Higgs boson measurements in its decays into bosons and in combined analyses with the ATLAS experiment

Benjamin Jäger (SFU)
On behalf of the ATLAS Collaboration

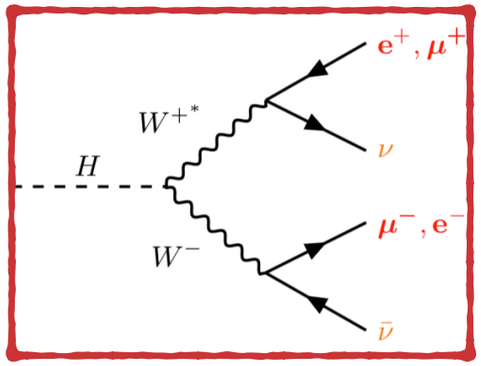
ICNFP 2021

24/08/2021

Higgs Decays To Bosons

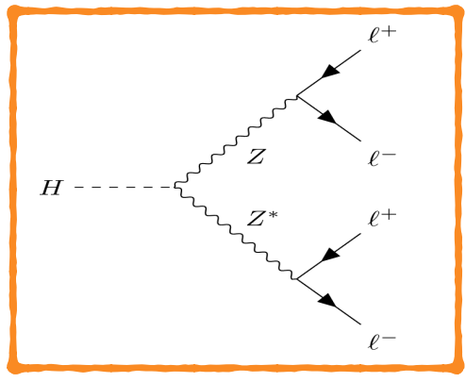
H -> WW*

BR: 21%



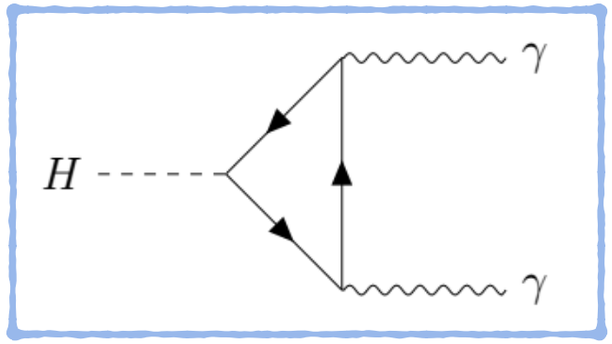
H -> ZZ*

BR: 3%

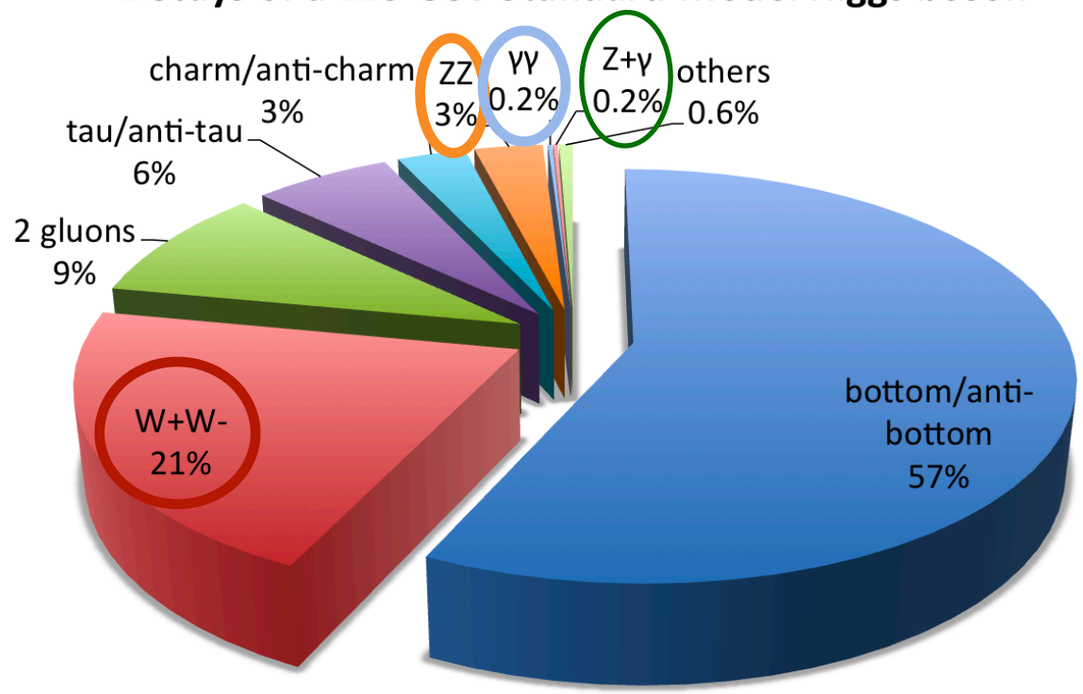


H -> γγ

BR: 0.2%



Decays of a 125 GeV Standard-Model Higgs boson



Then (2012)

Crucial Channels for Higgs Discovery

Now (and in this talk)

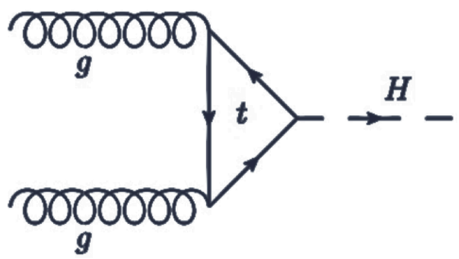
Excellent for Higgs precision & properties measurements

Now (and in this talk) and Future

Sensitive Inputs to Constrain EFT & Other Model Parameters

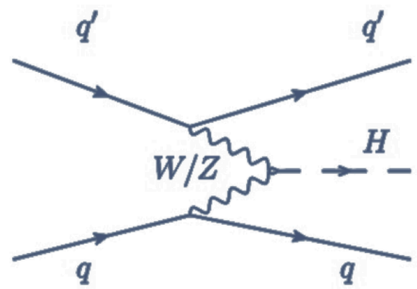
Main Higgs Production Modes

Gluon Fusion



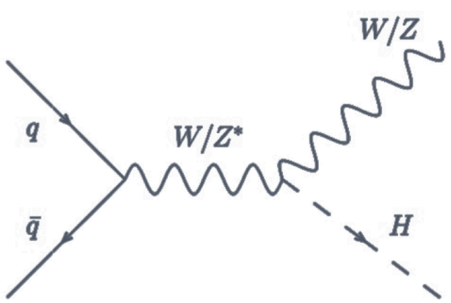
$\sigma_{H,ggF}$ ~ 49 pb

Vector Boson Fusion



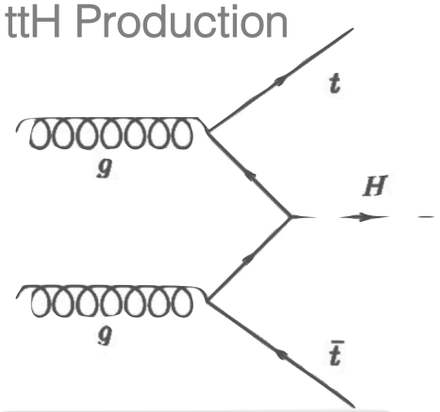
σ_{VBF}~ 3.8 pb

Higgs-Strahlung

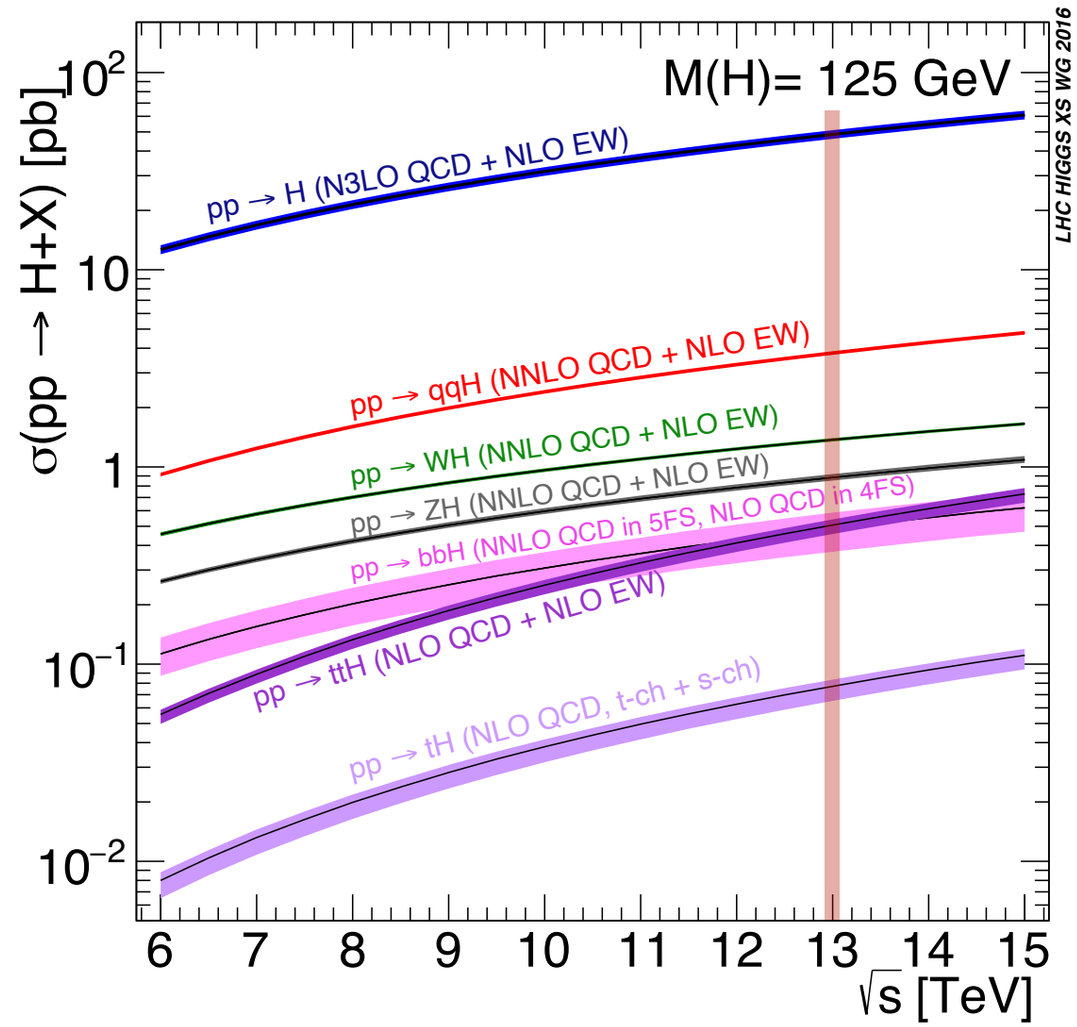


$\sigma_{W/Z+H}$ ~ 1.4/0.9 pb

ttH Production



σ_{ttH} ~ 0.507 pb



Different production and decay modes provide many handles for precision measurements in various regions of phase space

Different Higgs Measurements

Inclusive cross-section (σ) of production mode

- Measure inclusive σ per production mode
- Maximum sensitivity but model dependent

Fiducial / differential cross-sections

- Most model independent but less sensitive (use “simple” analysis cuts)
- Measure σ in fiducial volume and multiple distributions

Simplified Template Cross Sections (STXS) *

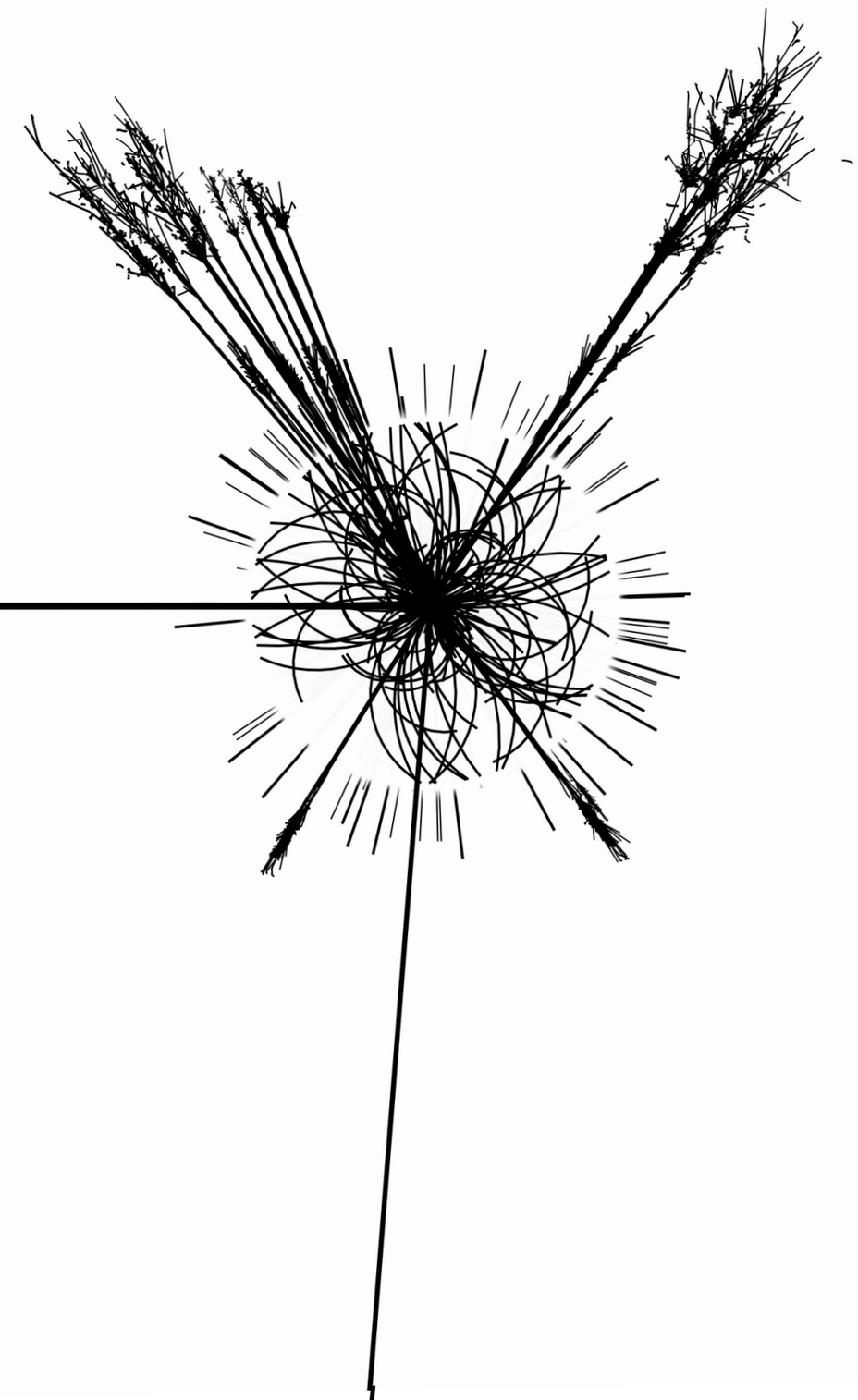
- Measure σ in STXS regions defined per production mode and agnostic to Higgs decay
- Combinations encouraged
- Optimized for sensitivity while reducing theory dependence

EFT & other interpretations

- Look for new physics (see later slides)

* https://arxiv.org/abs/2003.01700

Production & STXS Cross-section Measurements



$H \to ZZ^*$ & $H \to \gamma\gamma$ Prod./STXS Cross-sections

Production: ggF, VBF, VH, ttH+tH, bbH (only H->ZZ)

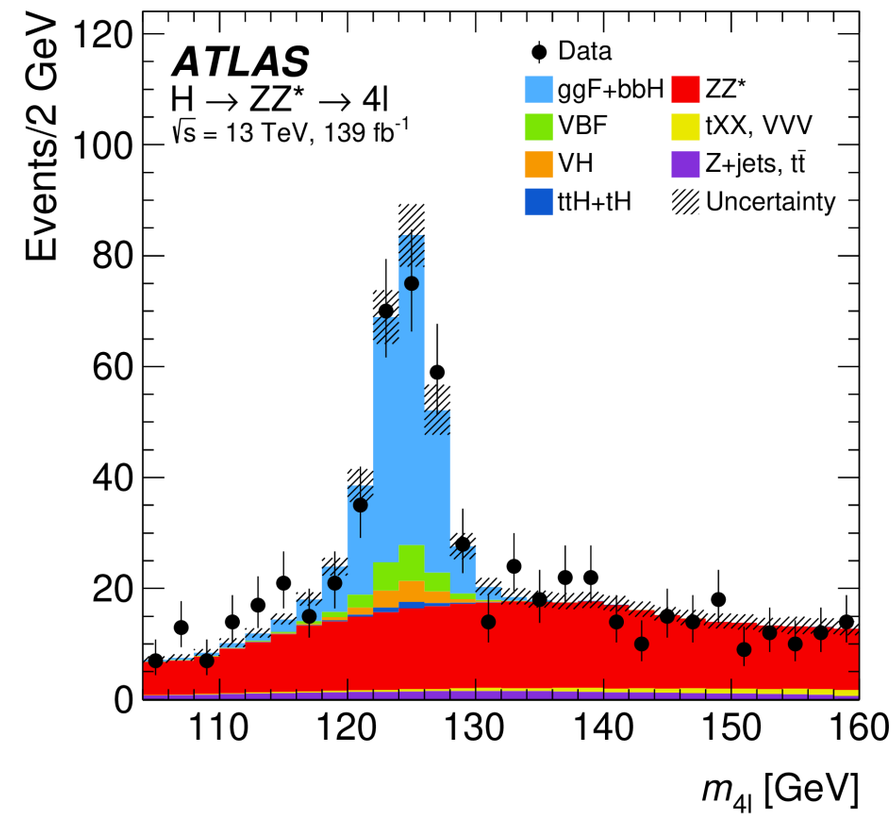
$H \to ZZ^*$

Characteristics

- "Cleanest" Higgs channel, highest signal / bkg

Strategy

- Neural networks (NNs) used in individual categories
- Extract cross-sections from fit to NN output



Eur. Phys. J. C (2020) 80:957

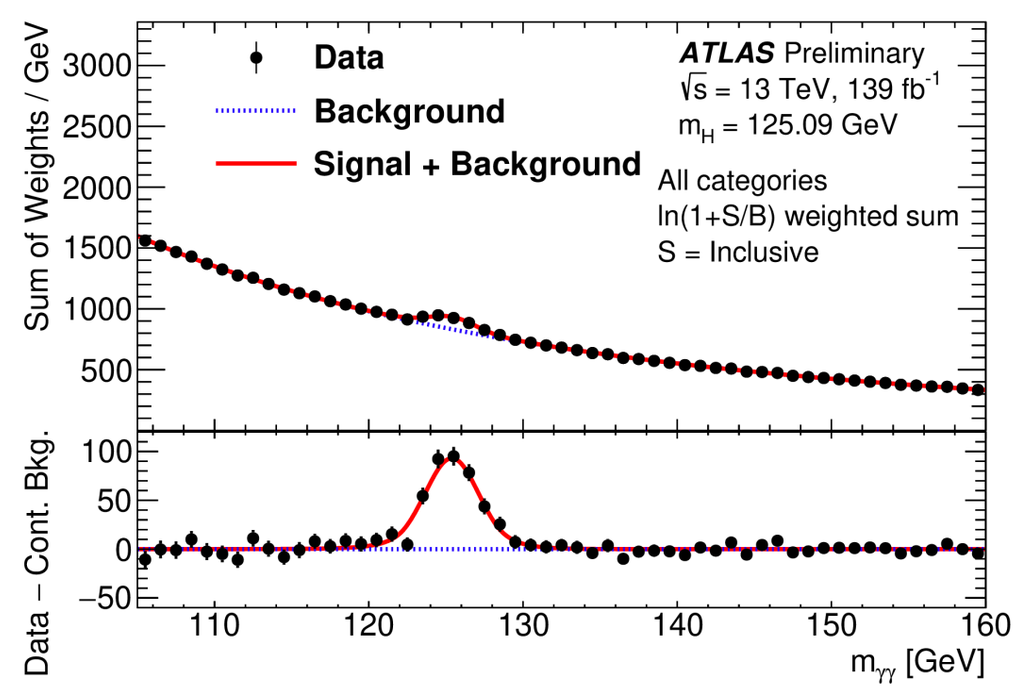
$H \to \gamma\gamma$

Characteristics

- Excellent control over background with an analytical model

Strategy

- Cascade of boosted decision trees (BDTs)
  - Multi-class BDT to separate signal events from different STXS regions (mitigating migrations!)
  - Binary BDT to separate signal from bkg
- Extract cross-sections from fit to $m_{\gamma\gamma}$



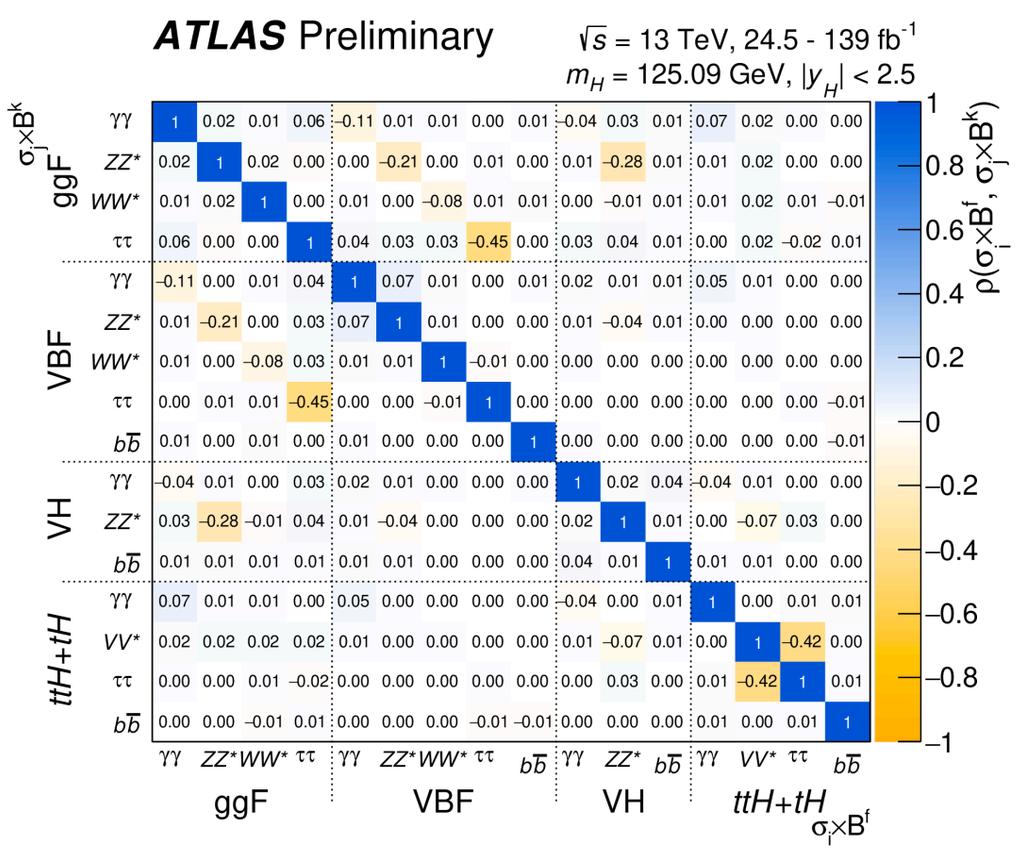
ATLAS-CONF-2020-026

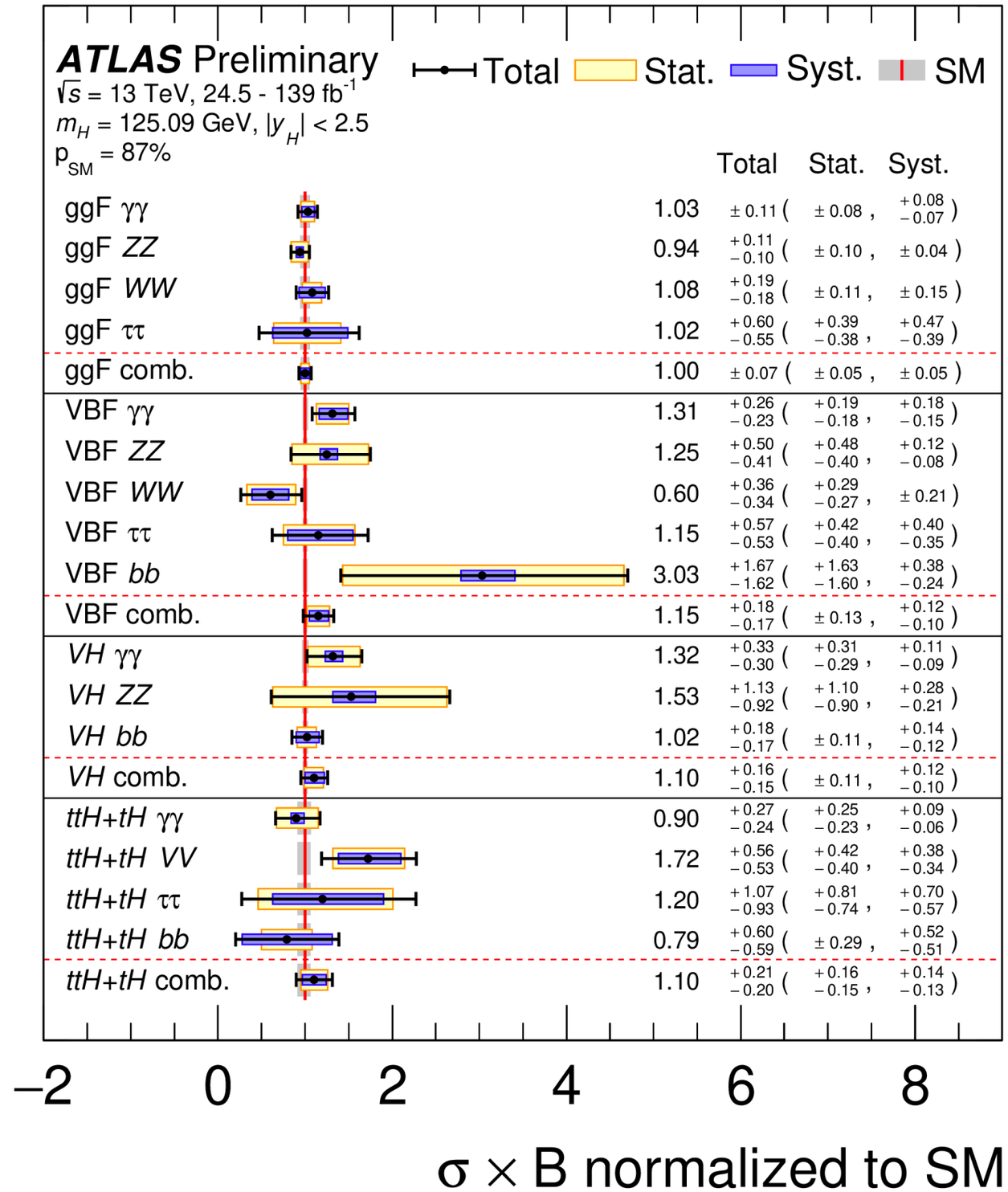
Combined Production Cross-sections

ATLAS-CONF-2020-027

Global signal strength: $\mu = 1.06 \pm 0.07 = 1.06 \pm 0.04\,(\text{stat.}) \pm 0.03\,(\text{exp.})\,^{+0.05}_{-0.04}\,(\text{sig. th.}) \pm 0.02\,(\text{bkg. th.})$

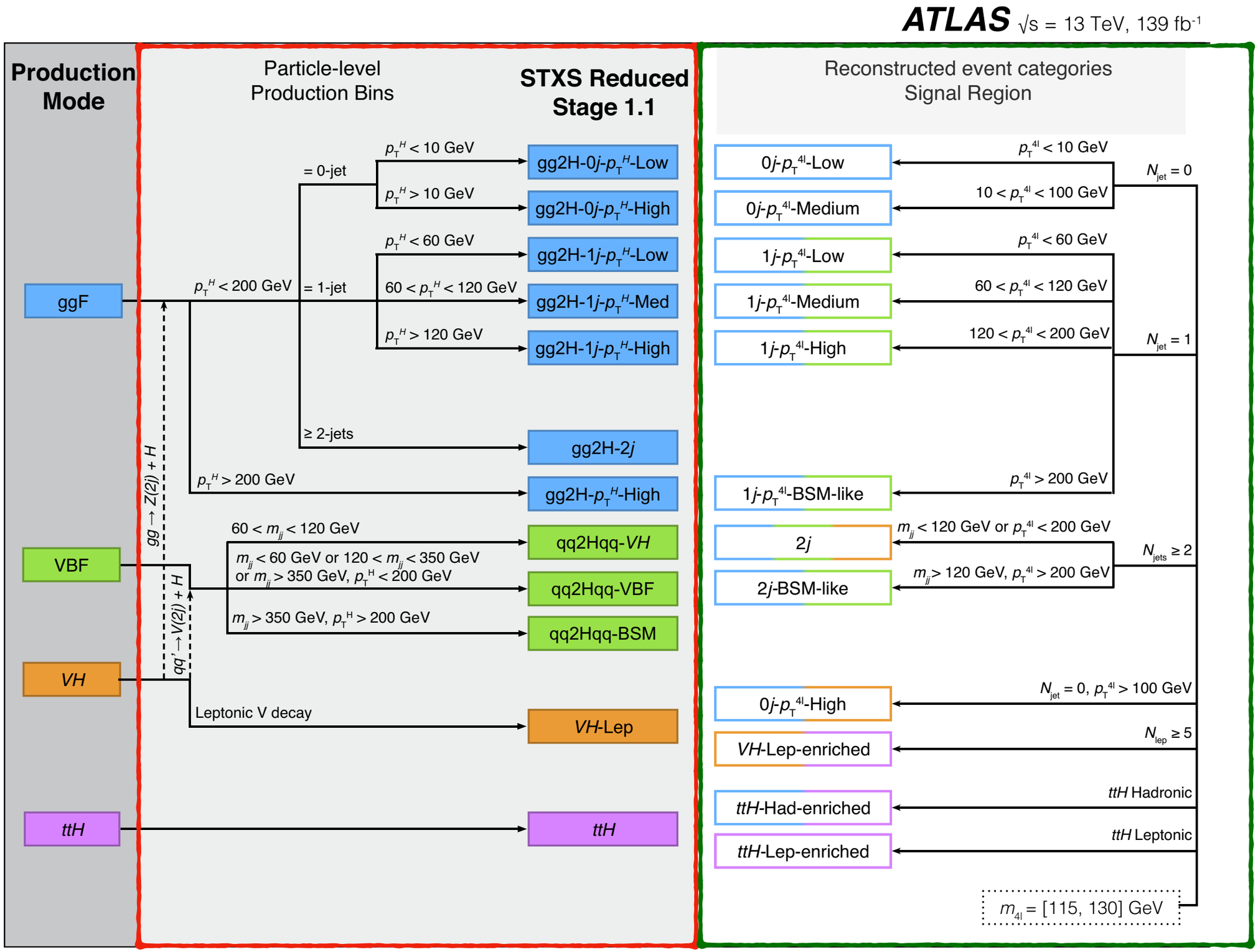
- Inputs: *H->ZZ**, *H->γγ*, *H->WW** (36 fb^{-1}), *H->ττ* (36 fb^{-1}), *H->bb* (24.5-139 fb^{-1})
- Simultaneous fit to all channels with 16 parameters of interest (POIs)
- Results in agreement with SM prediction (compatibility: p = 87%)





$H \to ZZ^*$ STXS Definition (Example)

Eur. Phys. J. C (2020) 80:957



$H \to ZZ^*$ STXS Definition (Example) Ct'd

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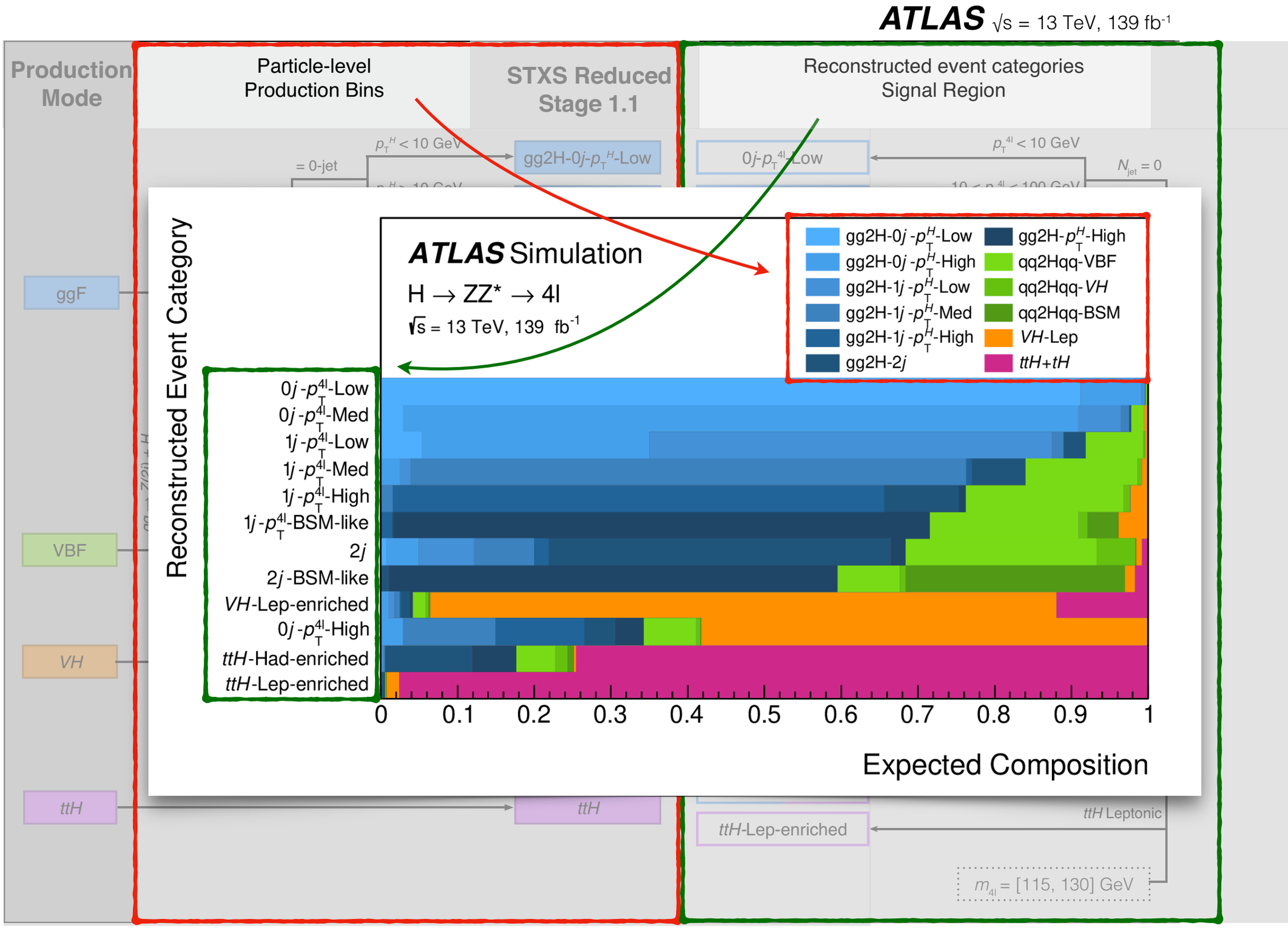
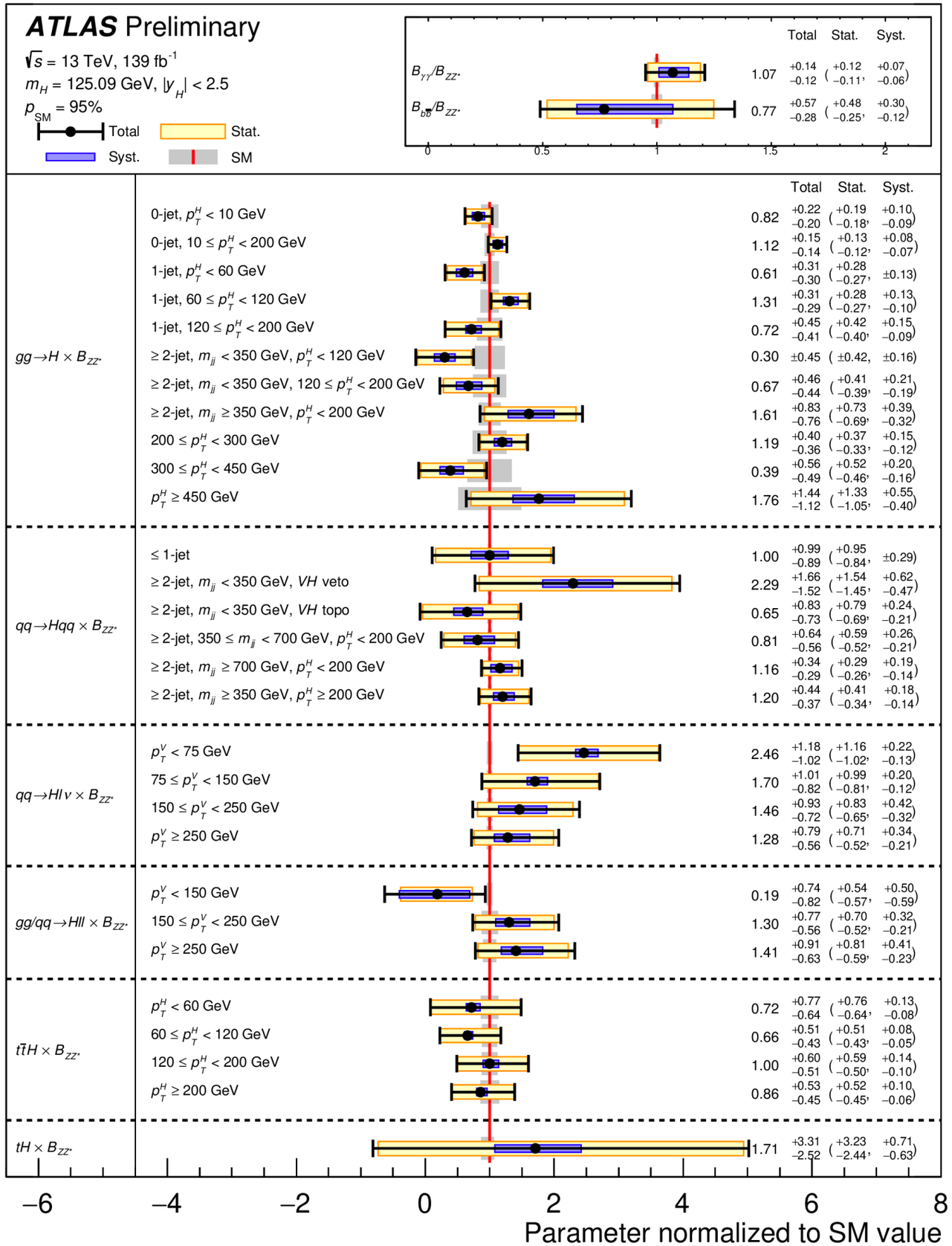


ATLAS Latest STXS **Combination**

ATLAS-CONF-2020-027

- **Inputs**: *H->ZZ**, *H->γγ*, (*VH*) *H->bb* (no *H->WW**)
- Full Run 2 STXS Stage 1.2 Preliminary Combination
- Some bins merged due to limited sensitivity
- **Limited by data stat.**
- Results in agreement with SM prediction (compatibility: p = 95%)
- Input to κ-framework, Two-Higgs-Doublet Models (not shown), and EFT interpretation (in later slide!)



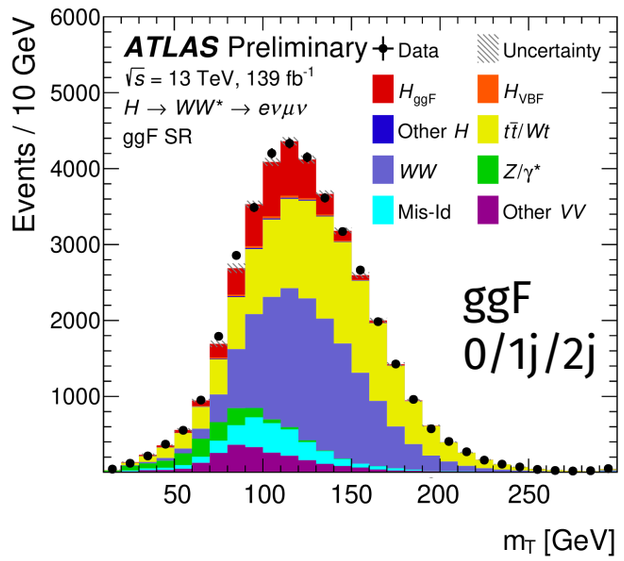
H -> WW -> eνμν* Prod./STXS Cross-sections

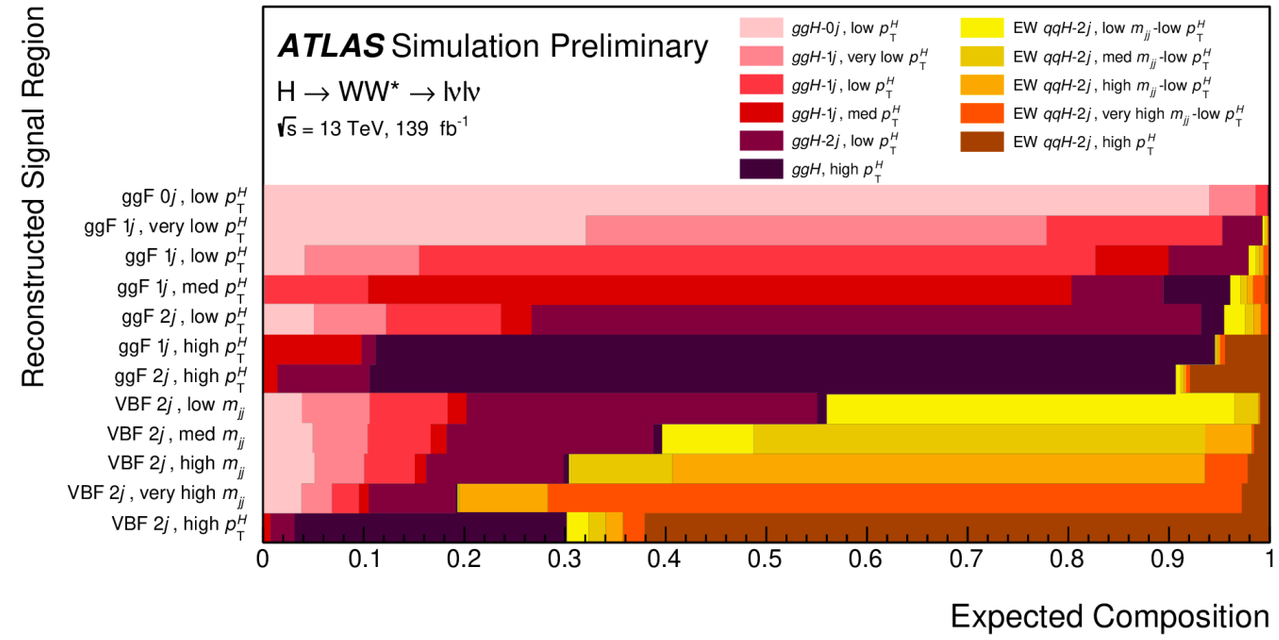
ATLAS-CONF-2021-014
Production: ggF, VBF

New

Characteristics

- Complex set of backgrounds with large unc. (top, WW, Mis-ID)





Strategy

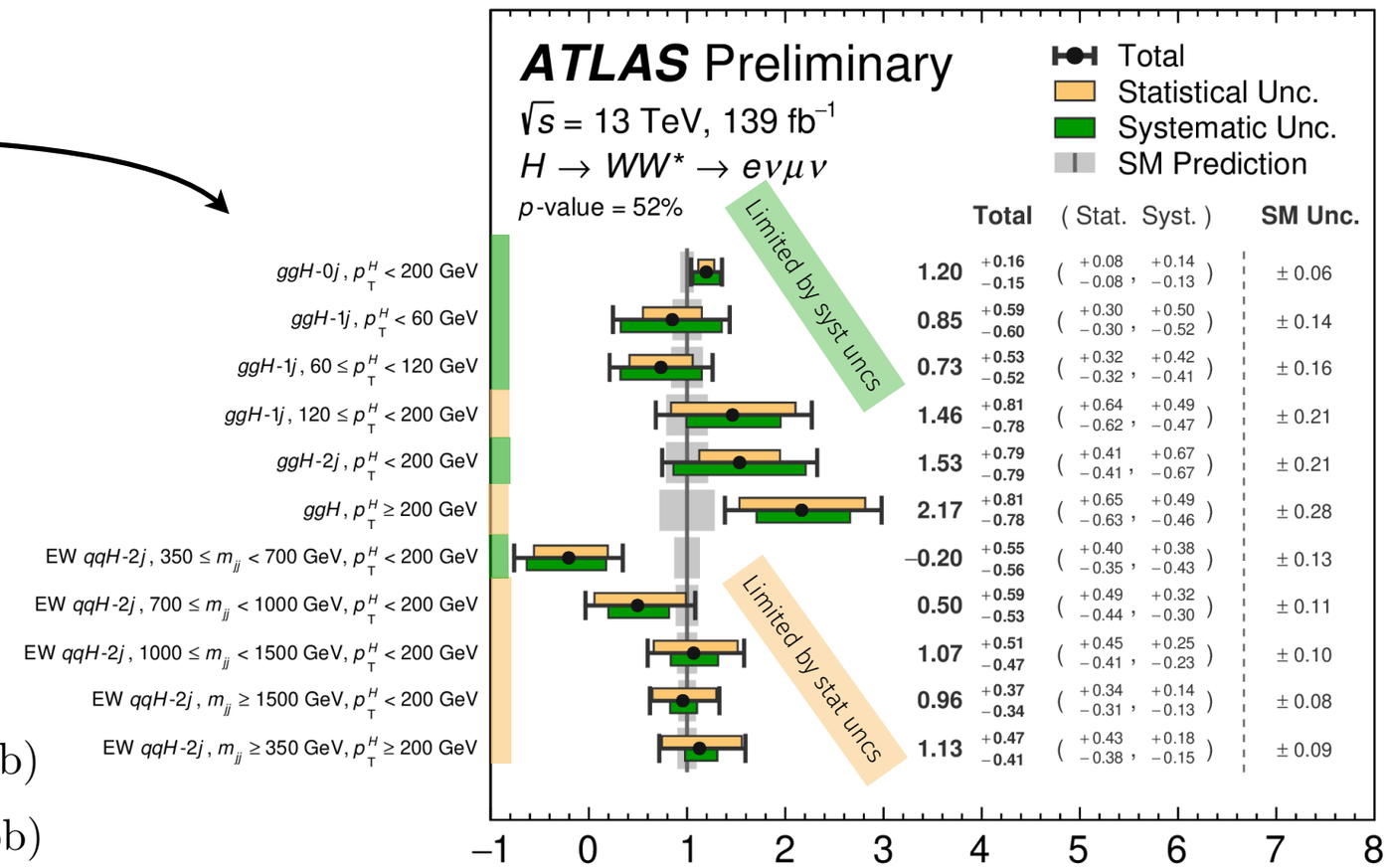
- **Cut-based** approach with fit to m_T in **ggF** regions, fit to **NN** in **VBF-enriched** regions
- Extract 6 (ggF) + 5 (VBF) STXS bins

Results

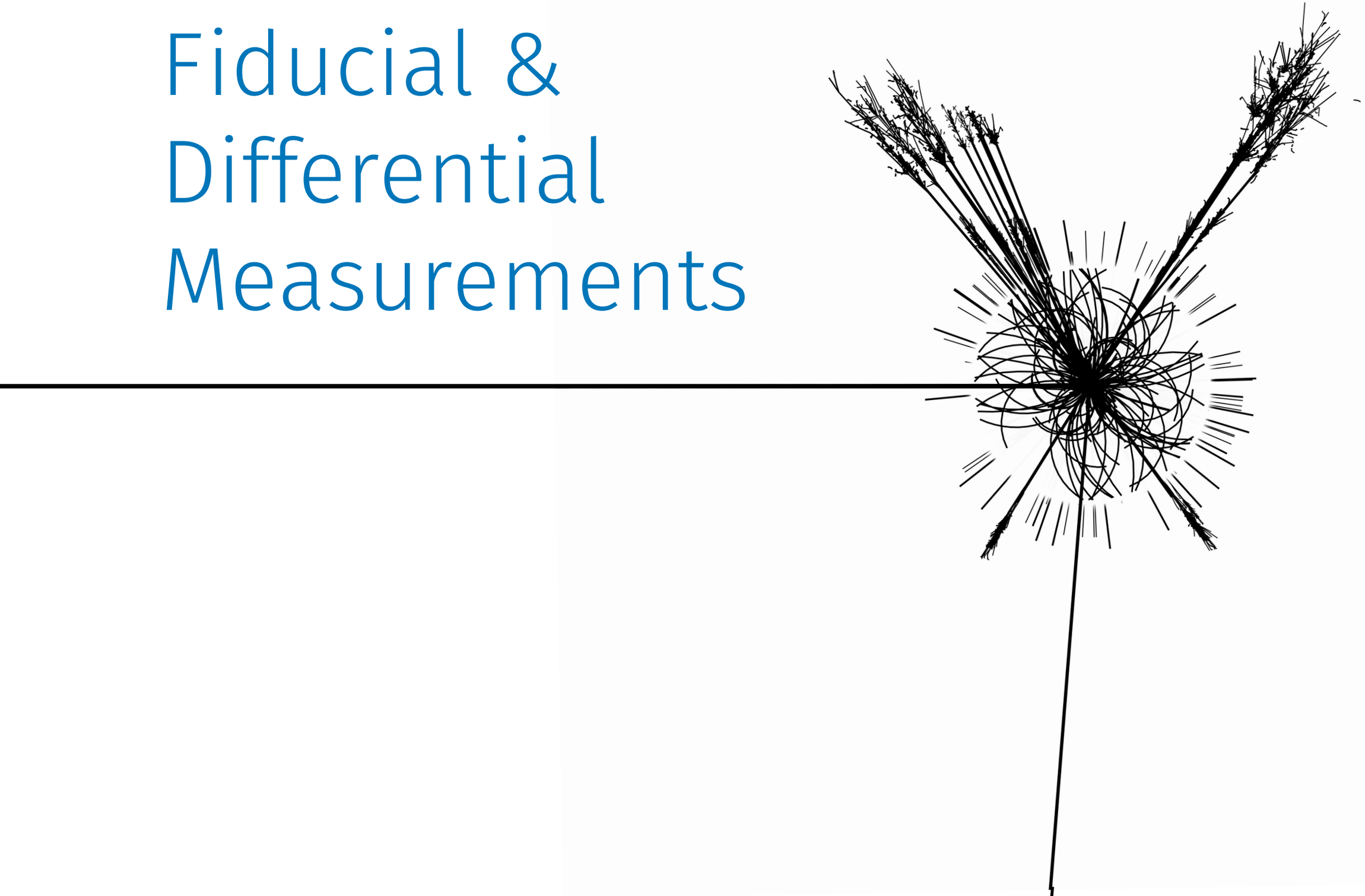
- **SM compatibility: 52%**
- Several regions limited by theoretical uncertainties!
- **σ per production (ggF, VBF)**

$$(\sigma_{\mathrm{ggF}} \times B_{H\to WW})_{\mathrm{obs}} = 12.4 \pm 1.5\,\mathrm{pb}\ (\mathrm{SM}:\ 10.4 \pm 0.6\,\mathrm{pb})$$

$$(\sigma_{\mathrm{VBF}} \times B_{H\to WW})_{\mathrm{obs}} = 0.79^{+0.19}_{-0.16}\,\mathrm{pb}\ (\mathrm{SM}:\ 0.81 \pm 0.02\,\mathrm{pb})$$



Fiducial & Differential Measurements



*H->ZZ** & *H -> γγ* Fiducial & Differential

Production: ggF, VBF, VH, ttH+tH, bbH

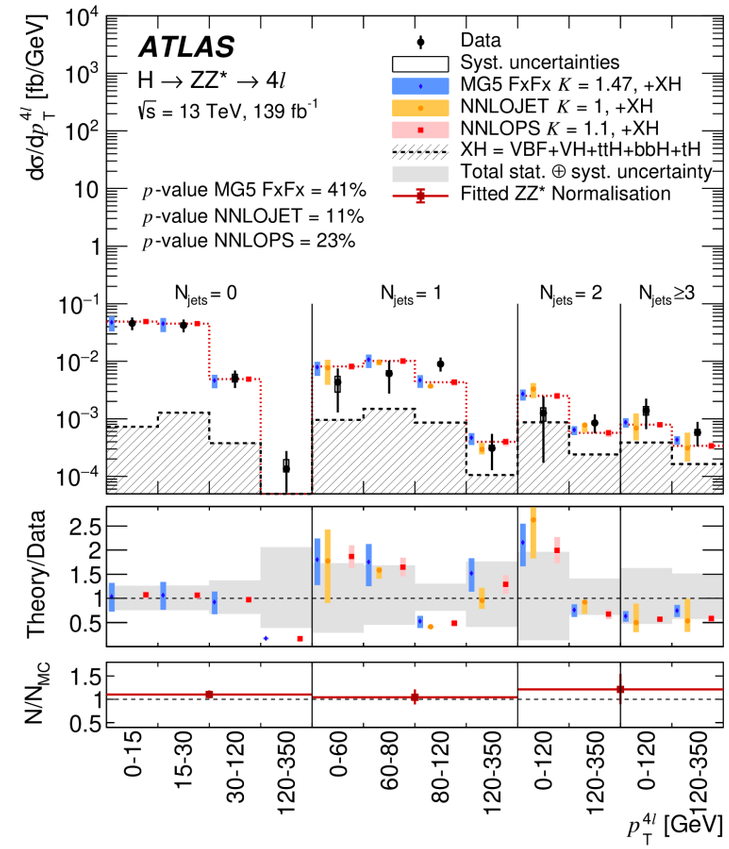
Many distributions measured regarding Higgs kinematics and decays as well as jet activities (p_T^H, Y_H, m_{jj}, $\Delta\Phi_{jj}$, many more) that are sensitive to possible BSM effects

*H -> ZZ**

$$\sigma_{\text{fid}} = 3.28 \pm 0.30\,(\text{stat}) \pm 0.11\,(\text{sys})\,\text{fb}$$

$$\sigma_{\text{fid, SM}} = 3.41 \pm 0.18\,\text{fb}$$

- Includes several **double-differential distributions** →
- Results used to constrain anomalous Higgs <-> SM particles interaction



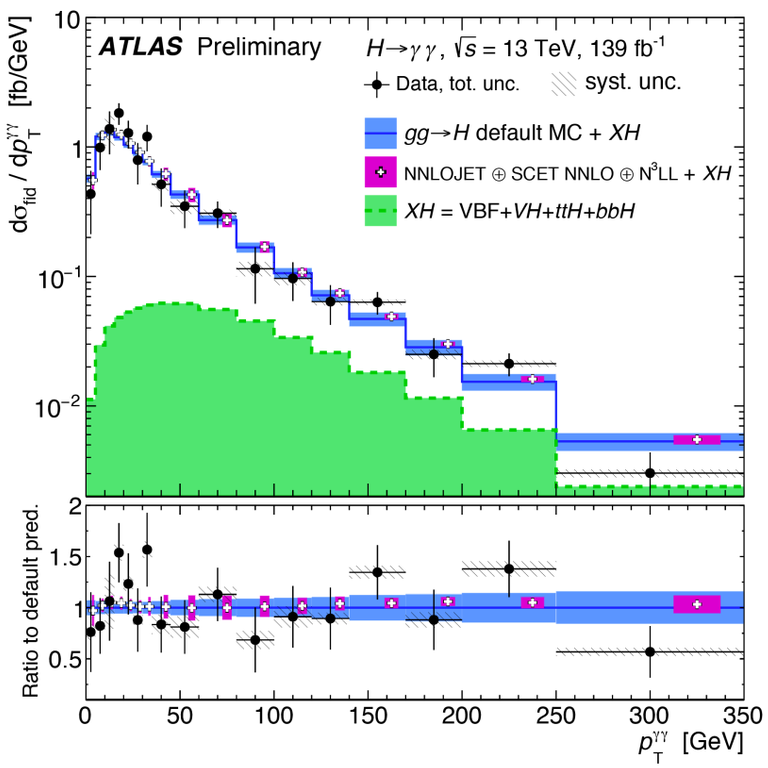
Eur. Phys. J. C 80 (2020) 942

H -> γγ

$$\sigma_{\text{fid}} = 65.2 \pm 4.5\,(\text{stat}) \pm 5.6\,(\text{sys}) \pm 0.3\,(\text{theo})\text{fb}$$

$$\sigma_{\text{fid, SM}} = 63.6 \pm 3.3\,\text{fb}$$

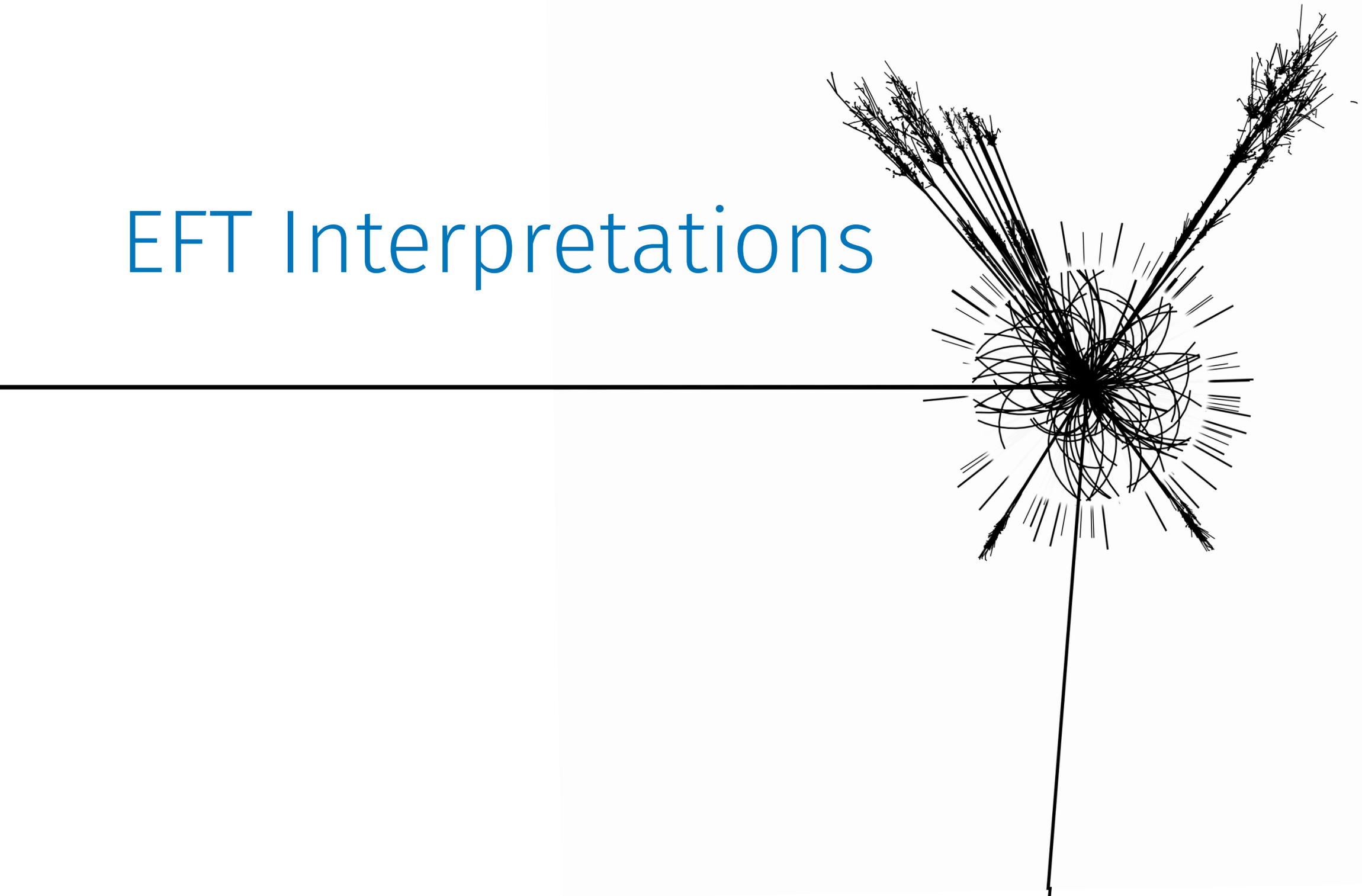
- Limit set on c-quark Yukawa couplings from $p_T^{\gamma\gamma}$ spectrum →
- Constraints set on EFT parameters



ATLAS-CONF-2019-029

Observed good agreement with SM expectation

EFT Interpretations



From Production Cross-sections to EFT Interpretations

Inclusive prod. xsecs → Fiducial / differential / STXS → EFT Interpretation / constraints

Reconstructed distributions

(Pseudo-)unfolded

Re-parametrized in SMEFT using generator-level simulation

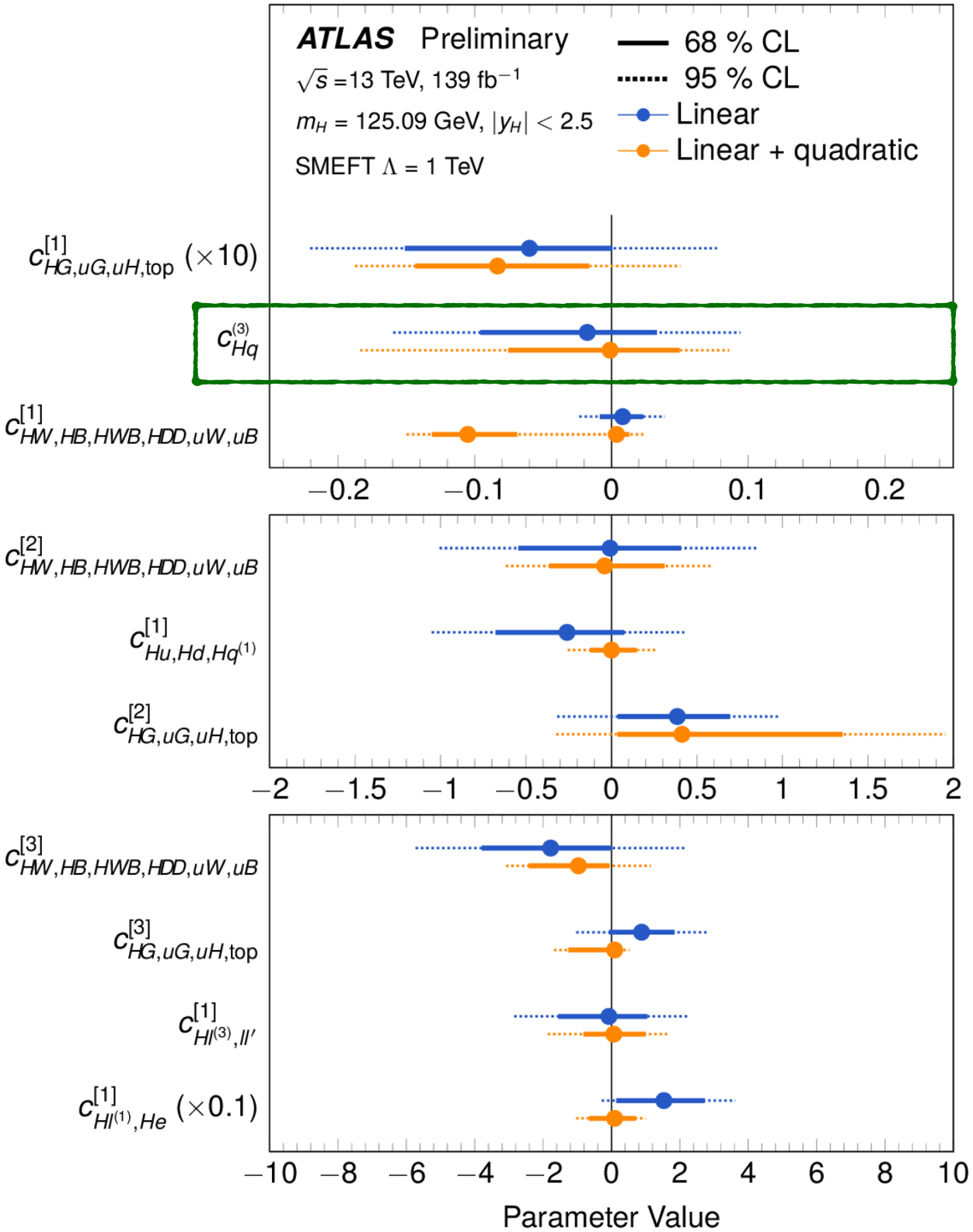
$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda_i} \mathcal{O}_i^{(5)} + \boxed{\sum_i \frac{c_i^{(6)}}{\Lambda_i^2} \mathcal{O}_i^{(6)}} + \ldots$$

- 76 dim-6 operators when assuming $U(3)^5$ flavour symmetry
- Wilson coefficients $c_i^{(6)}$ can be constrained experimentally
- Often further # parameter reduction: Identifying groups of Wilson coefficients with similar effect on the available data (**P**rincipal **C**omponent **A**nalysis)
- Many more details in Brian Moser @Higgs2020, Philip Windischhofer @ HEFT 2021

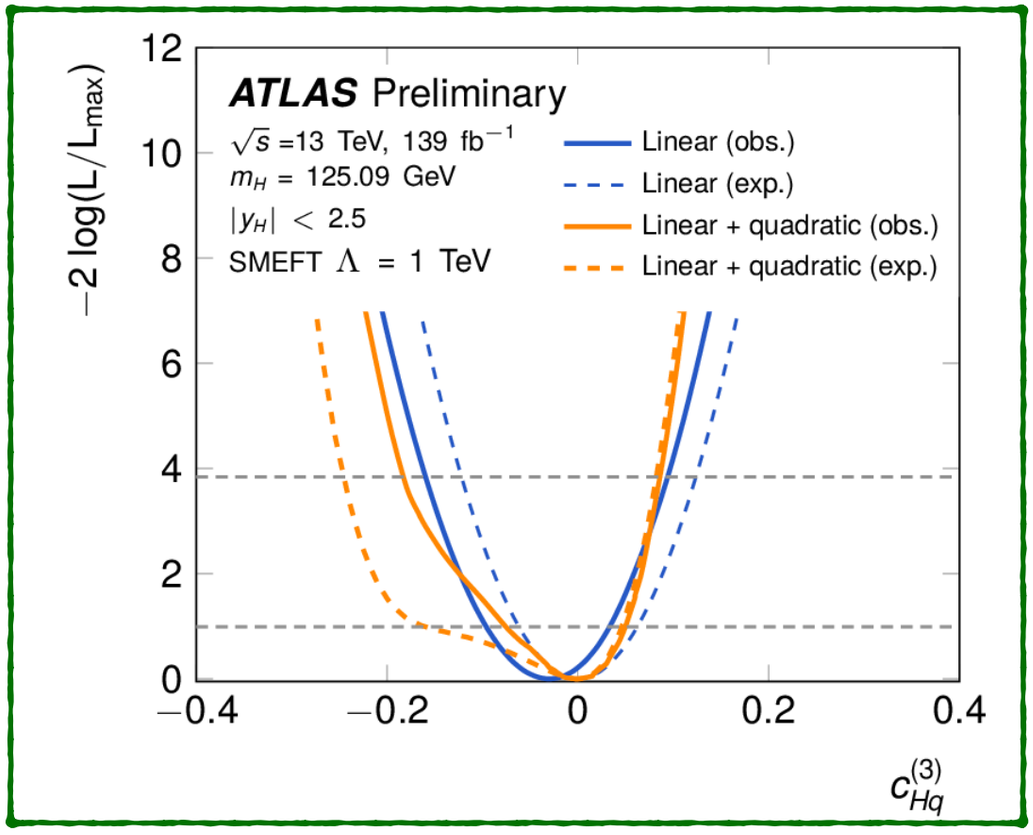
Combined STXS EFT Interpretation

ATLAS-CONF-2020-053
Inputs: *H->ZZ*, H->γγ, (VH) H->bb*

New



- Targets CP-even operators
- Simultaneous fit to 10 combinations of coefficients (PCA) with **excellent sensitivity**
- Reinterpret combined STXS results in linear and linear+quadratic SMEFT model
- Results consistent with the SM expectation
- $c_{Hq}^{(3)}$ constrained to $\mathcal{O}(0.1)$ probing scales up to **3 TeV**!



Combined *H->WW* and *pp->WW* EFT

ATL-PHYS-PUB-2021-010

New

- Challenging combination (overlapping regions) of

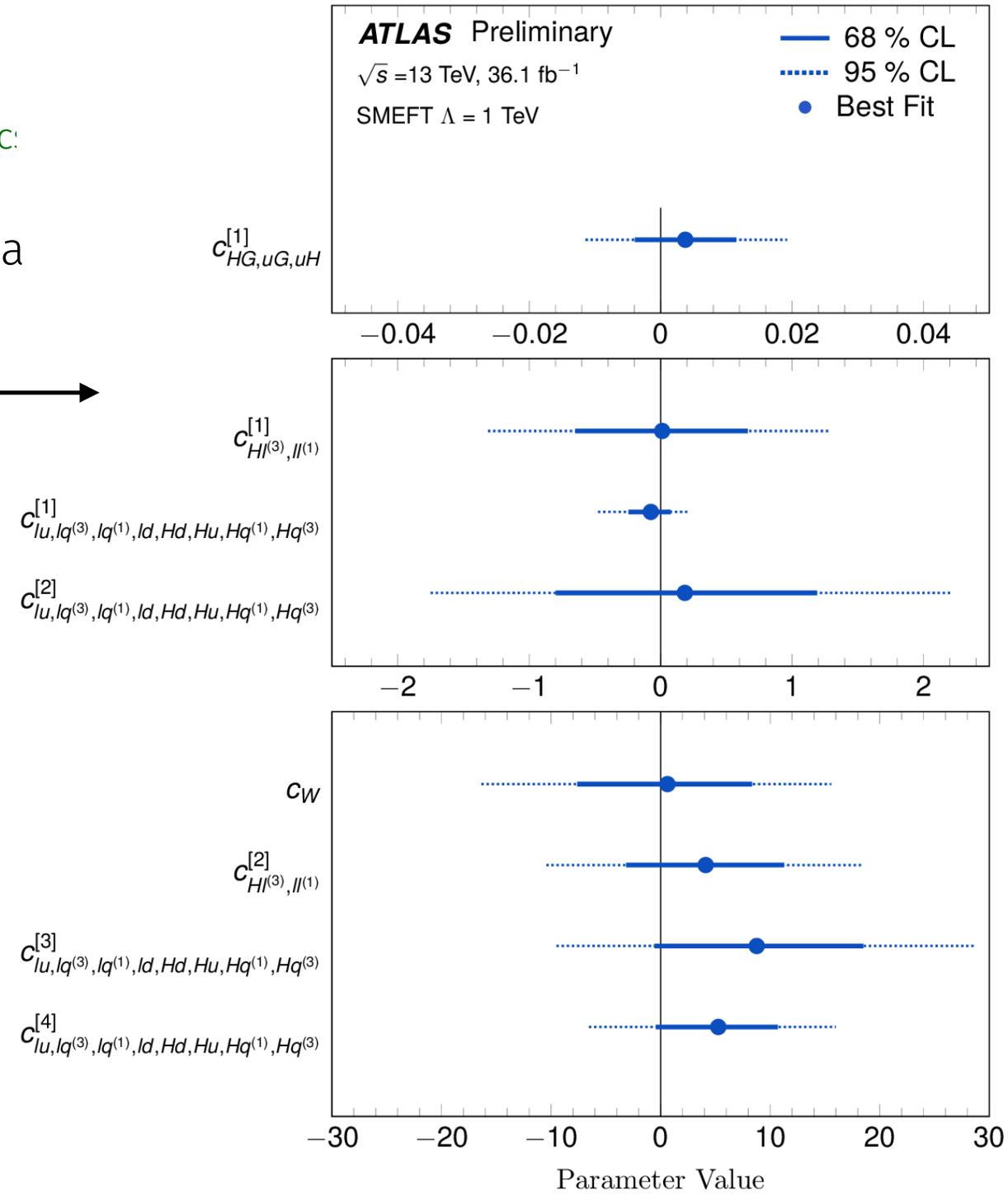
H->WW

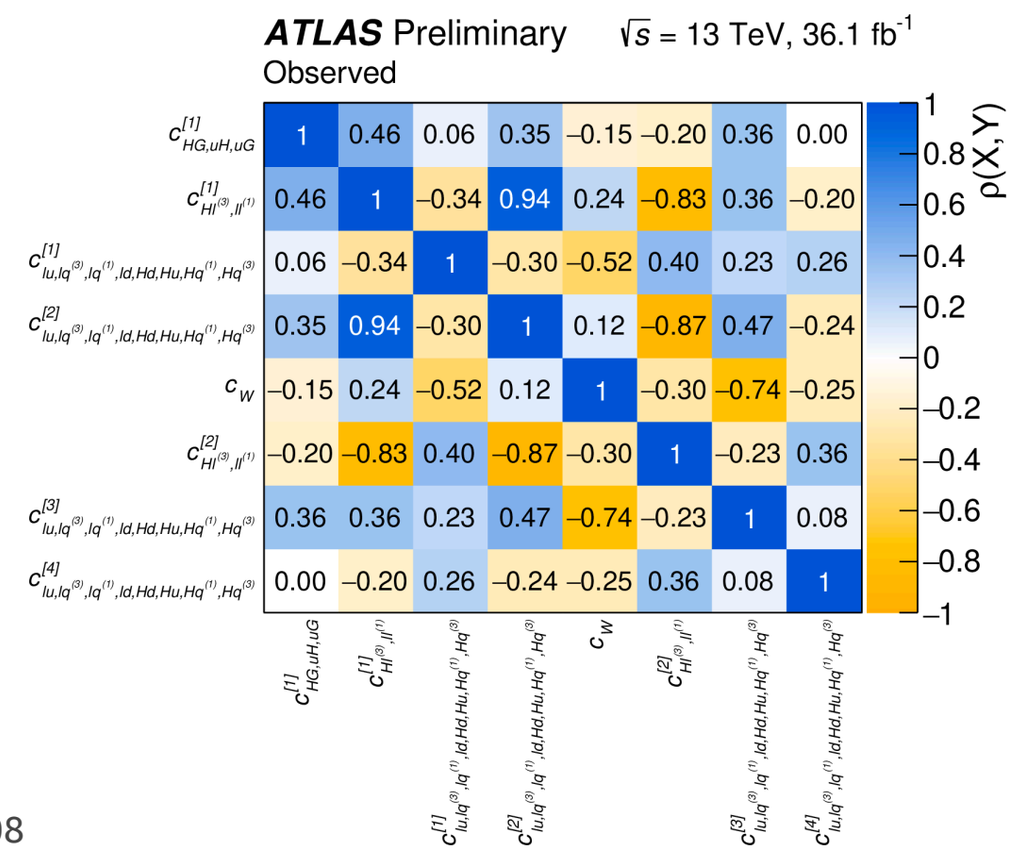
ggF+VBF signal strengths

pp->WW

Lead lep. p_T differential xsec

- Exploits complementary analyses sensitive to a similar set of dim-6 SMEFT operators
- Fits to 20 individual and 8 combined Wilson coefficients (PCA) in linearized model
- Paving the way for future EFT combinations!





CP & Higgs Properties

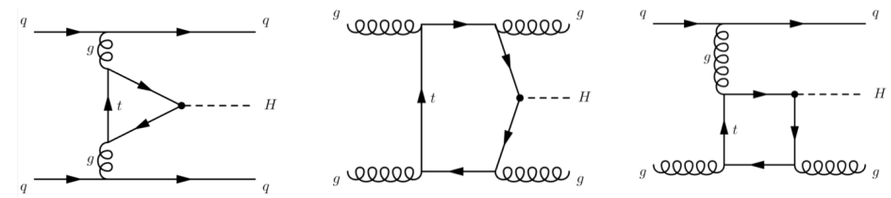
*H->WW** 2-jet CP & W/Z Polarisation

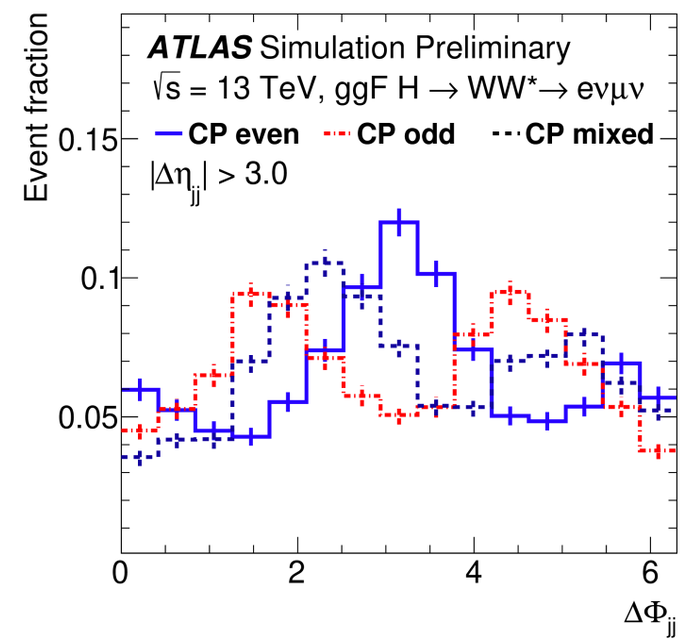
ATLAS-CONF-2020-055

New

Motivation

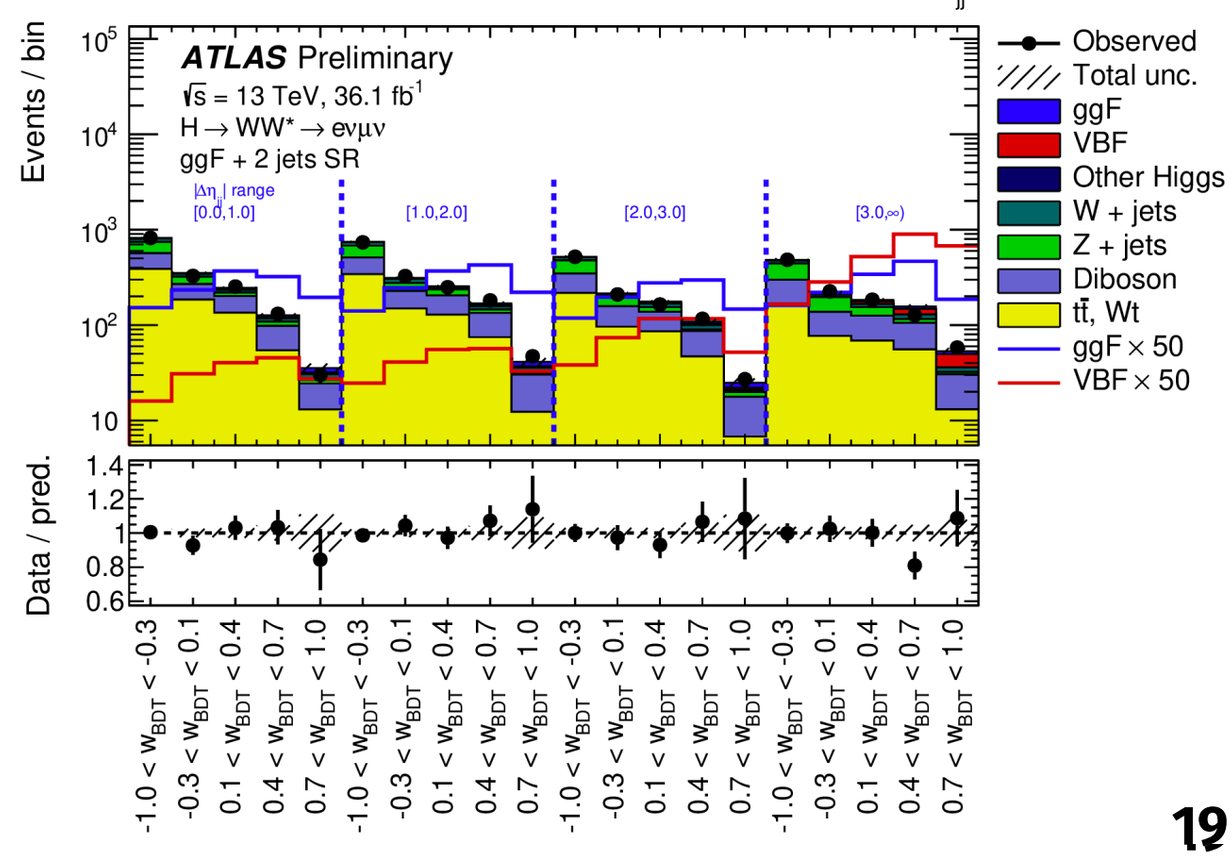
- ggF + 2-jet sensitive to CP properties of effective Higgs-gluon vertex





ggF Strategy

- BDTs to distinguish signal from background
- Fit to 12 categories defined by BDT and $\Delta\eta_{jj}$



Results

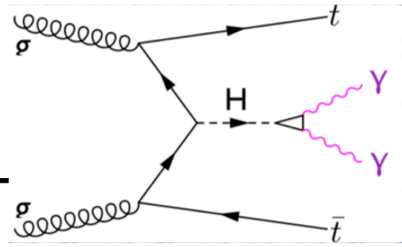
- Ratio of CP-odd to CP-even coupling strengths of the effective Higgs-gluon vertex constrained to

$$\kappa_{Agg}/\kappa_{Hgg} = 0.0 \pm 0.4\,(\text{stat}) \pm 0.3\,(\text{sys})$$

- VBF production used to set constraints on W & Z polarization-dependent coupling-strengths (not shown here)

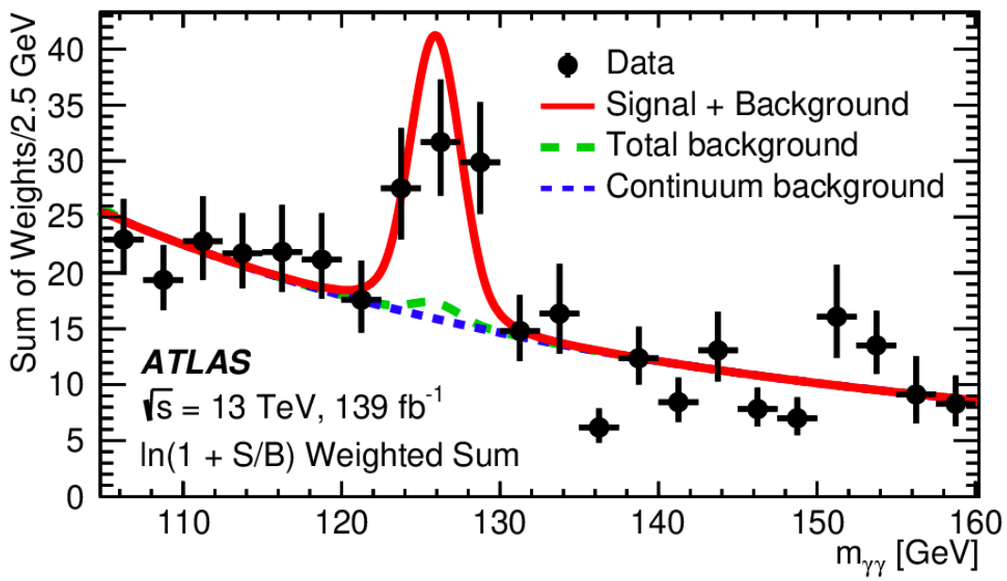
ttH, *H->γγ* CP measurements

Phys. Rev. Lett. 125 (2020) 061802



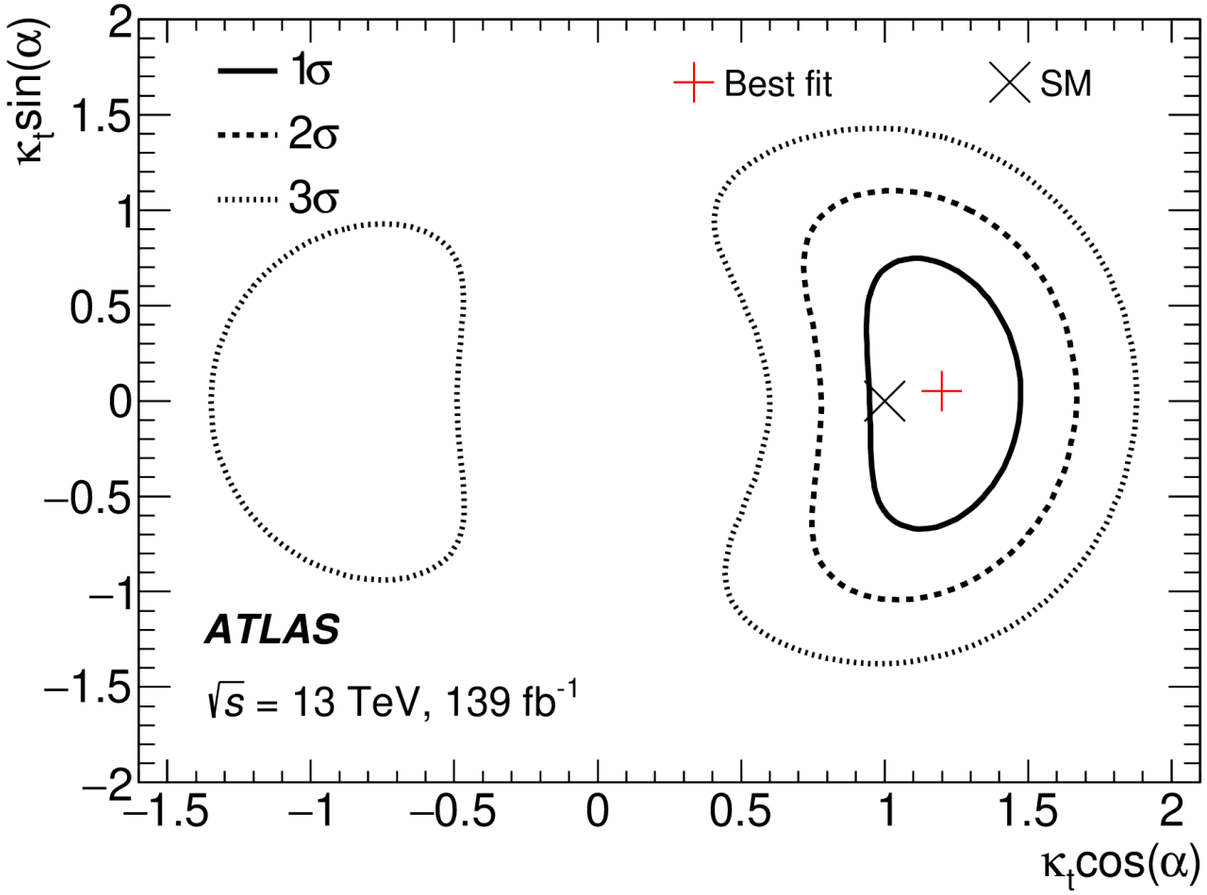
Motivation

- Observed **ttH Higgs** production in 2018*
- Direct probe of CP properties of top-Higgs interaction
- CP-odd contributions are not suppressed by $1 / \Lambda^2$



Strategy

- Simultaneous fit to $m_{\gamma\gamma}$ in 20 categories defined by two BDTs
- ggF, H → γγ constrained by the Higgs boson coupling combination



Results

- **CP-mixing angle greater than 43° excluded at 95% CL**
- All measurements statistically limited

* Phys. Lett. B 784, 173 (2018), Phys. Rev. Lett. 120, 231801 (2018)

Rare Decays and Searches

More Results in the Higgs <-> Bosons Realm

Combination of *H*->Invisible New

ATLAS-CONF-2020-052

upper limit on the H→invisible branching ratio of 0.11 ($0.11^{+0.04}_{-0.03}$) at 95% CL is observed (expected)

H->Zγ (Z->ee/μμ) Search

Phys. Lett. B 809 (2020) 135754

Upper limit of 3.6 (2.6) times the SM exception at 95% CL (with SM Higgs)

H->llγ (Low Mass) New

Phys. Lett. B 819 (2021) 136412

"Evidence for the H->llγ process (with m_{ll} < 30 GeV) is found with a significance of 3.2 over the background-only hypothesis"

Summary

Summary

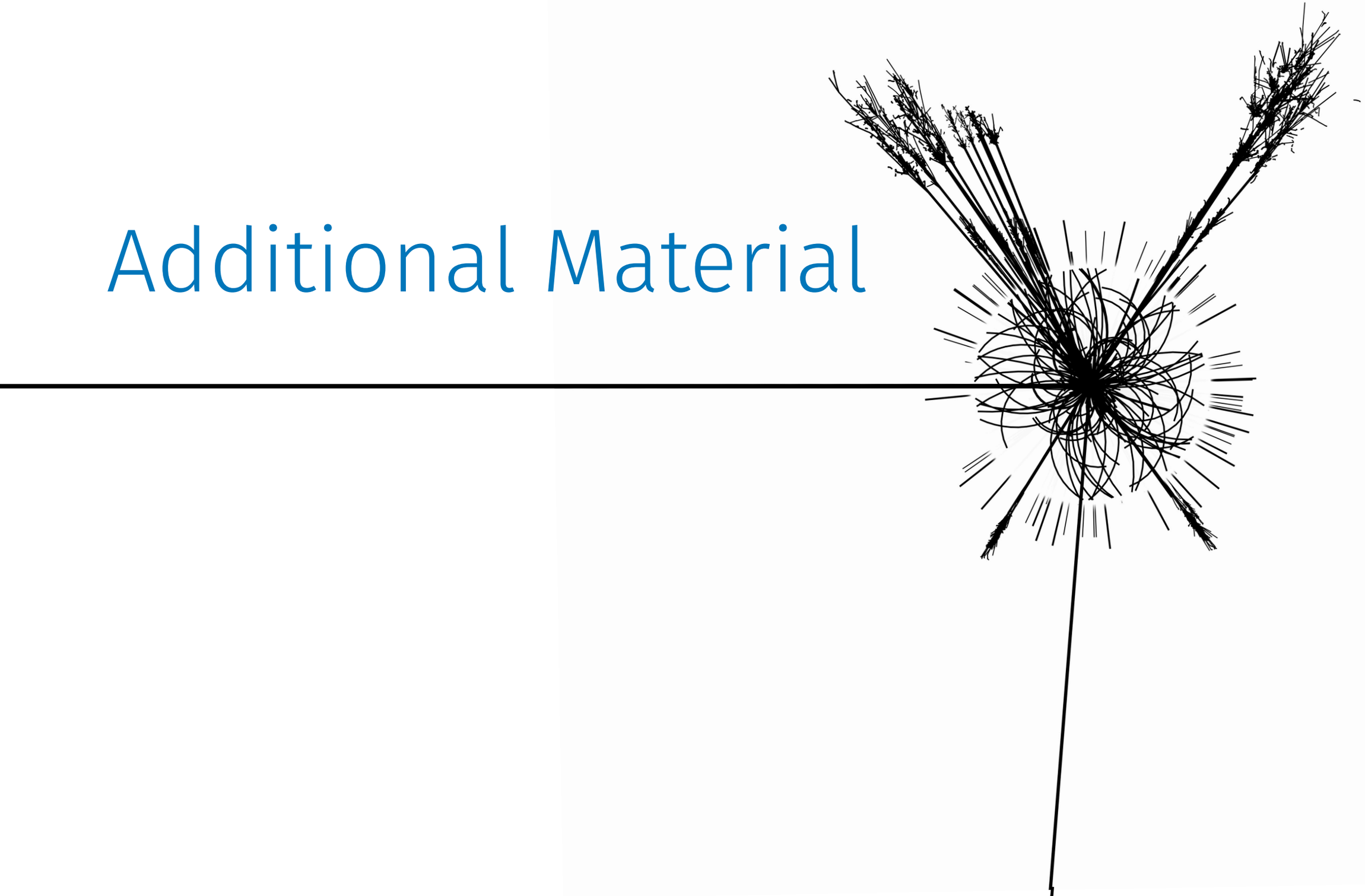
- First Full Run 2 STXS measurements and combinations provide **unprecedented sensitivity** of measured Higgs cross-sections
- Exciting new EFT interpretations with excellent sensitivity
  - **Stepping stone for future global combinations!**

- Higgs properties measurement and searches show no sign of BSM physics yet...
- ...but many more analyses are under way, and Run 3 around the corner so...

Stay Tuned!

Thank you for your attention!

Additional Material



H -> WW^* -> eνμν Prod./STXS Cross-sections

ATLAS-CONF-2021-014

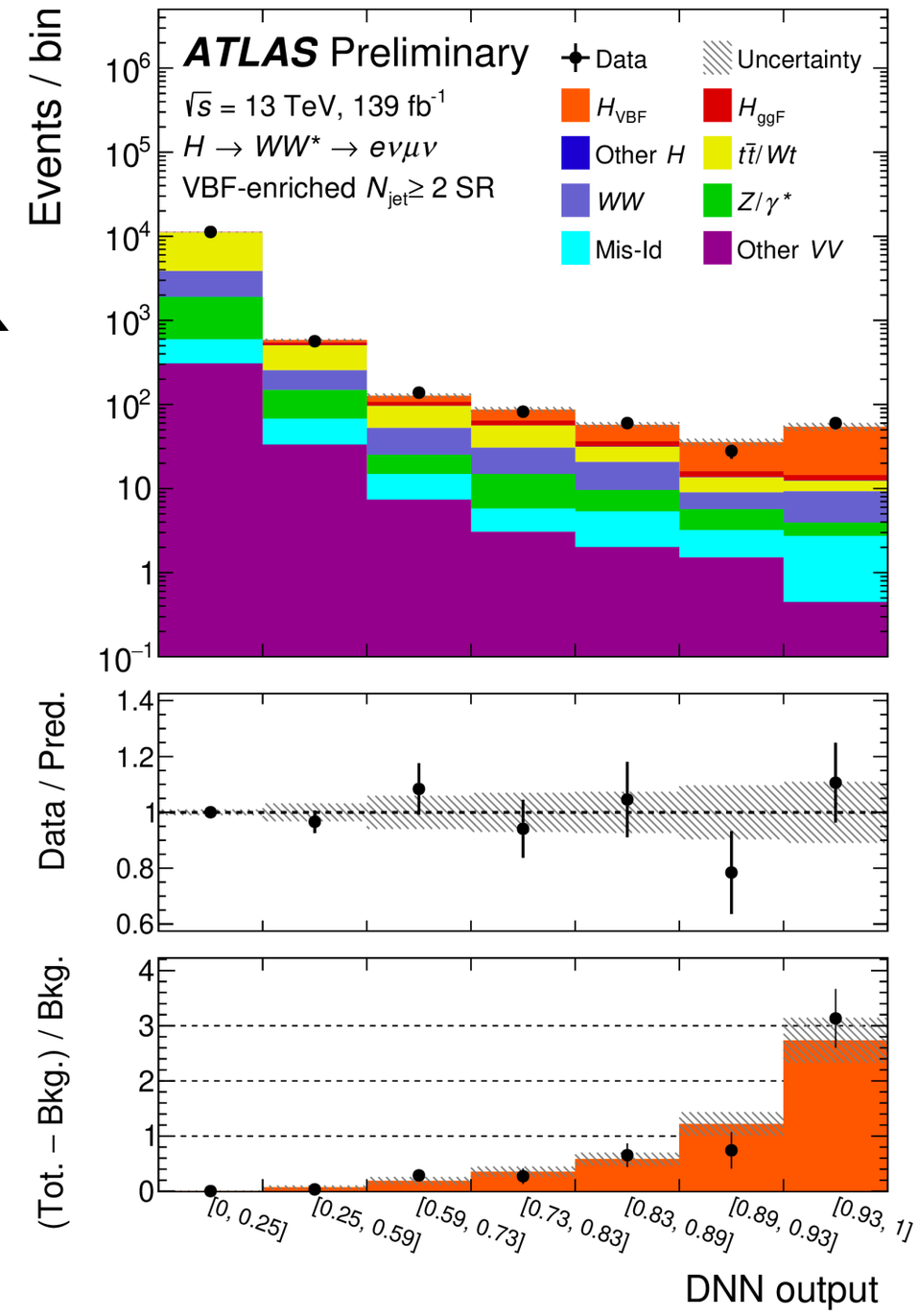
Strategy

- Signal regions split by number of jets
  - ggF 0, 1, 2-jet*, and VBF SR
- VBF analysis uses DNN trained with 15 variables

VBF topology: $\Delta y_{jj}, m_{jj}, \eta_{\ell}^{\text{centrality}}, m_{\ell 1 j1}, m_{\ell 1 j2}, m_{\ell 2 j1}, m_{\ell 2 j2},$
$p_{\mathrm{T}}^{\text{jet}_1}, p_{\mathrm{T}}^{\text{jet}_2}, p_{\mathrm{T}}^{\text{jet}_3}$

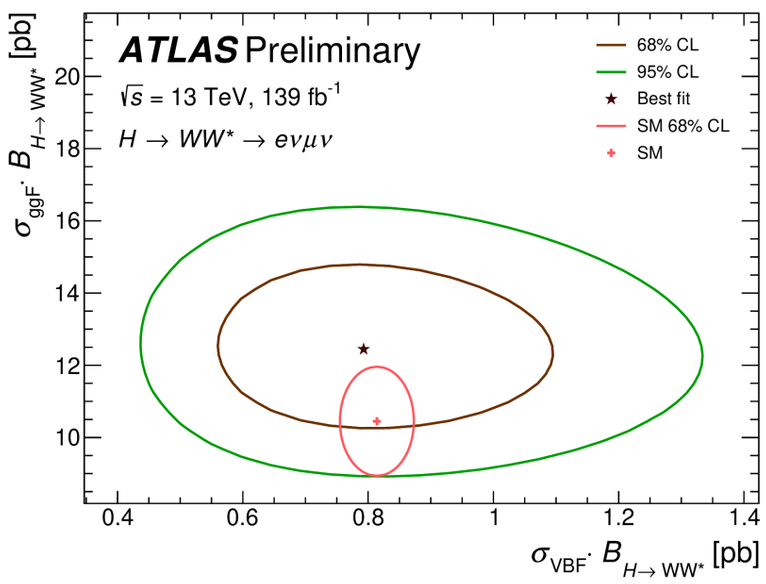
$H \to WW$ decay: $\Delta\phi_{\ell\ell}, m_{\ell\ell}, m_{\mathrm{T}},$

Top suppression: $p_{\mathrm{T}}^{\text{tot}}$, MET significance



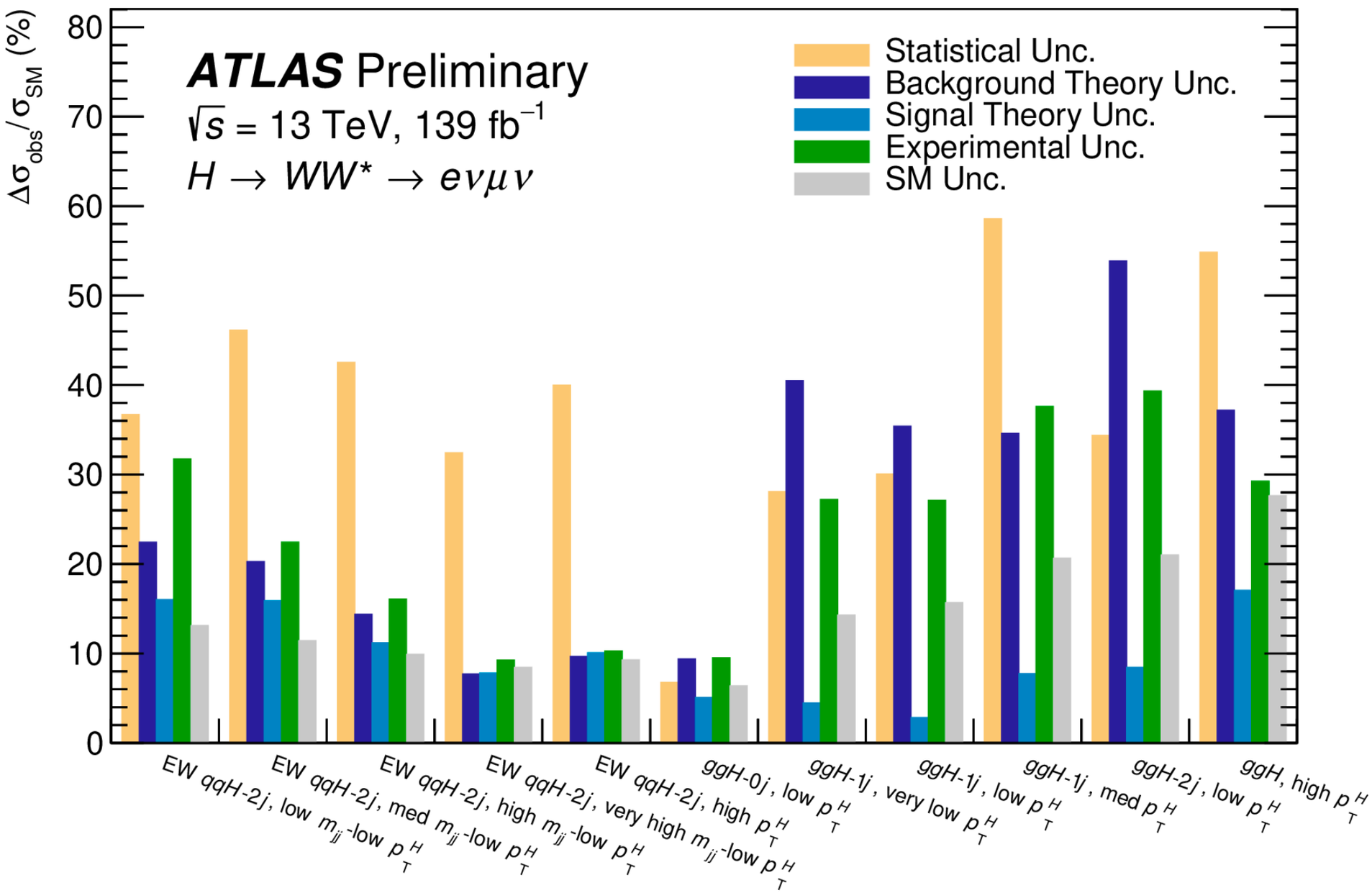
Results

$$\sigma_{\text{ggF}} \cdot \mathcal{B}_{H\to WW^*} = 12.4 \pm 1.5 \text{ pb}$$
$$= 12.4 \pm 0.6 \text{ (stat.)} \pm 0.9 \text{ (exp syst.)} \,^{+0.7}_{-0.6} \text{ (sig theo.)} \pm 1.0 \text{ (bkg theo.) pb}$$
$$\sigma_{\text{VBF}} \cdot \mathcal{B}_{H\to WW^*} = 0.79 \,^{+0.19}_{-0.16} \text{ pb}$$
$$= 0.79 \,^{+0.11}_{-0.10} \text{ (stat.)} \,^{+0.06}_{-0.05} \text{ (exp syst.)} \,^{+0.13}_{-0.09} \text{ (sig theo.)} \,^{+0.08}_{-0.06} \text{ (bkg theo.) pb,}$$



Uncertainty Breakdown for *H->WW** STXS Cross-sections

ATLAS-CONF-2021-014



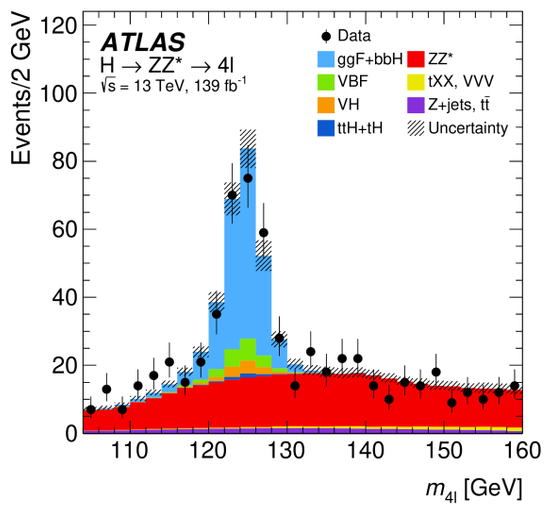
H -> ZZ^* Prod./STXS Cross-sections

Eur. Phys. J. C (2020) 80:957

Production: ALL (ggF, VBF, VH, bbH, ttH+tH)

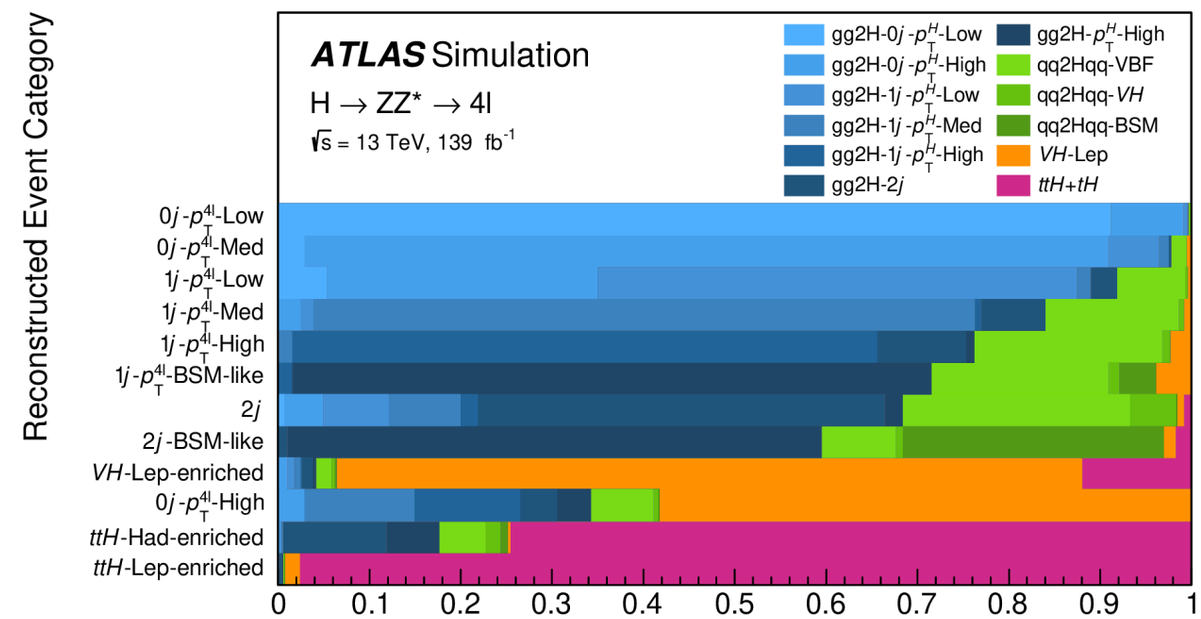
Characteristics

- "Cleanest" Higgs channel, highest S/B



Strategy

- **N**eural **n**etworks used in individual categories as discriminant in stat. Analysis
- Measure 6 (ggF) + 3 (EW qqH) + VH-lep + ttH STXS regions



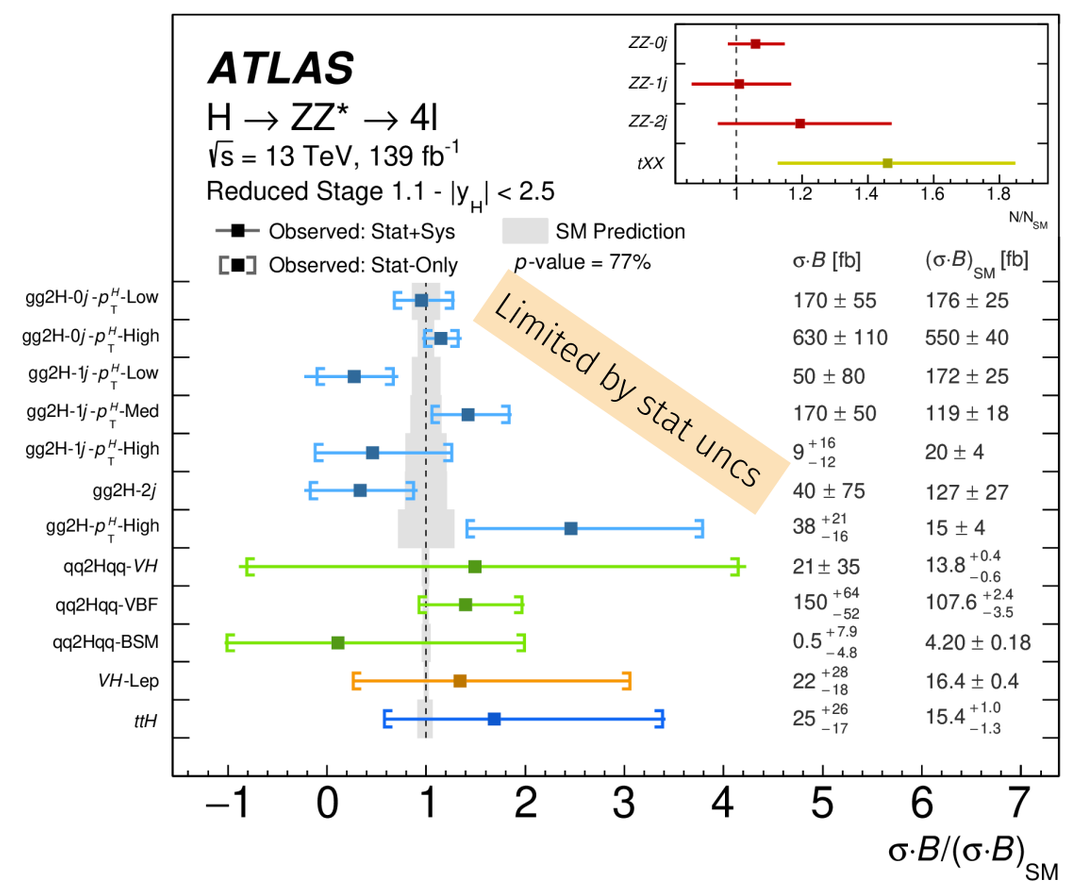
Results

- **Results in STXS bins in agreement with SM prediction (compatibility: 77%)**
- Xsecs per production (ggF, VBF, VH, ttH) and **inclusively**

$$(\sigma \times B_{H\to ZZ})_{\text{obs}} = 1.34 \pm 0.12\,\text{pb}\ (\text{SM: } 1.33 \pm 0.08\,\text{pb})$$

Limited by stat uncs

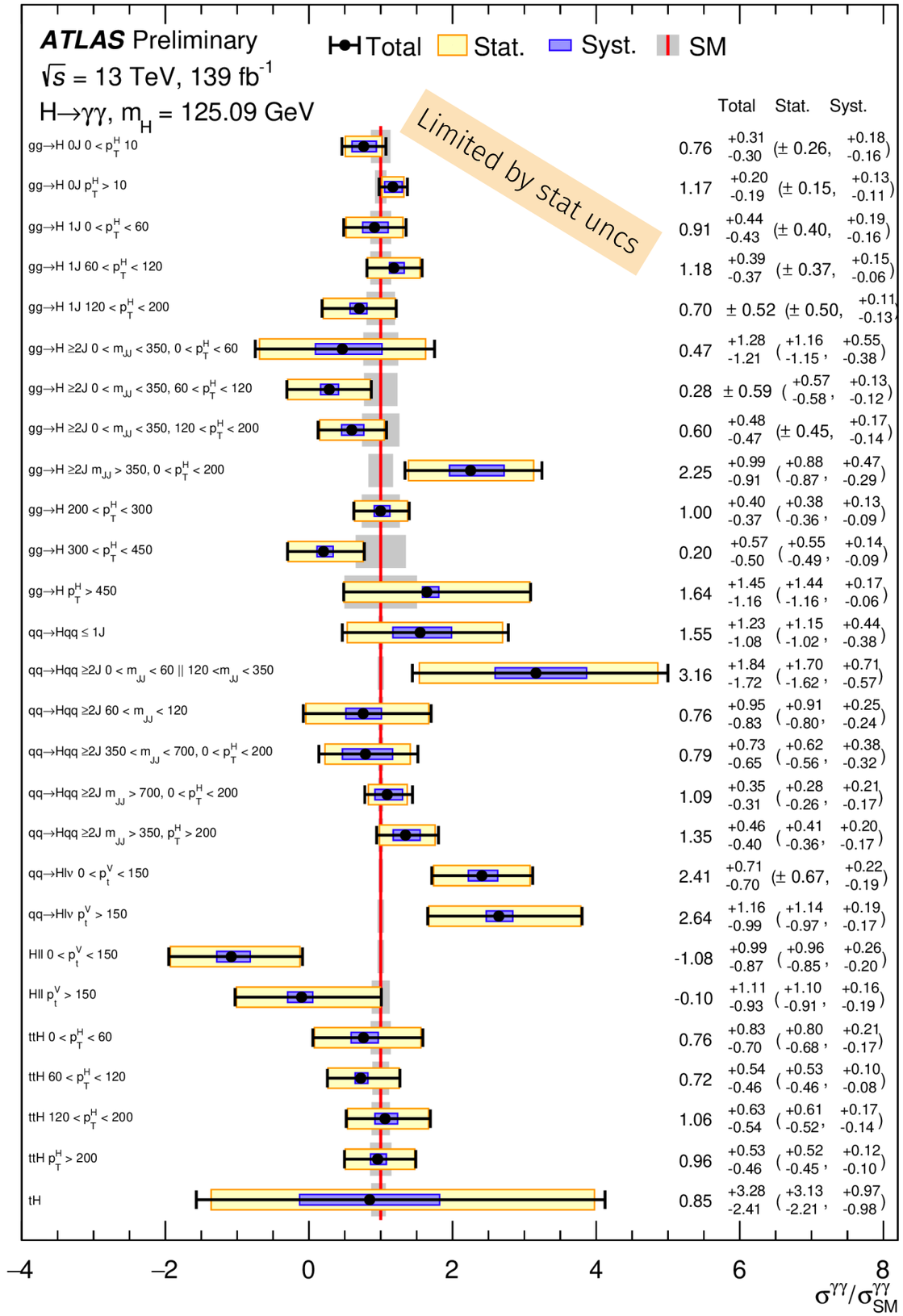
- Results also interpreted with k-framework and EFT



$H \to \gamma\gamma$ Prod./STXS Cross-sections

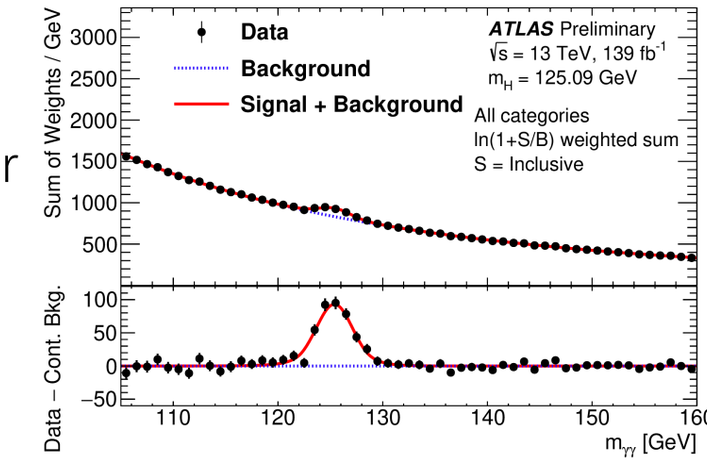
ATLAS-CONF-2020-026

Production: ggF, VBF, VH, ttH+tH



Characteristics

- Excellent control over background with an analytical model



Strategy

- Cascade of BDTs:
  - Multi-class BDT to separate signal events from different STXS regions (mitigating migrations!)
  - Binary BDT to separate signal from bkg
- Measure 27 STXS regions by fitting $m_{\gamma\gamma}$

Results

- **Results in STXS bins in agreement with SM prediction (compatibility: 60%)**
- Xsecs per production (ggF+bbH, VBF, ZH, WH, ttH+tH) and **inclusively ($|y_H| < 2.5$)**

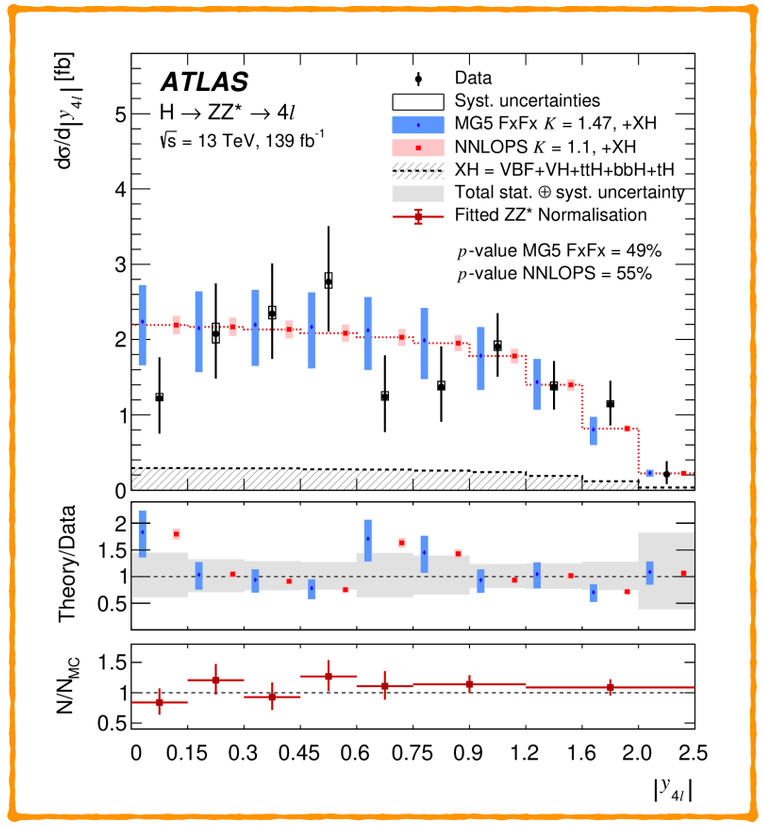
$$(\sigma \times B_{H\to\gamma\gamma})_{\text{obs}} = 127 \pm 7\,(\text{stat}) \pm 7\,(\text{sys})\,\text{fb}\ \ (\text{SM: } 116 \pm 5\,\text{pb})$$

*H->ZZ** Fiducial & Differential

Eur. Phys. J. C 80 (2020) 942

Strategy

- Many unfolded distributions measured
  - Higgs kinematics: p_T, $|y_{4l}|$
  - Higgs decay information: invariant masses of the lepton pairs, angular variables (sensitive to anomalous H->ZZ couplings)
  - Jet activities: **# jets**, # b-jets, p_T^{jet1}, m_{jj}, $\Delta\Phi_{jj}$
  - Several **double-differential distributions**



Results

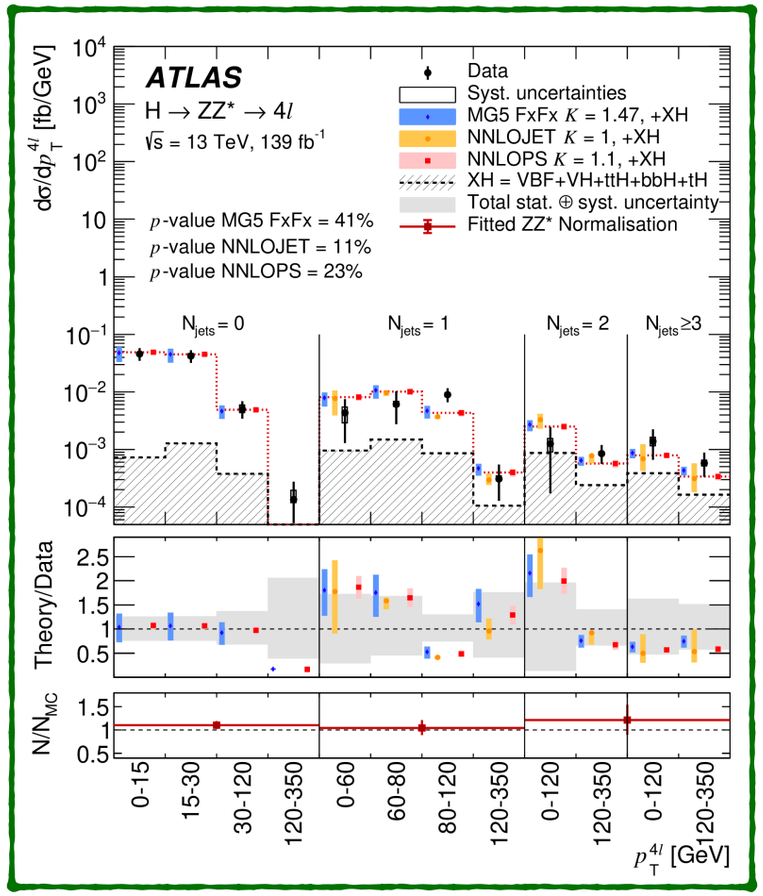
- Inclusive fiducial cross section

$$\sigma_{\text{fid}} = 3.28 \pm 0.30\,(\text{stat}) \pm 0.11\,(\text{sys})\,\text{fb}$$

$$\sigma_{\text{fid, SM}} = 3.41 \pm 0.18\,\text{fb}$$

Limited by stat uncs

- Overall good agreement with the SM expectation
- Results used to constrain anomalous Higgs <-> SM particles interaction



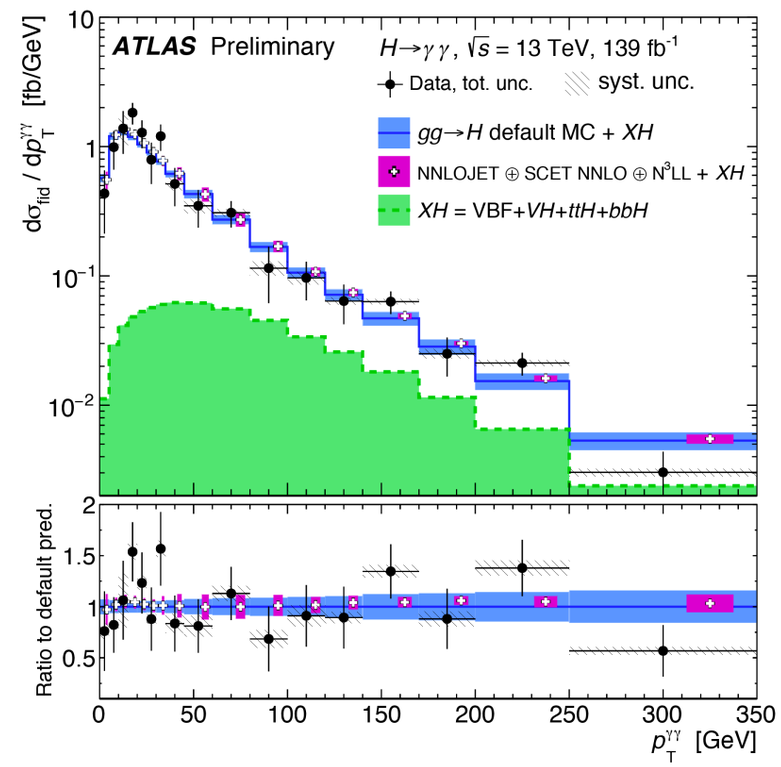
$H \to \gamma\gamma$ Fiducial & Differential

ATLAS-CONF-2019-029

Strategy

- Several distributions sensitive to new physics effects
- Many unfolded distributions measured
  - Higgs kinematics: $p_T^{\gamma\gamma}$, $|y_{\gamma\gamma}|$
  - Jet activities: # jets, p_T^{jet1}, m_{jj}, $\Delta\Phi_{jj}$

sensitive to the b and c-quark Yukawa coupling

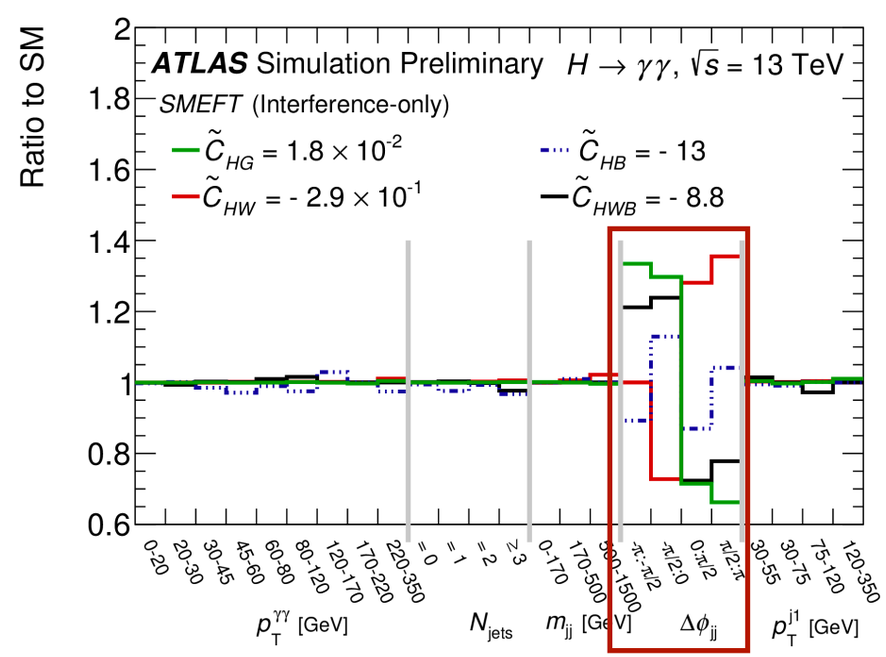


Results

- Inclusive fiducial cross-section

$$\sigma_{\text{fid}} = 65.2 \pm 4.5\,(\text{stat}) \pm 5.6\,(\text{sys}) \pm 0.3\,(\text{theo})\text{fb}$$
$$\sigma_{\text{fid, SM}} = 63.6 \pm 3.3\,\text{fb}$$

- Limit set on c-quark Yukawa couplings from $p_T^{\gamma\gamma}$ spectrum
- Constraints set on EFT parameters
  - Example: Effect of CP-odd SMEFT Wilson coefficients on 5 of the measured distributions

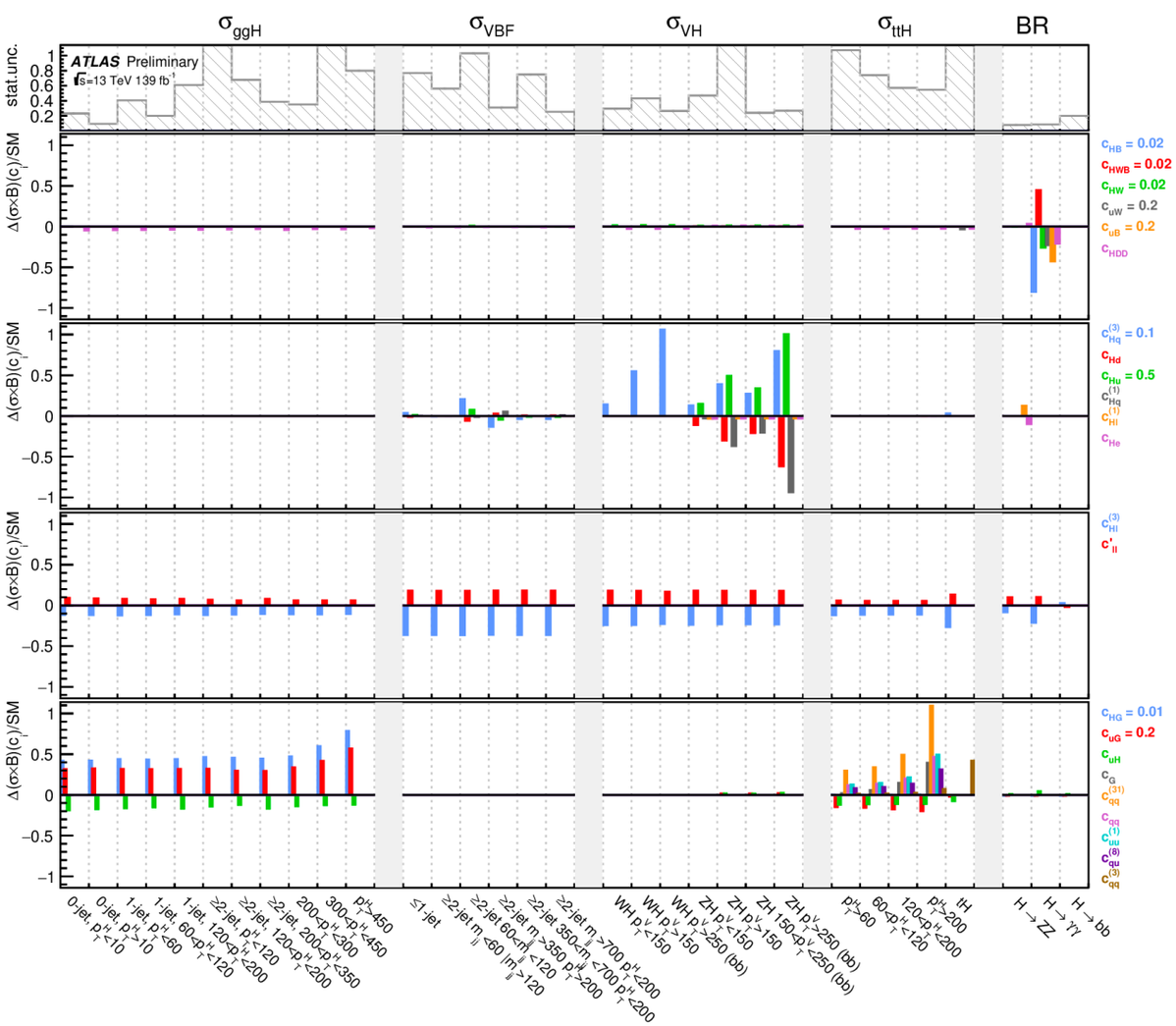


Impact of Wilson Coefficients On STXS EFT Interpretation

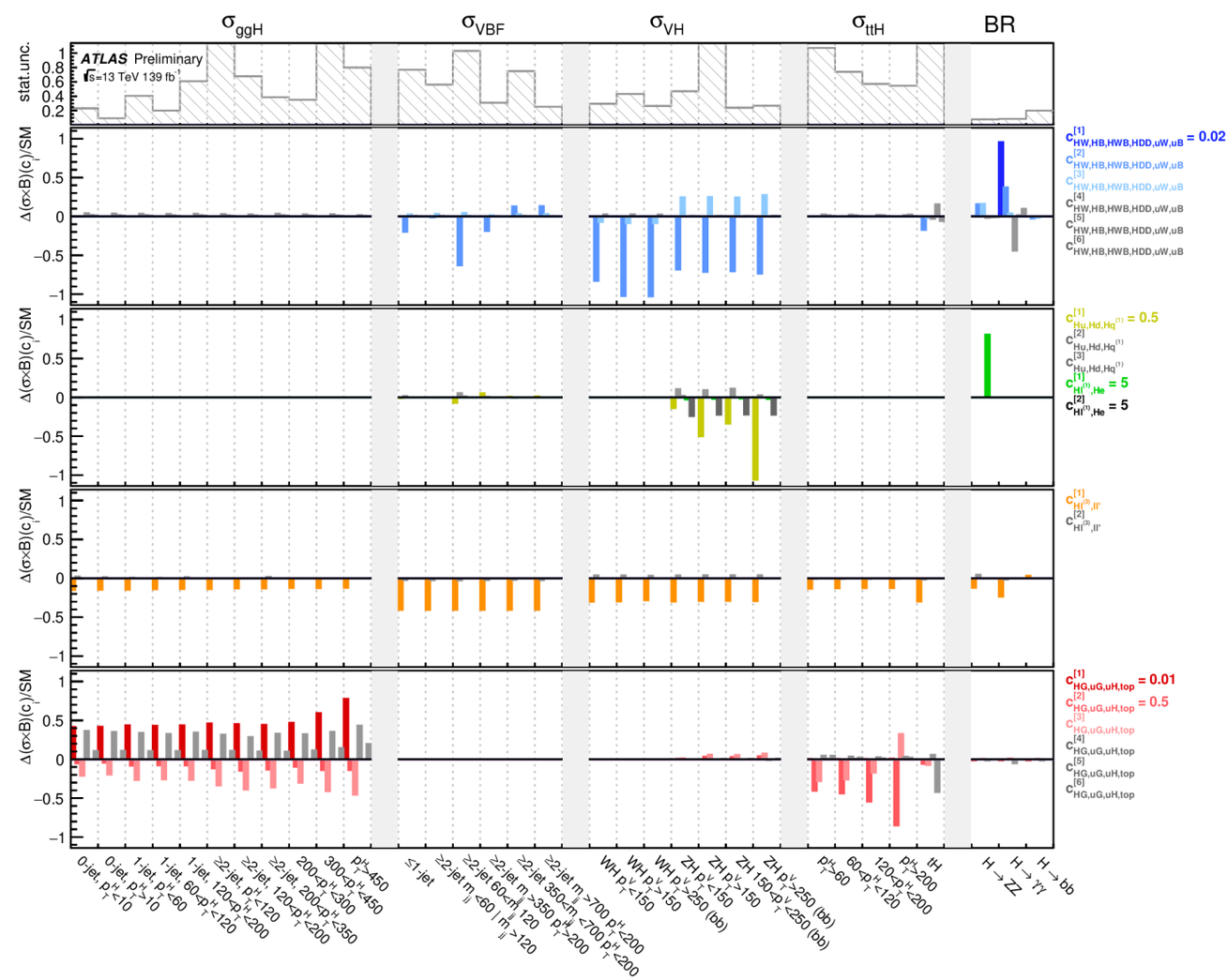
ATLAS-CONF-2020-053

Analysis: EFT Interpretation of Comb. STXS Results

In Warsaw Basis



After Principal Component Analysis



Combination of *H*->Invisible

ATLAS-CONF-2020-052

New

Motivation

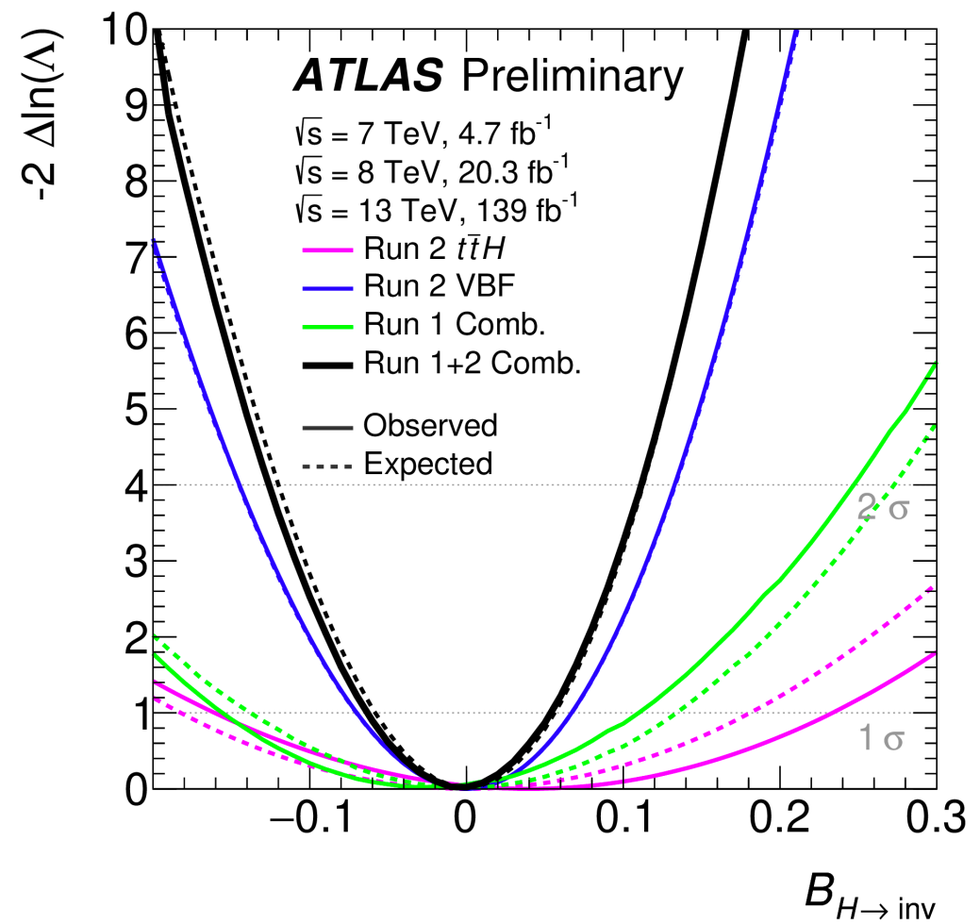
- Many **d**ark **m**atter models predict that light DM can be produced in Higgs decays at the LHC, **invisible** to the detector

Strategy

- Combination of **VBF, H->Inv** and **ttH, H->inv** as well as **Run 1 combination** of H->Inv

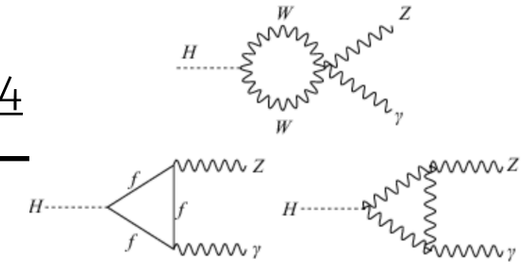
Results

- upper limit on the $H \rightarrow$ **invisible** branching ratio of 0.11 ($0.11^{+0.04}_{-0.03}$) at 95% CL is observed (expected)
- Results also interpreted in Higgs portal dark matter models



$H \to Z\gamma$ ($Z \to ee/\mu\mu$) Search

Phys. Lett. B 809 (2020) 135754



Motivation

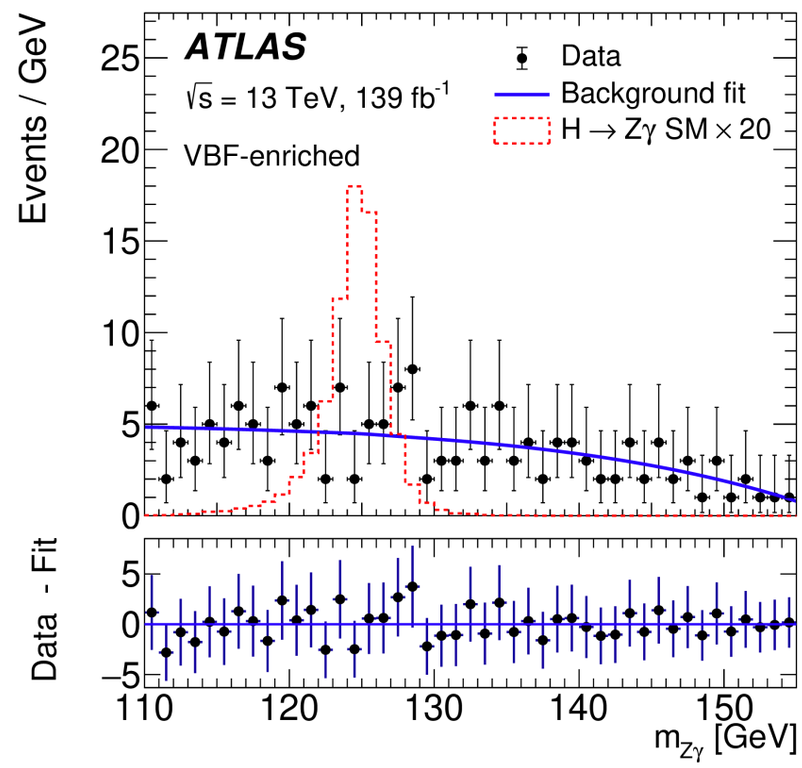
- Decay possible through loop diagrams, $B(H \to Z\gamma) = \mathcal{O}(10^{-3})$
- Differences from SM expected for several scenarios, for example: Composite state Higgs, additional colourless charged scalars, leptons or vector bosons with Higgs couplings

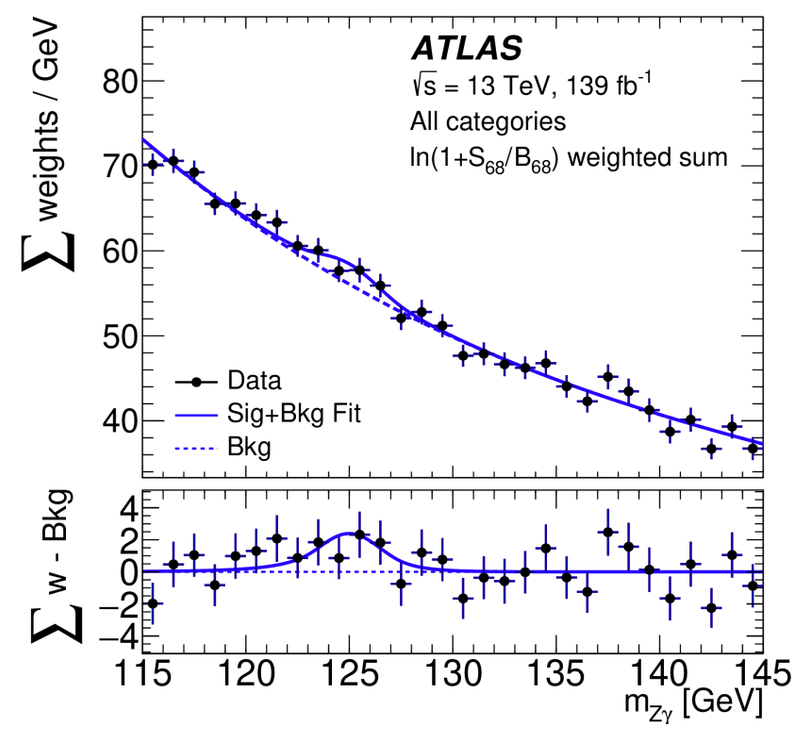
Strategy

- Fit to $m_{Z\gamma}$ in 6 categories separating production modes and lepton flavours and p_{Tt} = 40 GeV

Results

- Upper limit of 3.6 (2.6) times the SM exception at 95% CL (with SM Higgs)
- $\mu = 2.0^{+1.0}_{-0.9}$ *Limited by stat uncs*



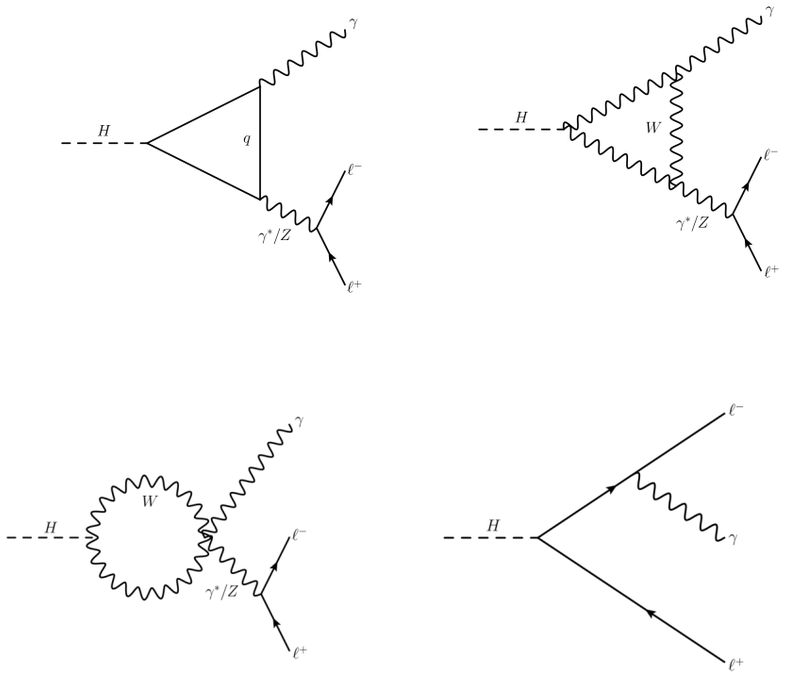


$H\to ll\gamma$ (Low Mass)

Phys. Lett. B 819 (2021) 136412

Motivation

- Rare decays sensitive to possible new physics



Strategy

- Different categories defined depending on the lepton types and event topologies
- Simultaneous fit to $m_{ll\gamma}$ with analytical modelling for background

Results