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Higgs boson differential cross section measurements in the four-leptons final state

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On behalf of the **CMS collaboration**

Highlights

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

✴This analysis expands the previous $H \to ZZ \to 4\ell$ [EPJC81(2021)488] analysis (Run 2)

✴Increase of the number of differential observables (from 4 to 32)

✴**Latest Run 2 CMS objects calibration**

✴Reduction of the experimental systematic uncertainties (*improved* measurements of lepton scale factors)

✴**Interpretation** of the p_T^H spectrum:

- ◉Higgs boson trilinear self-coupling (κ_λ)
- ◉c/b quark couplings (κ_b κ_c)

Event selection and reconstructions

✳Z candidate

◉Any OS-SF pair that satisfies $12 < m_{ll(\gamma)} < 120$ GeV

✳Build all possible ZZ candidates defined as pairs of non-overlapping Z candidate; define Z_1 candidate with $m_{ll(\gamma)}$ closest to the PDG m(Z) mass

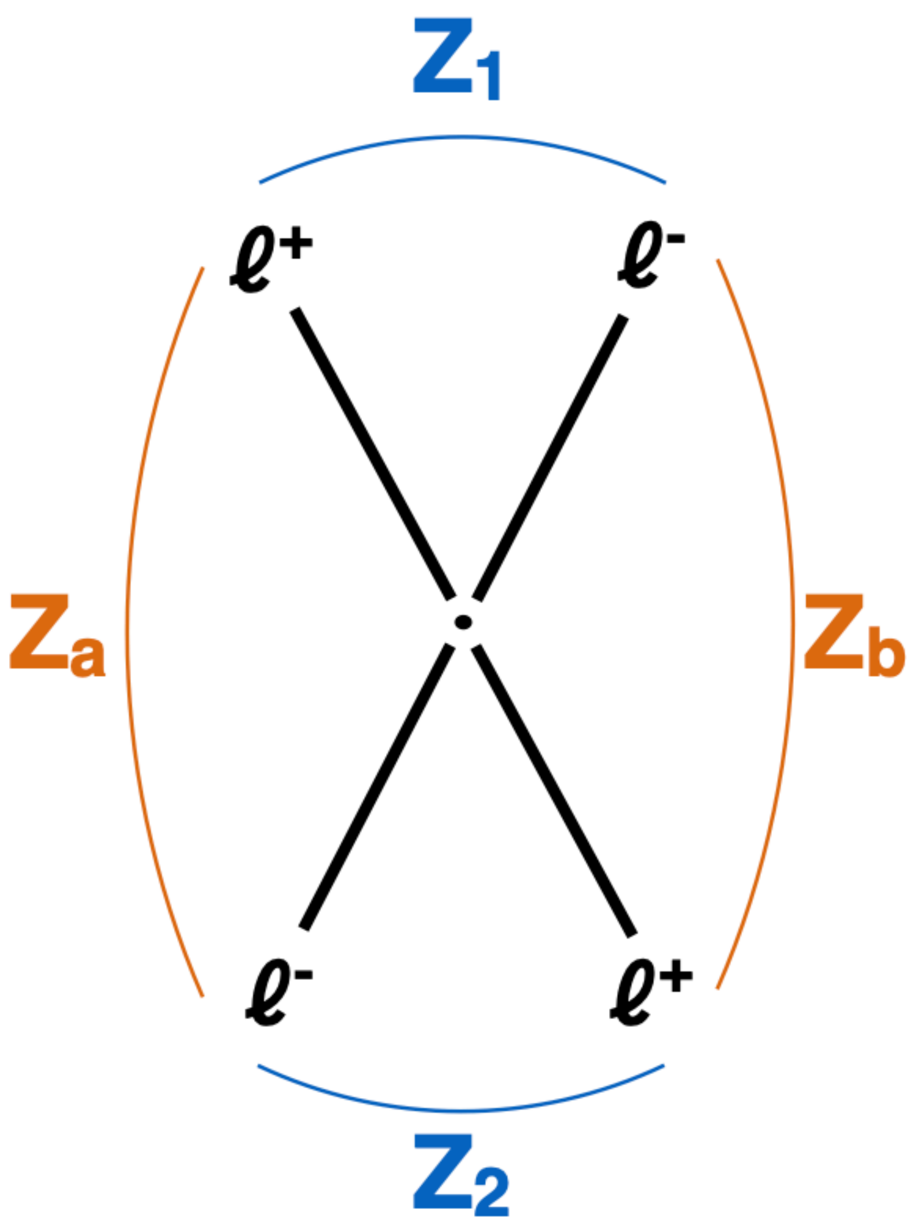
◉$m_{Z1} > 40$ GeV; $P_T(l1) > 20$ GeV; $P_T(l2) > 10$ GeV

◉ $\Delta R > 0.02$ between each of the four leptons

◉$m_{ll} > 4$ GeV for OS pairs (regardless of flavor)

◉Reject 4μ and 4e candidates where the alternative pair Z_aZ_b satisfies $\left|m_{Za} - m_Z\right| < \left|m_{Z1} - m_Z\right|$ and $m_{Zb} < 12$ GeV

◉$m_{4l} > 70$ GeV



✳If more than one ZZ candidate is left, take the one with Z_1 mass closest to m_Z and the Z_2 from the candidates whose lepton give higher pT sum.

EPJC81(2021)488

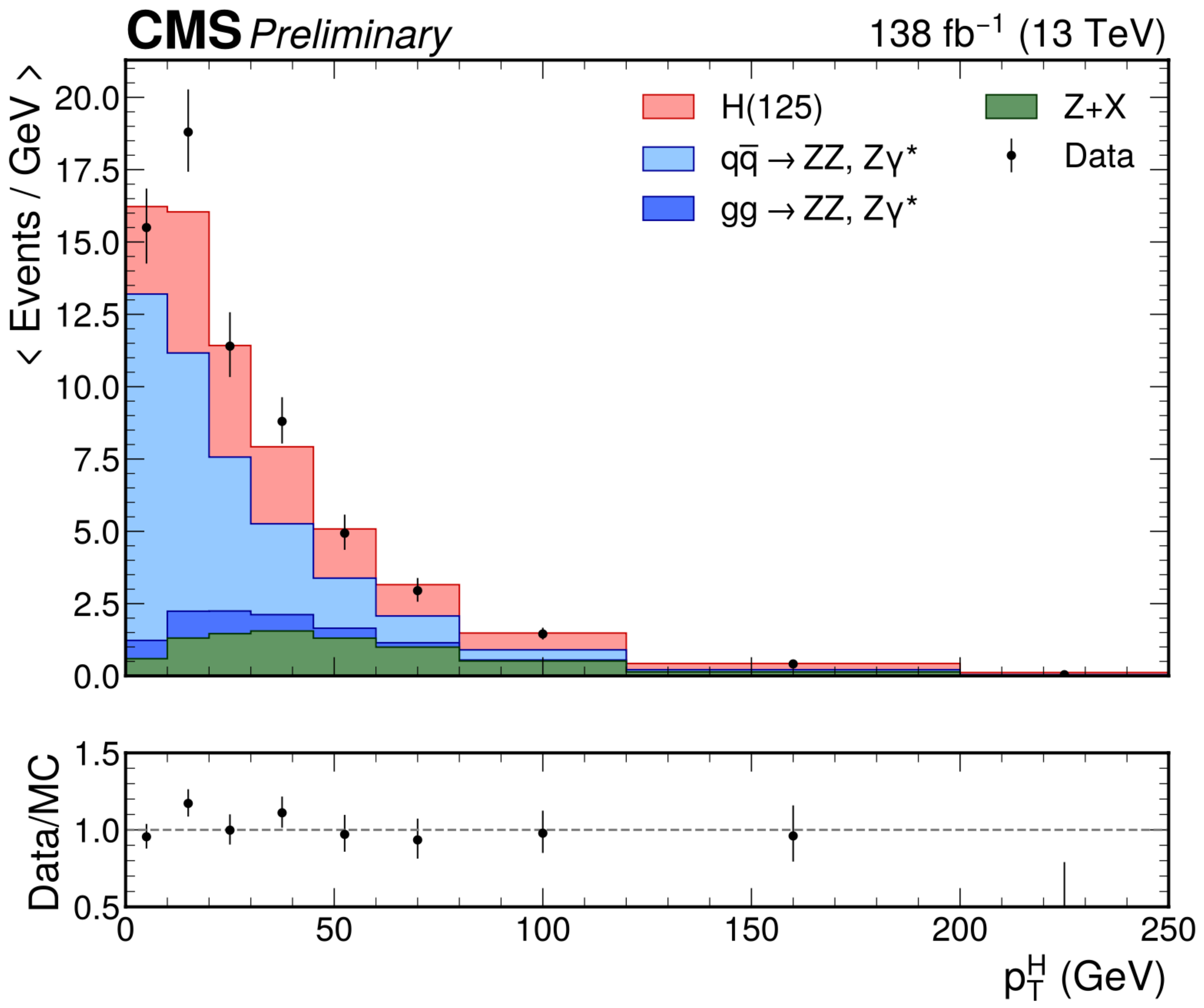
Background Estimation

✴Irreducible background

- ◉Production of ZZ via $q\bar{q}$ annihilation or gluon fusion
- ◉Estimated using simulation

✴Reducible background

- ◉Light flavor hadrons misidentified as leptons
- ◉Heavy flavor jets produce secondary leptons through the decay of heavy flavor mesons
- ◉Two independent methods used to estimated Z+X background: OS and SS
    - Fake rates calculated in Z+l control region
    - Z+X yields estimated in orthogonal regions of Z+ll control region
    - Final estimate combination of 2 methods
- ◉Templates are built from the control regions in data



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Systematic Uncertainties

✳Experimental uncertainties

◉Integrated luminosity

◉Lepton identification and reconstruction efficiency → →

◉Reducible background

◉Lepton scale and resolution

◉Jet energy scale

✳Theoretical uncertainties

◉**QCD uncertainty** from renormalization and factorization scale

◉Uncertainty on the Choice of **PDF set** is determined following the PDF4LHC recommendations

◉Uncertainty of 2% on H → 4l **branching ratio** affects only signal yields

The uncertainties of lepton reconstruction and selection range for
- 4μ channel 0.8 - 1.9%
- 4e channel 6.5 - 11%

A reduction of about 5% in the 4e uncertainties thanks to a dedicated RMS method.

EPJC81(2021)488

Summary of inclusive theory uncertainties	
QCD scale (gg)	$\pm$ 3.9 %
PDF set (gg)	$\pm$ 3.2 %
gg $\to$ ZZ k-factor (gg)	$\pm$ 10 %
QCD scale ($q\bar{q} \to$ ZZ)	+3.2/-4.2 % %
PDF set ($q\bar{q} \to$ ZZ)	+3.1/-3.4 %
Electroweak corrections ($q\bar{q} \to$ ZZ)	$\pm$ 0.1 %
QCD scale (VBF)	+0.4/-0.3 %
PDF set (VBF)	$\pm$ 2.1 %
QCD scale (WH)	+0.5/-0.7 %
PDF set (WH)	$\pm$ 1.9 %
QCD scale (ZH)	+3.8/-3.1 %
PDF set (ZH)	$\pm$ 1.6 %
QCD scale ($t\bar{t}$H)	+5.8/-9.2 %
PDF set ($t\bar{t}$H)	$\pm$ 3.6 %
BR(H $\to$ ZZ $\to 4\ell$)	2 %

Common experimental uncertainties			
	2016	2017	2018
Luminosity uncorrelated	1 %	2 %	1.5 %
Luminosity corr 16 17 18	0.6 %	0.9 %	2 %
Luminosity corr 17 18	-	0.6 %	0.2 %
Lepton id/reco efficiencies	0.7–10 %	0.6 – 8.5 %	0.6 – 9.5 %
Background related uncertainties			
Reducible background (Z+X)	25 – 43 %	23 – 36 %	24 –36 %
Signal related uncertainties			
Lepton energy scale	0.01%(μ) - 0.06%(e)	0.01%(μ) - 0.06%(e)	0.01%(μ) - 0.06%(e)
Lepton energy resolution	3%(μ) - 10%(e)	3%(μ) - 10%(e)	3%(μ) - 10%(e)

Fiducial/Differential Cross Section measurement

EPJC81(2021)488

✳ Definition of the fiducial phase space of $H \to ZZ \to 4l$

✳ Number of events of different final state f and different year y in the given bin i are expressed as a function of 4l invariable mass

$$\sigma_i = \frac{N_{reco,\ i}}{C_i * A_i * L * B} \quad \rightarrow \rightarrow \quad \sigma_{fid,\ i} * B = \frac{N_{reco,\ i}}{C_i * L}$$

$$\begin{aligned} N_{\mathrm{obs}}^{f,i,y}(m_{4\ell}) &= N_{\mathrm{fid}}^{f,i,y}(m_{4\ell}) + N_{\mathrm{nonfid}}^{f,i,y}(m_{4\ell}) + N_{\mathrm{nonres}}^{f,i,y}(m_{4\ell}) + N_{\mathrm{bkg}}^{f,i,y}(m_{4\ell}) \\ &= \sum_{j}^{\mathrm{genBin}} \epsilon_{i,j,y}^{f,y} \cdot (1 + f_{\mathrm{nonfid}}^{f,i,y}) \cdot \sigma_{\mathrm{fid}}^{f,j,y} \cdot \mathcal{L} \cdot \mathcal{P}_{\mathrm{res}}^{f,y}(m_{4\ell}) \\ &+ N_{\mathrm{nonres}}^{f,i,y} \cdot \mathcal{P}_{\mathrm{nonres}}^{f,y}(m_{4\ell}) + N_{\mathrm{bkg}}^{f,i,y} \cdot \mathcal{P}_{\mathrm{bkg}}^{f,i,y}(m_{4\ell}) \end{aligned}$$

✳ Fiducial + non-fiducial resonances signal contribution:
- ◉ Shape is described by double-sided Crystal Ball function.
- ◉ Normalization is proportional to the fiducial cross section.

✳ Non-resonant signal contribution
- ◉ Arises from WH, ZH ttH where one of the leptons from Higgs is lost or not selected.
- ◉ Modeled by Landau distribution
- ◉ Treated as background

Requirements for the $H \to 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20$ GeV
Sub-leading lepton p_T	$p_T > 10$ GeV
Additional electrons (muons) p_T	$p_T > 7(5)$ GeV
Pseudorapidity of electrons (muons)	$\|\eta\| < 2.5$ (2.4)
Sum of scalar p_T of all stable particles within $\Delta R < 0.3$ from lepton	$< 0.35 p_T$
Event topology	
Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Inv. mass of the Z_1 candidate	$40 < m_{Z_1} < 120$ GeV
Inv. mass of the Z_2 candidate	$12 < m_{Z_2} < 120$ 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	$m_{\ell^+\ell'^-} > 4$ GeV
Inv. mass of the selected four leptons	$105 < m_{4\ell} < 160$ GeV

Results

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} $D_{\Lambda1}^{dec}$ $D_{\Lambda1}^{Z\gamma,dec}$ D_{int}^{dec}

Double-differential observables

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}

Interpretations

k_λ, k_c, k_b

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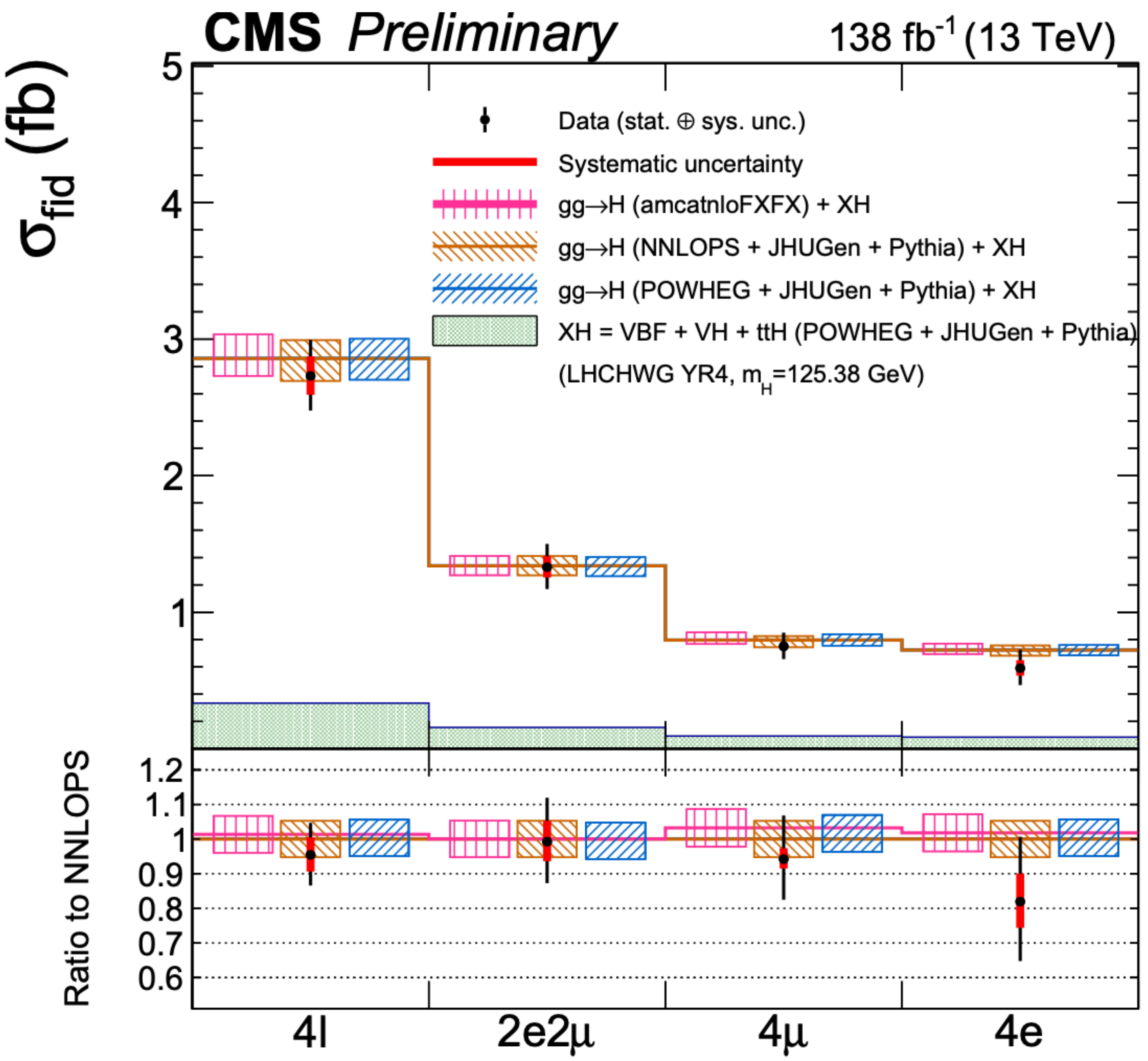
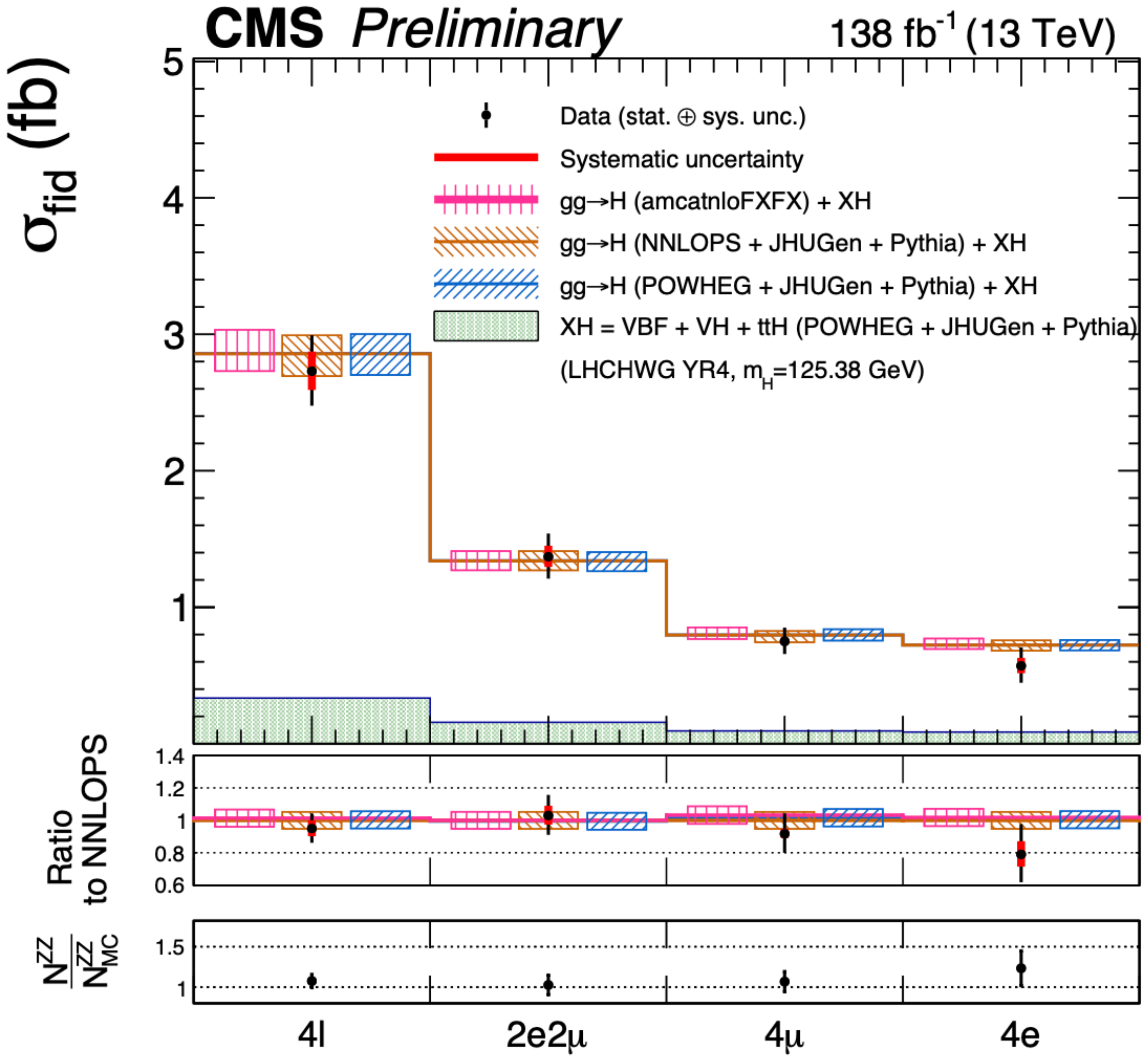
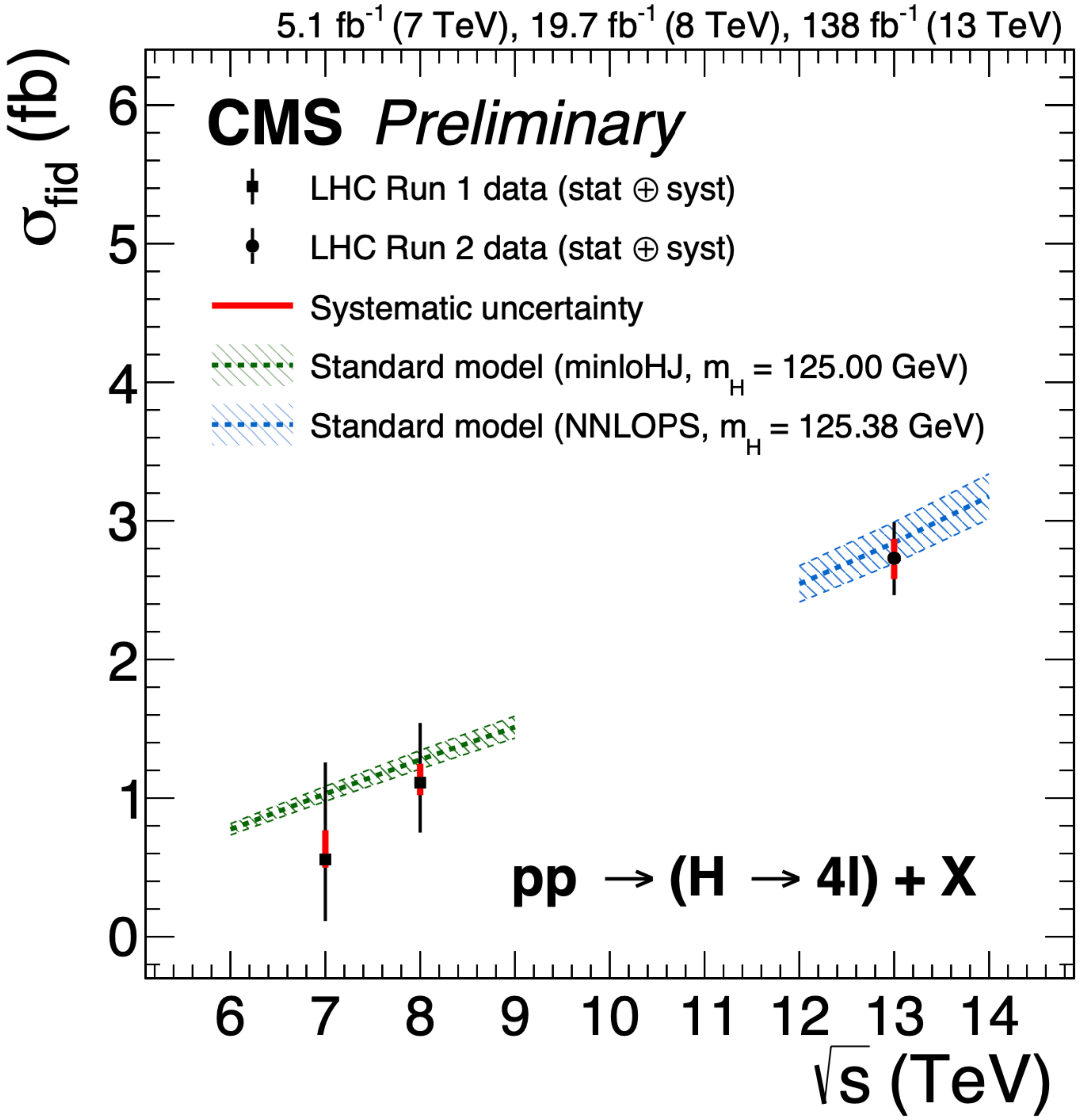
Interpretations

k_λ, k_c, k_b

Results: Inclusive

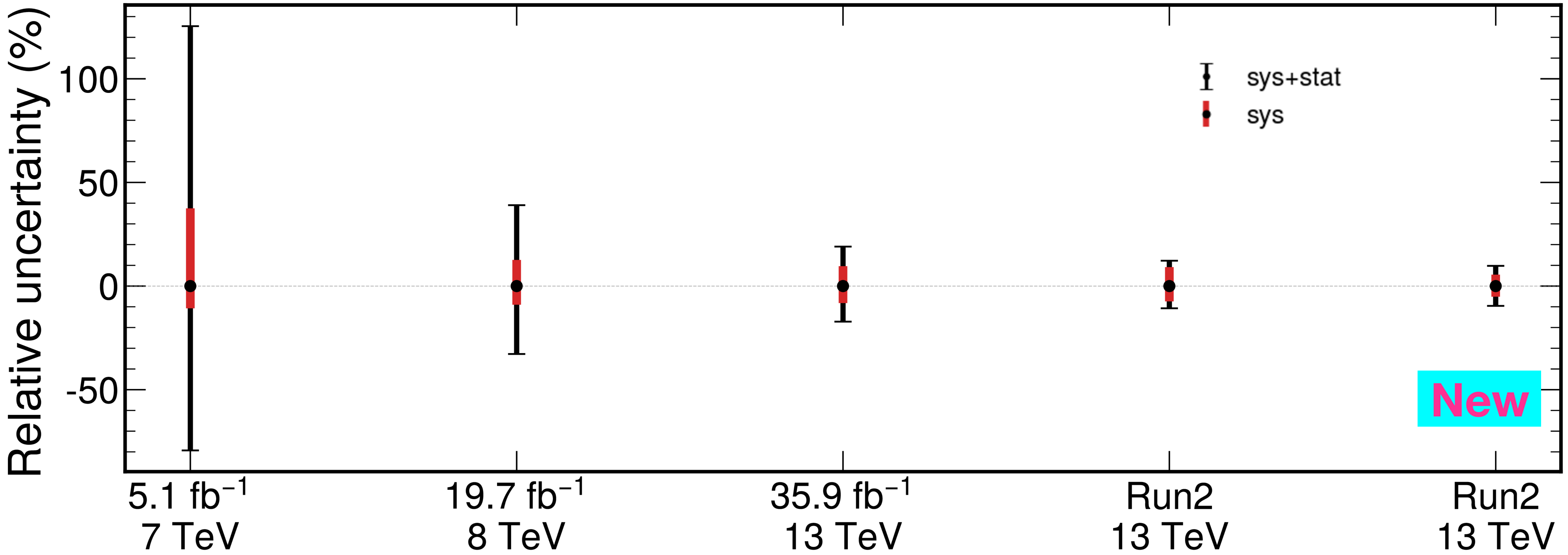




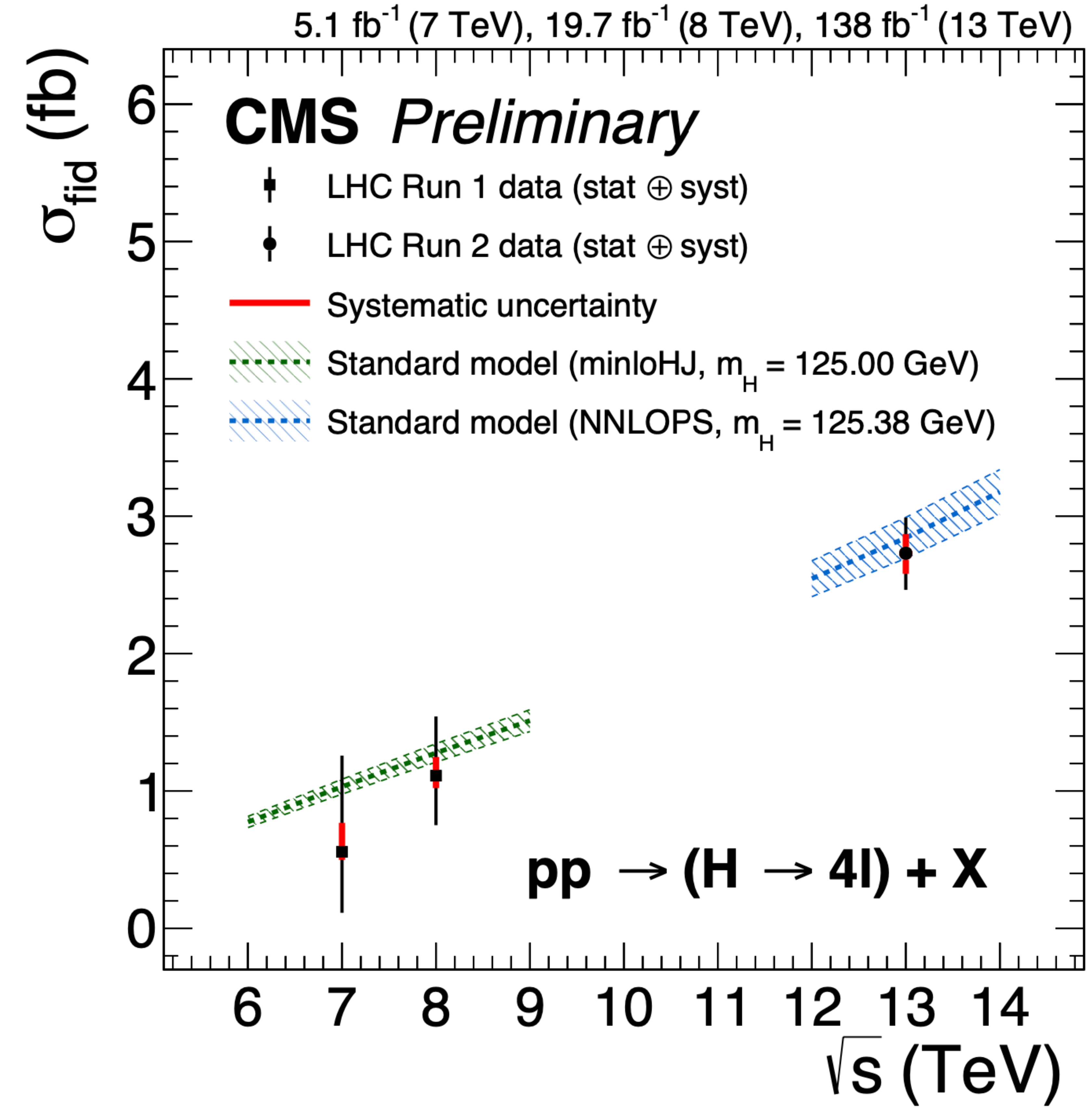


- ✳ Standard approach (left): extract both the shape and the normalisation of the ZZ irreducible background from the simulation
- ✳ **Alternative strategy (middle): Measuring together the inclusive fiducial cross section and the ZZ normalisation**
    - ◉ Remove the impact of nuisances on ZZ normalisation
    - ◉ Being sensitive to BSM effects in the background
    - ◉ Reduction of the systematic component on the XS wrt standard approach, but not yet enough number of events to profit from this method for **differential** measurements

Results: Inclusive (all channels)

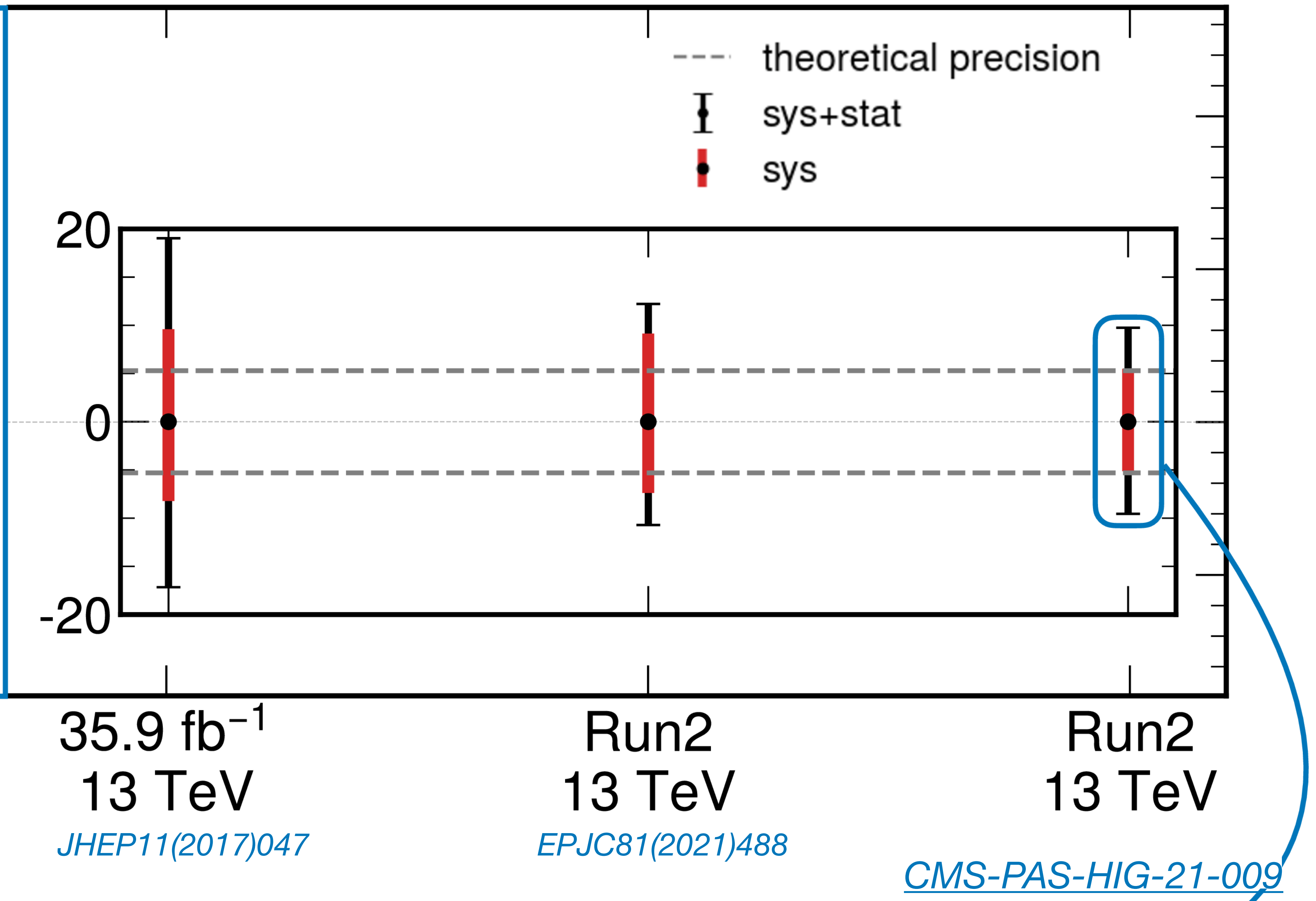


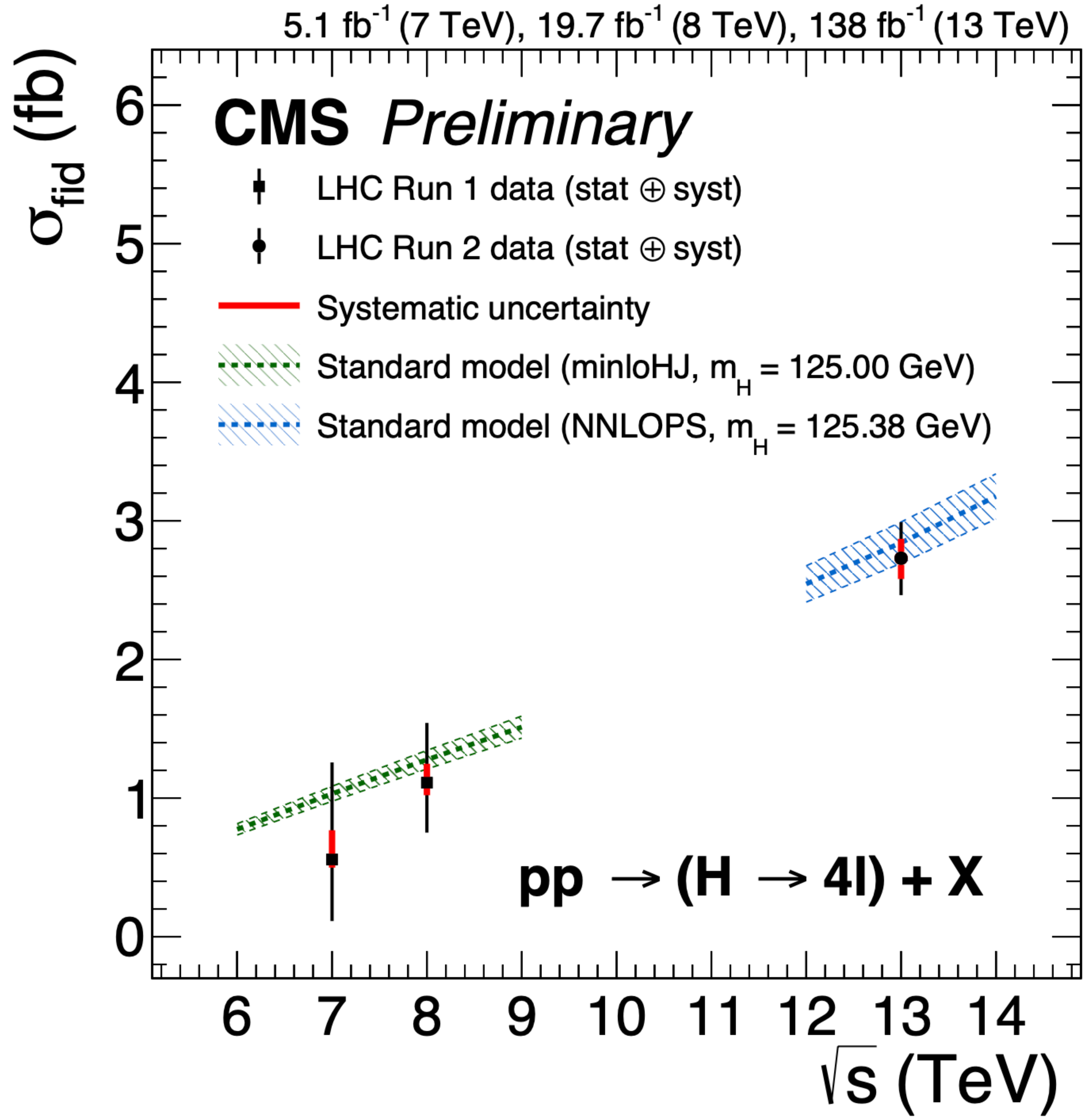
JHEP04(2016)005 *JHEP04(2016)005* *JHEP11(2017)047* *EPJC81(2021)488* [*CMS-PAS-HIG-21-009*]



Results: Inclusive (all channels)

- Precision @ **10%**
- **40% decrease of the systematic component** due to the reduction of the main lepton nuisances
- **Electron-related nuisances** are the leading contribution to the systematic uncertainty but their value is halved
- Systematic component at the same level of the theoretical precision





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

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Interpretations

k_λ, k_c, k_b

Results: Differential

✴**Revised binning** w.r.t previous analyses

✴*$p_T(H)$* spectrum measured with an average precision of **35%** (in some bins down to 20%)

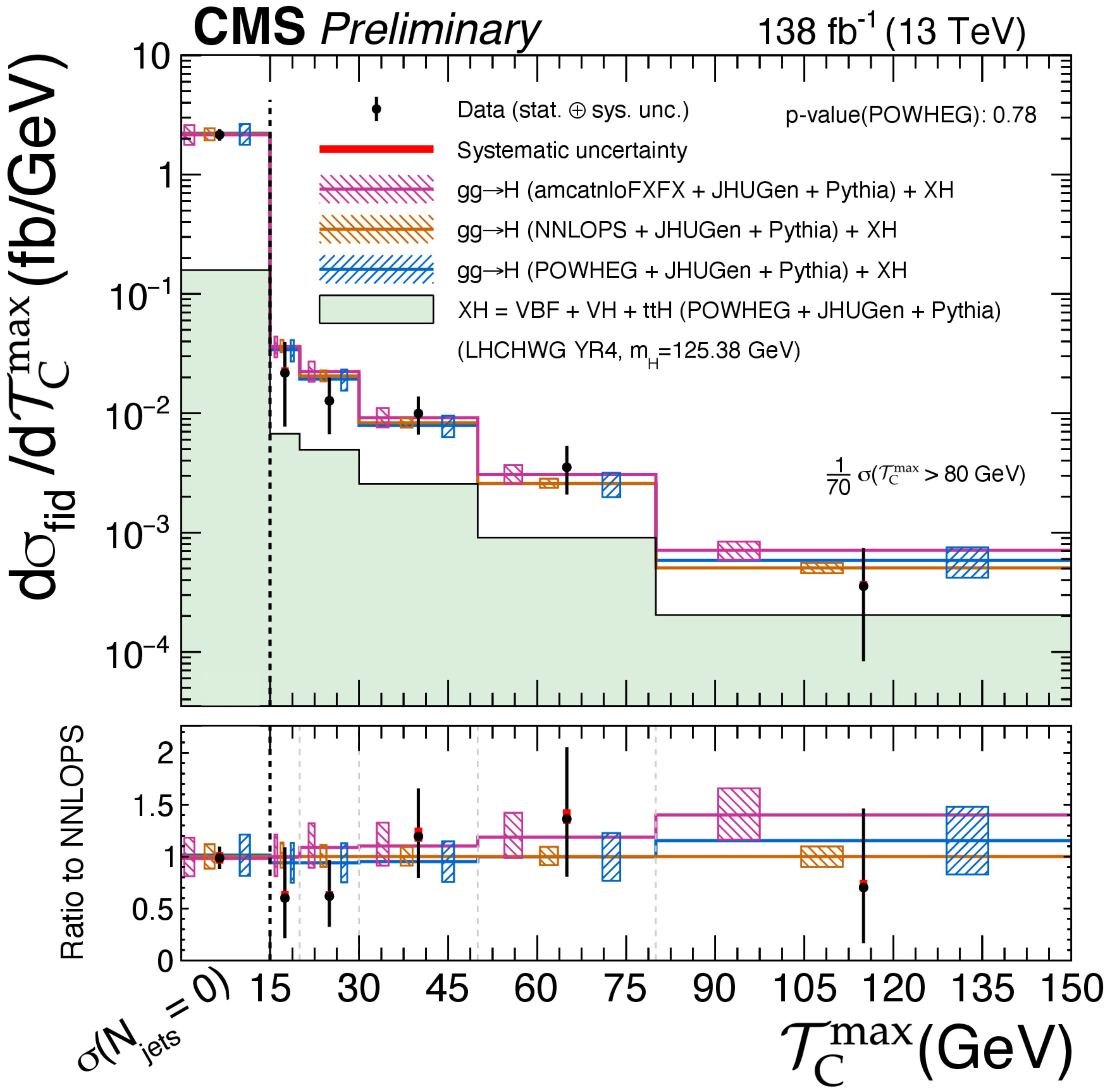
✴**Extension of the jet phase space** (from $|\eta_{jet}| < 2.5$ to $|\eta_{jet}| < 4.7$); thanks to the improved CMS jet reconstruction

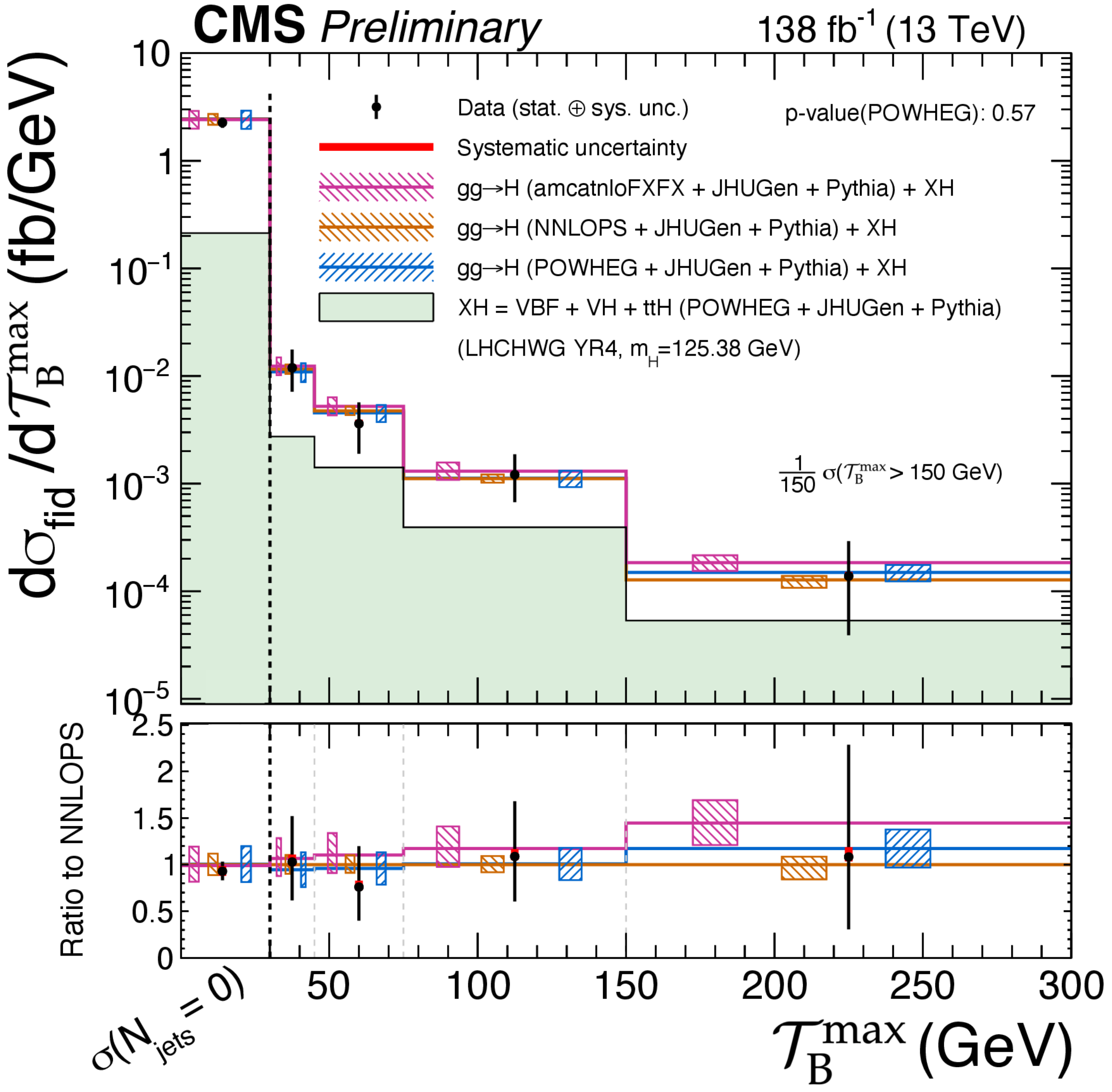
Results: Differential- Rapidity-weighted jet observables

Observables defined as the **transverse momentum of the jet weighed by a function of its rapidity.** They can be factorised and re-summed 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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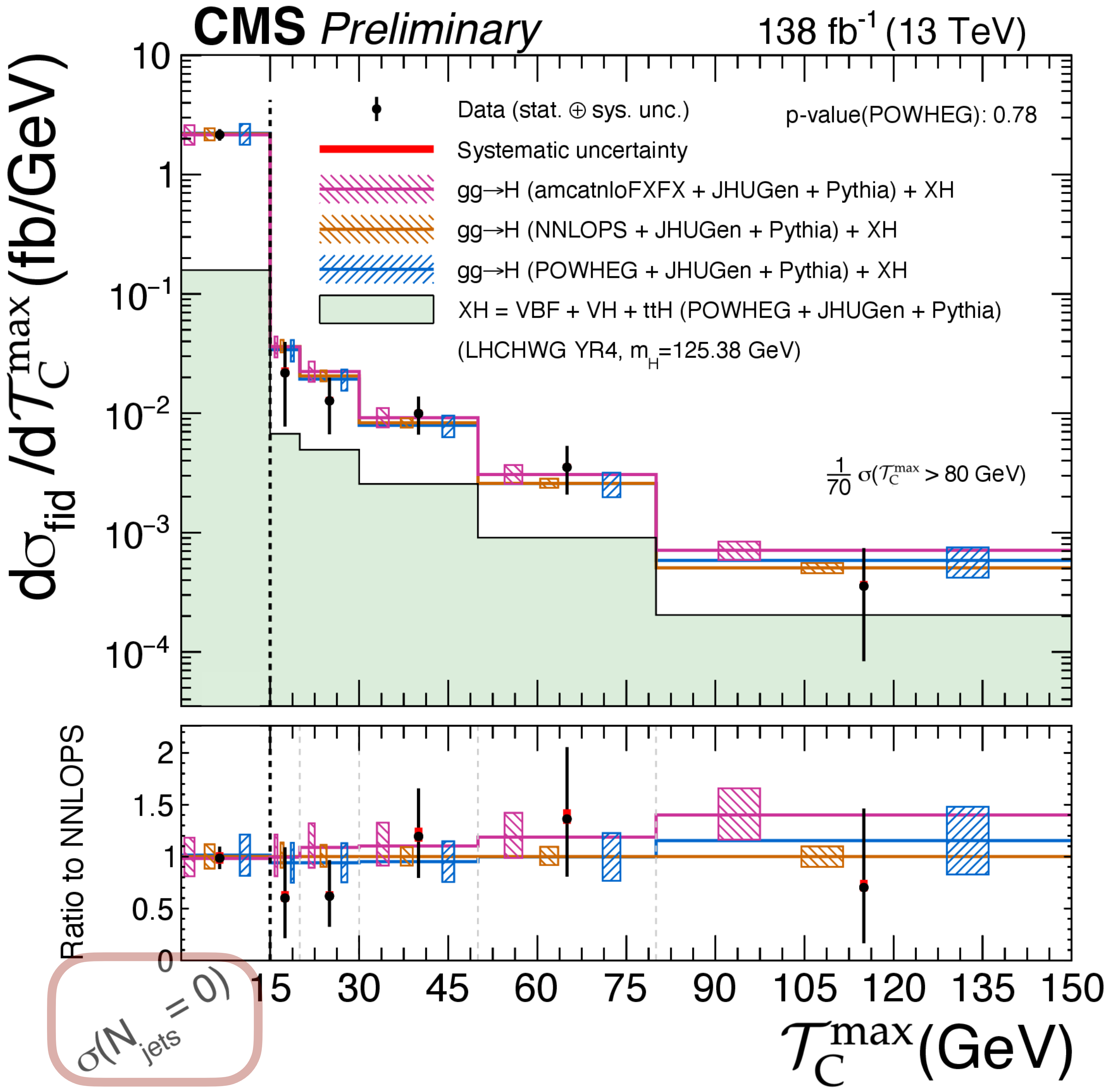
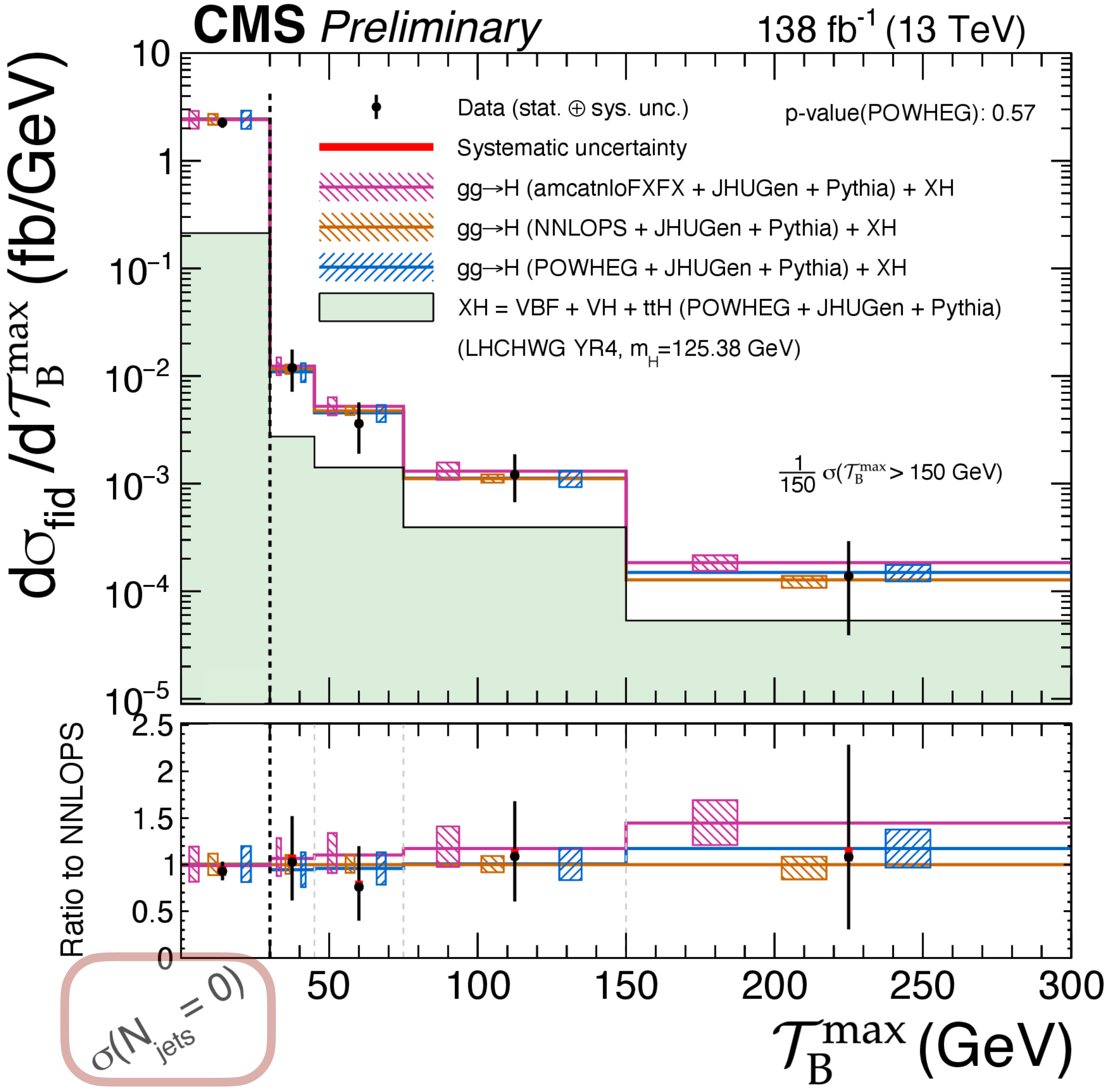
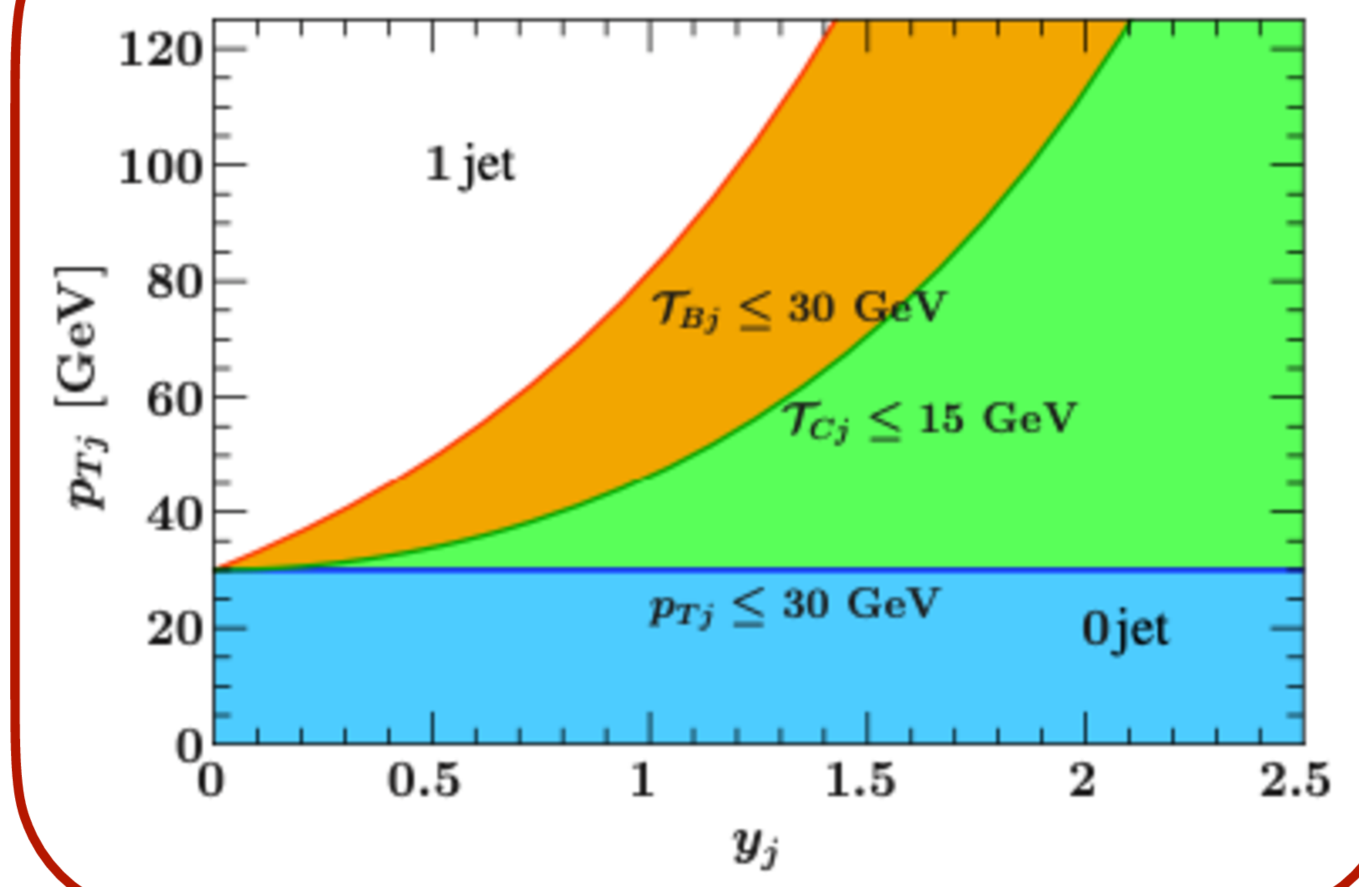




Redefinition of the 0-jet phase space



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Inclusive fiducial cross section

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Double-differential observables

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$|y_H|$ vs p_T^H p_T^{j1} vs p_T^{j2}

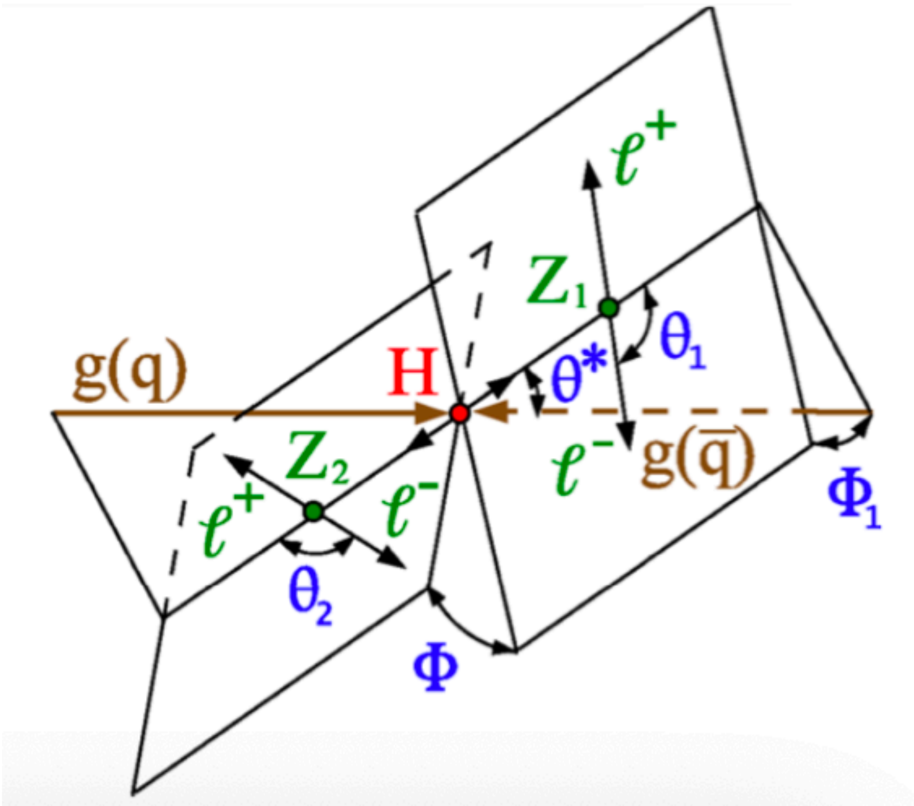
Interpretations

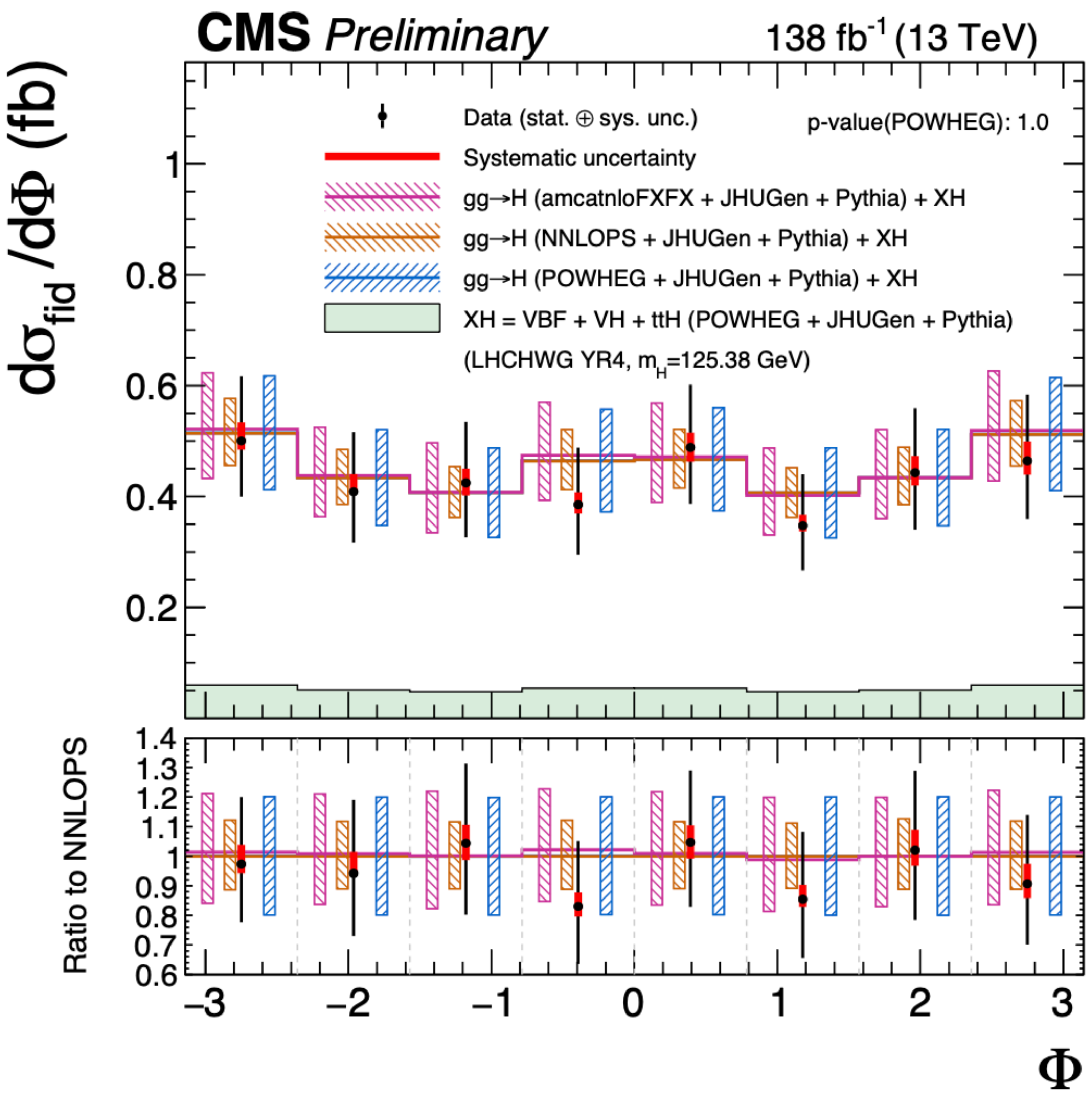
k_λ, k_c, k_b

Results: Differential- 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** (**Z1** and **Z2**)
- **Three angles** describing the **fermion kinematics** (Φ, $\cos\theta_2$, $\cos\theta_1$)
- **Two angles** connecting **production to decay** (Φ_1, $\cos\theta^*$)





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

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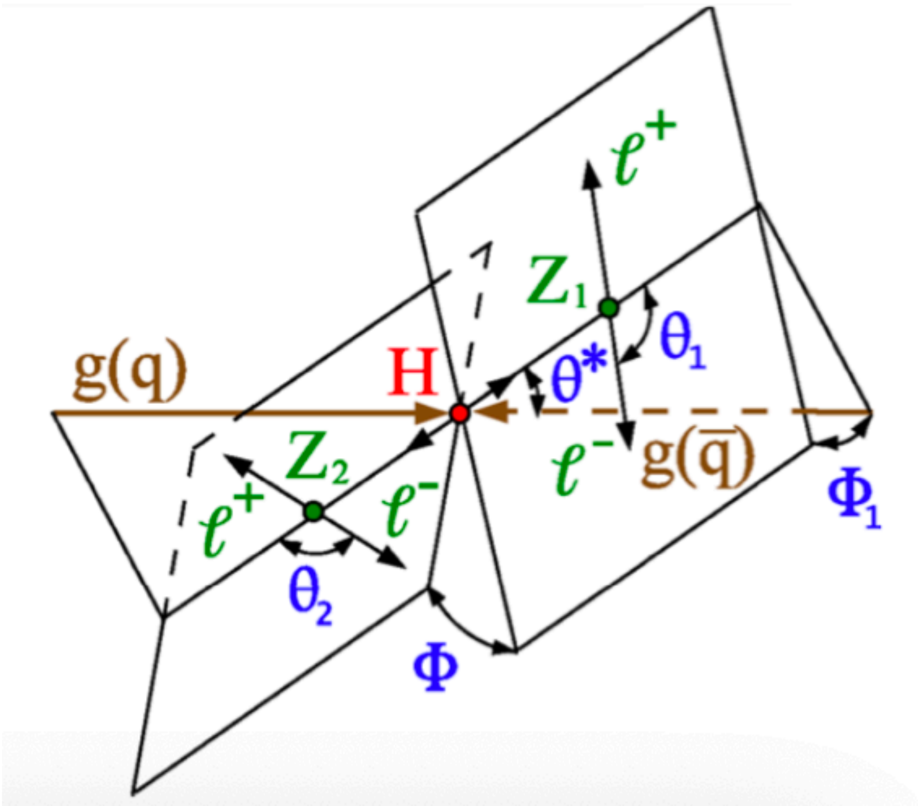
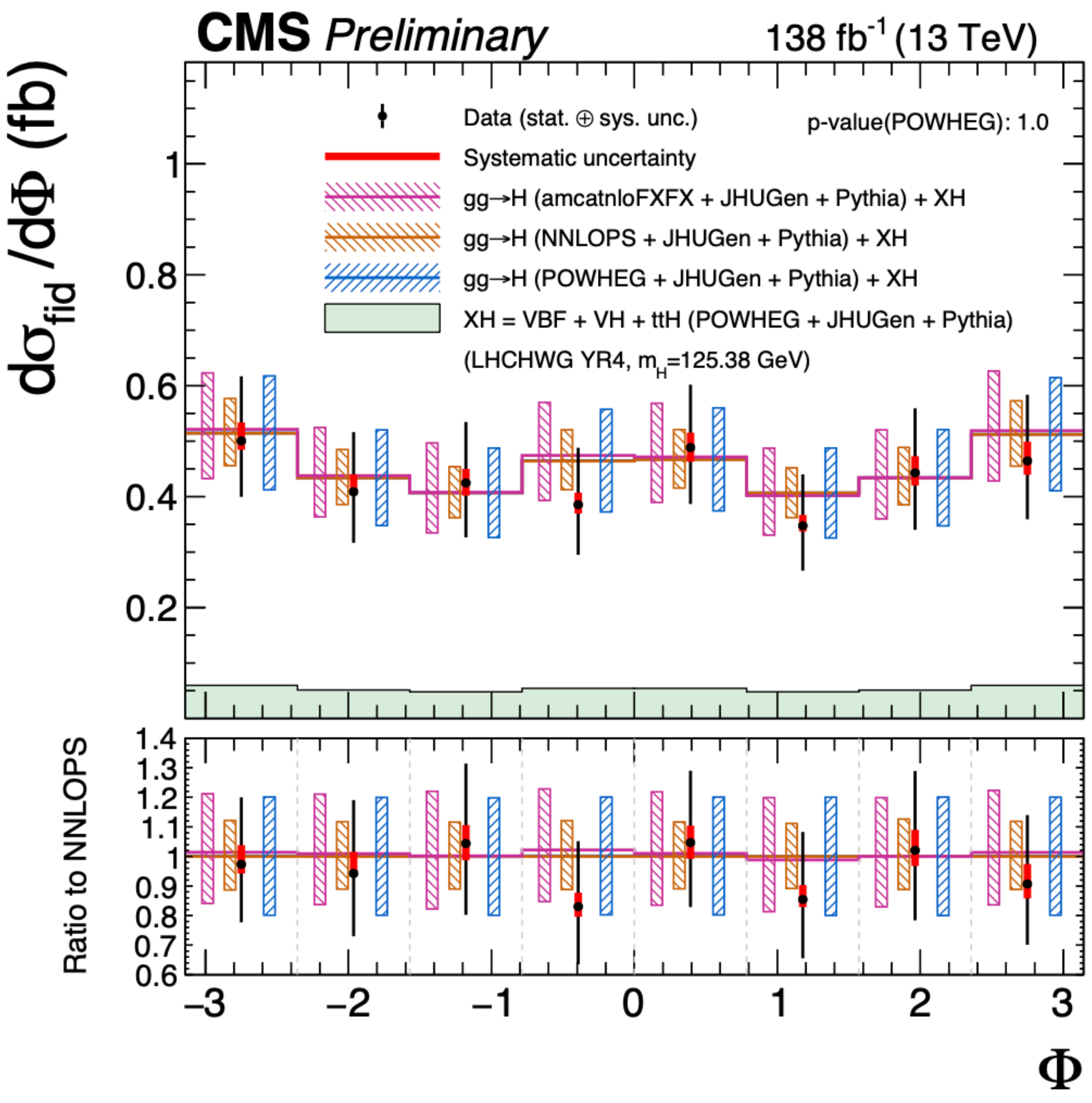
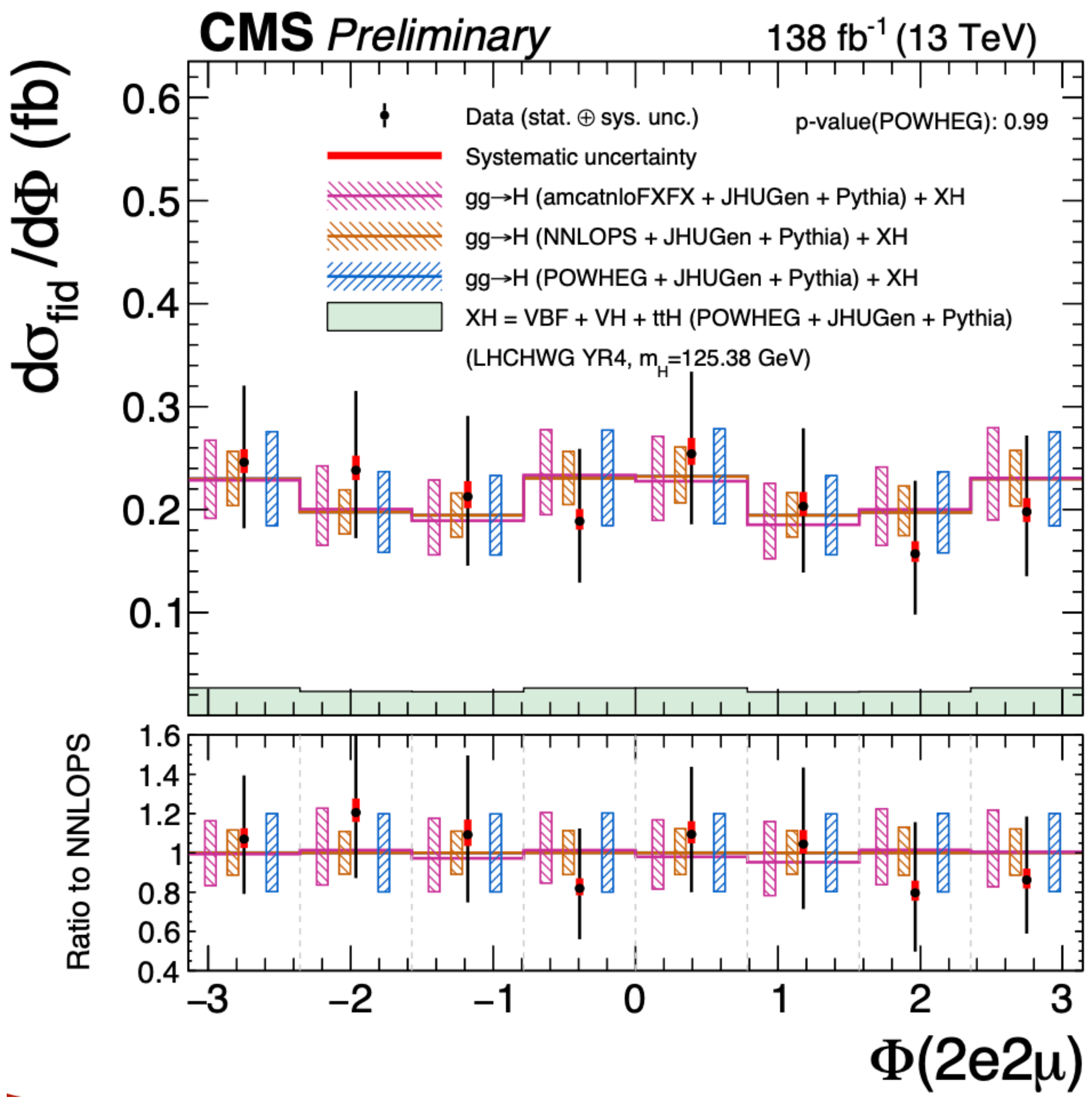
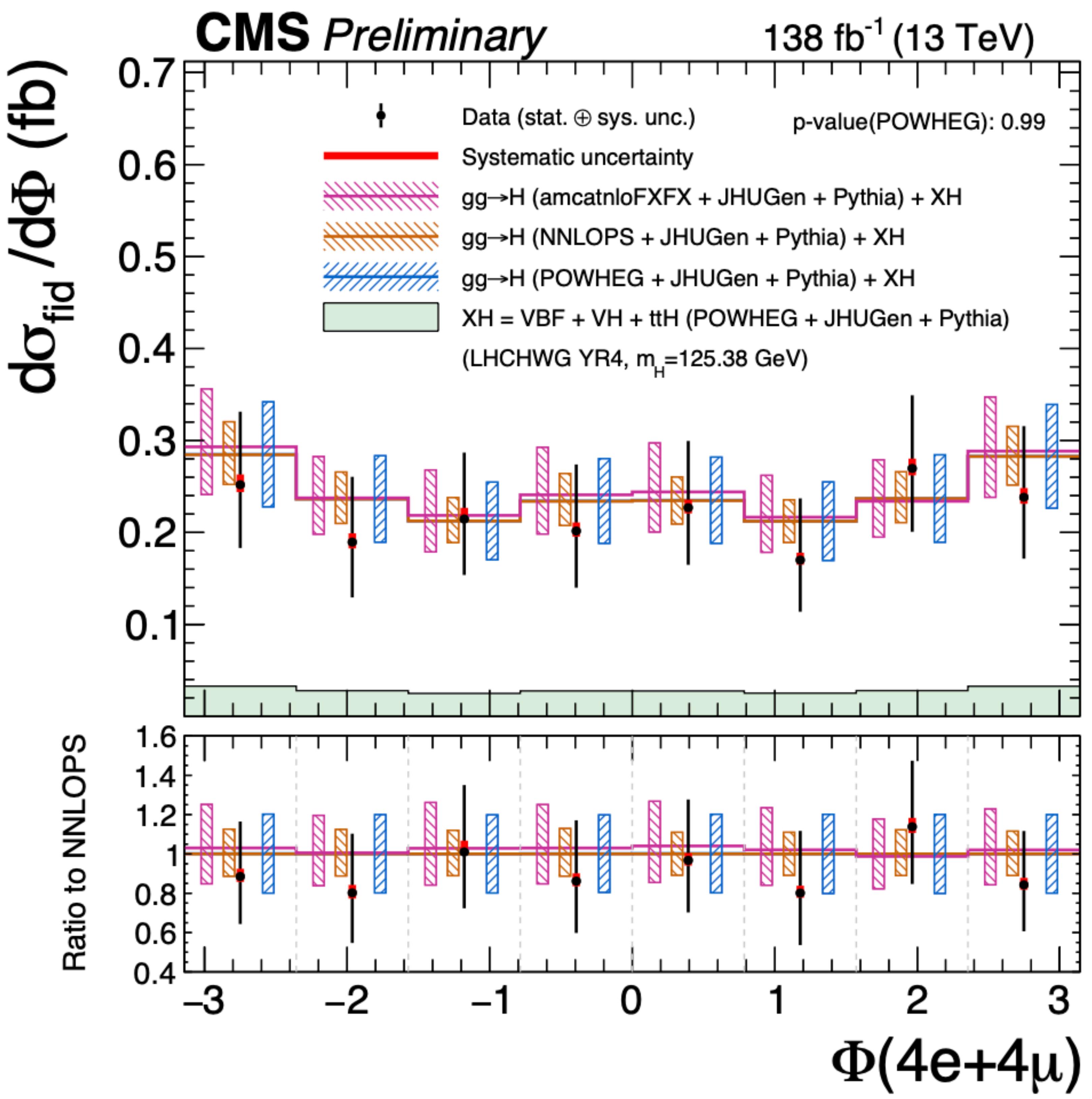








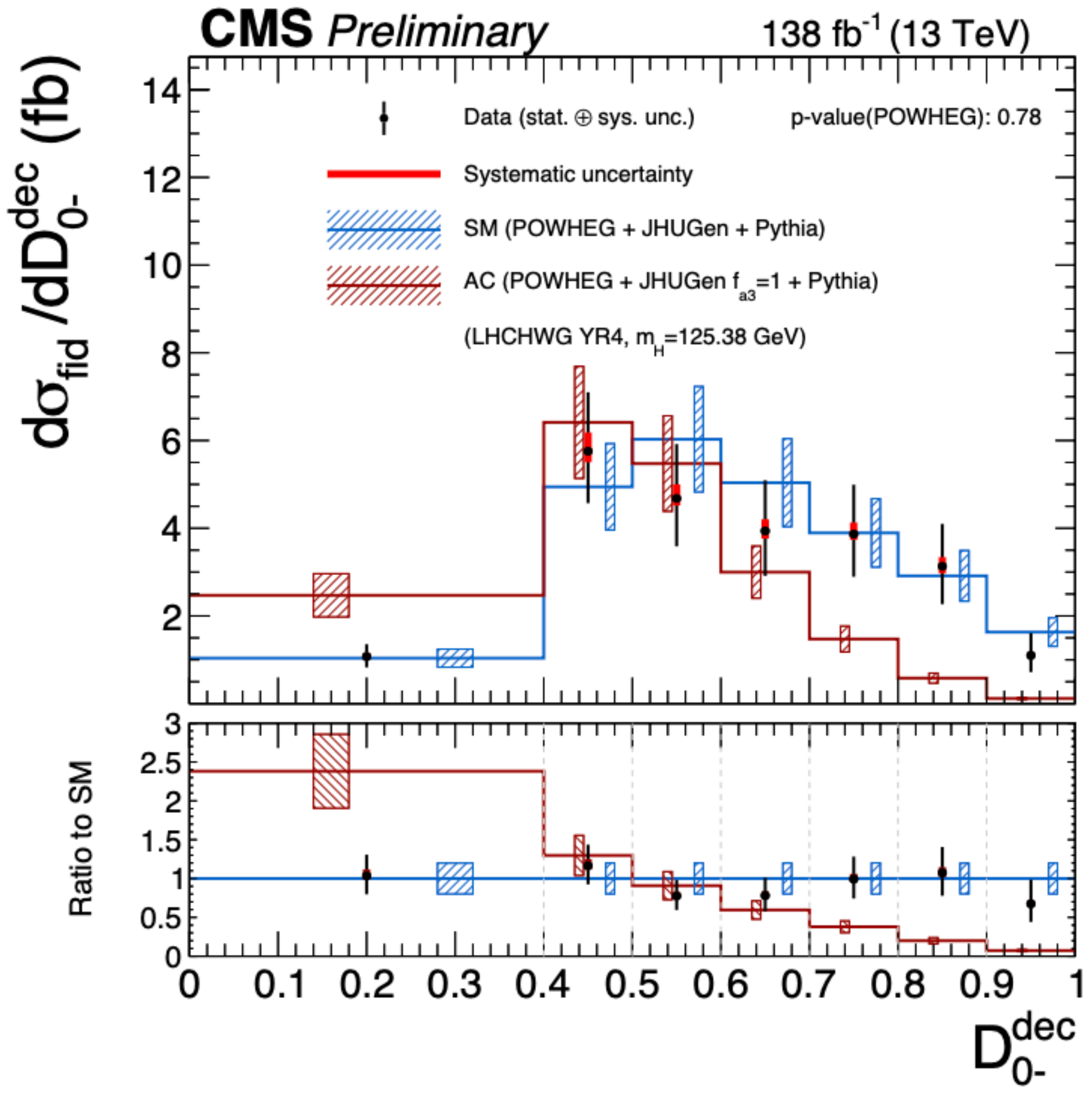
Results: Differential- Matrix Elements Discriminants

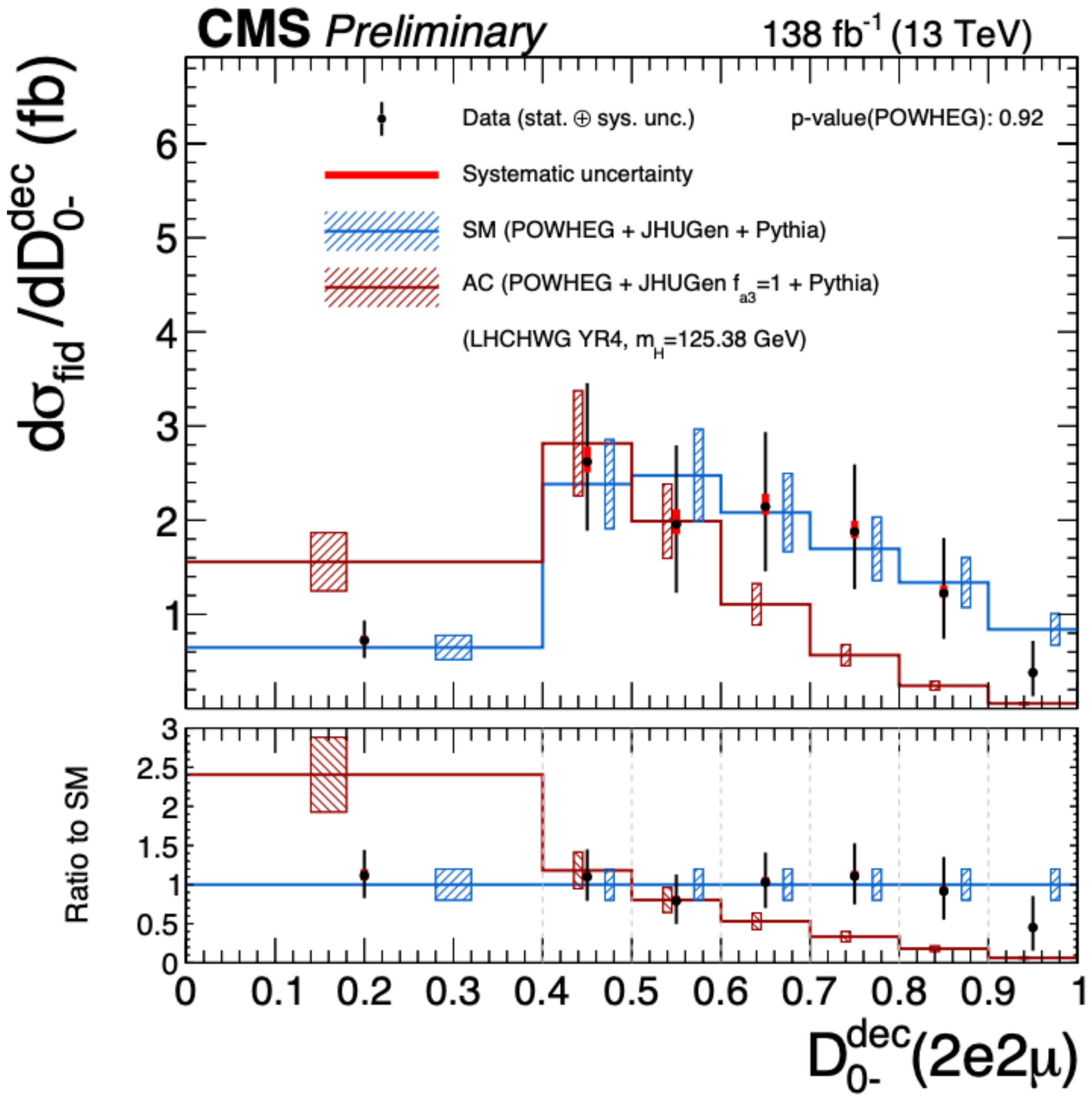
Probe **HZZ vertex** via **Matrix-Element discriminants** sensitive to BSM physics

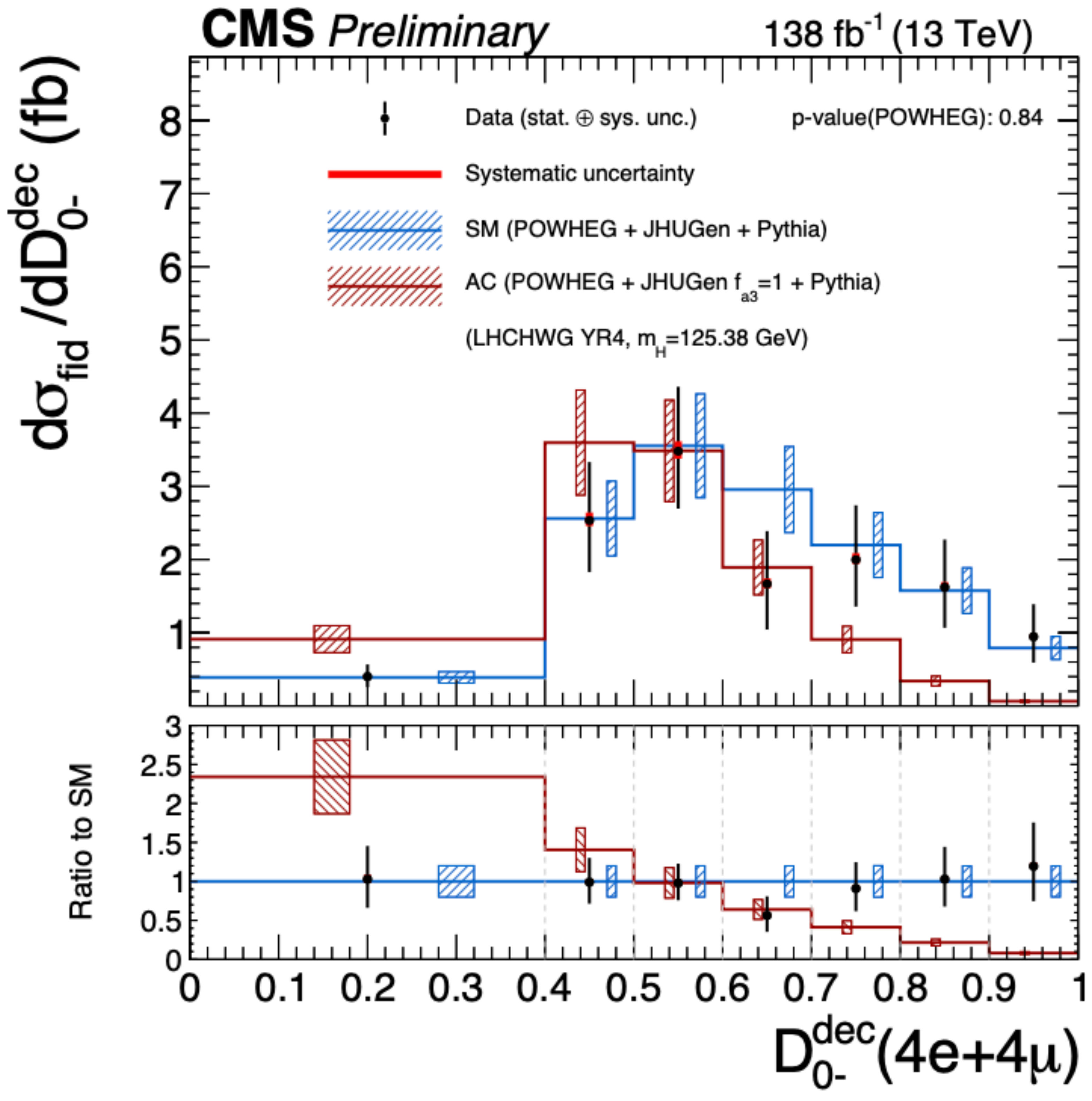
$$A(HV_1V_2) = \frac{1}{v}\left\{ M_{V_1}^2 \left(\boxed{g_1^{VV}} + \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{\left(\Lambda_1^{VV}\right)^2} + \frac{\kappa_3^{VV}(q_1+q_2)^2}{\left(\Lambda_Q^{VV}\right)^2} + \frac{2 q_1 \cdot q_2}{M_{V_1}^2} g_2^{VV} \right)(\varepsilon_1 \cdot \varepsilon_2)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

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

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	$\mathscr{D}_{CP}^{dec}$	$\mathscr{D}_{int}^{dec}$	-	-







Inclusive fiducial cross section

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$|y_H|$ vs p_T^H p_T^{j1} vs p_T^{j2}

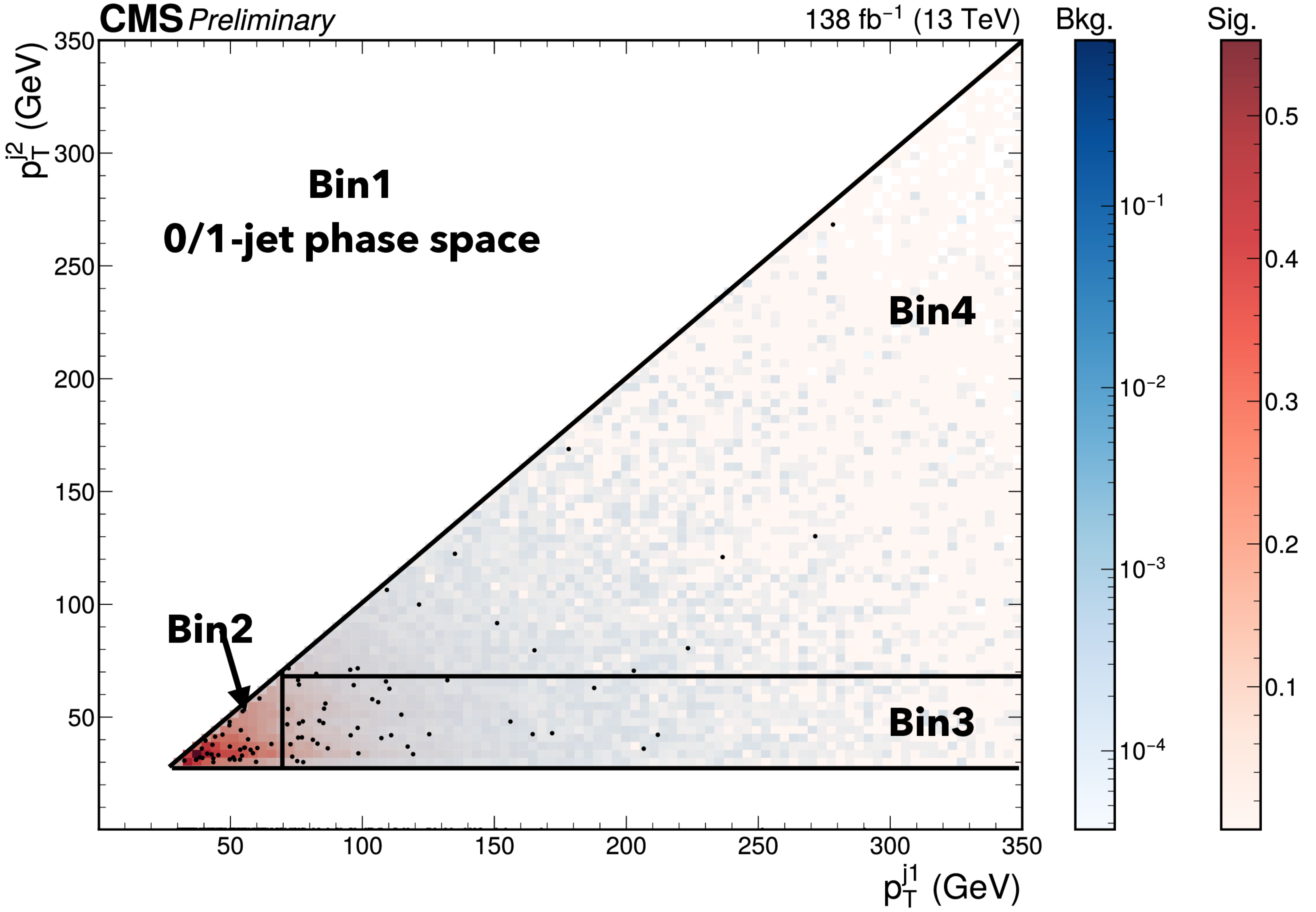
Interpretations

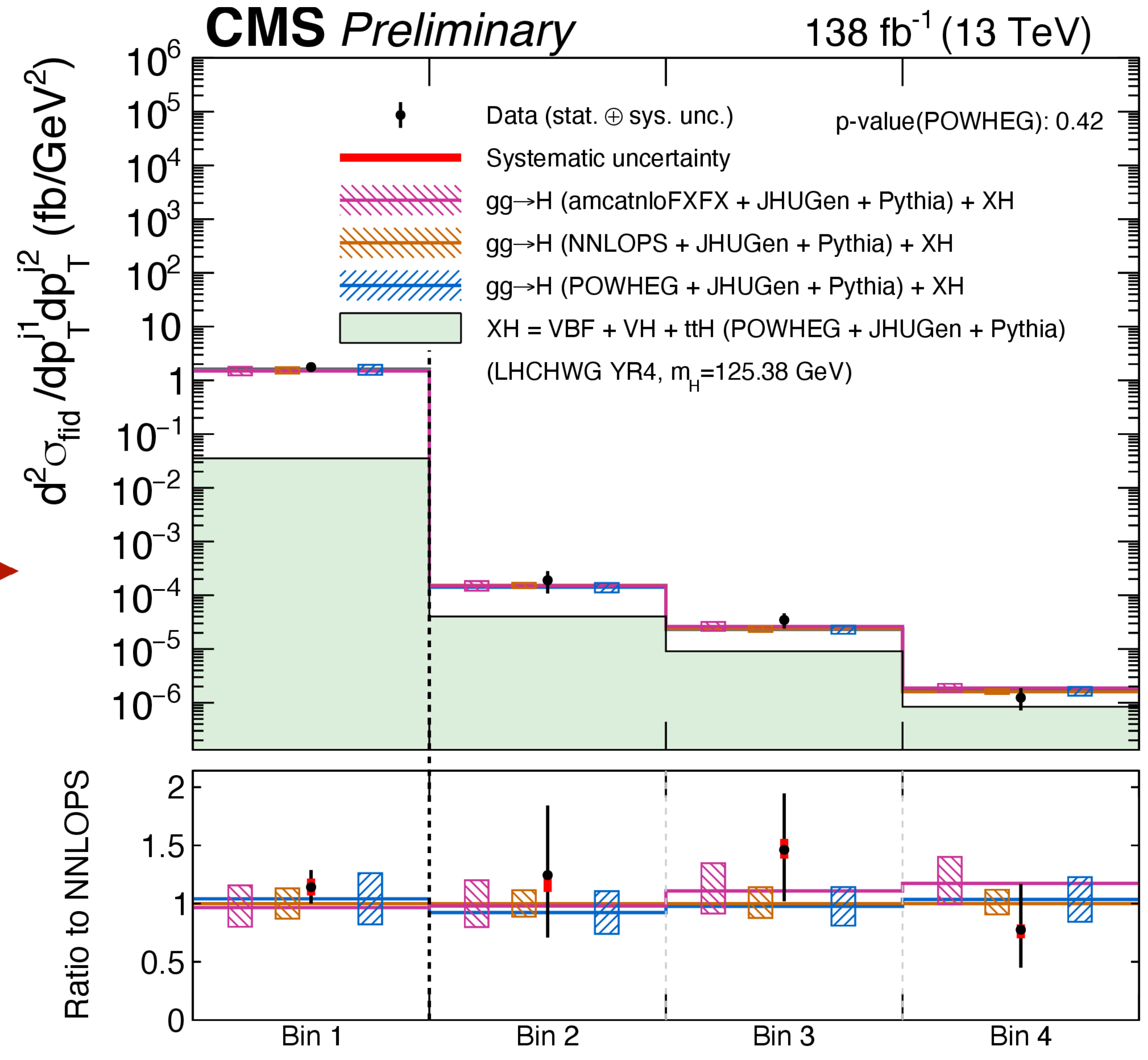
k_λ, k_c, k_b

Results: Differential- Decay observables

An extensive set of **double** differential observables to probe specific phase space regions

(i) τ_C^{max} vs p_T^H (ii) m_{Z1} vs m_{Z2} (iii) N_{jet} vs p_T^H (iv) p_T^H vs p_T^{Hj} (v) $|y_H|$ vs p_T^H (vi) **p_T^{j1} vs p_T^{j2}**





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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}

N_{jet} vs p_T^H p_T^H vs p_T^{Hj}

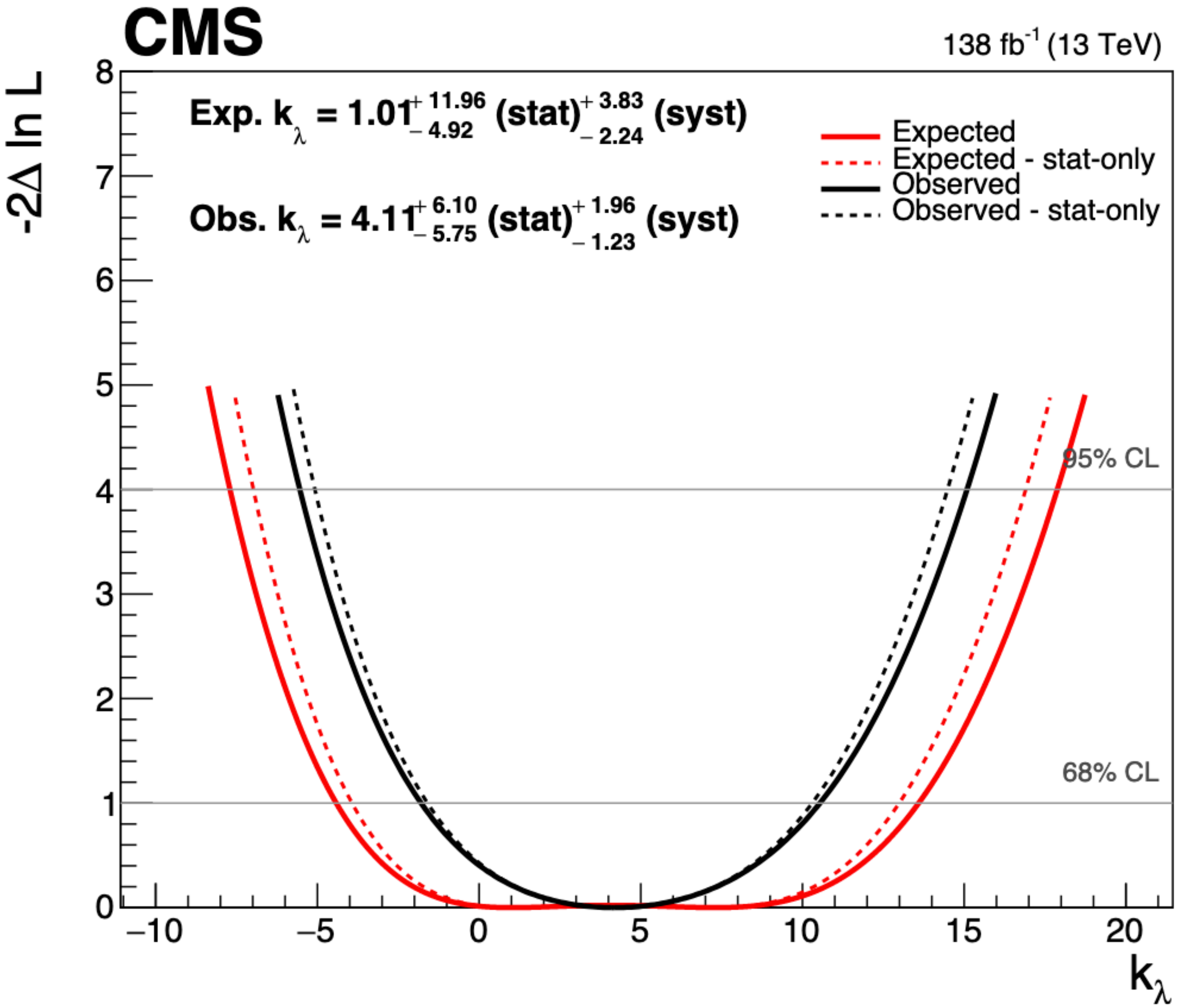
$|y_H|$ vs p_T^H p_T^{j1} vs p_T^{j2}

Interpretations

k_λ, k_c, k_b

Results: Higgs boson self-coupling κ_λ

The **transverse momentum** is used to set constraint on κ_λ since it is the most sensitive observable to probe the H boson self-coupling via single Higgs production that is sensitive to κ_λ at NLO EW



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

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

Differential theoretical predictions are available for VBF, VH, and ttH; the inclusive parametrisation is used for ggH

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

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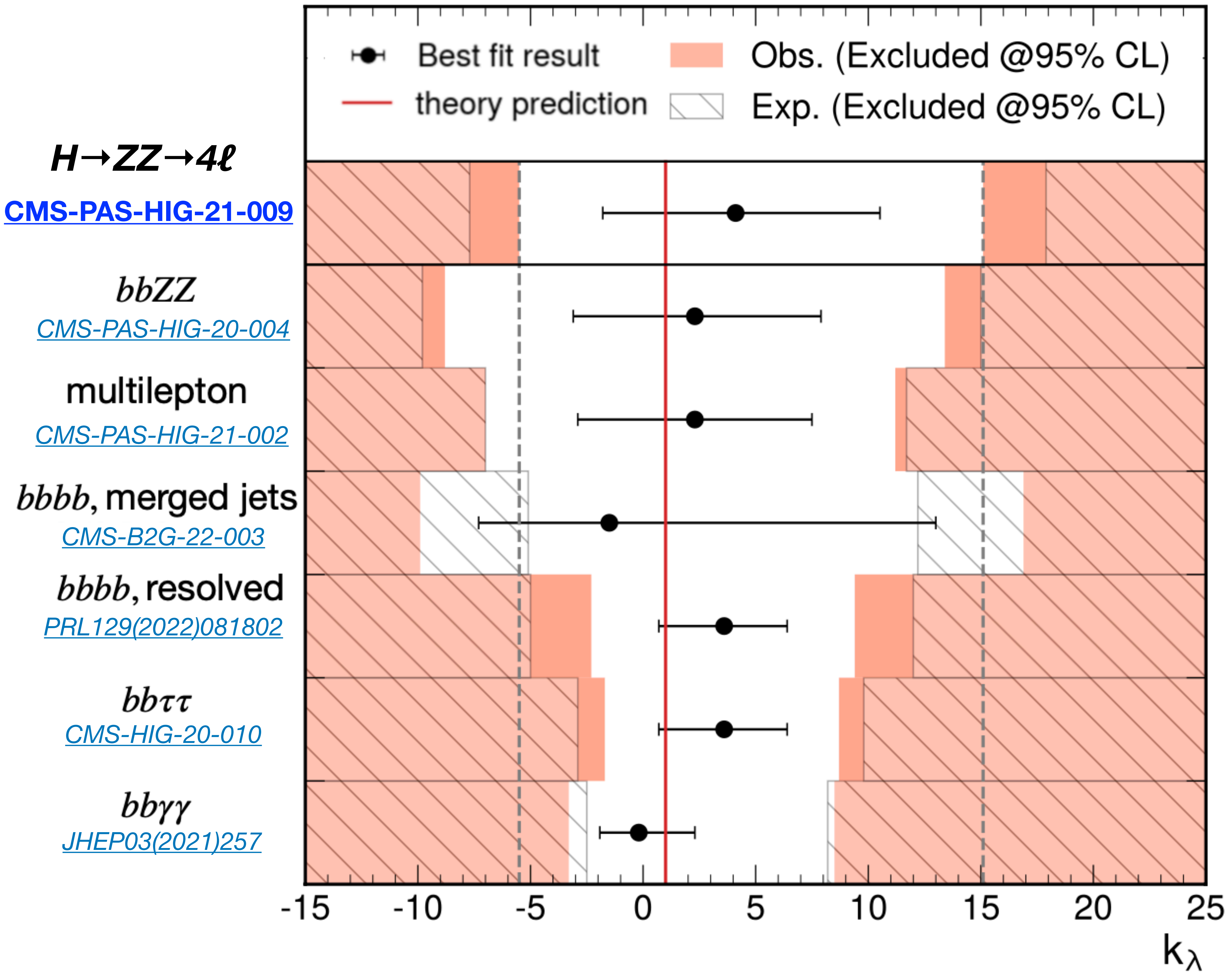

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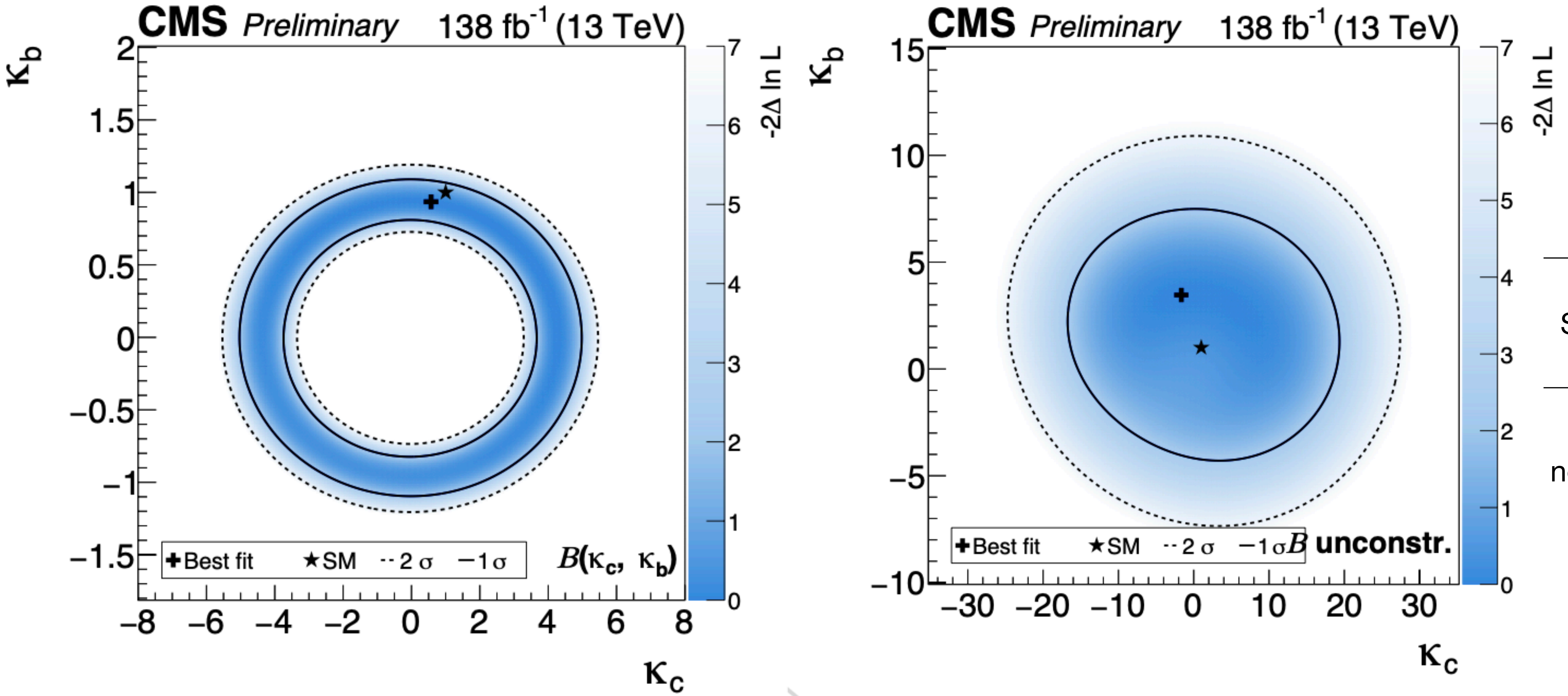
First time the result is presented in a **fiducial** analysis of **single-Higgs** production

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

Results: Higgs boson coupling to b/c quarks (κ_b, κ_c)

Previously at 35.9 fb^{-1}
Phys.Lett.B 792 (2019) 369-396

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



		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]
Shape+ normalization	k_b	[-1.1, 1.1]	[-1.3, 1.2]
	k_c	[-5.3, 5.2]	[-5.7, 5.7]

- ✳Simultaneous fit for coupling modifier k_b, k_c assuming (strongly depending on the *assumption* of the branching ratios)
  - ◉(left) coupling dependence of the branching fractions (*shape+normalization*)
  - ◉(right)branching fractions implemented as nuisance parameters with no prior constraint (*shape-only*)
- ✳Observed and expected 95% confidence intervals for the Yukawa coupling modifiers

Summary

✳ 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)

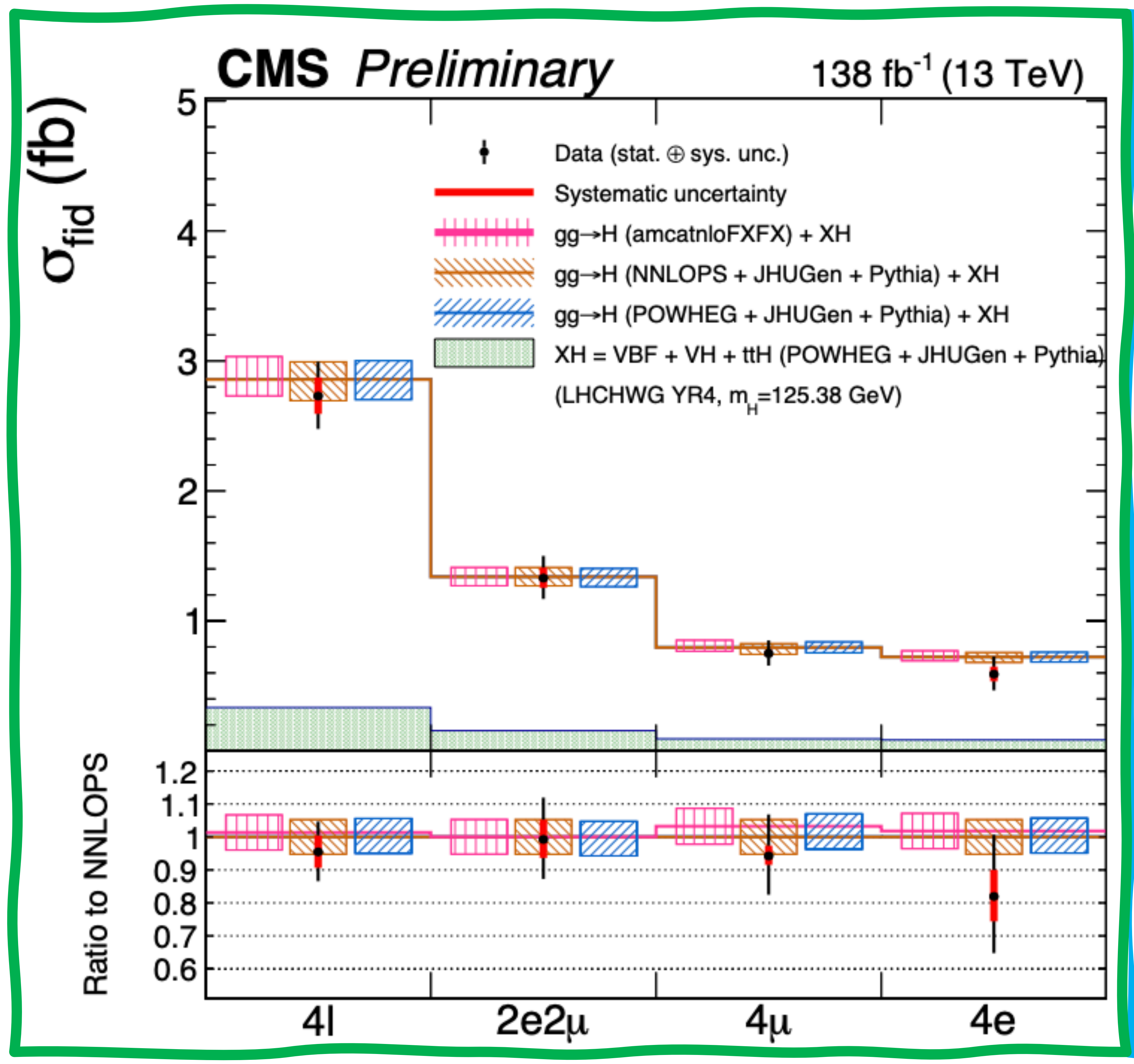
✳ **Better CMS objects calibration** and **improvements in the analysis strategy** led to very **precise measurements** (less than 10% inclusively)

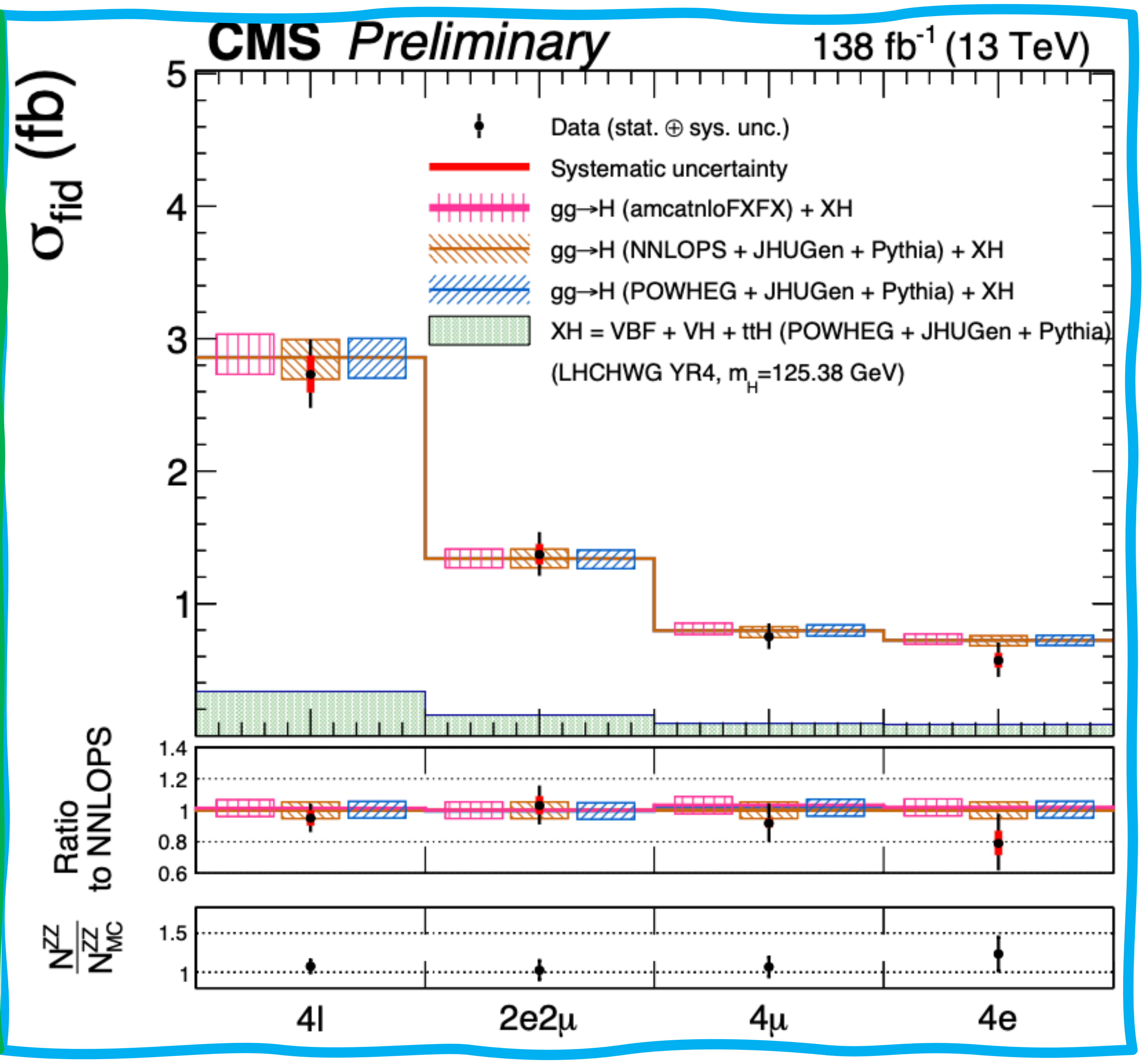
✳ We are on the verge of probing the scalar sector with very high precision


Thank
you

BACKUP SLIDES

Inclusive cross section measurement comparison





✳ Measured inclusive fiducial cross section of two methods

$$\sigma^{fid} = 2.73^{+0.22}_{-0.22}(\text{stat})^{+0.15}_{-0.14}(\text{sys})\,\text{fb}$$

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

✳The measured inclusive fiducial cross section of

- ◉ (left) *Different final states* with the irreducible background normalization taken from MC simulation
- ◉ (right) *Different final states* with the irreducible backgrounds normalization ZZ floating in the fit
  - Bottom panel shows ration between measured ZZ normalization and prediction from MC.

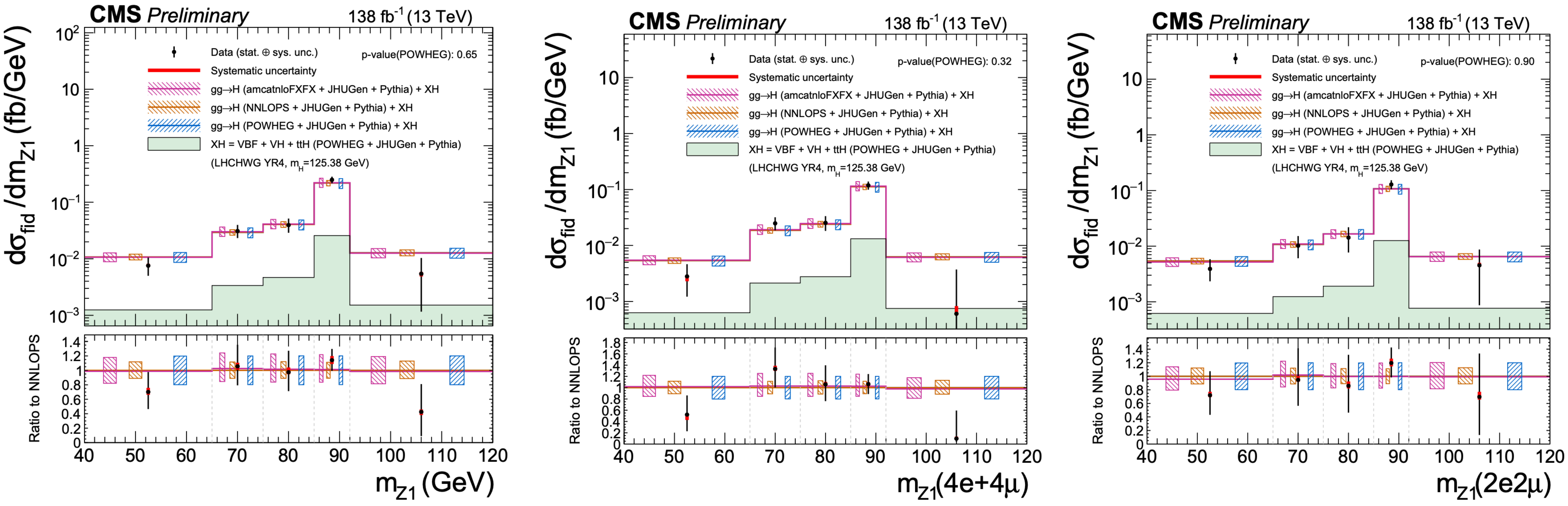
Results of 1D Differential Cross Section

✳ Differential cross sections for observables of **Higgs boson and jet system**

✳ The acceptance and theoretical uncertainties in the differential bins are calculated using the POWHEG (blue), NNLOPS (orange), and MadGraph aMC@NLO (pink) generators.

✳ The sub-dominant component of the the signal (VBF + VH + ttH) is denoted as XH.

Results of 1D Differential Cross Section

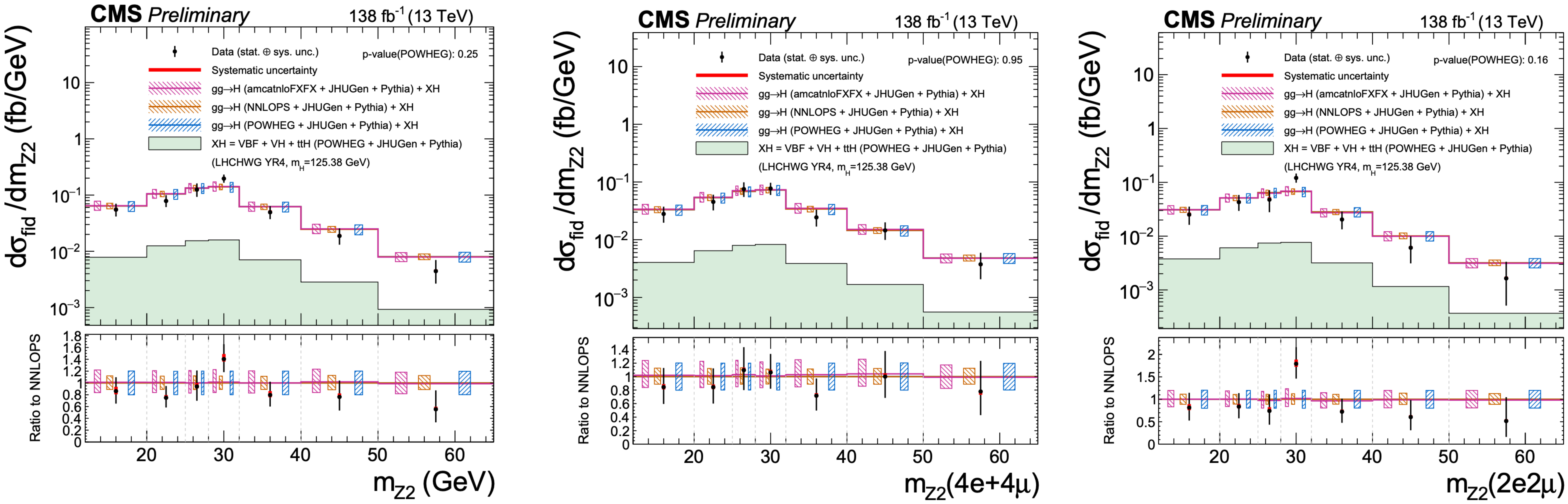


✳ Differential cross section as function of $\mathbf{m_{Z1}}$

✳ The acceptance and theoretical uncertainties in the differential bins are calculated using the POWHEG (blue), NNLOPS (orange), and MadGraph aMC@NLO (pink) generators.

✳ The sub-dominant component of the the signal (VBF + VH + ttH) is denoted as XH.

Results of 1D Differential Cross Section

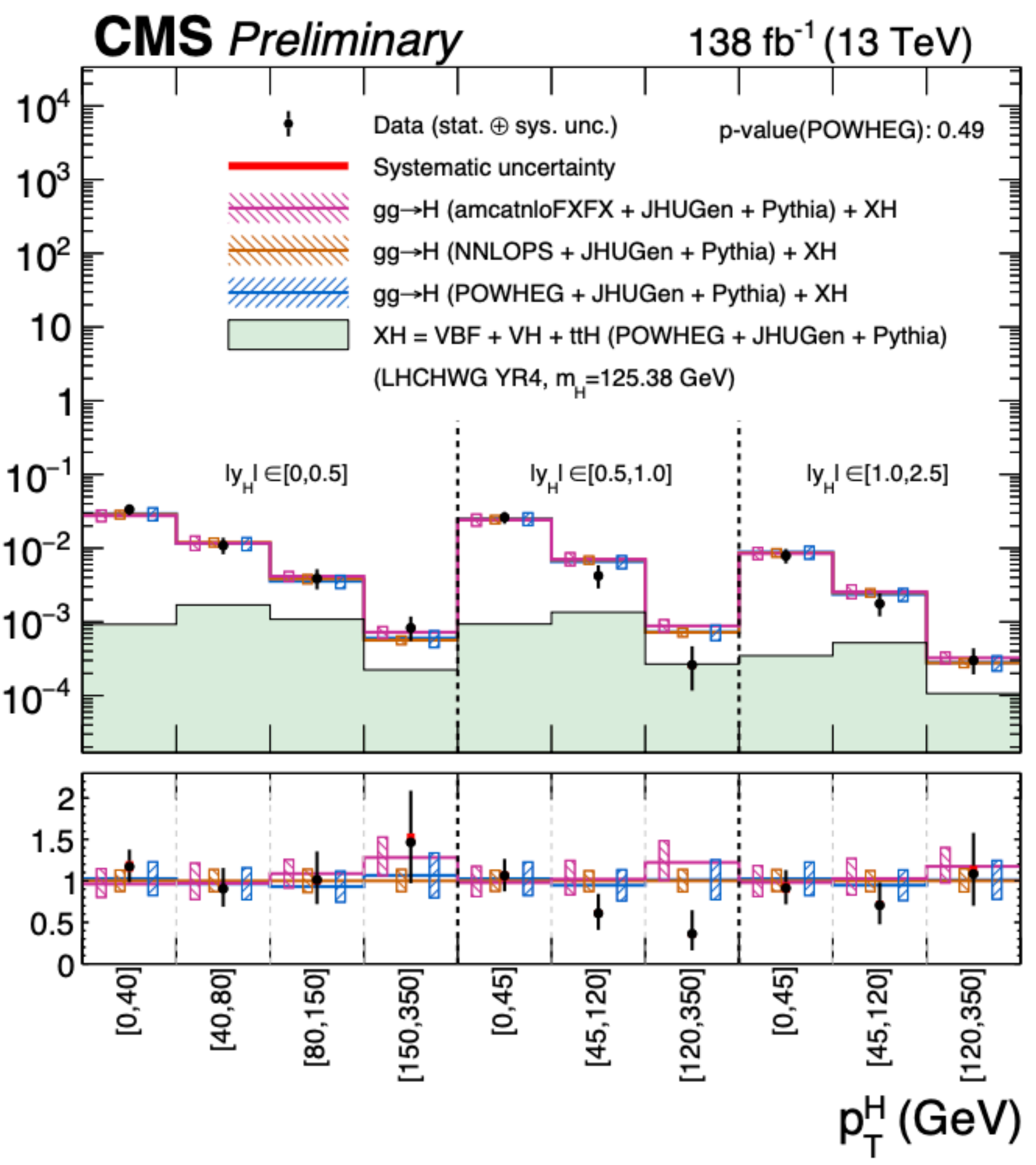


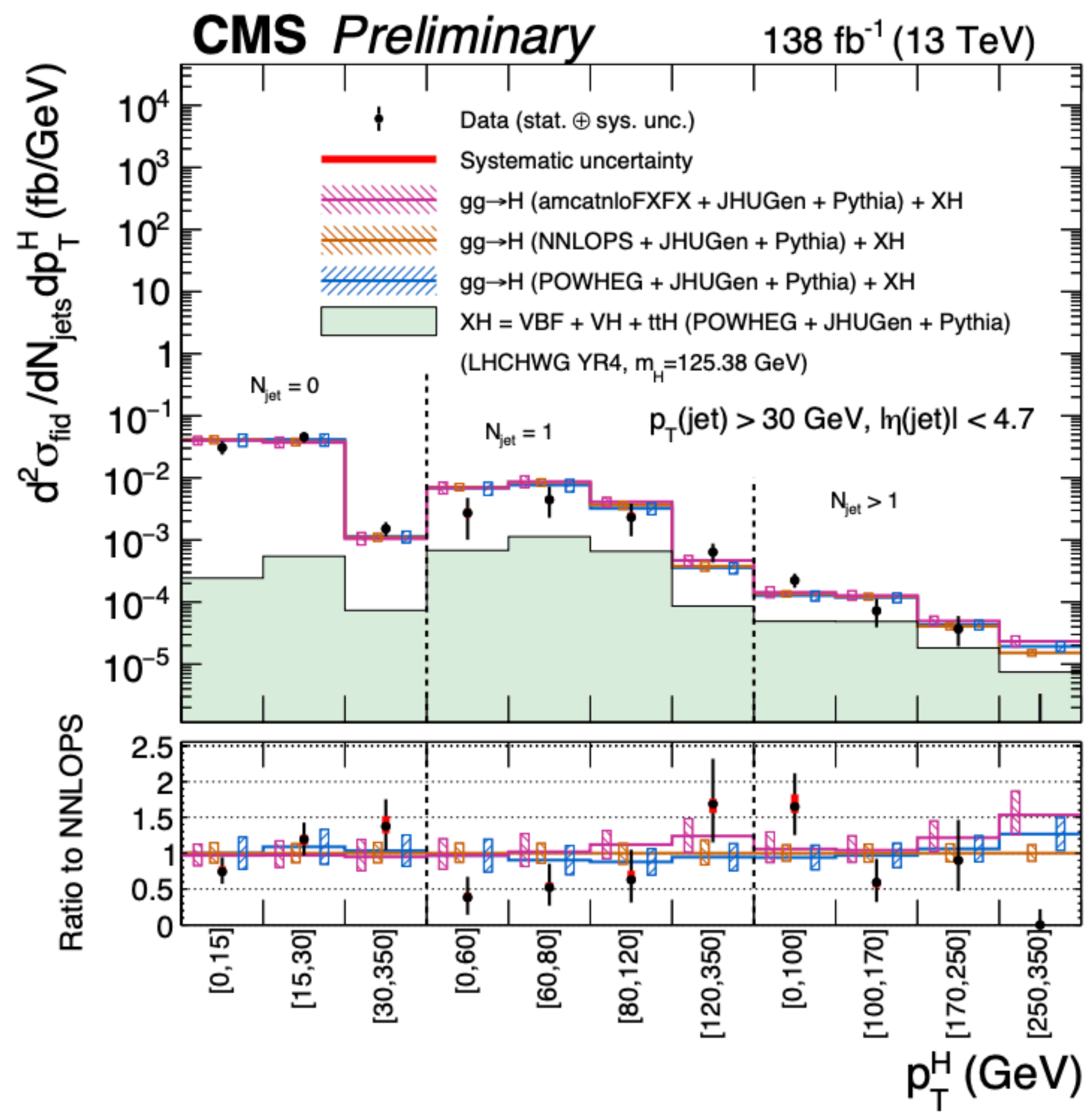
✳ Differential cross section as function of **m_{Z2}**

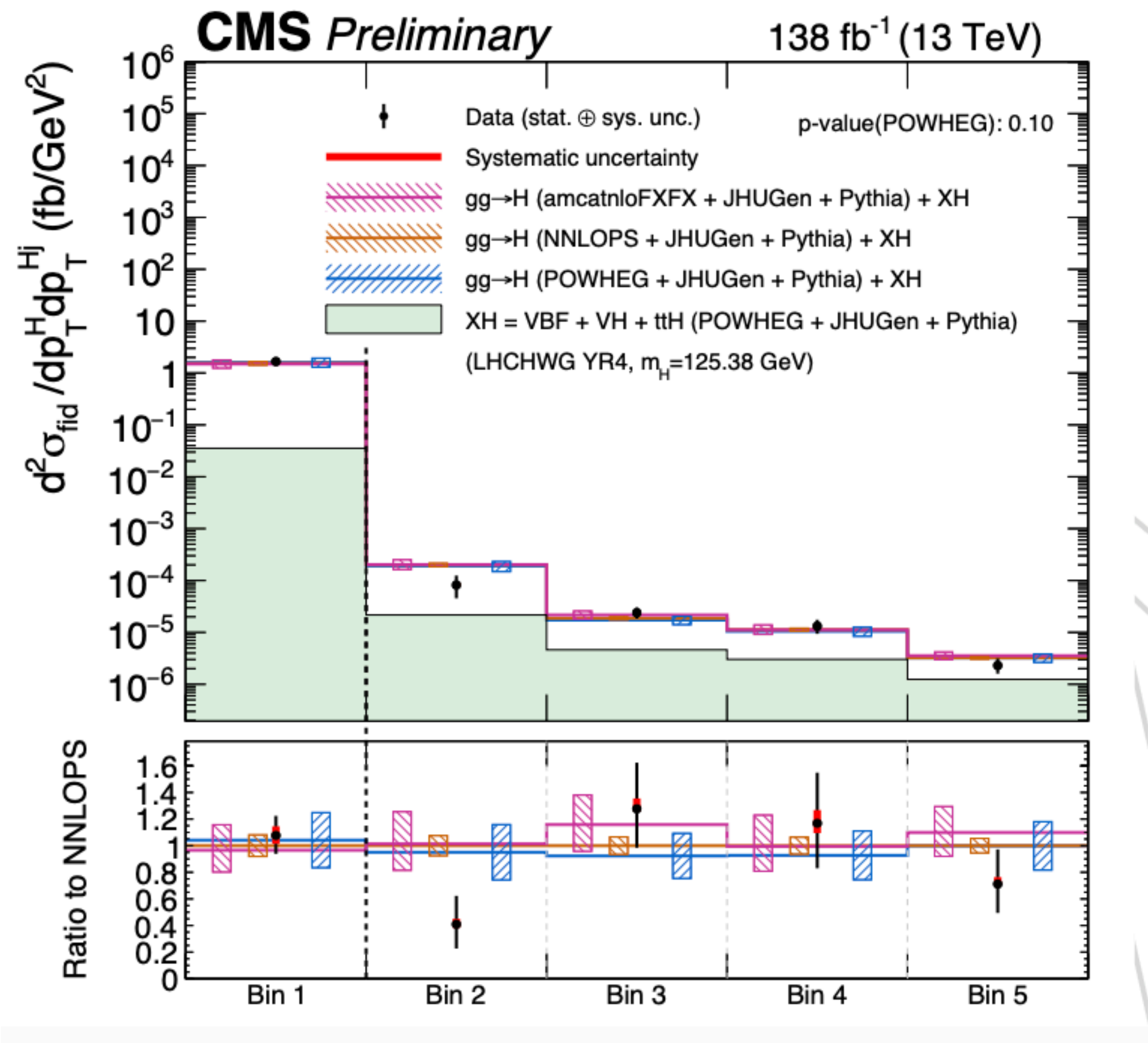
✳ The acceptance and theoretical uncertainties in the differential bins are calculated using the POWHEG (blue), NNLOPS (orange), and MadGraph aMC@NLO (pink) generators.

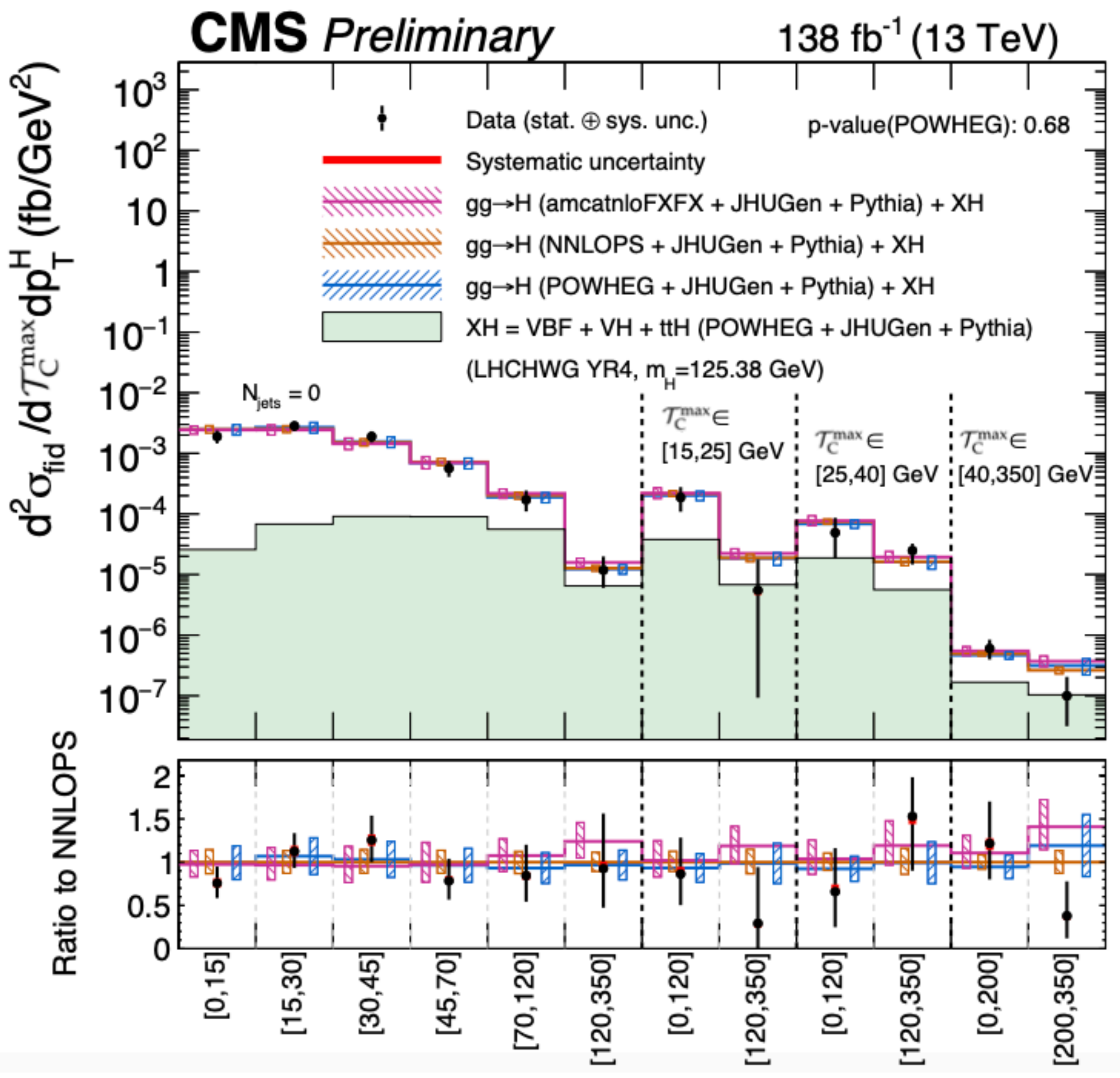
✳ The sub-dominant component of the the signal (VBF + VH + ttH) is denoted as XH.

Results of 2D Differential Cross Section measurements









- ✳ Double Differential cross sections results
- ✳ The acceptance and theoretical uncertainties in the differential bins are calculated using the POWHEG (blue), NNLOPS (orange), and MadGraph aMC@NLO (pink) generators.
- ✳ The sub-dominant component of the the signal (VBF + VH + ttH) is denoted as XH.

Matrix Element Discriminants

✳HVV scattering amplitude of a spin-0 boson H and two spin-one gauge bosons

$$A(HV_1V_2) = \frac{1}{v}\left[\boxed{a_1^{VV}} + \frac{k_1^{VV} q_{V1}^2 + k_2^{VV} q_{V2}^2}{(\Lambda_1^{VV})^2} + \frac{k_3^{VV}(q_{V1}+q_{V2})^2}{(\Lambda_Q^{VV})^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + \boxed{a_2^{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \boxed{a_3^{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

CP even
- SM-like spin-zero 0^+: $a_1^{ZZ}=a_1^{WW}=2$
- Higher order spin-zero 0_h^+: a_2

CP odd
- Pseudoscalar spin-zero 0^- : a3

✳Observables sensitive to HVV anomalous couplings using kinematics of leptons in decay

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

✳Six discriminants implemented in the MELA package to completely characterize the HZZ4l decay

	$\mathcal{D}_{\text{alt}}$				$\mathcal{D}_{\text{int}}$	
	Coupling					
	a_3	a_2	κ_1	$\kappa_2^{Z,\gamma}$	a_3	a_2
Discriminant	$\mathcal{D}_{0-}$	$\mathcal{D}_{0h+}$	$\mathcal{D}_{\Lambda 1}$	$\mathcal{D}_{\Lambda 1}^{Z,\gamma}$	$\mathcal{D}_{CP}$	$\mathcal{D}_{\text{int}}$

Interpretations -- Constraints on the H boson self-coupling

Probing k_λ via single-Higgs decay

✳ Differential XS measurement as a function of p_T^H ⇨ extract limits on H boson self coupling.

$$\mu_i^f = \mu_i \times \mu^f = \frac{\sigma^{NLO}}{\sigma_{SM}^{NLO}} \frac{BR(H \to ZZ)}{BR^{SM}(H \to ZZ)} = \underbrace{\frac{1 + k_\lambda C_{1,i} + \delta Z_H}{(1 - (k_\lambda^2 - 1)\delta Z_H)(1 + C_{1,i} + \delta Z_H)}}_{\text{production}} \times \underbrace{\left[1 + \frac{(k_\lambda - 1)(C_1^{\Gamma_{ZZ}} - C_1^{\Gamma_{tot}})}{1 + (k_\lambda - 1)C_1^{\Gamma_{tot}}}\right]}_{\text{decay}}$$

✳ The cross sections of the different production mechanisms of the H boson

- Parameterized as a function of $k_\lambda = \lambda_3 / \lambda_{SM}$,
- To account for NLO terms arising from the H boson trilinear self-coupling
- Where $\delta Z_H = -1.536 \times 10^{-3}$ is a universal quantity, $C_1(p_n)$ is dependent on H production model and kinematics;
- $C_1^{\Gamma_{ZZ}} = 0.0082$ and $C_1^{\Gamma_{tot}} = 2.5 \times 10^{-3}$

Constraints on H boson self-coupling -- C1 coefficients

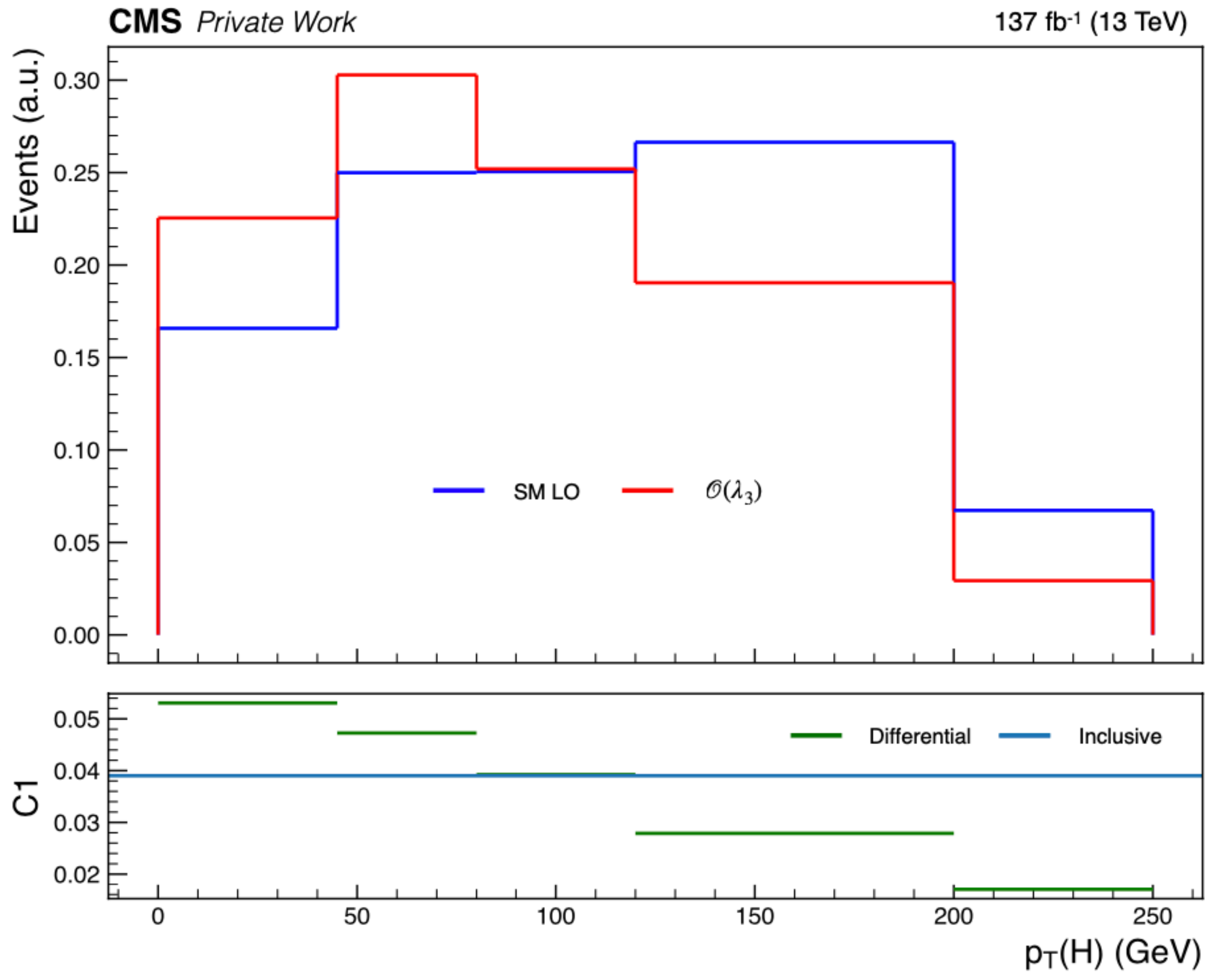
- ✳ In order to compute the scaling functions, $\mu_{i,j}(k_\lambda)$
  - ◉ Madgraph5 dedicated hhh-model and reweight tool
  - ◉ Generate LO events for each production models
  - ◉ Reweigh to take into account NLO EW corrections
    - Extracted on an event-by-event basis:

$$C_1 = xsec_{\mathcal{O}(\lambda_3)}/xsec_{LO}$$

    - As input for $\mu_{i,j}(k_\lambda)$

$$\mu_i^f = \frac{1 + k_\lambda C_{1,i} + \delta Z_H}{(1 - (k_\lambda^2 - 1)\delta Z_H)(1 + C_{1,i} + \delta Z_H)} \times \left[1 + \frac{(k_\lambda - 1)(C_1^{\Gamma^{ZZ}} - C_1^{\Gamma^{tot}})}{1 + (k_\lambda - 1)C_1^{\Gamma^{tot}}}\right]$$

    - Differential predictions are available only for VBF, VH, and ttH
    - Inclusive value for the parametrization of the H boson cross section for ggH process

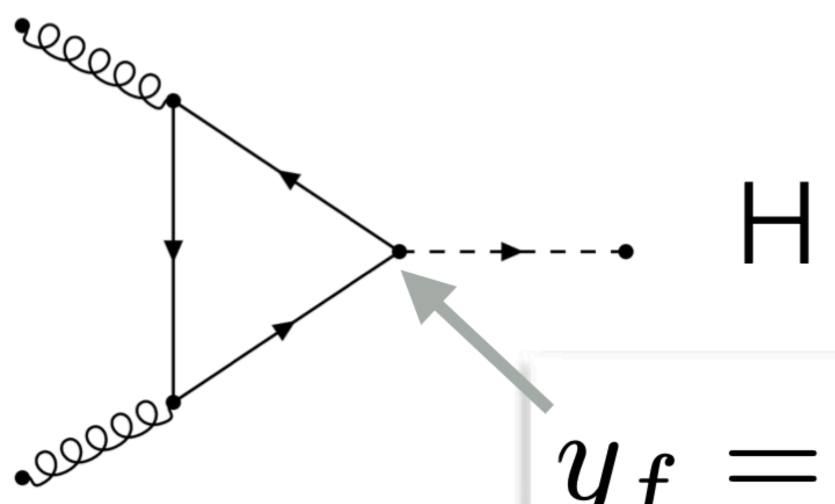


Constraints on Higgs boson couplings modifier

✳ The **transverse momentum spectrum of Higgs boson**

- ◉ provides a novel approach to constrain the Higgs boson couplings to bottom, and charm quarks.

✳ The coupling modifiers are described in the context of the κ-framework.



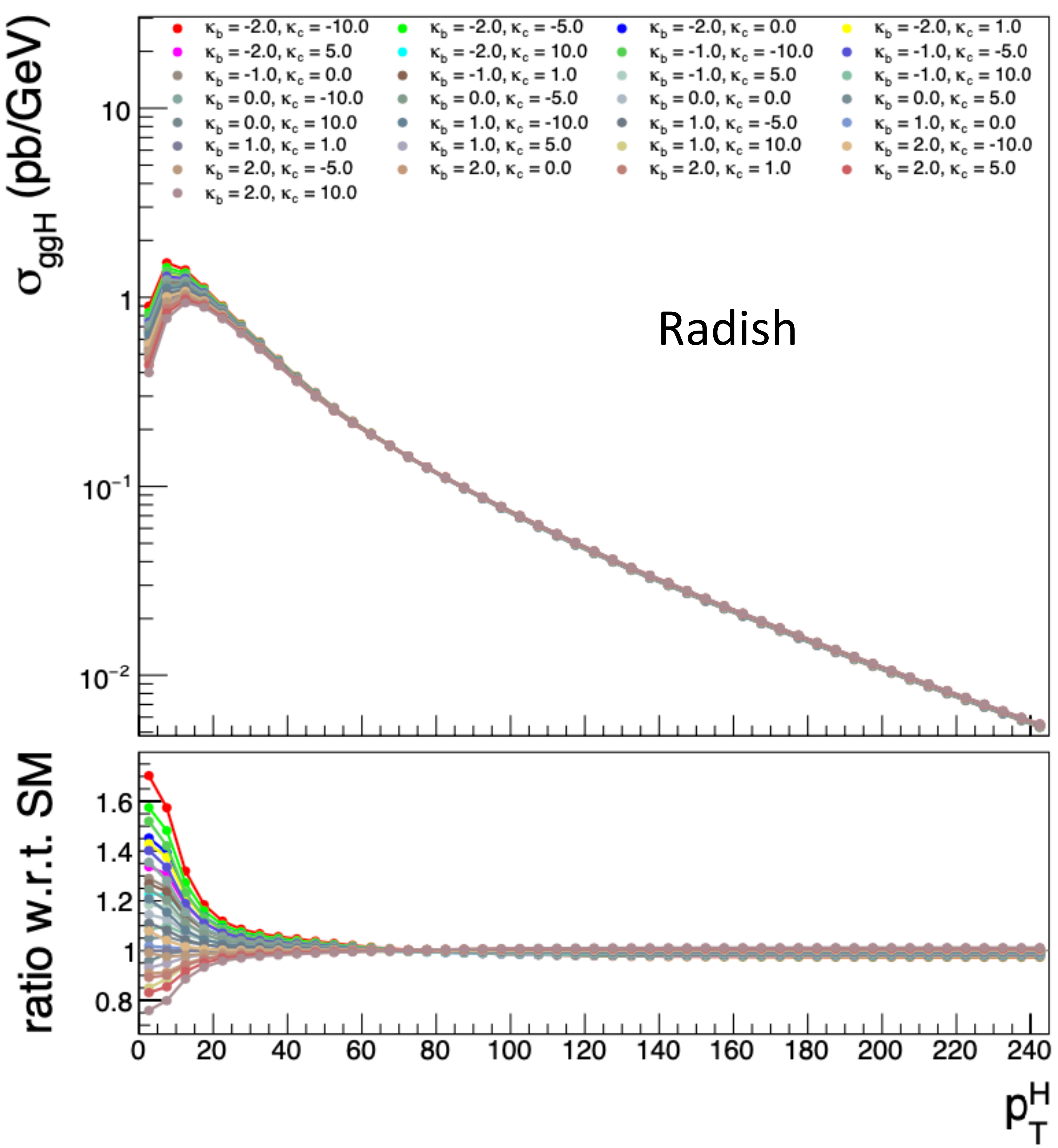
$$y_f = \kappa_f \cdot y_f^{SM}$$

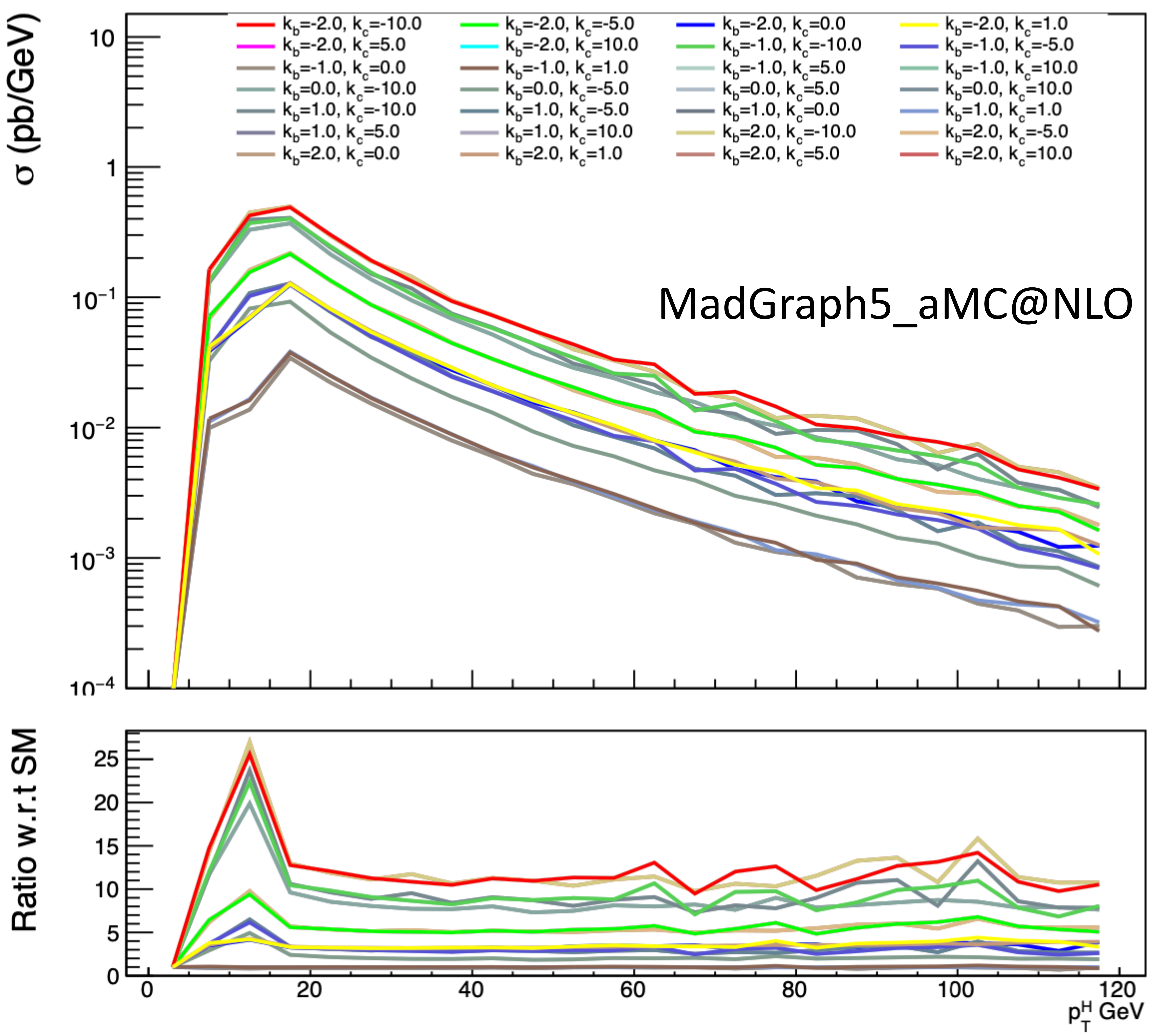
✳ Interpreting the P_H^T spectrum for **gluon fusion** in terms of modifications of the couplings of the Higgs boson of the combination of two models:

- ◉ **Radish:** contributions of b and c quarks to the loop-induced ggF production
  - Sensitive to the low pT region

- ◉ **MadGraph5_aMC@NLO:** the quark-initiated production of the Higgs boson.
  - Sensitive to the High pT region

Interpretation by kappa framework via P_H^T spectrum

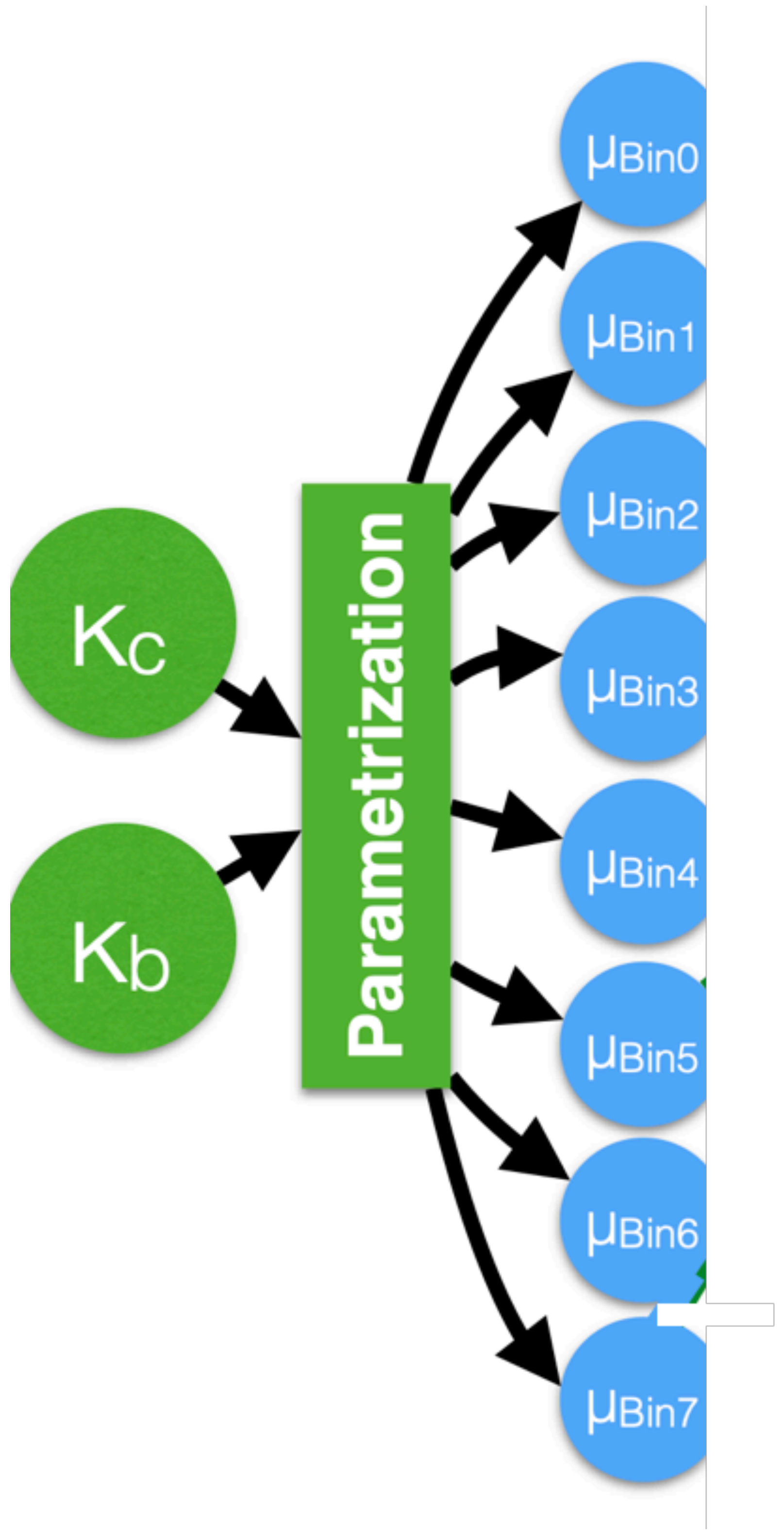




✳The cross section value varies following the P_H^T of different kb, kc parameter values.

✳The high pT region has been improved by newly running with new setting and high statistics of MadGraph5_aMC.

Parameterization of $k_b, \ k_c$



- ✳ Obtain 2D likelihood by varying kc and kb: $\overrightarrow{\Delta\sigma} \rightarrow \overrightarrow{\Delta\sigma}\ (k_b, k_c)$
- ✳ Signal model split into ggH and xH processes and the contributions from xH (not ggH) are set to SM
- ✳ We assume a parabolic function for the cross section
- ✳ $$\sigma_{ggH} = \left| \sum_i A_i k_i \right|^2 = Ak_b^2 + Bk_c^2 + Ck_t^2 + Dk_b k_c + Ek_b k_t + Fk_c k_t$$
- ✳ Find the cross section for any set of the *k*'s if we know the coefficients A, …, F
- ✳ Use 6 known points: $\sigma_1(\overrightarrow{k_1})\sigma_6(\overrightarrow{k_6})\ ,\sigma_5(\overrightarrow{k_5})\ ,\sigma_4(\overrightarrow{k_4})\ ,\sigma_3(\overrightarrow{k_3})\ ,\sigma_2(\overrightarrow{k_2})$,
- ✳ Find values of the coefficients by simple matrix inversion
- ✳ k_t set to 1.0 (SM) for the $k_b, \ k_c$ analysis

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} = \begin{bmatrix} \kappa_{b,1}^2 & \kappa_{c,1}^2 & \kappa_{t,1}^2 & \kappa_{b,1}\kappa_{c,1} & \kappa_{b,1}\kappa_{t,1} & \kappa_{c,1}\kappa_{t,1} \\ \kappa_{b,2}^2 & \kappa_{c,2}^2 & \kappa_{t,2}^2 & \kappa_{b,2}\kappa_{c,2} & \kappa_{b,2}\kappa_{t,2} & \kappa_{c,2}\kappa_{t,2} \\ \kappa_{b,3}^2 & \kappa_{c,3}^2 & \kappa_{t,3}^2 & \kappa_{b,3}\kappa_{c,3} & \kappa_{b,3}\kappa_{t,3} & \kappa_{c,3}\kappa_{t,3} \\ \kappa_{b,4}^2 & \kappa_{c,4}^2 & \kappa_{t,4}^2 & \kappa_{b,4}\kappa_{c,4} & \kappa_{b,4}\kappa_{t,4} & \kappa_{c,4}\kappa_{t,4} \\ \kappa_{b,5}^2 & \kappa_{c,5}^2 & \kappa_{t,5}^2 & \kappa_{b,5}\kappa_{c,5} & \kappa_{b,5}\kappa_{t,5} & \kappa_{c,5}\kappa_{t,5} \\ \kappa_{b,6}^2 & \kappa_{c,6}^2 & \kappa_{t,6}^2 & \kappa_{b,6}\kappa_{c,6} & \kappa_{b,6}\kappa_{t,6} & \kappa_{c,6}\kappa_{t,6} \end{bmatrix} \begin{bmatrix} A \\ B \\ C \\ D \\ E \\ F \end{bmatrix}$$

Statistical analysis of $k_b,\ k_c$

✳ An extended likelihood function is reconstructed by

$$\mathscr{L}(\overrightarrow{\Delta\sigma}\,|\,\vec{\theta}) = \prod_{i=1}^{n_{bins}^{reco}}\prod_{k=1}^{n_{cat}}\prod_{l=1}^{n_{\mathcal{O}}}(pdf_i^k(\mathcal{O}_l\,|\,\overrightarrow{\Delta\sigma},\vec{\theta}))^{N_{obs}^{ikl}} \times Poisson(N_{obs}^{ik}\,|\,n_i^{sig,k}(\overrightarrow{\Delta\sigma}\,|\,\vec{\theta}) + n_i^{bkg,k}(\vec{\theta})) \times pdf(\vec{\theta})$$

✳ n_{bins}^{reco} is the number of reconstructed bins, n_{cat} is the number of categories for the decay channel, and $n_{\mathcal{O}}$ is the number of bins for observable $\mathcal{O}$.

✳ $pdf_i^k\left(\mathcal{O}_l\,|\,\overrightarrow{\Delta\sigma},\vec{\theta}\right)$ describes the probability to find an event measuring observable $\mathcal{O}$ in reconstructed bin i.

✳ An overall probability distribution function for the observable $\mathcal{O}$ is constructed by summation of the signal and background distributions of the observable.

✳ In the case of fitting k’s, parameter cross section in terms of k’s

✳ $\overrightarrow{\Delta\sigma} \rightarrow \overrightarrow{\Delta\sigma}\,(k_b, k_c)$

Two methods applied in the constrain of $k_b\ k_c$

✴ The obtained results vary strongly depending on the assumption of the branching ratios.

✴ The **overall discrimination** power is from both the **shape and normalization** of the theory coupling variations.

✴ ***The branching ratios depend on the couplings***

- Results obtained this way show the maximum amount of discrimination power including the Impact on the overall expected normalization, through modifications of **branching ratios** scaled with coupling modifications and also the constrain by the **Higgs decay width**.

✴ ***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**.

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)