Higgs boson fiducial cross section measurements in the four-lepton final state

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On behalf of the **CMS collaboration**

IRN Terascale @ LPSC Grenoble
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Overview

CMS PAS HIG-21-009

New analysis whose aim is a **complete characterisation of the Higgs-to-four-lepton channel** using **fiducial** cross section measurements

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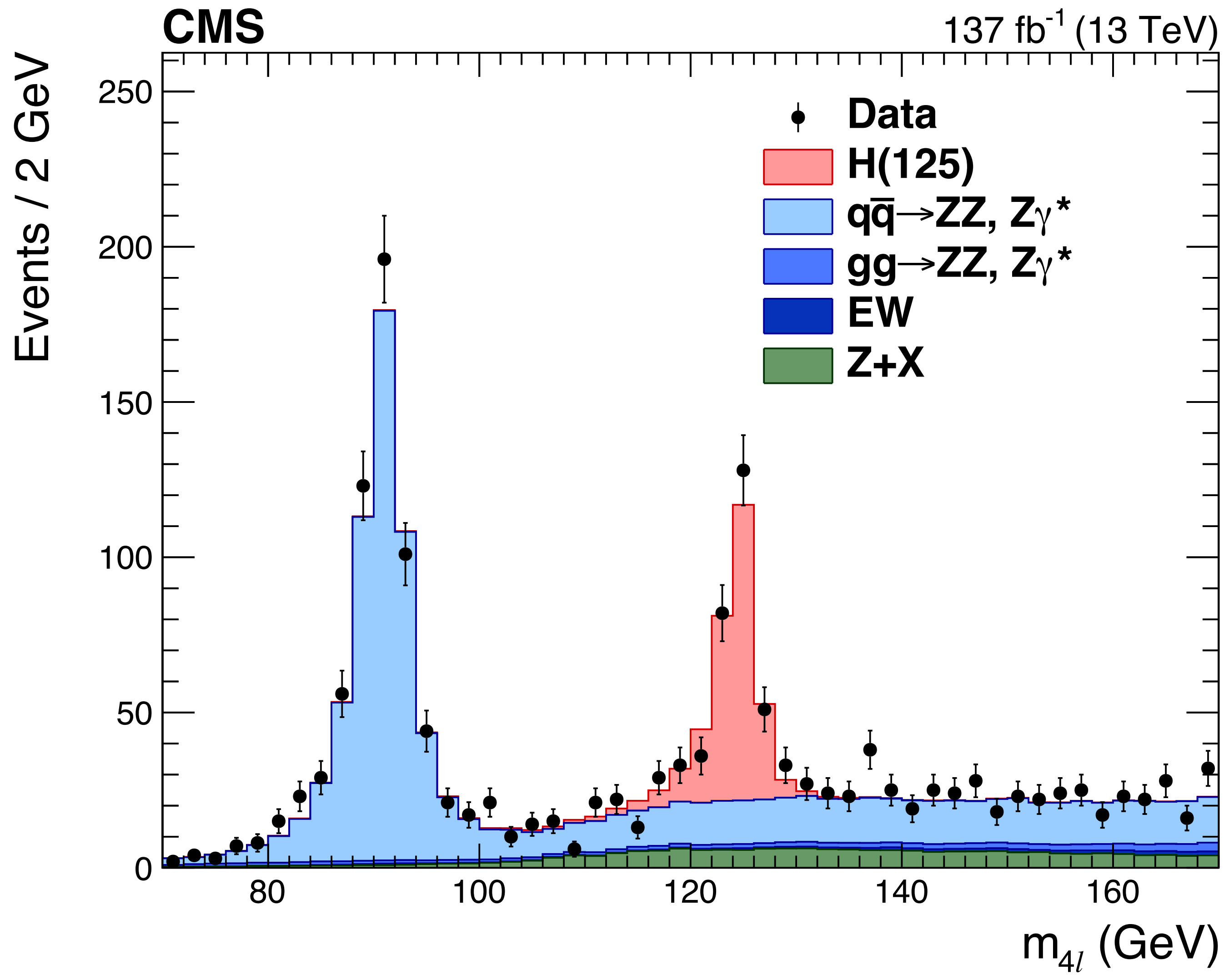
- High S/B (~2)
- Complete reconstruction of the final state
- Excellent momentum resolution
- Small BR (0.028%)



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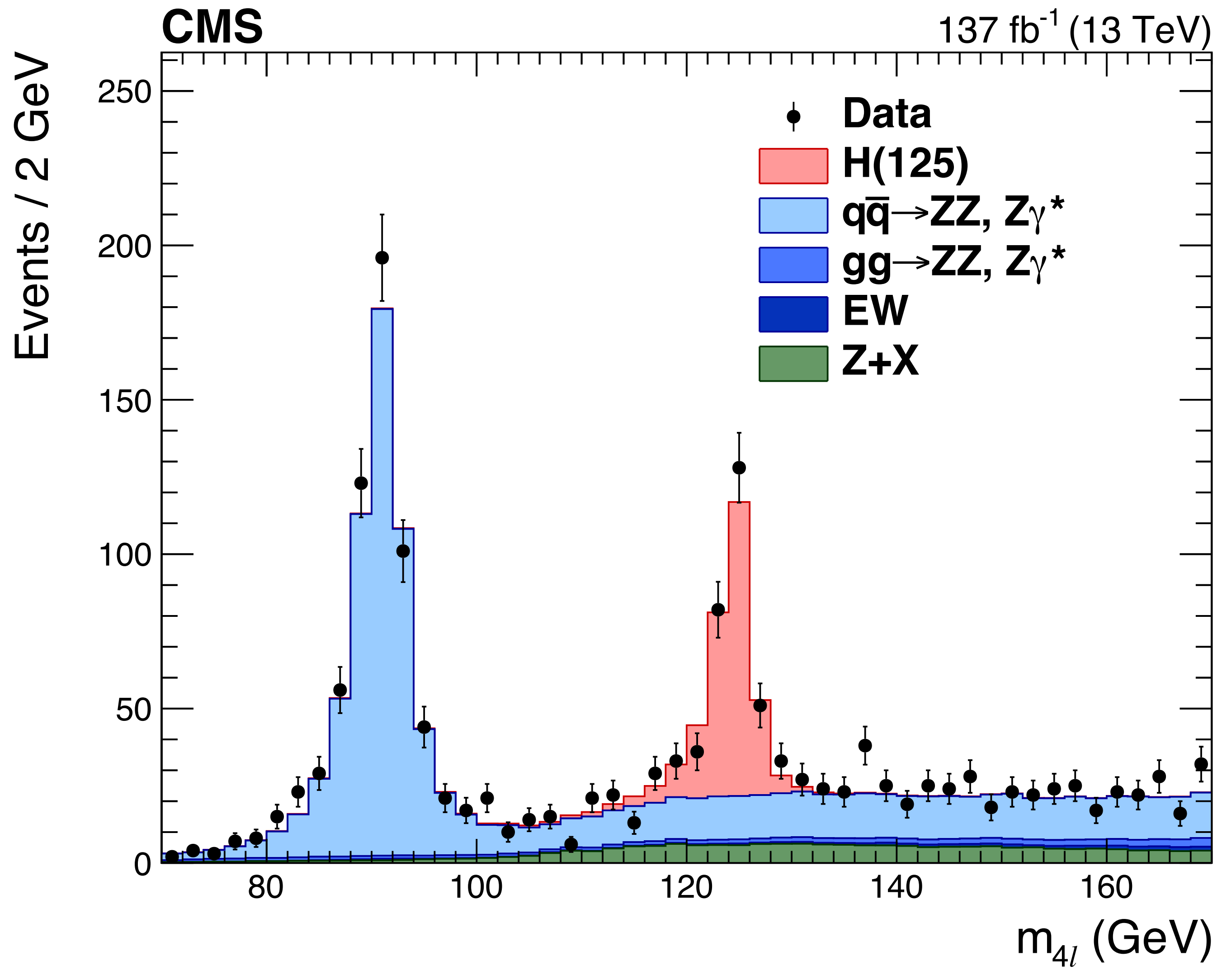
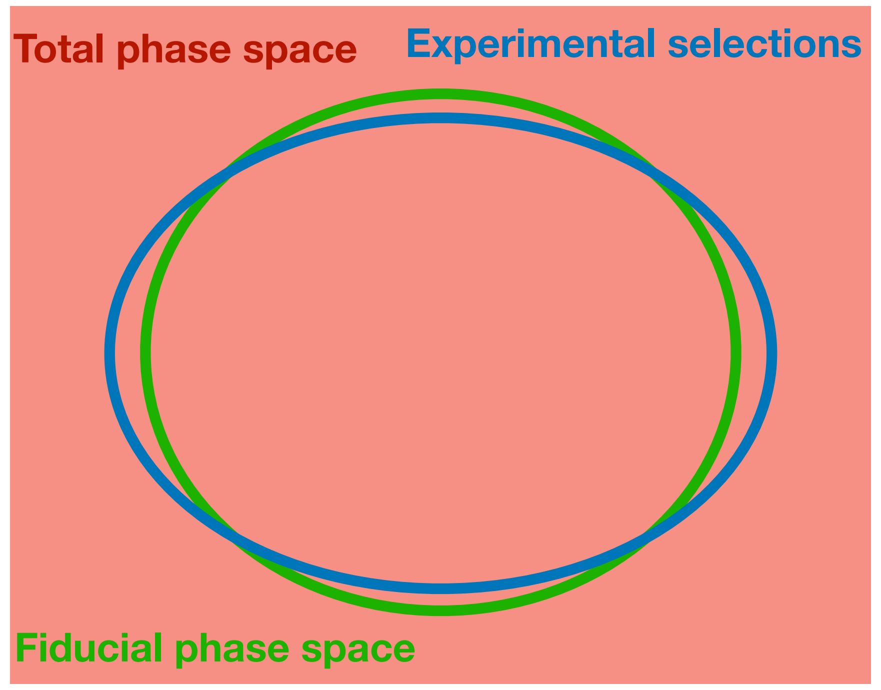
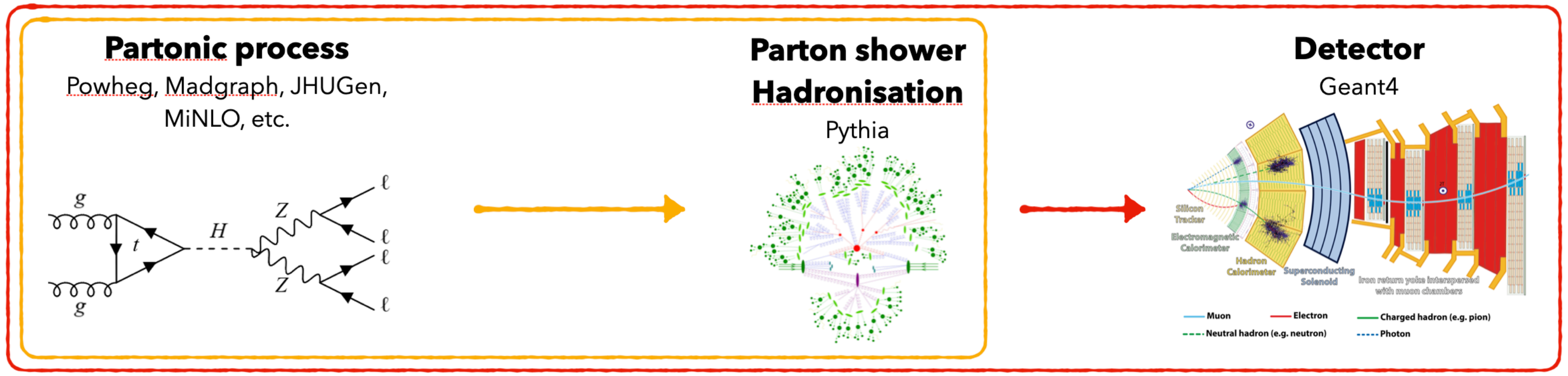


Cross sections are measured in **bins of kinematic observables** by **unfolding** experimental data to the **fiducial phase space**

- 👍 High-longevity of the measurement
- 👍 Direct comparison with theoretical models
- 👍 Combination with other channels and experiments
- 👍 Model independent result





gen-level — *generator level* — What one would measure with an ideal detector

UNFOLDING ←

reco-level — *reconstruction level* — What one actually measures

Inclusive fiducial cross section

Differential production observables

p_T^H $|y_H|$ p_T^{j1} N_{jets}

p_T^{Hj} m_{Hjj} p_T^{j2} T_B^{max} T_C^{max}

p_T^{Hjj} m_{jj} $|\Delta\eta_{jj}|$ $|\Delta\phi_{jj}|$

Differential decay observables

m_{Z1} m_{Z2} Φ Φ_1

$\cos(\theta_1)$ $\cos(\theta^*)$ $\cos(\theta_2)$

D_{0-}^{dec} D_{CP}^{dec} D_{0h+}^{dec} $D_{\Lambda 1}^{dec}$ $D_{\Lambda 1}^{Z\gamma,dec}$ D_{int}^{dec}

Double-differential observables

T_C^{max} vs p_T^H m_{Z1} vs m_{Z2}

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Interpretations

k_λ, k_c, k_b

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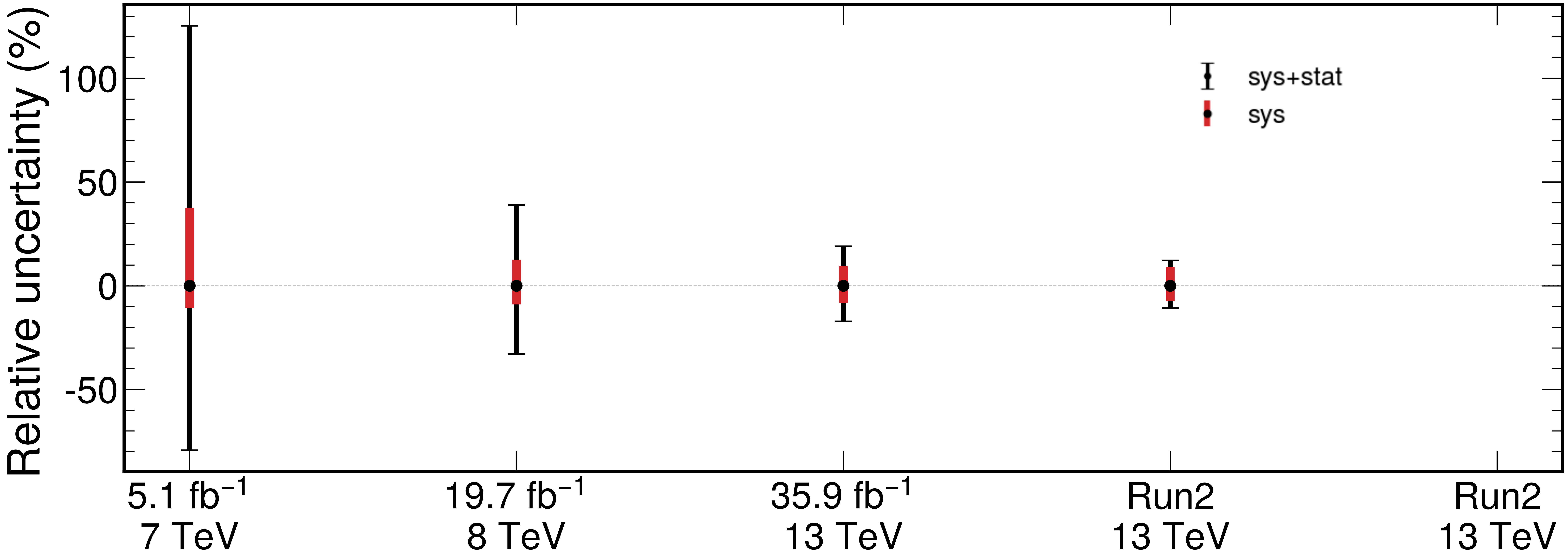

JHEP04(2016)005 *JHEP04(2016)005* *JHEP11(2017)047* *EPJC81(2021)488*

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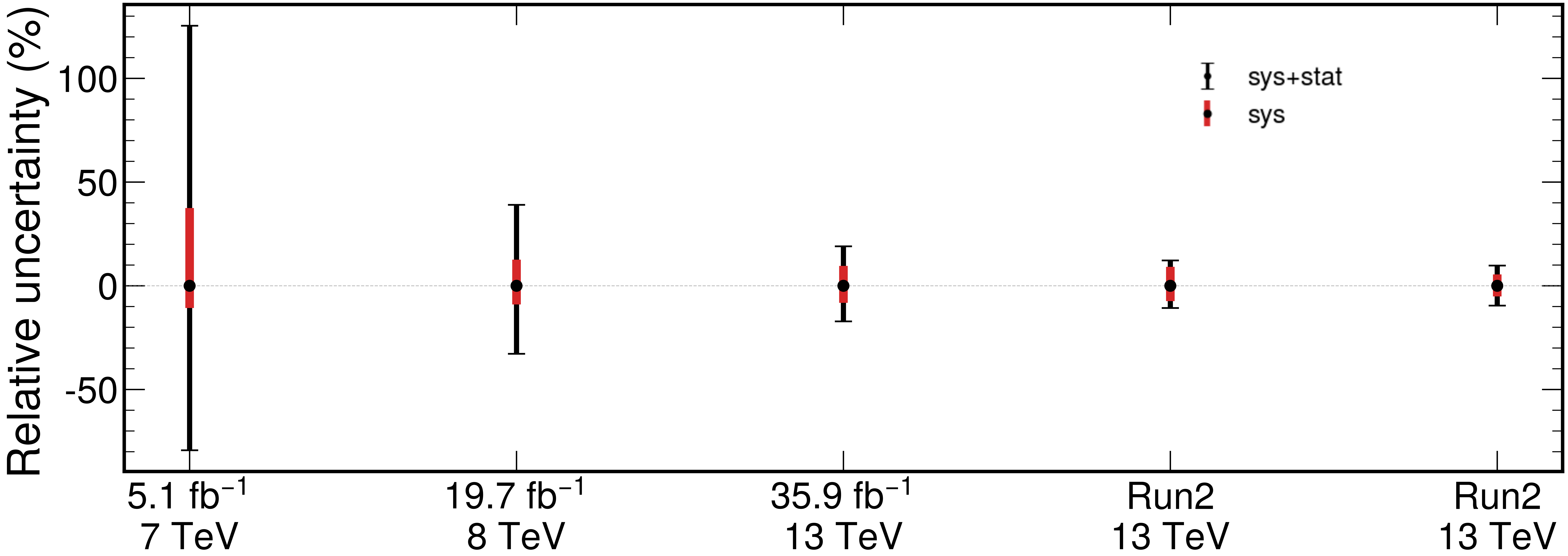
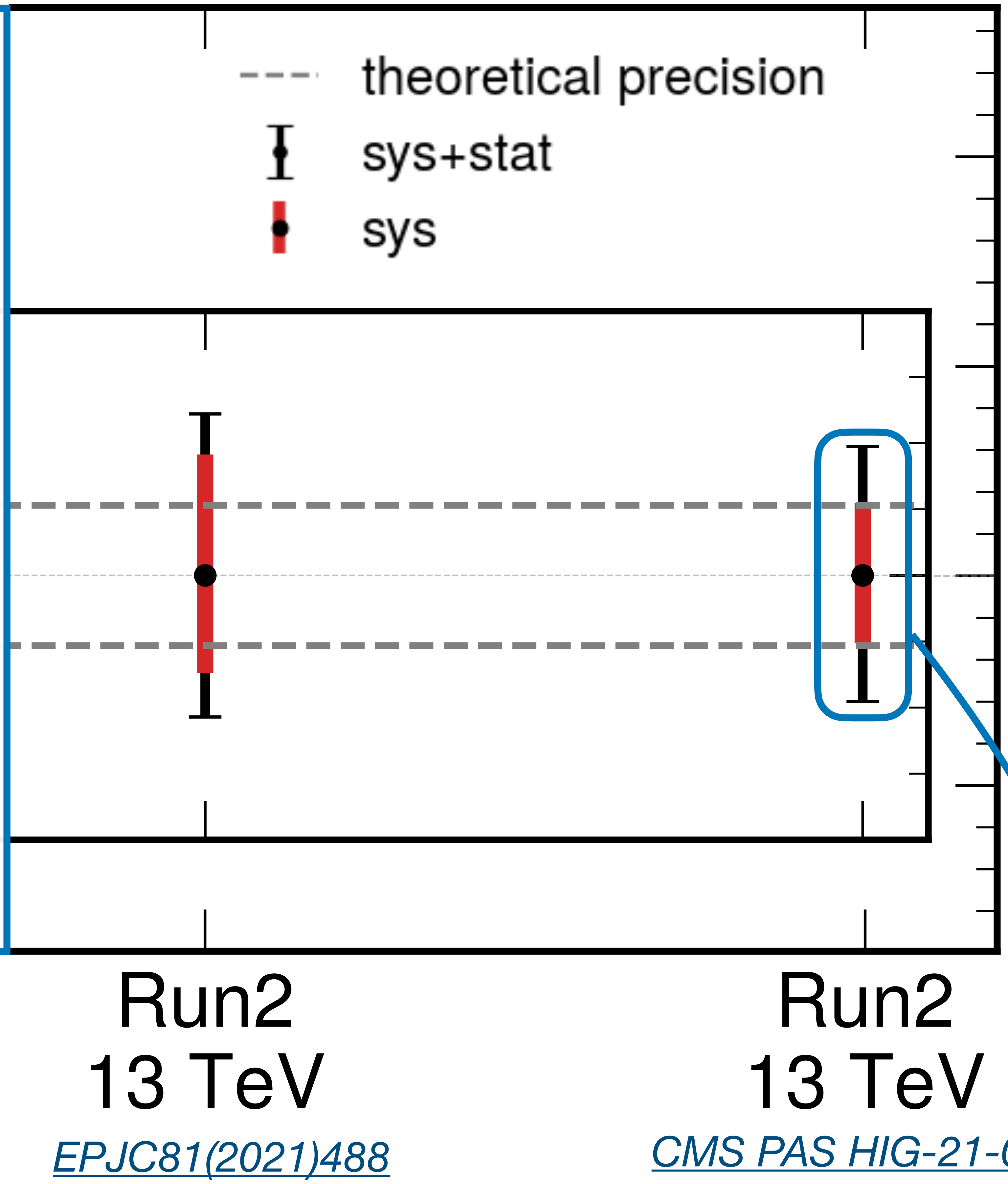


JHEP04(2016)005 | JHEP04(2016)005 | JHEP11(2017)047 | EPJC81(2021)488 | **NEW!**

Inclusive fiducial cross section

- Precision @ **10%**
- **40% decrease of the systematic component:**
  - Latest CMS run 2 objects calibrations
  - Revised measurement for the estimation of the electron scale factors uncertainties
- **Electron-related nuisances** are the leading contribution to the systematic uncertainty but their value is halved wrt previous run 2 result
- Systematic component at the same level of the theoretical precision



$$\sigma^{\text{fid}} = 2.73^{+0.22}_{-0.22}\ (\text{stat})^{+0.15}_{-0.14}\ (\text{sys})\ \text{fb} = 2.73^{+0.22}_{-0.22}\ (\text{stat})^{+0.12}_{-0.12}\ (\text{ele})^{+0.06}_{-0.05}\ (\text{lumi})^{+0.04}_{-0.04}\ (\text{bkg})^{+0.03}_{-0.03}\ (\text{muons})\ \text{fb}$$

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Quintessential fiducial observables

- **Finer binning** wrt previous analyses
- **Extension of the jet phase space** (from $|\eta_{jet}| < 2.5$ to $|\eta_{jet}| < 4.7$) thanks to the improved CMS jet reconstruction
- Three MC SM benchmarks: **POWHEG**, **NNLOPS**, and **MadGraph**

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Matrix-element discriminats

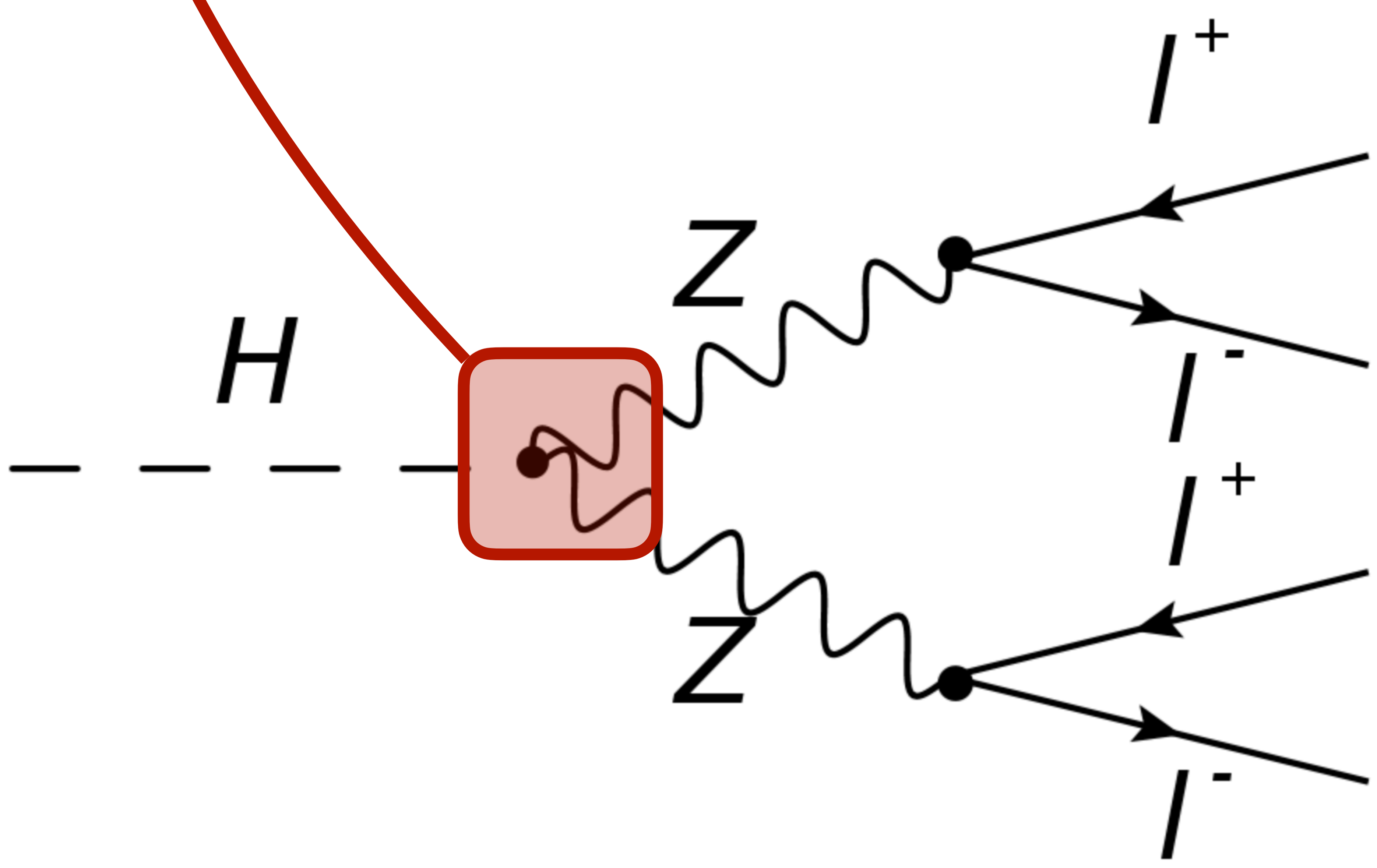
First-time

Probe **HZZ vertex** via **Matrix-Element discriminants** sensitive to BSM physics

$$A(HV_1V_2) = \frac{1}{v}\left\{ M_{V_1}^2 \left(g_1^{VV} + \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{\left(\Lambda_1^{VV}\right)^2} + \frac{\kappa_3^{VV}(q_1+q_2)^2}{\left(\Lambda_Q^{VV}\right)^2} + \frac{2 q_1 \cdot q_2}{M_{V_1}^2} g_2^{VV} \right)(\varepsilon_1 \cdot \varepsilon_2) - 2 g_2^{VV} (\varepsilon_1 \cdot q_2)(\varepsilon_2 \cdot q_1) - 2 g_4^{VV} \varepsilon_{\varepsilon_1 \varepsilon_2 q_1 q_2} \right\}$$

Tree-level SM

g_1^{ZZ} = g_1^{WW} = 2



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Tree-level SM
$g_1^{ZZ} = g_1^{WW} = 2$

To use discriminants we have to define two hypotheses

SM Hypothesis $g_1^{ZZ} = 2$

Alternative hypothesis $g_i^{ZZ} \neq 0$ or $\Lambda_i^{ZZ,Z\gamma} \neq 0$

The MELA package [1] allows to compute the matrix-element probability for an event to be produced at a particular point of the phase space –> $\mathscr{P}_{SM}$ and $\mathscr{P}_{AC}$

By the Neyman-Pearson lemma, the optimal way to distinguish between two hypothesis is the ratio (or a function of the ratio) between the probabilities:

$$\mathscr{D}_{alt} = \frac{\mathscr{P}_{AC}(\vec{\Omega})}{\mathscr{P}_{AC}(\vec{\Omega}) + \mathscr{P}_{SM}(\vec{\Omega})} \qquad \mathscr{D}_{interference} = \frac{\mathscr{P}_{interference}(\vec{\Omega})}{2\sqrt{\mathscr{P}_{AC}(\vec{\Omega}) \cdot \mathscr{P}_{SM}(\vec{\Omega})}}$$

Coupling	g_4^{ZZ}	g_2^{ZZ}	k_1^{ZZ}	$k_2^{Z\gamma}$
Discriminants to separate hypothesis	$\mathscr{D}_{0-}^{dec}$	$\mathscr{D}_{0h+}^{dec}$	$\mathscr{D}_{\Lambda 1}^{dec}$	$\mathscr{D}_{\Lambda 1}^{Z\gamma,dec}$
Interference discriminants	$\mathscr{D}_{CP}^{dec}$	$\mathscr{D}_{int}^{dec}$	-	-

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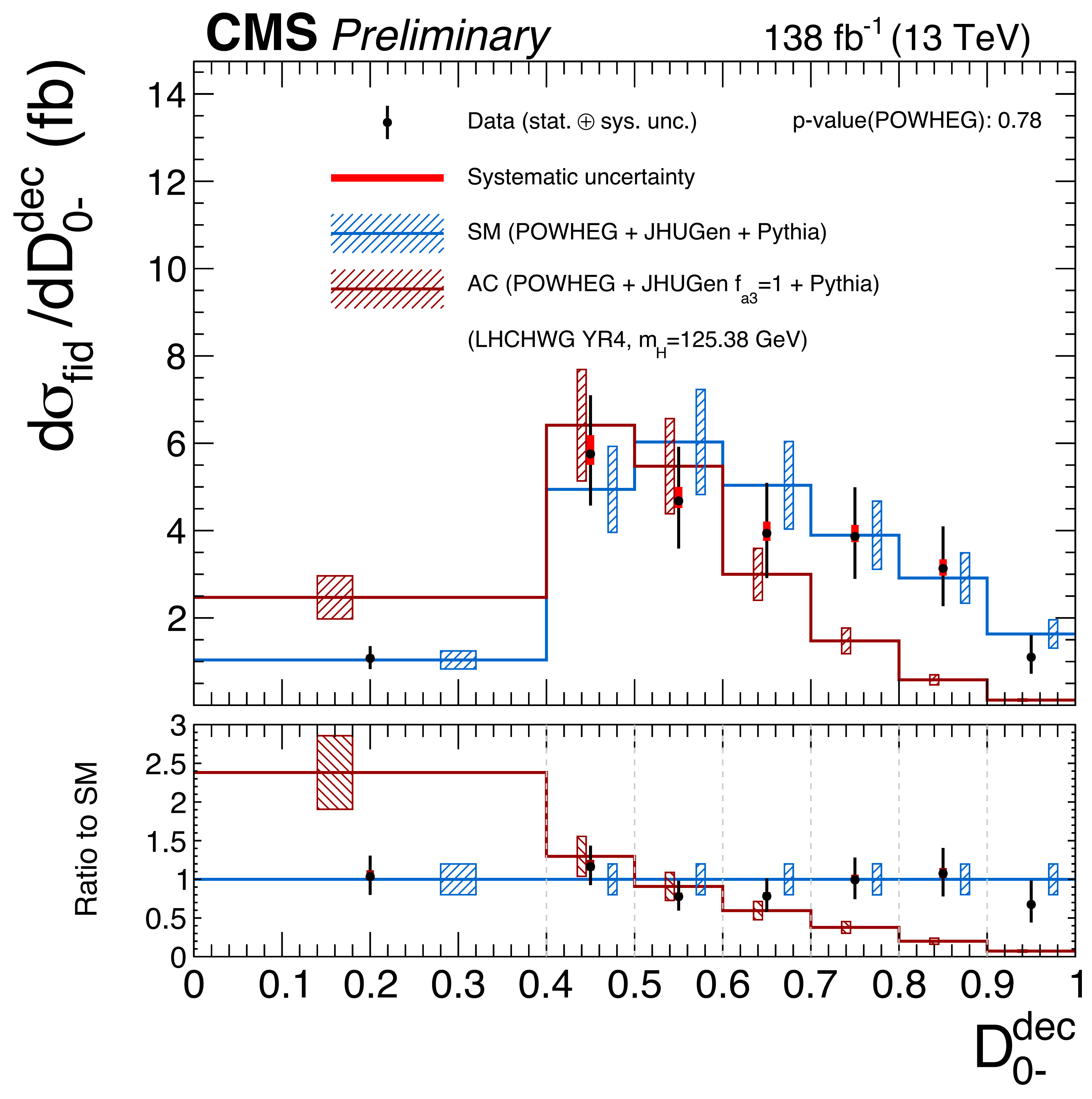

Results for decay observables are presented in **2e2mu** and **4e+4mu** final states as well.

The **same-flavour lepton interference** makes the shapes in 2e2mu and 4e/4mu final states different

Matrix-element discriminats

First-time

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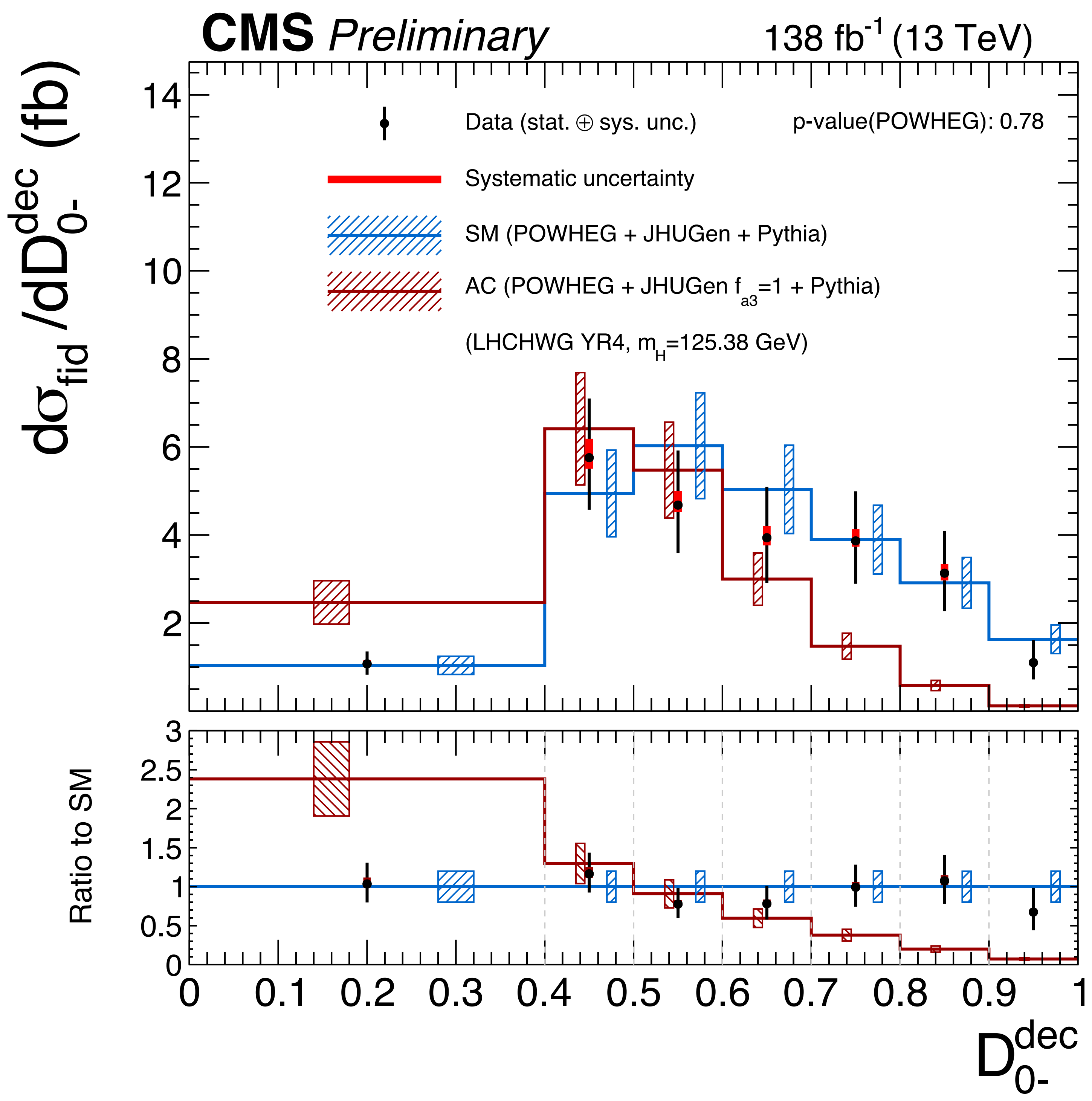

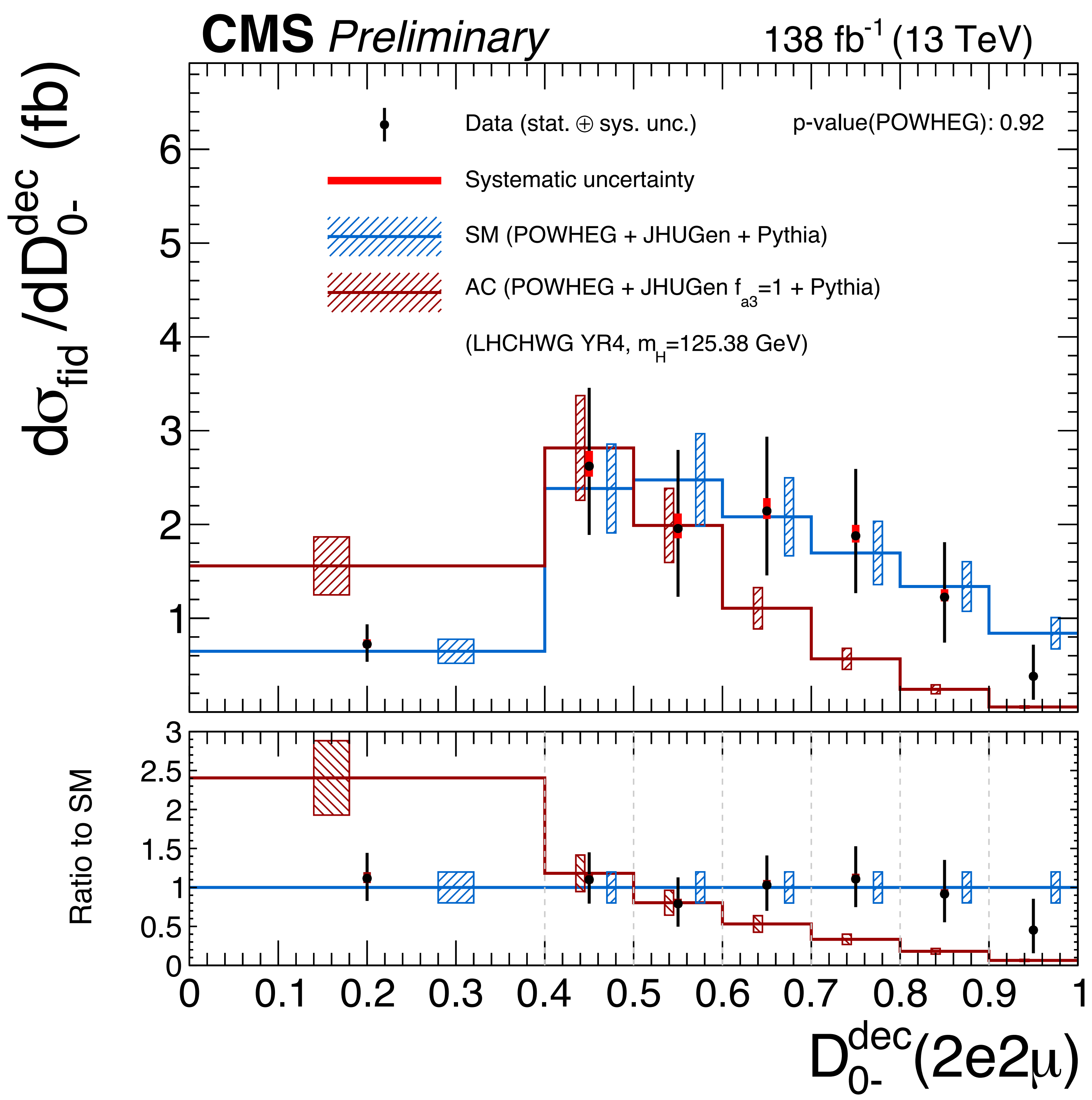

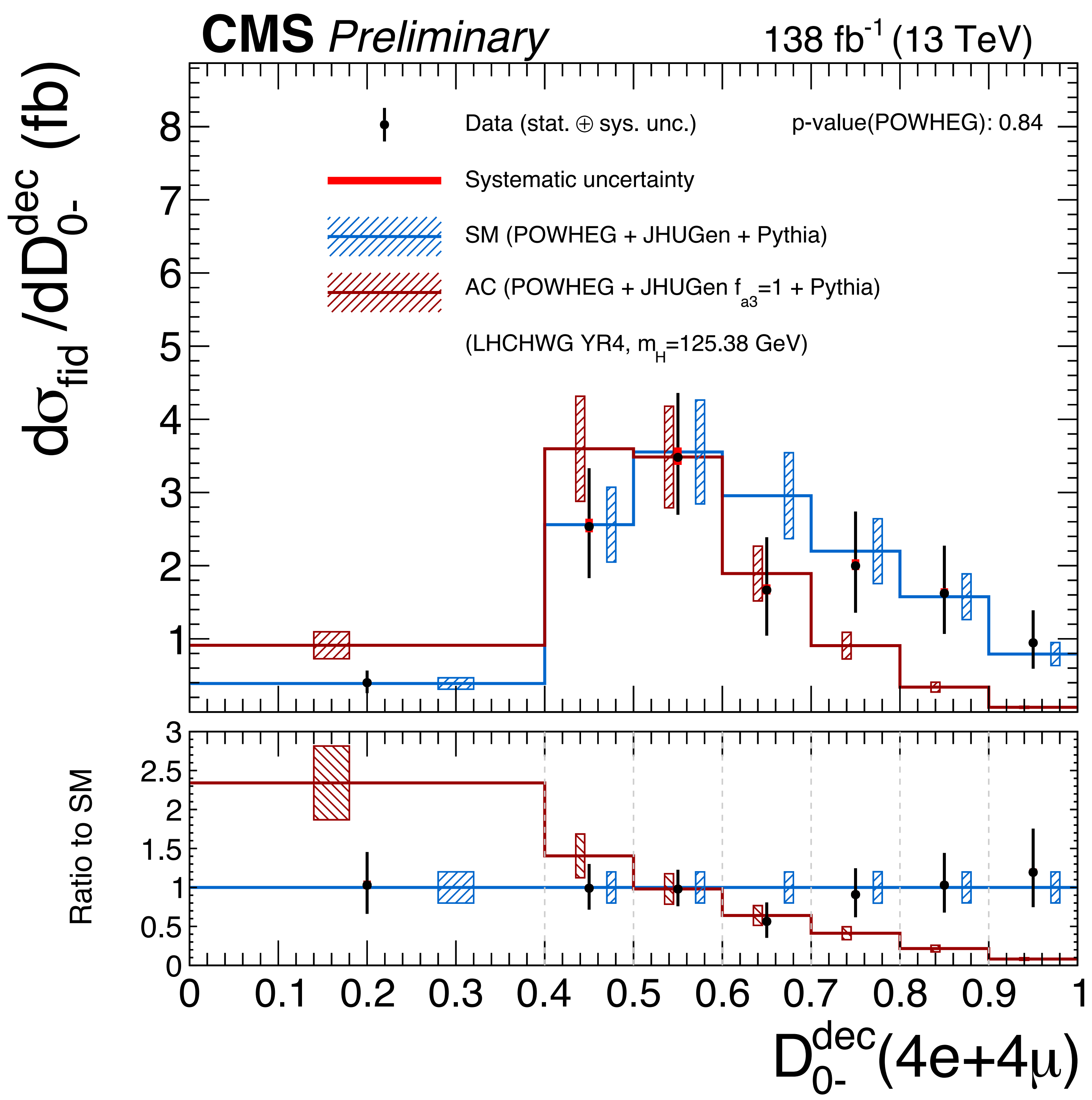

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Interpretations

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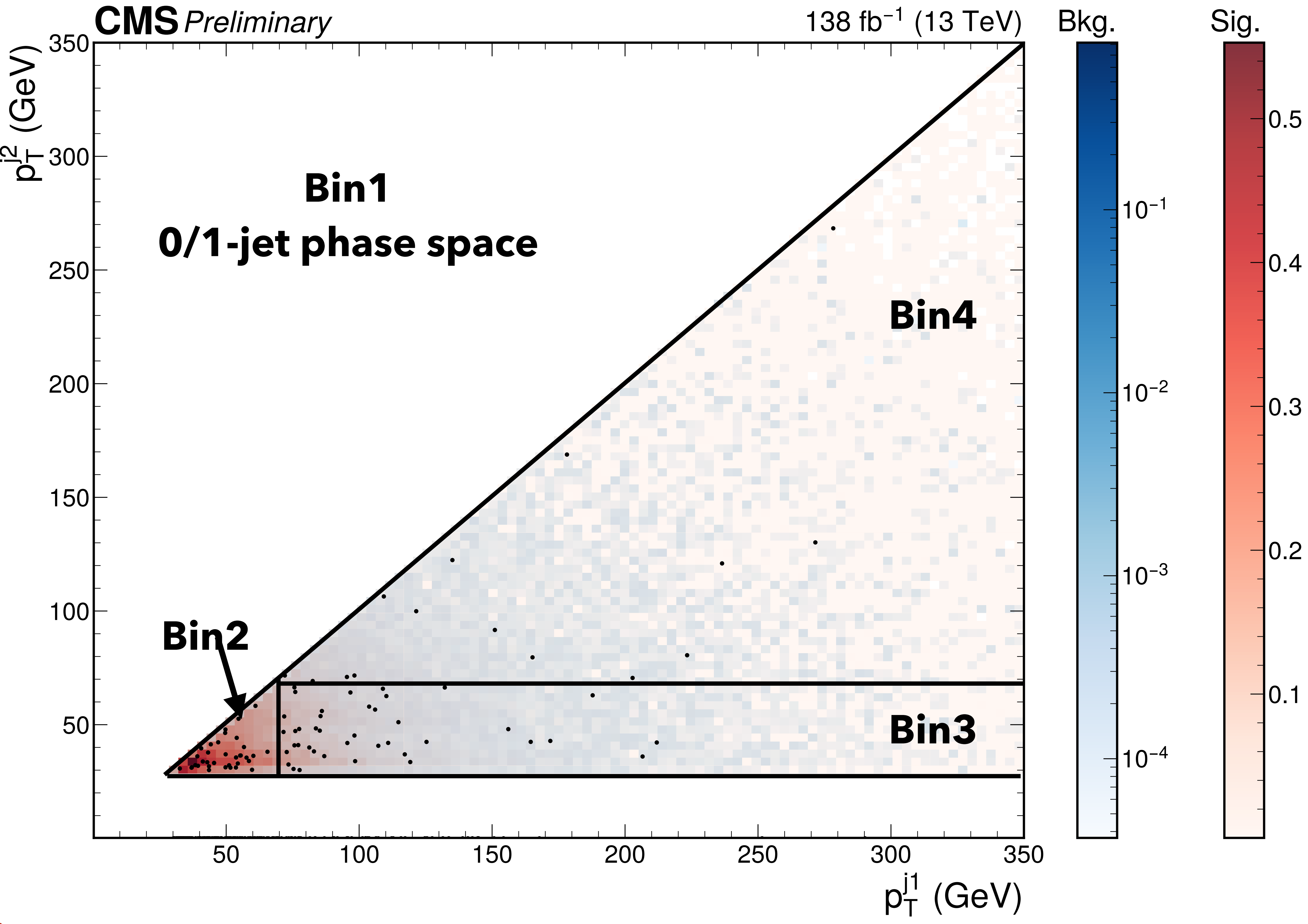
Double-differential observables

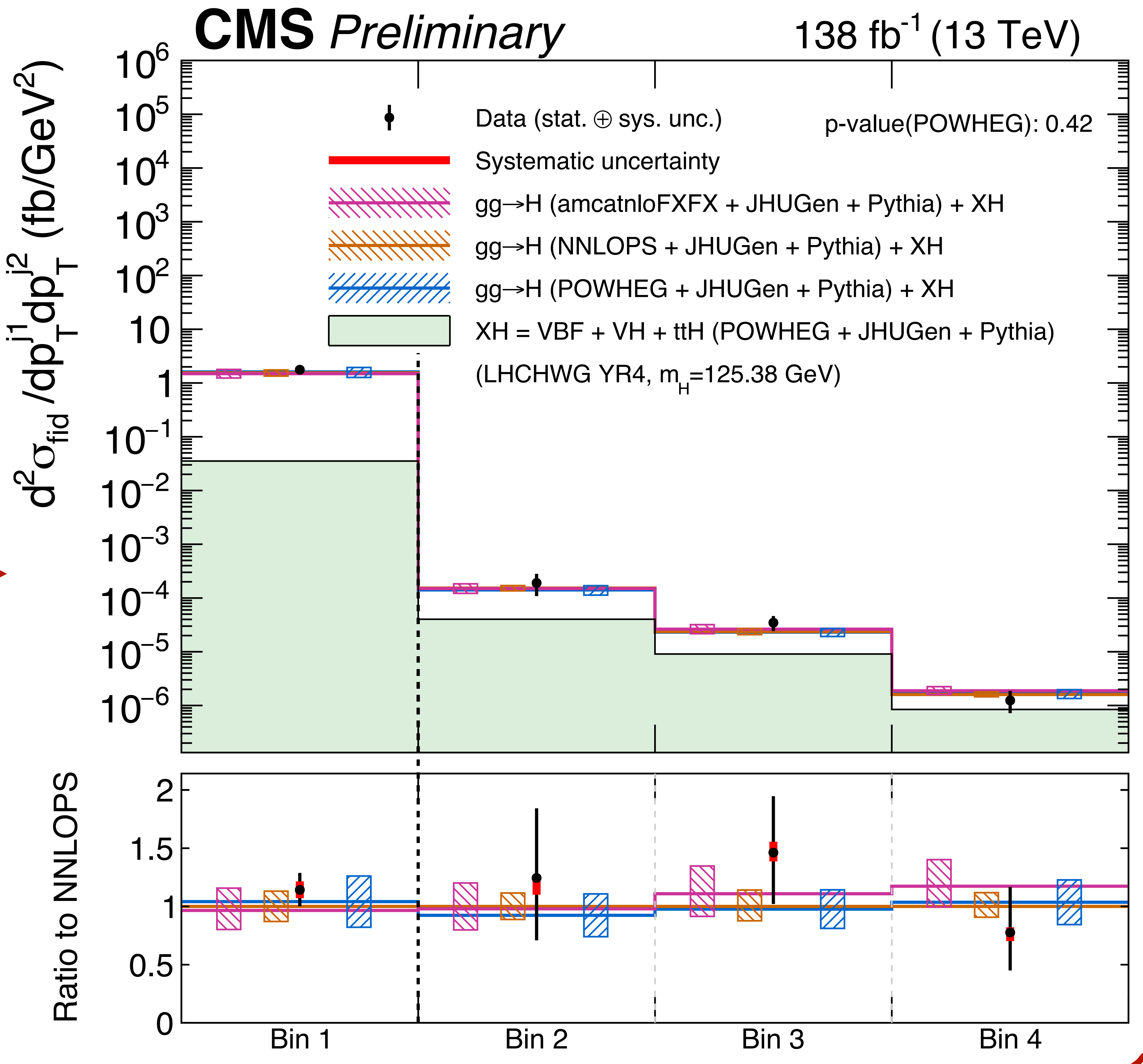
First-time

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

T_C^{max} vs p_T^H m_{Z1} vs m_{Z2} N_{jet} vs p_T^H p_T^H vs p_T^{Hj} $|y_H|$ vs p_T^H p_T^{j1} vs p_T^{j2}

Example: pTj1 vs pTj2





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Higgs boson trilinear self-coupling

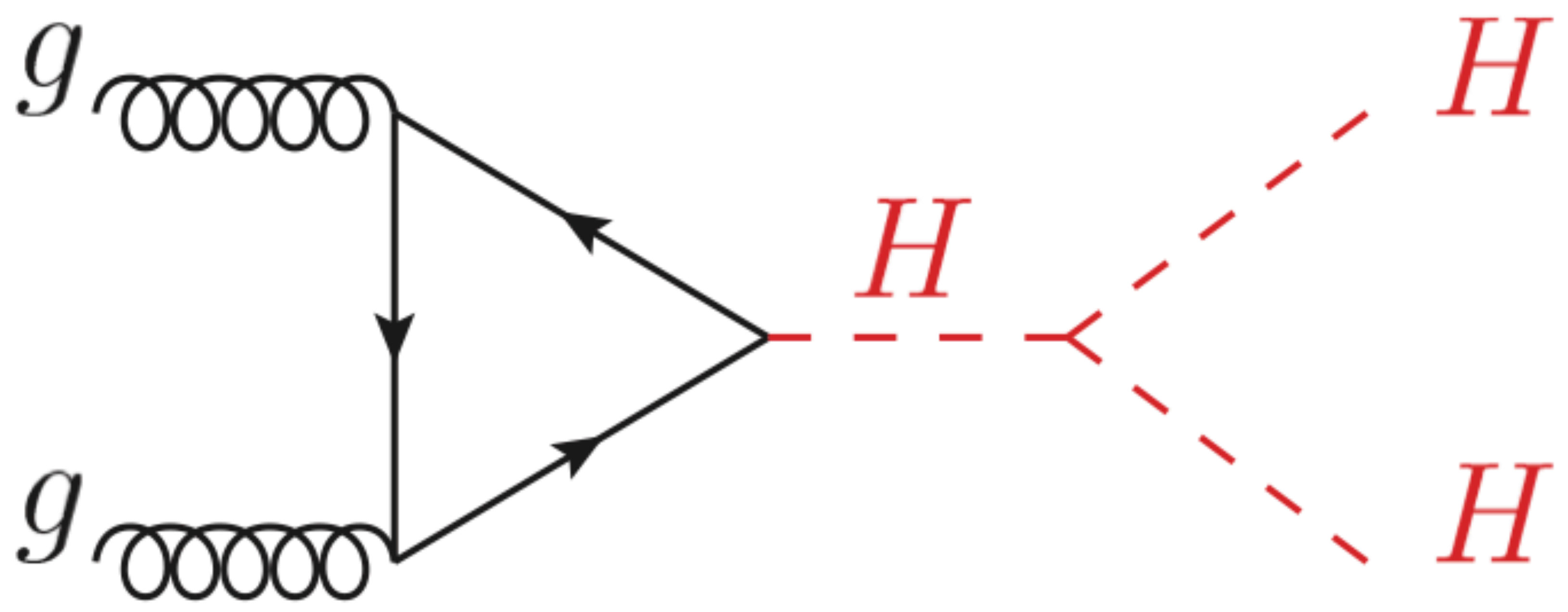
First-time

The Higgs boson is the only particle in the SM that can couple with itself.

The measurement of λ_3 is one of the main physics goal of the LHC since it provides a **direct test of the EW symmetry breaking** and it is linked to **fundamental questions** in particle physics and cosmology.

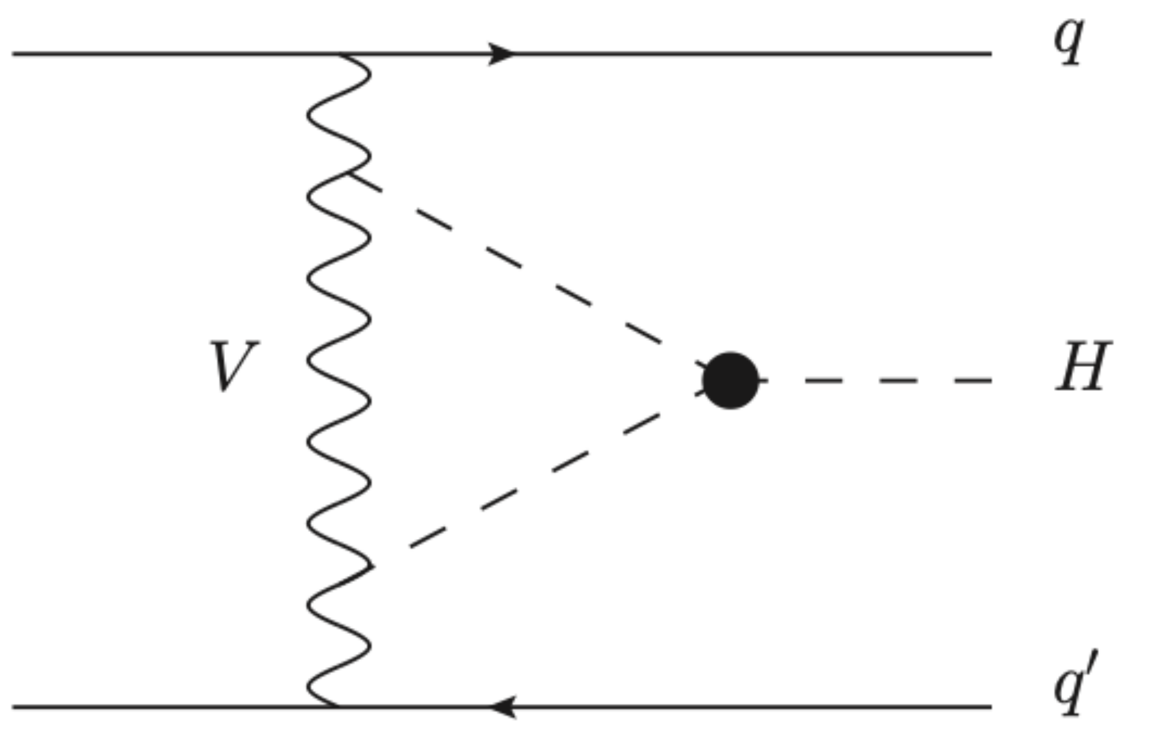
Direct measurement in HH production

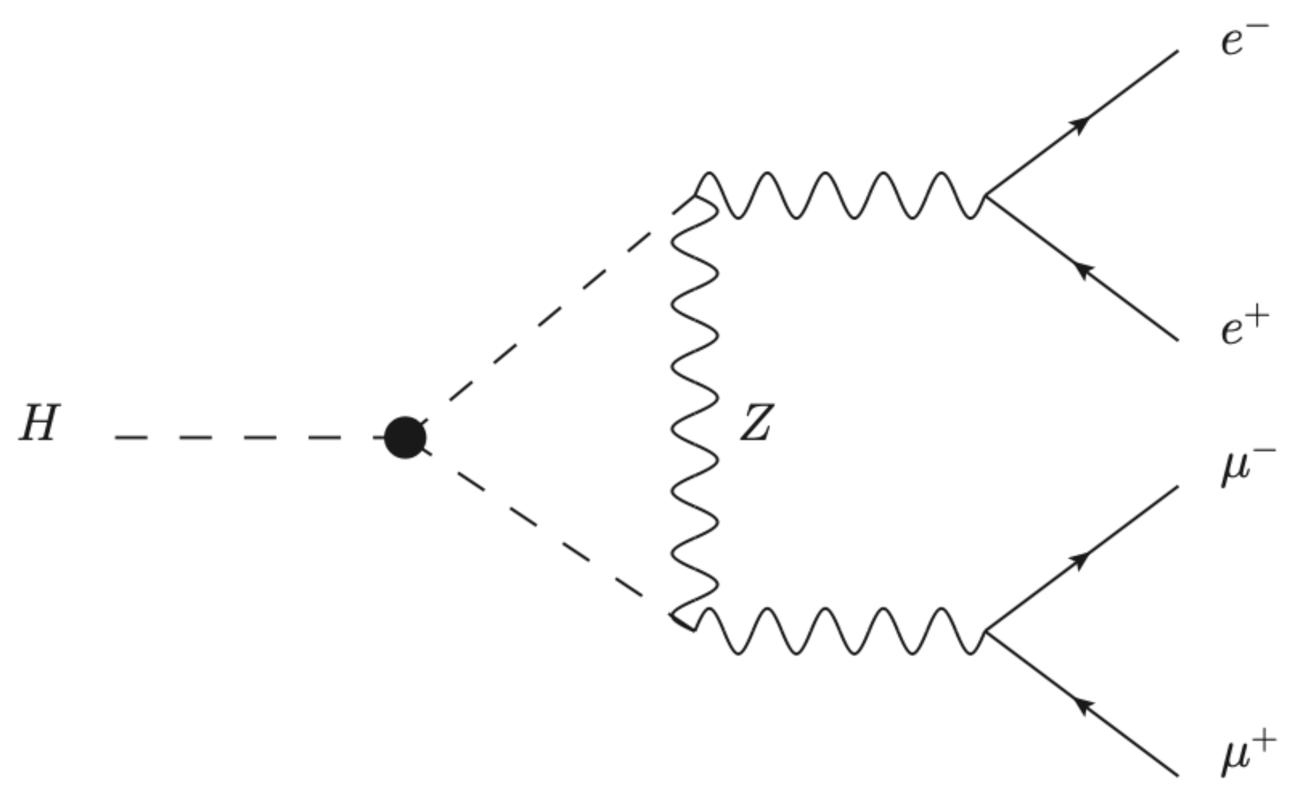
- Rare processes that are experimentally challenging
- LO dependence on λ_3



Indirect measurement in H production

- Benefit from larger XS for single-H production ($\sim 1000 \times \sigma_{HH}$)
- NLO EW dependence on λ_3





10.1140/epjc/s10052-017-5410-8 10.1007/JHEP12(2016)080

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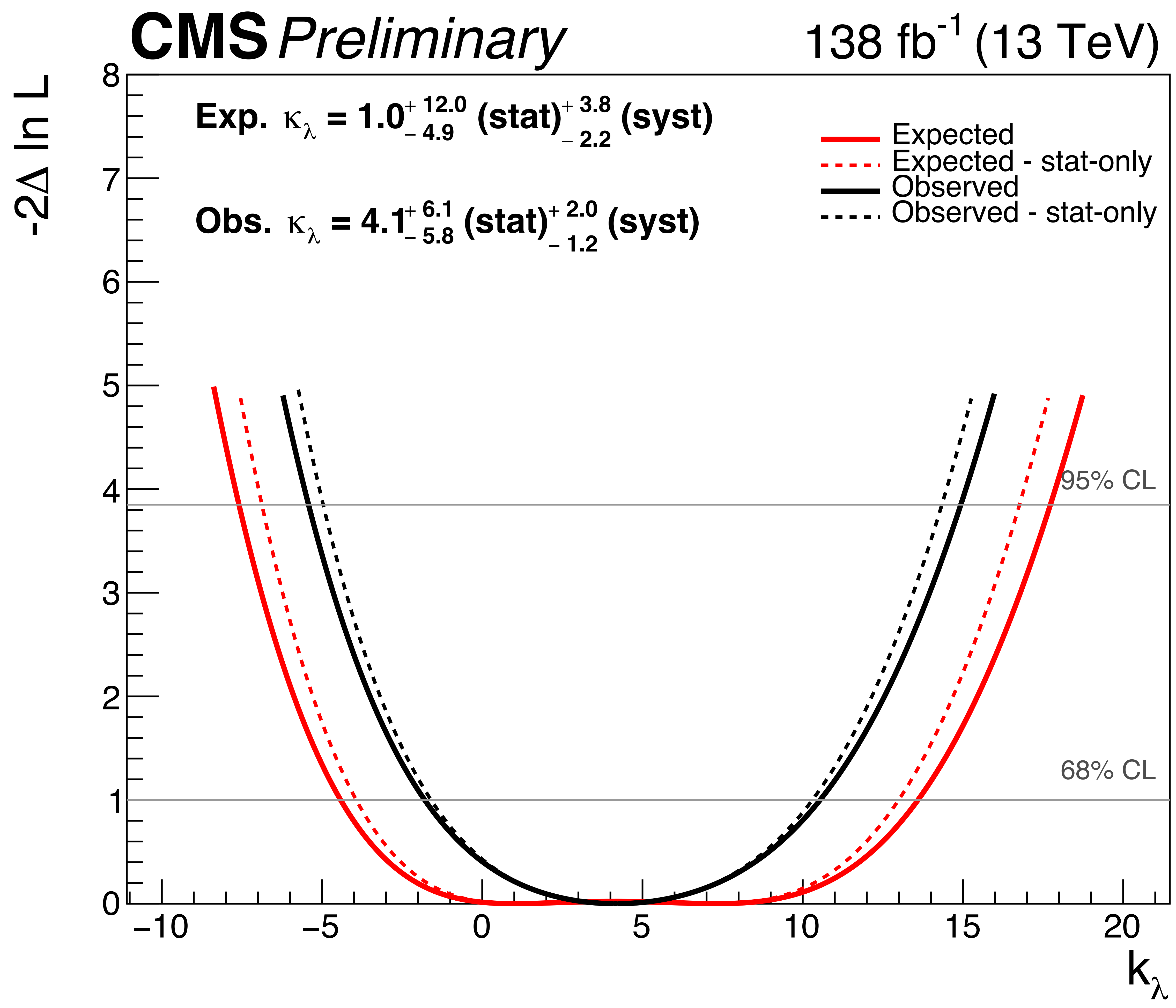
The **transverse momentum** is used to set constraint on $\kappa_\lambda = \lambda_3/\lambda_3^{SM}$ since it is the most sensitive observable to probe the H boson self-coupling



Observed (expected) excluded κ_λ range from @ 95% CL:

$-5.5\ (-7.7) < \kappa_\lambda < 15.1\ (17.9)$

First time the result is presented in a **fiducial** analysis of **single-Higgs** production

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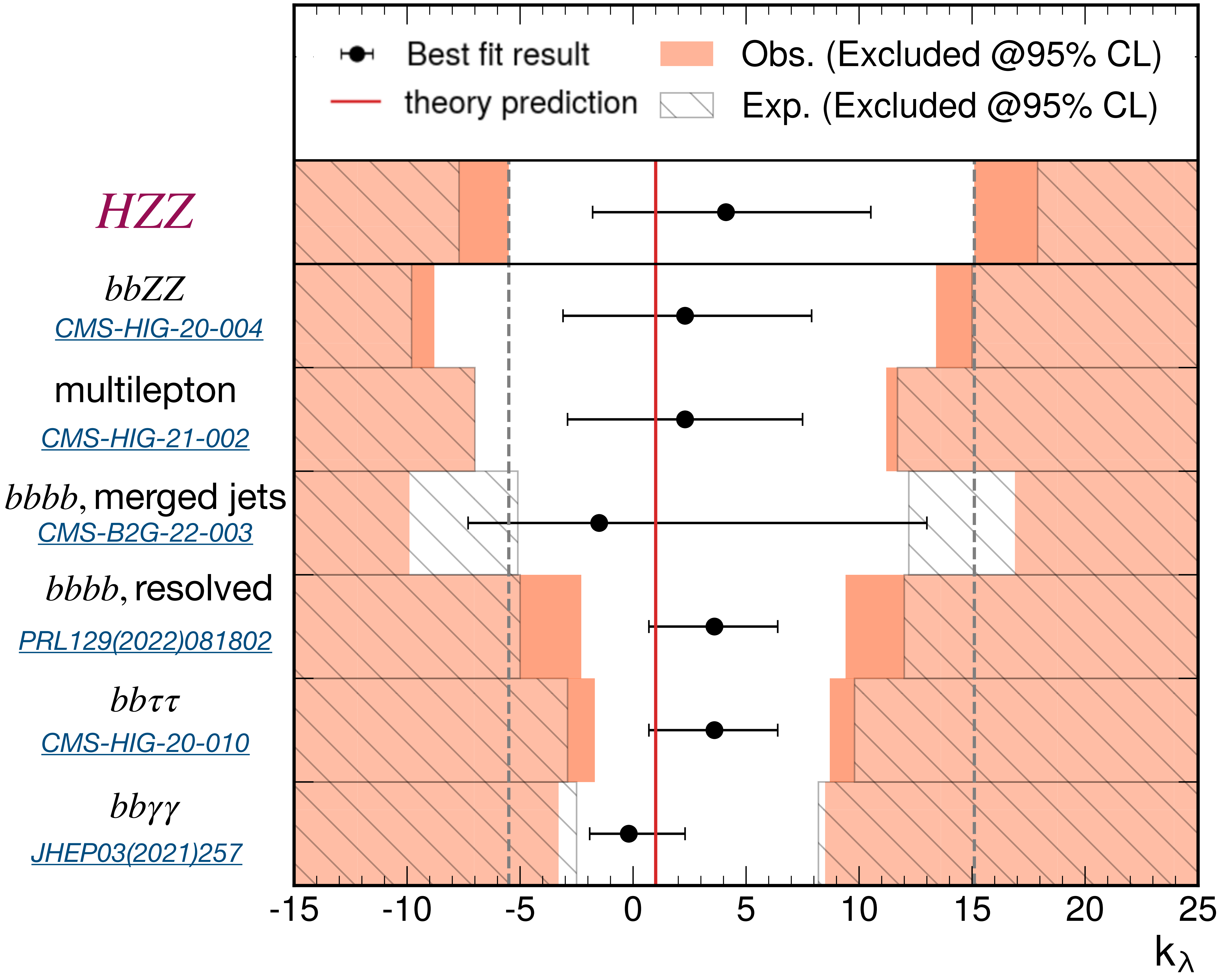

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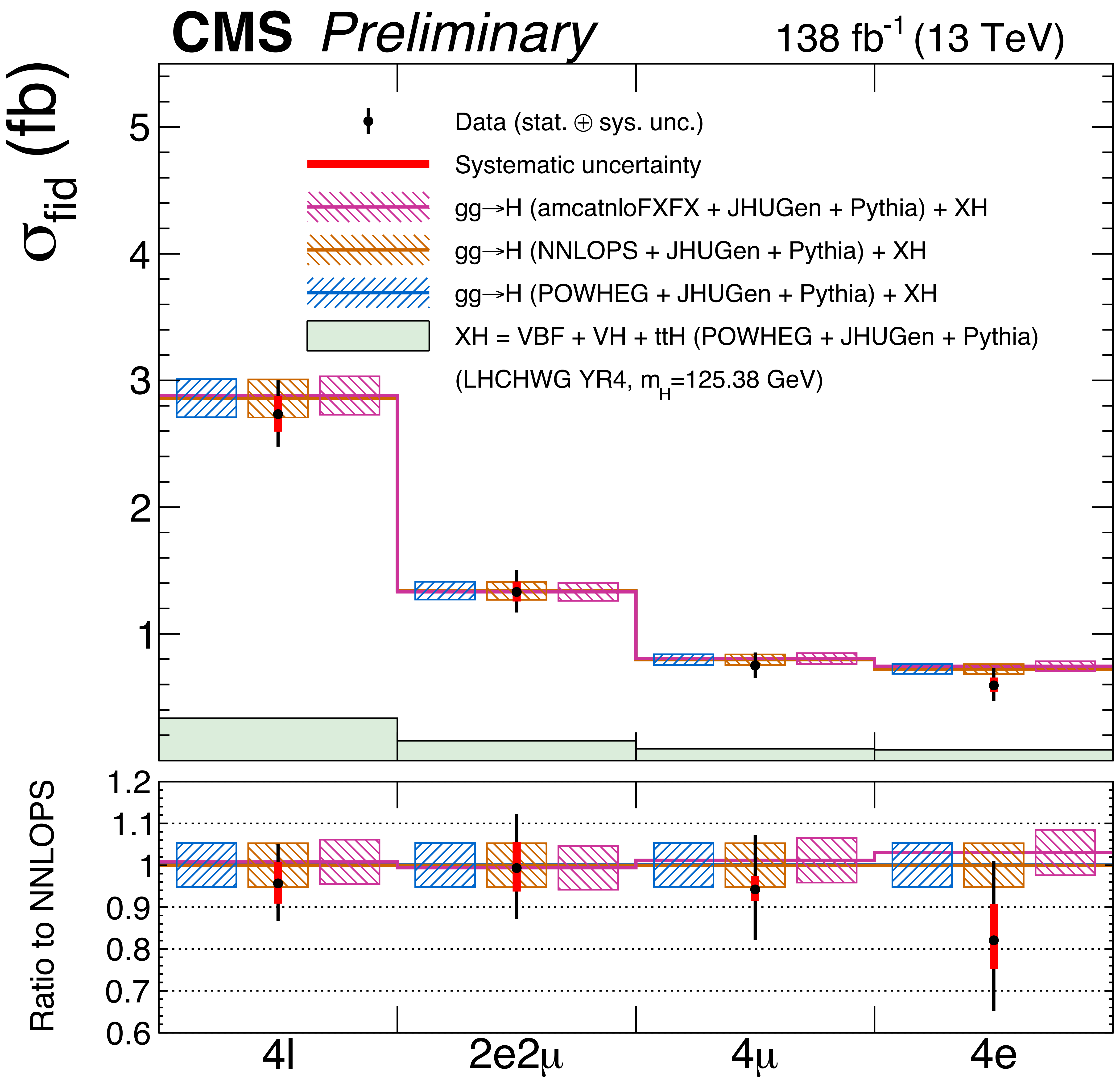
Competitive with many HH analyses (direct search), i.e. **bbZZ**, **bbbb merged**, and **multi-lepton**

Conclusions

- The analysis provides a **comprehensive characterisation of the Higgs-to-four-lepton channel** using differential and fiducial **cross section measurements** and **interpretations**
- All results show an overall good agreement with the SM
- **60 fiducial XS results**, **33 observables** (28 of them are new!), and **3 interpretations** make this paper one of the most extensive fiducial analysis ever performed (today shown only a small subset of the results)
- **Better CMS objects calibration** and **improvements in the analysis strategy** led to very **precise measurements** (~ 10% inclusively)
- We are on the verge of probing the scalar sector with very high precision

Backup

Inclusive fiducial cross section



Cross section compared to three generators modelling the production

POWHEG

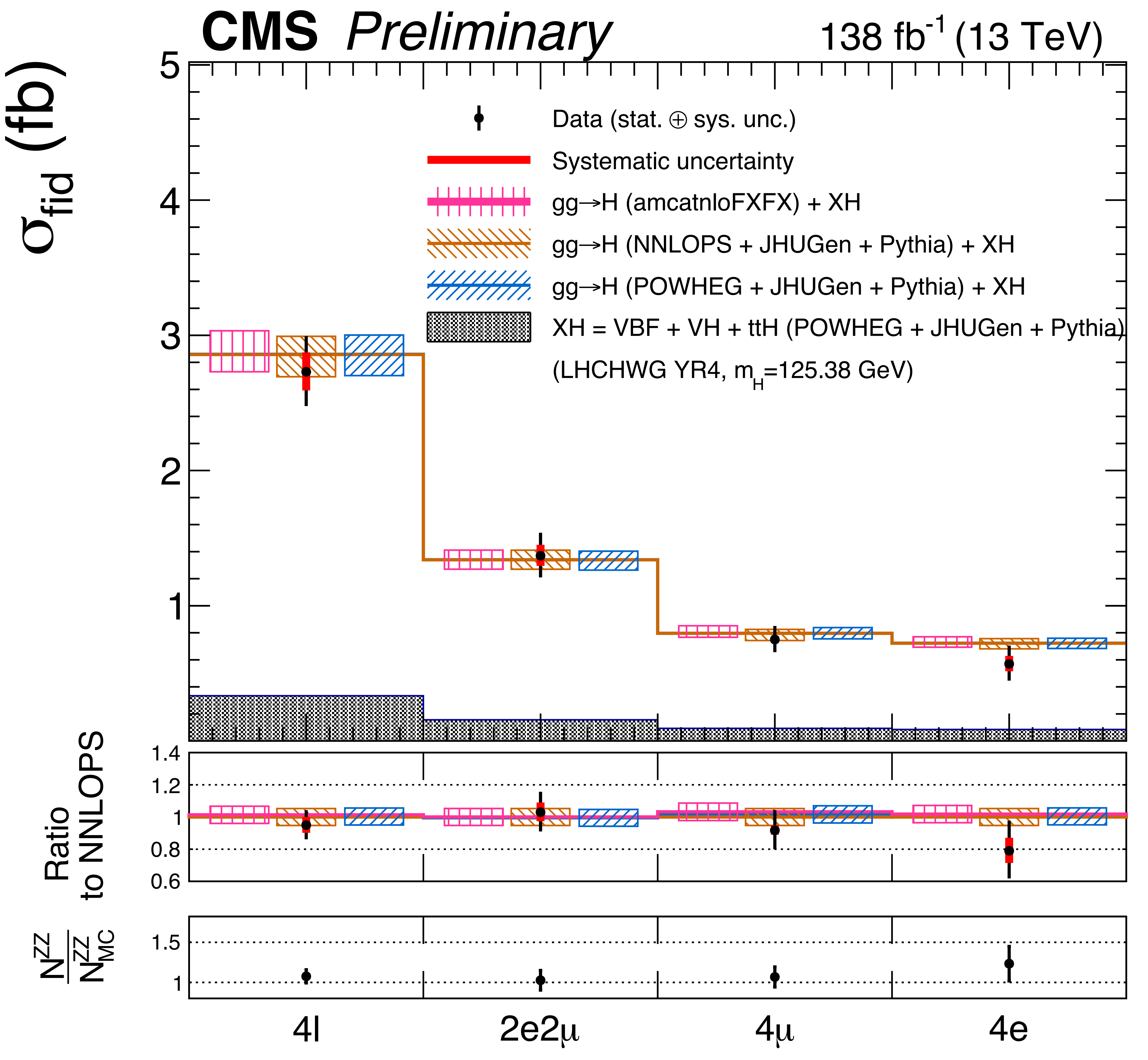
NNLOPS

New SM benchmark!

MadGraph5_aMC@NLO

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**



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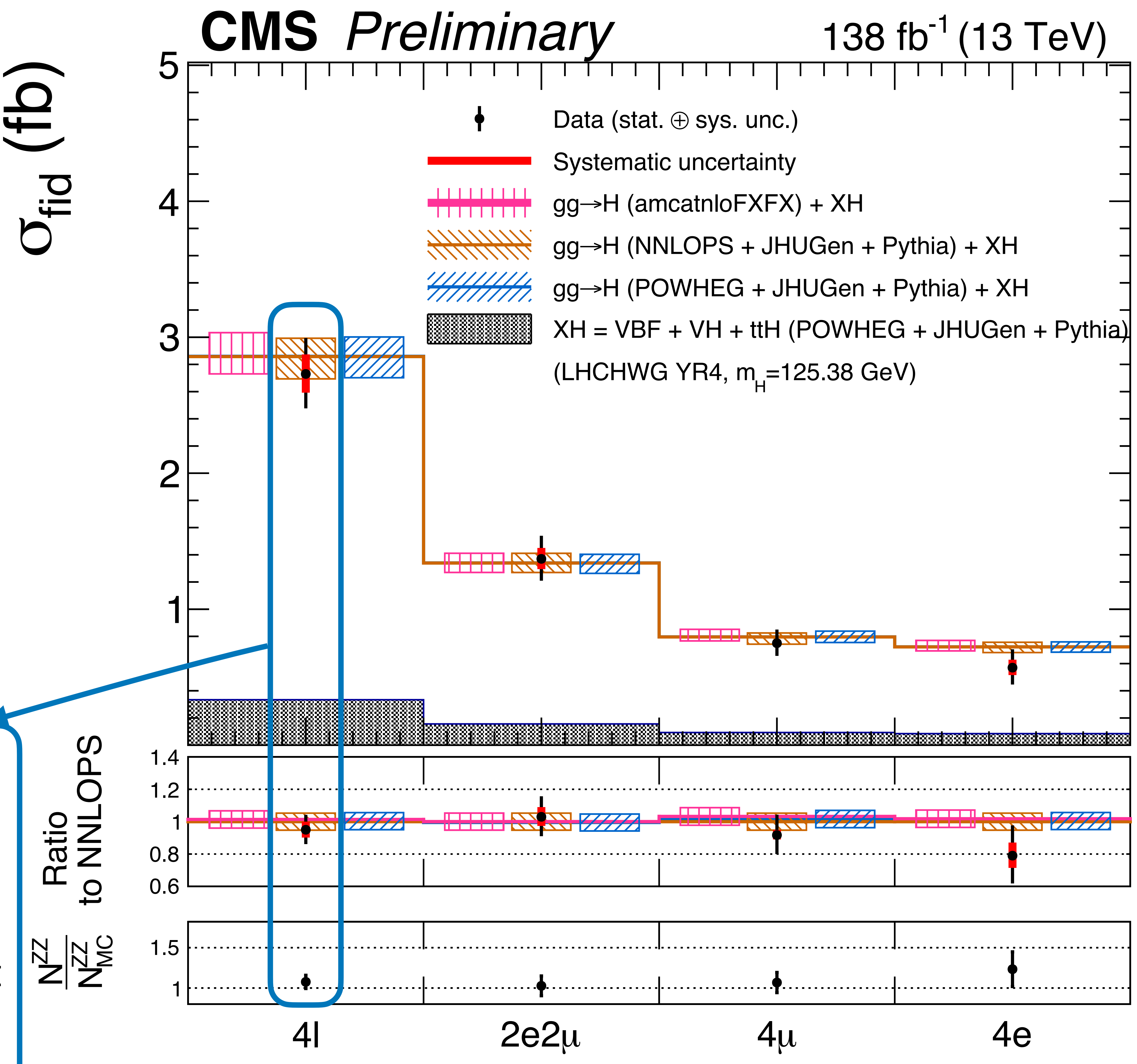


$$\sigma^{\text{fid}} = 2.74^{+0.24}_{-0.23}\ (\text{stat})^{+0.14}_{-0.11}\ (\text{sys})$$

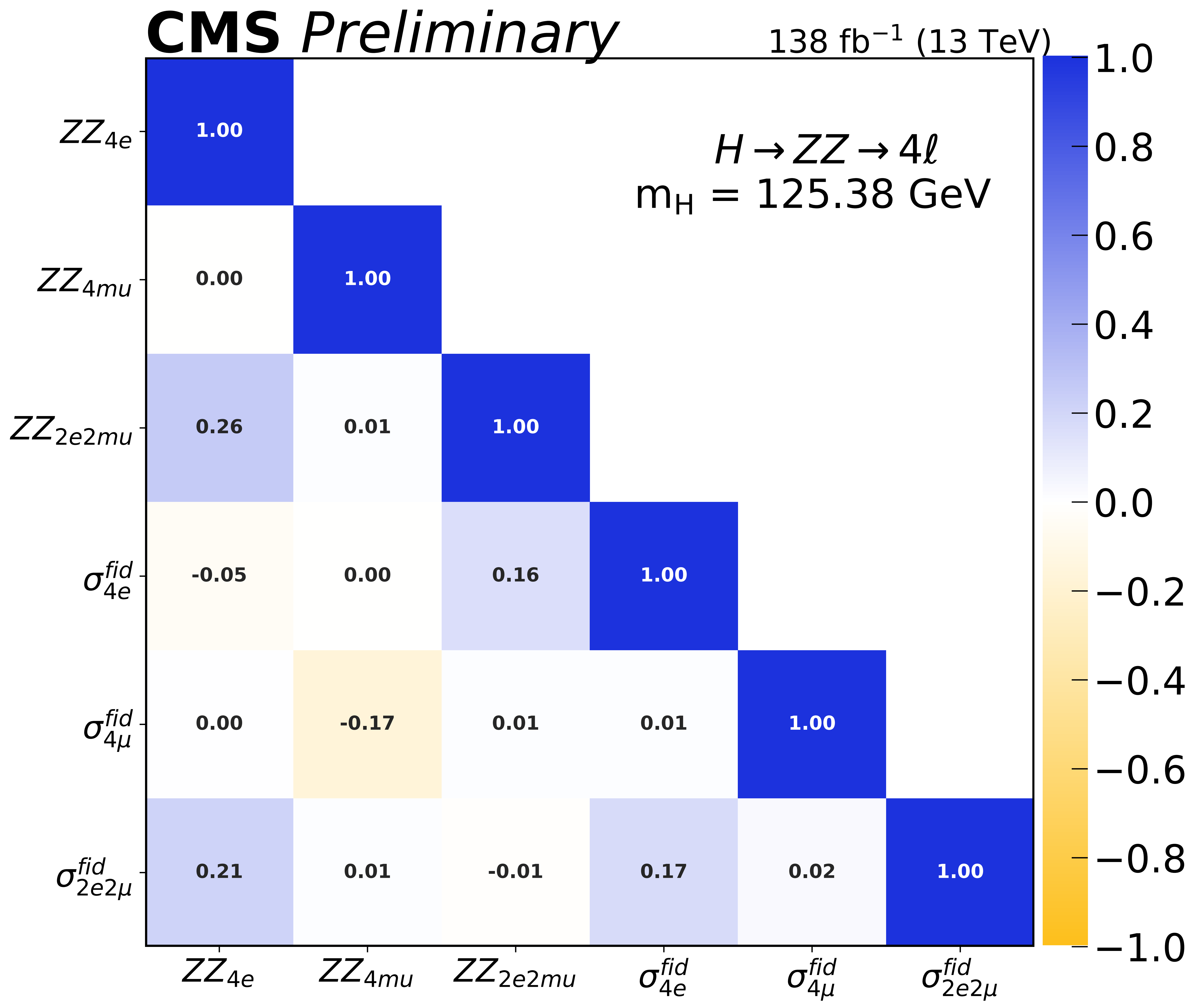
$$ZZ_{\text{norm}} = 445^{+27}_{-26}\ (\text{stat})^{+21}_{-19}\ (\text{sys})$$

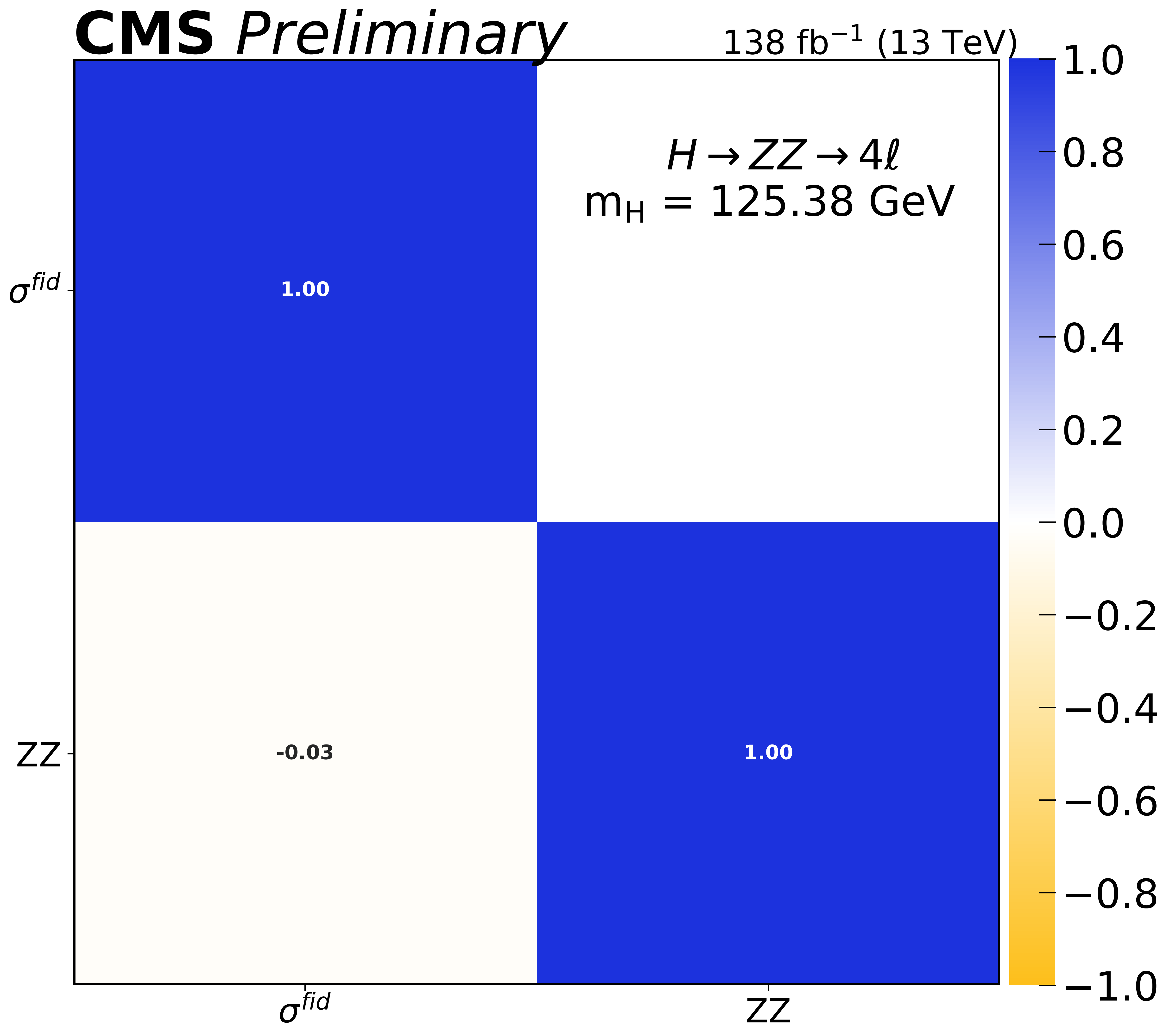
Reduction of the systematic component on the XS wrt std approach, but not yet enough number of events to profit from this method differentially

Inclusive fiducial cross section

	$2e2\mu$	4μ	$4e$	Inclusive
σ_{fid}	$1.33^{+0.17}_{-0.16}$ fb	$0.75^{+0.10}_{-0.09}$ fb	$0.59^{+0.13}_{-0.12}$ fb	$2.73^{+0.22}_{-0.22}$ (stat) $^{+0.15}_{-0.14}$ (syst) fb
σ_{fid}	$1.37^{+0.17}_{-0.16}$ fb	$0.75^{+0.10}_{-0.09}$ fb	$0.57^{+0.15}_{-0.12}$ fb	$2.74^{+0.24}_{-0.23}$ (stat) $^{+0.14}_{-0.11}$ (syst) fb
ZZ norm.	193^{+23}_{-21}	162^{+19}_{-18}	92^{+16}_{-13}	445^{+27}_{-26} (stat) $^{+21}_{-19}$ (syst)

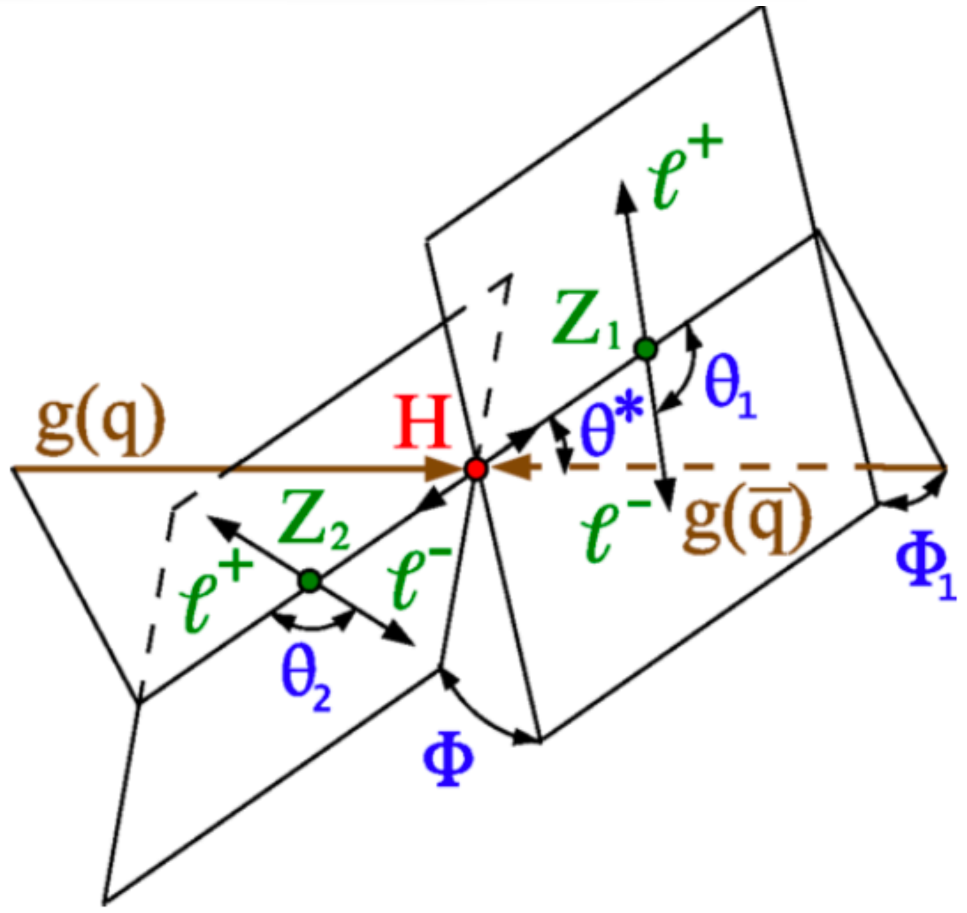
Correlation matrix for inclusive XS with floating bkg





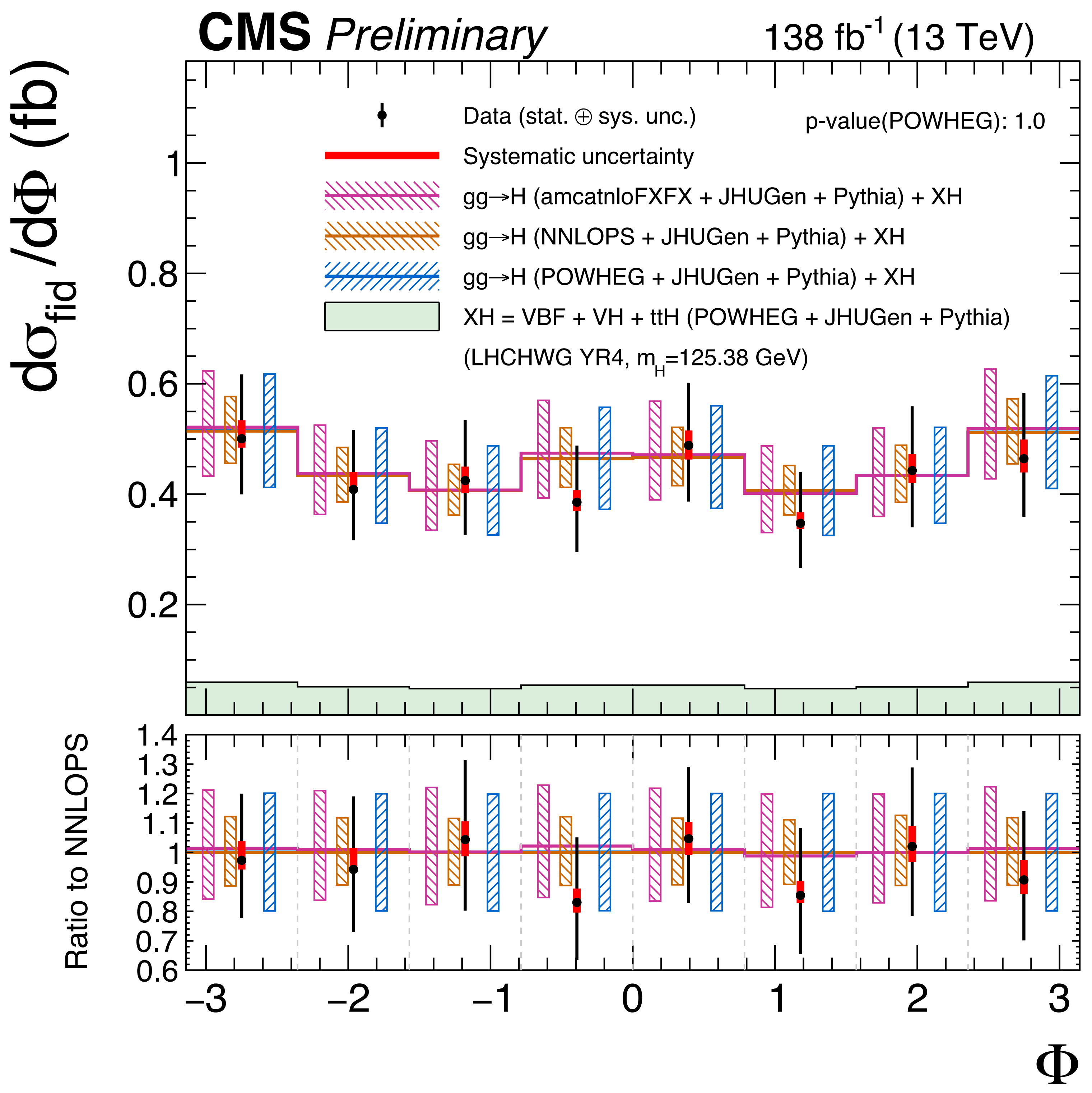
Decay observables

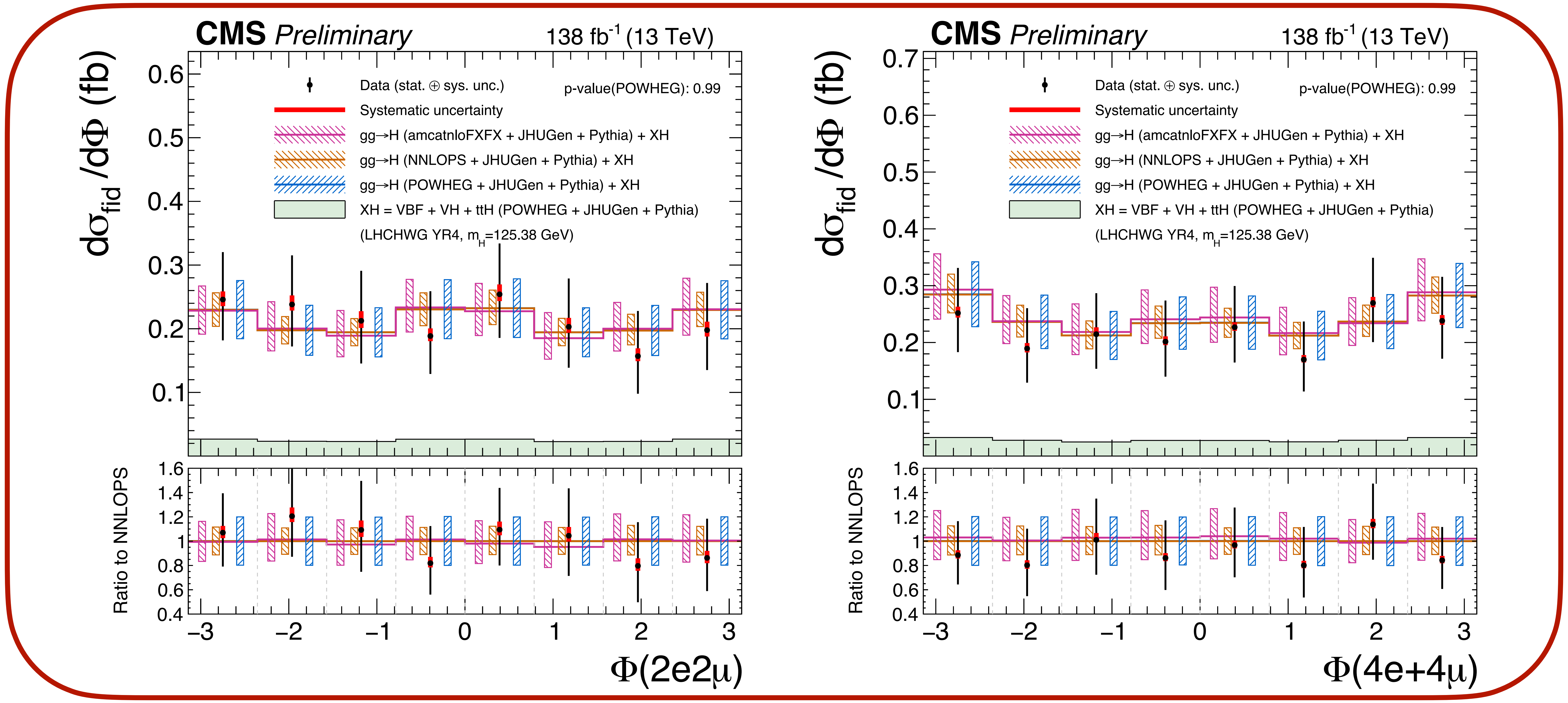
First-time



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** (**Z1** and **Z2**)
- **Three angles** describing the **fermion kinematics** ($\Phi, \cos\theta_2, \cos\theta_1$)
- **Two angles** connecting **production to decay** ($\Phi_1, \cos\theta*$)





Matrix-element discriminats

HVV scattering amplitude of a spin-0 boson H and two vector bosons

$$A(HV_1V_2) = \frac{1}{v} \left\{ M_{V_1}^2 \left(\boxed{g_1^{VV}} + \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{\left(\Lambda_1^{VV}\right)^2} + \frac{\kappa_3^{VV} (q_1 + q_2)^2}{\left(\Lambda_Q^{VV}\right)^2} + \frac{2 q_1 \cdot q_2}{M_{V_1}^2} \boxed{g_2^{VV}} \right) (\varepsilon_1 \cdot \varepsilon_2) - \boxed{2 g_2^{VV}} (\varepsilon_1 \cdot q_2)(\varepsilon_2 \cdot q_1) - \boxed{2 g_4^{VV}} \varepsilon_{\varepsilon_1 \varepsilon_2 q_1 q_2} \right\}$$

CP even

- **Tree-level SM g1ZZ = g1WW = 2**
- Loop induced SM processes contribute effectively via g2VV → small

CP odd

- SM processes at three-loop level g4VV → tiny

Matrix-element discriminats

$$A(HV_1V_2) = \frac{1}{v}\left\{ M_{V_1}^2 \left(g_1^{VV} + \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{\left(\Lambda_1^{VV}\right)^2} + \frac{\kappa_3^{VV}(q_1+q_2)^2}{\left(\Lambda_Q^{VV}\right)^2} + \frac{2 q_1 \cdot q_2}{M_{V_1}^2} g_2^{VV} \right)(\varepsilon_1 \cdot \varepsilon_2) - 2 g_2^{VV}(\varepsilon_1 \cdot q_2)(\varepsilon_2 \cdot q_1) - 2 g_4^{VV} \varepsilon_{\varepsilon_1 \varepsilon_2 q_1 q_2} \right\}$$

To use discriminants we have to define two hypotheses

SM Hypothesis $g_1^{ZZ} = 2$

Alternative hypothesis $g_i^{ZZ} \neq 0$ or $\Lambda_i^{ZZ} \neq 0$

For each event with measured variables $\vec{\Omega}$, we have to calculate the probability to produce an event at $\vec{\Omega}$ under the two hypotheses -> $\mathscr{P}_{SM}$ and $\mathscr{P}_{AC}$ (Computed with MELA)

$$\mathscr{D}_{alt} = \frac{\mathscr{P}_{AC}(\vec{\Omega})}{\mathscr{P}_{AC}(\vec{\Omega}) + \mathscr{P}_{SM}(\vec{\Omega})}$$

$$\mathscr{D}_{interference} = \frac{\mathscr{P}_{interference}(\vec{\Omega})}{2\sqrt{\mathscr{P}_{AC}(\vec{\Omega}) \cdot \mathscr{P}_{SM}(\vec{\Omega})}}$$

Coupling	g_4^{ZZ}	g_2^{ZZ}	k_1^{ZZ}	$k_2^{Z\gamma}$
Discriminants to separate hypothesis	$\mathscr{D}_{0-}^{dec}$	$\mathscr{D}_{0h+}^{dec}$	$\mathscr{D}_{\Lambda 1}^{dec}$	$\mathscr{D}_{\Lambda 1}^{Z\gamma,dec}$
Interference discriminants	$\mathscr{D}_{CP}^{dec}$	$\mathscr{D}_{int}^{dec}$	-	-

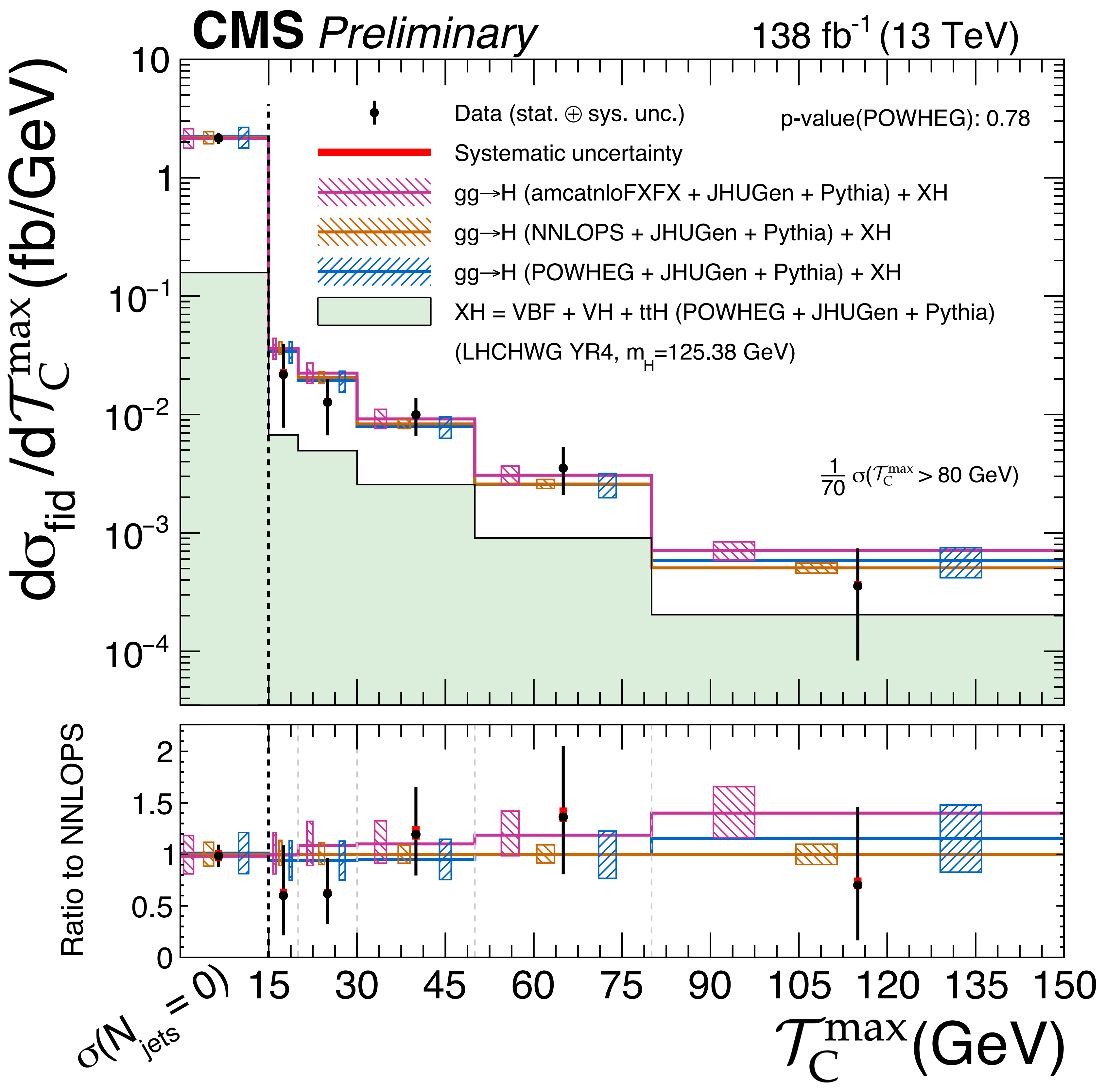
Rapidity-weighed jet observables

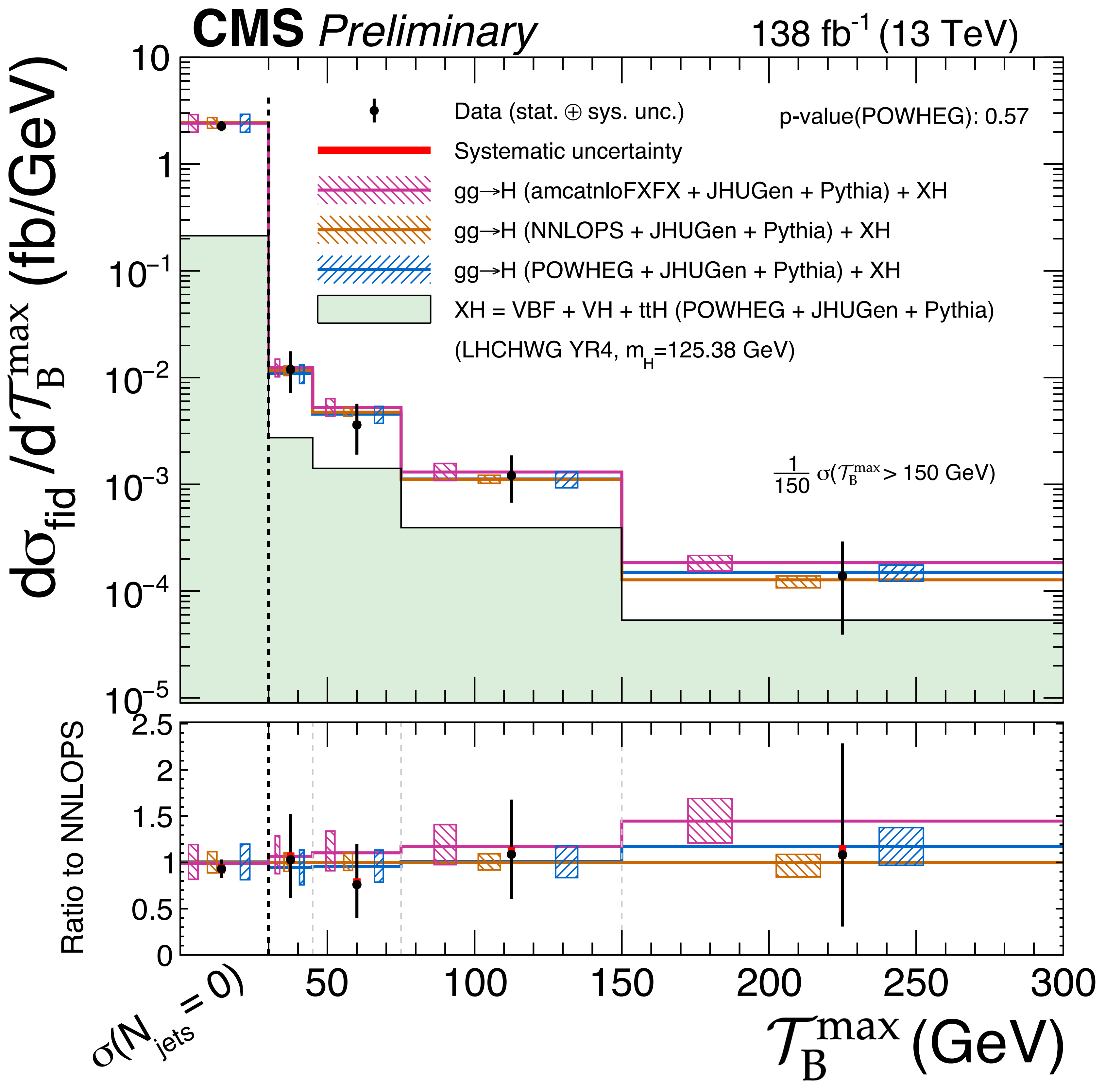
First-time

Observables defined as the **transverse momentum of the jet weighed by a function of its rapidity.** They can be factorised and resummed allowing for **precise theory predictions** and can be used as a test of **QCD resummation** since their resummation structure is different from p_T^{jet}.

$$\mathcal{T}_C^j = \frac{m_T^j}{2\cosh(y_j - Y_H)}$$

$$\mathcal{T}_B^j = m_T^j e^{-|y_j - Y_H|}$$





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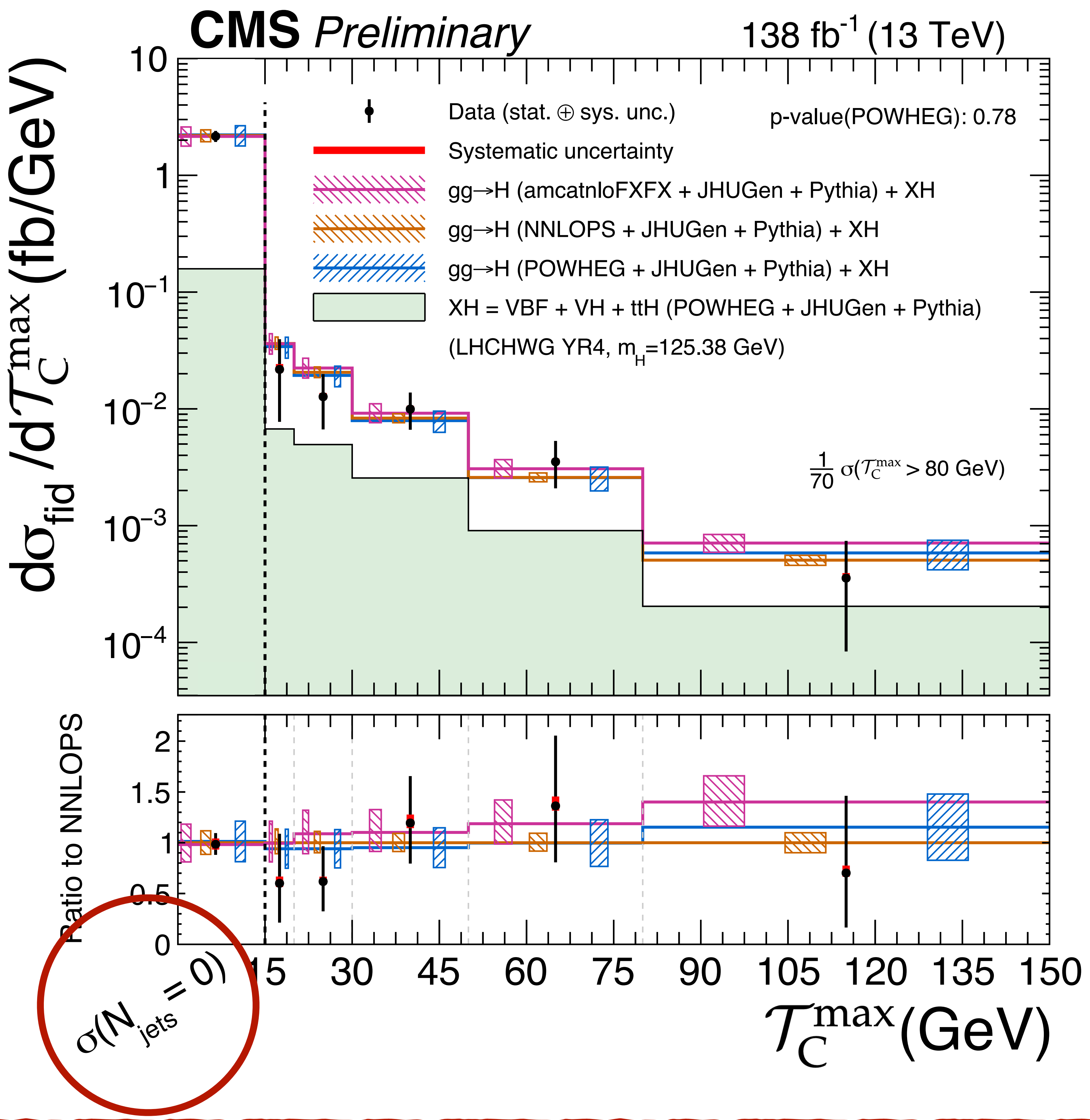
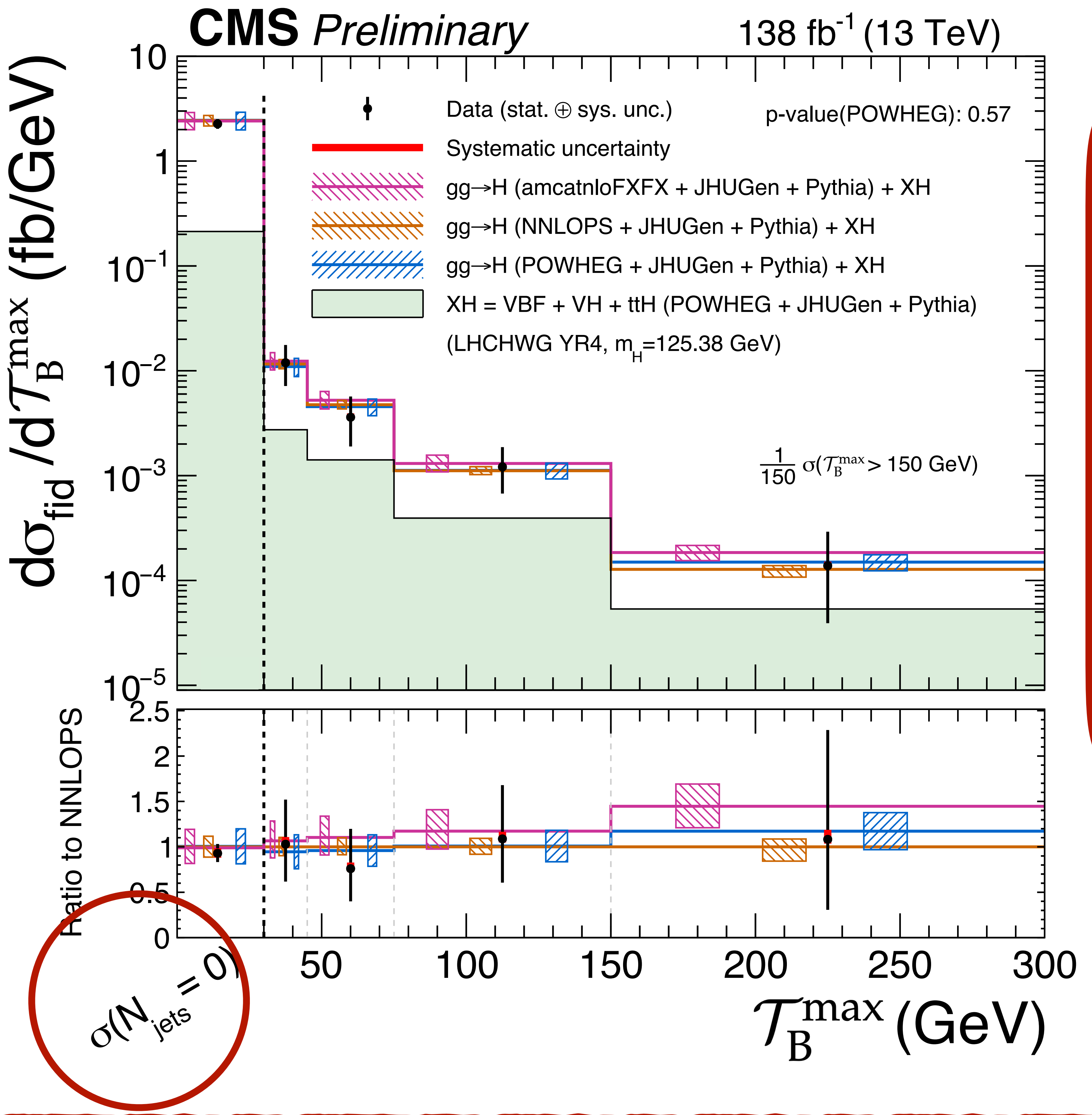
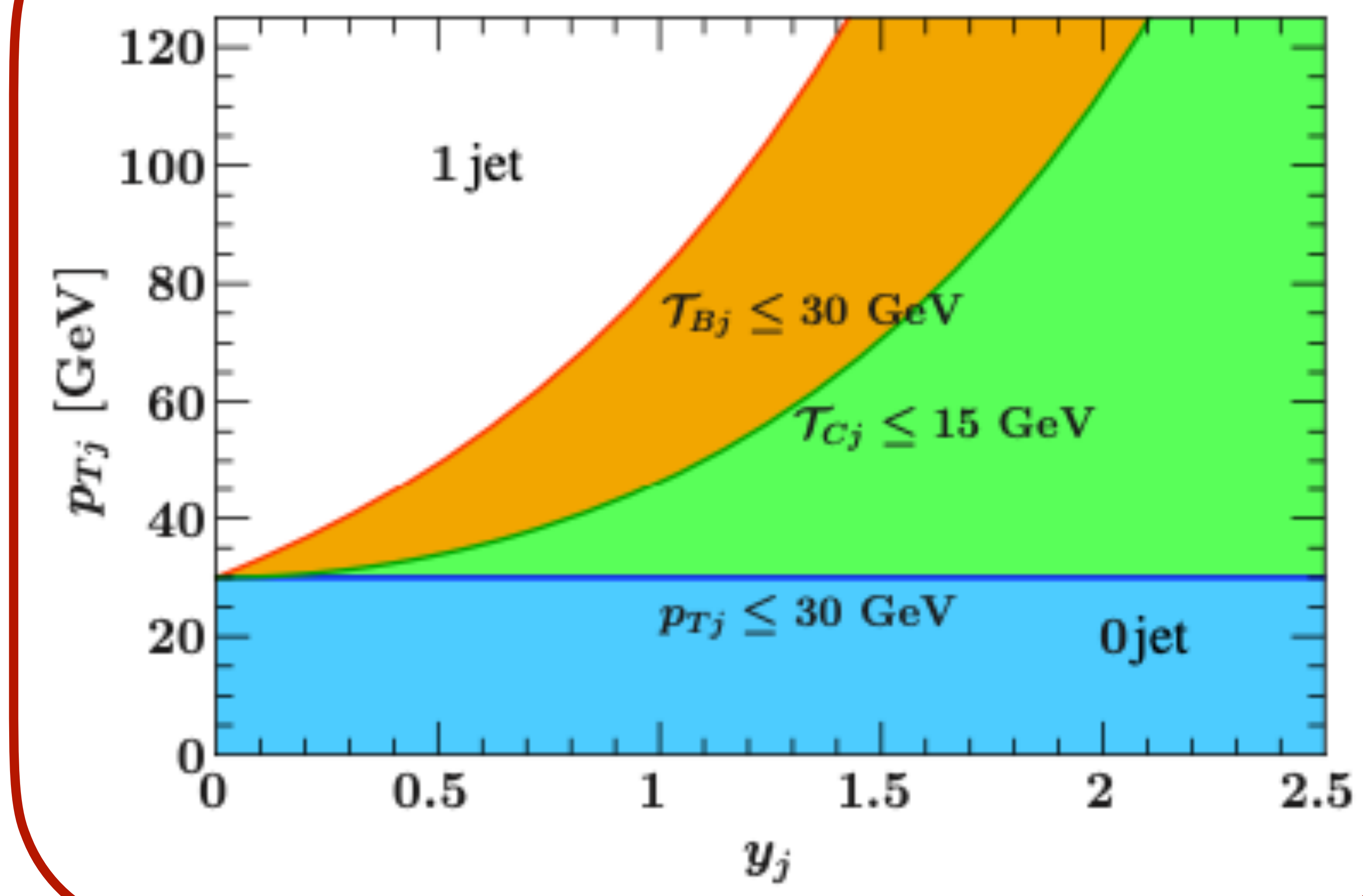




Redefinition of the 0-jet phase space



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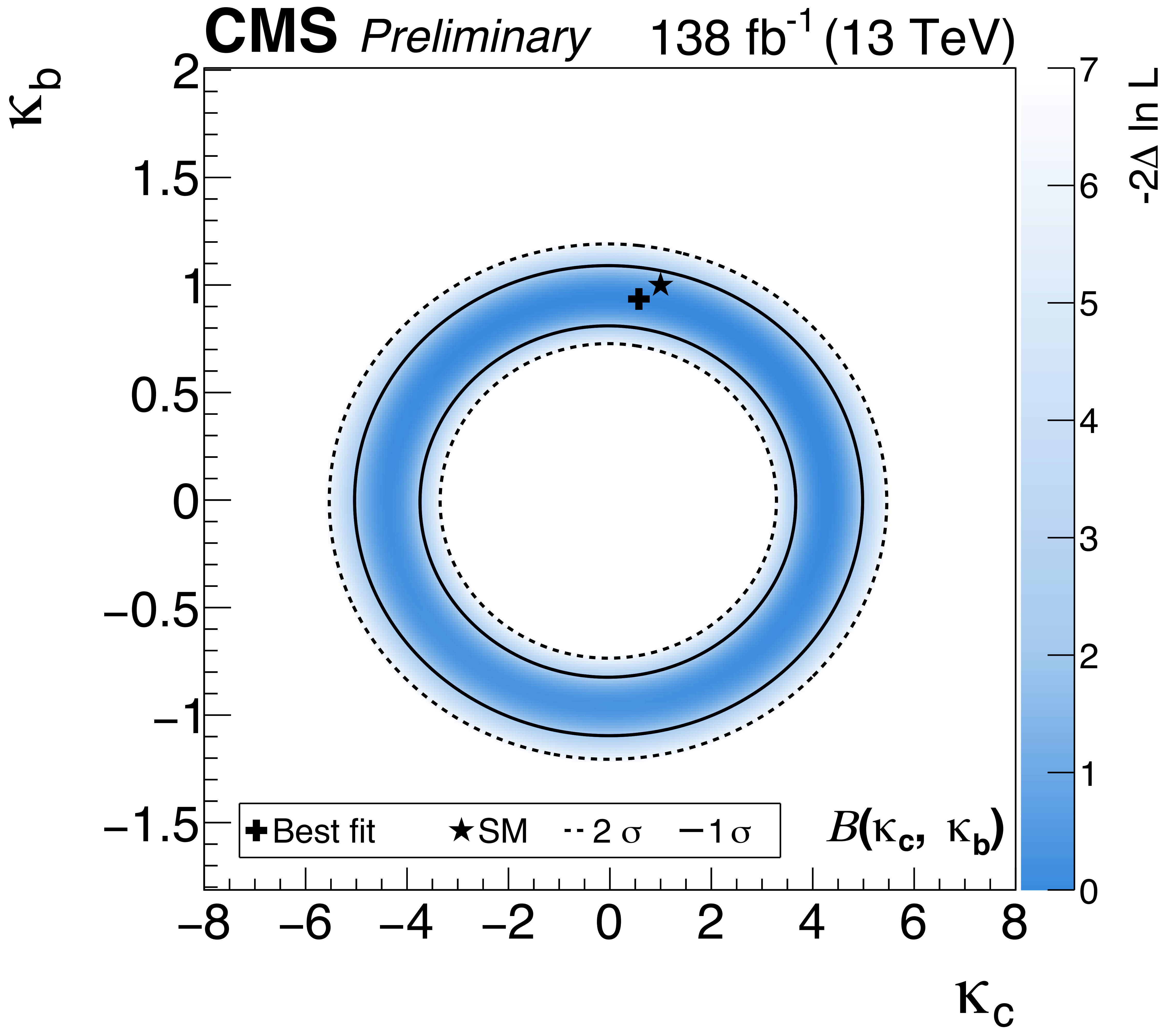
c/b quark couplings κ_b, κ_c

The **ggH transverse momentum** is used to set constraint on κ_c/κ_b by using information from both the **shape** and the variation of the **normalisation**



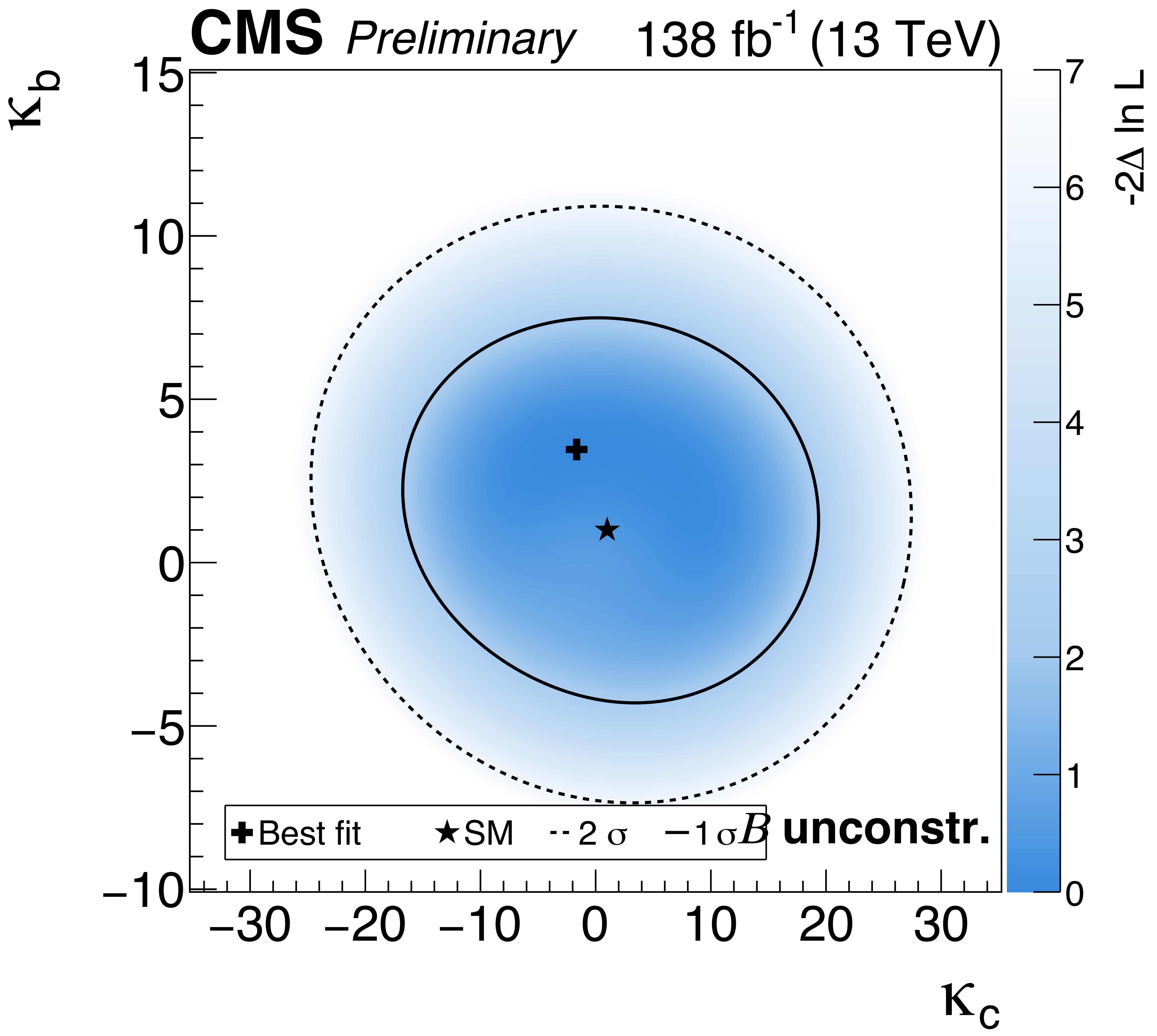
Observed (expected) excluded κ_c range from @ 95% CL:

$-5.3\ (-5.7) < \kappa_c < 5.2\ (5.7)$

Observed (expected) excluded κ_b range from @ 95% CL:

$-1.1\ (-1.3) < \kappa_b < 1.1\ (1.2)$

c/b quark couplings κ_b, κ_c



Freely floating branching ratios

The normalization of the parametrization and coupling dependence of BRs are eliminated, and what remains is purely the constraints from only the shape

		Full Run2 Ultra Legacy Floating kb kc	
		Observed 95% confidence interval	**Expected** 95% confidence interval
Shape-Only	k_b	[-5.6, 8.9]	[-5.5, 7.4]
	k_c	[-20, 23]	[-19, 20]

Higgs potential

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4 + \mathcal{O}(H^5)$$

In the SM

$$\lambda_3 = 4\lambda_4 = \frac{m_H^2}{v^2}$$

Electron efficiency nuisance

New method to compute uncertainties from T&P measurements for electrons based on RMS

- Scale factors and corresponding uncertainties enter the final result with the power of four –> **Electron reconstruction and selection efficiency** is by far the **leading nuisance** in $H \to ZZ \to 4\ell$
- Computation done with **Tag-and-Probe** (TnP) method
- Challenge: **low-pT electron region** (7-20 GeV) where it is hard to distinguish signal from QCD background –> Large systematic uncertainty from this region
- **<u>Current method for sys unc</u>**: Summing in quadrature four variations of the nominal setting
  - Very sensitive to outliers
  - Adding more variations lead to bigger uncertainty
  - Correlations not taken into account
- **<u>New method for sys unc</u>**: Combining the four variations by using the **RMS**
  - Less sensitive to outliers
  - Adding more variations does not lead to bigger uncertainty
  - Reduced uncertainty in the low-pT region (~40% improvement in the precision)