ATLAS and CMS Differential Higgs measurements

Fábio Lucio Alves (Nanjing University)
on behalf of the ATLAS and CMS Collaborations

SM@LHC 2021 Standard Model at the LHC 2021

Motivation

- *Differential Fiducial Higgs measurements:*
  - ***Test the SM Higgs boson properties and probe for BSM contributions:***
    - p_T^H, $|y^H|$, N_{jets}, …
    - measured differential cross-sections distributions are compared to state-of-the-art SM predictions
    - ***Measurements methodology and fiducial definition (nicely introduced in Nicolas's slides)***
- ***Presented in this talk:*** $H \rightarrow \gamma\gamma$, $H \rightarrow 4l$, $H \rightarrow W^-W^+$ ***and*** $H \rightarrow b\bar{b}$ ***channels:***
  - ***Differential measurement of observables in CMS and ATLAS***
    - Combination and interpretations of the measurements

Differential observables

A wide spectra of observables based on Higgs boson properties and jet-kinematics activity in the event

Highlighted observables discussed throughout this talk:

$p_T(H)$: *Low pT(H): sensitive to bottom and charm Yukawa couplings*
High pT(H): sensitive to new heavy particle coupling to the Higgs boson and top-quark mass effects

$|y(H)|$: *Sensitive to the gluon distribution in the proton and QCD radiative corrections*

N_{jets}: *Jet multiplicity provides sensitivity to Higgs boson production mechanism and theoretical modelling of high pT quark and gluon emissions*

Double differential observables sensitive to the Higgs properties, production mode and spin-CP properties

Higgs boson kinematics observables

$$p_T(H),\ |y(H)|\ ,\ m_{12}\ ,\ m_{34}\ ,\ |cos\theta^*|\ ,\ cos\theta_1\ ,\ cos\theta_2\ ,\theta,\theta_1$$

Jet-kinematics observables

$$N_{jets},\ N_{b-jets}\ ,\ p_T^{j1}\ ,\ p_T^{j2}\ ,\ m_{jj}\ ,\ |\Delta\eta_{jj}|\ ,\ |\Delta\phi_{jj}|$$

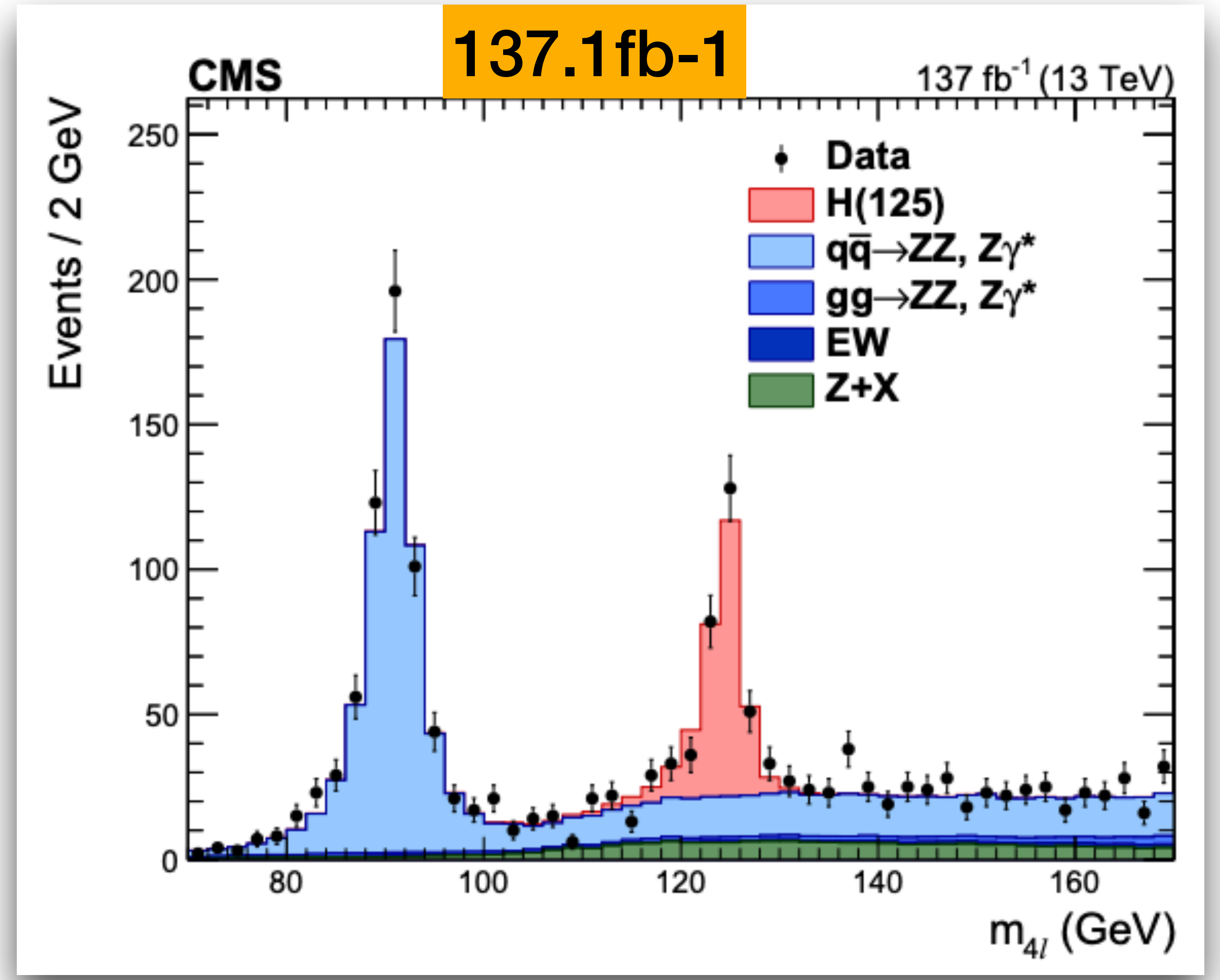
Higgs boson and jet-kinematics observables

$$p_T(H)\ vs\ |y(H)|,\ p_T(H)\ vs\ N_{jets},\ p_T(H)\ vs\ p_T^{j1}\ ,\ p_T(H)\ vs\ p_T^{Hj1}\ ,\ p_T^{Hj1}\ vs\ m_{Hj1}\ ,\ p_T^{j1}\ vs\ p_T^{j2}\ ,\ p_T^{j1}\ vs\ |y^{j1}|$$

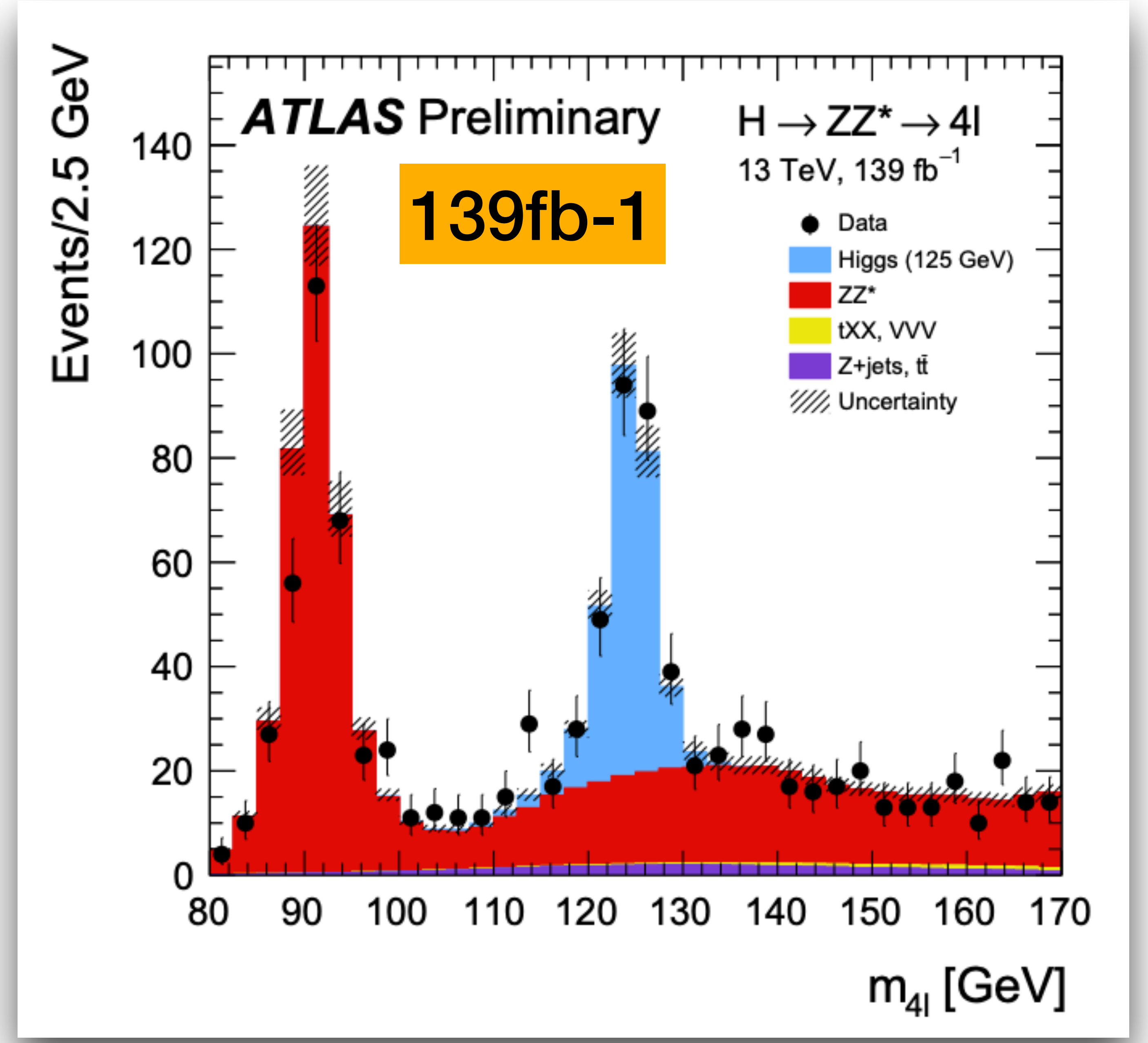
$H \to ZZ^* \to 4l$ channel

- ***Signature:*** 4 isolated leptons (muons or electrons)
  - 2 lepton pairs SFOS are formed; m12 (leading pair) and m34 (sub-leading pair)
  - ***high signal-to-background ratio:*** (~2:1)
    - fully reconstructed final state as well as excellent lepton momentum resolution
  - ***excellent mass resolution:*** 1-2% m_H
- ***Main background sources:***
  - Non-resonant ZZ^* (**dominant contribution**):
    - MC simulation only (**CMS**)
    - constrained in data sidebands (**ATLAS**)
  - Smaller contributions from: Z+jets and $t\bar{t}$ (Control regions in data)

arXiv:2103.04956v1 (Submitted EPJC)



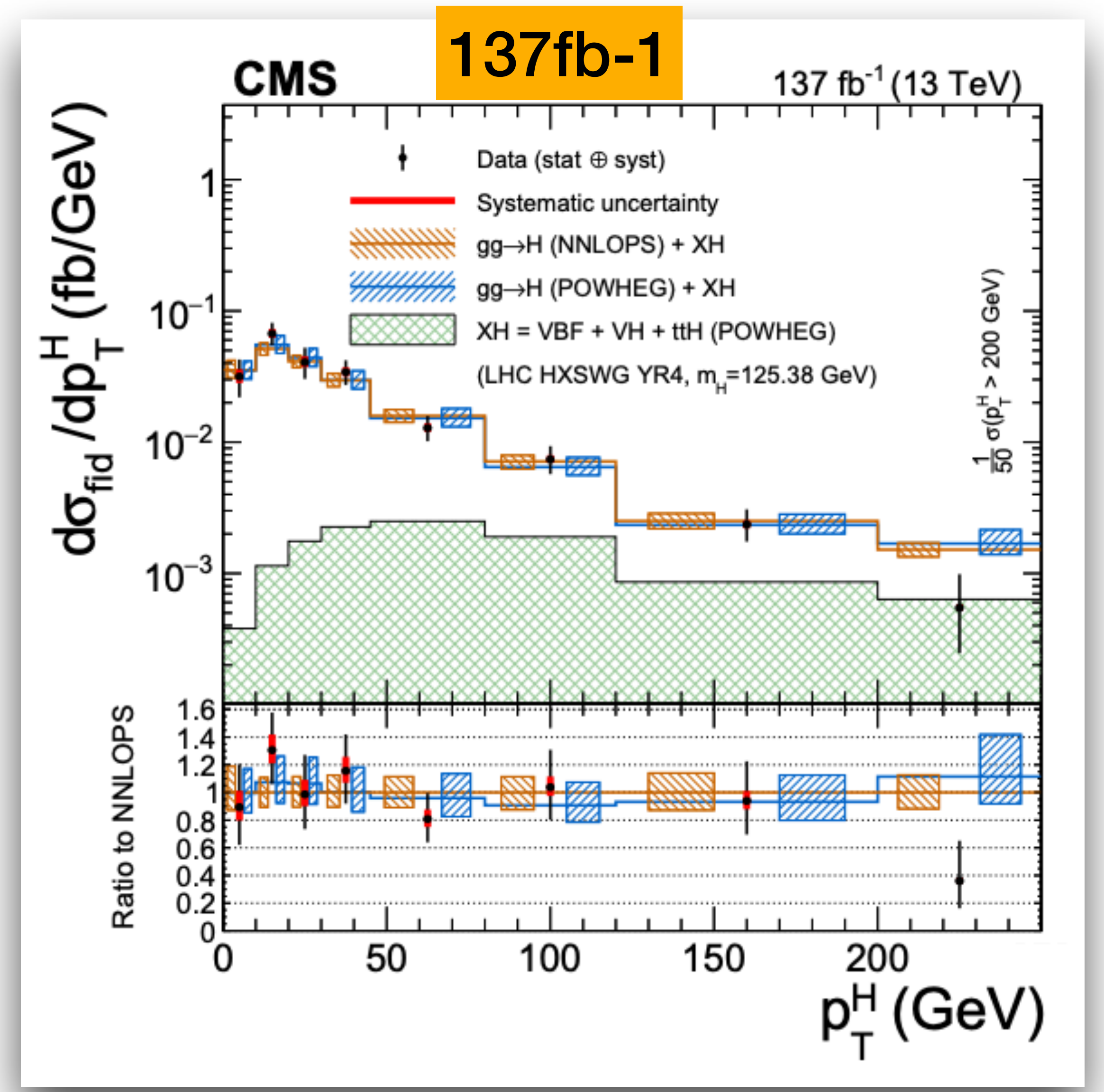
Eur. Phys. J. C (2020) 942

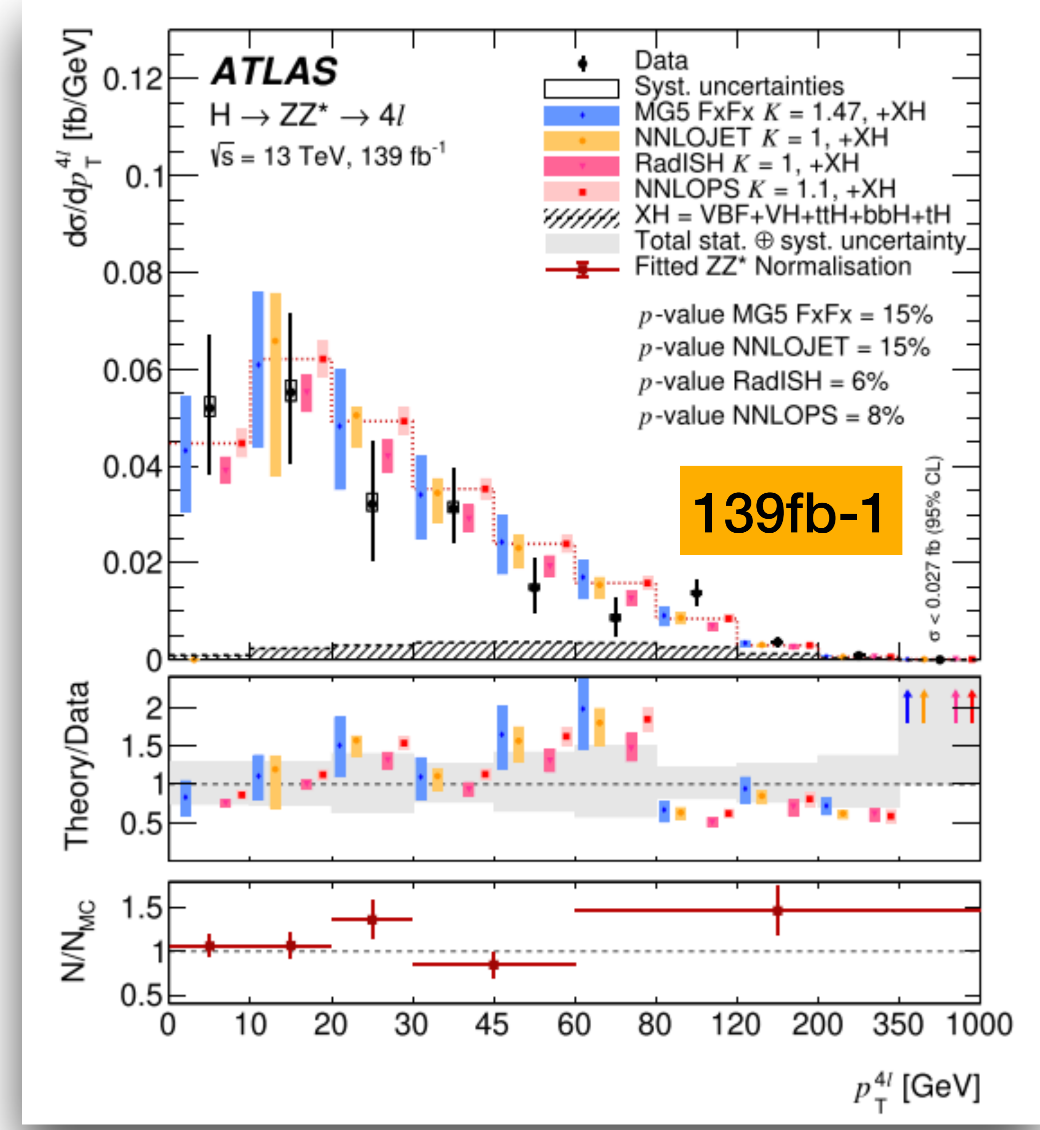


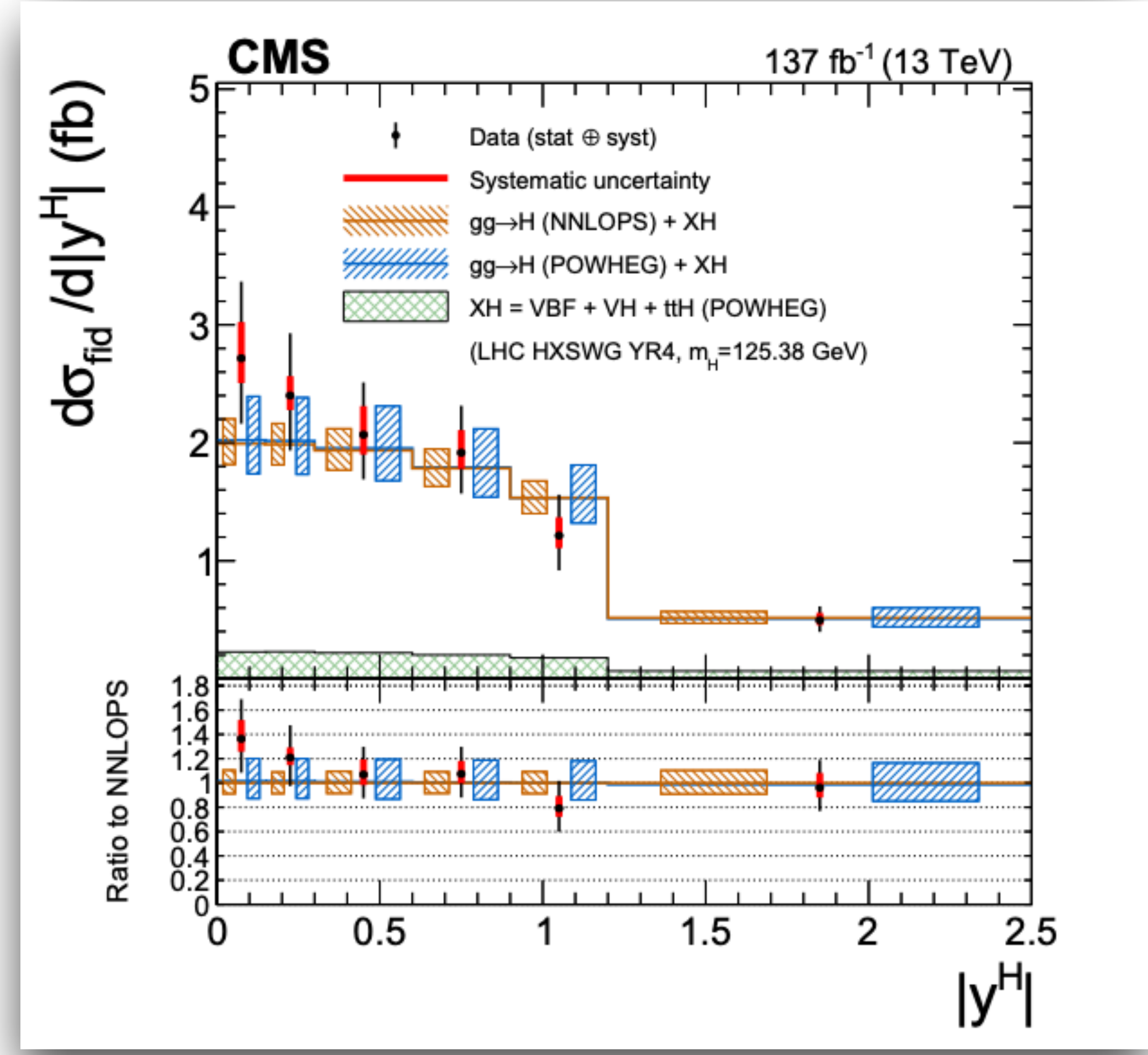
$H \to ZZ^* \to 4l$: pT(H) and y(H) differential measurements

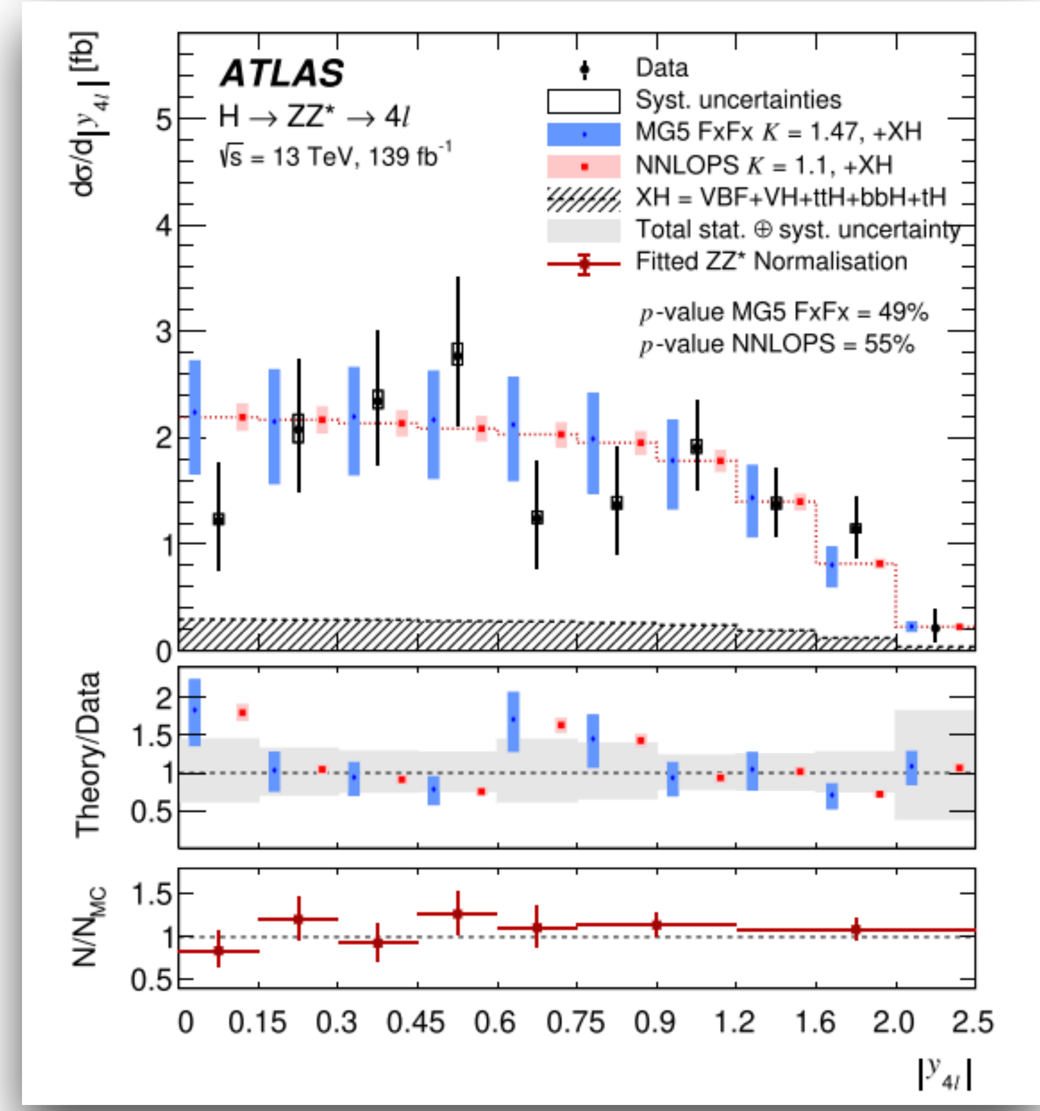
arXiv:2103.04956v1 (Submitted EPJC)

Eur. Phys. J. C (2020) 942









- **Predictions:**
  - **ATLAS:** MG5 FxFx and NNLOPS scaled to N^3LO
    - additional predictions as NNLOJET and RadISH
  - **CMS:** POWHEG (NLO) and NNLOPS (NNLO accuracy)
  - sub-leading modes added as **XH** (VBF+VH+ttH)
- **ATLAS:** ZZ normalization obtained in each bin of the observable and compared to the MC prediction (N/N_{MC})
  - correlation among measured cross-sections and ZZ normalization factors are overall not significant

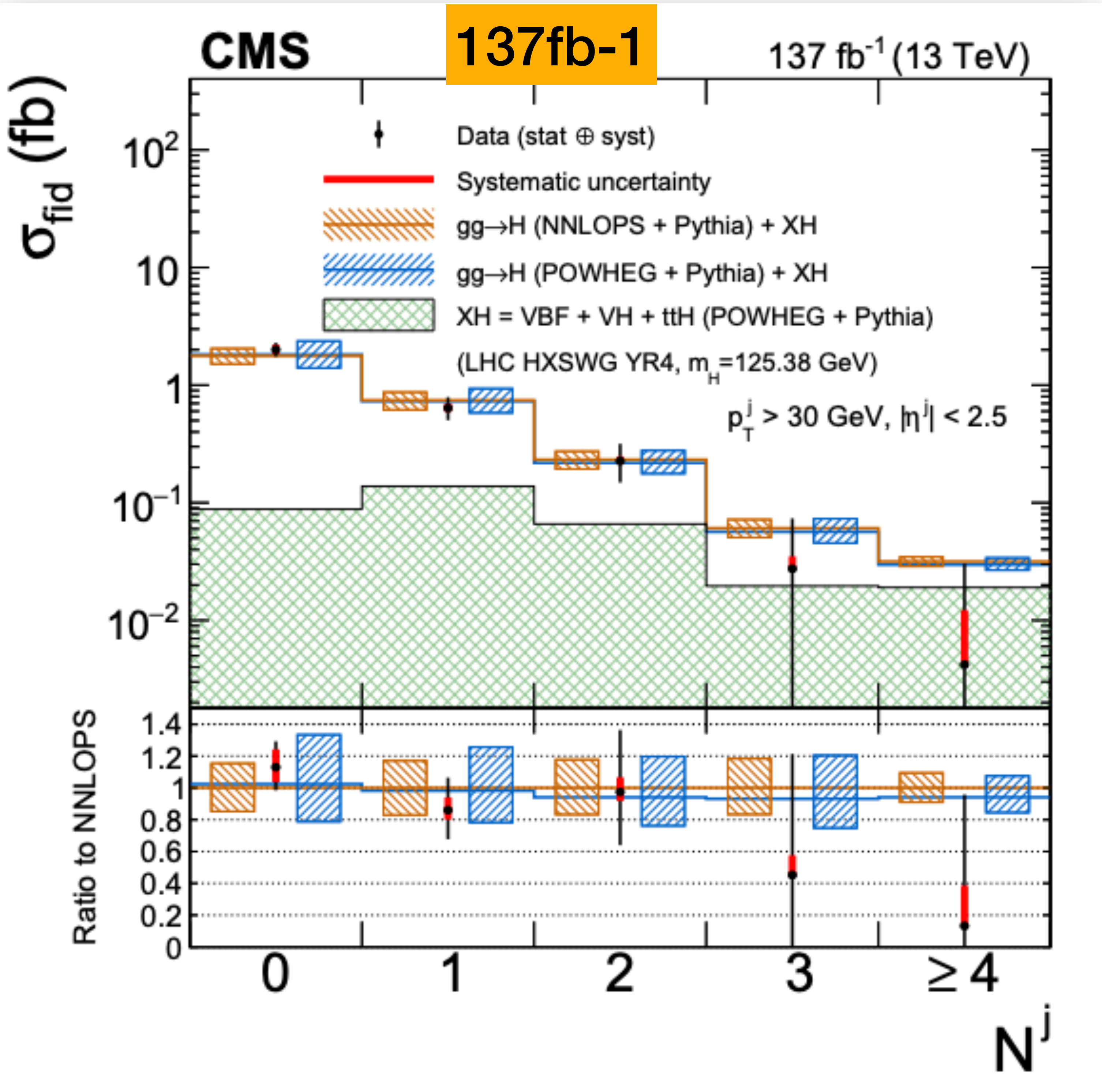
- **Dominant systematics uncertainties:**
  - **ATLAS/CMS**: luminosity, lepton reconstruction and identification and ZZ^* theoretical uncertainties
- Measurements are ***statistically dominated***

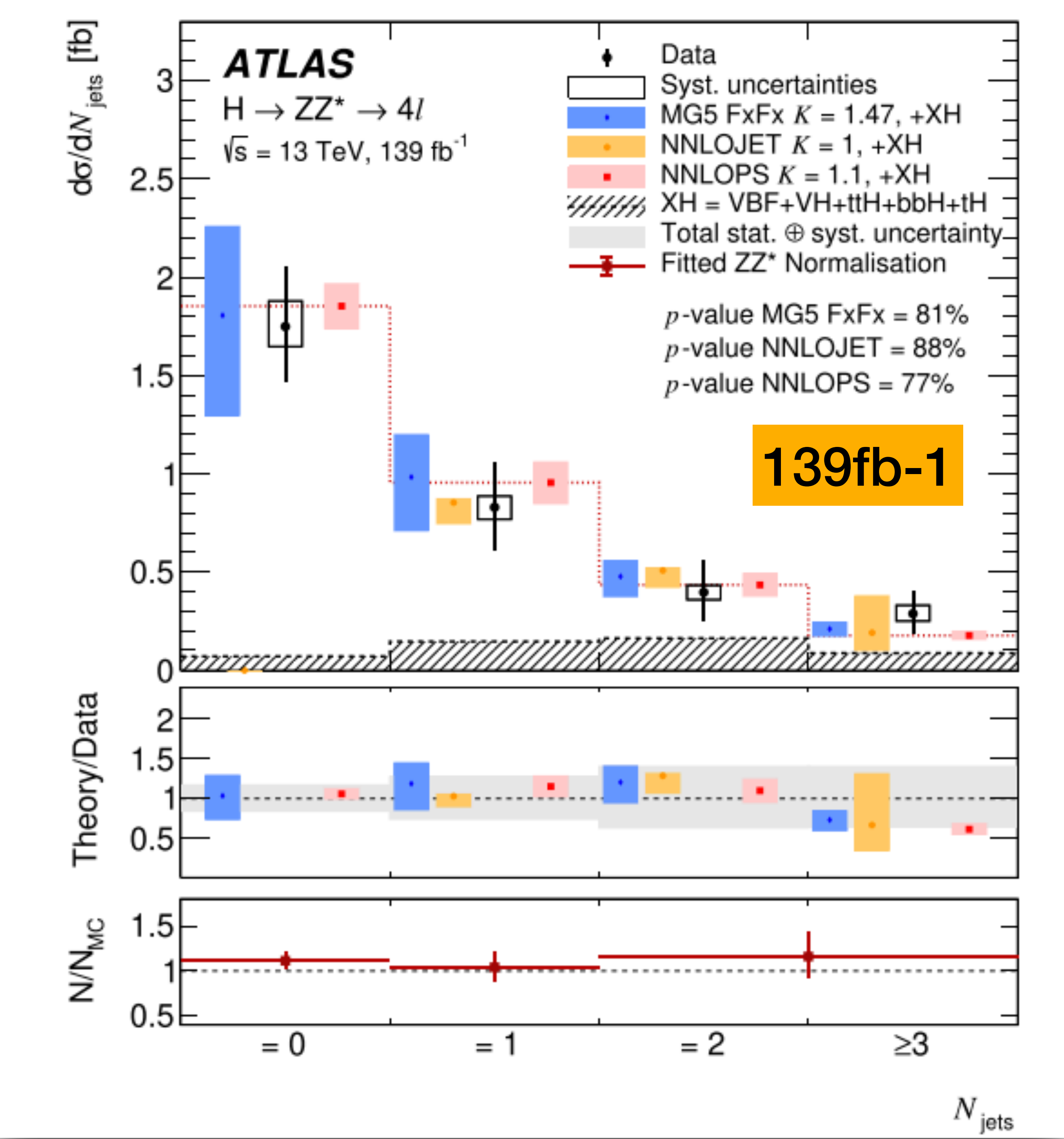
- **Good agreement with the SM predictions within the uncertainties:**
  - **ATLAS pT(H)** $p(\chi^2)$ = 15% (MG5 FxFx and NNLOJET)
  - **ATLAS y(H)** $p(\chi^2)$ = 55% (NNLOPS)

$H \rightarrow ZZ^* \rightarrow 4l$: Jet-kinematics differential measurement

- **ATLAS:** jets pT > 30 GeV and |y| < 4.4
- **CMS:** jets pT > 30 GeV and $|\eta|$ < 2.5
  - reduce the experimental uncertainties

- **Predictions** (**ATLAS**):
  - **ATLAS:** MG5 FxFx and NNLOPS scaled to N^3LO
    - NNLOJET normalized to predicted cross-sections





- **Dominant systematics uncertainties:**
  - **ATLAS/CMS**: luminosity, JES+JER and signal theory uncertainty
- Measurements are ***statistically dominated***

- ***Good agreement with the SM predictions within the uncertainties:***
  - **ATLAS** $p(\chi^2)$ = 88% (NNLOJET)

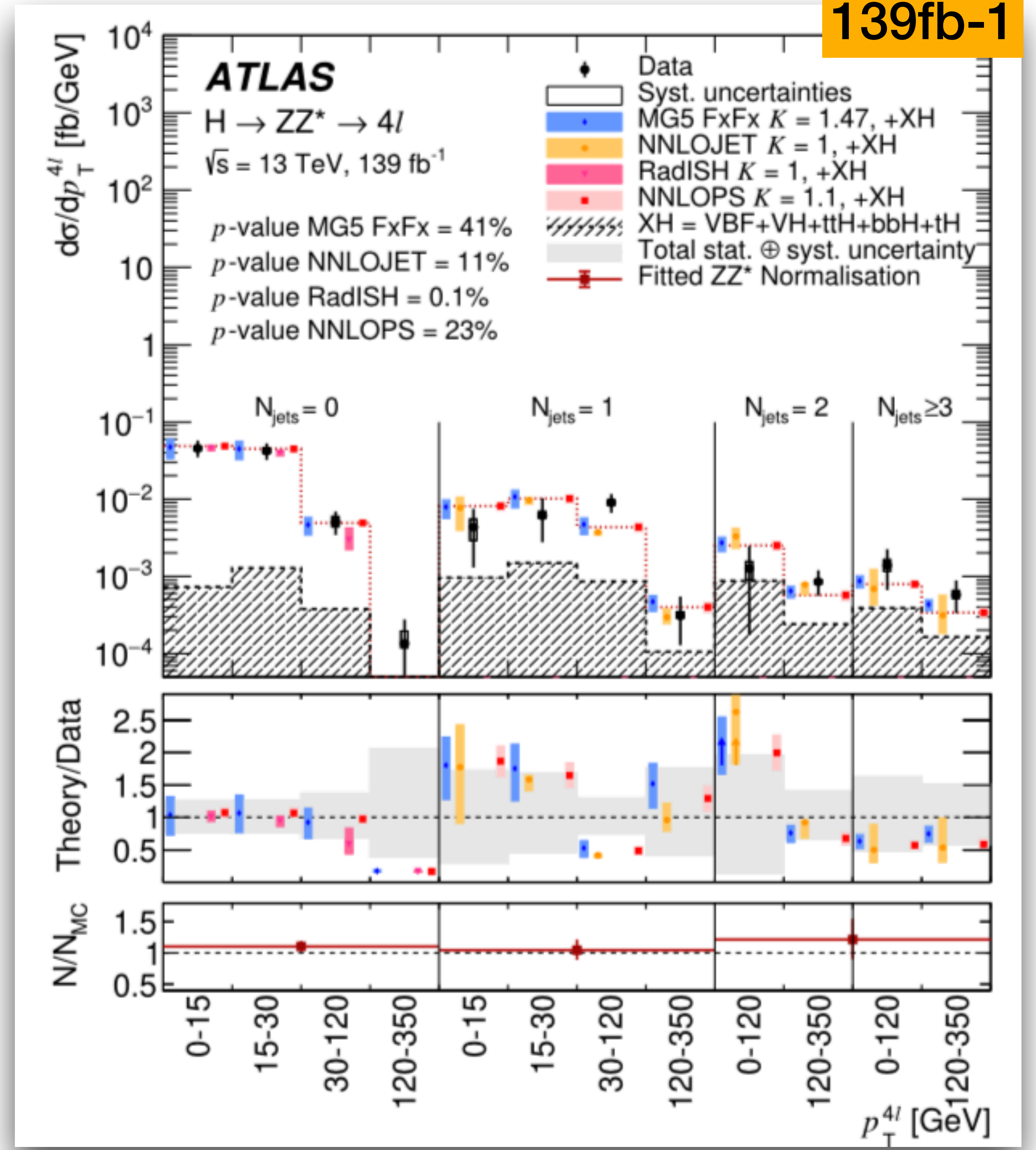
$H \rightarrow ZZ^* \rightarrow 4l$: double differential measurement

- **ATLAS:** jets pT > 30 GeV and |y| < 4.4

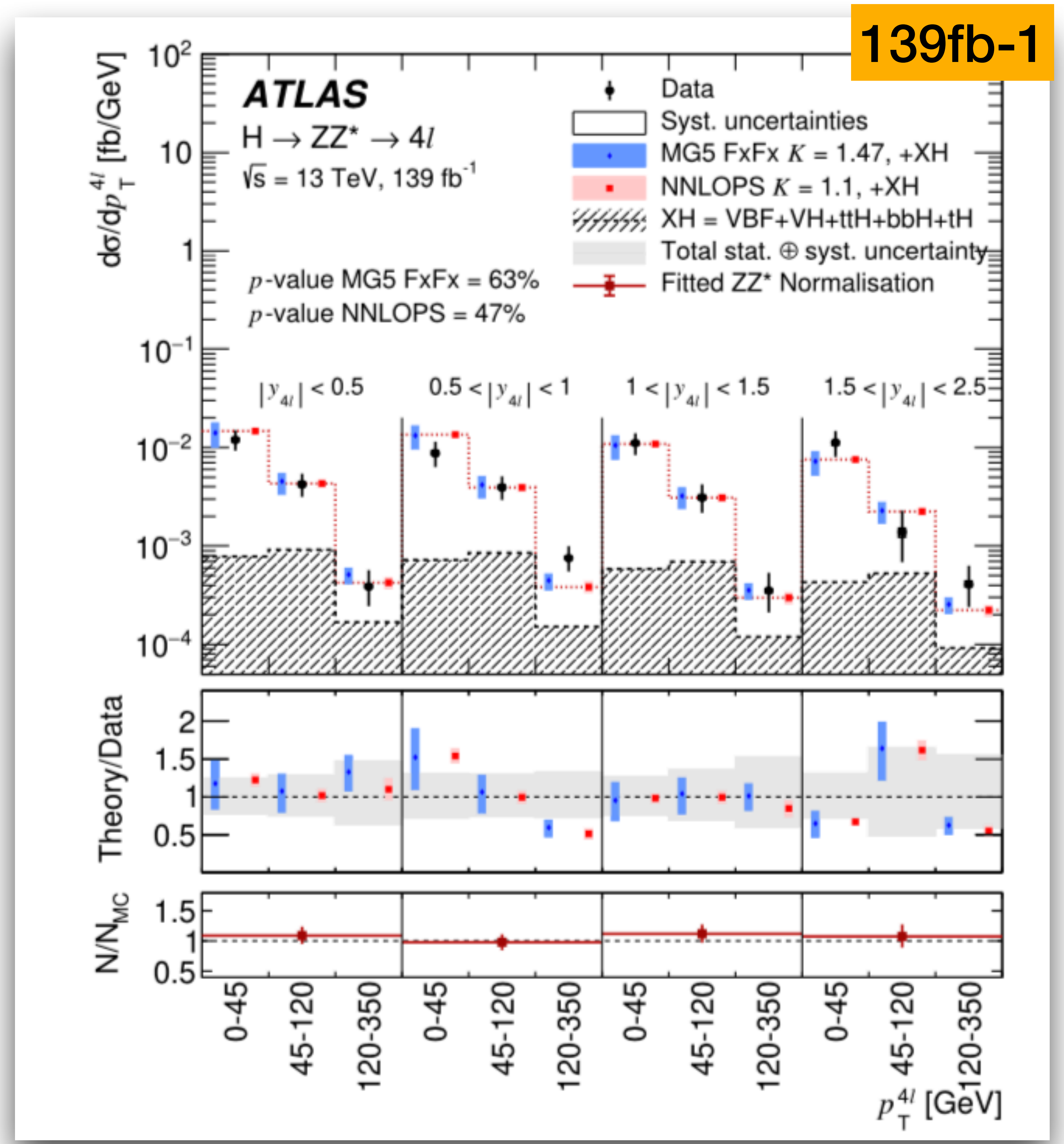
- **Predictions** (ATLAS):
  - **ATLAS:** MG5 FxFx and NNLOPS scaled to N^3LO
    - NNLOJET and RadISH normalized to predicated cross-sections

- **Dominant systematics uncertainties:**
  - lepton reconstruction and identification, jet reconstruction and signal theory uncertainty
- Measurement is ***statistically dominated***

139fb-1



139fb-1

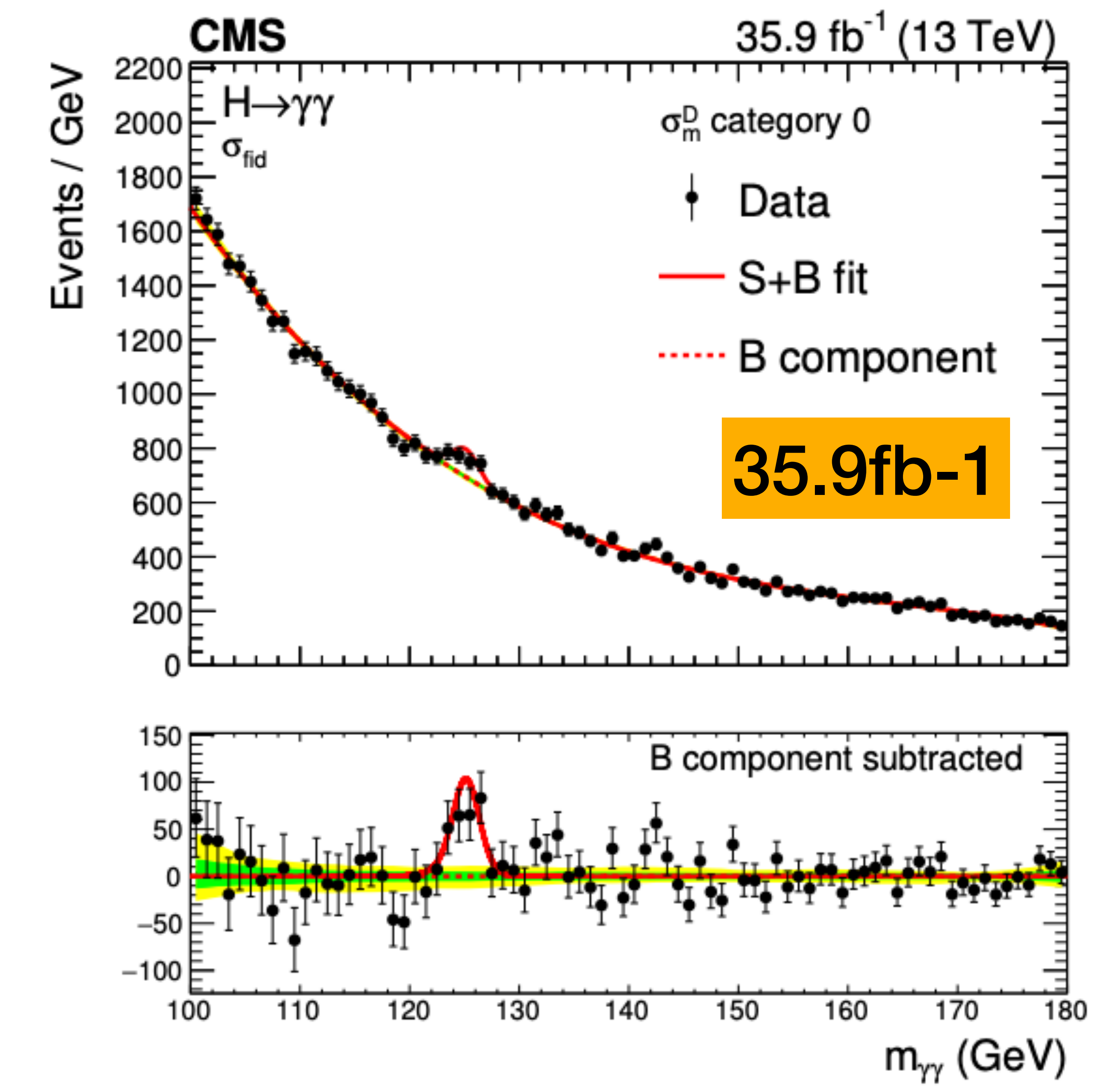


- ***Good agreement with the SM predictions within the uncertainties:***
  - **ATLAS** p_T^{4l} *vs* N_{jets} $p(\chi^2) = 41\%$ (MG5 FxFx)
  - **ATLAS** p_T^{4l} *vs* $|y_{4l}|$ $p(\chi^2) = 63\%$ (MG5 FxFx)

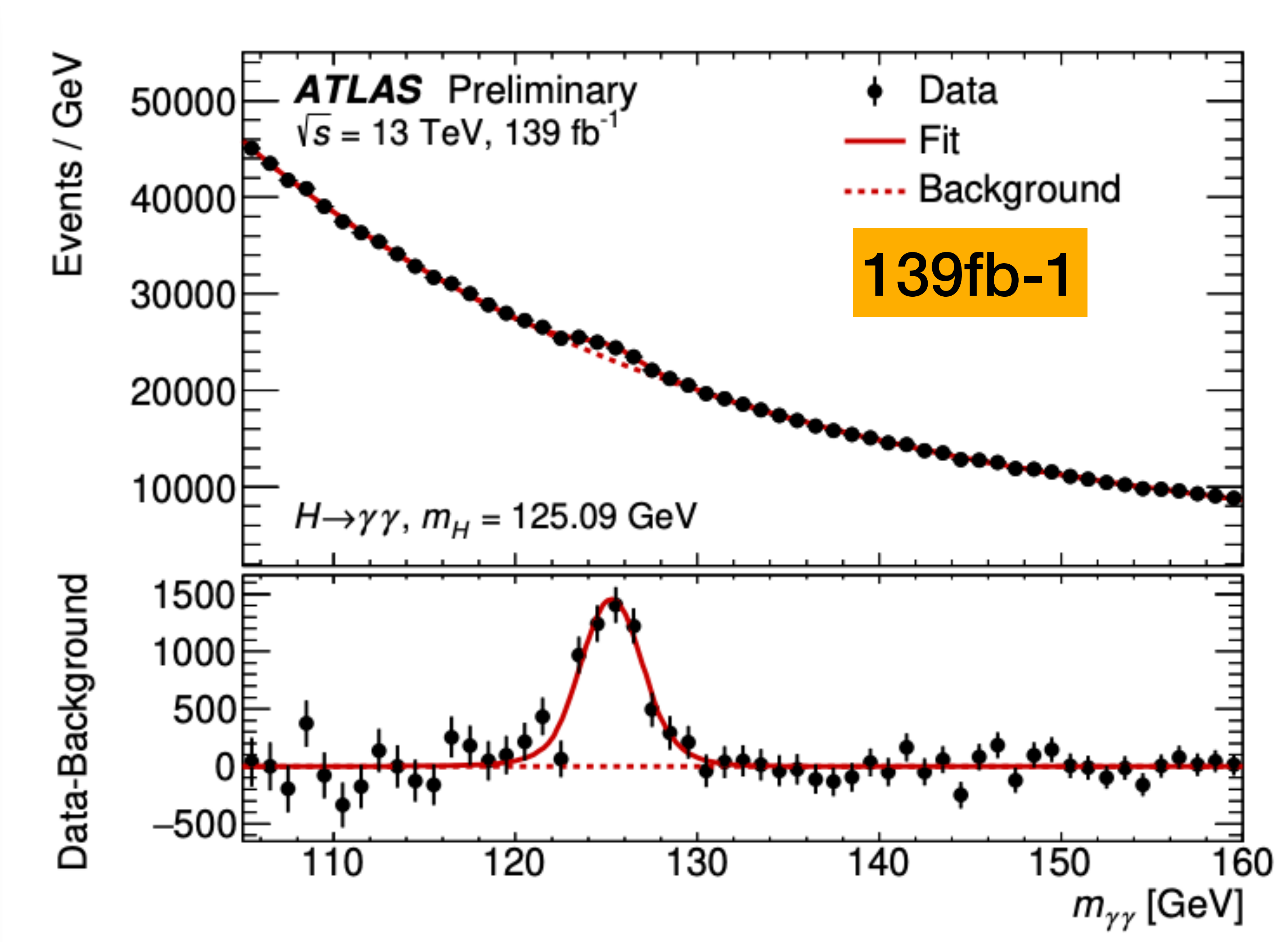
$H \to \gamma\gamma$ channel

- ***Signature:*** two reconstructed isolated photons
  - narrow peak over smoothly falling background (excellent photon energy resolution)
  - ***diphoton vertex requeriment:***
    - **CMS:** BDT (reconstructed vertex discriminants as input)
    - **ATLAS:** NN algorithm (track + primary vertex + directions of the photons as input)
  - ***excellent mass resolution*** of the diphoton system: 1-3% m_H
- ***Main background sources:*** continuum $\gamma\gamma$ production (irreducible), $\gamma - jet$ and $jet - jet$ (reducible ones)
- Events are categorized using a mass resolution estimator (**CMS**)

JHEP01(2019)183



ATLAS-CONF-2019-029



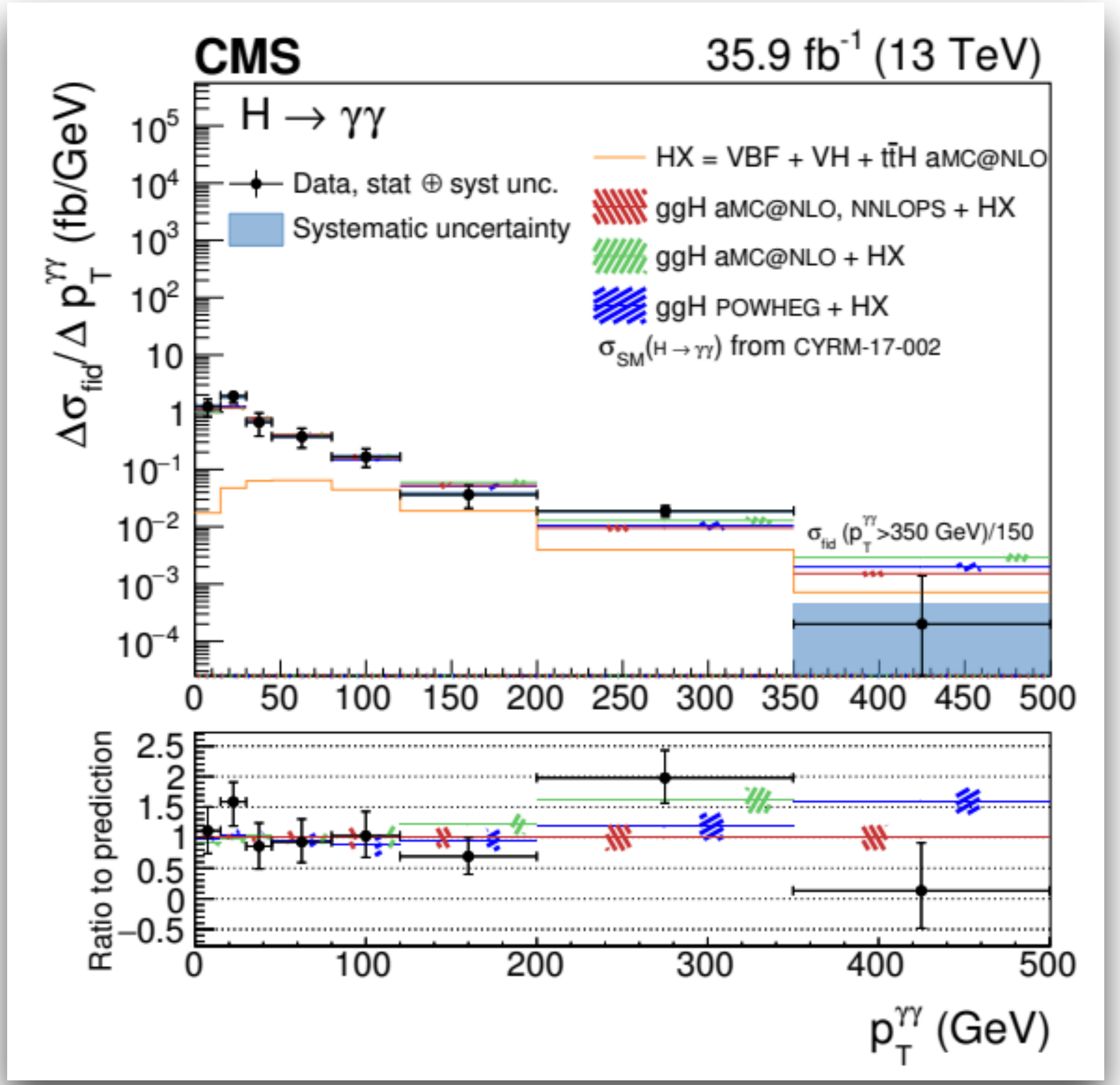
$H \to \gamma\gamma$: pT(H) differential measurement

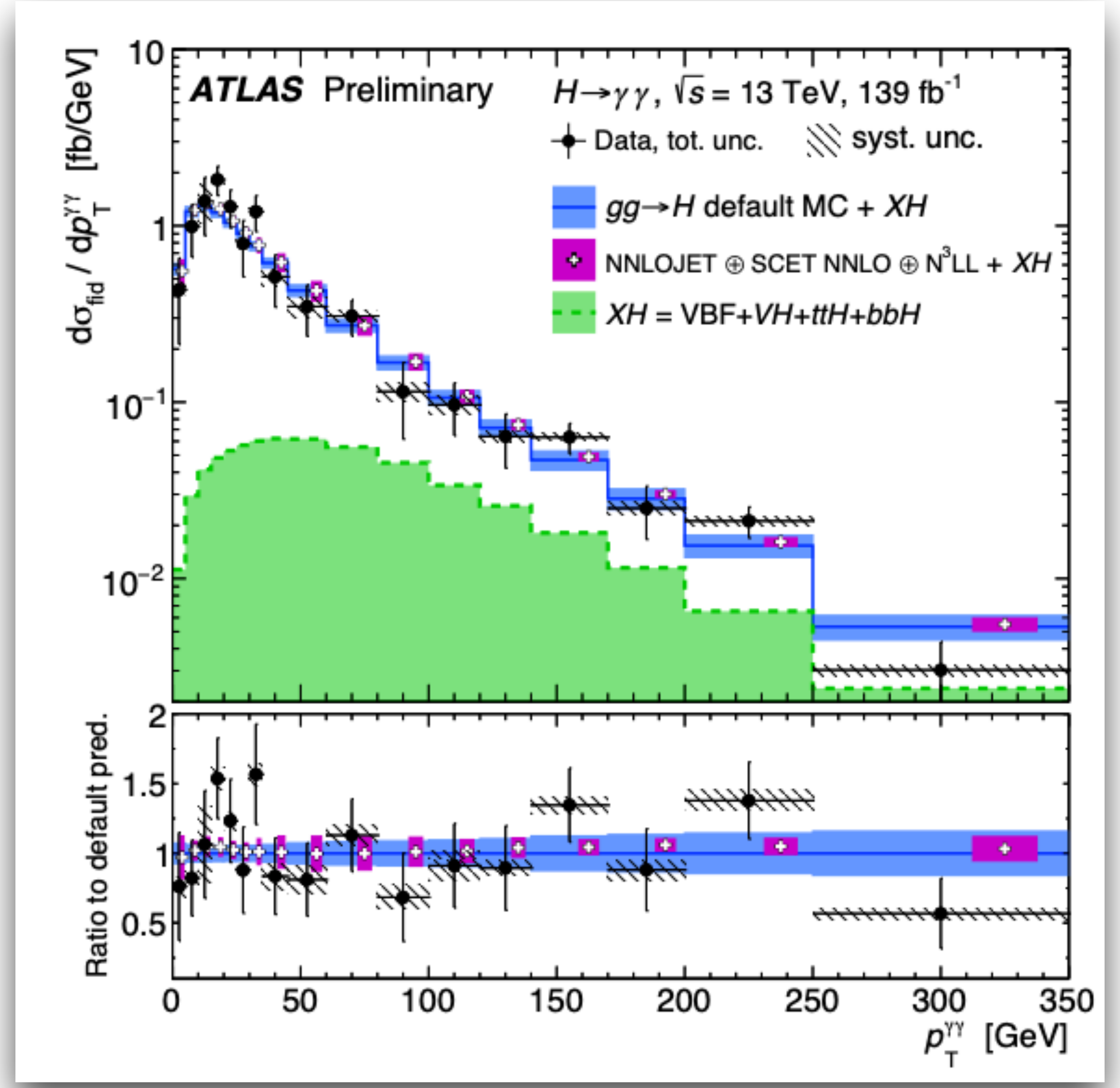
JHEP01(2019)183 35.9fb-1

ATLAS-CONF-2019-029 139fb-1

- **ATLAS (*default ggF prediction*)**: PowHeg NNLOPS normalized to N^3LO (QCD)+NLO (EW)
- **CMS (*ggF MC predictions*)**: MG5 amc@nlo and PowHeg
  - MG5 amc@nlo: events weighted to match NNLOPS (NNLO accuracy)

- **Dominant systematics uncertainties:**
  - **ATLAS:** photon energy scale/resolution, background modelling
  - **CMS:** photon ID BDT score and per-photon energy resolution
- Measurement is ***statistically dominated***



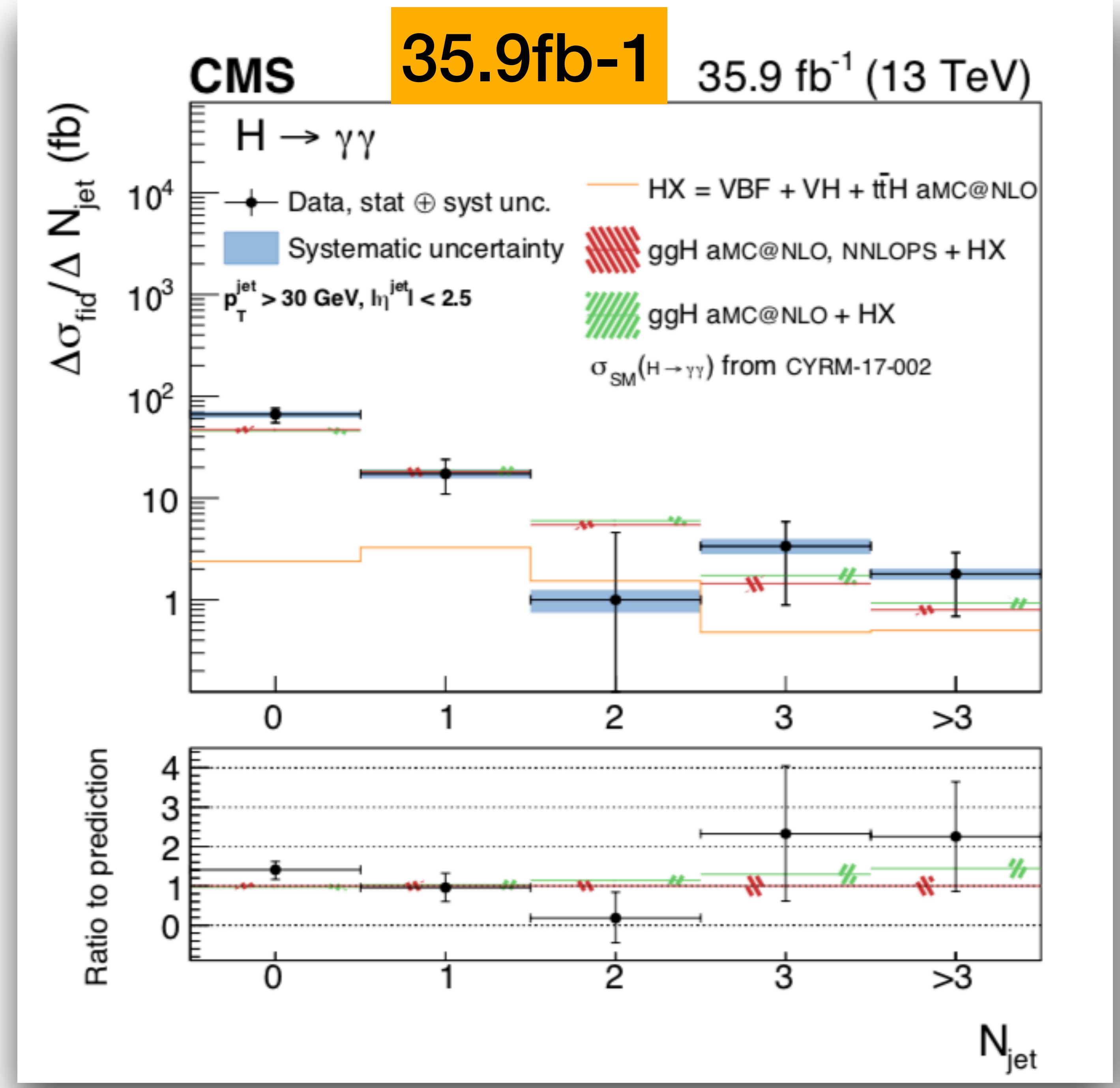


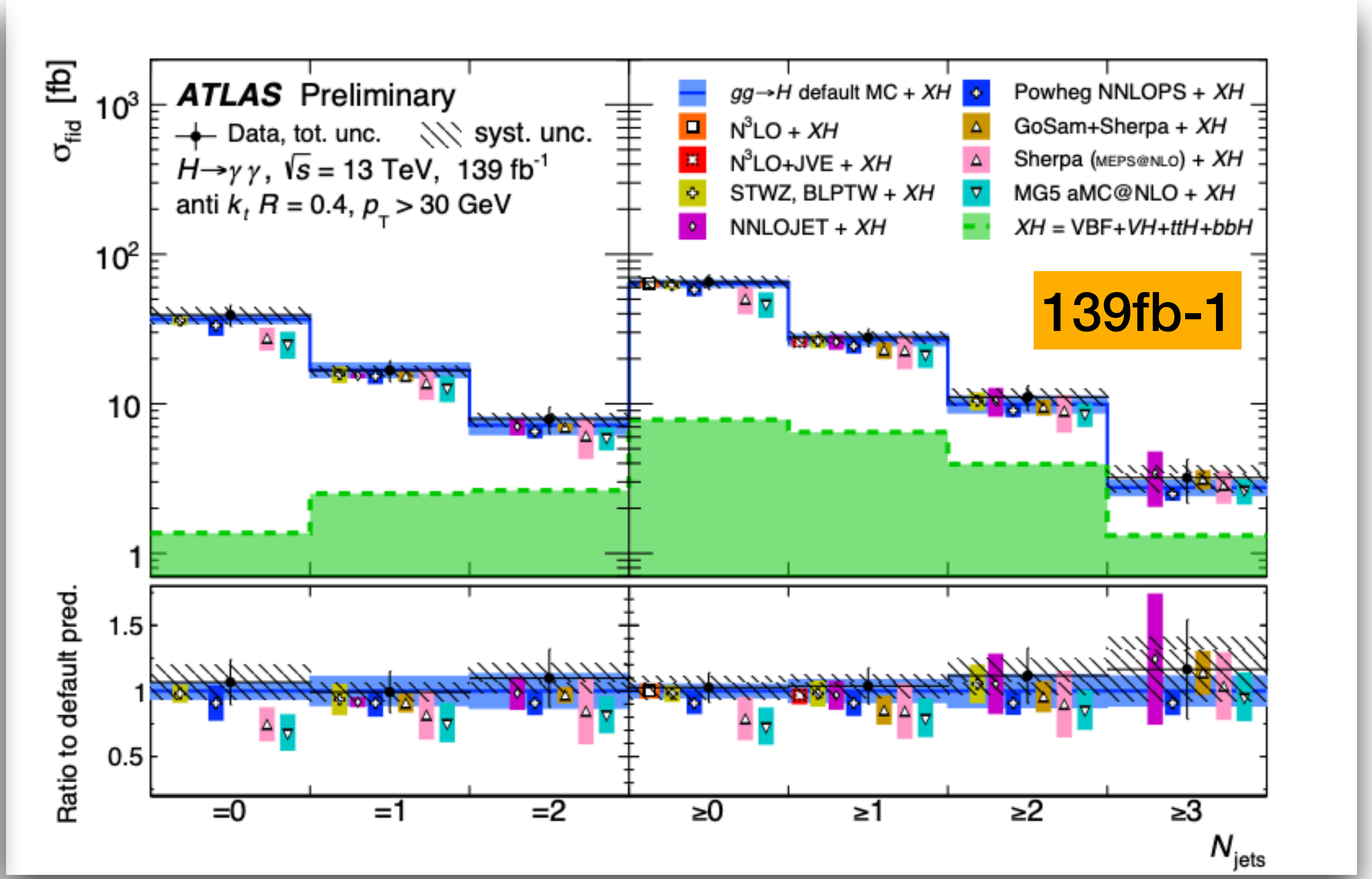
- ***Good agreement with the SM predictions within the uncertainties:***
  - ATLAS $p(\chi^2)$ = 44% (default MC prediction)
- ***pT(H) > 250 GeV:*** expected top quark-mass effects to be sizable (inconclusive due to the large stats in the last bin)

$H \to \gamma\gamma$: Jet-kinematics differential measurement

- **ATLAS:** jets pT > 30 GeV and |y| < 4.4
- **CMS:** jets pT > 30 GeV and $|\eta|$ < 2.5

- **ATLAS**: ggF default and additional predictions added to the same XH component
- **CMS**: MG5 amc@nlo, NNLOPS and MG5 amc@nlo





- ***Systematic uncertainties:***
  - **ATLAS:** jet energy scale and resolution
  - **CMS:** jet energy scale and resolution corrections

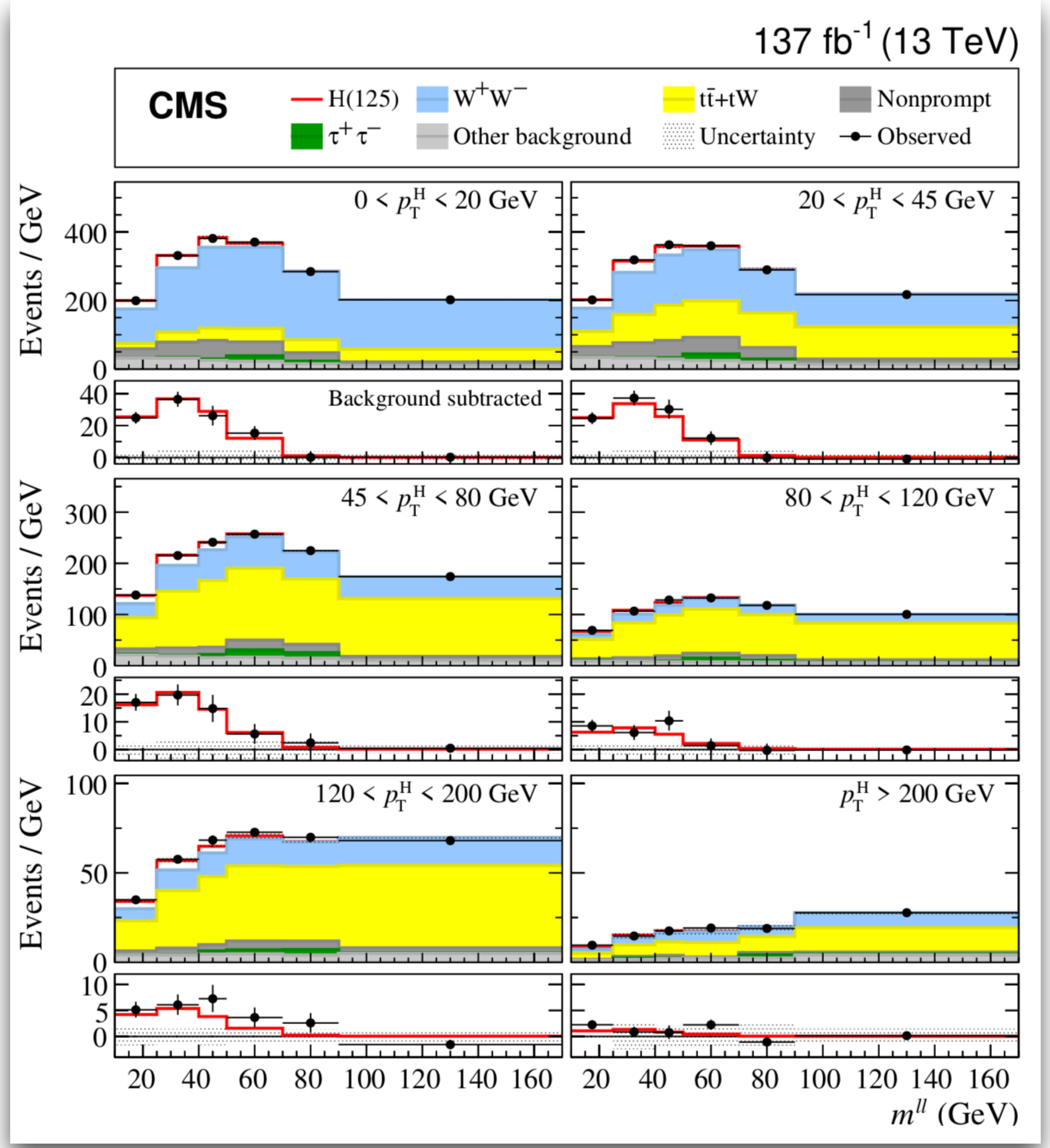
- ***Good agreement with the SM predictions within the uncertainties:***
  - N_jets $p(\chi^2)$ = 96% (**ATLAS,** default MC prediction)
    - N^3LO scaling improves agreement with data

$H \to W^+W^-$ channel

JHEP03(2021)003 137fb-1

- ***Signature:*** at least two isolated opposite sign leptons ($e^\pm\mu^\mp$) and missing transverse energy (MET) from $\nu\bar{\nu}$
  - requirement on being an electron and a muon suppress DY background contribution
  - ***powerful discriminant variables:*** di-lepton mass (m_{ll}) and transverse mass of the Higgs boson (m_T^H)
- ***Main background sources:*** W^+W^-, $t\bar{t} + tW$, $\tau^+\tau^-$
  - modeled in MC simulation and normalization from data

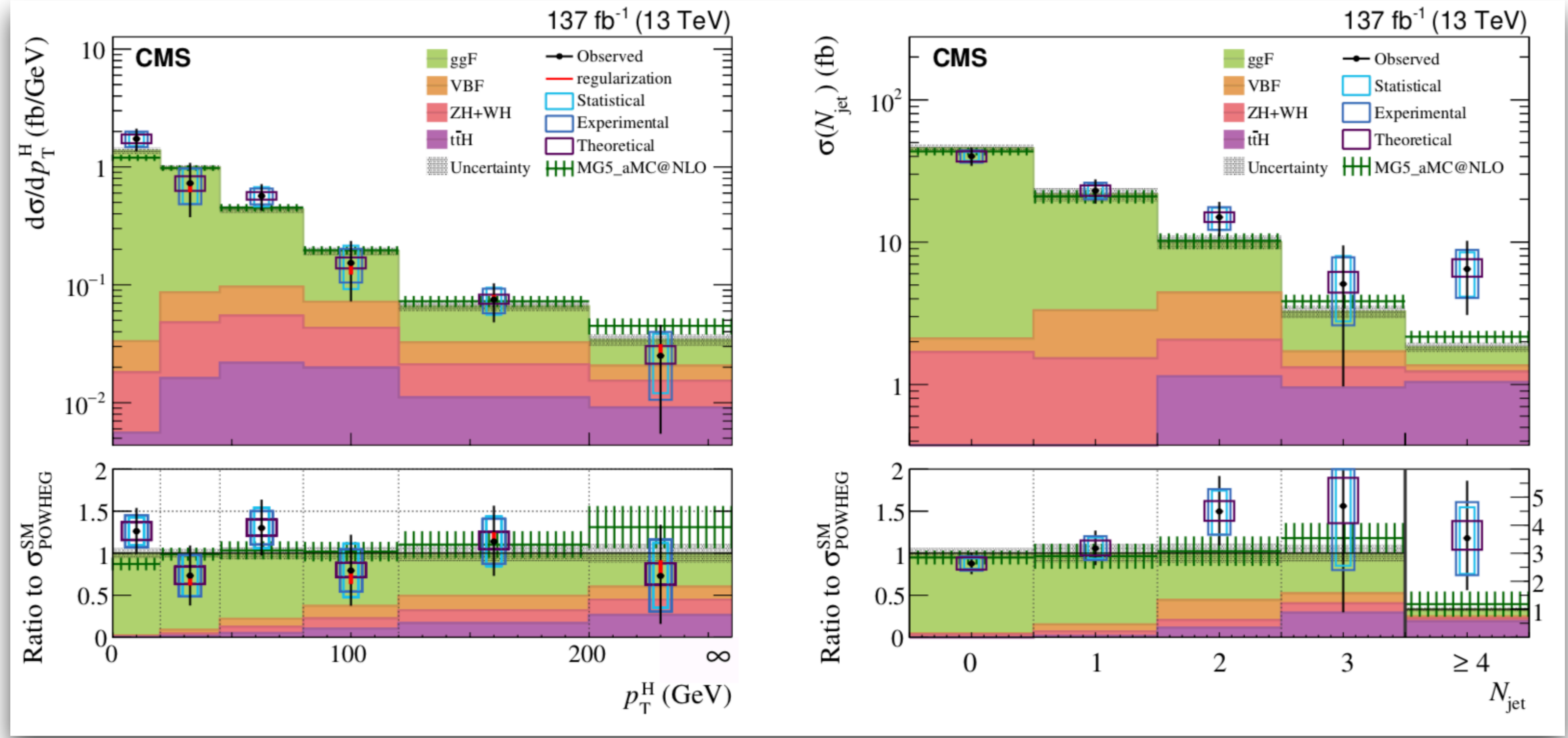
$$m_{\mathrm{T}}^{\mathrm{H}} = \sqrt{2 p_{\mathrm{T}}^{ll} p_{\mathrm{T}}^{\mathrm{miss}} \left[1 - \cos\Delta\phi\left(\vec{p}_{\mathrm{T}}^{ll}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}\right)\right]}$$



$H \to WW$: pT(H) and N_jets differential measurements

JHEP03(2021)003 137fb-1

- ***Observables: pT(H) and N_jets***
    - **pT(H):** magnitude of the vectorial sum of of the transverse momentum of two leptons and $\overrightarrow{p_T}^{miss}$
    - **N_jets:** number of jets ($p_T > 30\ GeV$, $|\eta| < 4.7$)
- ***Number of signal events*** extracted from fitting 2d distributions (m_{ll}, m_T^H) in each bin of the observables
- ***Experimental systematic uncertainties (dominant ones):***
    - lepton reconstruction and identification, lepton momentum, jet scale and $\overrightarrow{p_T}^{miss}$
- Comparable statistical and systematic uncertainties

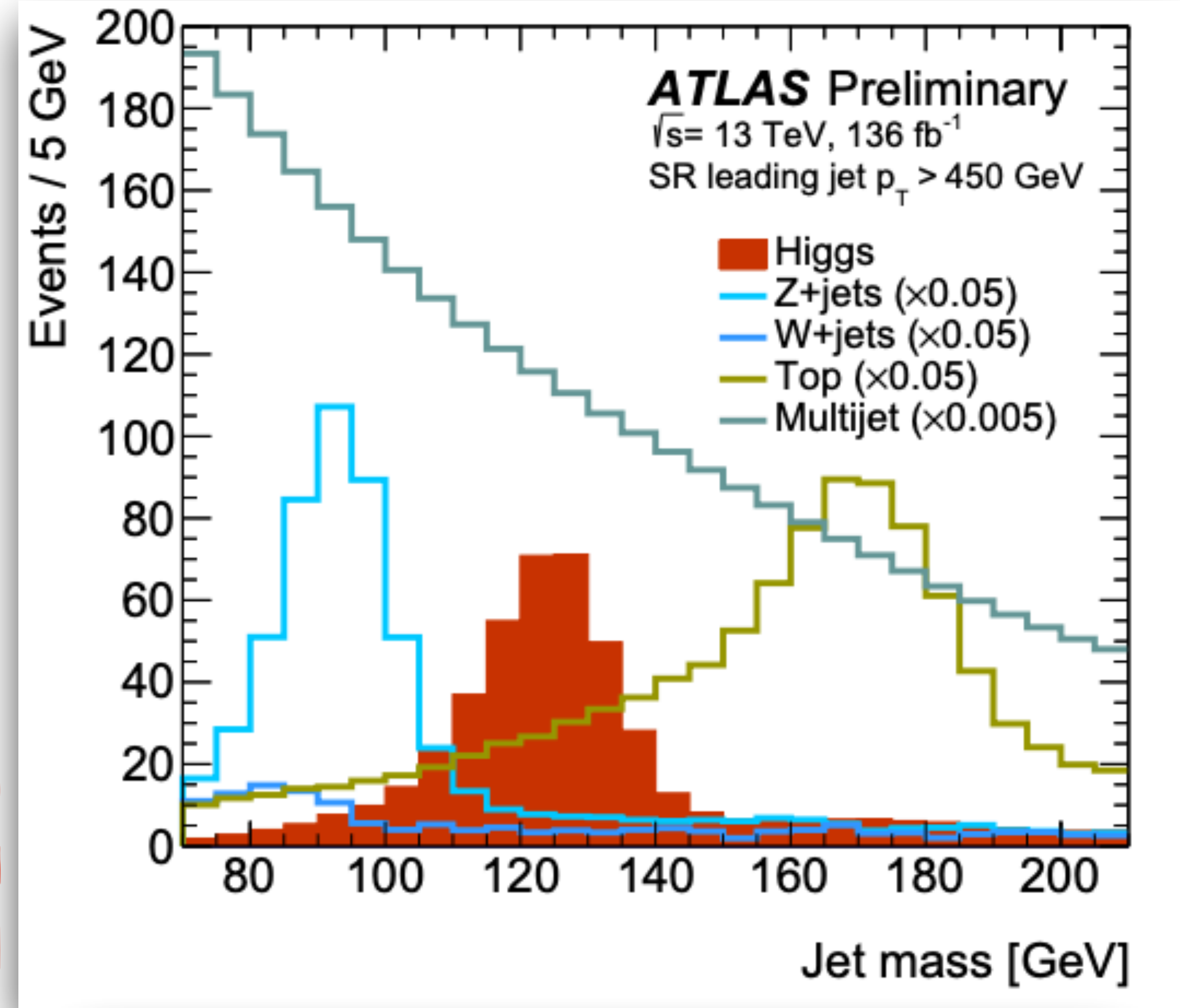


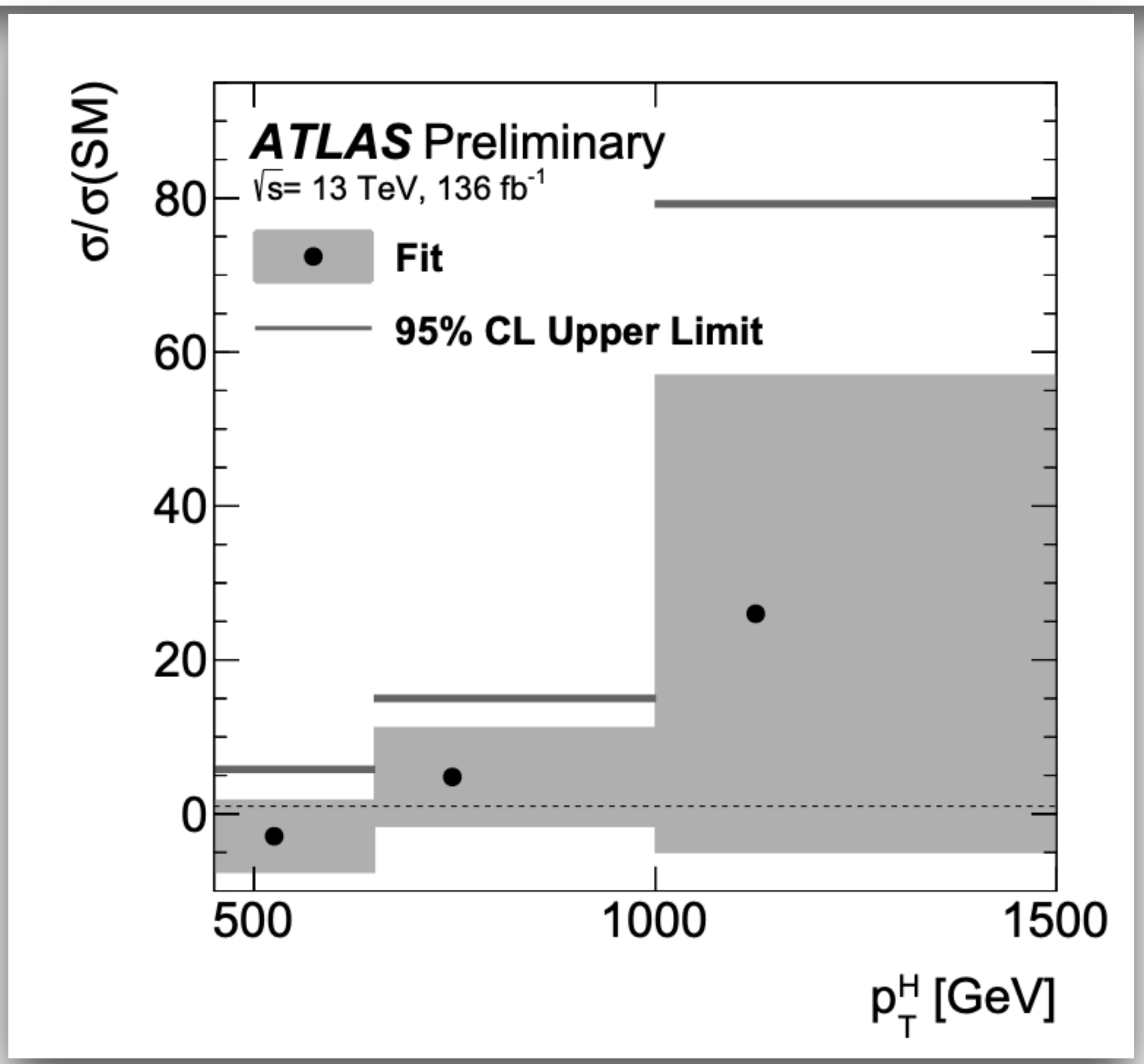
- *Measurements are consistent with SM predictions within the uncertainties*

$H \rightarrow b\bar{b}$: pT(H) differential measurement

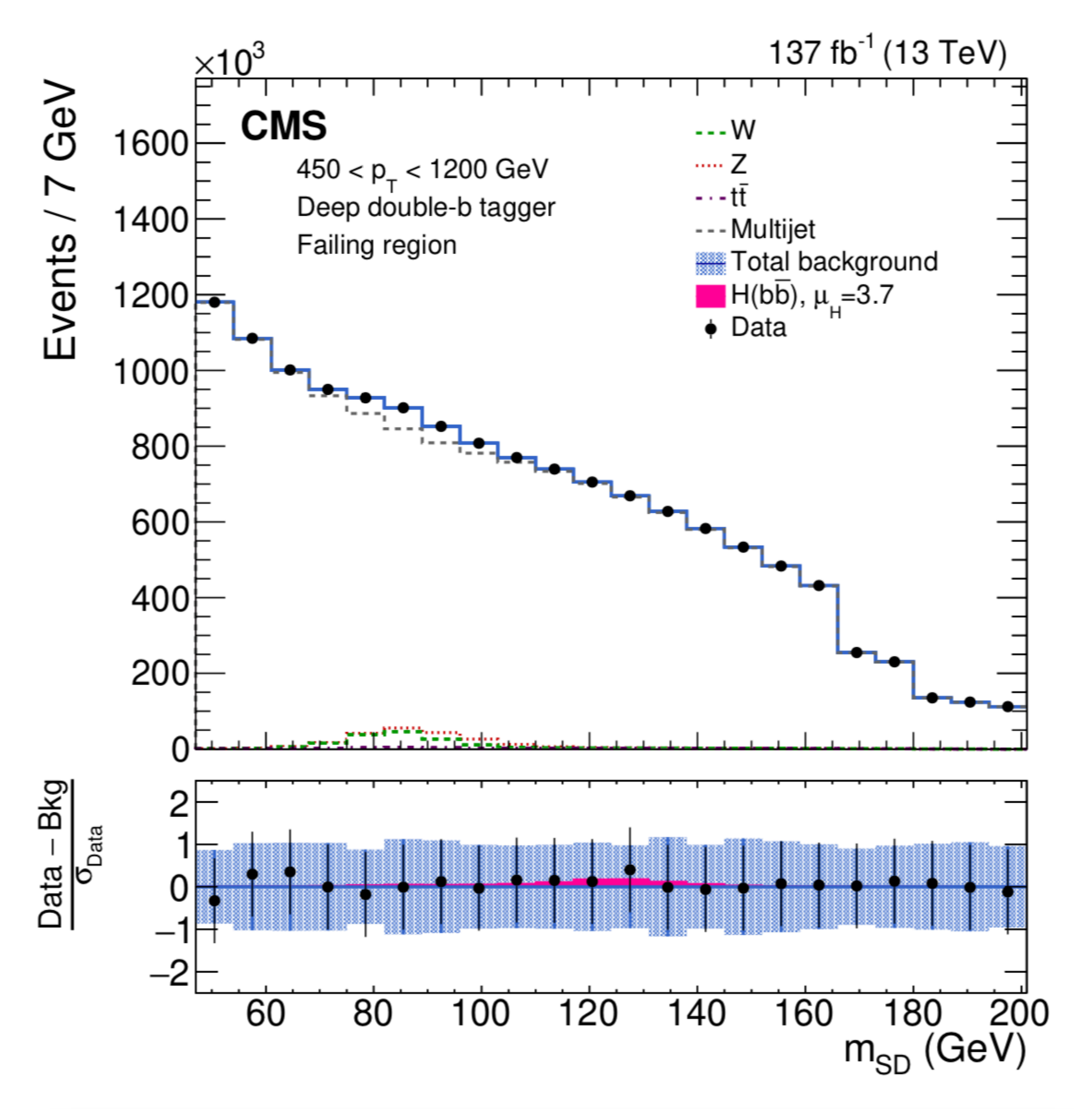
- ***Motivation:*** explore the high pT(H) region which is sensitive to contributions of new physics:
- **Signal region**:
  - Reconstructed Higgs bosons with large Lorentz boost from single large-radius jets:
    - **ATLAS:** at least 2 jets: leading and sub-leading jet with pT > 450 GeV and pT > 250 GeV respectively
    - **CMS:** jet candidates with pT > 450 GeV (jet substructure techniques (SD) applied)
- ***Main background sources (ATLAS and CMS):***
  - Multijet production (dominant source) , Z/W+jets and $t\bar{t}$ *and tW*
    - multijet production modeled in SR in data
- ***ATLAS:*** results are compatible with SM predictions within the uncertainties
- ***CMS:*** excess with local significance of 2.6σ wrt to SM predictions (further reduced to 1.9σ considering all 3 bins simultaneously)

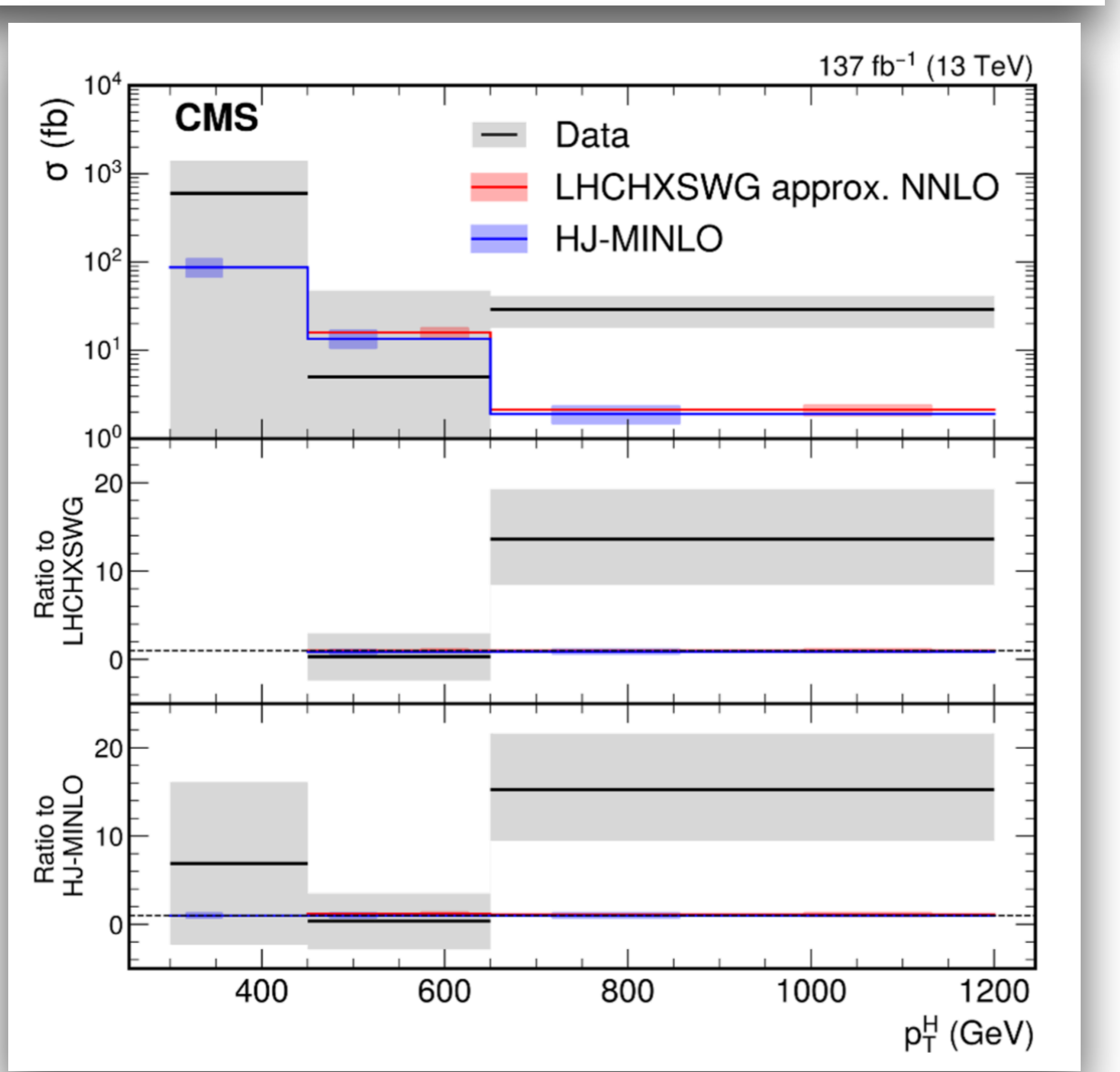
ATLAS-CONF-2021-010 136fb-1





JHEP12(2020)085 137fb-1

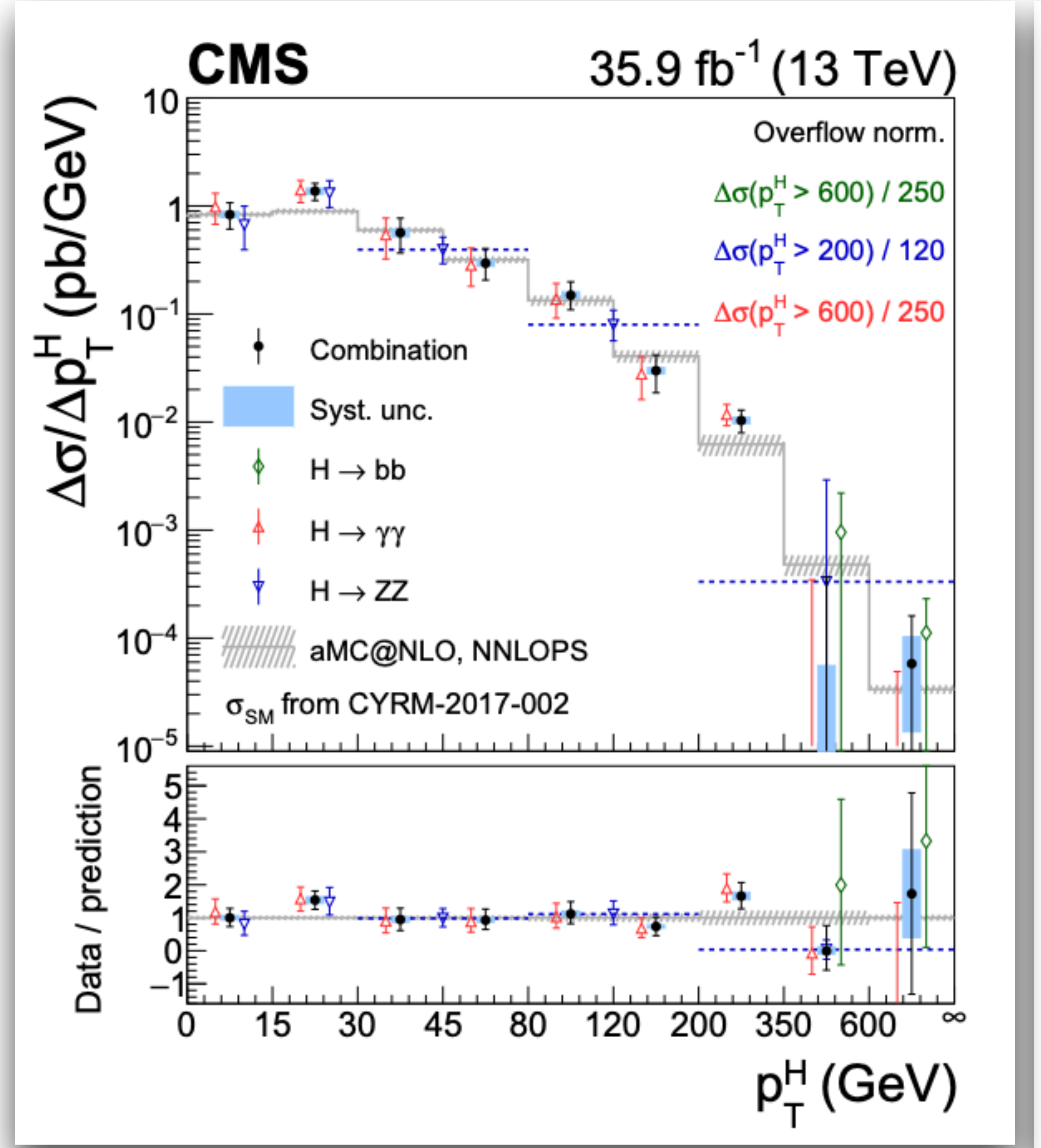




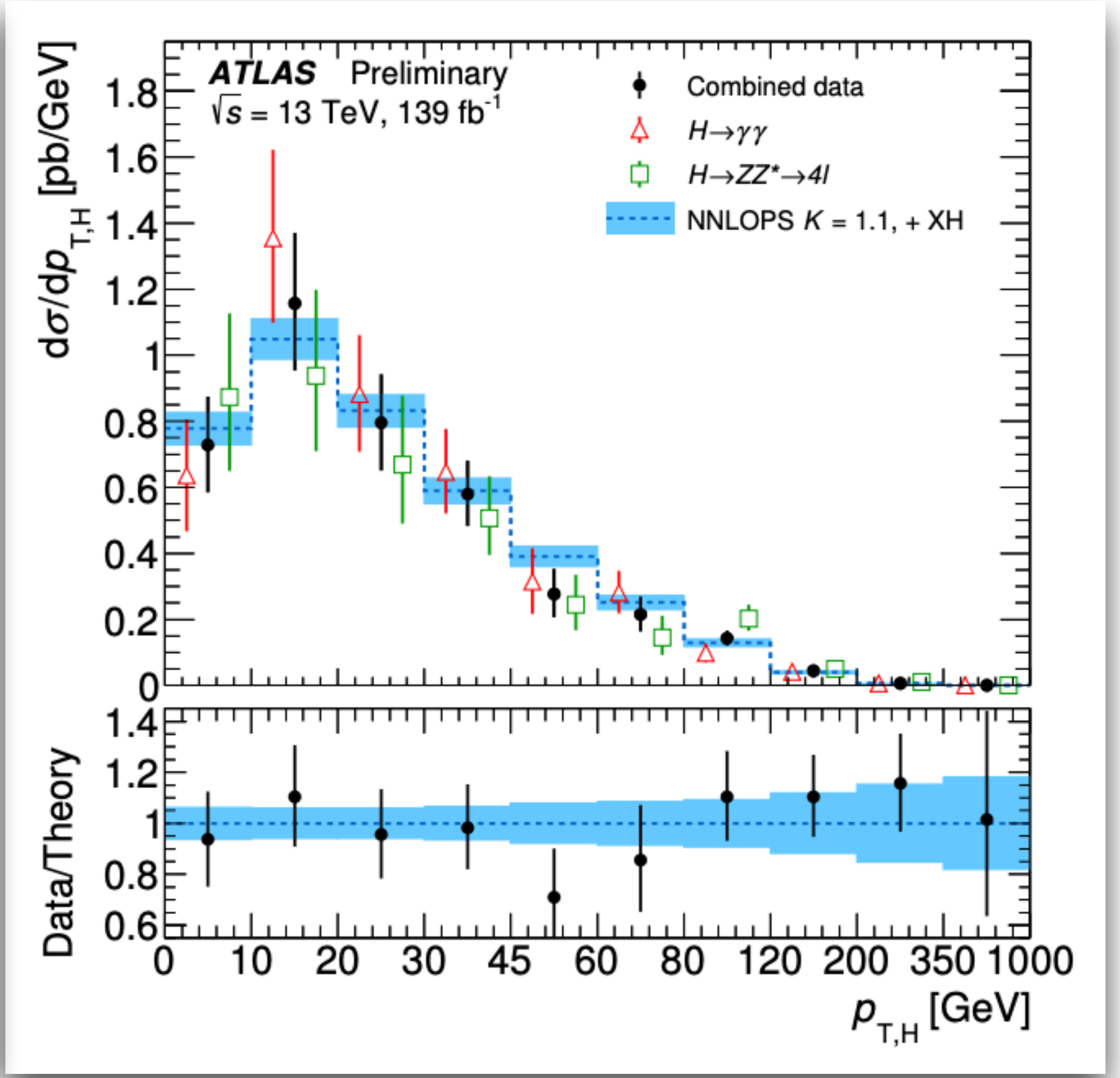
Combination of the differential measurements

- Combined measurement allows to improve the statistical precision of the individual channel measurements
  - extrapolation to the full phase space:
    - acceptance factors and correction factors computed from SM predictions
- ***Combined result from CMS (35.9 fb-1):***
  - ***input channels:*** $H \to \gamma\gamma, H \to 4l$ and $H \to b\bar{b}$
  - ***Good agreement with the SM predictions***
  - $H(b\bar{b})$ contribution is significant in last pT(H) bin (CMS)
- ***Combined result from ATLAS (139 fb-1):***
  - ***input channels:*** $H \to \gamma\gamma, H \to 4l$
  - ***Good agreement with the SM predictions:*** $p(\chi^2) = 78\%$
  - ***Largest systematic:*** background modelling ($H \to \gamma\gamma$) and luminosity
- pT(H) measurement still ***statistically dominated***

Physics Letters B 792 (2019) 35.9fb-1



ATLAS-CONF-2020-027 139fb-1



$H \to \gamma\gamma$: interpretations

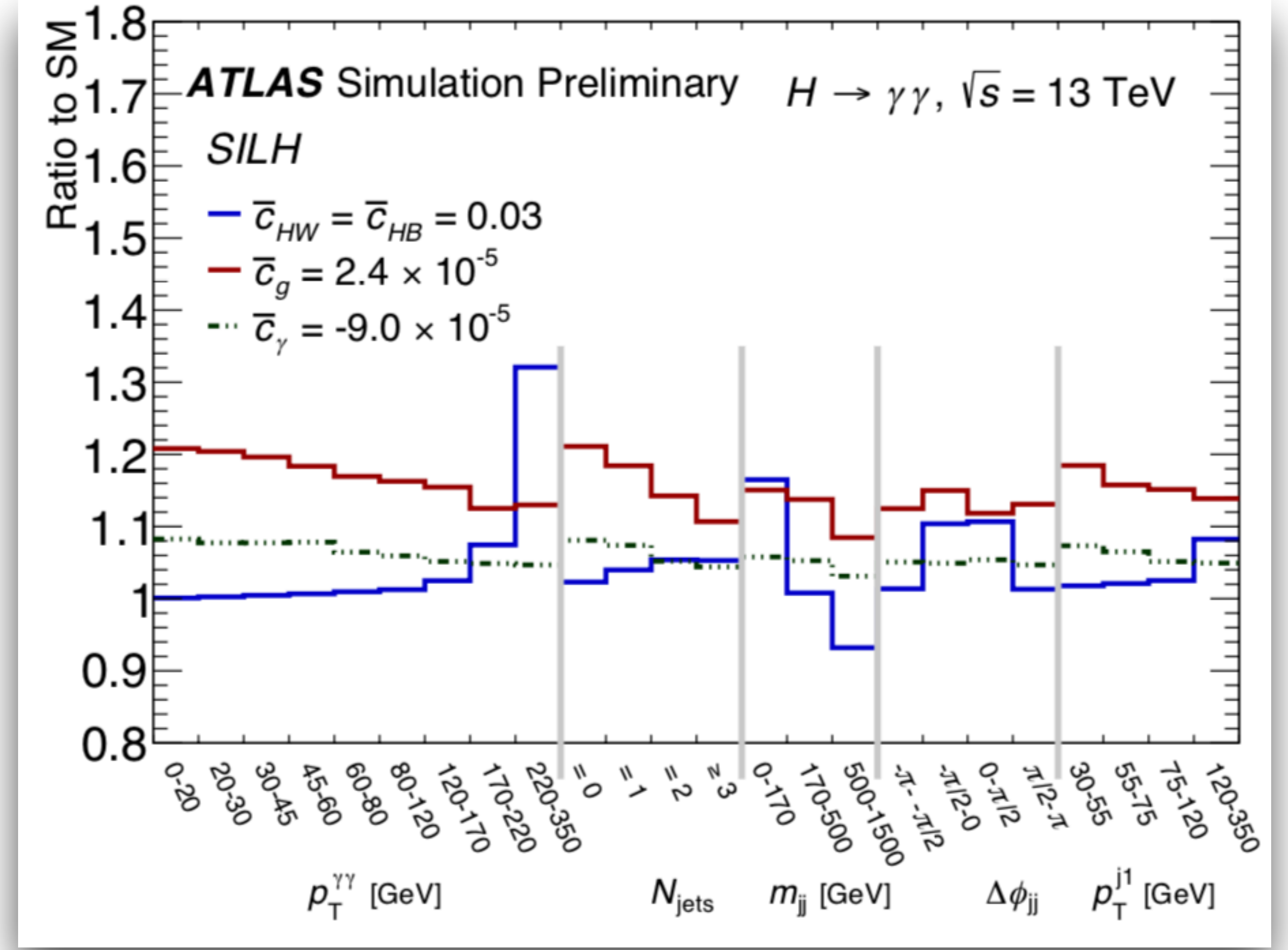
ATLAS-CONF-2019-029 139fb-1

- ***Strength and Tensor structure of the interactions of the Higgs boson:*** Effective Field Theory (addition of new interactions CP-even and CP-odd)
  - BSM contributions probed as non-zero Wilson coefficients
  - Basis of parametrization SILH and SMEFT: $c_i/\tilde{c}_i$ (Wilson coefficients); $O_i/\tilde{O}_i$ (6d operators that introduce new interactions)

- Simultaneous fit on $p_T^{\gamma\gamma}$, **N_jets**, m_{jj}, $\Delta\phi_{jj}$ **and** p_T^{j1} in order to set limits on the Wilson coefficients
  - correlations among them included (statistical, systematic and theoretical)

CP-even CP-odd

$$\mathcal{L}_{eff}^{SILH} \supset \bar{c}_g O_g + \bar{c}_\gamma O_\gamma + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O_{HB} + \tilde{c}_g \tilde{O}_g + \tilde{c}_\gamma \tilde{O}_\gamma + \tilde{c}_{HW} \tilde{O}_{HW} + \tilde{c}_{HB} \tilde{O}_{HB}$$

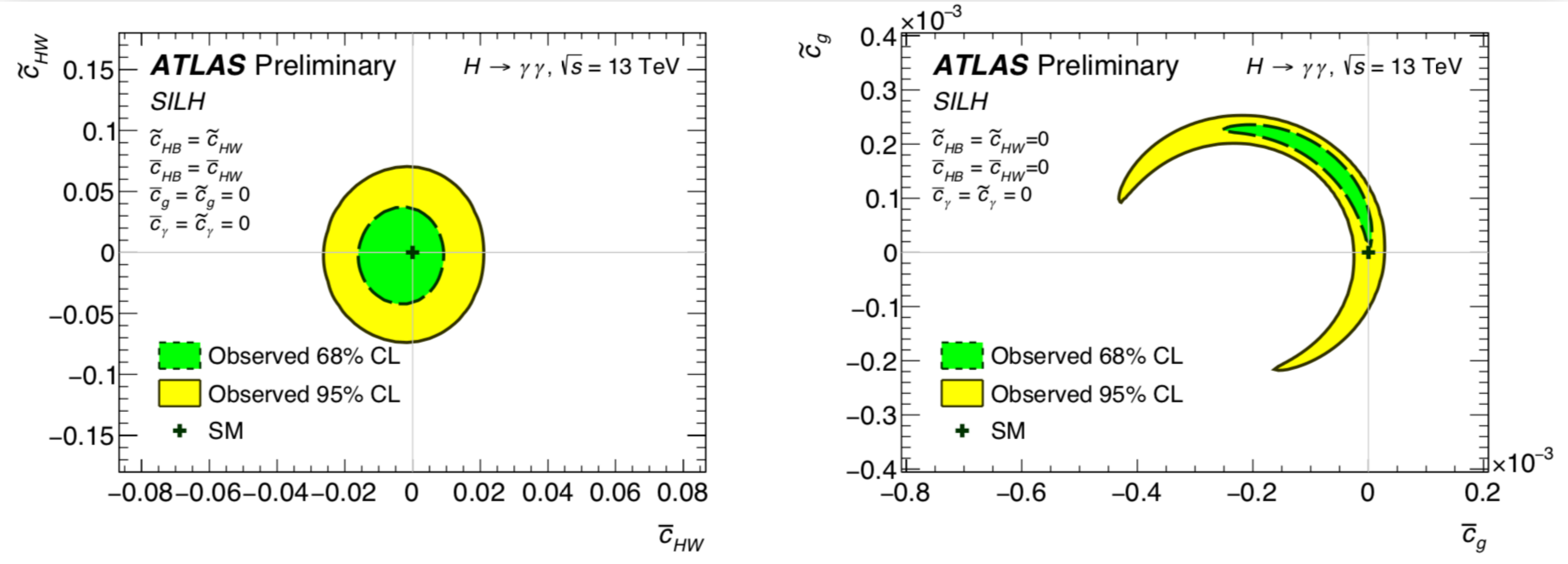


$\bar{c}_g$ *and* $\tilde{c}_g$

impact on overall normalization (ggH)

$\bar{c}_{HW}, \bar{c}_{HB}$ *and* $\tilde{c}_{HW}, \tilde{c}_{HB}$

large shapes changes for all observables (VBF/VH)



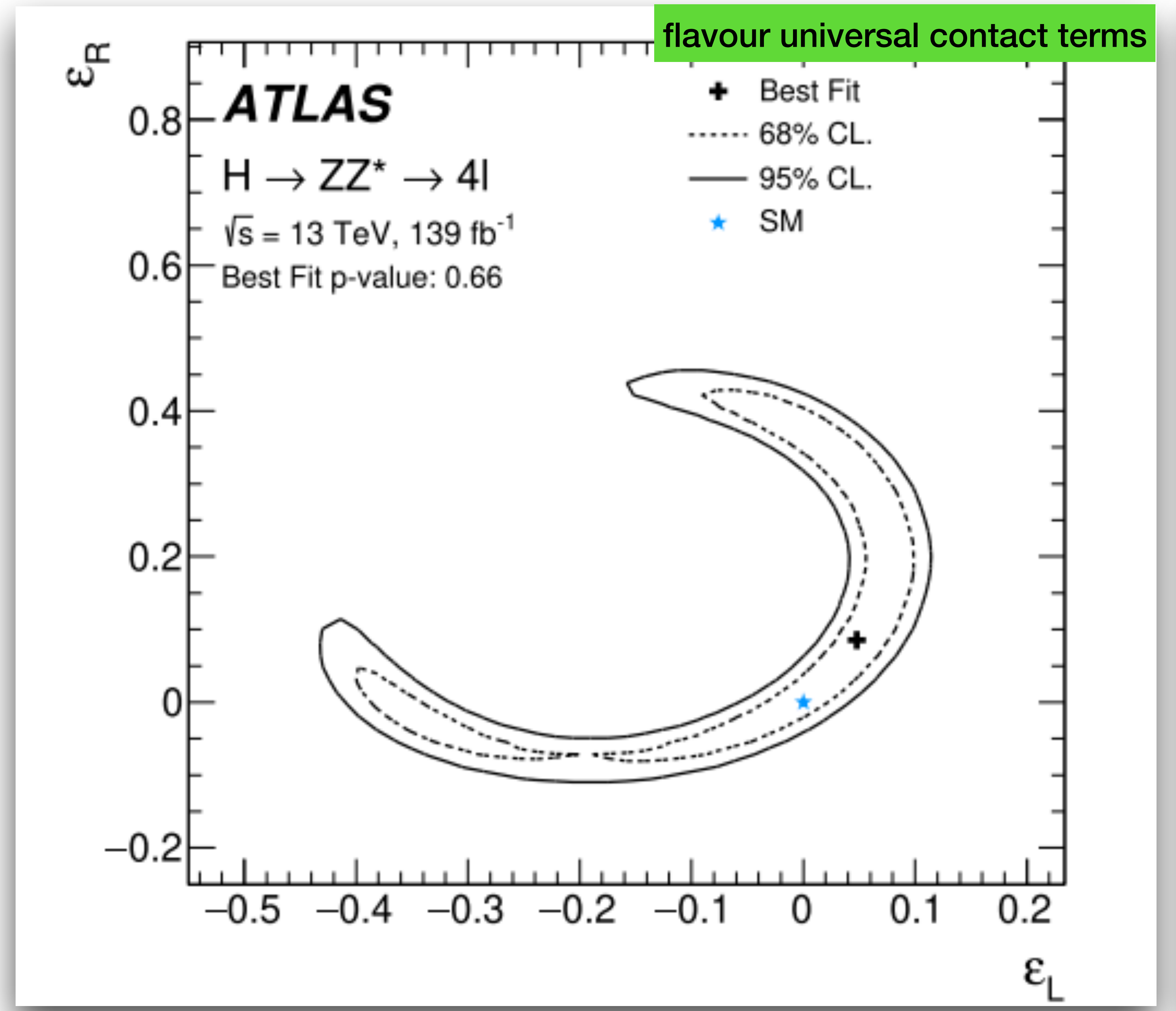
No significant BSM physics contributions are observed

More on EFT: Friday @ 14:50

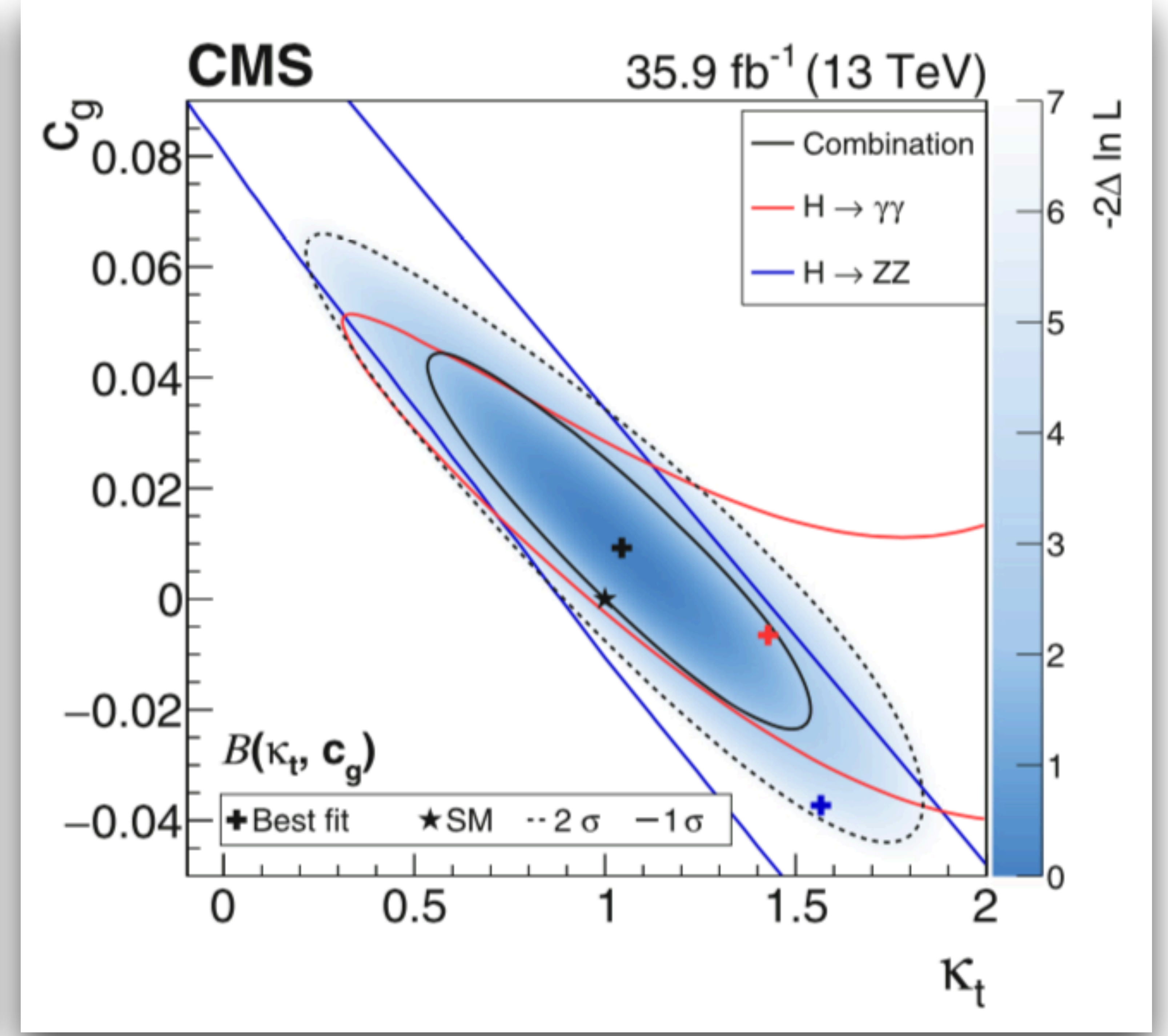
$H \to ZZ^* \to 4l$: interpretations

- ***Interpretations using the pseudo-observables (PO) framework (ATLAS):***
  - modified contact terms between H/Z bosons and left- and right-handed leptons (ϵ_{Z,l_L}, ϵ_{Z,l_R})
    - **m12 vs m34** (leading vs sub-leading Z boson mass) used for constraining the modified contact terms inside PO framework
- ***Interpretations using the k-framework (CMS):***
  - Simultaneous variations of κ_t, c_g *and* κ_b adding 6D operators (EFT approach) [1,2]
  - BR dependency on couplings and shape of pT(H) spectrum are taken into account

Eur. Phys. J. C (2020) 942 139fb-1



Physics Letters B 792 (2019) 35.9fb-1



No significant deviation is observed for ATLAS and CMS results

More on EFT: Friday @ 14:50

Yukawa coupling interpretations

- ◉ *Low pT(H) region provides sensitivity to Yukawa couplings of bottom and charm quarks:*
    - Indirect constraint using the **pT(H) shape only** ($H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$)
        - ***pT(H) < 140 GeV*** (most sensitive region) ($H \rightarrow \gamma\gamma$)
    - $H \rightarrow ZZ^* \rightarrow 4l$ also includes constrain using **pT(H) shape and modifications on total width and branching ratio**
    - **Stronger limits (charm quark)** @ 95% CL from $H \rightarrow ZZ^* \rightarrow 4l$ compared to $H \rightarrow \gamma\gamma$
- ◉ $H \rightarrow \gamma\gamma$: Less stringent limits compared to direct searches ($VH, H \rightarrow c\bar{c}$) but still complementary
- ◉ $H \rightarrow ZZ^* \rightarrow 4l$: comparable results to the direct searches ($VH, H \rightarrow c\bar{c}$)

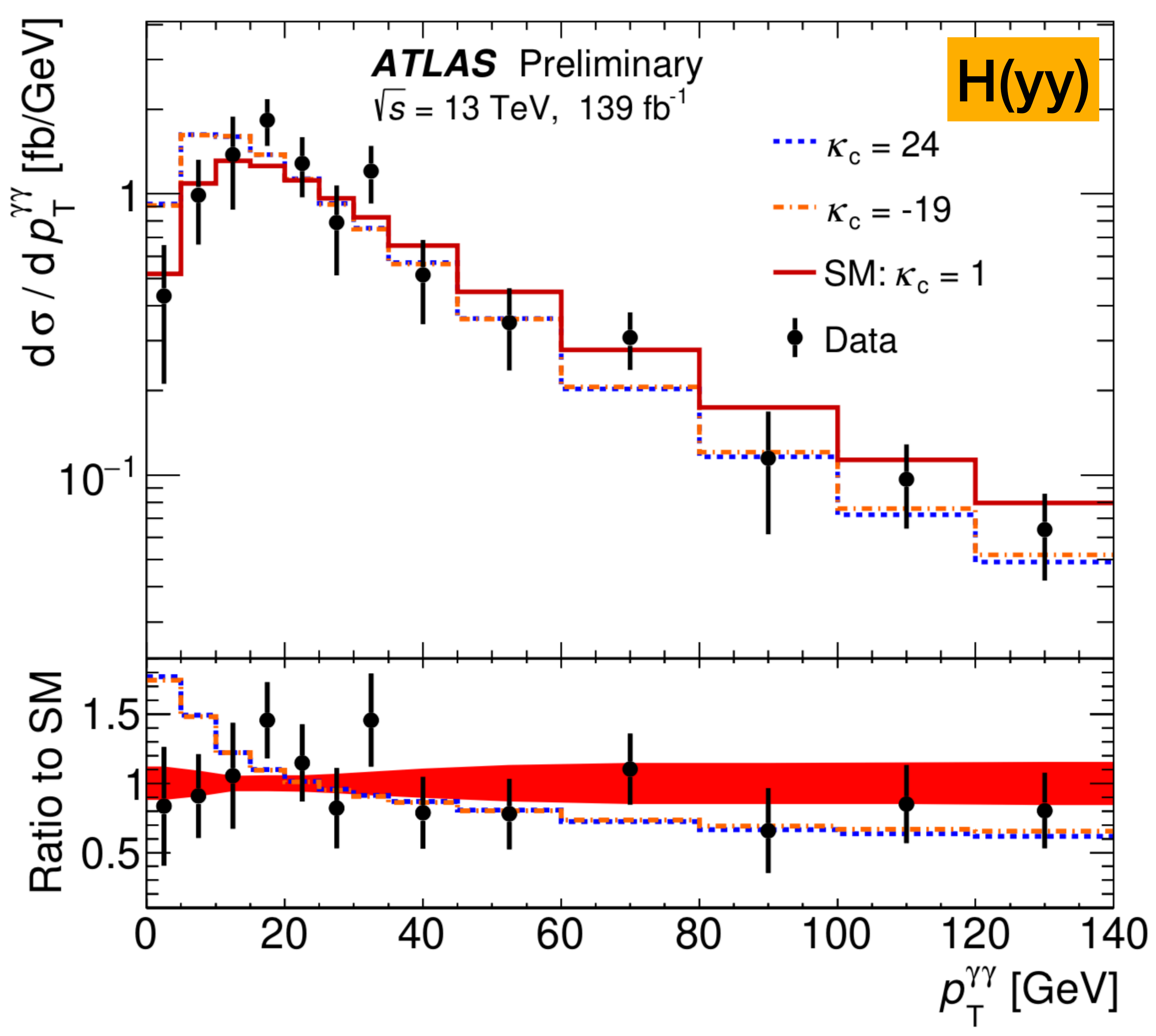
ATLAS-CONF-2019-029

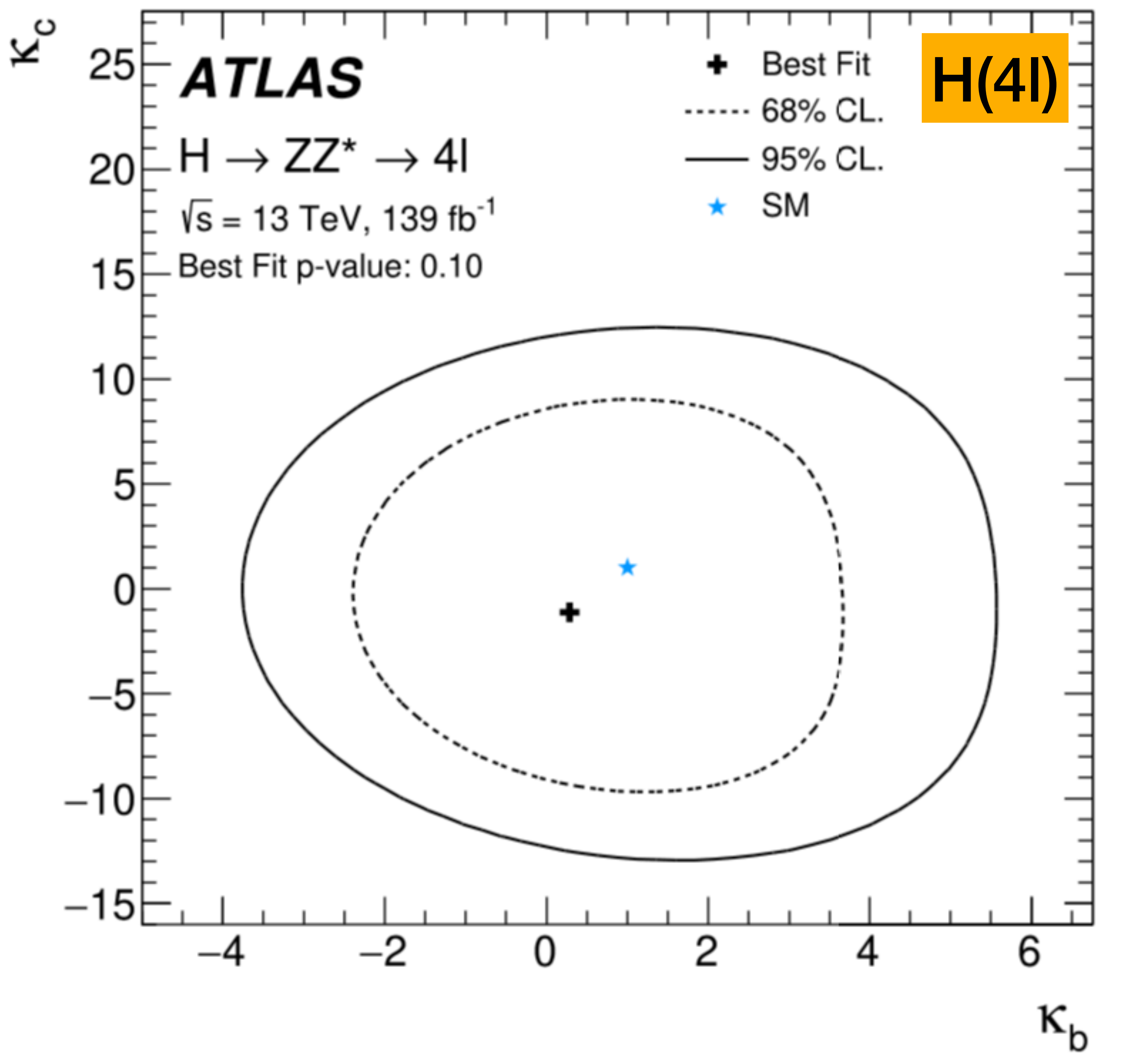
139fb-1

Eur. Phys. J. C (2020) 942

Coefficient	Observed 95% CL limit	Expected 95% CL limit
κ_c	[−19, 24]	[−15, 19]

Interpretation	Parameter best-fit value	95% confidence interval
Modifications to only $p_T^{4\ell}$ shape	$\kappa_c = -1.1$	[−11.7, 10.5]
	$\kappa_b = 0.28$	[−3.21, 4.50]
Modifications to $p_T^{4\ell}$ predictions	$\kappa_c = 0.66$	[−7.46, 9.27]
	$\kappa_b = 0.55$	[−1.82, 3.34]





Summary

✓ *Higgs Differential measurements in ATLAS and CMS experiments have been presented in the $H \to \gamma\gamma$, $H \to 4l$, $H \to W^-W^+$ and $H \to b\bar{b}$ channels:*

- ◉ Higgs boson properties and probe to new physics contributions in many observables exploring ***Higgs kinematic and jet-kinematic activity in the events***
- ◉ *Very good agreement between the measurements and SM predictions:*
  - Statistical uncertainty still the dominant uncertainty source in most channels
  - H(WW): statistical and systematic uncertainties are comparable
  - H($b\bar{b}$) measurement allowing exploration of high pT(H) region (pT > 1 TeV)
- ◉ ***Measurements are interpreted in the context of:*** EFT, k-framework, Yukawa couplings and POs
  - No significant BSM contributions are observed
- ◉ ***More results to come with the Full Run2 data-set:*** STAY TUNED!!!!

Back-up slides

Measurement methodology

- ***Fiducial region:*** defined to closely match the detector-level analysis and object selections

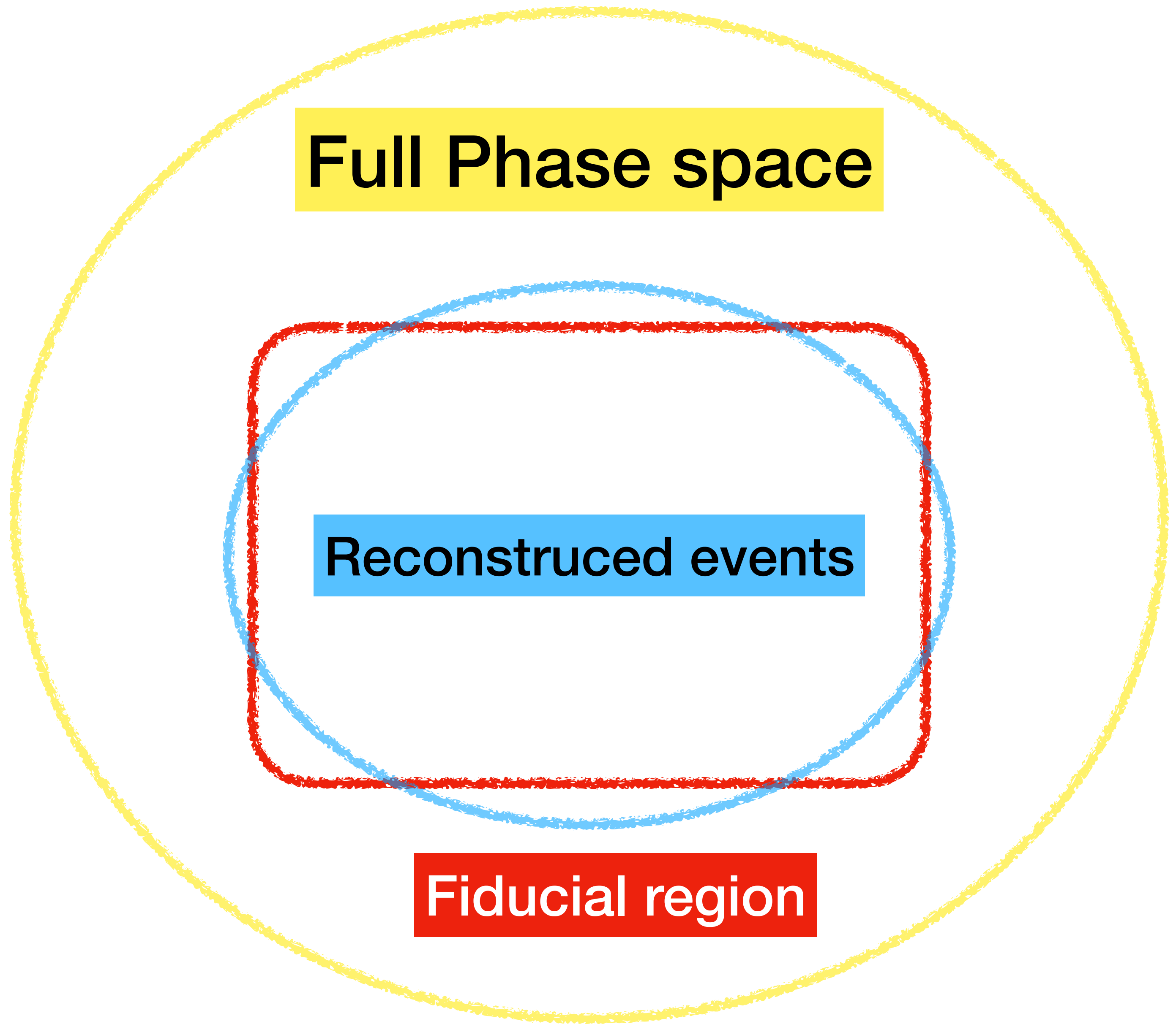
- ***Differential fiducial cross-section (ATLAS $H \rightarrow \gamma\gamma$ as an example)*** are measured in bins of the studied observable (bin i of a variable x)

  ✓ N_i^{sig} ***(measured signal yield):*** extracted signal events in data

  ✓ Δx ***(bin width):*** choice based on significance (more than 2σ) and minimize migrations

  ✓ c_i ***(correction factor):*** accounts for detector inefficiencies and resolutions effects as well as migrations in and out of fiducial region

  - ***unfolding techniques:*** ***bin-by-bin***, matrix inversion, regularized and un-regularized methods…

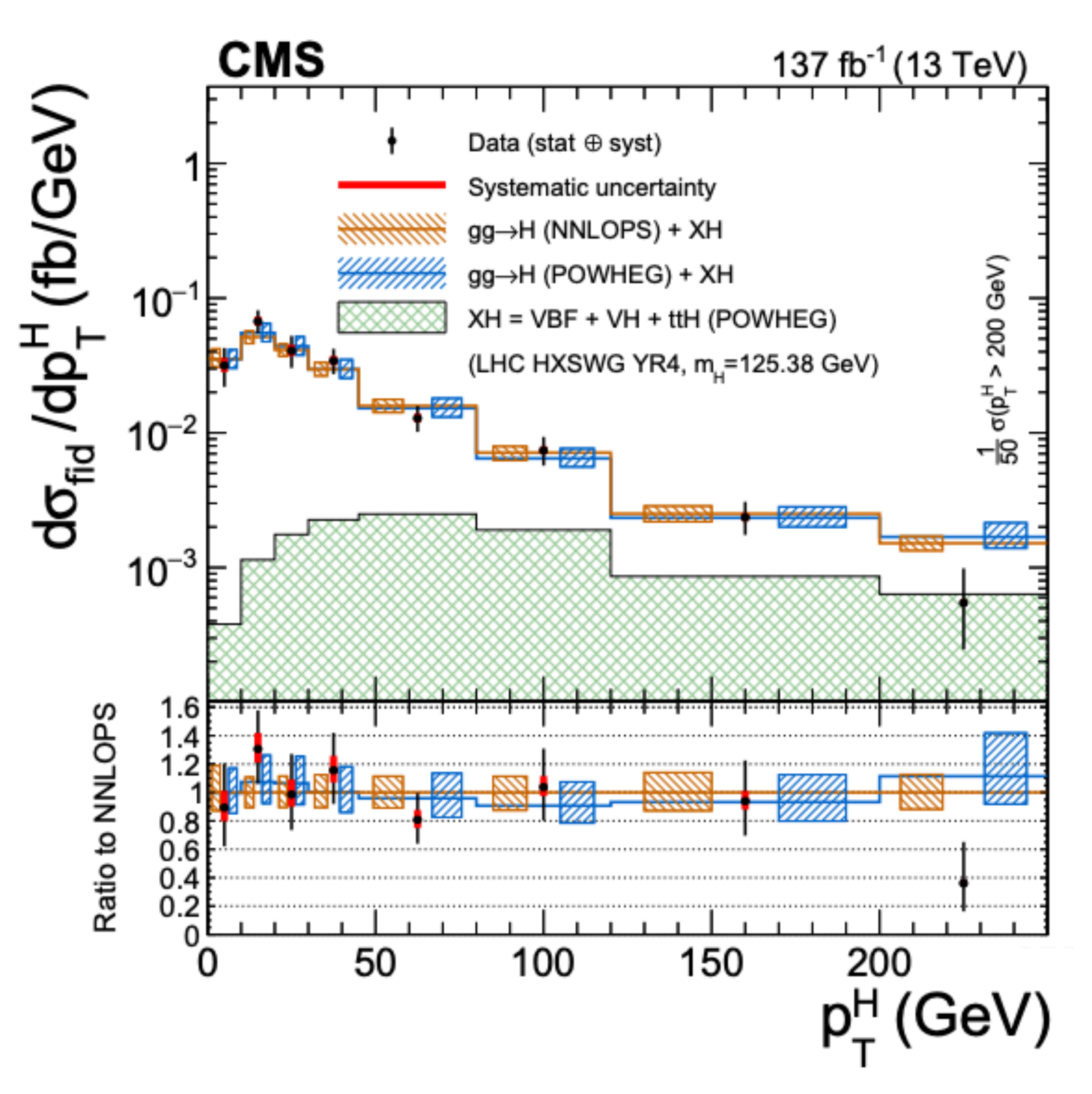


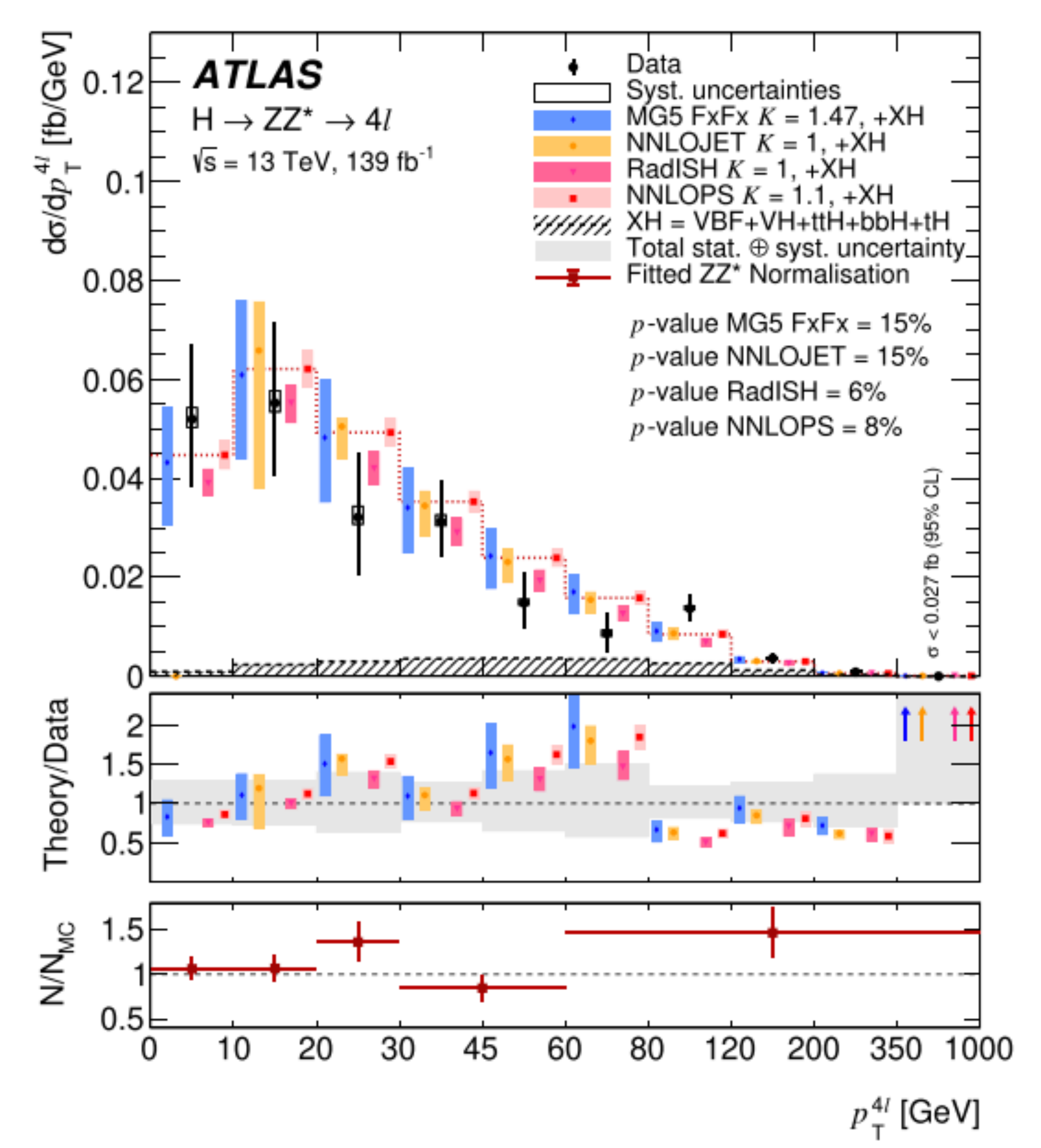
$$\frac{d\sigma_i}{dx} = \frac{N_i^{sig}}{c_i \Delta x \mathscr{L}}$$

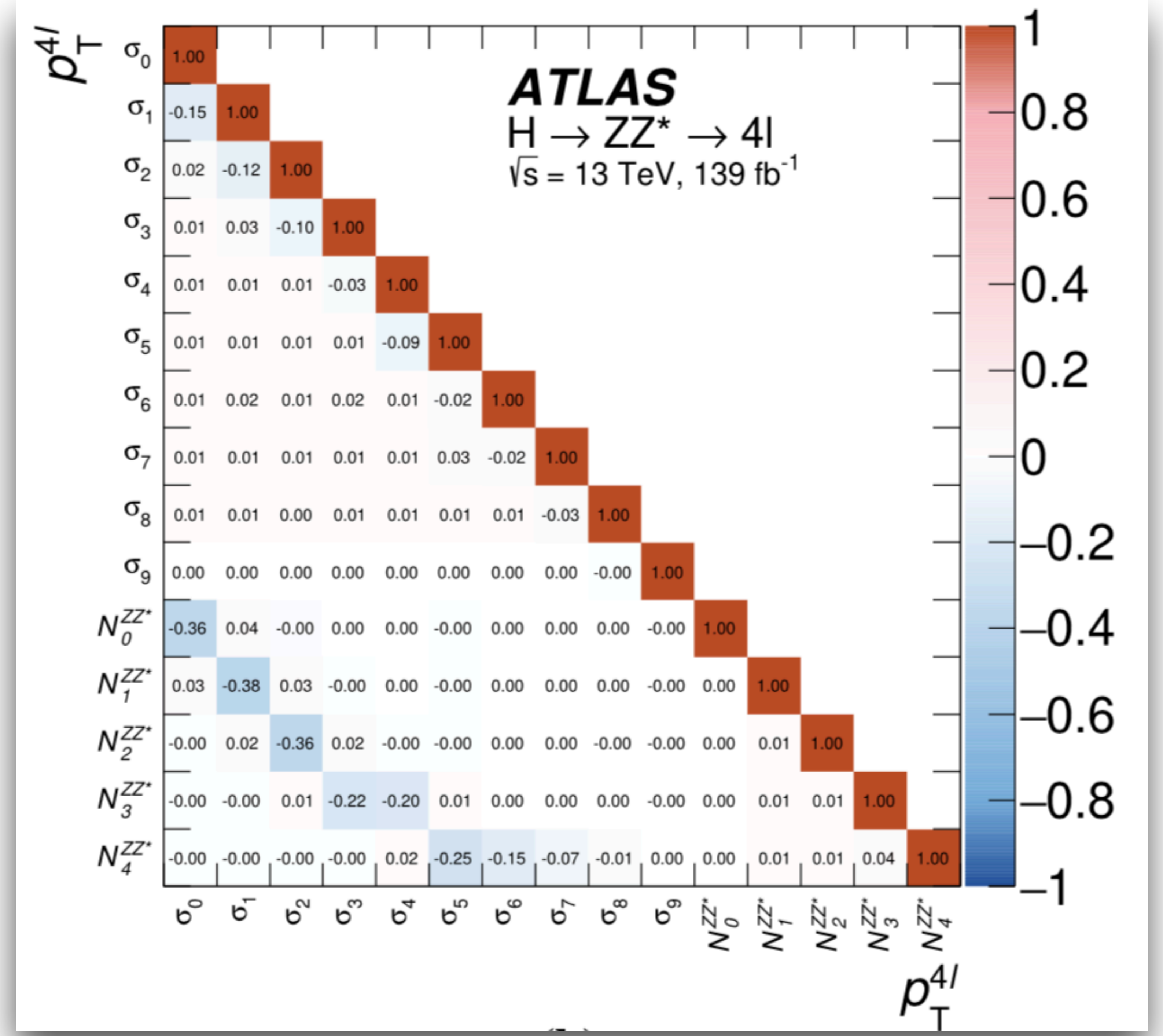
$H \to ZZ^* \to 4l$: pT(H) differential measurement

arXiv:2103.04956v1 (Submitted EPJC) 137fb-1

Eur. Phys. J. C (2020) 942 139fb-1







- **ATLAS:** ZZ normalization obtained in each bin of the observable and compared to the MC prediction (N/N_{MC})

- ***Good agreement with the SM predictions within the uncertainties:***
  - **ATLAS** $p(\chi^2)$ = 15% (MG5 FxFx and NNLOJET)

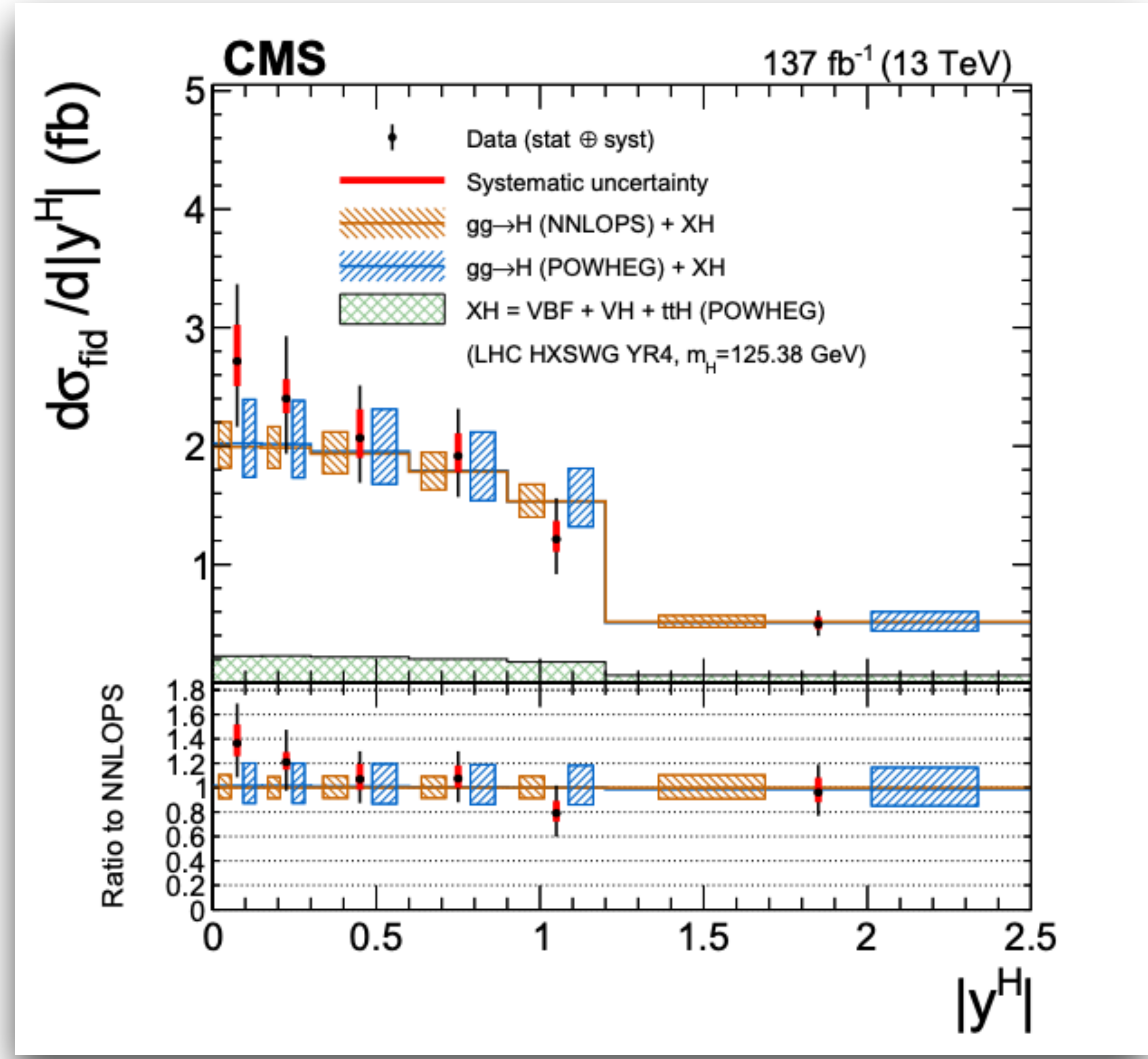
- ***Systematics uncertainties:***
  - **ATLAS**: luminosity (1.7%), lepton reconstruction and identification (1-3%) and ZZ^* theoretical uncertainties (1-6%)
  - **CMS**: luminosity (1.8%), lepton reconstruction and identification (1 to 2.3% (4μ) and 11 to 15.5% ($4e$))

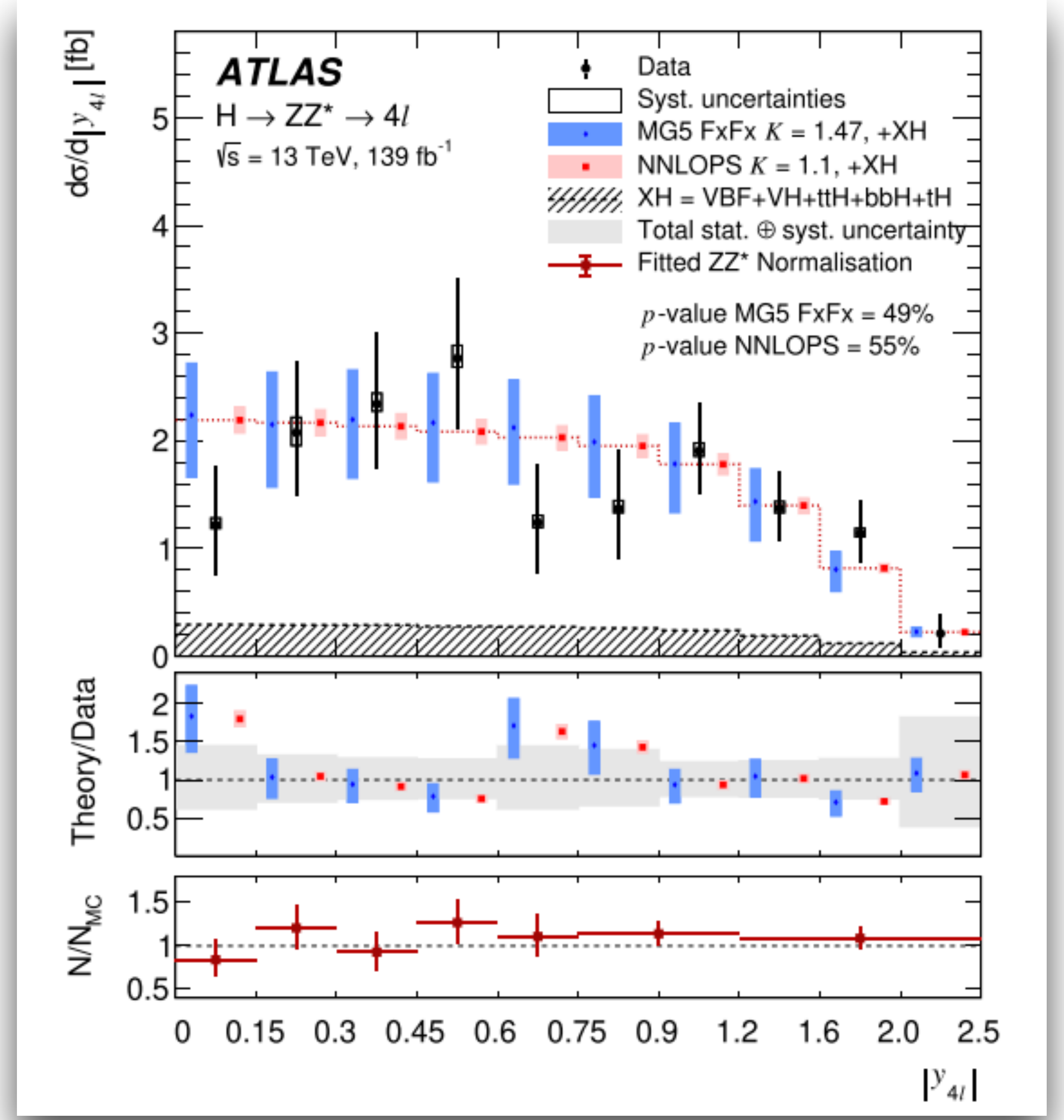
- Measurements are ***statistically dominated***

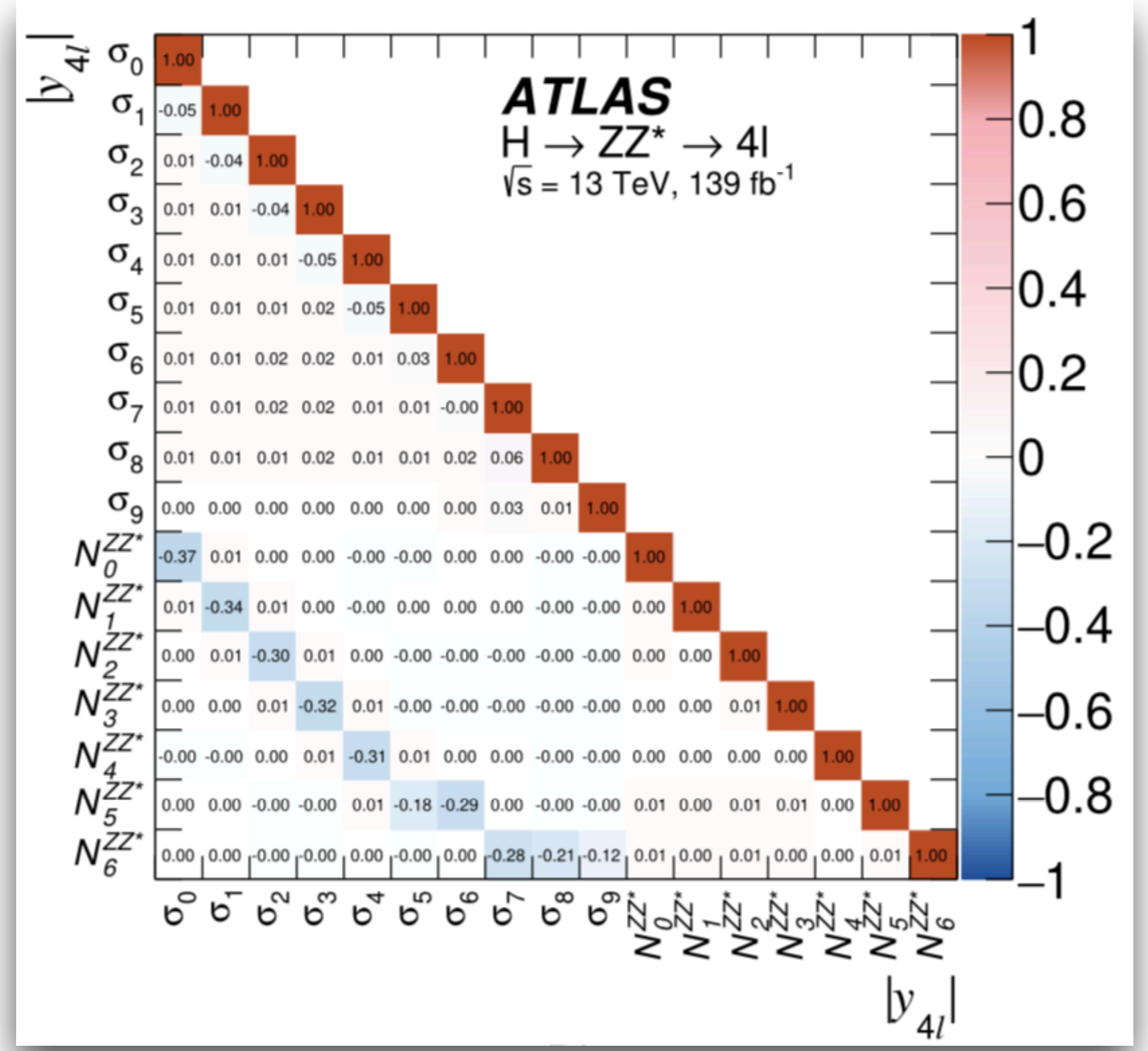
$H \to ZZ^* \to 4l$: y(H) differential measurement

arXiv:2103.04956v1 (Submitted EPJC) 137.1fb-1

Eur. Phys. J. C (2020) 942 139fb-1





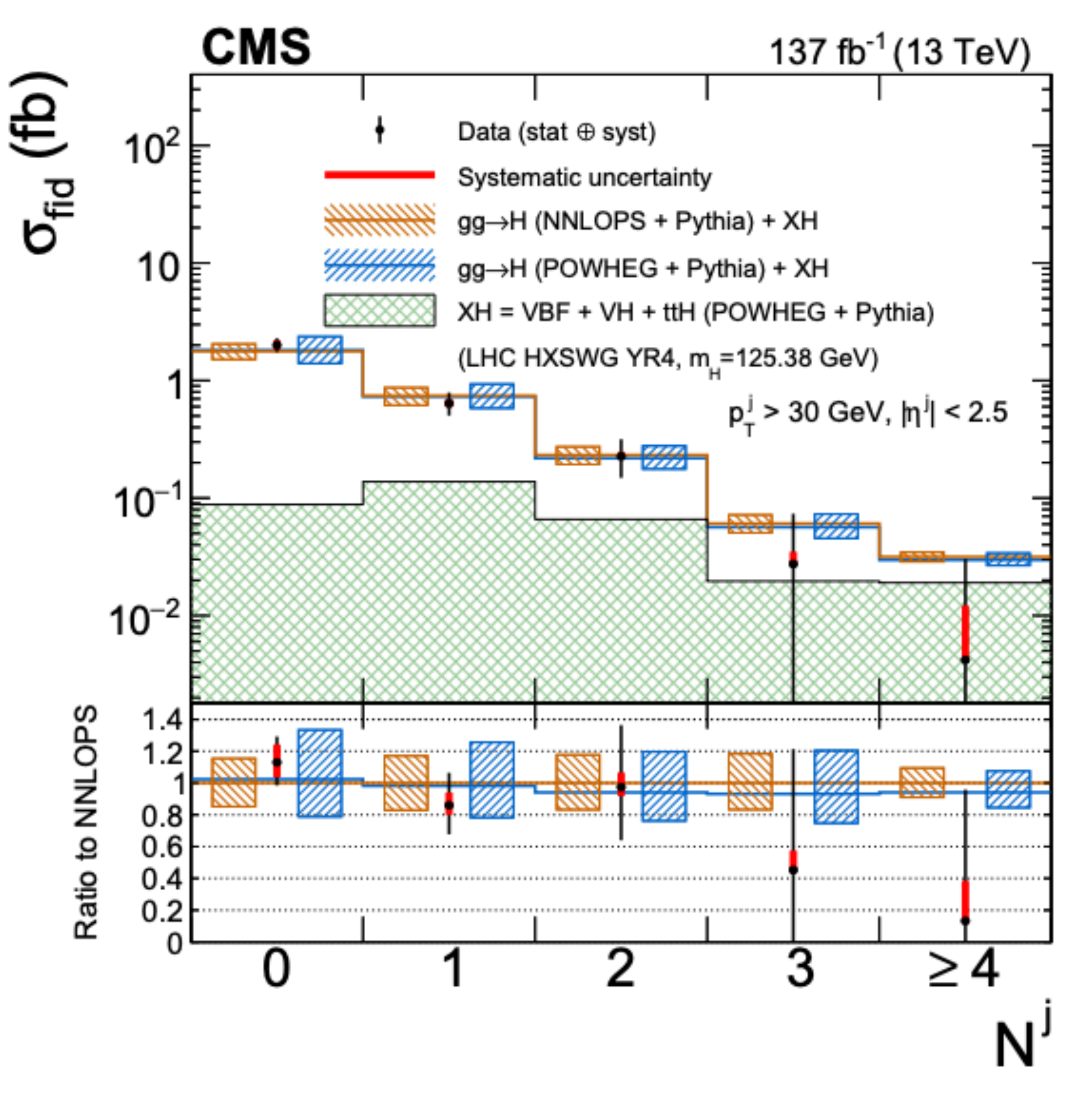


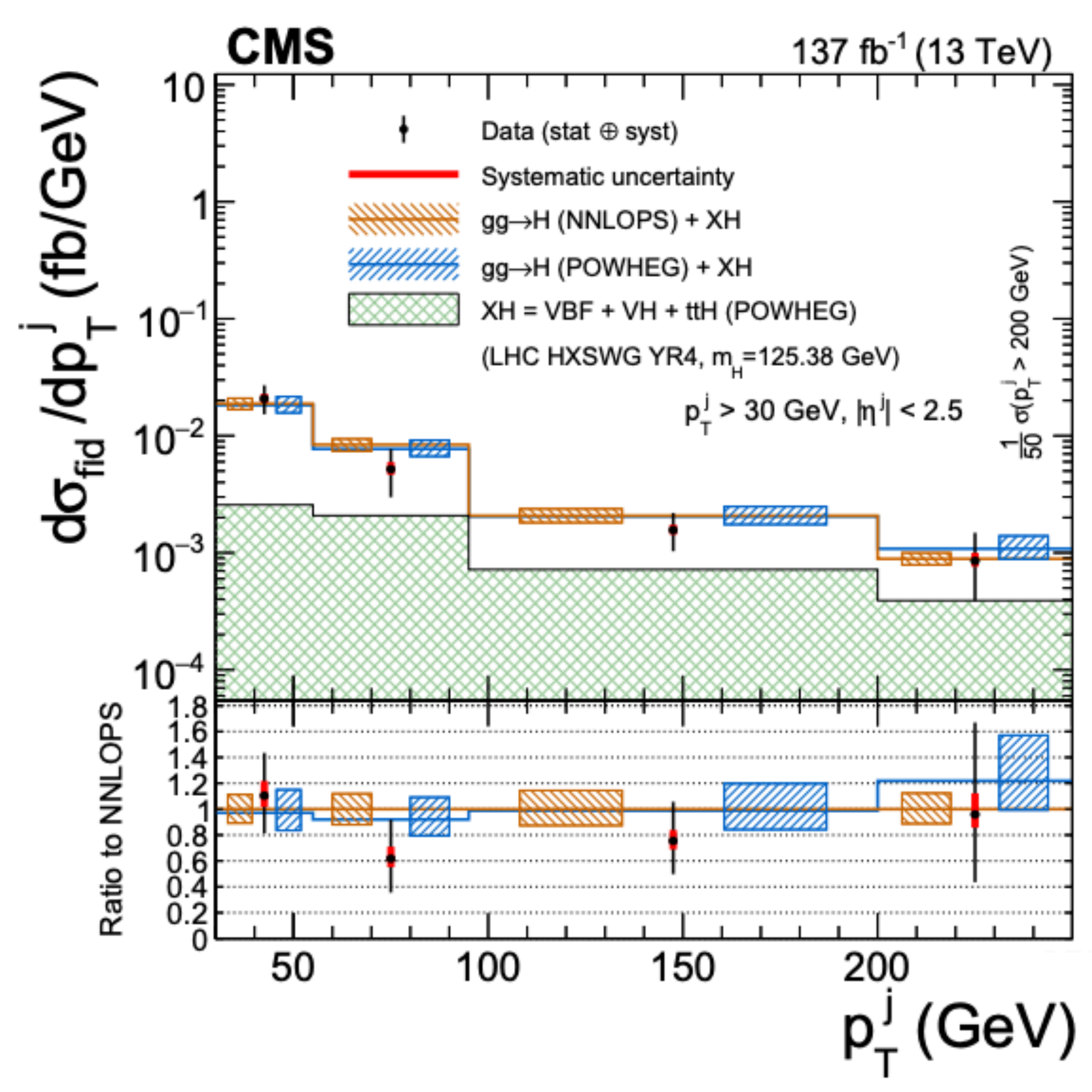
- *Good agreement with the SM predictions within the uncertainties:*
  - **ATLAS** $p(\chi^2)$ = 49% (MG5 FxFx)
  - **ATLAS** $p(\chi^2)$ = 49% (NNLOPS)

- ***Systematics uncertainties:***
  - **ATLAS**: luminosity (1.7%), lepton reconstruction and identification (2-3%) and ZZ^* theoretical uncertainties (1-5%)
  - **CMS**: luminosity (1.8%), lepton reconstruction and identification (1 to 2.3% (4μ) and 11 to 15.5% ($4e$))
- Measurements are ***statistically dominated***

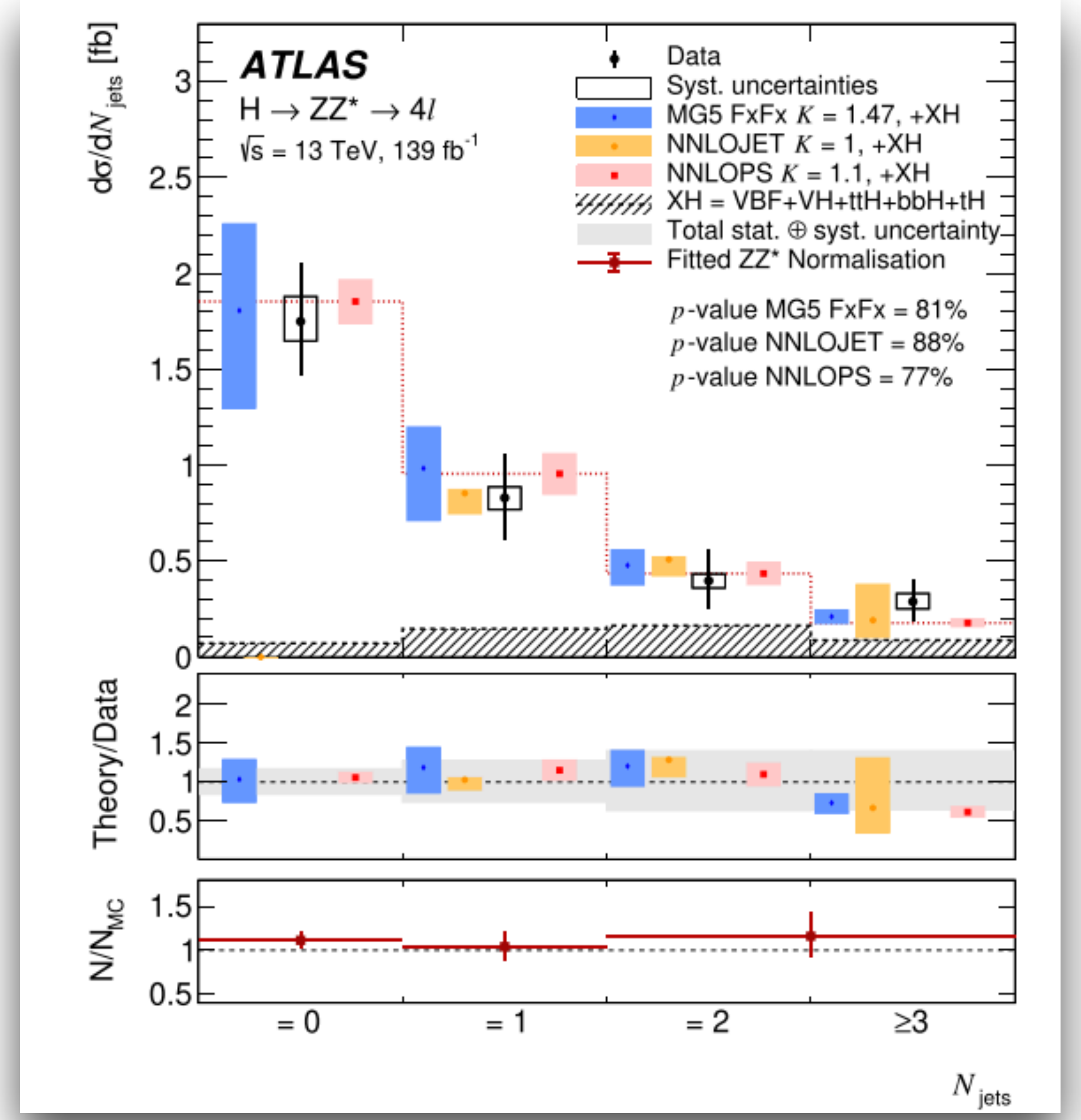
$H \to ZZ^* \to 4l$: Jet-kinematics differential measurement

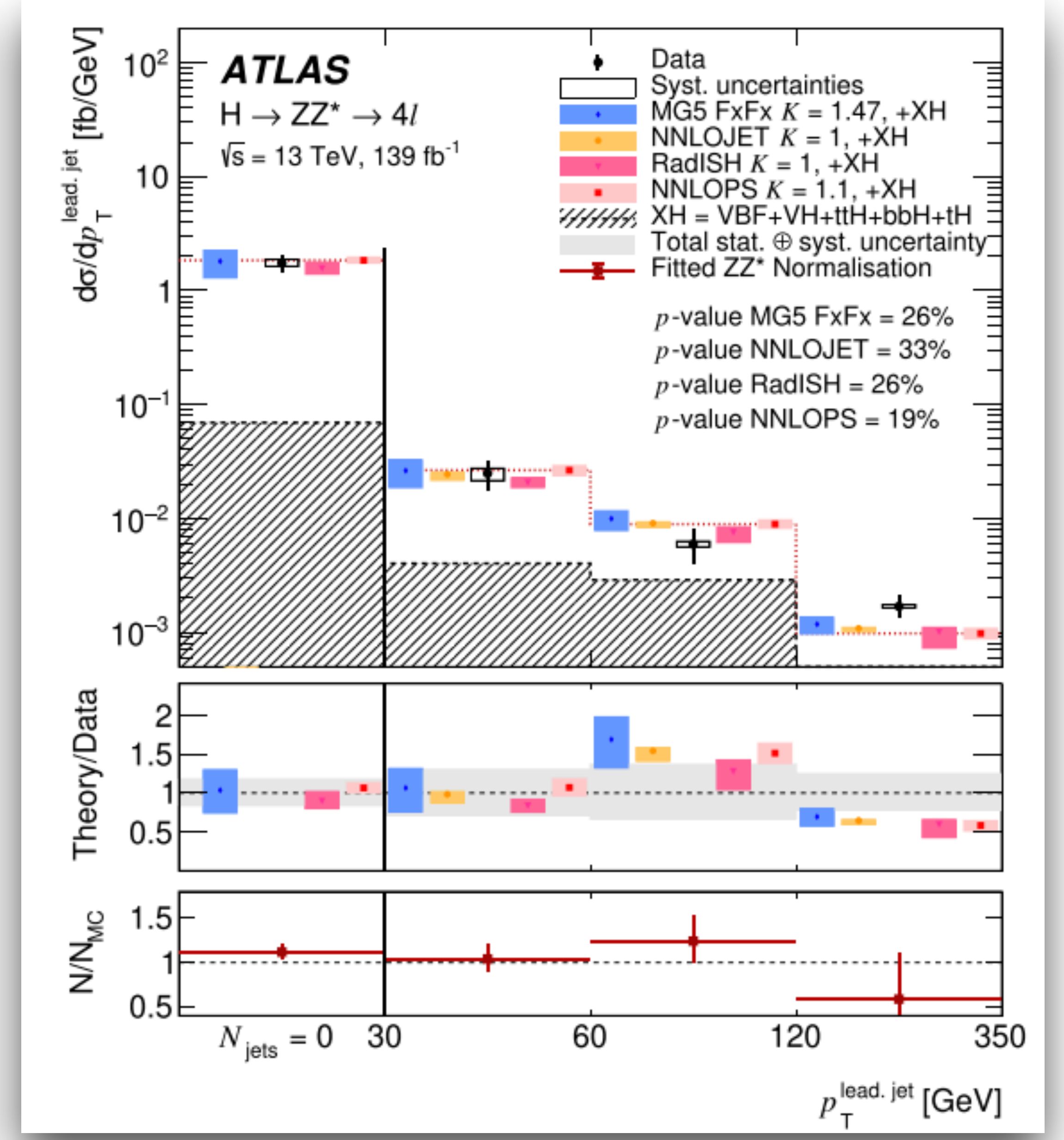
arXiv:2103.04956v1 (Submitted EPJC) 137fb-1





Eur. Phys. J. C (2020) 942 139fb-1





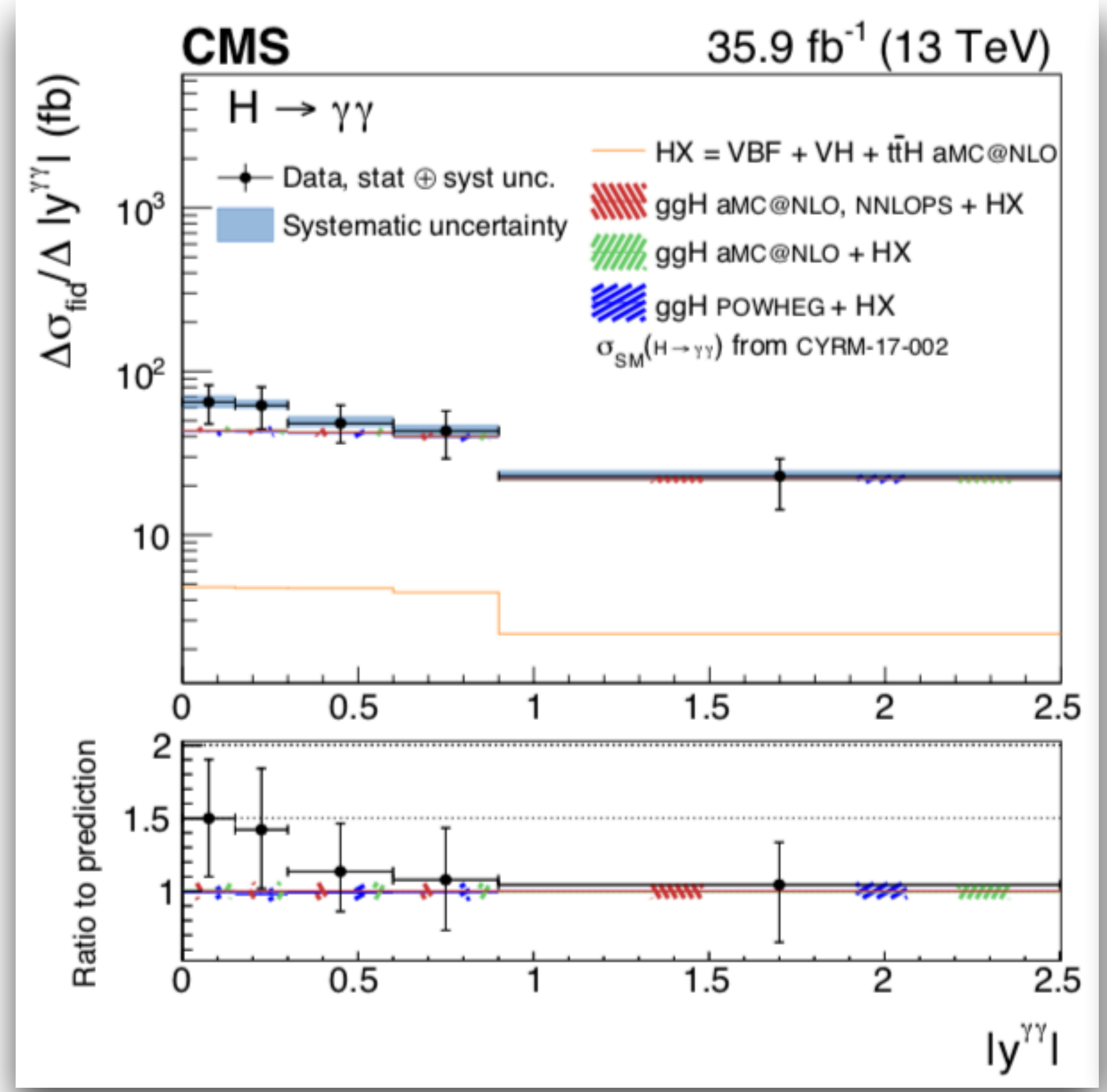
- **ATLAS:** jets pT > 30 GeV and |y| < 4.4
- **CMS:** jets pT > 30 GeV and $|\eta|$ < 2.5

- *Good agreement with the SM predictions within the uncertainties:*
  - **ATLAS** $p(\chi^2)$ = 88% (NNLOJET)
  - **ATLAS** $p(\chi^2)$ = 81% (MG5 FxFx)

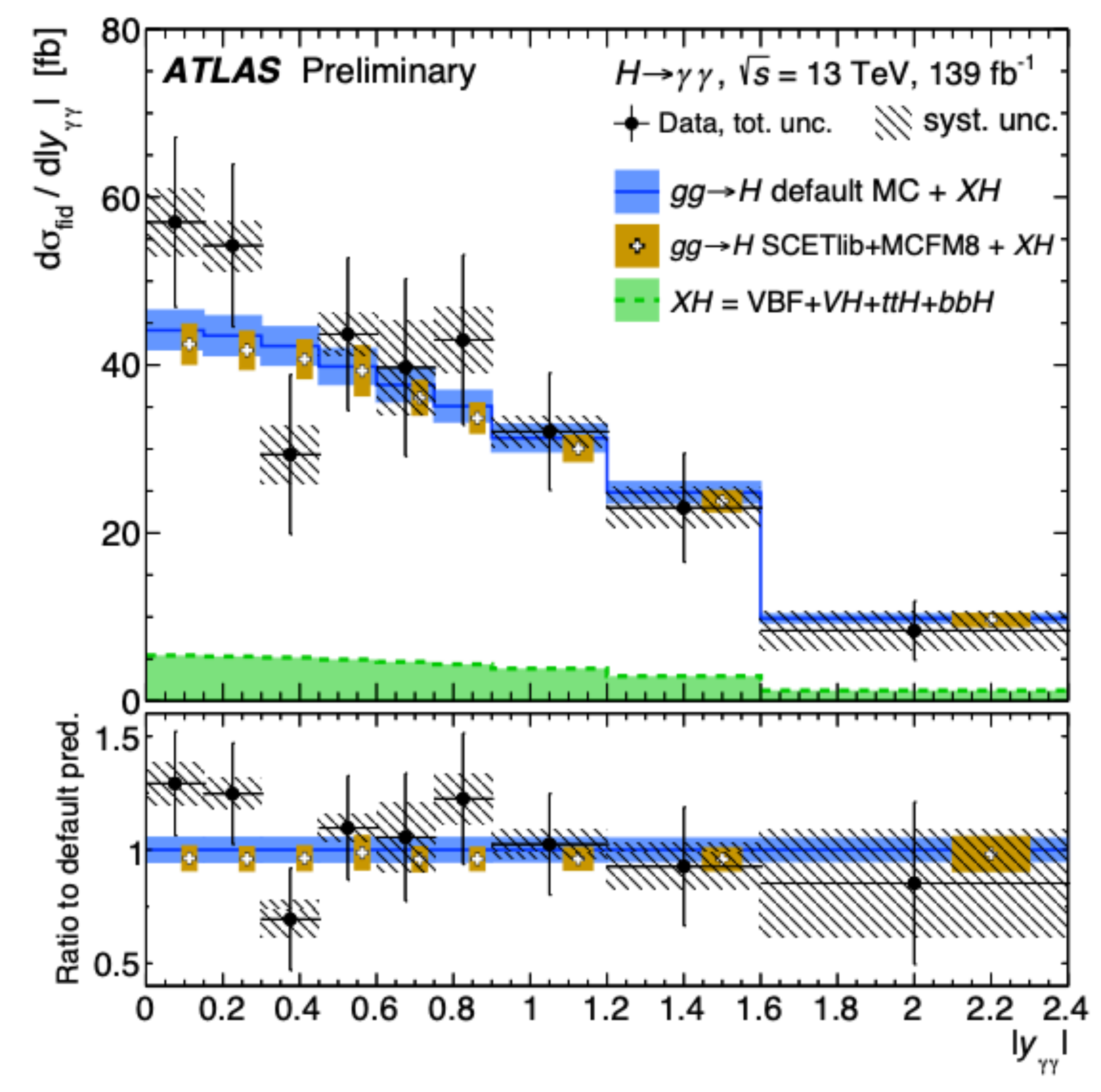
- ***Dominant systematics uncertainties:***
  - **ATLAS/CMS**: luminosity, lepton reconstruction and identification and ZZ^* theoretical uncertainties
- Measurements are ***statistically dominated***

$H \to \gamma\gamma$: y(H) differential measurement

JHEP01(2019)183 35.9fb-1



ATLAS-CONF-2019-029 139fb-1



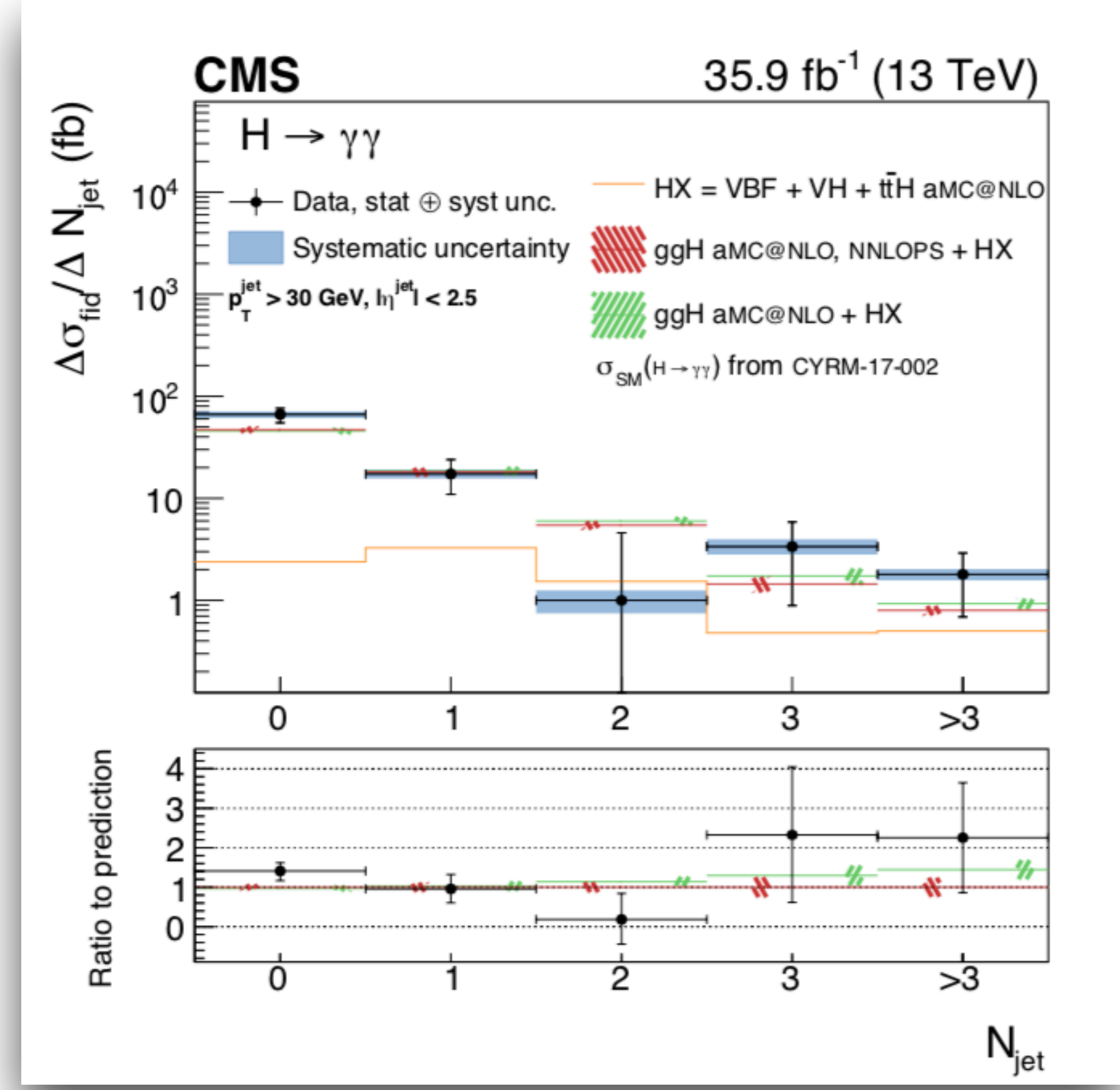
- *Good agreement with SM predictions within the uncertainties:*
  - ATLAS $p(\chi^2)$ = 68% (default MC prediction)
- Measurement is ***statistically dominated***

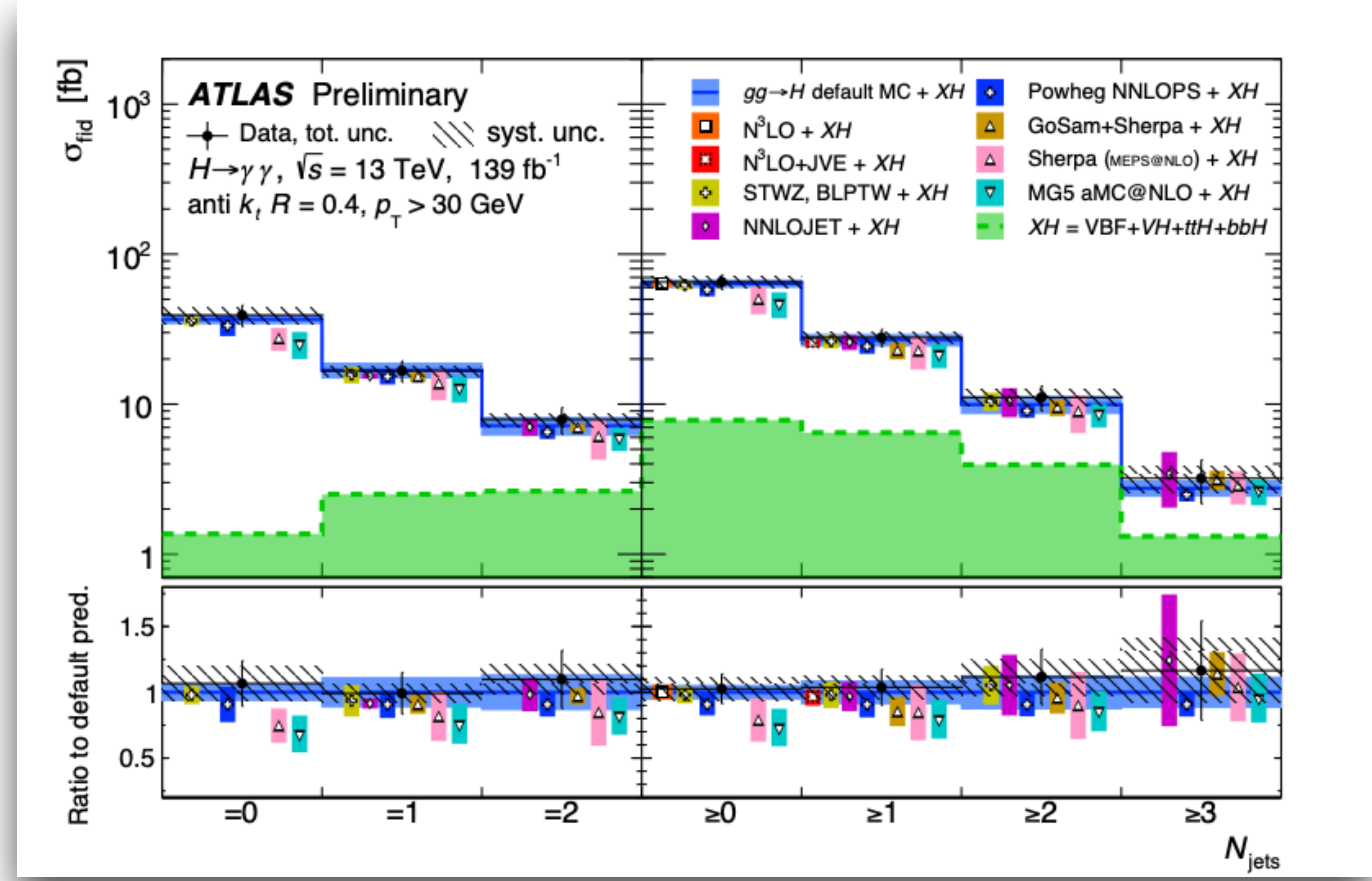
- ***Systematic uncertainties:***
  - **ATLAS:** luminosity (1.7%), photon energy scale and resolution and background modelling (up to 20%)
  - **CMS:** luminosity (2.5%), photon selection (0.3-3.2%), photon ID BDT score (3-5% depending on category), per-photon energy resolution (± 5 %)

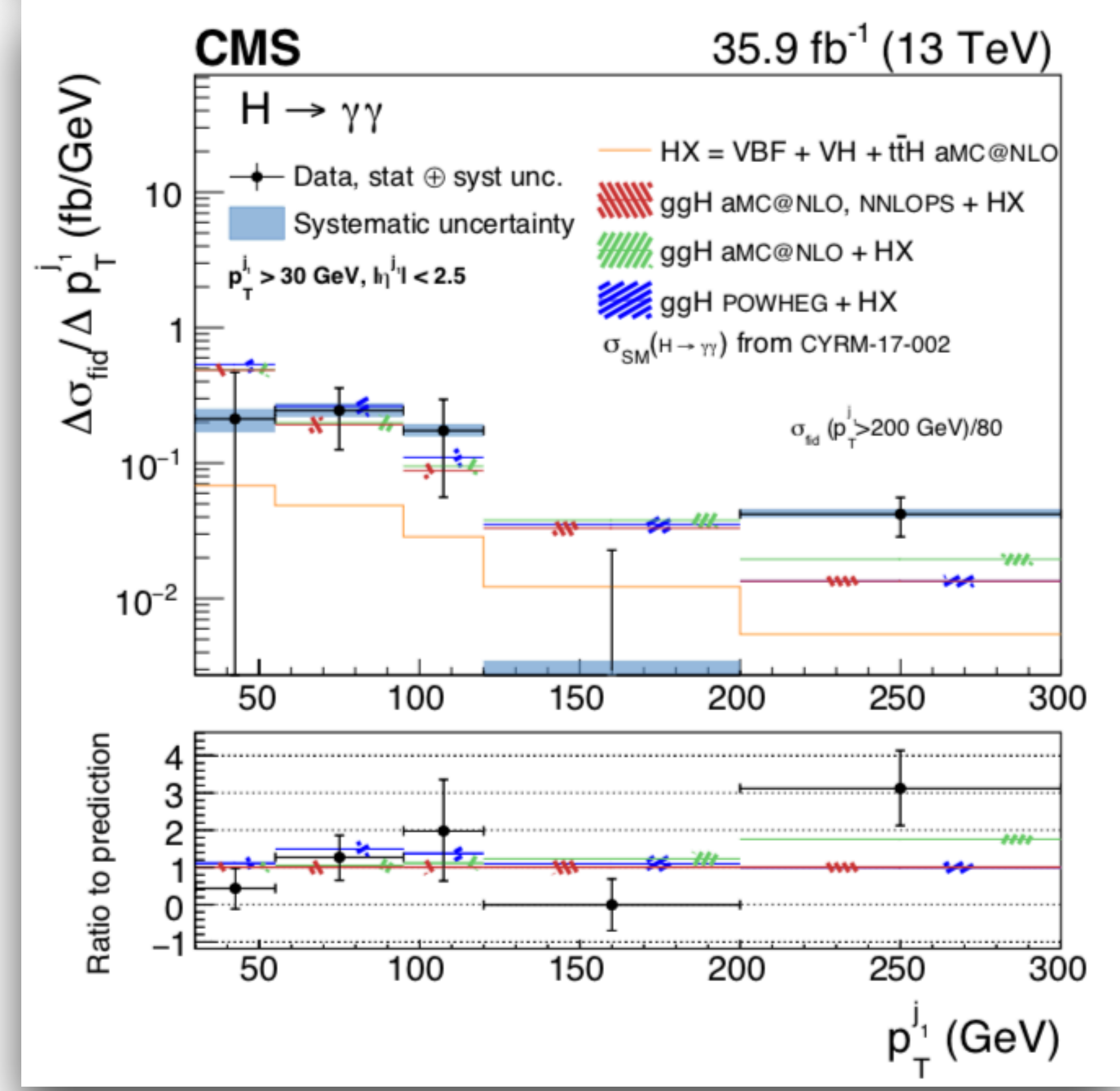
$H \to \gamma\gamma$: Jet-kinematics differential measurement

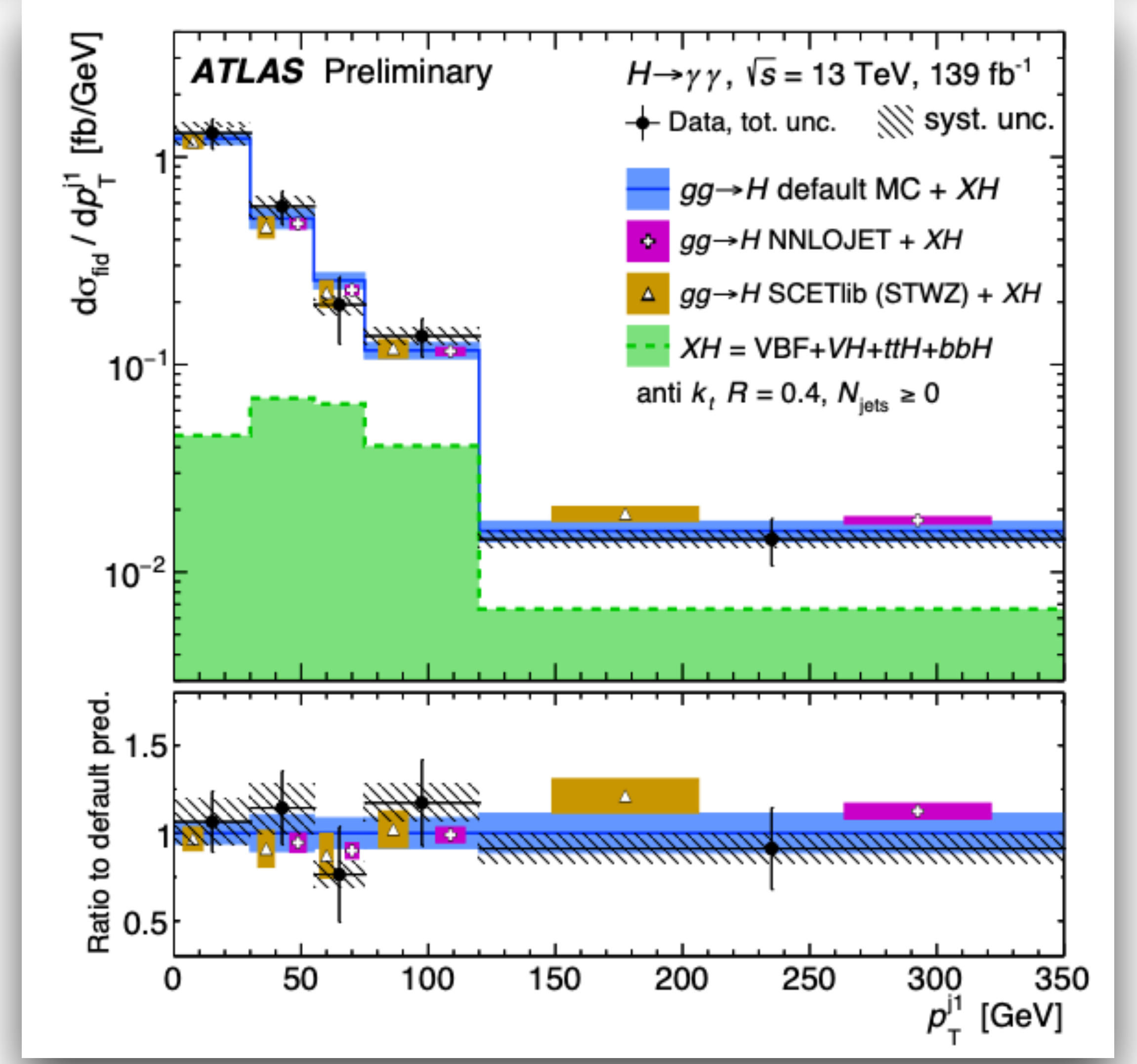
JHEP01(2019)183 35.9fb-1

ATLAS-CONF-2019-029 139fb-1









- **ATLAS:** jets pT > 30 GeV and |y| < 4.4
- **CMS:** jets pT > 30 GeV and $|\eta|$ < 2.5

- ***Good agreement with the SM predictions within the uncertainties:***
  - N_jets $p(\chi^2)$ = 96% (**ATLAS,** default MC prediction)
  - pT_j1(($p(\chi^2)$ = 77%) (**ATLAS,** default MC prediction)

- ***Systematic uncertainties:***
  - **ATLAS:** luminosity (1.7%), photon energy scale and resolution and background modelling (up to 20%) and JER+JES (up to 25%)
  - **CMS:** luminosity (2.5%), photon selection (0.3-3.2%), photon ID BDT score (3-5% depending on category), per-photon energy resolution (±5 %) and jet energy scale and resolution corrections (10-20%)

$H \to \gamma\gamma$: ATLAS/CMS binning

- Binning choice based on:
  - more than 2σ (statistical significance) for signal process
  - minimize migration between bins

- Bin boundaries for the different observables measured by the CMS experiment in H(yy) channel

139fb-1 (ATLAS)

Eur. Phys. J. C (2020) 942

Higgs boson kinematic-related variables	
$p_T^{4\ell}$, $\lvert y_{4\ell}\rvert$	Transverse momentum and rapidity of the four-lepton system
m_{12}, m_{34}	Invariant mass of the leading and subleading lepton pair
$\lvert\cos\theta^*\rvert$	Magnitude of the cosine of the decay angle of the leading lepton pair in the four-lepton rest frame relative to the beam axis
$\cos\theta_1$, $\cos\theta_2$	Production angles of the anti-leptons from the two Z bosons, where the angle is relative to the Z vector.
ϕ, ϕ_1	Two azimuthal angles between the three planes constructed from the Z bosons and leptons in the Higgs boson rest frame.
Jet-related variables	
N_{jets}, $N_{b\text{-jets}}$	Jet and b-jet multiplicity
$p_T^{\text{lead. jet}}$, $p_T^{\text{sublead. jet}}$	Transverse momentum of the leading and subleading jet, for events with at least one and two jets, respectively. Here, the leading jet refers to the jet with the highest p_T in the event, while subleading refers to the jet with the second-highest p_T.
m_{jj}, $\lvert\Delta\eta_{jj}\rvert$, $\Delta\phi_{jj}$	Invariant mass, difference in pseudorapidity, and signed difference in ϕ of the leading and subleading jets for events with at least two jets
Higgs boson and jet-related variables	
$p_T^{4\ell j}$, $m_{4\ell j}$	Transverse momentum and invariant mass of the four-lepton system and leading jet, for events with at least one jet
$p_T^{4\ell jj}$, $m_{4\ell jj}$	Transverse momentum and invariant mass of the four-lepton system and leading and subleading jets, for events with at least two jets

35.9fb-1 (CMS)

JHEP01(2019)183

Phase space region	Observable	Bin boundaries								
	$p_T^{\gamma\gamma}$ (GeV)	0	15	30	45	80	120	200	350	∞
	N_{jet}	0	1	2	3	4	∞			
Baseline	$\lvert y^{\gamma\gamma}\rvert$	0	0.15	0.3	0.6	0.9	2.5			
$p_T^{\gamma_1}/m_{\gamma\gamma} > 1/3$	$\lvert\cos(\theta^*)\rvert$	0	0.1	0.25	0.35	0.55	1			
$p_T^{\gamma_2}/m_{\gamma\gamma} > 1/4$	$p_T^{\gamma\gamma}$ (GeV), $N_{\text{jet}} = 0$	0	20	60	∞					
$\lvert\eta^\gamma\rvert < 2.5$	$p_T^{\gamma\gamma}$ (GeV), $N_{\text{jet}} = 1$	0	60	120	∞					
$\text{Iso}_{\text{gen}}^{\gamma} < 10\,\text{GeV}$	$p_T^{\gamma\gamma}$ (GeV), $N_{\text{jet}} > 1$	0	150	300	∞					
	$N_{\text{jet}}^{\text{b}}$	0	1	2	∞					
	N_{lepton}	0	1	2	∞					
	p_T^{miss} (GeV)	0	100	200	∞					
1-jet	$p_T^{j_1}$ (GeV)	0	45	70	110	200	∞			
Baseline + $\geq$1 jet	$\lvert y^{j_1}\rvert$	0	0.5	1.2	2	2.5				
$p_T^j > 30\,\text{GeV}$, $\lvert\eta^j\rvert < 2.5$	$\lvert\Delta\phi^{\gamma\gamma,j_1}\rvert$	0	2.6	2.9	3.03	π				
	$\lvert\Delta y^{\gamma\gamma,j_1}\rvert$	0	0.6	1.2	1.9	∞				
	$p_T^{j_2}$ (GeV)	0	45	90	∞					
	$\lvert y^{j_2}\rvert$	0	1.2	2.5	4.7					
2-jets	$\lvert\Delta\phi^{j_1,j_2}\rvert$	0	0.9	1.8	π					
Baseline + $\geq$2 jets	$\lvert\Delta\phi^{\gamma\gamma,j_1j_2}\rvert$	0	2.9	3.05	π					
$p_T^j > 30\,\text{GeV}$, $\lvert\eta^j\rvert < 4.7$	$\lvert\overline{\eta}_{j_1j_2} - \eta_{\gamma\gamma}\rvert$	0	0.5	1.2	∞					
	$m^{j_1j_2}$ (GeV)	0	100	150	450	1000	∞			
	$\lvert\Delta\eta^{j_1,j_2}\rvert$	0	1.6	4.3	∞					
VBF-enriched	$p_T^{j_2}$ (GeV)	0	45	90	∞					
2-jets + $\lvert\Delta\eta^{j_1,j_2}\rvert > 3.5$, $m^{j_1j_2} > 200\,\text{GeV}$	$\lvert\Delta\phi^{j_1,j_2}\rvert$	0	0.9	1.8	π					
	$\lvert\Delta\phi^{\gamma\gamma,j_1j_2}\rvert$	0	2.9	3.05	π					

ATLAS HL-LHC: systematic uncertainties @ pT(H) binning

ATL-PHYS-PUB-2018-040

pT(H), H->yy

Bin [GeV]	Relative uncertainty [%] Without Sys.	Relative uncertainty [%] With Unscaled Syst.	Relative uncertainty [%] With Scaled Syst.
0, 10	4.7	6.5	5.3
10, 20	3.9	5.9	4.6
20, 30	4.3	6.2	4.9
30, 45	4.1	6.0	4.7
45, 60	4.9	6.5	5.4
60, 80	5.0	6.7	5.7
80, 120	4.3	6.0	4.9
120, 200	3.4	5.4	4.2
200, 350	3.9	6.3	5.1
350, 1000	7.4	9.5	8.7

pT(H), H->4l

Bin [GeV]	Relative uncertainty [%] Without Sys.	Relative uncertainty [%] With Unscaled Syst.	Relative uncertainty [%] With Scaled Syst.
0, 10	5.5	9.0	8.3
10, 15	6.1	8.1	7.6
15, 20	6.2	8.9	8.3
20, 30	4.6	6.9	6.3
30, 45	4.3	6.3	5.7
45, 60	5.2	6.8	6.2
60, 80	5.4	6.8	6.3
80, 120	4.9	6.2	5.7
120, 200	5.6	6.7	6.4
200, 350	9.4	13.2	13.1
350, 1000	23	24	23

pT(H), Combination

Bin [GeV]	Relative uncertainty [%] Without Sys.	Relative uncertainty [%] With Unscaled Syst.	Relative uncertainty [%] With Scaled Syst.
0, 10	3.2	5.5	4.5
10, 20	3.0	4.8	3.8
20, 30	2.8	5.0	3.9
30, 45	2.7	4.7	3.6
45, 60	3.2	5.0	4.1
60, 80	3.3	5.1	4.2
80, 120	2.9	4.6	3.7
120, 200	2.7	4.4	3.5
200, 350	3.4	5.4	4.5
350, 1000	6.8	8.7	8.2

CMS HL-LHC: systematic uncertainties @ pT(H) binning

CMS PAS FTR-18-011

Systematic uncertainties and expected improvements

Source	Component	Run 2 uncertainty	Projection minimum uncertainty
Muon ID		1–2%	0.5%
Electron ID		1–2%	0.5%
Photon ID		0.5–2%	0.25–1%
Hadronic tau ID		6%	2.5%
Jet energy scale	Absolute	0.5%	0.1–0.2%
	Relative	0.1–3%	0.1–0.5%
	Pileup	0–2%	Same as Run 2
	Method and sample	0.5–5%	No limit
	Jet flavour	1.5%	0.75%
	Time stability	0.2%	No limit
Jet energy res.		Varies with p_T and η	Half of Run 2
MET scale		Varies with analysis selection	Half of Run 2
b-Tagging	b-/c-jets (syst.)	Varies with p_T and η	Same as Run 2
	light mis-tag (syst.)	Varies with p_T and η	Same as Run 2
	b-/c-jets (stat.)	Varies with p_T and η	No limit
	light mis-tag (stat.)	Varies with p_T and η	No limit
Integrated lumi.		2.5%	1%

Run2 systematic uncertainties

$p_T(H)$ (GeV)	0-15	15-30	30-45	45-80	80-120	120-200	200-350	350-600	600-∞
$H \to \gamma\gamma$	7.2%	6.8%	7.1%	6.9%	7.1%	6.7%	7.1%	9.9%	32.5%
$H \to ZZ$	6.2%	5.7%	5.0%		5.5%		9.6%		
$H \to bb$	*None*							38.2%	37.1%
Combination	4.7%	4.4%	5.0%	4.7%	4.8%	4.7%	5.2%	8.5%	25.4%

Yellow Report 18 systematic uncertainties

$p_T(H)$ (GeV)	0-15	15-30	30-45	45-80	80-120	120-200	200-350	350-600	600-∞
$H \to \gamma\gamma$	5.1%	4.6%	5.1%	4.8%	4.9%	4.5%	5.1%	8.6%	32.2%
$H \to ZZ$	5.4%	4.8%	4.1%		4.7%		9.1%		
$H \to bb$	*None*							31.4%	36.8%
Combination	3.7%	3.3%	4.2%	3.7%	4.0%	3.8%	4.4%	8.0%	24.5%

High Luminosity (LHC): ATLAS prospects @ 3000fb-1

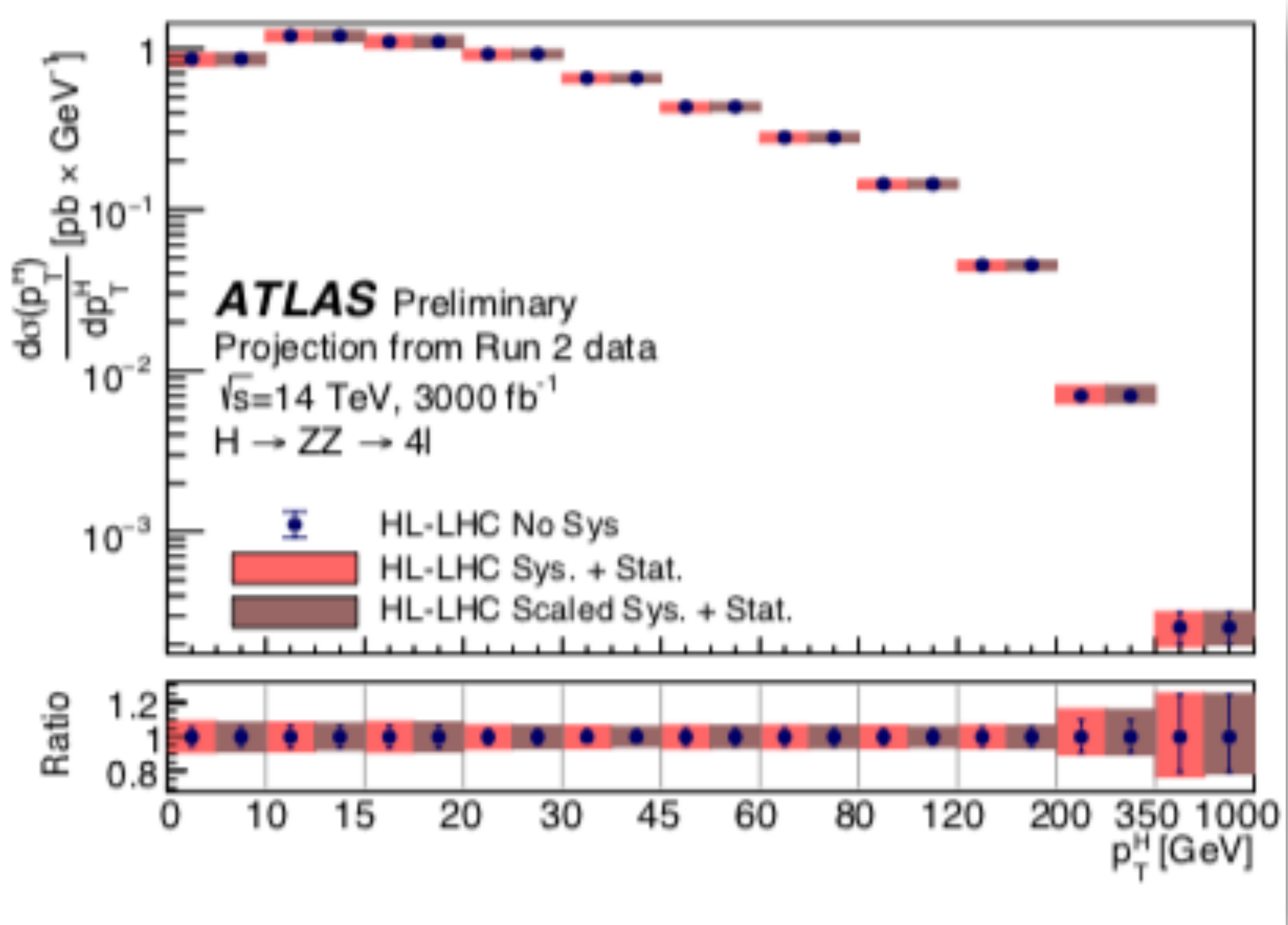
$H \to ZZ^* \to 4l$ channel

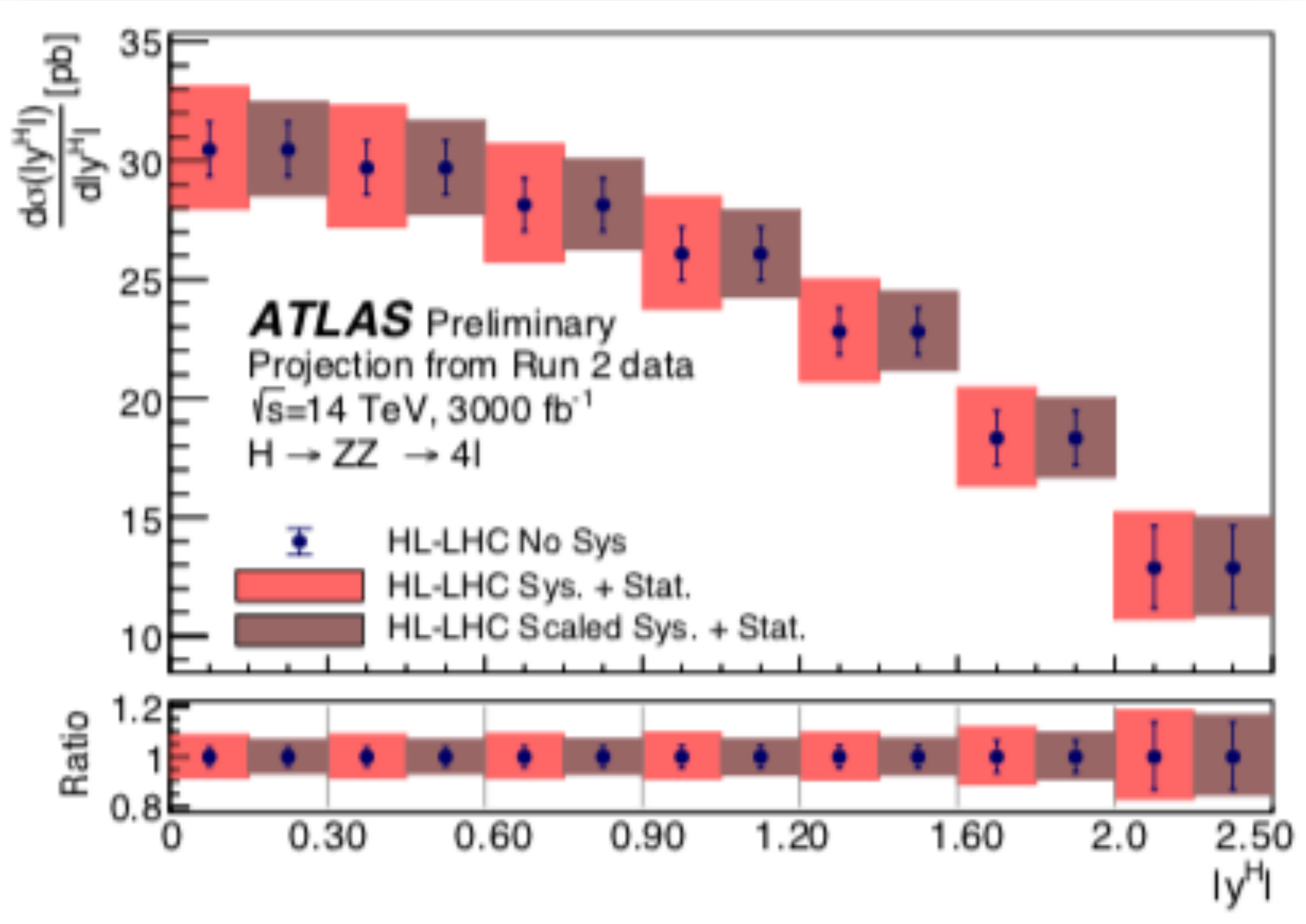
ATL-PHYS-PUB-2018-040

- **Analysis prospect @ 3000 fb-1:**
- **Scenarios considered:**
  - Systematic uncertainties as Run2 analysis
  - Systematic uncertainties with expected improvements (scaled)
- ***expected the normalization of the dominant background component from m4l sidebands (in contrast with Run2 analysis, MC-based)***
- ***Low pT(H) [0 GeV, 200 GeV]: not statistically dominated, largest statistical uncertainty ~6.2%***
- ***High pT(H) [350 GeV, 1 TeV]: still statistically dominated, measured with a precision of about 23%***

Systematic uncertainties expected to be improved and amount of scaling considered in the prospect analysis

Systematic Uncertainties	Scale Factor
Jet energy scale, forward region	Set to 0
Jet energy scale, Jet punch-through	Set to 0
High-p_T jet energy scale	Set to 0
$H \to \gamma\gamma$ background modeling	Set to 0
4ℓ m_H	Scaled by 0.25
PDF	Scaled by 0.41
Jet flavor	Scaled by 0.5
Jet energy scale	Scaled by 0.5
Pileup modelling	Scaled by 0.5
QCD scale	Scaled by 0.5
Underlying event and parton shower modeling	Scaled by 0.5
Higgs branching ratios	Scaled by 0.5
Photon energy scale and resolution	Scaled by 0.8 [1]
Photon reconstruction, ID, and isolation	Scaled by 0.8
$qq \to ZZ$ irreducible background	Set to 2%
Luminosity	Set to 1% of expected integrated luminosity





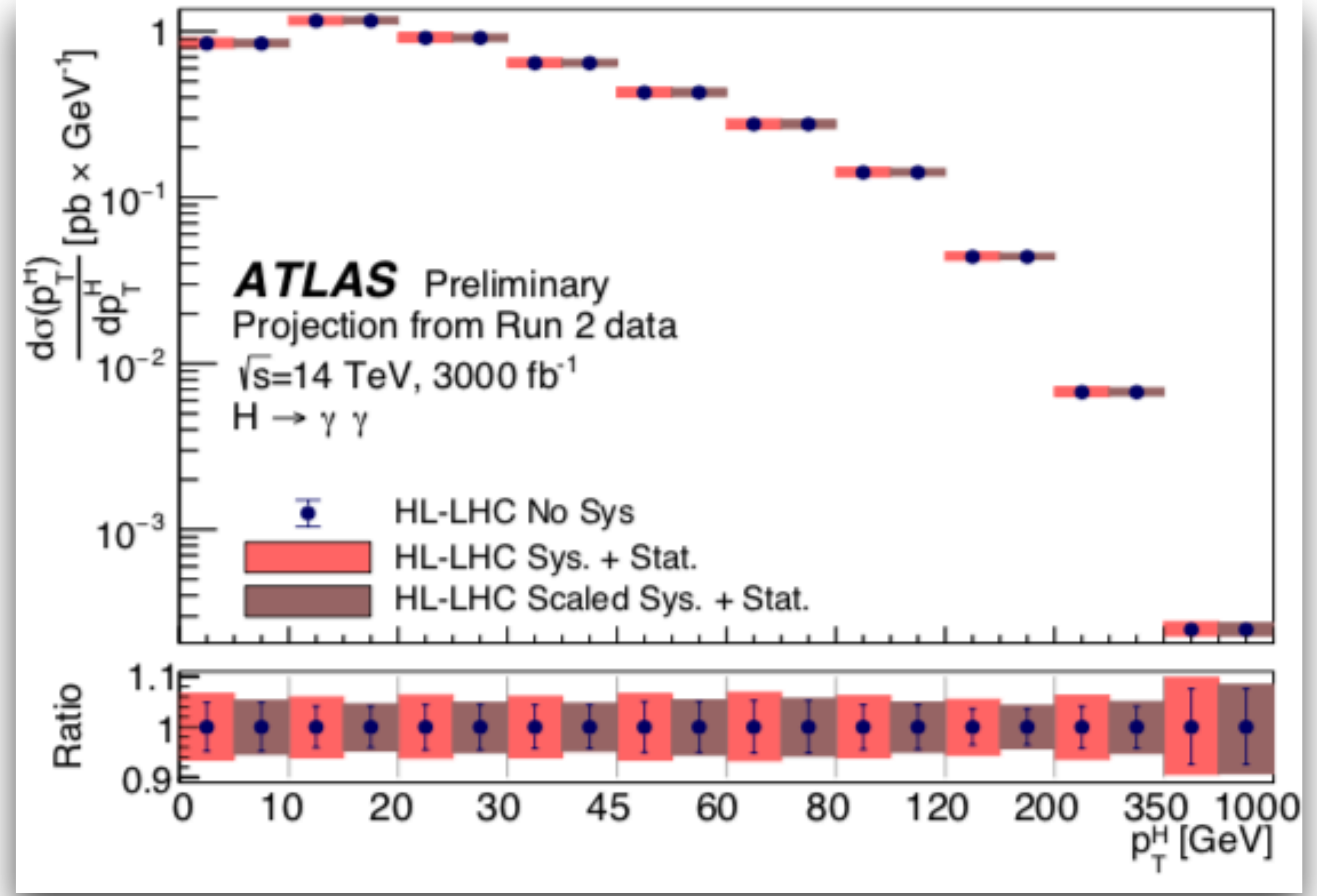
High Luminosity (LHC): ATLAS prospects @ 3000fb-1

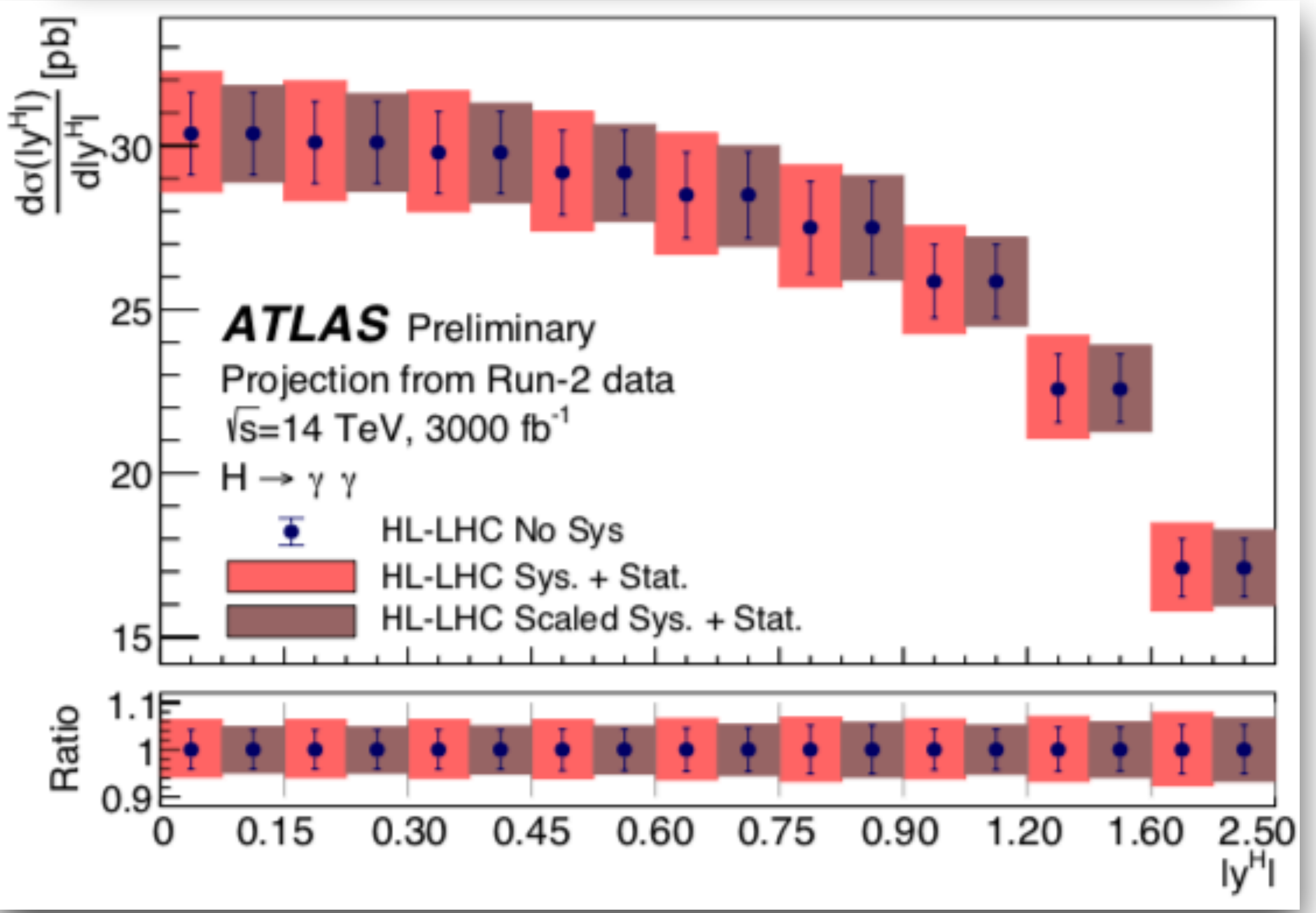
$H \to \gamma\gamma$ channel   ATL-PHYS-PUB-2018-040

- **Scenarios considered:**
  - Systematic uncertainties as Run2 analysis
  - Systematic uncertainties with expected improvements (scaled)
- ***expected the decrease of the uncertainties from the background parametrization (spurious signal)***
- ***Statistical uncertainty is reduced, ranging from ~5% to ~8%***
- ***High pT(H) [350 GeV, 1TeV] bin measured with a precision of about ~9%***

Systematic uncertainties expected to be improved and amount of scaling considered in the prospect analysis

Systematic Uncertainties	Scale Factor
Jet energy scale, forward region	Set to 0
Jet energy scale, Jet punch-through	Set to 0
High-p_T jet energy scale	Set to 0
$H \to \gamma\gamma$ background modeling	Set to 0
4ℓ m_H	Scaled by 0.25
PDF	Scaled by 0.41
Jet flavor	Scaled by 0.5
Jet energy scale	Scaled by 0.5
Pileup modelling	Scaled by 0.5
QCD scale	Scaled by 0.5
Underlying event and parton shower modeling	Scaled by 0.5
Higgs branching ratios	Scaled by 0.5
Photon energy scale and resolution	Scaled by 0.8 [1]
Photon reconstruction, ID, and isolation	Scaled by 0.8
$qq \to ZZ$ irreducible background	Set to 2%
Luminosity	Set to 1% of expected integrated luminosity



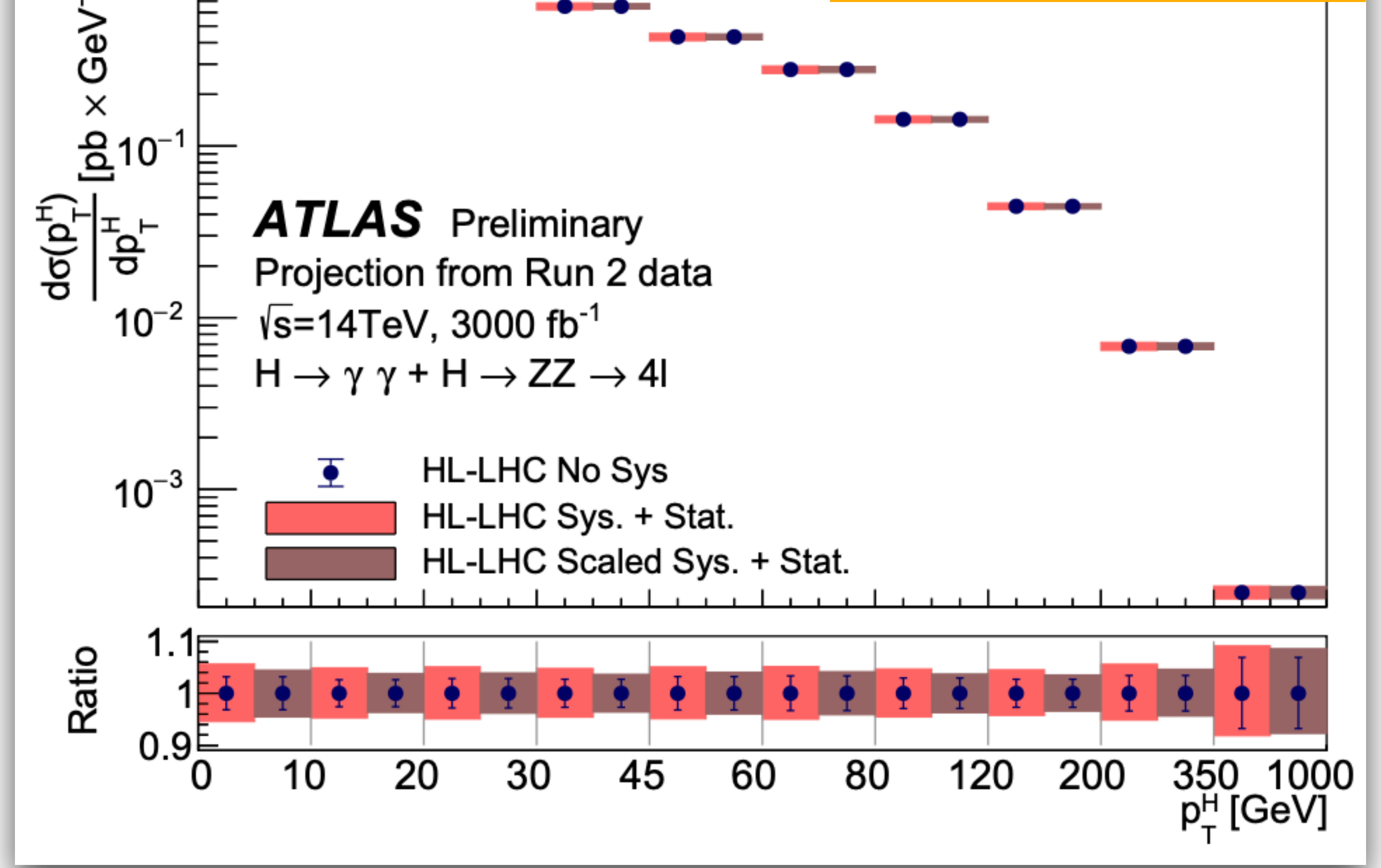


ATLAS and CMS prospects @ 3000 fb^{-1}

- ***ATLAS and CMS use common scenarios for prospects:***
  - ***Scenario 1:*** Systematic uncertainties as Run2 analysis
  - **Scenario 2:**
    - **ATLAS:** systematic uncertainties with expected improvements (scaled)
    - **CMS:** theoretical uncertainties scaled down by a factor of 2 and experimental uncertainties reduced with integrated luminosity until expected minimum uncertainty reached (Yellow Report)

Low pT(H) [0 GeV, 350 GeV]: largest total uncertainty ~4.5%
High pT(H) [350GeV GeV, 1TeV]: measured with a precision of about 10%

ATL-PHYS-PUB-2018-040



Low pT(H) [0 GeV, 350 GeV]: comparable to ATLAS, largest total uncertainty ~5.2%
High pT(H) [350 GeV, 1TeV]: average precision about ~16%

CMS PAS FTR-18-011