Higgs boson measurements in decays to boson final states in ATLAS

Giovanni Marchiori
(APC-Paris CNRS/IN2P3)

on behalf of the ATLAS Collaboration

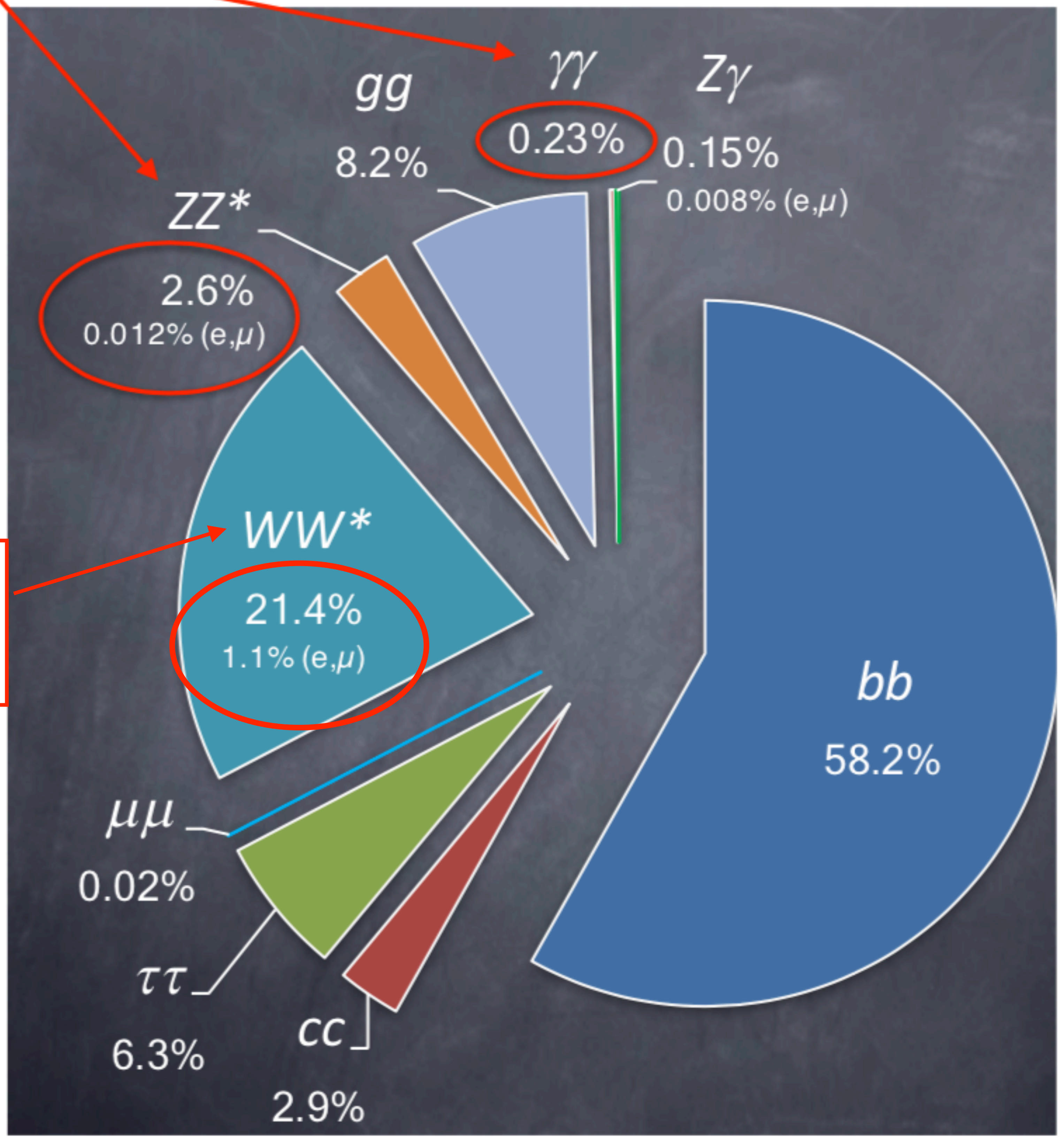
Higgs Hunting online, 20 September 2021

Introduction

- This talk will focus on:
  - **Higgs mass measurement w/ H→ZZ*→4l (l=e,μ) and H→γγ**
  - **Fiducial and simplified template cross sections with H →**
    - **ZZ* → 4l**
    - **γγ**
    - **WW* → eνμν**
- **Almost all results** (except mass w/ H→yy) **w/ full ATLAS Run2 data** (139/fb). **Improvements wrt previous publications**:
  - 4x more data
  - improved electron, photon and jet reconstruction, lepton selection and calibration, b-tagging ..
  - Improvements in analysis-techniques (in violet in the following)

ZZ, γγ: high mass resolution channels mass and precise differential measurements

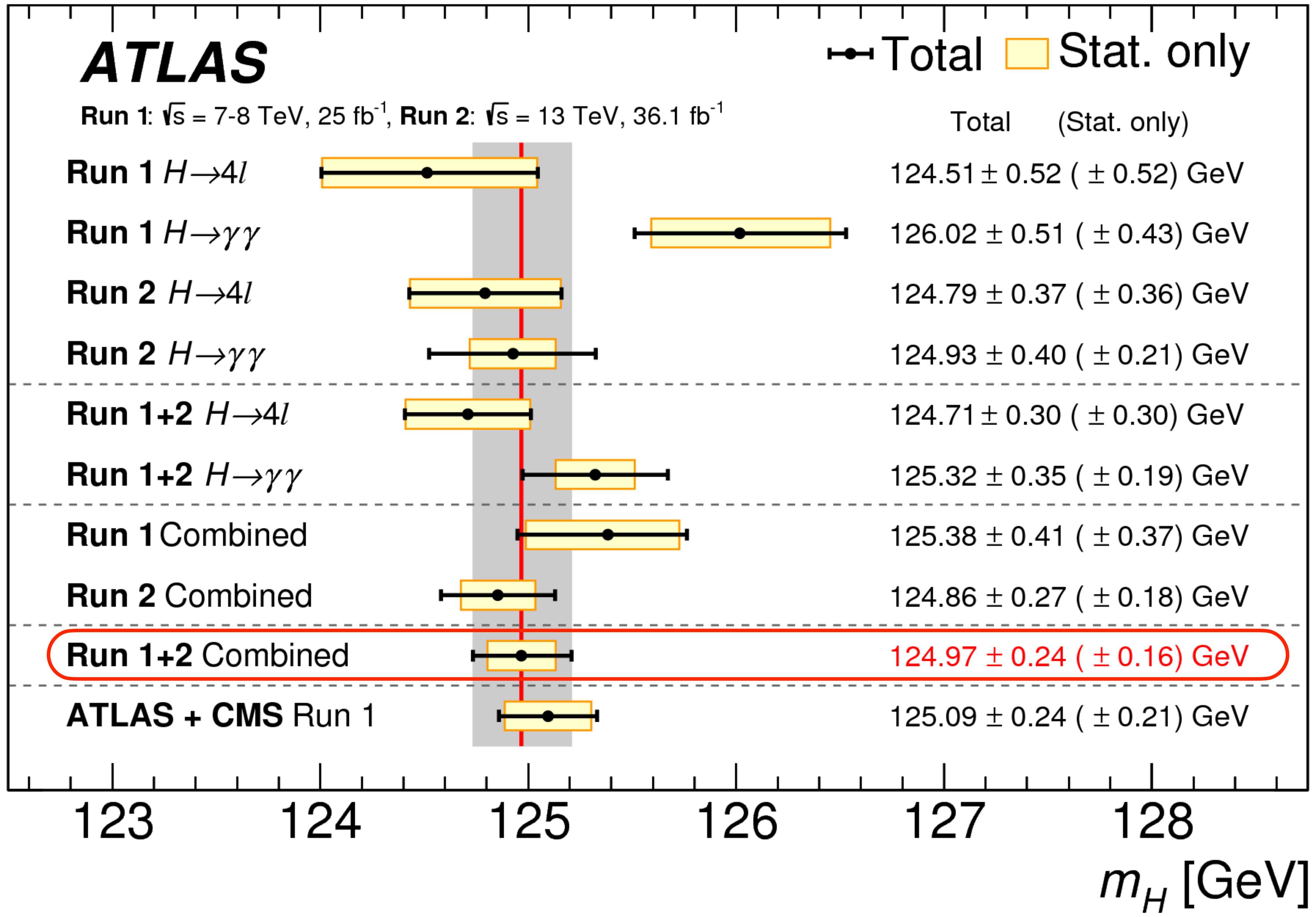
WW: High BR, but low mass resolution



Higgs mass

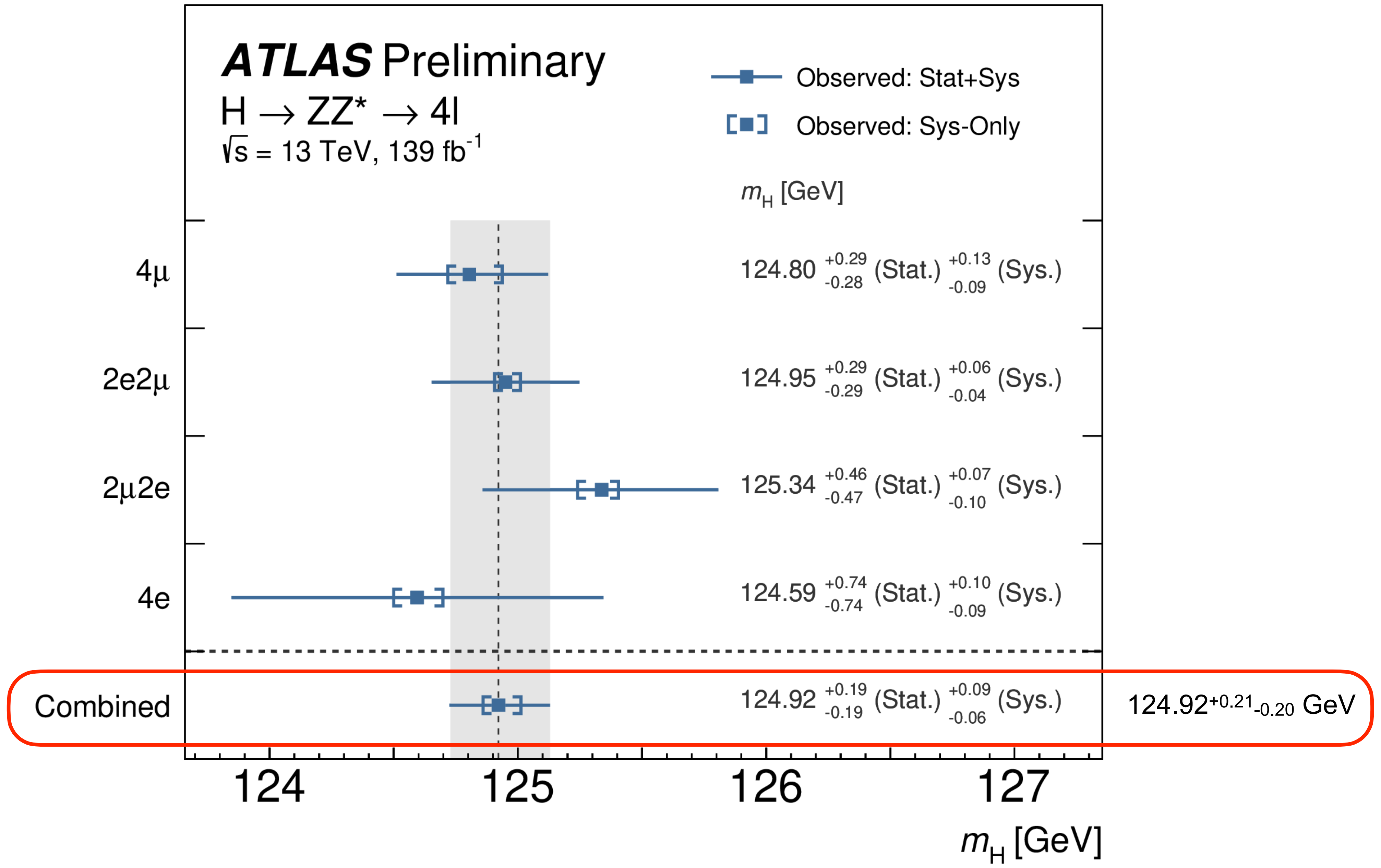
- **Only free parameter in SM Higgs sector**, fixes all other properties. Measured in the channels with the best resolution: H→ZZ*→4l and H→γγ
- **Legacy Run1 ATLAS+CMS** m_H measurement: 125.09 ± 0.24 GeV **(0.19% uncertainty)** Phys. Rev. Lett. 114 (2015) 191803
- **Updated measurements** performed by ATLAS using:

H→ZZ→4l + H→γγ, 36/fb* Phys. Lett. B 784 (2018) 345



- Run2 (36/fb): 0.22% precision (0.30% ZZ*, 0.32% γγ)
- **Run1 + partial Run2**: **0.19%**

H→ZZ→4l, 139/fb, preliminary* ATLAS-CONF-2020-005



- **Full Run2: 0.16%** precision
- Main **improvements** wrt previous publication:
  - per-event resolution estimated with quantile regression NN
  - m_{4l} fit range increased to float normalisation of main bkg (ZZ*)

Good agreement between final states and with Run1. Work ongoing to finalise lepton/photon calibrations and update H→γγ measurement

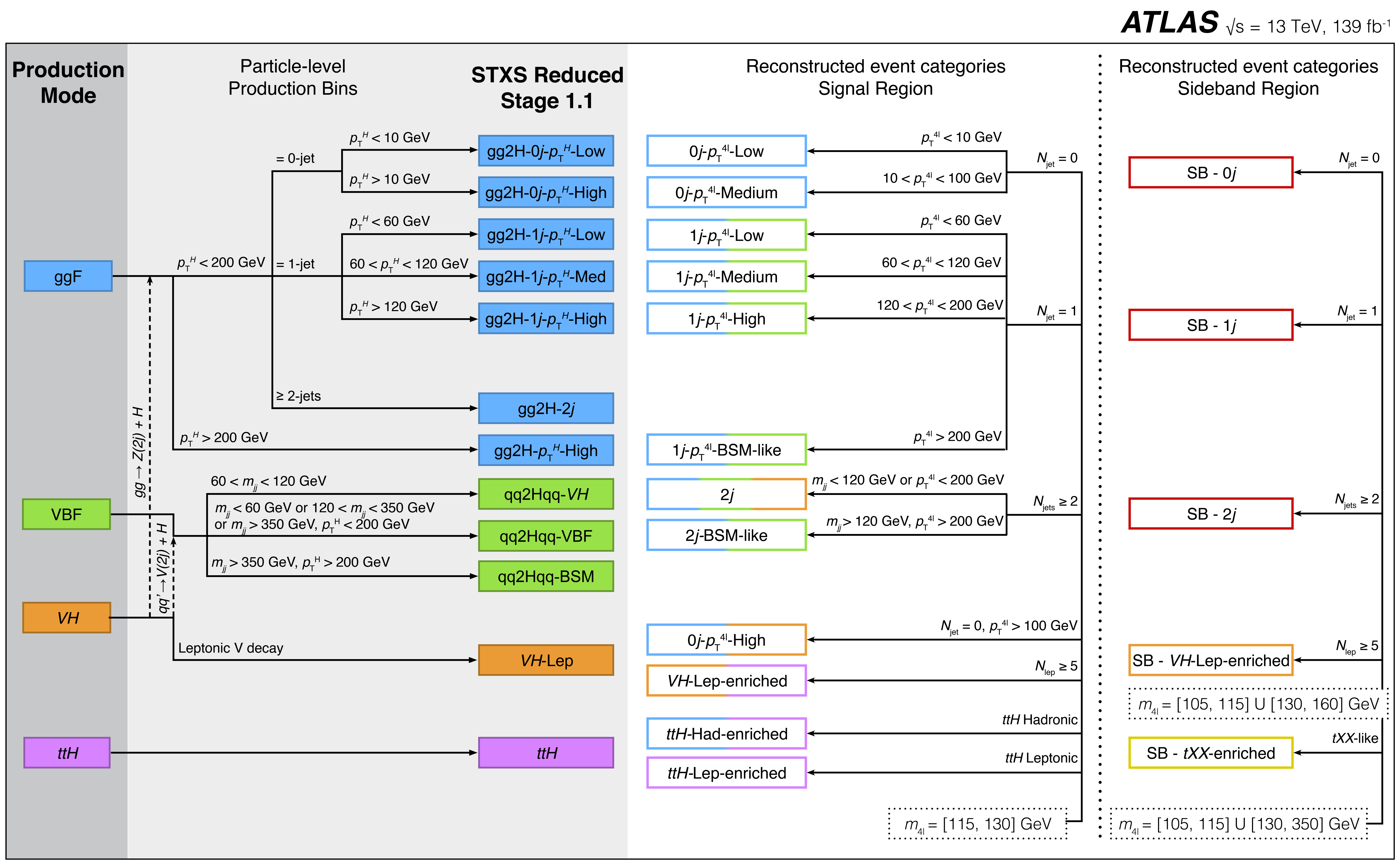
$H \to ZZ^* \to 4l$

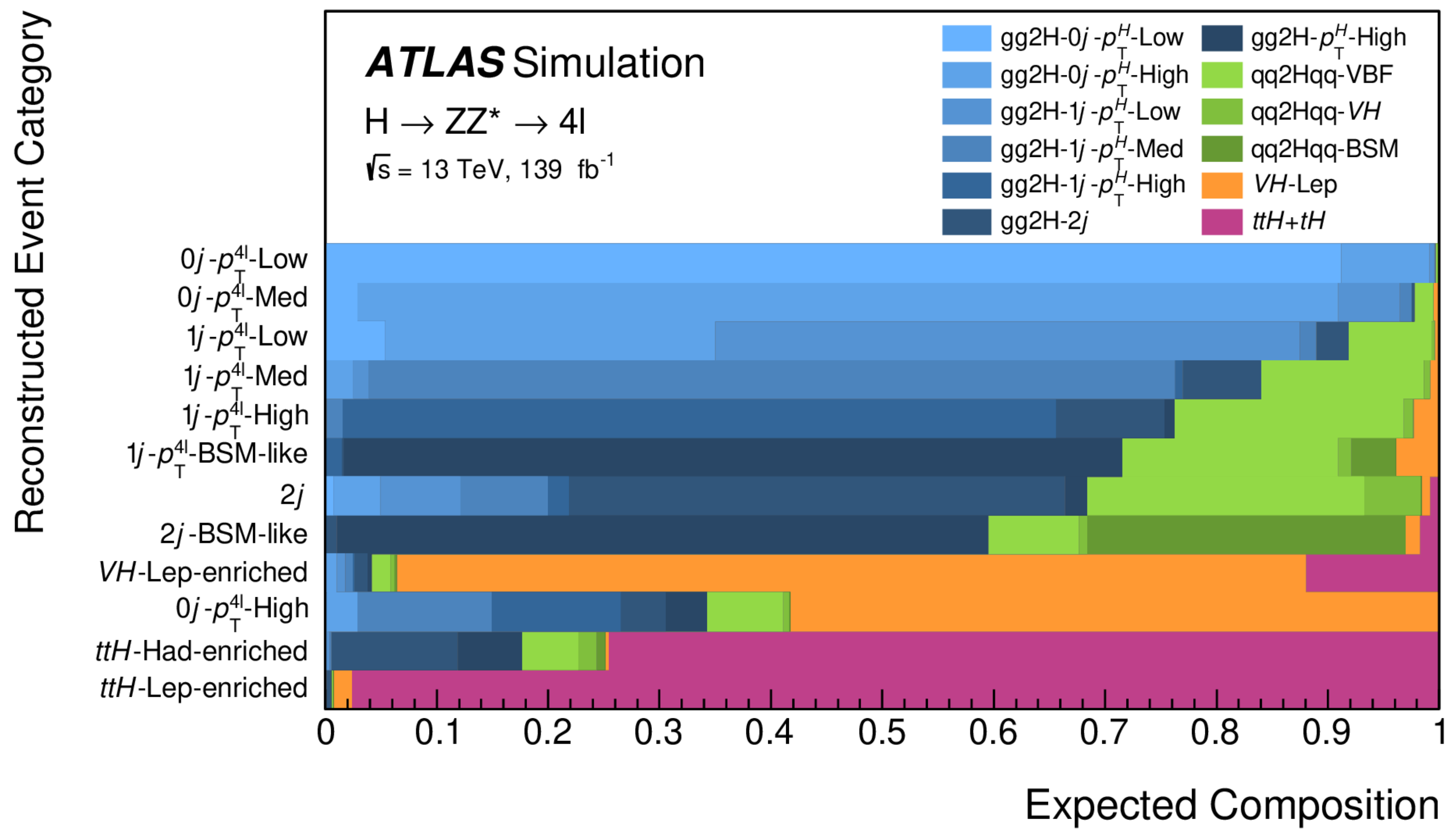
- **Lowest BR but very clean** final state. Main bkg: ZZ*, from data+simulation
- **Fiducial and simplified template cross sections measured w/ full Run2 data** *Eur. Phys. J. C 80 (2020) 942* *Eur. Phys. J. C 80 (2020) 957*

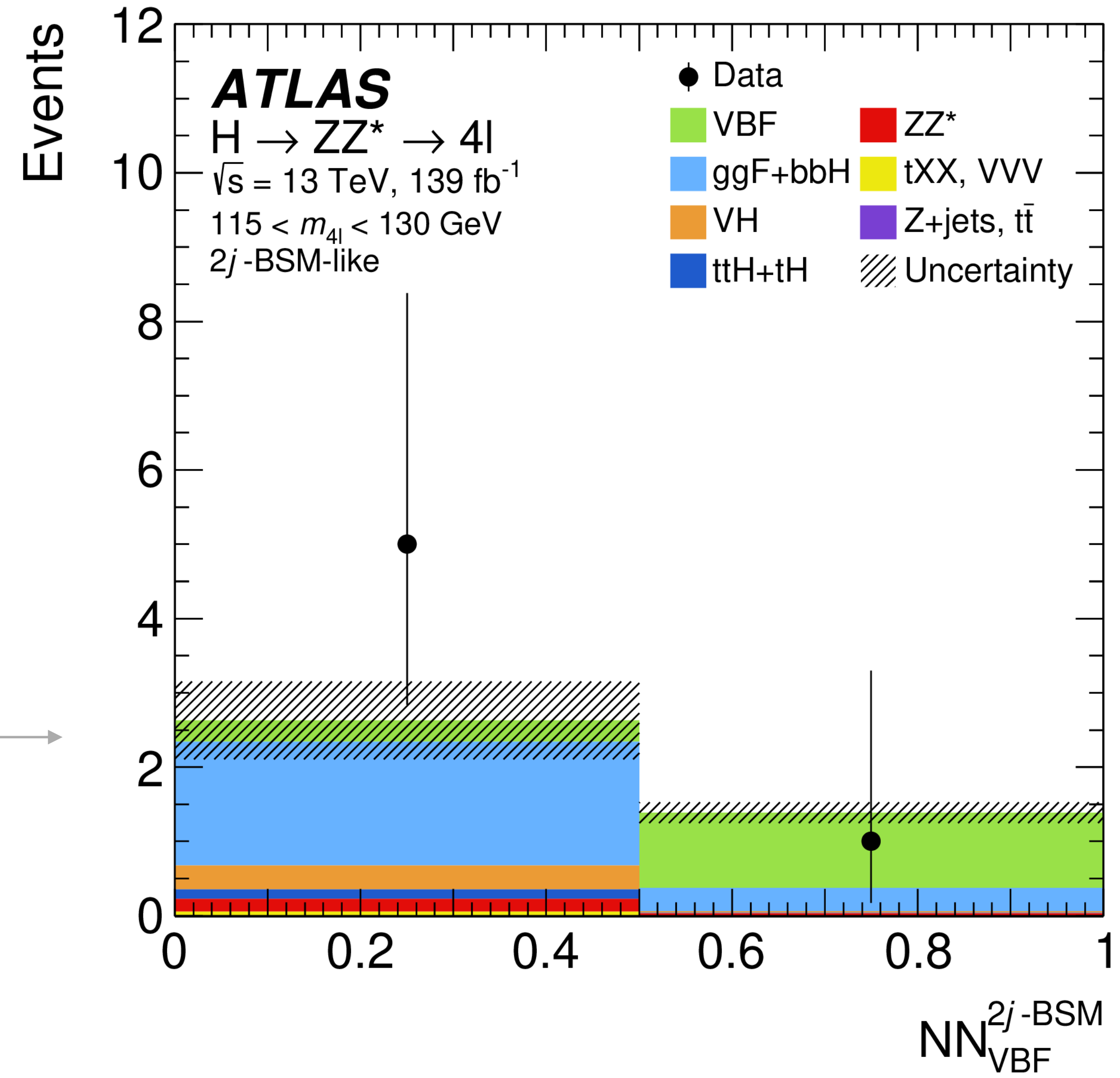
- Main **improvements** wrt previous ATLAS publications
  - Larger m_{4l} sidebands, used to constrain ZZ background directly from the data (free normalisation in the fit) rather than from theory predictions
  - STXS:
    - More event categories for more granular measurement
    - New, more performing discriminants to separate the various production modes (BDTs → DNNs)
    - Control region for main background (top processes) in ttH categories
  - Fiducial cross-sections:
    - Unfolding based on response matrix (rather than bin-by-bin corrections), implemented in likelihood function
    - More cross sections measured

H→ZZ*→4l STXS: analysis strategy

- 12 **categories** (N_{jets}, p_T^{4l}, m_{jj}, extra leptons..) in m_{4l} **signal region** (SR) to target 12 "reduced-stage 1.1" STXS bins ; 5 extra categories, in **sidebands** (SB) of m_{4l}, to constrain main backgrounds (ZZ, tXX)



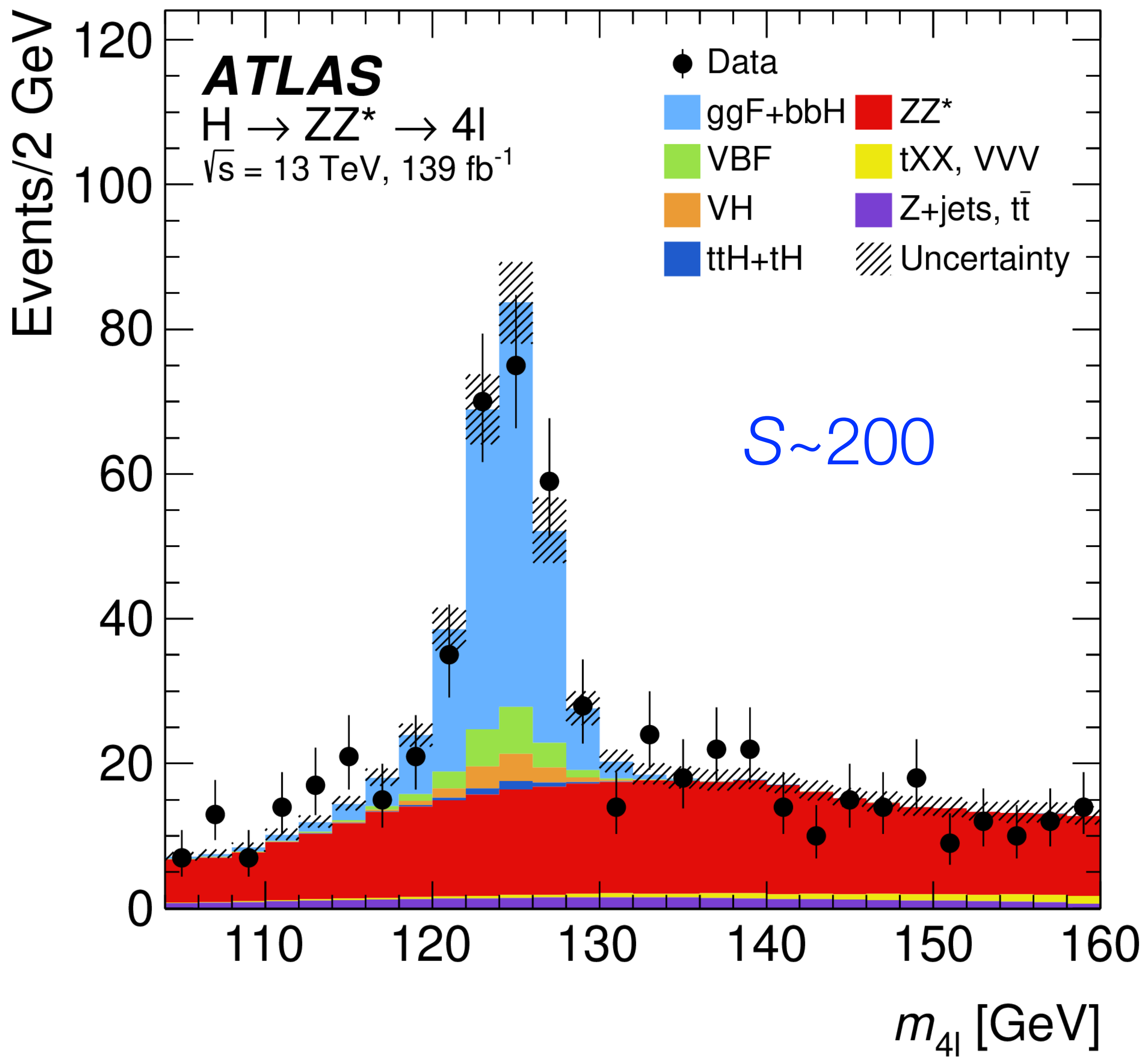




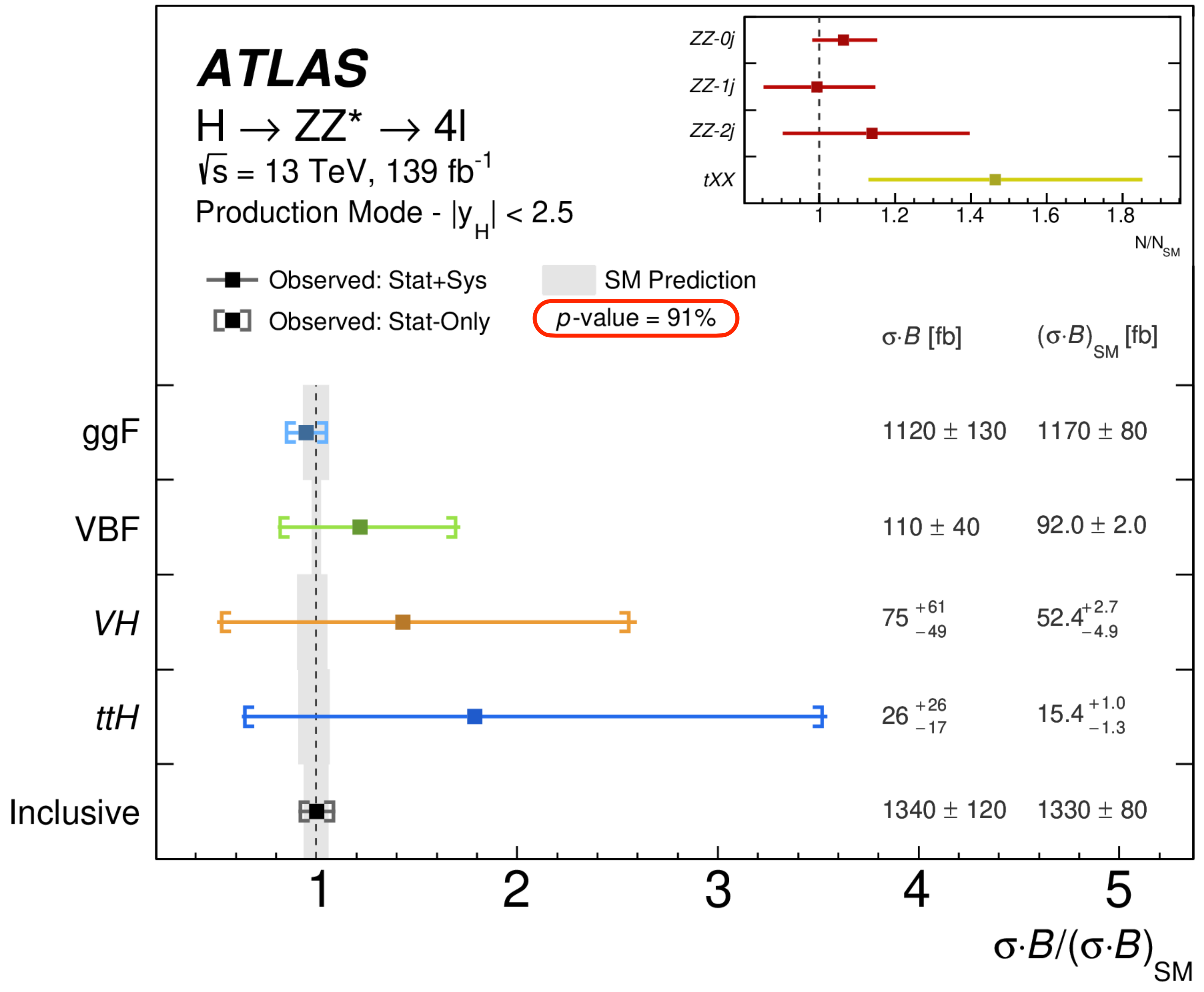
- Final separation among production modes and vs bkg obtained through **fit to production mode discriminants (neural nets)** or event yields in SR and SB categories

H→ZZ*→4l STXS: results

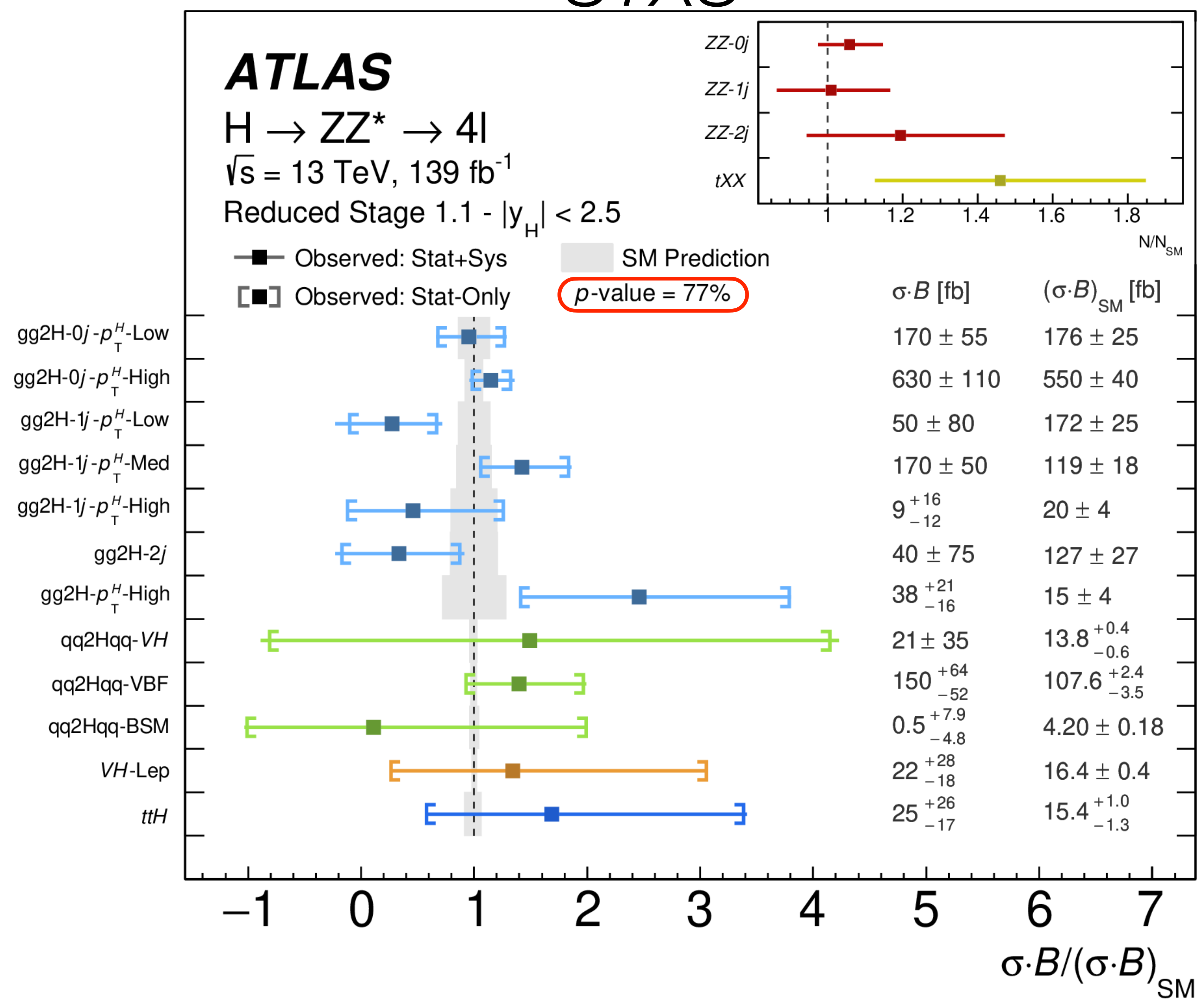
Data vs fit



Production mode xsections



STXS



- Good agreement between data and fit (left)
- Good agreement between observed and expected xsections: inclusive & production mode (middle) and reduced Stage-1.1 STXS (right)
- All measurements are (still) statistically limited
- Statistical and experimental systematic errors down by 40% wrt previous publication, similar theory uncertainty

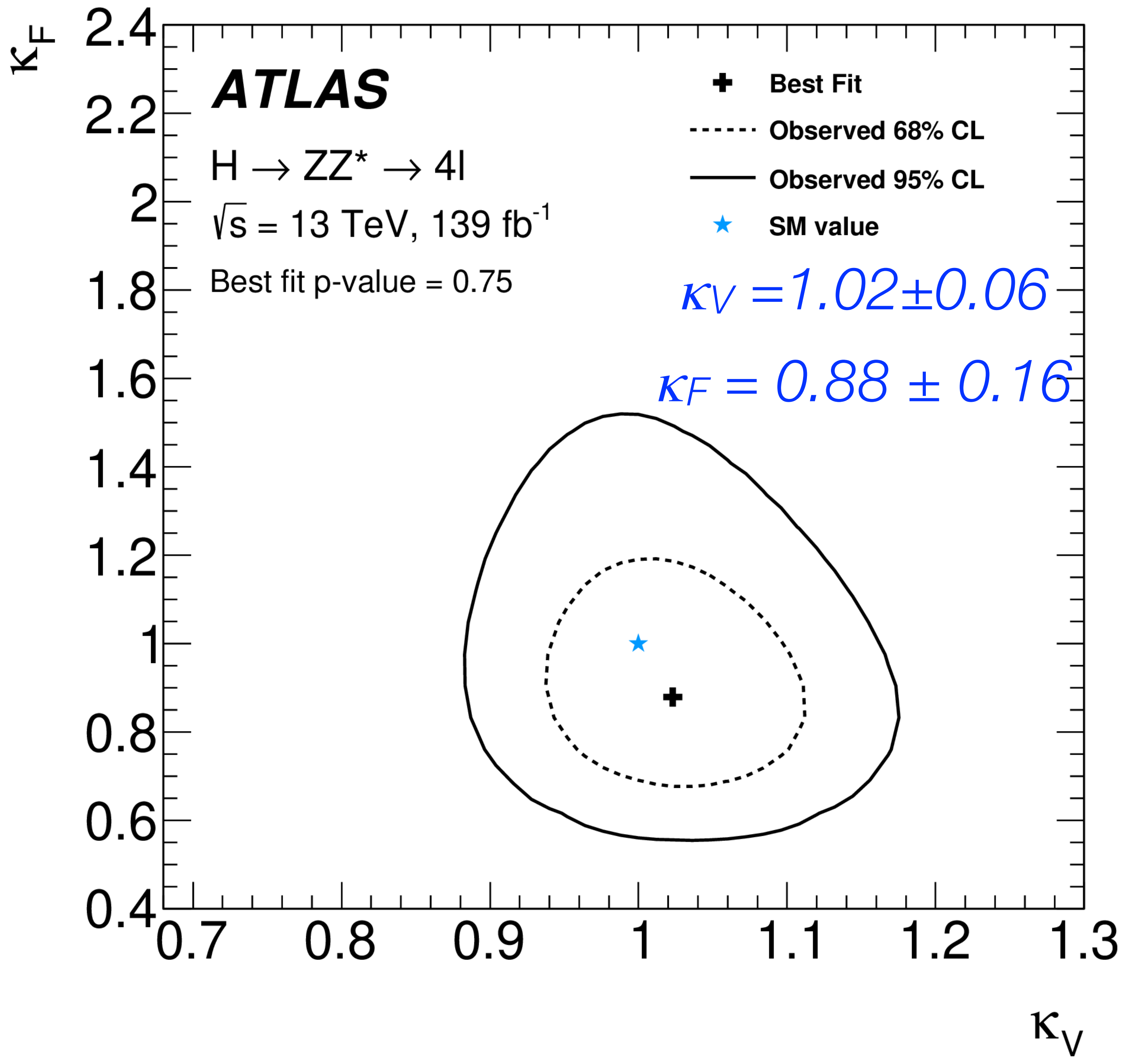
H→ZZ*→4l STXS: interpretations

- Results are used to **constrain Higgs boson couplings to SM particles (left)** and **BSM couplings to gauge bosons and up-type quarks (right)**

SM couplings (k framework)

$$\sigma \cdot \mathcal{B}\,(i \to H \to f) = \kappa_i^2 \cdot \kappa_f^2 \cdot \sigma_i^{\mathrm{SM}} \cdot \frac{\Gamma_f^{\mathrm{SM}}}{\Gamma_H(\kappa_i^2, \kappa_f^2)}.$$

Assume $\mathrm{BR}_{\mathrm{inv}}$ = 0 and universal fermion and boson coupling modifiers



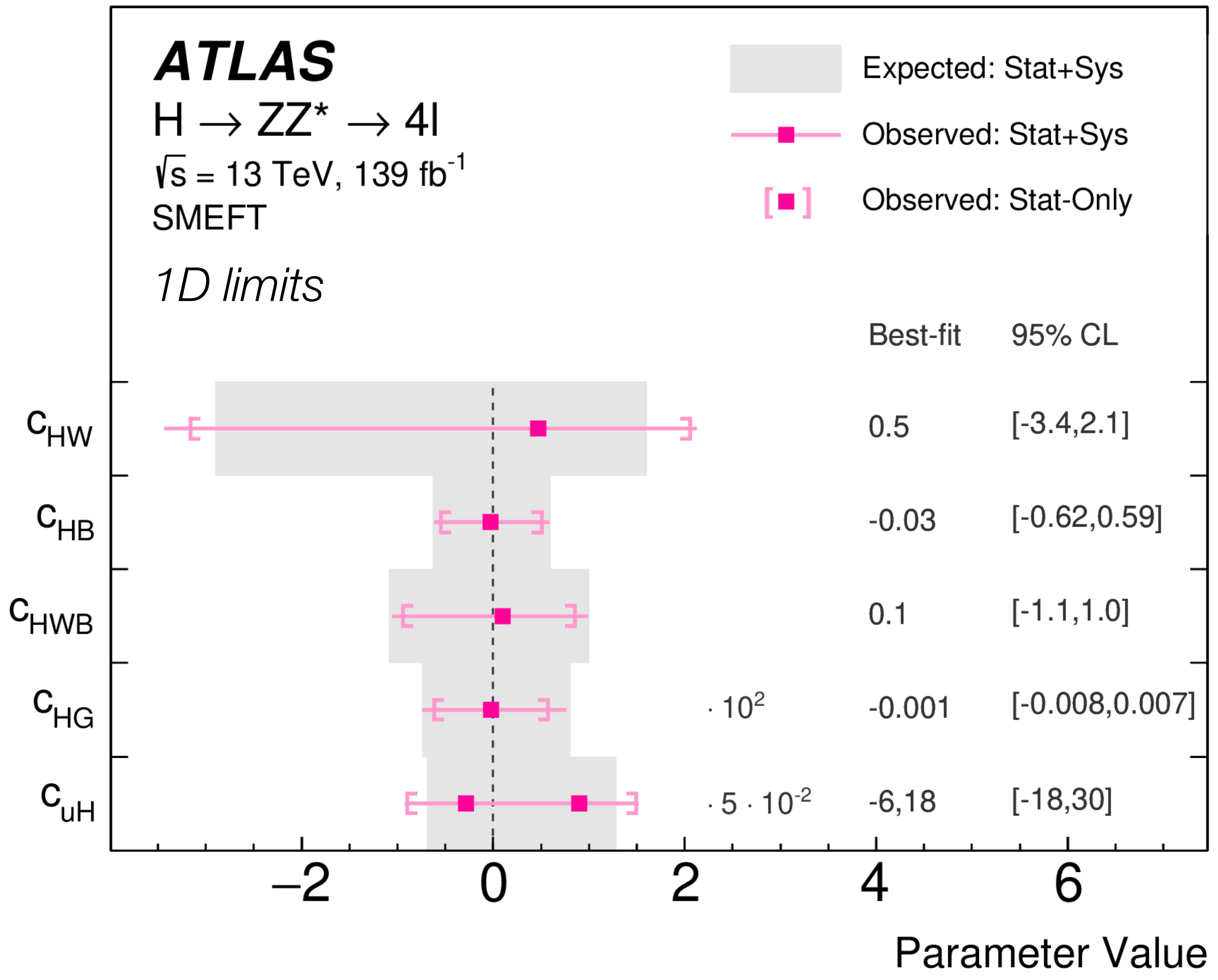
BSM couplings (SMEFT, Warsaw basis)

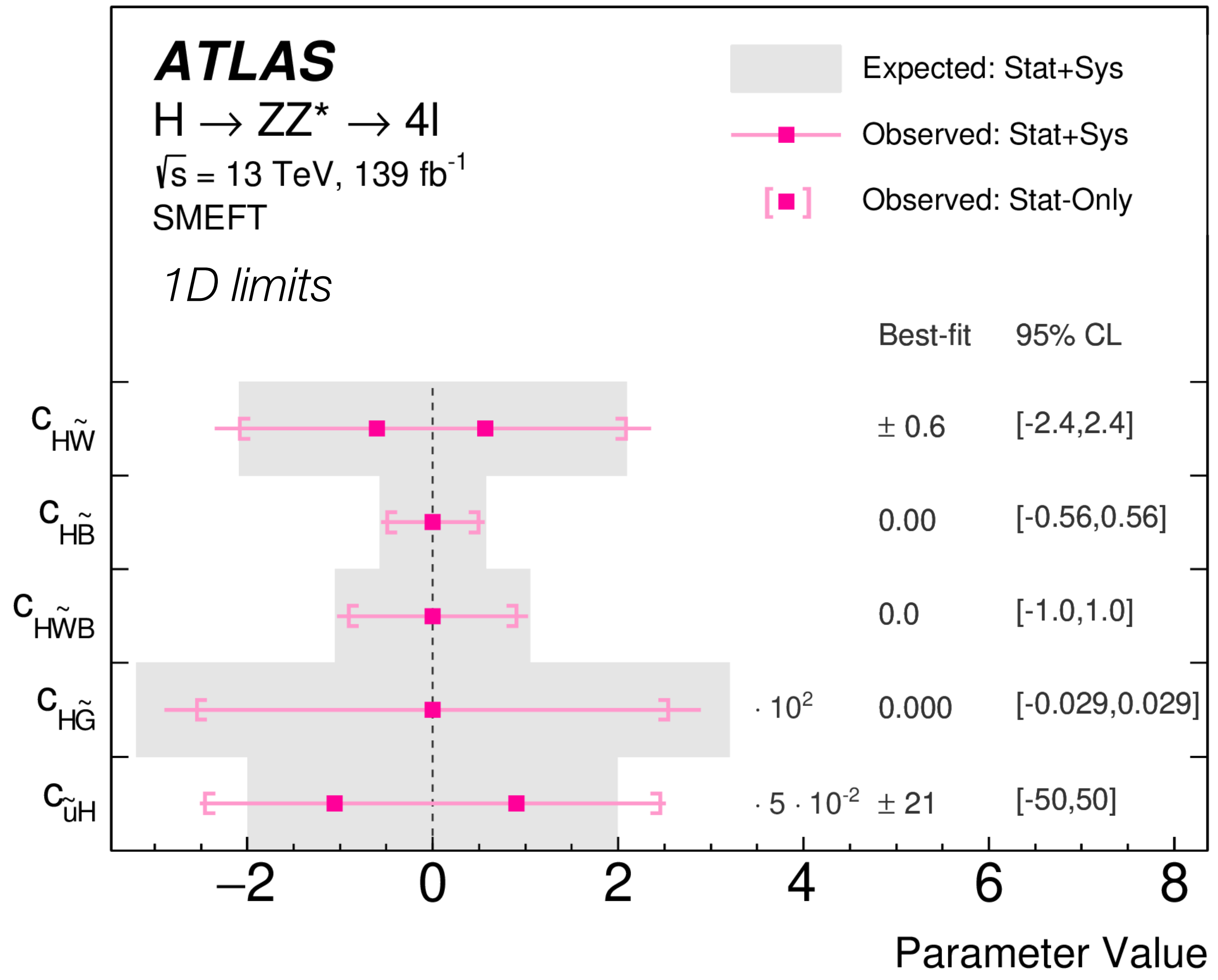
$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)} \quad \text{for } d > 4.$$ d=6, Λ=1 TeV

CP-even			CP-odd			Impact on	
Operator	Structure	Coeff.	Operator	Structure	Coeff.	production	decay
O_{uH}	$HH^\dagger \bar{q}_p u_r \tilde{H}$	c_{uH}	O_{uH}	$HH^\dagger \bar{q}_p u_r \tilde{H}$	$c_{\tilde{u}H}$	ttH	-
O_{HG}	$HH^\dagger G^A_{\mu\nu} G^{\mu\nu A}$	c_{HG}	$O_{H\tilde{G}}$	$HH^\dagger \tilde{G}^A_{\mu\nu} G^{\mu\nu A}$	$c_{H\tilde{G}}$	ggF	Yes
O_{HW}	$HH^\dagger W^l_{\mu\nu} W^{\mu\nu l}$	c_{HW}	$O_{H\widetilde{W}}$	$HH^\dagger \widetilde{W}^l_{\mu\nu} W^{\mu\nu l}$	$c_{H\widetilde{W}}$	VBF, VH	Yes
O_{HB}	$HH^\dagger B_{\mu\nu} B^{\mu\nu}$	c_{HB}	$O_{H\tilde{B}}$	$HH^\dagger \tilde{B}_{\mu\nu} B^{\mu\nu}$	$c_{H\tilde{B}}$	VBF, VH	Yes
O_{HWB}	$HH^\dagger \tau^l W^l_{\mu\nu} B^{\mu\nu}$	c_{HWB}	$O_{H\widetilde{W}B}$	$HH^\dagger \tau^l \widetilde{W}^l_{\mu\nu} B^{\mu\nu}$	$c_{H\widetilde{W}B}$	VBF, VH	Yes

Effects on signal acceptance included, effects on bkg. neglected

Left: CP-even, right-CP-odd couplings

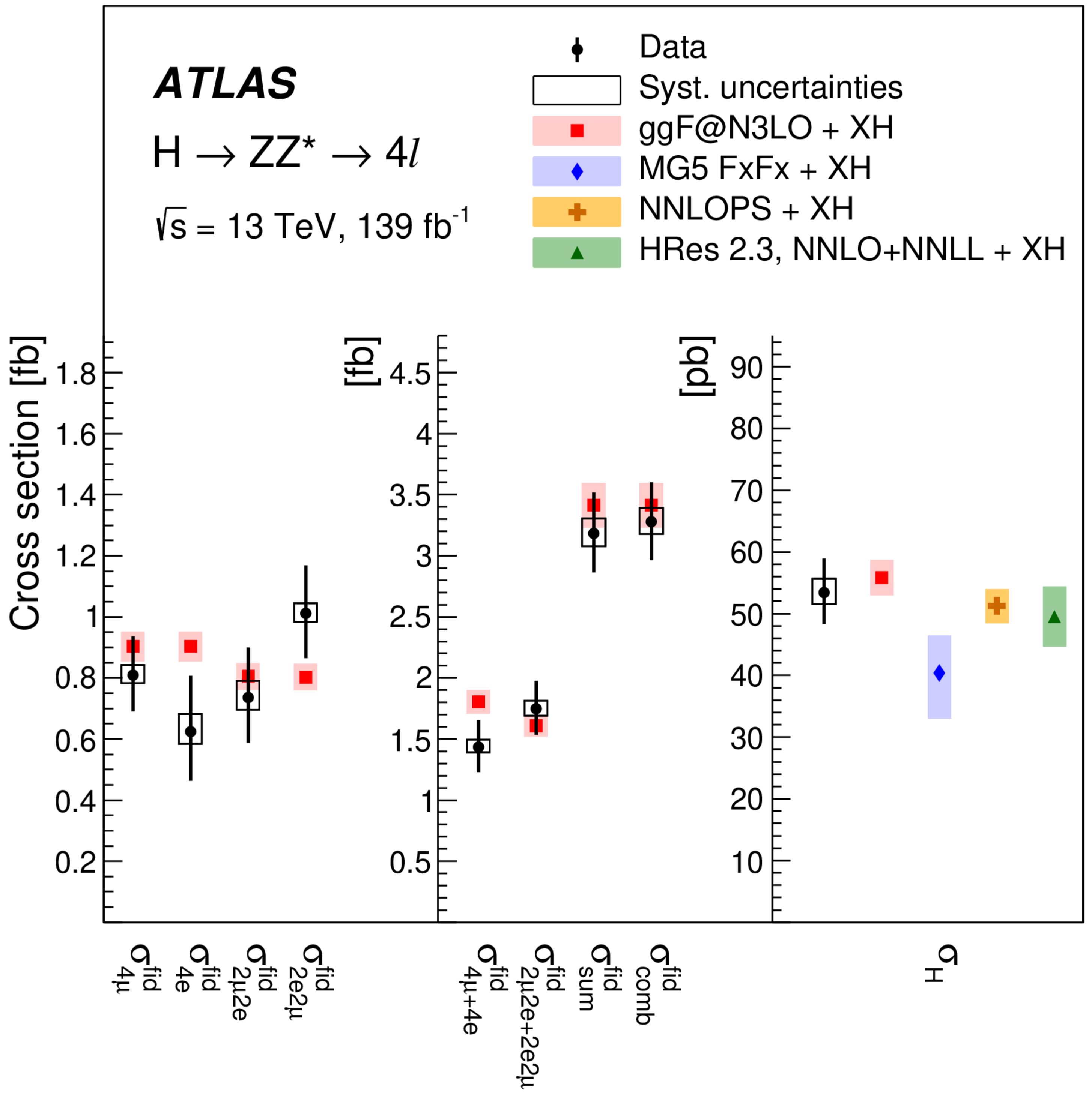


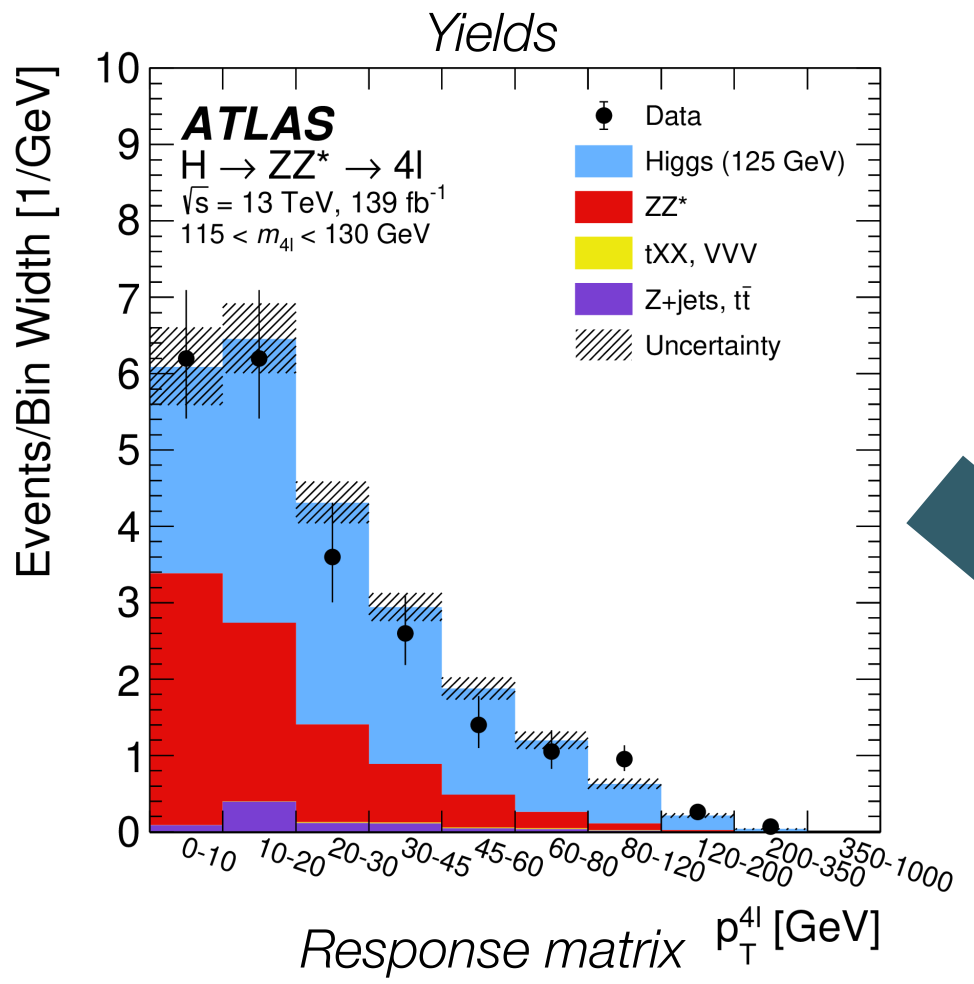


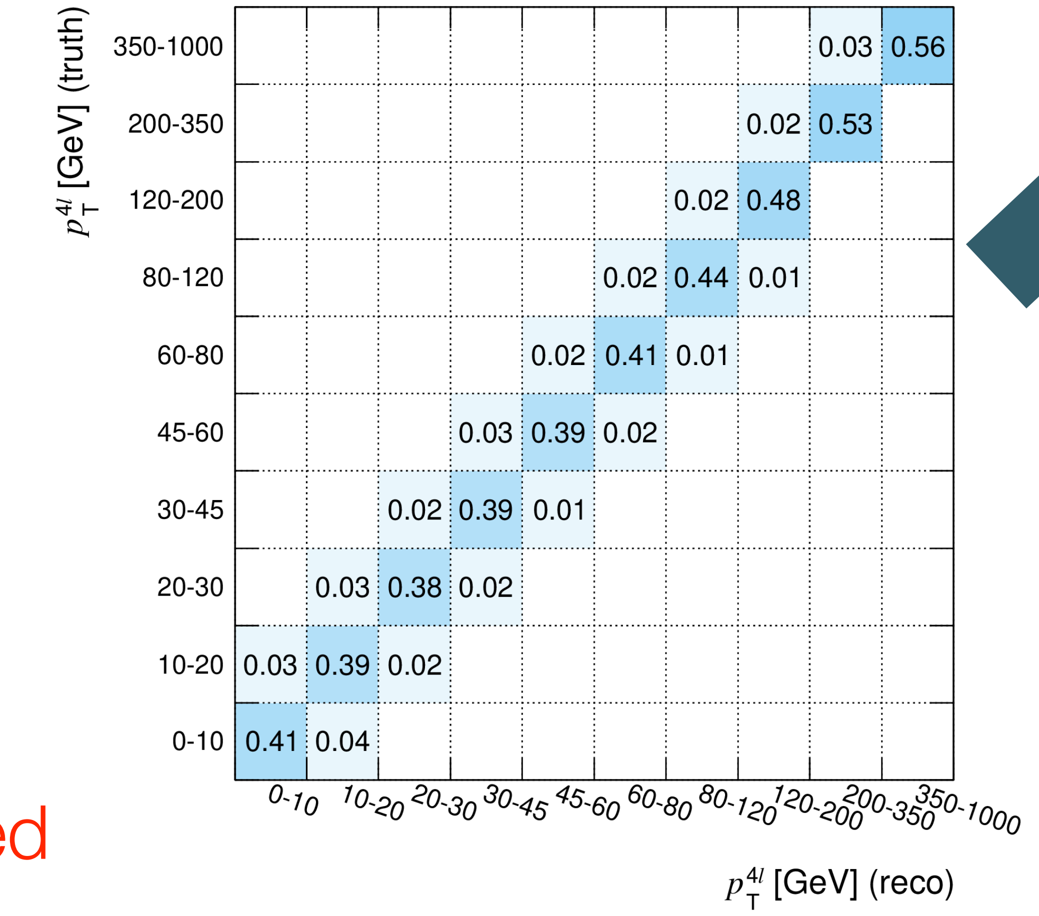
H→ZZ*→4l fiducial cross sections: analysis strategy

- Xsections measured **inclusively and differentially** wrt quantities (p_T^H, y^H, m_{12}, m_{34}, angular & jet variables) **probing in detail Higgs boson production**
- Signal yields in each bin of a differential distribution from **S+B fits to the m_{4l} distribution**
- **Unfolding** to particle-level σ*BR using response matrix method, implemented directly in likelihood function

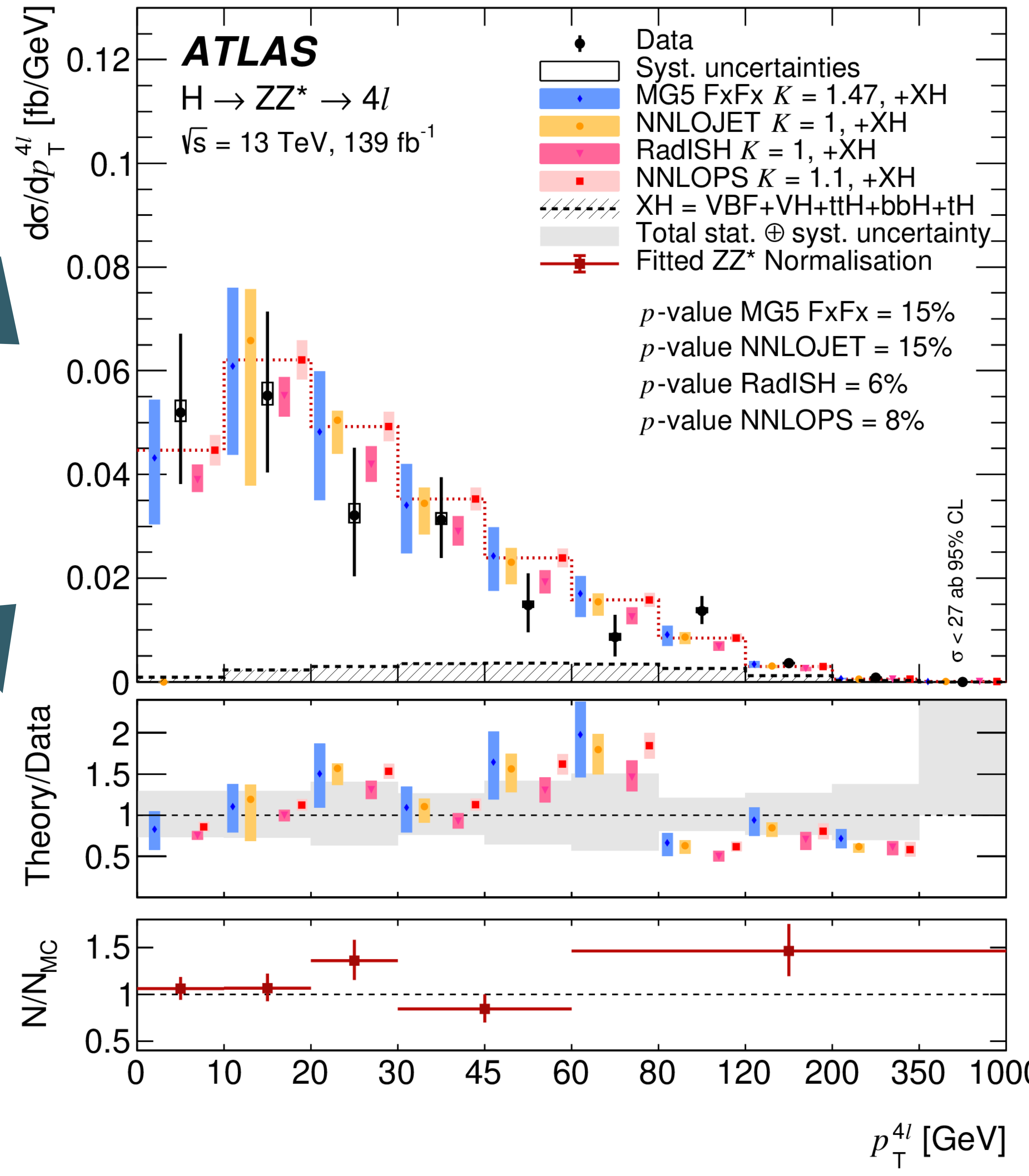
Fiducial and total xsections







Diff. fiducial xsections

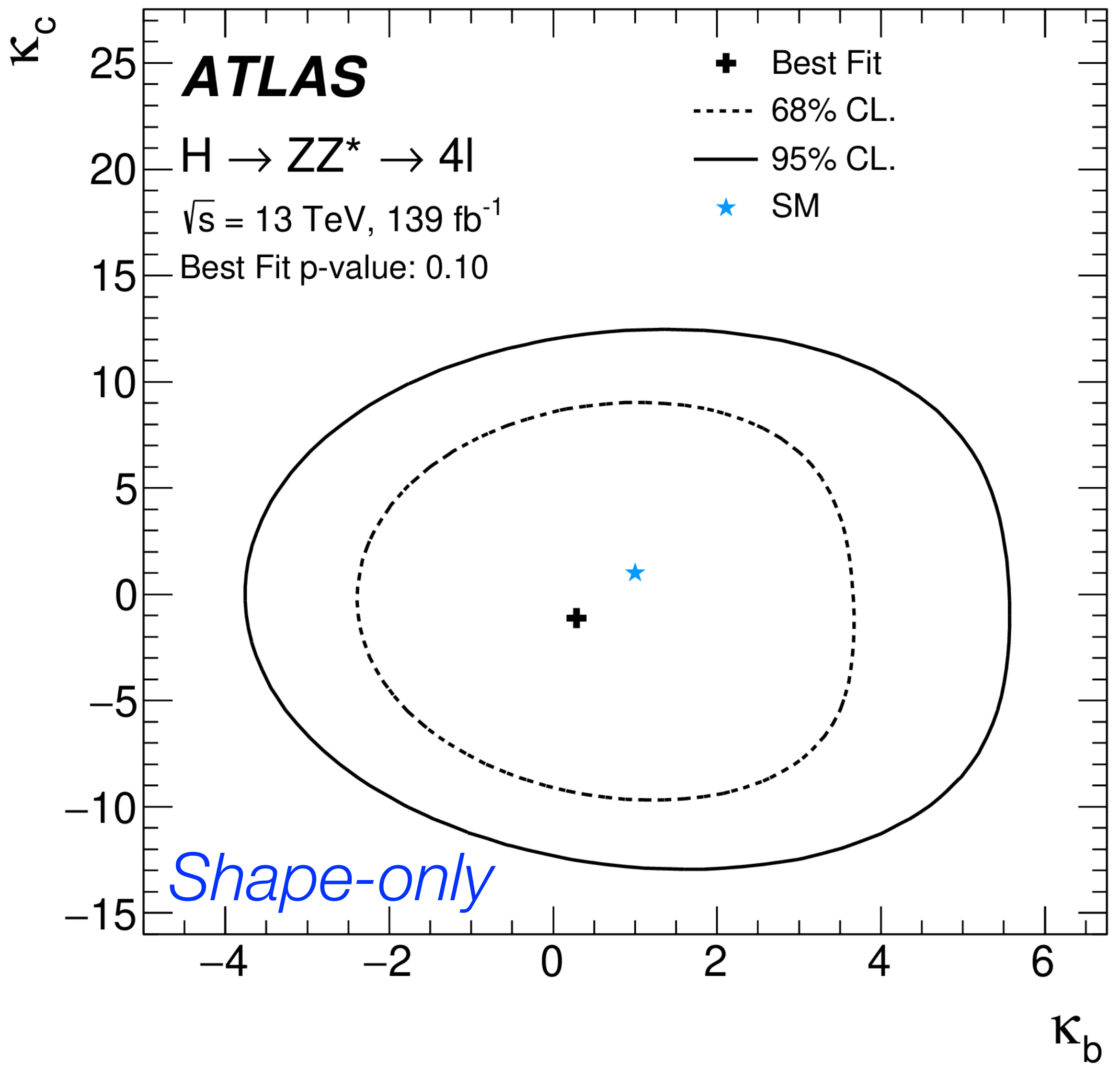


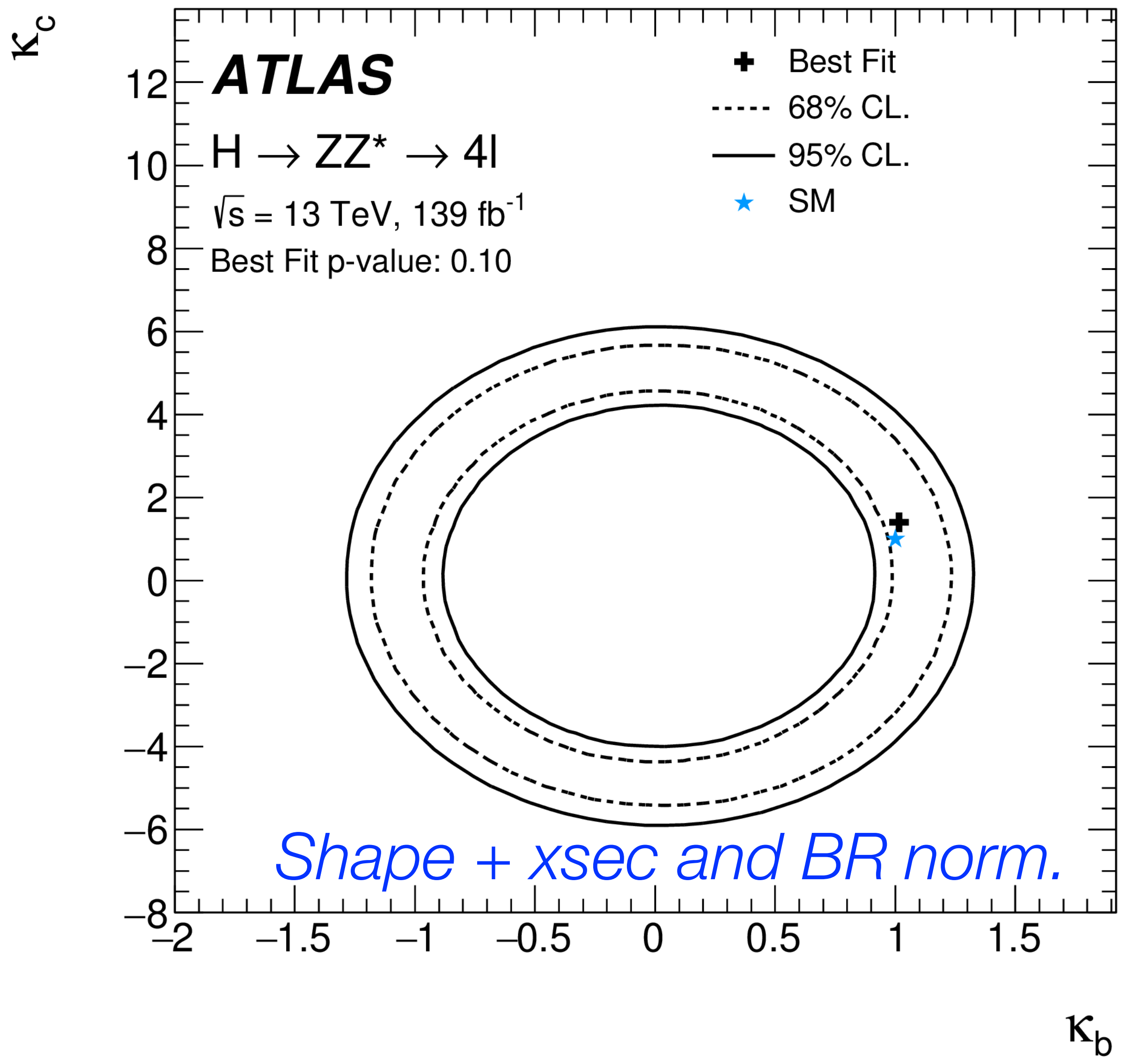
Good agreement w/ SM, measurements statistically limited

H→ZZ*→4l fiducial cross sections: interpretations

- **p_T(4l)** fid. xsection → constrain **bottom and charm Yukawa couplings (left)**
  - y_b and y_c affect both ggF, qq→H + qg→qH, and BR(ZZ) through modifications of the Γ_{bb} and Γ_{cc} partial widths ⇒ effect on normalisation and shape
- **m_{12} and m_{34}** fid xsections → constrain **BSM contact terms between the Higgs, the Z, and left- or right-handed leptons** ($\varepsilon_{Z,lL}$ and $\varepsilon_{Z,lR}$) **(right)**
  - 4 scenarios w/ different assumptions on structure of interactions keeping same Lorentz structure of SM (angular distributions are not affected)

b, c Yukawa couplings

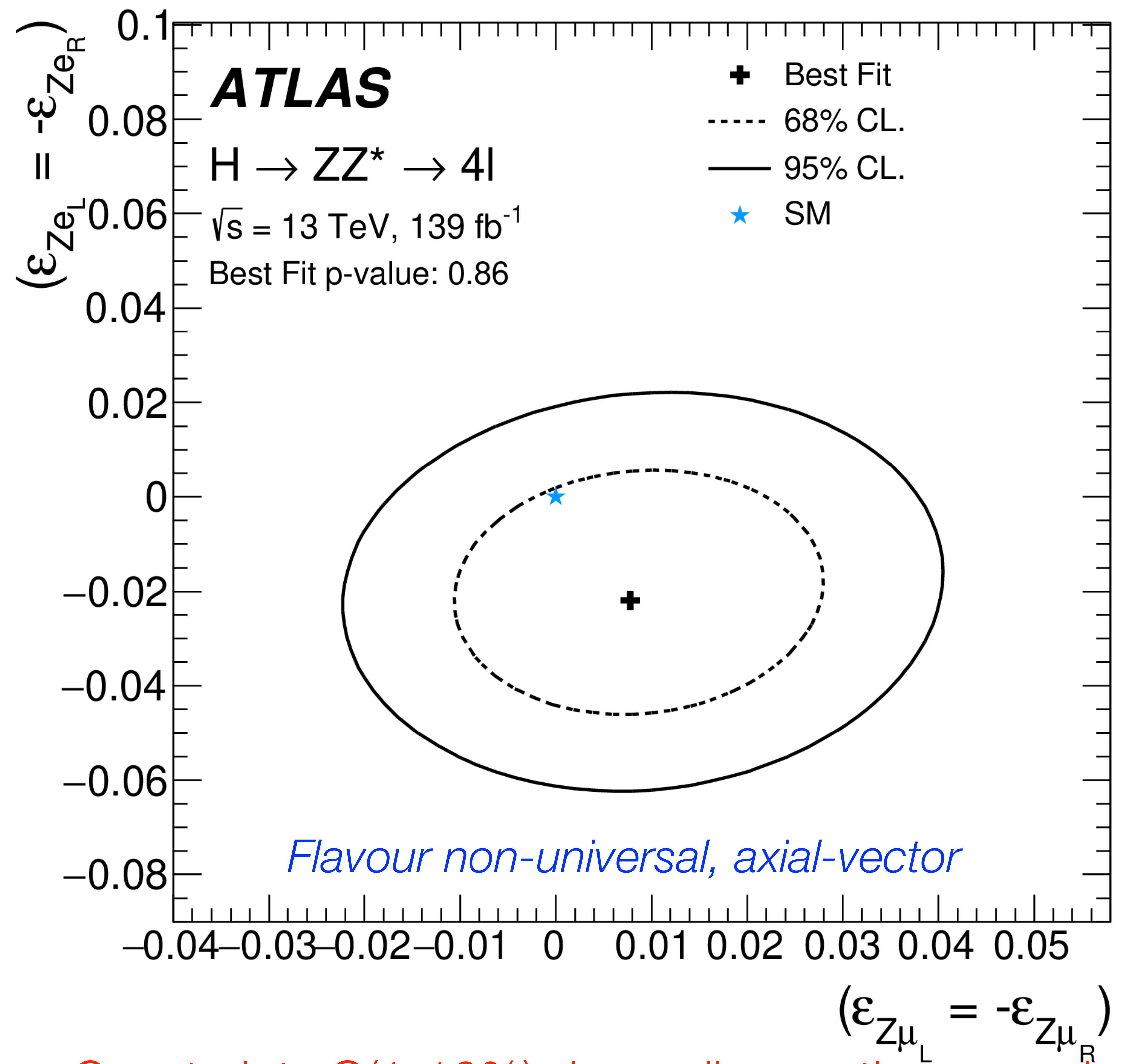




Interpretation	Parameter best-fit value	95% confidence interval
Modifications to only $p_T^{4\ell}$ shape	$\kappa_c = -1.1$	$[-11.7,\ 10.5]$
	$\kappa_b = 0.28$	$[-3.21,\ 4.50]$
Modifications to $p_T^{4\ell}$ predictions	$\kappa_c = 0.66$	$[-7.46,\ 9.27]$
	$\kappa_b = 0.55$	$[-1.82,\ 3.34]$

Constraints on k_c similar to those from direct searches

anomalous HZl contact terms

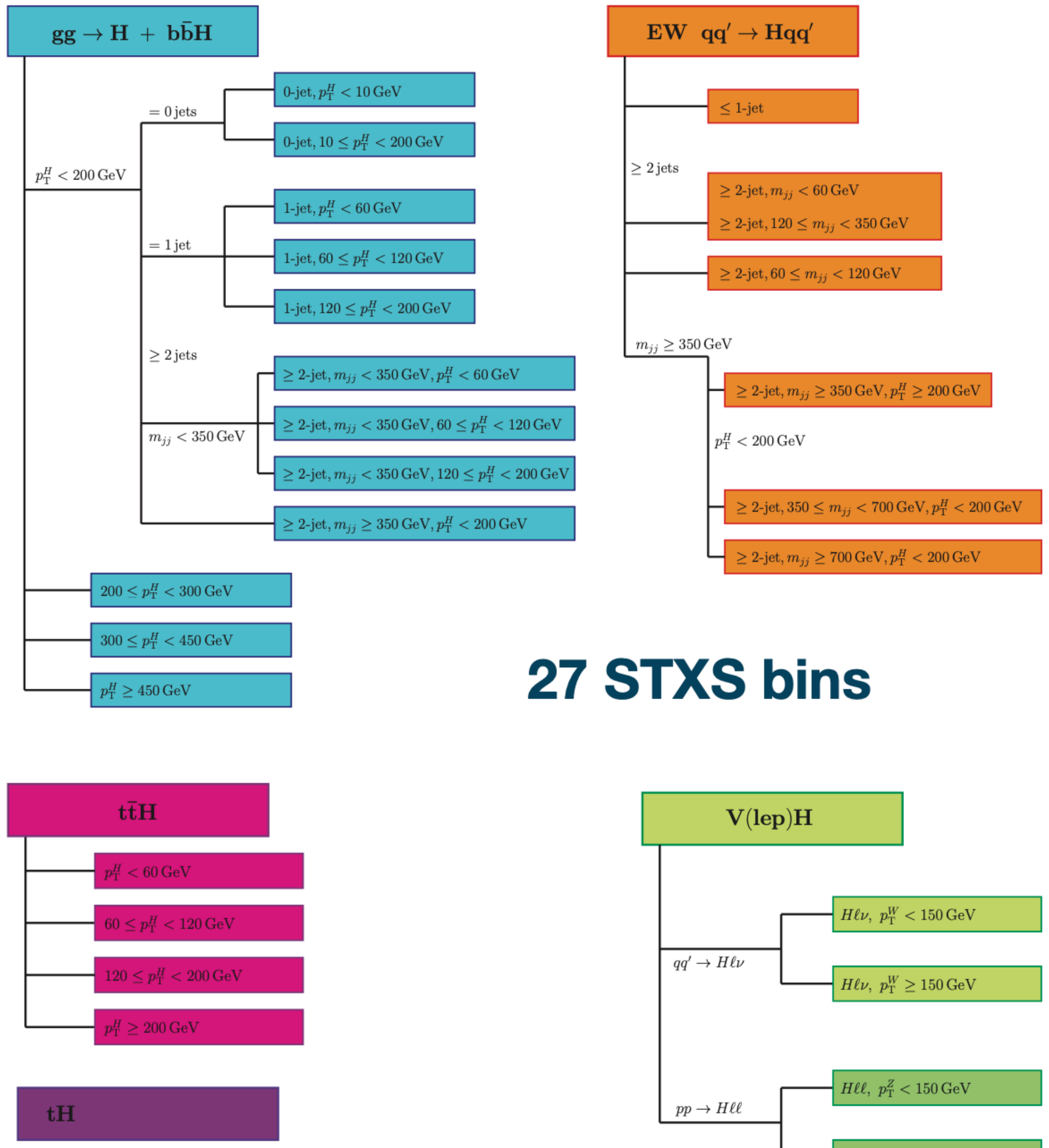


Constraints O(1-10%) depending on the scenario

$H \rightarrow \gamma\gamma$

- **Higher BR; but larger background, estimated robustly from data sidebands**
- **Fiducial and STXS (reduced Stage-1.2) measured w/ full Run2 data** [ATLAS-CONF-2019-029] [ATLAS-CONF-2020-026]
- S+B fit to $m_{\gamma\gamma}$ in each category of the STXS analysis or bin of the differential observables of the fiducial measurement. Response matrix implemented in the likelihood function

- Main **improvements** wrt previous ATLAS publications
  - STXS:
    - More event categories for more granular measurement (including differential ttH measurement)
    - New categorisation reduces uncertainties and correlations
  - Fiducial cross-sections:
    - Unfolding based on response matrix approach
    - Finer binning, higher p_T reach

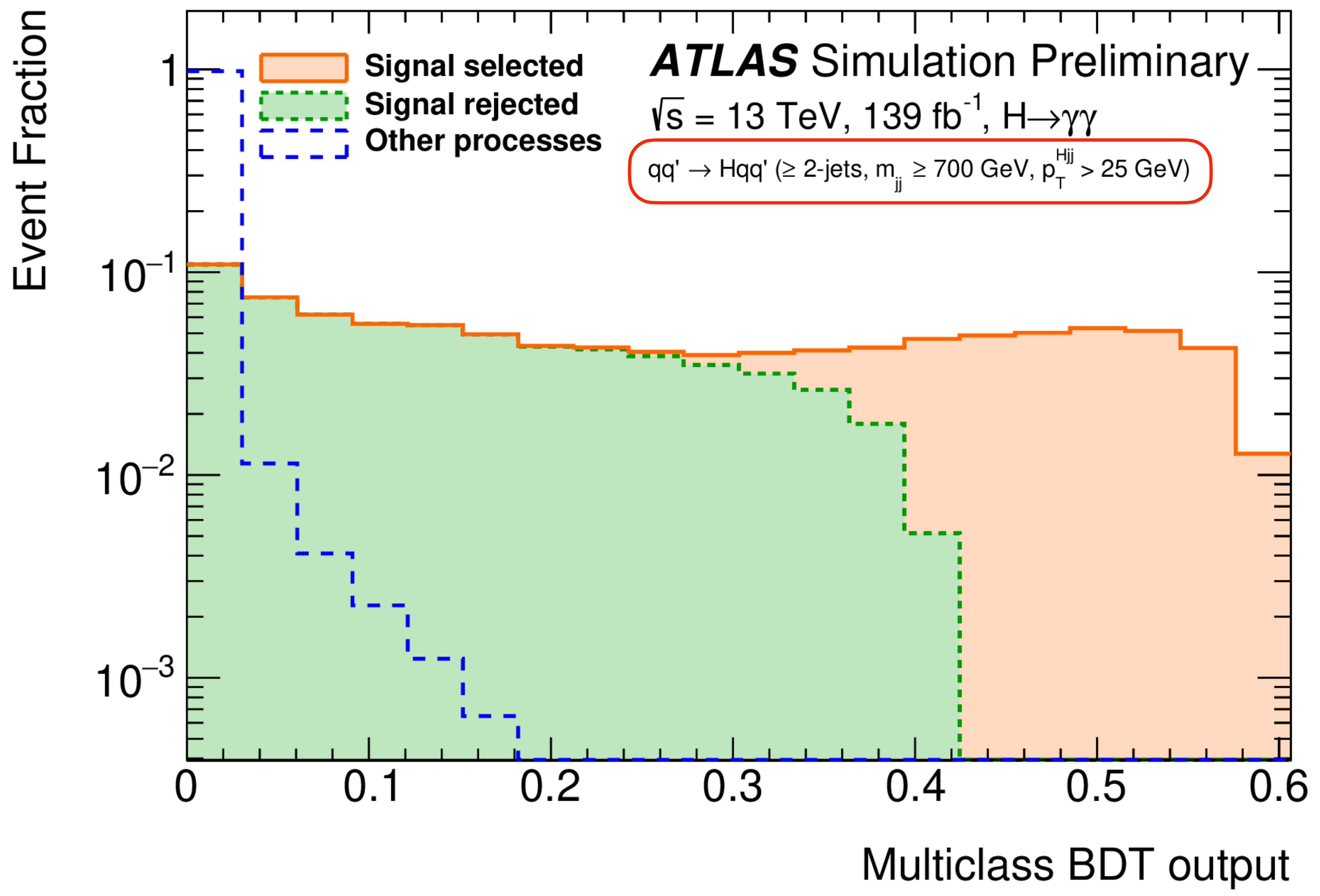


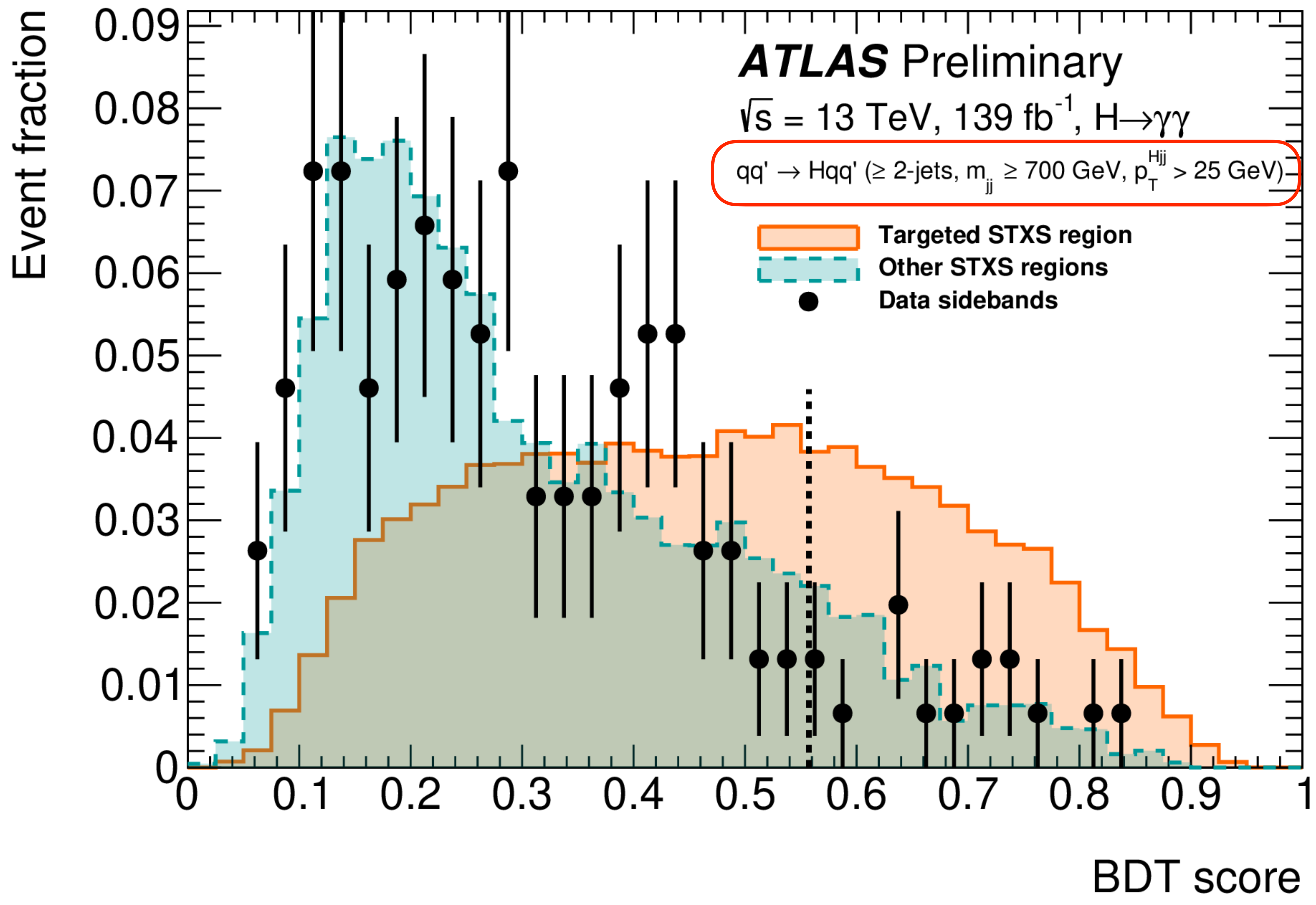
6 differential fiducial xsections

$p_T^{\gamma\gamma}$
$\lvert y_{\gamma\gamma} \rvert$
$p_T^{j_1}$
N_{jets}
$\Delta\phi_{jj}$
m_{jj}

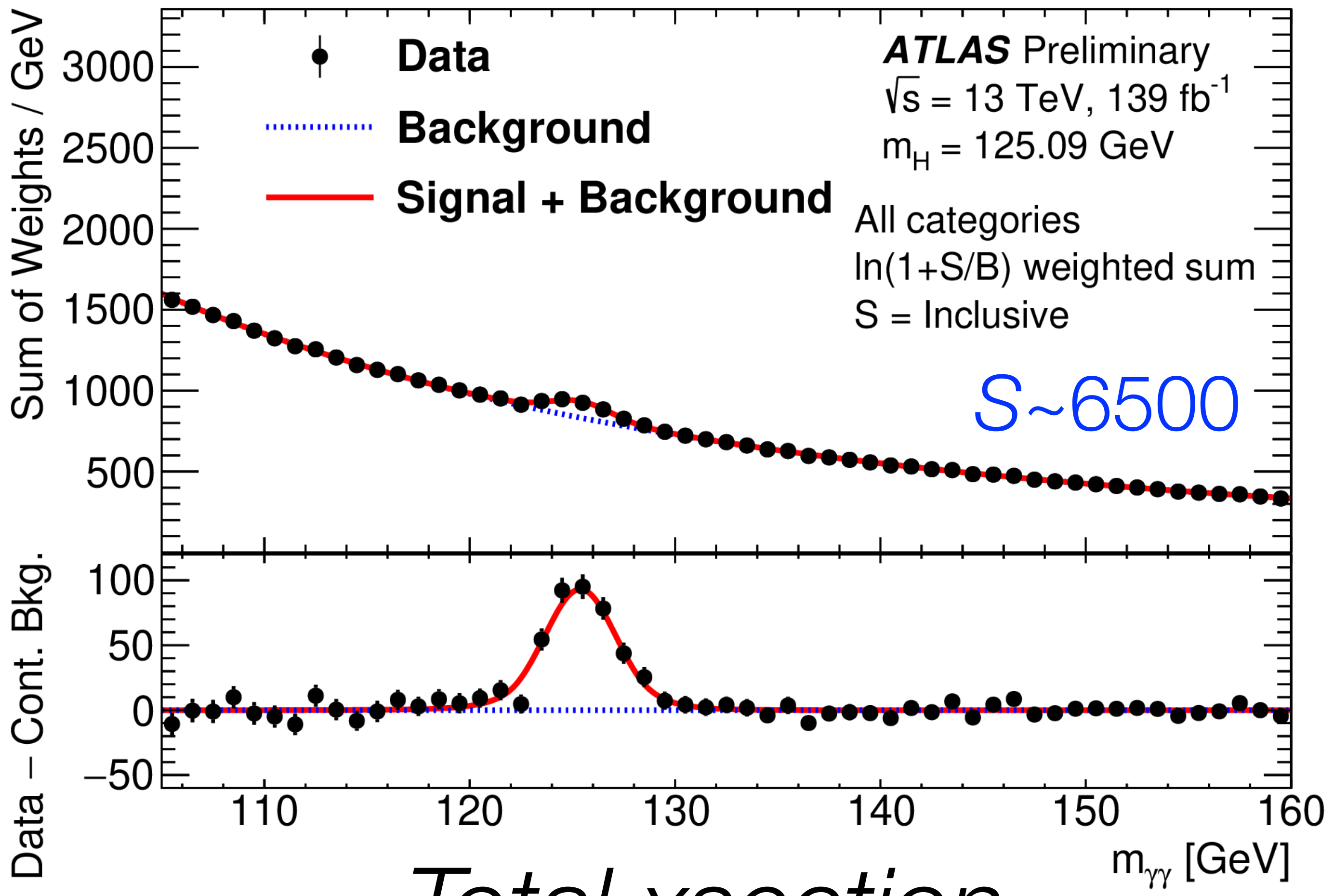
H→γγ STXS: event categories

- Main effort for **optimisation of event classification**, with **more granular** measurement and categories **better aligned** with STXS bins (higher purity ⇒ lower correlations, better precision). **Multi-step** approach:
    - **Multiclass BDT** trained to **separate signal events** from different STXS bins
    - **Optimisation of event classification based on BDT output** minimising the expected covariance of the measurements
    - Each category further split in (up to 3) subcategories of different S/B based on **binary BDT classifier** trained to **distinguish signal from bkg**





H→γγ STXS: results

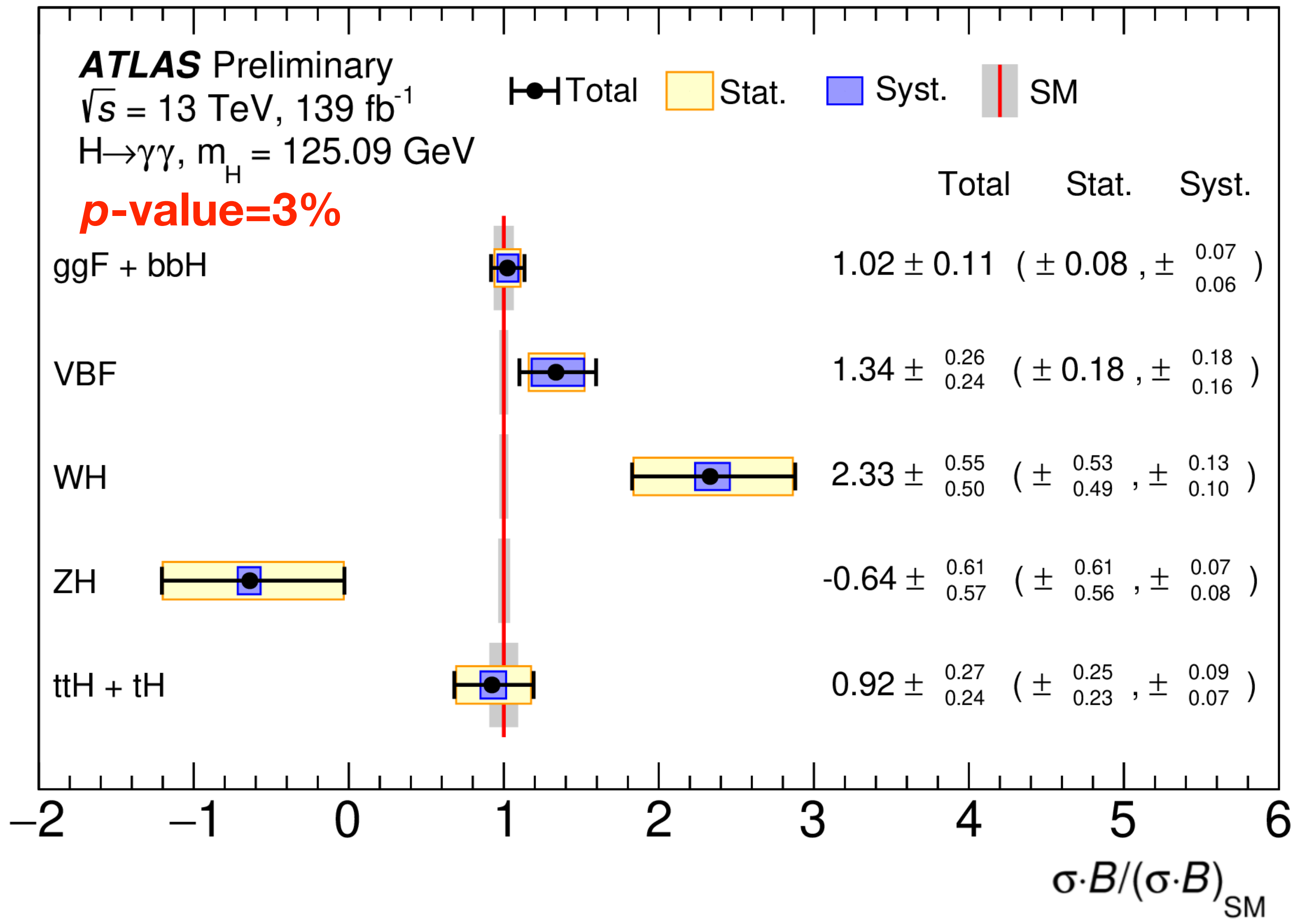


Total xsection

$\sigma \cdot B$ = 127±7(stat.)±7(syst.) fb = 127±10 fb

$(\sigma \cdot B)_{SM}$ = 116 ± 5 fb

Production mode xsections



7.5σ

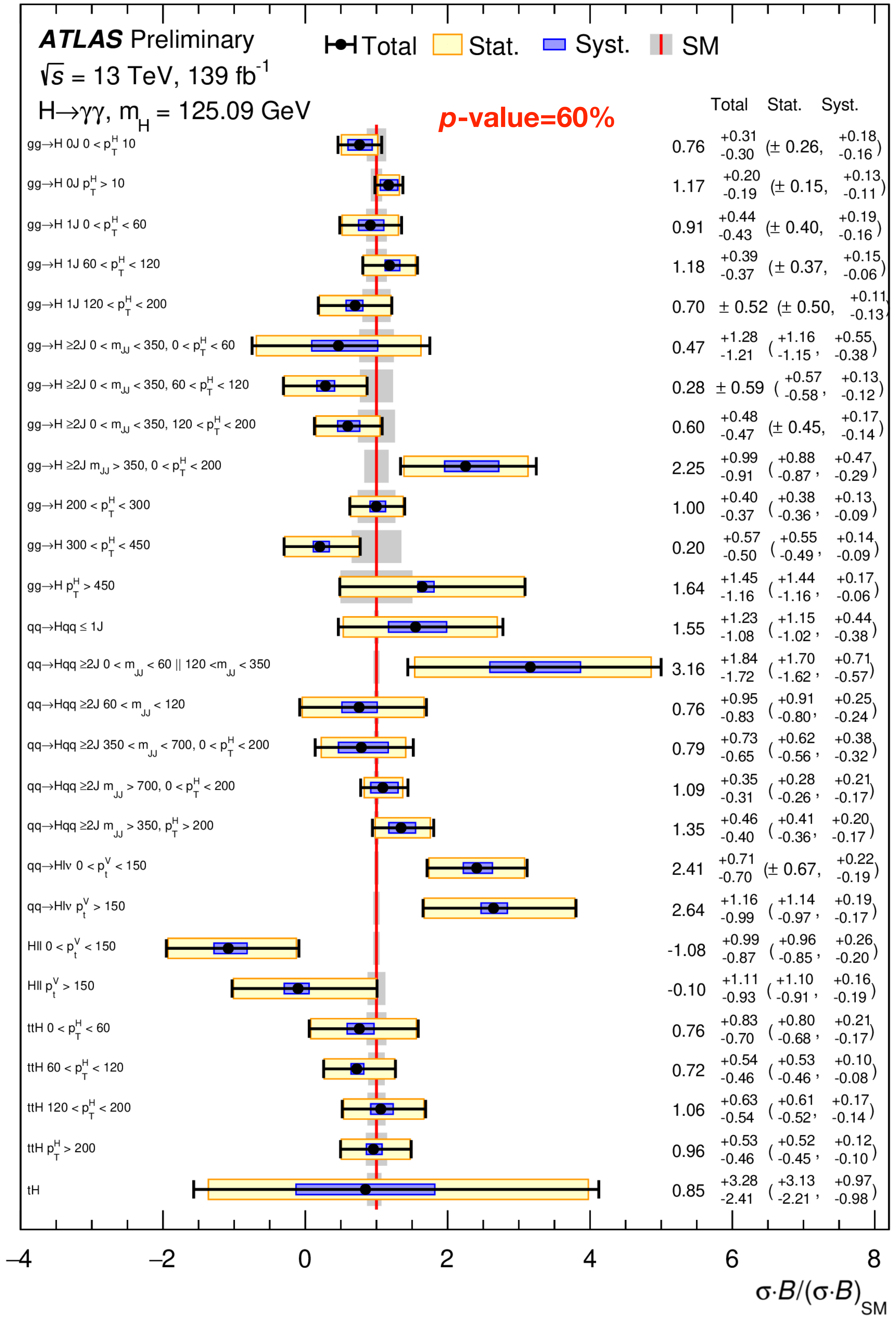
5.6σ

4.7σ

Large negative correlation (-42%) between WH and ZH.

Sum: $\sigma \cdot B$=5.9±1.4 fb, $(\sigma \cdot B)_{SM}$=4.53±0.12 fb, p-value = 50%

STXS



- No significant deviations from the SM expectation are observed
- Uncertainties: 8% → >100%
- Most of measurements stat limited, except inclusive ggF and VBF and 0-jet ggF regions where $err_{stat} \sim err_{syst}$
  - Main syst: bkg modelling / photons (resolution + efficiency) / parton shower modelling
  - Larger uncertainties in regions of low stat (high p_T^H for ggF, high p_T^V for VH, low m_{jj} for qq→Hqq)
- Production mode uncertainties improved by ~x2 or more wrt previous publication
- Upper limit of ~8x SM on tH $\sigma \cdot B$

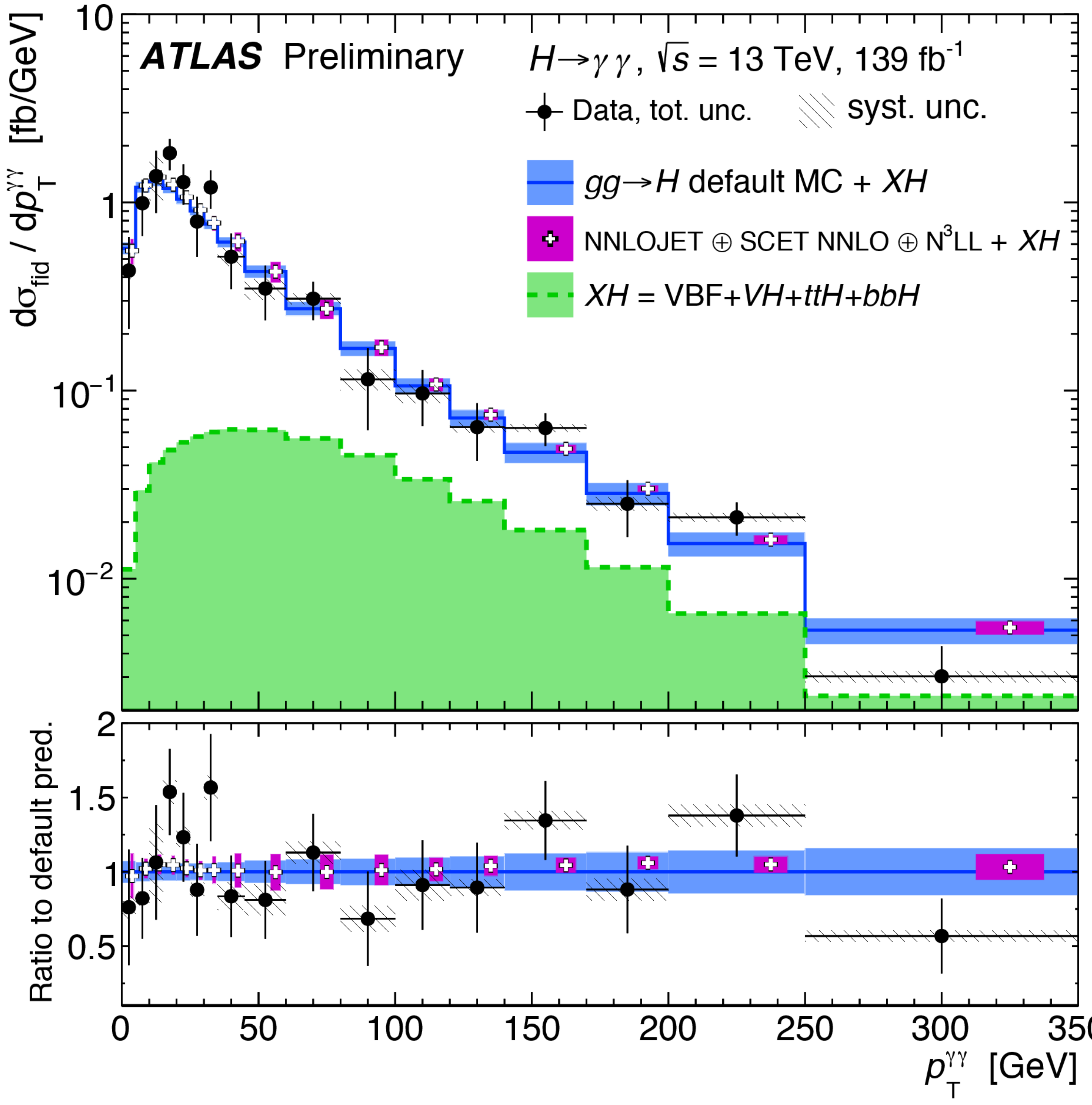
H→γγ fiducial xsections: results

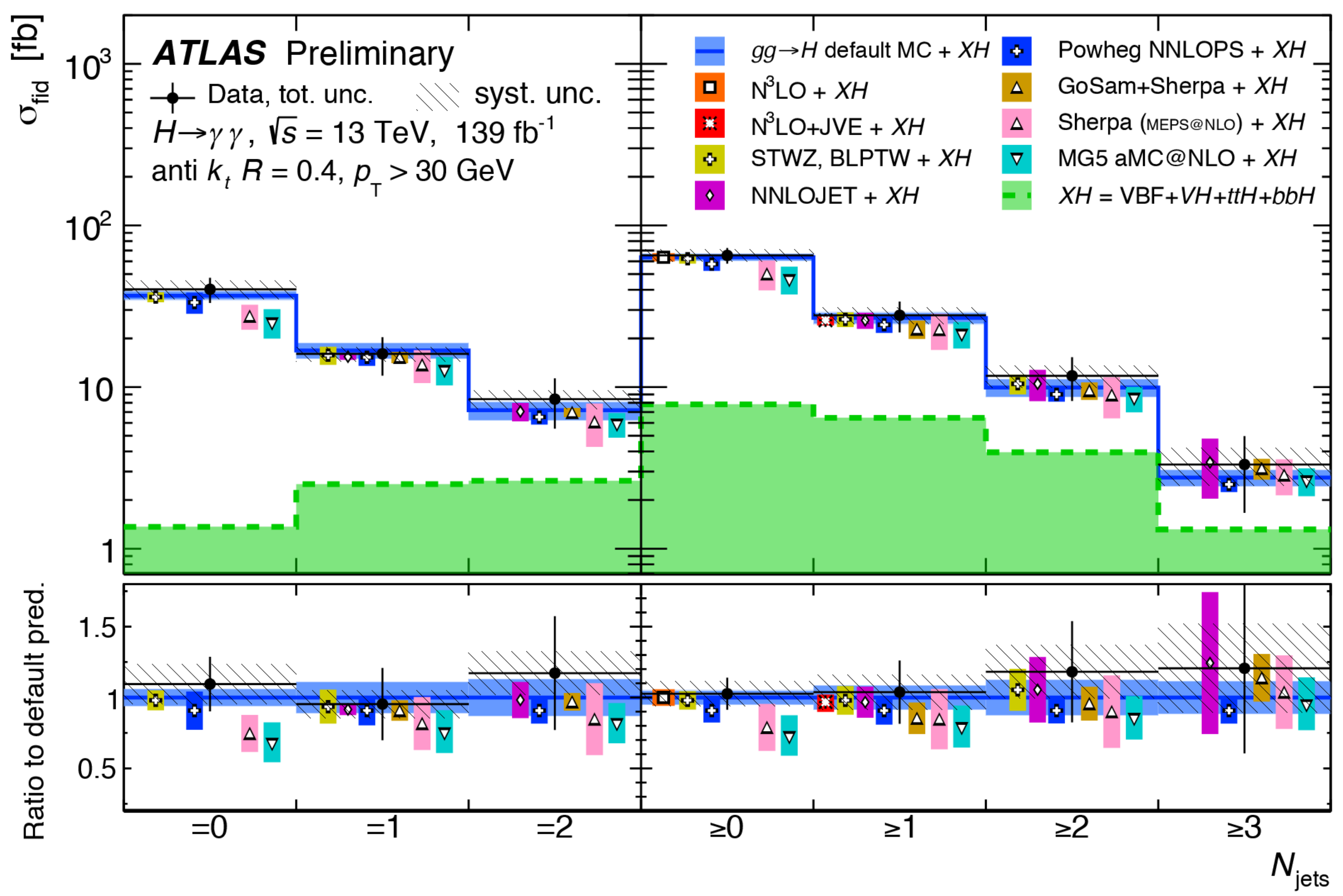
Fiducial xsection

$\sigma_{fid} \cdot B$ = 65.2 ± 7.1 fb

$(\sigma_{fid} \cdot B)_{SM}$ = 63.6 ± 3.3 fb

Diff. fiducial xsections





Distribution	$p(\chi^2)$ with Default MC Prediction
$p_T^{\gamma\gamma}$	44%
$\lvert y_{\gamma\gamma} \rvert$	68%
$p_T^{j_1}$	77%
N_{jets}	96%
$\Delta\phi_{jj}$	82%
m_{jj}	75%

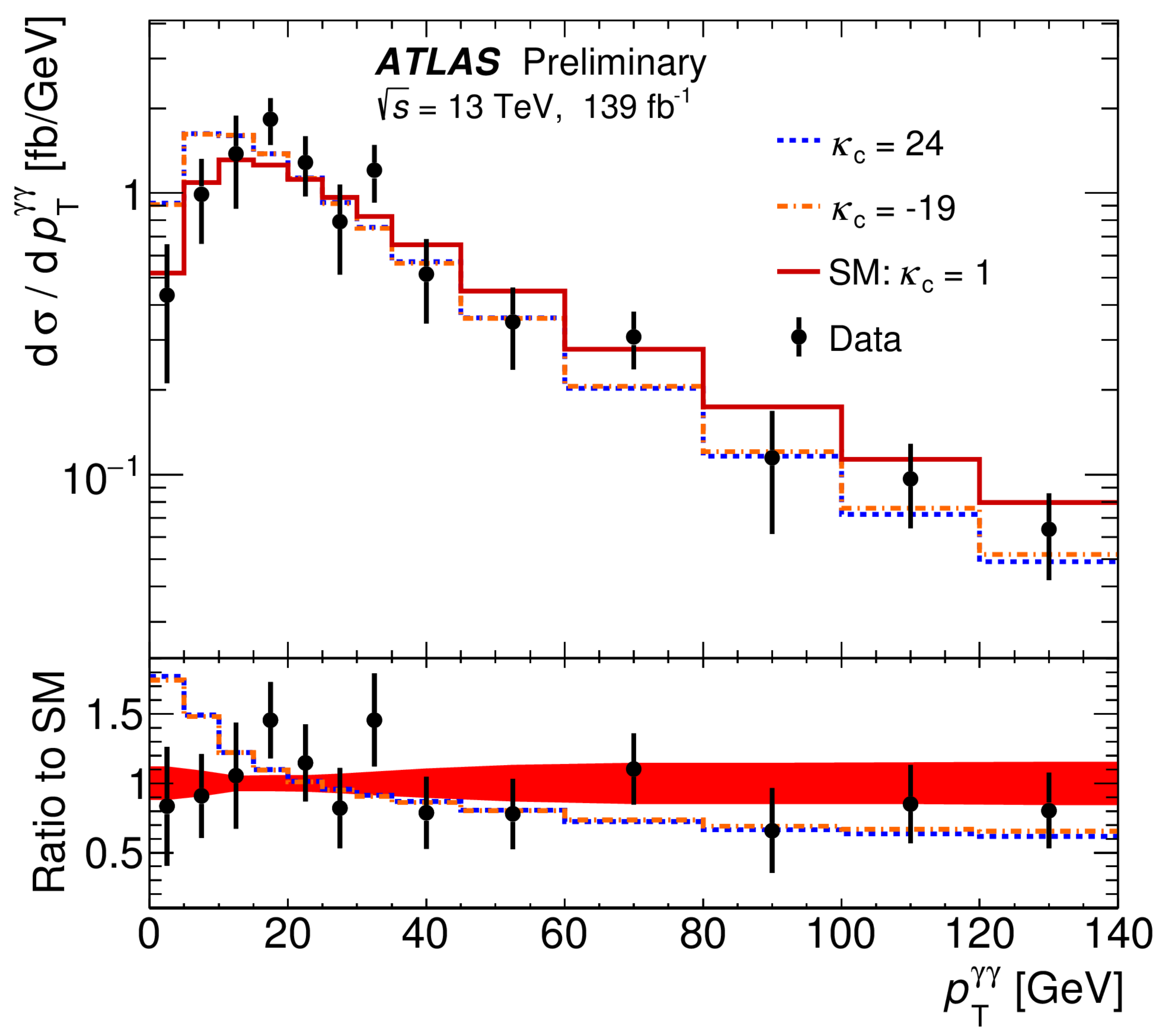
- Good agreement with SM
- Differential measurements stat limited, inclusive one has err_{stat} ~ err_{syst}
  - Main systematic uncertainties: bkg modelling / photon (energy scale/resolution + efficiency)
- Uncertainty improved by ~x2 wrt previous publication (a bit less in inclusive measurement due to larger impact of bkg modelling)

H→γγ fiducial xsections: interpretations

- **$p_T(\gamma\gamma)$** fid. xsec → constrain the **charm Yukawa coupling (left),** with approach similar to H→4l, using shape-information only
- **5/6** differential fiducial xsections → constrain **anomalous Higgs couplings to gauge bosons (right)** in an EFT approach similar to H→4l (SMEFT, Warsaw basis, dim-6 operators)

c Yukawa coupling

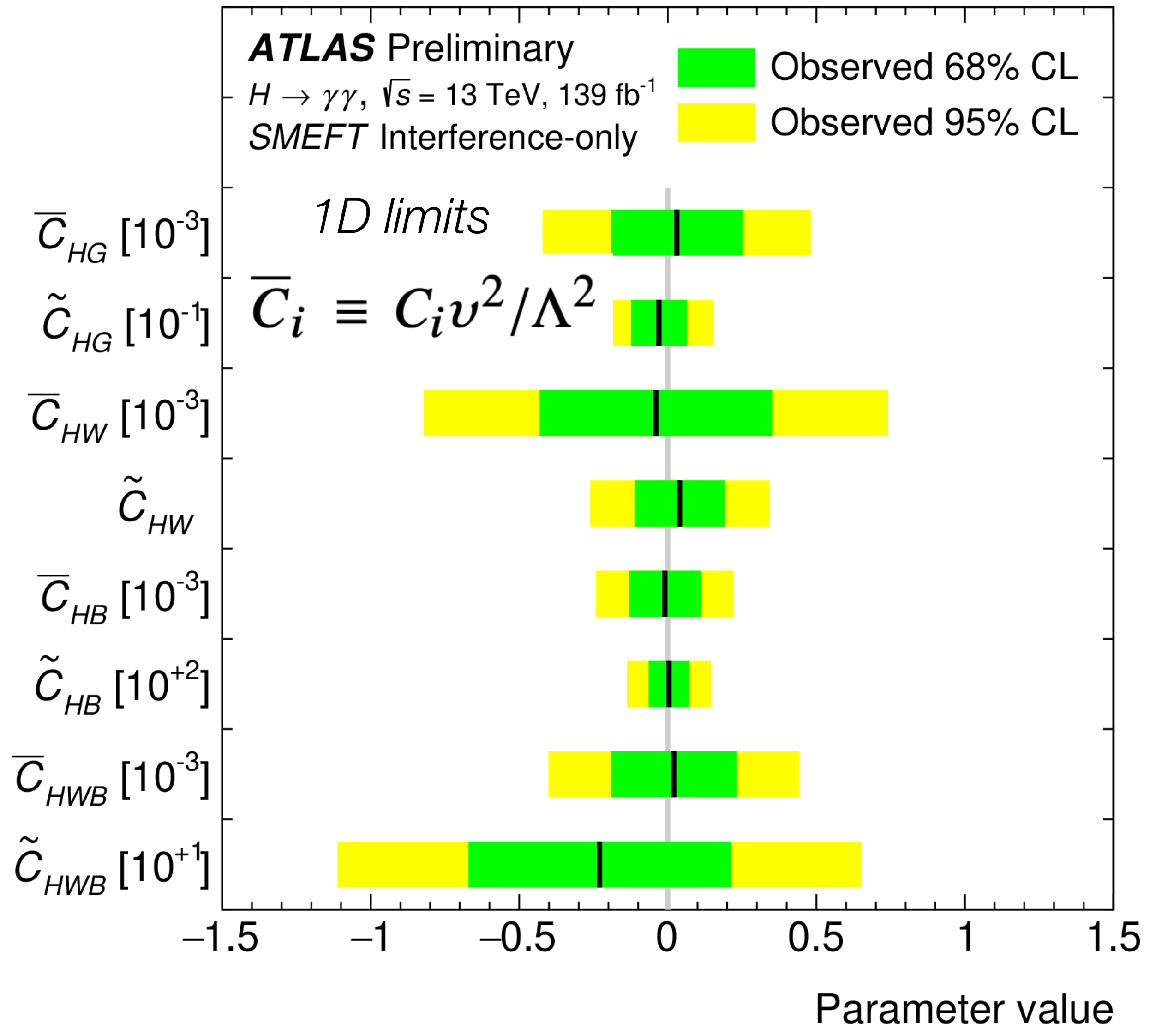
Coefficient	Observed 95% CL limit	Expected 95% CL limit
κ_c	$[-19, 24]$	$[-15, 19]$



Sensitivity mainly driven by low $p_T(H)$ region

Constraints on k_c and c_{HG} in same ballpark as H → 4l, but much stronger on c_{HW}, c_{HB}, c_{HWB} (large impact on the Hγγ partial width)

BSM couplings to gauge bosons (EFT)



Sensitivity for most variables (when interference only considered) driven by overall normalisation except

- $\bar{C}_{HG}$: impact on various shapes
- CP-odd couplings: impact on $\Delta\Phi_{jj}$ shape

Coefficient	95% CL, interference-only terms	95% CL, interference and quadratic terms
$\bar{C}_{HG}$	$[-4.2, 4.8] \times 10^{-4}$	$[-6.1, 4.7] \times 10^{-4}$
$\tilde{C}_{HG}$	$[-2.1, 1.6] \times 10^{-2}$	$[-1.5, 1.4] \times 10^{-3}$
$\bar{C}_{HW}$	$[-8, 2, 7.4] \times 10^{-4}$	$[-8.3, 8.3] \times 10^{-4}$
$\tilde{C}_{HW}$	$[-0.26, 0.33]$	$[-3.7, 3.7] \times 10^{-3}$
$\bar{C}_{HB}$	$[-2.4, 2.3] \times 10^{-4}$	$[-2.4, 2.4] \times 10^{-4}$
$\tilde{C}_{HB}$	$[-13.0, 14.0]$	$[-1.2, 1.1] \times 10^{-3}$
$\bar{C}_{HWB}$	$[-4.0, 4.4] \times 10^{-4}$	$[-4.2, 4.2] \times 10^{-4}$
$\tilde{C}_{HWB}$	$[-11.1, 6.5]$	$[-2.0, 2.0] \times 10^{-3}$

H→WW*→eνμν

- **Largest BR but worst resolution due to neutrinos.** Provides **extra valuable information** especially in regions of phase space where the xsection is small
- **Lepton angular correlations** help **suppressing main bkg (WW*)**
- **Production cross sections and STXS (reduced Stage 1.2) measured w/ full Run2 data**

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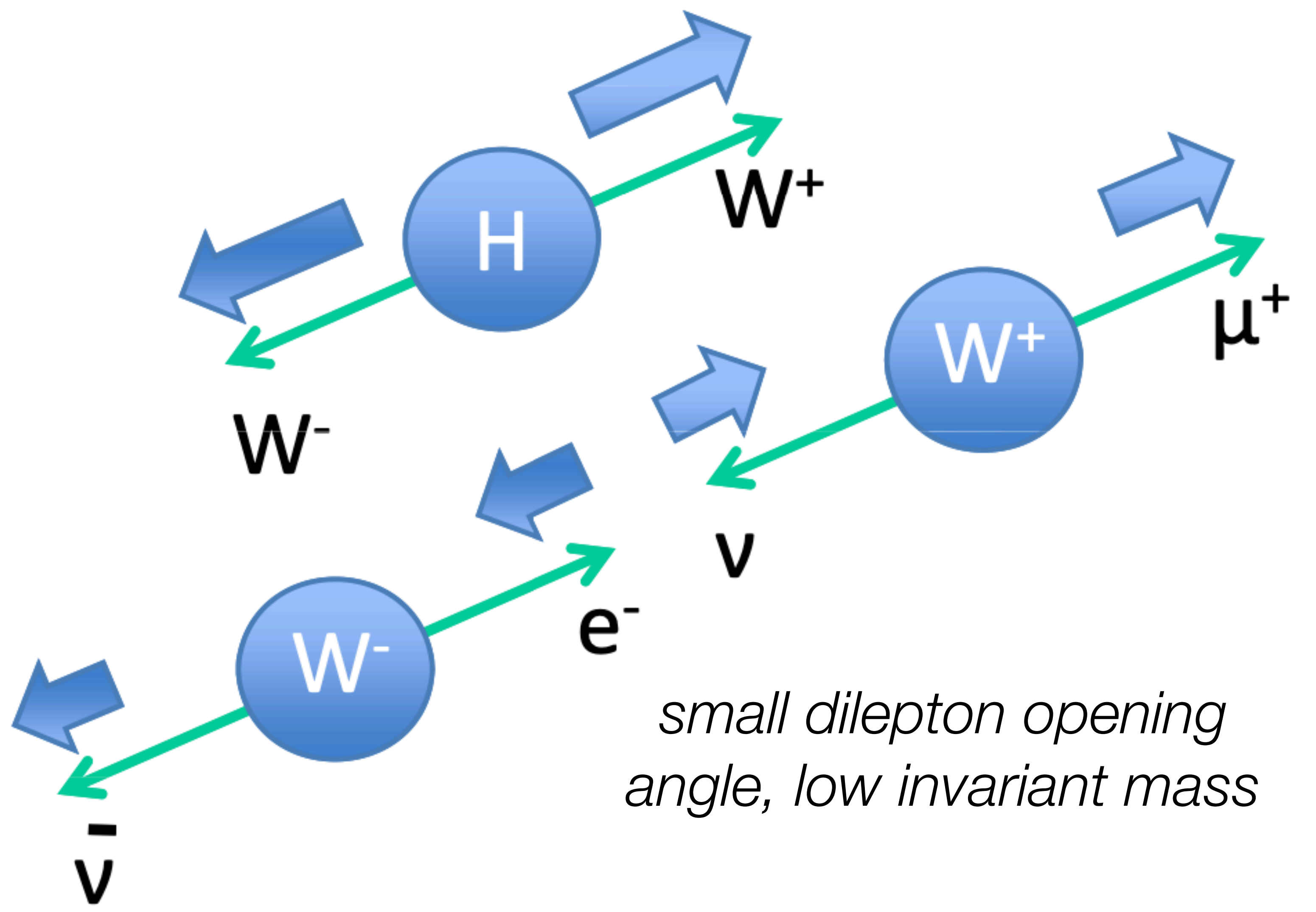
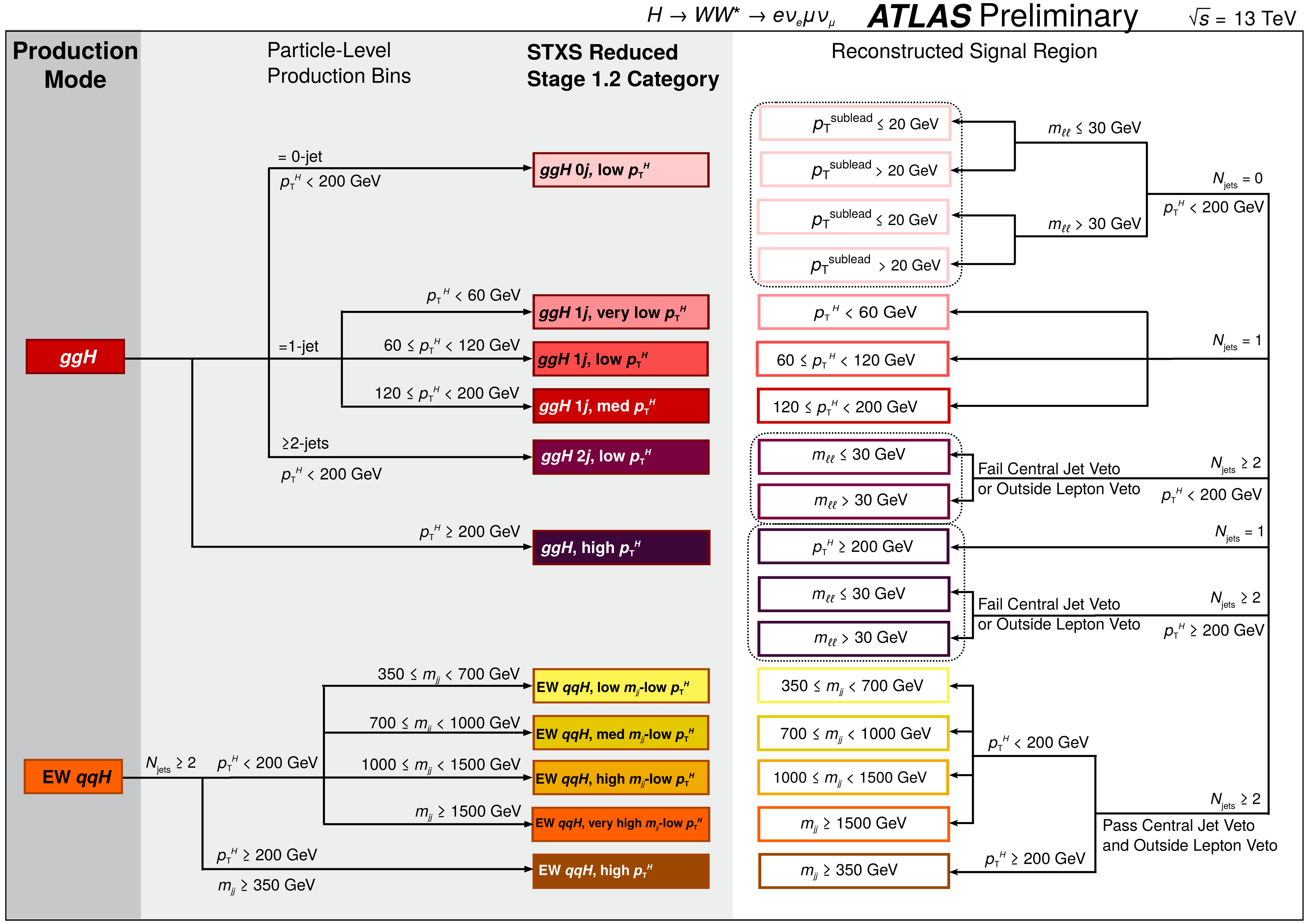


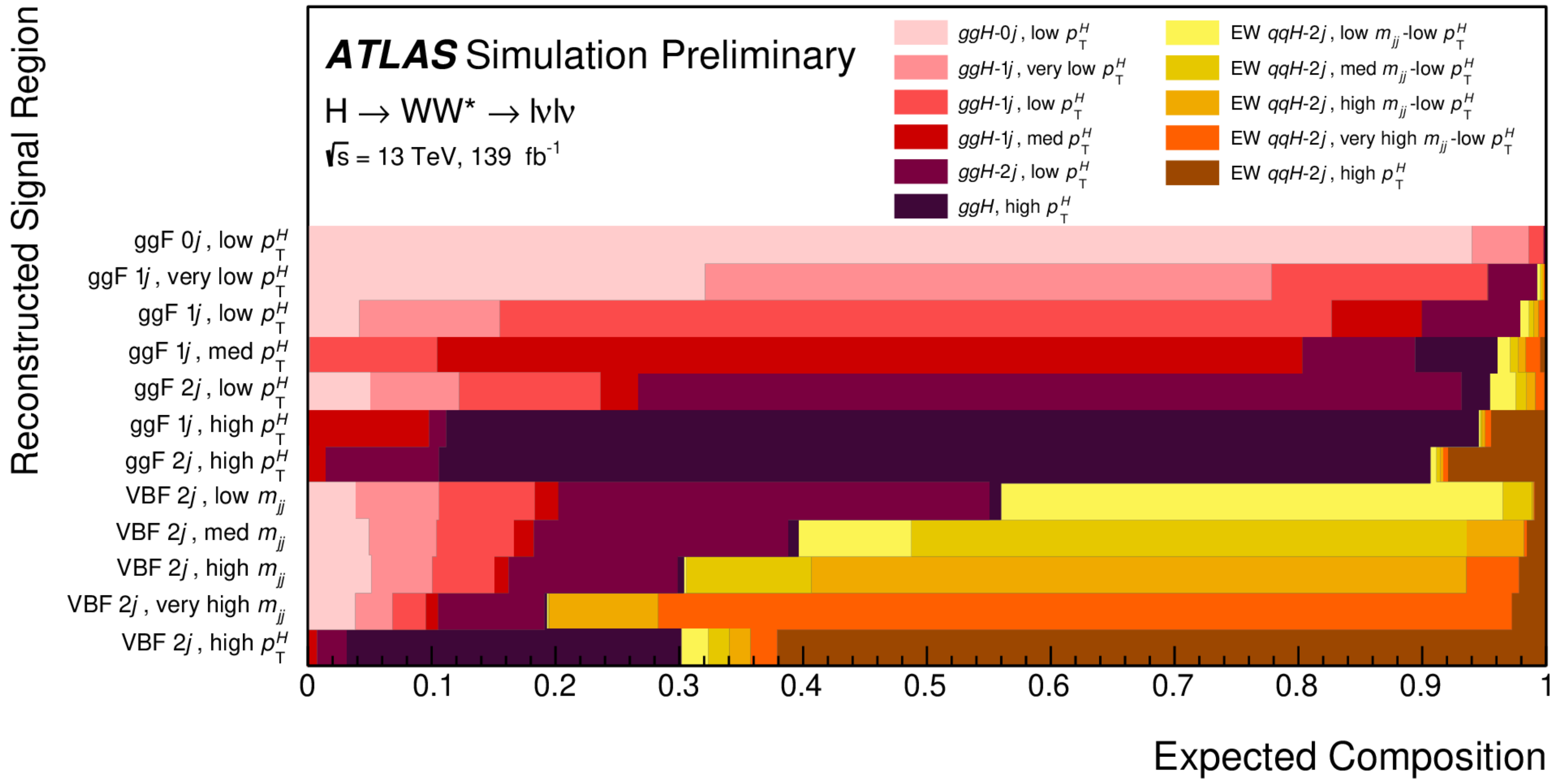
- Main **improvements** wrt previous ATLAS publications
  - Measured ggF in 2-jet region
  - Higher sensitivity to VBF due to new discriminant (BDT→DNN), with more input variables and finer binning
  - First STXS measurement (in ggF and VBF regions) in this channel (11 bins of reduced-stage 1.2)
  - Improved modelling of ttbar background

More details in Robin Hayes' talk this afternoon..

H→WW*→eνμν: analysis strategy

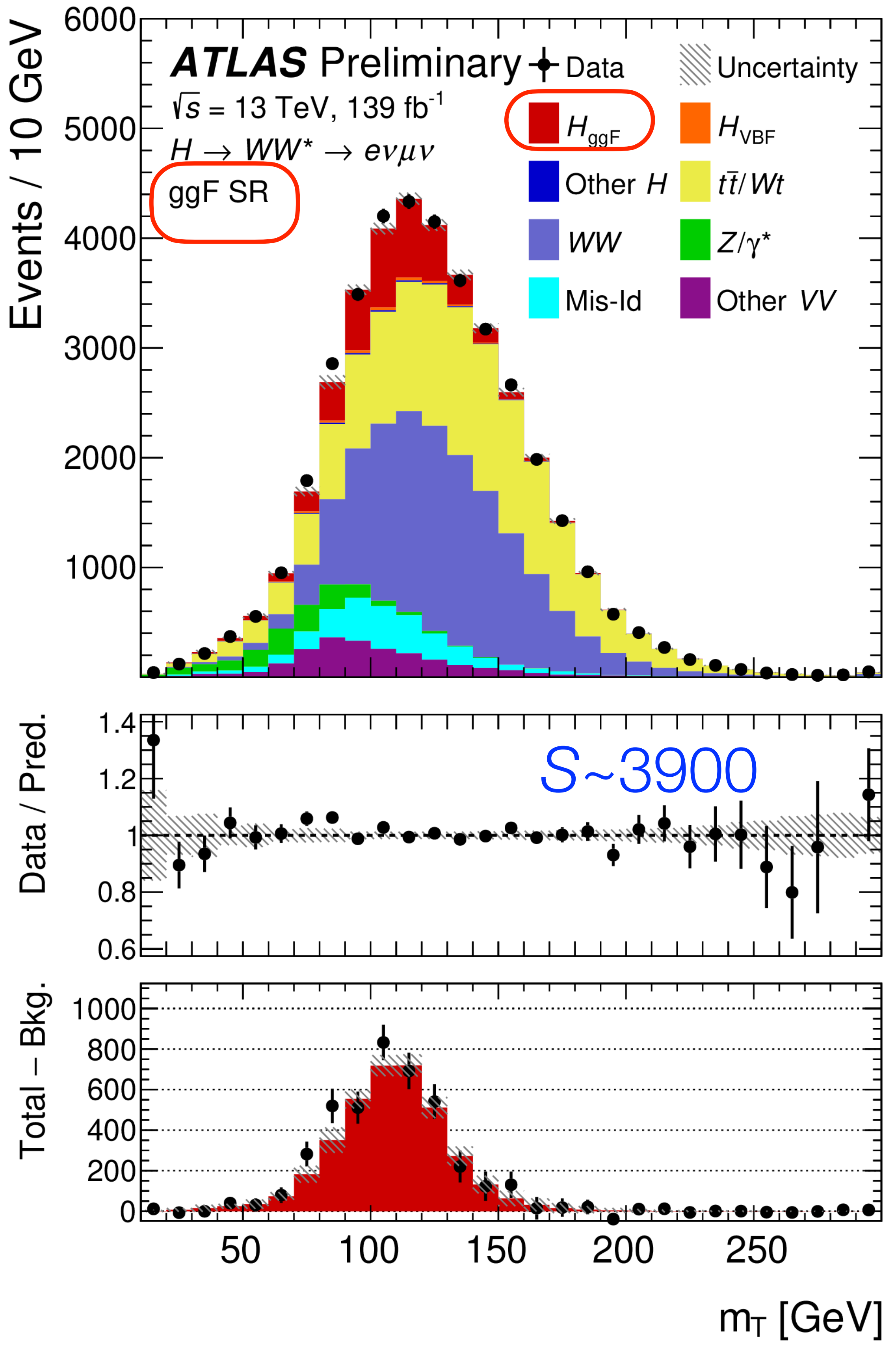
- Separate events in **jet multiplicity bins**: 0, 1, 2+ (ggF-like), 2+ (VBF-like)
- Further split events in **categories** with different S/B, and aligned with STXS regions for STXS measurement, based on m_{ll}, p_T^{l2}, p_T^H and m_{jj}

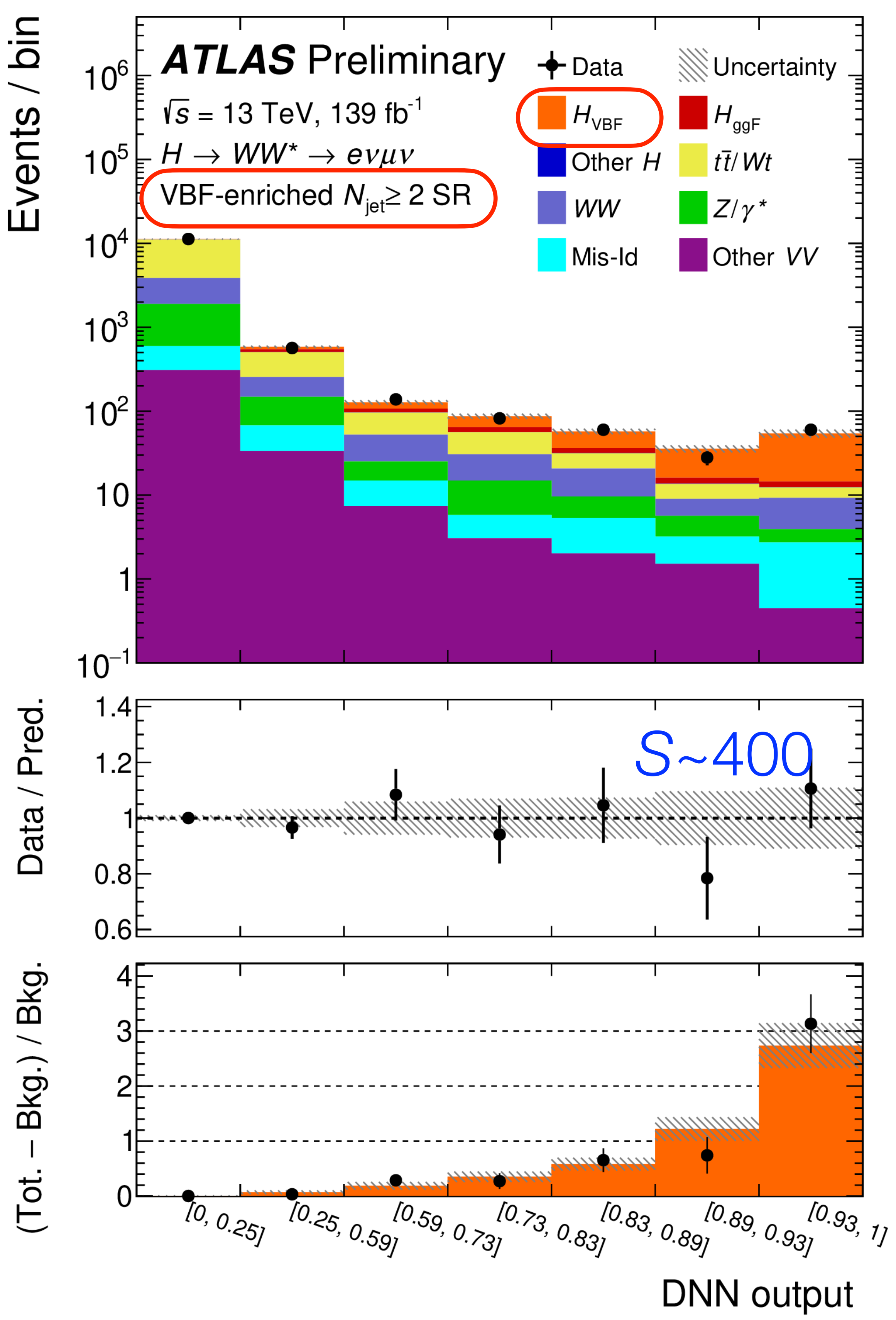




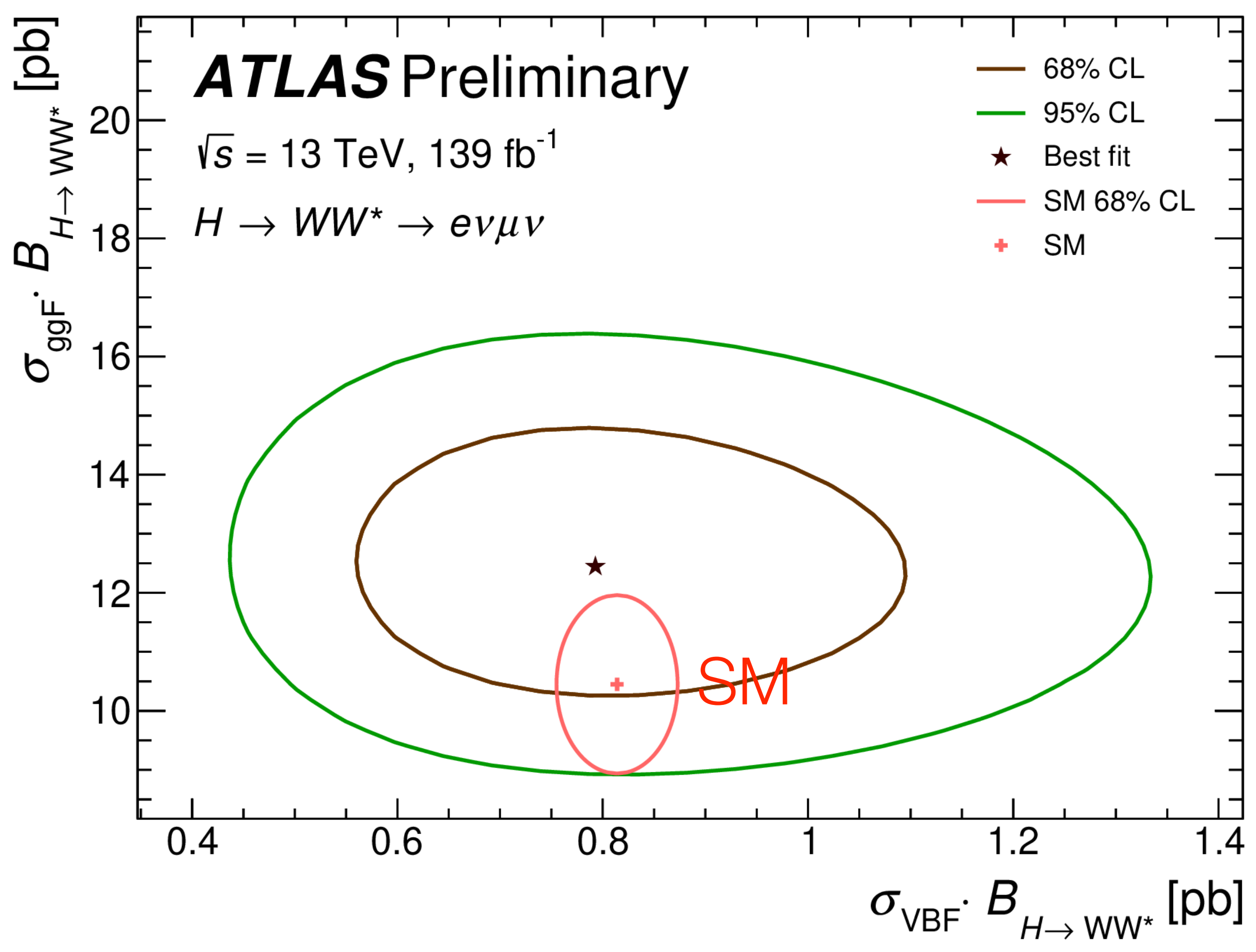
- Cross sections measured from **simultaneous fit to data signal regions + bkg control regions (WW/top/Z(ττ)+jets) in the various categories** (fit m_T for ggF categories, DNN for VBF categories)

H→WW*→eνμν: results



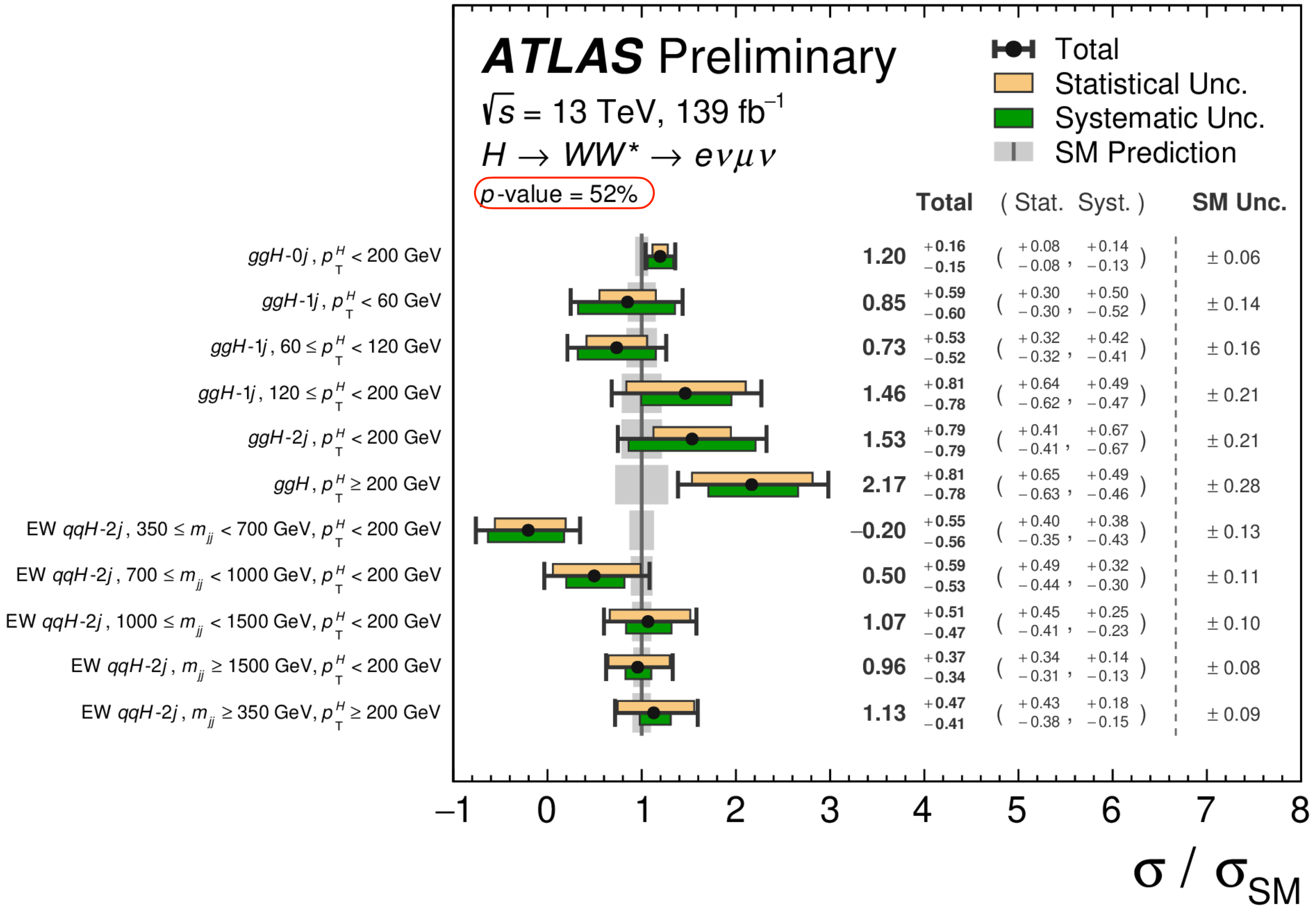


- Good agreement data/fit (left), post-fit bkg normalisation factors ~1
- Good agreement of measured xsections with SM (right)
- ggF and VBF inclusive XS and ggF STXS low p_T^H syst. dominated, other STXS stat. limited
    - Large impact from theory uncertainties (esp. VBF)



VBF significance 6.6σ (6.1 expected)

Uncertainty improved by 50% in ggF and x2.5 in VBF wrt previous publication



EW qqH sensitivity comparable to H→γγ

Conclusion

- Full-Run2 results provide high sensitivity to Higgs boson mass (0.16%) and cross sections (few % inclusive, ~10% ggF, ..)
- Fiducial and simplified template cross section measurements probe the Higgs properties with high granularity and negligible or reduced model dependence
- Still room to improve full Run 2 results, update partial-Run 2 ones, perform combinations and interpretations