UNFOLDED DIFFERENTIAL HIGGS BOSON MEASUREMENTS AT LHC

Toni Šćulac

on behalf of ATLAS and CMS Collaborations

Higgs2023 Beijing, China 27 November 2023

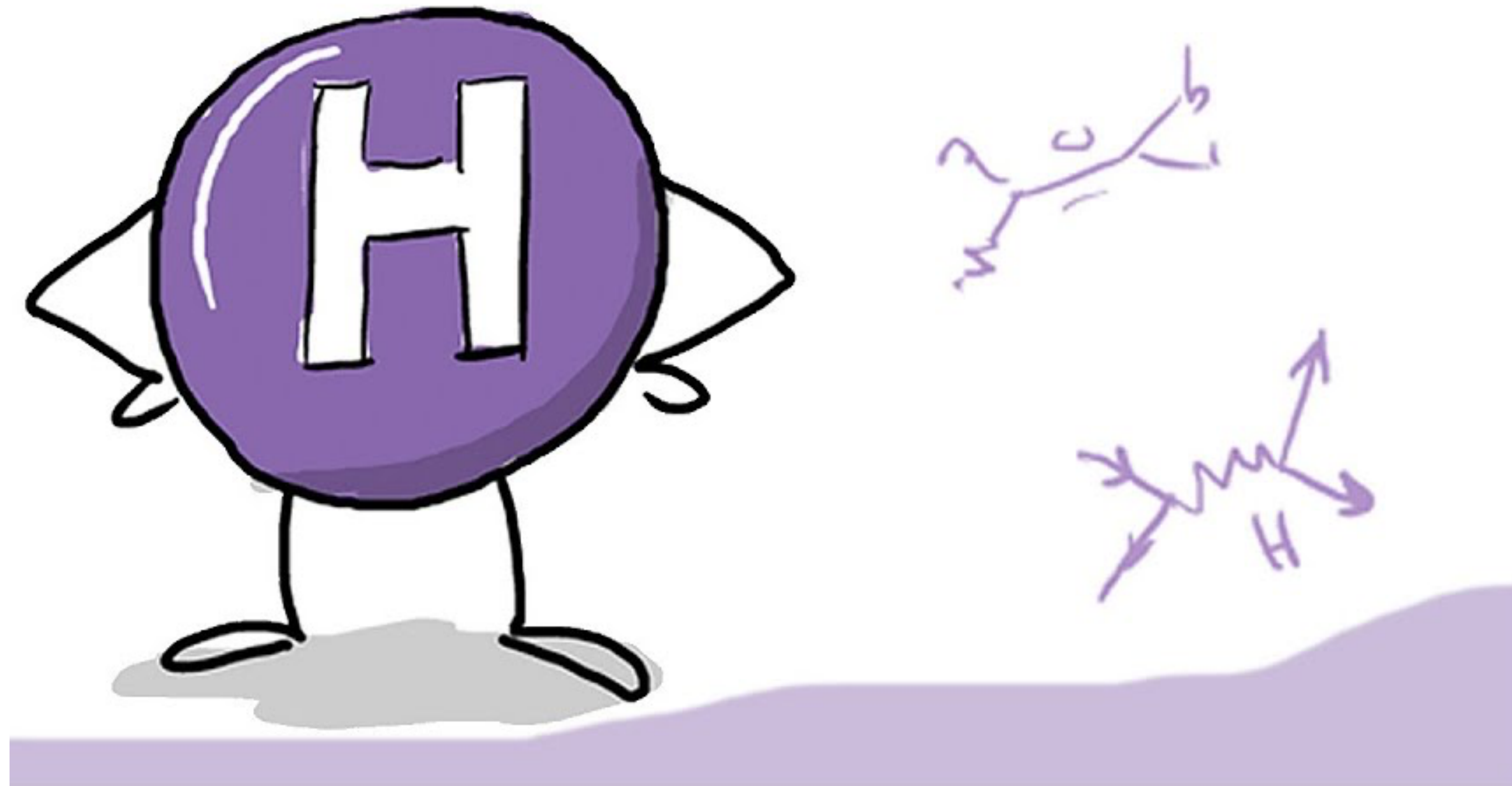
INTRODUCTION

- LHC Run 1 was the era of the **Higgs** boson **discovery**
- LHC Run 2,3 are the era of **Higgs** boson **properties** measurements

- **Differential cross sections** measured in fiducial phase spaces:
  - Largely model independent
  - Results can be compared between experiments and with many theories and models

- Exploring Higgs production differentially key to:
  - test SM predictions for full spectra of observables of interest
  - probe for **BSM hints**

- Five decay channels considered with **latest** public **results** from **ATLAS** and **CMS**:
  - all results based on full Run2 data ~137 fb^{-1}
  - first inclusive fiducial cross section measurement at 13.6 TeV

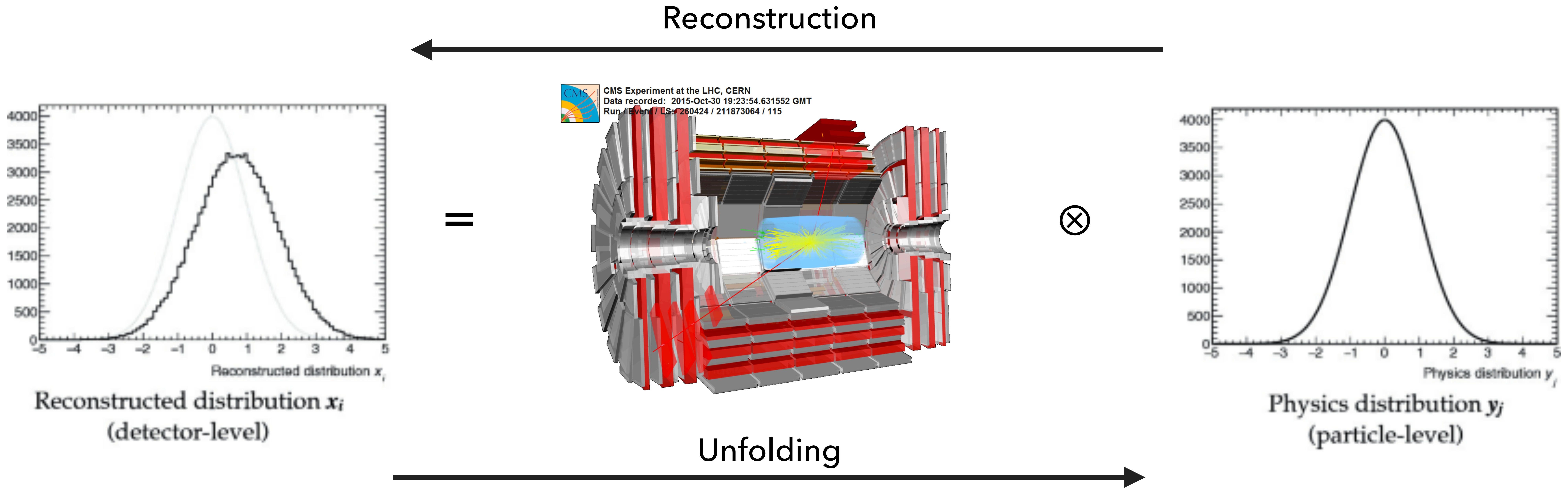


CHANNELS

	Channel	Dataset	Publication
CMS	H→$\gamma\gamma$	138 fb^{-1} (Run2)	JHEP08(2023)040
CMS	H→ZZ→4l	137 fb^{-1} (Run2)	JHEP07(2023)091
ATLAS	H→$\gamma\gamma$ H→ZZ→4l	139 fb^{-1}(Run2)	JHEP05(2023)028
ATLAS	H→$\gamma\gamma$ H→ZZ→4l	31.4 fb^{-1} (Run 3, 2022) 29.0 fb^{-1} (Run 3, 2022)	Submitted to EPJC
CMS	H→WW	137 fb^{-1}(Run2)	JHEP03(2021)003
ATLAS	ggH→WW VBFH→WW	139 fb^{-1}(Run2)	EPJC83(2023)774 Phys. Rev. D 108, 072003
CMS	H→$\tau\tau$	138 fb^{-1} (Run2)	Phys. Rev. Lett. 128,081805
CMS	H→bb	137 fb^{-1}(Run2)	JHEP12(2020)085
ATLAS	H→bb	136 fb^{-1}(Run2)	Phys. Rev. D 105, 092003
ATLAS CMS		3 ab^{-1}(HL-LHC prospects)	ATL-PHYS-PUB-2022-018 CMS PAS FTR-22-001

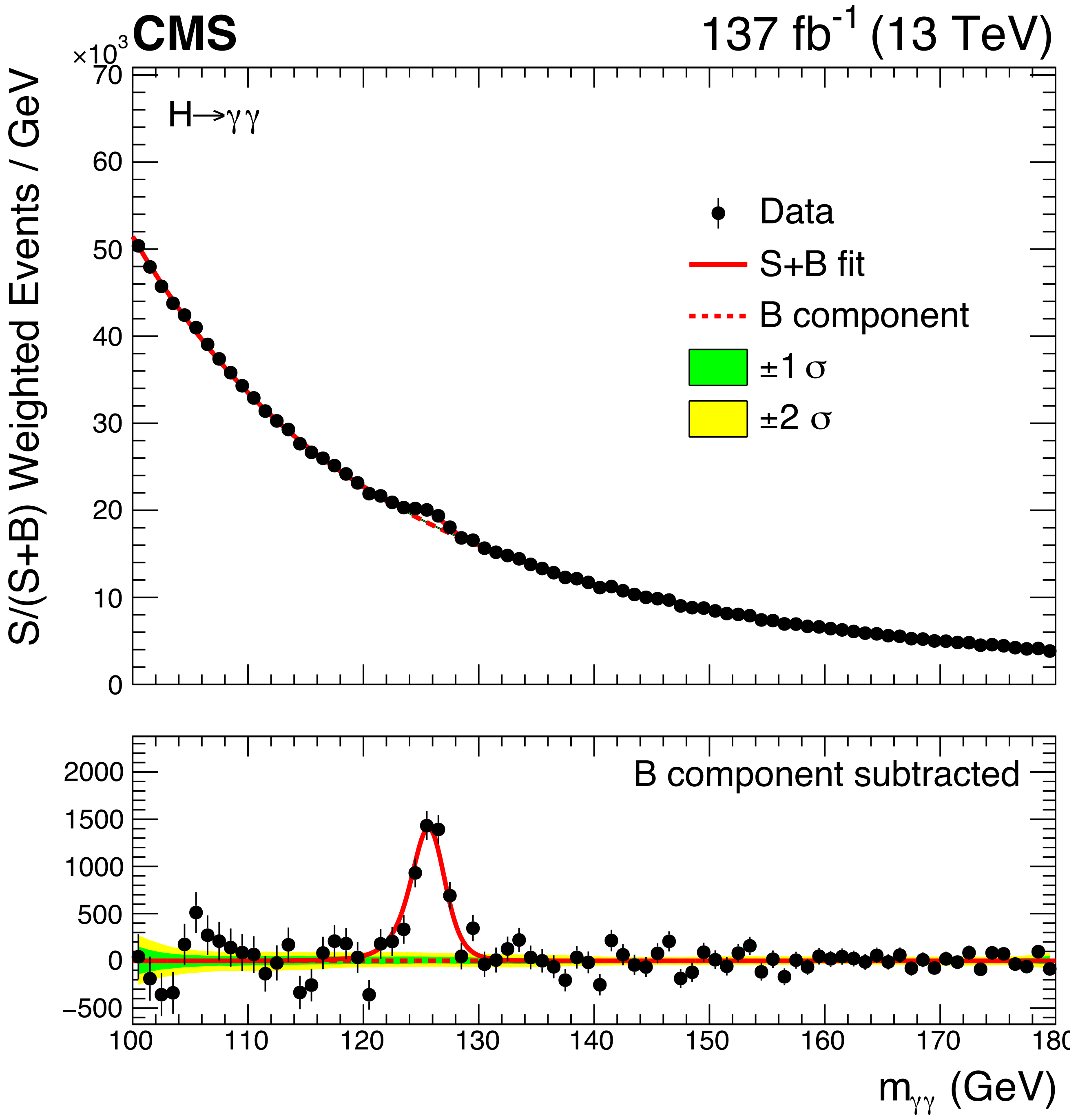
FIDUCIAL CROSS SECTION

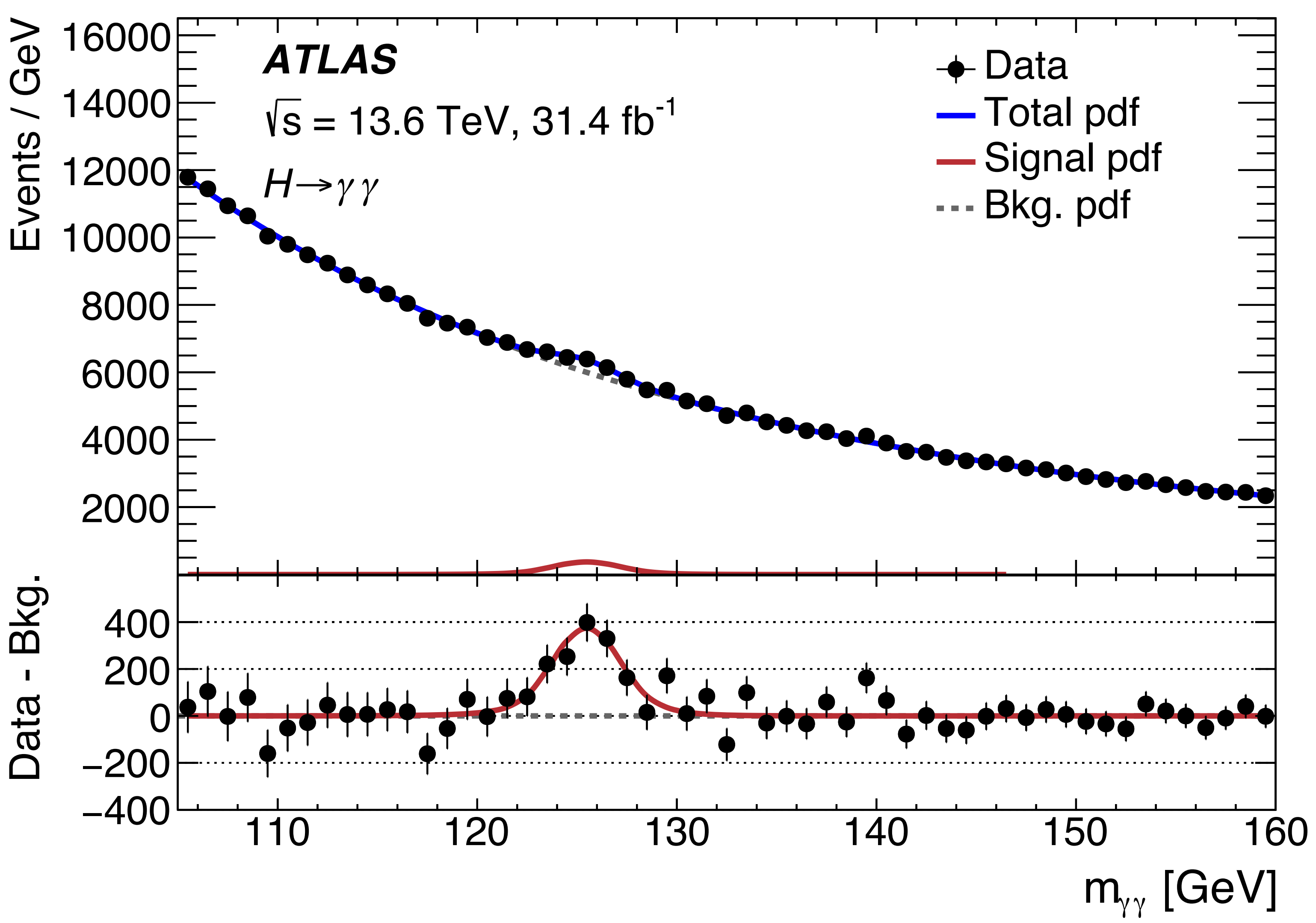
- Fiducial cross section measurements aim at providing the **least model-dependent characterization** of the Higgs boson properties
  - However, **SM assumed** when calculating acceptance
- Measured data **unfolded to correct for the detector effects**, allowing for direct comparison with different theoretical predictions
- **Fiducial phase space** defined to closely match experimental acceptance and analysis selection
- Fiducial cross section measured differentially with **many kinematical variables** sensitive to **BSM effects** considered



H→$\gamma\gamma$

- Signal is reconstructed by **two energetic photons**
- Backgrounds are from **SM γγ,γj**, and **jj**
- Vertex assignment
  - ATLAS : **neural network**(vertex/track, calorimeter pointing)
  - CMS: **BDT** combines tracking and calorimeter information
- Differential cross sections extracted from **$m_{\gamma\gamma}$ fits**
- **Large number** of kinematic observables
- **Double-differential** measurements





	13 TeV	
$\sigma_{\text{fid}} = 73.4^{+5.4}_{-5.3}(\text{stat})^{+2.4}_{-2.2}(\text{sys})\,\text{fb}$		$\sigma_{\text{fid}} = 67 \pm 5(\text{stat}) \pm 4(\text{sys})\,\text{fb}$
$\sigma^{\text{th}}_{\text{fid}} = 75.4 \pm 4.1\,\text{fb}$		$\sigma^{\text{th}}_{\text{fid}} = 64.2 \pm 3.4\,\text{fb}$

13.6 TeV

$\sigma_{\text{fid}} = 76^{+14}_{-13}\,\text{fb}$

$\sigma^{\text{th}}_{\text{fid}} = 67.6 \pm 3.7\,\text{fb}$

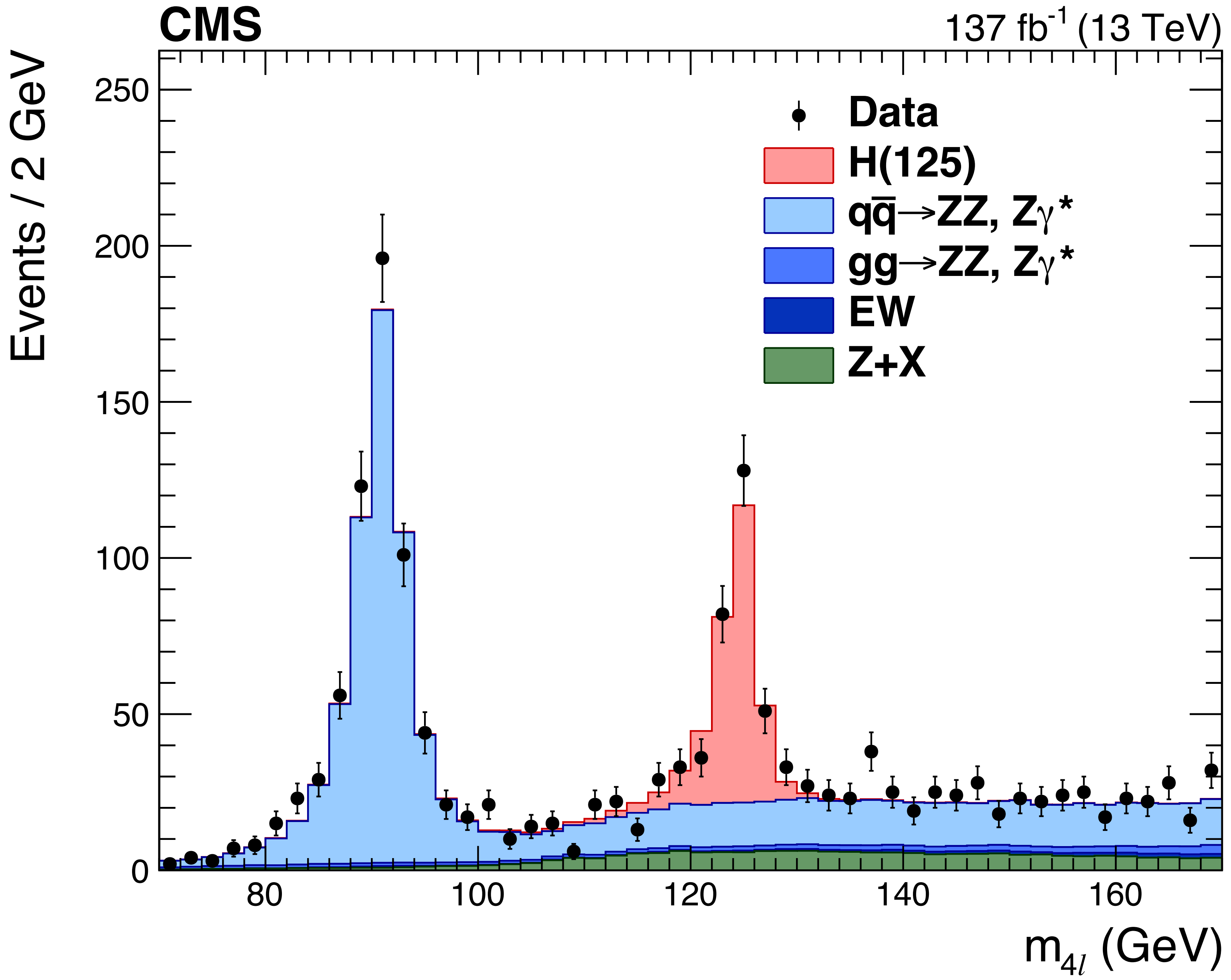
https://arxiv.org/abs/2208.12279

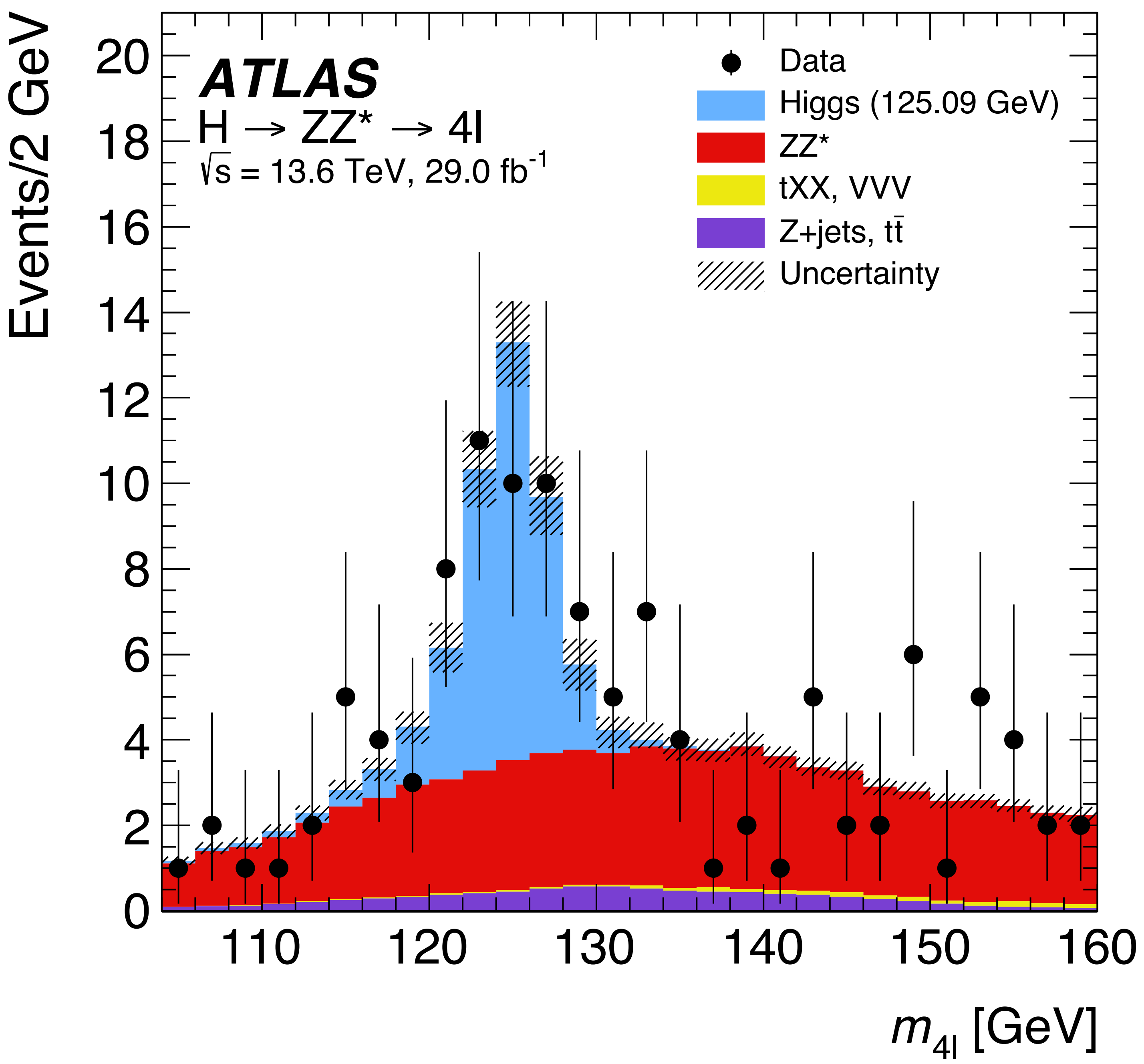
https://arxiv.org/abs/2306.11379

H→ZZ→4L

- Signal is fully reconstructed using **four leptons**
- SM backgrounds: **qqZZ**, **ggZZ** and **Z+X**
- Large **S/B ratio ~2:1** under the Higgs peak

- **Full kinematic information** due to great reconstruction of all final state objects
- Many observables sensitive to **production and decay explored**





13 TeV

$\sigma_{\text{fid}} = 2.73 \pm 0.22(\text{stat}) \pm 0.15(\text{sys})\,\text{fb}$

$\sigma_{\text{fid}}^{\text{th}} = 2.86 \pm 0.15\,\text{fb}$

$\sigma_{\text{fid}} = 3.28 \pm 0.3(\text{stat}) \pm 0.11(\text{sys})\,\text{fb}$

$\sigma_{\text{fid}}^{\text{th}} = 3.41 \pm 0.18\,\text{fb}$

13.6 TeV

$\sigma_{\text{fid}} = 2.80 \pm 0.74\,\text{fb}$

$\sigma_{\text{fid}}^{\text{th}} = 3.67 \pm 0.19\,\text{fb}$

https://arxiv.org/abs/2305.07532

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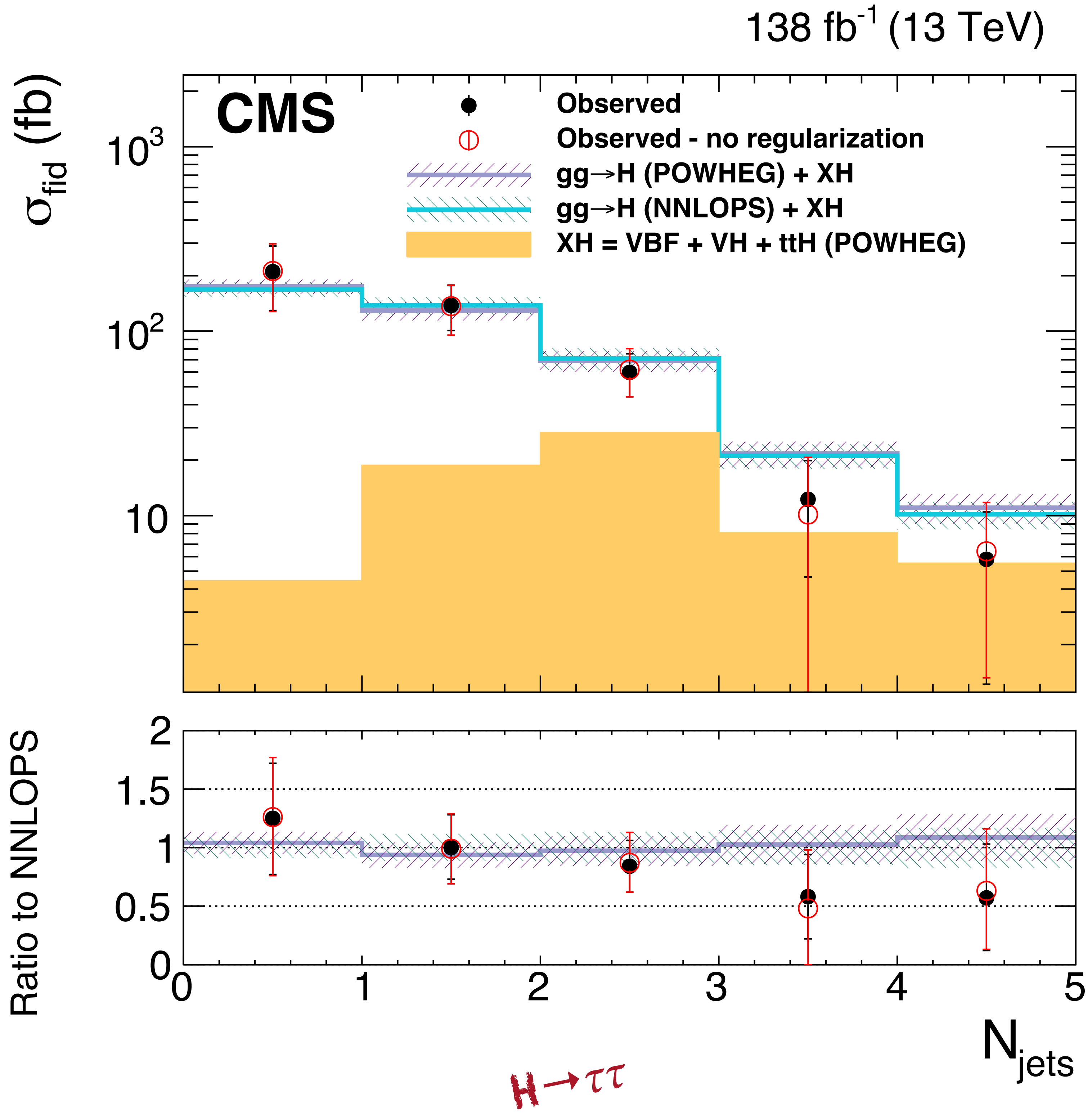
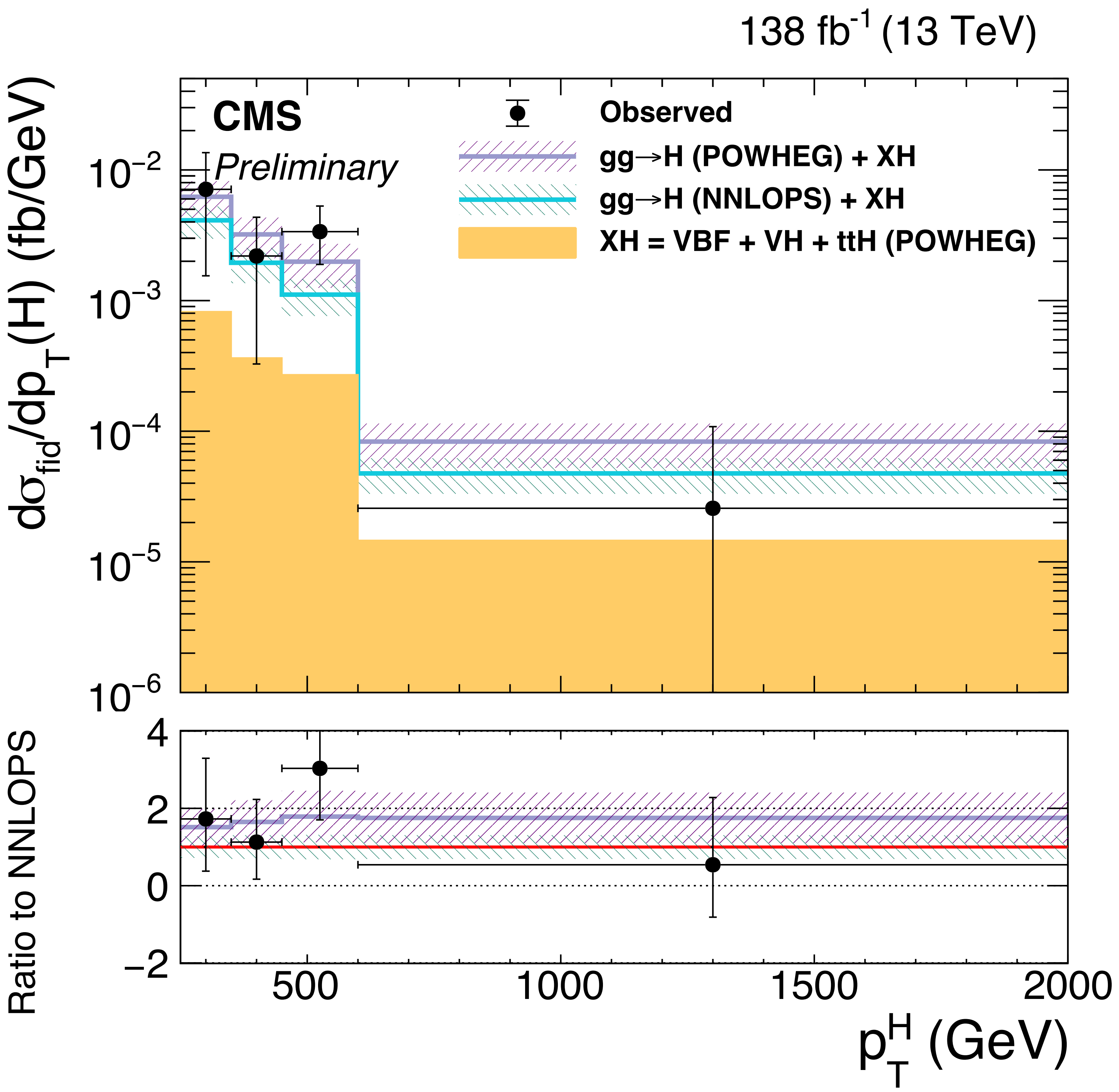
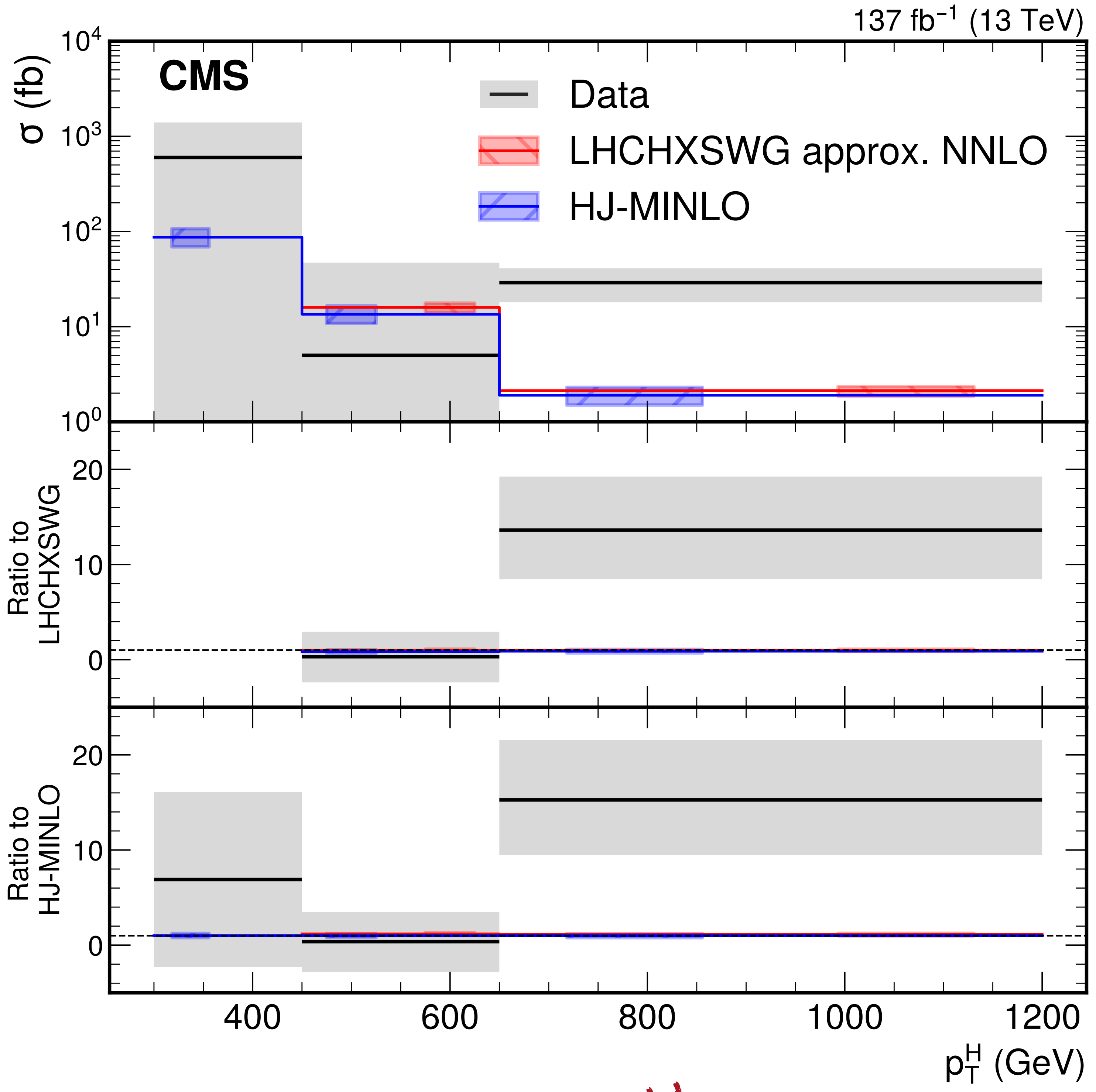
H→BB AND H→$\tau\tau$



H→ττ



H→ττ

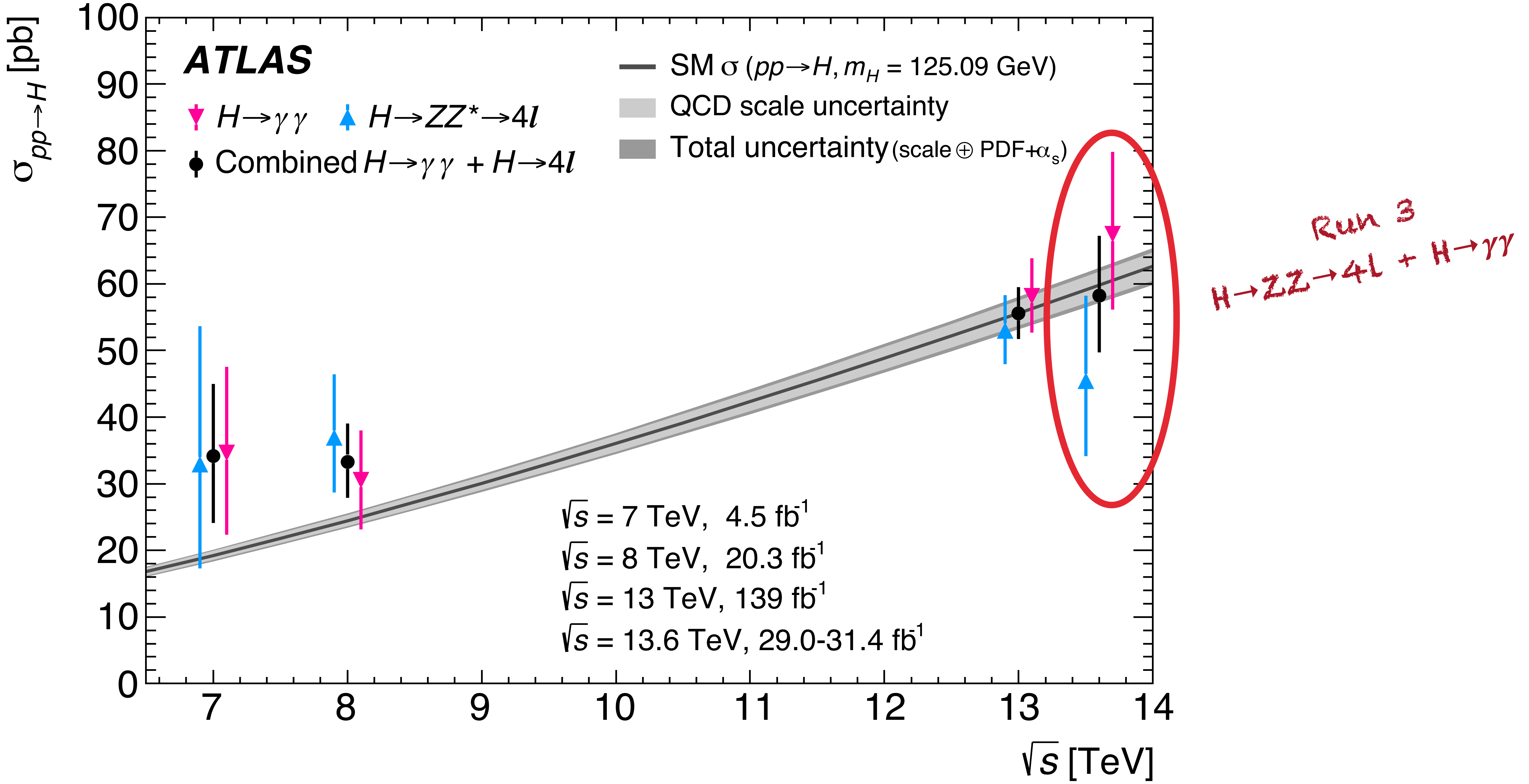


H→bb

- **First ever differential cross section** measurement in the **H→$\tau\tau$ channel**!
- Both measurements **statistically dominated**
- These channels are great handles for the **large jet multiplicity** and **high Higgs boson p_T** regions for the future combination

https://arxiv.org/abs/2107.11486v2 https://cds.cern.ch/record/2868084 https://arxiv.org/abs/2006.13251v2

INCLUSIVE

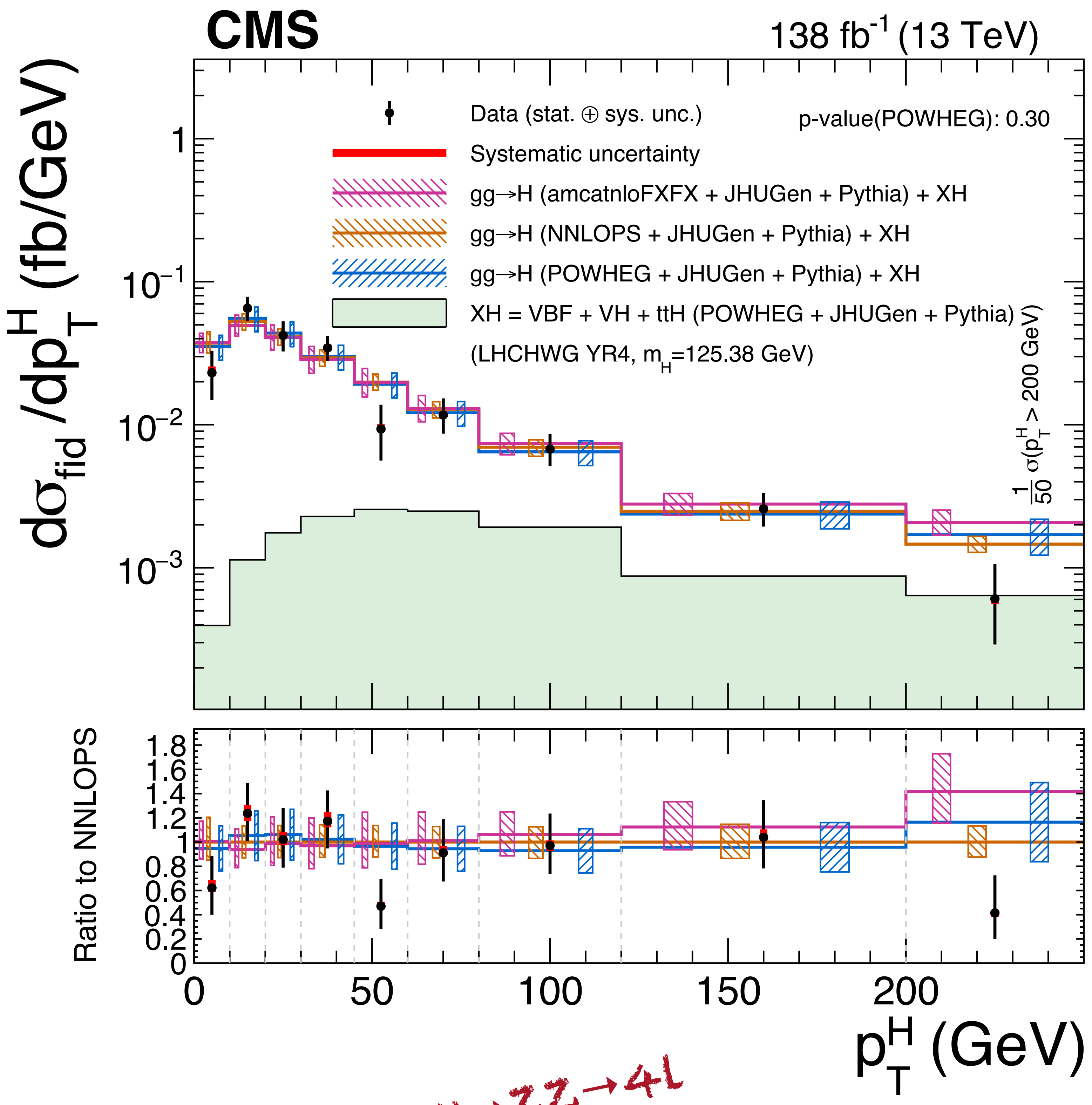


- **Run 3** first time part of the fiducial cross section as a function of sqrt(s)
- Several **assumptions and extrapolations** from Run2 for the early Run3 result that is statistically dominated
- Assuming SM values for fiducial acceptance and BR results **extrapolated to full phase space**

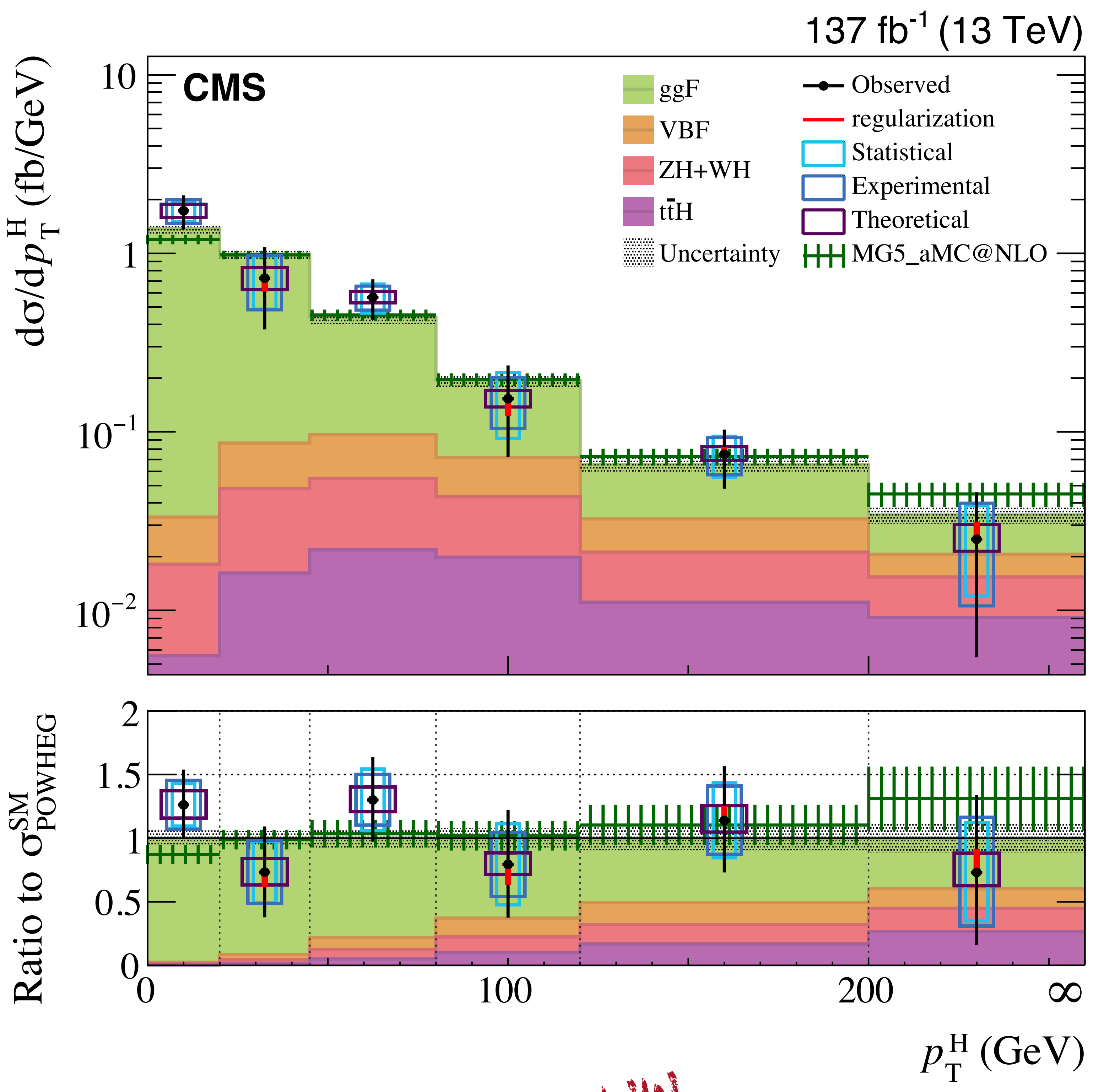
https://arxiv.org/abs/2306.11379

HIGGS P_T

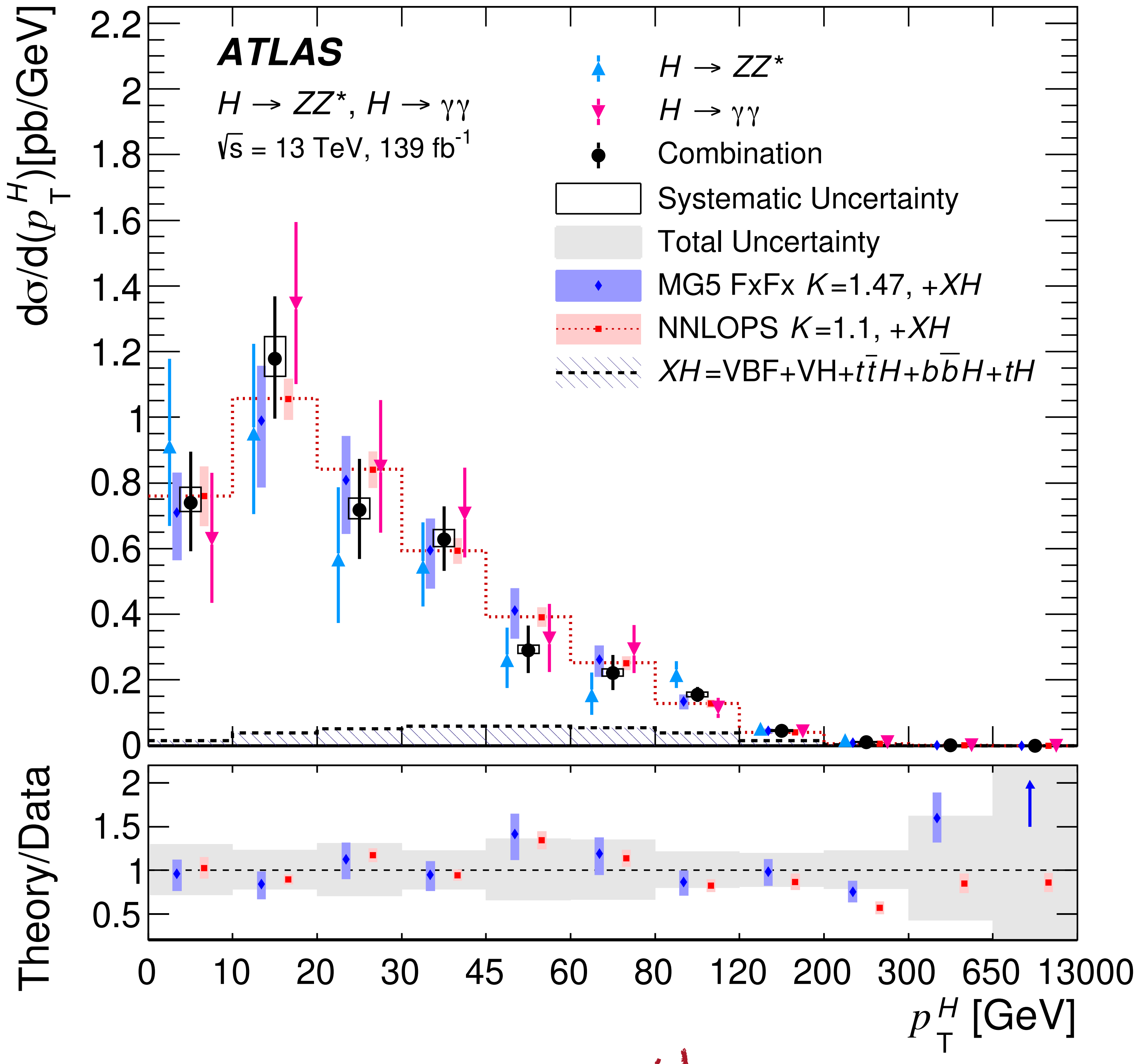
- $p_T(H)$ probes the perturbative **QCD modelling** of Higgs production
  - 20 - 30% precision with full Run 2 statistics
- Variations of couplings **distort the shape** of $p_T(H)$
- Different models are provided by theorists to describe the shape distortions



H→ZZ→4l



H→WW



H→ZZ→4l

H→γγ

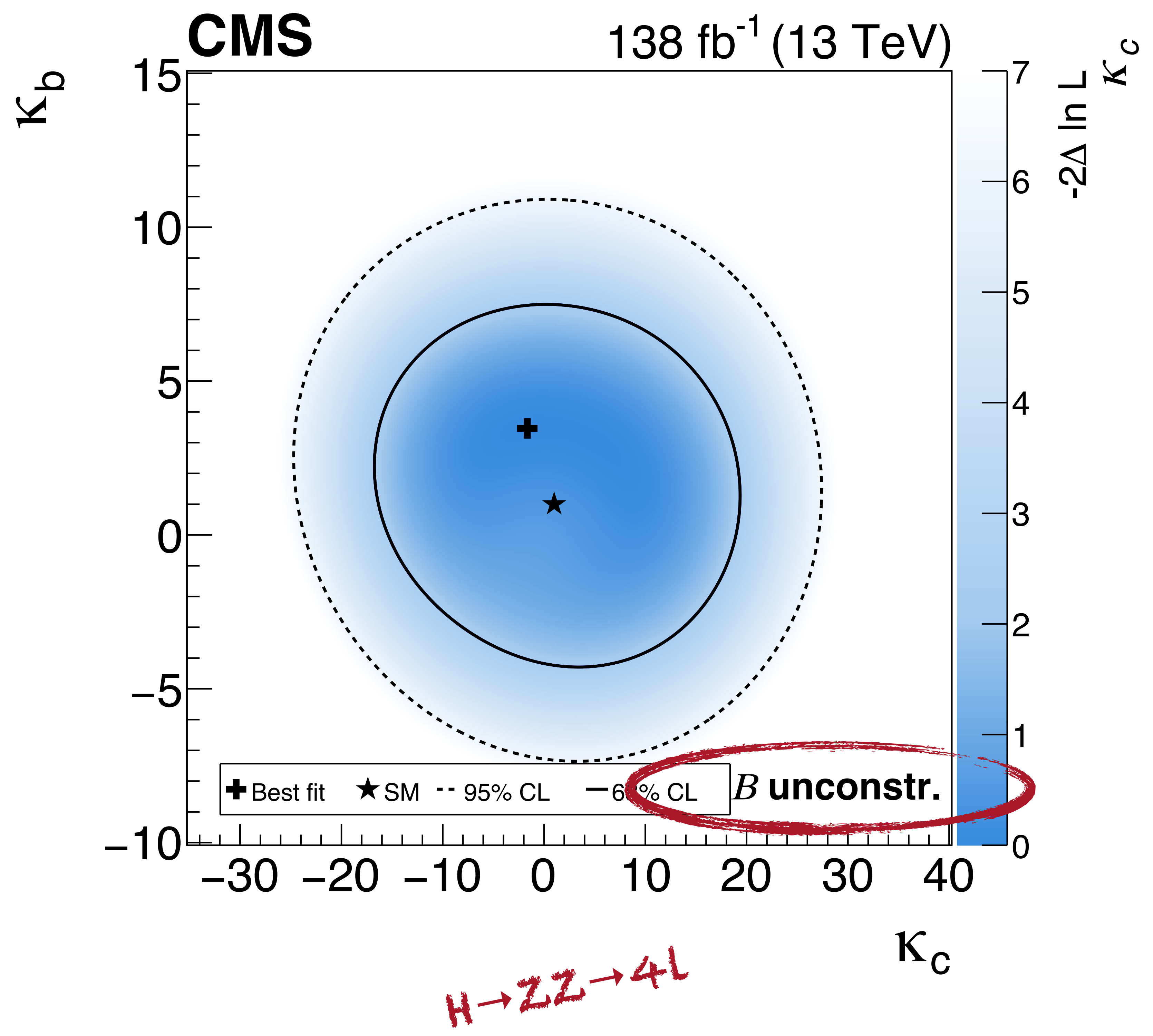
https://arxiv.org/abs/2305.07532

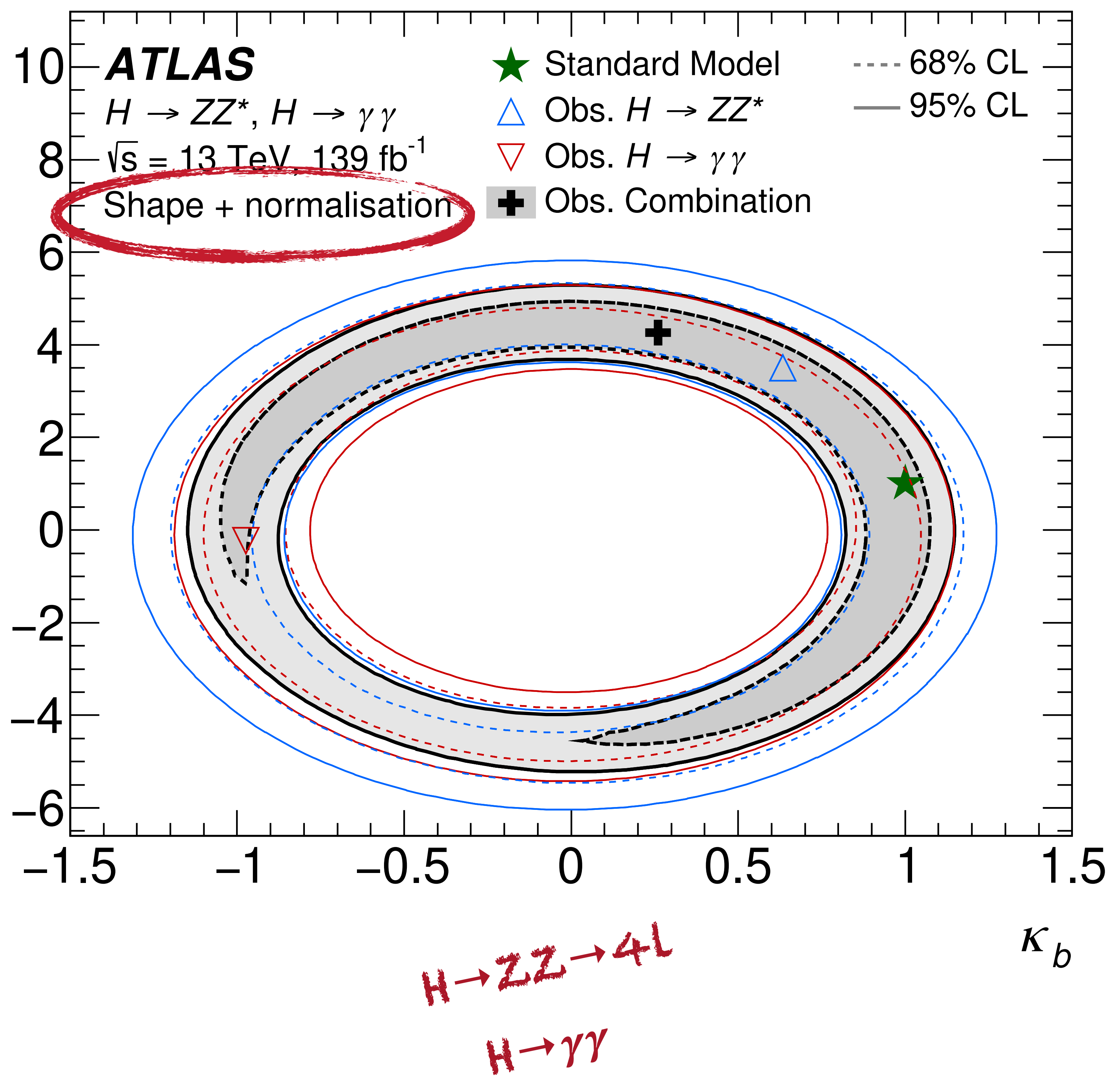
https://arxiv.org/abs/2007.01984

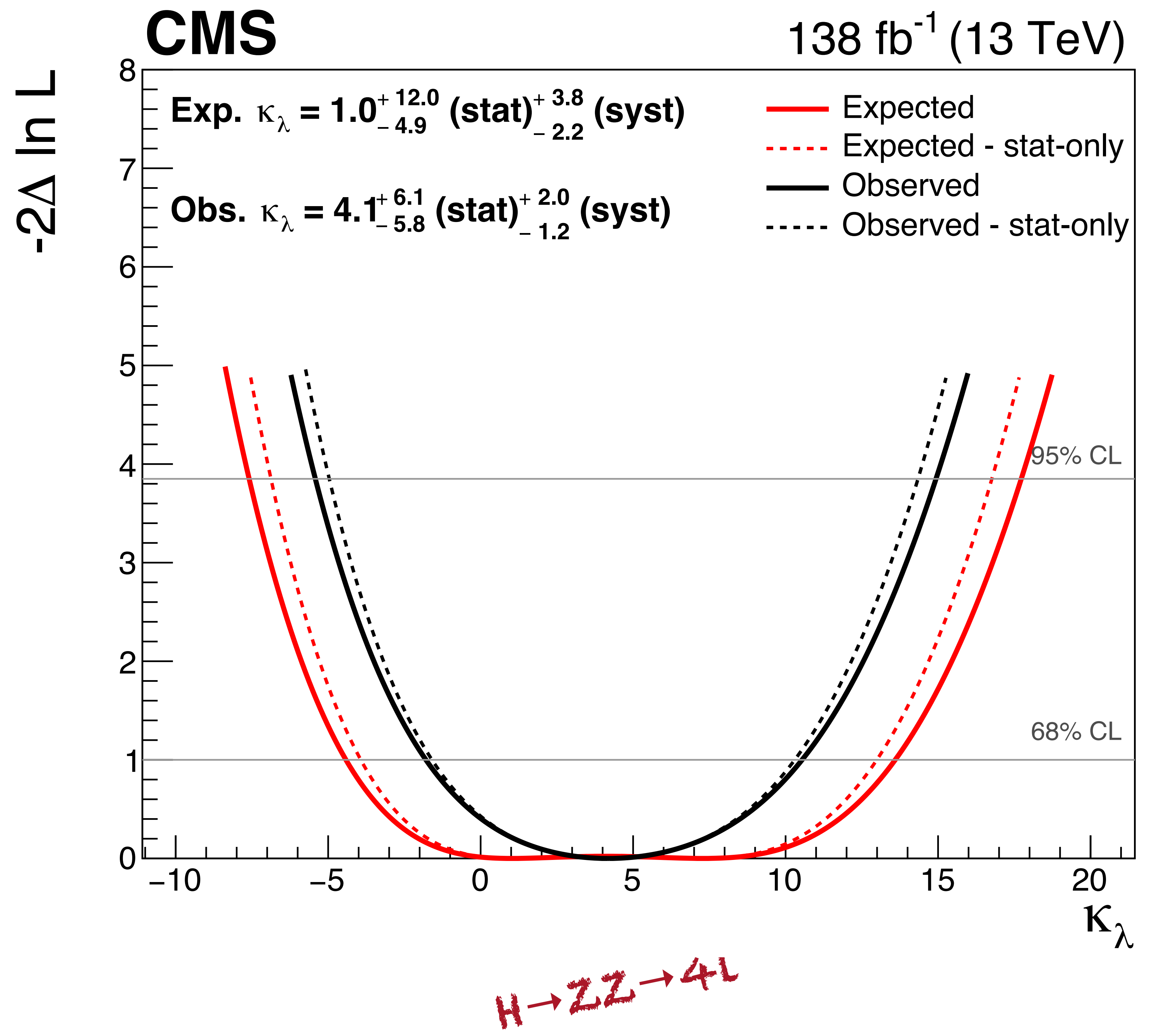
https://arxiv.org/abs/2207.08615

HIGGS p_T INTERPRETATIONS

- ggH $p_T(H)$ spectrum sensitive to anomalous values of Higgs **couplings** to **b** and **c quarks**
  - results with **BR freely floating** vs **BR scaling** with κ_b and κ_c
- ttH and VH $p_T(H)$ spectrum **sensitive** to Higgs boson **self coupling**





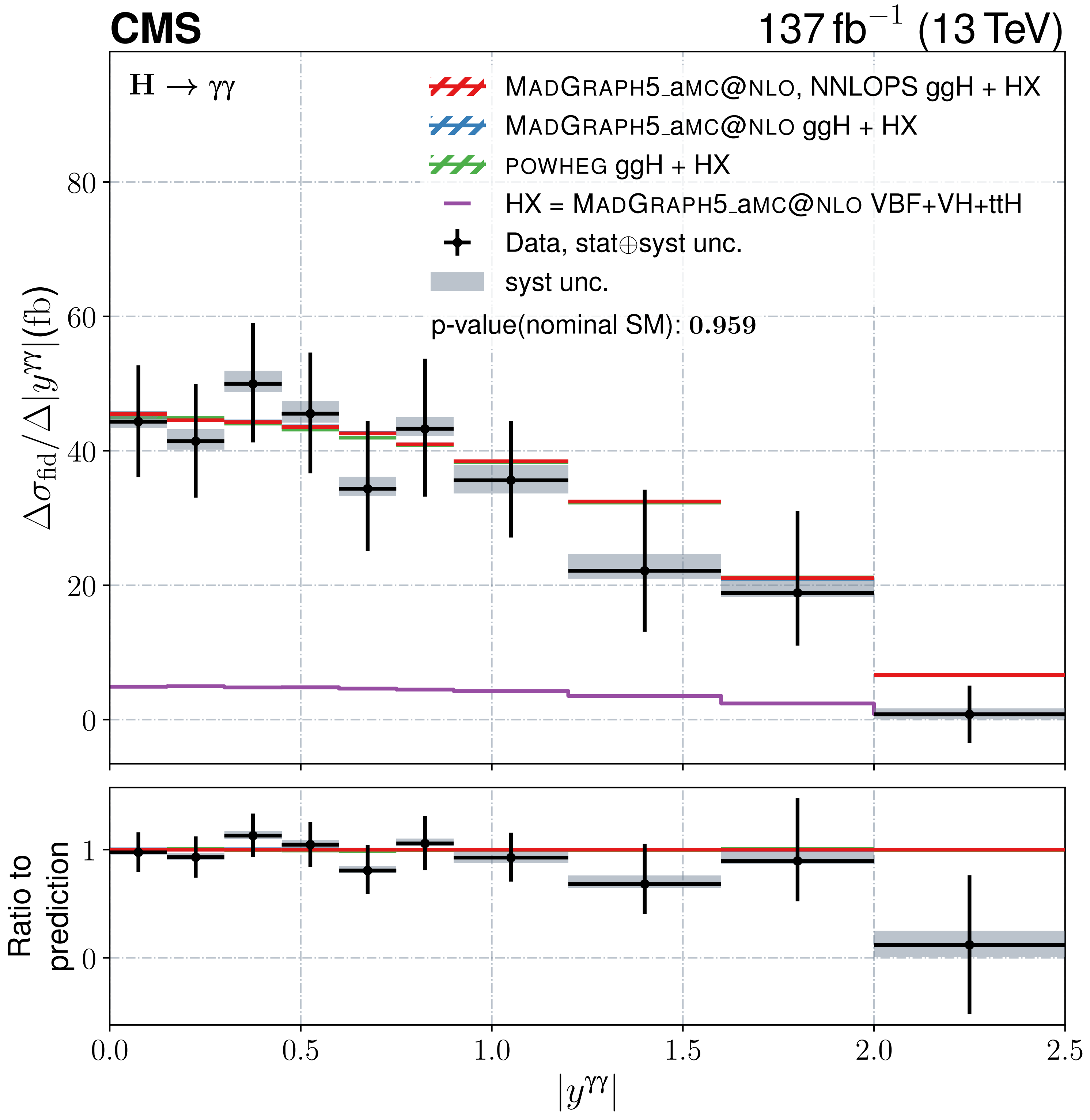


https://arxiv.org/abs/2305.07532 https://arxiv.org/abs/2207.08615 https://arxiv.org/abs/2305.07532

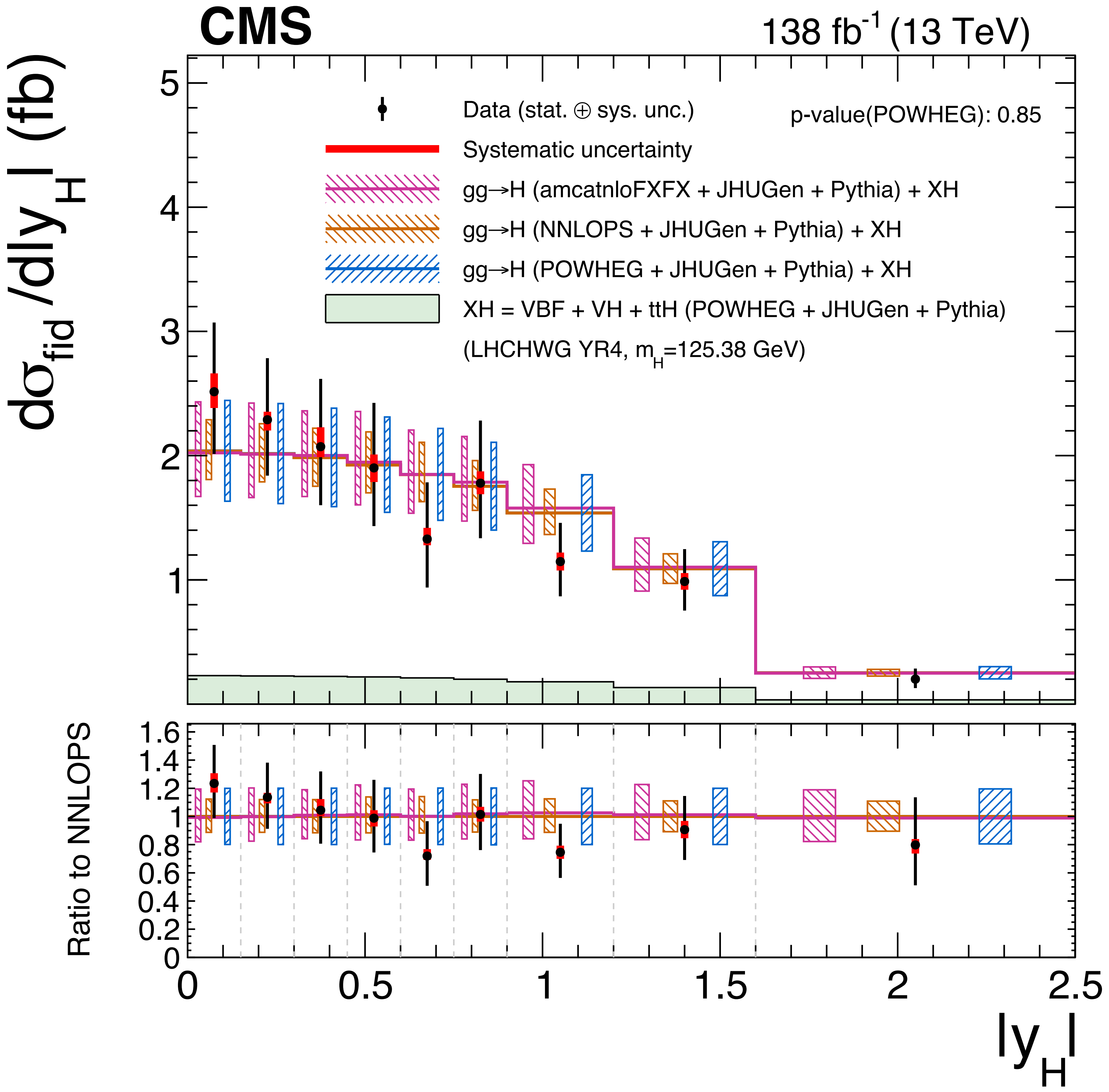
*Many more interpretations in the dedicated EFT talk by Chen Zhou on Wednesday 29/11

HIGGS RAPIDITY

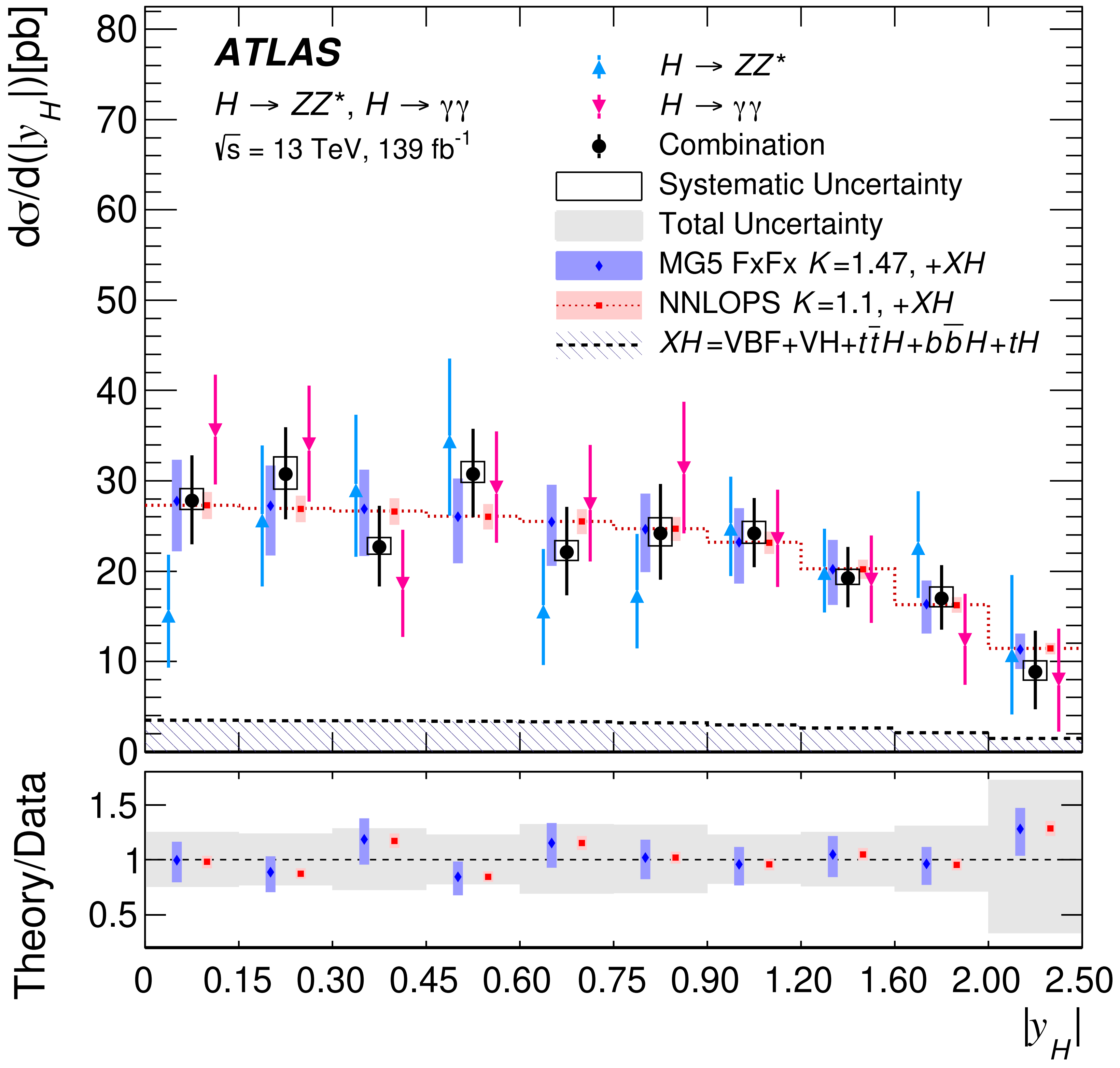
- y(H) probes the **PDFs** and Higgs **production** mode
  - measurement precision **statistically dominated**
  - 20 - 30% precision with full Run 2 statistics



H→γγ



H→ZZ→4l



H→ZZ→4l
H→γγ

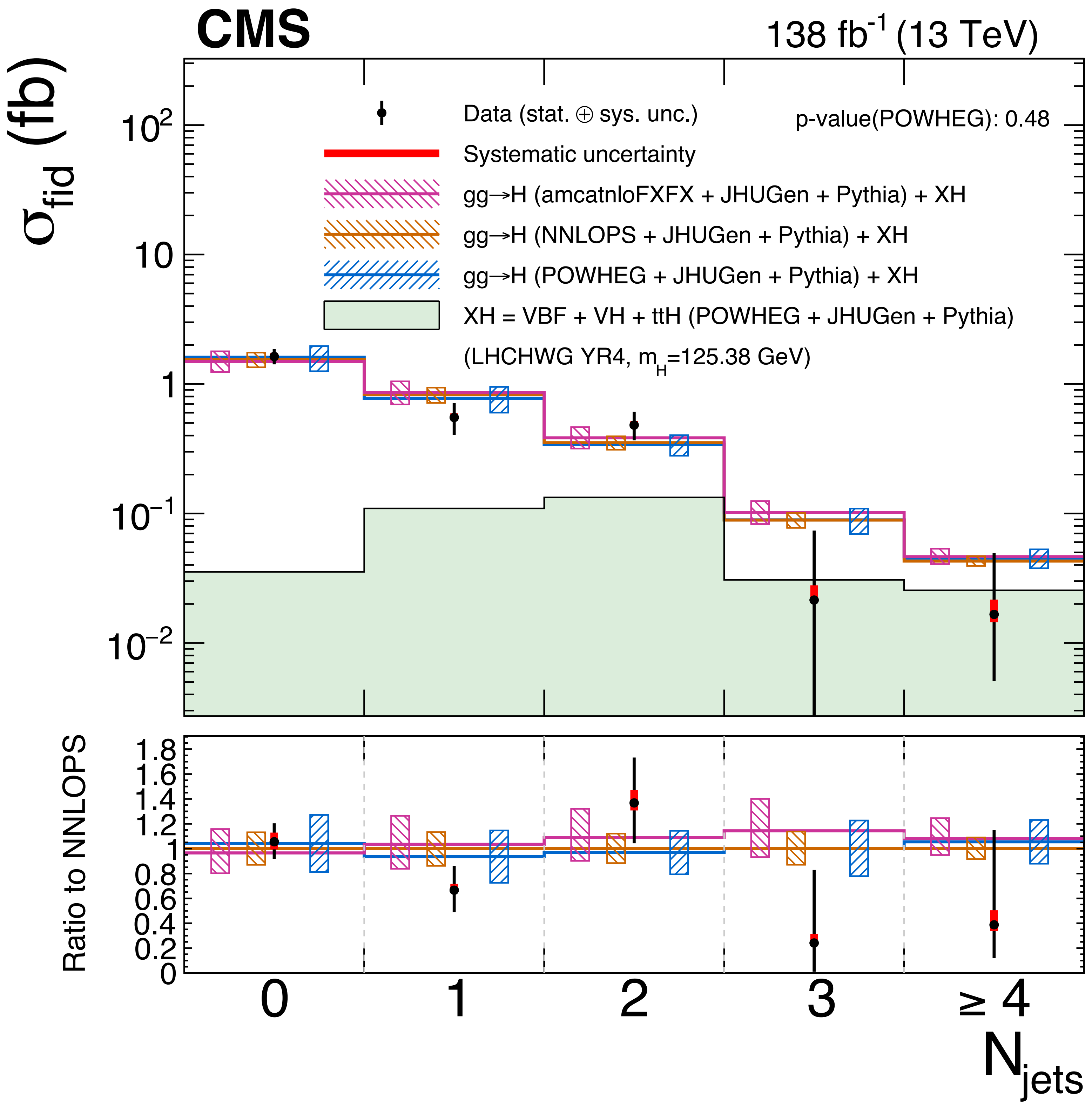
https://arxiv.org/abs/2208.12279

https://arxiv.org/abs/2305.07532

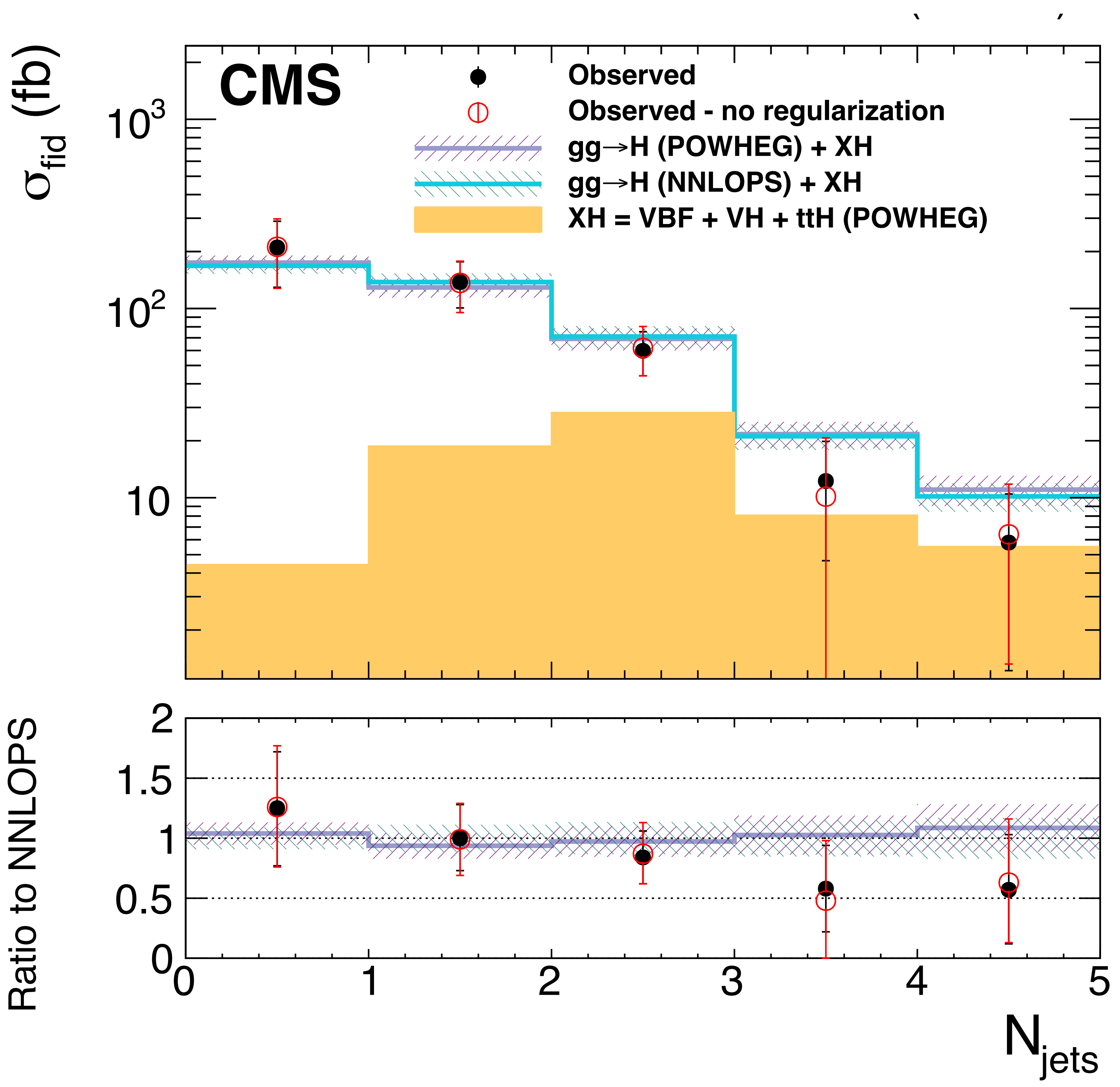
https://arxiv.org/abs/2207.08615

NUMBER OF JETS

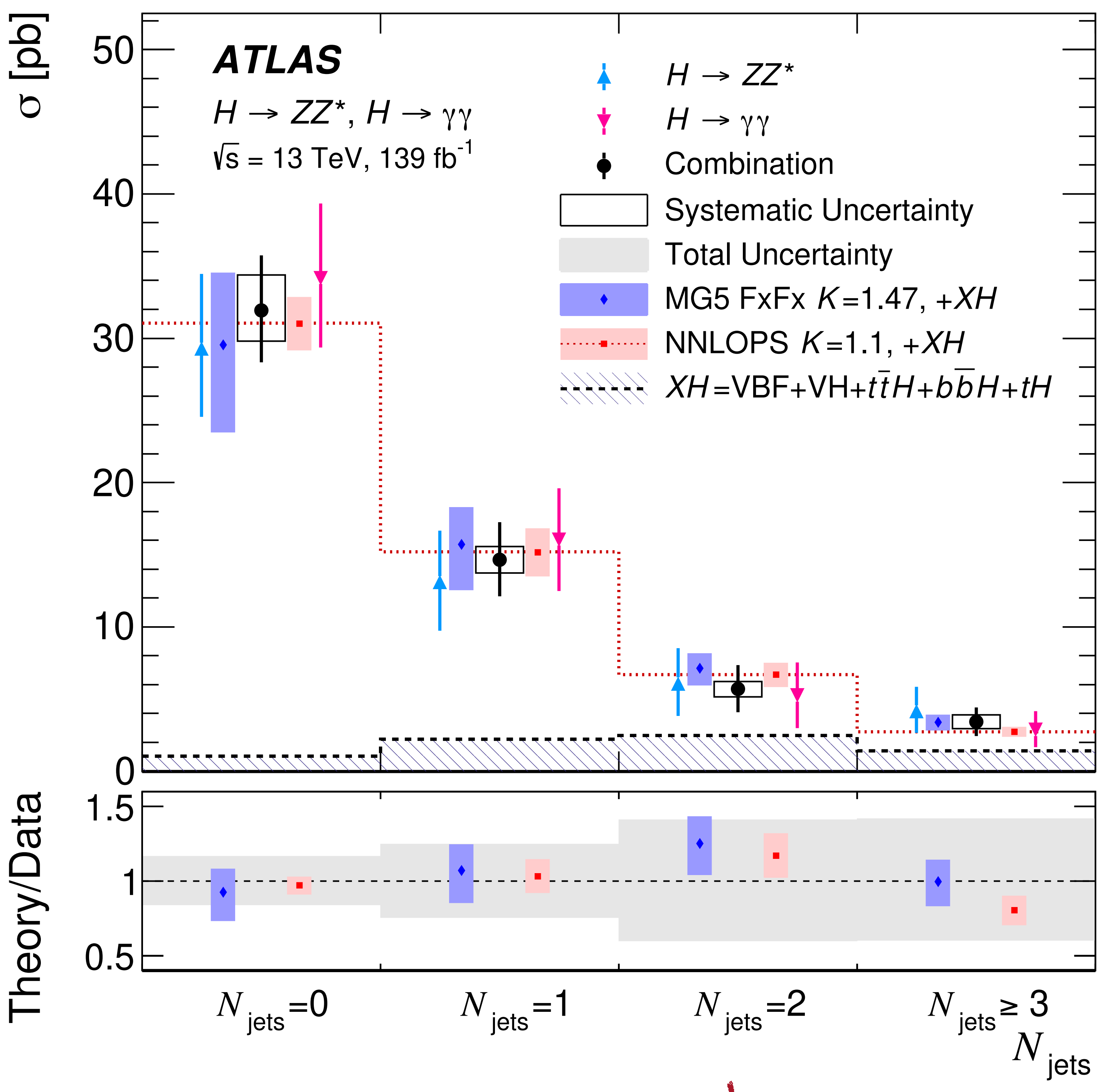
- Jet kinematics useful for test of **modelling of QCD radiation** and **production mechanism**:
  1) Number of central jets



H→ZZ→4l



H→ττ

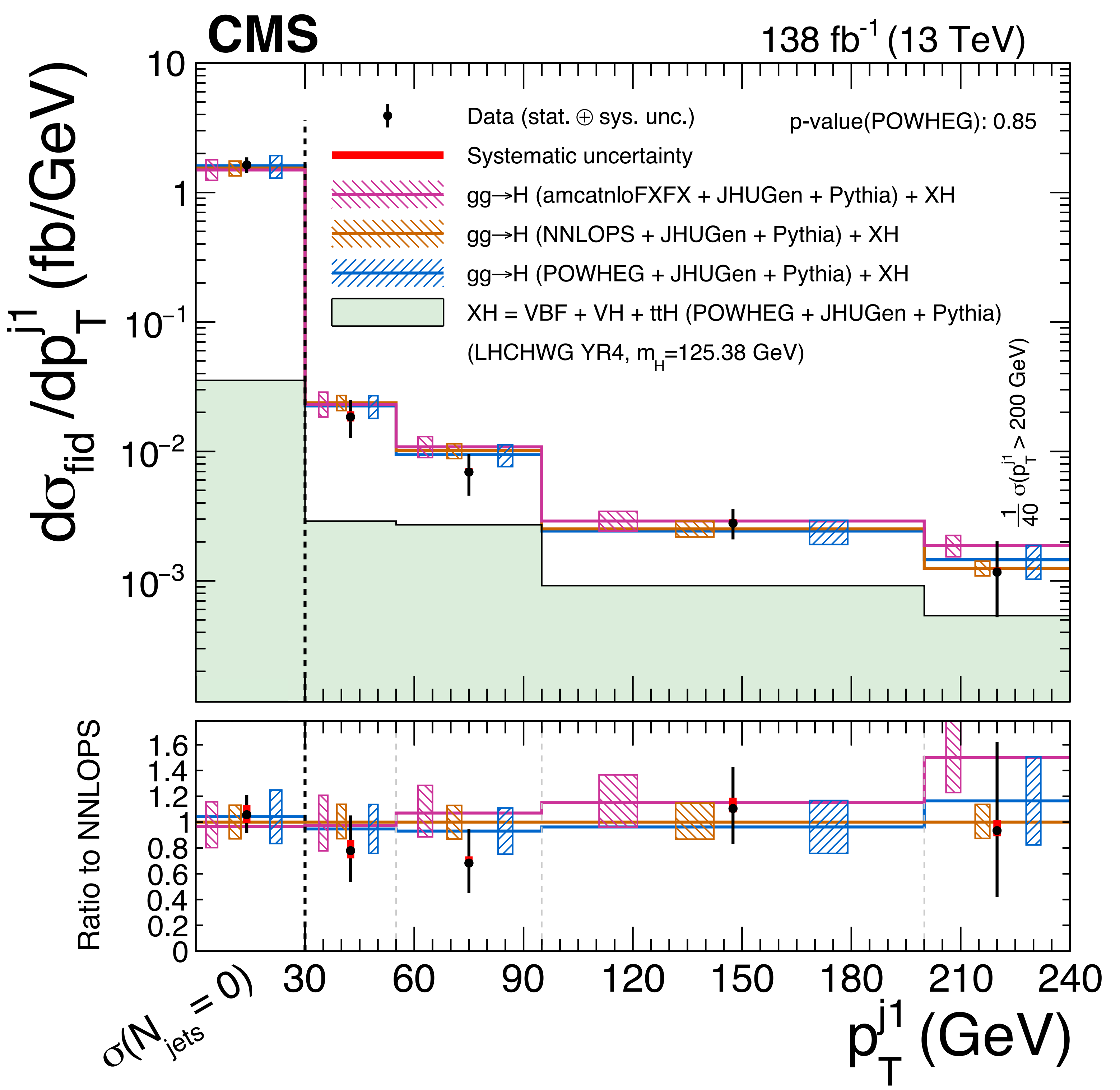


H→ZZ→4l
H→γγ

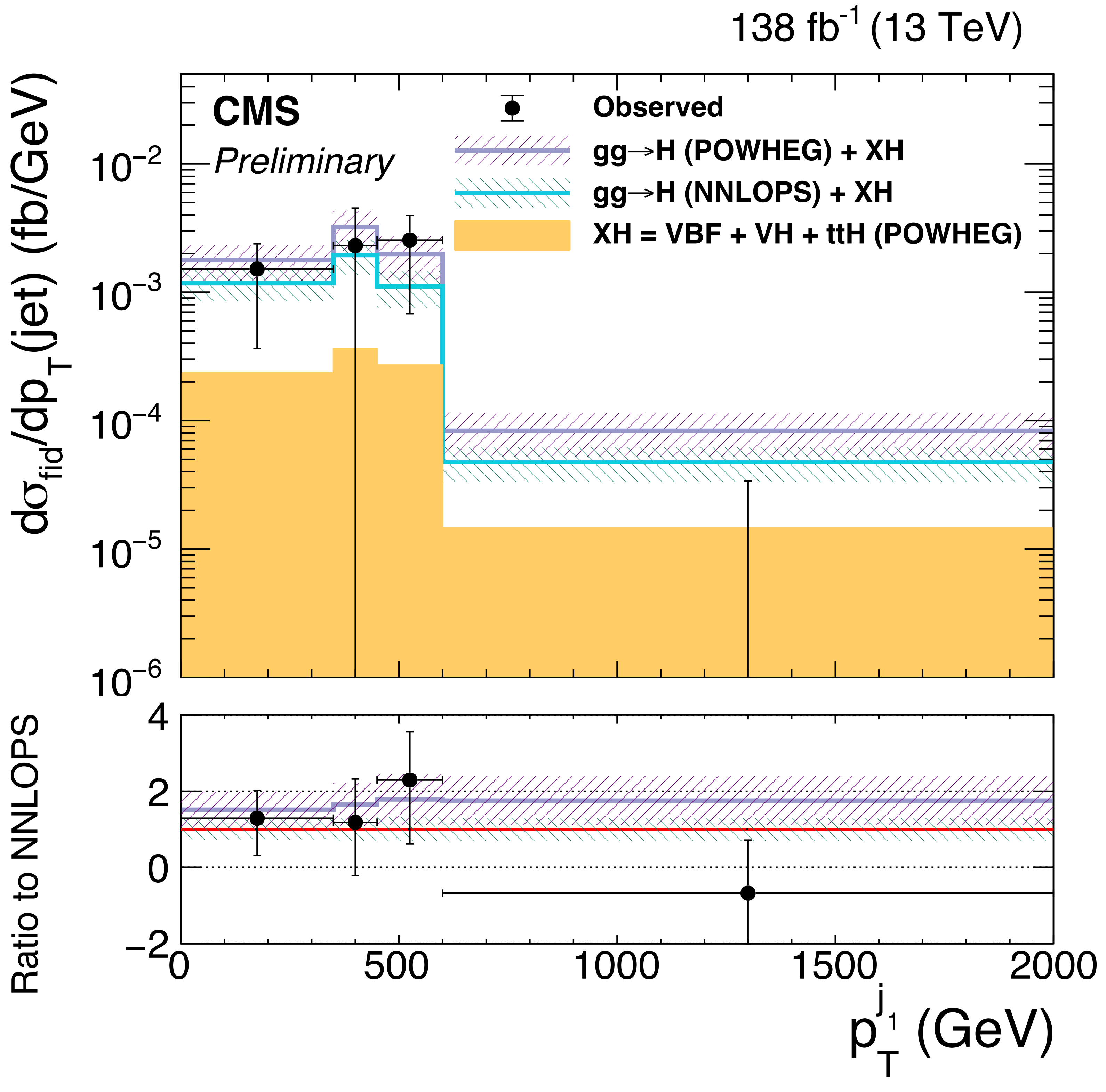
https://arxiv.org/abs/2305.07532 https://arxiv.org/abs/2107.11486v2 https://arxiv.org/abs/2207.08615

p_T OF LEADING JET

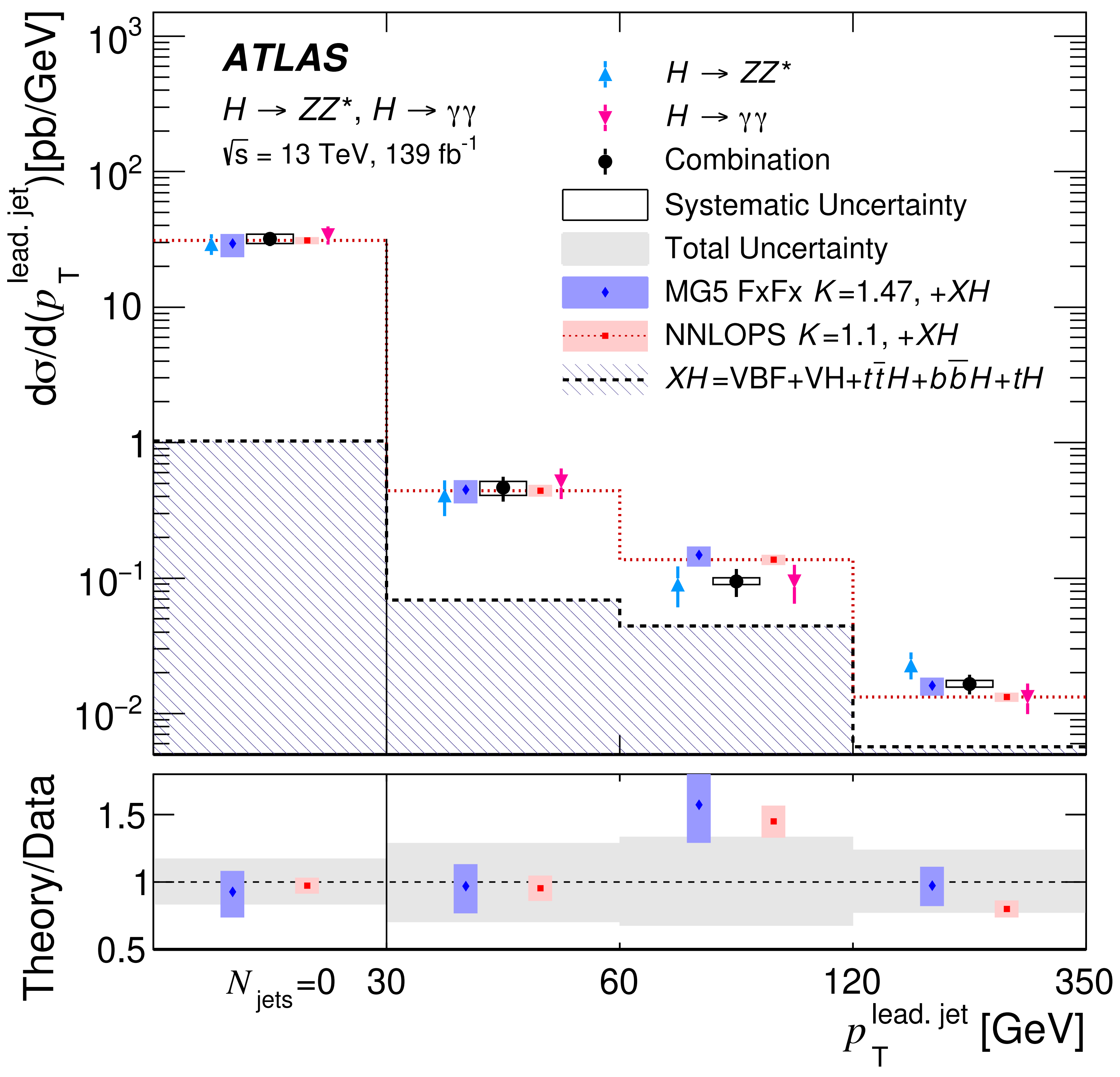
- Jet kinematics useful for test of **modelling of QCD radiation** and **production mechanism**:
  1) Number of central jets
  2) p_T of leading jet



H→ZZ→4l



H→ττ



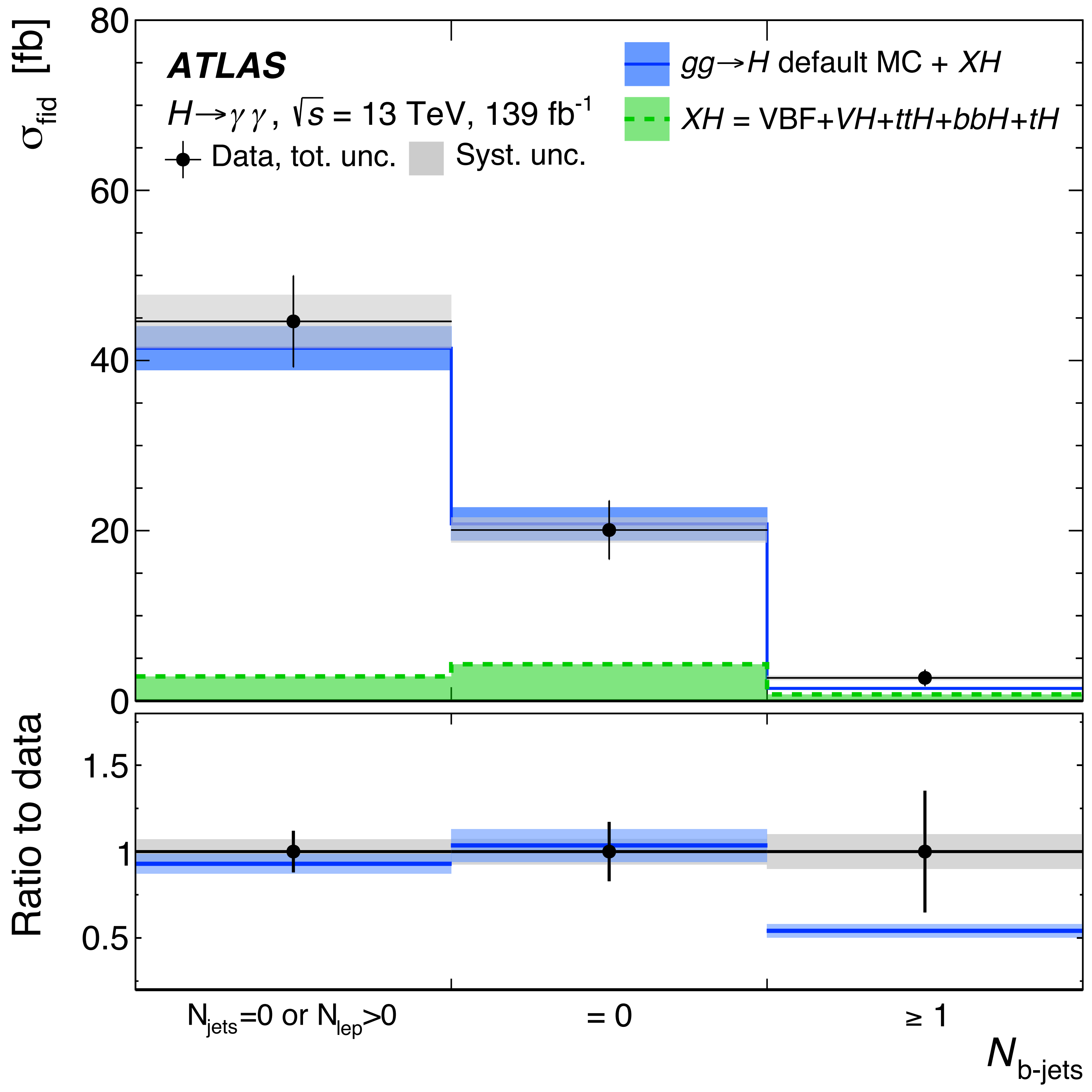
H→ZZ→4l

H→γγ

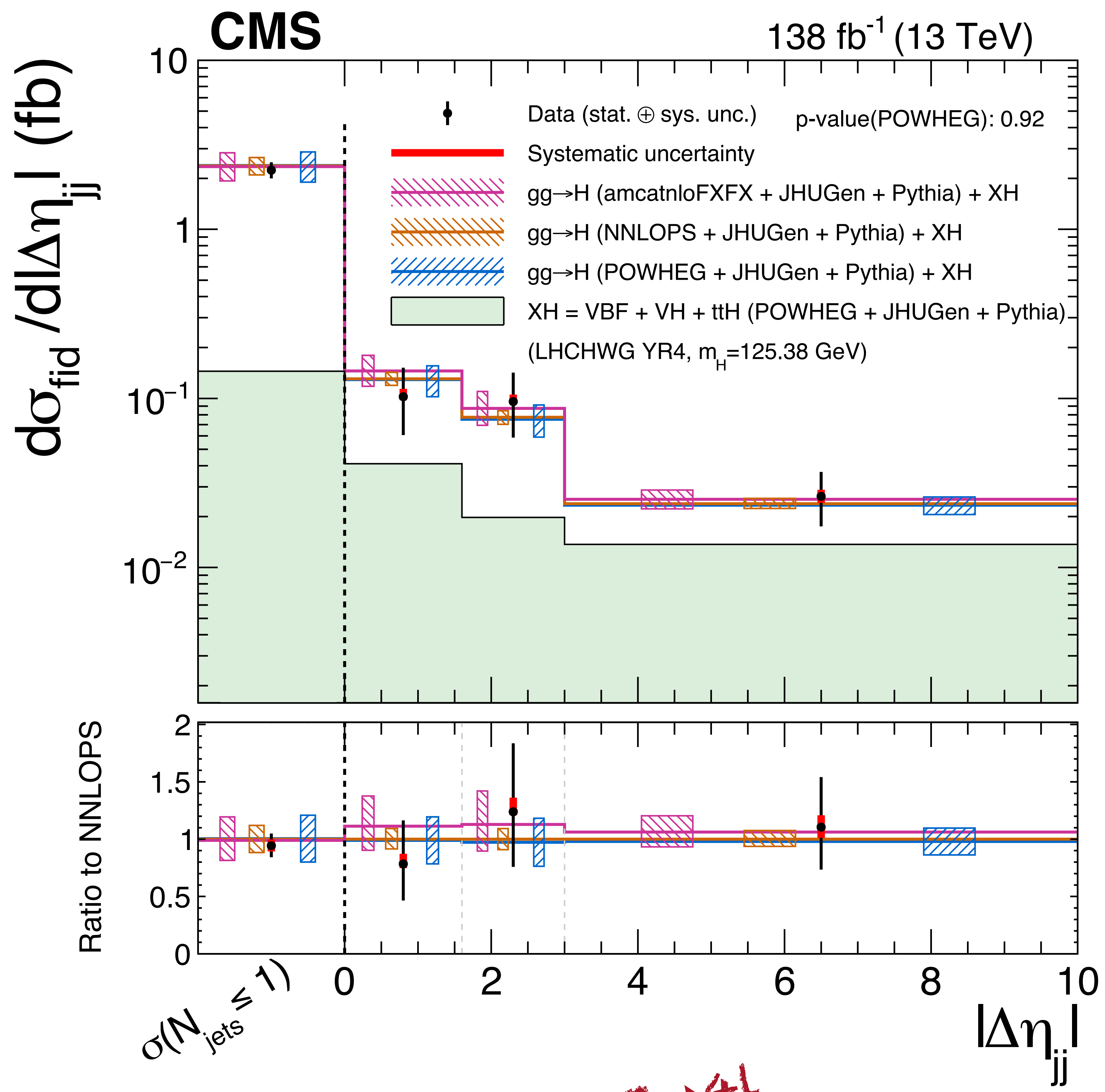
https://arxiv.org/abs/2305.07532 https://cds.cern.ch/record/2868084 https://arxiv.org/abs/2207.08615

OTHER JET KINEMATICS

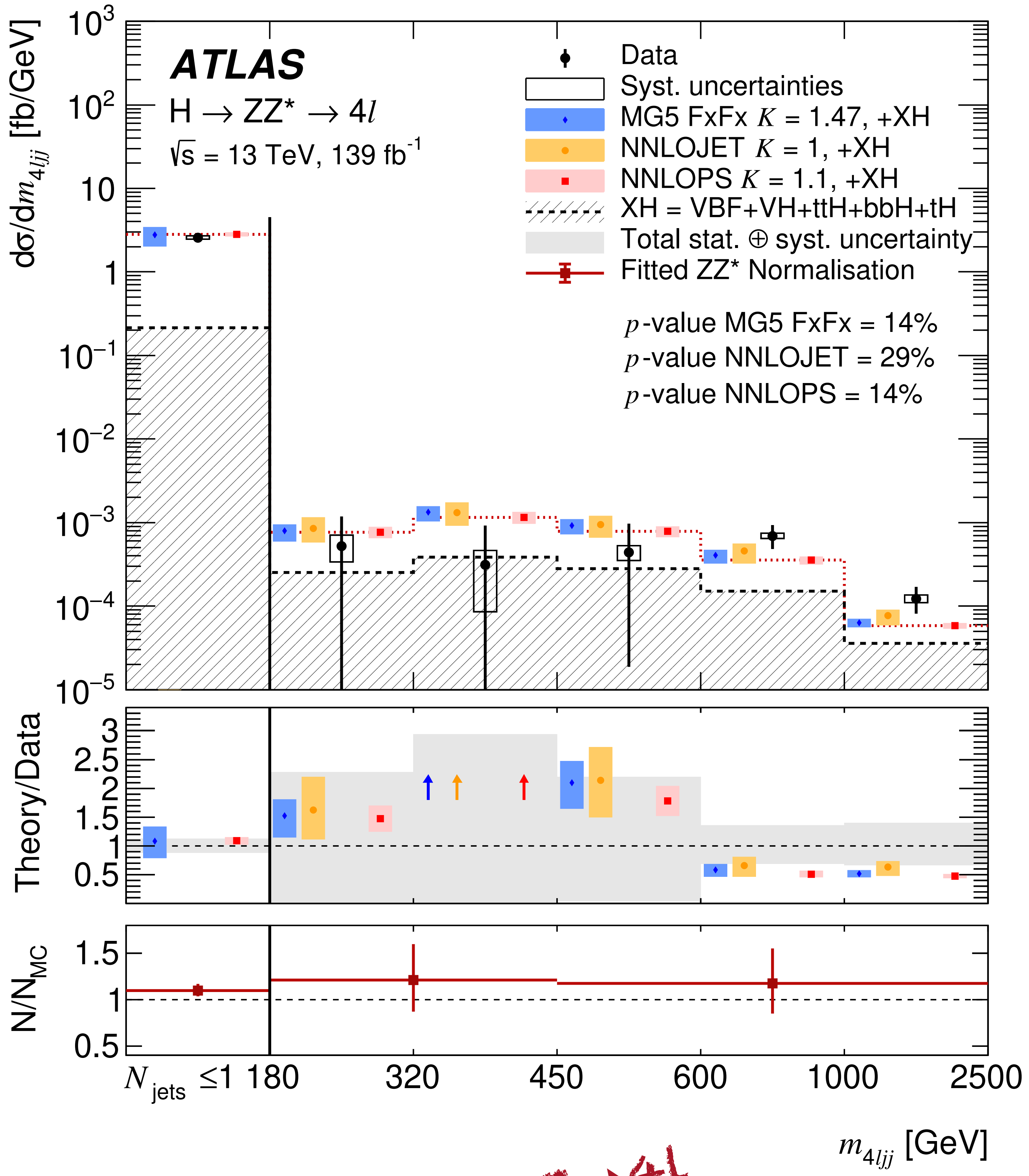
- Jet kinematics useful for test of **modelling of QCD radiation** and **production mechanism**:
    1) Number of central jets
    2) p_T of leading jet
    3) Number of b-jets, di-jet kinematics, and many more



H→γγ



H→ZZ→4l

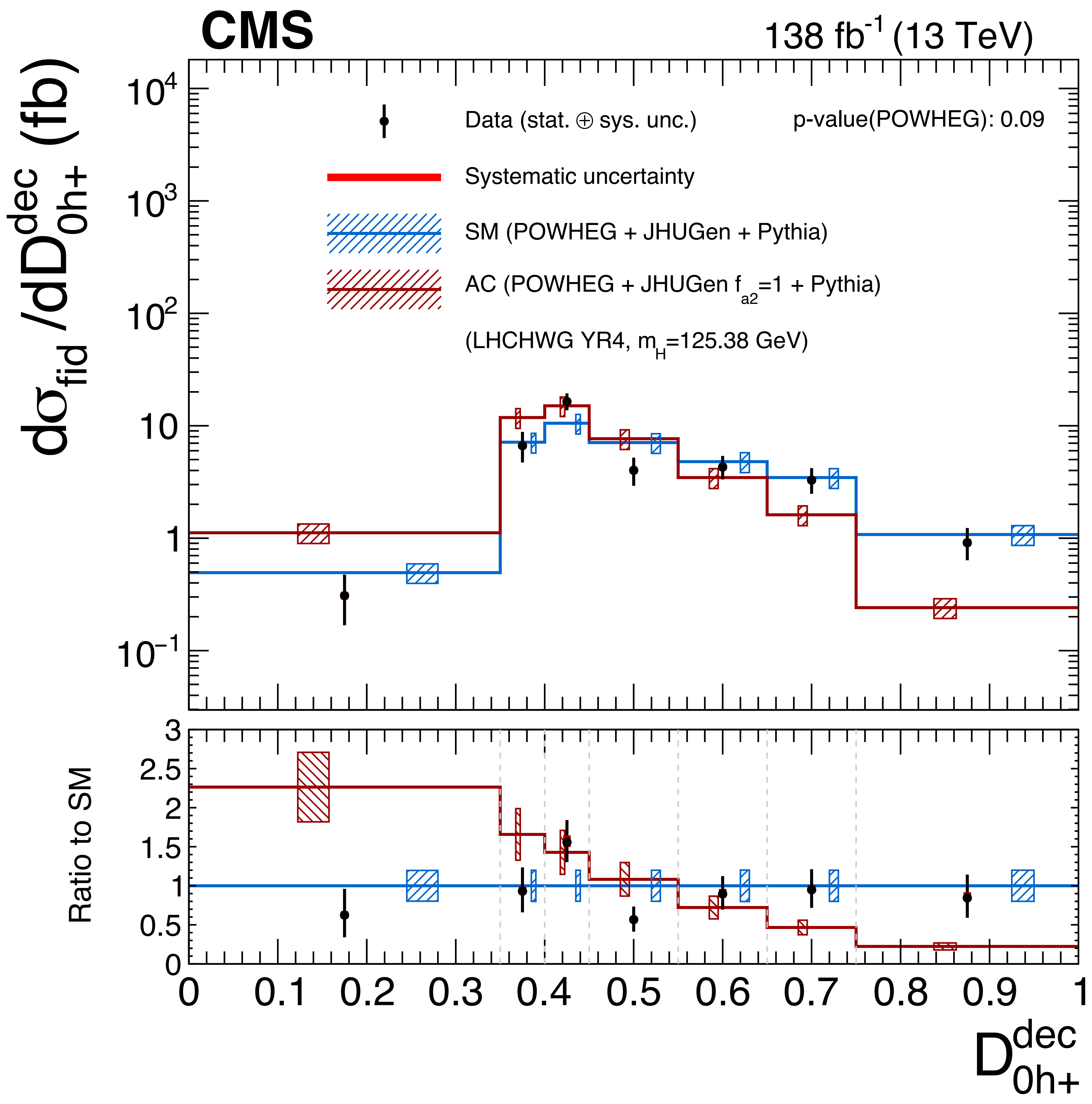


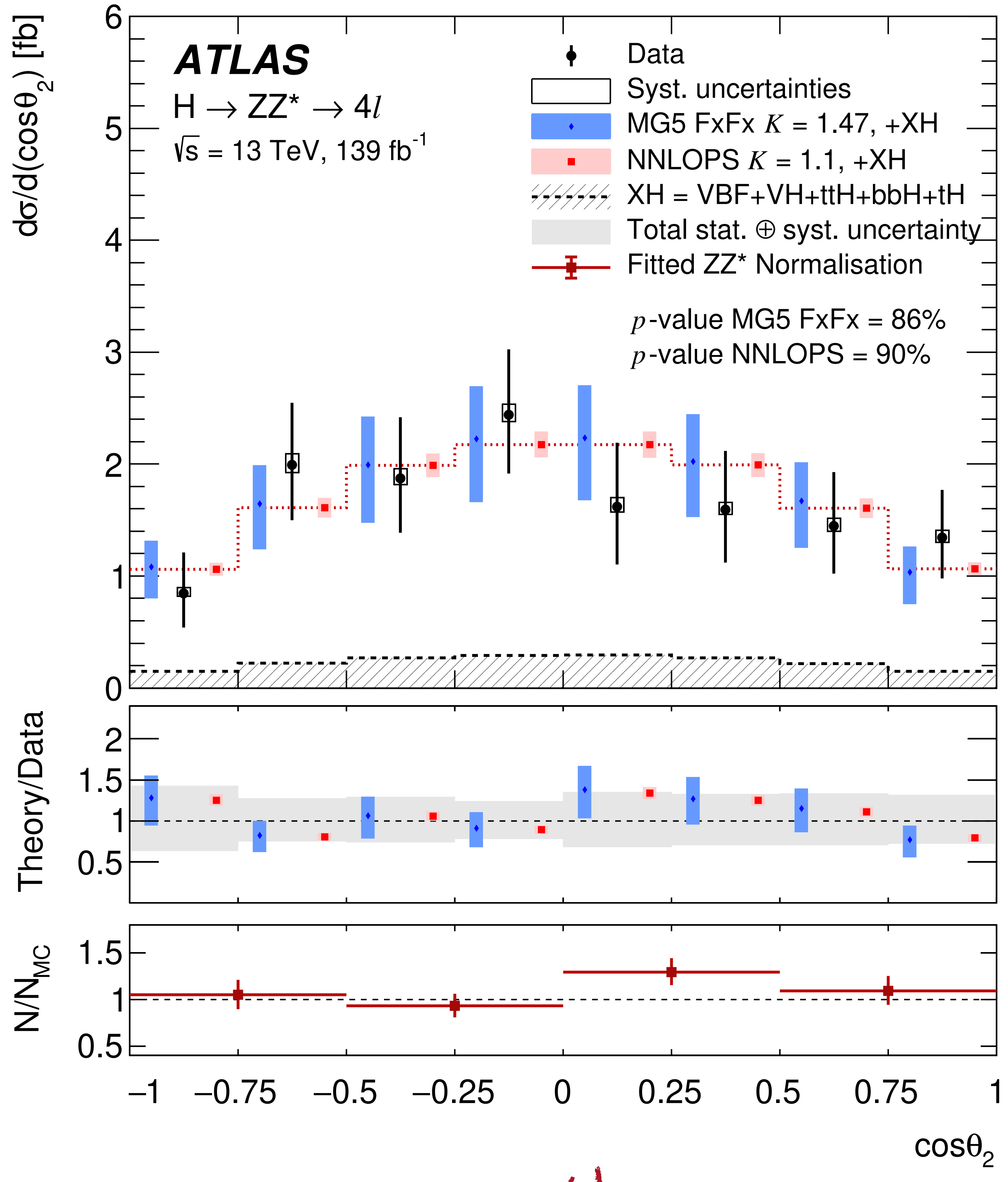
H→ZZ→4l

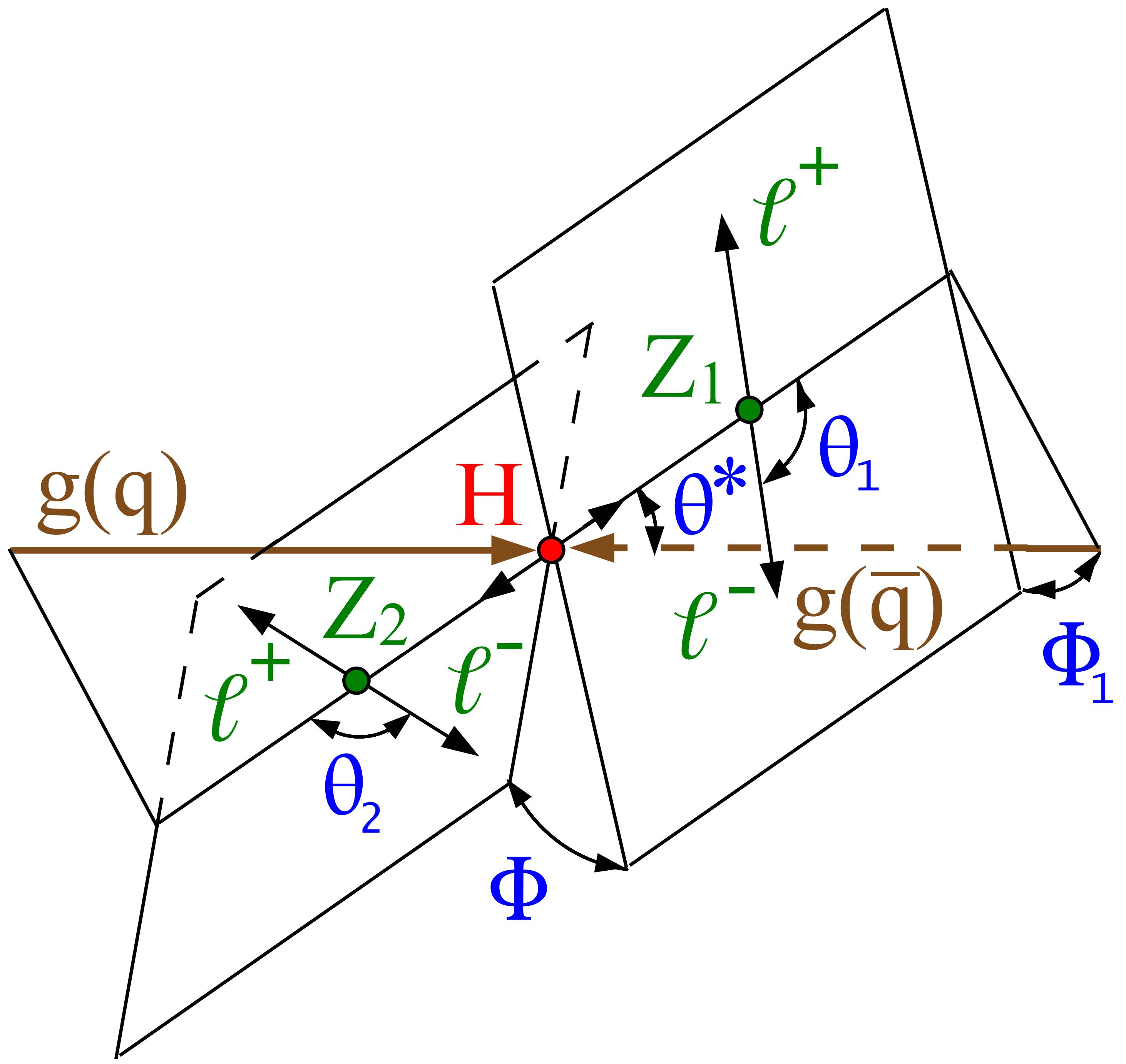
https://arxiv.org/abs/2202.00487 https://arxiv.org/abs/2305.07532 https://arxiv.org/abs/2004.03969

DECAY OBSERVABLES

- Differential measurements with respect to observables sensitive to **H decay**
  1) Decay angles in the Higgs rest frame
  2) Matrix element discriminants







H→ZZ→4l

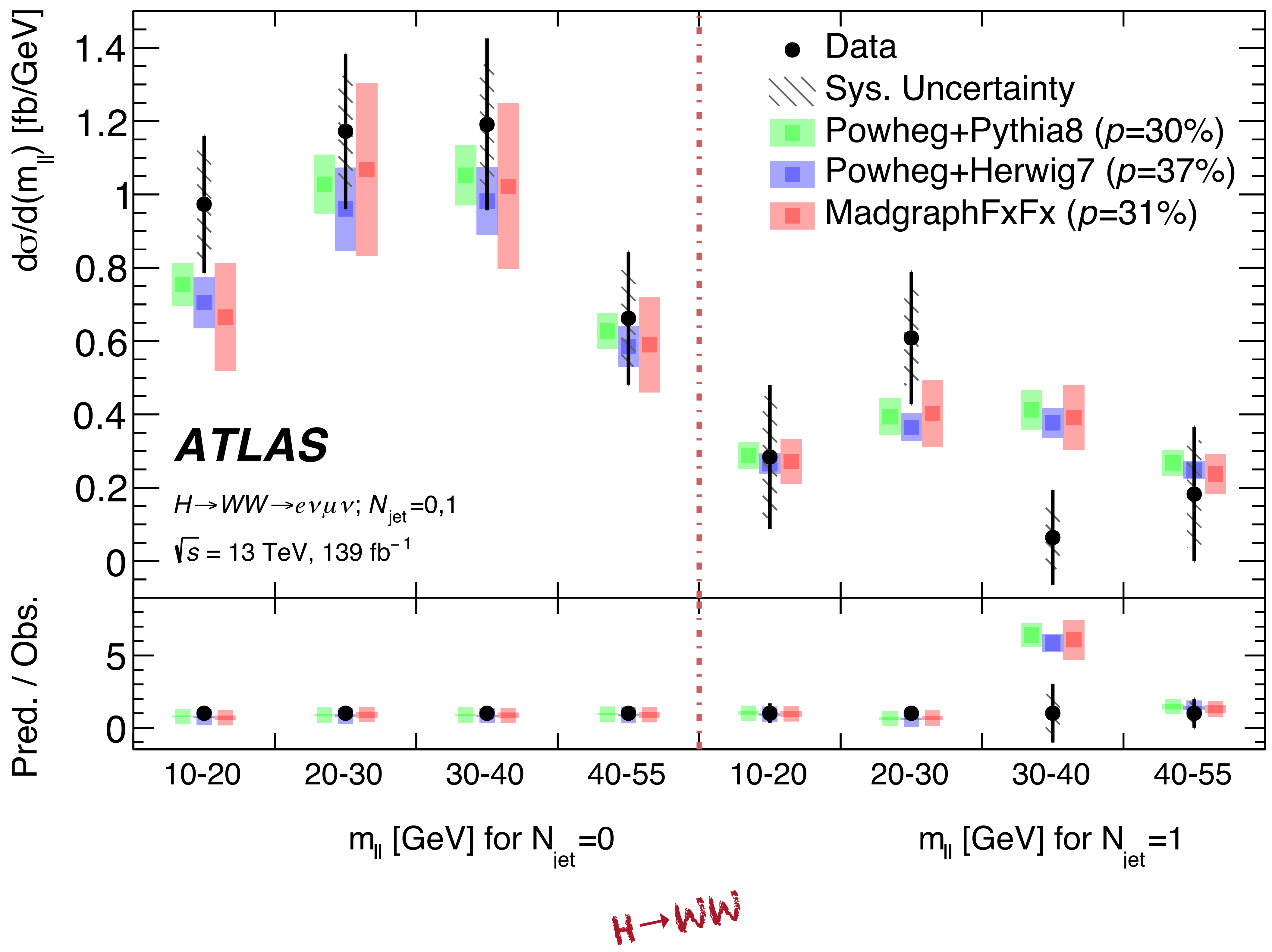
H→ZZ→4l

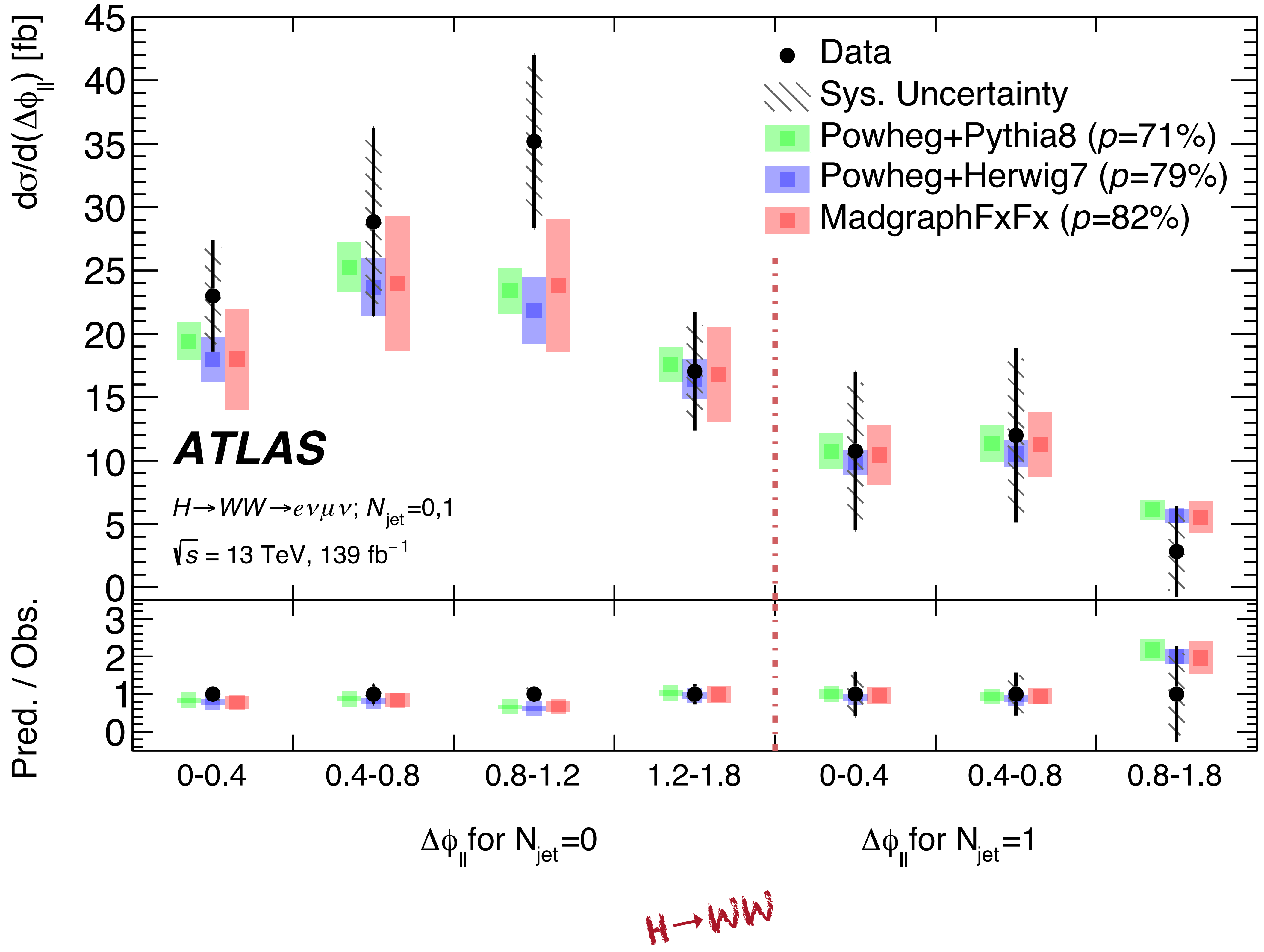
https://arxiv.org/abs/2305.07532

https://arxiv.org/abs/2004.03969

DOUBLE DIFFERENTIAL

- Lepton kinematics vs number of jets in H→WW





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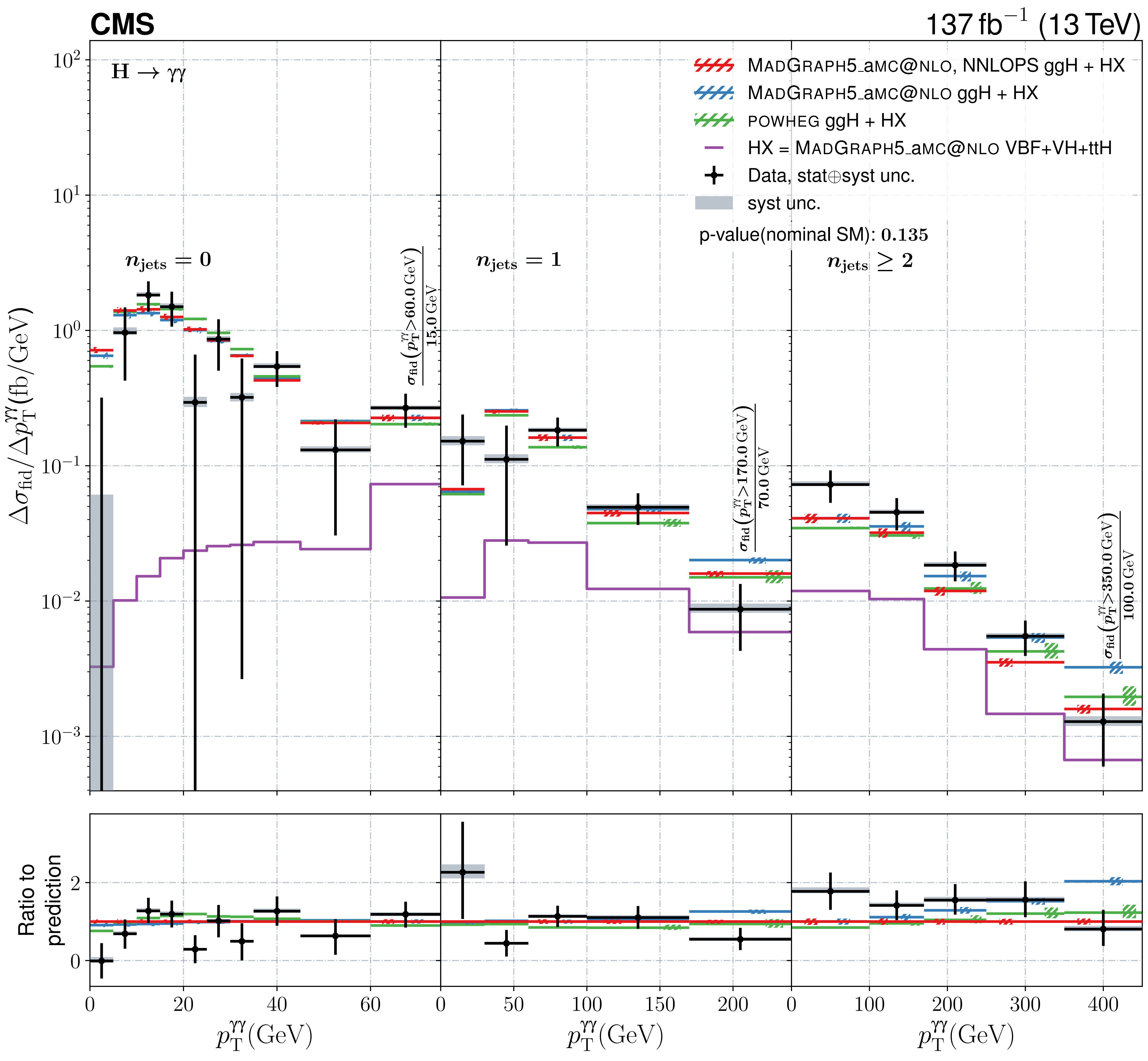
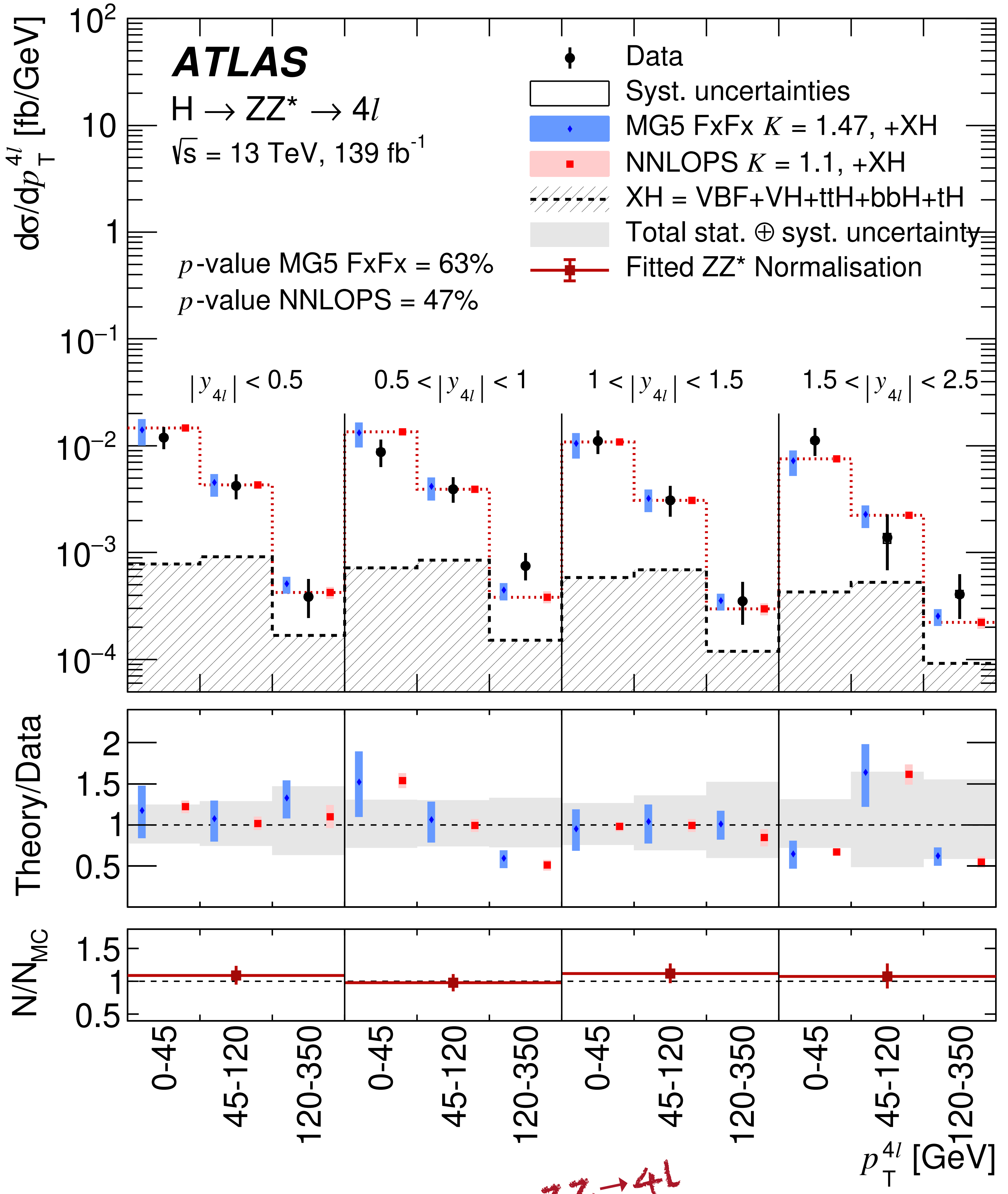
DOUBLE DIFFERENTIAL

- Transverse momentum vs number of jets in H→$\gamma\gamma$ and H→ZZ→4l



H→γγ



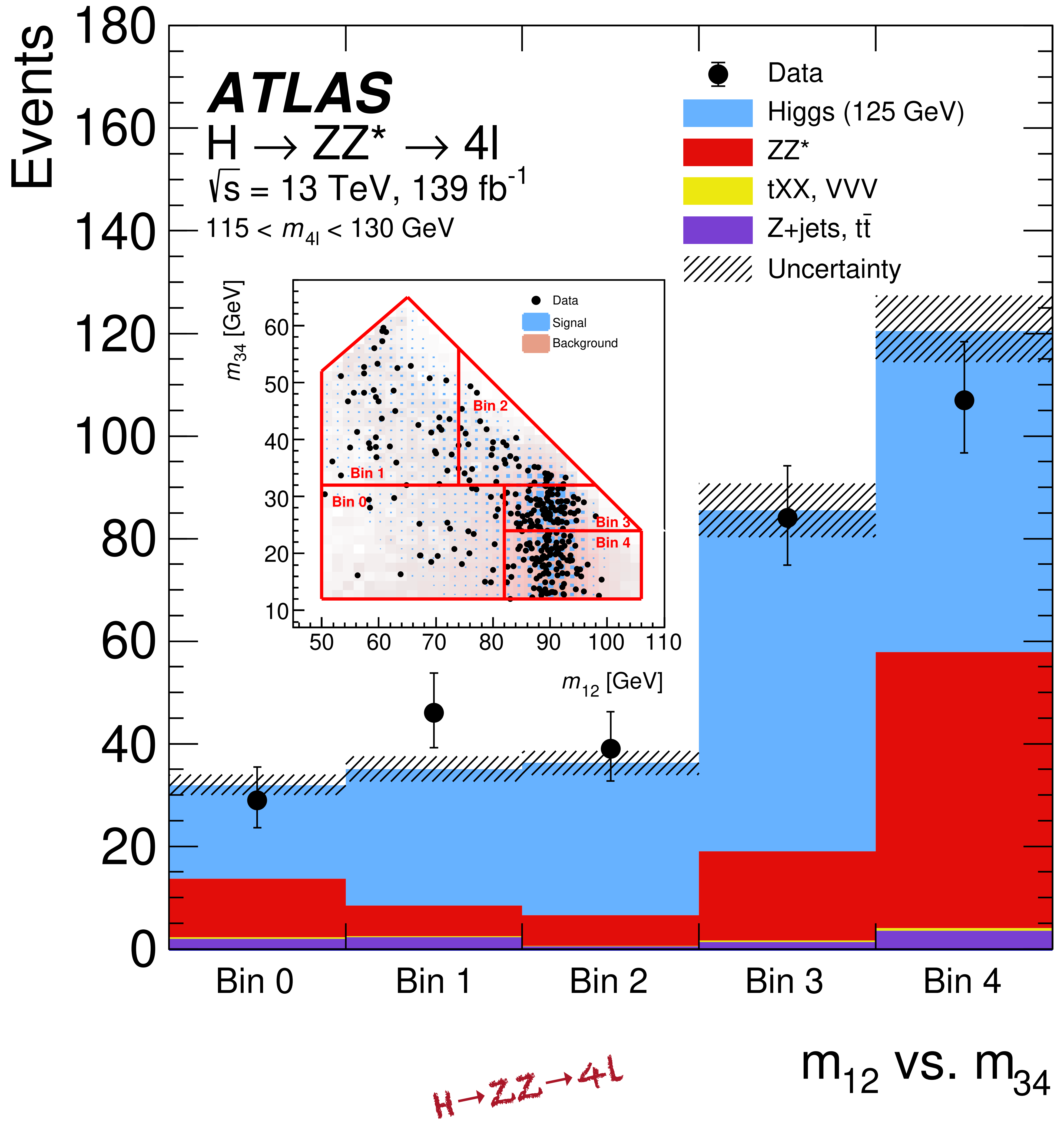
H→ZZ→4l

https://arxiv.org/abs/2208.12279

https://arxiv.org/abs/2004.03969

DOUBLE DIFFERENTIAL

- Z_1 vs Z_2 mass in H→ZZ→4l



H→ZZ→4l

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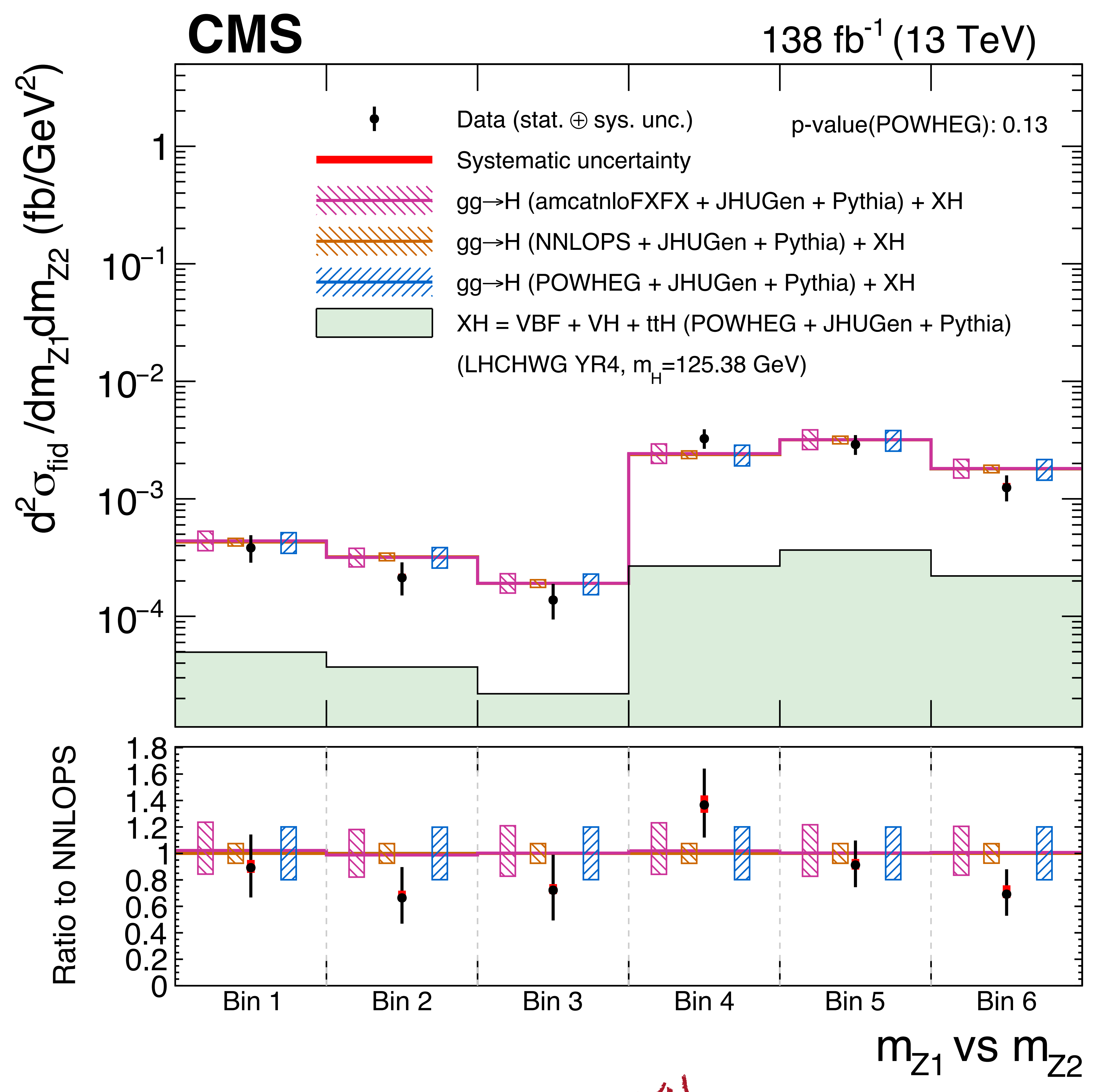


H→ZZ→4l

https://arxiv.org/abs/2305.07532

CONCLUSION

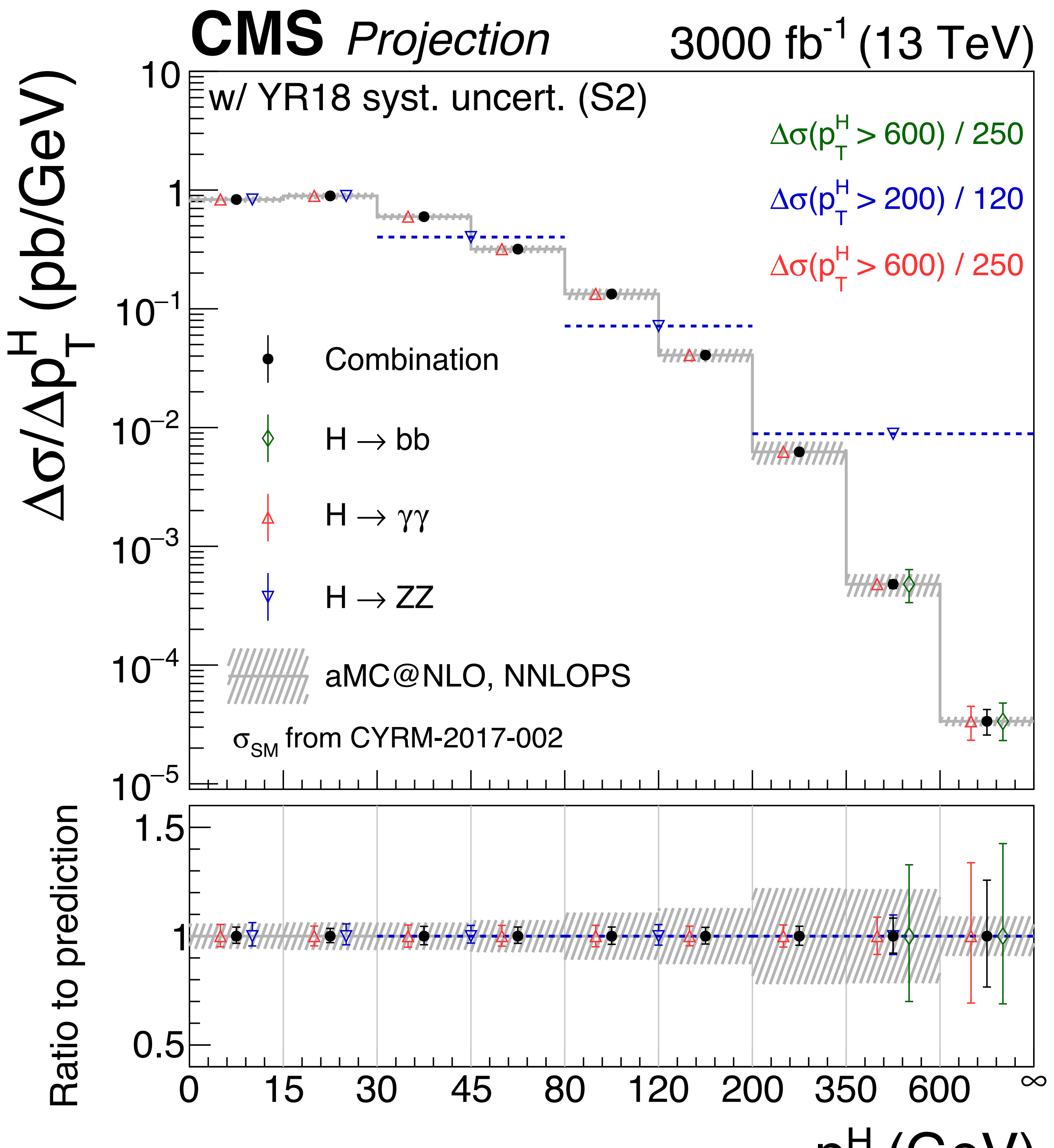
- Run2 data set allows extensive study of differential Higgs boson cross sections

- A variety of measurements are reported using five decay channels and their combinations from ATLAS and CMS Collaborations:
  - Observables targeting production and decay
  - Double differential cross sections
  - Many interesting variables not shown in this talk

- Differential distributions provide a handle to set limits on various BSM couplings:
  - Keeping in mind that SM used to calculate acceptance effects

- No tension with SM predictions

- Precision in measurements is still largely statistically limited
  - Many ideas ready for HL-LHC statistics!



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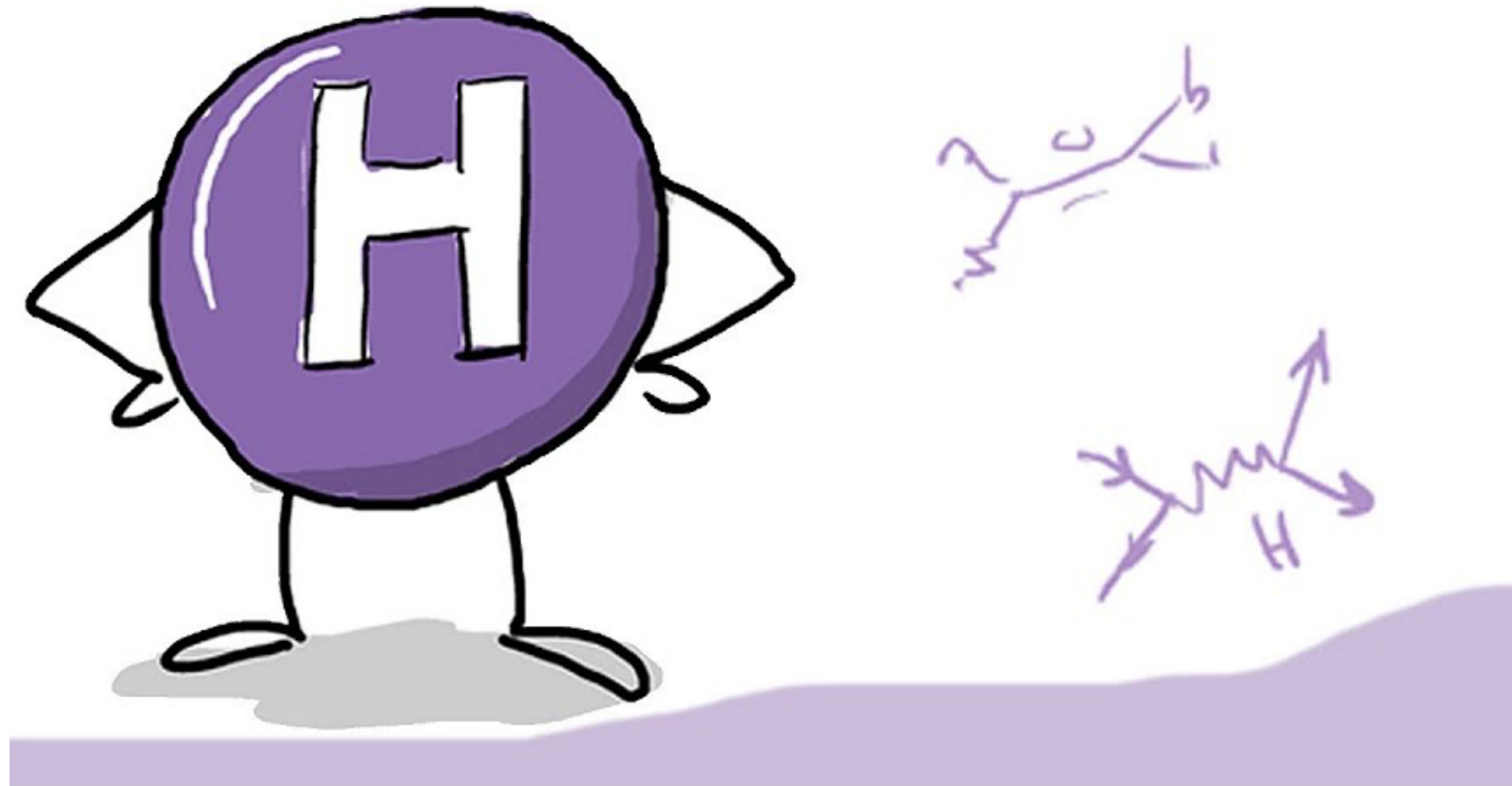
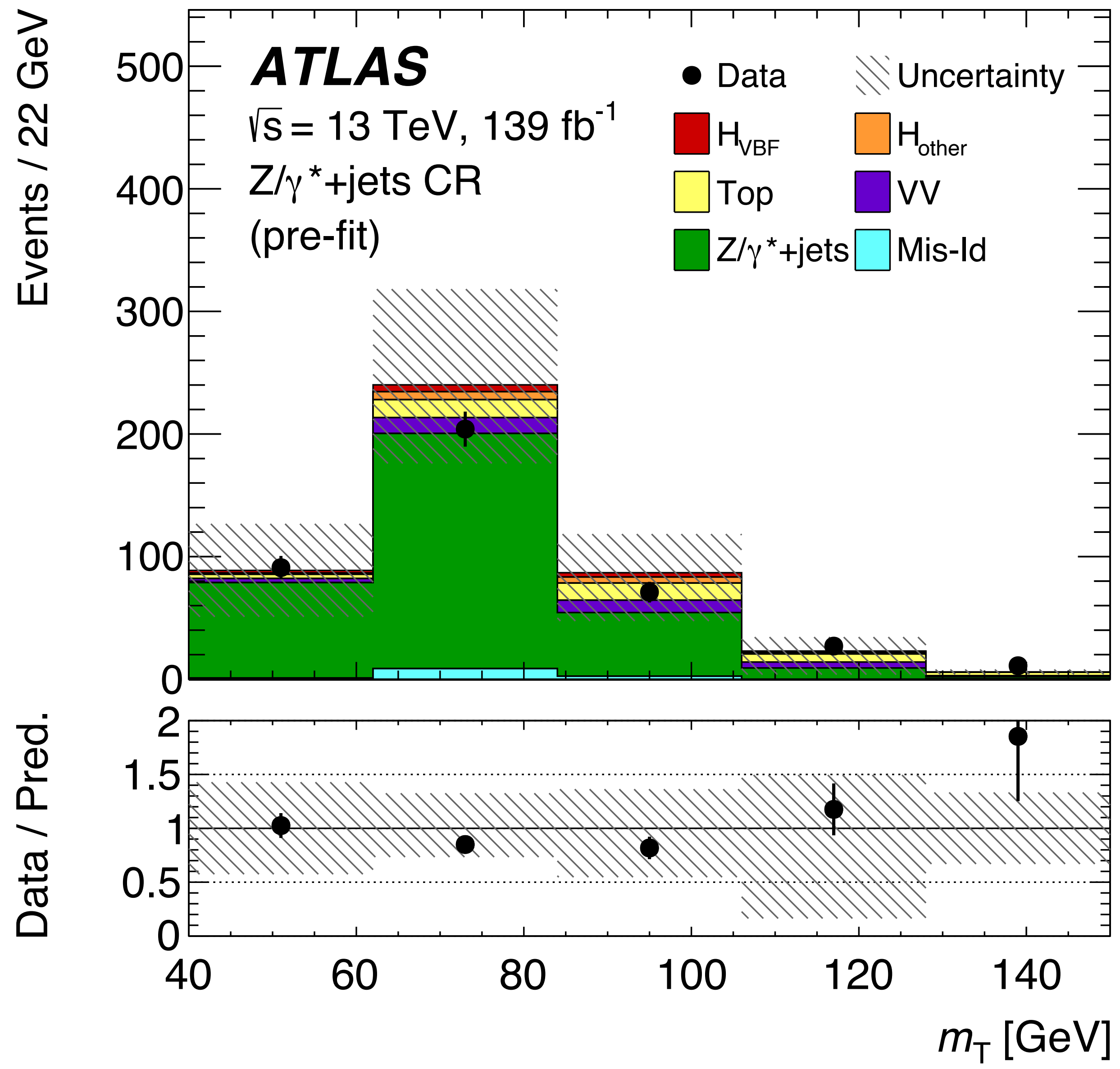
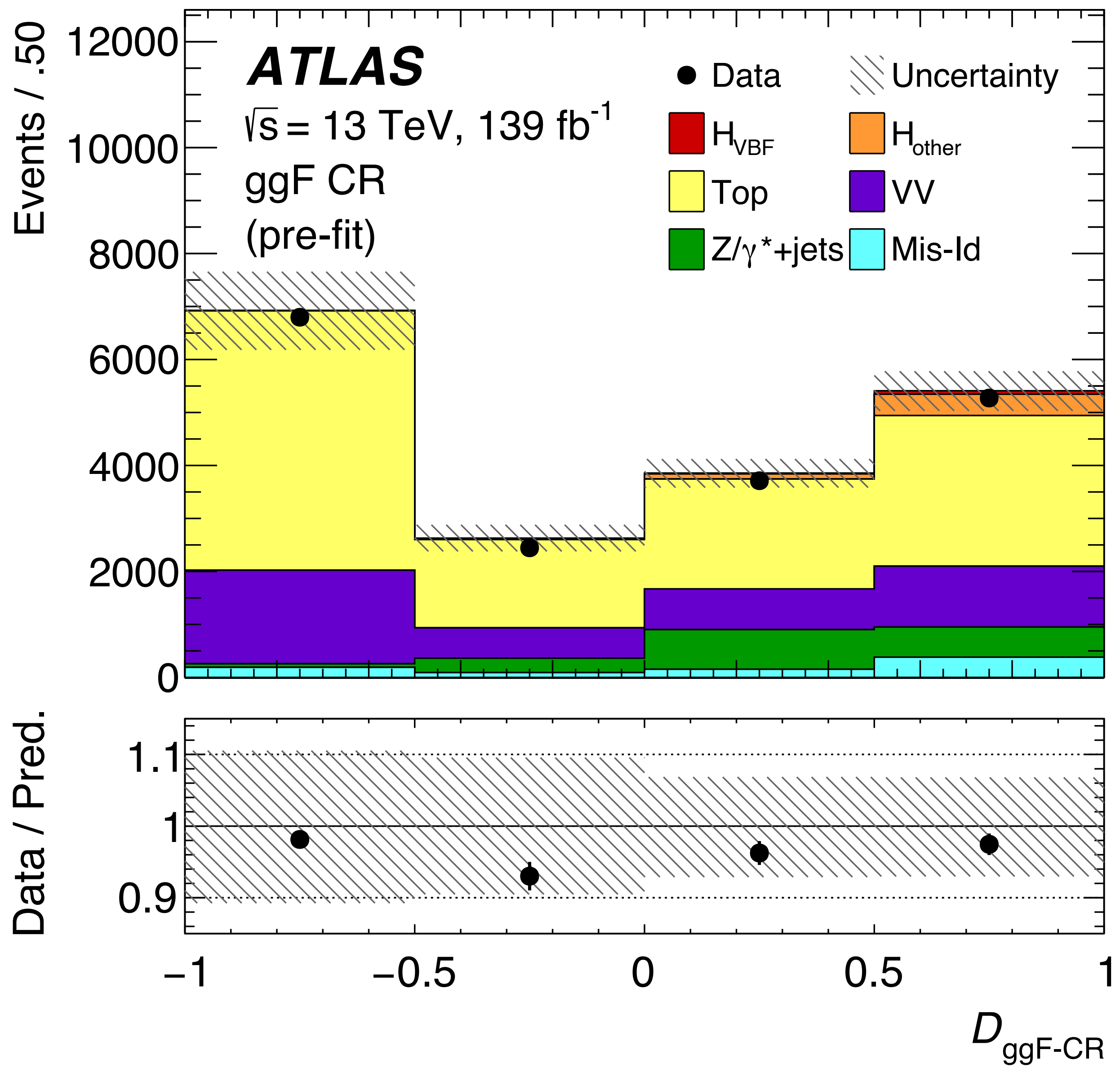


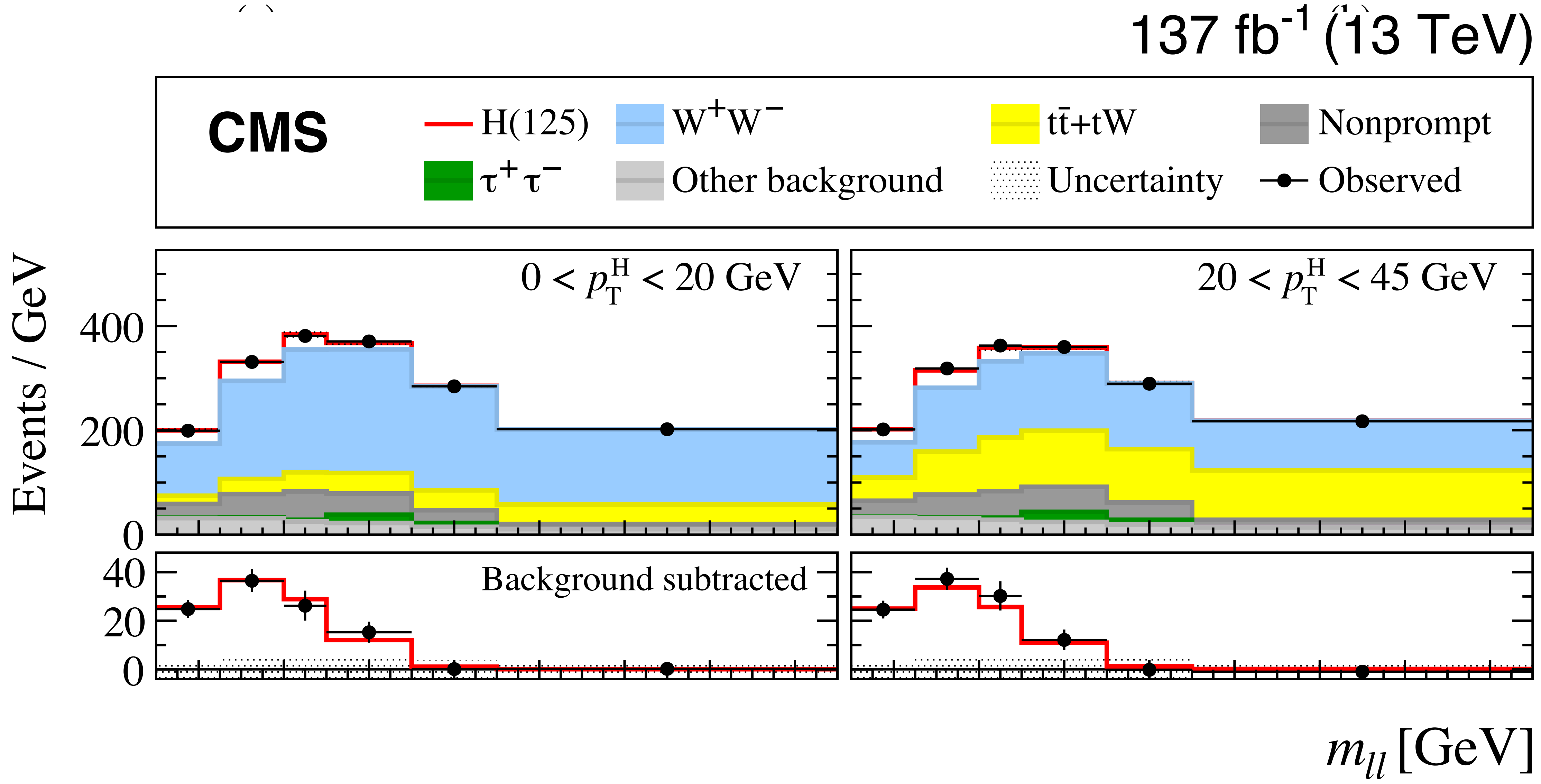
BACKUP

H→WW

- **Di-lepton** events with **missing p_T**
- SM background: **WW**, **tt+tW**, and $\tau\tau$
- **BDTs** used for better signal separation
- Template fits to **m_T / m_{ll}**
- ATLAS has a **dedicated analysis** for ggH and VBFH



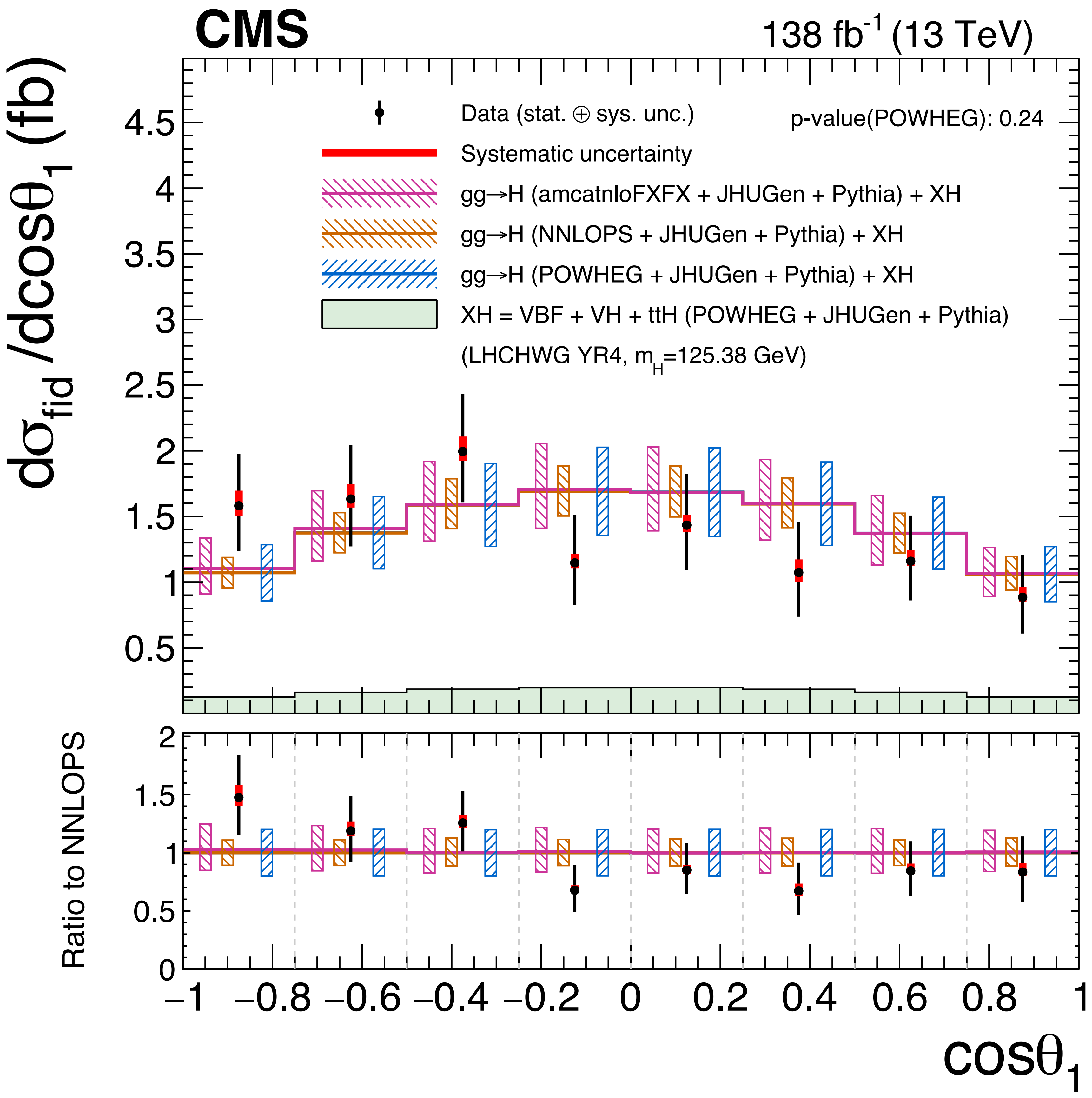




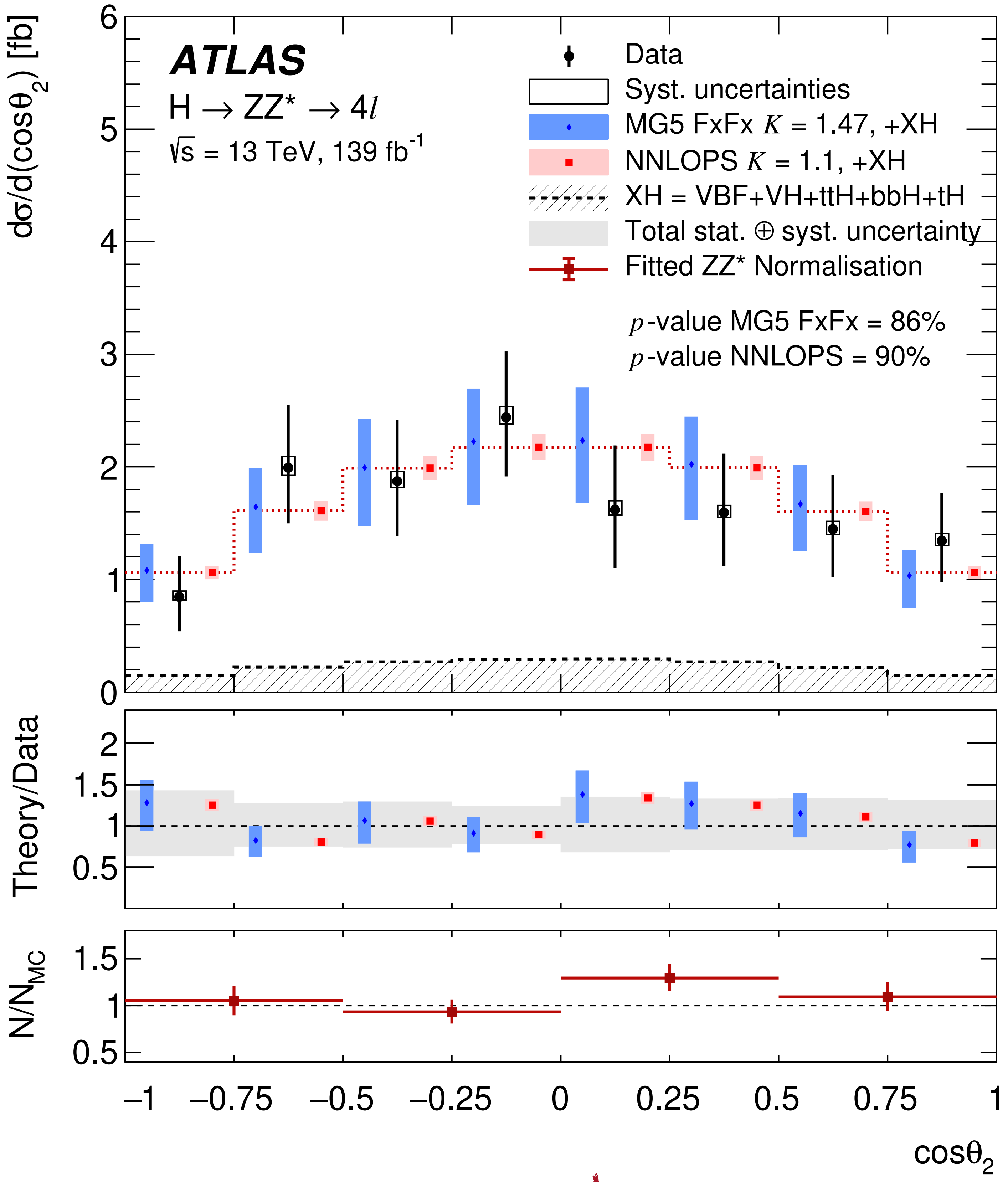
DECAY OBSERVABLES

◉ Differential measurements with respect to observables sensitive to **H decay**

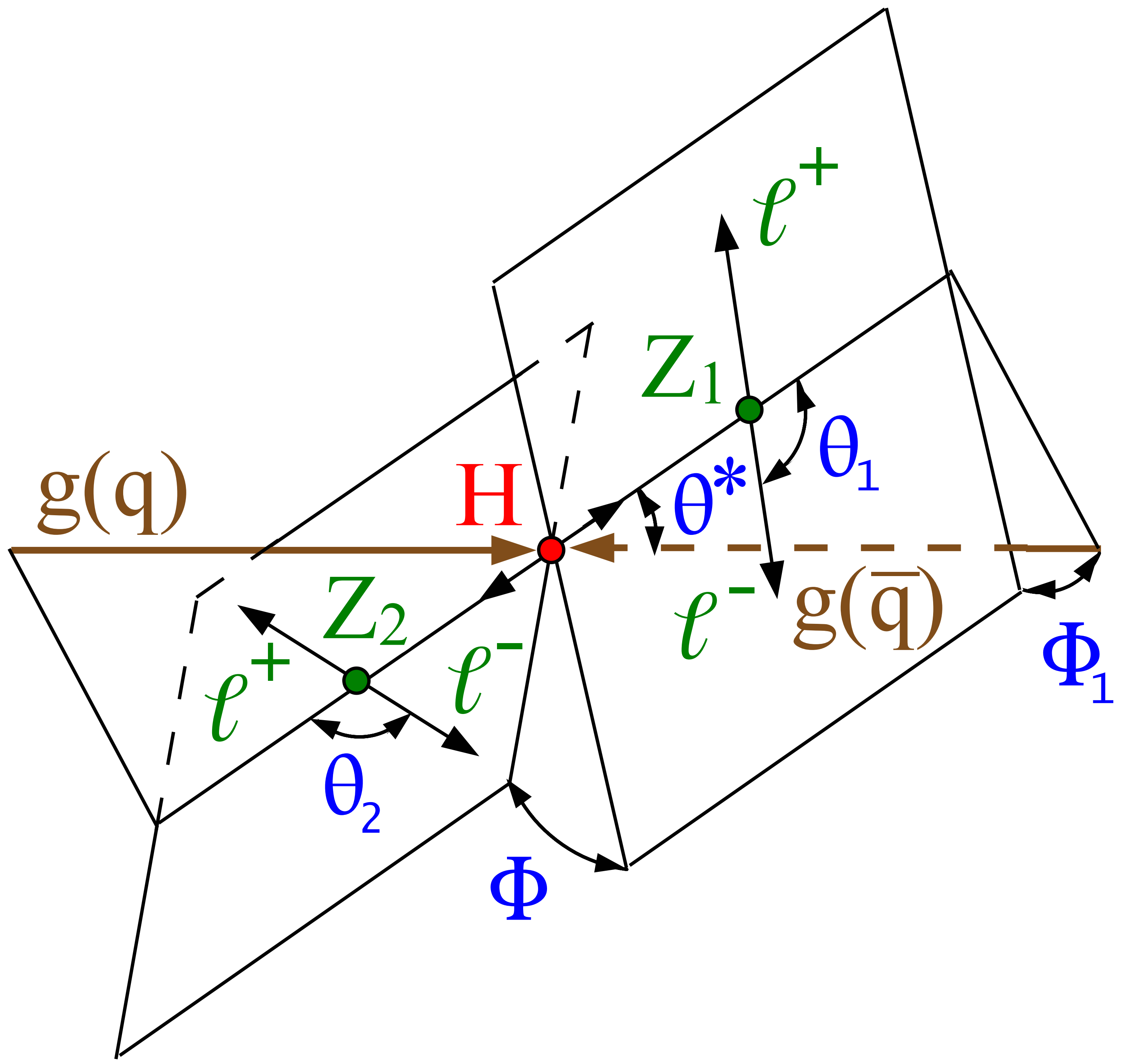
1) Decay angles in the Higgs rest frame



H→ZZ→4l



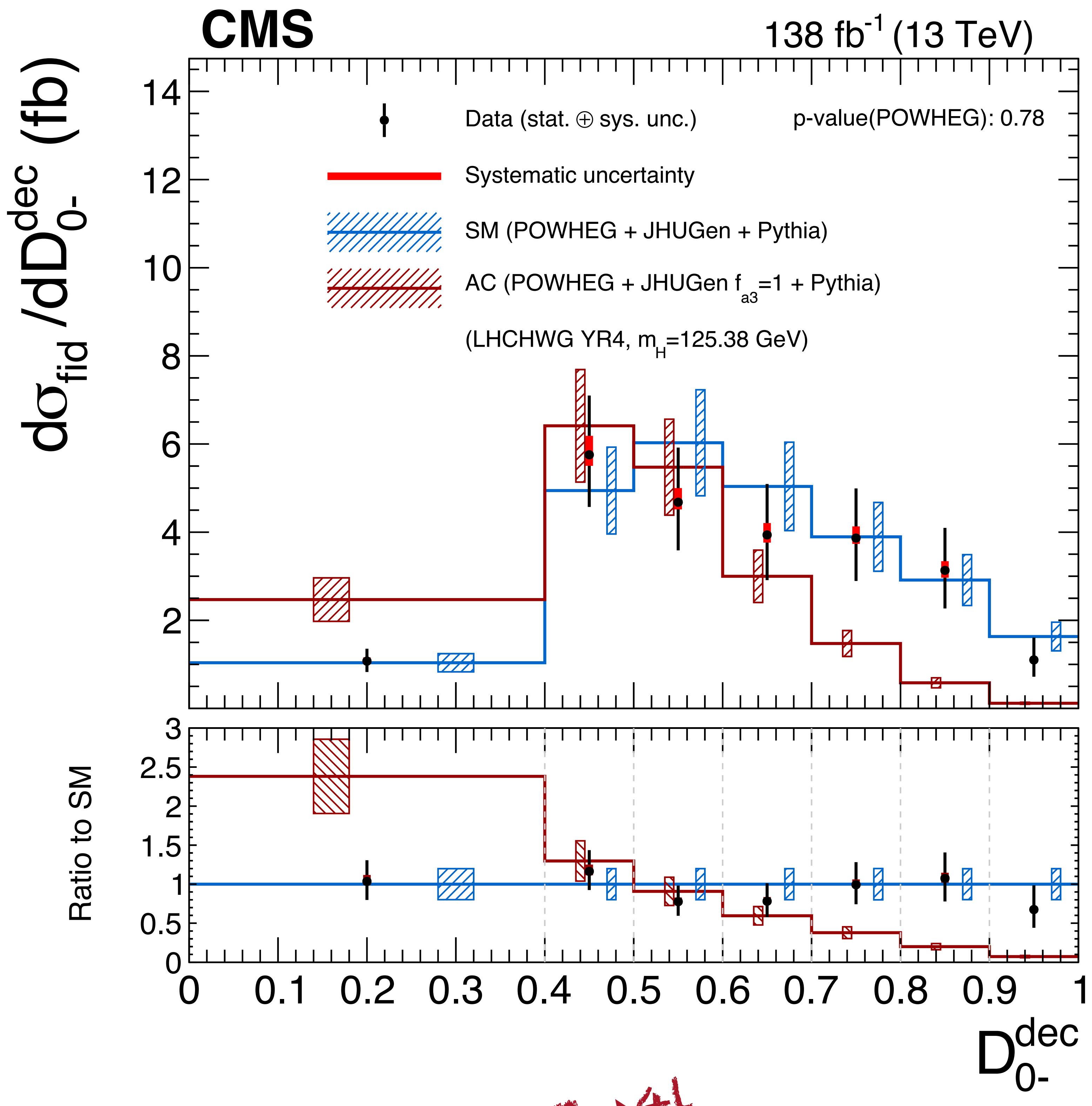
H→ZZ→4l



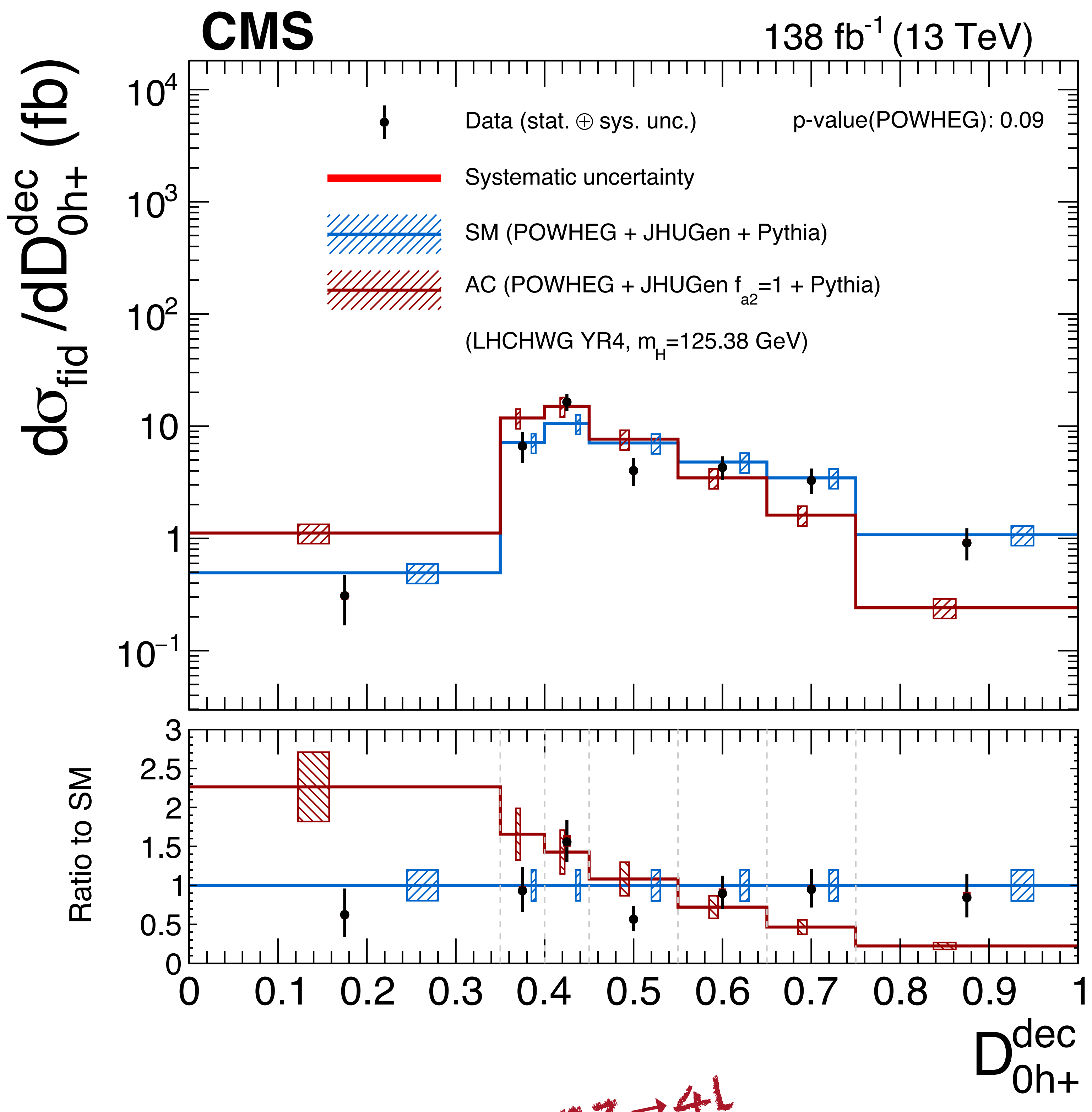
DECAY OBSERVABLES

- Differential measurements with respect to observables sensitive to **H decay**
  1) Decay angles in the Higgs rest frame
  2) Matrix element discriminants

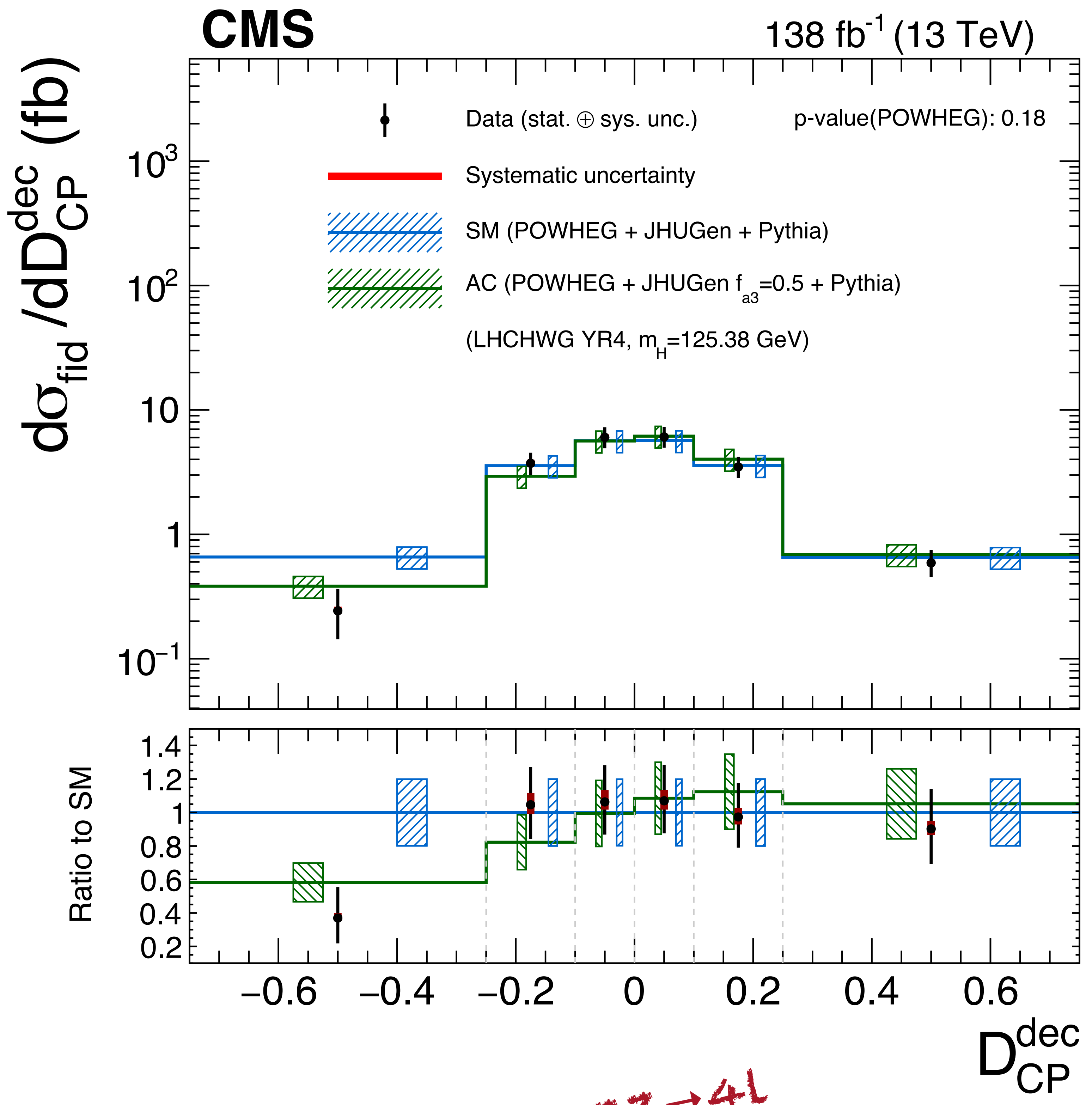
$$\mathcal{D}_{\text{alt}}\left(\vec{\Omega}\right) = \frac{\mathcal{P}_{\text{sig}}\left(\vec{\Omega}\right)}{\mathcal{P}_{\text{sig}}\left(\vec{\Omega}\right) + \mathcal{P}_{\text{alt}}\left(\vec{\Omega}\right)}, \qquad \mathcal{D}_{\text{int}}\left(\vec{\Omega}\right) = \frac{\mathcal{P}_{\text{int}}\left(\vec{\Omega}\right)}{2\sqrt{\mathcal{P}_{\text{sig}}\left(\vec{\Omega}\right)\,\mathcal{P}_{\text{alt}}\left(\vec{\Omega}\right)}},$$



H→ZZ→4l



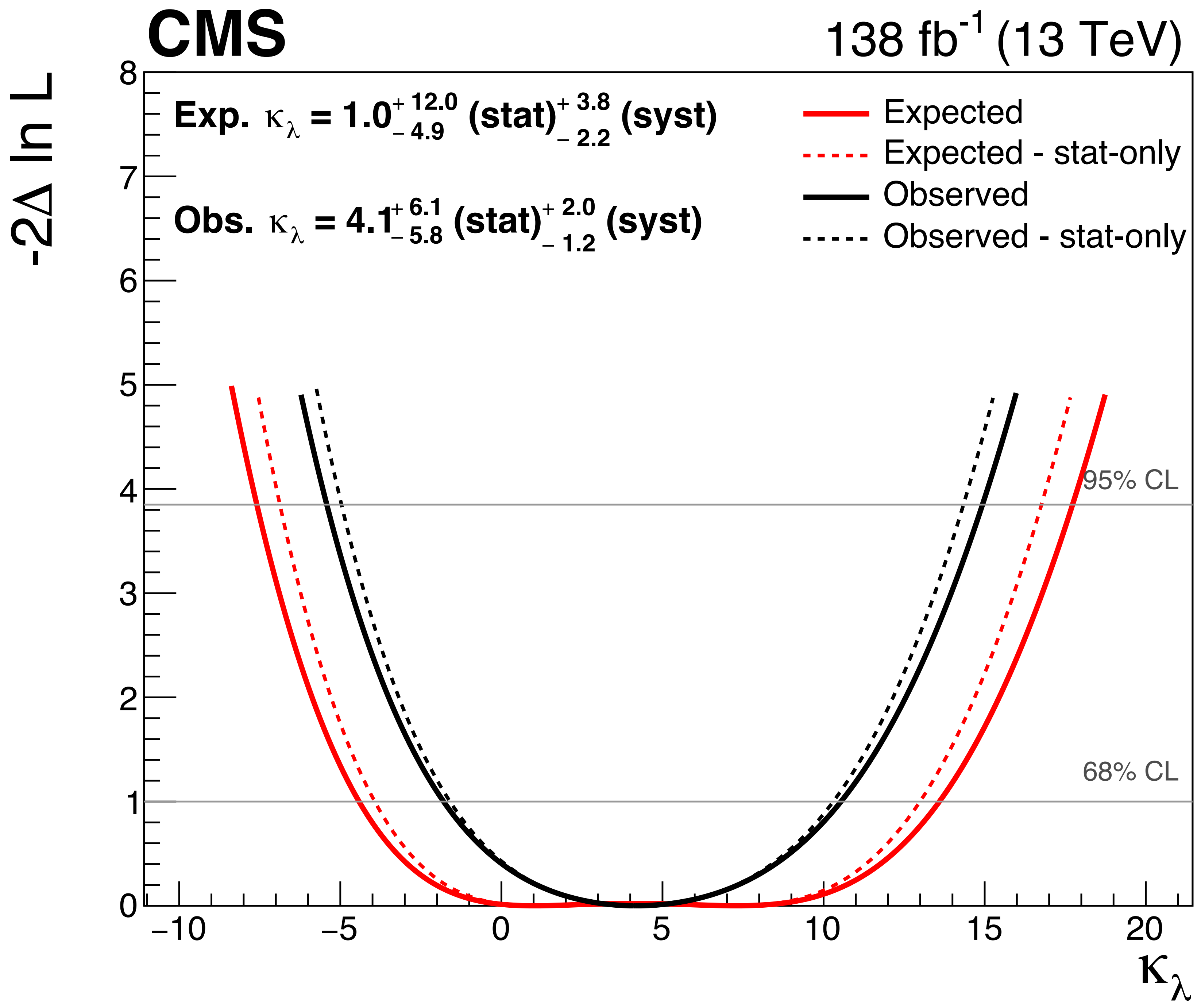
H→ZZ→4l



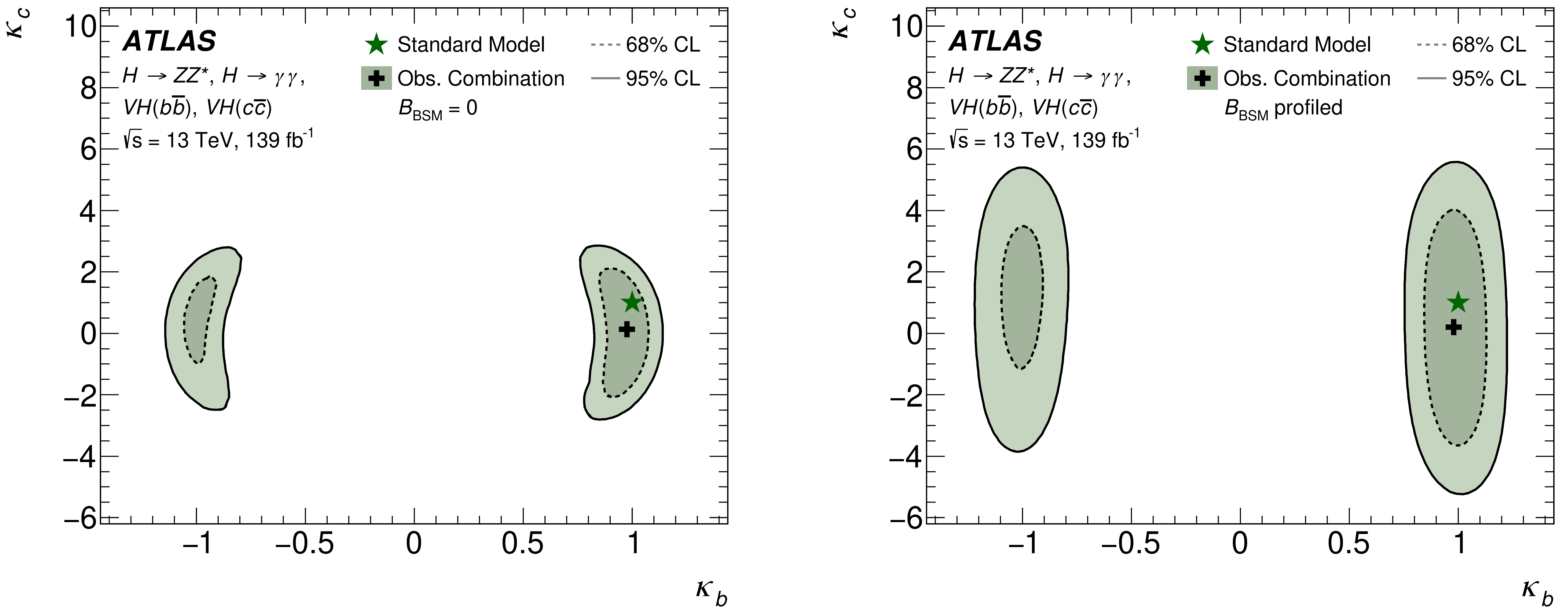
H→ZZ→4l

HIGGS P_T INTERPRETATIONS

- ttH and VH $p_T(H)$ spectrum **sensitive** to Higgs boson **self coupling**
  - possible to extract κ_λ limits from the differential cross section
- ATLAS made a **combined fit** to p_T Higgs differential distributions (from **H→ZZ→4l** and **H→$\gamma\gamma$**) and MVA distributions from **VHbb** and **VHcc** analysis to extrct κ_b and κ_c



H→ZZ→4l



(a) (b)

H→ZZ→4l

H→$\gamma\gamma$

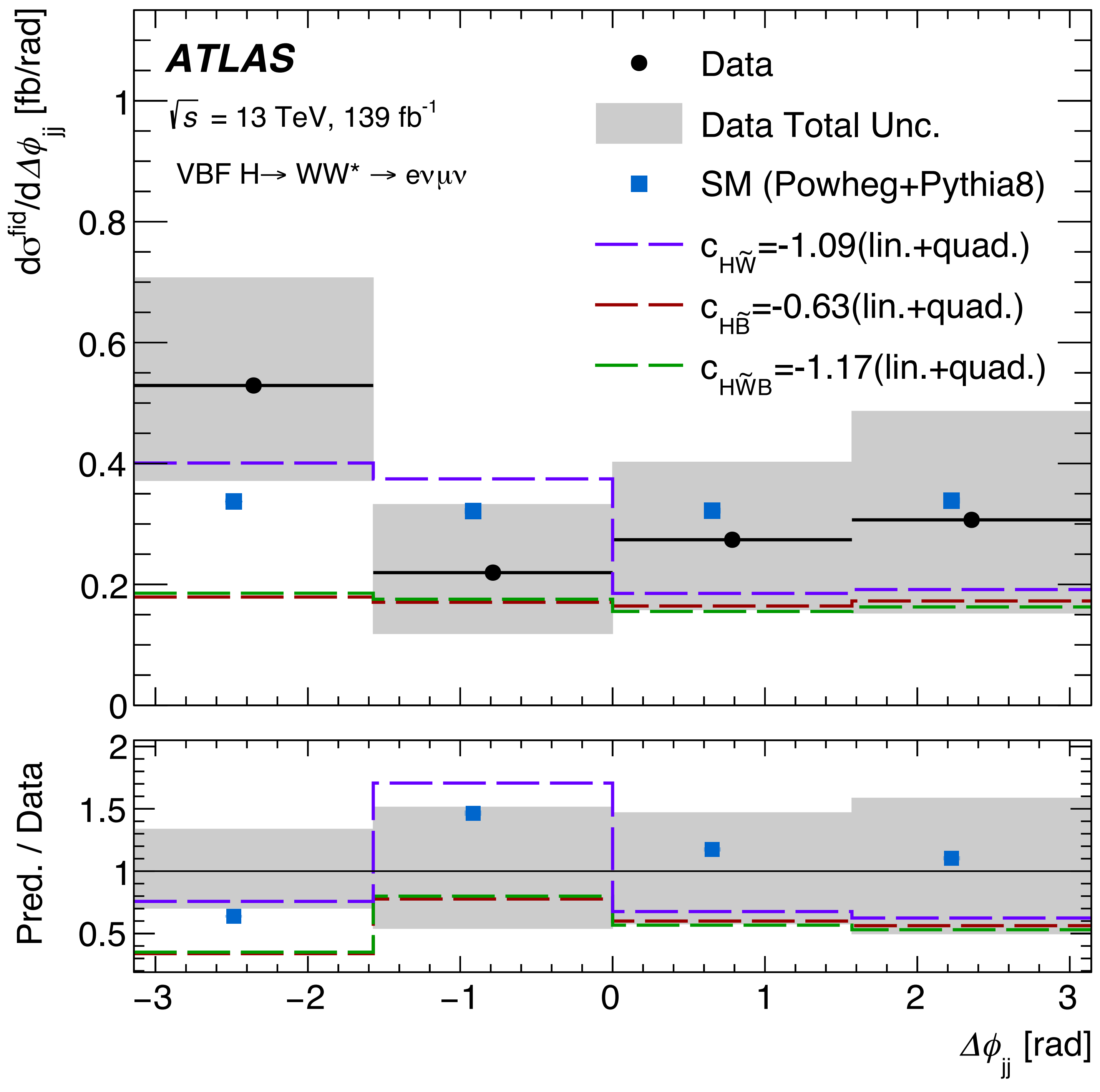
VH→bb

VH→cc

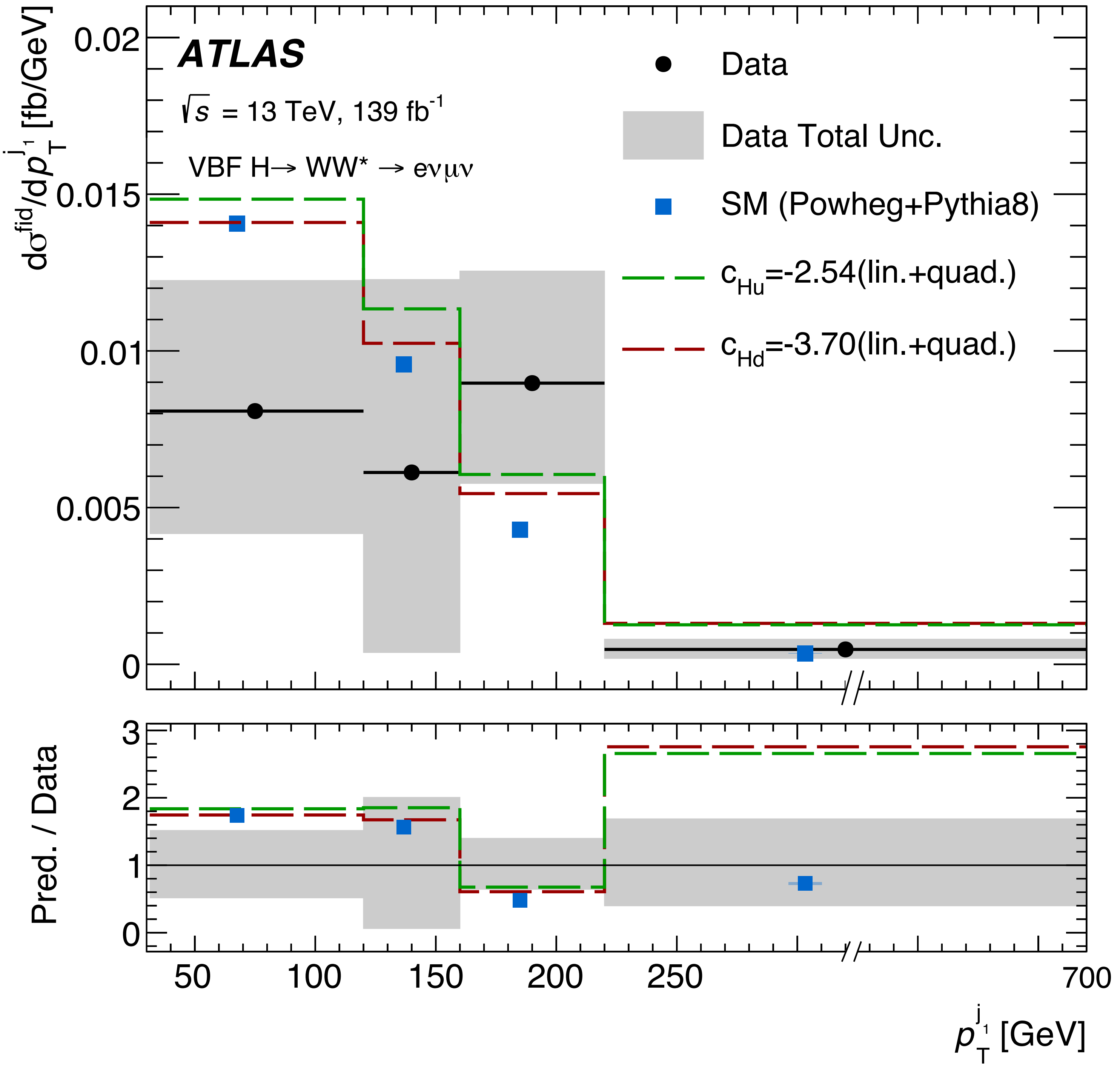
DIJET INTERPRETATIONS

- In VBFH→WW constrains on **Wilson coefficients** defined in SMEFT
  - No sensitivity for a simultaneous fit, **one coefficient at the time**
  - $\Delta\phi_{jj}$ and $p_{\perp}^{j_1}$ are the most **sensitive variables**
  - **Two scenarios** if pure dimension 6 operators are considered or not

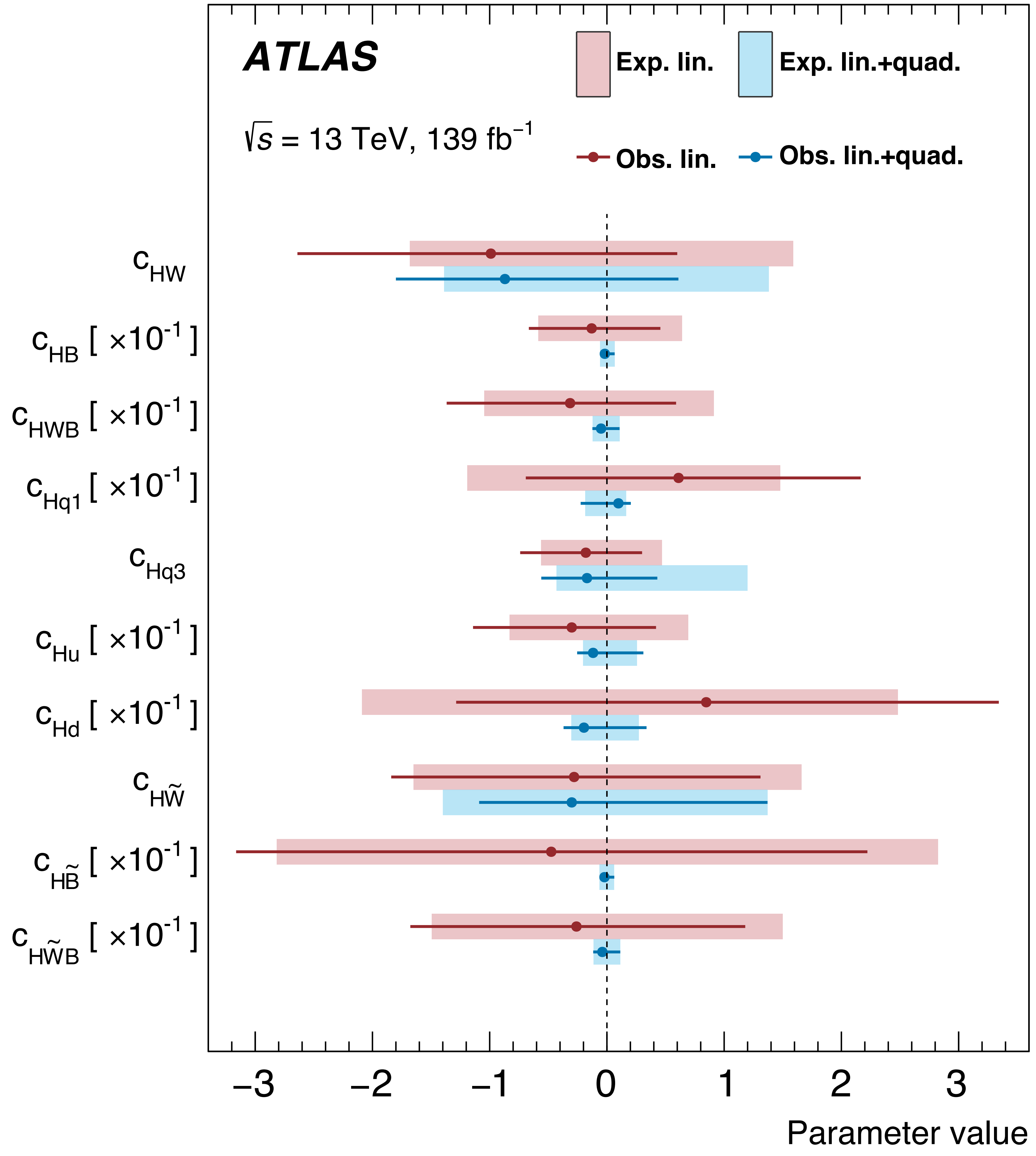
$$\sigma \propto |\mathcal{M}_{\mathrm{EFT}}|^2 = |\mathcal{M}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{M}_i|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + \boxed{2\sum_i \frac{c_i}{\Lambda^2} Re(\mathcal{M}_{\mathrm{SM}}^*\mathcal{M}_i)} + \boxed{\sum_{i,j} \frac{c_i c_j}{\Lambda^4} Re(\mathcal{M}_i^*\mathcal{M}_j)}.$$



H→WW

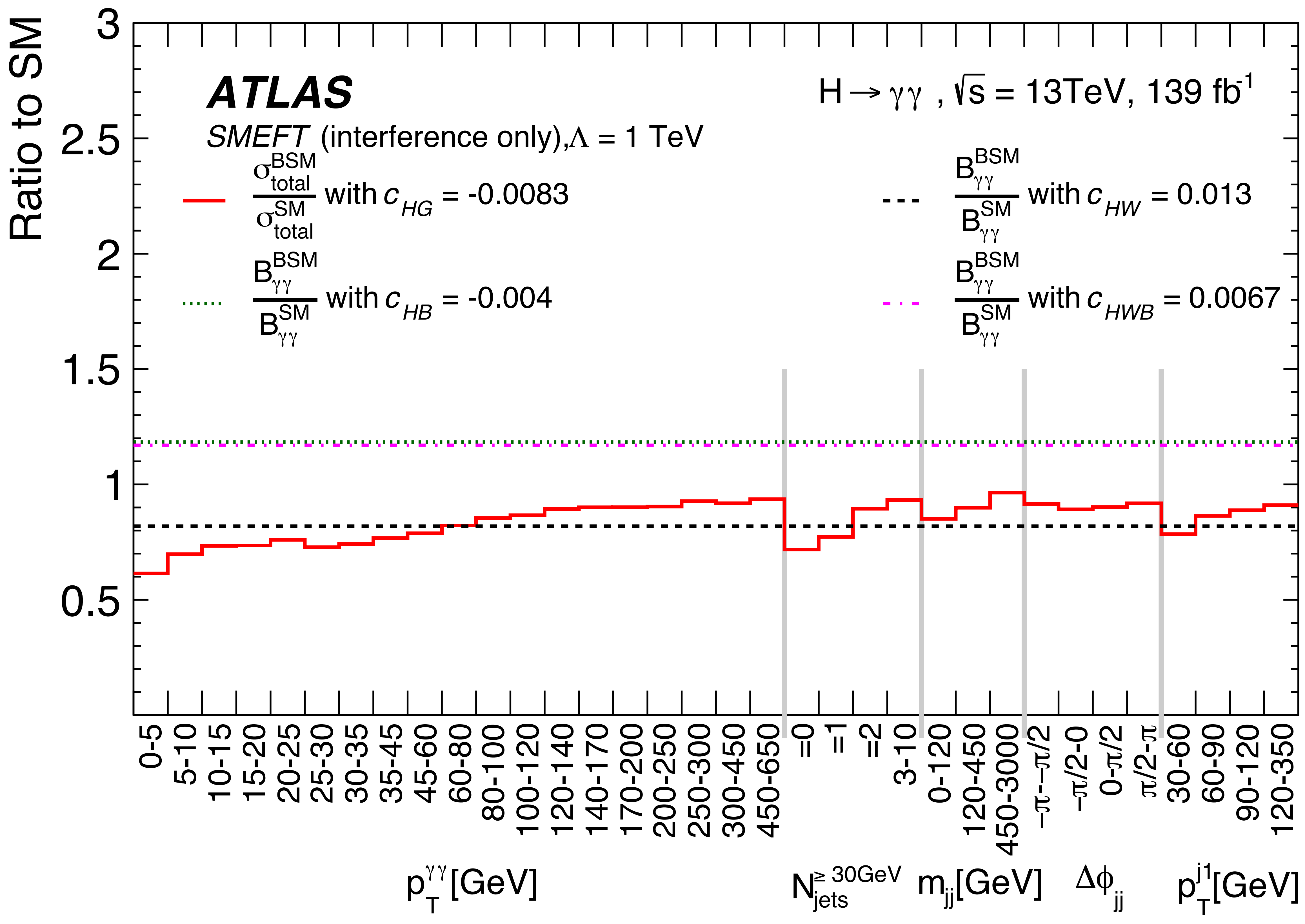


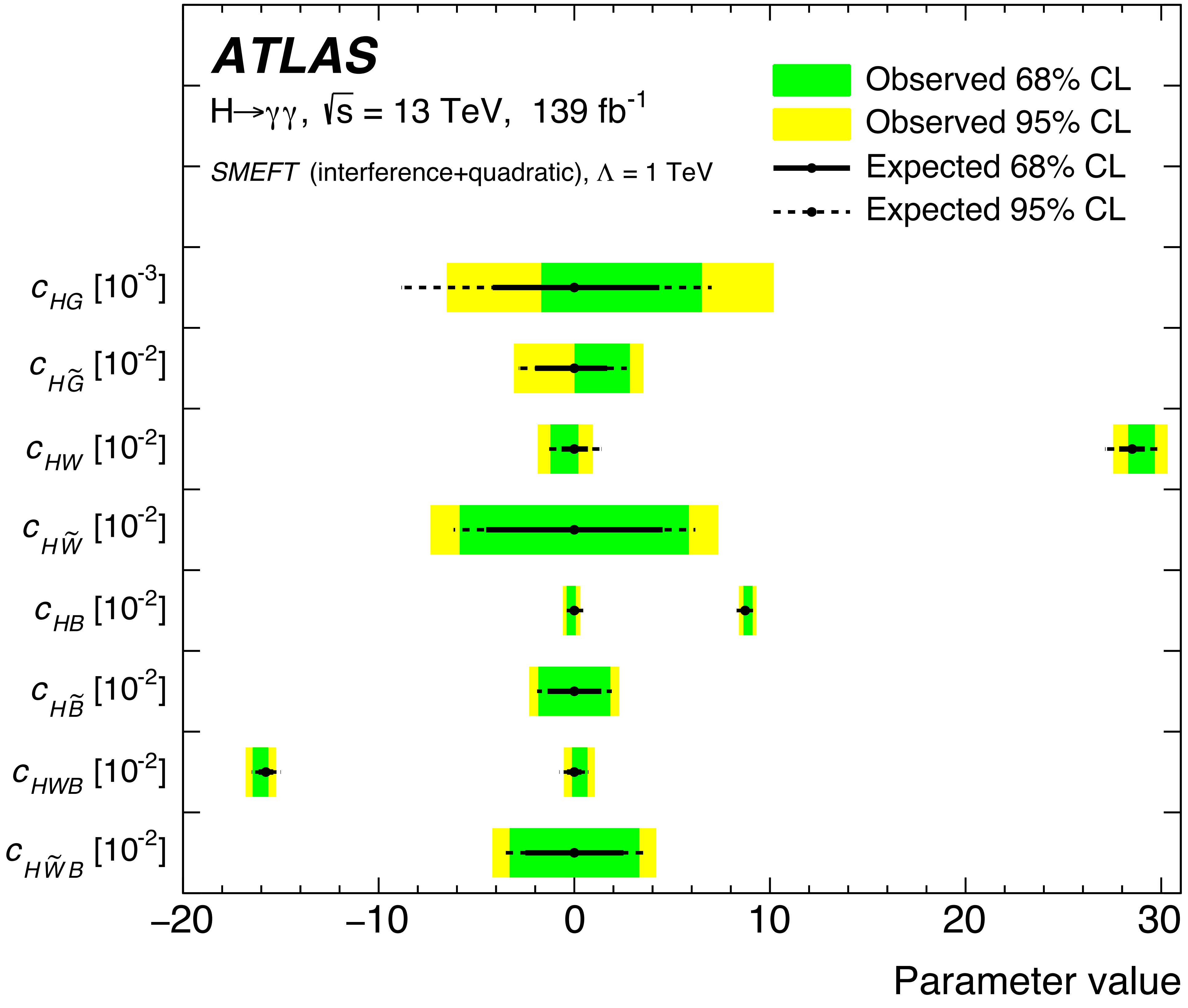
H→WW



DIJET INTERPRETATIONS

- Similar analysis in H→$\gamma\gamma$, setting constrains on **Wilson coefficients**
  - No sensitivity for a simultaneous fit, **one coefficient at the time**
  - Five differential distributions used to set limits
  - **Two scenarios** if pure dimension 6 operators are considered or not





INTERPRETATIONS

- Z_1 mass vs Z_2 mass in H→ZZ→4l can be used to set limits on modifications of couplings with **left** and **right** handed **leptons**
  - Pseudo-observables affecting angular distributions set to 0
  - di-lepton invariant mass only sensitive variable
  - **Four scenarios** considered