Latest results from the LHC and the search for new physics

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27ème Congrès Général de la SFP, Troyes

Precision tests of the Standard Model and the Higgs boson at the LHC

- Recent results from the **ATLAS and CMS** collaborations have sharpened our understanding of the **electroweak sector** as well of the **scalar sector** (**Higgs boson**), testing the **Standard Model (SM)** with unprecedented accuracy

- **Precision Tests:**
  - Standard Model: Updated measurements of **W boson mass and width**
  - Detailed studies of **Higgs boson properties**: mass, decay width, and couplings

- Results are broadly consistent with SM predictions, given the current experimental and theoretical precision, but still leave considerable room for BSM contributions.

- **Interpretation with Effective Field Theory (EFT)**
  - EFT provides a model-independent framework to explore BSM physics
  - Describes potential new interactions via higher-dimensional operators
  - Sharpens sensitivity to small deviations from SM behaviour

Electroweak physics

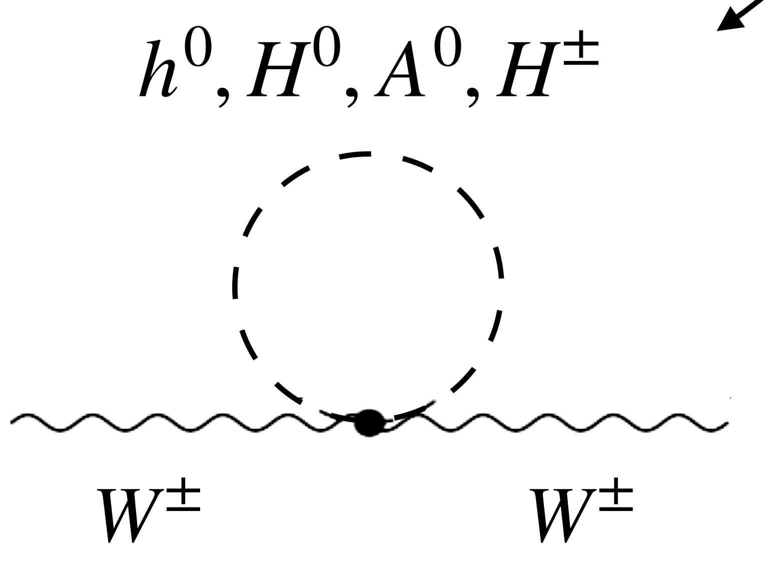
W mass & width

A precise measurement of the W boson mass, m_W, and of its width, Γ_W, connected with its lifetime, is an essential test of the SM as any deviation could provide hints towards BSM physics

W mass:

- Predicted with a precision of 6 MeV, but measurement in data less sensitive (c.f. m_Z ~ 2 MeV uncertainty)
  - Neutrino forces us to use less direct observables to infer constraints on the mass ⇒ many systematic uncertainties to control
- Sensitive to loop corrections from heavy particles (Higgs, top quark, or new physics).
  - Deviations from SM predictions suggest potential BSM physics.
  - Recently measured by CDF in 2022 was most precise to date (9.4 MeV uncertainty) but in significant tension with other measurements

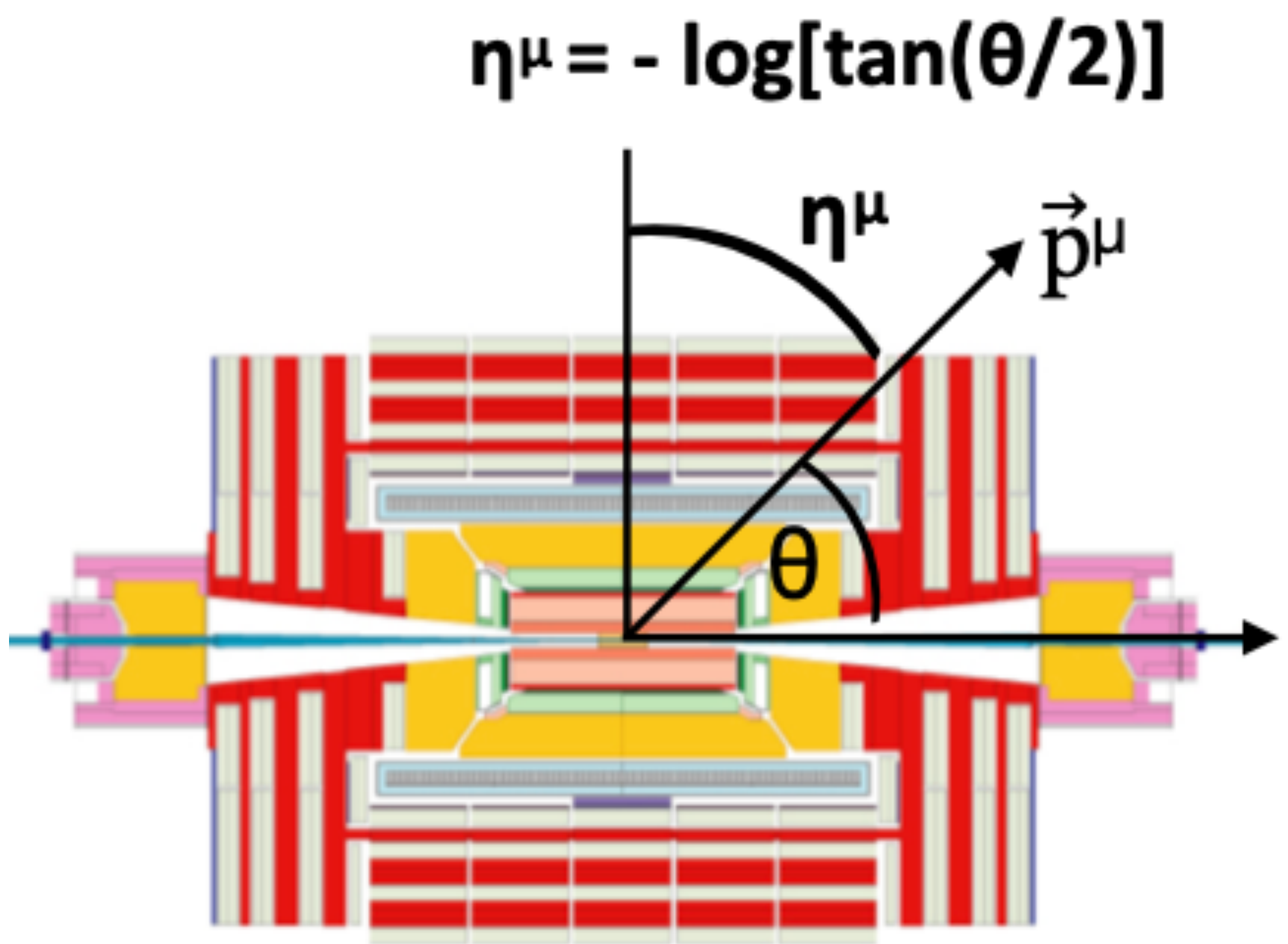
$$m_W^2 = \frac{m_Z^2}{2}\left(1 + \sqrt{1 - \frac{\sqrt{8}\pi\alpha(1+\Delta r)}{G_F m_Z^2}}\right)$$



W width:

- Sensitive to the total decay rate of the W boson → tests electroweak theory and couplings
- Precision measurements constrain possible invisible or exotic decays

W boson mass in CMS



Dataset Overview

- Based on a well-understood subset of 13 TeV data (~16.8 fb^{-1} from the 2016 run with an average pileup of ~30)
- Large statistics: over 100 million W → μν events

Theoretical Modeling

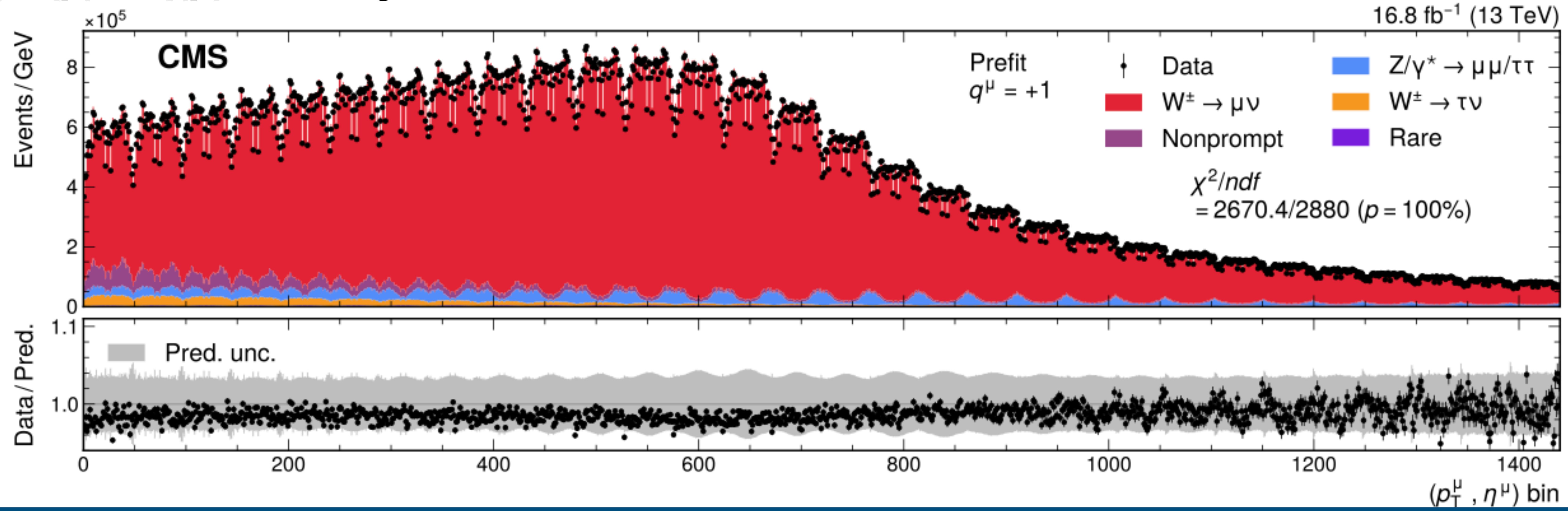
- Uses the most accurate theoretical models and uncertainty estimates available
- In-situ constraints derived directly from the W → μν data sample

Muon Calibration

- Primary calibration from J/ψ → μμ, validated using Z → μμ

Fit in fine bins of pT(μ) × η(μ) × charge

CMS-SMP-23-002



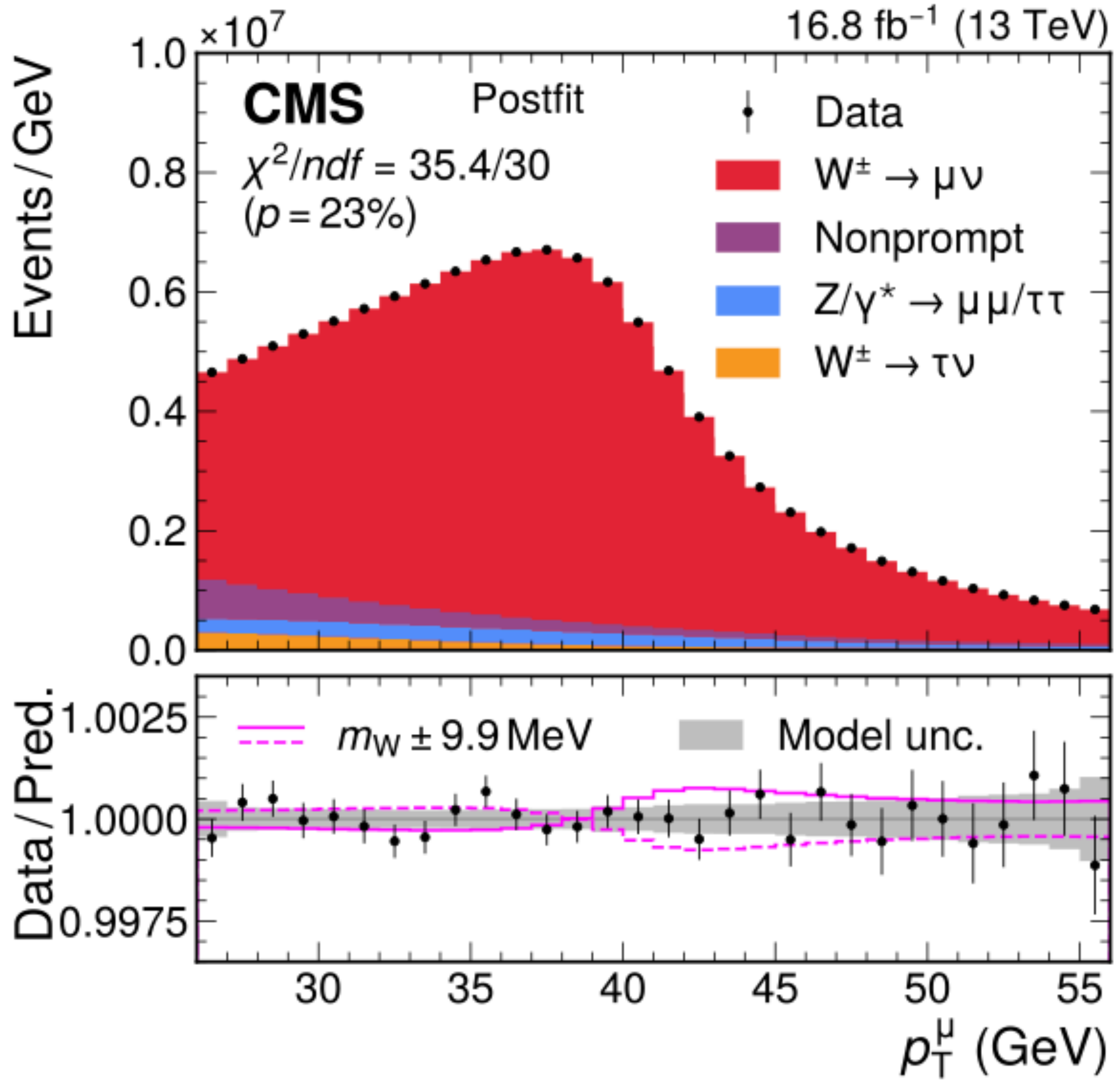
W boson mass in CMS

Most precise m_W measurement at the LHC:

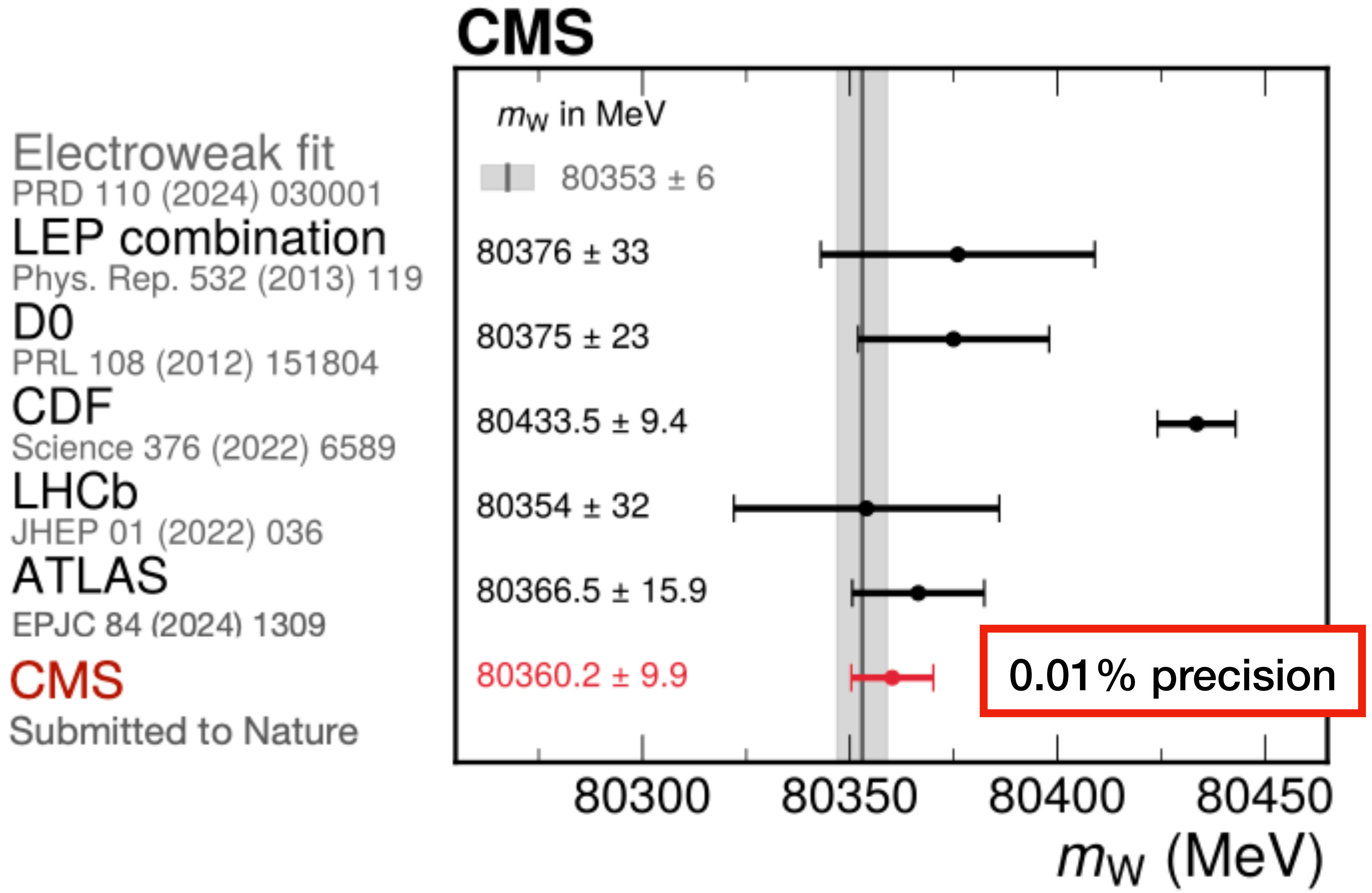
- Measured with **uncertainty of 9.9 MeV**
- Comparable to CDF precision but consistent with SM

m_W = 80360.2 +/- 9.9 MeV

Source of uncertainty	Impact (MeV) Nominal	Impact (MeV) Global
Muon momentum scale	4.8	4.4
Muon reco. efficiency	3.0	2.3
W and Z angular coeffs.	3.3	3.0
Higher-order EW	2.0	1.9
p_T^V modeling	2.0	0.8
PDF	4.4	2.8
Nonprompt background	3.2	1.7
Integrated luminosity	0.1	0.1
MC sample size	1.5	3.8
Data sample size	2.4	6.0
Total uncertainty	9.9	9.9



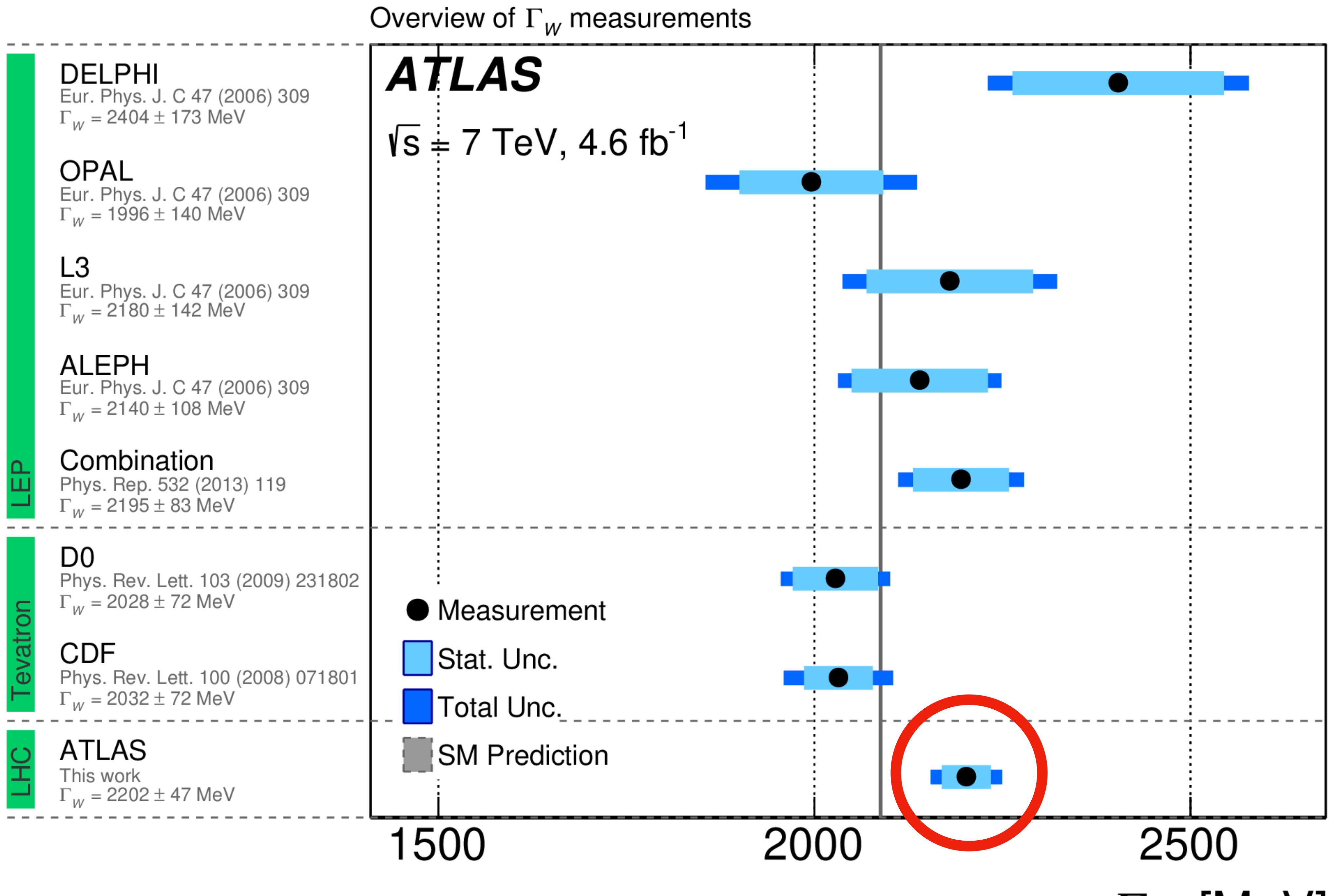
CMS-SMP-23-002



W boson mass and width in ATLAS

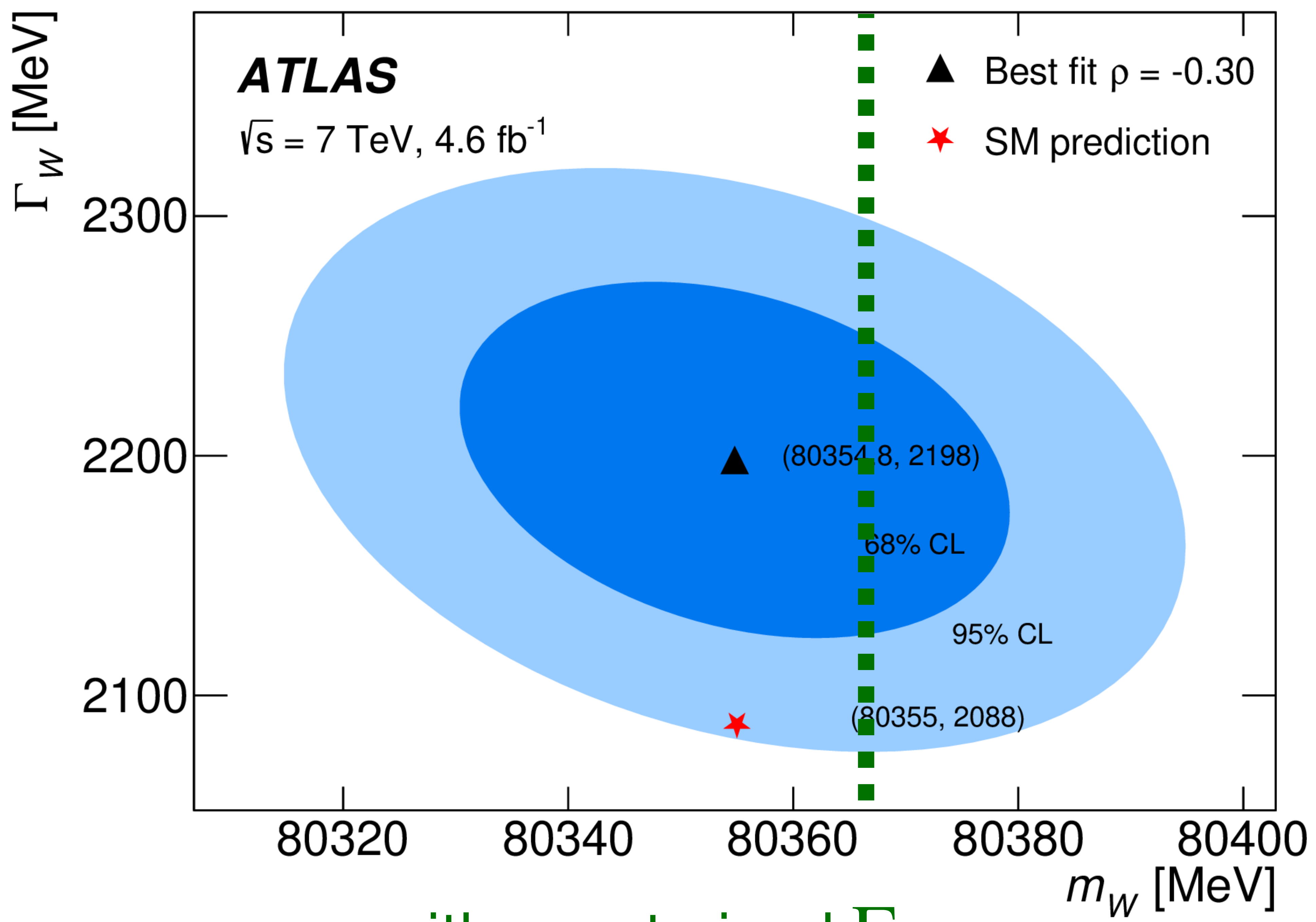
ATLAS performed the first measurement of Γ_W at the LHC, most precise from single experiment

- $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ candidate event, subset of 7 TeV data (~4.6 fb^{-1} from the 2011 run with an average pileup of ~9)
- Both m_W and Γ_W extracted from simultaneous fit to p_T^l, and m_T^l
- Extensive comparison to different PDF sets, and new conservative baseline PDF CT18 was selected



Γ_W =2202 ± 47 (± 32 ± 34) MeV

EPJC 84 (2024) 1309



m_W with constrained Γ_W

Higgs physics

The Higgs Boson: from discovery to precision

- The **discovery of the Higgs boson in 2012 by ATLAS and CMS** was a milestone that opened the door to the study of a new sector of fundamental physical interactions

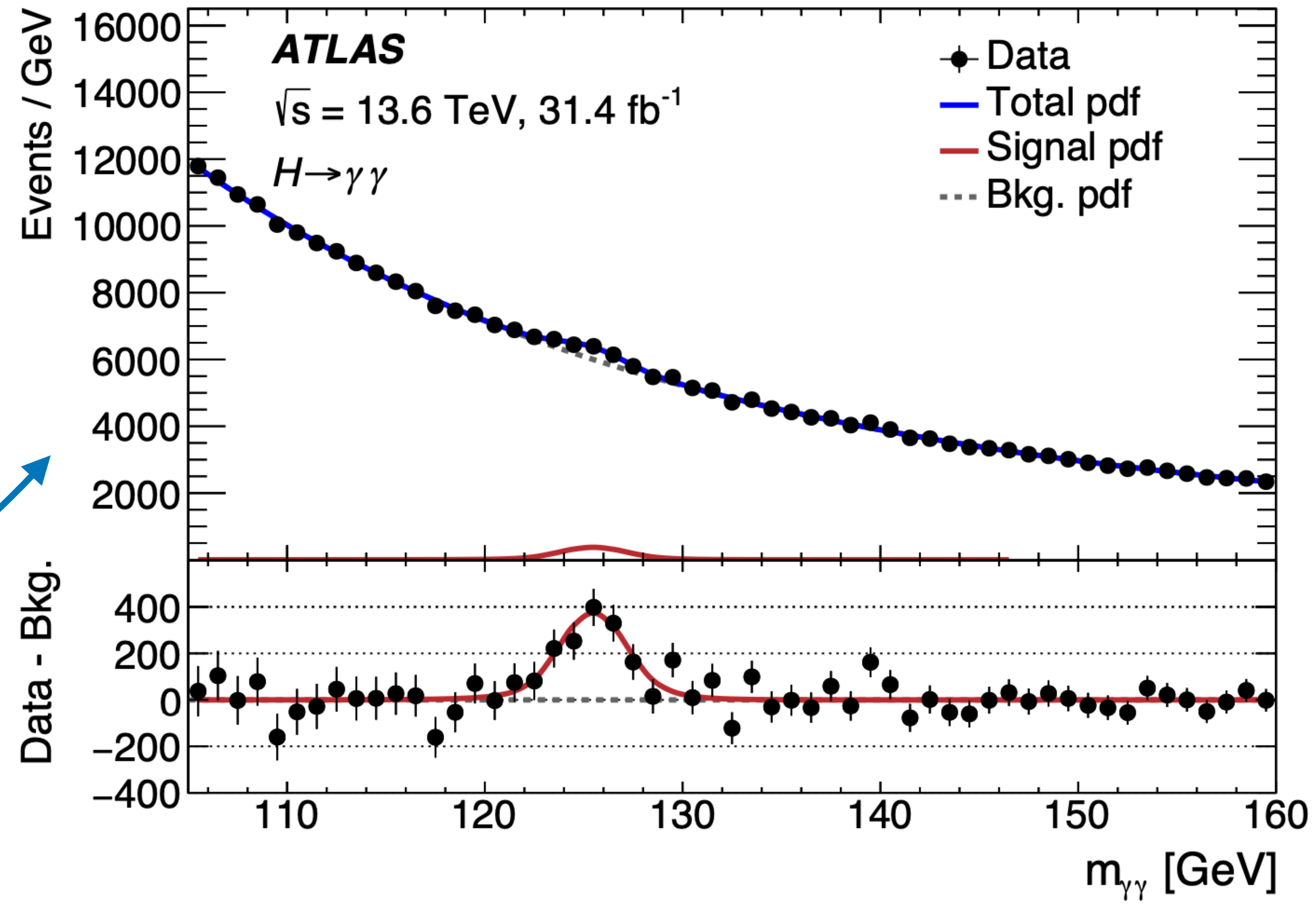
- Since then, extensive measurements have been conducted to study **its properties**, including **mass, decay width, spin, CP properties, production cross-sections, and couplings**

- With **Run 2 data (2015–2018)** ATLAS and CMS entered the **Higgs precision era**

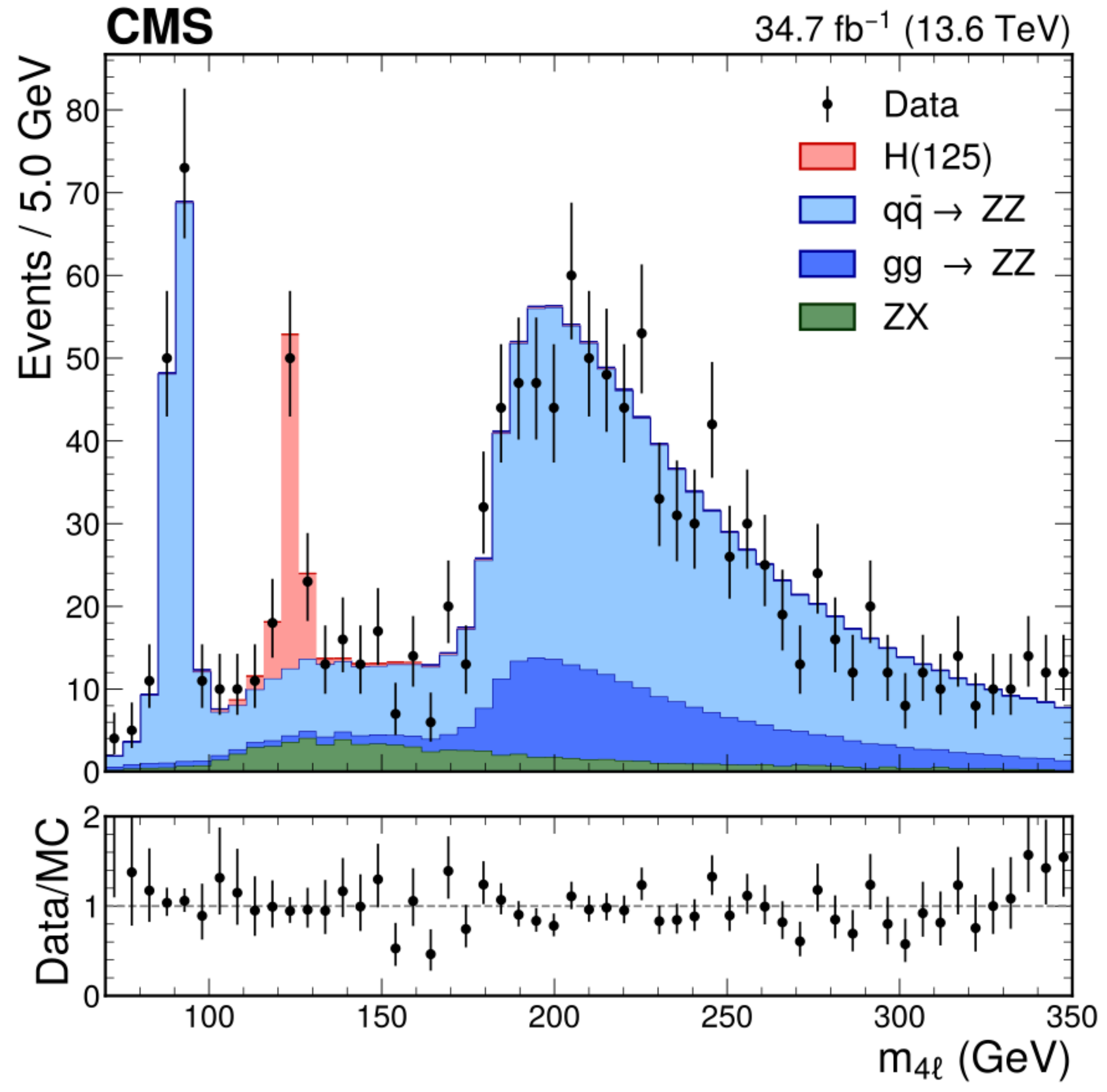
- In 2022, collision energy increased from **13 to 13.6 TeV**, boosting Higgs production cross-sections by about 8%.

- Analyses with **early Run 3 data (2022)** in key final states performed by ATLAS and CMS

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



Submitted to J. High Energy Phys.

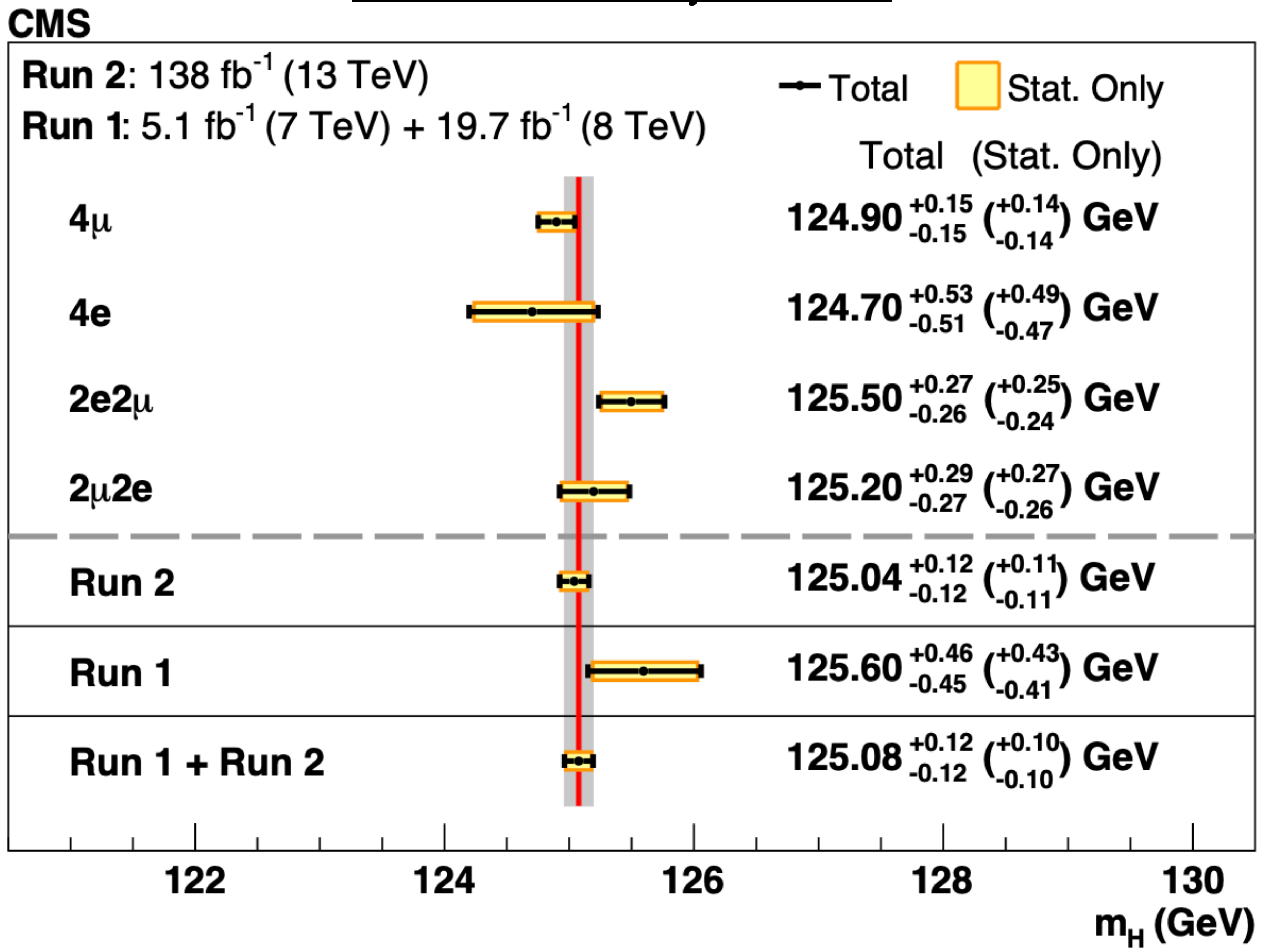


Higgs mass

- m_H is a fundamental/free parameter of the Standard Model
- **Two golden channels**: $H \to \gamma\gamma$ and $H \to ZZ \to 4l$ for m_H measurements

Precision at the end of Run 1: **~2‰, **achieved from both ATLAS and CMS (H → γγ and H → ZZ)
Current Precision: **~1‰**, with statistical limitations still in play

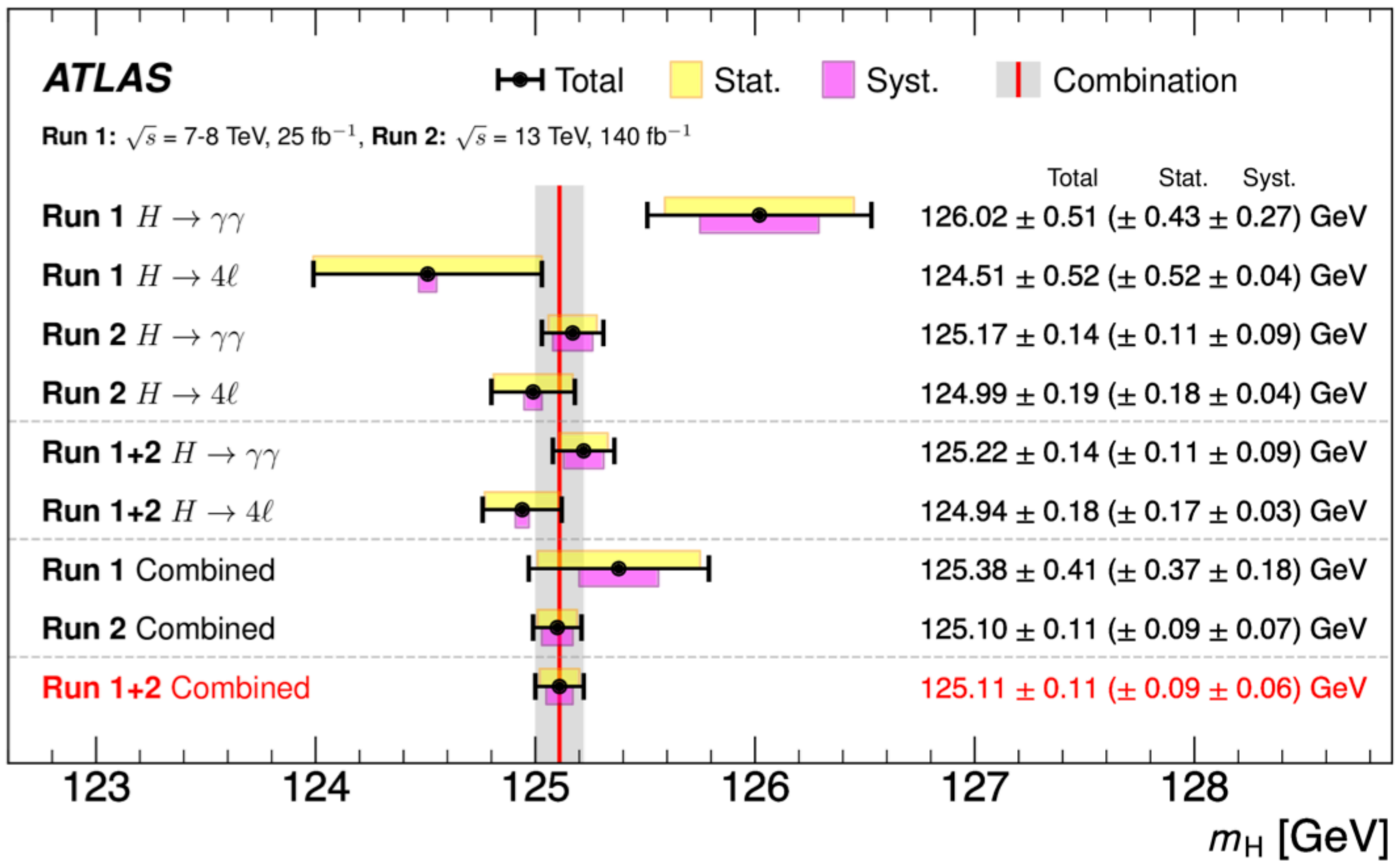
Submitted to Phys. Rev. D



CMS Run1 + Run2 ($H \to ZZ$):

m_H = 125.08±0.09 (stat.)±0.07(syst.) = **125.08±0.12GeV**

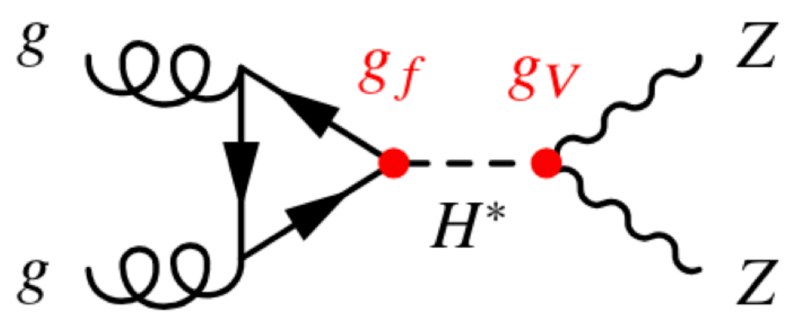
PhysRevLett.131.251802



ATLAS Run 1 + Run2 ($H \to ZZ$ + $H \to \gamma\gamma$):

m_H = 125.11±0.09 (stat.)±0.06(syst.) = **125.11±0.11GeV**

Higgs total width



- **In the SM scenario no direct measurement possible** due to detector resolution *O(1.5-3 GeV)*
- Measurements of Γ_H in $H \to ZZ$ channel comparing **off-shell** and **on-shell** production
- Use of $H \to ZZ \to 4l$ + $H \to ZZ \to 2l2\nu$ to **enhance sensitivity**

The ratio off-shell to on-shell is sensitive to Γ_H assuming same on/off-shell couplings

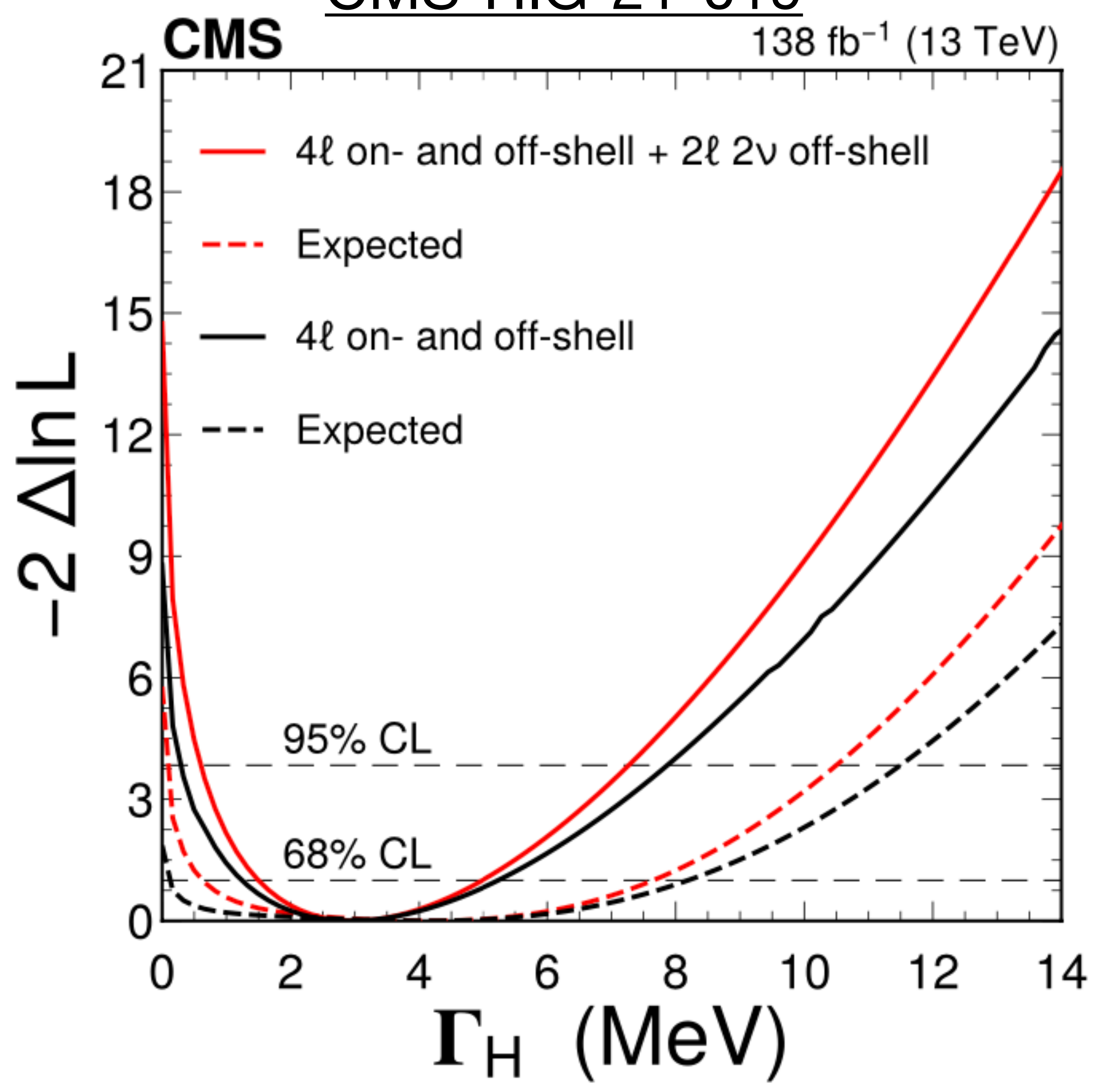
$$\Gamma_H^{SM} = 4.10\ MeV$$

$$\sigma_{on-shell}^{gg \to H \to VV} \propto \frac{g_{Hgg}^2 g_{HVV}^2}{m_H \Gamma_H}$$

$$\sigma_{off-shell}^{gg \to H \to VV} \propto \frac{g_{Hgg}^2 g_{HVV}^2}{m_{VV}}$$

Measured Higgs width is compatible with the SM predictions

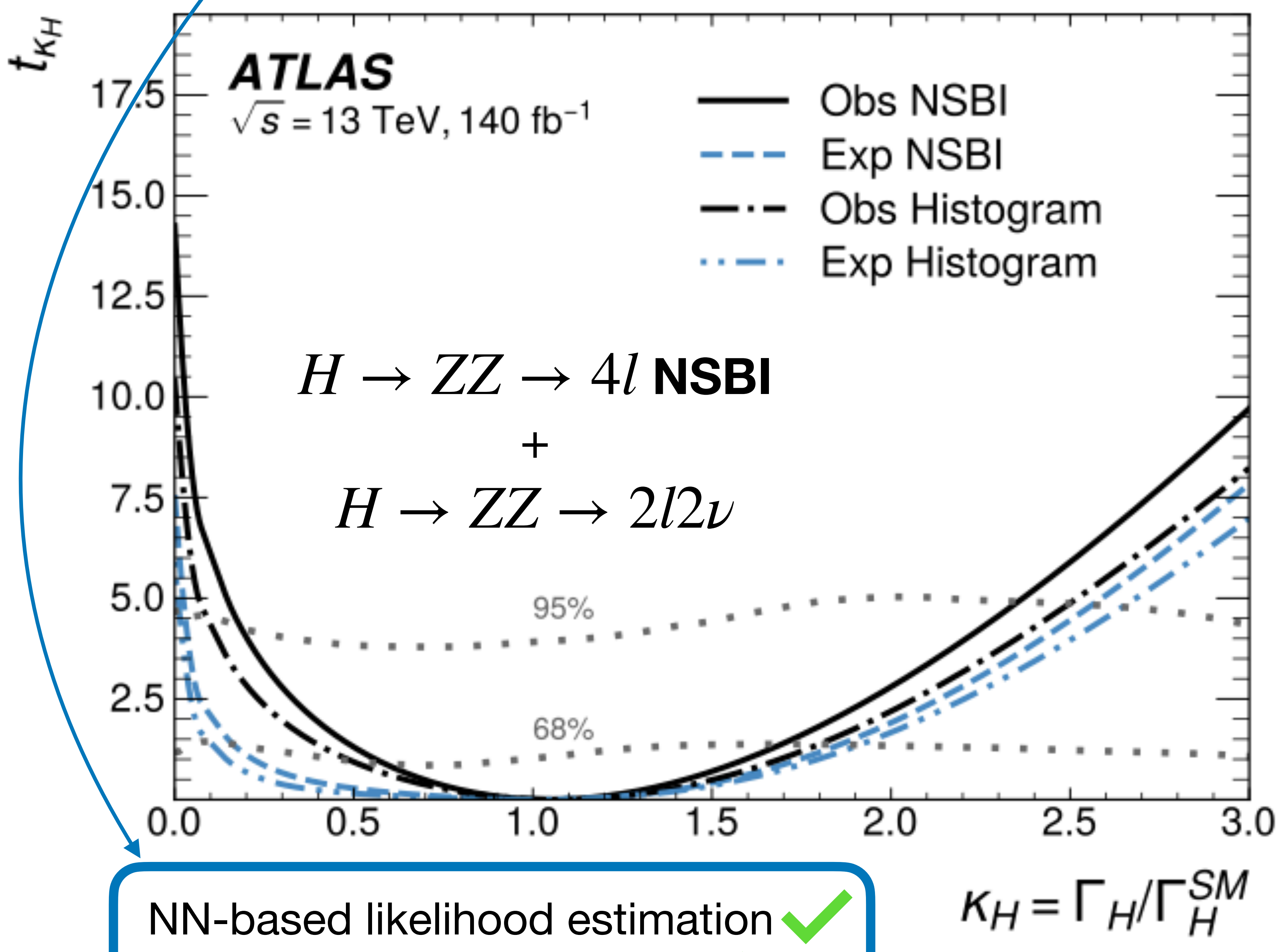
CMS-HIG-21-019



CMS: $\Gamma_H = 3.0^{+2.0}_{-1.5}(4.1^{+3.5}_{-3.5}) MeV$

New innovative AI technique from ATLAS
Neural simulation based inference (NSBI)

Submitted to Rep. Prog. Phys.



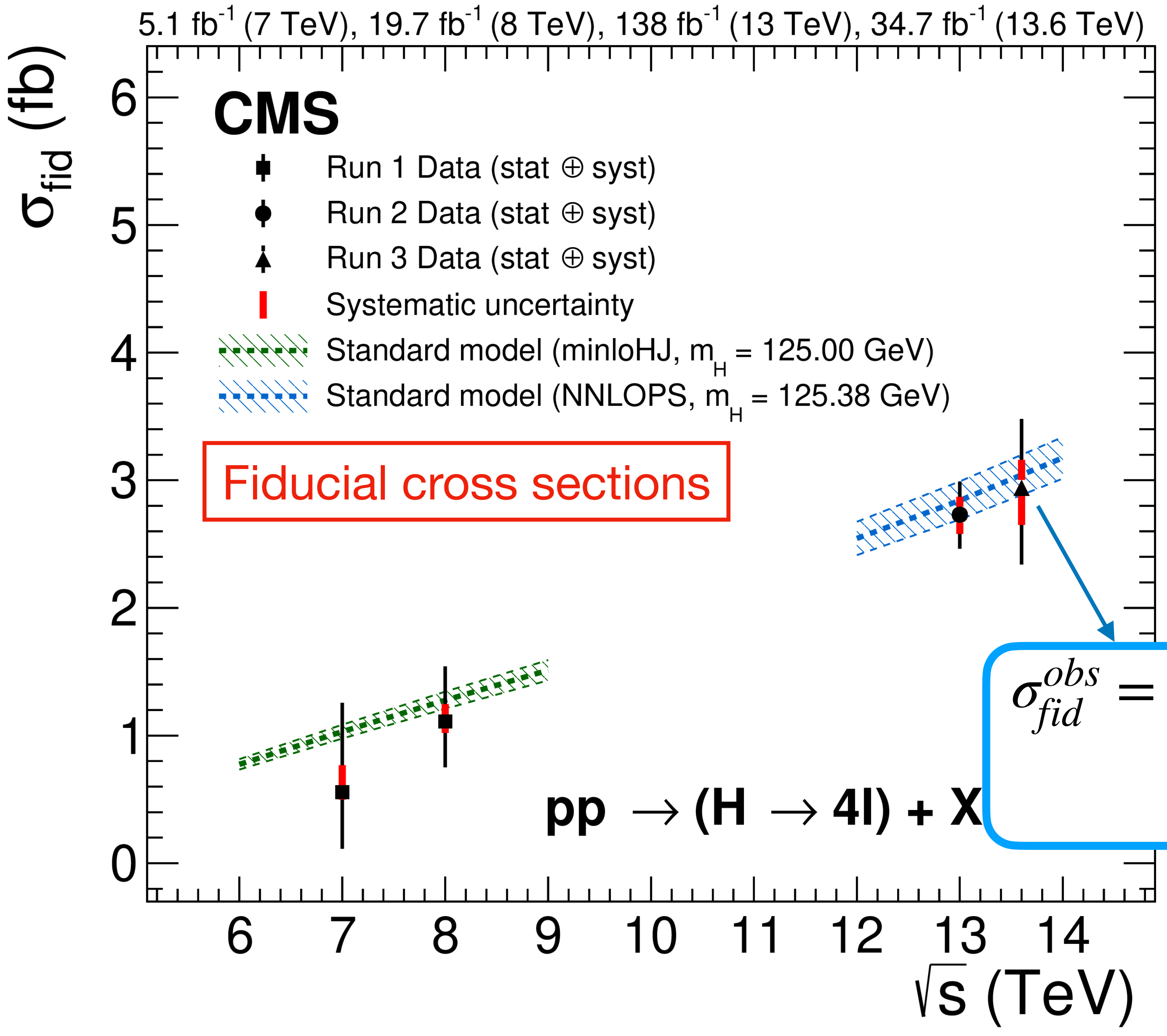
NN-based likelihood estimation ✓
Enhanced sensitivity ✓
Unbinned analysis ✓

ATLAS: $\Gamma_H = 4.3^{+2.7}_{-1.9}(4.1^{+3.5}_{-3.4}) MeV$

Inclusive fiducial cross sections measurements

- **Fiducial measurements** represent the most **model-independent** way to measure H boson production cross section
- First inclusive fiducial cross section measurements by ATLAS and CMS at $\sqrt{s}$ = **13.6 TeV** performed in $H \rightarrow ZZ \rightarrow 4l$ and $H \rightarrow \gamma\gamma$

Submitted to J. High Energy Phys



CMS-PAS-HIG-23-014

$H \rightarrow ZZ \rightarrow 4l$

$$\sigma_{fid}^{obs} = 2.89^{+0.53}_{-0.49}(stat.)^{+0.29}_{-0.21}(syst.)\ fb$$
$$\sigma_{fid}^{exp} = 3.09^{+0.27}_{-0.24}\ fb$$

$H \rightarrow \gamma\gamma$

$$\sigma_{fid}^{obs} = 78 \pm 11(stat.)\ ^{+6}_{-5}(syst.)\ fb = 78^{+13}_{-12}\ fb$$
$$\sigma_{fid}^{exp} = 68.7 \pm 3.8\ fb$$

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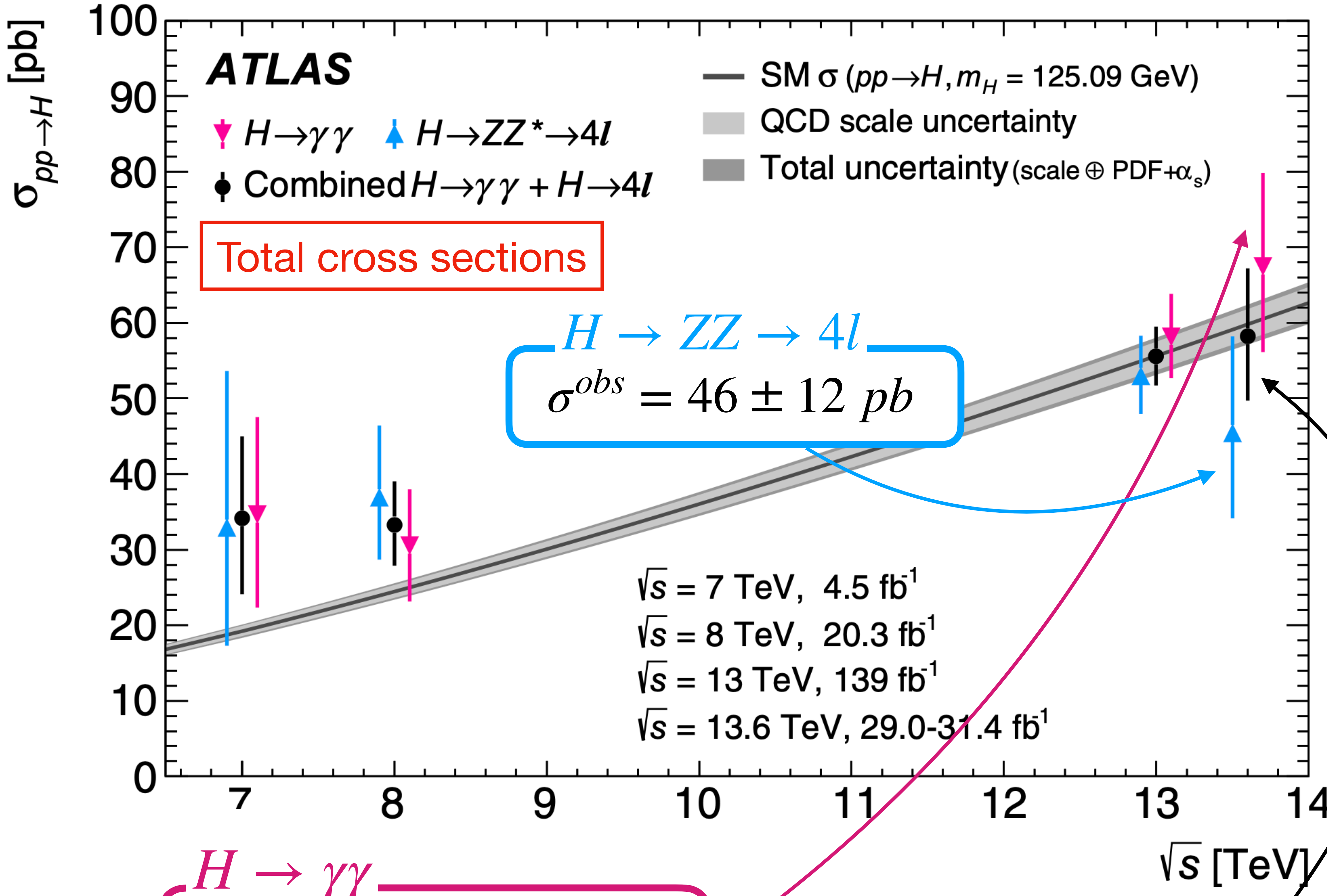


$H \rightarrow ZZ \rightarrow 4l$

$$\sigma^{obs} = 46 \pm 12\ pb$$

$H \rightarrow \gamma\gamma$

$$\sigma^{obs} = 67^{+12}_{-11}\ pb$$

Combined

$$\sigma^{obs} = 58.2 \pm 8.7\ pb$$
$$\sigma^{exp} = 59.9 \pm 2.6\ pb$$

Measurements are in agreement with SM predictions within uncertainties

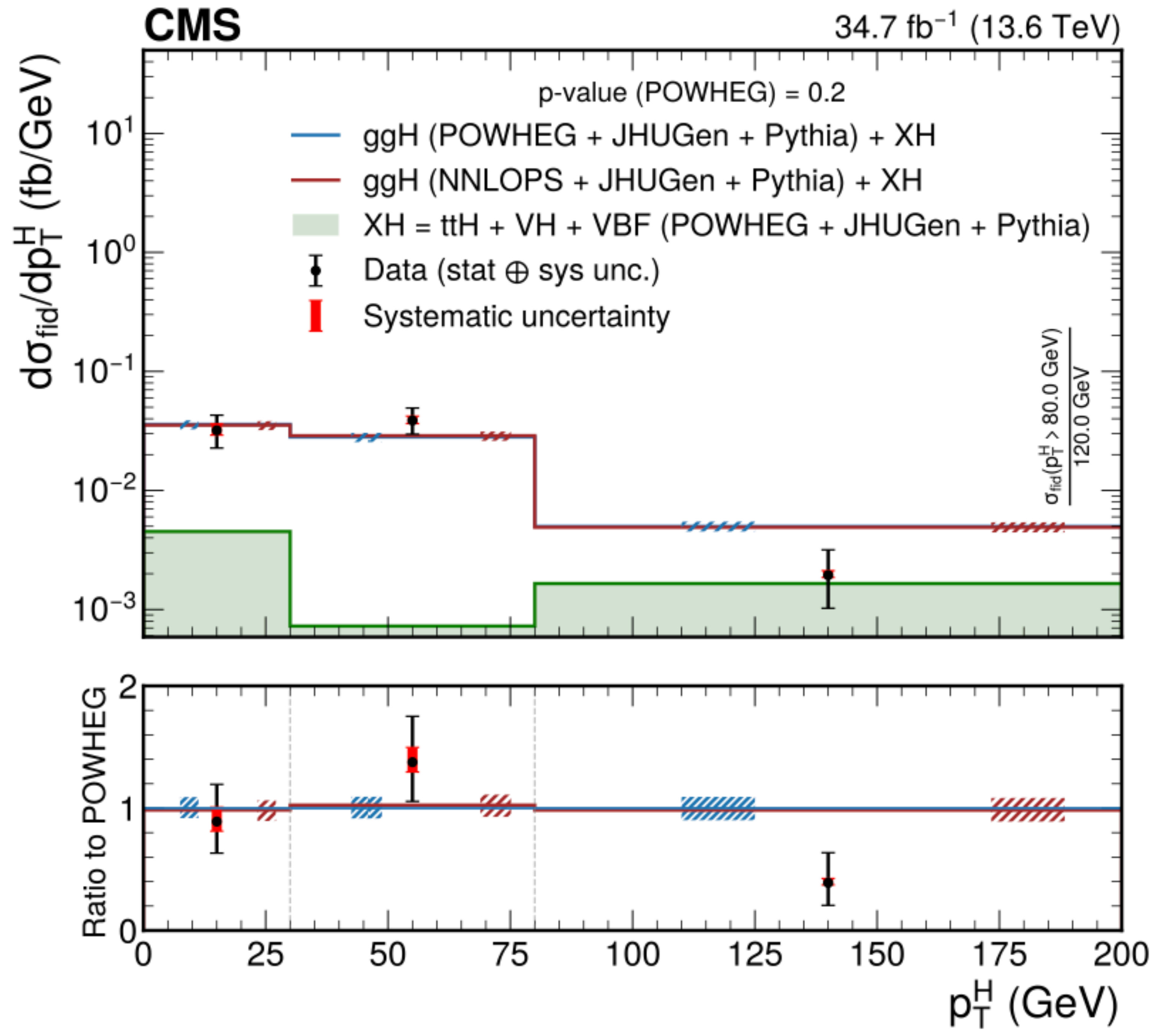
Differential cross sections measurements

- The differential cross section of the Higgs boson provides a **more granular view** of its production mechanisms and decay channels
- It describes **how the production rate varies with respect to kinematic variables** $(p_T^H, y_H, Njets \ldots)$
- Analysing these distributions allows us to **probe the underlying dynamics of Higgs production and to identify deviations from the SM predictions**

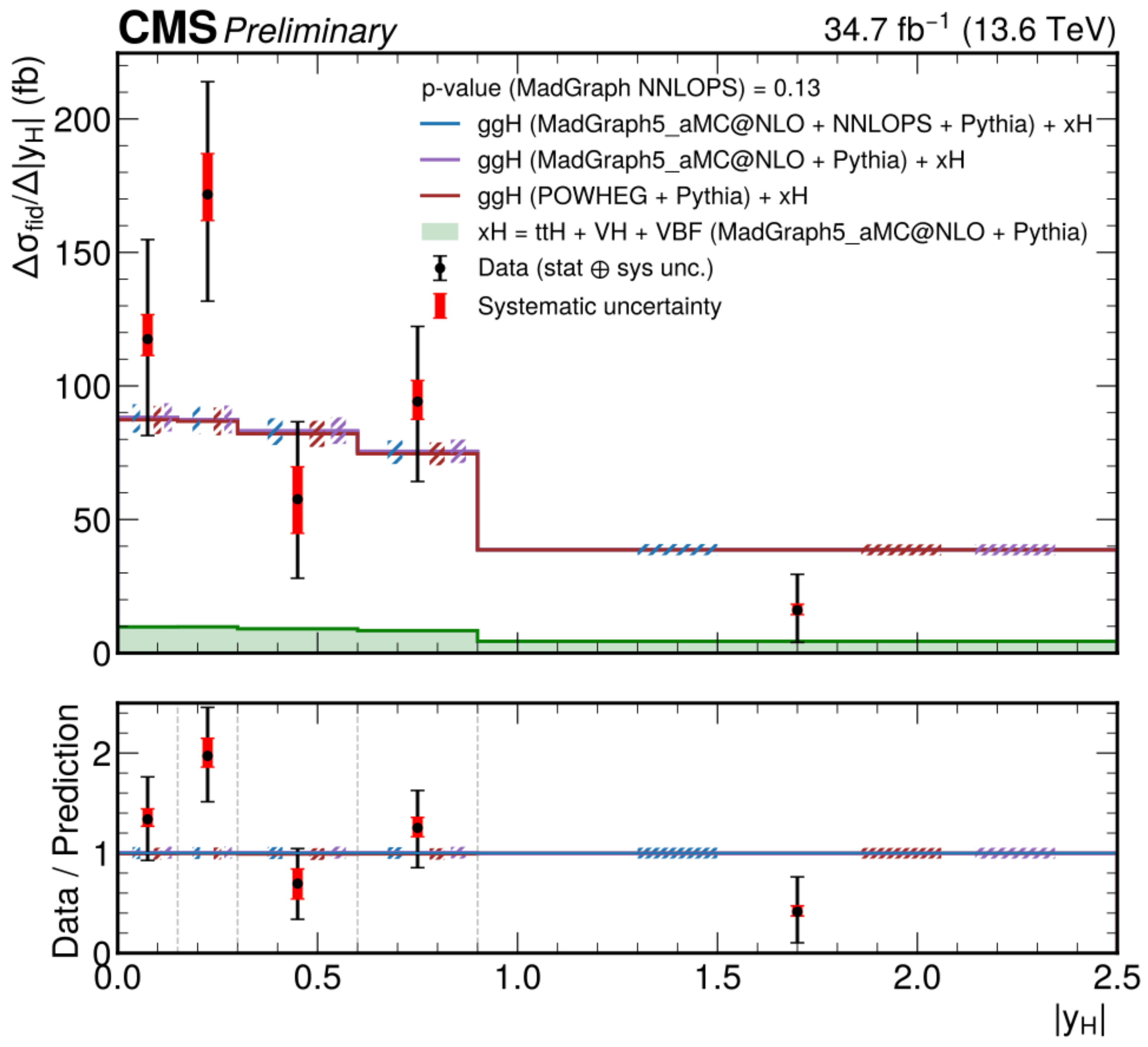
Run 3 results

$H \to ZZ \to 4l$

Submitted to J. High Energy Phys



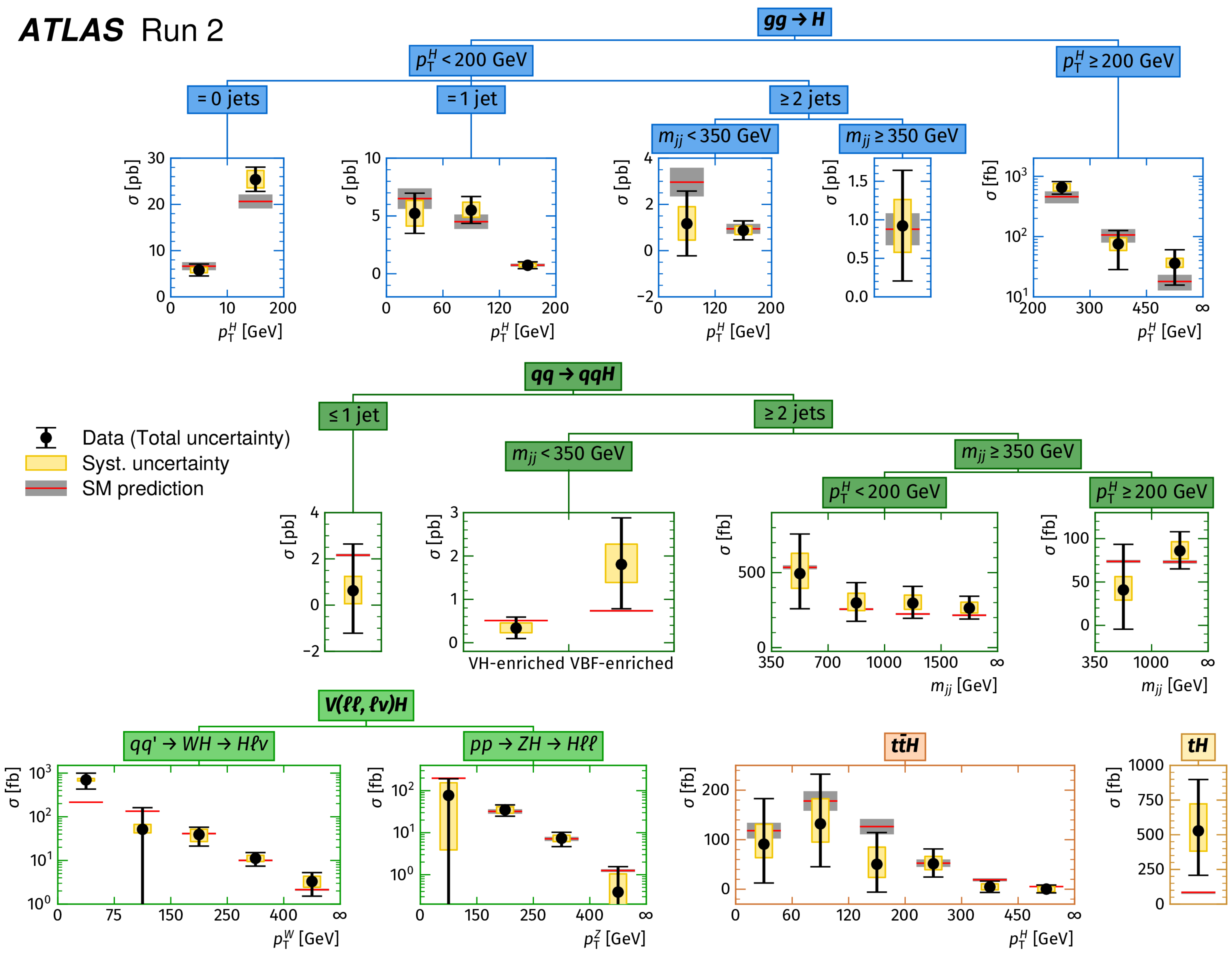
$H \to \gamma\gamma$



CMS-PAS-HIG-23-014

Simplified template cross section (STXS)

- Measure production modes separately, **categorising each into bins of key quantities** (p_T^H, N_{jets}, m_{jj})
- Chosen as most sensitive variables for theory predictions / signal sensitivity / new physics
- Framework provided **in different stages** (e.g. stage 0, stage 1, stage 1.2) with increasing degrees of granularity
- Provides a common guideline for analysis in all decay modes **for comparison and combinations**



Nature 607, 52-59(2022)

Legacy Run 2 STXS Combination by CMS

- **Ultimate precision via statistical combinations**

- Evolution of Nature Combination [Nature 607, 60–68 (2022)] ,with new input analysis and results

- New/updated channels + many more interpretations

- H→$\gamma\gamma$, H→ZZ*→4l, H→WW*→lνlν, H→$\tau\tau$, H→bb, H→μμ, H→Zγ
  - Each channel targets multiple production modes

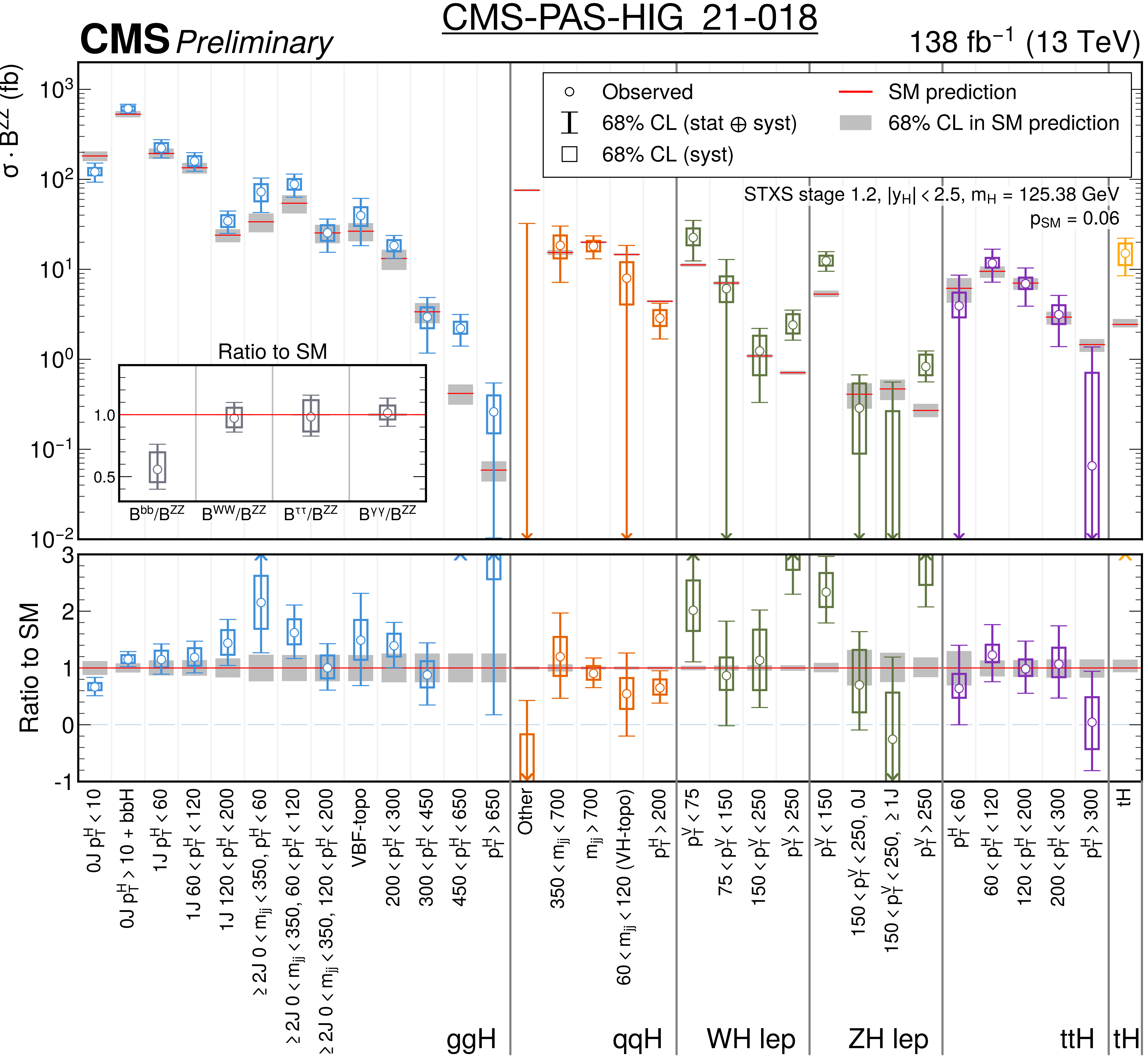
$$L(\vec{x};\vec{\alpha},\vec{\theta}) = \prod_r L_r(\vec{x};\vec{\alpha},\vec{\theta}) \prod_l p_l(y_l;\theta_l)$$

Analysis regions:
Signal and control regions (>1K)

Nuisance parameters
Common sources correlated (>10K)

First combined STXS (1.2) measurement from CMS

CMS-PAS-HIG 21-018



STXS Combination

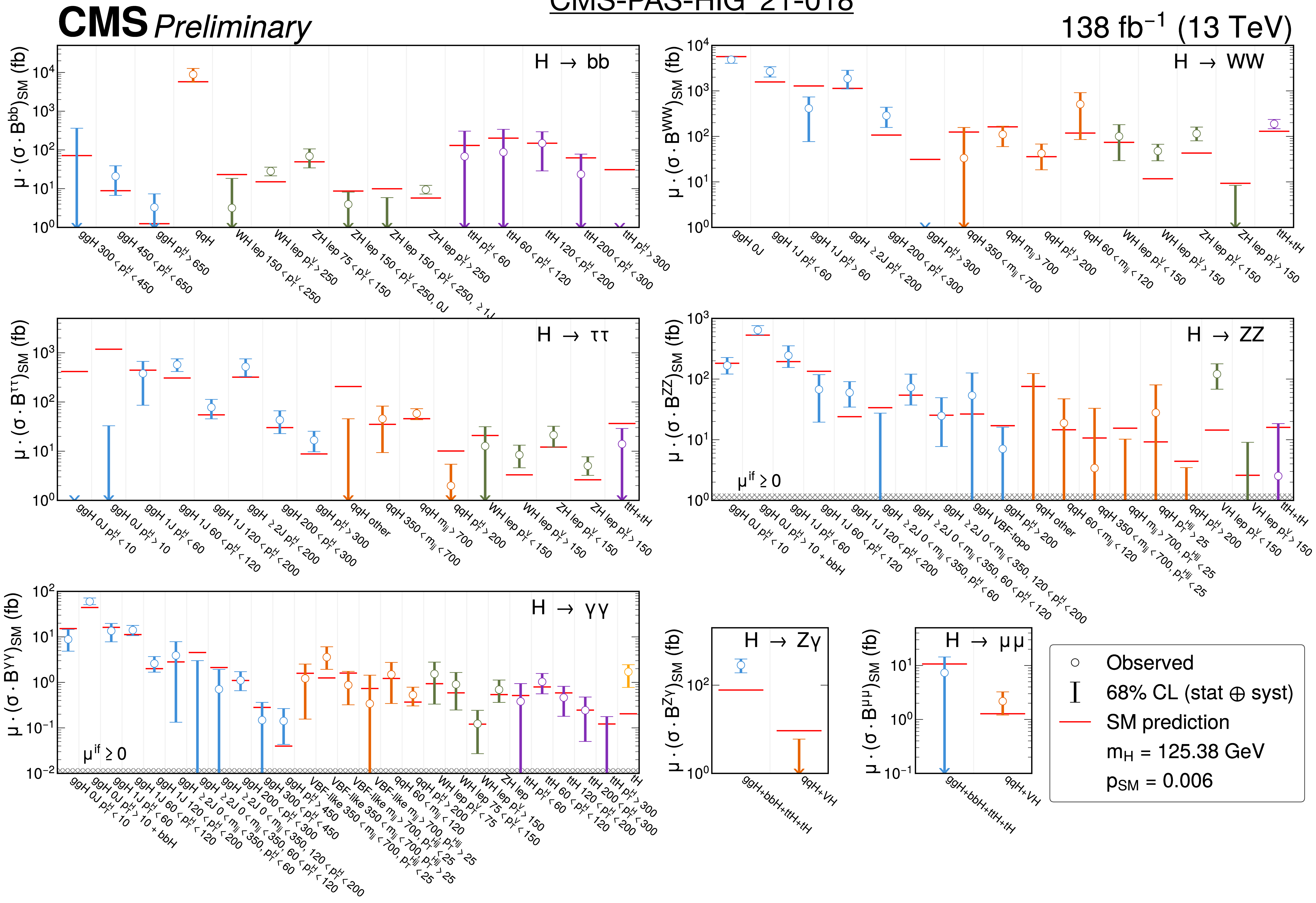
$$\mu^{i,f} = \frac{[\sigma^i \times \mathcal{B}^f]_{obs}}{[\sigma^i \times \mathcal{B}^f]_{\mathrm{SM,HO}}(\vec{\theta}'_{\mathrm{th,norm}})}$$

- Fit with separate parameter per cross section-times-branching fraction (97 POIs in total)

- **Most granular fit ever performed by CMS experiment in Higgs sector**

- Extremely valuable for BSM interpretations

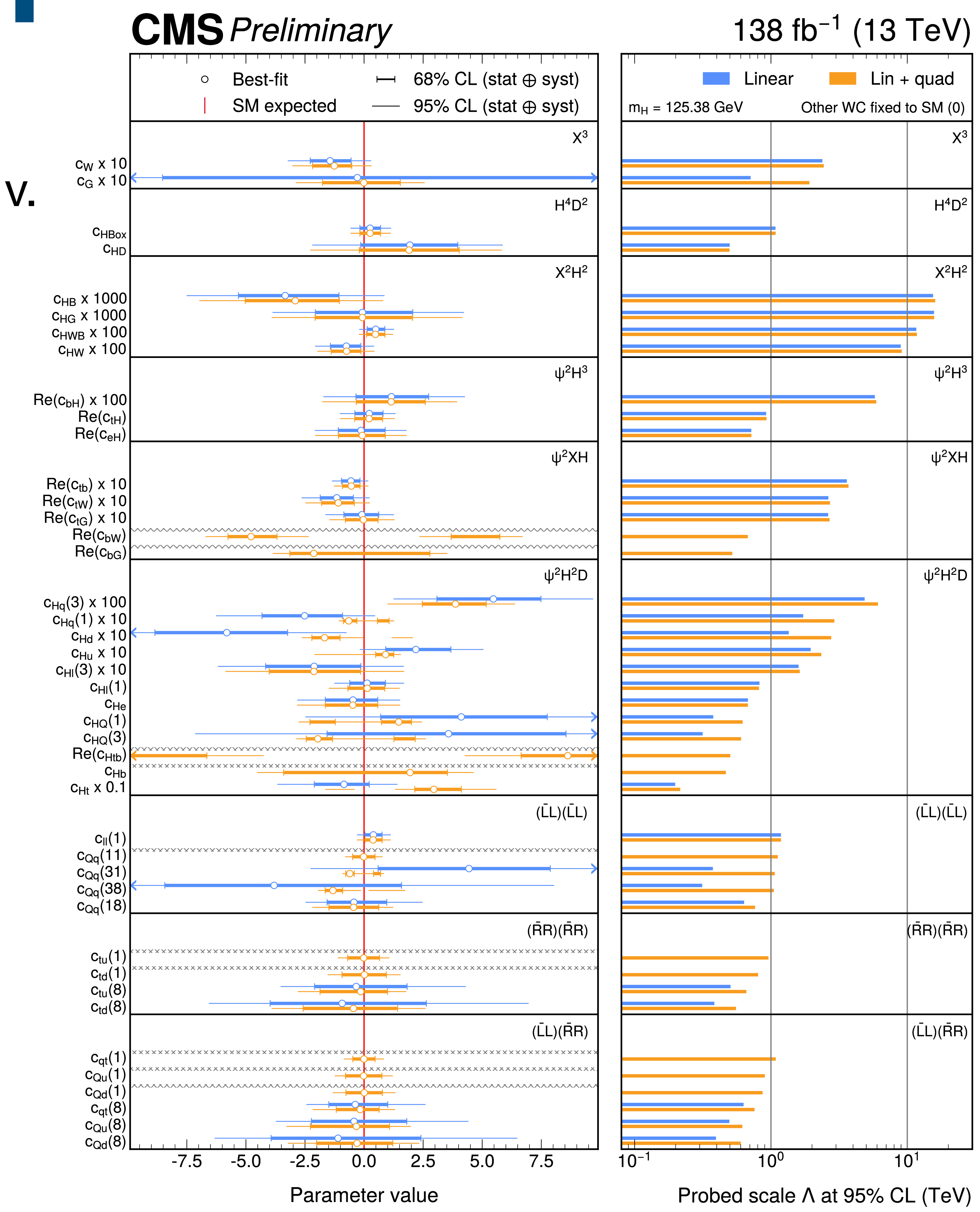
CMS-PAS-HIG 21-018



STXS Combination - SMEFT

- **SMEFT** introduces higher-dimensional operators to the SM Lagrangian, capturing effects of heavy new physics at a scale $\Lambda \gg v$.
- It offers a model-independent way to probe BSM physics via deviations in SM processes,

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{d}^{N} \sum_{j \in \mathcal{O}^{(d)}} \frac{c_j^{(d)}}{\Lambda^{d-4}} \mathcal{O}_j^{(d)}$$

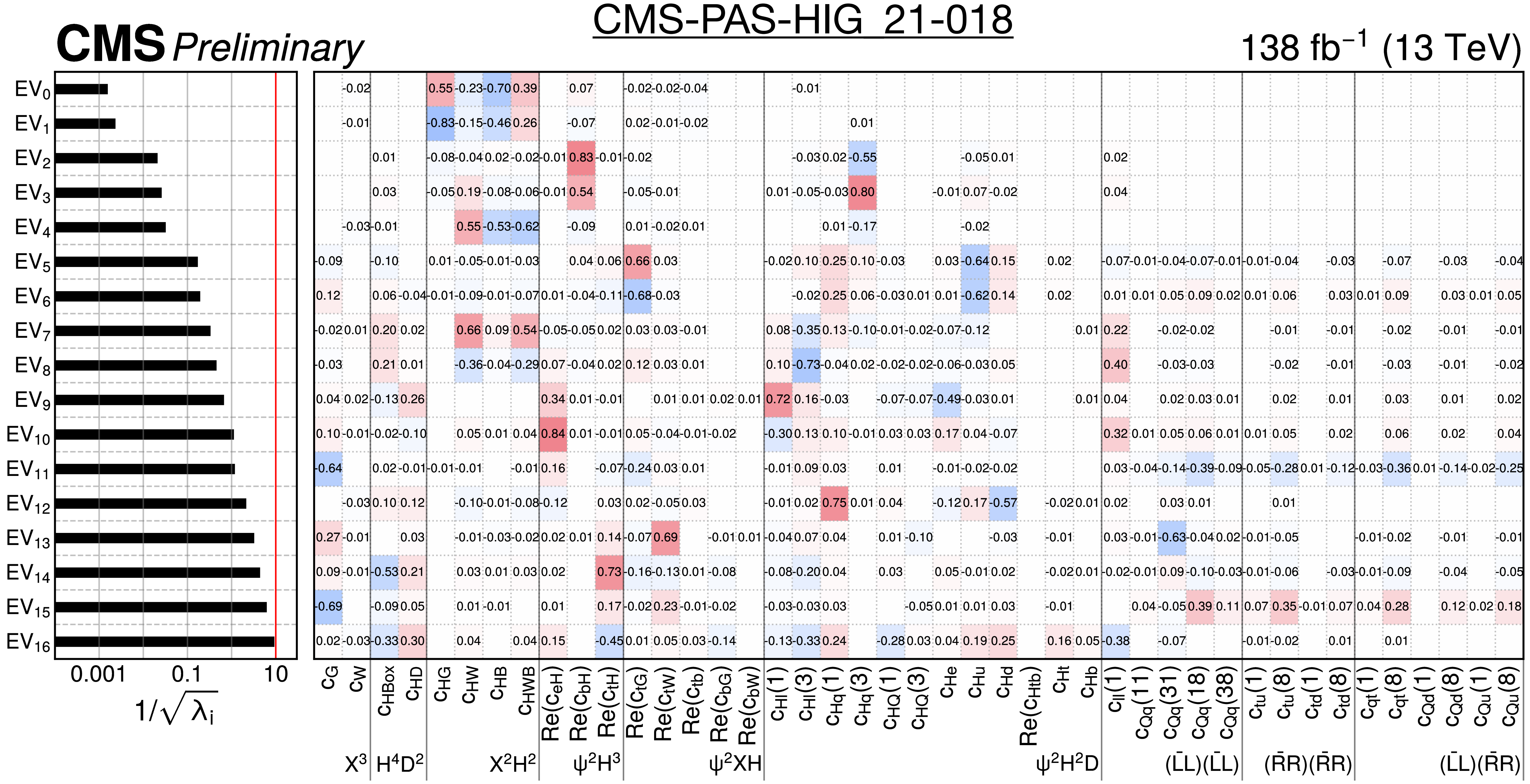


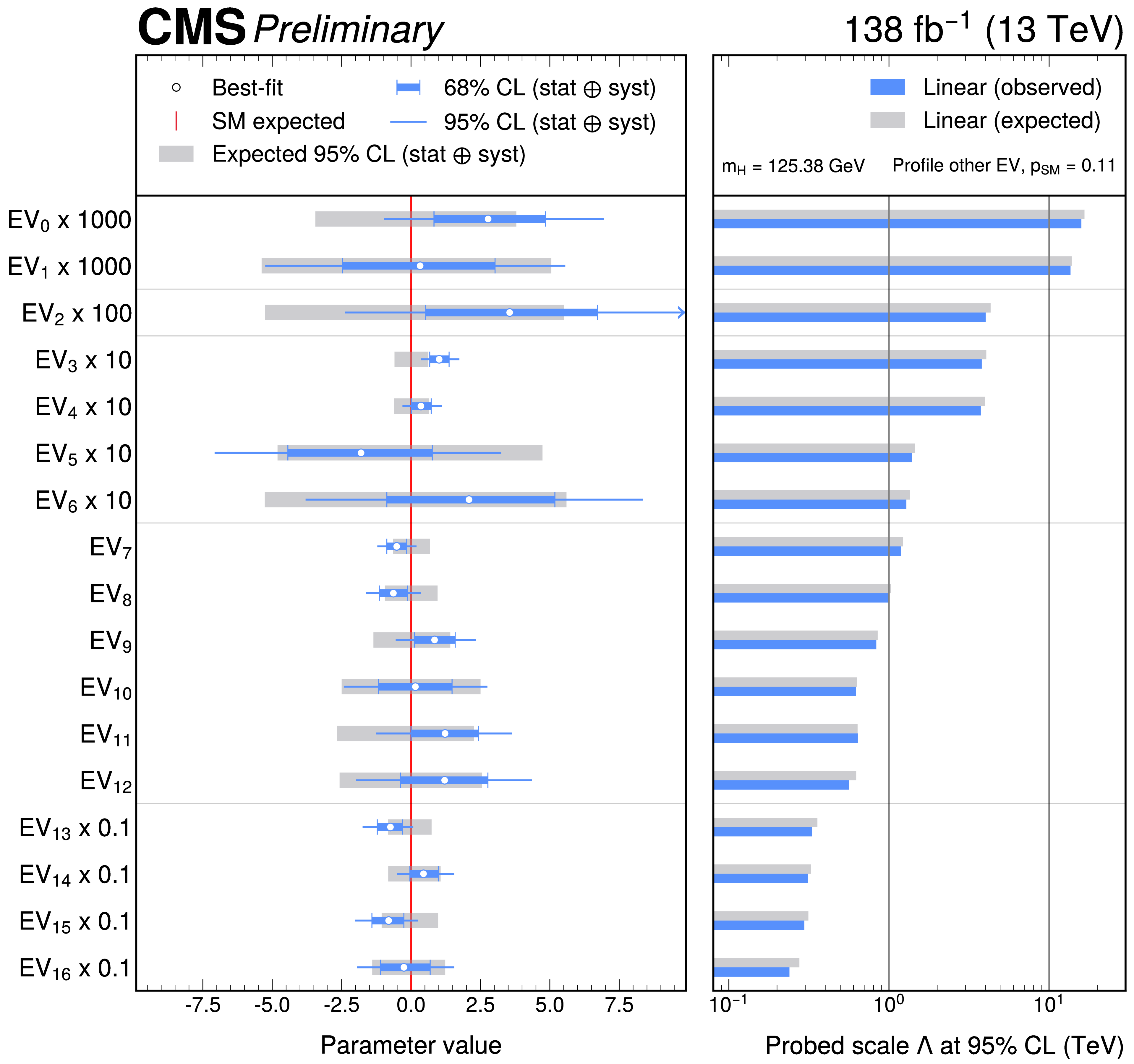
- **Fitting one operator at a time, other fixed at SM (=0)**
- Providing results for linear and linear+quadratic constraints
- Overall agreement with SM

STXS Combination - SMEFT

- BSM physics typically affects multiple SMEFT operators simultaneously
- **PCA procedure** on 97 POI covariance matrix to identify sensitive directions
- Simultaneous fit to **17 linear combinations of SMEFT Wilson Coefficients**

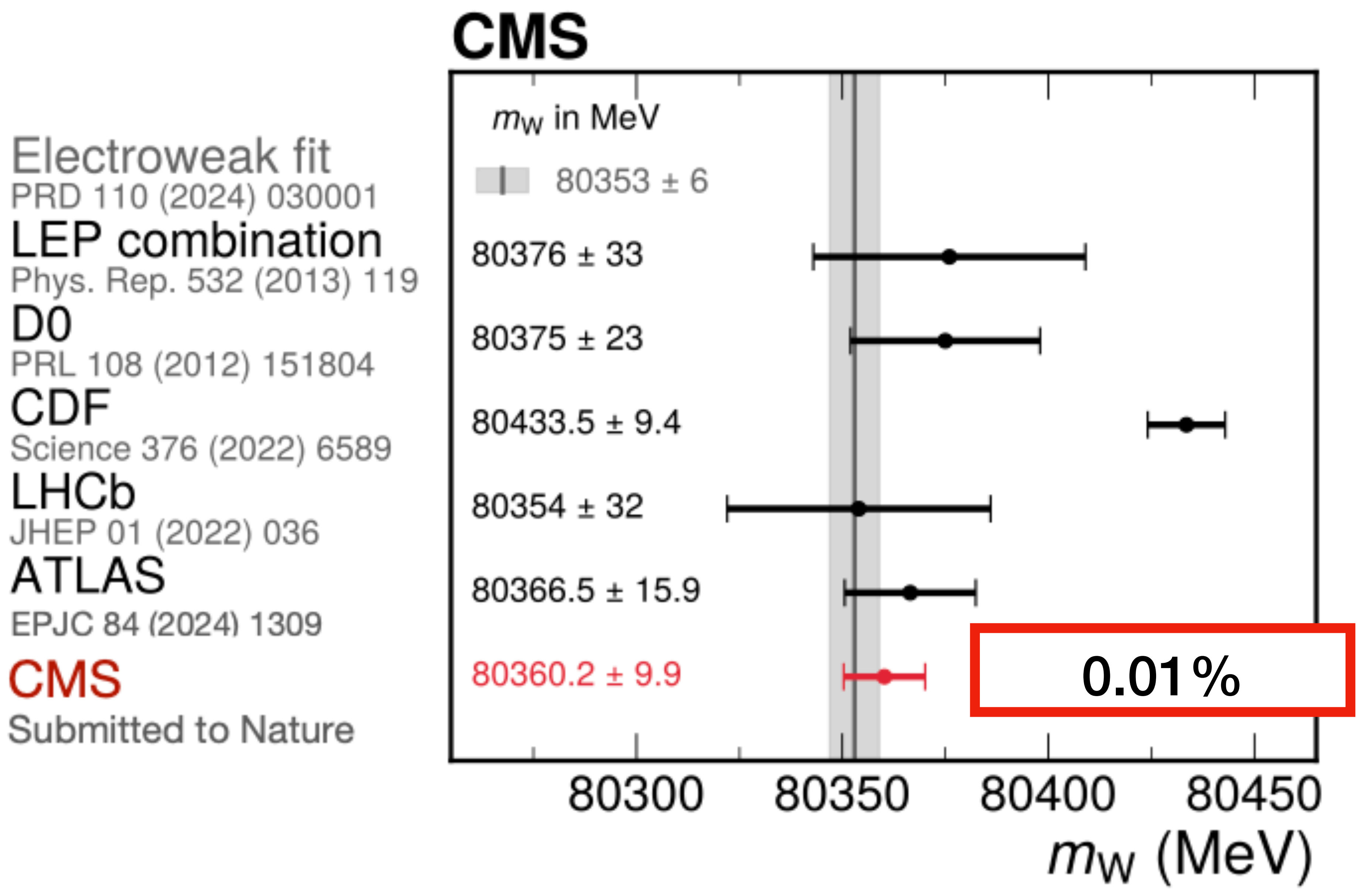
CMS-PAS-HIG_21-018

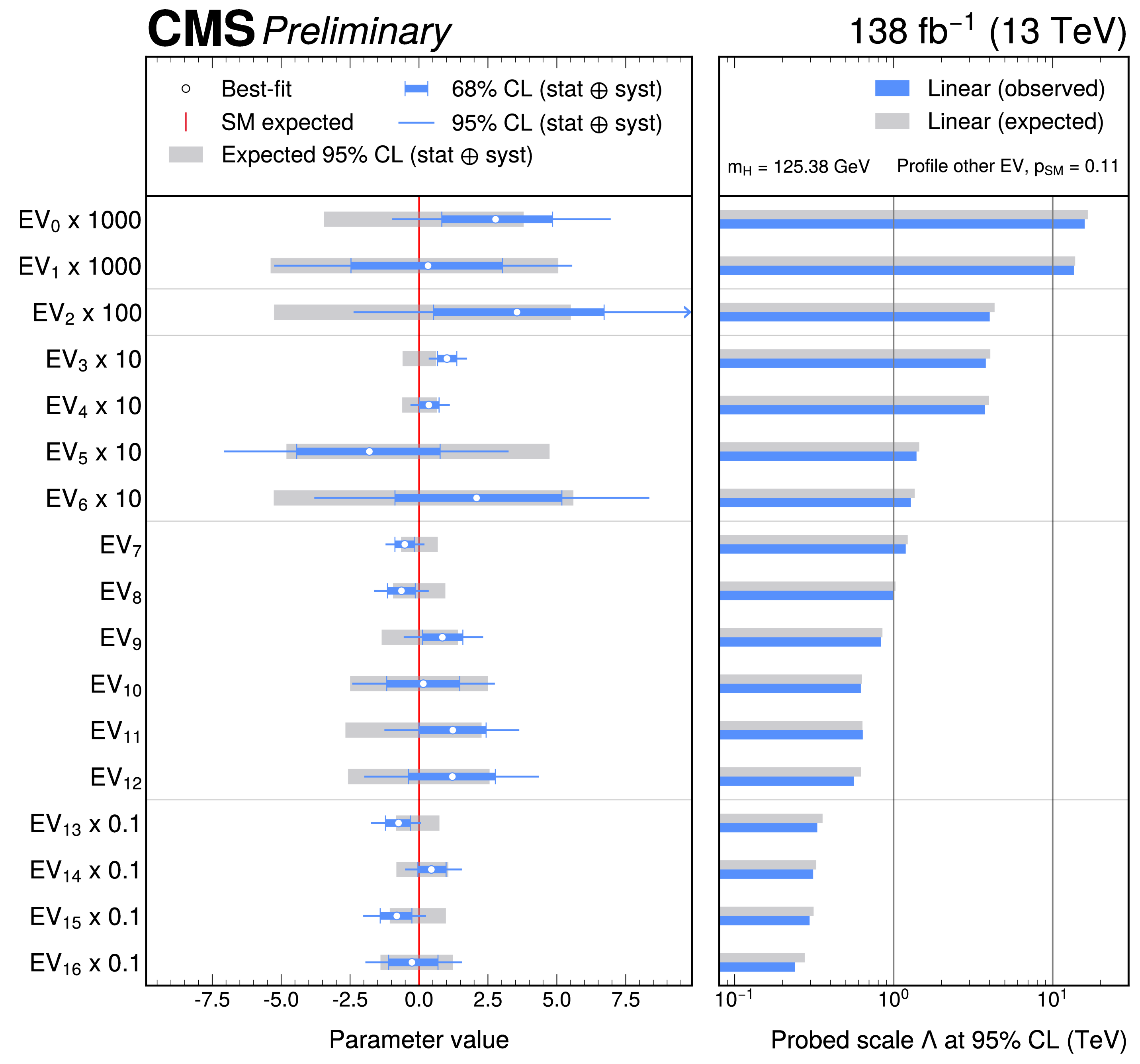




Summary and outlooks

- **W boson and Higgs boson properties have been measured with unprecedented precision by ATLAS and CMS experiments**
- Observations remain consistent with SM predictions, but small deviations and uncertainties leave space for **potential BSM effects.**
- **Model-independent approaches like SMEFT** sharpen sensitivity to subtle signs of new physics.
- **HL-LHC** and future facilities will **push precision further** and may uncover signs of BSM physics





BACK UP

STXS Combination - SMEFT

- SMEFT model is the most used and accepted theory [arxiv:2012.11343]
- Parametrise STXS & decay rates as a function of Wilson Coefficients (WC)

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d}^{N} \sum_{j \in \mathcal{O}^{(d)}} \frac{c_j^{(d)}}{\Lambda^{d-4}} \mathcal{O}_j^{(d)}$$

Total scaling

$$\mu^{i,f}(\vec{c}) = \mu^i_{\mathrm{prod}} \cdot \mu^f_{\mathrm{decay}} = \frac{\left(1 + \sum_j A^i_j c_j + \sum_{j,k} B^i_{jk} c_j c_k\right) \cdot \left(1 + \sum_j A^f_j c_j + \sum_{j,k} B^f_{jk} c_j c_k\right)}{\left(1 + \sum_j A^{\mathrm{tot}}_j c_j + \sum_{j,k} B^{\mathrm{tot}}_{jk} c_j c_k\right)}$$

- **Linear expansion**

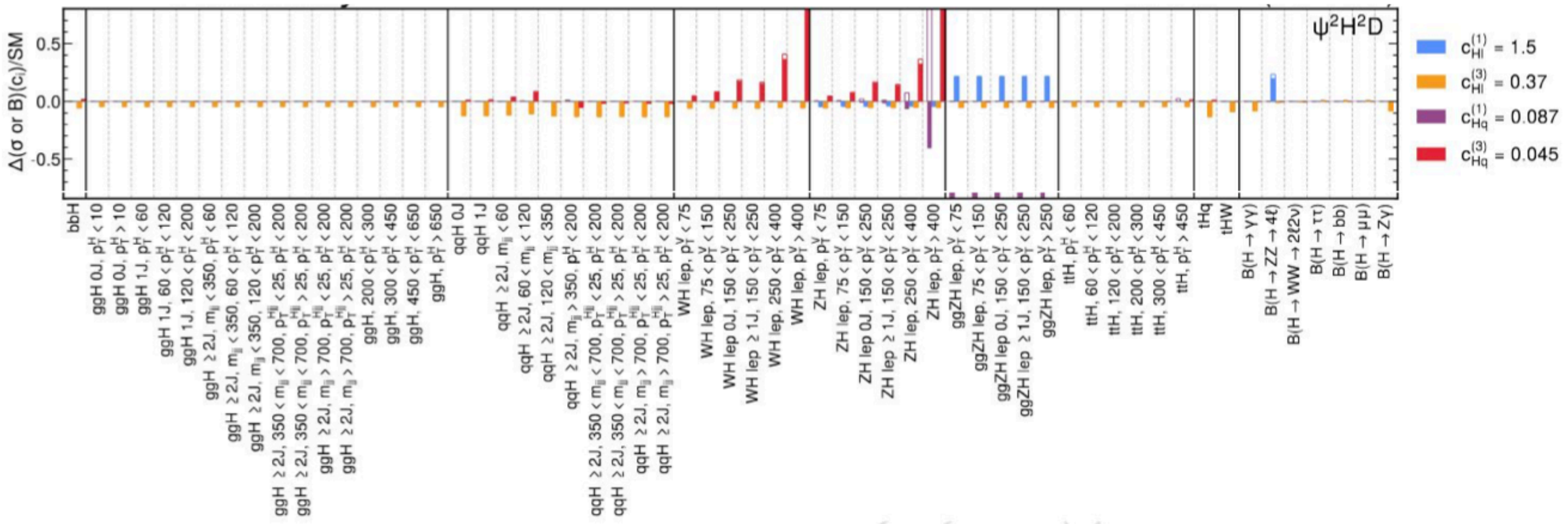
$$\mu^{i,f}(\vec{c}) = 1 + \sum_j (A^i_j + A^f_j - A^{\mathrm{tot}}_j) c_j$$

- **Linear + quadratic expansion**

$$\mu^{i,f}(\vec{c}) = 1 + \sum_j (A^i_j + A^f_j - A^{\mathrm{tot}}_j) c_j + \sum_{jk} (B^i_{jk} + B^f_{jk} - B^{\mathrm{tot}}_{jk}) c_j c_k + (\sum_j A^i_j c_j)(\sum_j A^f_j c_j) - (\sum_j A^i_j c_j)(\sum_j A^{\mathrm{tot}}_j c_j) - (\sum_j A^f_j c_j)(\sum_j A^{\mathrm{tot}}_j c_j) + (\sum_j A^{\mathrm{tot}}_j c_j)^2$$

STXS Combination - SMEFT

- Generally good agreement with the SM
  - Few sizeable deviations e.g. $c_{Hq}^{(3)}$ (p_{SM}=0.01)



Driven by excess in VH lep high $p_T(V)$ STXS bins

N.B. ATLAS do not see same excess in latest [VHbb results](#)