



  - Cross-section

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



Nat. Phys. 18 (2022) 1329

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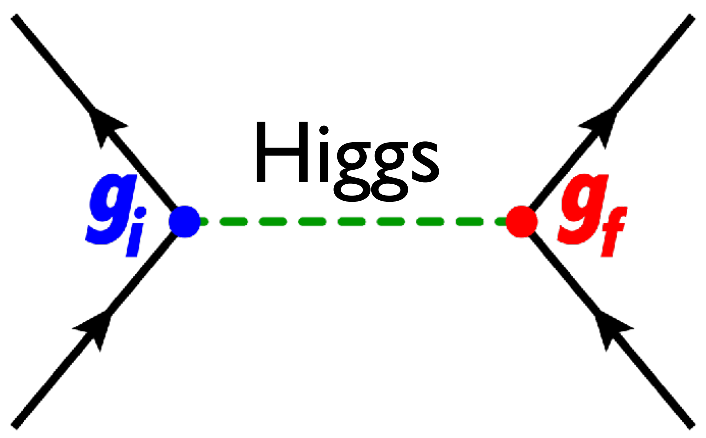
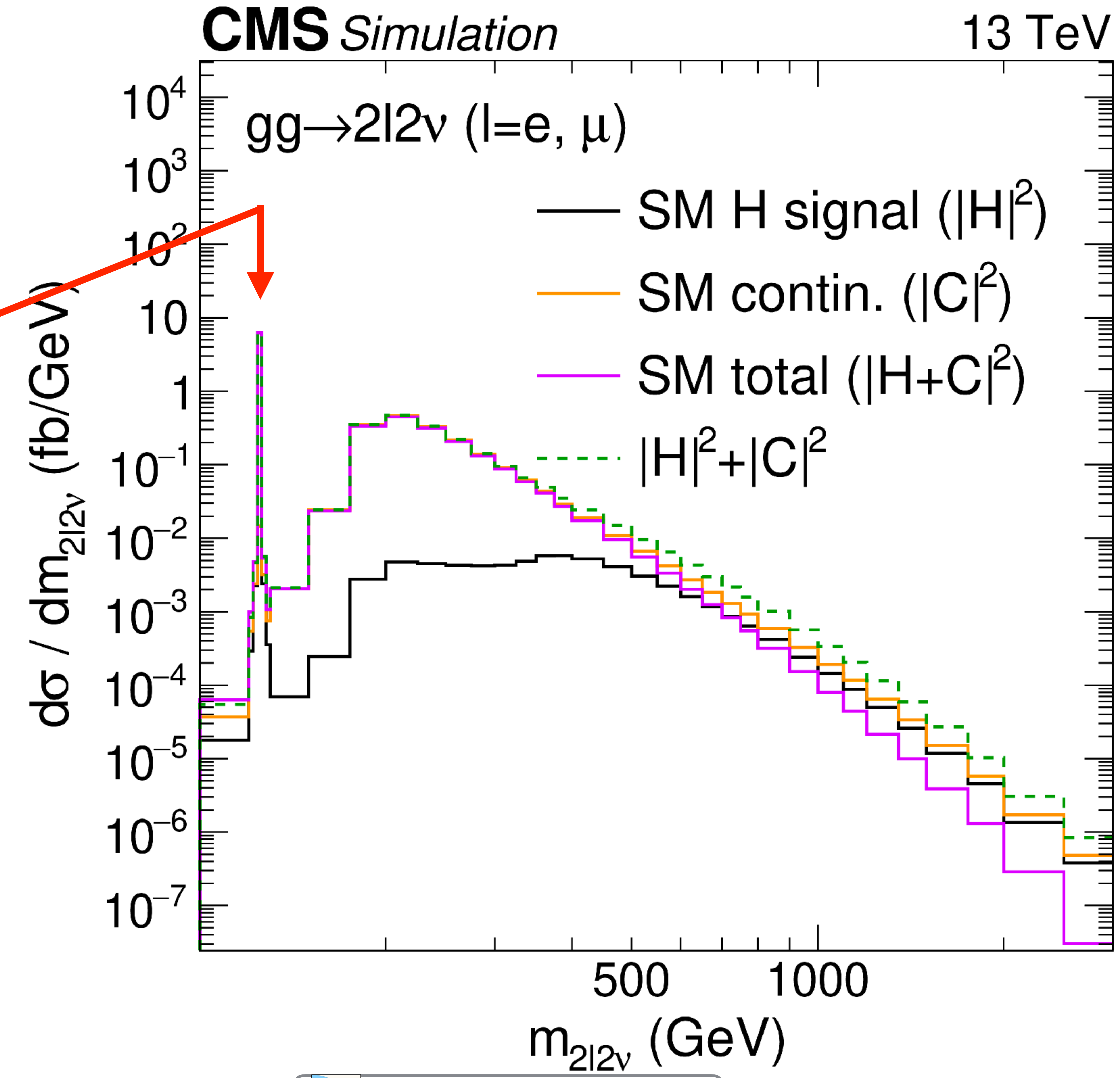


  - Cross-section on-resonance:

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



Nat. Phys. 18 (2022) 1329

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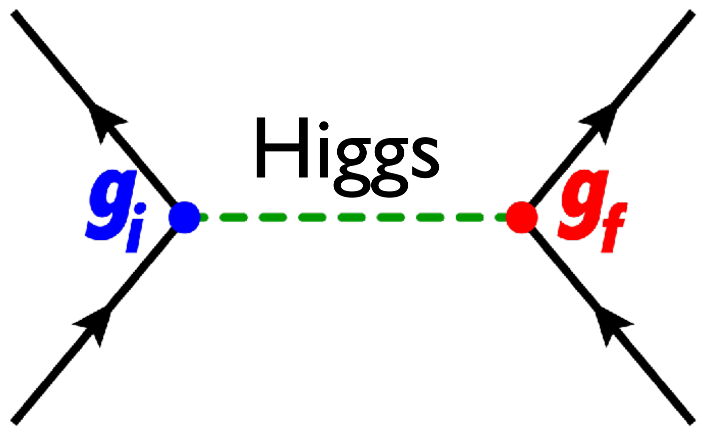

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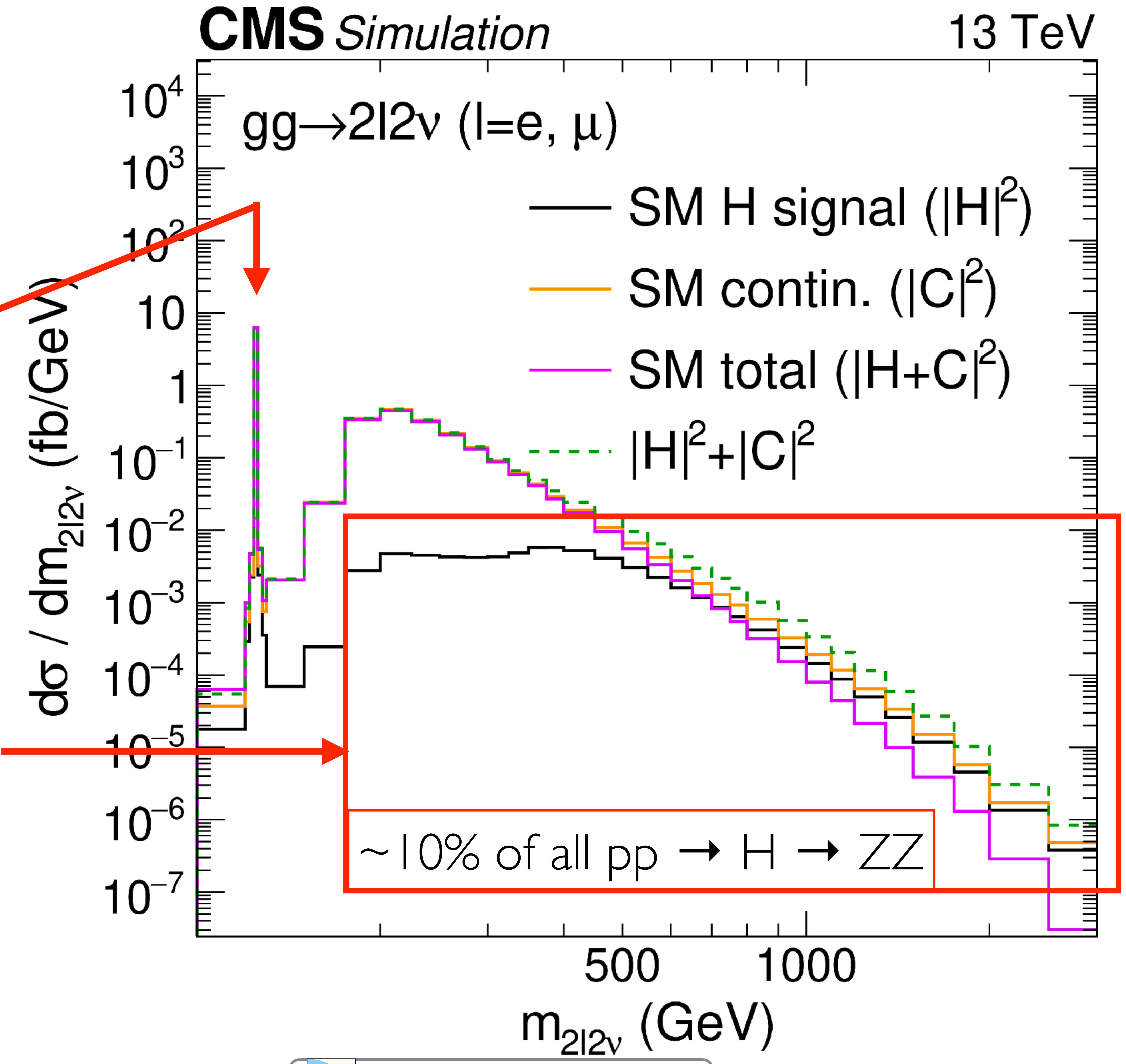
  - Cross section far above resonance ("off-shell"):

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



Nat. Phys. 18 (2022) 1329

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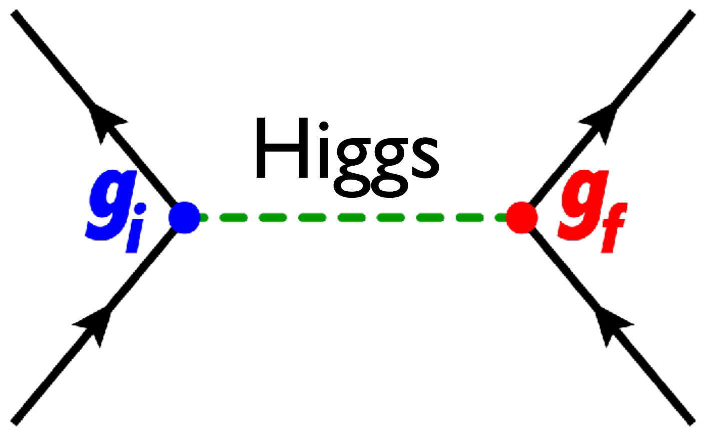

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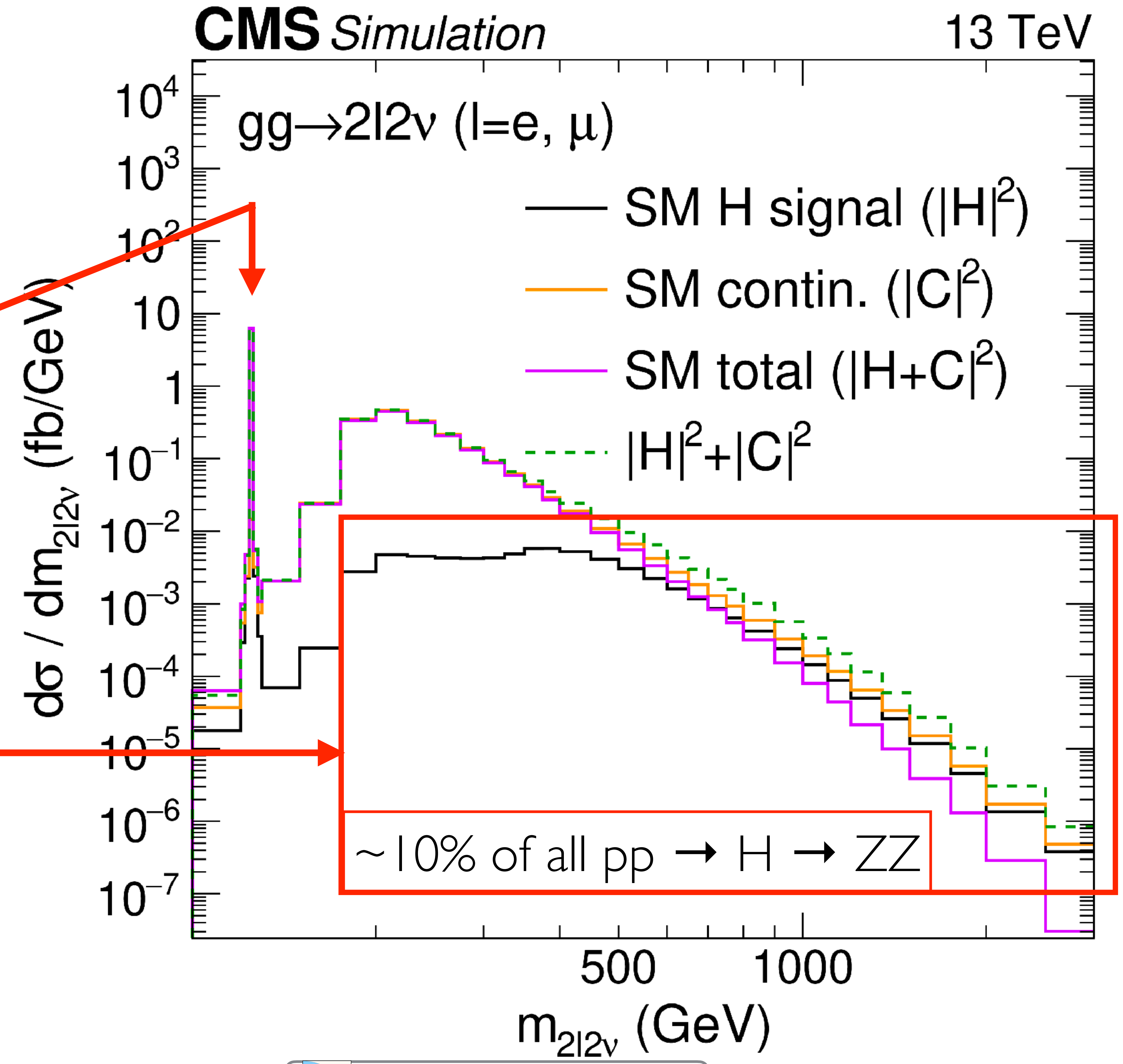
  - Measure ratio of both: $\Gamma_H \propto \frac{\sigma_{\rm off}}{\sigma_{\rm on}}$



Nat. Phys. 18 (2022) 1329

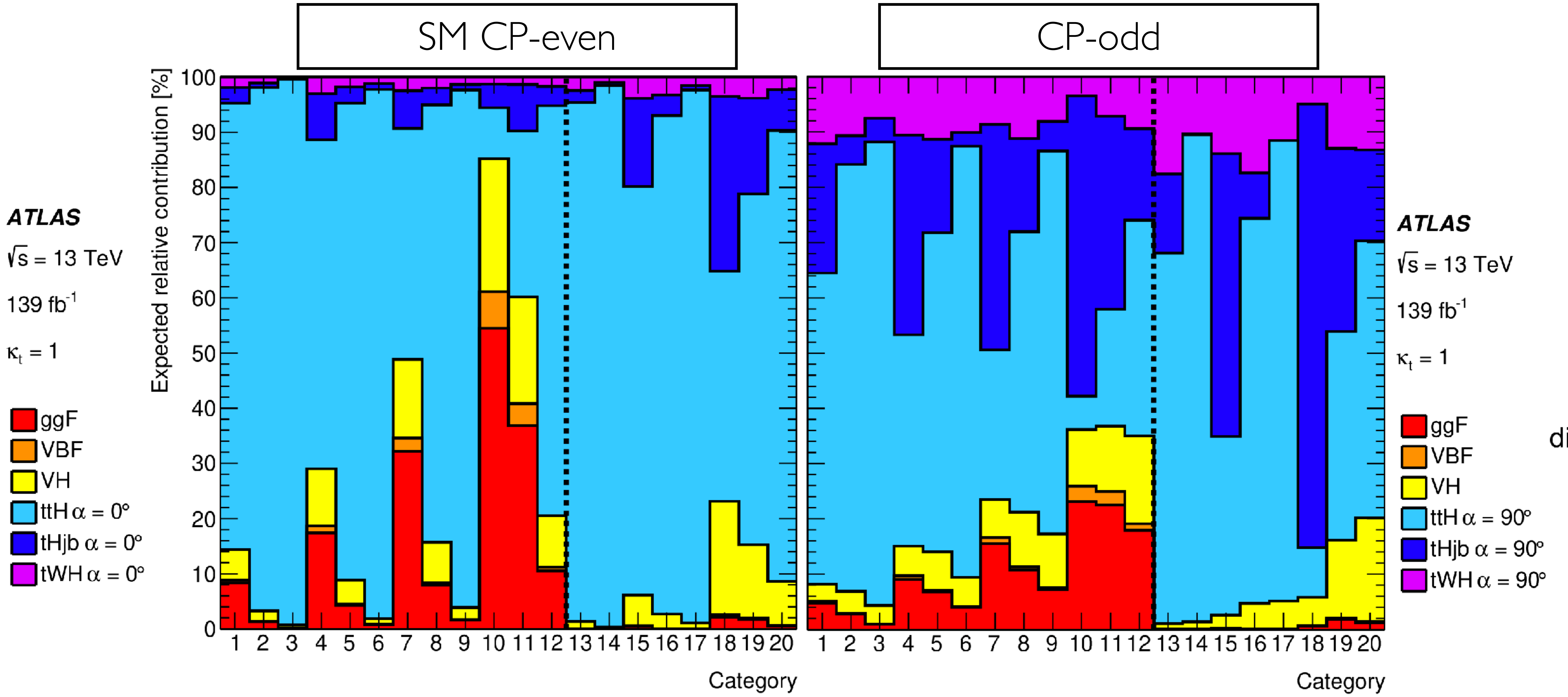
CP Measurements

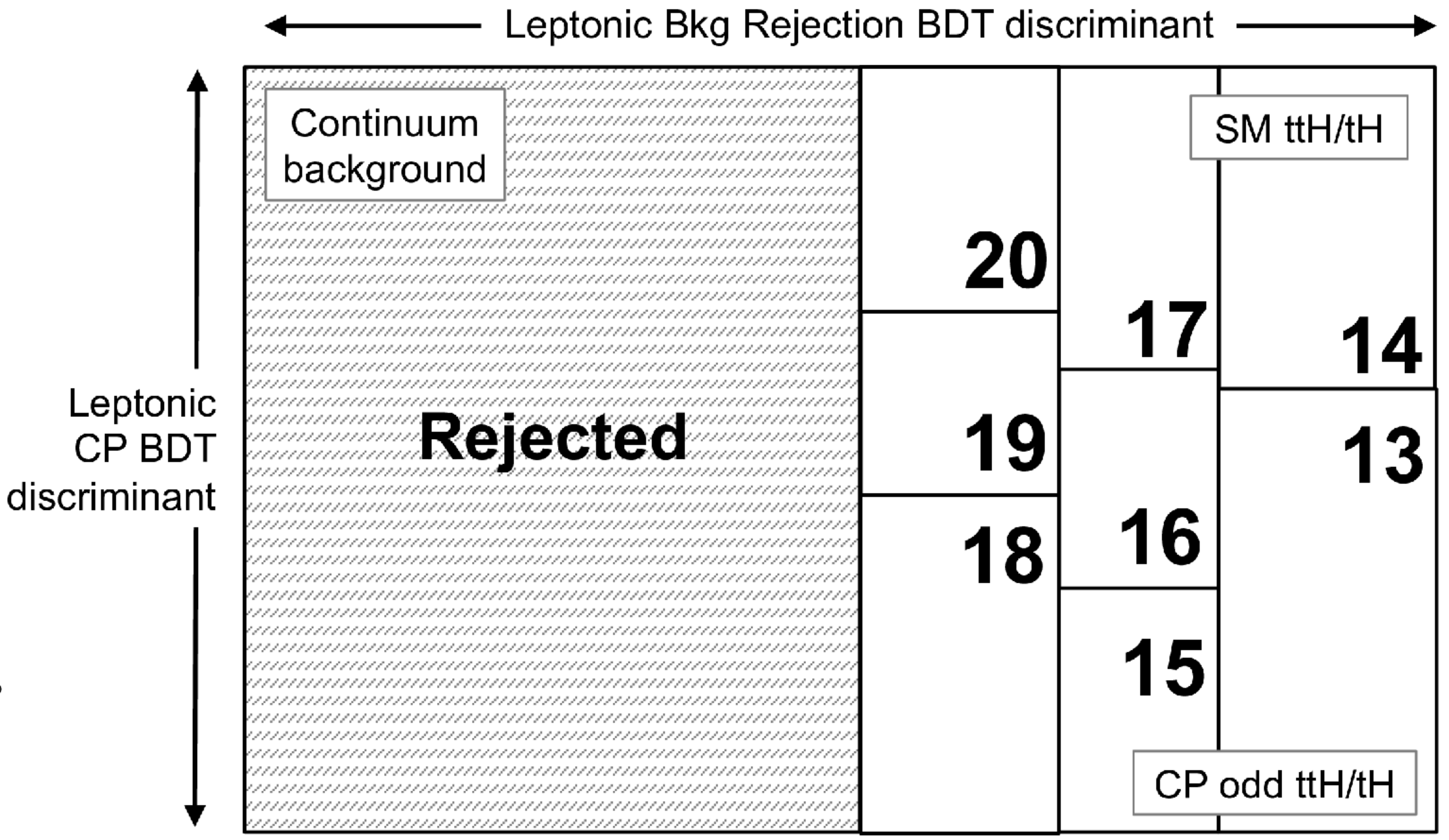
- CP-odd in Higgs-Gauge interactions need higher-order operators
- CP-odd in Higgs-fermion interactions (top-Yukawa) can be **tree-level**

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

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

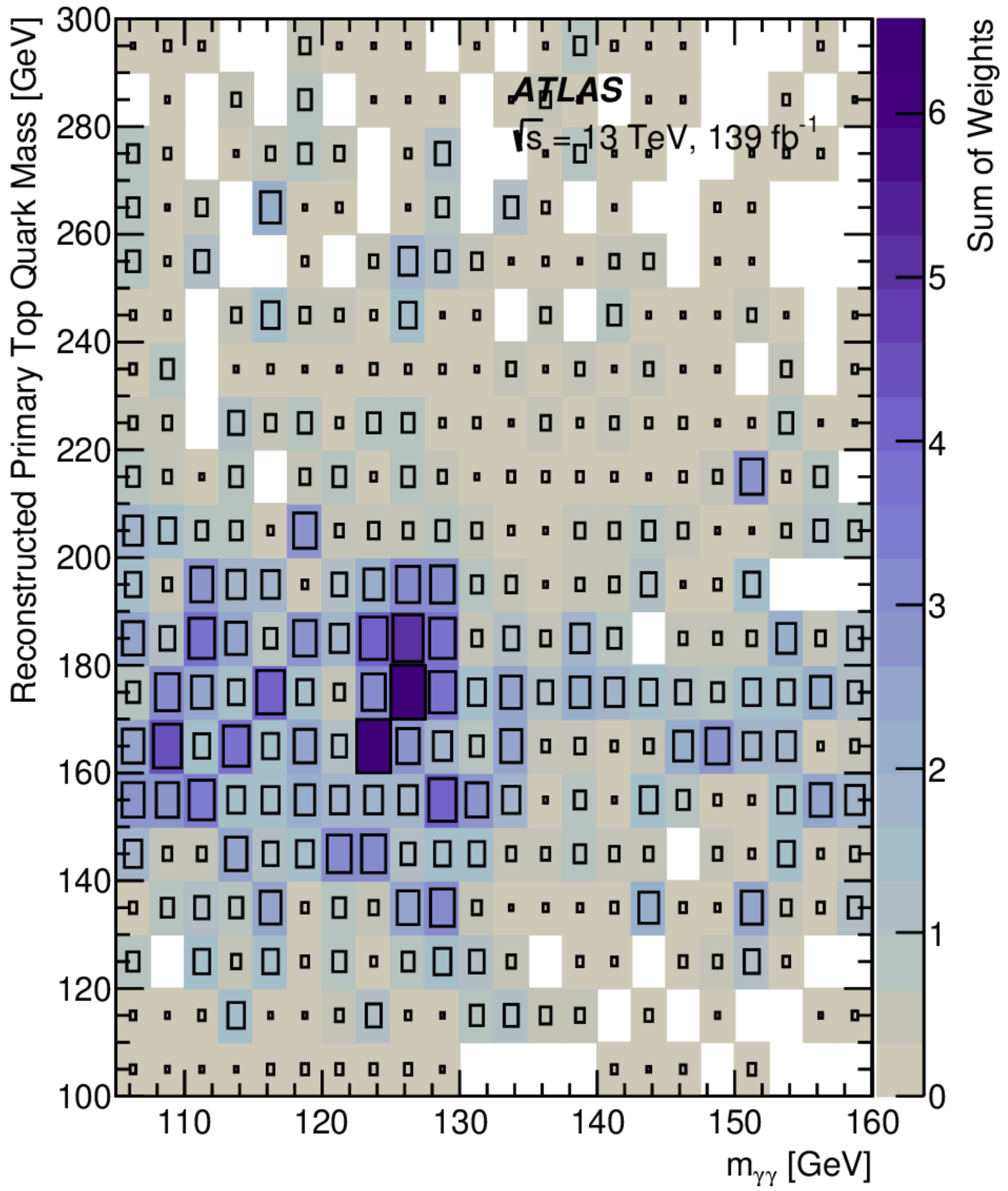
- Analysis strategy:
  - Identify CP-sensitive variables (angular variables, p_T(H),…)
  - Often use multivariate analysis to:
    - combine CP-sensitive information
    - separate signal from background

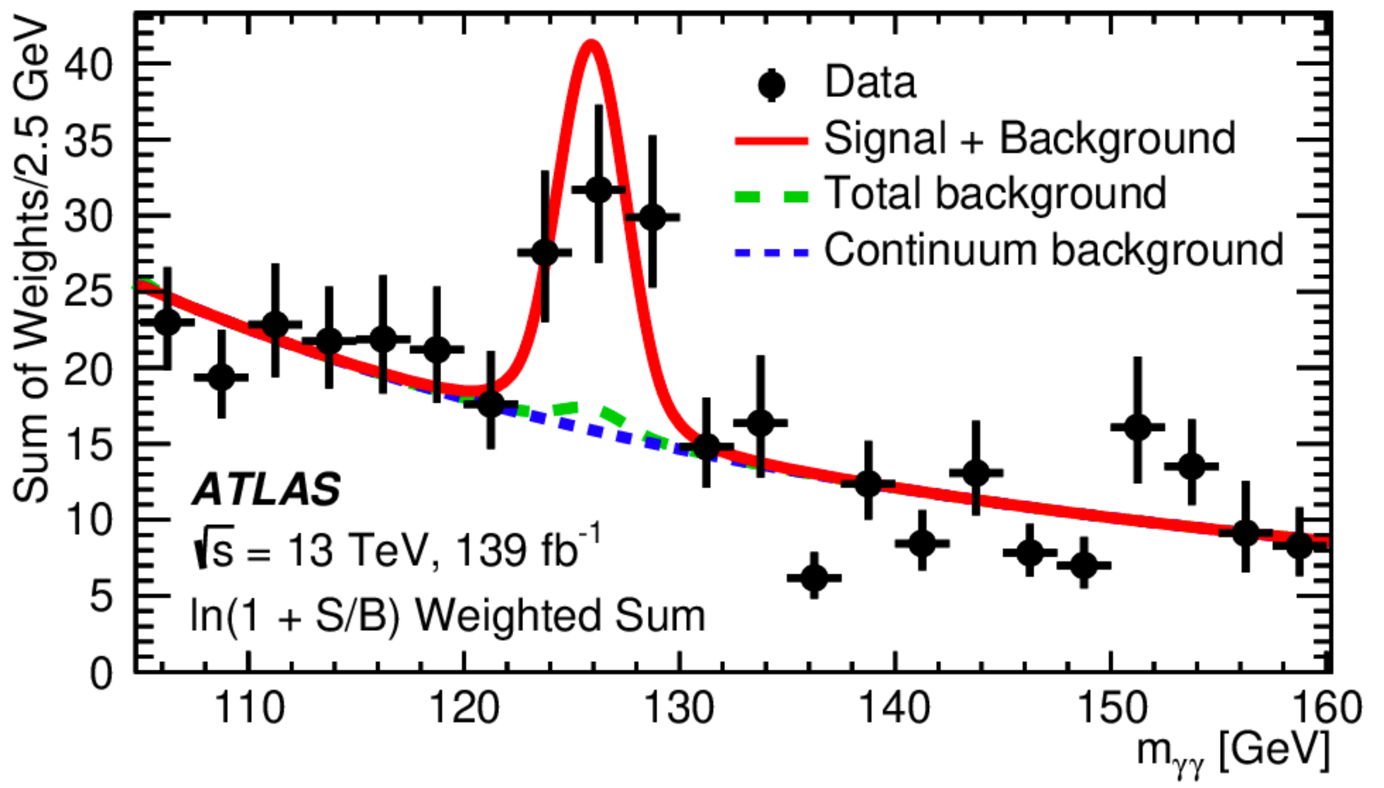


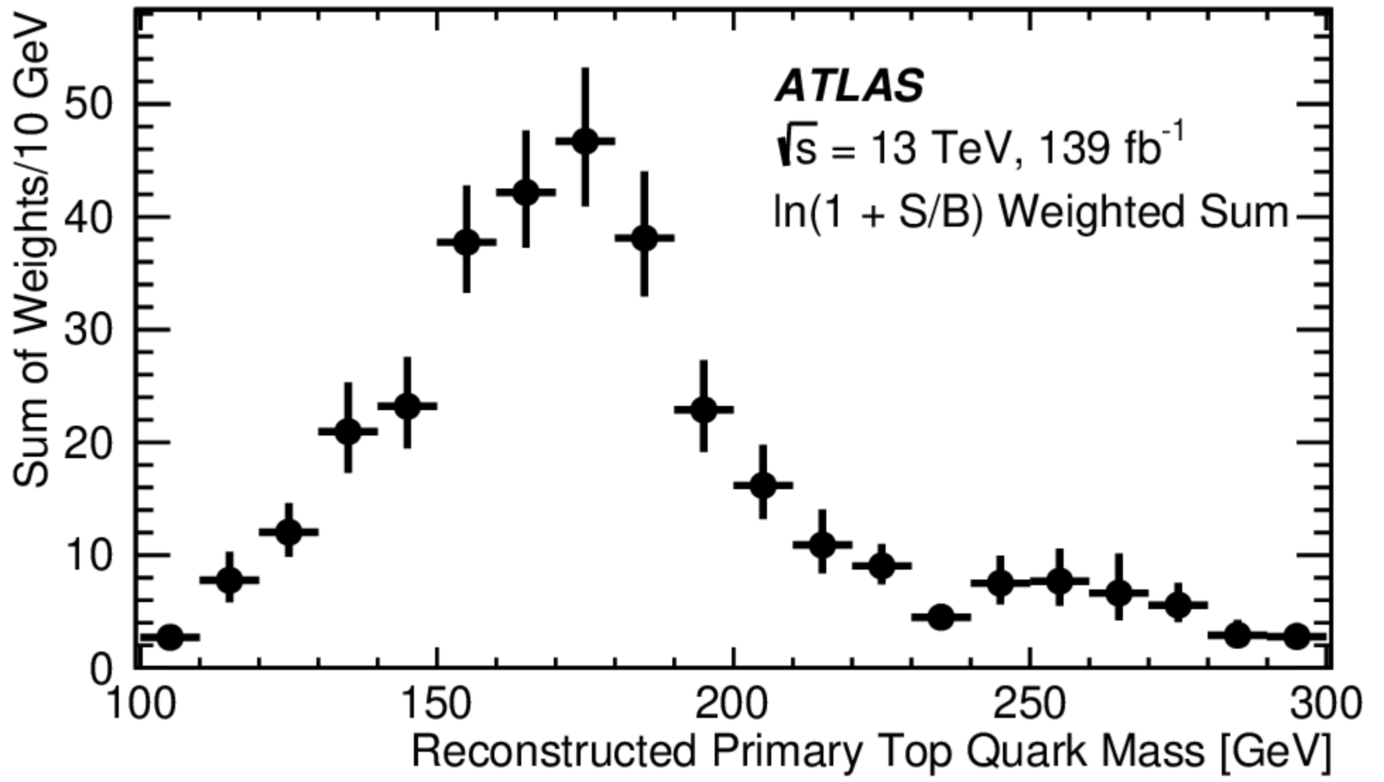


CP Measurement in ttH Production with H → γγ

- 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

CP Measurement in t(t)H Production

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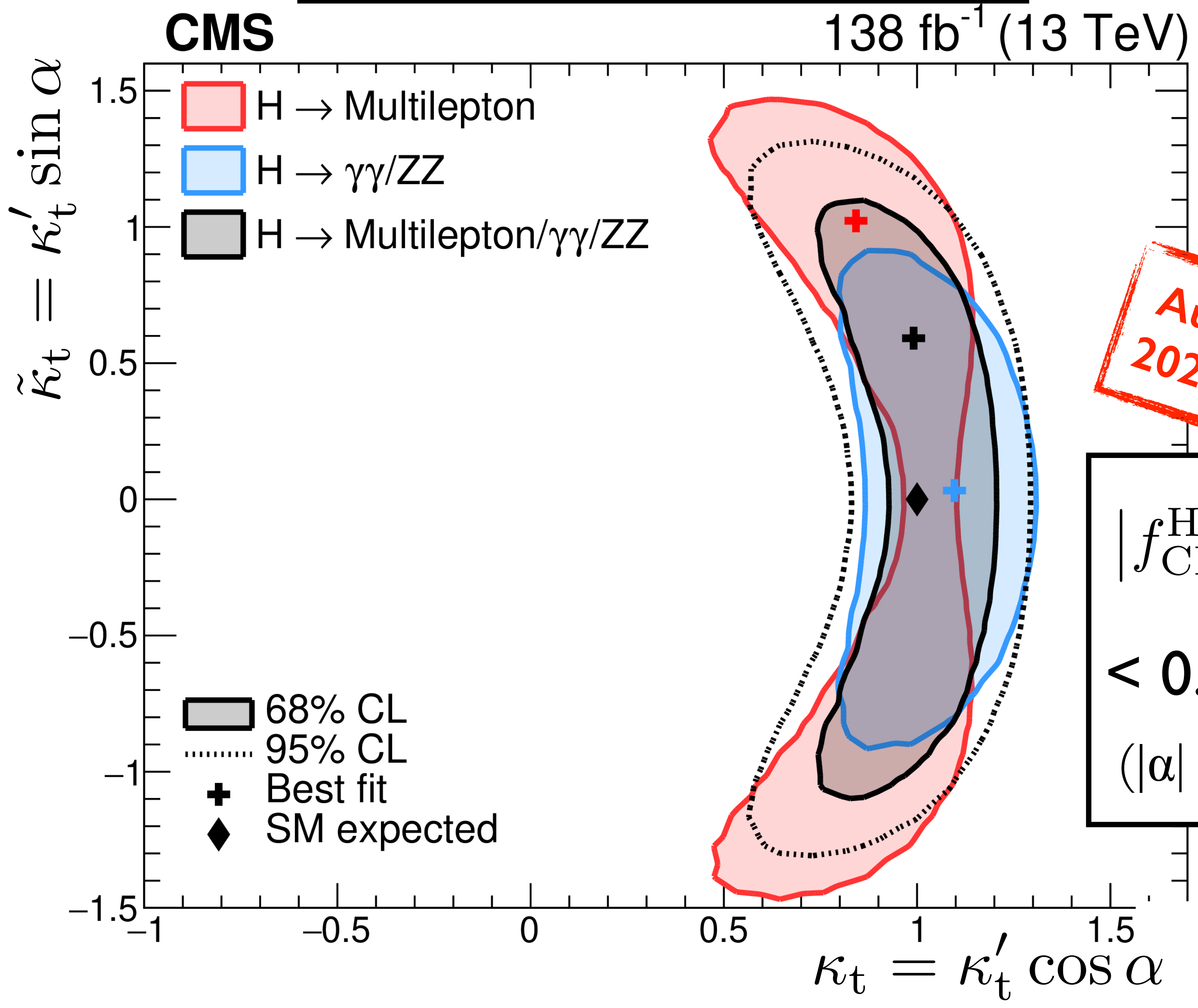
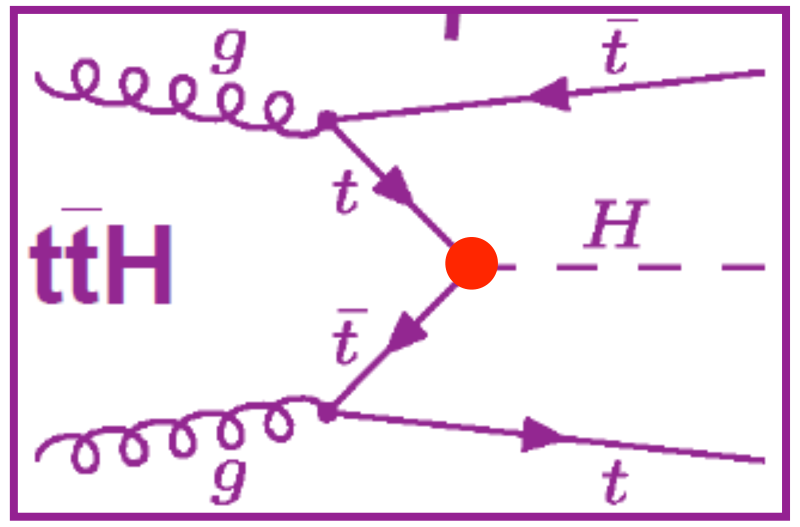
"**multilepton**" topology
Combine with γγ and ZZ*

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

ttH, H → γγ topology



Aug 2022

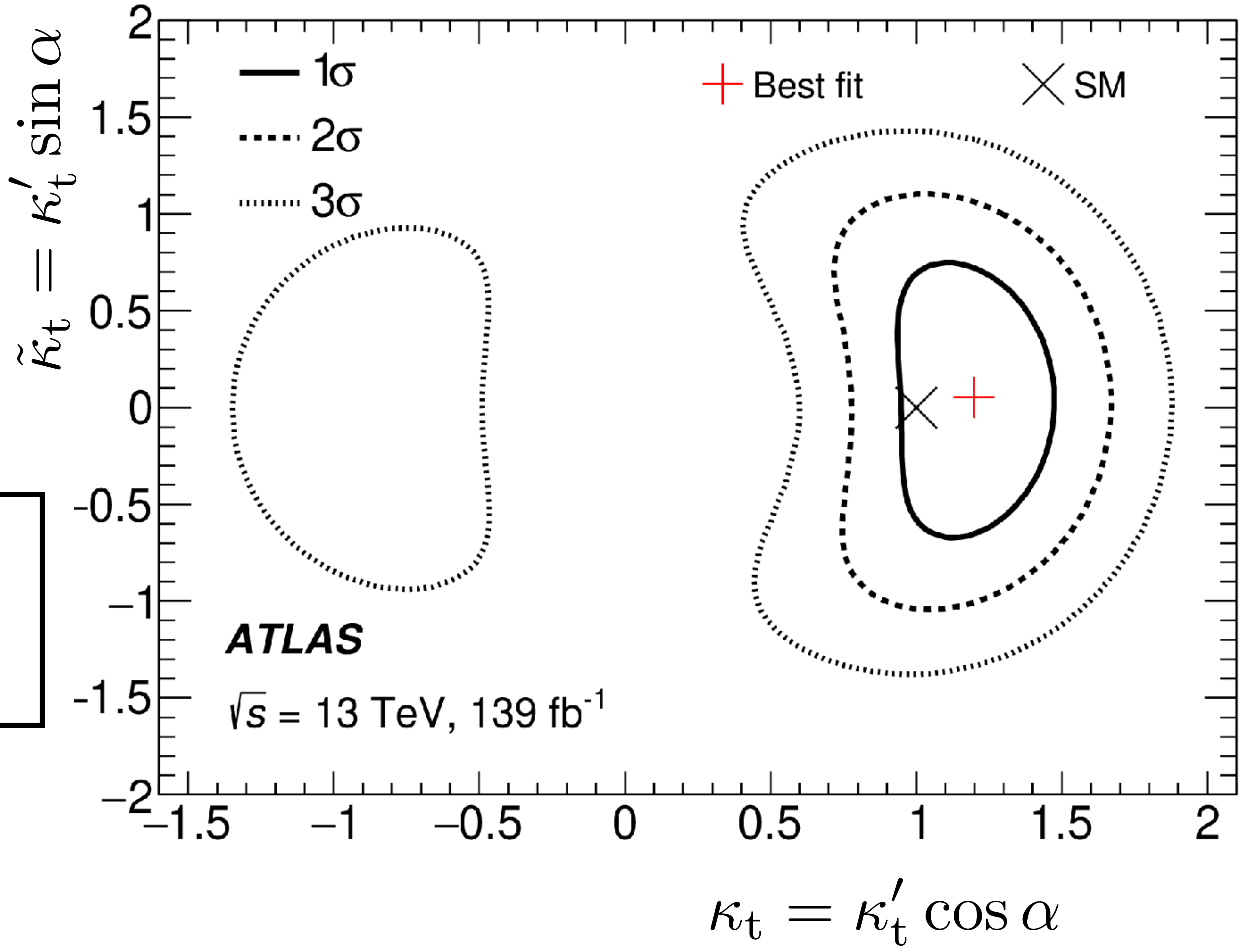


$$|f_{CP}^{Htt}| = \left|\frac{\tilde{\kappa}_t^2}{\tilde{\kappa}_t^2 + \kappa_t^2}\right|$$

< 0.55 @ 68% C.L.

(|α| < 48° @ 68% C.L.)

|α| < 43°
@ 95% C.L.



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

JHEP 07 (2023) 092

Phys. Rev. Lett. 125 (2020) 061802

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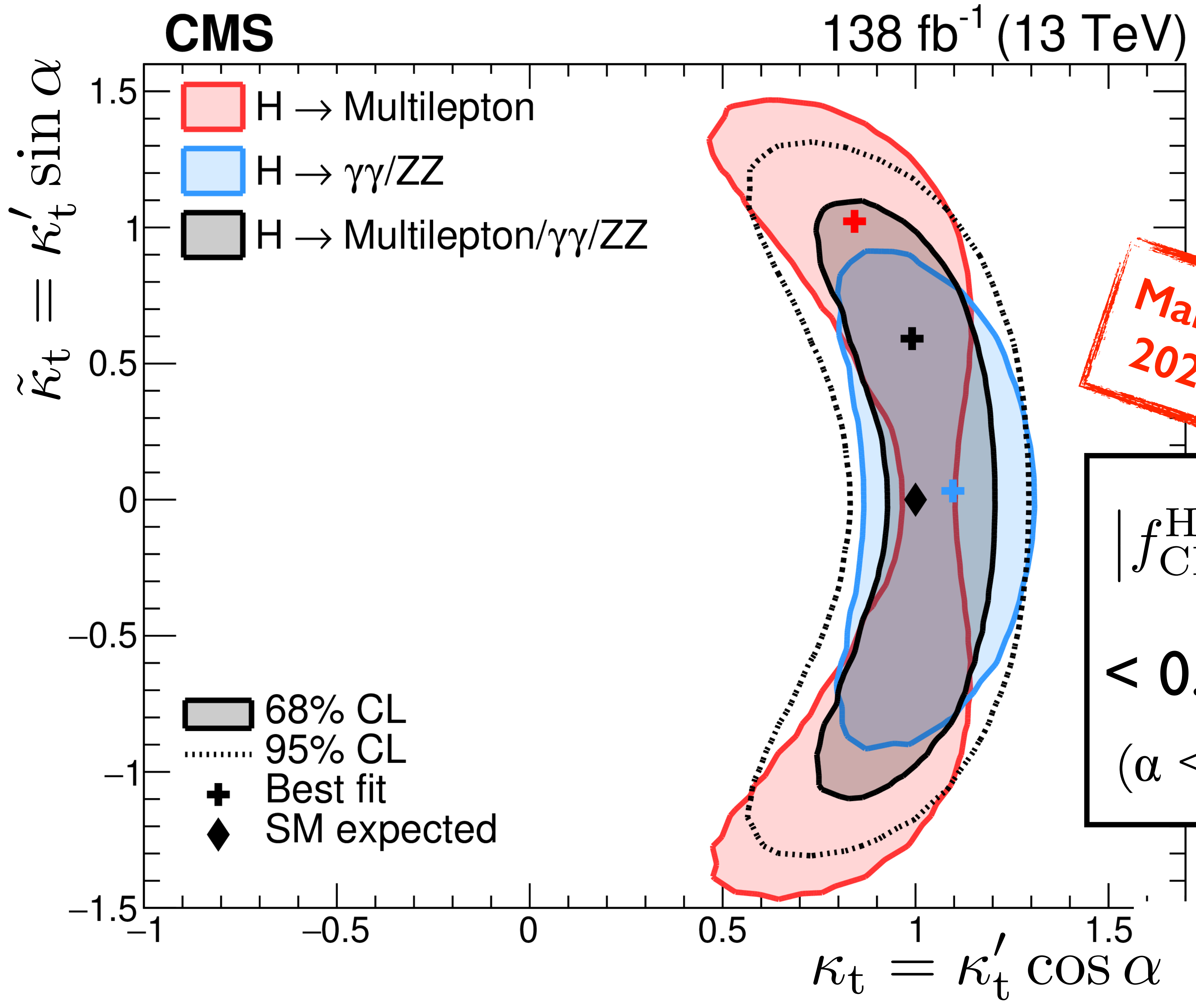
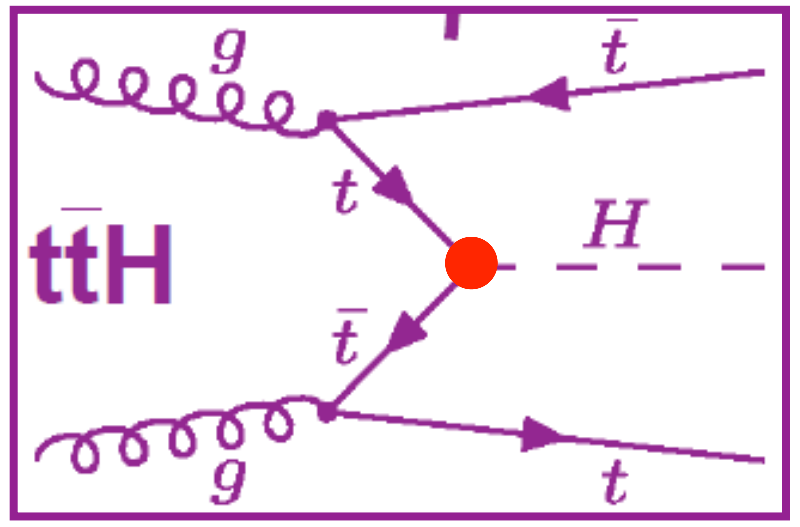
"**multilepton**" topology
Combine with $\gamma\gamma$ and ZZ*

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

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





March 2022

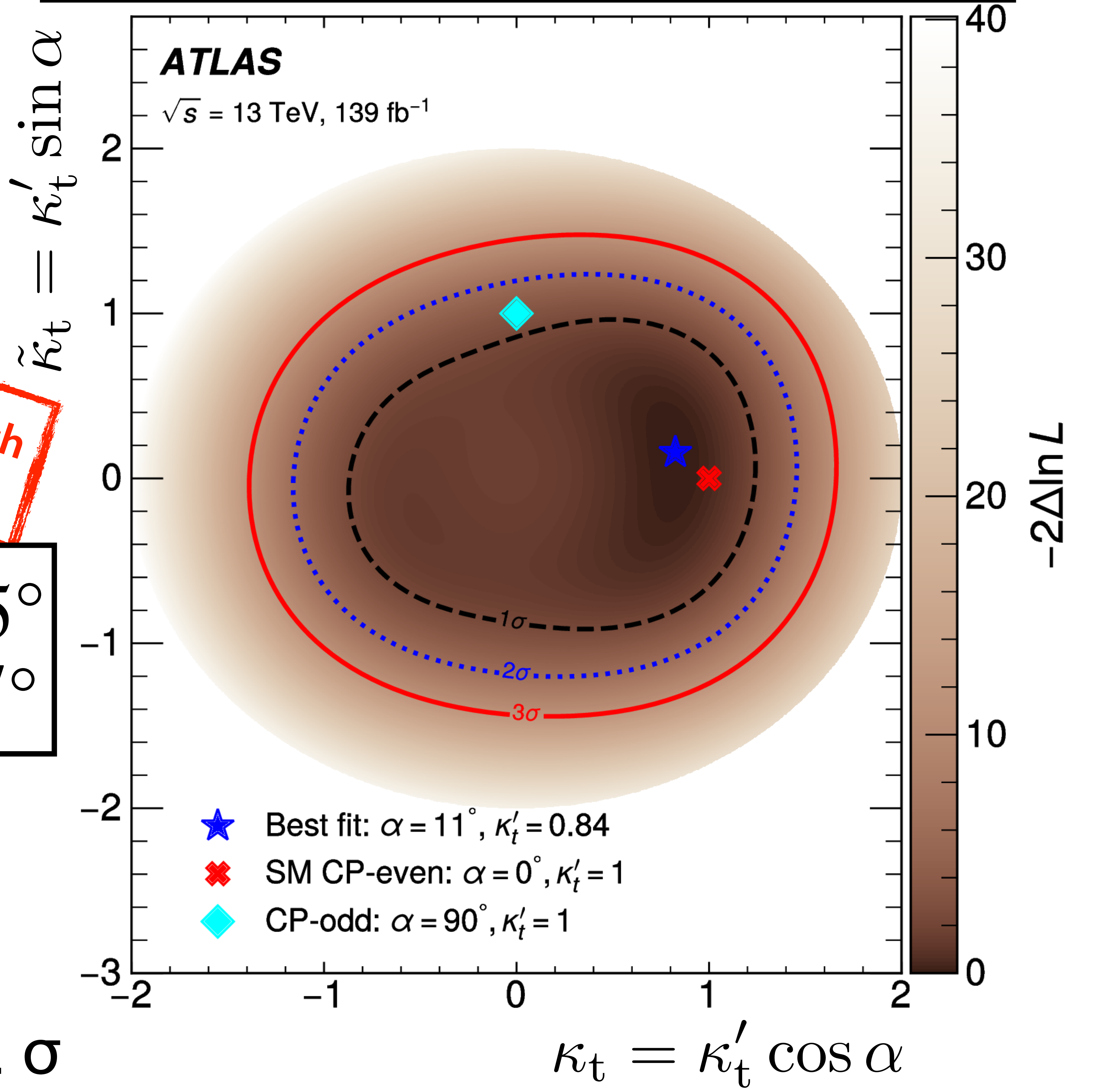
$$\left|f_{CP}^{Htt}\right| = \left|\frac{\tilde{\kappa}_t^2}{\tilde{\kappa}_t^2 + \kappa_t^2}\right|$$

< 0.55 @ 68% C.L.

(α < 48° @ 68% C.L.)

March 2022

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



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JHEP 07 (2023) 092

Phys. Lett. B 849 (2024) 138469

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

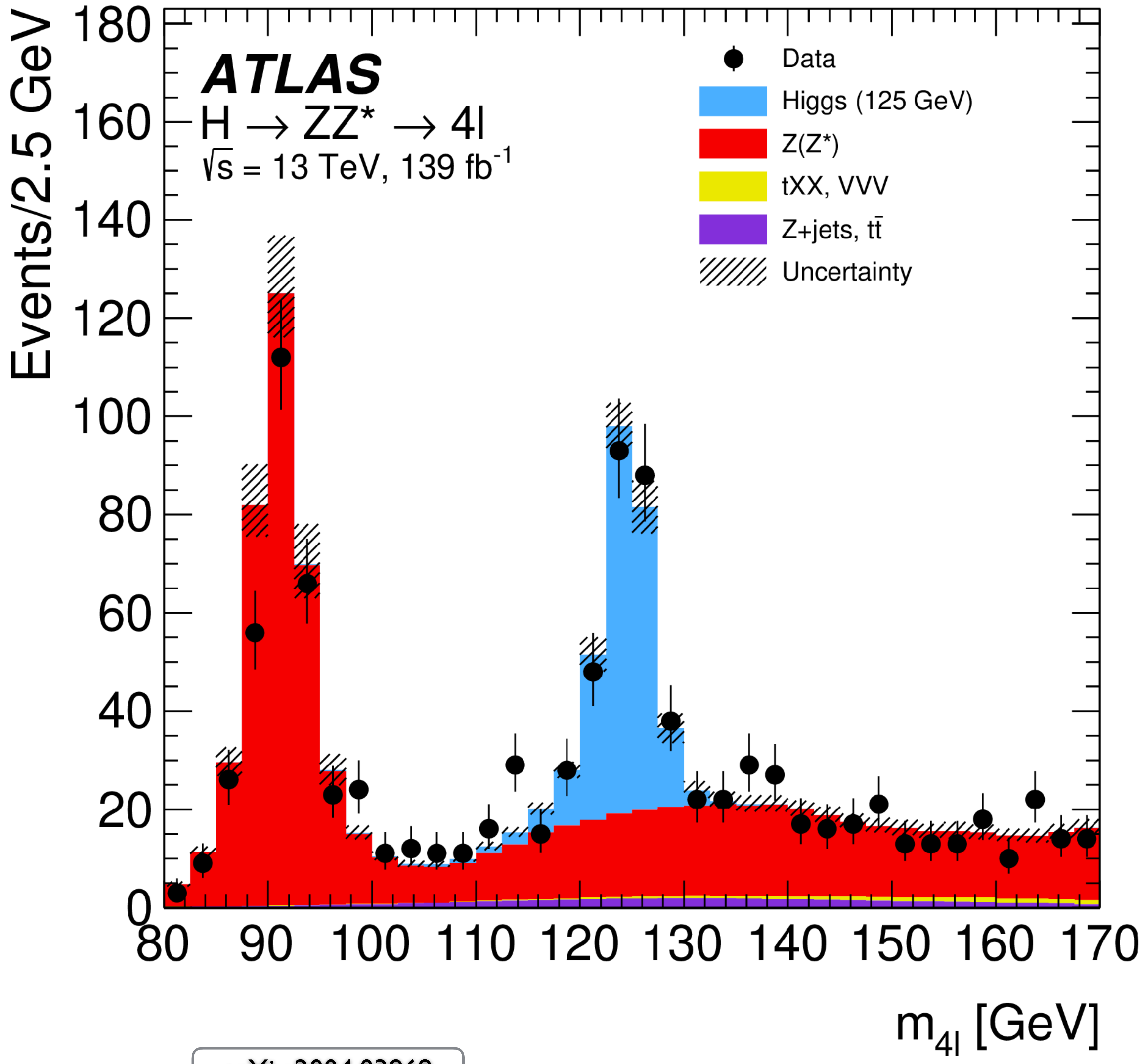
- **$BR_{SM}(H \to ZZ^*) \approx 2.6\%$**
  - $BR_{SM}(Z \to \ell\ell) \approx 3.4\%$

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

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

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

- Fiducial cross-section measurement:
  - Observed: $\sigma_{fid}(H \to ZZ^* \to 4\ell)$ = **3.28 ± 0.32 fb**
  - Expected: $\sigma_{fid,SM}(H \to ZZ^* \to 4\ell)$ = **3.41 ± 0.18 fb**



arXiv:2004.03969

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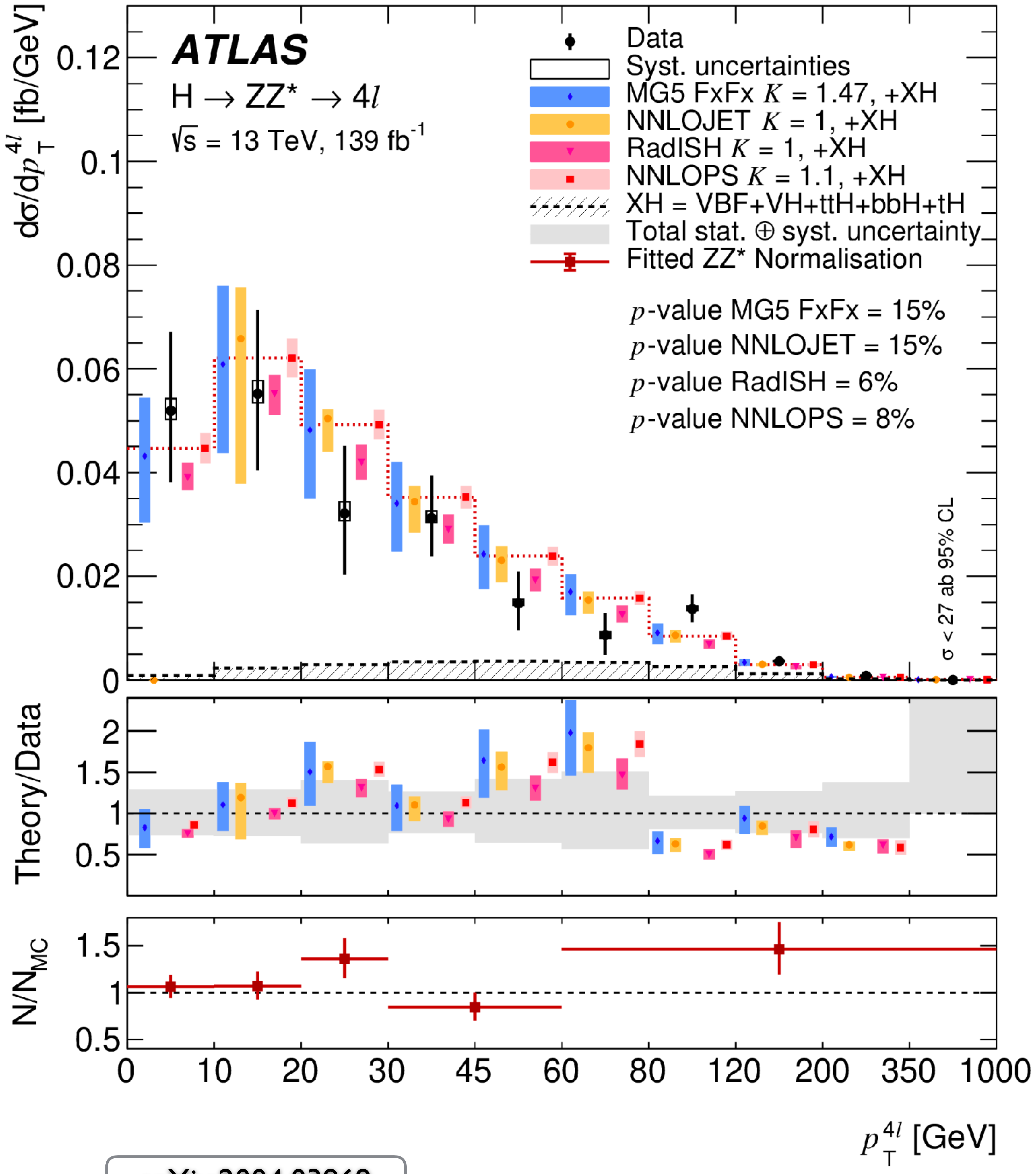

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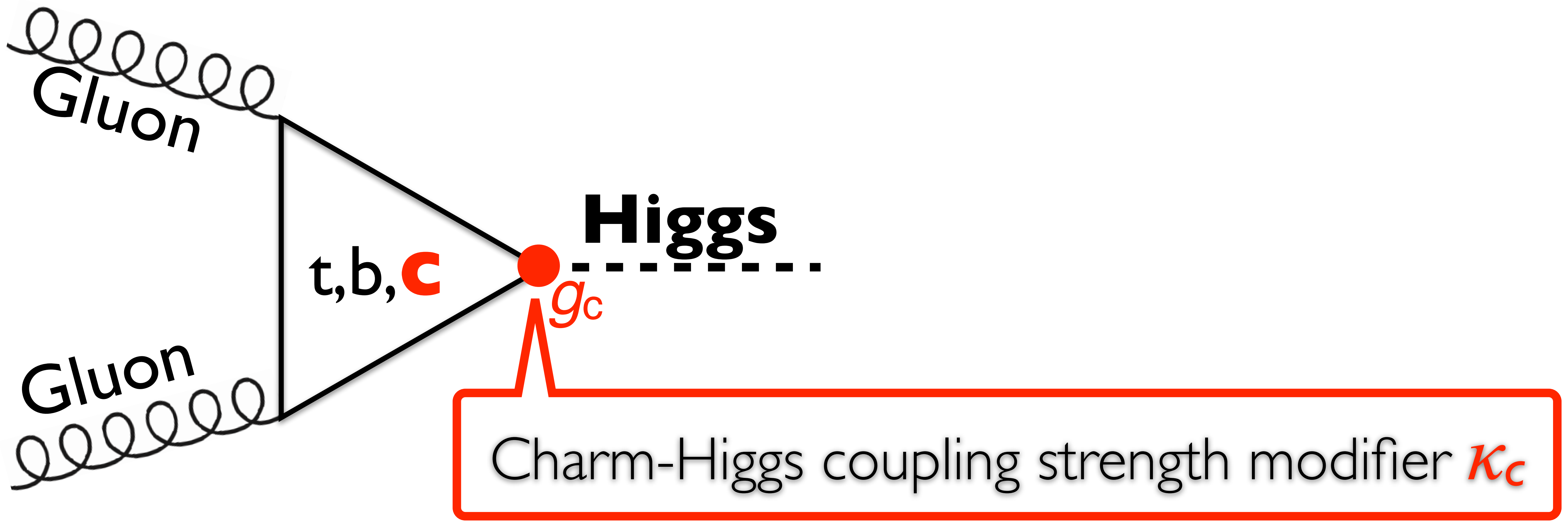
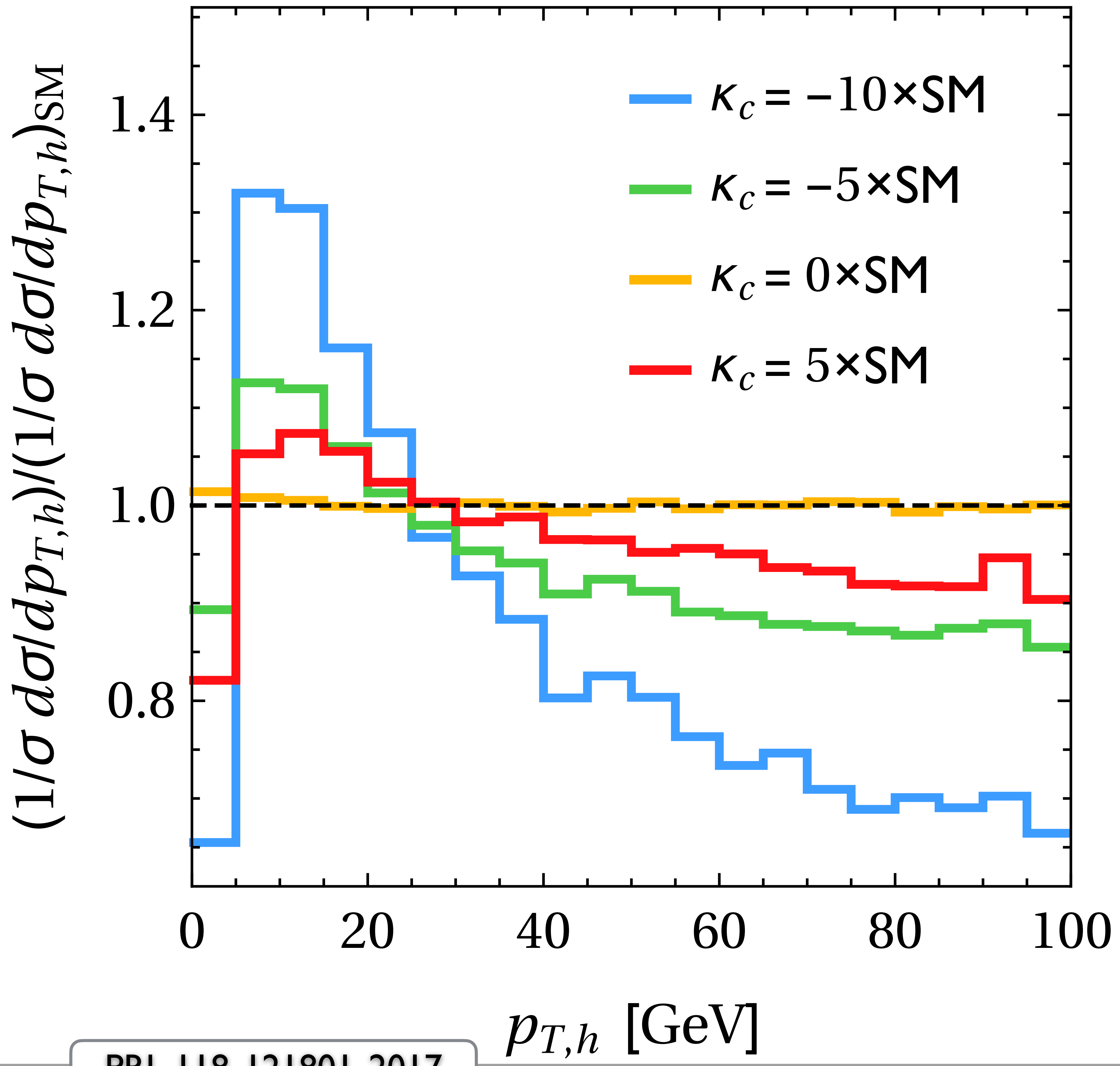
  $\Rightarrow$ Differential cross-section measurements; Comparison with theory predictions

arXiv:2004.03969

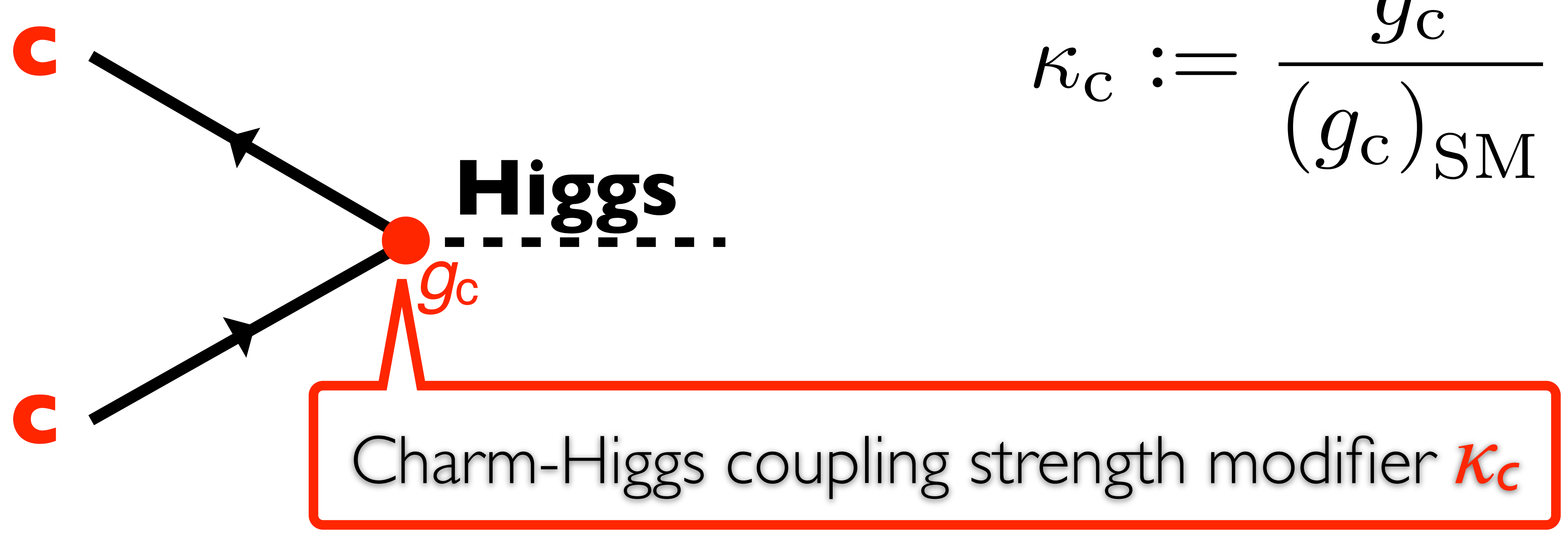
Charm-Higgs Coupling from $p_T(H)$

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





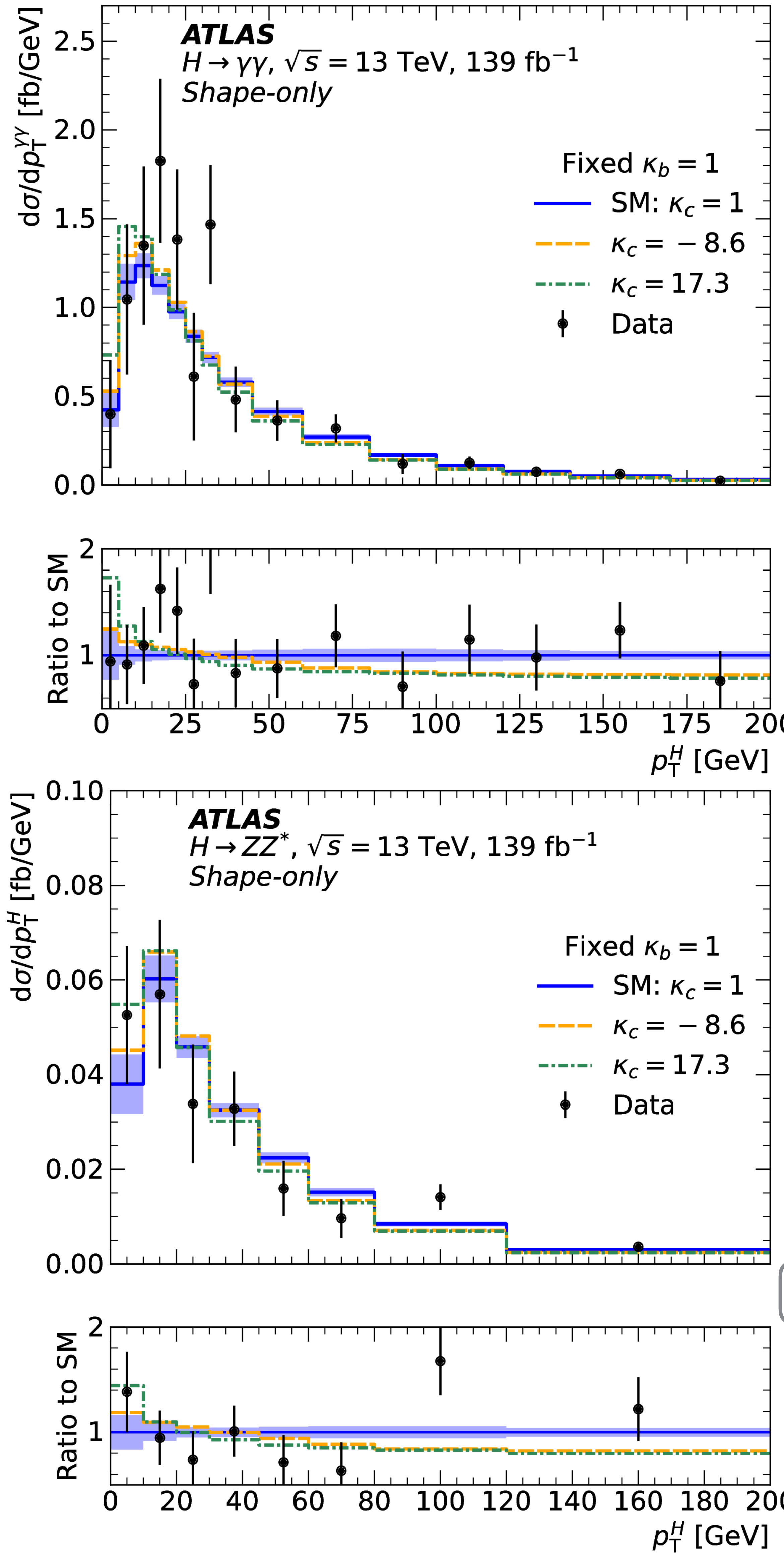
  - Direct cc → H production



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

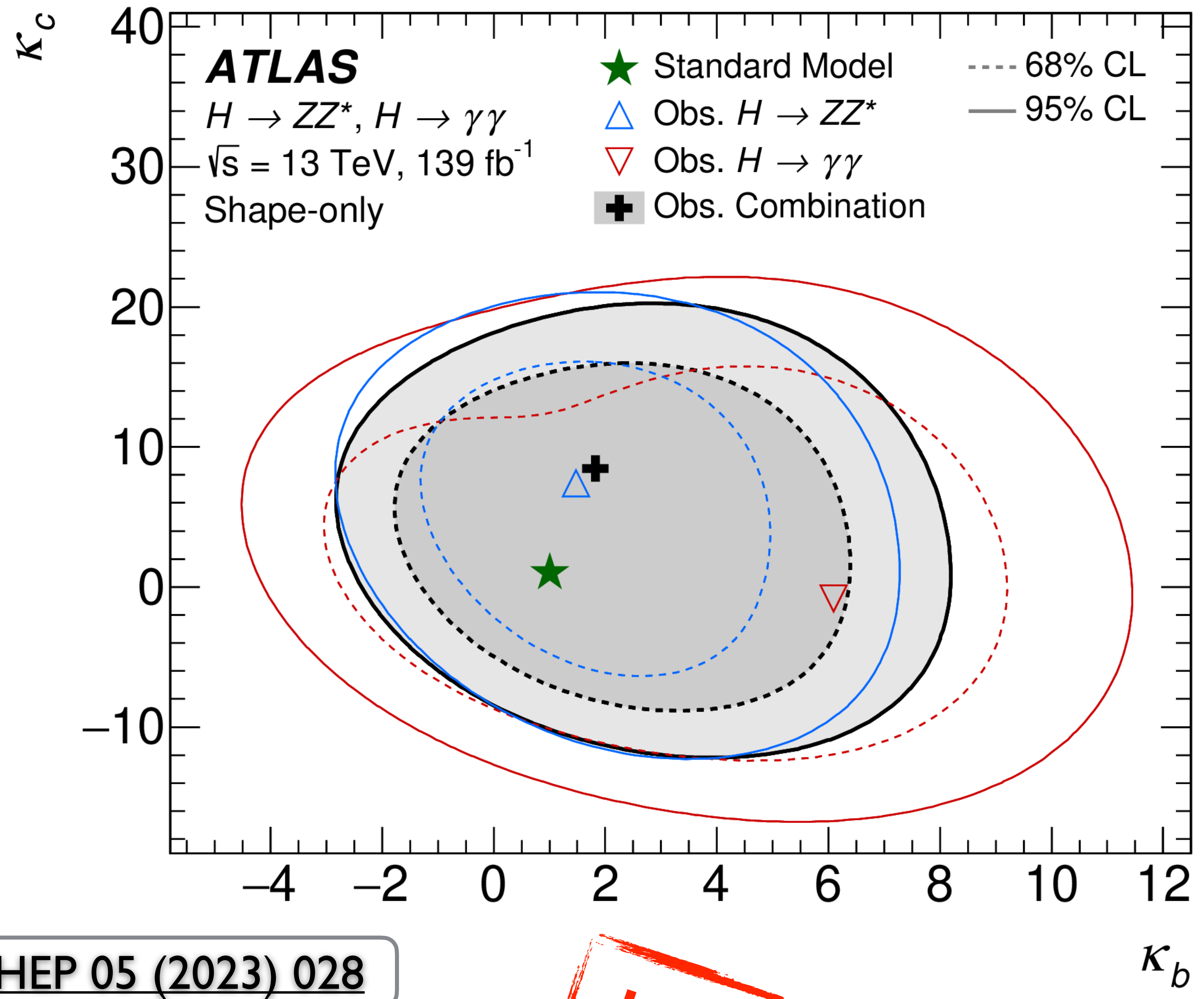
PRL 118, 121801, 2017

Combination: $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$



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

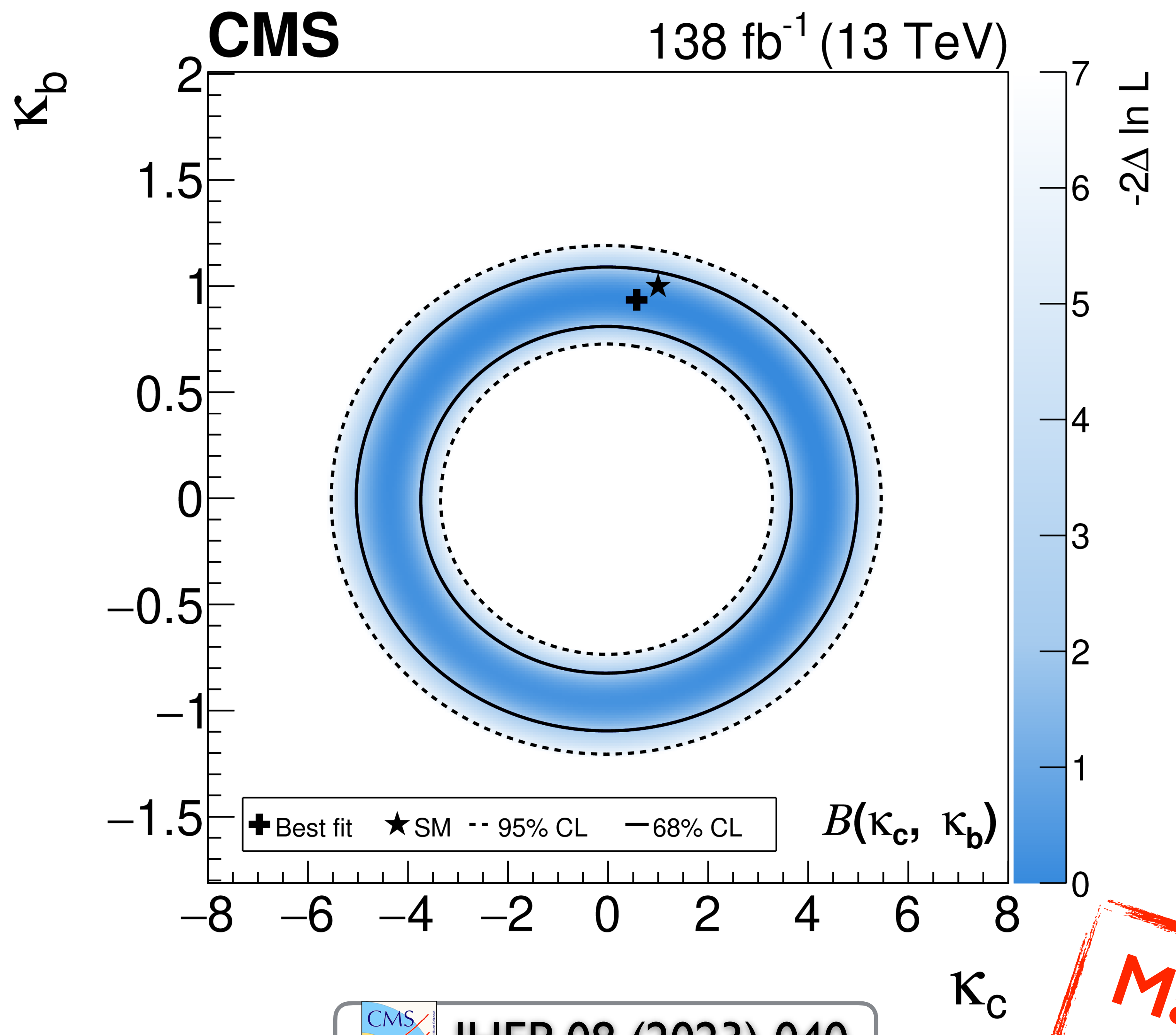
Only modifications to $p_T(H)$ shape



JHEP 05 (2023) 028

July 2022

Shape & coupling dependent on BR



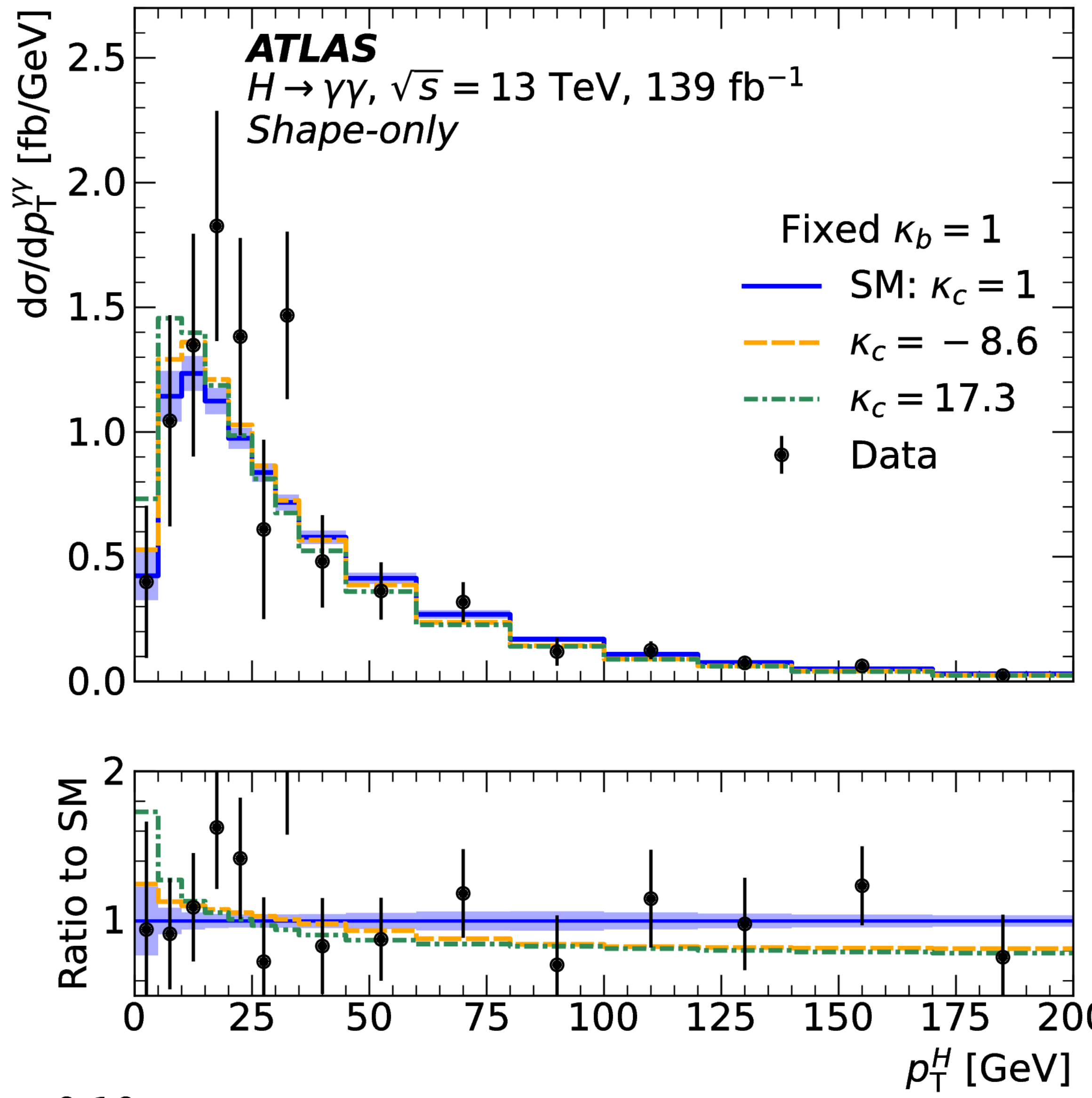
JHEP 08 (2023) 040

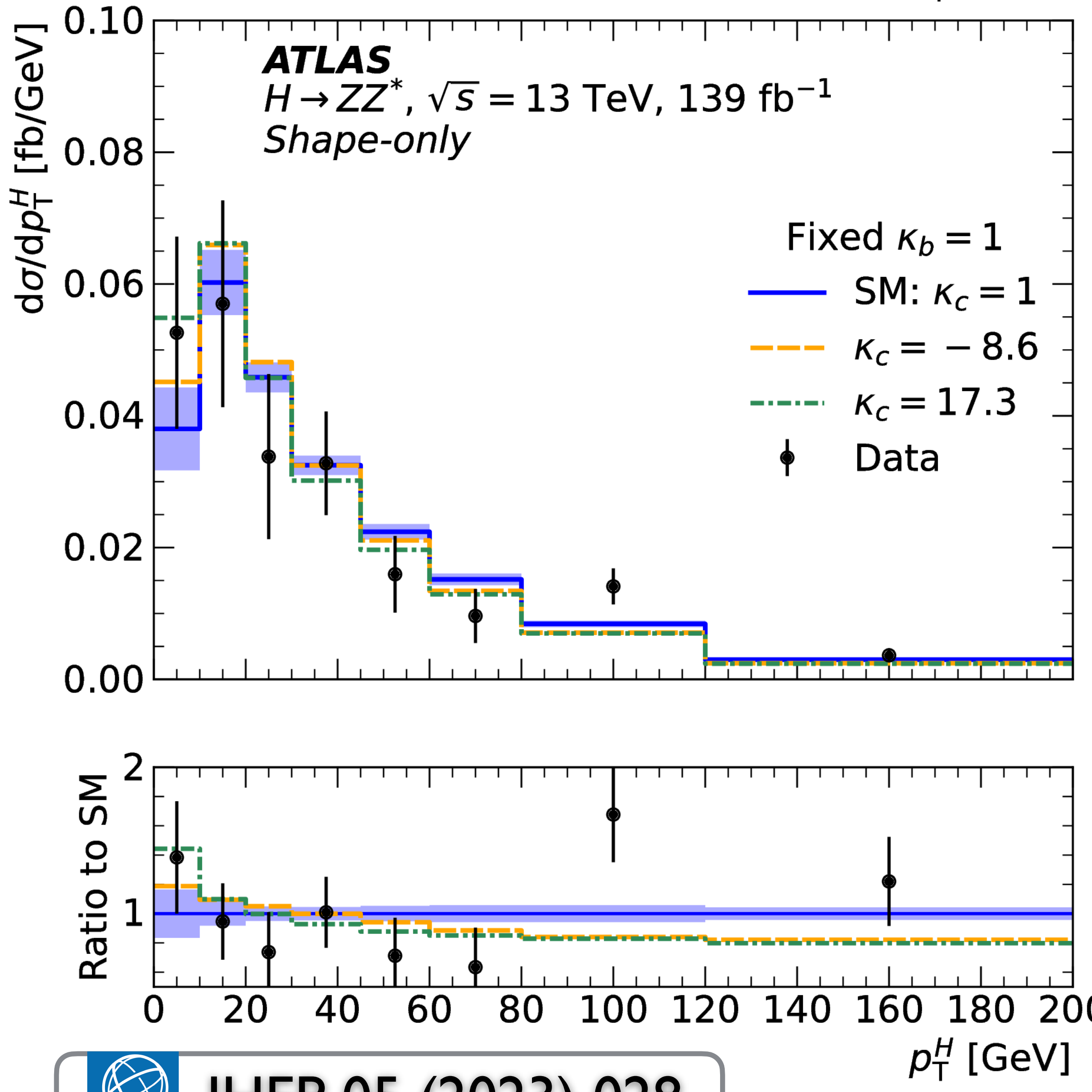
May 2023

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

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

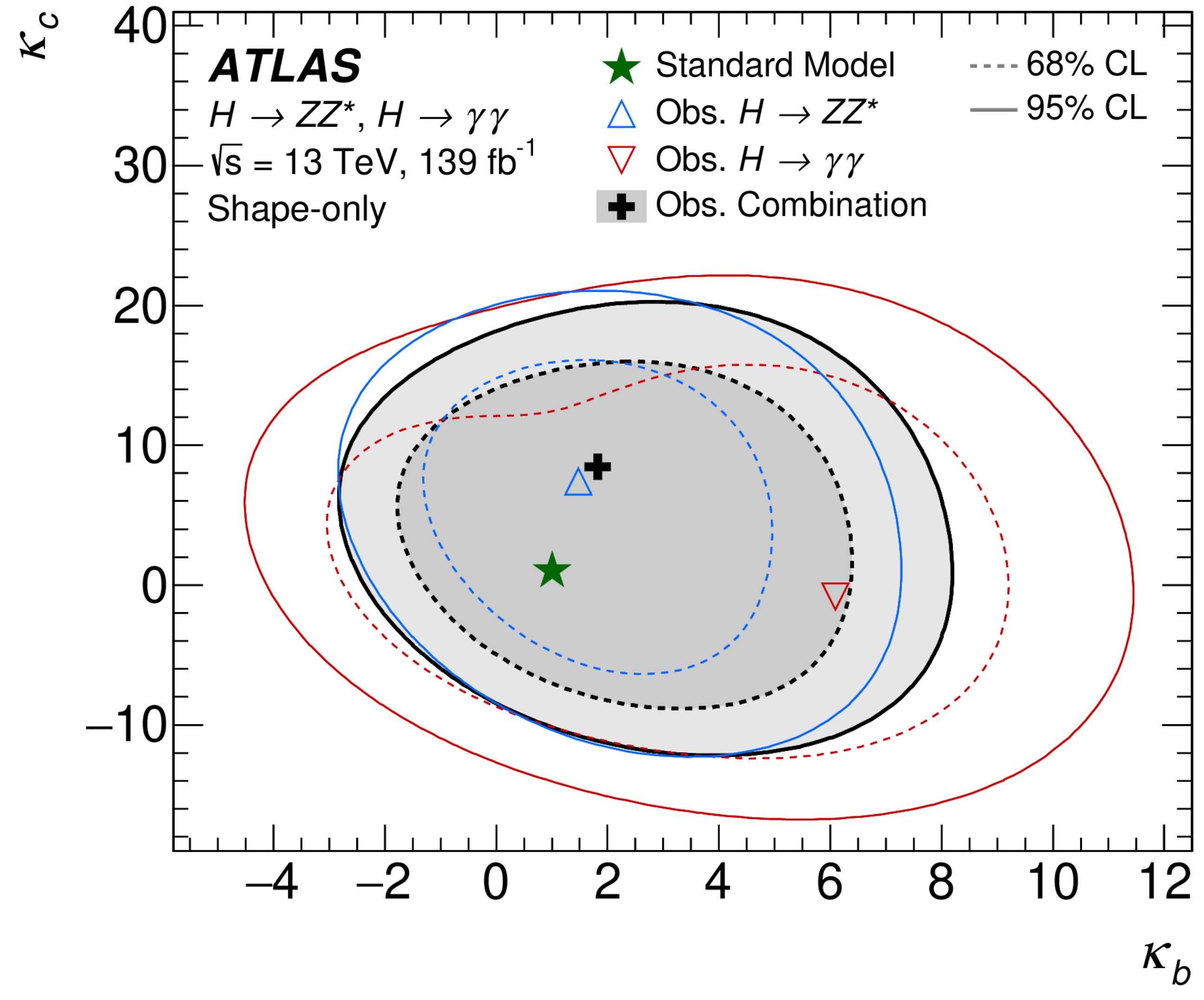
July 2022

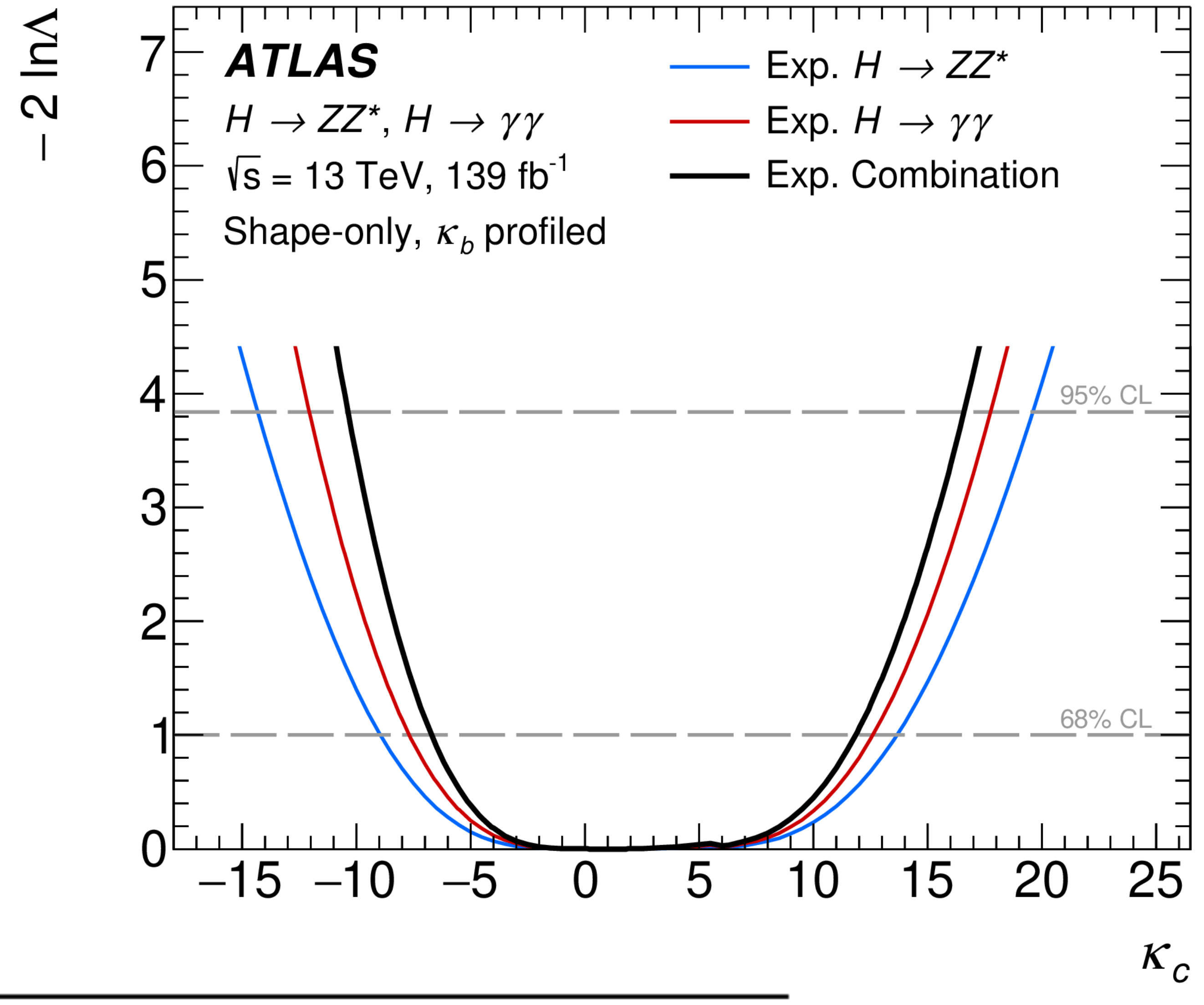




JHEP 05 (2023) 028

- 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



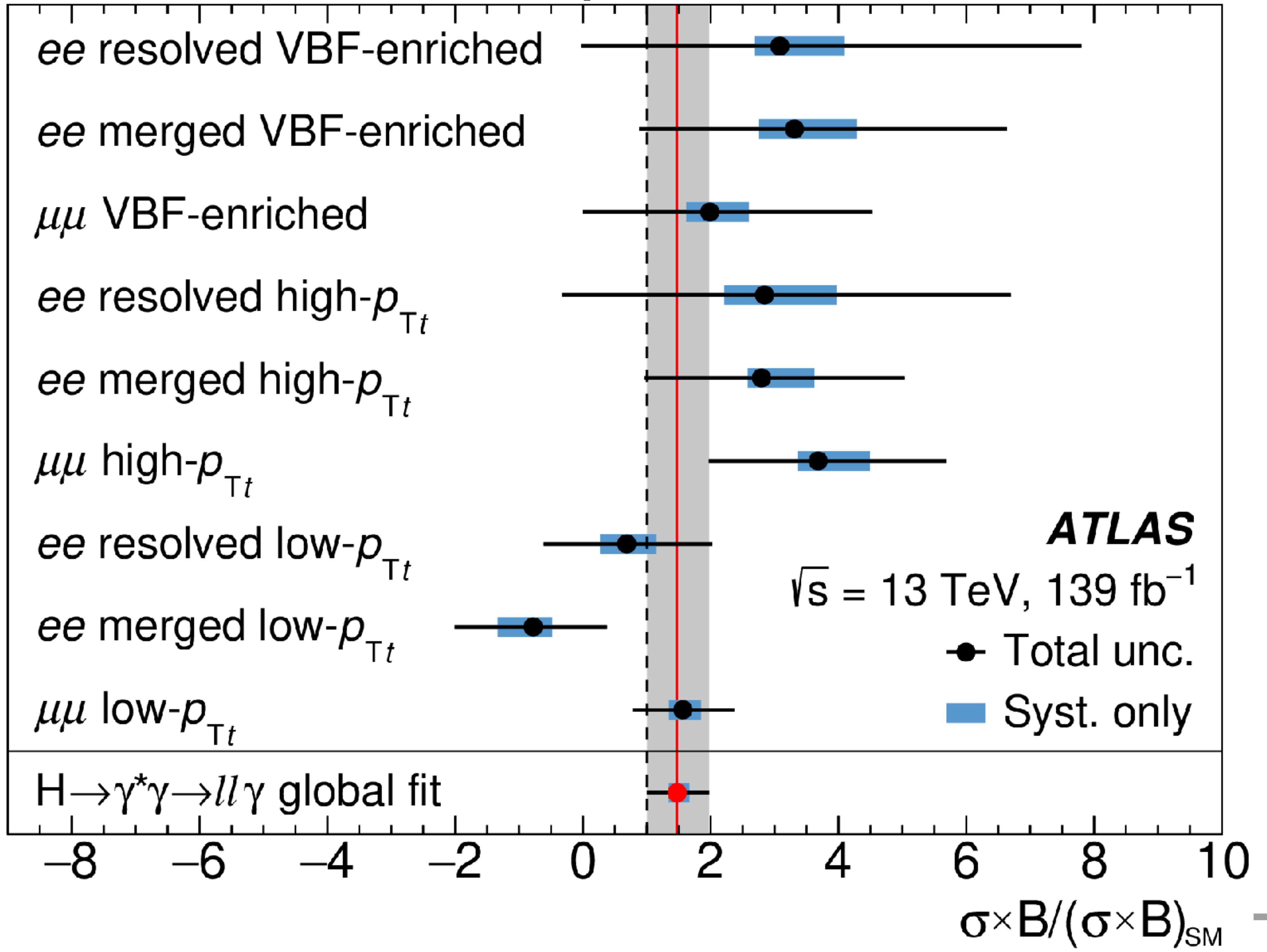


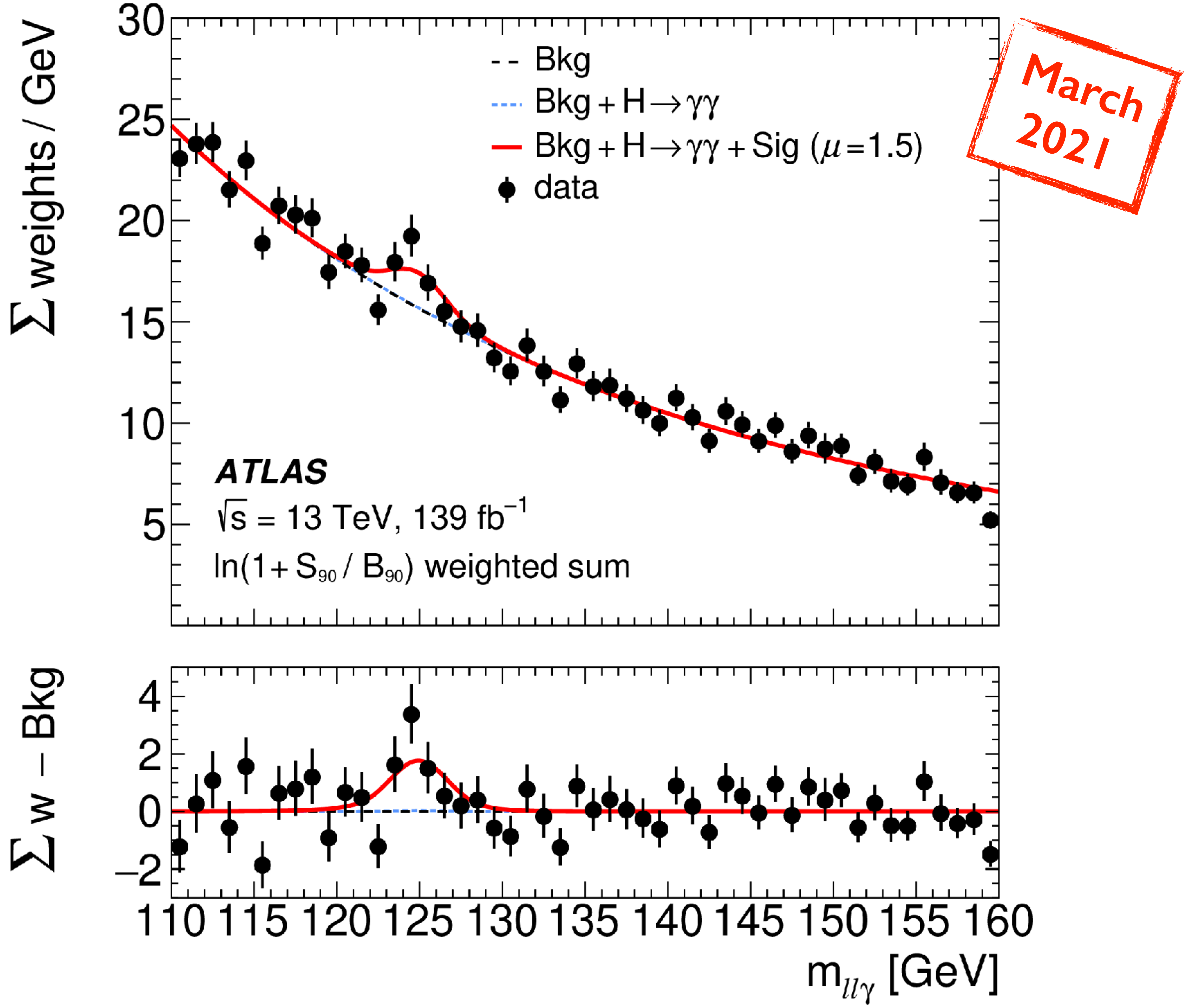
Channel	Parameter	Observed 95% confidence interval	Expected 95% confidence interval
$H\to ZZ^*\to 4\ell$	κ_b	[−2.1, 6.1]	[−3.6, 9.3]
	κ_c	[−9.4, 18.5]	[−14.3, 19.6]
$H\to\gamma\gamma$	κ_b	[−3.8, 10.2]	[−2.8, 8.0]
	κ_c	[−14.5, 18.9]	[−12.1, 17.8]
Combined	κ_b	[−2.3, 7.3]	[−2.2, 7.4]
	κ_c	[−10.5, 18.0]	[−10.4, 16.6]

$H \rightarrow \ell\ell\gamma$

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

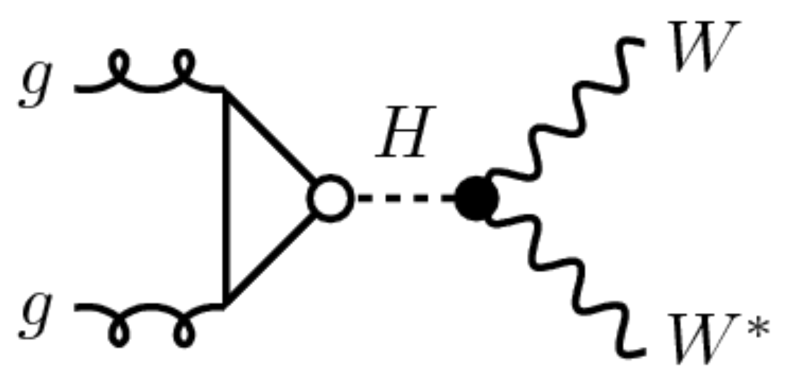
    $BR_{SM}(H \rightarrow \mu\mu\gamma)|_{m_{\ell\ell}<30\ \text{GeV}} = 3.42 \times 10^{-5}$
  - ~1200 $H \rightarrow \ell\ell\gamma$ events in 139 fb^{-1}



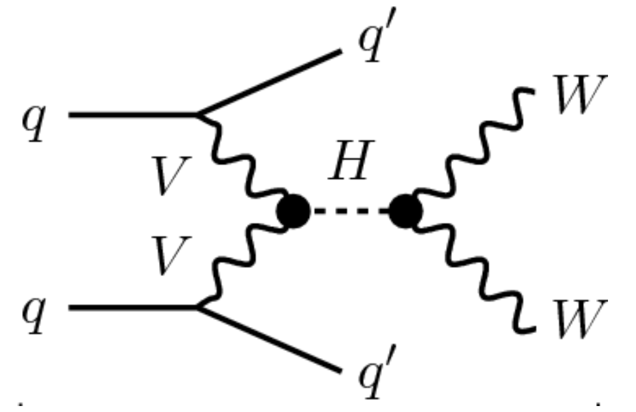


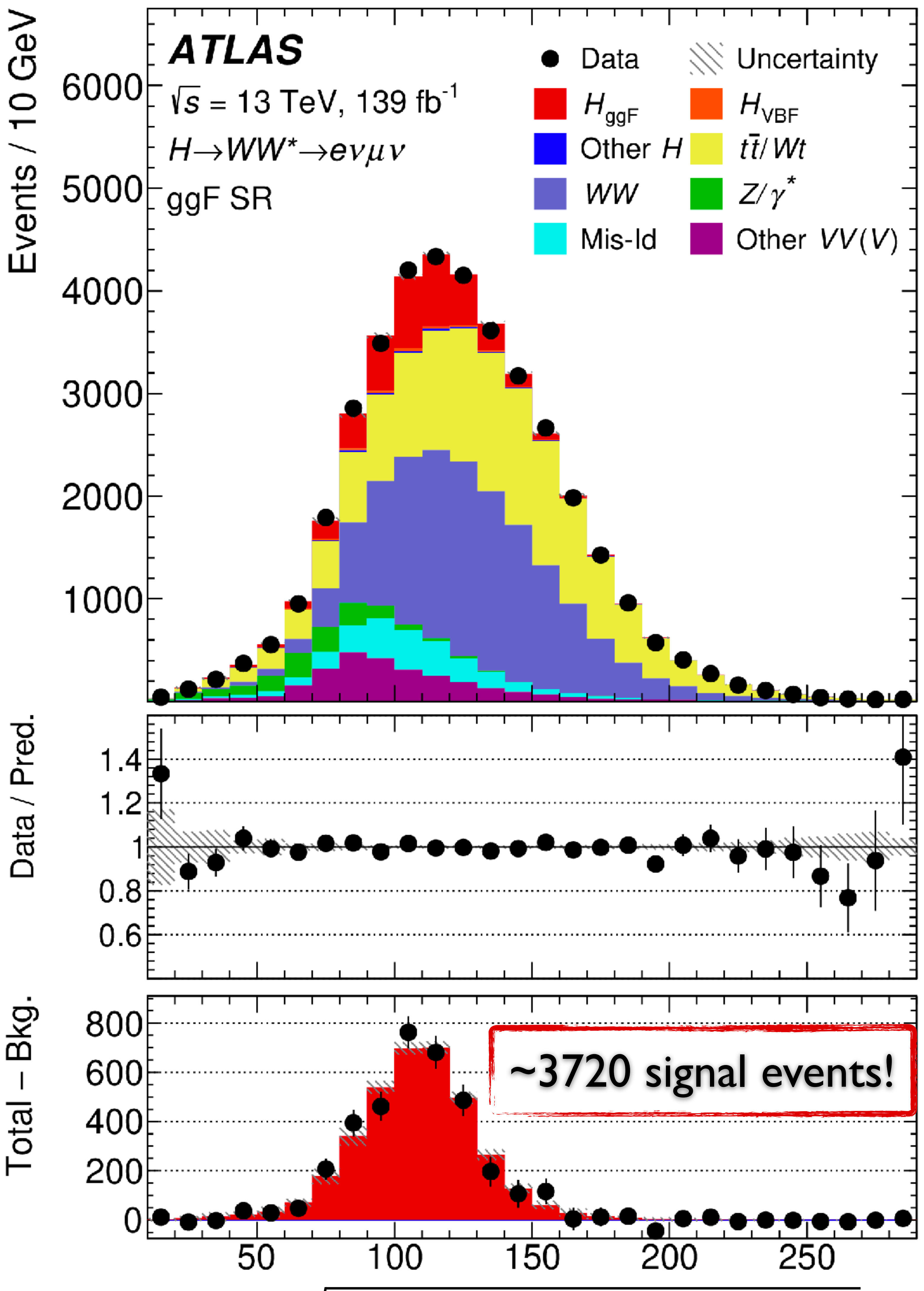
- Observed (expected) significance: **3.2 σ** (2.1 σ)

Phys. Lett. B 819 (2021) 136412



H → WW* → eνμν





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

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

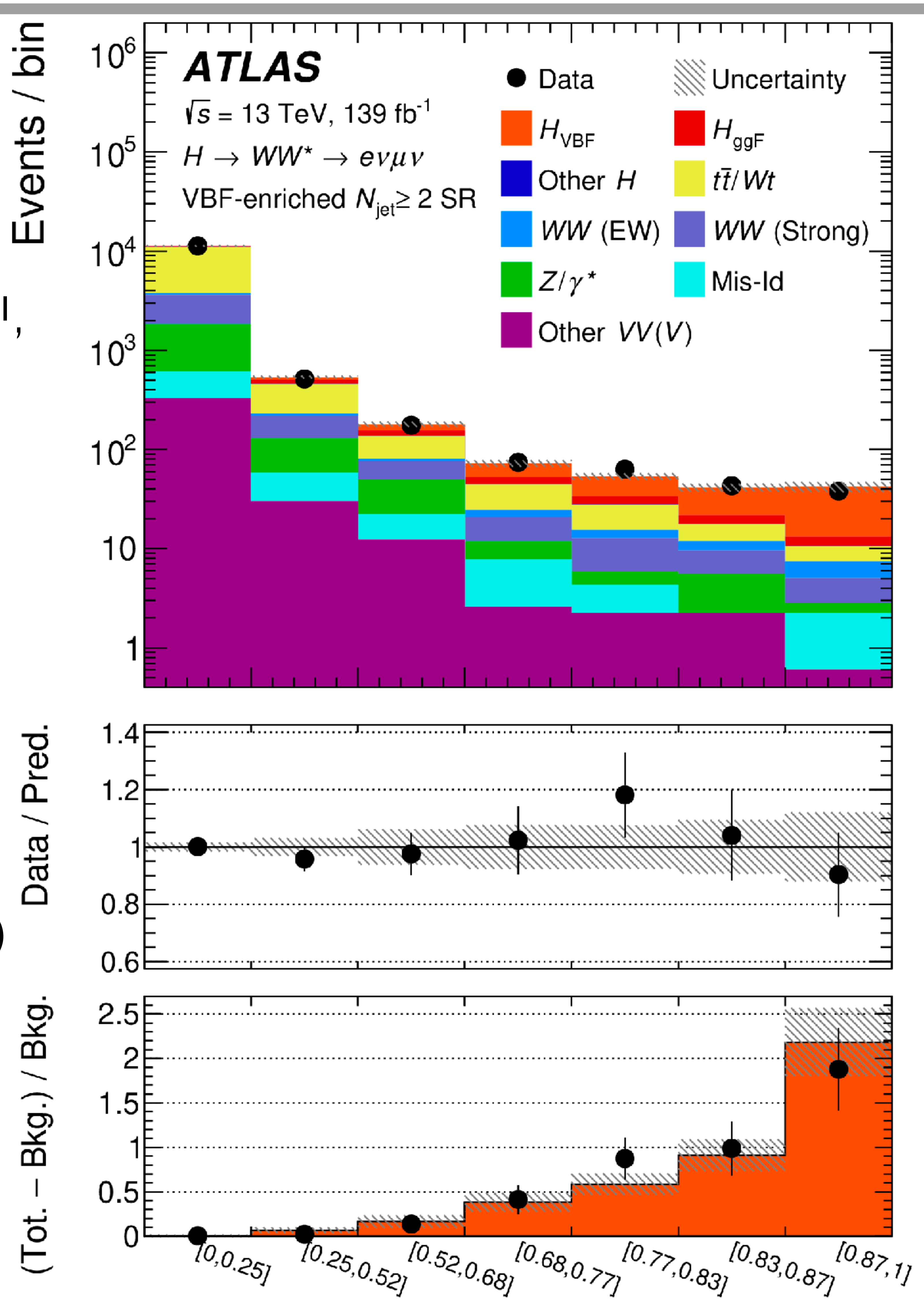
⇒ **~40 000 $H \to WW^* \to e\nu\mu\nu$ events in 139 fb^{-1}**, but difficult backgrounds…

Signal strength:

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

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

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



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

arXiv:2207.00338

H → WW* → ℓνℓν

- STXS comparison

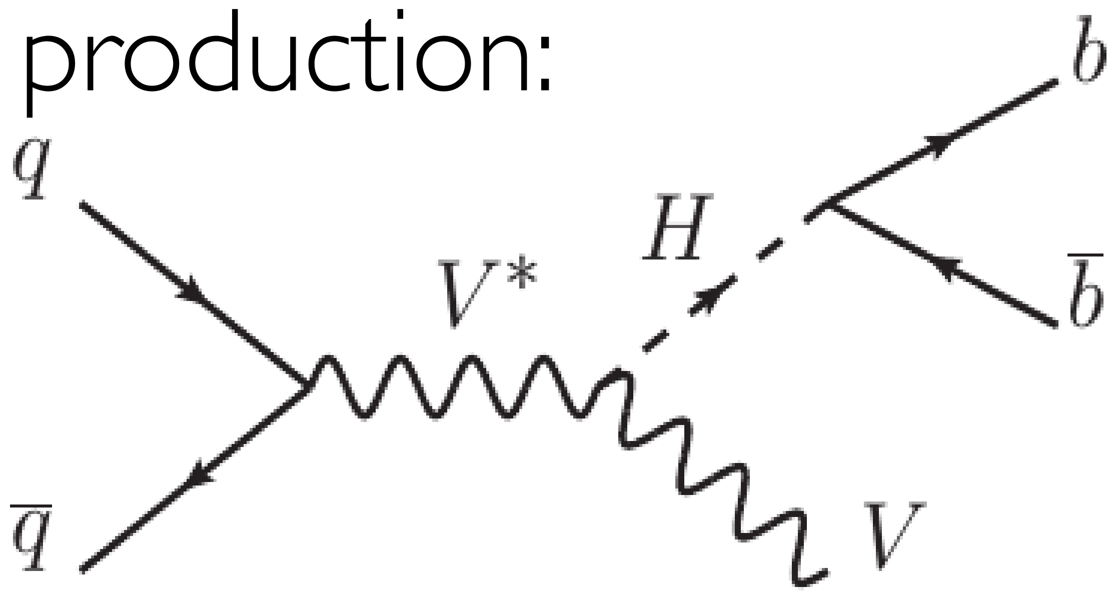
ATLAS-CONF-2021-014

⇒ Back

CMS-PAS-HIG-20-013

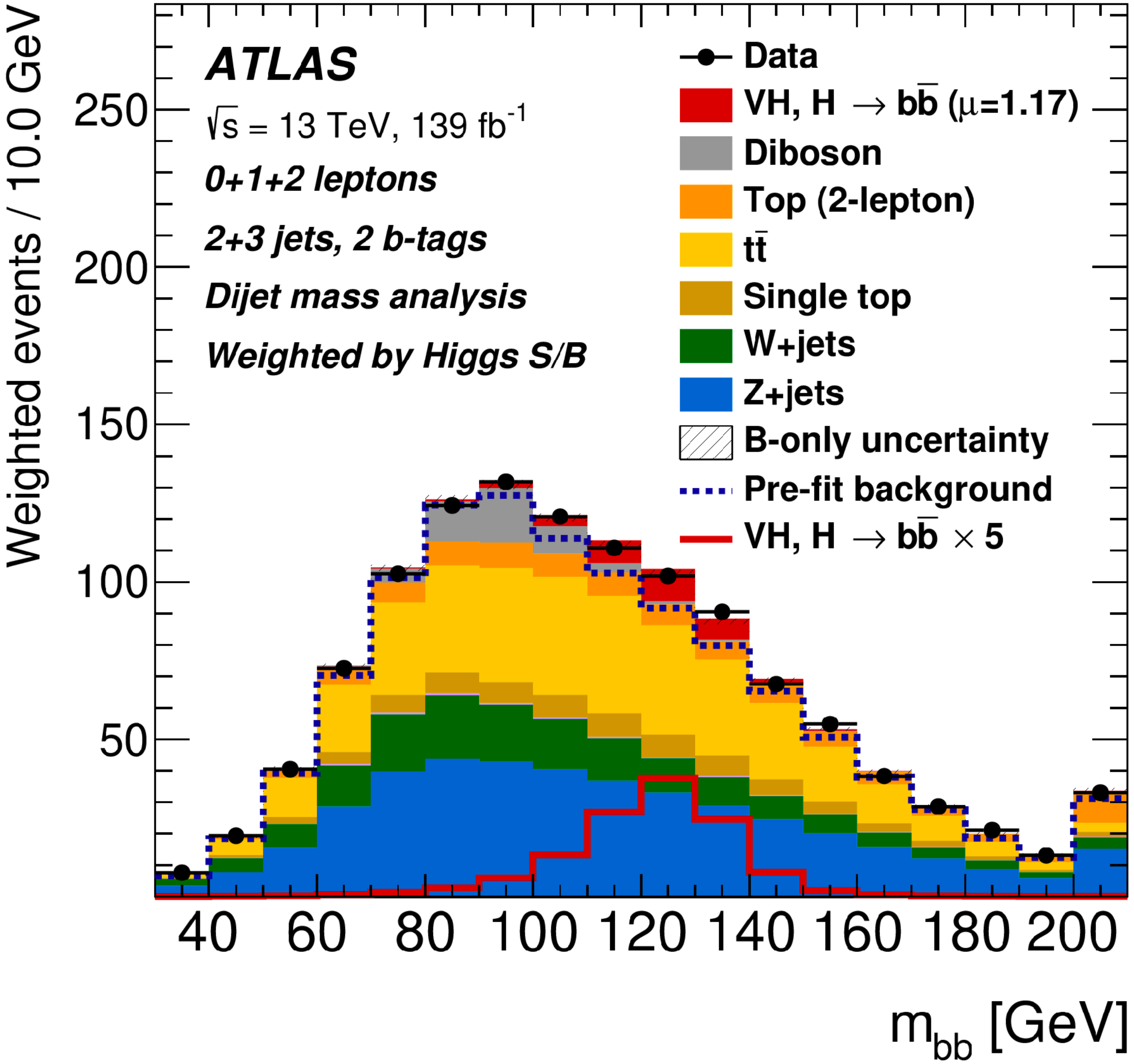
H → $b\bar{b}$

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



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

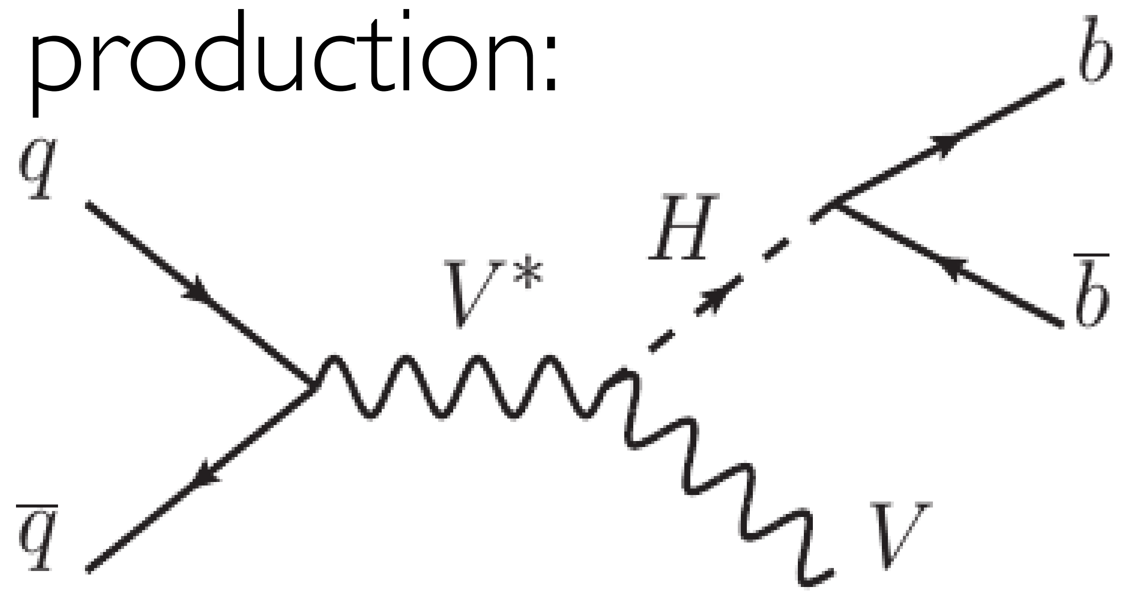
July 2020



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

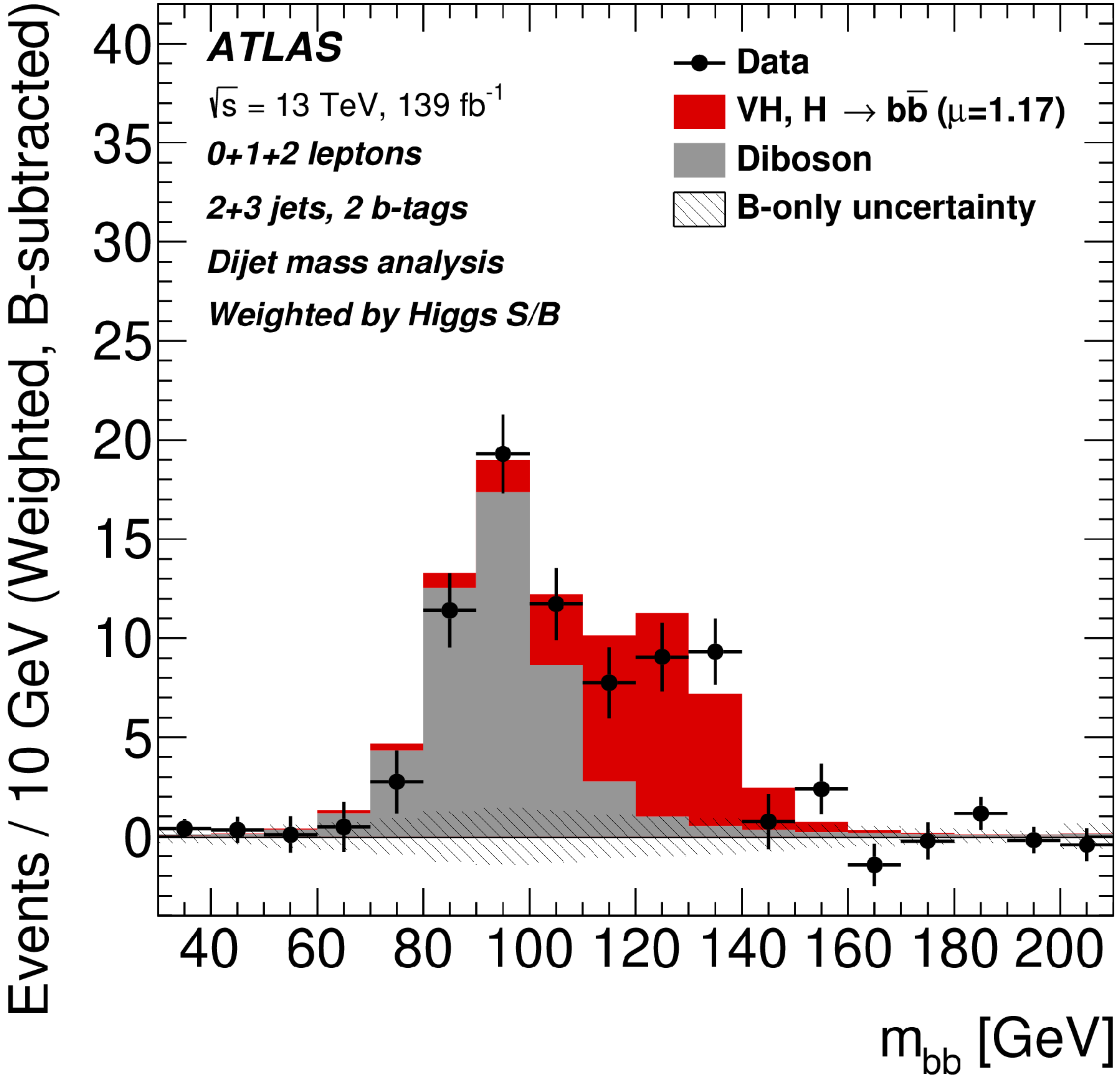
H → b$\bar{b}$

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



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

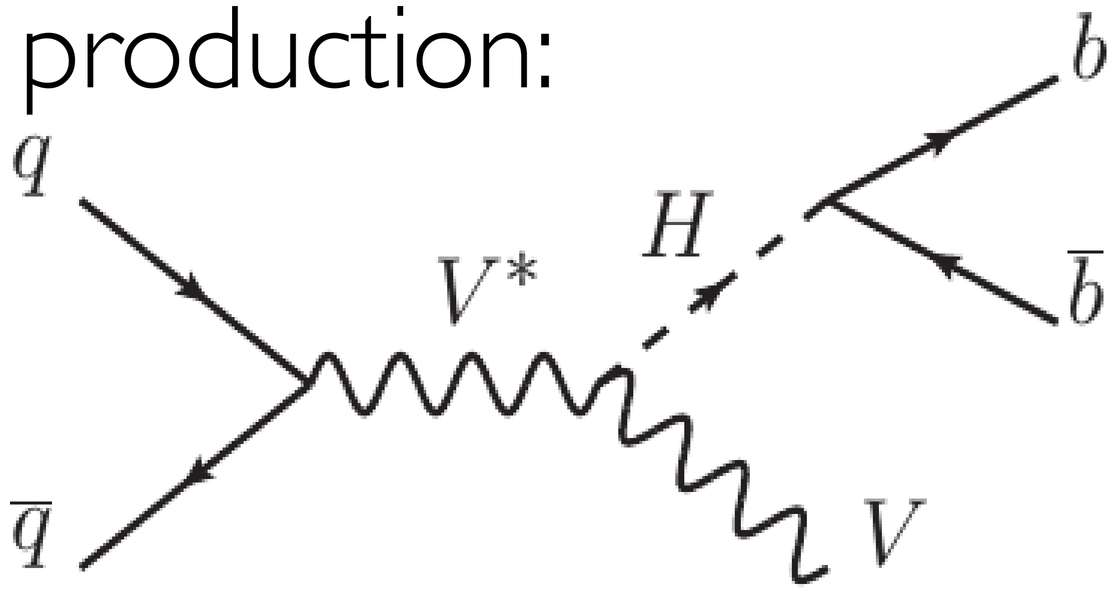
July 2020



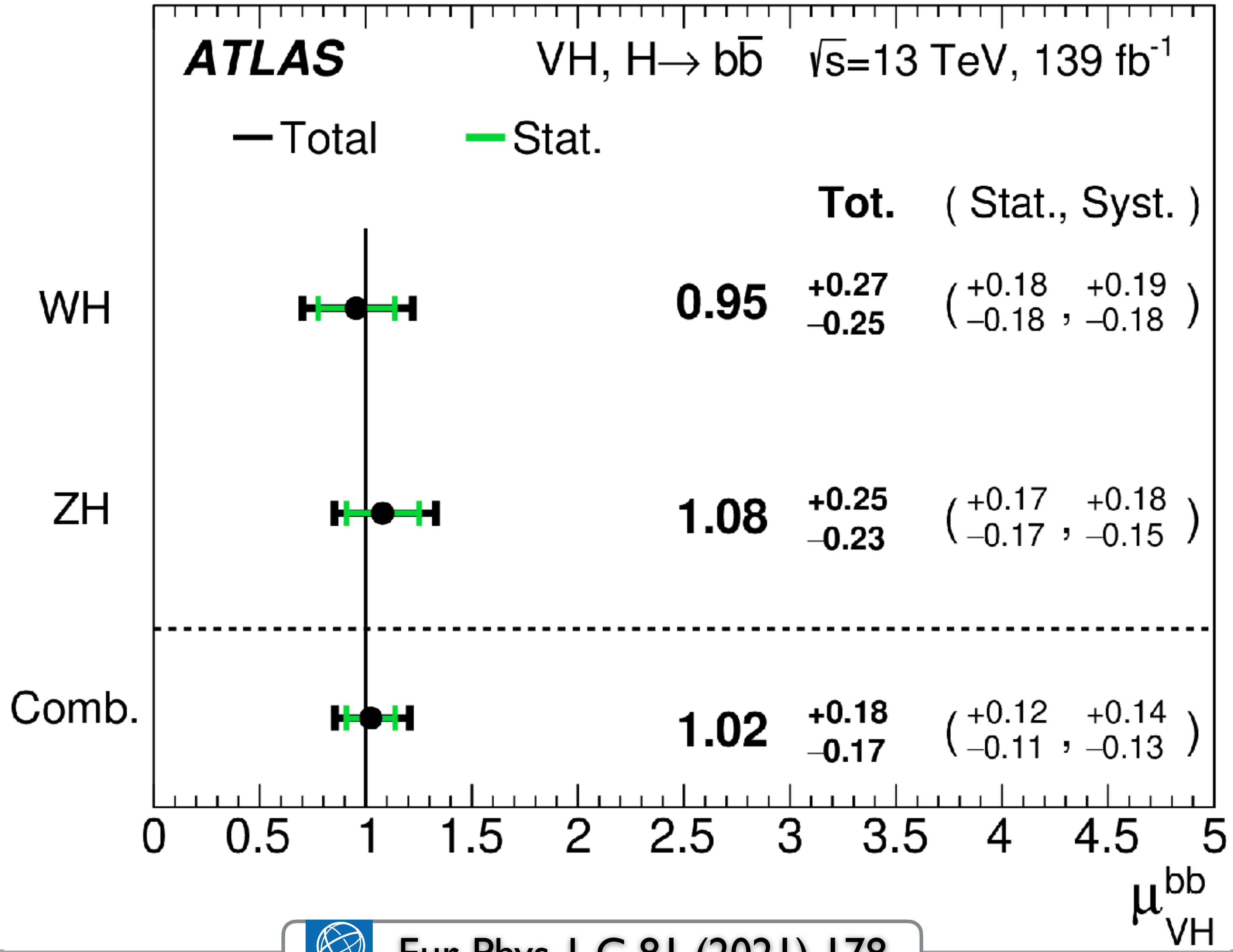
Eur. Phys. J. C 81 (2021) 178

$H \to b\bar{b}$

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



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

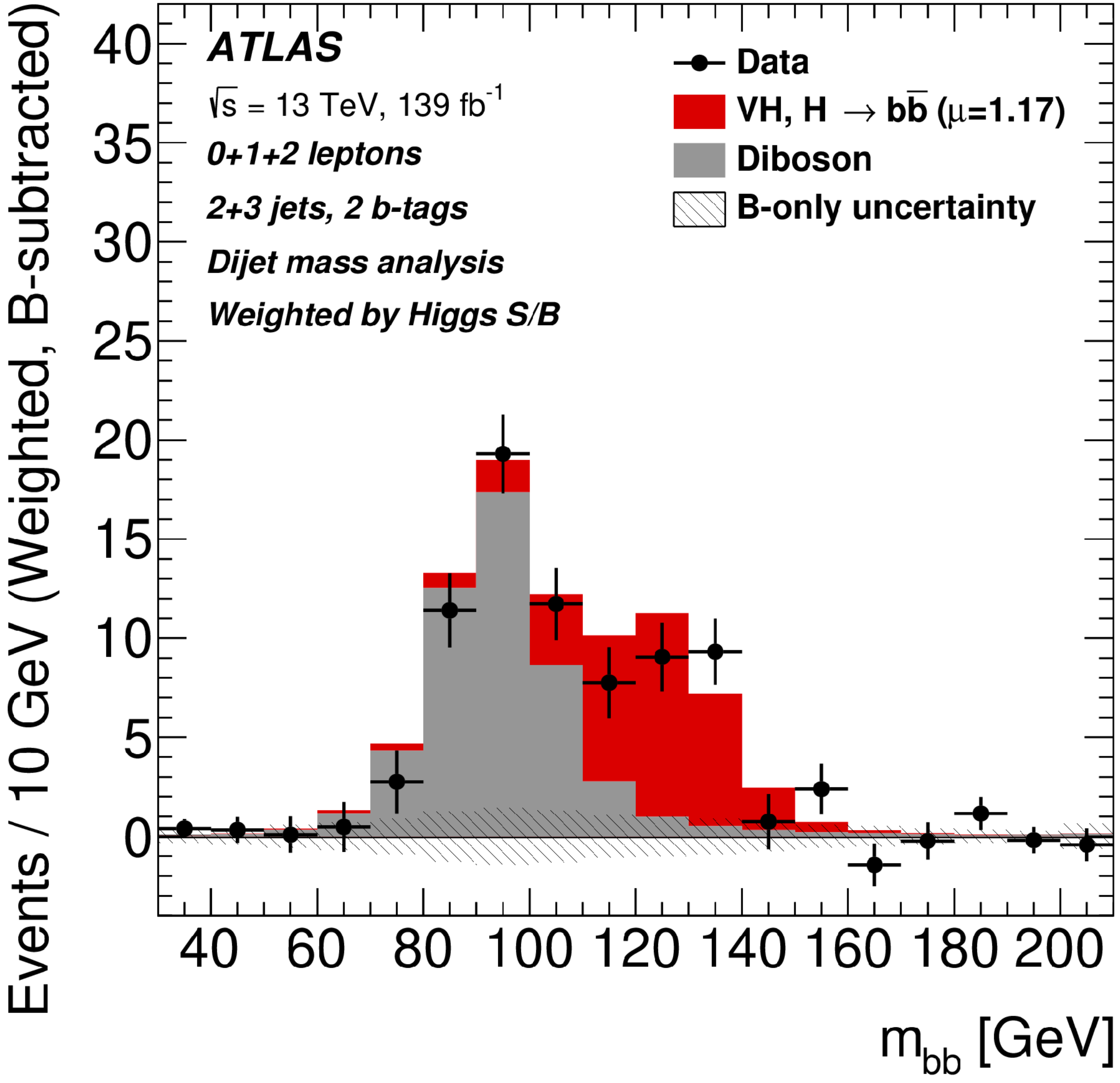


4.0 σ

5.3 σ

6.7 σ

July 2020



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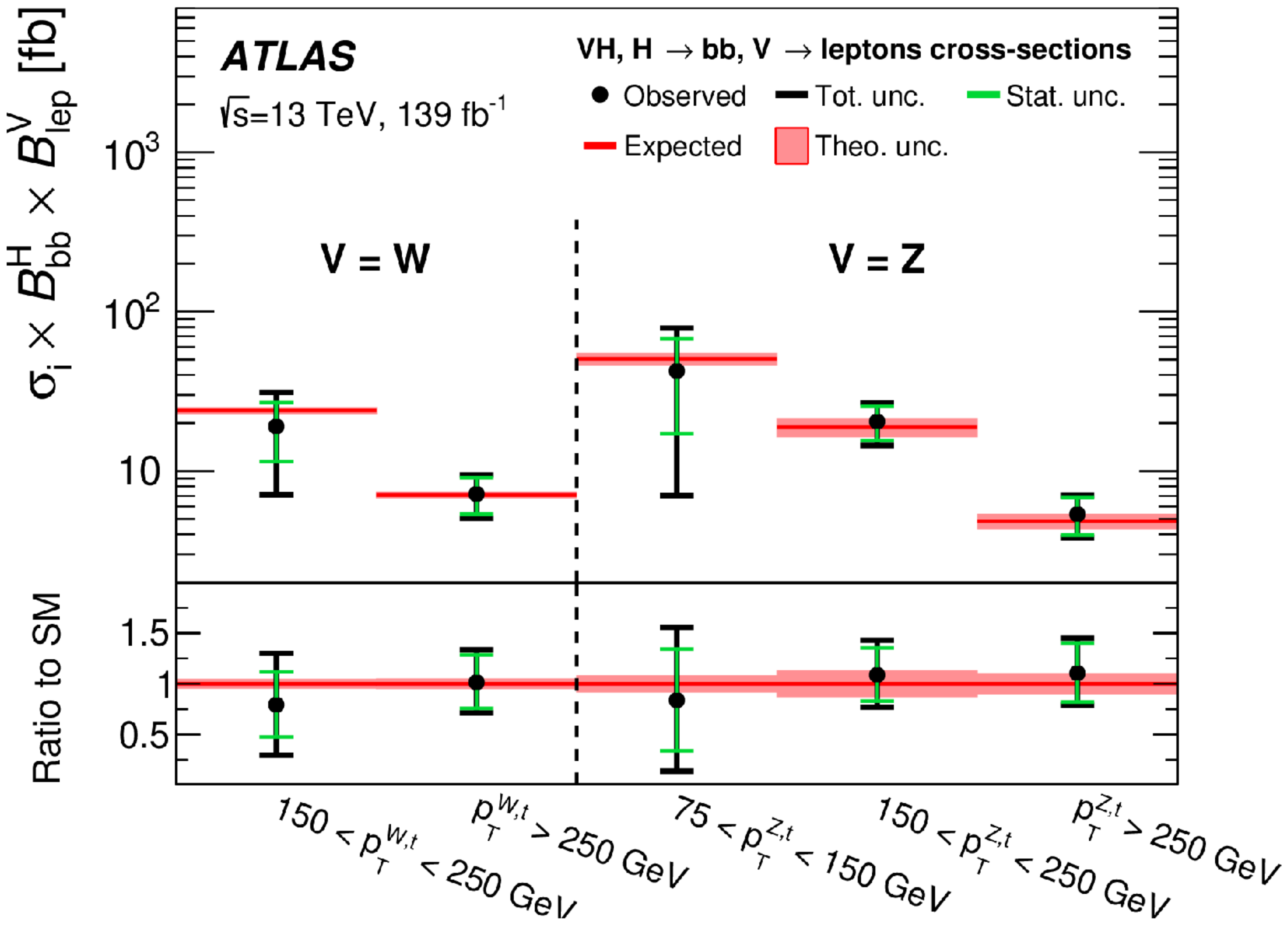
$H \to b\bar{b}$

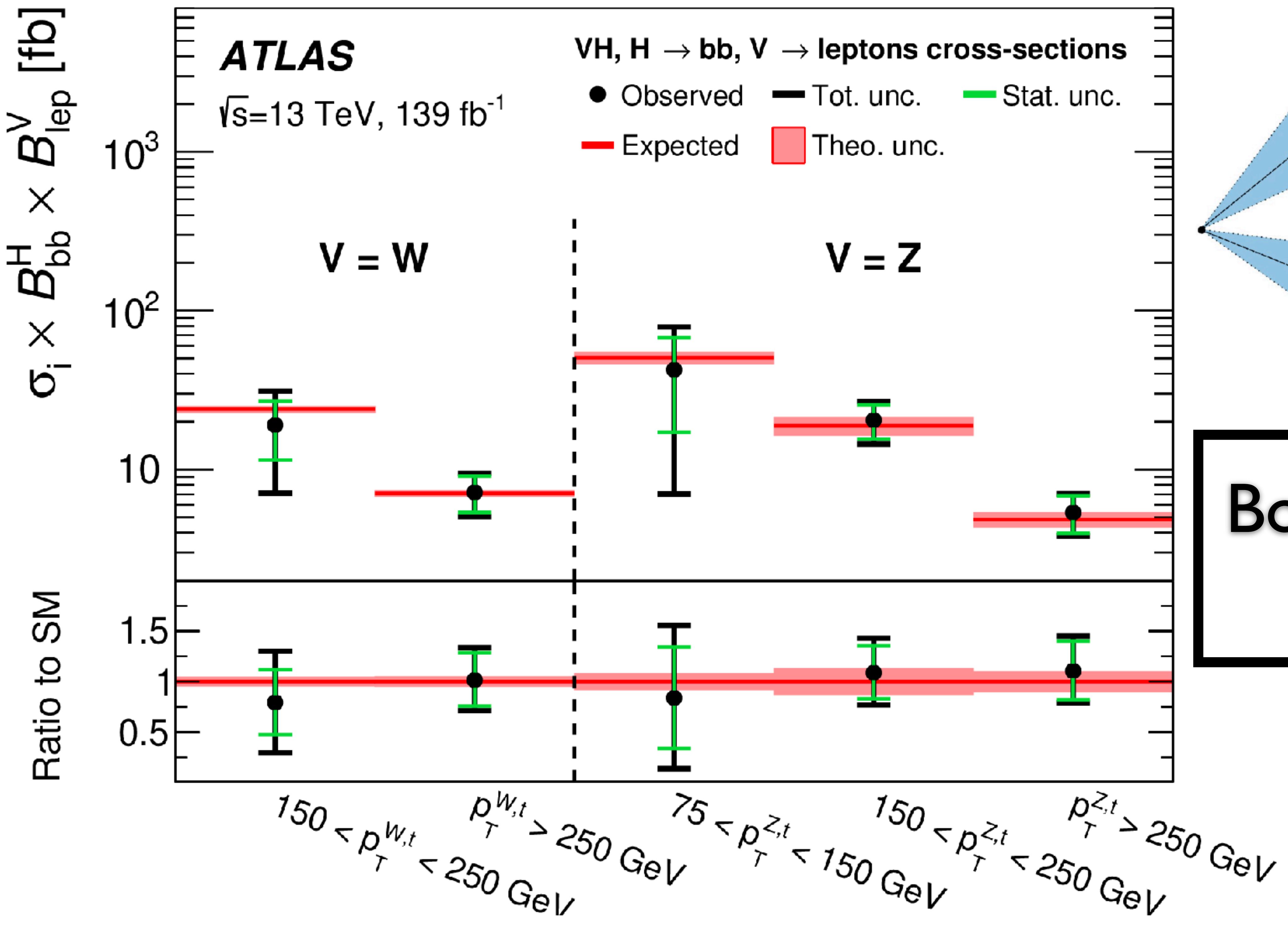
- Cross-section measurements as function of $p_T(V)$

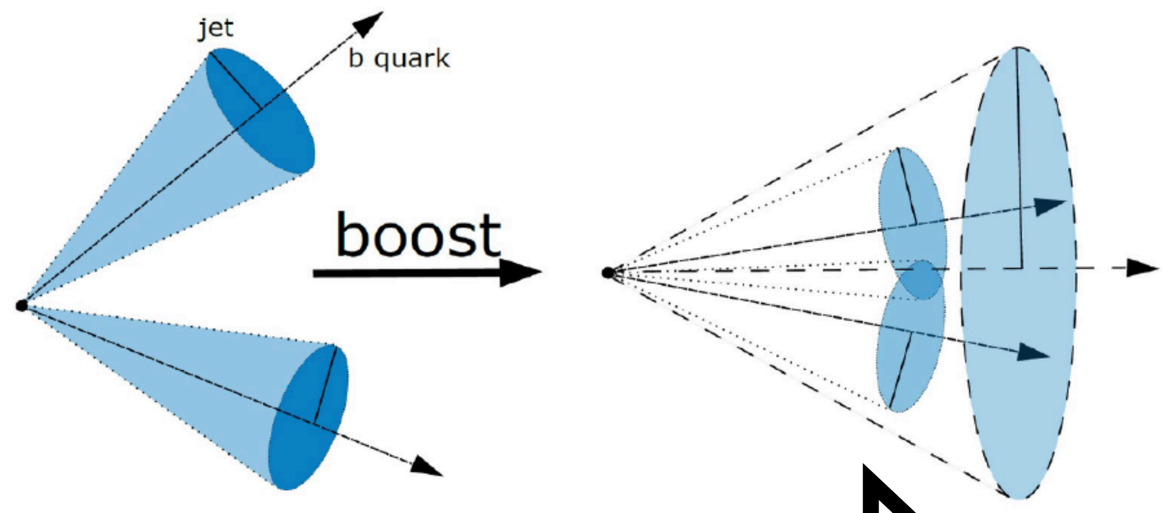


Eur. Phys. J. C 81 (2021) 178

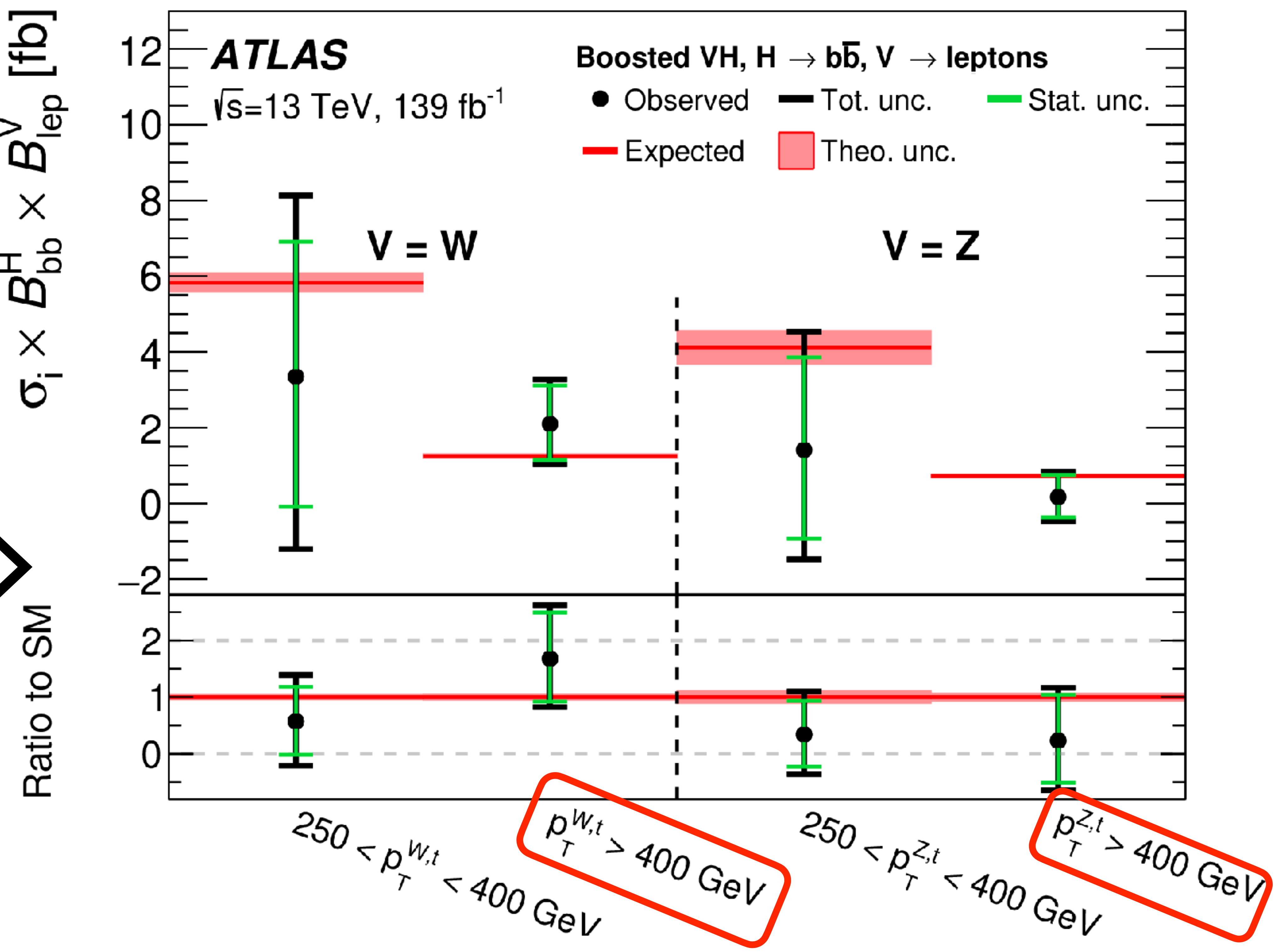
$H \to b\bar{b}$

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





Boosted Higgs-boson decay topology



- Explores higher $p_T(V)$

  $\Rightarrow$ Increase sensitivity to BSM

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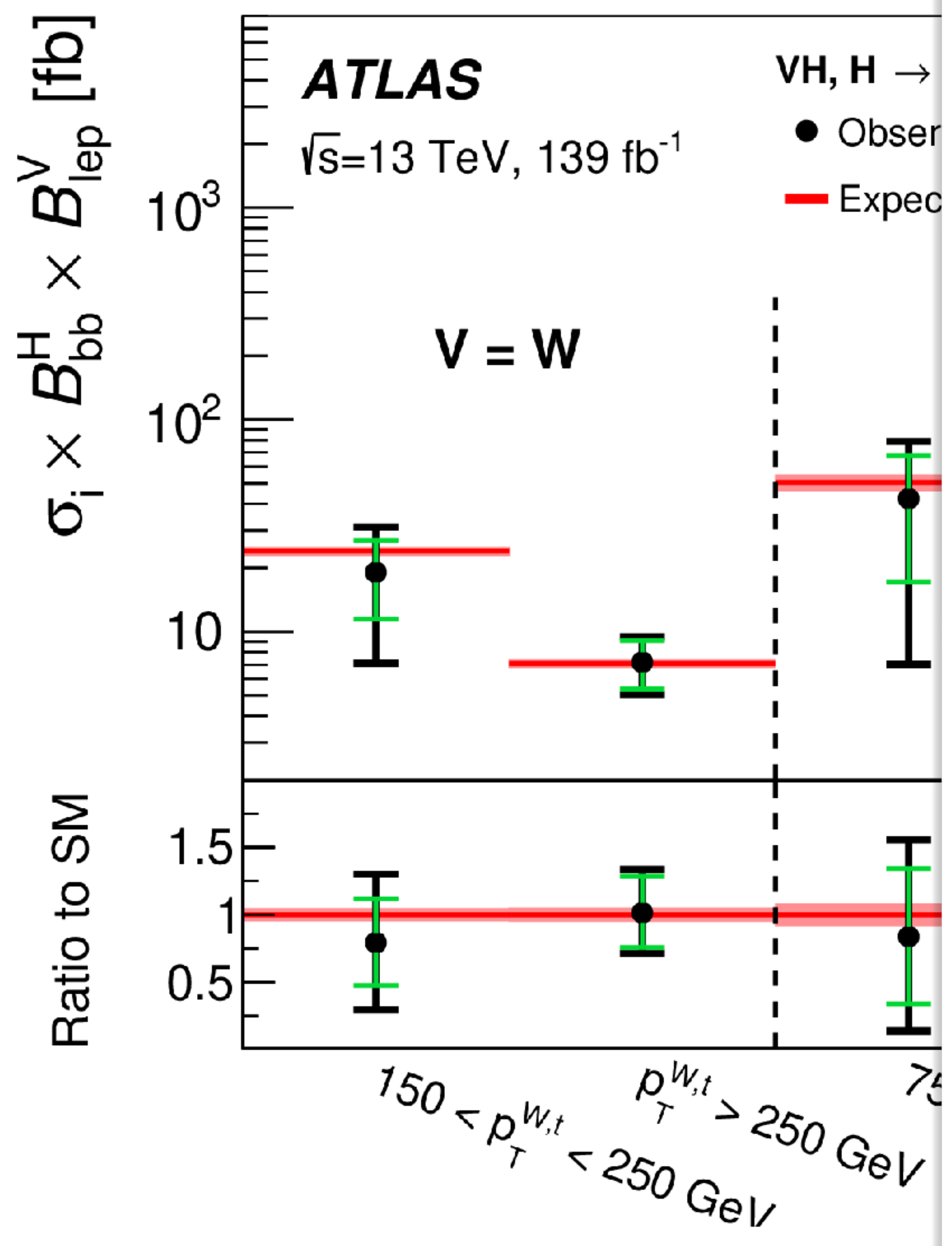
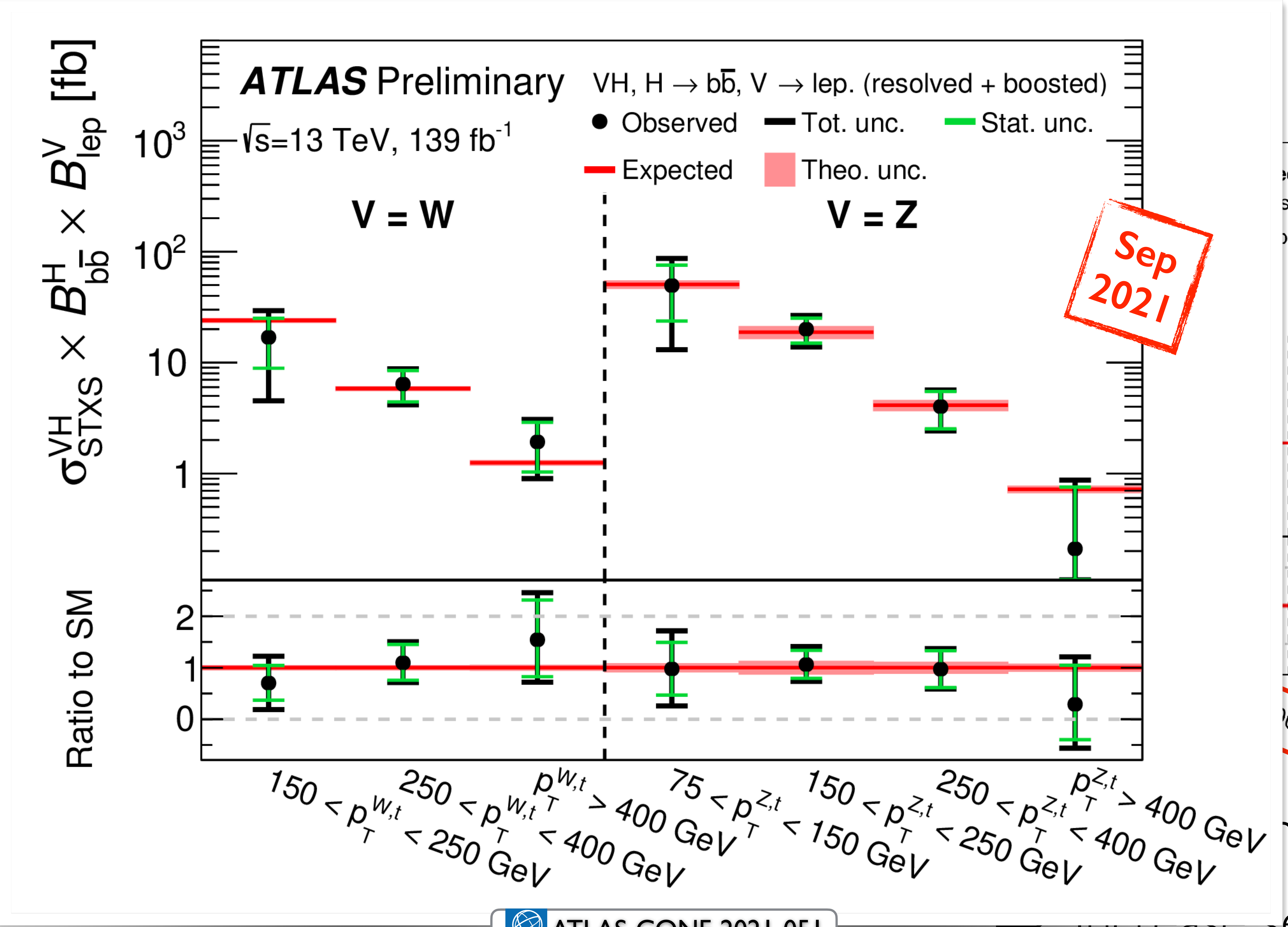
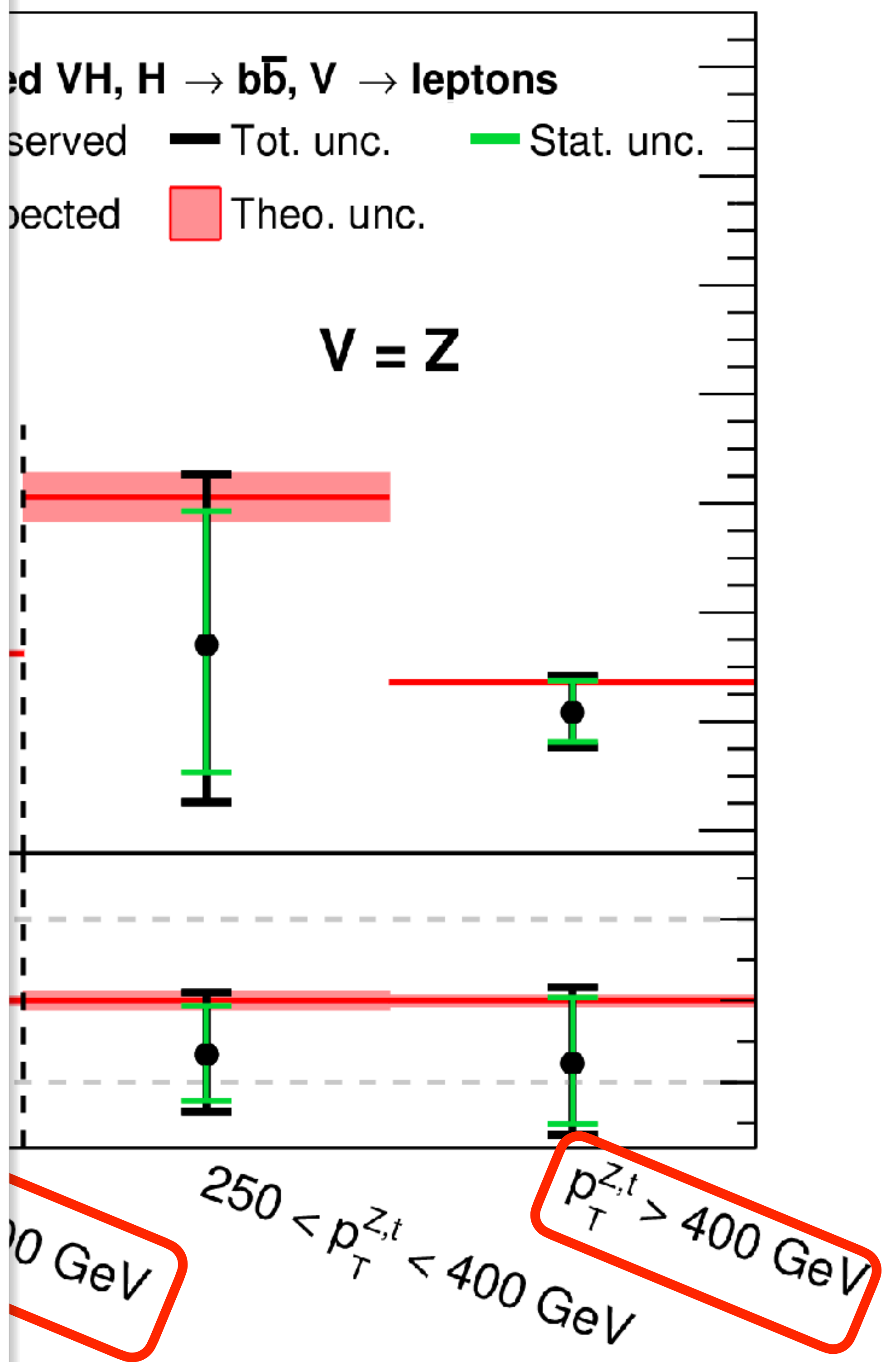
Phys. Lett. B 816 (2021) 136204

$H \to b\bar{b}$

- Cross-section







...her $p_T(V)$

→ increase sensitivity to BSM

ATLAS-CONF-2021-051

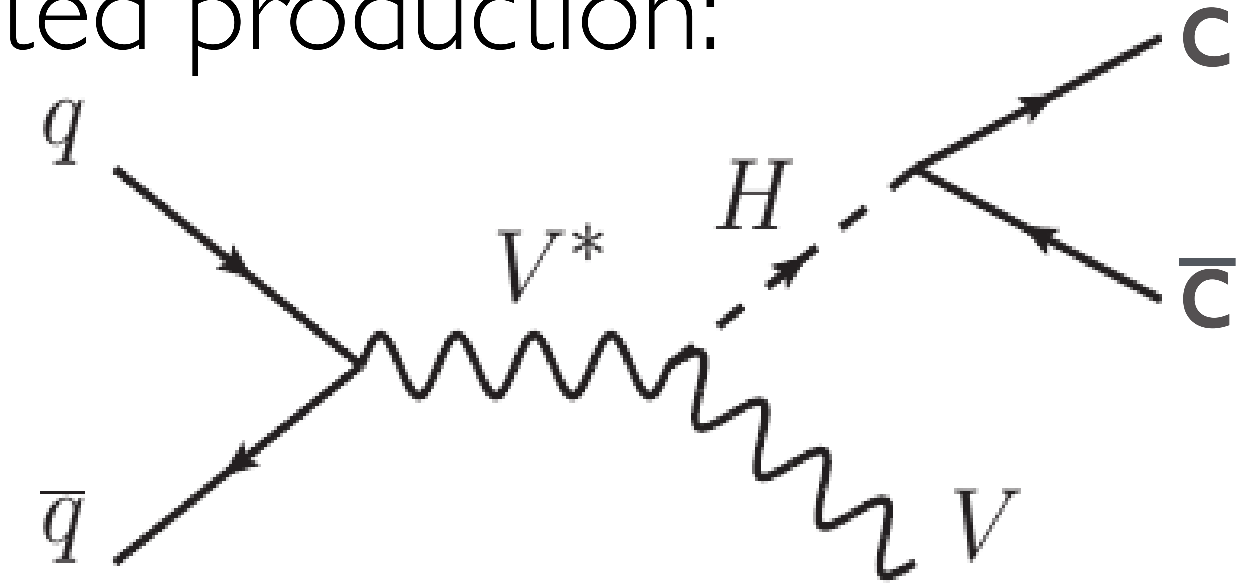
Eur. Phys. J. C 81 (2021) 178

Phys. Lett. B 816 (2021) 136204

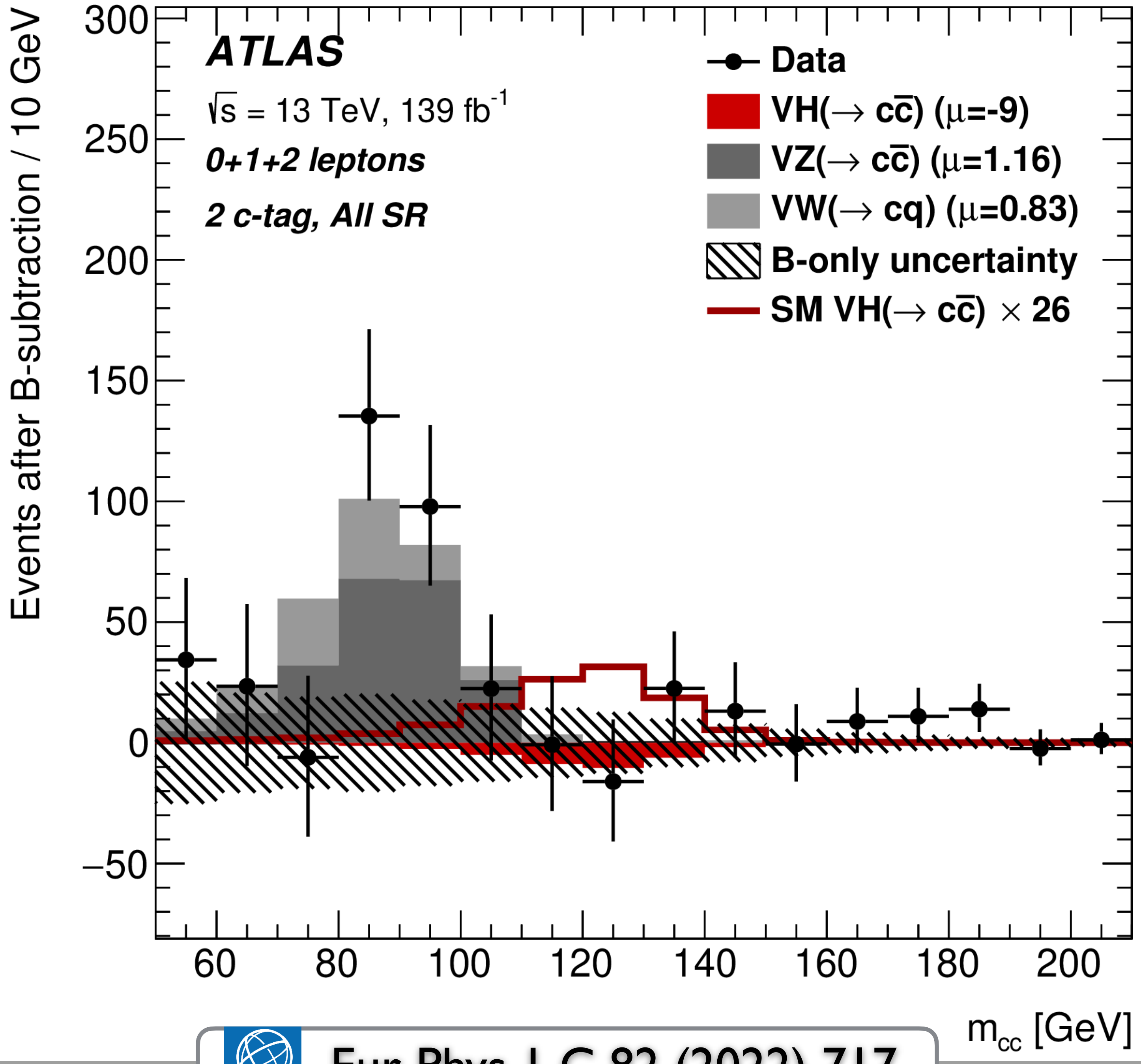
$H \to c\bar{c}$

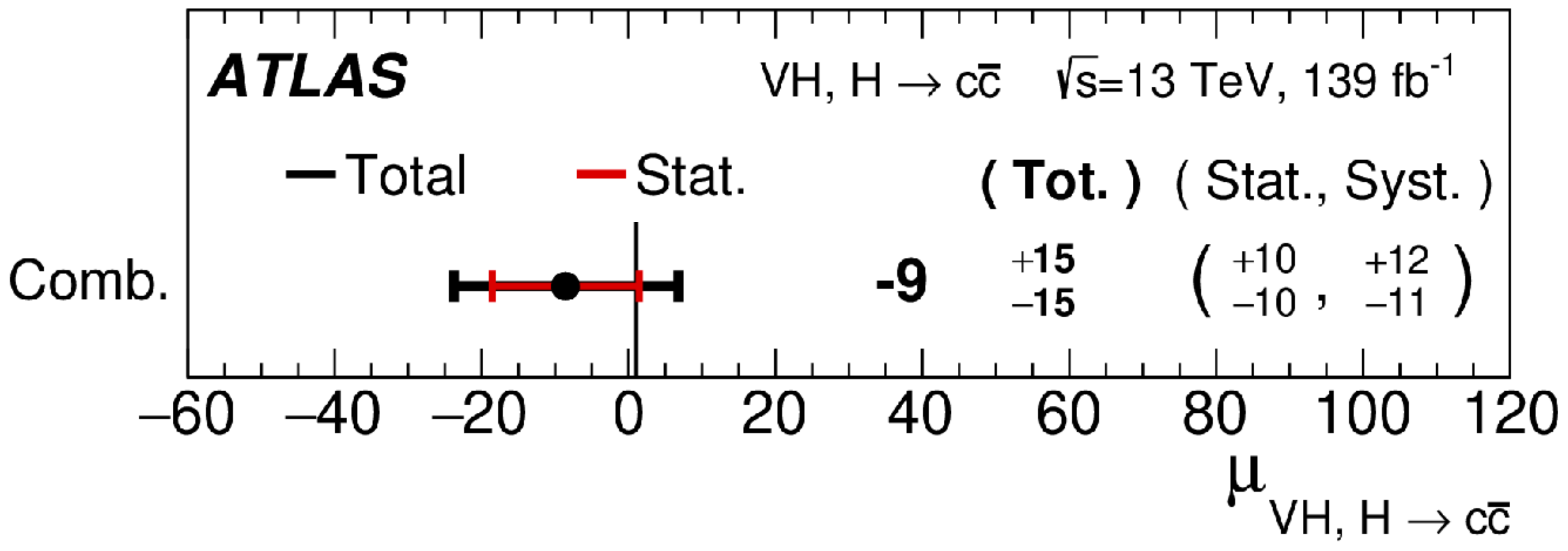
Jan 2022

- $H \to cc$ 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 ($Z \to \ell\ell$)

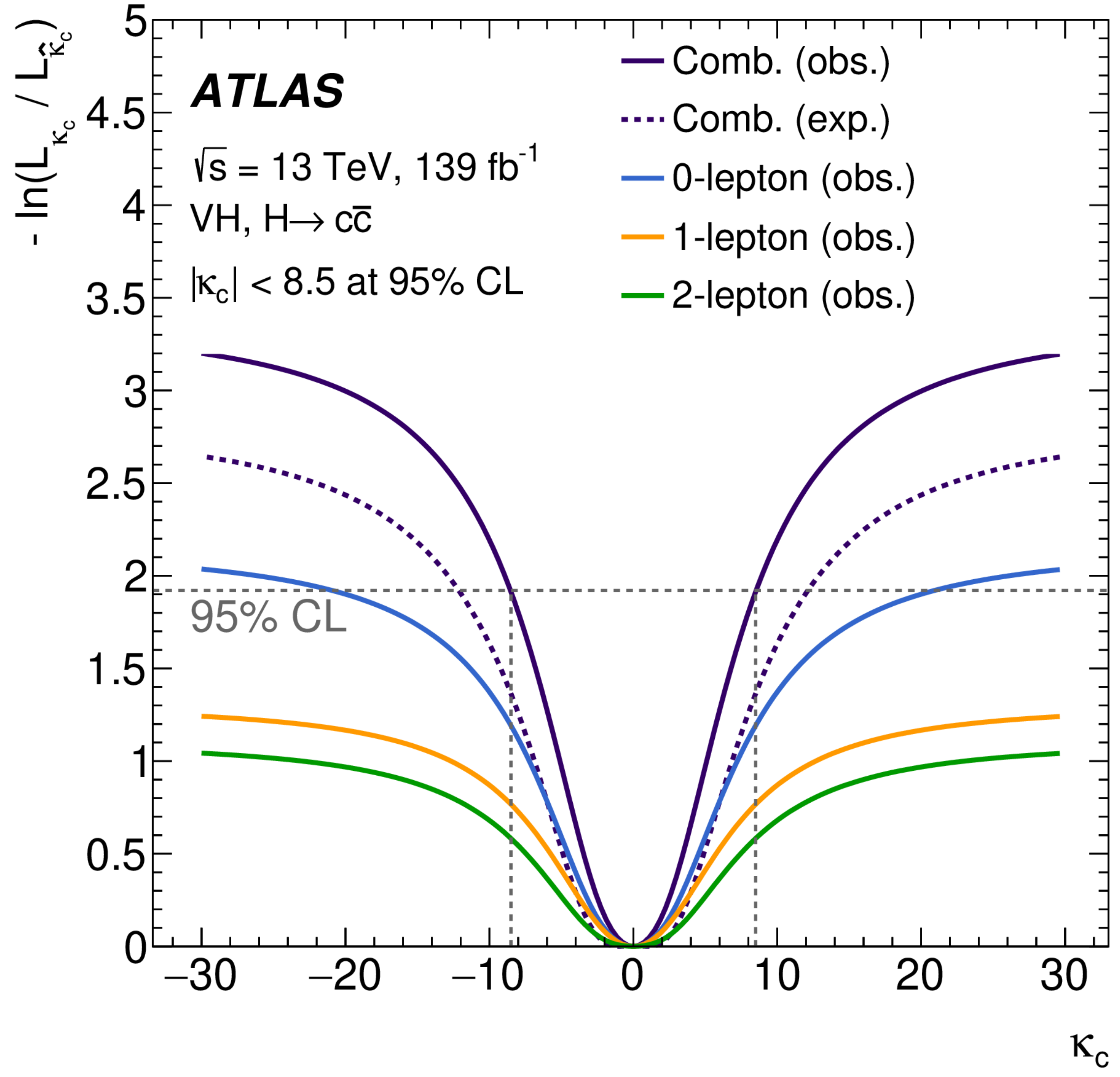


⇒ **~1500 V(→leptons)H(→cc) events in 139 fb^{-1}**





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



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

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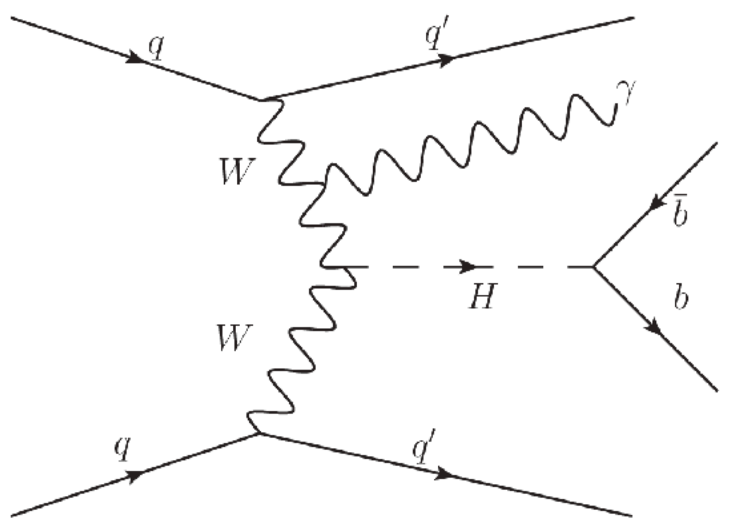
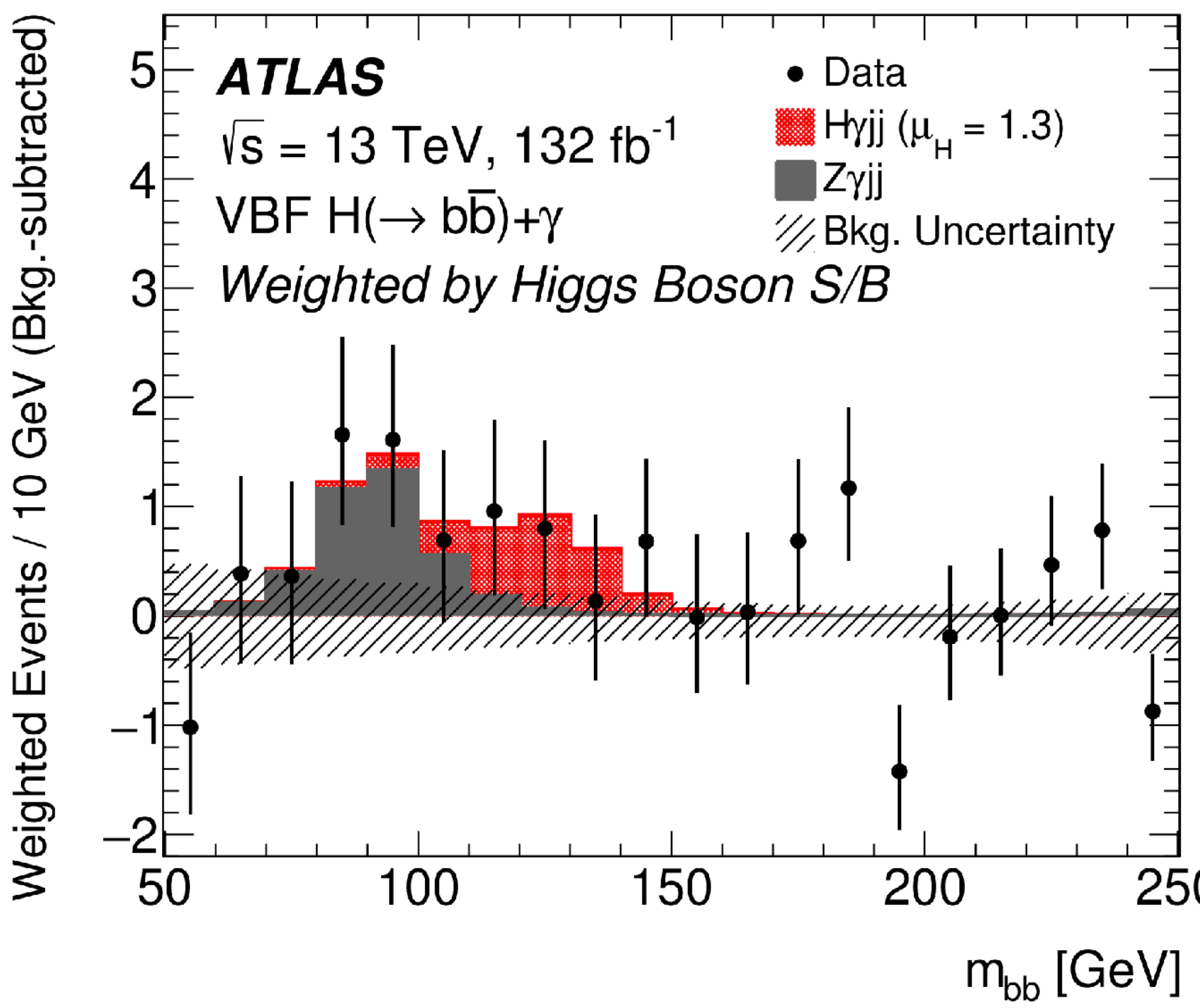
⇒ Back

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

- Photon tagged





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

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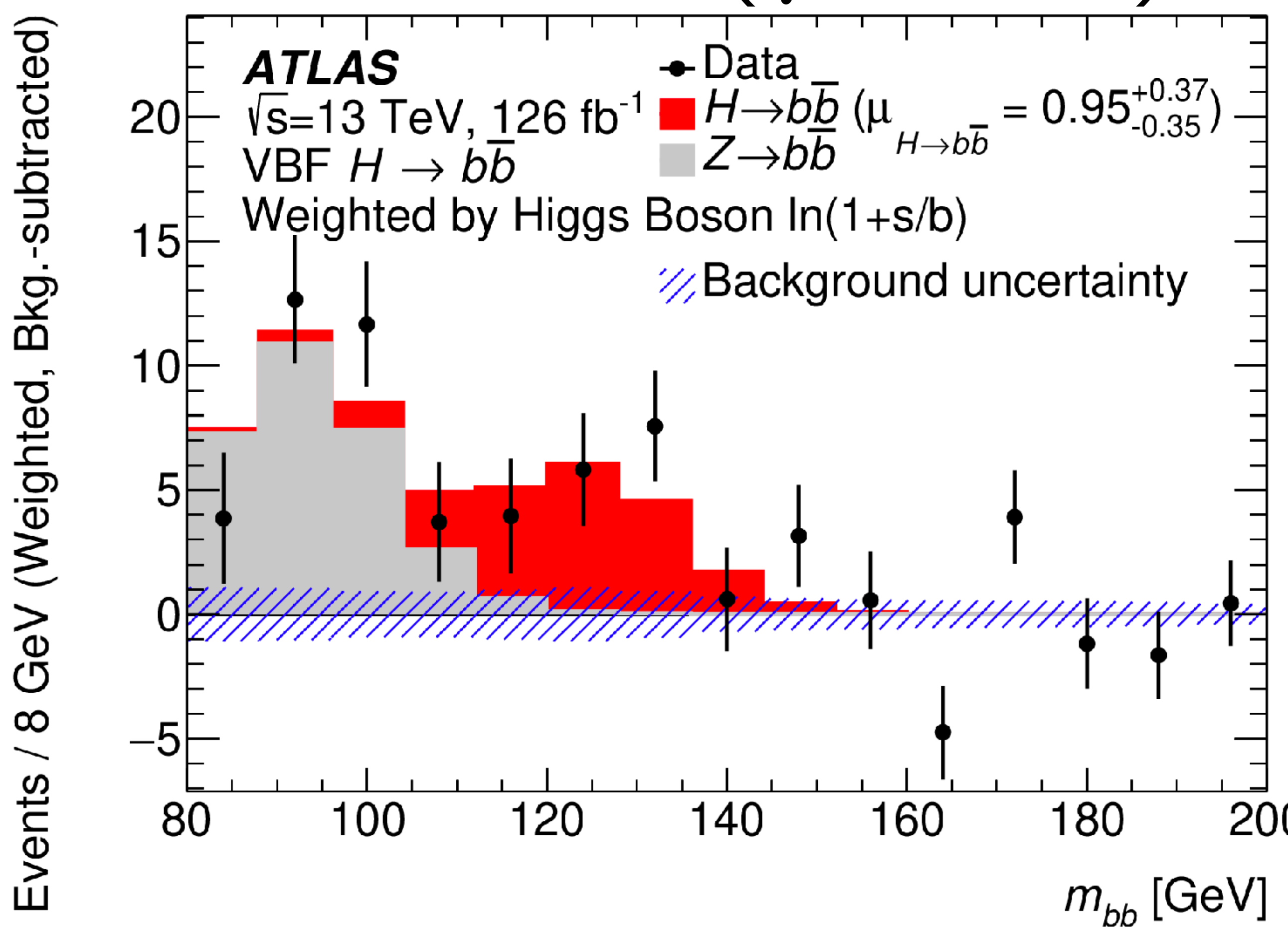
- Inclusive (γ veto):



Inclusive Production:	VBF Production:
μ = 0.95 +0.37 -0.35	μ = 0.95 +0.38 -0.36
Obs. (exp.) significance: 2.7 (2.9) σ	Obs. (exp.) significance: 2.6 (2.8) σ

- Combination:

Inclusive Production:	VBF Production:
μ = 0.99 +0.35 -0.33	μ = 0.99 +0.36 -0.34
Obs. (exp.) signif.: 3.0 (3.0) σ	Obs. (exp.) signif.: 2.9 (2.9) σ

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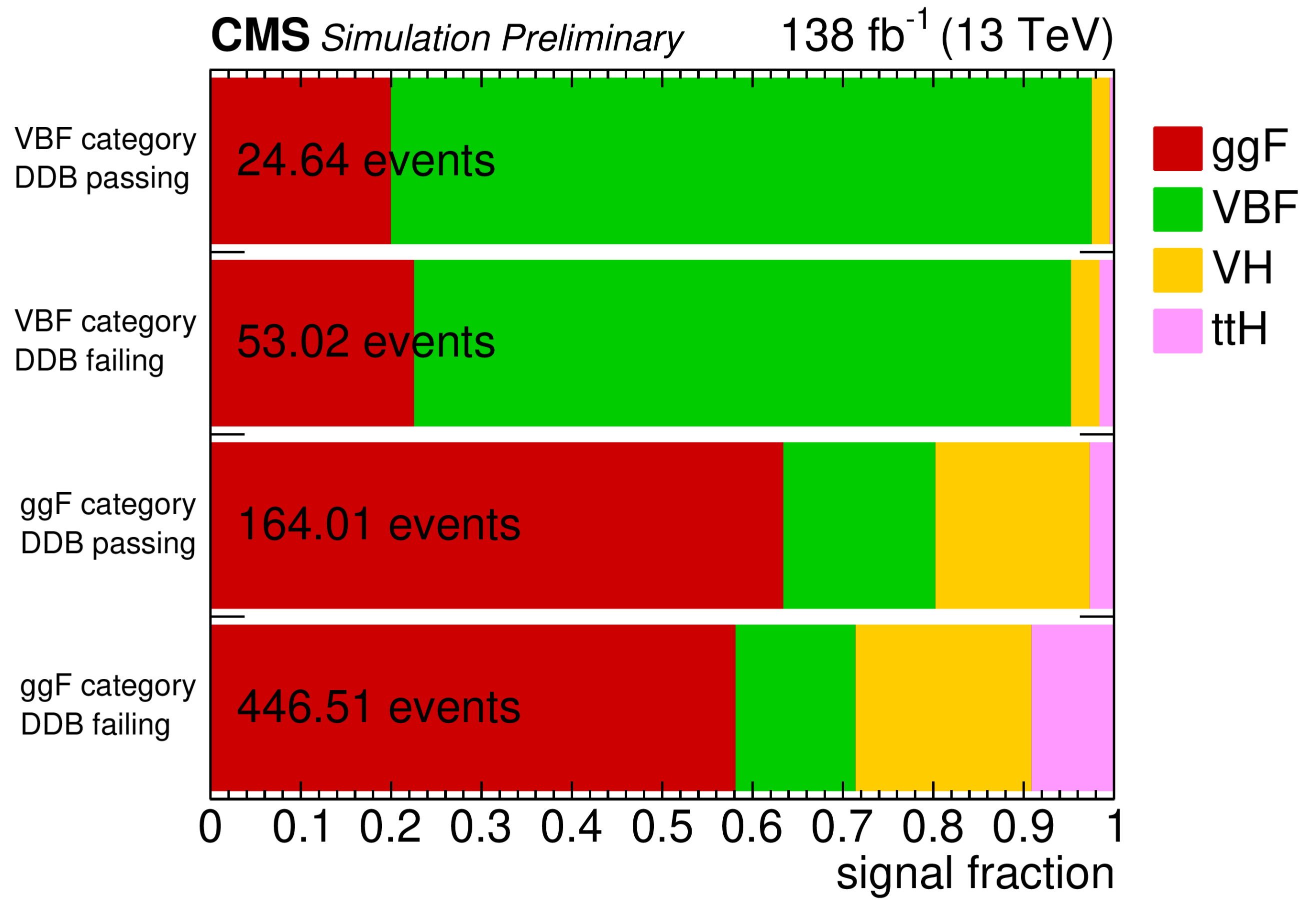
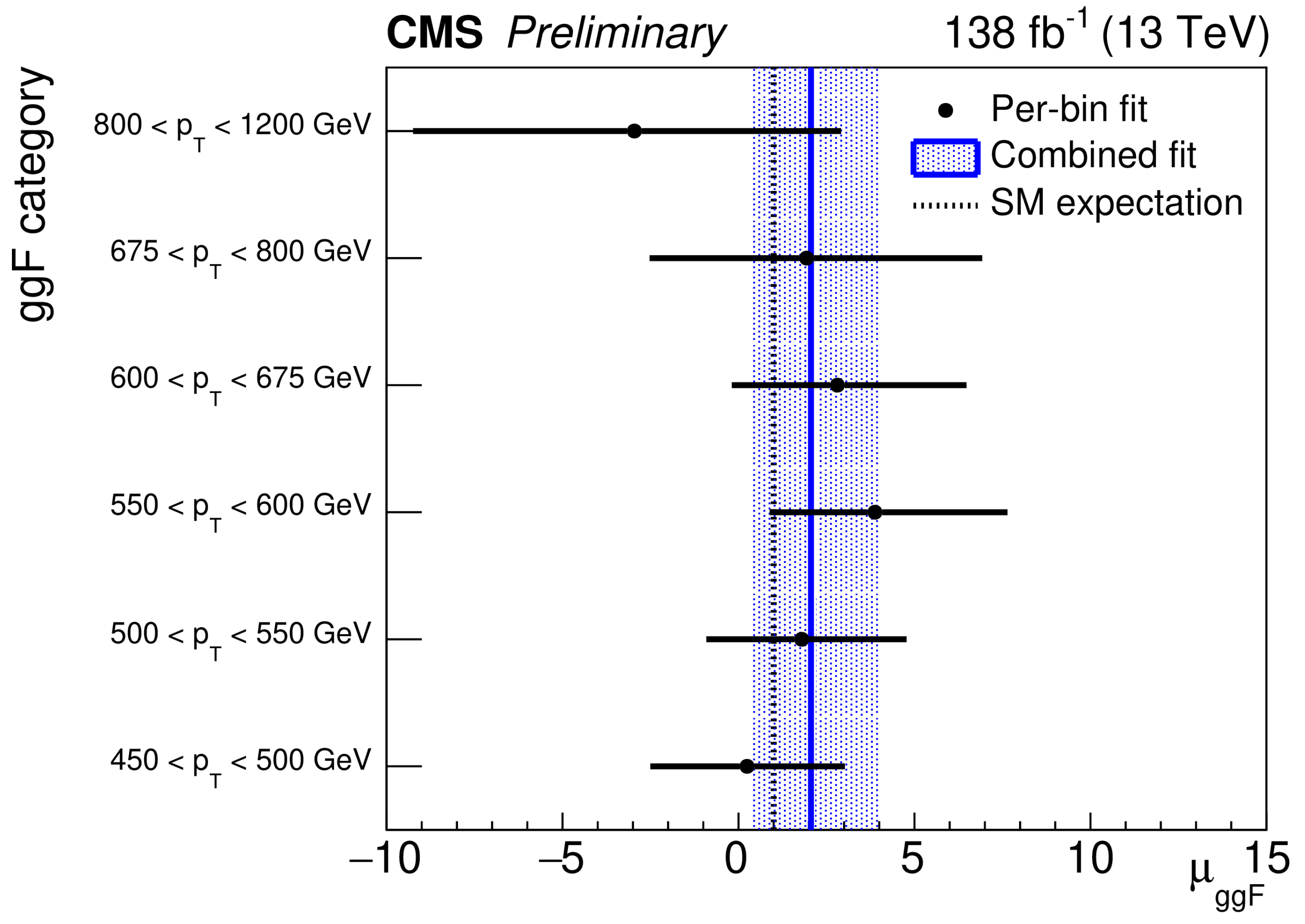
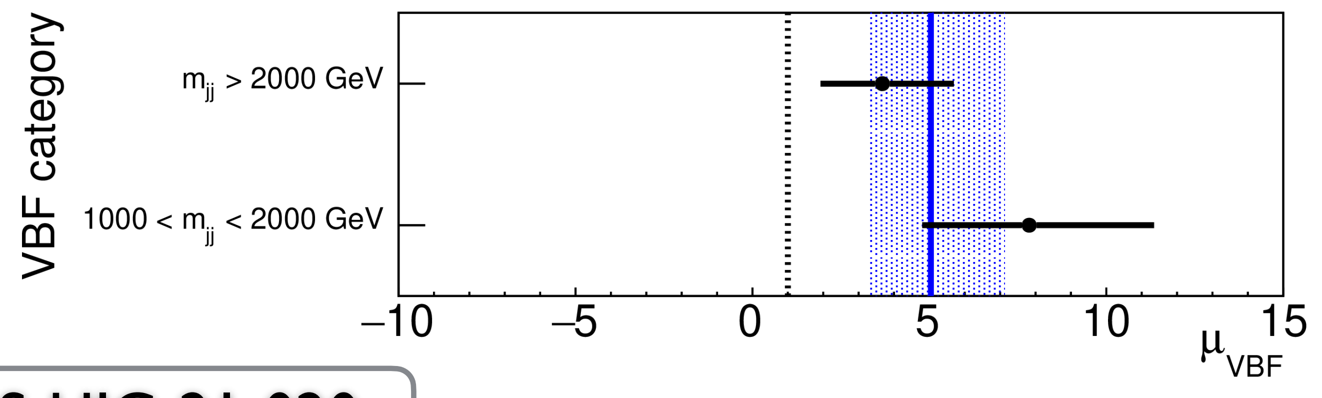
- Boosted:
  - Improved H → bb boosted tagger (DBB)
  - 1st measurement of VBF at high p_T,
  - Most precise measurement of boosted ggF to date
  - ggF:
    - $\mu = 2.1^{+1.9}_{-1.7}$
    - Obs. (exp.): **1.2 σ** (0.9 σ)
  - VBF:
    - $\mu = 5.0^{+2.1}_{-1.8}$
    - Obs. (exp.): **3 σ** (0.9 σ)





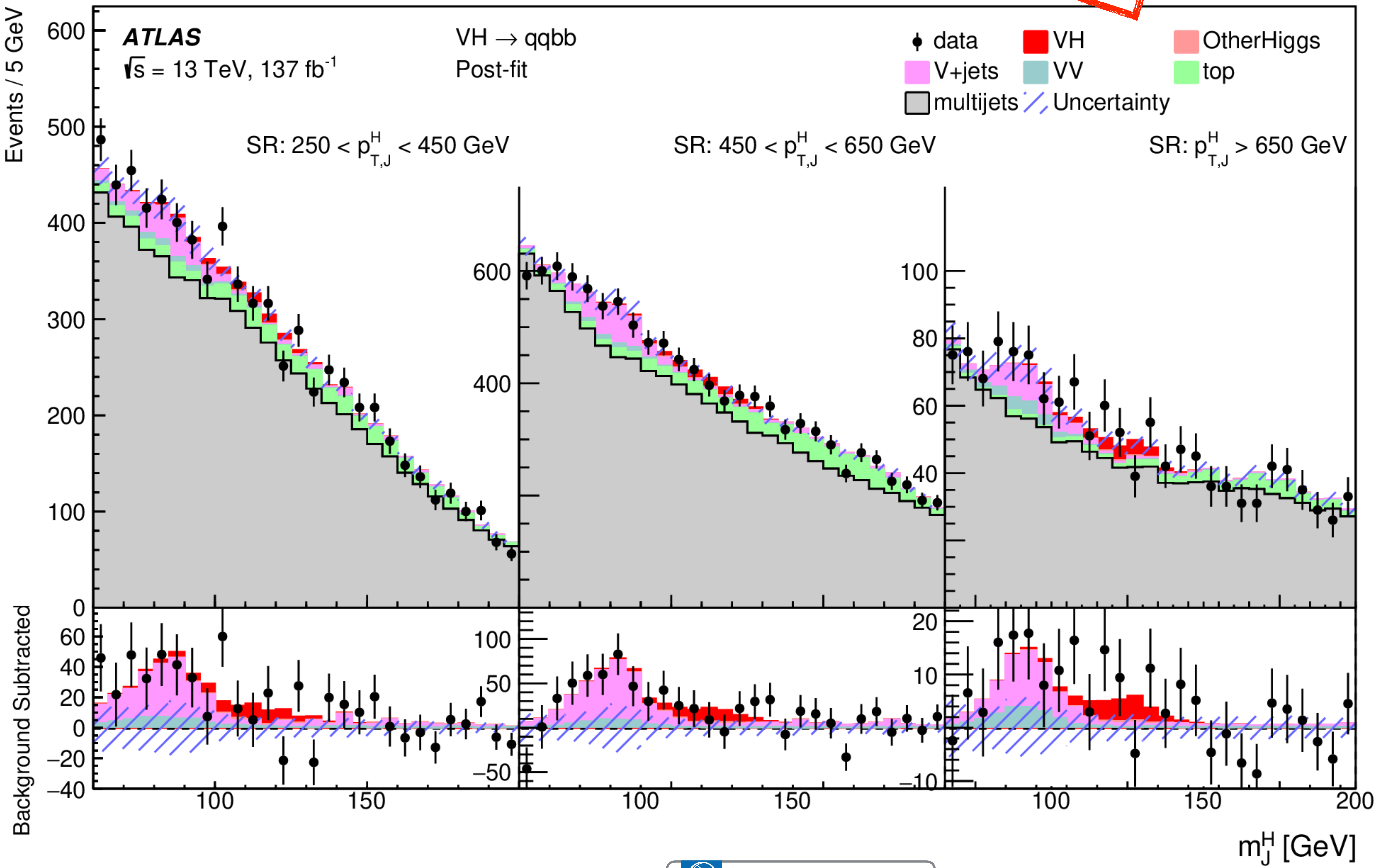


CMS-PAS-HIG-21-020

V(qq)H(bb) at high p_T

Dec 2023

- Fully-hadronic final state
  - Challenging at pp collider!
  - 2 boosted large-R jets
- Inclusive result:
  - $\mu = 1.4^{+1.0}_{-0.9}$
  - Obs. (exp.) significance: **1.7** σ (1.2 σ)
- Also in 3 p_T(H) bins

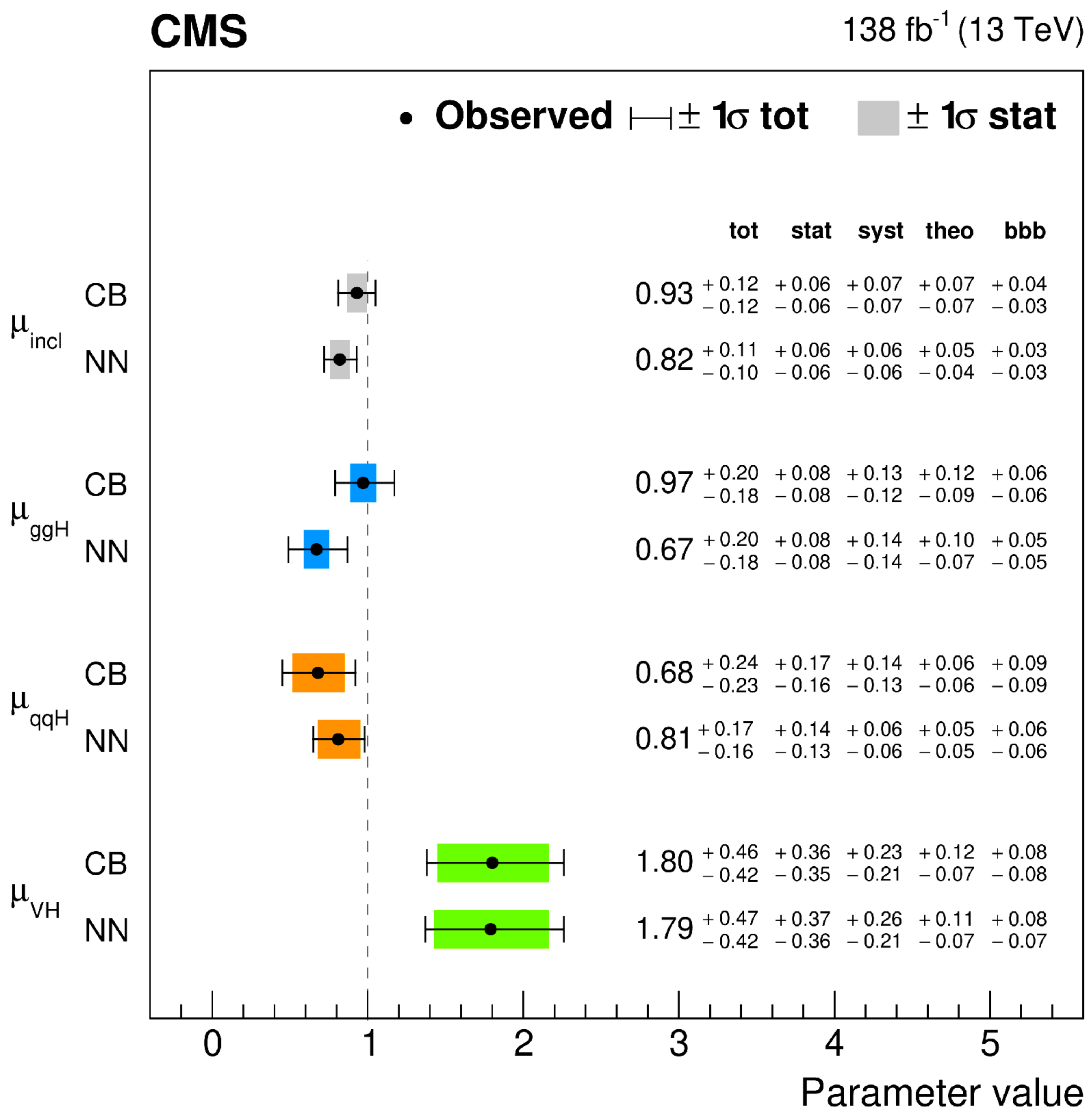


arXiv:2312.07605

$H \to \tau\tau$

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

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



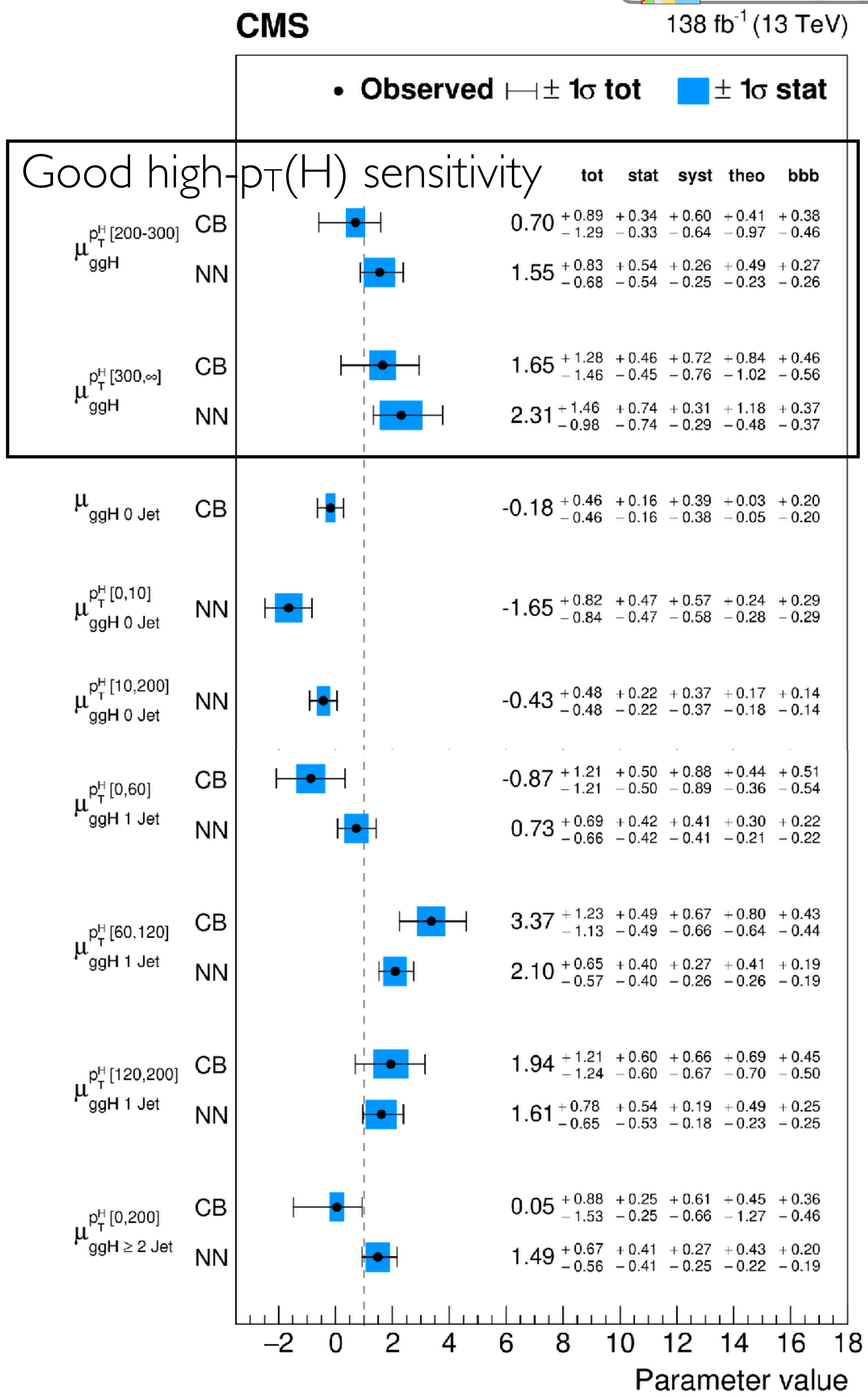
Expected uncertainty NN (CB) [symmetrized]

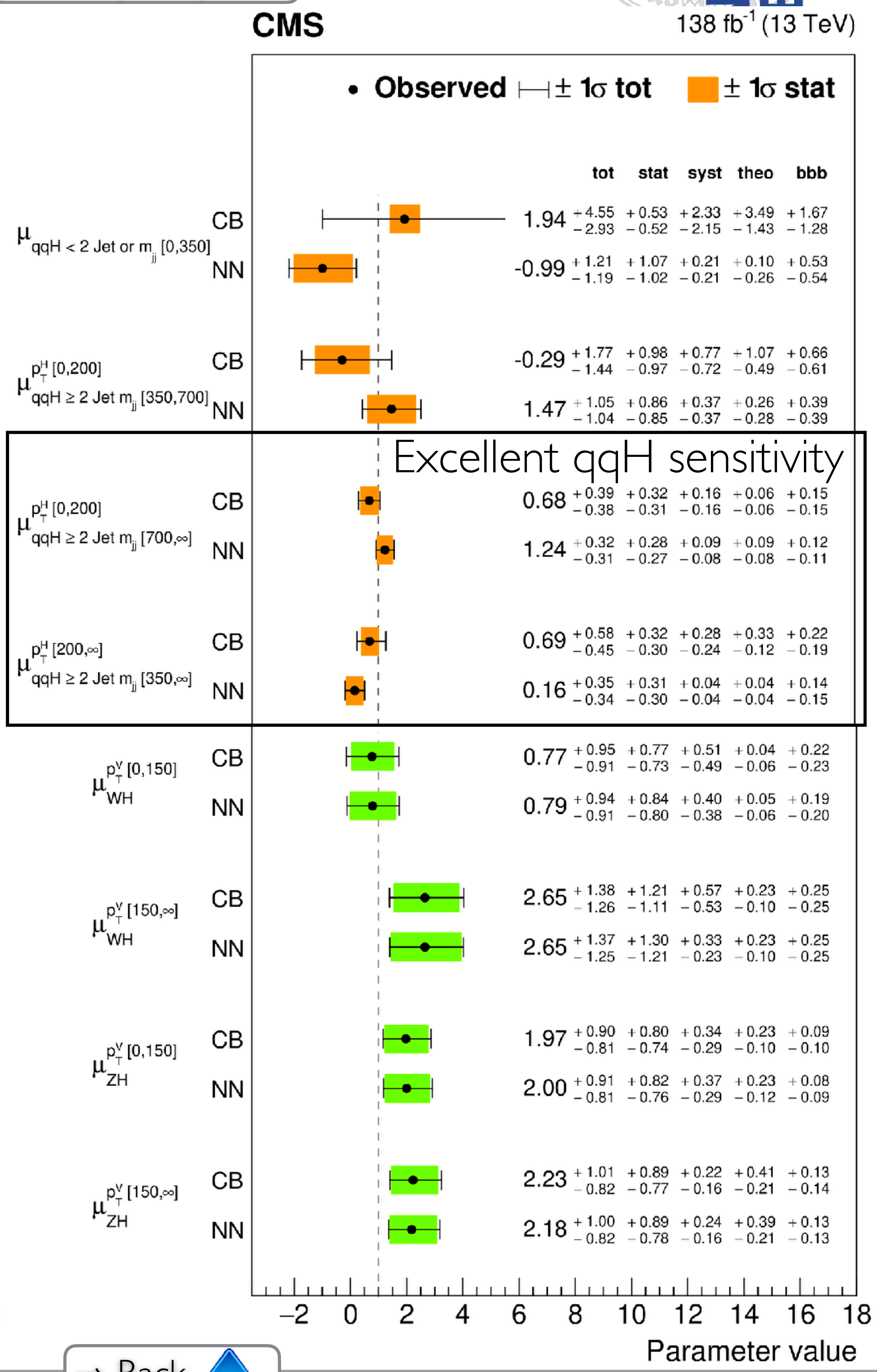
12% (13%)

25% (23%)

17% (24%)

39% (39%)





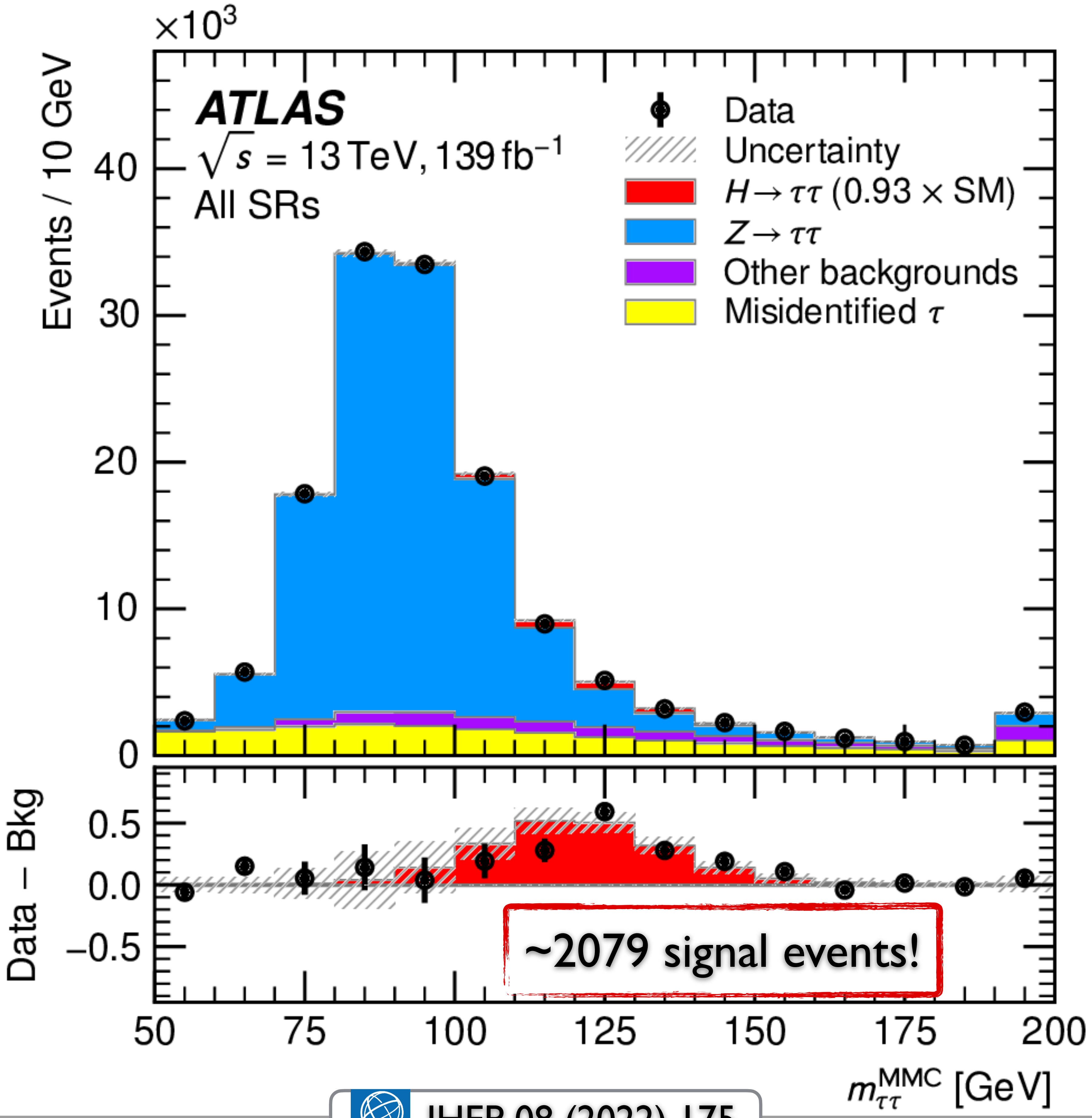
⇒ Back

$H \rightarrow \tau\tau$

Jan 2022

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

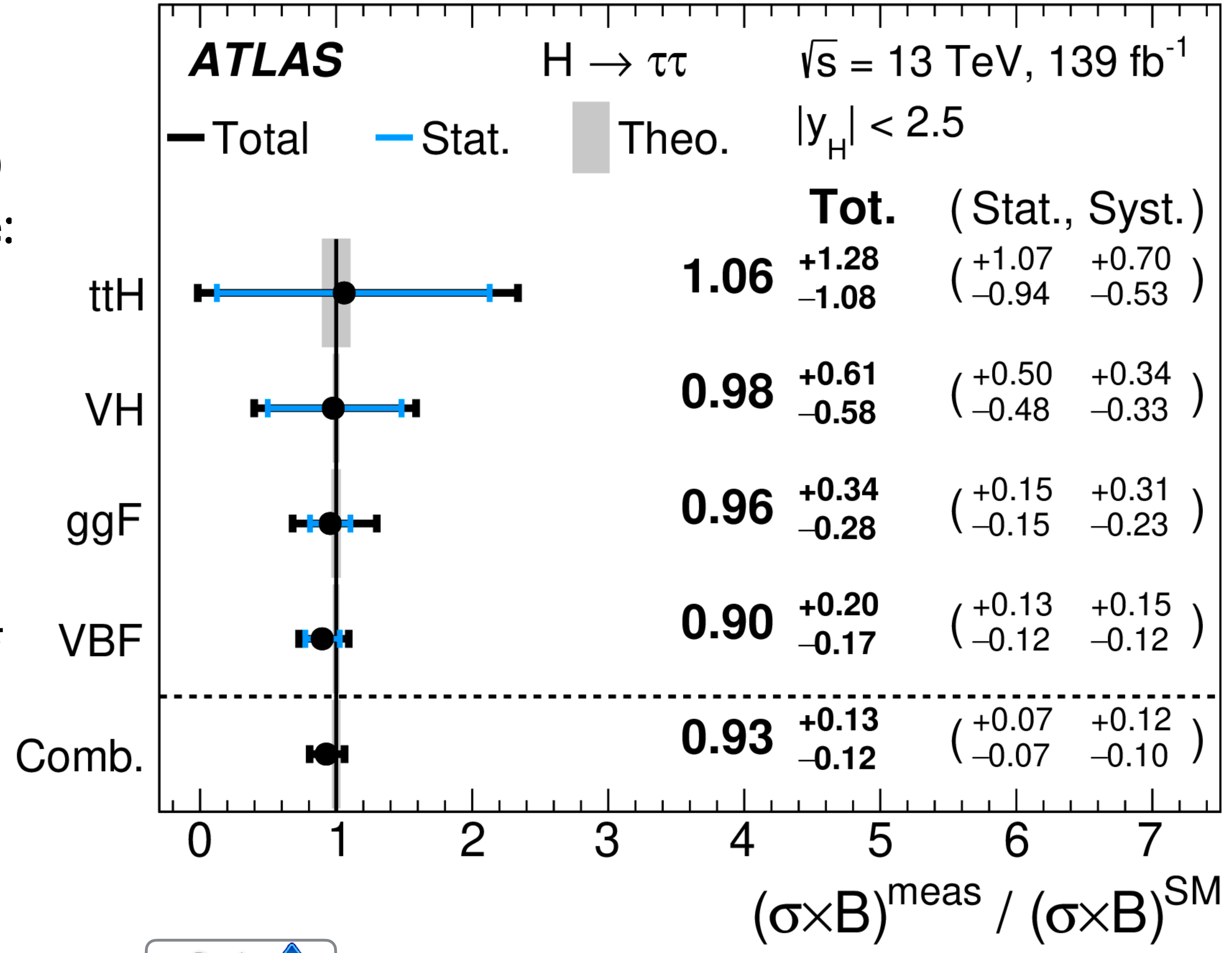
$\Rightarrow$ **~480 000 $H \rightarrow \tau\tau$ events in 139 fb^{-1}**



Observed (expected) significance:

ggF: 3.9 (4.6) σ

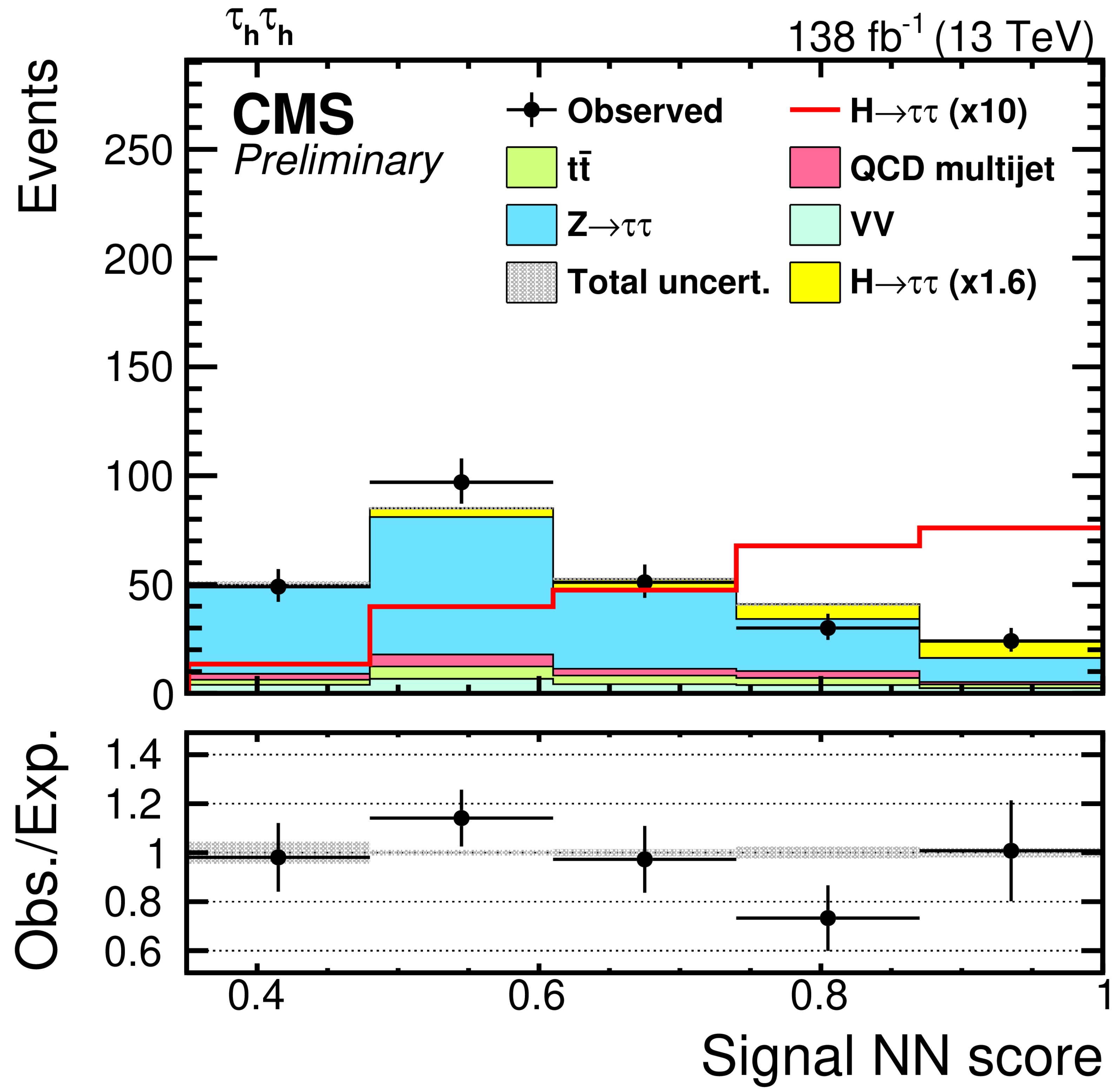
VBF: 5.3 (6.2) σ



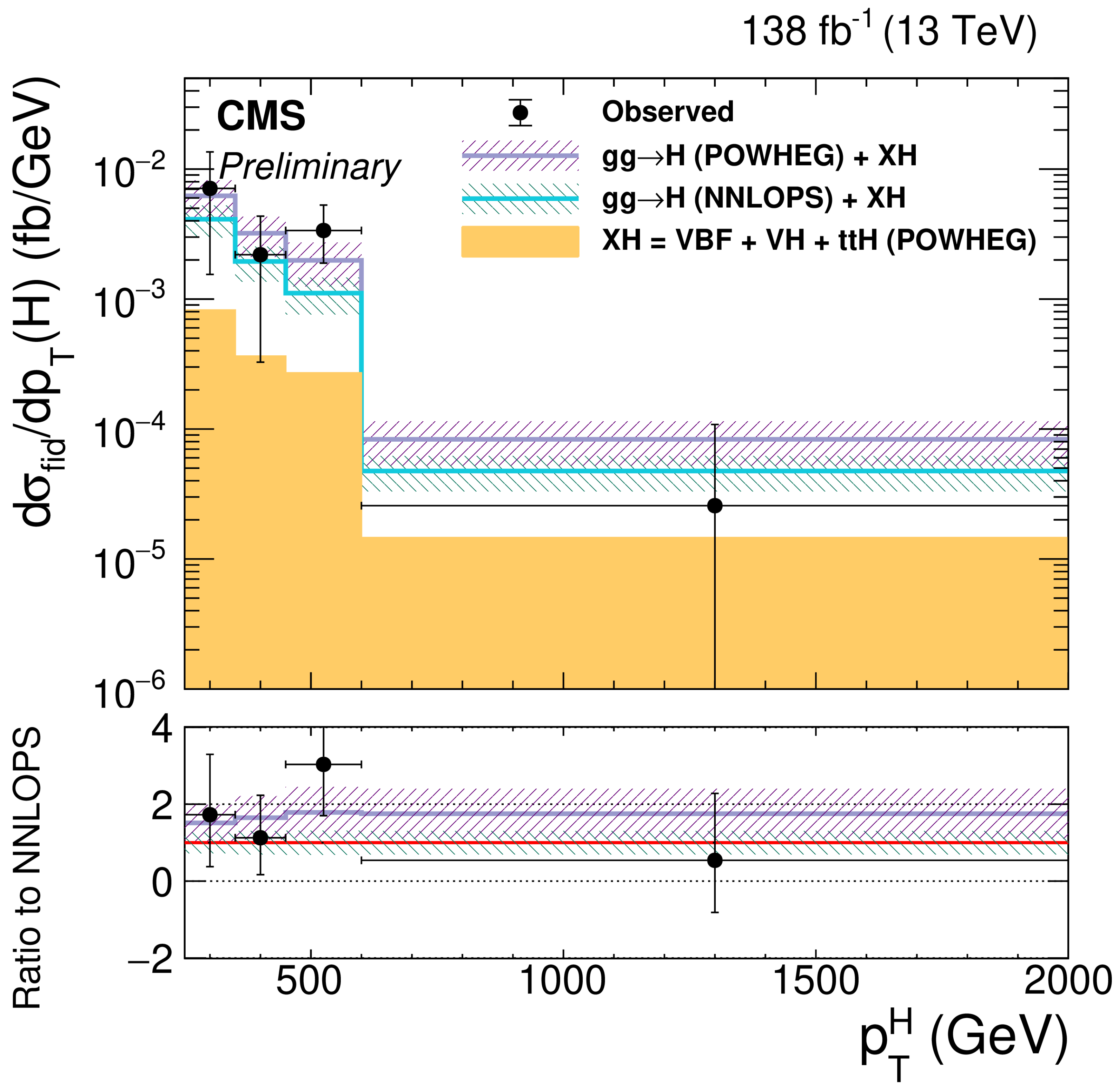
Boosted H → ττ

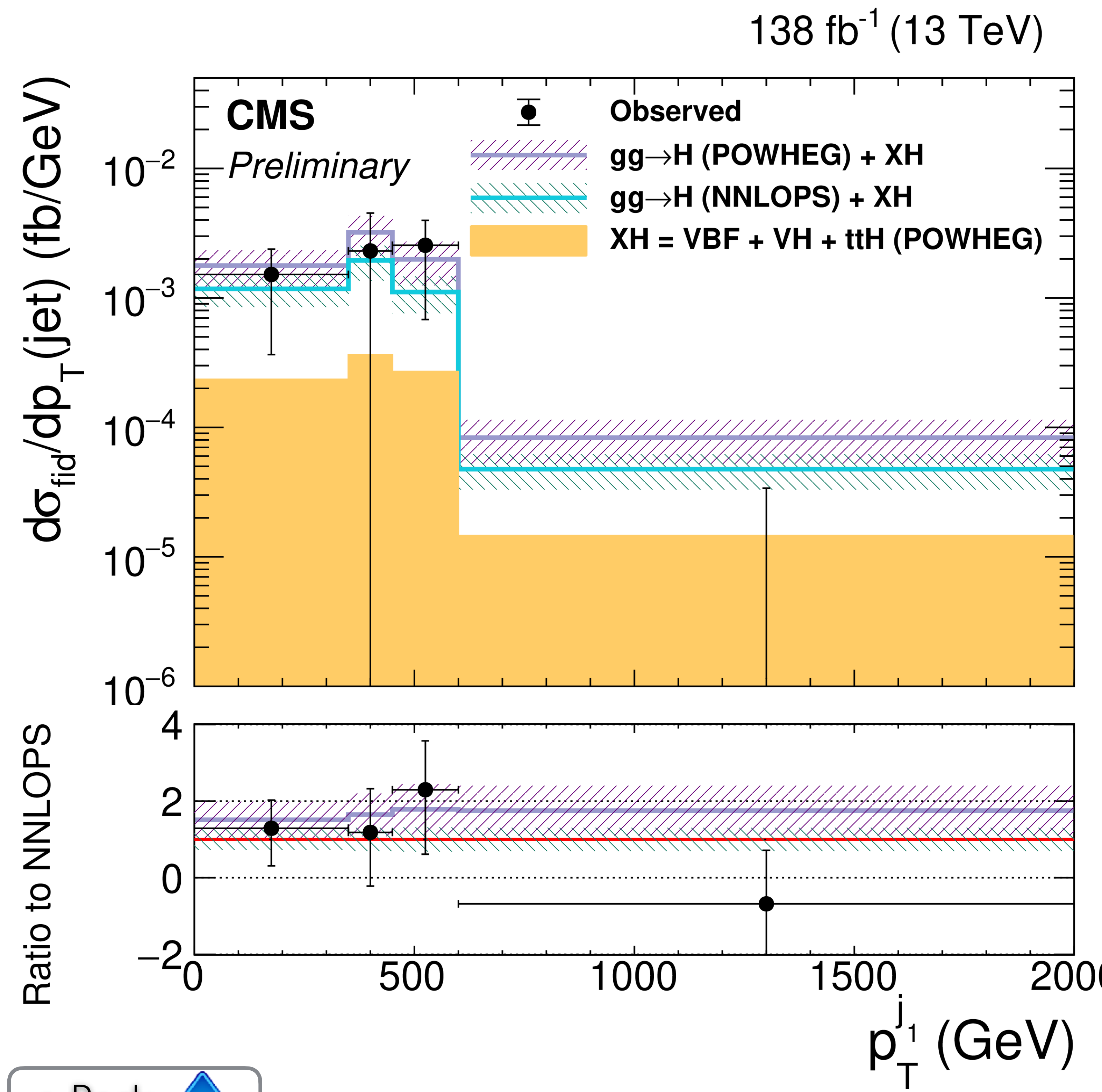
CMS-PAS-HIG-21-017

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



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



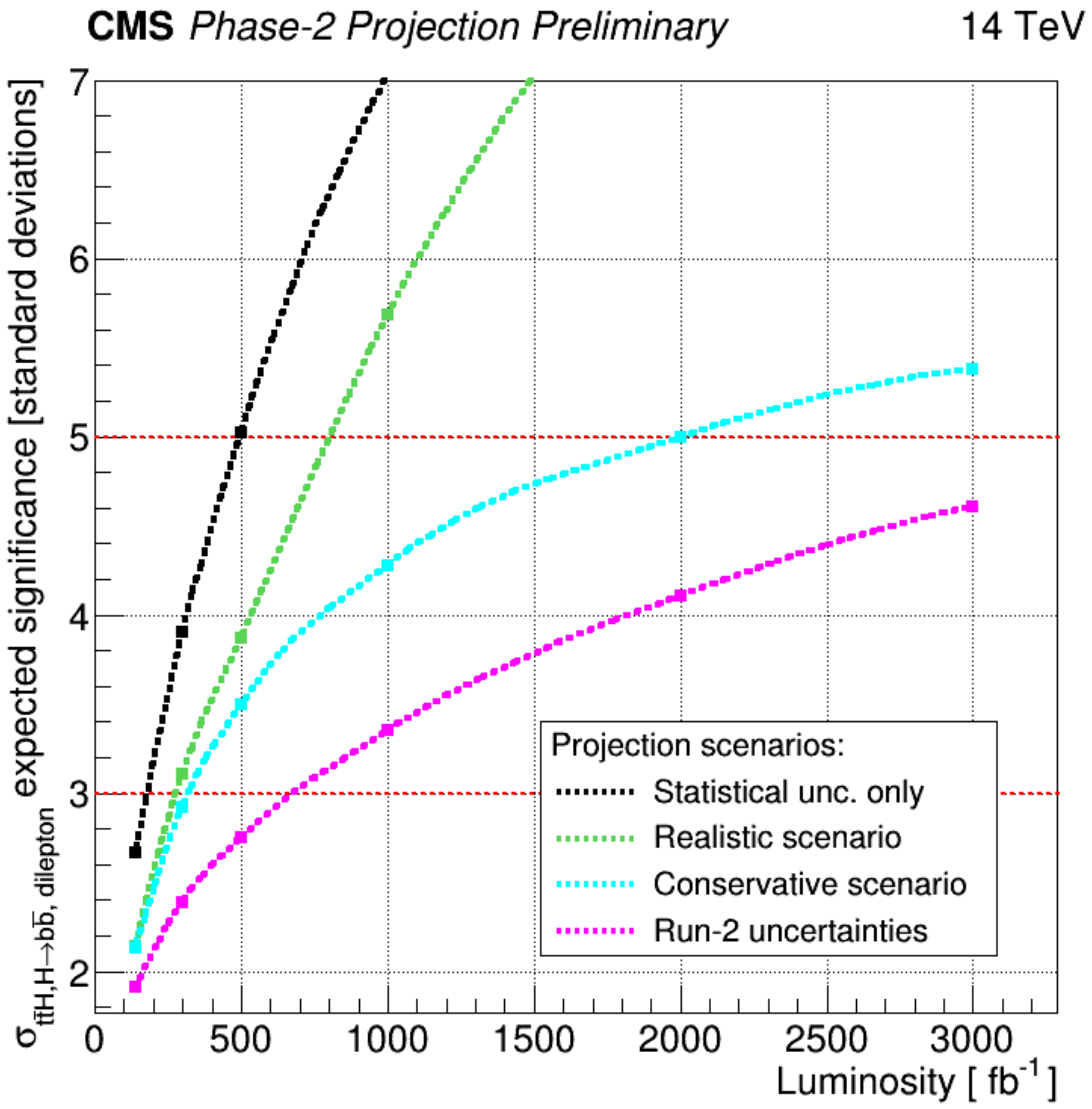


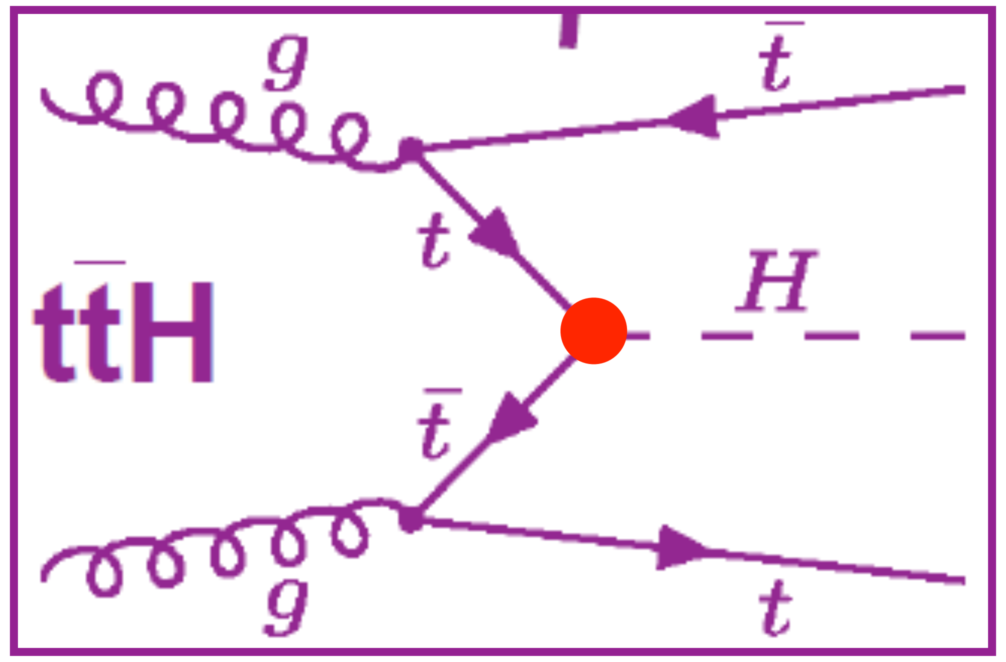
⇒ Back

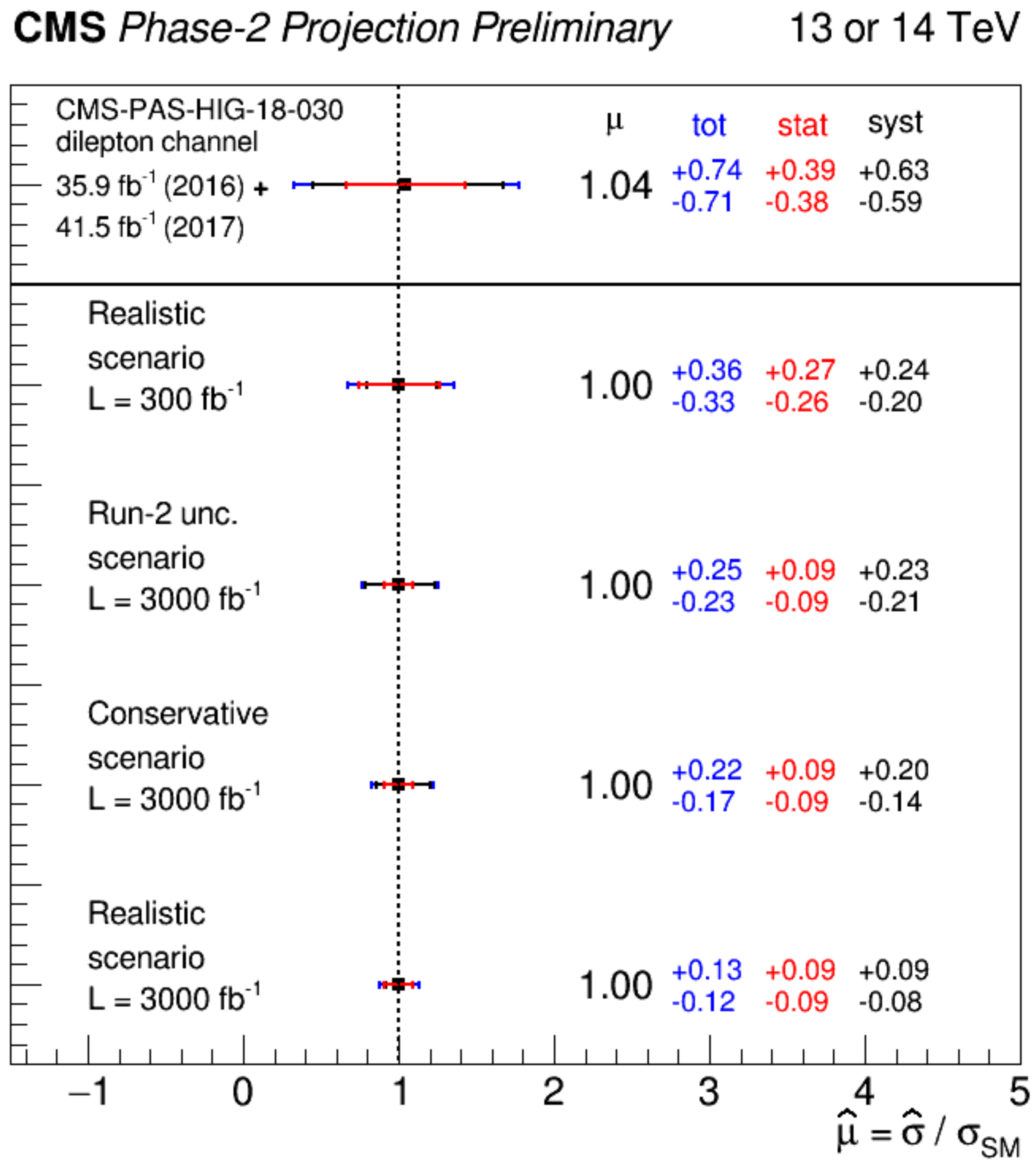
HL-LHC ttH, H → $b\bar{b}$

CMS-PAS-FTR-21-002

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







HH: Twice the Higgs, twice the fun

- Probing the Higgs potential via HHH coupling:

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

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

Expand $\phi(x)$ around vacuum:

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

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H self interactions

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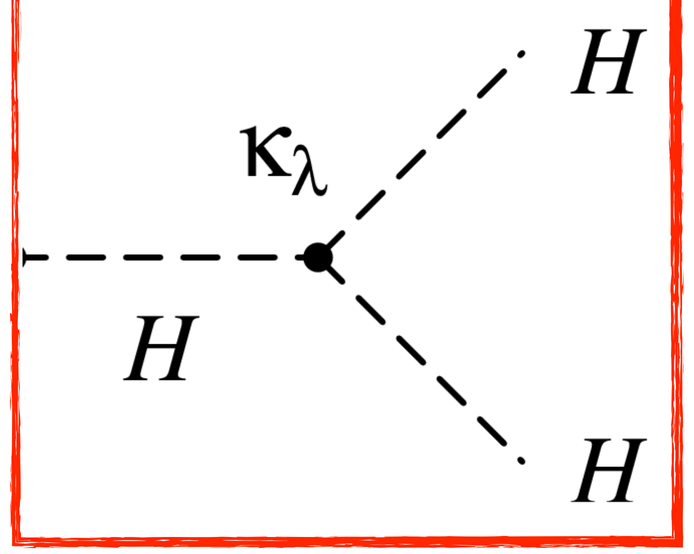
H self interactions



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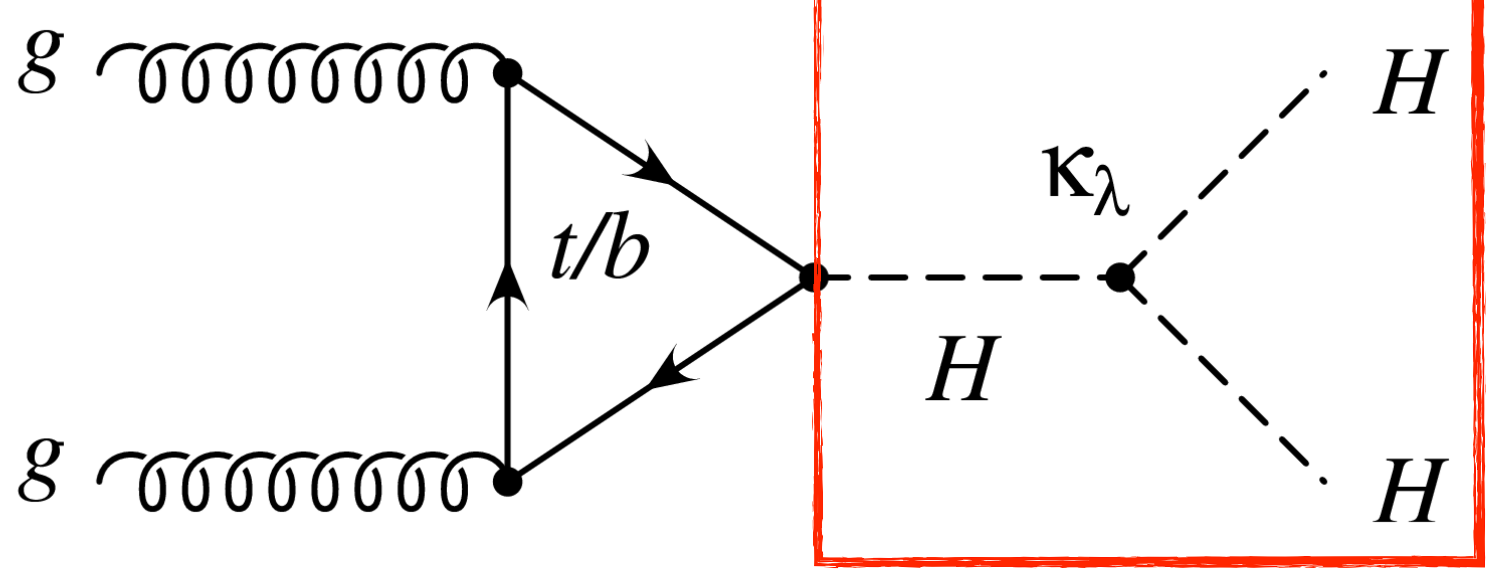
H self interactions



HH: Twice the Higgs, twice the fun

- Probing the Higgs potential via HHH coupling:

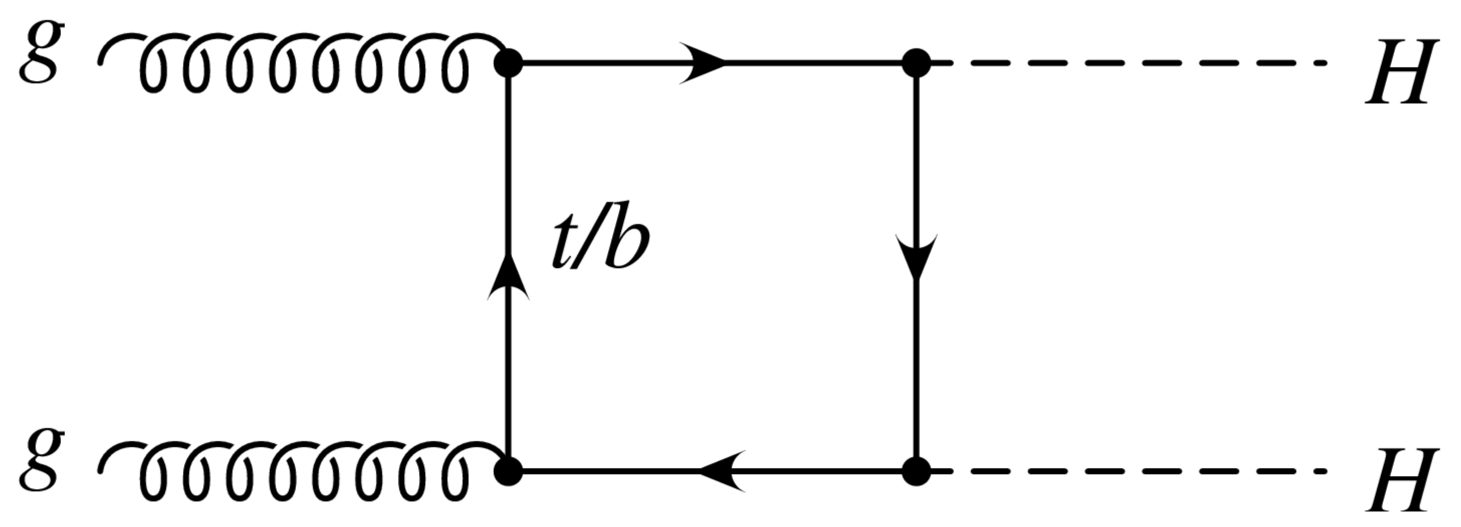
Expand $\phi(x)$ around vacuum:

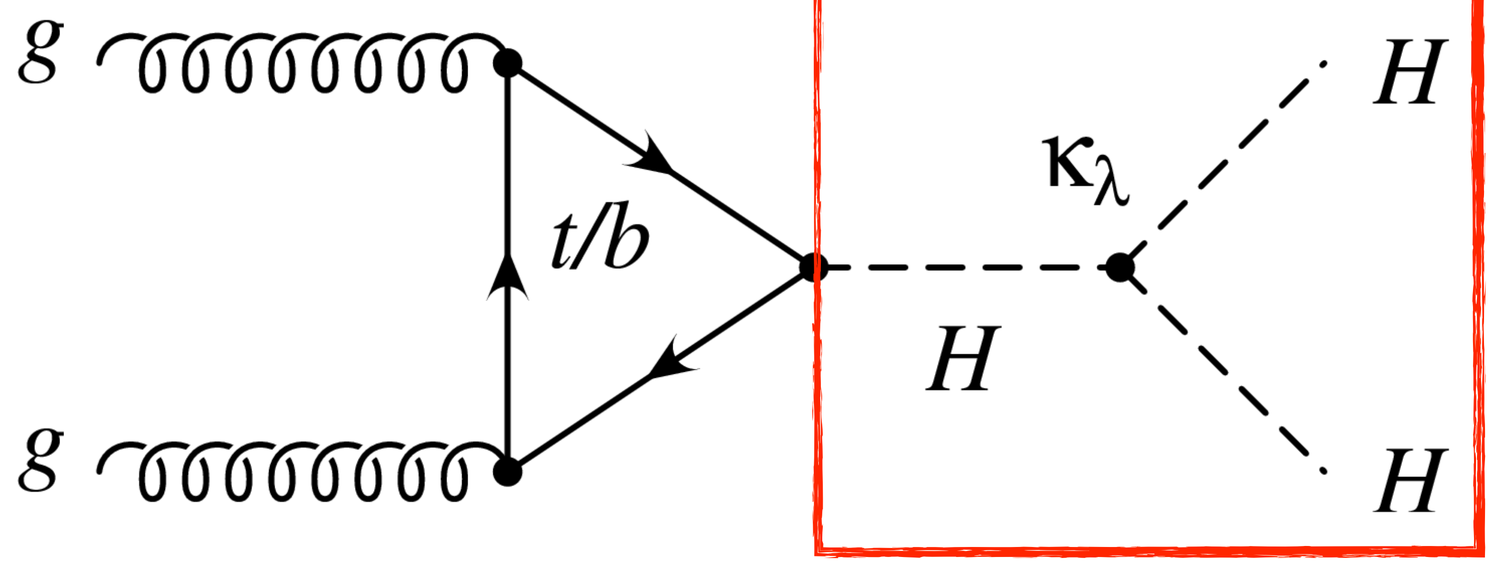
$$\phi(x) = \frac{1}{\sqrt{2}}(v + H(x))$$

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

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

H self interactions





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- Probing the Higgs potential via HHH coupling:

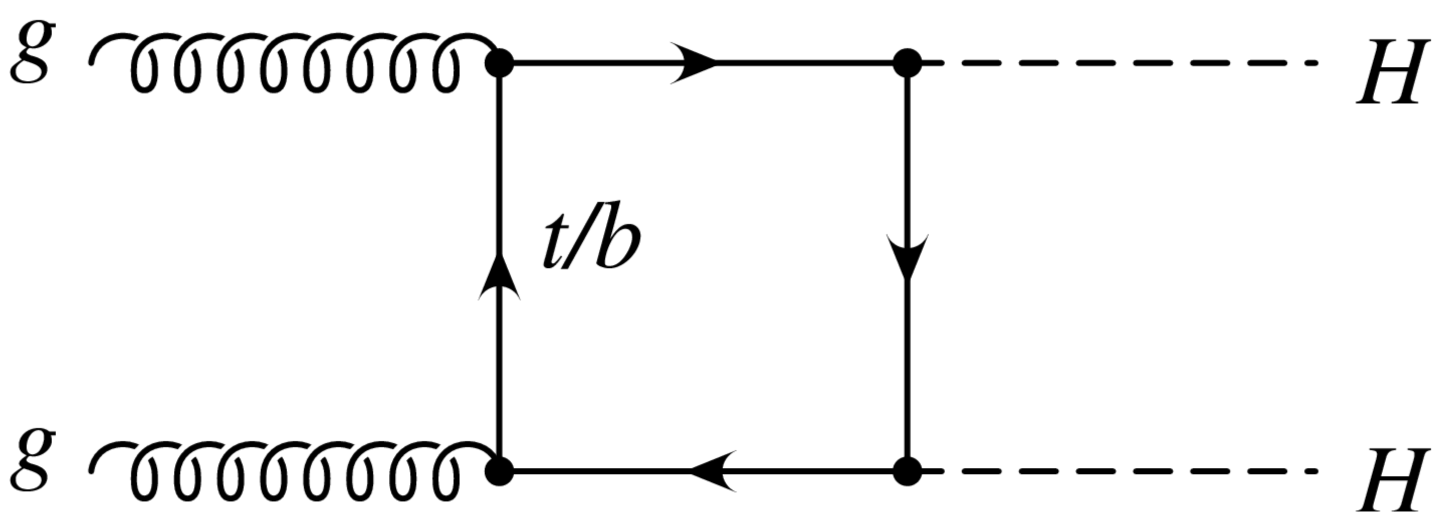
Expand $\phi(x)$ around vacuum:

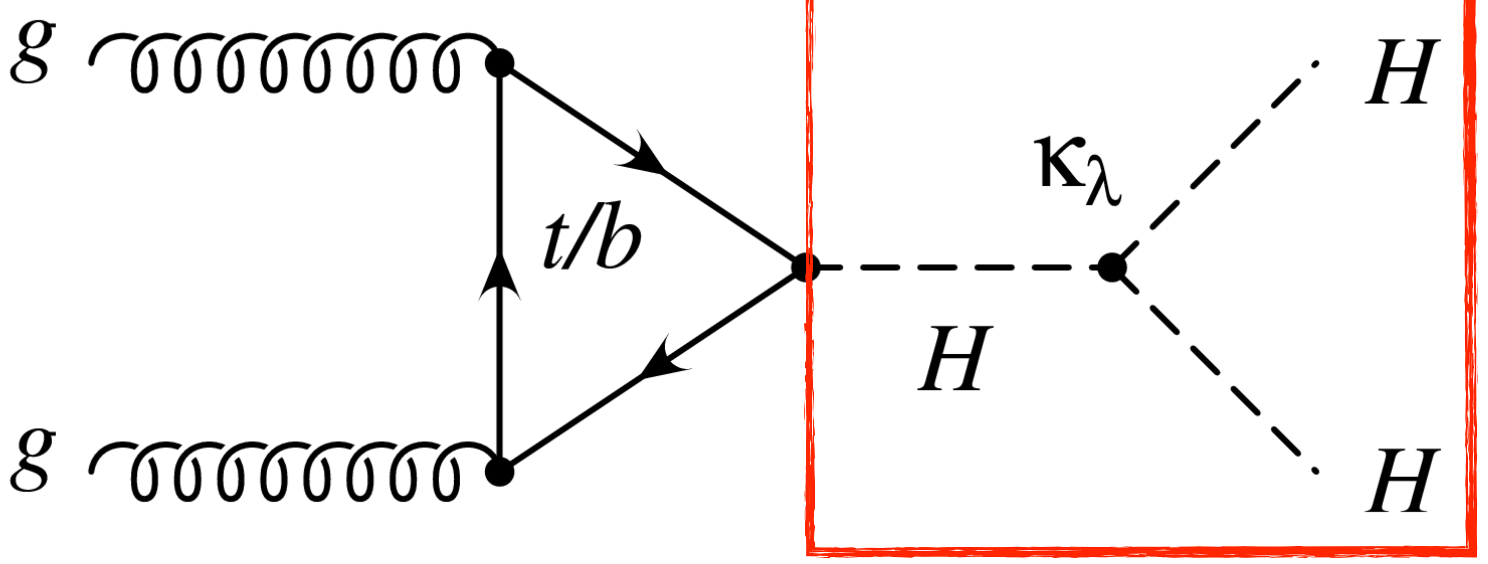
$$\phi(x) = \frac{1}{\sqrt{2}}(v + H(x))$$

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

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

H self interactions





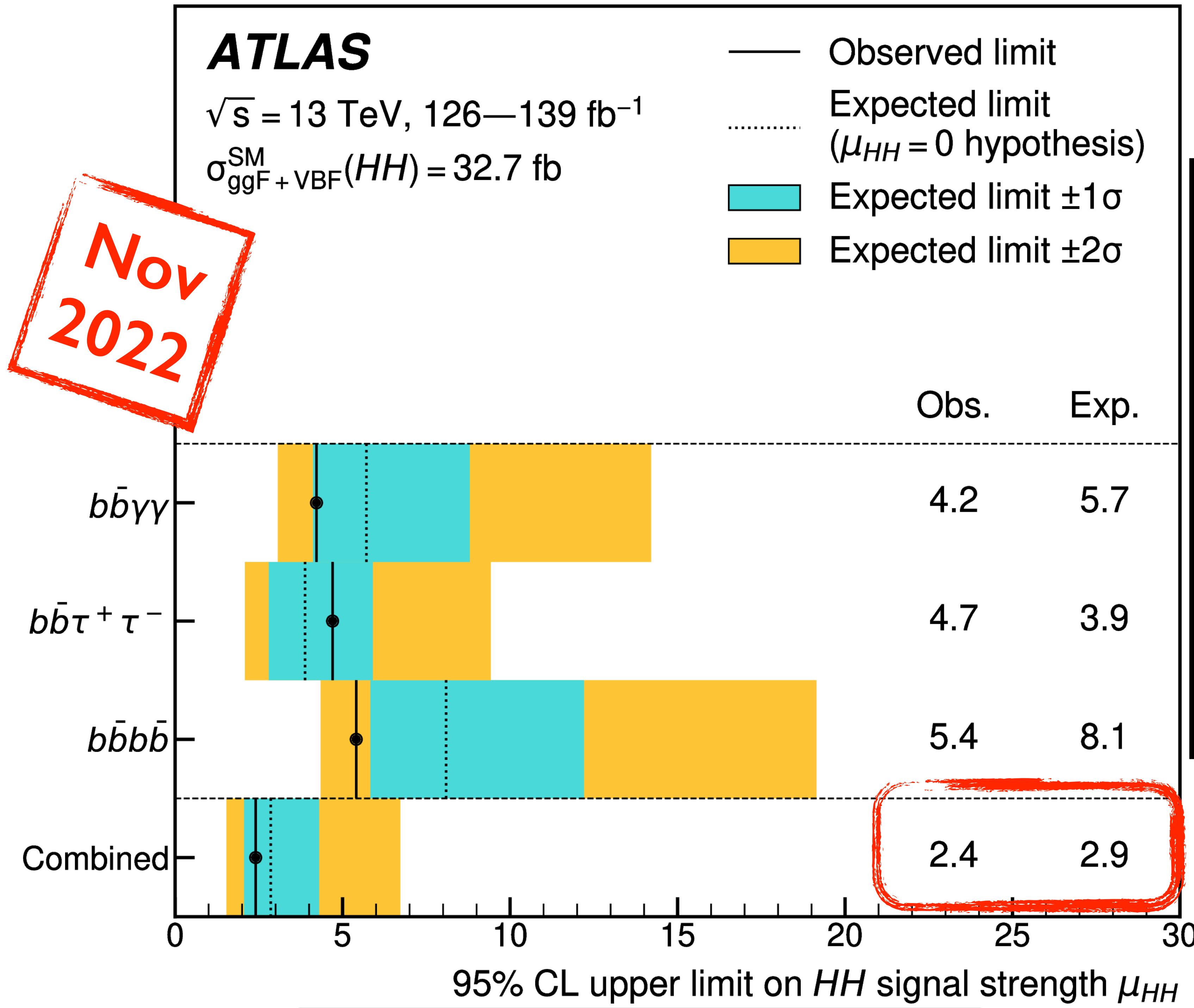
Destructive interference!

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

Di-Higgs Production

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

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



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Improved results:

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

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

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

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

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

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

Combination of H and HH

CMS H+HH Combination

Observed constraint on trilinear coupling at 95% CL:

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

Expected range:

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

Nov 2023

CMS-PAS-HIG-23-006

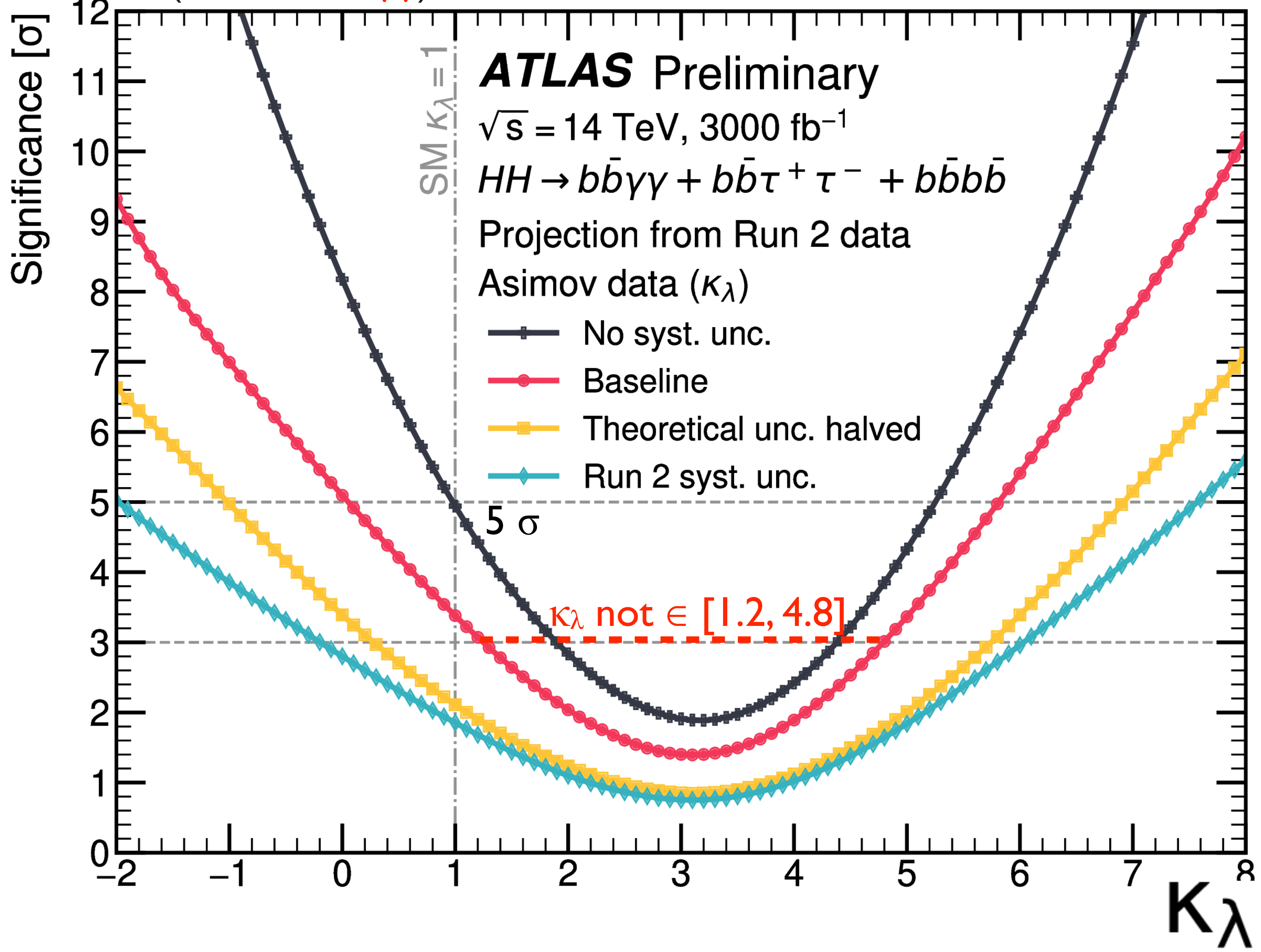
HH at HL-LHC

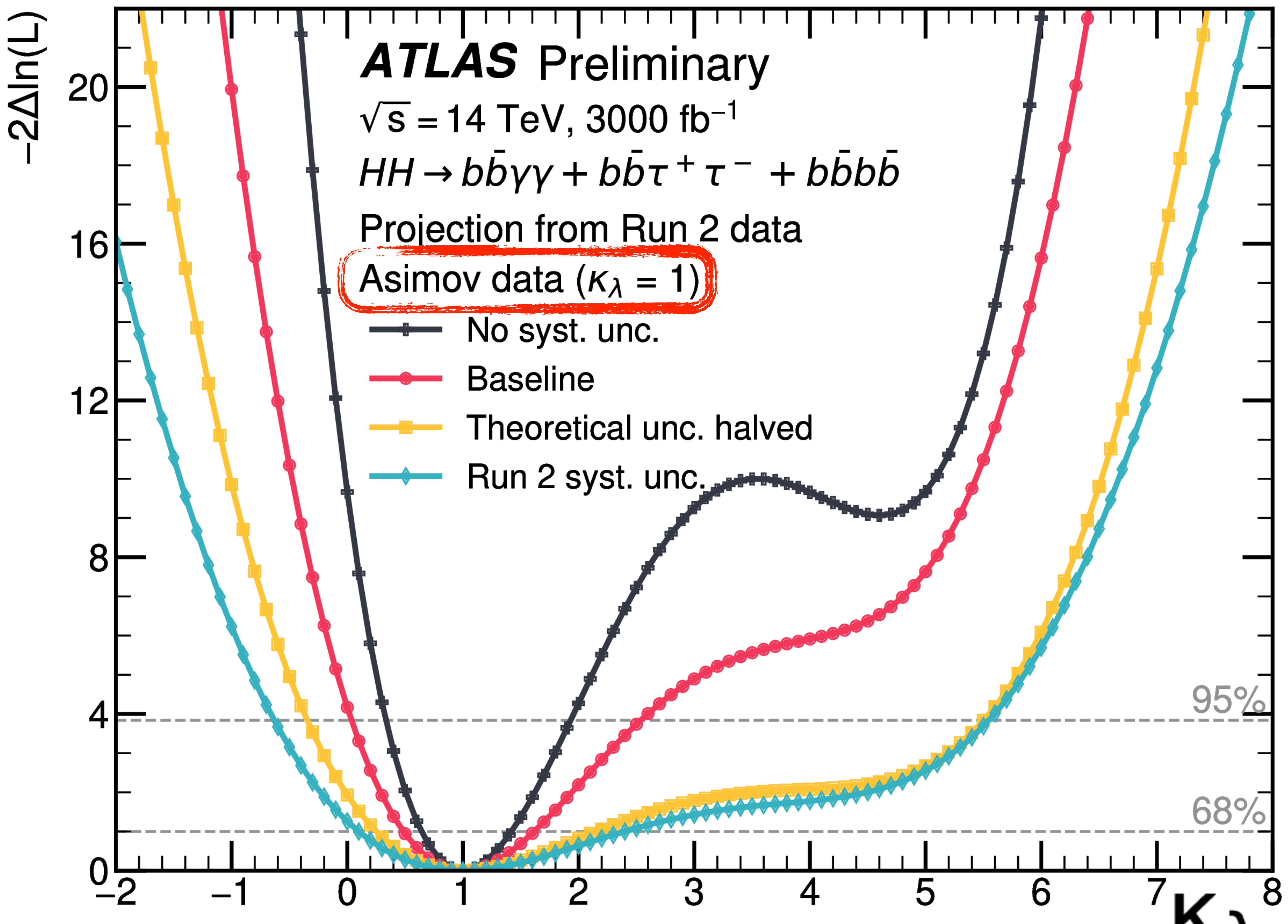
[ATL-PHYS-PUB-2022-053]

Uncertainty scenario	Significance [σ] $b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	$b\bar{b}b\bar{b}$	Combination	Combined signal strength precision [%]
No syst. unc.	2.3	4.0	1.8	4.9	−21/+22
Baseline	2.2	2.8	0.99	3.4	−30/+33
Theoretical unc. halved	1.1	1.7	0.65	2.1	−47/+48
Run 2 syst. unc.	1.1	1.5	0.65	1.9	−53/+65

Nov 2022

- HL-LHC extrapolation from full Run 2 combination of:
  - $BR_{SM}(HH \rightarrow bbbb)$ = 33% ⇒ ~38400 events in 3000 fb^{-1}
  - $BR_{SM}(HH \rightarrow bb\tau\tau)$ = 7.4% ⇒ ~6900 events in 3000 fb^{-1}
  - $BR_{SM}(HH \rightarrow bb\gamma\gamma)$ = 0.26% ⇒ ~240 events in 3000 fb^{-1}



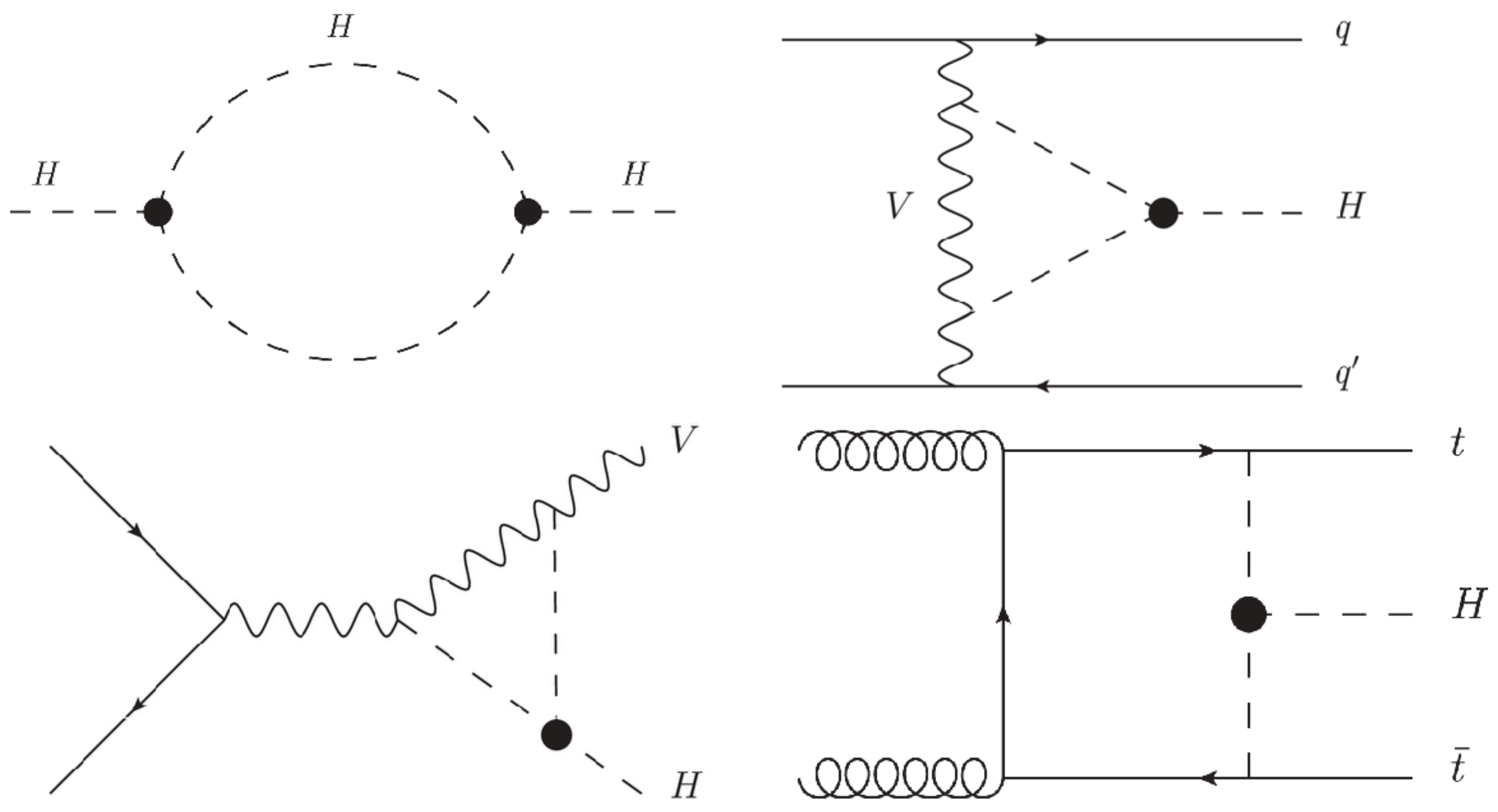


Uncertainty scenario	κ_λ 68% CI	κ_λ 95% CI
Baseline	[0.5, 1.6]	[0.0, 2.5]

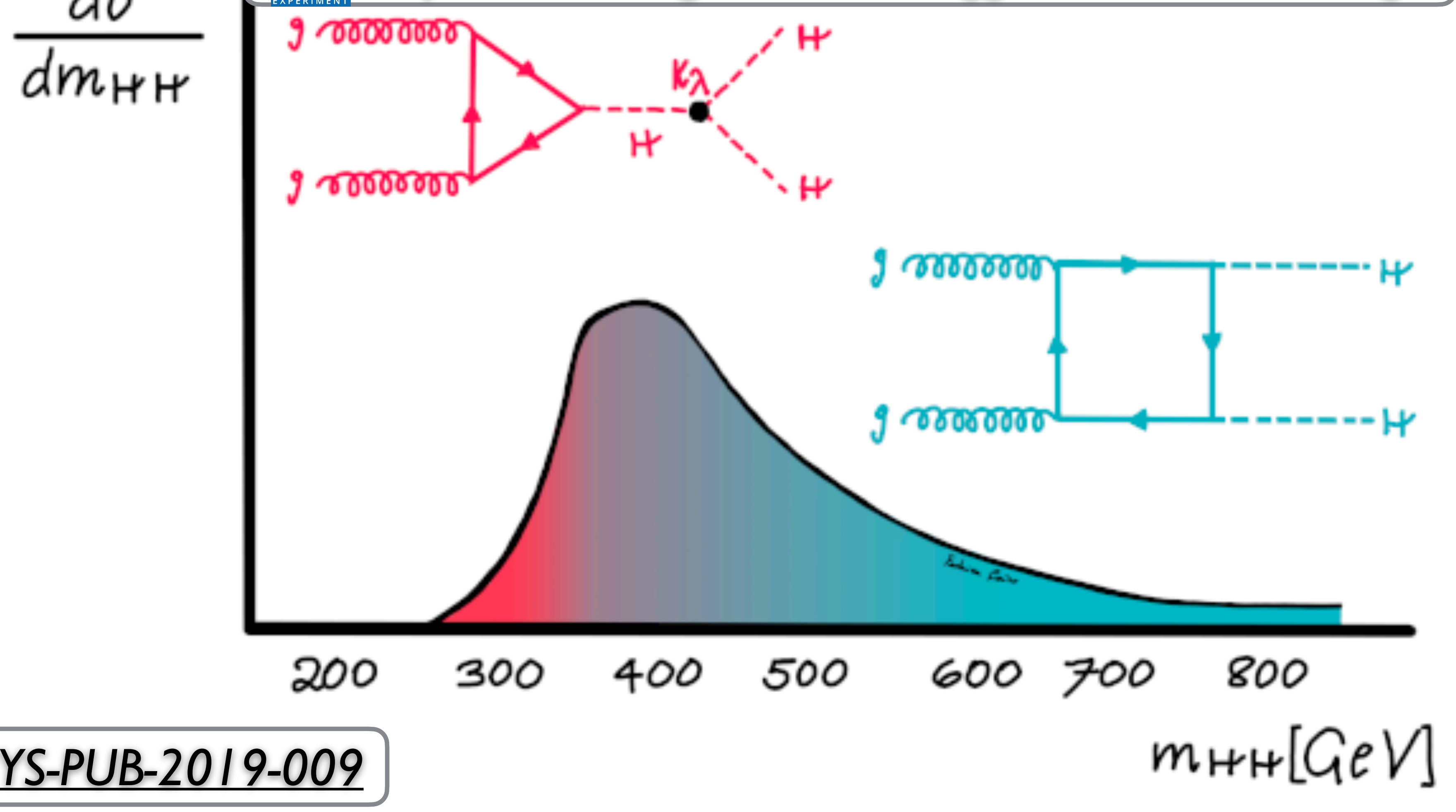
⇒ CMS $bb\gamma\gamma$ expected significance at 3000 fb^{-1}: 2.16 σ [CMS-PAS-FTR-21-004]

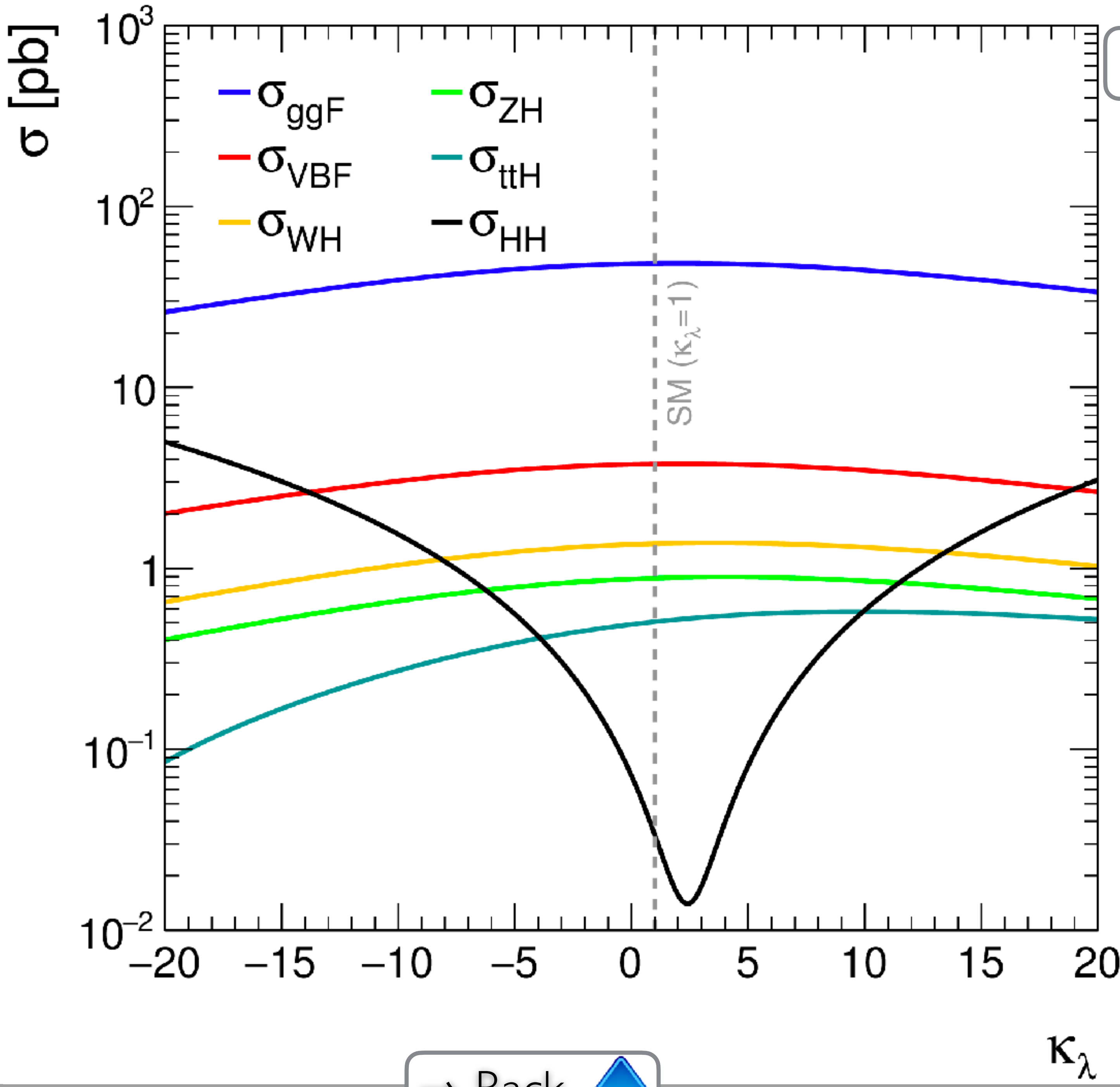
⇒ ATLAS + CMS (3+3 ab^{-1}, all channels) from CERN HL-LHC Yellow Report (w/ systematics): HH significance: 4.0 σ and $0.52 < \kappa_\lambda < 1.5$ @ 68% C.L.

Extracting κ_λ



Physics Briefing *Twice the Higgs, twice the challange*





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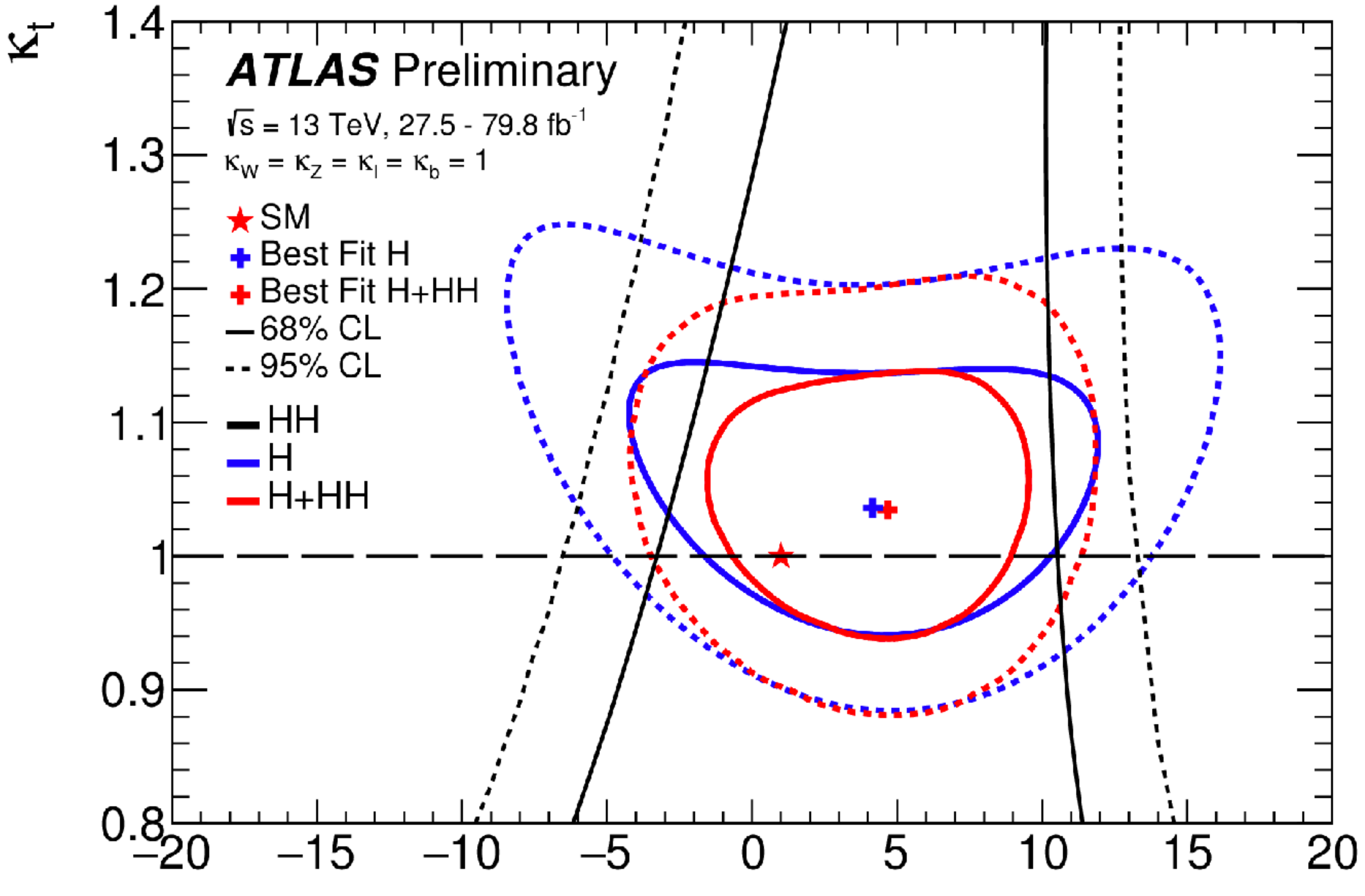
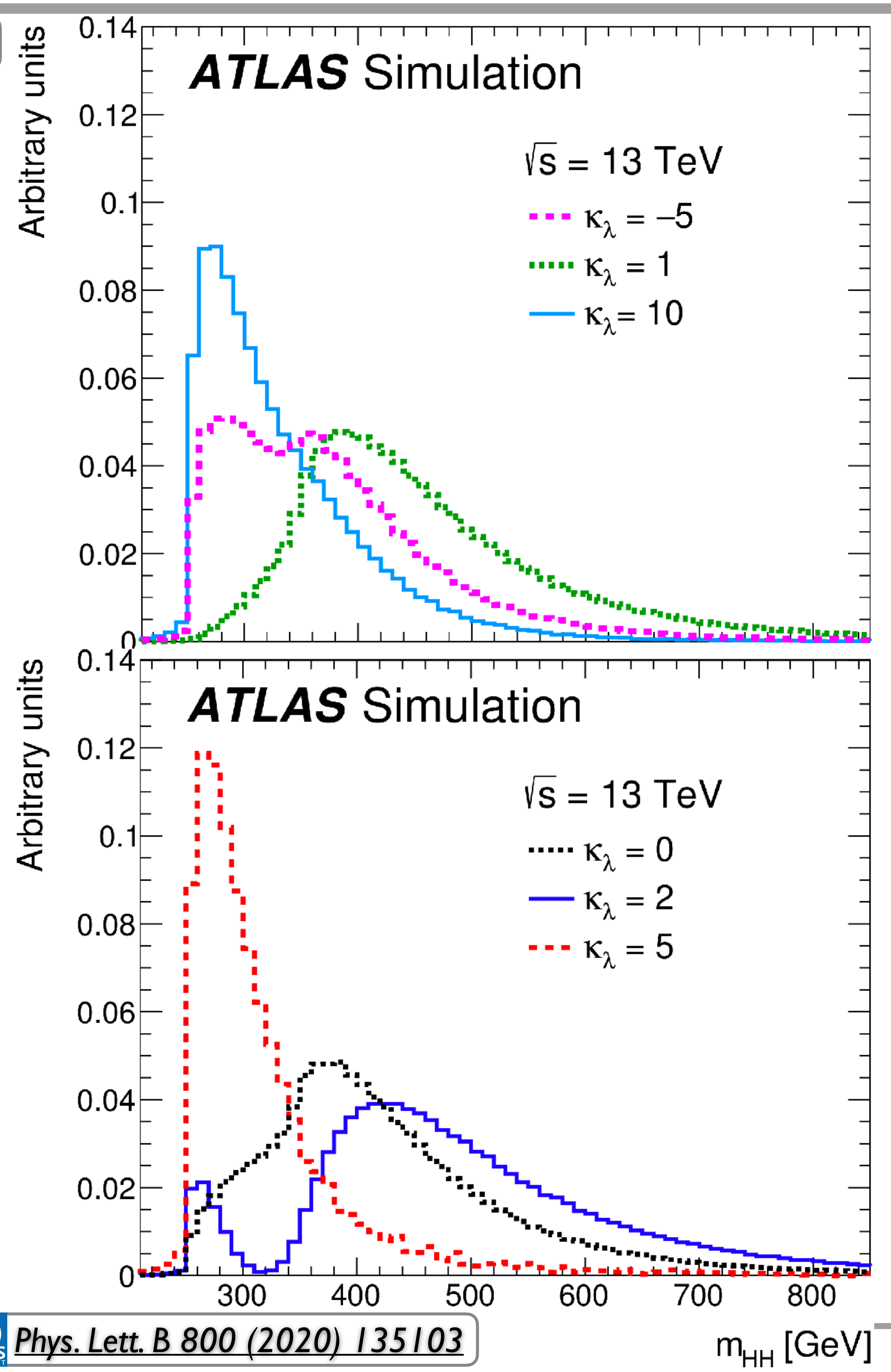


$-3.7 < \kappa_\lambda < 11.5$ ($-6.2 < \kappa_\lambda < 11.6$)



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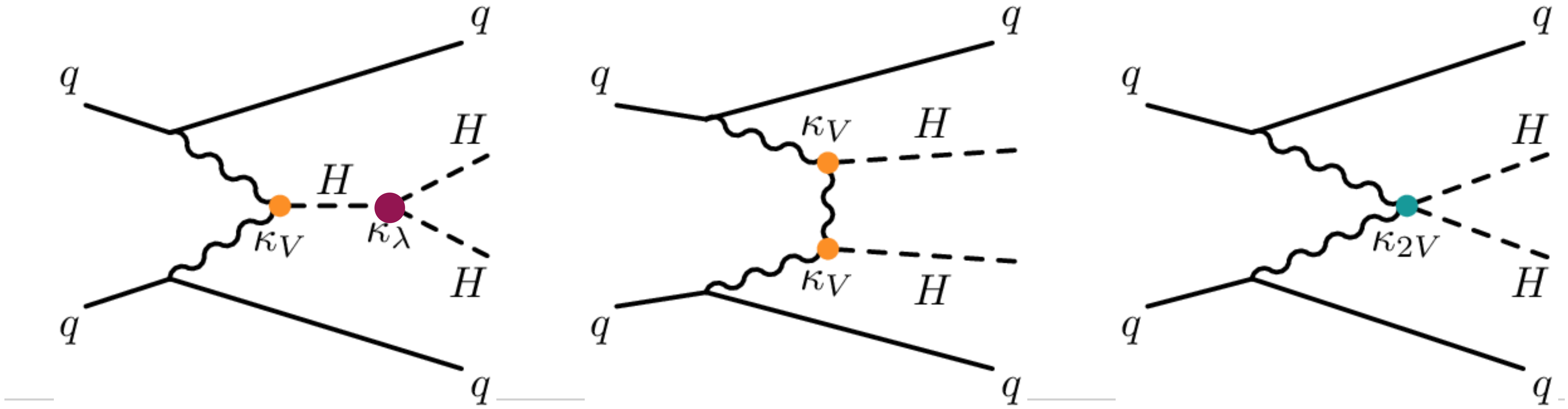
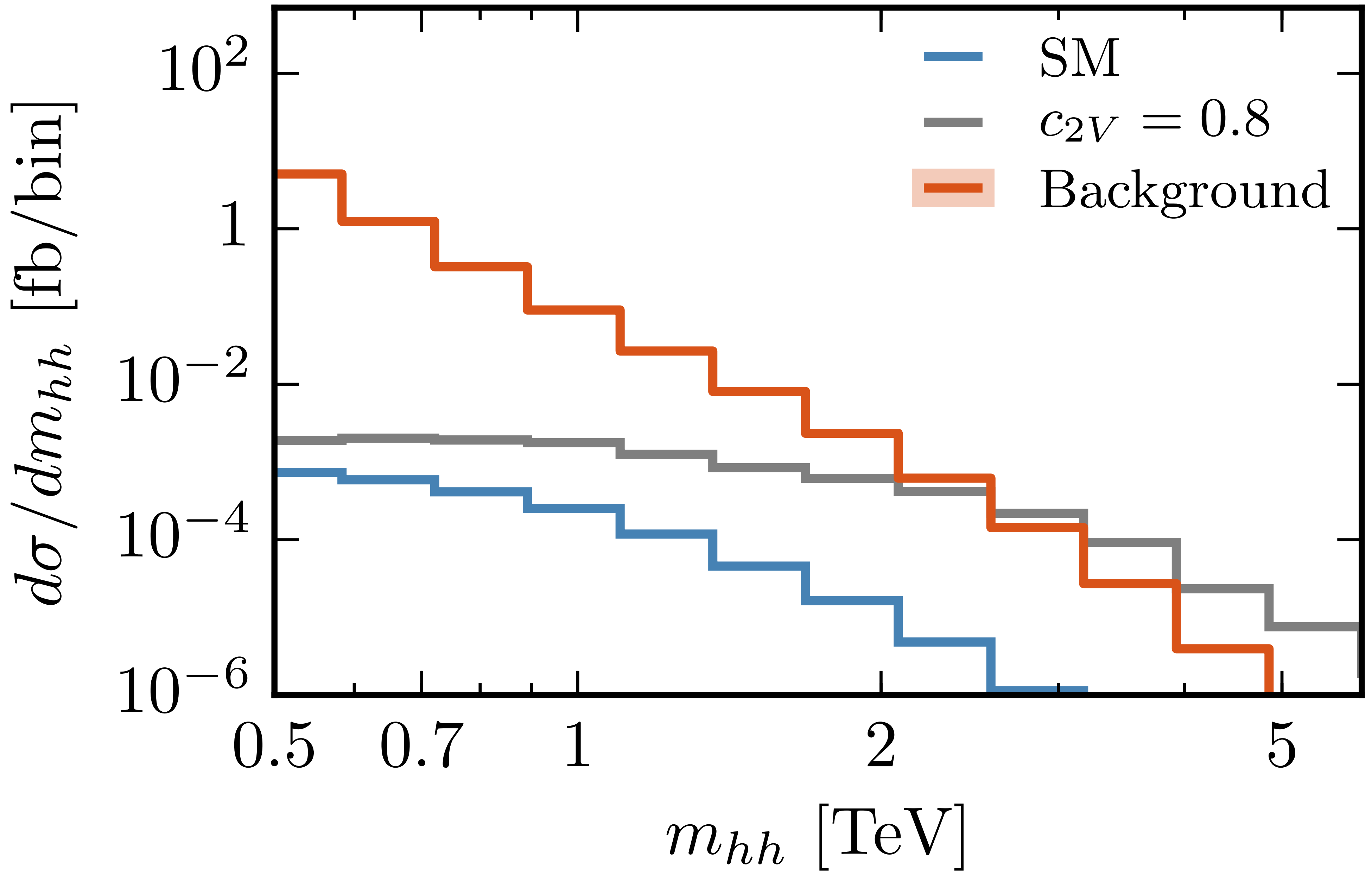
⇒ Back

Extracting κ_{2V}



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

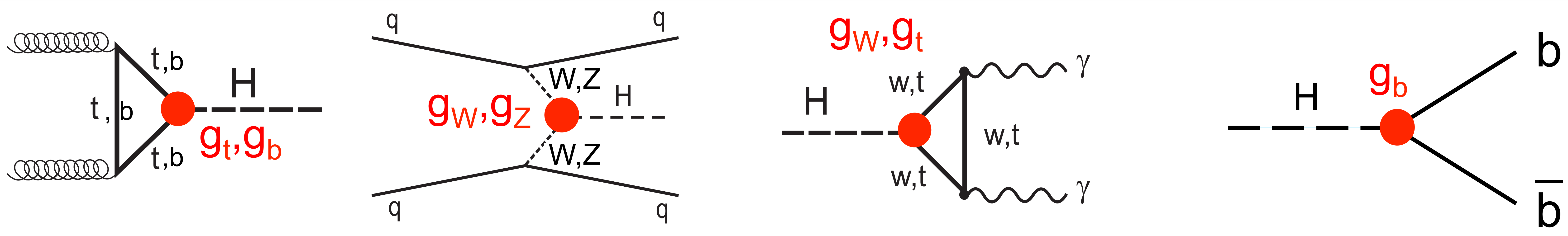
arXiv:1611.03860 LHC 14 TeV



⇒ Back

The κ Framework

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



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

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

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

Assumption:

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

LHC Higgs XS WG (arxiv:1307.1347)

Production and Decay Modes

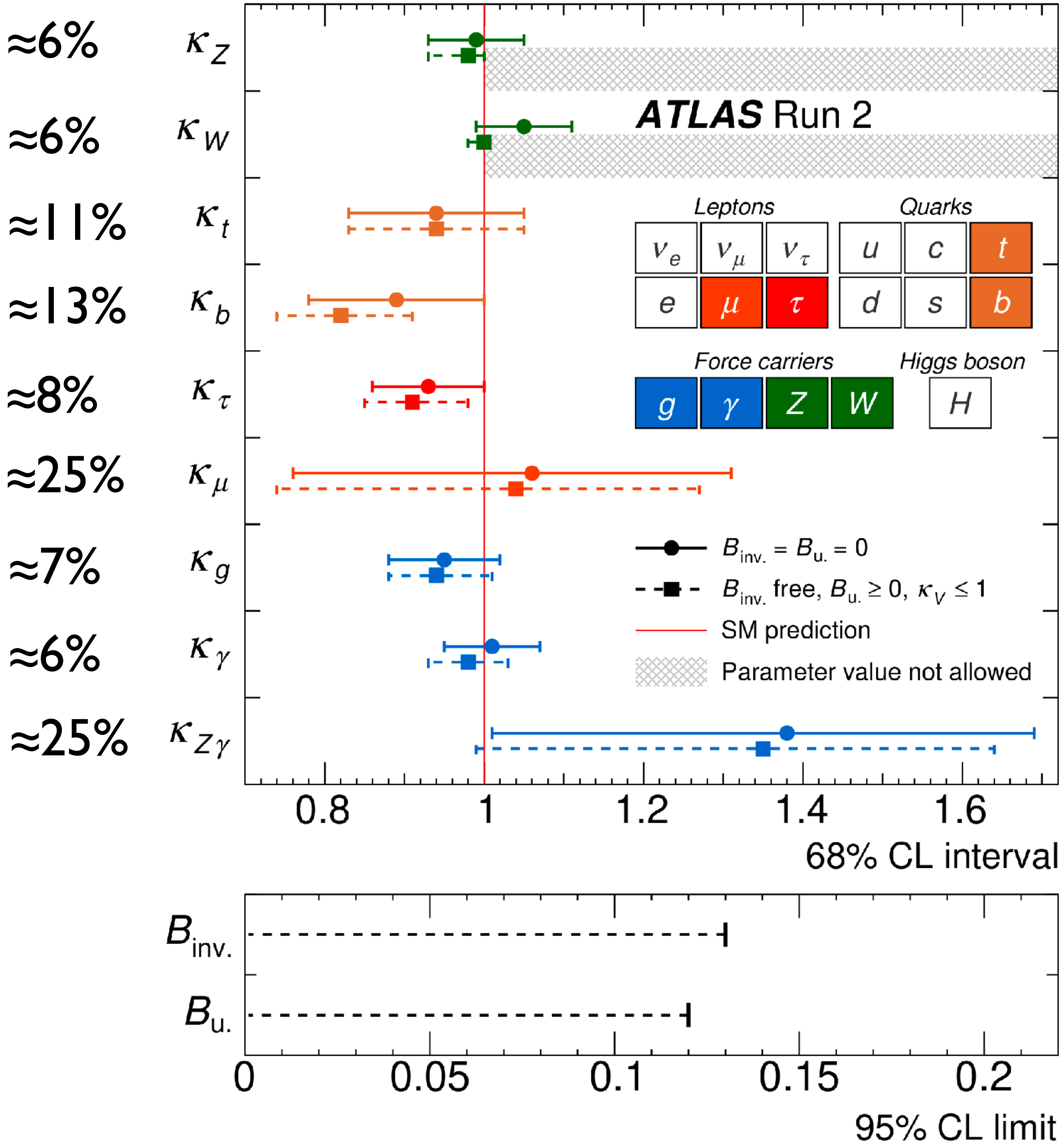
Nature 607, 52–59 (2022)

κ Coupling Modifiers

Nature 607, 52–59 (2022)

Assume:

No BSM contributions ($B_{inv} = B_{undet} = 0$)



Assume:

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

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

Add:

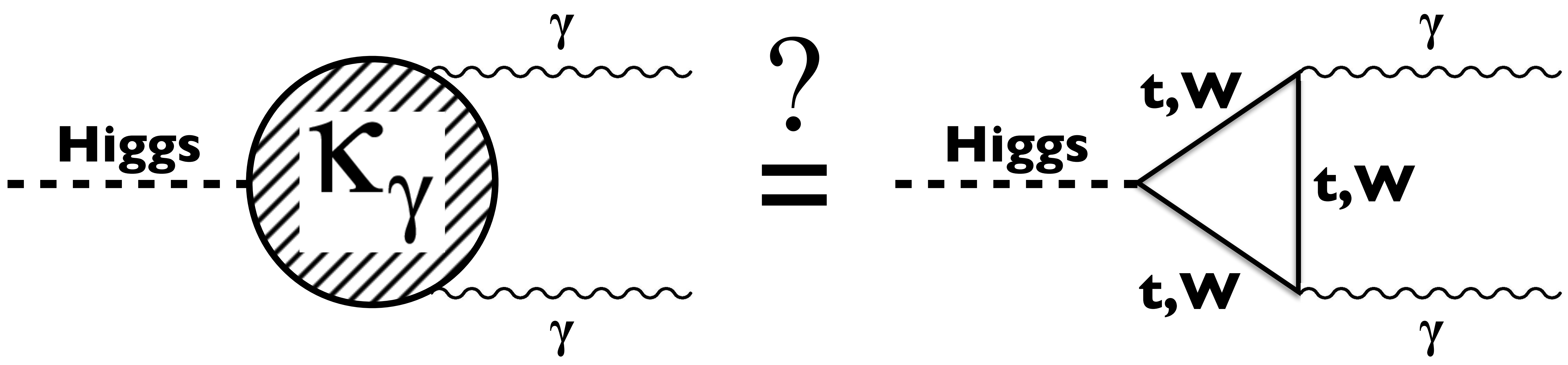
VBF H → invisible

Loop-induced Couplings

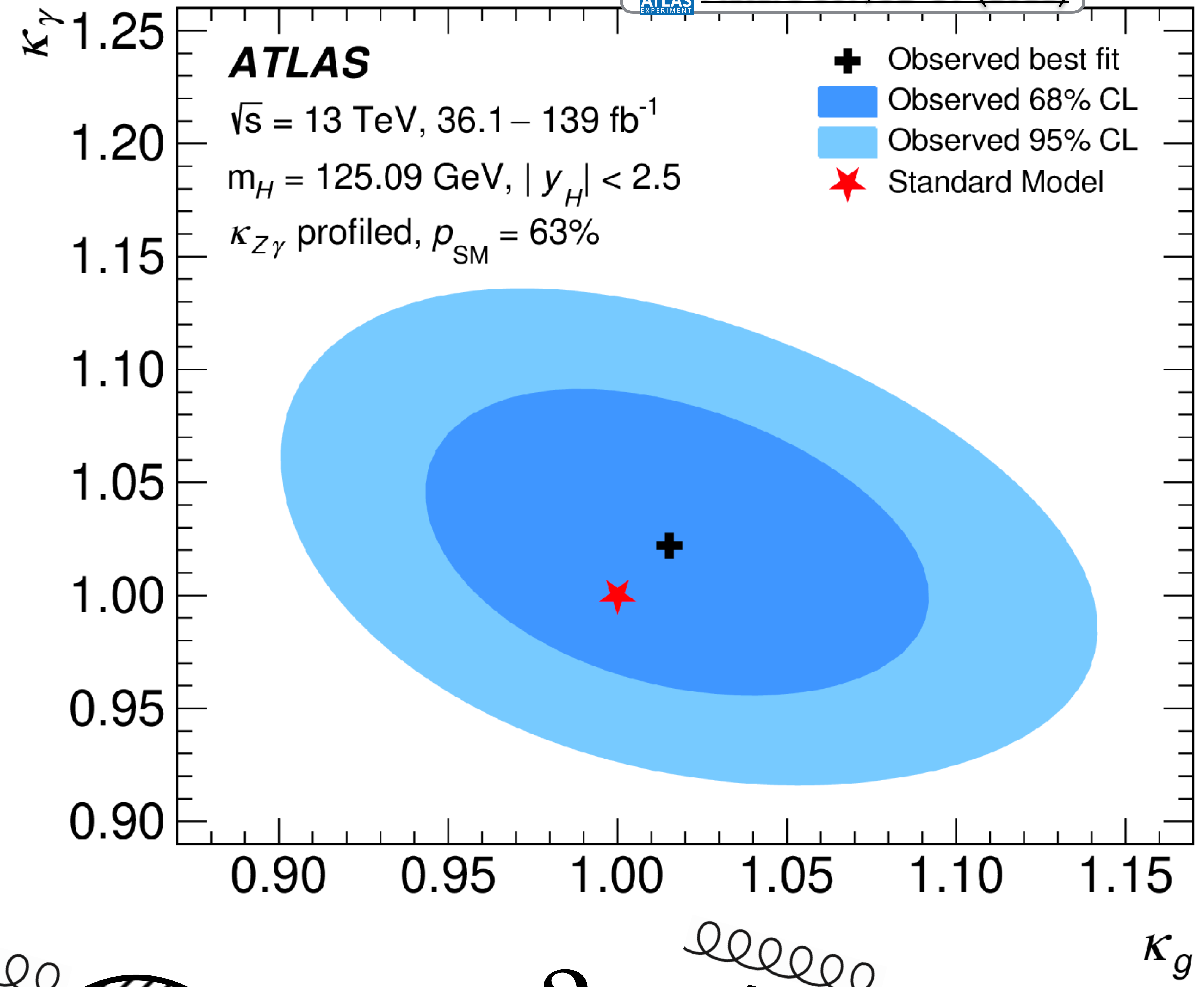
- SM: ggF and H → γγ are loop-induced
  - New particles could participate in the loop

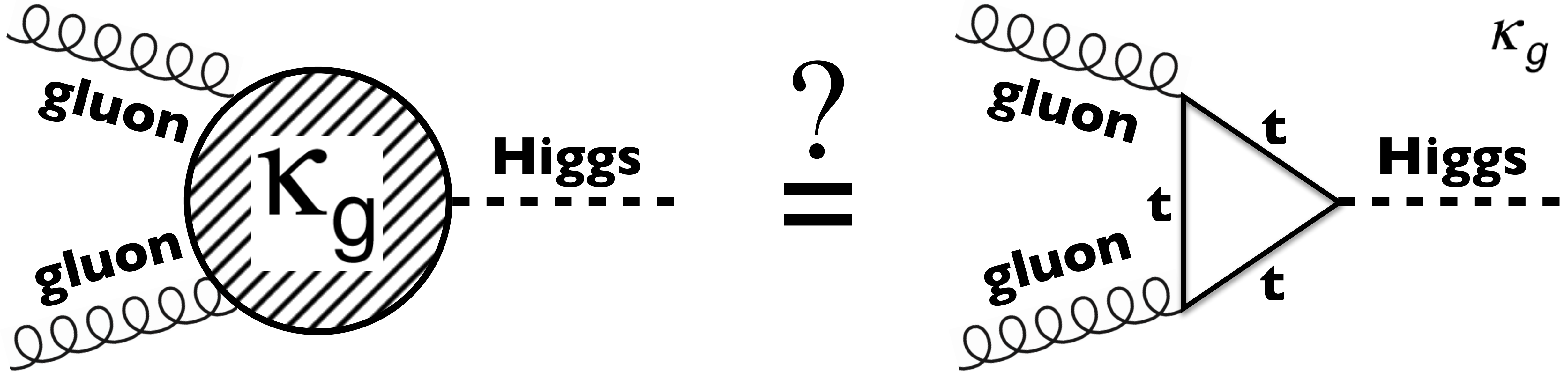
  ⇒ Contributions of BSM?

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



Nature 607, 52–59 (2022)

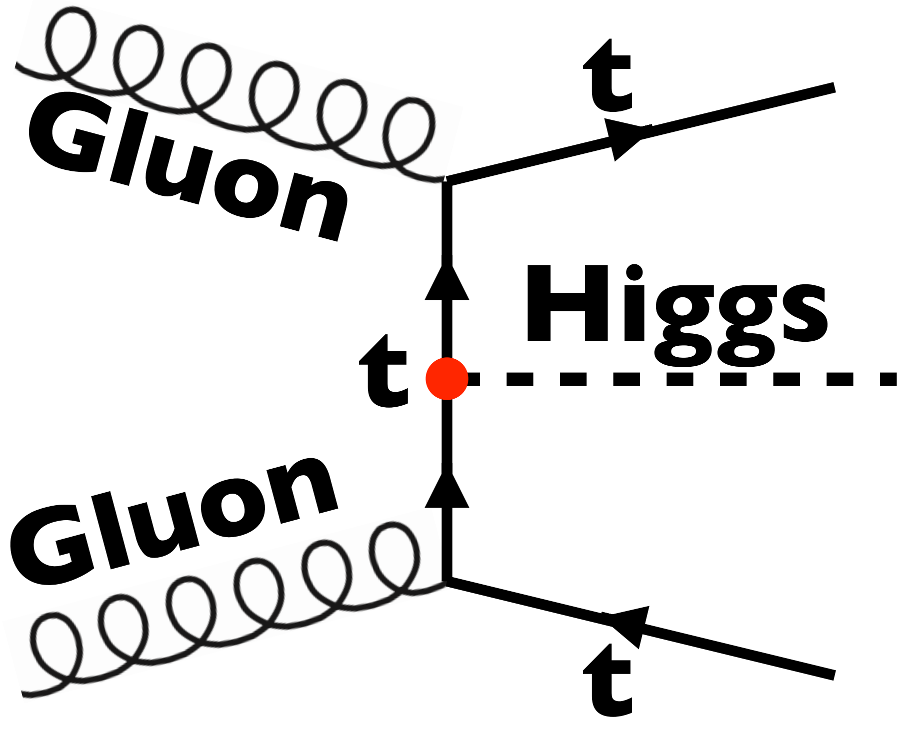


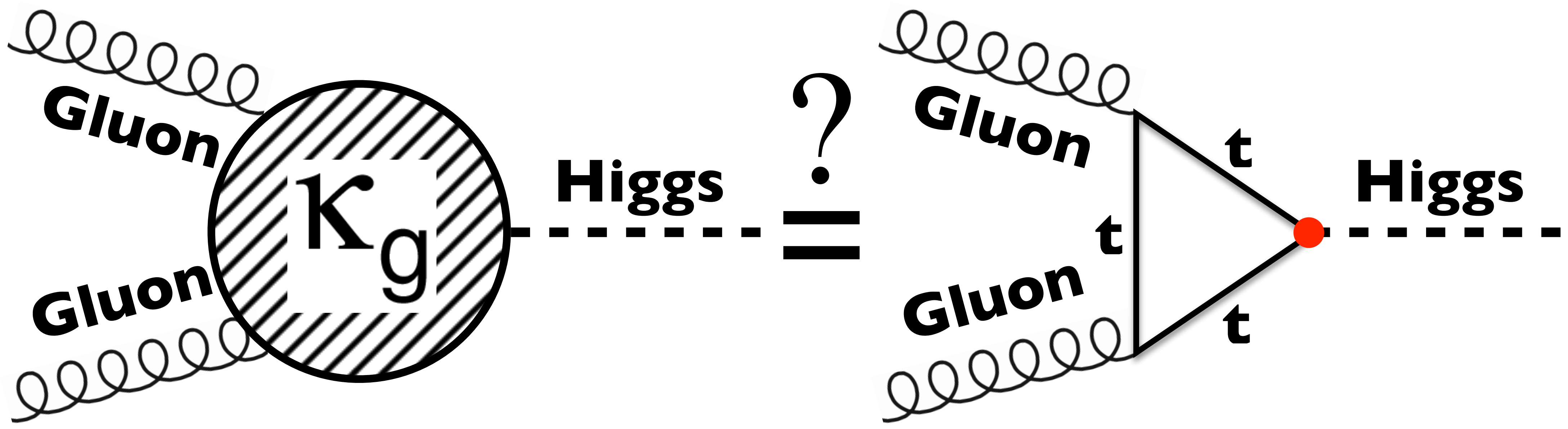


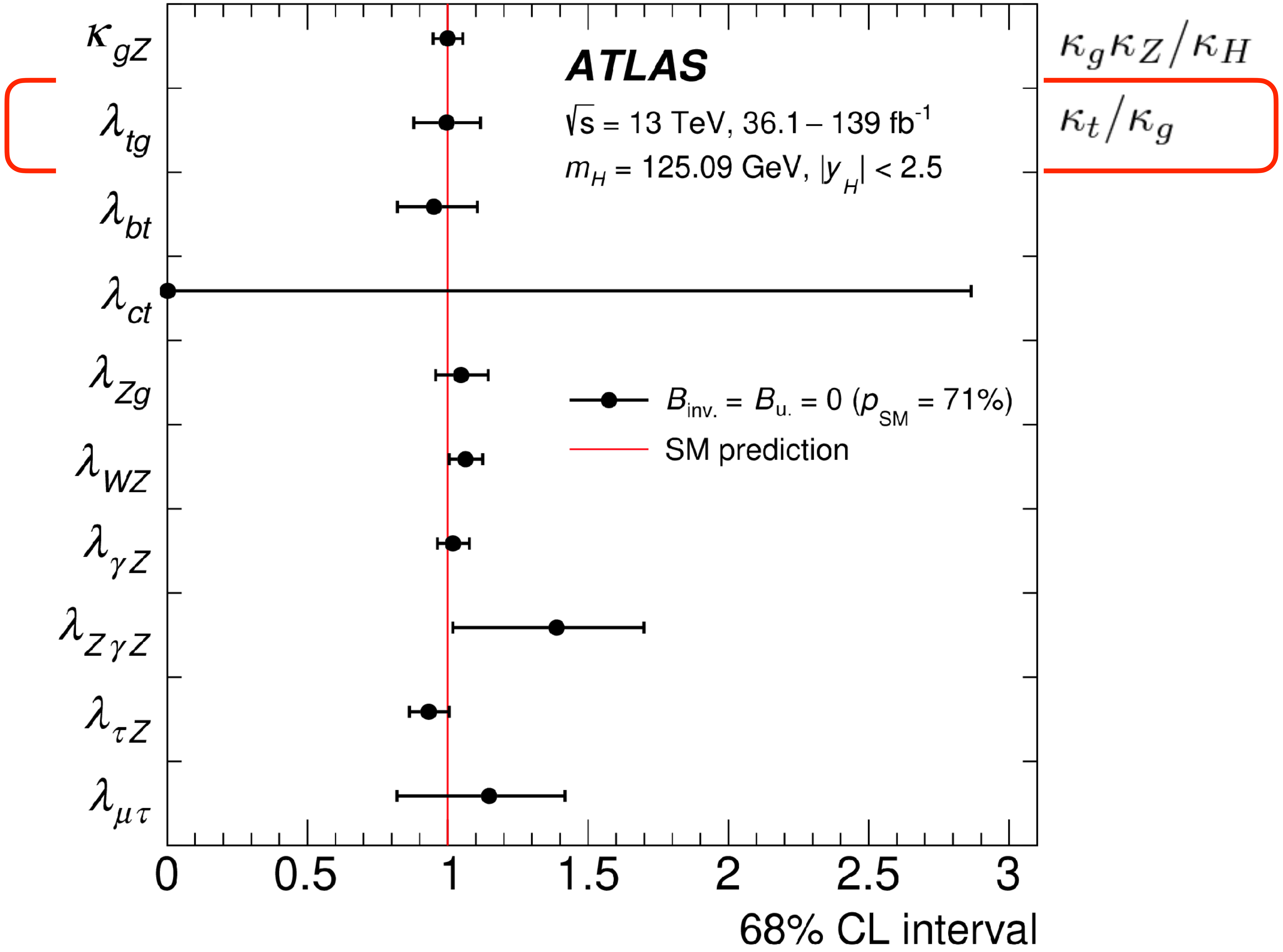
Ratio of Coupling Modifiers

Nature 607, 52–59 (2022)

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







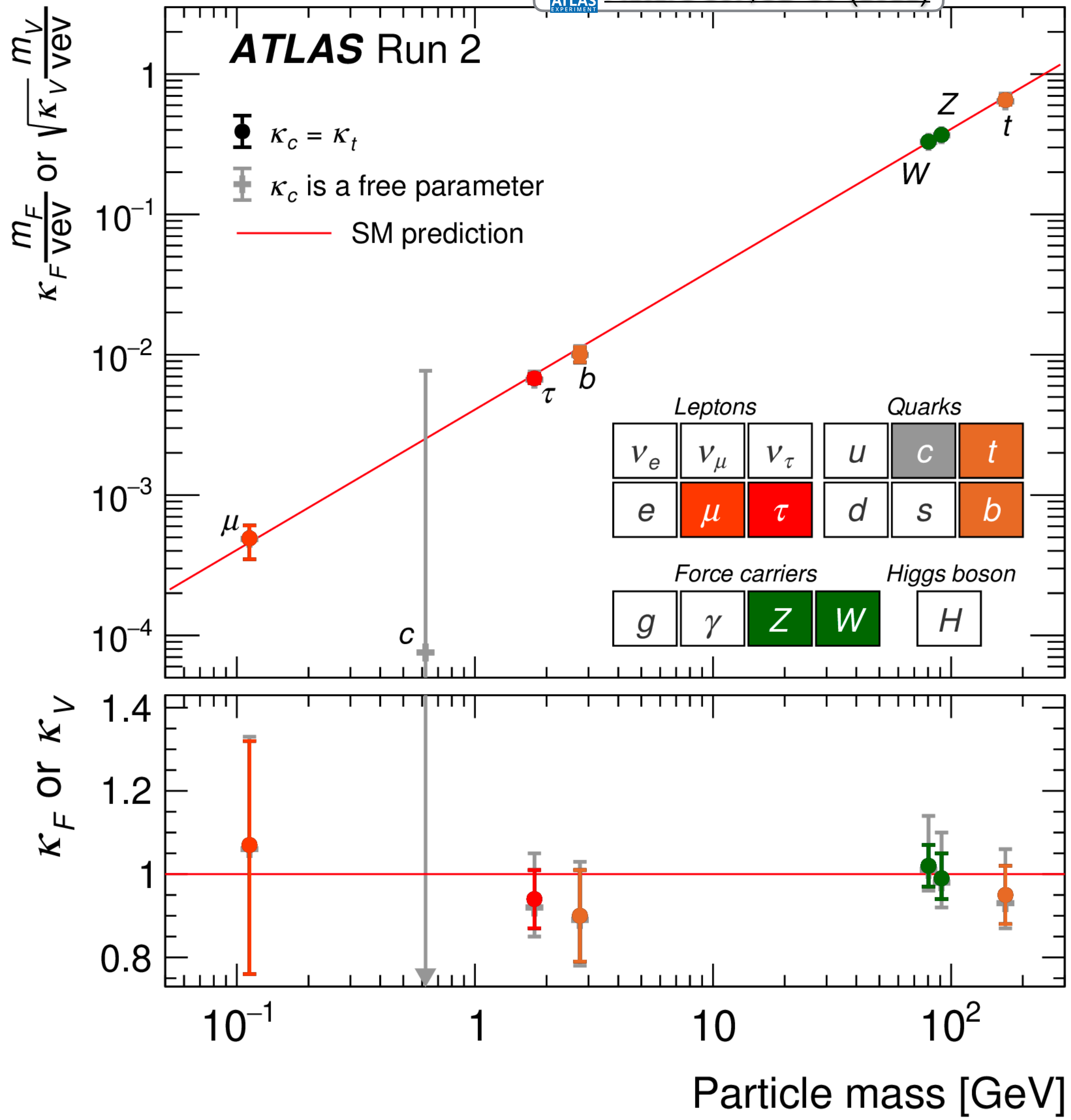
Mass ~ Coupling Strength?

Assumption:

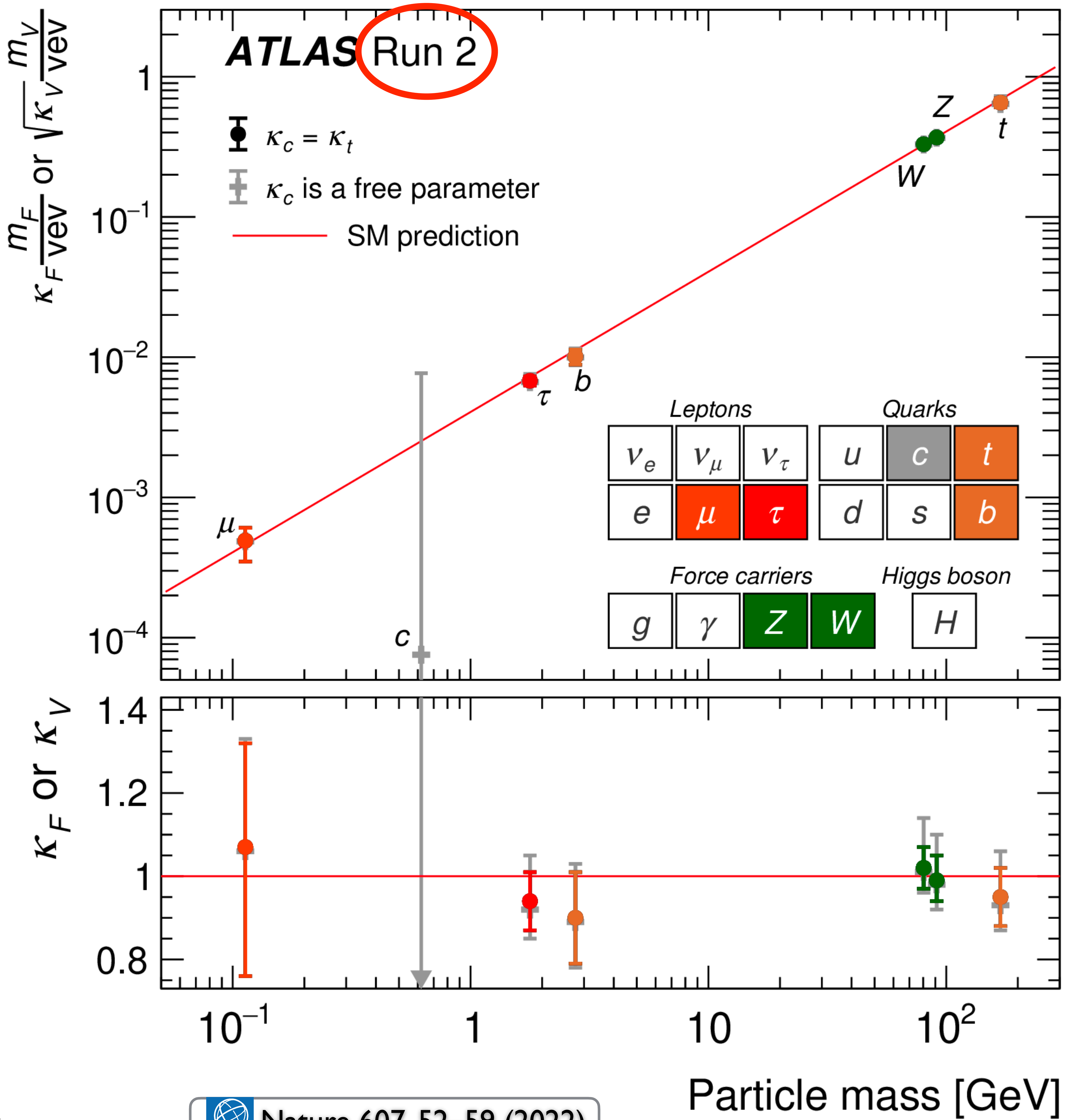
SM Higgs boson coupled only to SM particles, i.e. no "beyond SM physics (BSM)

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

Nature 607, 52–59 (2022)



Extrapolations



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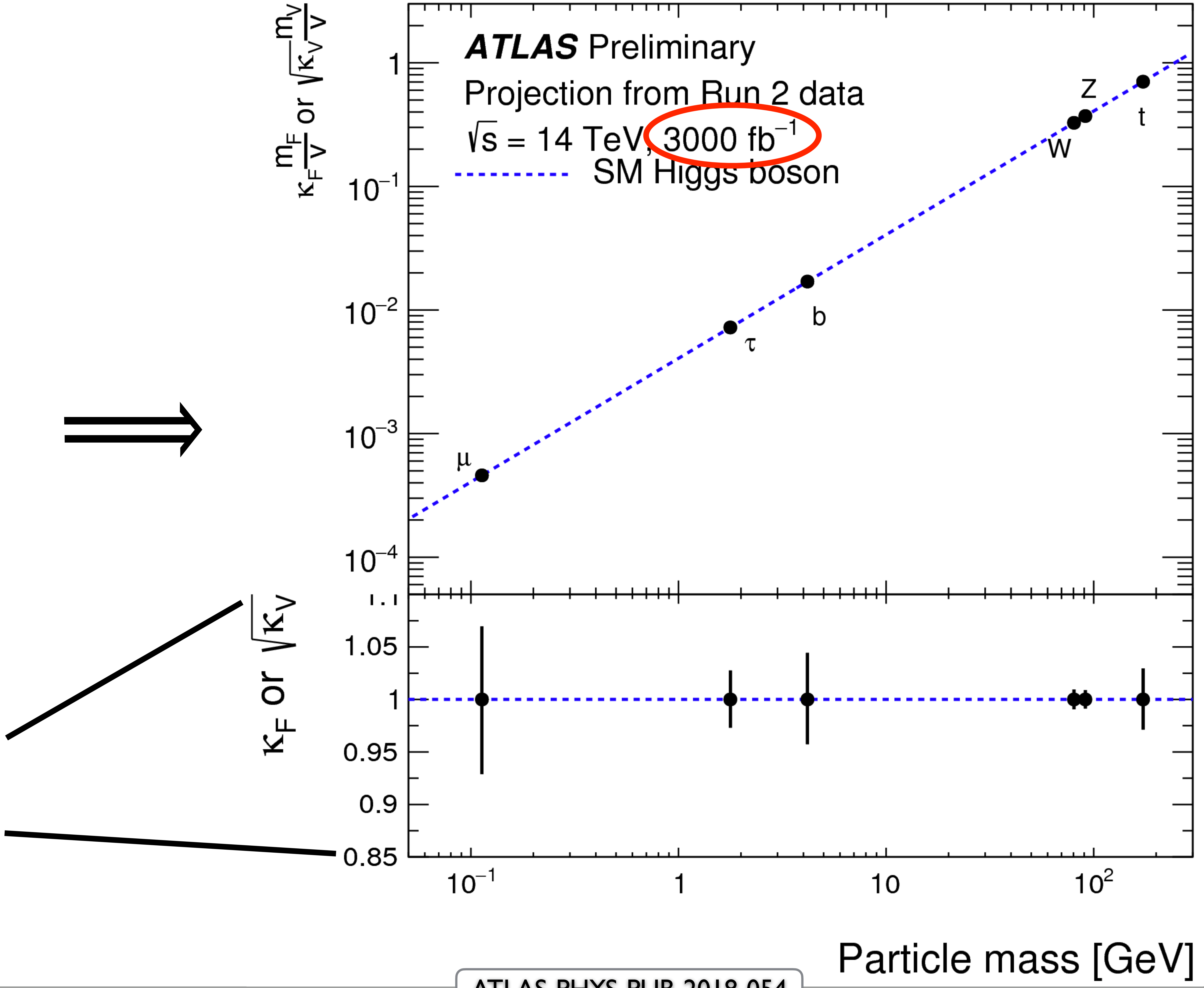
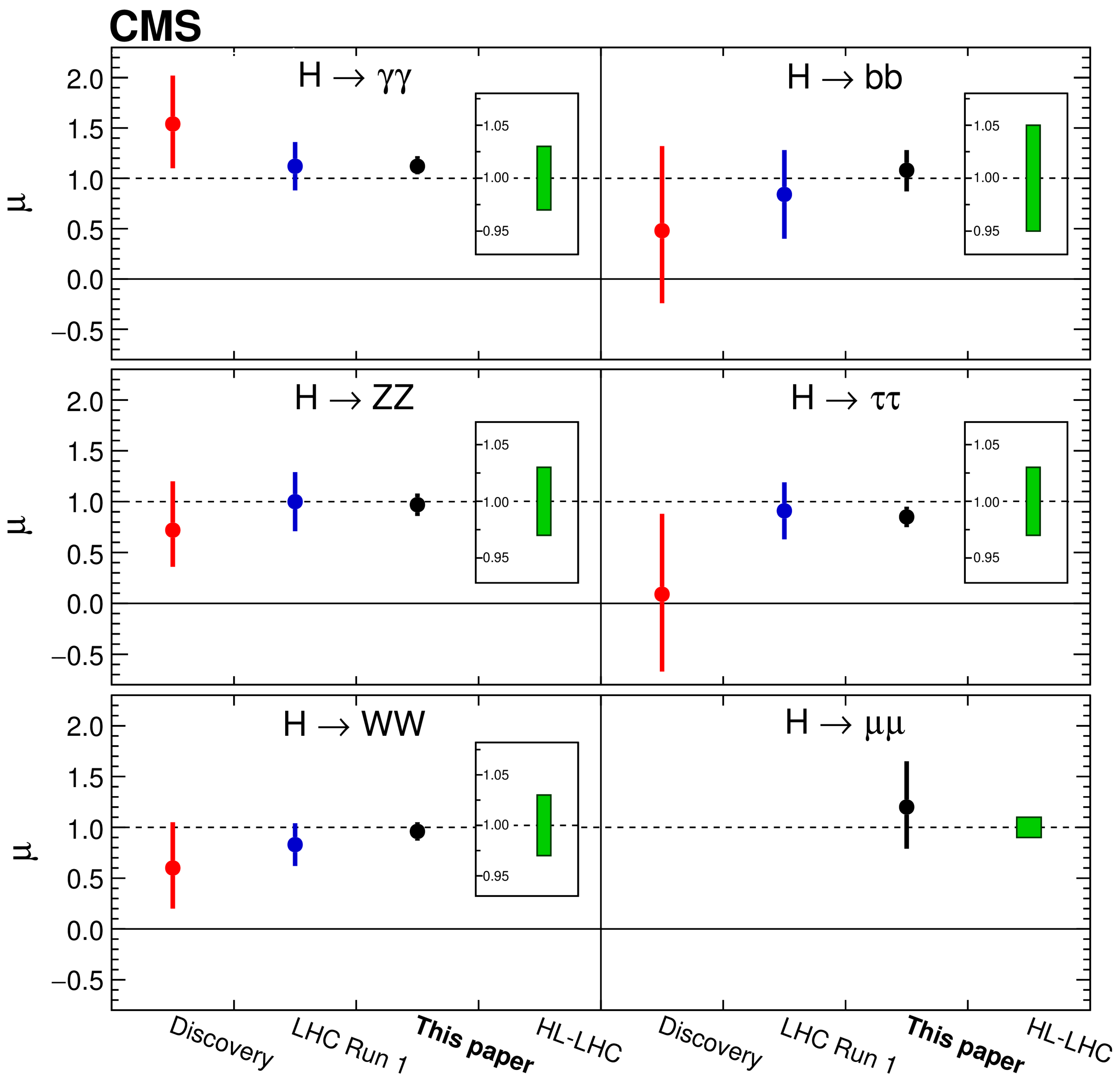


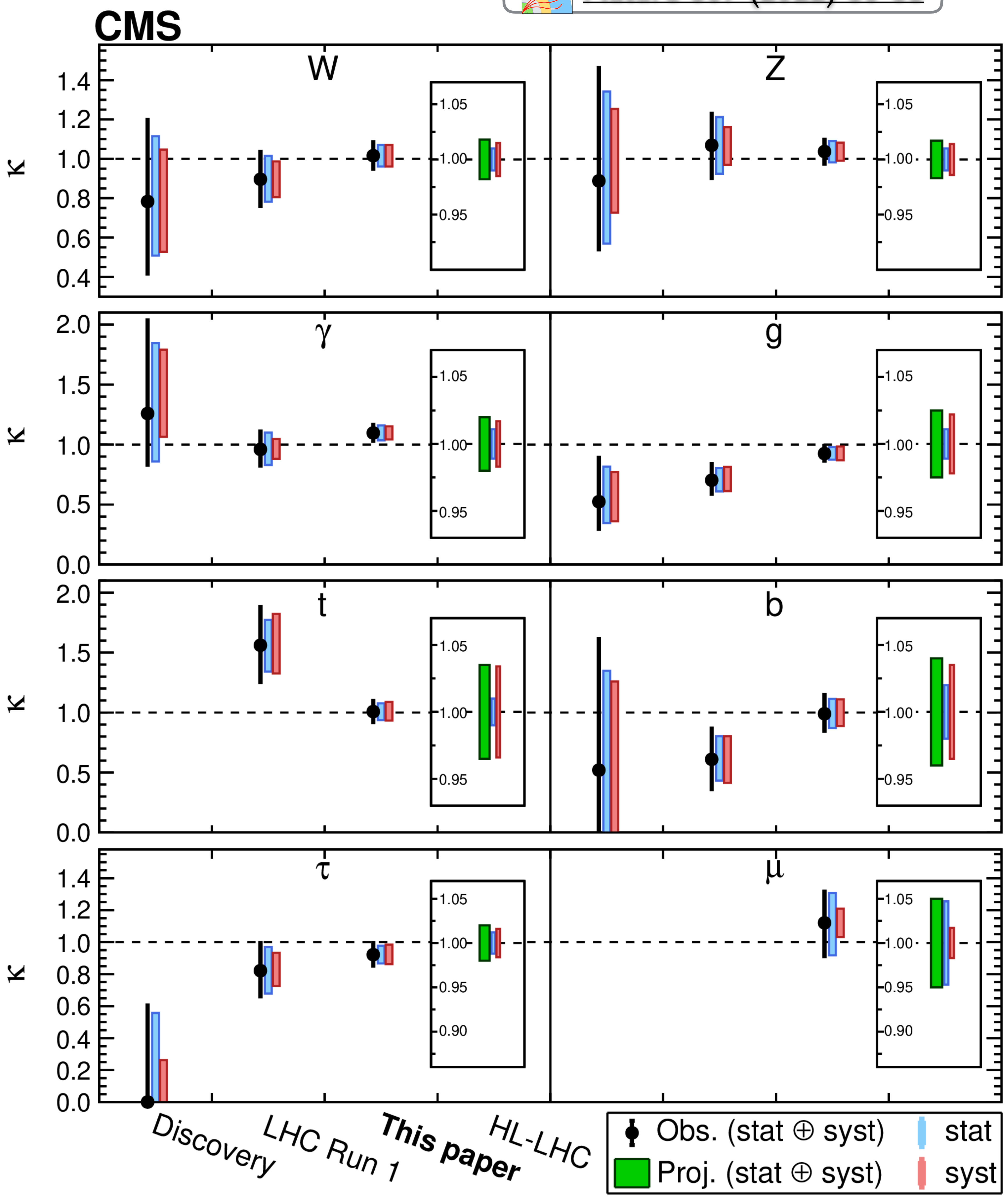
Nature 607, 52–59 (2022)

ATLAS-PHYS-PUB-2018-054

Coupling Combination and HL-LHC

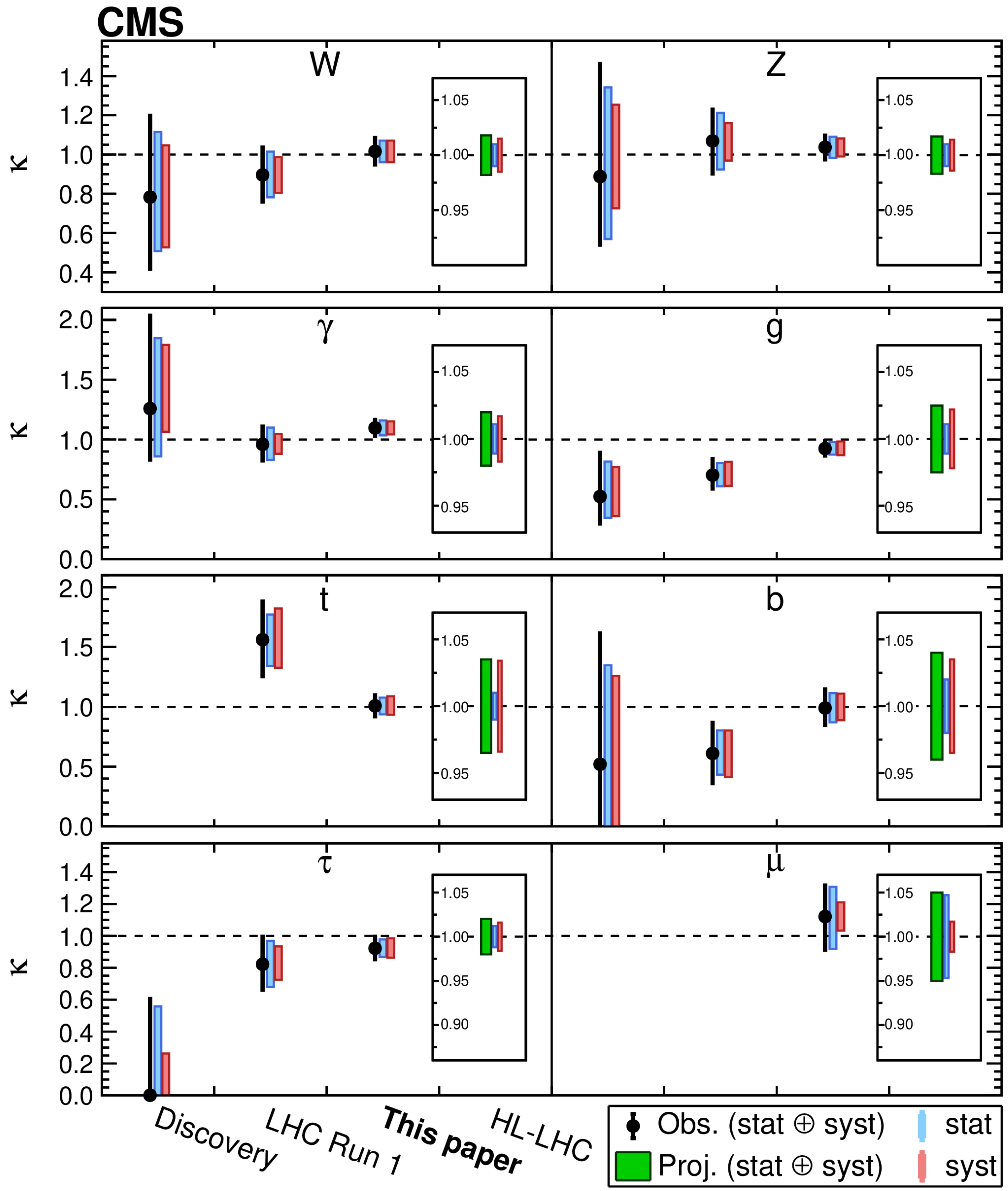
Nature 607 (2022) 60-68

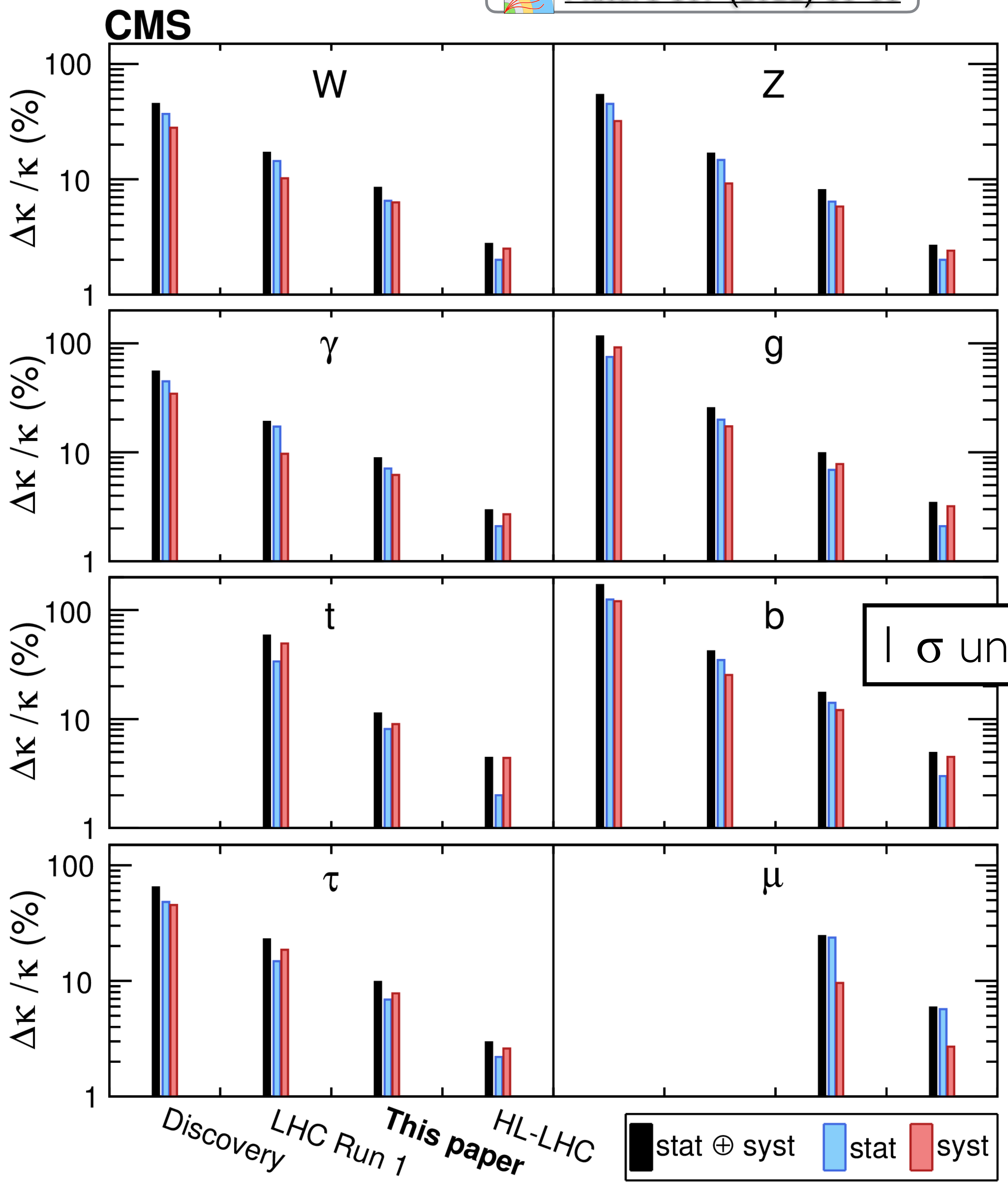




Coupling Combination and HL-LHC

Nature 607 (2022) 60-68



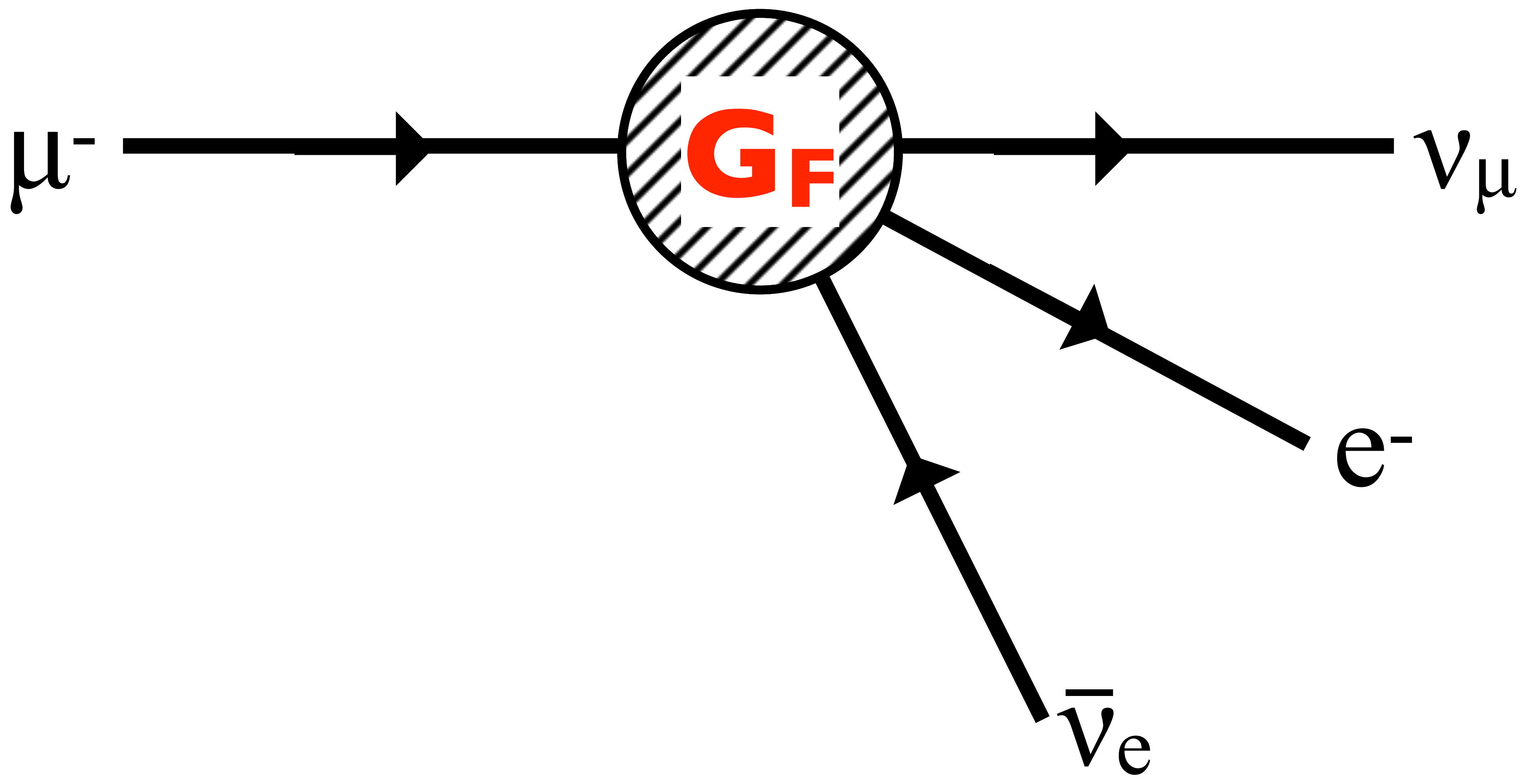


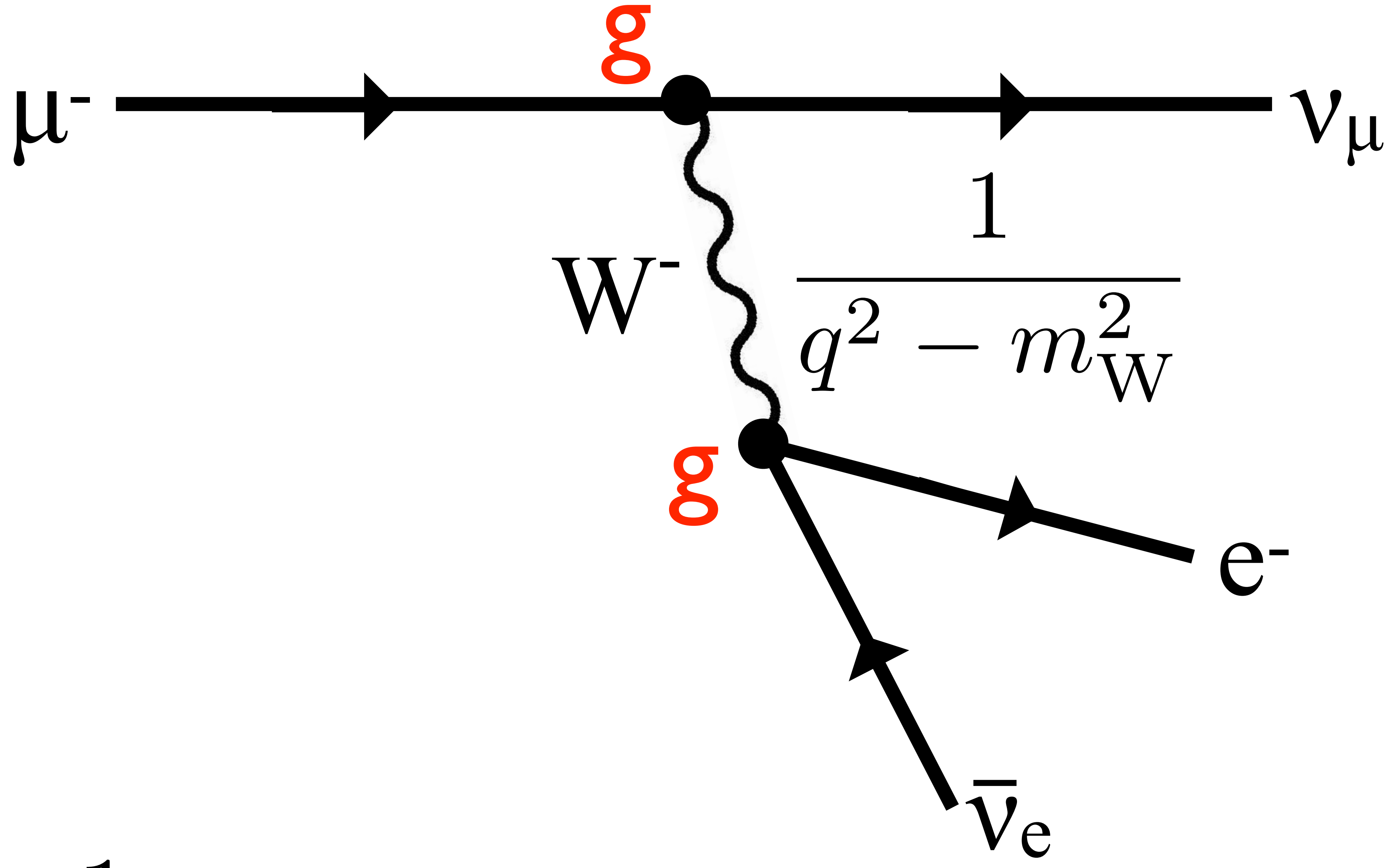
1 σ uncertainties

Effective Field Theories: Muon Decay

Fermi-Theory (1933)
Effective Field Theory

Theory of Weak Interaction
“Full" Field Theory

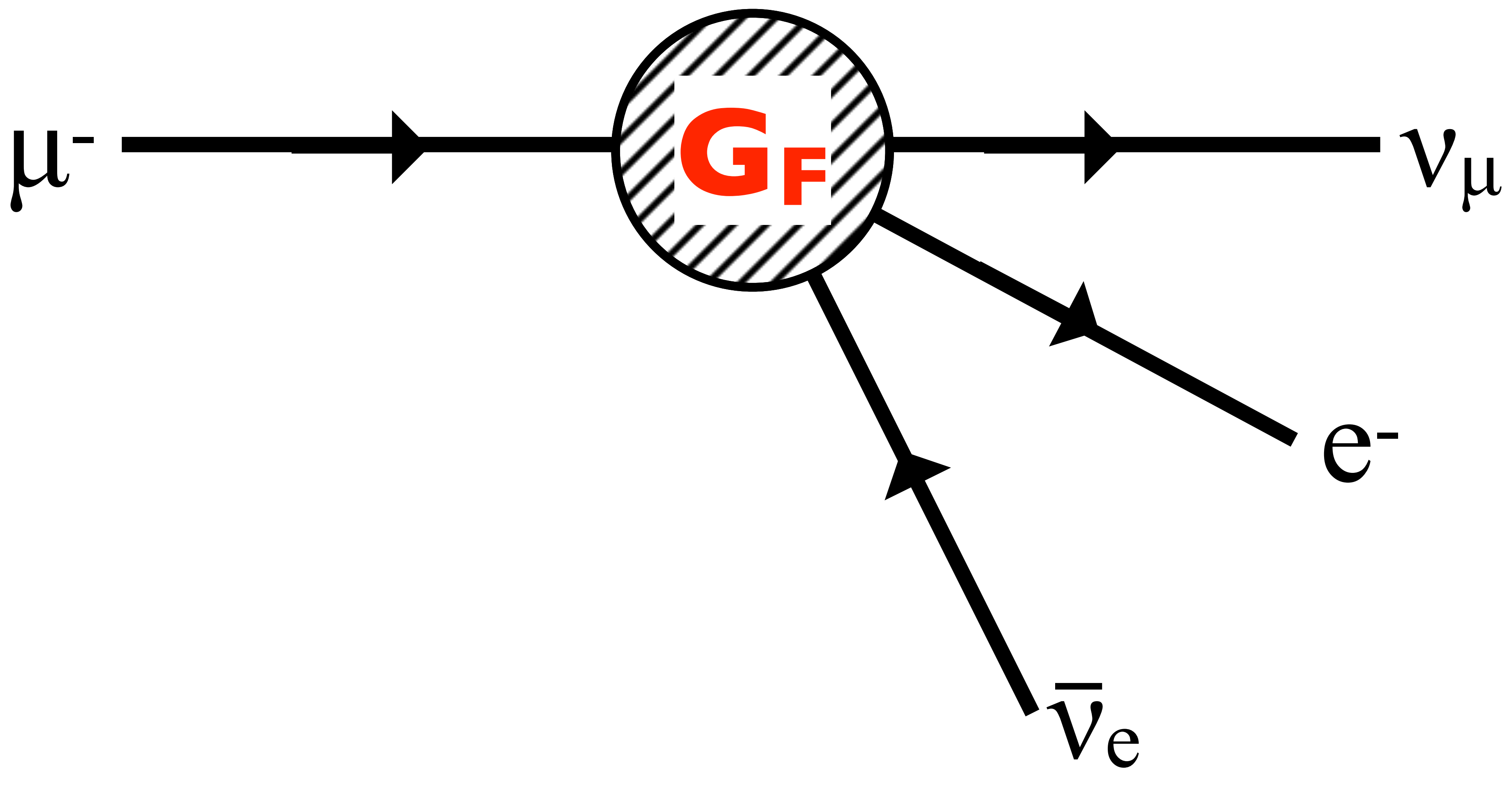




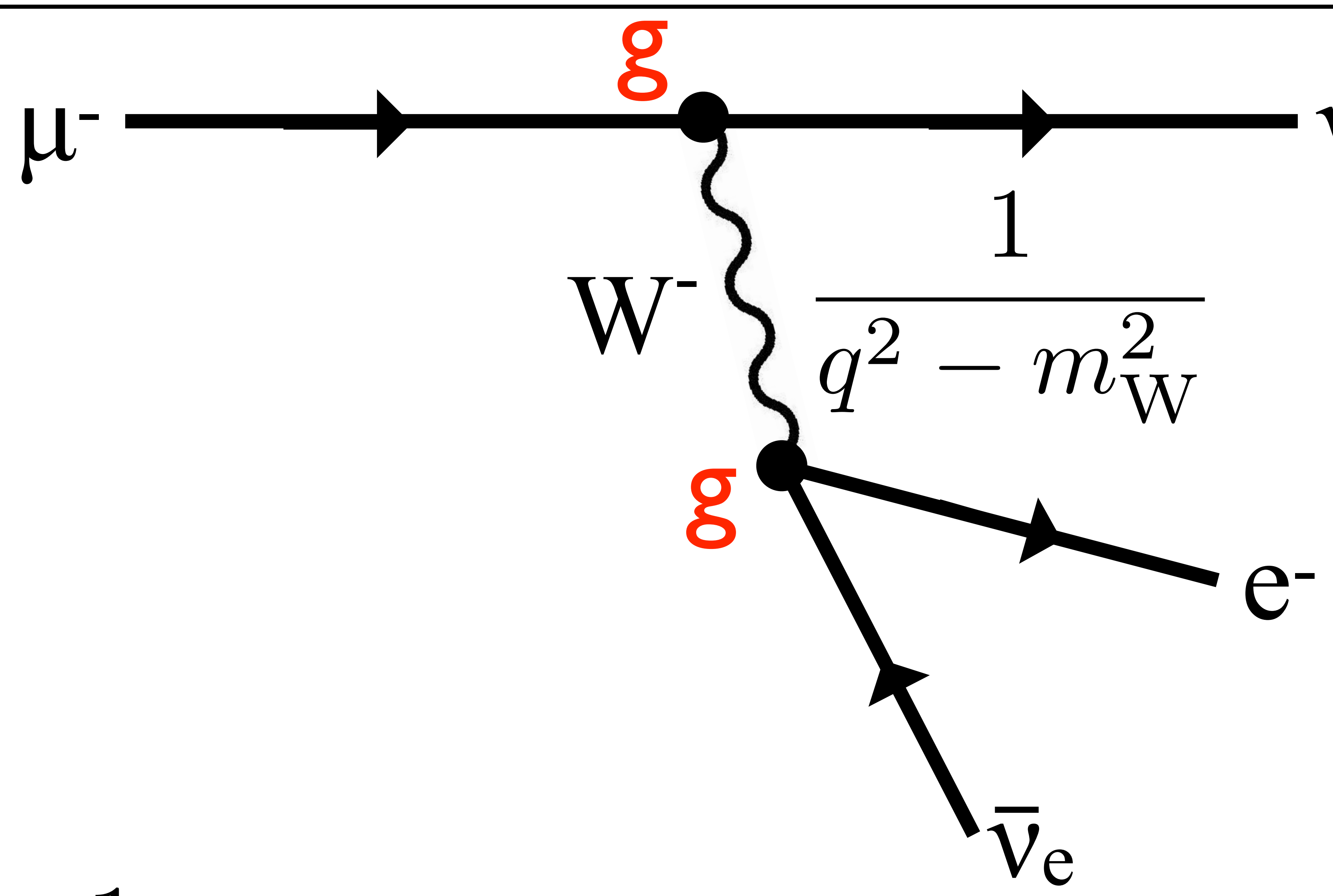
For $q^2 << m_W^2$ is $\frac{1}{q^2 - m_W^2} \to \frac{1}{-m_W^2}$ and $\frac{g^2}{8m_W^2} \to \frac{G_F}{\sqrt{2}}$

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 $\frac{g^2}{8m_W^2} \rightarrow \frac{G_F}{\sqrt{2}}$

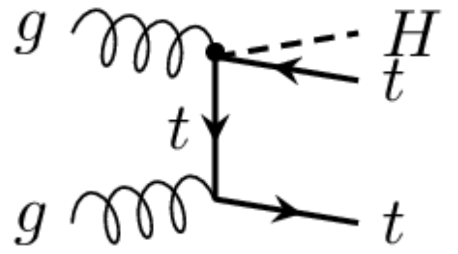
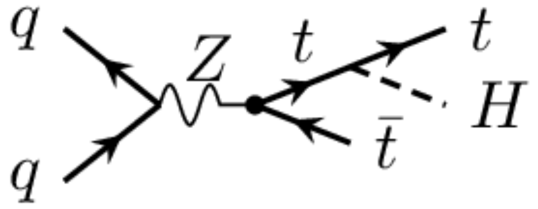
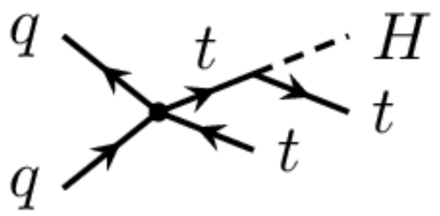
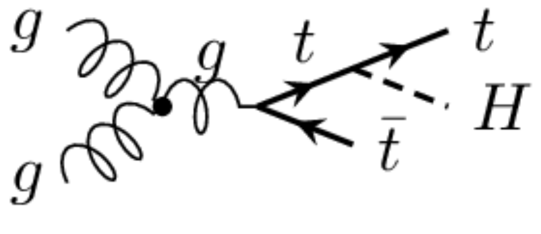
- Extend SM with new BSM operators: $\mathcal{L} = \mathcal{L}_{SM} + \sum_i c_i^{(6)} \mathcal{O}_i^{(6)} / \Lambda^2$
  - Assume: No new particles below Λ = 1 TeV

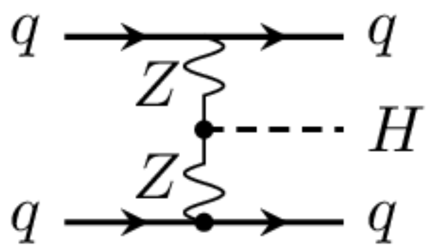
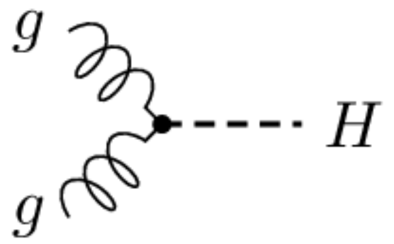
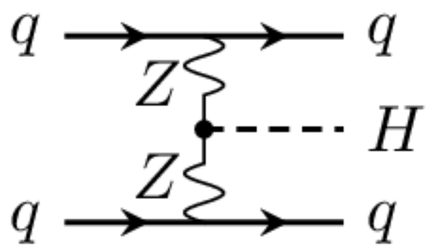
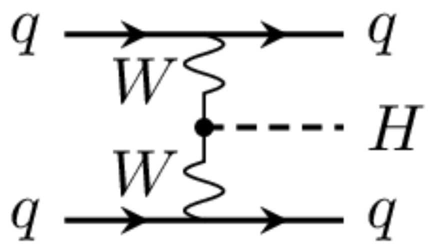
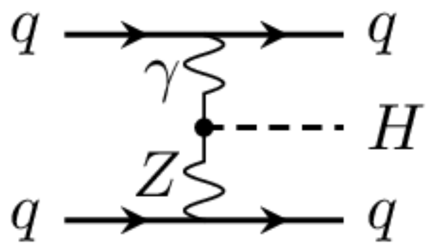
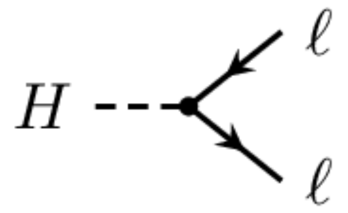
SMEFT

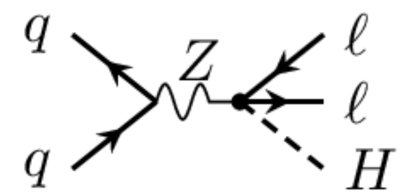
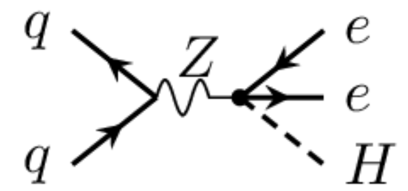
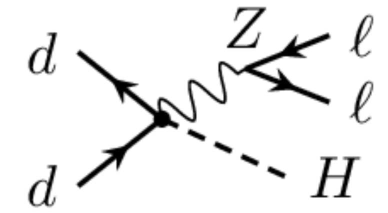
arXiv:2004.03447

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}	$\mathcal{O}_{uH}$	$HH^\dagger \bar{q}_p u_r \tilde{H}$	$c_{\widetilde{u}H}$	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

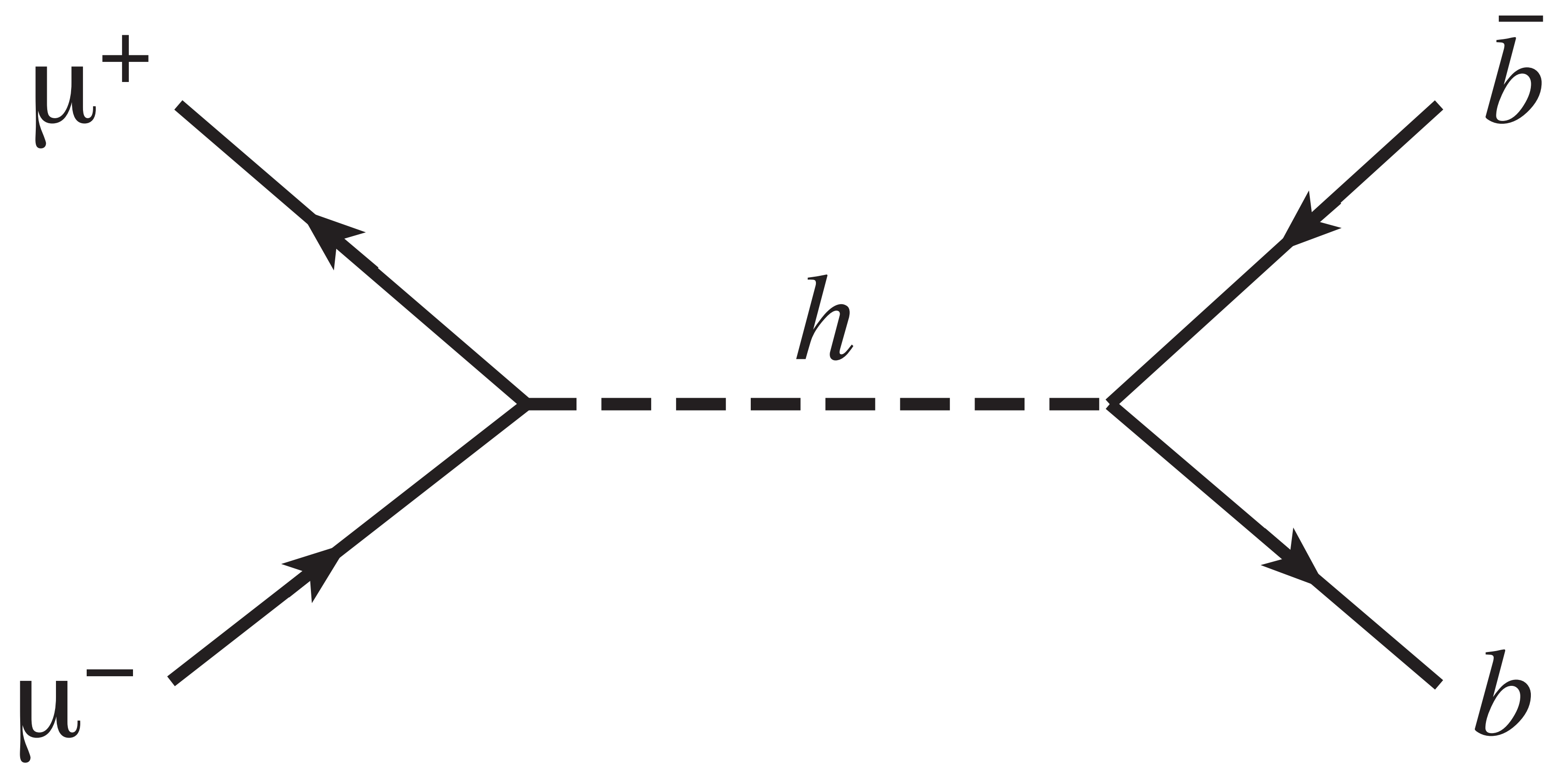
Coefficient	Operator	Example process
c_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G^A_{\mu\nu}$	
c_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W^I_{\mu\nu}$	
c_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$	
$c_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_t)(\bar{q}_r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

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

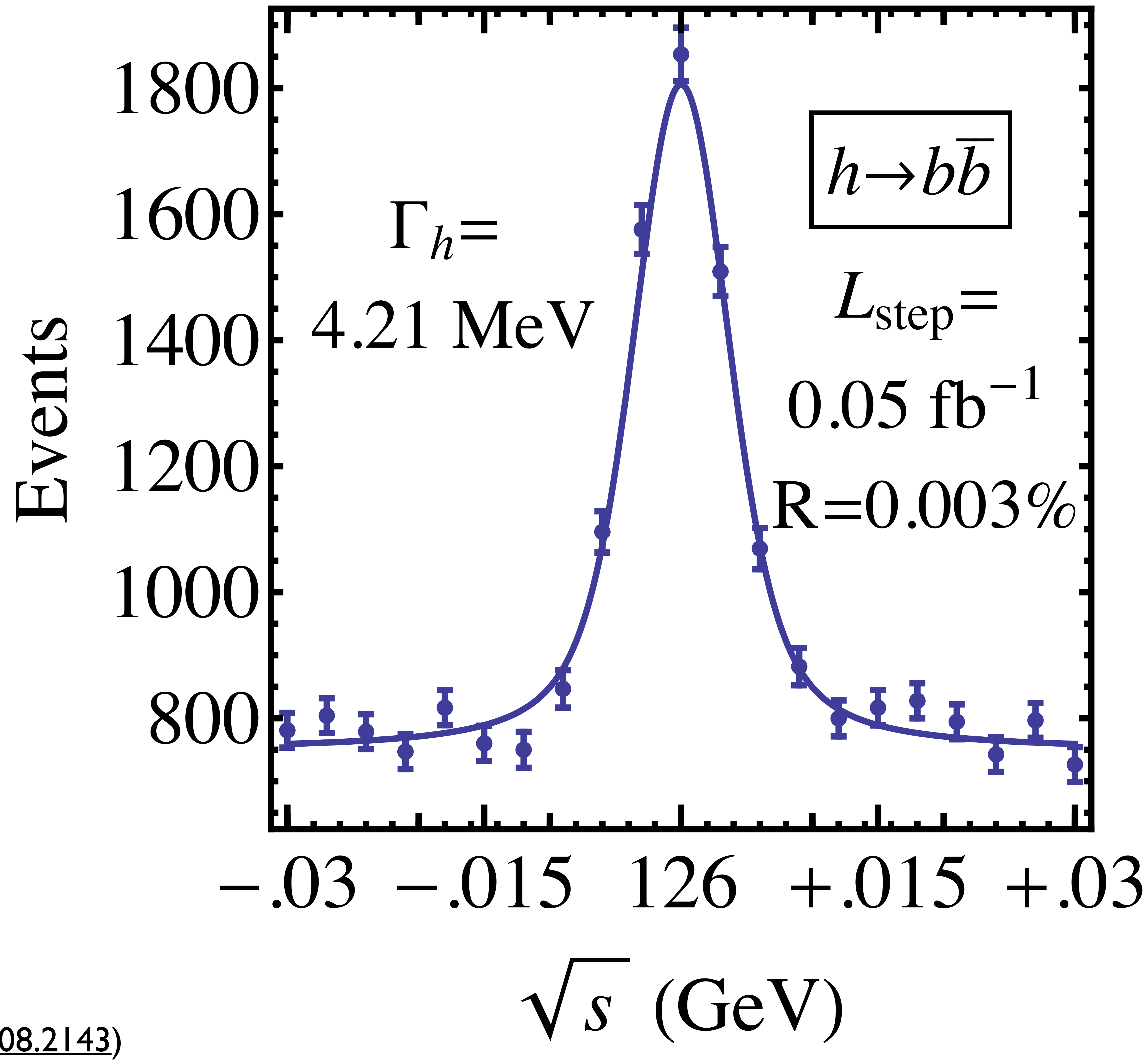
Coefficient	Operator	Example process
$c_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$	
$c_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	
c_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$	
$c_{Hq}^{(1)}$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

Only direct Width Measurement

- s-channel production at future muon collider:



- Precision ~5%



(arxiv:1308.2143)