Differential measurements on Higgs boson production using Run 3 data

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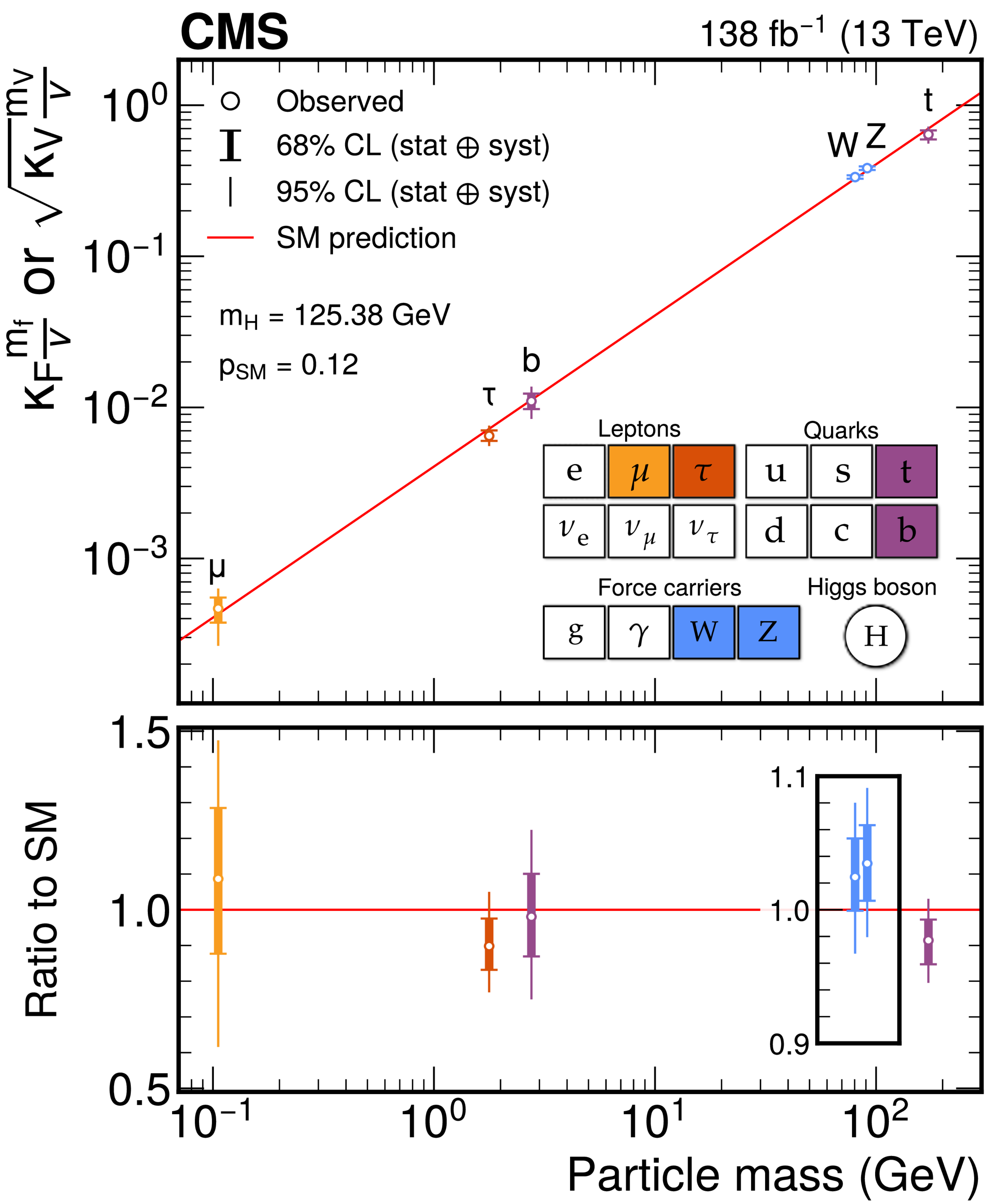
Moriond26 EW, 16-21 March 2026

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**
- Starting from 2022, collision energy increased from **13 to 13.6 TeV**, boosting Higgs production cross-sections by about 8%.
- Now, with **Run 3 data**, new analyses in key Higgs final states are **pushing precision even further**



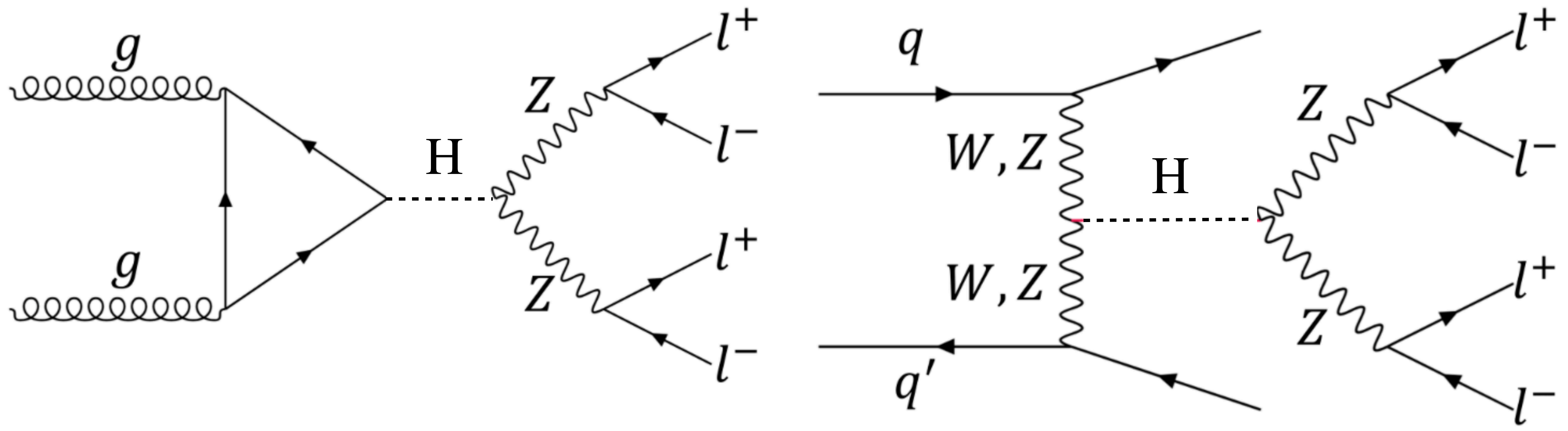
HIG-21-018

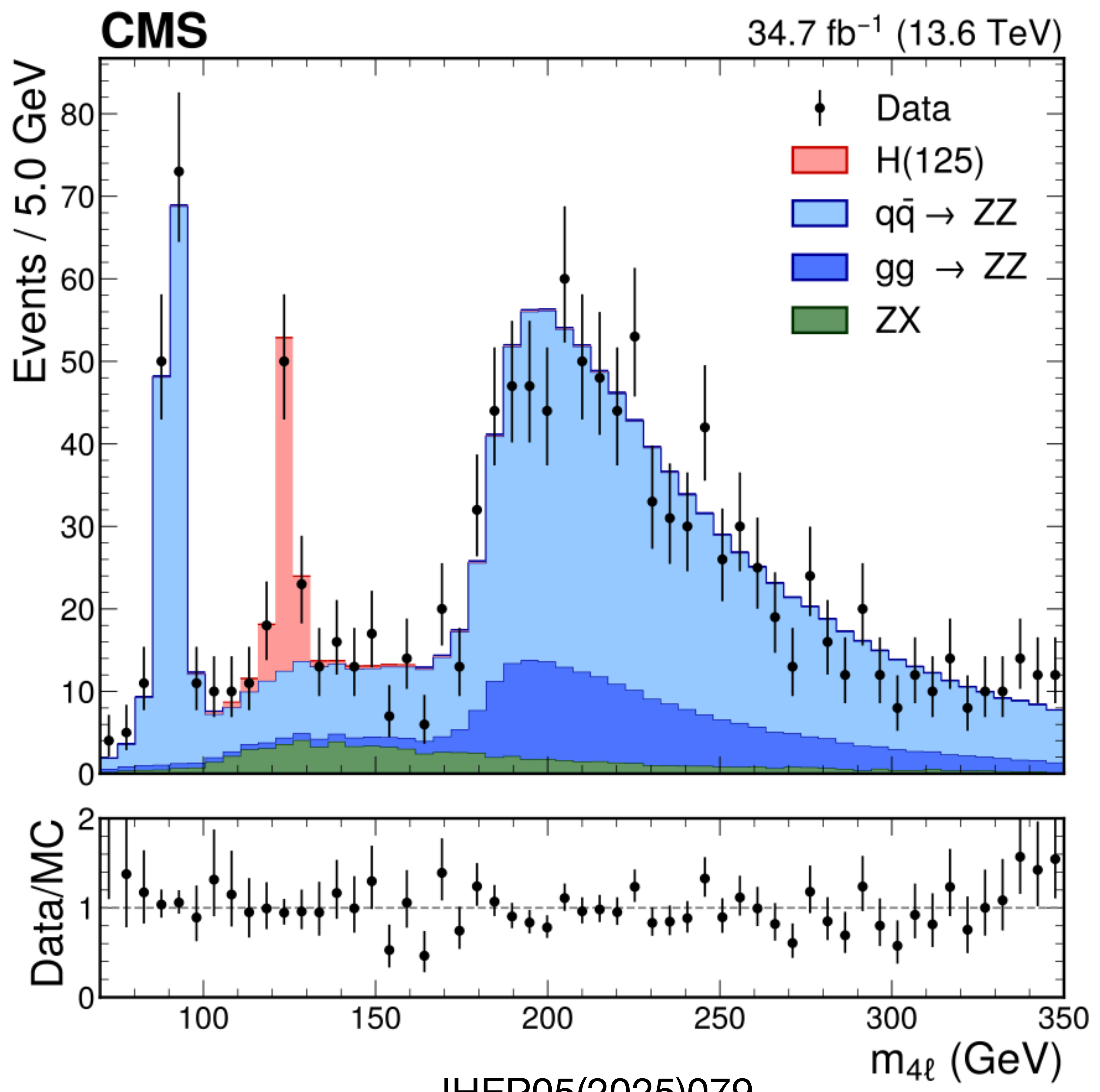
The H→ZZ→4l channel

H→ZZ→4ℓ channel has played a **central role in Higgs physics**, contributing significantly to the **search, discovery, and subsequent characterisation of the Higgs boson** in both the **CMS and ATLAS experiments**

The golden channel of Higgs physics:

- Clear mass peak over a nearly flat background
- Large signal-to-background ratio
- Fully reconstructible final state
- Excellent lepton reconstruction performance in CMS





JHEP05(2025)079

Why fiducial differential cross section measurements?

Fiducial differential measurements represent the most model-independent way to measure H boson production cross section

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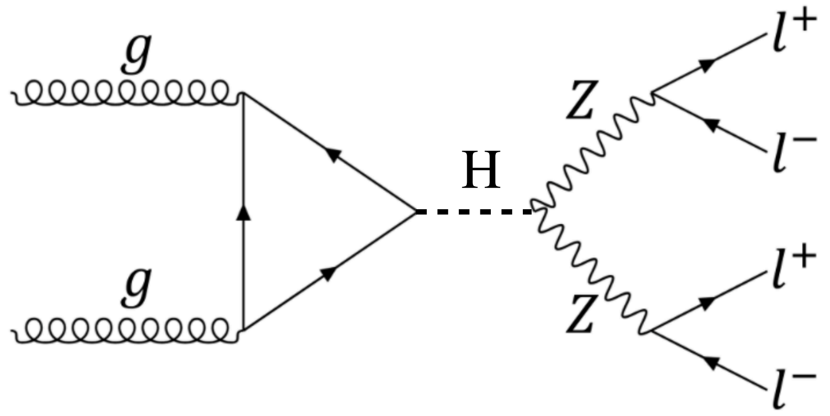
Fiducial differential measurements represent the most model-independent way to measure H boson production cross section

- Maximise the results re-interpretability and longevity
- Possibility of reinterpreting data with models that may not yet have been developed at the time of the measurements

Remove detector effects by **unfolding** data to the fiducial phase

Partonic process

Powheg, Madgraph, JHUGen, MiNLO, etc.

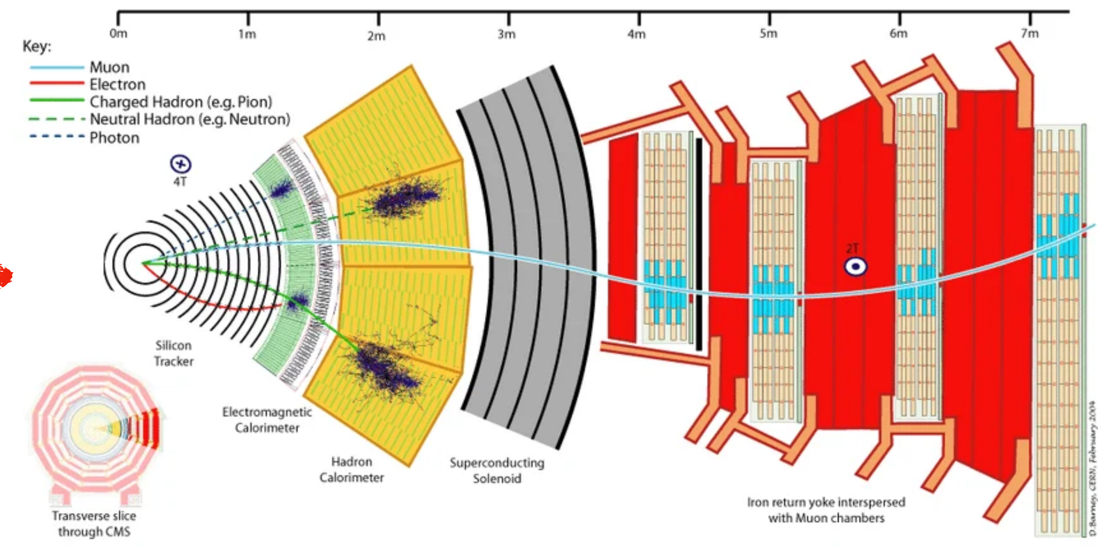


Parton shower hadronisation

Pythia

Detector

Geant4



Generator level

What one would measure with an ideal detector

UNFOLDING

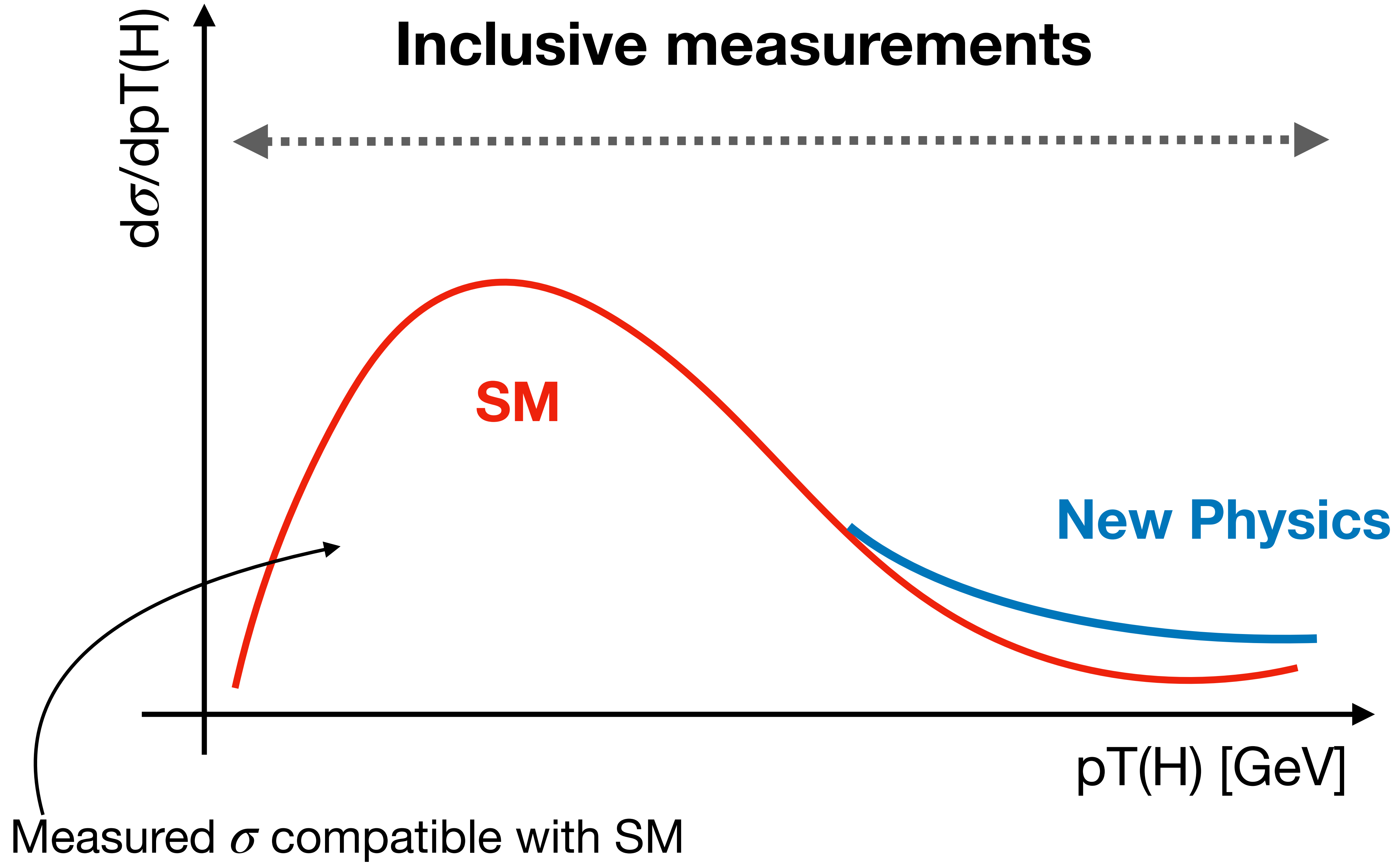
Reconstruction level

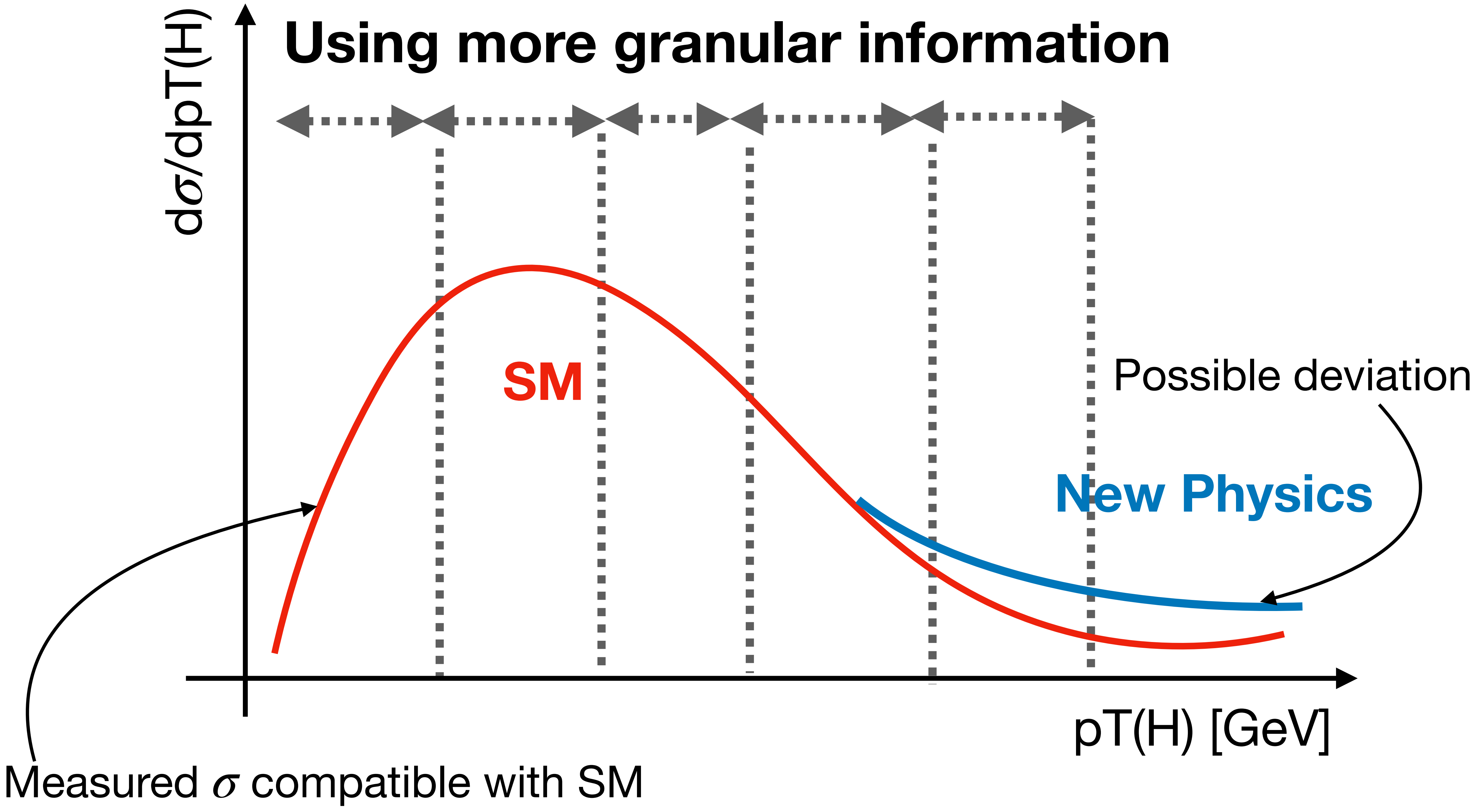
What one actually measures

Why fiducial differential cross section measurements?

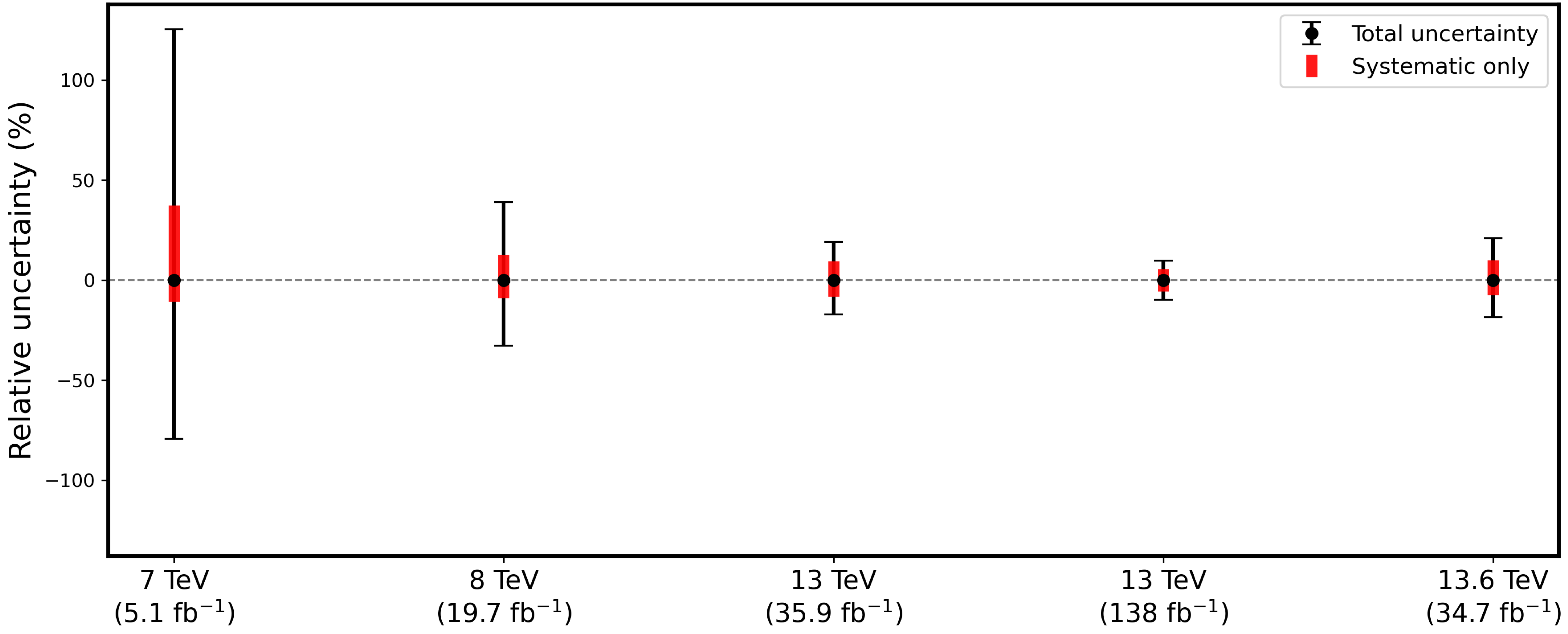
Fiducial differential measurements represent the most model-independent way to measure H boson production cross section

- Test the Standard Model with high precision
- Probe Higgs production mechanisms
- Search for deviations in specific kinematic regions





HZZ differential XS: Where do we come from?



JHEP04(2016)005 JHEP04(2016)005 JHEP11(2017)047 JHEP08(2023)040 JHEP05(2025)079

New Run 3 measurements

Measurements of Higgs boson production cross section in the four-lepton final state at $\sqrt{s}$ = 13.6 TeV with 2022, 2023 and 2024 data

- Includes **2022–2024 data (171 fb^{-1})**: 34.7 fb^{-1} (2022), 27.3 fb^{-1} (2023), 108.8 fb^{-1} (2024)→ surpassing the full Run 2 integrated luminosity
- **Set of measured observables significantly extended** with respect the early Run3 analysis:
  - **single** and **double** differential observables targeting both **production and decay**
  - new dedicated **VBF measurement**
- **Optimised binning strategy**
  - in place to both acquire statistical significance in each bin, as well as optimise the properties of the response matrix

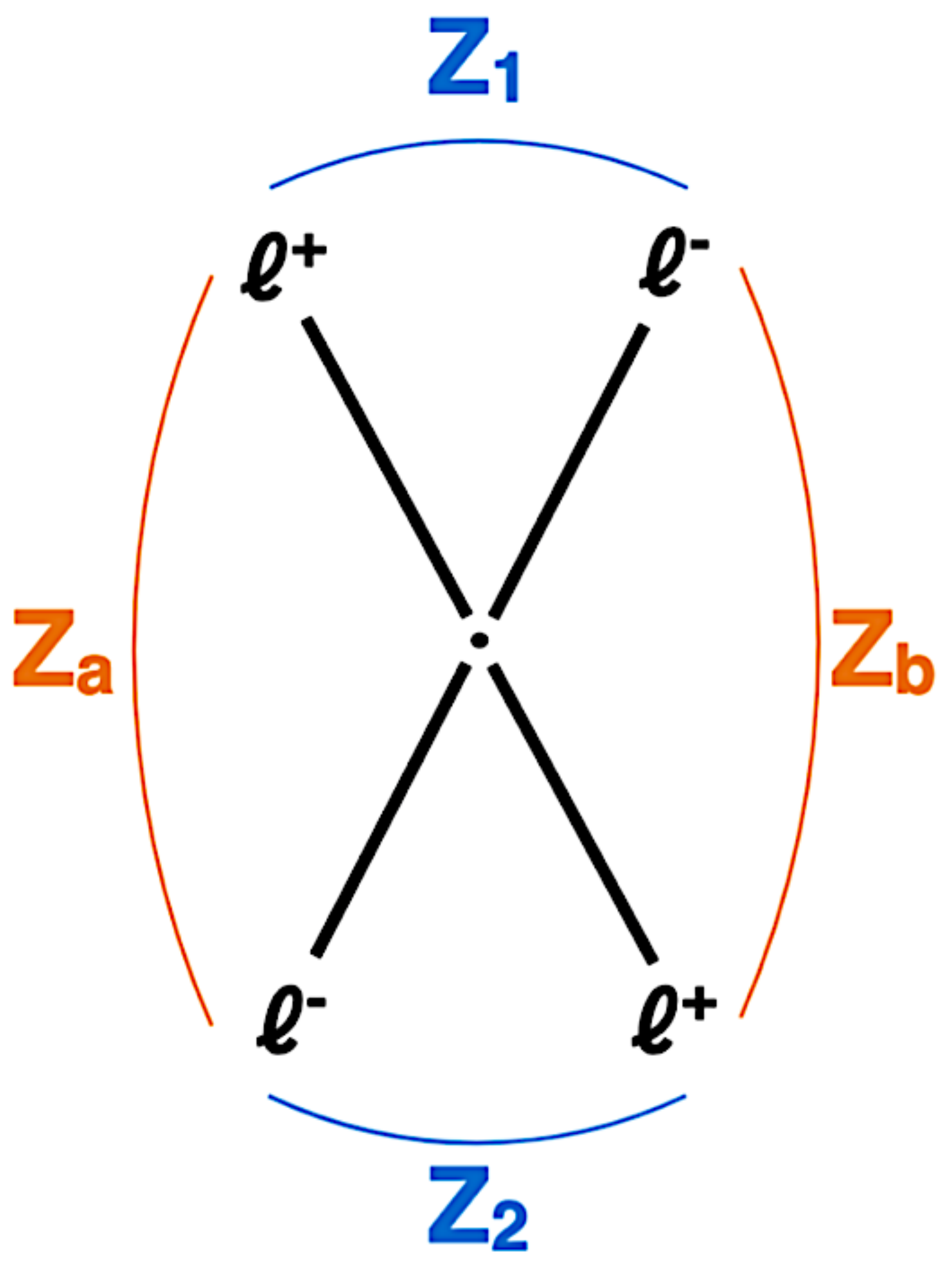
Analysis strategy

Object Selection:

- **Electrons** ($p_T > 7$ GeV) and **muons** ($p_T > 5$ GeV) within tracker acceptance are selected from PF candidates, required to be prompt
- These selections set the minimal lepton requirements (“loose leptons”) for signal or control regions
- Tighter selections applied to be considered as the signature of the golden channel

Event Selection:

- **Z Candidates:** any OS-SF pair that satisfies 12 < $m_{ll}(\gamma)$< 120 Gev/c^2
- **ZZ Candidates:** all possibile ZZs are built, defining Z_1 the candidate with $m_{ll}(\gamma)$ closest to the nominal Z mass.
- Additional kinematic selections applied to ensure a clean ZZ → 4ℓ topology, reject low-mass resonances and mispairings.



Analysis strategy

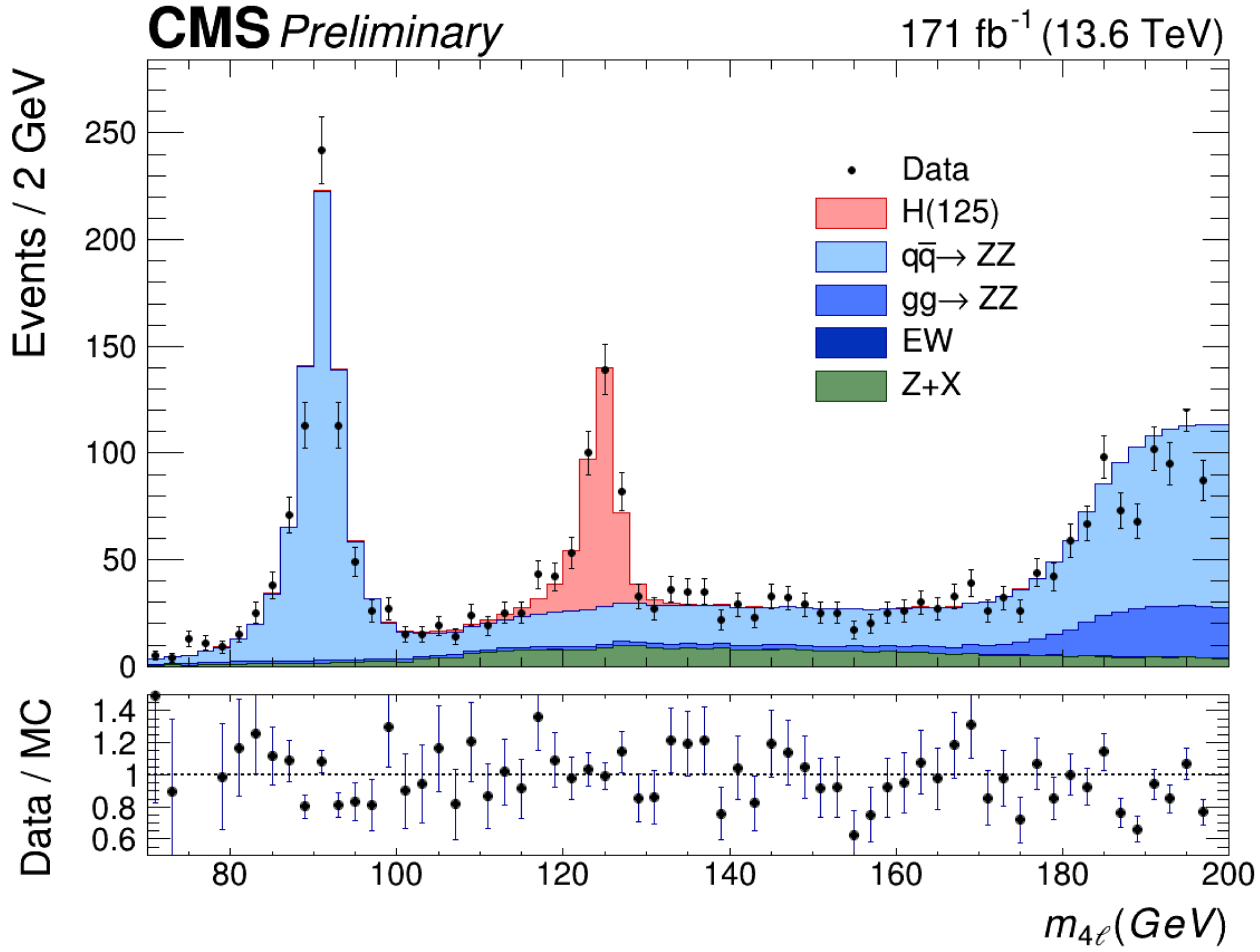
Signal & Background Modeling:

- **Background:**
  - Reducible background (Z+X): Data-driven method based on the computation of fake rates
  - Irreducible background (qq/gg → ZZ(γ^*) → 4l): Shape and normalisation from MC
- **Signal: Shape-based analysis using double-sided Crystal-Ball** function with parametrisation obtained from a simultaneous fit over 5 mass points in each final state and production mode

Statistical Model:

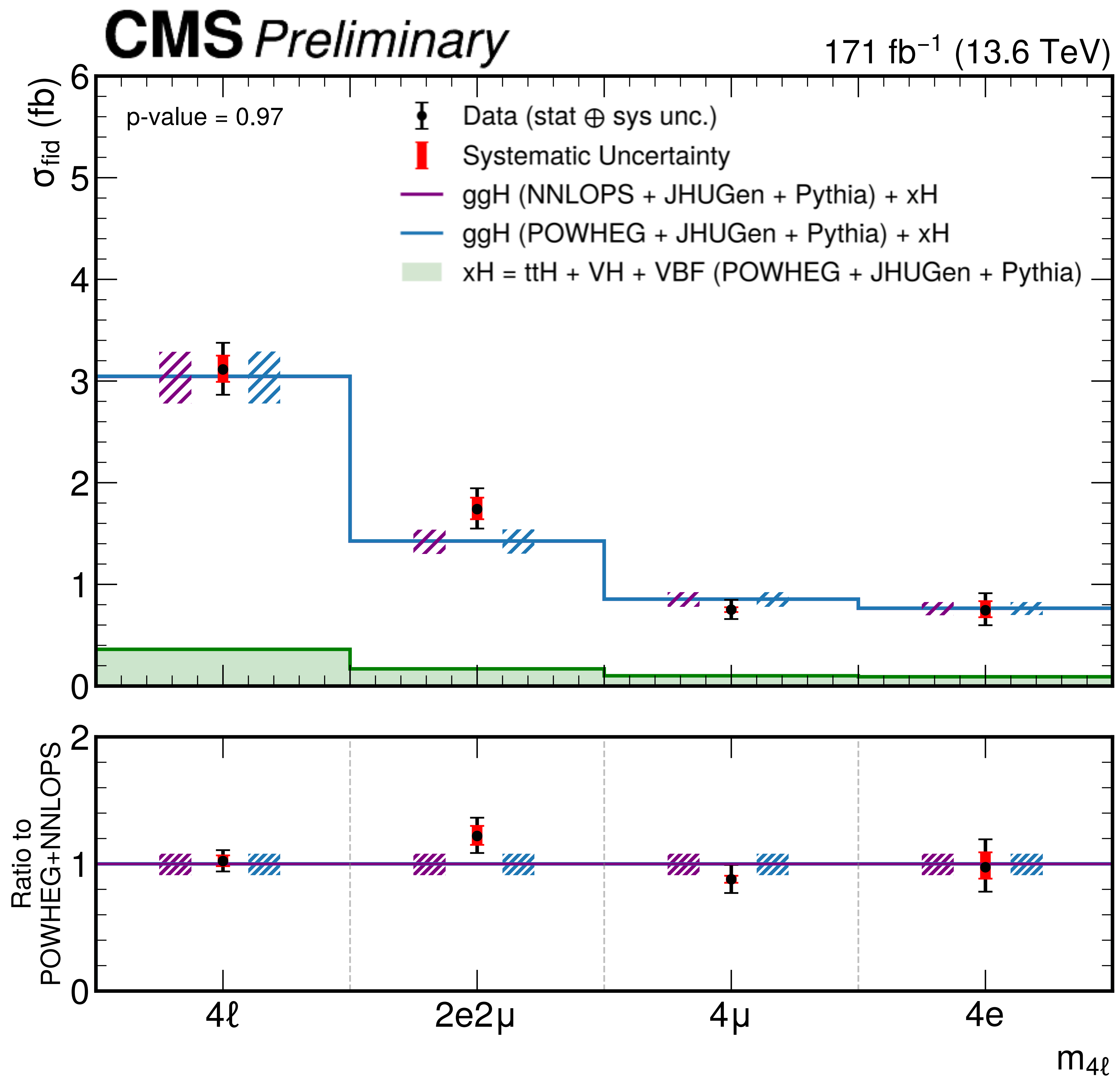
Simultaneous unbinned maximum likelihood fit in m4l across all years, final states $(4e, 4\mu, 2e2\mu)$ and reco bins in the mass range [105,160] GeV

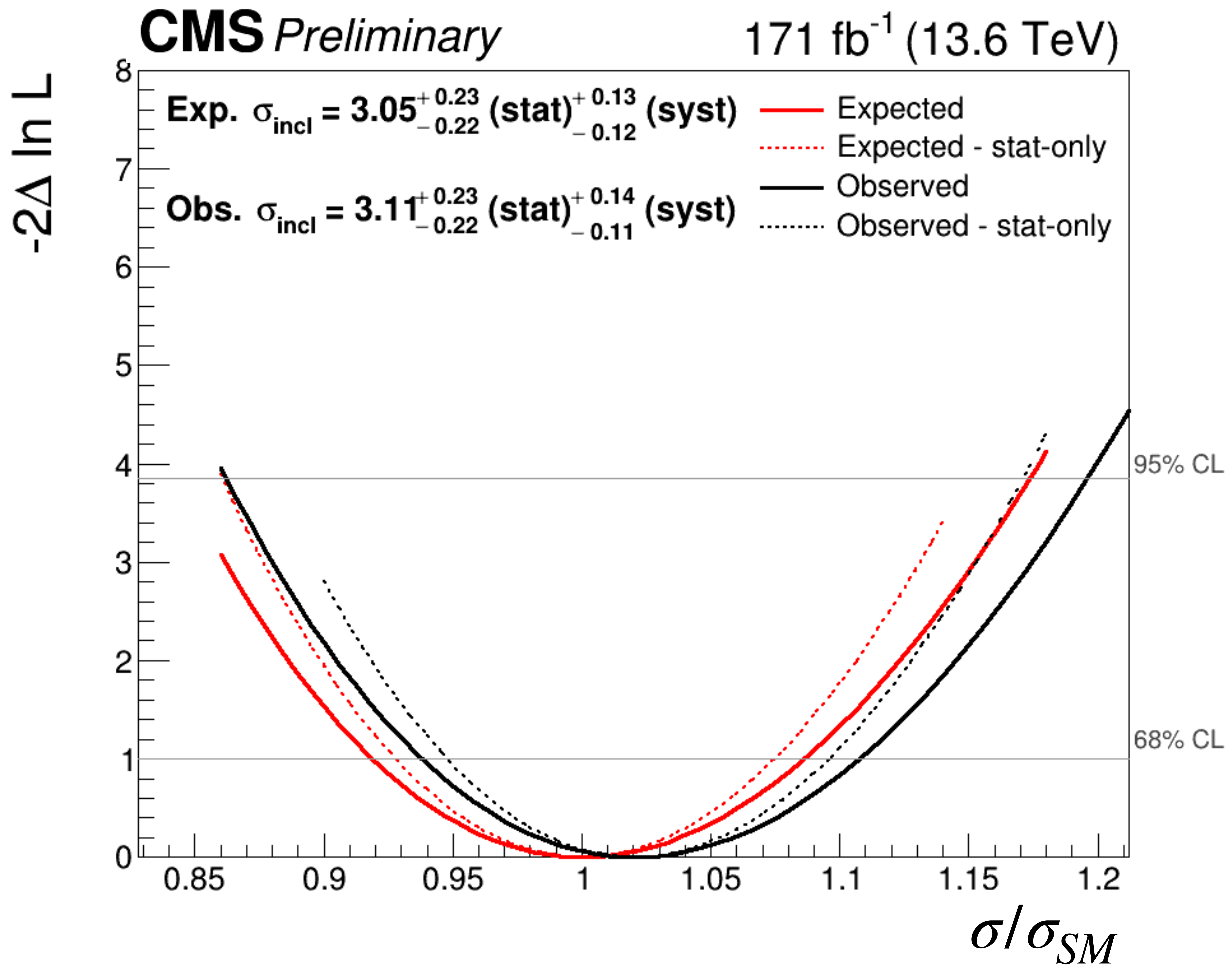
H→ZZ→4l mass spectrum with 171 fb^{-1} at 13.6 TeV: Still golden!



Inclusive fiducial XS at 13.6 TeV for 2022-2024

- Measurement is presented both **inclusively** and in the **three different final states**
- Inclusive fiducial cross section found to be **in good agreement with the SM expectation**



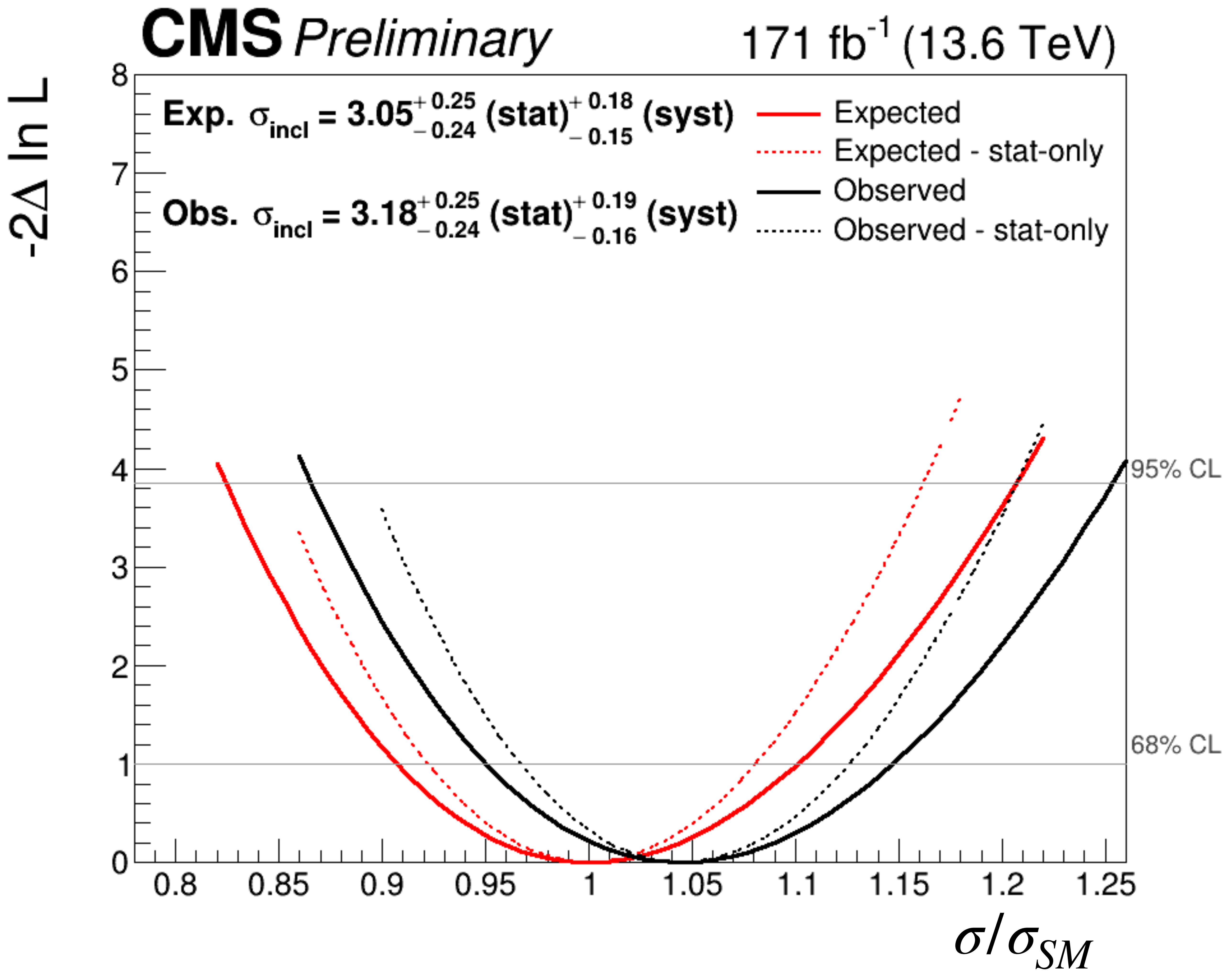


Inclusive XS with floating BRs

- **In order to increase the model independence, the BRs of the Higgs boson in 2e2μ, 4e, and 4μ are allowed to float in the fit procedure.**

- Two additional parameters are introduced to adjust the 4e and 4μ fractions, allowing the branching ratios to float while keeping the correlations between final states.

- The standard model scenario is recovered when these two parameters are set to 1.



Inclusive XS with floating ZZ normalisation

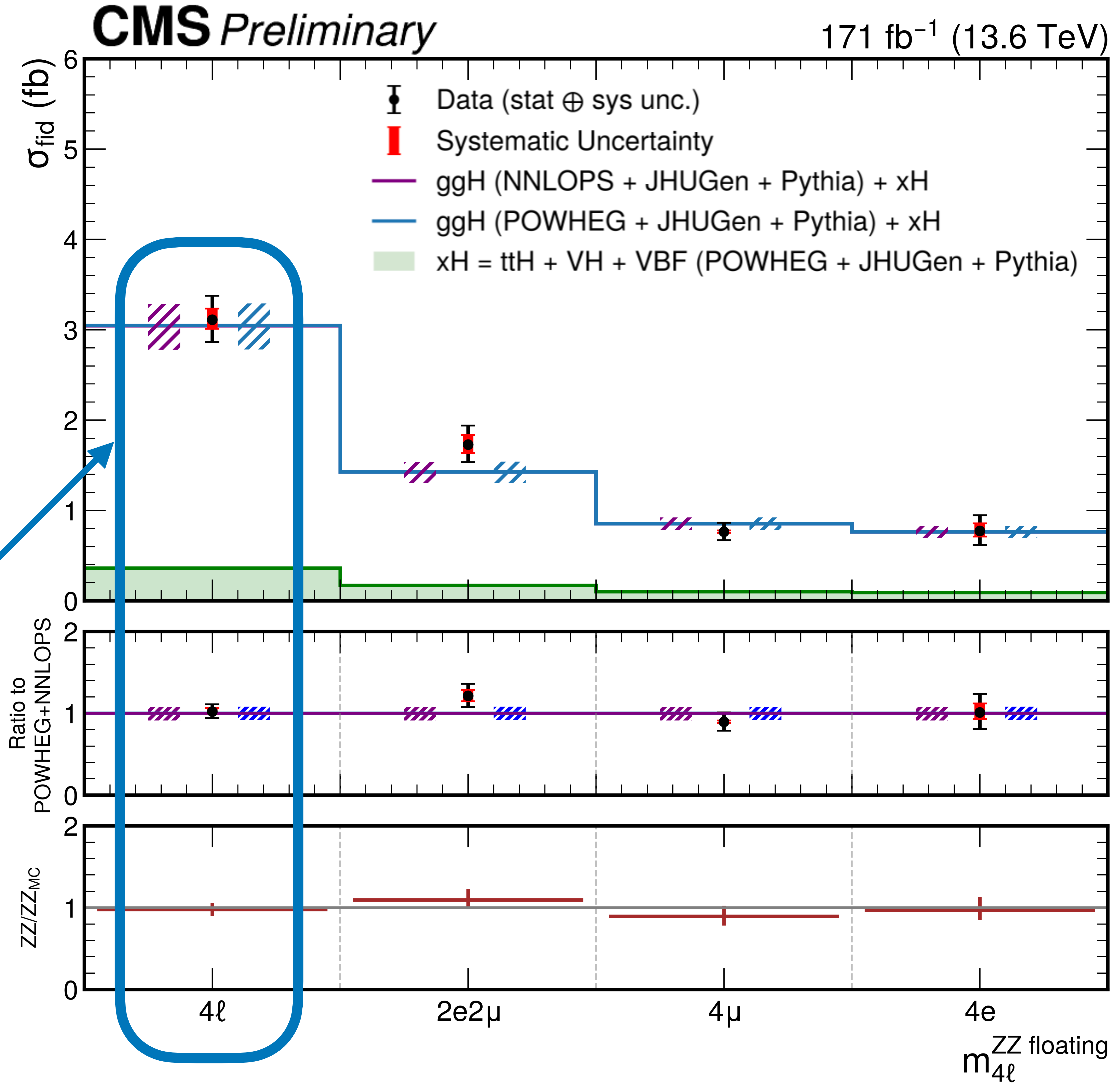
- **Standard approach:** extract both the shape and the normalisation of the ZZ irreducible background from simulation

- **Alternative strategy:** Measuring together the inclusive fiducial cross section and the ZZ normalisation
  - Remove the impact of nuisances on ZZ normalisation
  - Being sensitive to BSM effects in the background

$$\sigma^{fid} = 3.11^{+0.23}_{-0.23}\ (stat)\ ^{-0.12}_{-0.10}\ (syst)$$

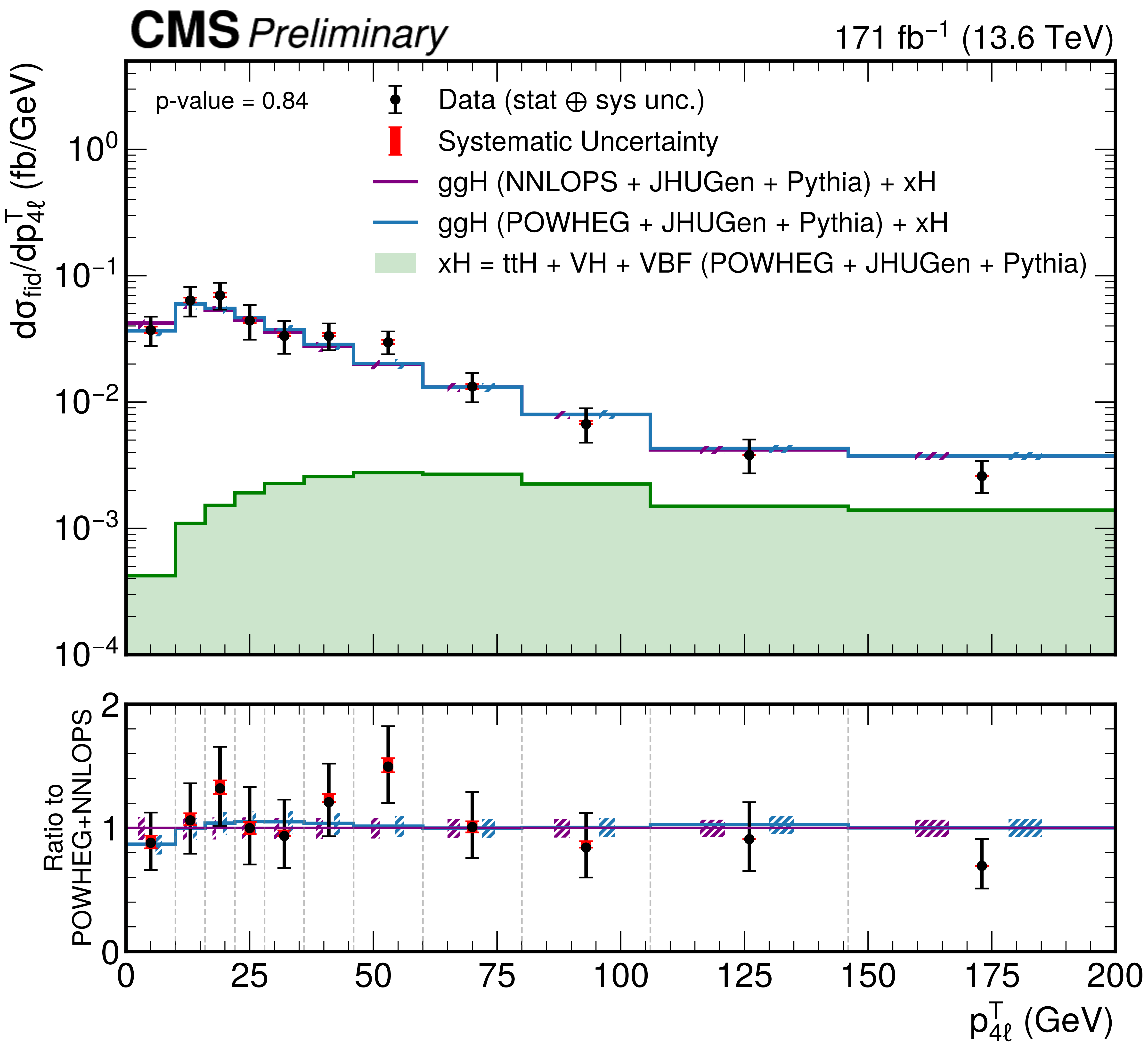
$$ZZ_{norm} = 490.63^{+29.57}_{-28.81}\ (stat)\ ^{+28.51}_{-28.30}\ (syst)$$

Reduction of the systematic component on the XS wrt std approach, but not yet enough number of events to profit from this method differentially

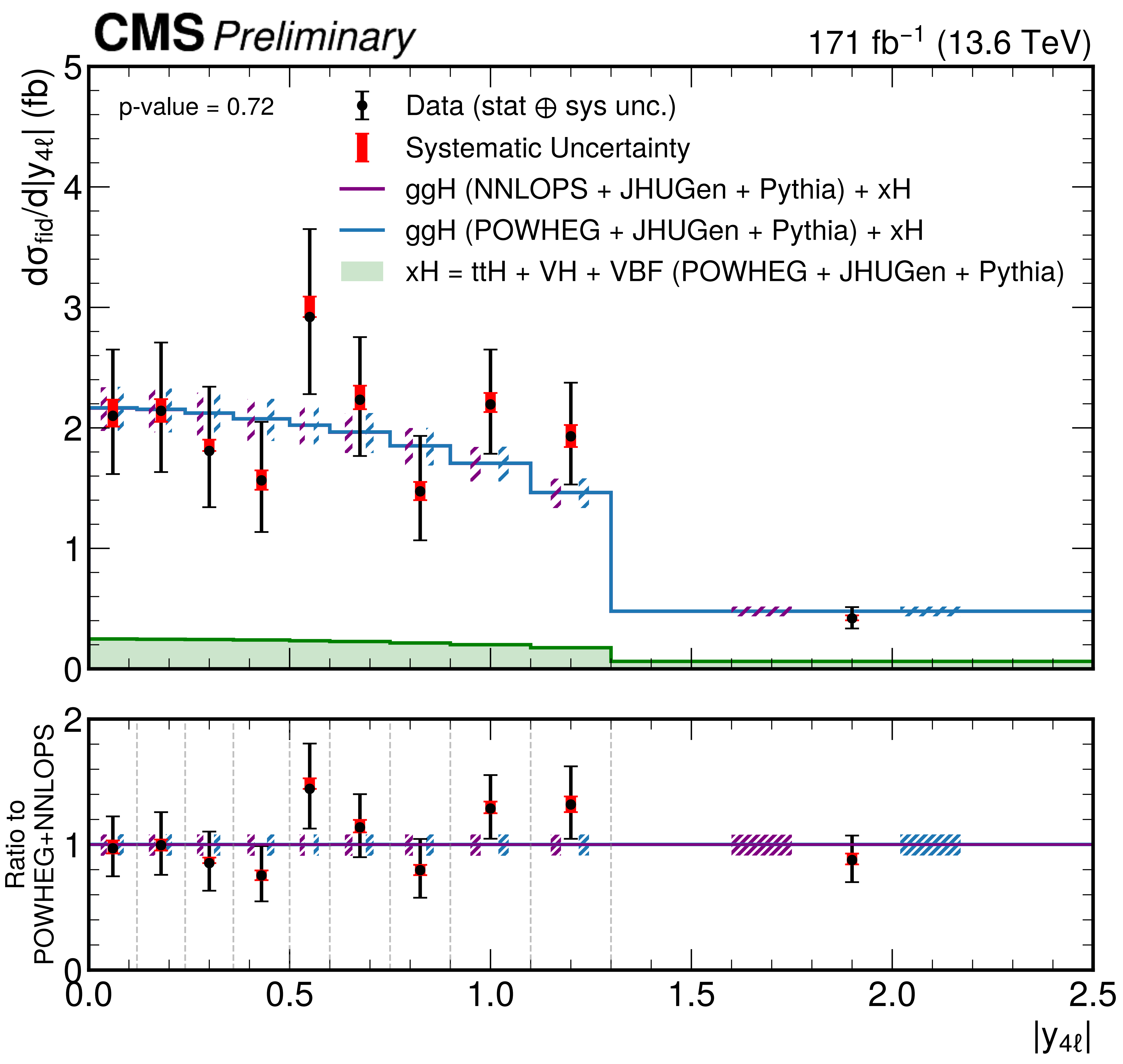


Quintessential fiducial observables

Transverse momentum of the Higgs boson

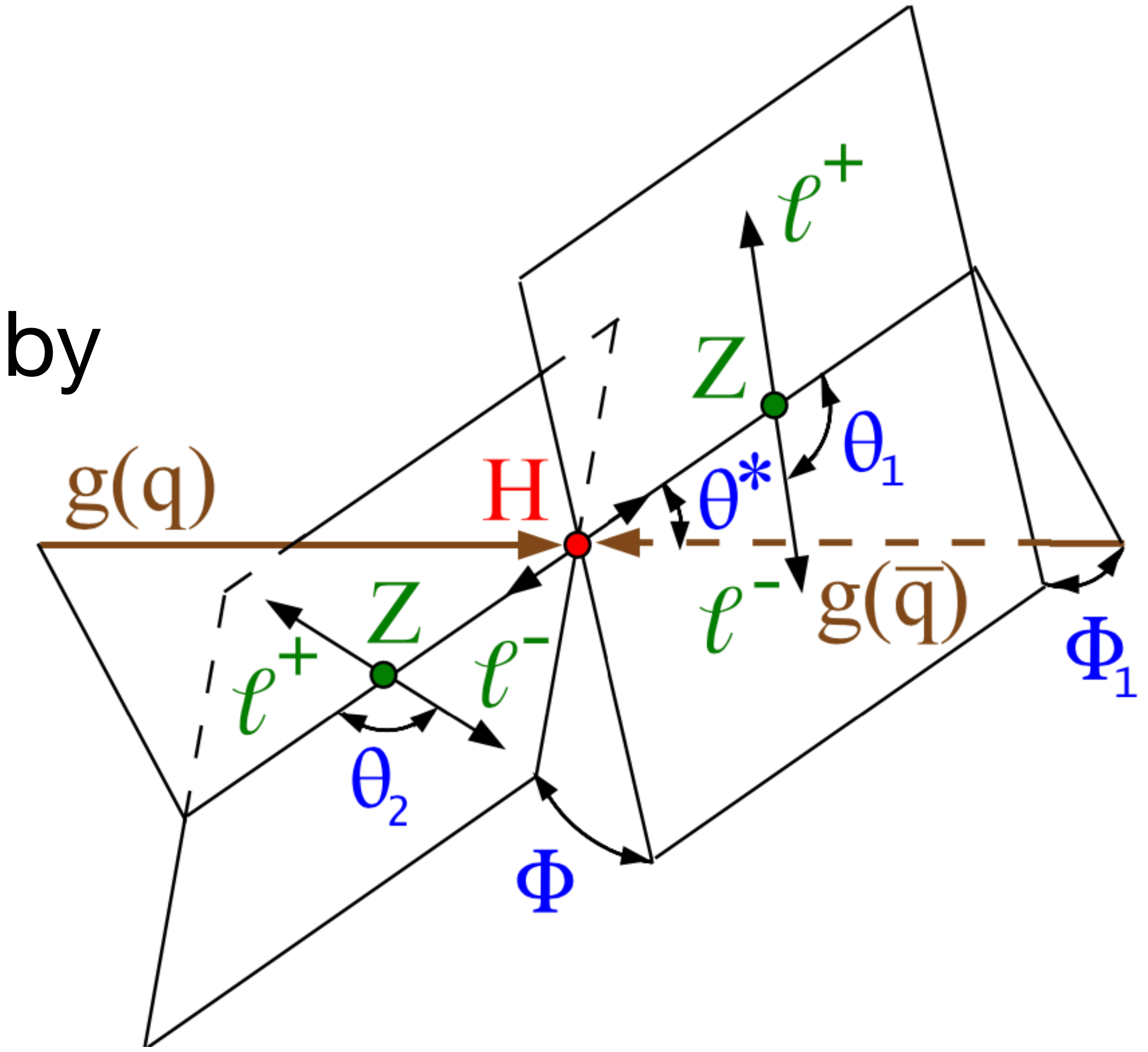


Absolute value of the rapidity of the Higgs boson

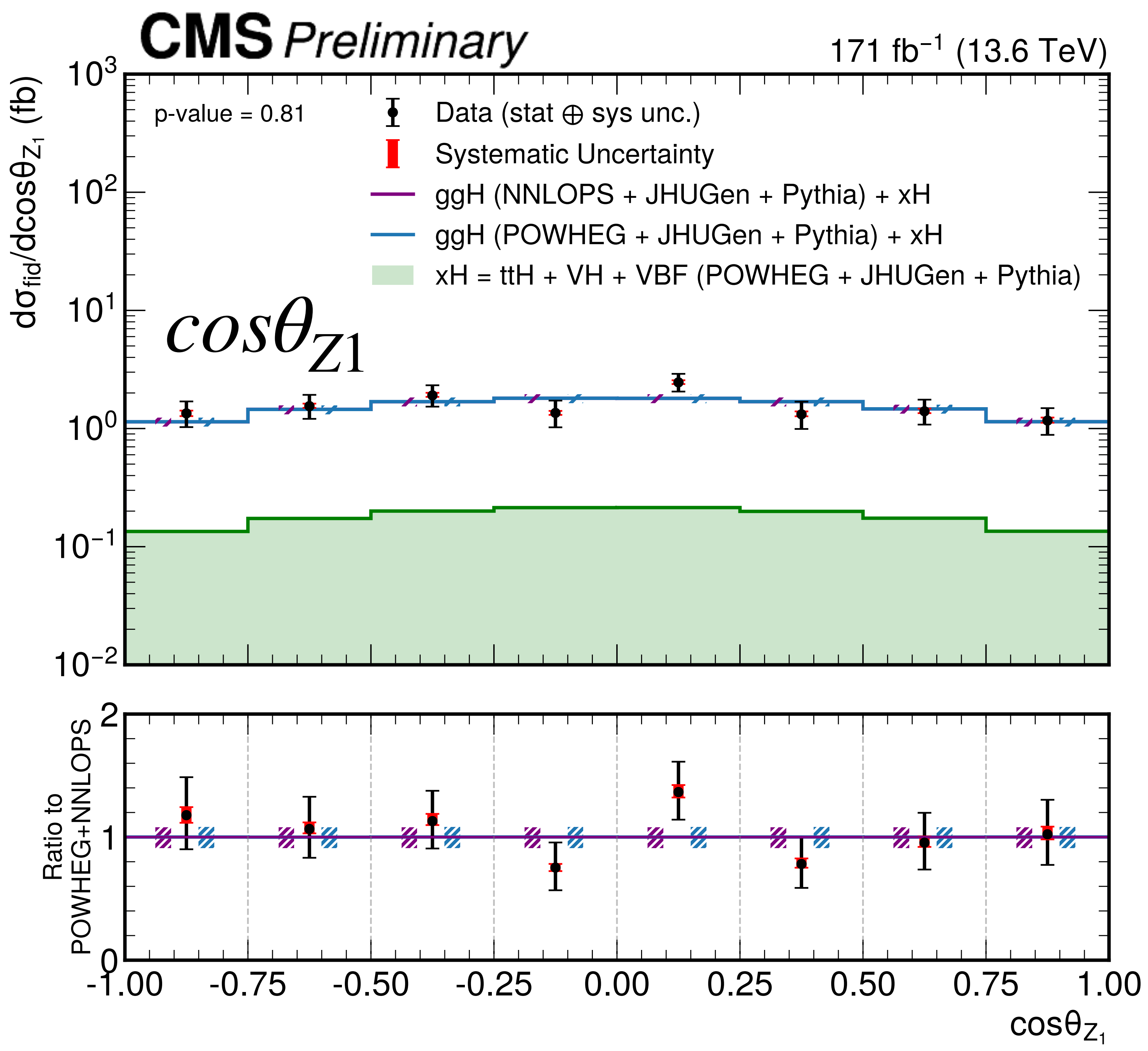


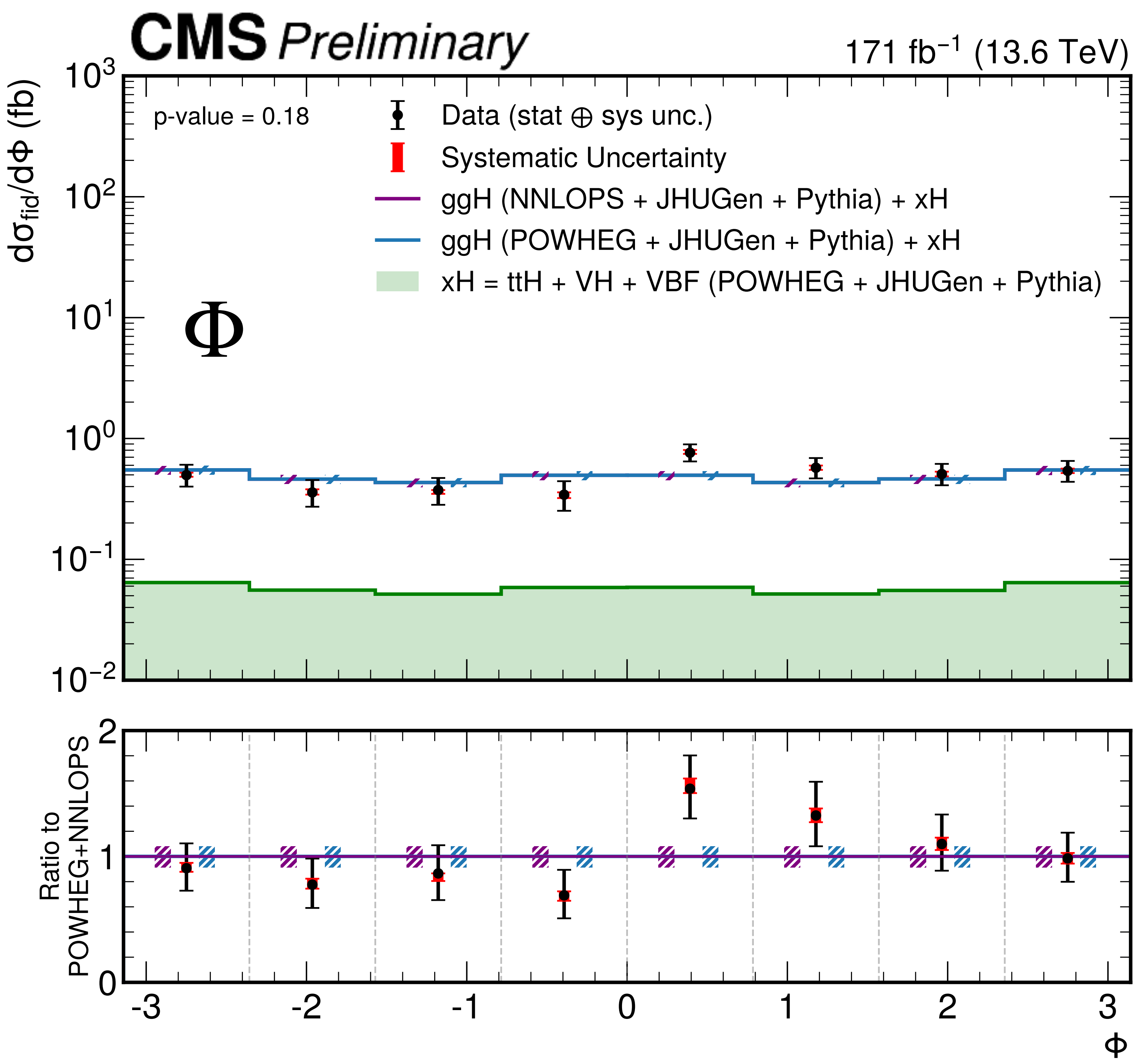
Decay observables

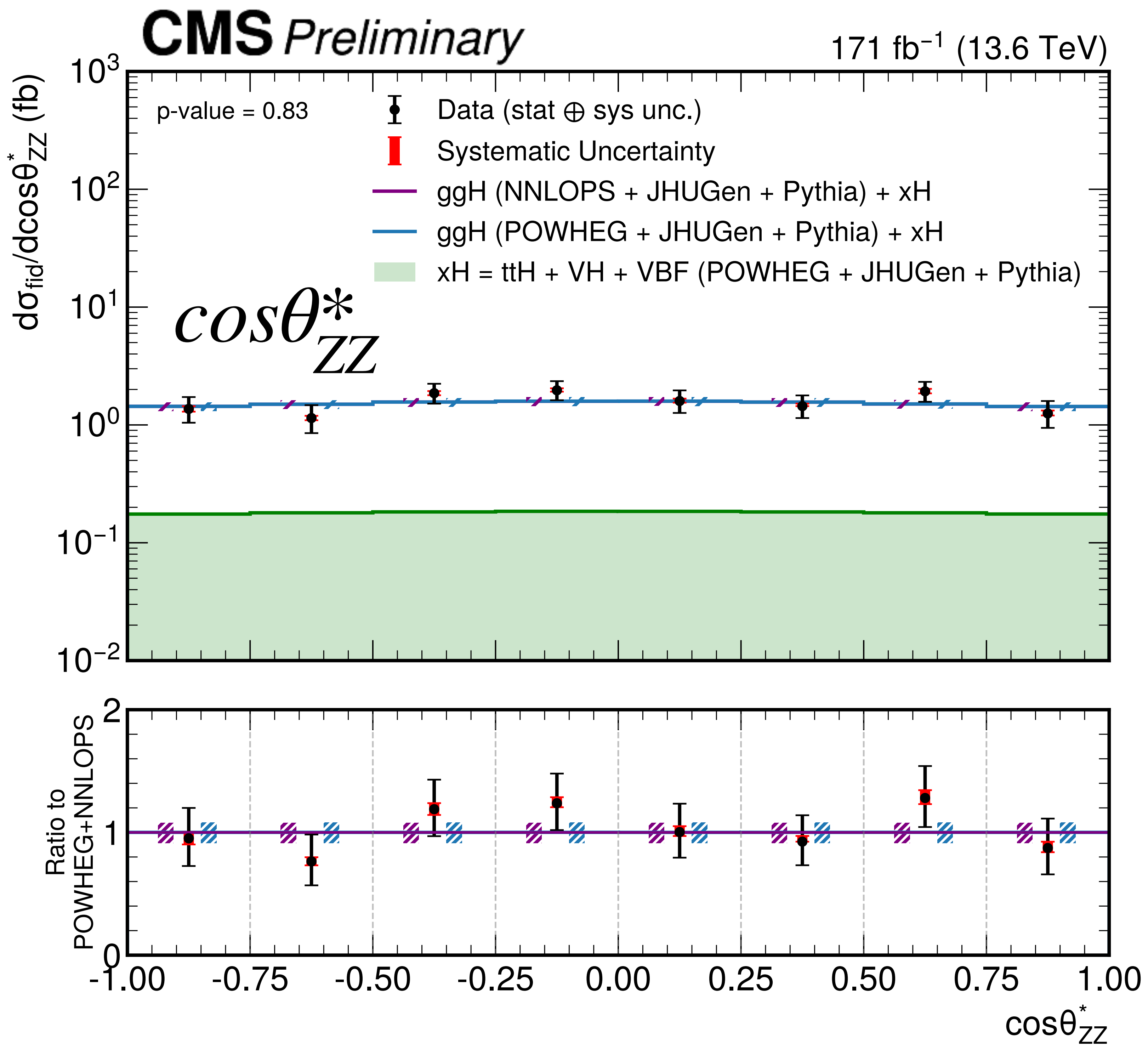
The kinematics of the decay of the H boson in 4 leptons is fully described by the Higgs boson's mass and 7 parameters:



- The two **Z masses**
- **Three angles** describing the **fermion kinematics** ($\Phi, cos\theta_{Z2}, cos\theta_{Z1}$)
- **Two angles** connecting **production to decay** ($\Phi_1, cos\theta^*_{ZZ}$)



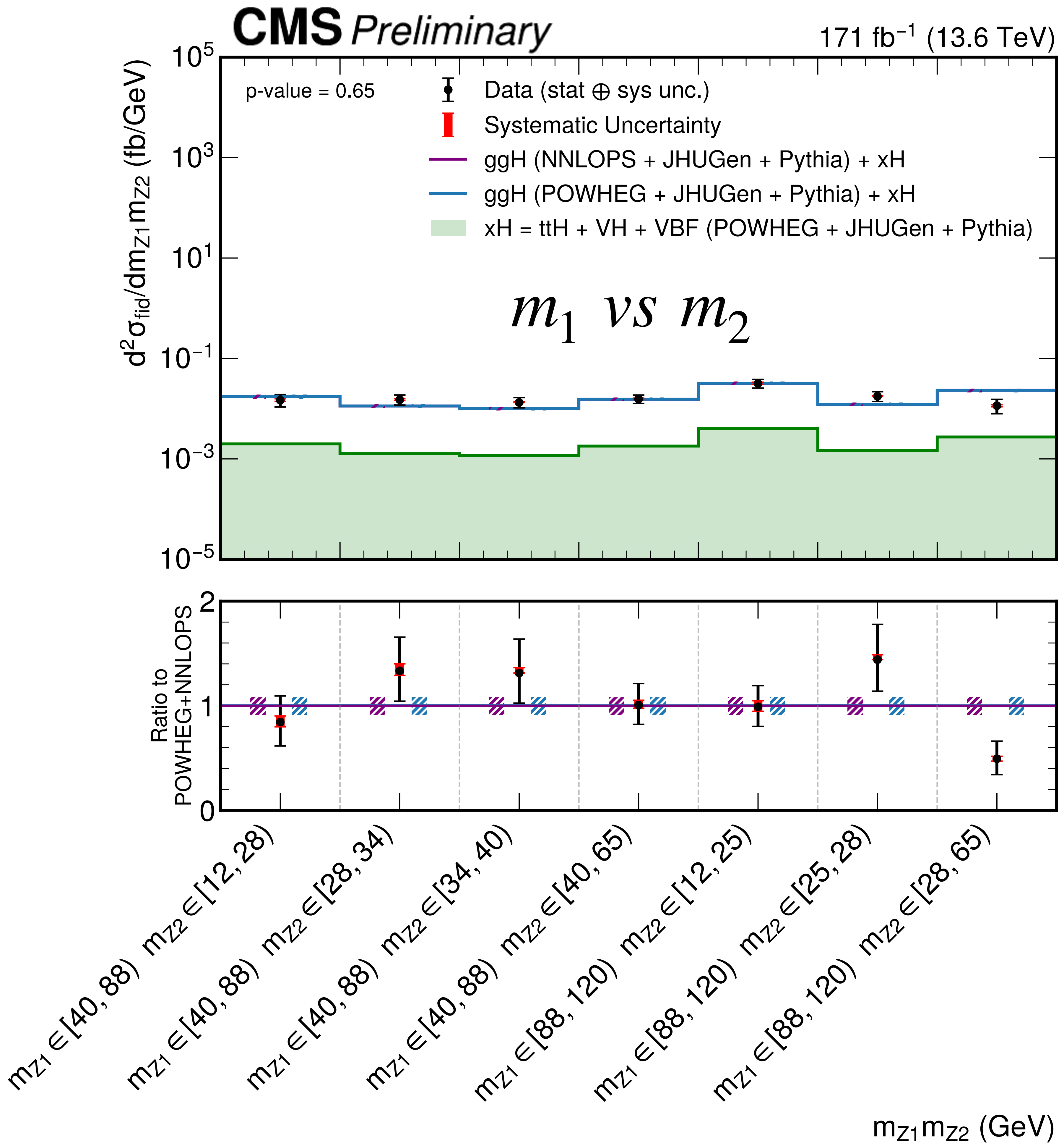


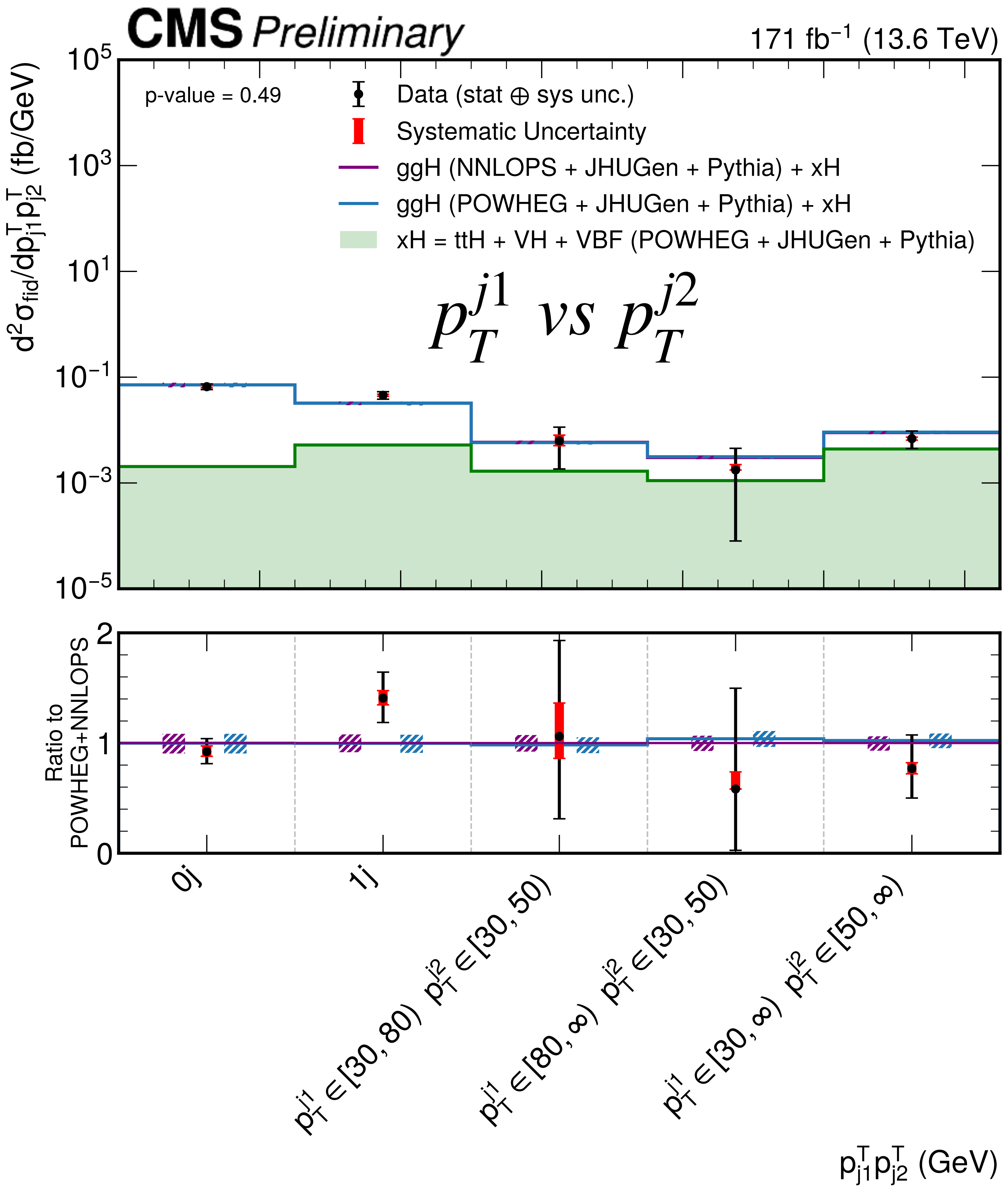


Double differential observables

Extensive set of double differential observables to probe specific phase space regions

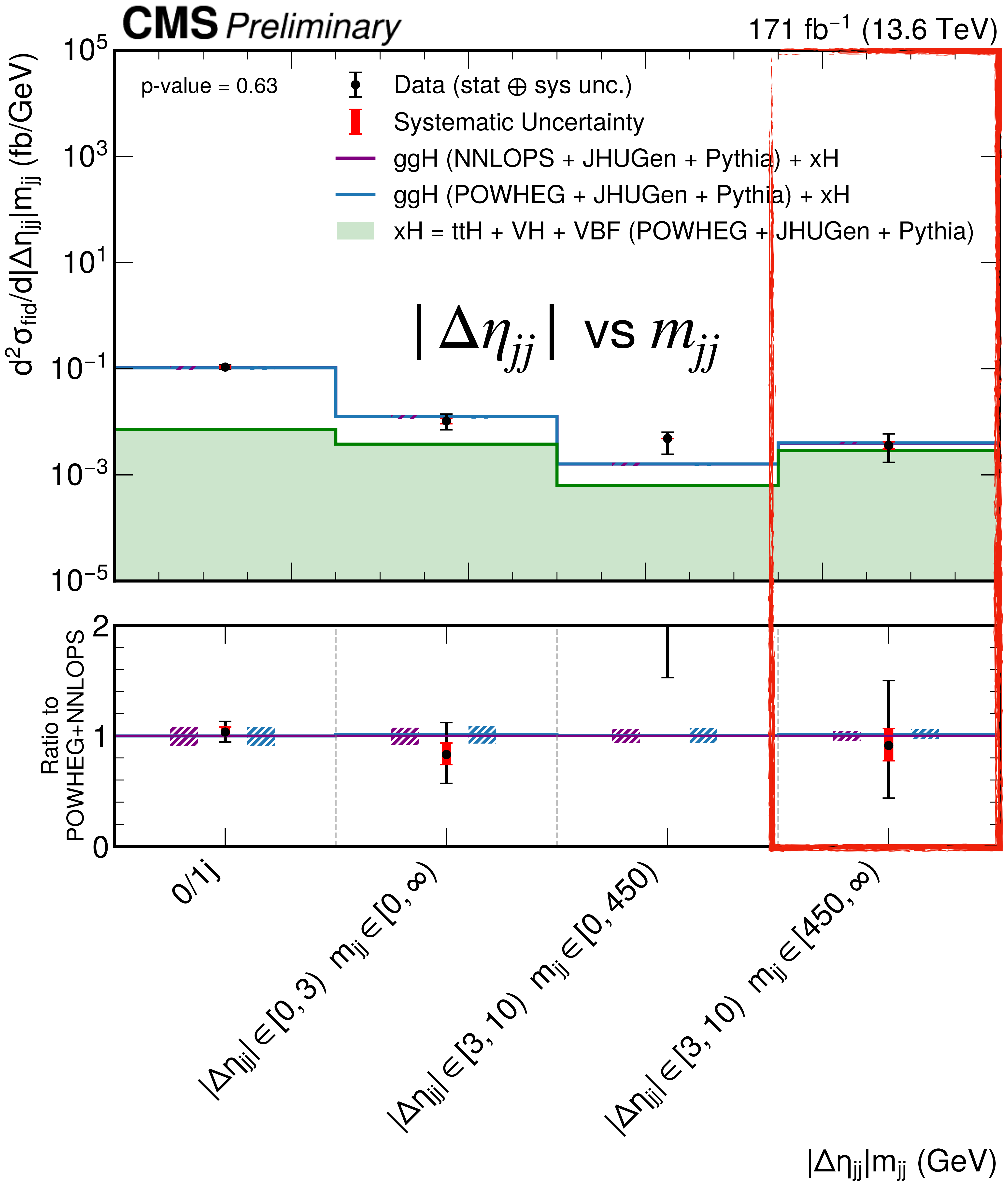
TC_{max} vs p_T^H m_1 vs m_2 N_j vs p_T^H p_T^H vs p_T^{Hj} $|y_H|$ vs p_T^H p_T^{j1} vs p_T^{j2}





VBF Measurement

- Double differential measurement $|\Delta\eta_{jj}|$ vs m_{jj} included for first time
- **Sensitive to VBF production in high $|\Delta\eta_{jj}|$, high m_{jj} range**
- Optimization studies performed to **maximize VBF purity**



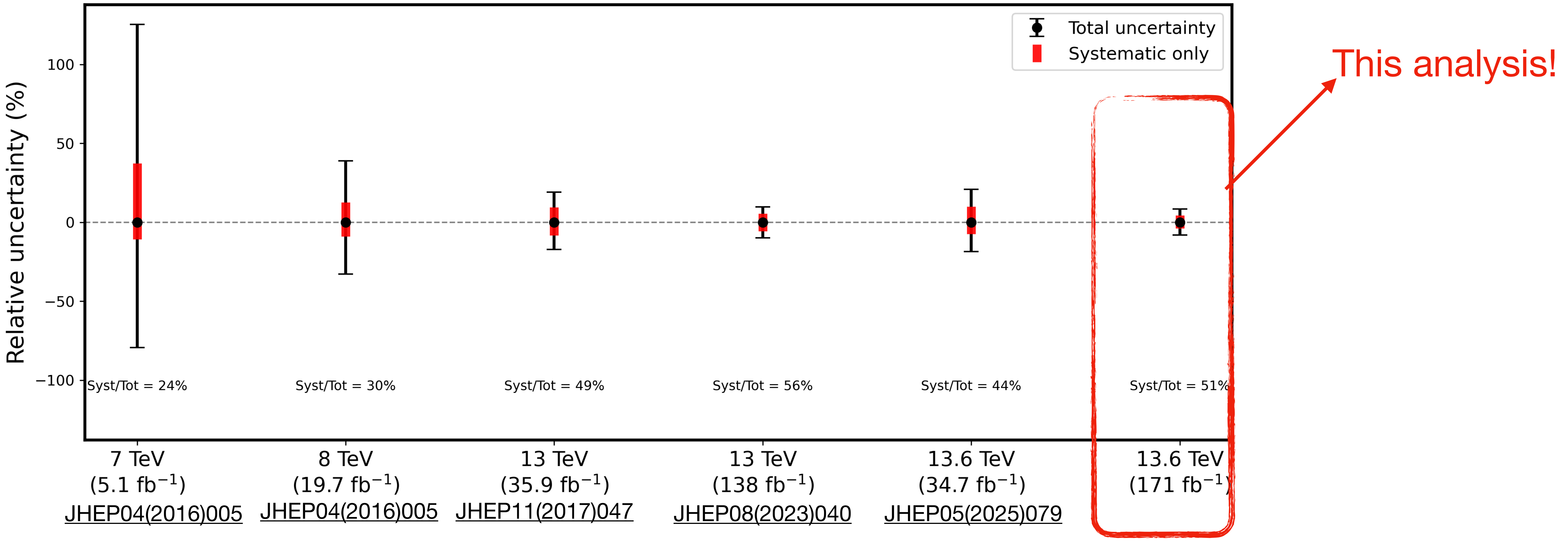
Conclusion

Newest HZZ Run 3 measurement: Higgs differential cross section measurements in the H → ZZ → 4ℓ channel at $\sqrt{s}$ = 13.6 TeV using 171 fb^{-1} (2022–2024)

- Already exceeding the full Run 2 dataset!

- Extended analysis with a total of 24 fiducial differential observables, including single- and double-differential measurements and a dedicated VBF study, with an optimised binning strategy.

General good agreement with the Standard Model: the H → ZZ → 4ℓ channel remains a powerful and model-independent probe of Higgs production and the scalar sector.



BACK UP

Events selections

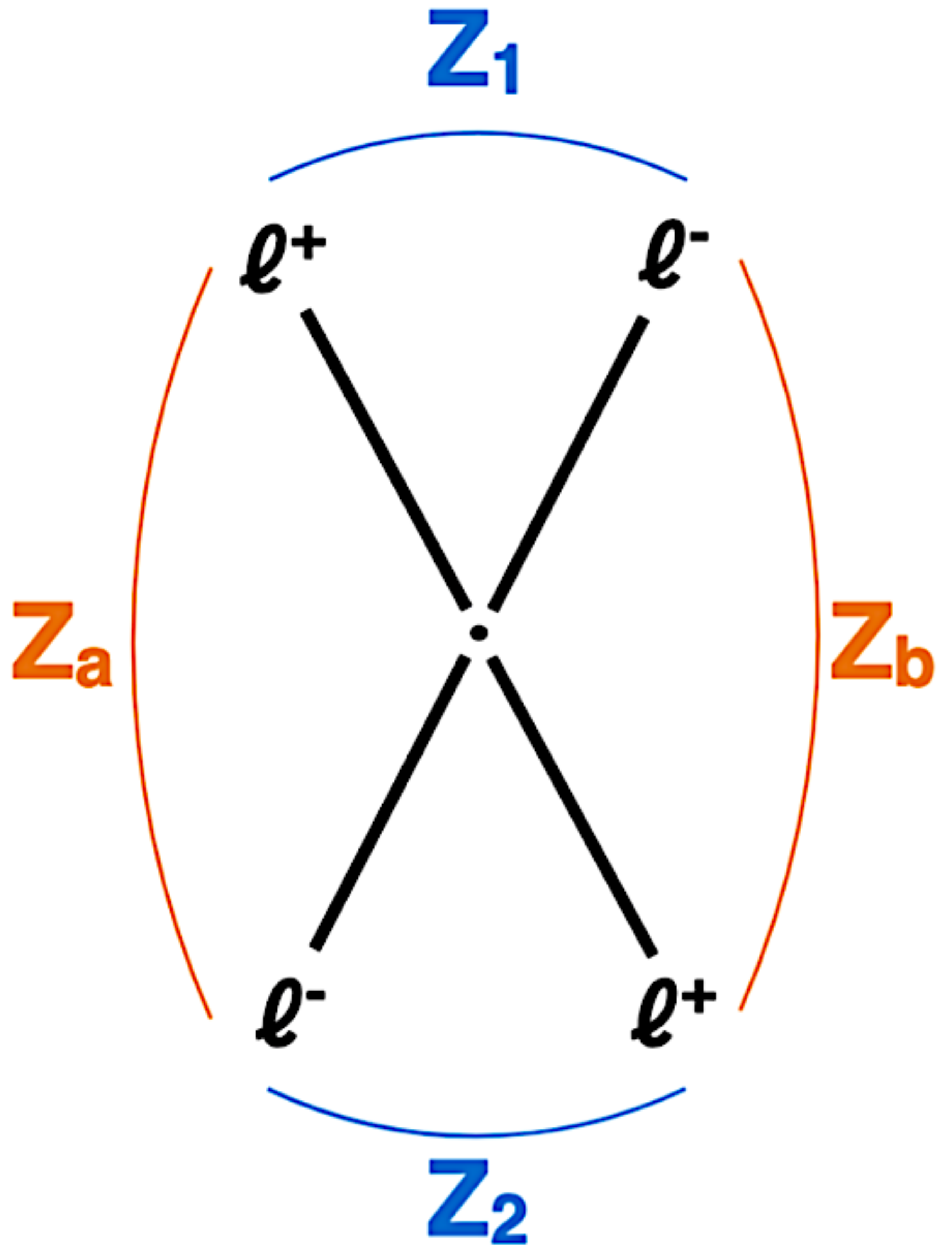
Z Candidates: any OS-SF pair that satisfies 12 < $m_{ll}(\gamma)$< 120 Gev/c^2

ZZ Candidates: all possibile ZZs are built, defining Z_1 the candidate with $m_{ll}(\gamma)$ closest to the nominal Z mass

- m_{Z_1} > 40 Gev/c^2
- $p_{T_{(l_1)}}$> 20 Gev/c^2, $p_{T_{(l_2)}}$> 10 Gev/c^2
- $\Delta R(\eta, \Phi)$ > 0.02 between each of the four leptons
- m_{ll} > 4 GeV for OS pair
- Reject 4μ and $4e$ candidates where the alternative pairing Z_aZ_b satisfies

$|m(Z_a) - m_Z| < |m_{Z_1} - m_Z|$ AND m_{Z_b}< 12 Gev/c^2

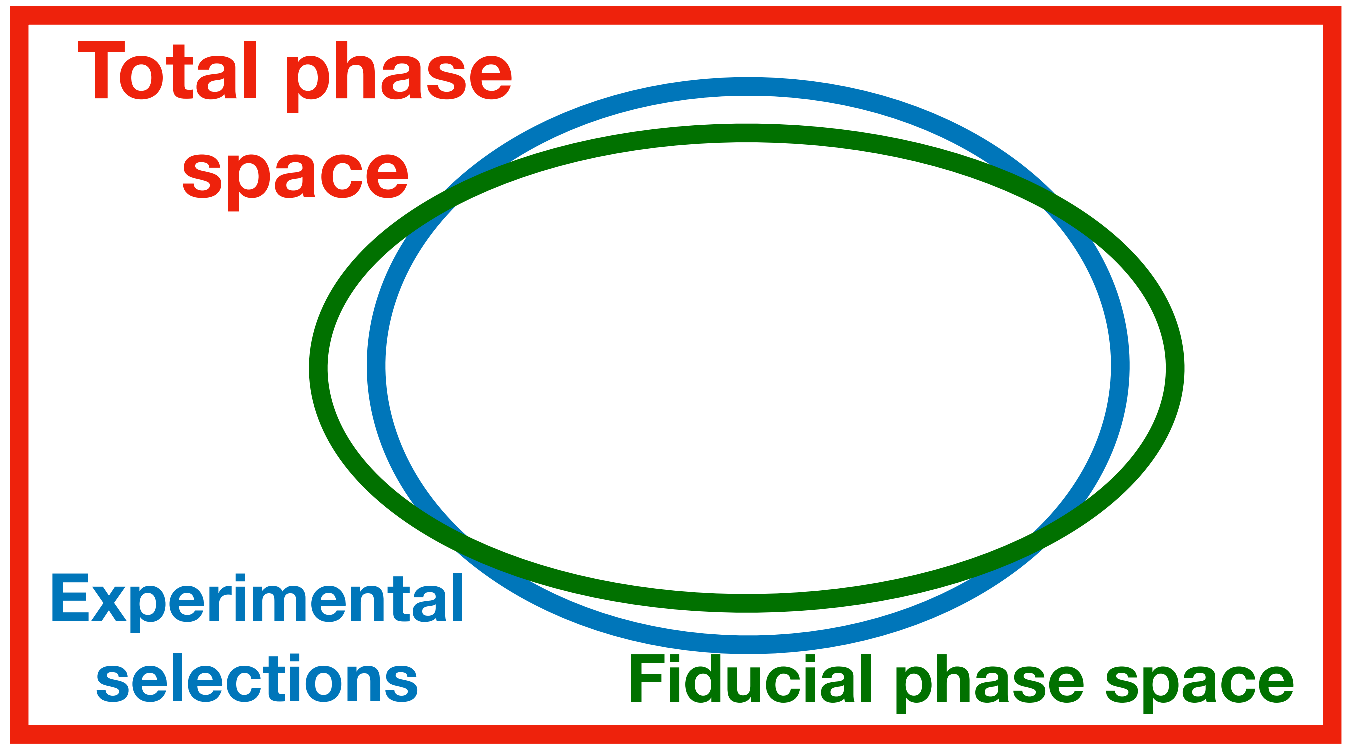
- m_{4l} > 70 GeV



Z1: candidate with invariant mass closest to the PDG Z
If multiple Z2s are present, the one with the largest pT sum of the leptons is retained

Fiducial phase space

- Cross section is measured by **unfolding** experimental data to the fiducial phase space at **generator level**
- The definition of the **phase space** is the same as in **HIG-21-009**



Model independent measurement ✓

Easy re-interpretability ✓

Z1: OSSF pair of leptons closest to the Z mass

Z2: second OSSF pair of leptons; in case of more than a pair the one with the highest scalar pT is chosen

Gen-level isolation is included to reduce the model dependence on the efficiency

Requirements for the $\mathrm{H} \to 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
leading lepton p_{T}	$p_{\mathrm{T}} > 20$ GeV
next-to-leading lepton p_{T}	$p_{\mathrm{T}} > 10$ GeV
additional electrons (muons) p_{T}	$p_{\mathrm{T}} > 7(5)$ GeV
pseudorapidity of electrons (muons)	$\lvert\eta\rvert < 2.5(2.4)$
p_{T} sum of all stable particles within $\Delta R < 0.3$ from lepton	less than $0.35 \cdot p_{\mathrm{T}}$
Event topology	
existence of at least two SFOS lepton pairs, where leptons satisfy criteria above	
inv. mass of the Z_1 candidate	$40\,\mathrm{GeV} < m(\mathrm{Z}_1) < 120\,\mathrm{GeV}$
inv. mass of the Z_2 candidate	$12\,\mathrm{GeV} < m(\mathrm{Z}_2) < 120\,\mathrm{GeV}$
distance between selected four leptons	$\Delta R(\ell_i \ell_j) > 0.02$ for any $i \neq j$
inv. mass of any opposite sign lepton pair	$\mathrm{m}(\ell^+ \ell'^-) > 4\,\mathrm{GeV}$
inv. mass of the selected four leptons	$105\,\mathrm{GeV} < m_{4\ell} < 160\,\mathrm{GeV}$
the selected four leptons must originate from the $\mathrm{H} \to 4\ell$ decay	

New binning strategy

✓ Ensures **statistical significance** per bin and **optimised response-matrix performance**

✓ Extends AMS-based binning by including:

- **Condition number** (stability)
- **Migration score** (purity) = $\dfrac{\sum_{i=1}^{N} C_{ii}}{\sum_{i=1}^{N}\sum_{j=1}^{N} C_{ij}}$

Merge bin i with bin $i+1$ if

$$P_{diag} = \varepsilon\,\Phi\left(\frac{\Delta}{2\sqrt{2}\sigma}\right) < M_{ii}$$

```
migration matrix:
[[0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.02 0.75]
 [0.00 0.00 0.00 0.00 0.00 0.00 0.01 0.06 0.68 0.10]
 [0.00 0.00 0.00 0.00 0.00 0.01 0.09 0.61 0.10 0.00]
 [0.00 0.00 0.00 0.01 0.01 0.11 0.55 0.13 0.01 0.01]
 [0.01 0.00 0.01 0.02 0.13 0.53 0.16 0.01 0.01 0.01]
 [0.01 0.01 0.02 0.14 0.50 0.16 0.01 0.01 0.01 0.01]
 [0.01 0.01 0.14 0.49 0.17 0.01 0.01 0.01 0.01 0.01]
 [0.01 0.06 0.51 0.18 0.01 0.01 0.01 0.01 0.01 0.01]
 [0.04 0.65 0.18 0.03 0.02 0.02 0.02 0.02 0.02 0.02]
 [0.92 0.26 0.14 0.13 0.14 0.14 0.14 0.14 0.14 0.09]]
```

Procedure:

Significance-based binning

- Place bin edges where the **AMS > 3**

Stability-based merging

- Ensure bins have sufficient **diagonal purity** using efficiency (ε), resolution (σ), and bin width (Δ)
- Merge bins if diagonal entries fall below a required threshold

Response-matrix optimisation

- Randomly shift bin edges (1k trials)
- Select binning with the **best migration score / condition number**

Observables

Variable	Description	Target	Type
$m_{4\ell}$	Invariant mass of the four-lepton system	Production	1D
$p_T^{4\ell}$	Transverse momentum of the four-lepton system	Production	1D
$y_{4\ell}$	Rapidity of the four-lepton system	Production	1D
N_j	Number of jets	Production	1D
p_T^{j1}	Transverse momentum of the leading jet	Production	1D
p_T^{j2}	Transverse momentum of the subleading jet	Production	1D
m_{jj}	Invariant mass of the dijet system	Production	1D
$\Delta\eta_{jj}$	Pseudorapidity difference between the leading jets	Production	1D
$\Delta\phi_{jj}$	Azimuthal angle difference between leading jets	Production	1D
m_{Hj_1}	Invariant mass of Higgs + leading jet	Production	1D
$p_T^{Hj_1}$	Transverse momentum of Higgs + leading jet	Production	1D
p_T^{Hjj}	Transverse momentum of Higgs + two leading jets	Production	1D
$(\mathcal{T}_C^{\max})$	Rapidity-weighted jet veto	Production	1D
$(\mathcal{T}_B^{\max})$	Rapidity-weighted jet veto	Production	1D
m_{Z_1}	Invariant mass of the leading lepton pair	Decay	1D
m_{Z_2}	Invariant mass of the subleading lepton pair	Decay	1D
$\cos\theta^*$	Cosine of angle between beam and Z_1 in Higgs rest frame	Decay	1D
$\cos\theta_1$	Cosine of angle between negative lepton and Z_1 in Z_1 rest frame	Decay	1D
$\cos\theta_2$	Cosine of angle between negative lepton and Z_2 in Z_2 rest frame	Decay	1D
Φ	Azimuthal angle between decay planes of the two Z bosons	Decay	1D
Φ_1	Azimuthal angle between production and decay planes	Decay	1D
$\|y(H)\|$ vs p_T^H	Rapidity vs transverse momentum of the 4ℓ system	Production	2D
$p_T^{j_1}$ vs $p_T^{j_2}$	Transverse momentum of the leading vs transverse momentum of the subleading jets	Production	2D
p_T^H vs N_j	Transverse momentum of 4ℓ system vs number of jets	Production	2D
p_T^H vs $p_T^{Hj_1}$	Transverse momentum of 4ℓ system vs transverse momentum of 4ℓ system + leading jet	Production	2D
$\|\Delta\eta_{jj}\|$ vs m_{jj}	Pseudorapidity gap vs invariant mass of two leading jets	Production	2D
$(\mathcal{T}_C^{\max})$ vs. $p_{\mathrm{T}}^{\mathrm{H}}$	Rapidity-weighted jet veto vs transverse momentum of the 4ℓ system	Production	2D
m_{Z_1} vs m_{Z_2}	Invariant masses of the two Z boson candidates	Decay	2D

Background modelling: ZX

Z+X: in-flight decays of light mesons, or misidentification of charged hadrons from π^0decay

- Data driven estimation from combination of two independent methods: OS and SS
- Fake rates calculated in Z + l control region
- Z+X yields estimated in 2 orthogonal regions of Z + ll control region

Inclusive XS with floating BRs

- In order to **increase the model independence**, the BRs of the Higgs boson in 2e2μ, 4e, and 4μ are allowed to float in the fit procedure

$$\sigma_{\text{fid}}^{f,j} = \sigma_{\text{fid}}^{j} \cdot f(\text{K1}^j,\ \text{K2}^j,\ \text{frac}(4\text{e})^j,\ \text{frac}(4\mu)^j)$$

$$\text{frac}(4\text{e})_j = \frac{\sigma(4\text{e})_j^{\text{fid}}}{\sigma_j^{\text{fid}}} \qquad \text{frac}(4\text{mu})_j = \frac{\sigma(4\text{mu})_j^{\text{fid}}}{\sigma_j^{\text{fid}}}$$

$$K1^j \rightarrow \left[0, \frac{1}{\text{frac}(4\text{e})^j}\right] \qquad K2^j \rightarrow \left[0, \frac{1 - \text{frac}(4\text{e})^j}{\text{frac}(4\mu)^j}\right]$$

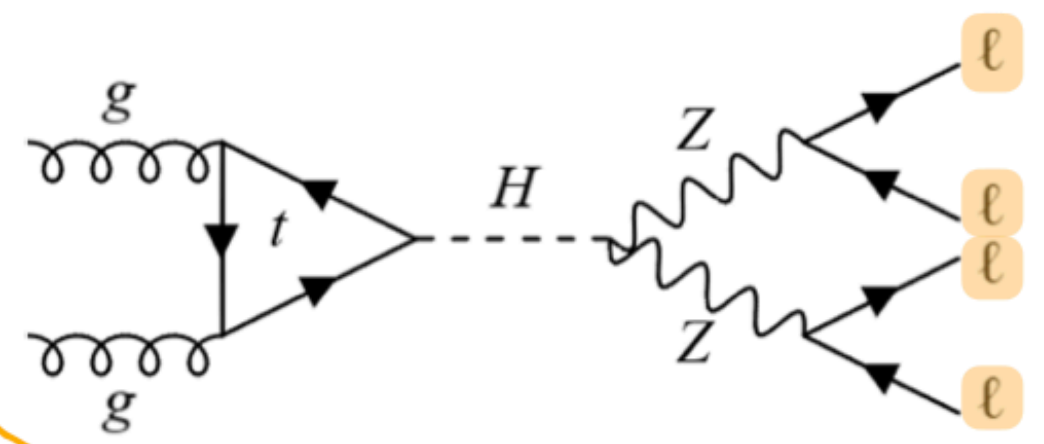
Parametrisation in a snapshot

For all years → $N_{f,i}(m4l) = N_{f,i}(m4l)^{fid} + N_{f,i}(m4l)^{nonfid} + N_{f,i}(m4l)^{nonres} + N_{f,i}(m4l)^{red/irred}$

Fiducial resonant contribution

Selected four leptons associated to the decay of the Z bosons coming from the decay of the H inside the fiducial volume

$$N^{fid}_{f,i}(m_{4\ell}) = \sum_j^{genBin} \epsilon^f_{i,j,f} \cdot \sigma^{fid}_{j,f} \cdot \mathscr{L} \cdot \mathscr{P}^{res}_f(m_{4\ell})$$



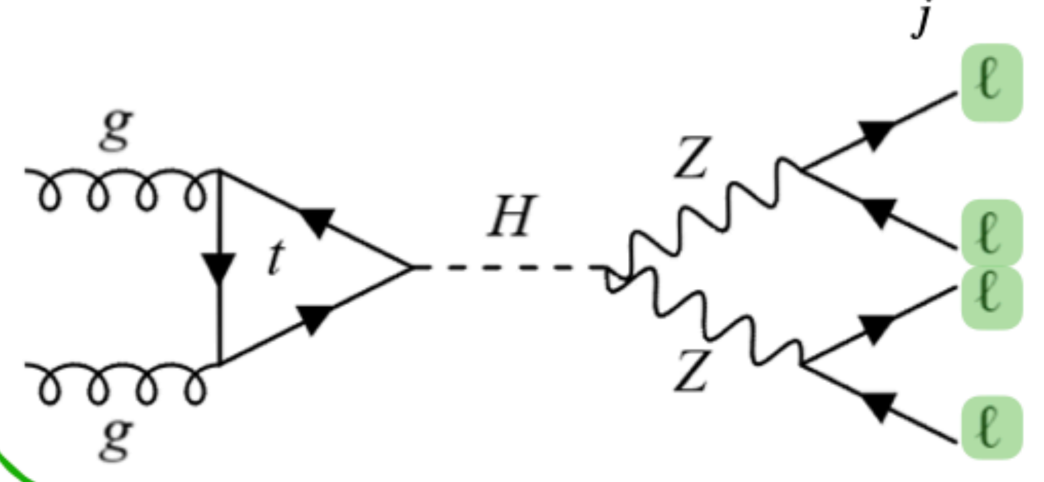
$\mathscr{P}_{res}(m_{4\ell})$ → Double-sided Crystal Ball

$$\epsilon_{i,j} = \frac{N(\text{fid}_j \to \text{reco}_i)}{N(\text{fid}_j)}$$

Non-fiducial resonant contribution

Selected four leptons associated to the decay of the Z bosons coming from the decay of the H outside the fiducial volume

$$N^{nonfid}_{f,i}(m_{4\ell}) = \sum_j^{genBin} \epsilon_{i,j,f} \cdot f^{nonfid}_{f,i} \cdot \sigma^{fid}_{j,f} \cdot \mathscr{L} \cdot \mathscr{P}^{res}_f(m_{4\ell})$$



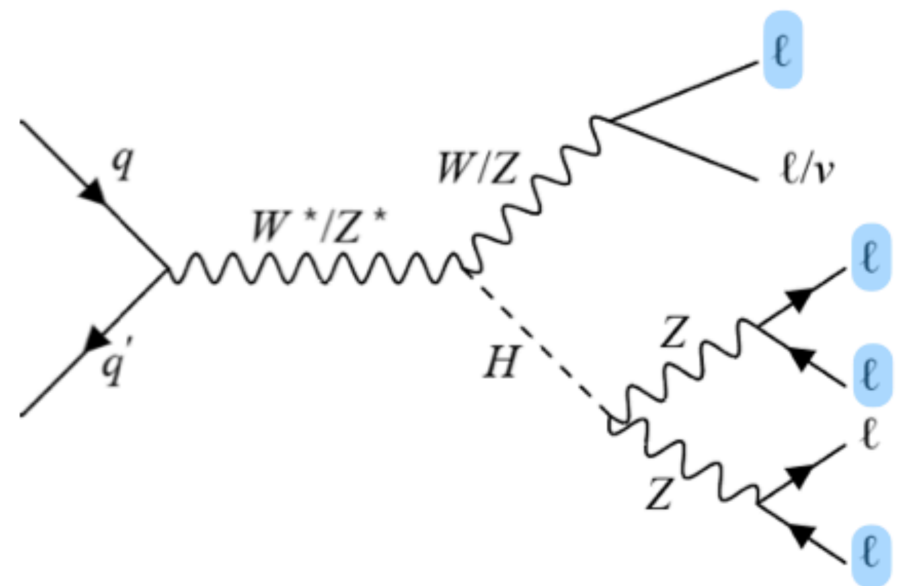
$\mathscr{P}_{res}(m_{4\ell})$ → Double-sided Crystal Ball

$$f^{i,j}_{nonfid} = \frac{N(\text{nonFid}_j \to \text{reco}_i)}{N(\text{fid} \to \text{reco}_i)}$$

Non-resonant background

Selected four leptons not associated to the decay of the H

$$N^{nonres}_{f,i}(m_{4\ell}) = N^{nonres}_{f,i} \cdot \mathscr{P}^{nonres}(m_{4\ell})$$



$\mathscr{P}_{nonres}(m_{4\ell})$ → Landau

Reducible and irreducible background

$$N^{red/irred}_{f,i}(m_{4\ell}) = \sum_b^{bkgs} N^{f,i}_b \cdot \mathscr{P}^{nonres}_{f,i}(m_{4\ell})$$

Irreducible backgrounds
- qq → ZZ
- gg → ZZ

Reducible backgrounds
- ZX = Z+jets & tt+jets & Zγ+jets & WW+jets & …

$\mathscr{P}_{nonres}(m_{4\ell})$ → Template from Monte Carlo or Control Region in data

RMS method reminder

- UL reprocessing enabled revision of the statistical method to a **Root-Mean-Square (RMS)** approach.
- **Conceptual Change:**
  - Alternative measurements are treated as **different fitting models** addressing the same systematic source.
  - Each fit represents an **equally valid measurement** on the same sample.
  - **RMS** captures the **spread** among these variations.
- **Implementation Details:**
  - **Central value:** Mean of all variations (including nominal).
  - **Uncertainty:** *RMS* / $\sqrt{N}$, where *N* = number of variations.
- **Outcome:**
  - **Reduced uncertainty** in low-p_T bins by **30–40%** compared to the previous method

New RMS method

$$SF = \frac{SF_{nom} + SF_{altSig} + SF_{altBkg} + SF_{altSigBkg}}{4}$$

$$RMS = \sqrt{\frac{\sum_i syst_i^2}{N-1}}$$

$$UNC_{total} = \sqrt{\left(\frac{RMS}{\sqrt{N}}\right)^2 + stat_{DATA}^2 + max(stat_{MC}^2, alt_{MC}^2)}$$

Old calculation

$$syst_i = SF_{alt} - SF_{nom}$$

$$UNC_{total} = \sqrt{\sum_i syst_i^2 + stat_{DATA}^2 + stat_{MC}^2}$$