Higgs couplings and mass measurements in the ZZ and WW decay channels with ATLAS and CMS

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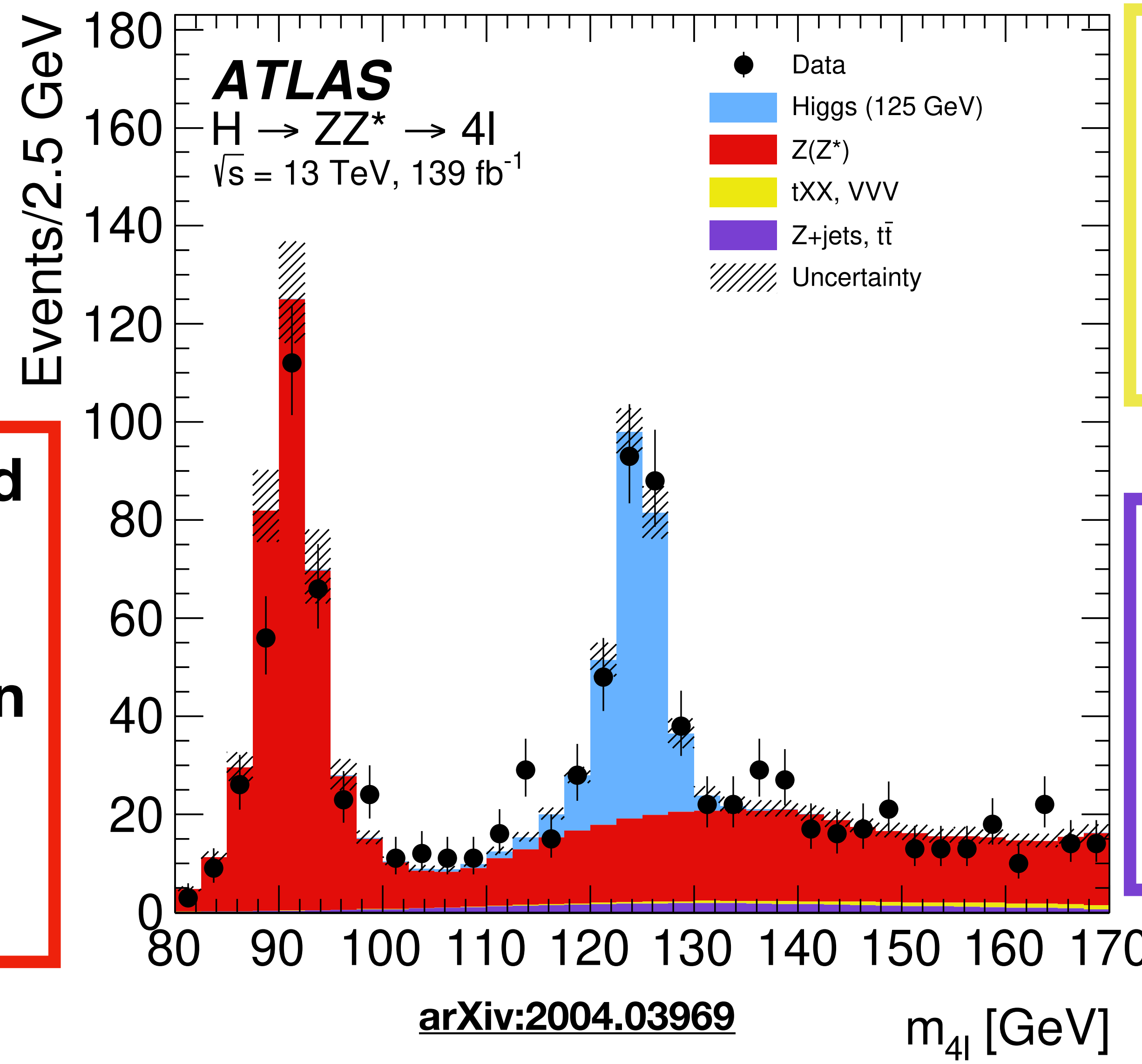
for the ATLAS and CMS Collaborations

H→ZZ*→4l Decay Channel



arXiv:2004.03969

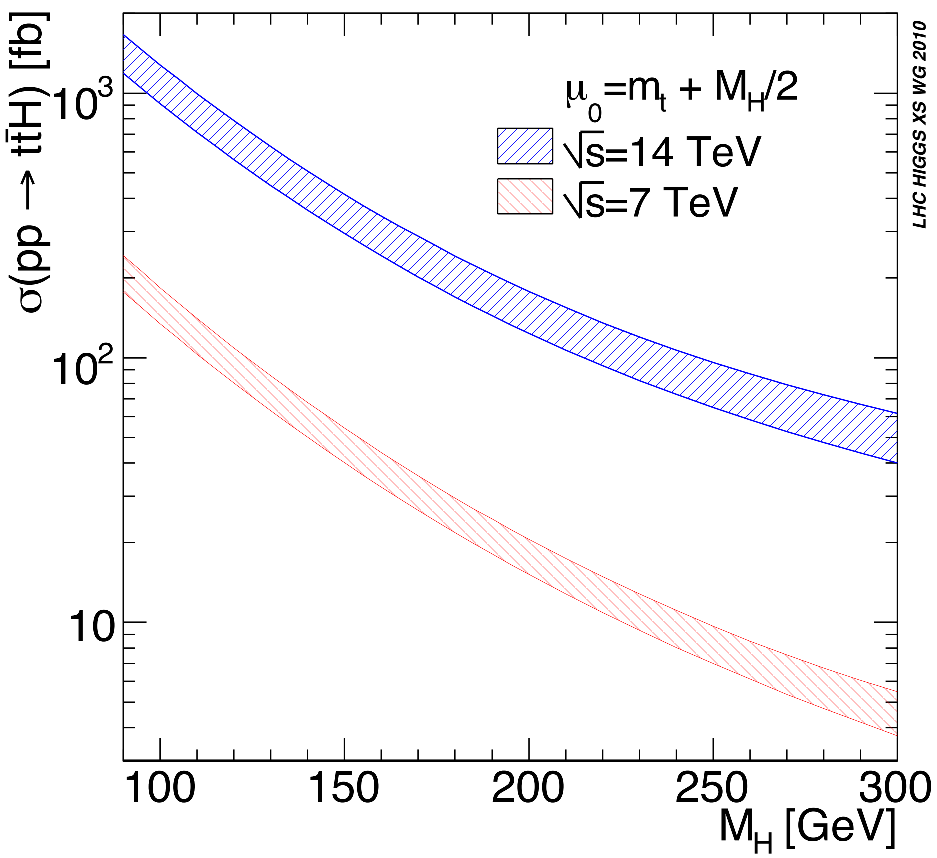
Dominant background from SM ZZ* production is estimated using MC in CMS; normalization constrained in sidebands in ATLAS

Background from ttV, ttt, ttVV can be constrained in sidebands or taken from MC; VVV from MC

Background from lepton fakes/heavy flavor decays estimated in data-driven fashion

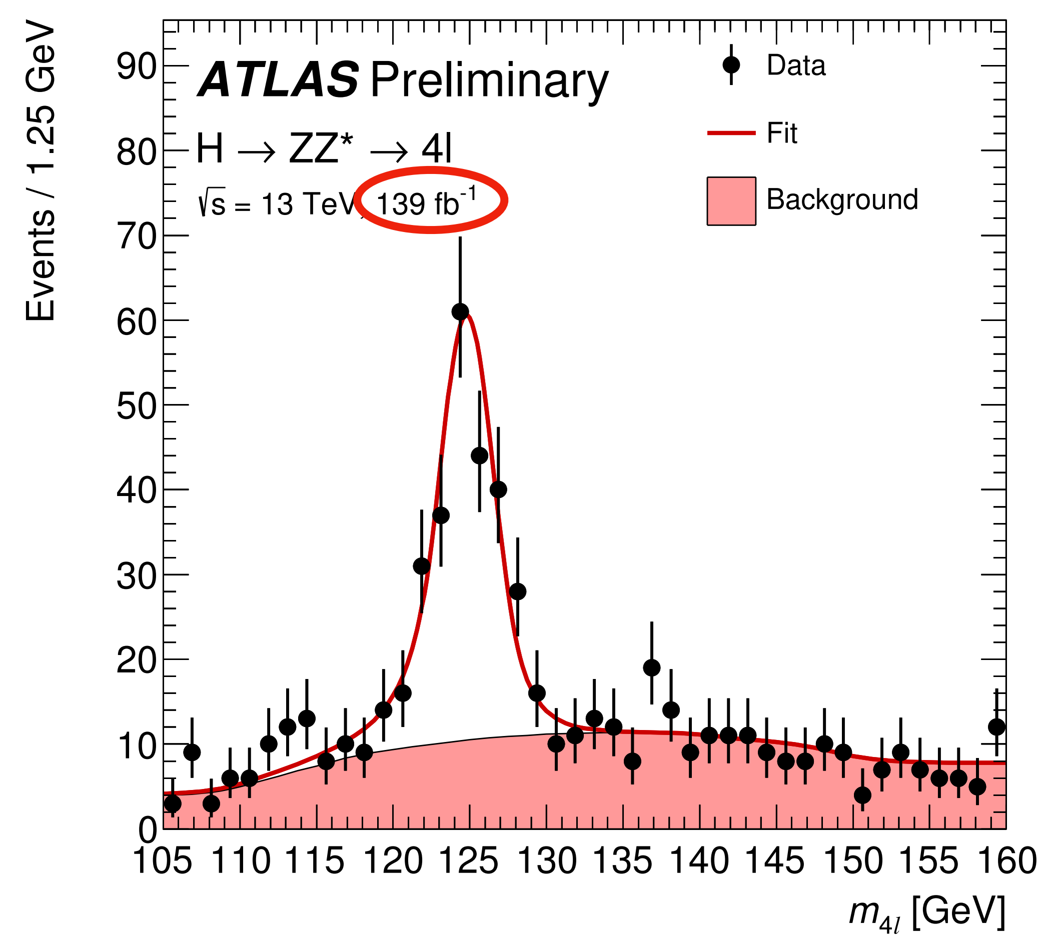
- Low BR of ~0.01%, but high purity with S/B~2 in the mass peak
- Useful for many Higgs boson properties measurements
- ATLAS and CMS both have ~200 signal events with the full Run-2 sample

Higgs Boson Mass



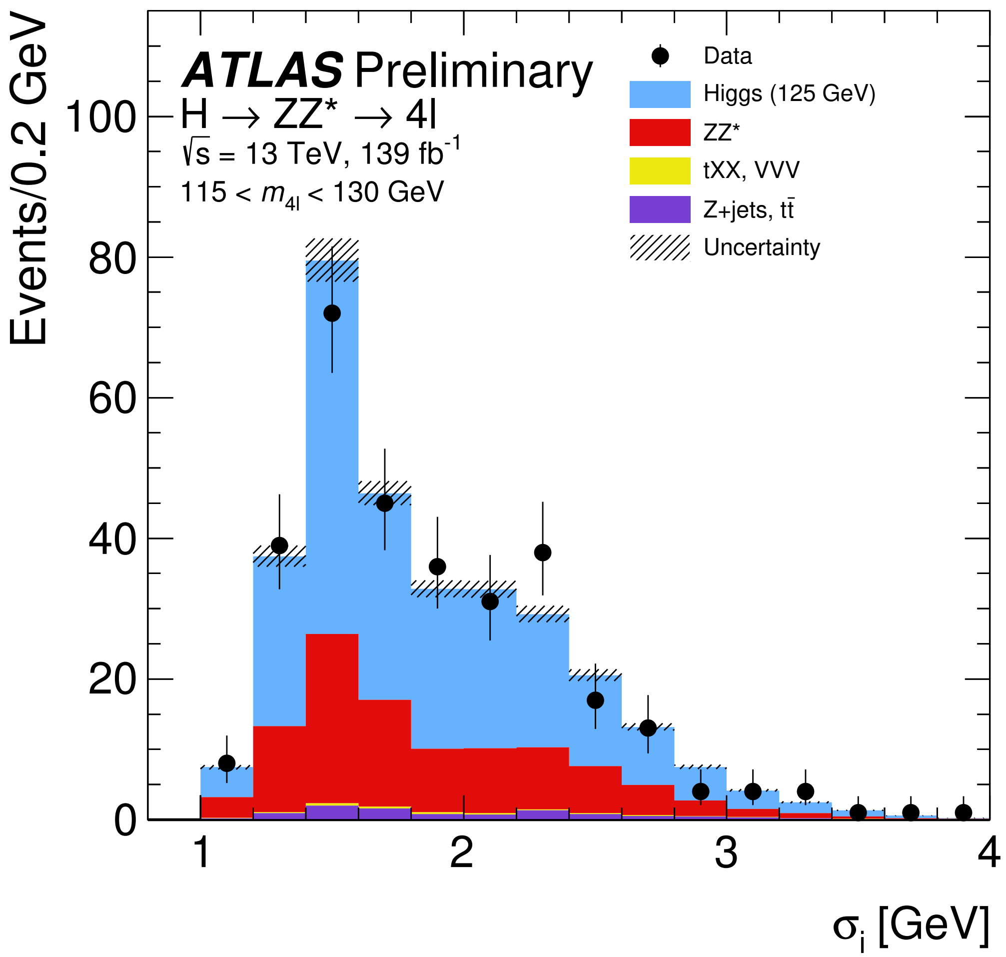
ATLAS-CONF-2020-005

- First mass measurement with full Run-2 dataset
- Recover FSR, constrain m_{12} to m_Z (15% resolution gain)
- Parametrize m_{4l} distribution as double-sided Crystal Ball function
  - Analysis categories based on final state (resolution) and BDT (for better S/B)
  - Background shapes from smoothed MC, ZZ^* norm floats



- Not a test of the Standard Model
  - m_H is a free parameter
- Important ingredient in SM predictions
- Best measured in clean channels like $H \to ZZ^* \to 4l$

Higgs Boson Mass



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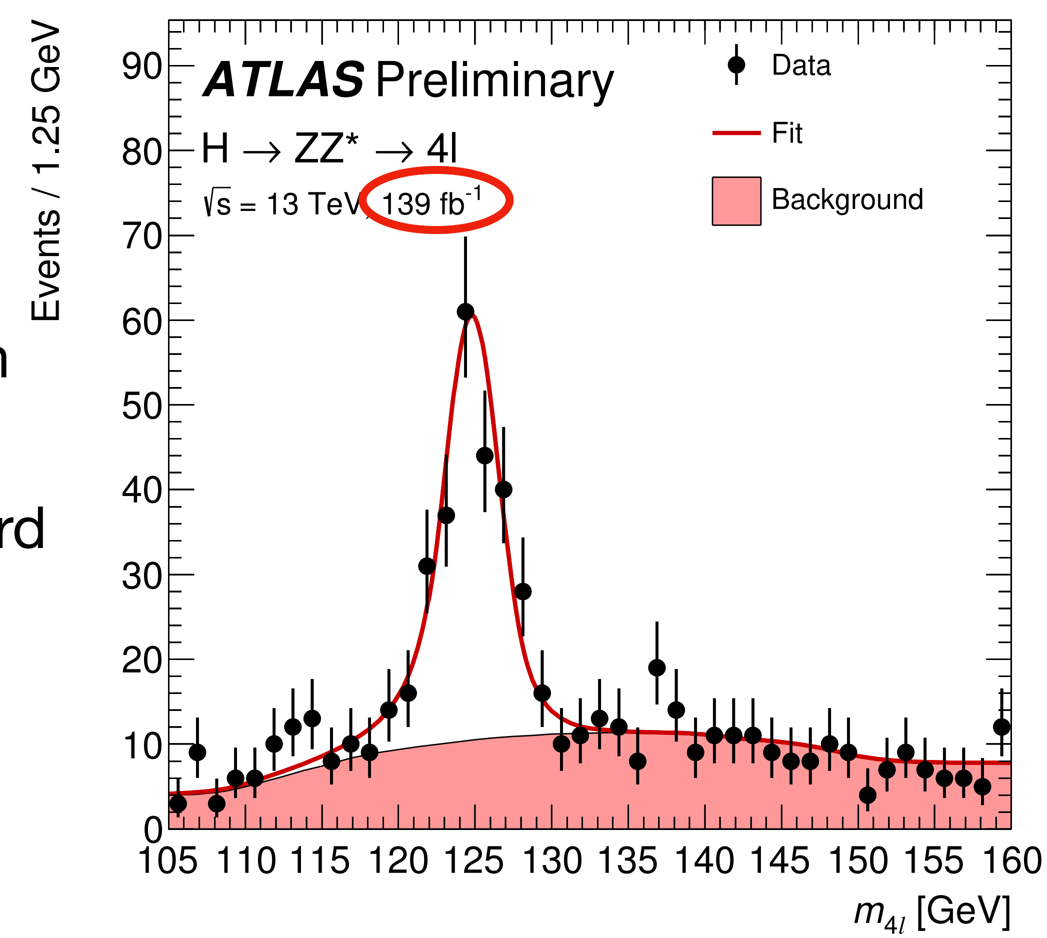
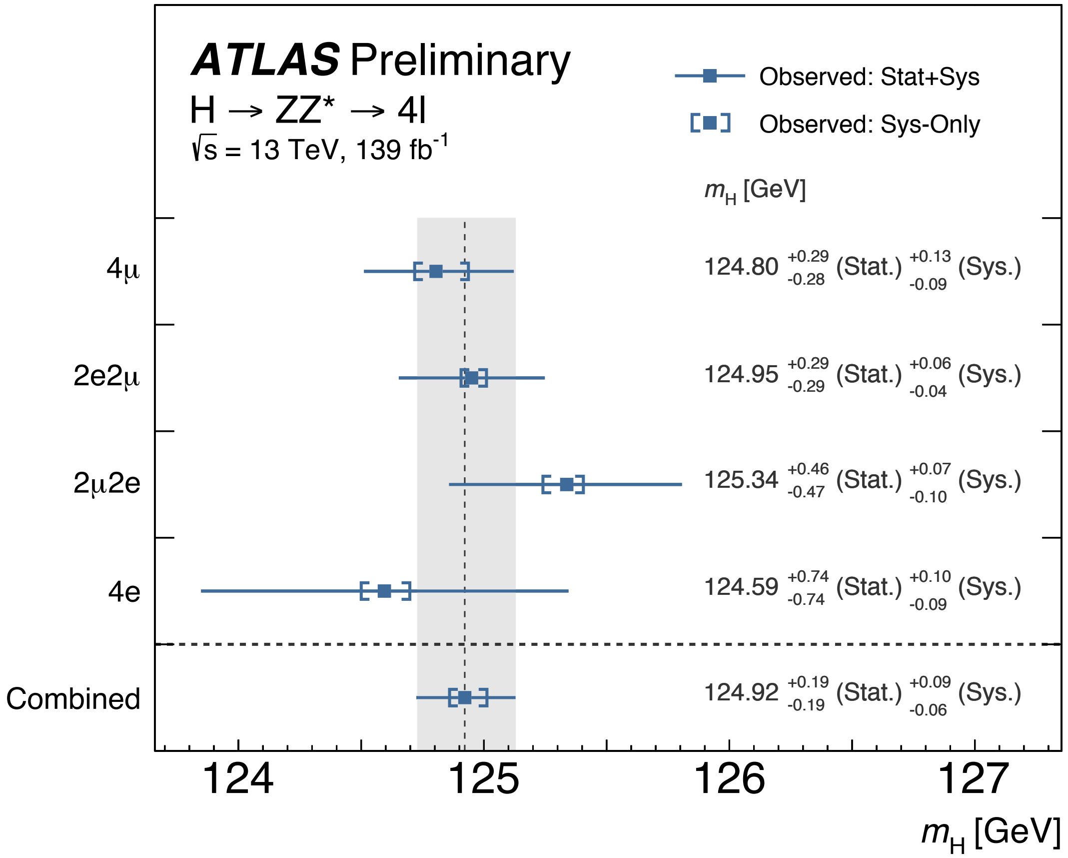


- Low stats → gain from using per-event m_{4l} resolution
  - ~2% better resolution, more robust to fluctuations
- Lepton momentum resolution is non-Gaussian → hard to calculate m_{4l} resolution from lepton resolutions
  - Constraint on m_{12} introduces correlations between leading leptons
- Train a NN to predict m_{4l} resolution using lepton and event-level information

Higgs Boson Mass



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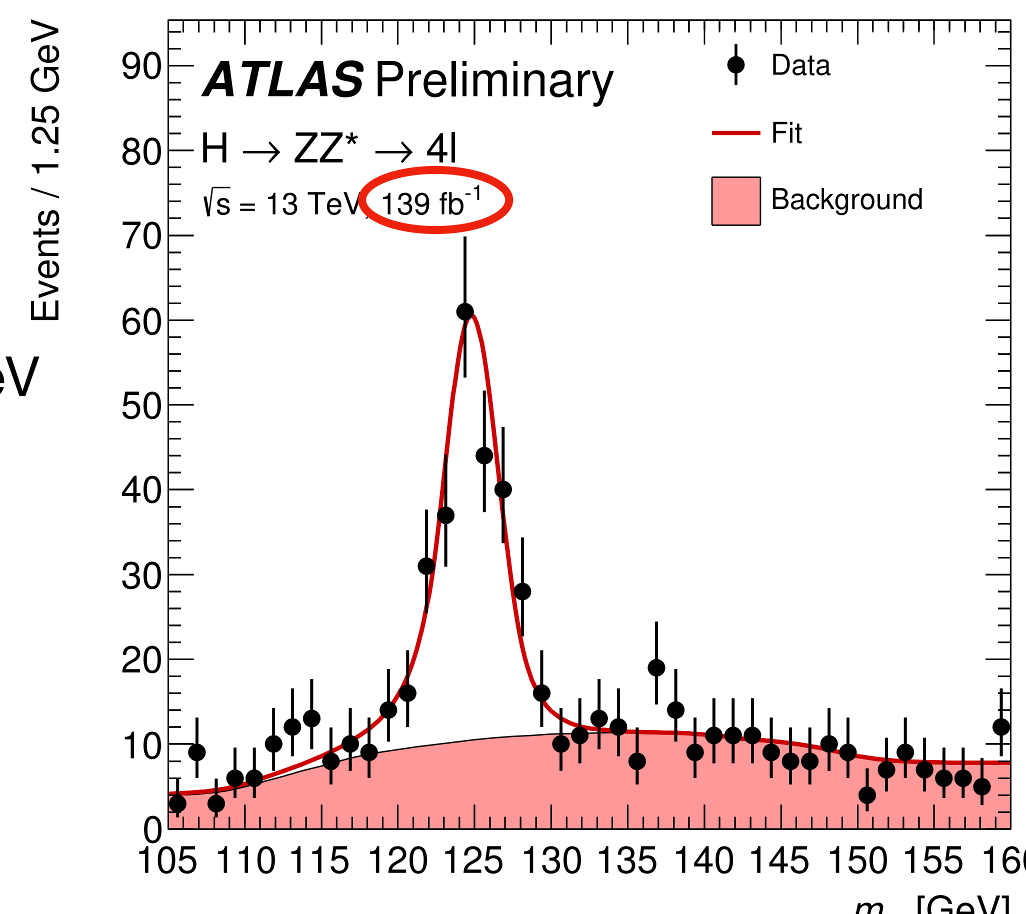
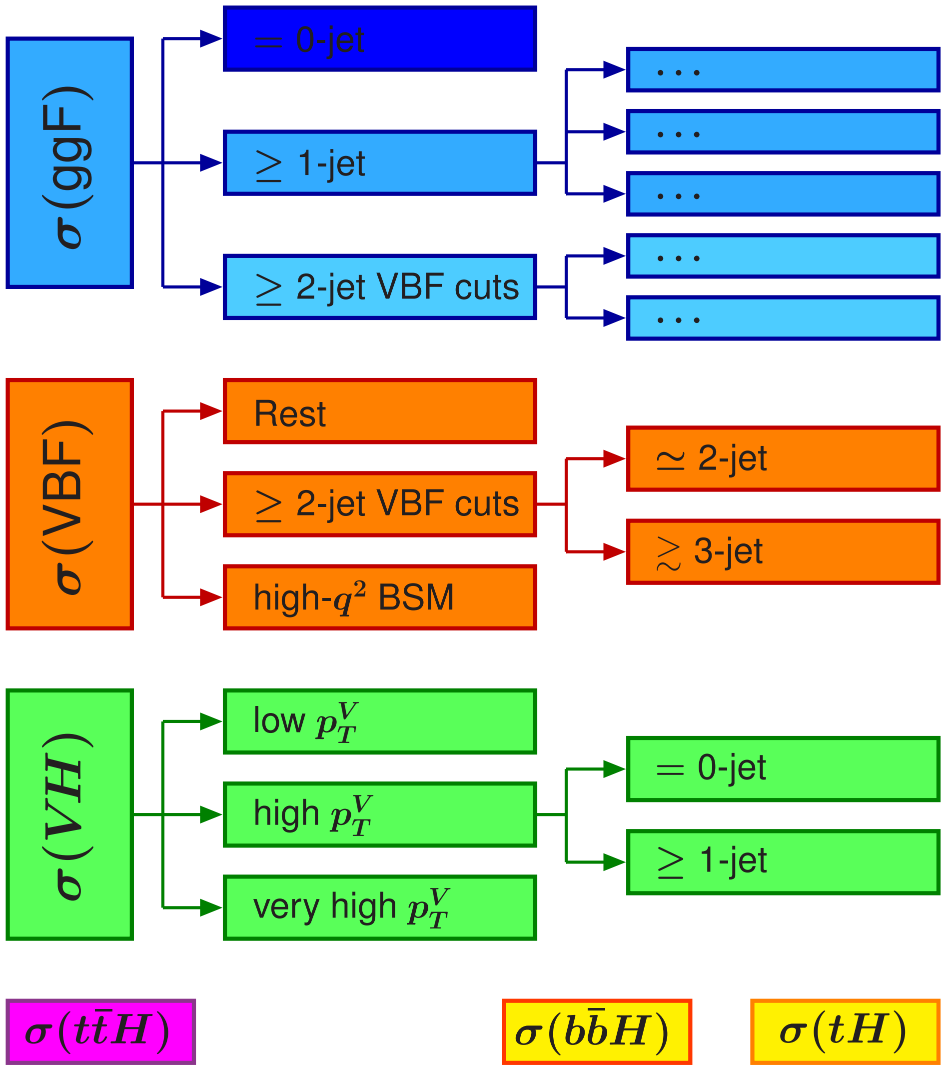


- Final result: m_H=124.92±0.21 GeV
  - Compare previous CMS 4l result 125.26±0.21 GeV
- 20% improvement on previous ATLAS result
- Still stat-dominated: leading systematic is muon momentum scale

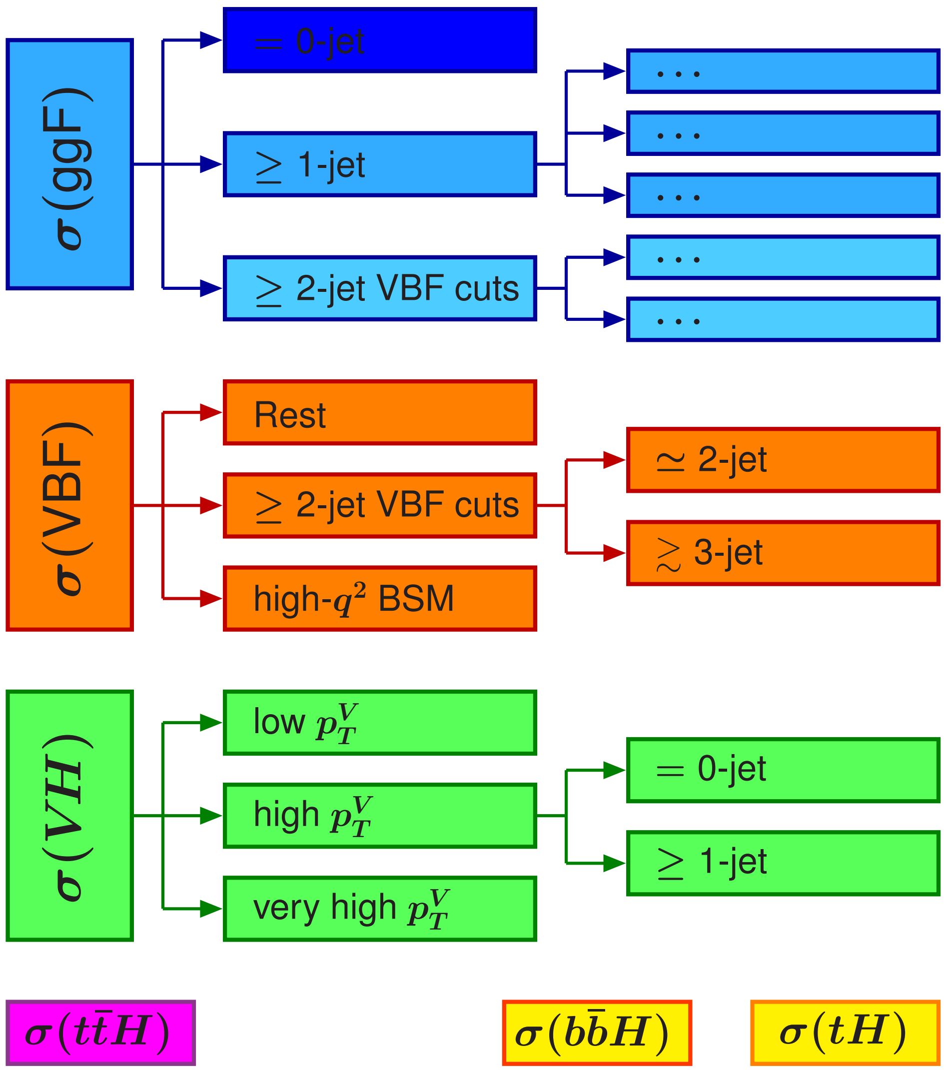
Systematic Uncertainty	Impact (GeV)
Muon momentum scale	+0.08,−0.06
Electron energy scale	±0.02
Muon momentum resolution	±0.01
Muon sagitta bias correction	±0.01

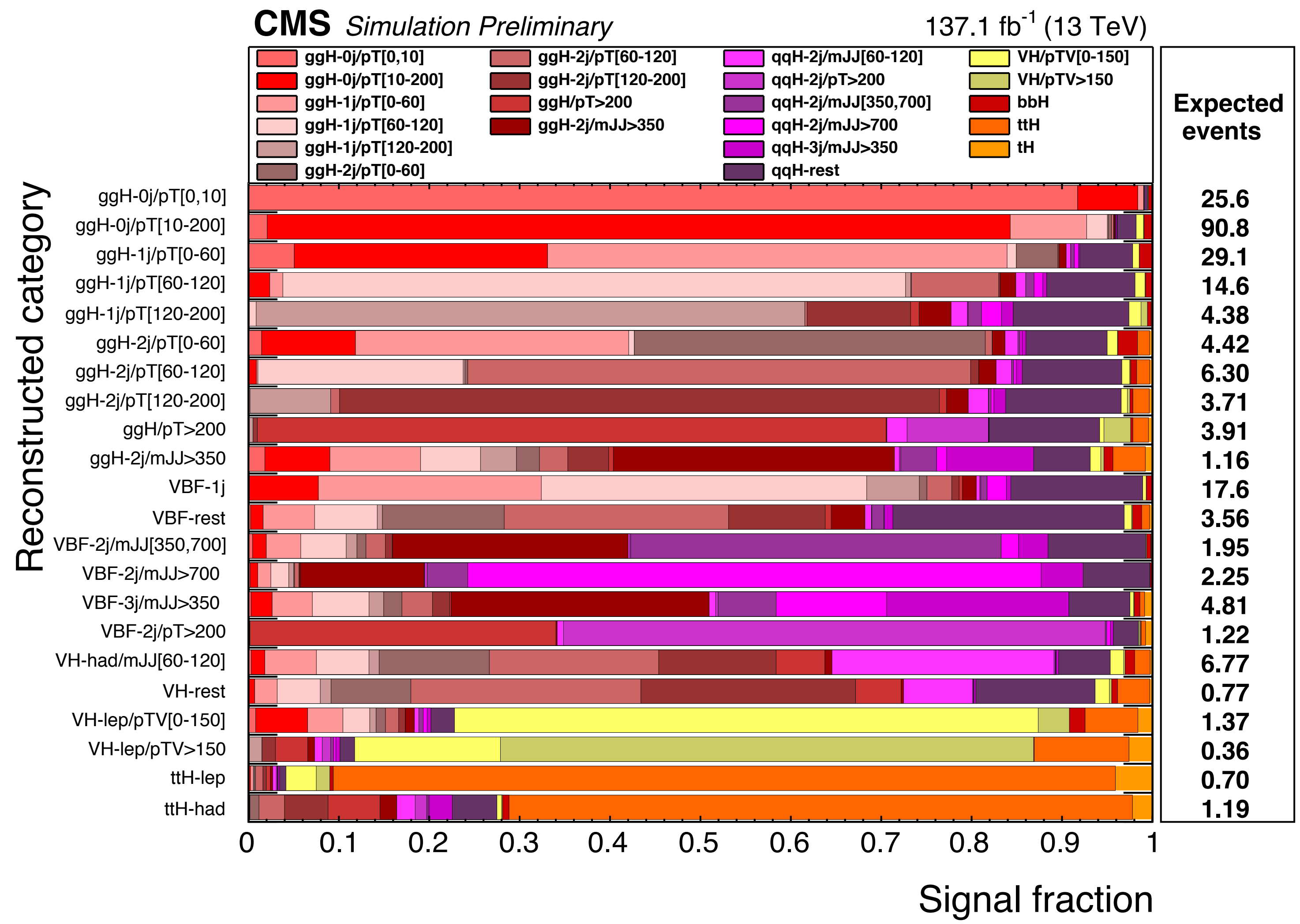
Simplified Template Cross Sections



- Target specific phase space regions within production modes
  - Using SM as a kinematic template
- Attempt to maximize experimental sensitivity and minimize dependence on theoretical uncertainties

Simplified Template Cross Sections



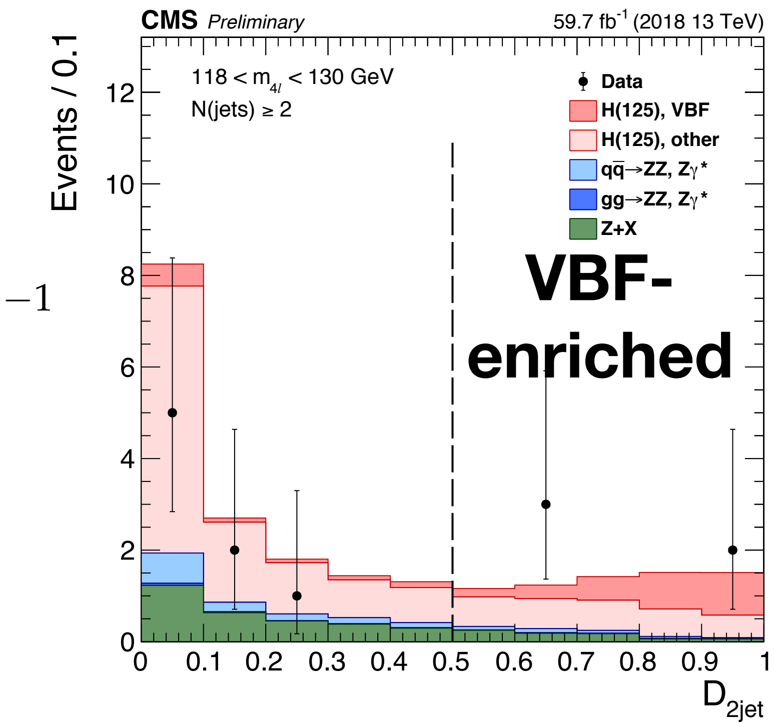


- Reconstructed categories are defined to target STXS bins
  - Both experiments use STXS Stage 1 with some bins merged
    - ATLAS: Reduced Stage 1.1; CMS: Stage 1.1
- Extract cross-sections in each bin from fit to values in categories

Kinematic Discriminants

All plots in the signal region 118<m$_{4l}$<130

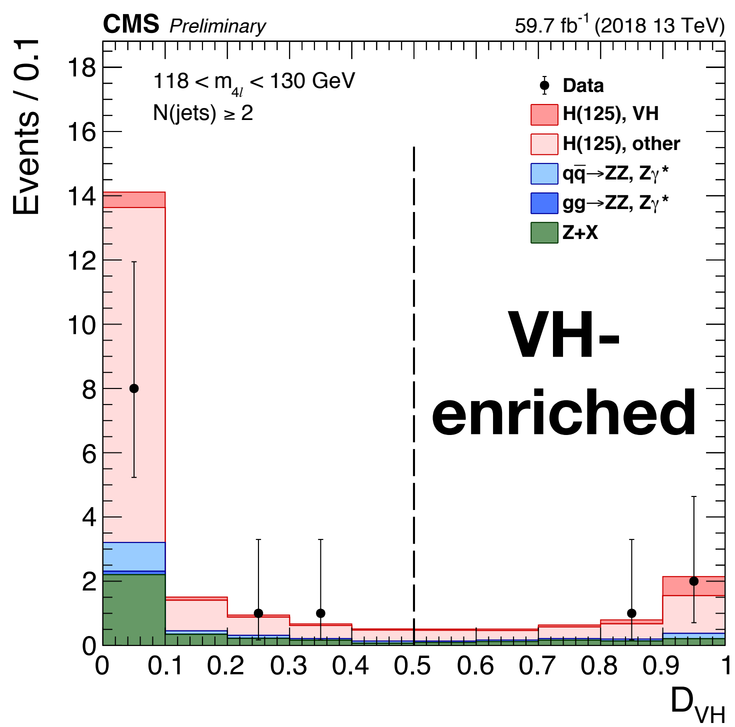
$$\mathcal{D}_{\rm 2jet} = \left[1 + \frac{\mathcal{P}_{\rm HJJ}(\vec{\Omega}^{\rm H+JJ}|m_{4\ell})}{\mathcal{P}_{\rm VBF}(\vec{\Omega}^{\rm H+JJ}|m_{4\ell})}\right]^{-1}$$



Target signal

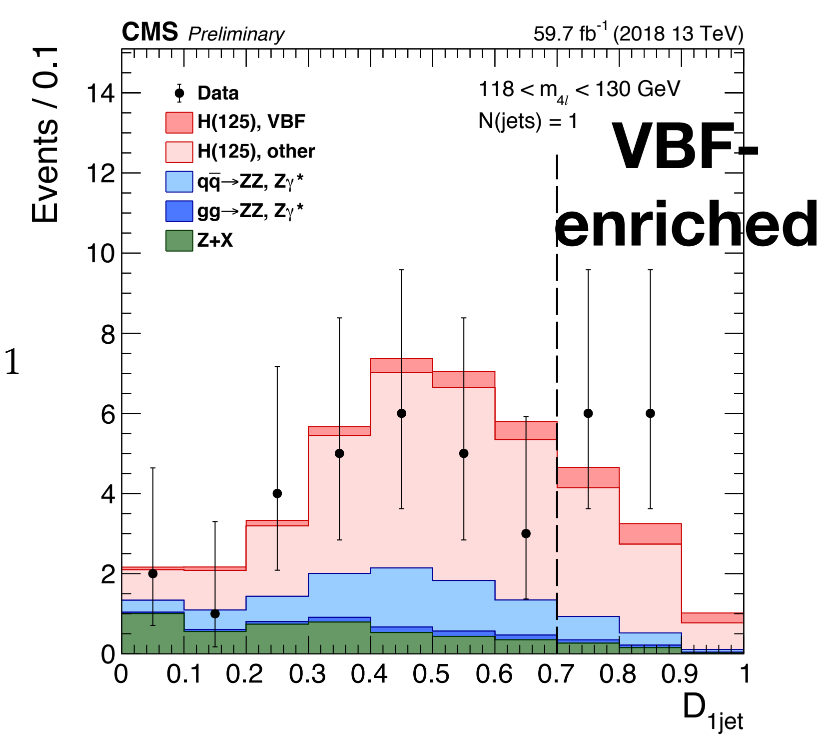
Background Signal

Cut value



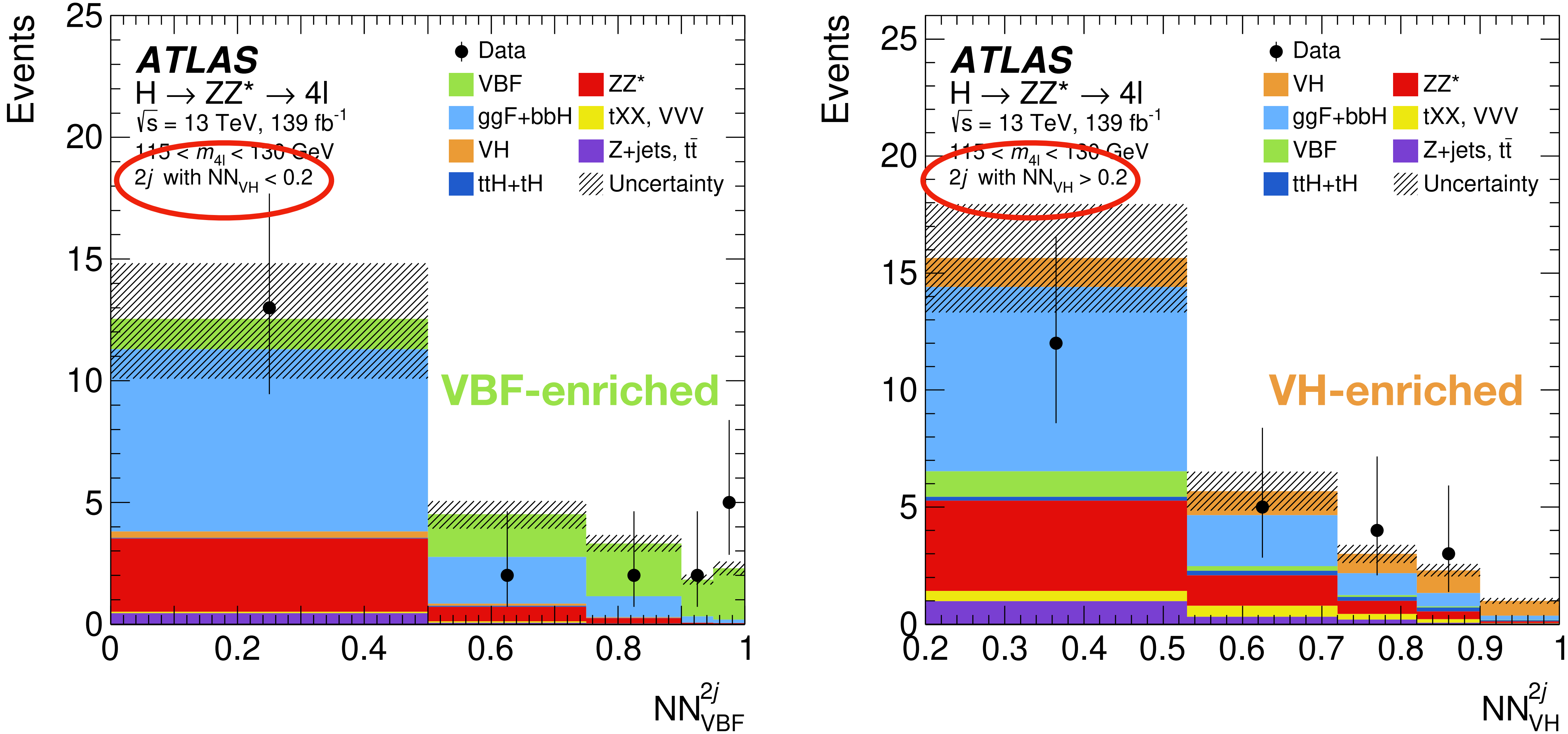
$$\mathcal{D}_{\rm VH} = \max\left(\left[1 + \frac{\mathcal{P}_{\rm HJJ}(\vec{\Omega}^{\rm H+JJ}|m_{4\ell})}{\mathcal{P}_{\rm WH}(\vec{\Omega}^{\rm H+JJ}|m_{4\ell})}\right]^{-1}, \left[1 + \frac{\mathcal{P}_{\rm HJJ}(\vec{\Omega}^{\rm H+JJ}|m_{4\ell})}{\mathcal{P}_{\rm ZH}(\vec{\Omega}^{\rm H+JJ}|m_{4\ell})}\right]^{-1} \right)$$

$$\mathcal{D}_{\rm 1jet} = \left[1 + \frac{\mathcal{P}_{\rm HJ}(\vec{\Omega}^{\rm H+J}|m_{4\ell})}{\int d\eta_{\rm J}\mathcal{P}_{\rm VBF}(\vec{\Omega}^{\rm H+JJ}|m_{4\ell})}\right]^{-1}$$



arXiv:2004.03447

Neural Networks

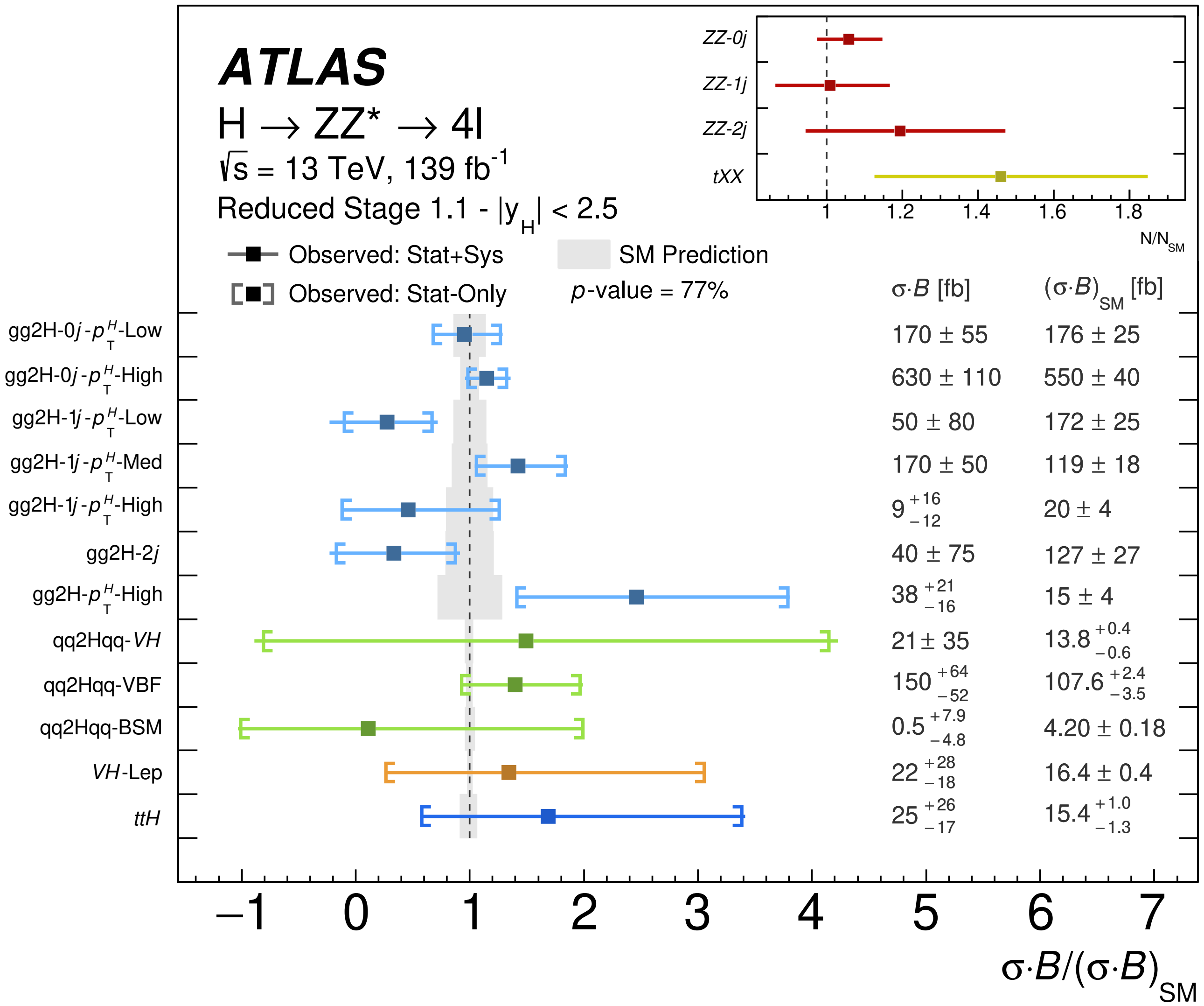


- ATLAS approach uses fewer categories to reduce migrations
- To maintain sensitivity, train NNs to optimize signal efficiency
  - These are also used to define some category boundaries
- Final fits use NN distributions inside categories

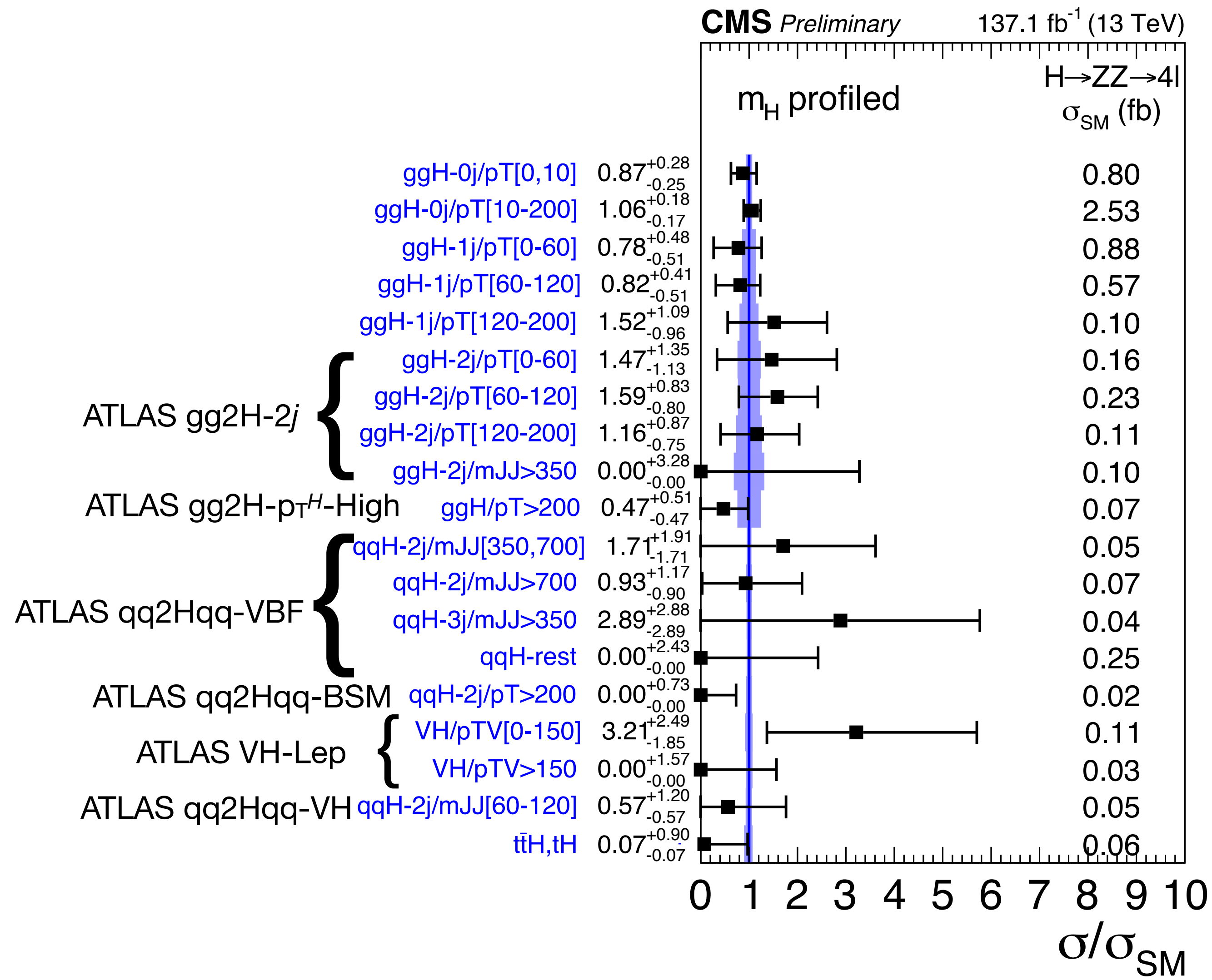
Please see the talk of N. Belyaev on Friday for EFT interpretations!

Results

arXiv:2004.03447



HIG-19-001



- Results obtained for (Reduced) STXS stage 1.1
  - Different bin mergings used by the 2 experiments
  - Note that ggZH is included in the ATLAS gg2H categories so the correspondence is not exact
- Good agreement with the SM observed in all cases

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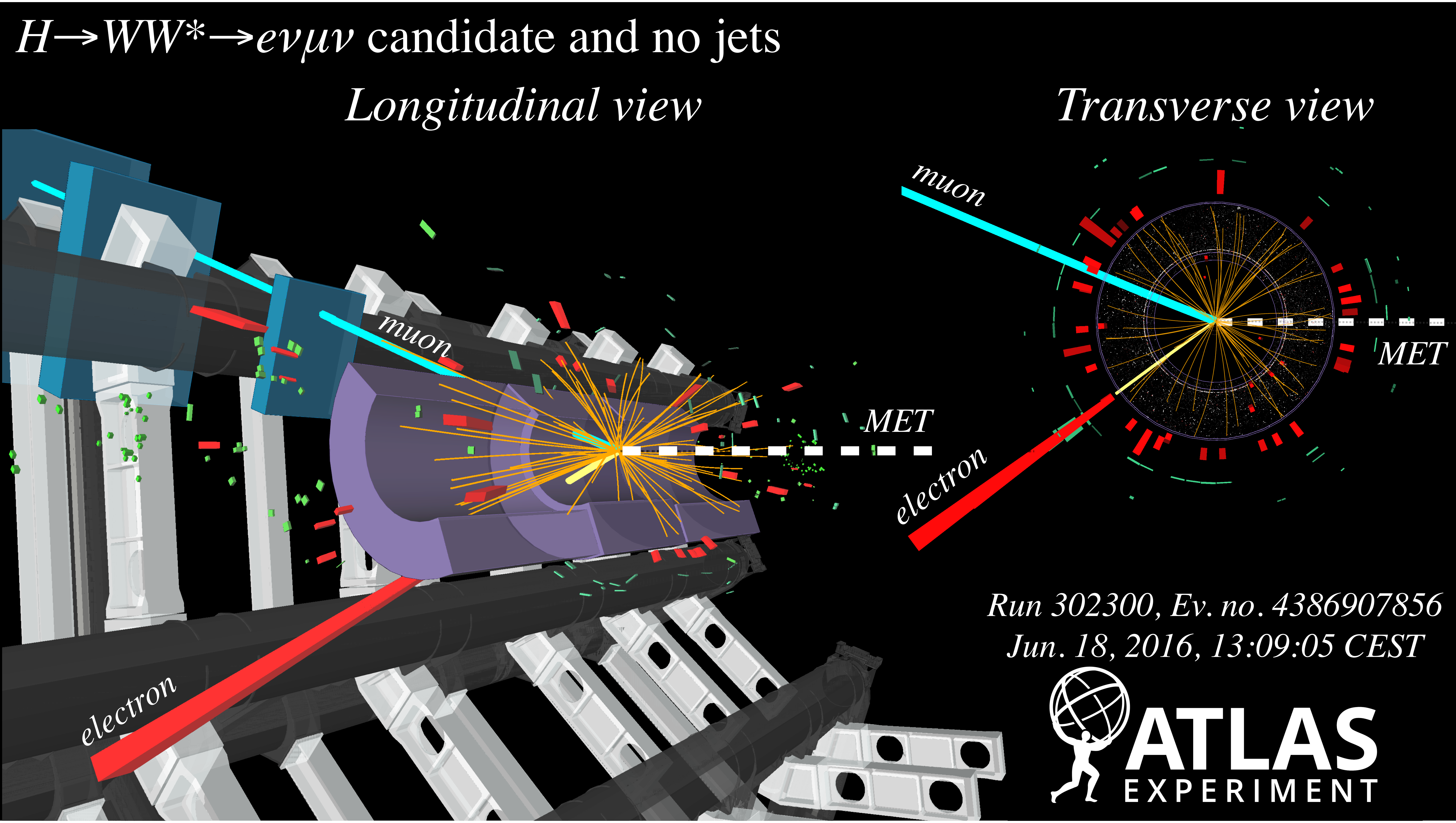
H→WW→llνν Decay Channel



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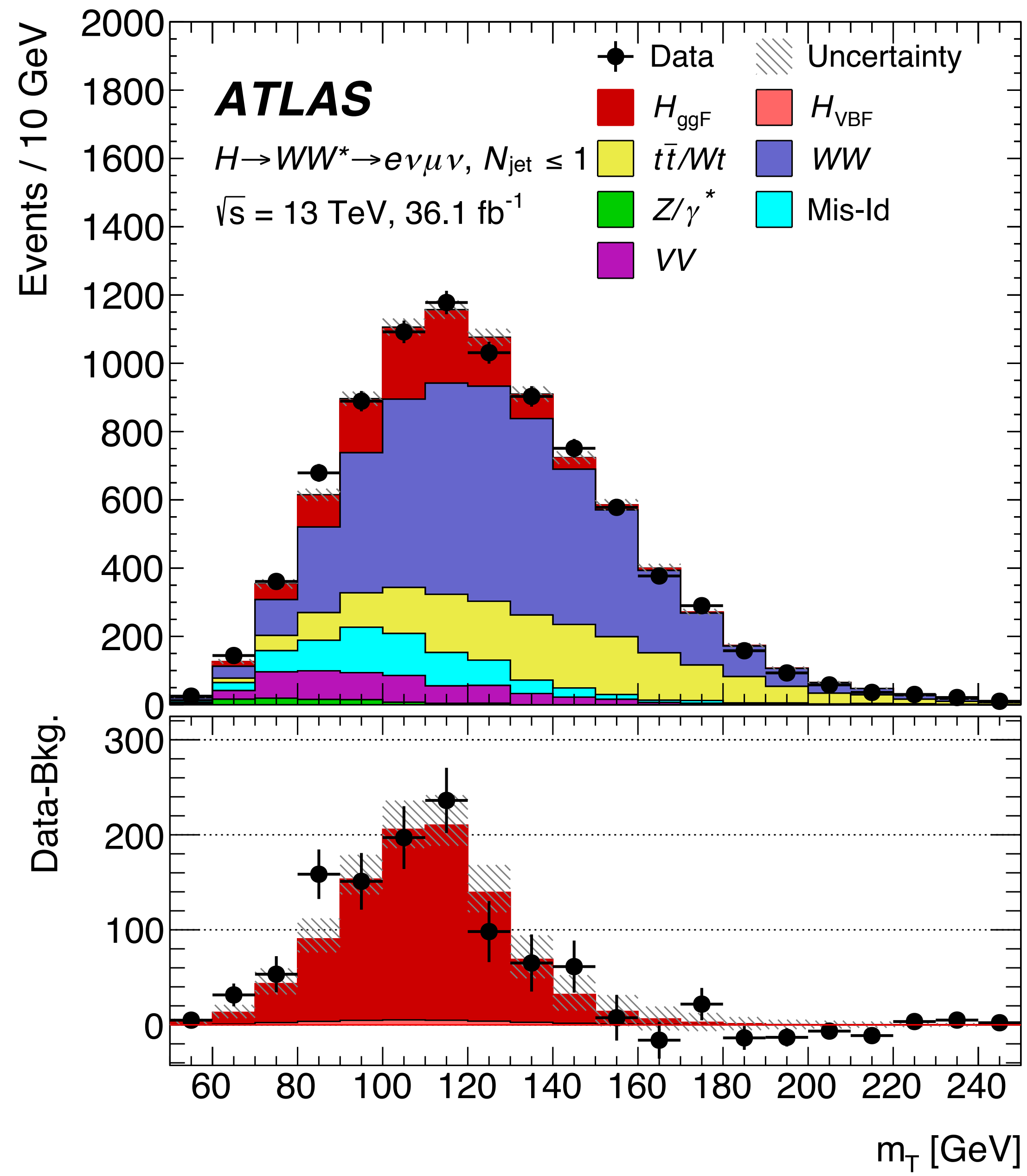
H→WW→llνν Decay Channel

WW background constrained by CR (ATLAS) or as part of the final fit (CMS)

Top quark and Drell-Yan backgrounds constrained by CR's



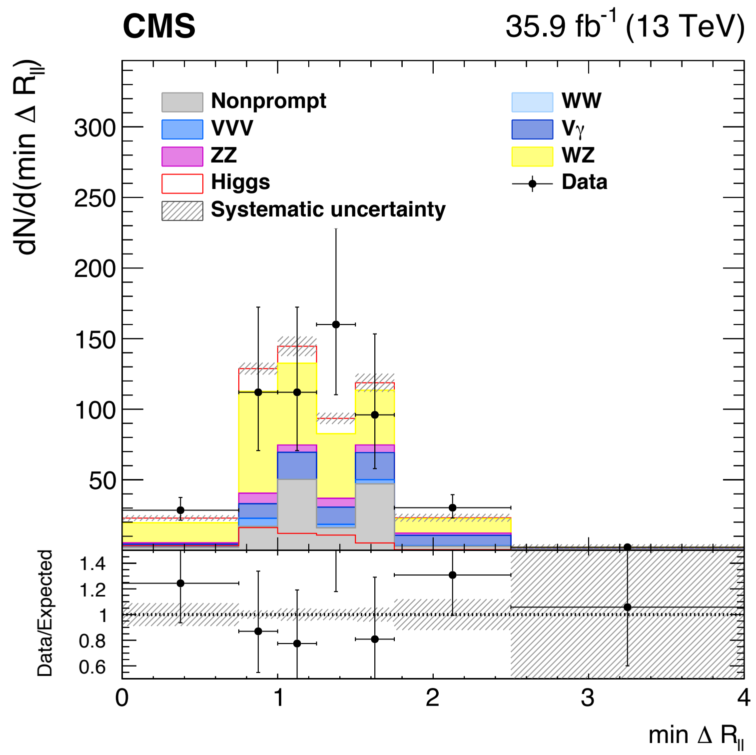
Non-WW diboson backgrounds constrained by CRs or taken from MC

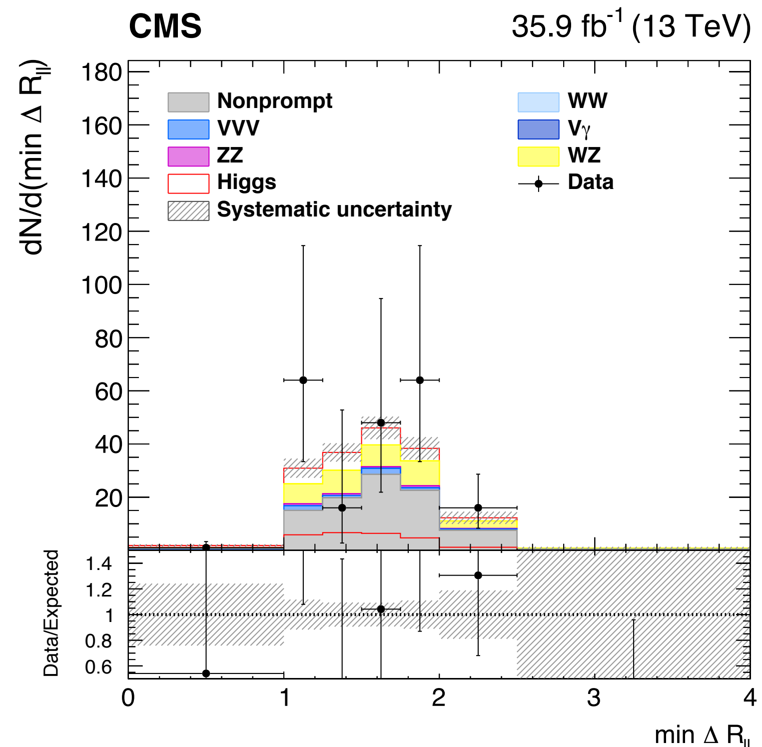
Misidentified lepton backgrounds estimated from data

- Much higher BR than $H \to ZZ^* \to 4l$, ~1%
- More backgrounds, final state not fully reconstructed
- STXS stage 1 difficult but stage 0 (production modes) possible

VH→WW: WH

min(ΔR$_{ll}$) between the oppositely charged leptons





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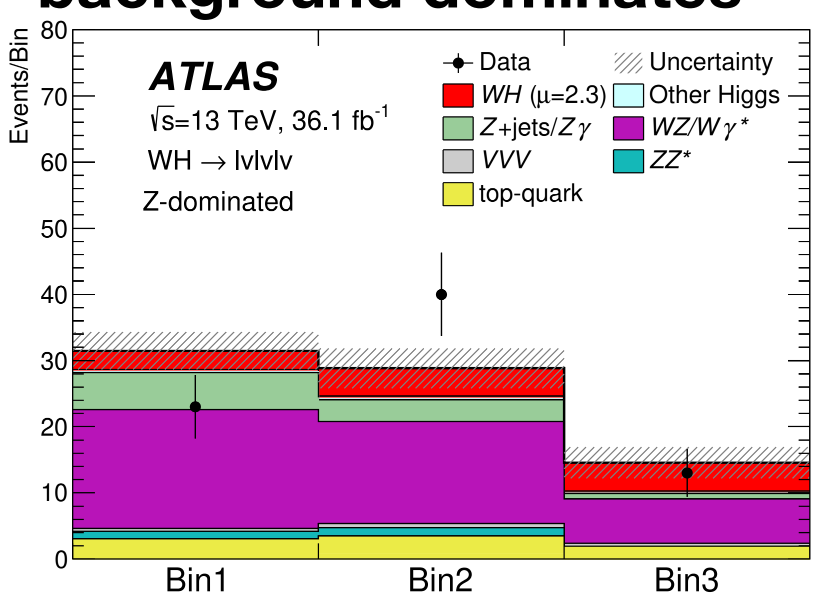
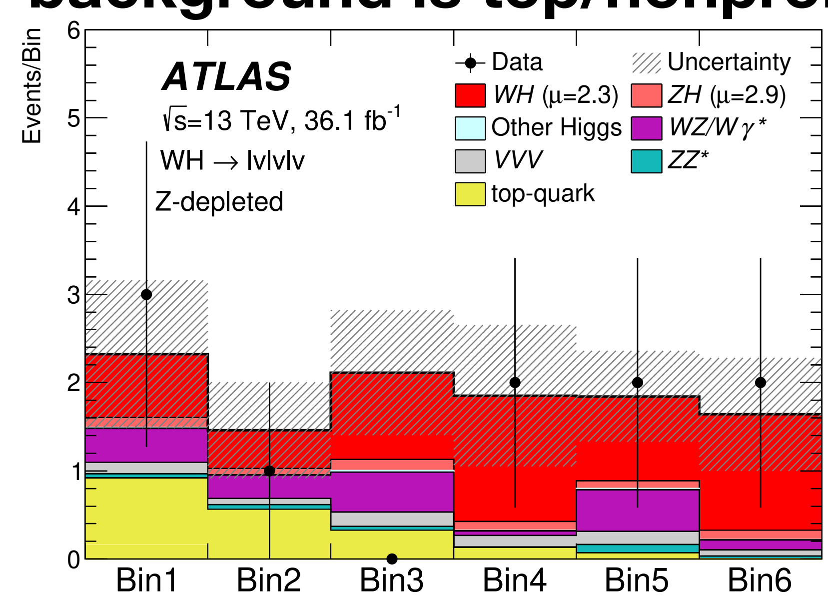
OSSF pair: less pure, WZ background dominates

SSSF pair: higher purity, leading background is top/nonprompt





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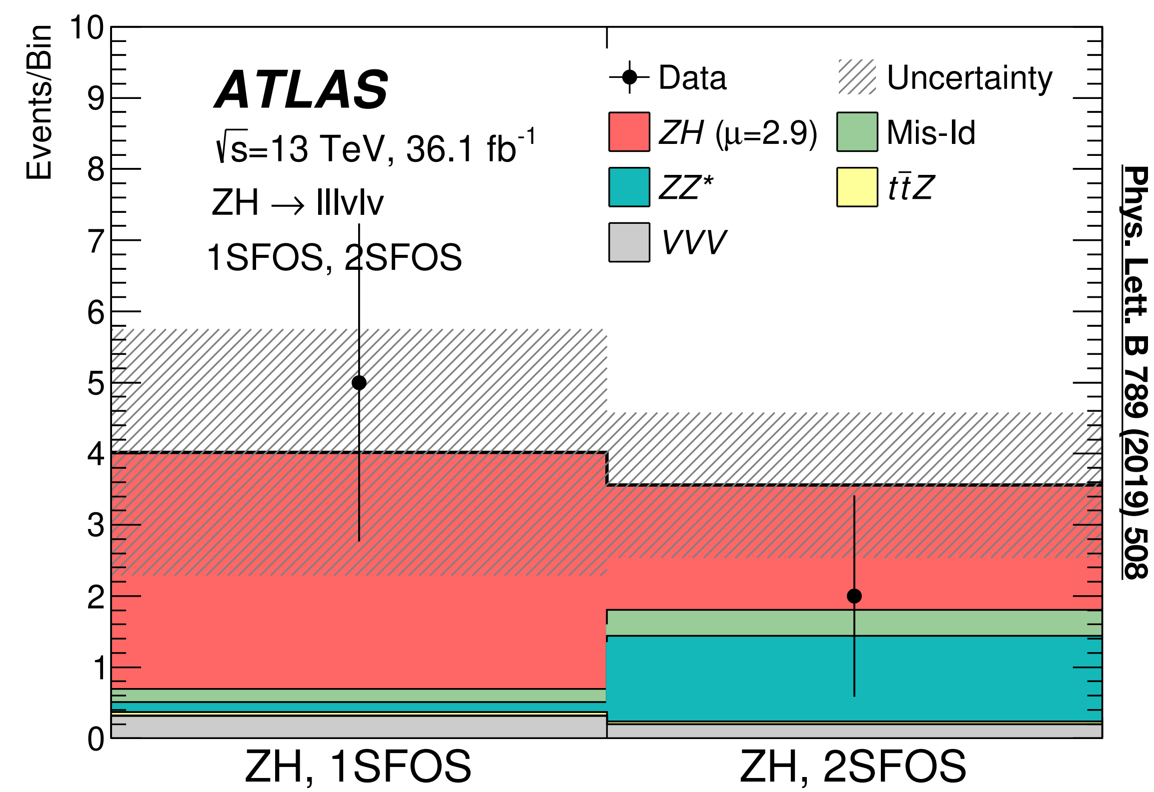
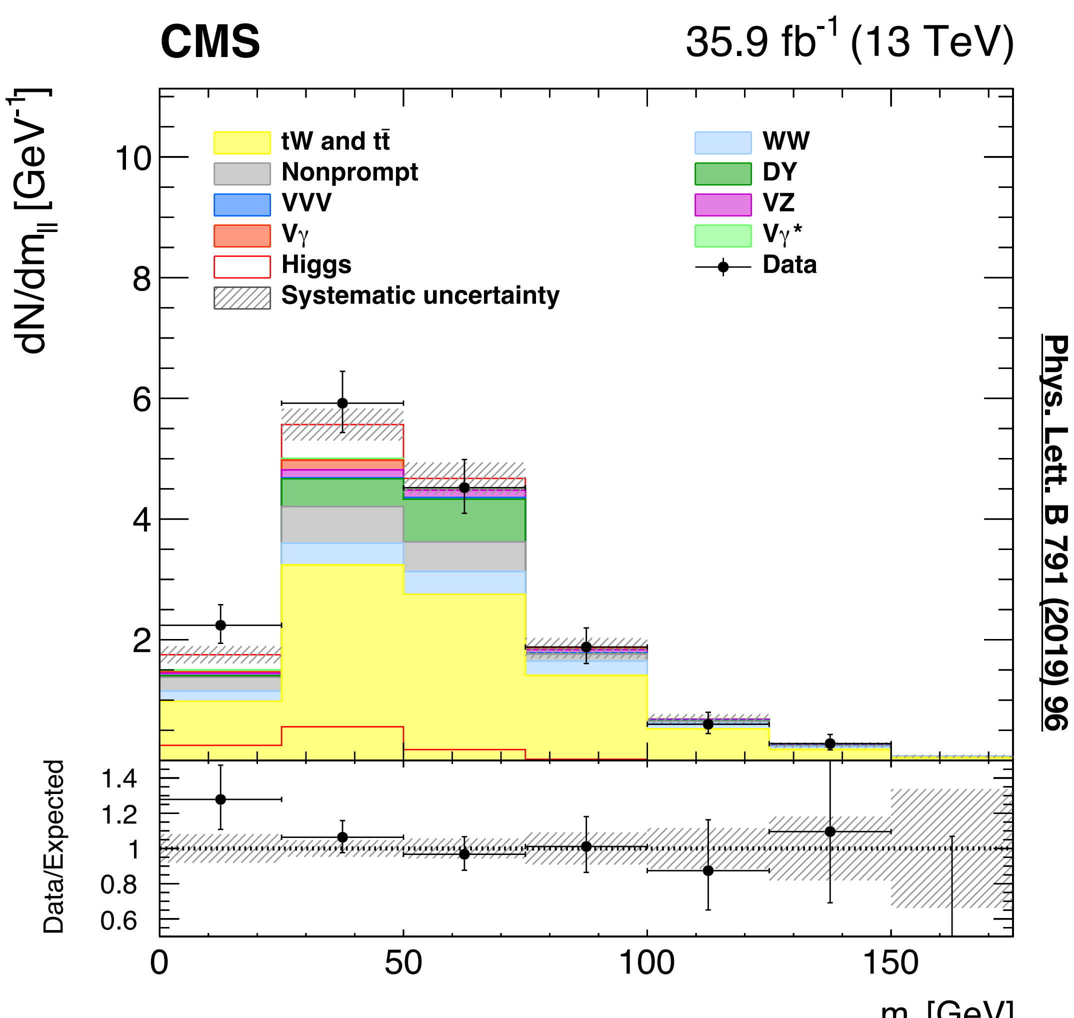
BDTs for S/B rejection (separate in each category)

VH→WW: ZH, VH(had)

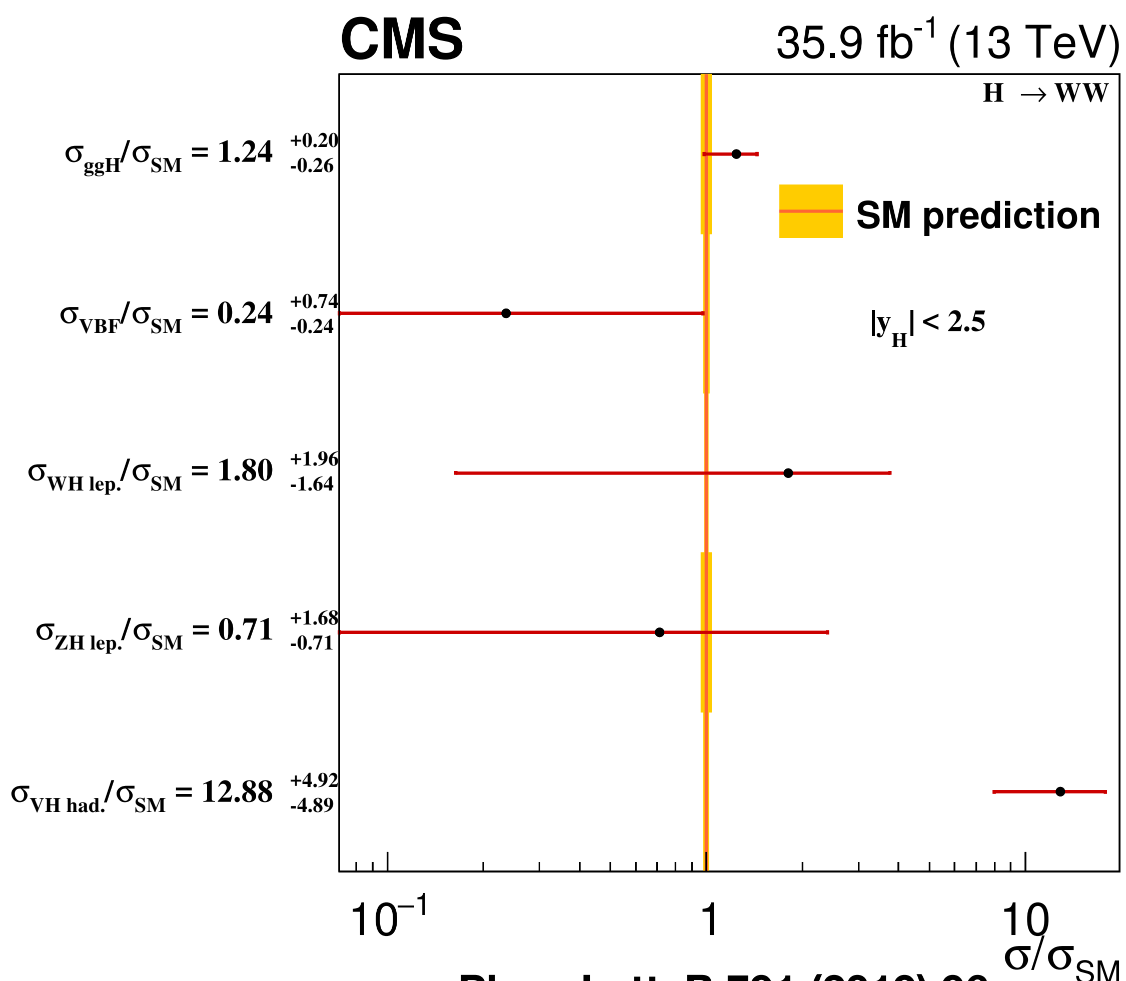
- ZH is fairly pure but low stats
- Split on # of SFOS lepton pairs
- Counting only





- V→2j has higher BR but much more background
- Dominantly from tW and ttbar
- Require central jets for b-tagging
- m_{ll} as variable

Couplings Measurements



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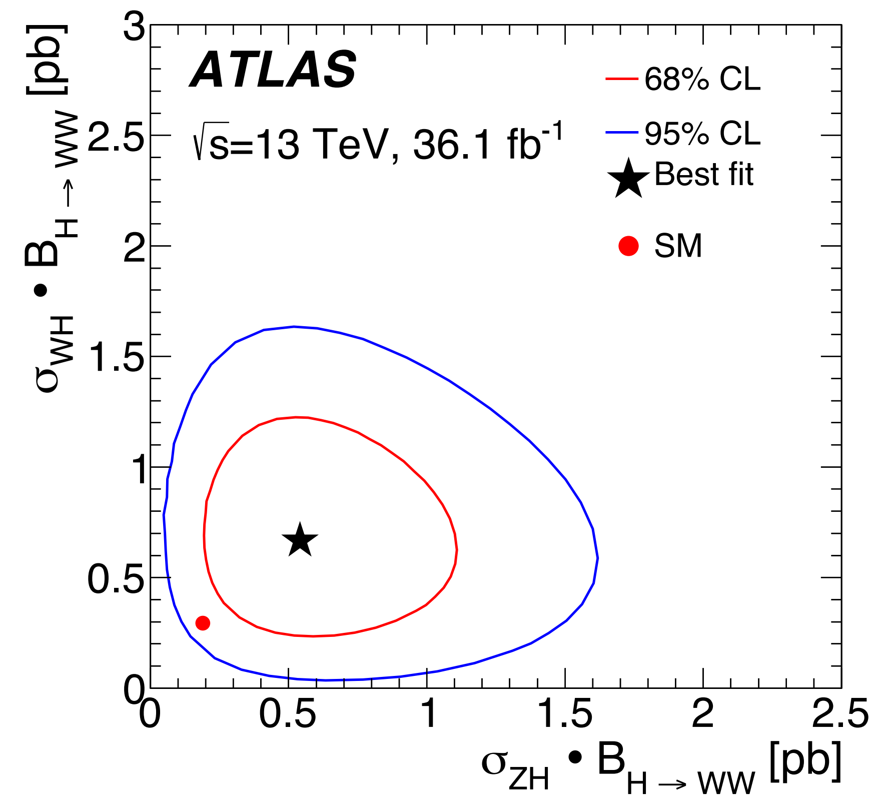

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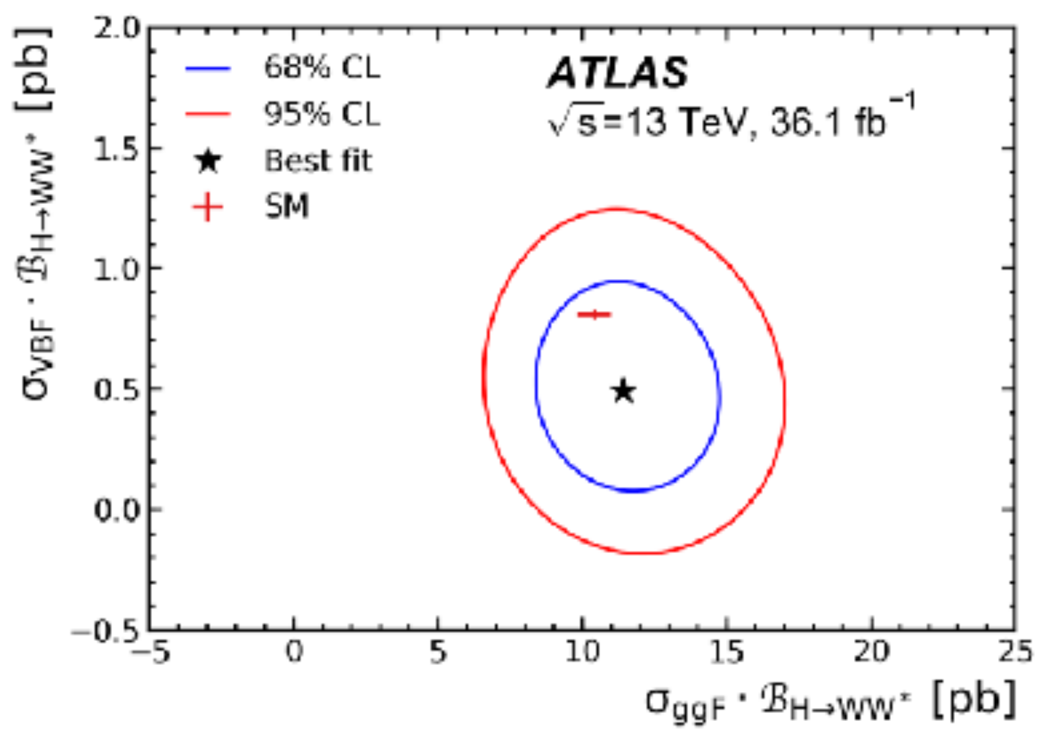


- Measure cross section in production modes
- Mostly good agreement with the SM observed

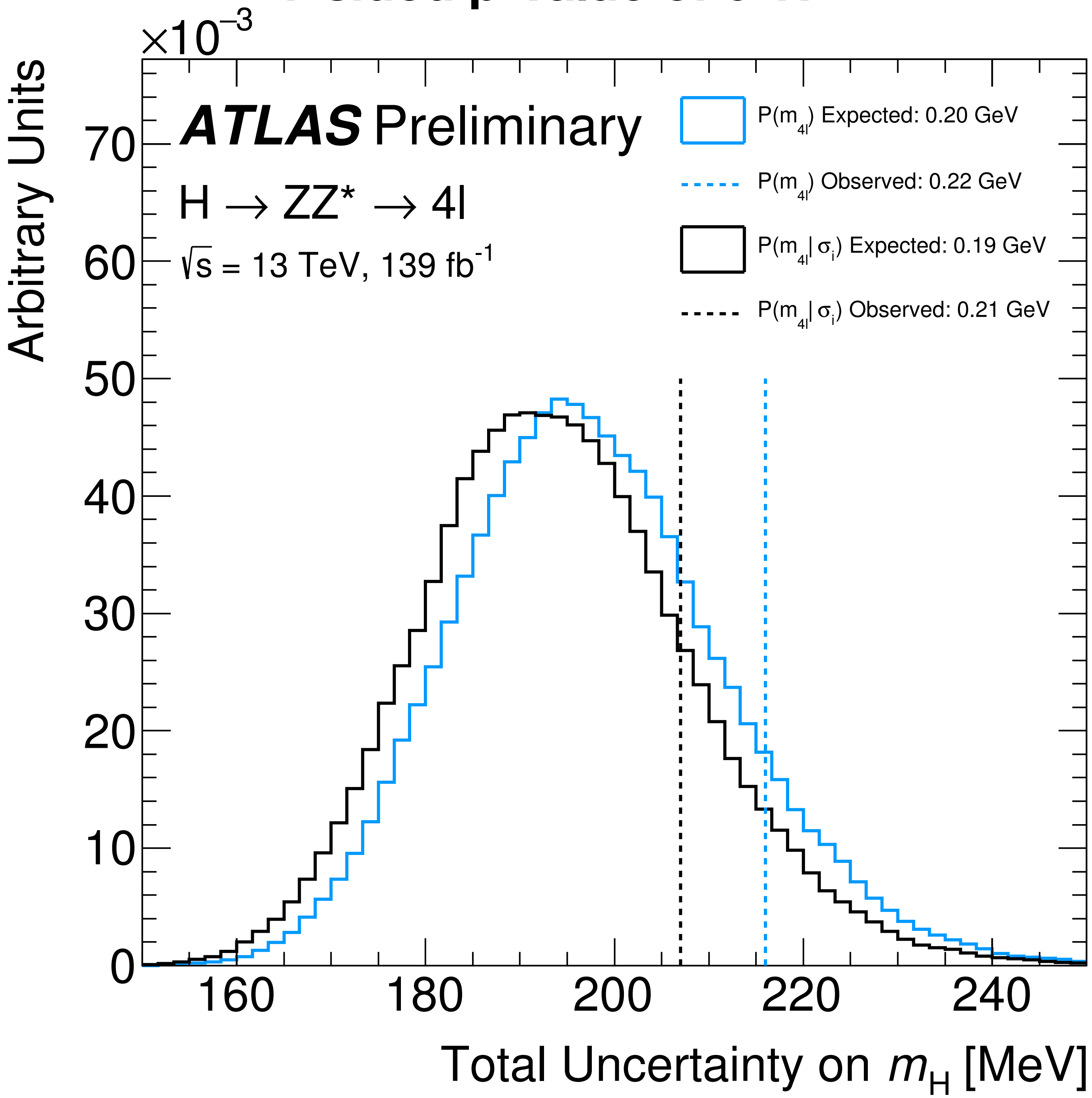
Summary

- Higgs decays to all-leptonic diboson final states provide valuable probes of its properties
- $H \rightarrow ZZ^* \rightarrow 4l$ can be used for precision measurements of the Higgs mass
- Both channels are used for couplings measurements in the STXS framework
- Final $H \rightarrow ZZ^* \rightarrow 4l$ results using Run-2 data are here
  - Though still room for more interpretations
- $H \rightarrow WW \rightarrow ll\nu\nu$ not yet exploiting the full dataset
- Stay tuned for more results!

Backup

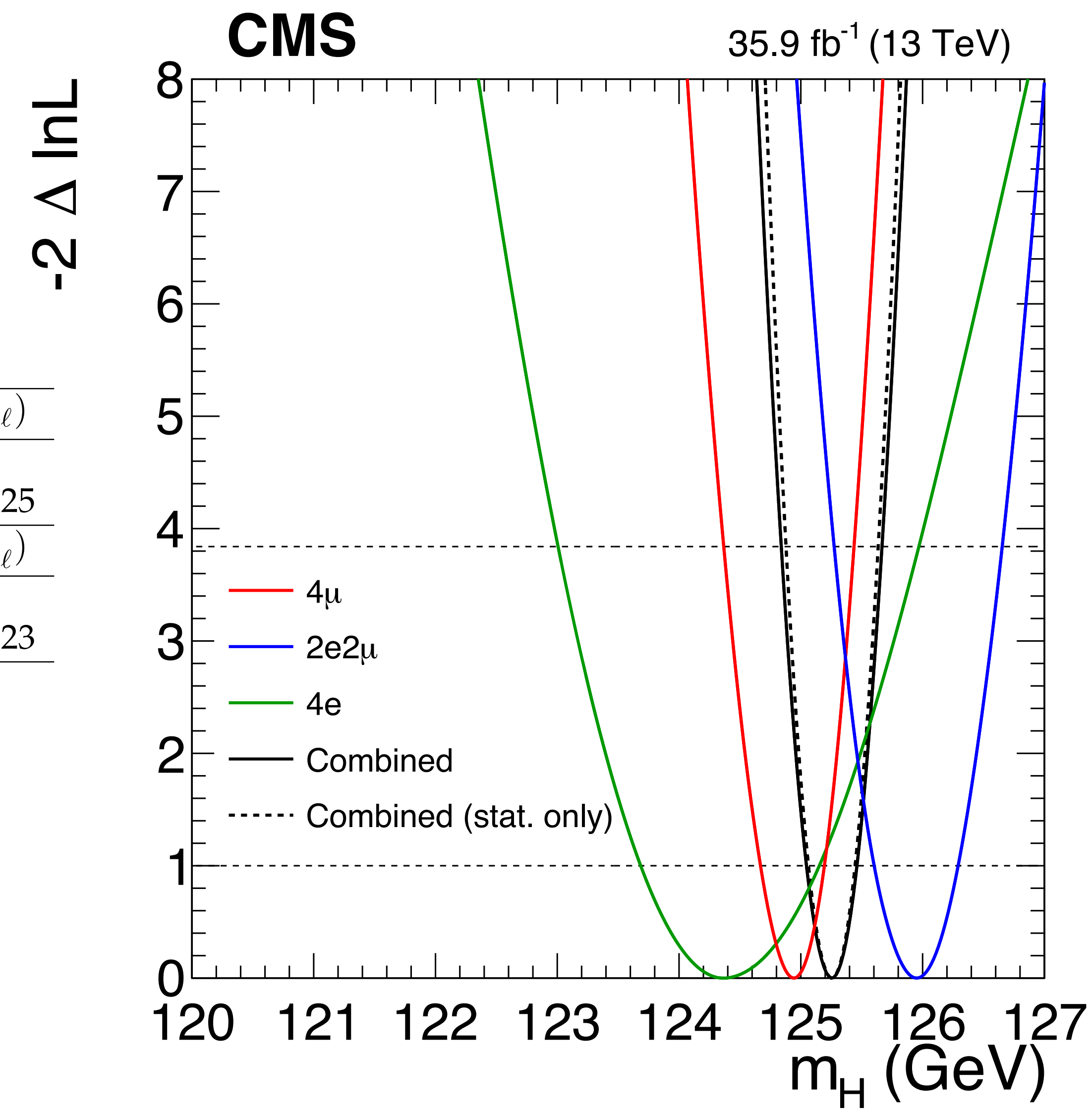
Expected vs. Measured m_H Uncertainty

1-sided p-value of 0.17



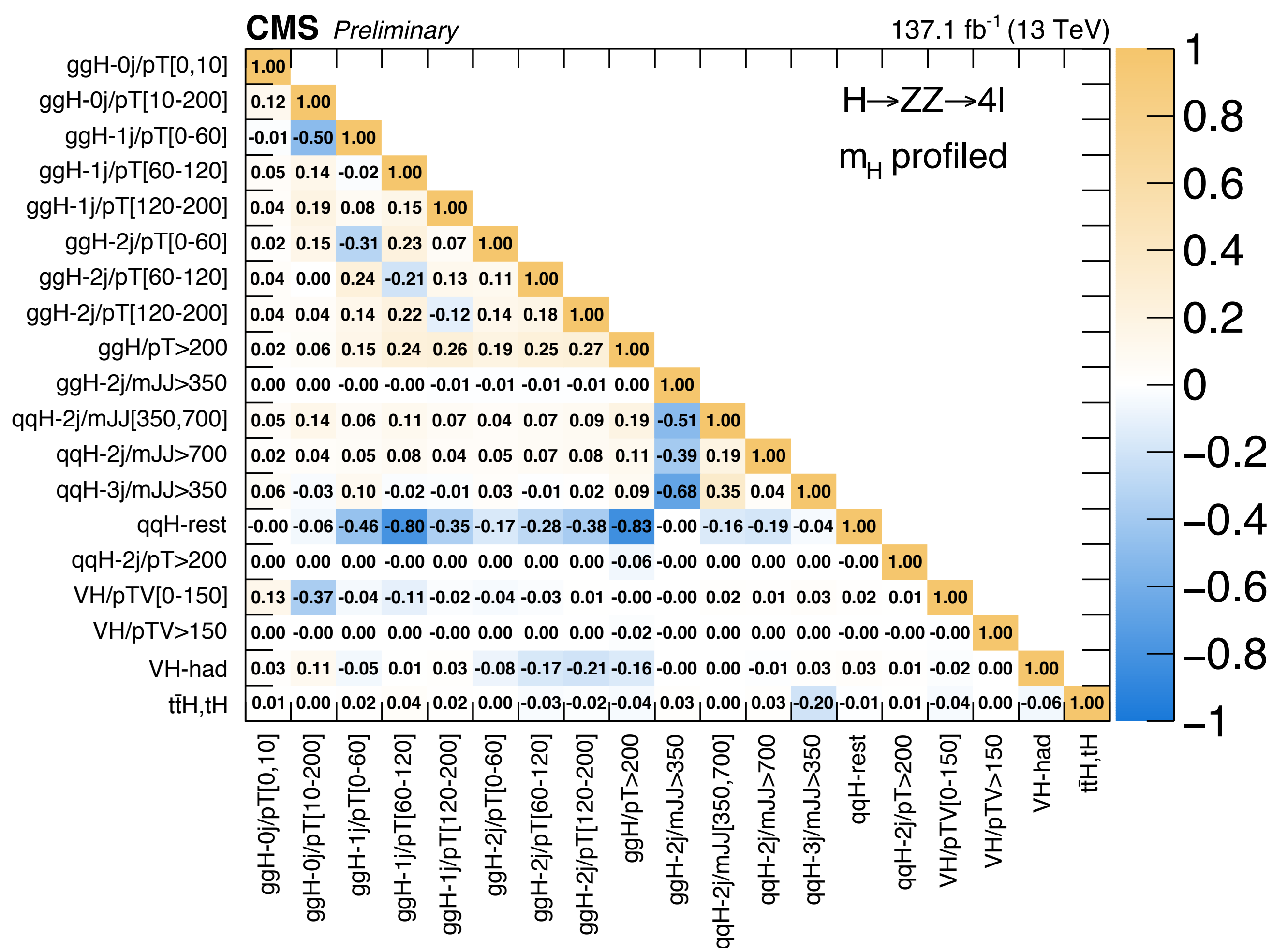
CMS 4l Mass Measurement

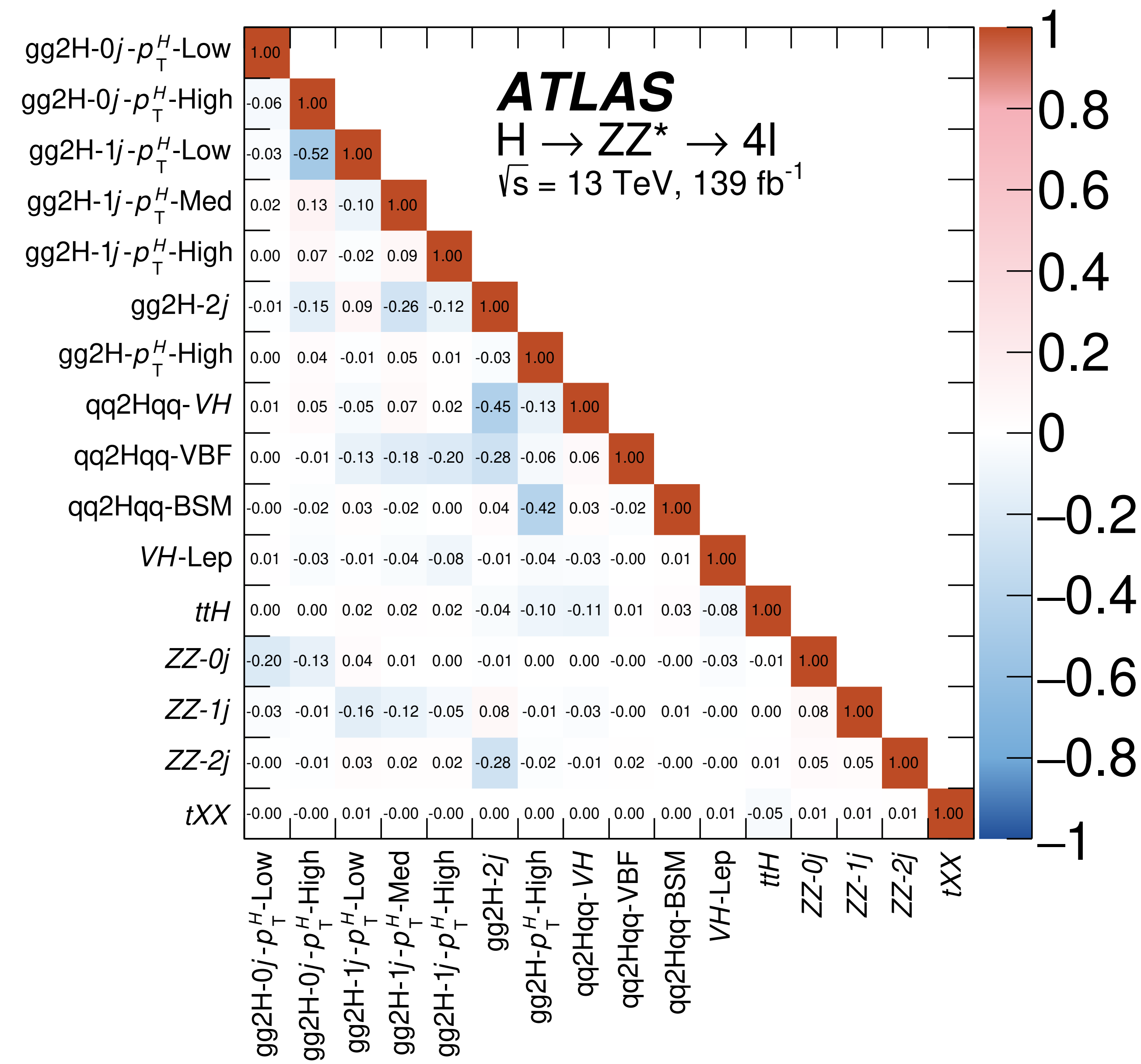
No $m(\mathrm{Z}_1)$ constraint	3D: $\mathcal{L}(m_{4\ell}, \mathcal{D}_{\mathrm{mass}}, \mathcal{D}_{\mathrm{bkg}}^{\mathrm{kin}})$	2D: $\mathcal{L}(m_{4\ell}, \mathcal{D}_{\mathrm{mass}})$	1D: $\mathcal{L}(m_{4\ell})$
Expected m_{H} uncertainty change	+8.1%	+11%	+21%
Observed m_{H} (GeV)	125.28±0.22	125.36±0.24	125.39±0.25
With $m(\mathrm{Z}_1)$ constraint	3D: $\mathcal{L}(m'_{4\ell}, \mathcal{D}'_{\mathrm{mass}}, \mathcal{D}_{\mathrm{bkg}}^{\mathrm{kin}})$	2D: $\mathcal{L}(m'_{4\ell}, \mathcal{D}'_{\mathrm{mass}})$	1D: $\mathcal{L}(m'_{4\ell})$
Expected m_{H} uncertainty change	—	+3.2%	+11%
Observed m_{H} (GeV)	$\boxed{125.26\pm0.21}$	125.30±0.21	125.34±0.23



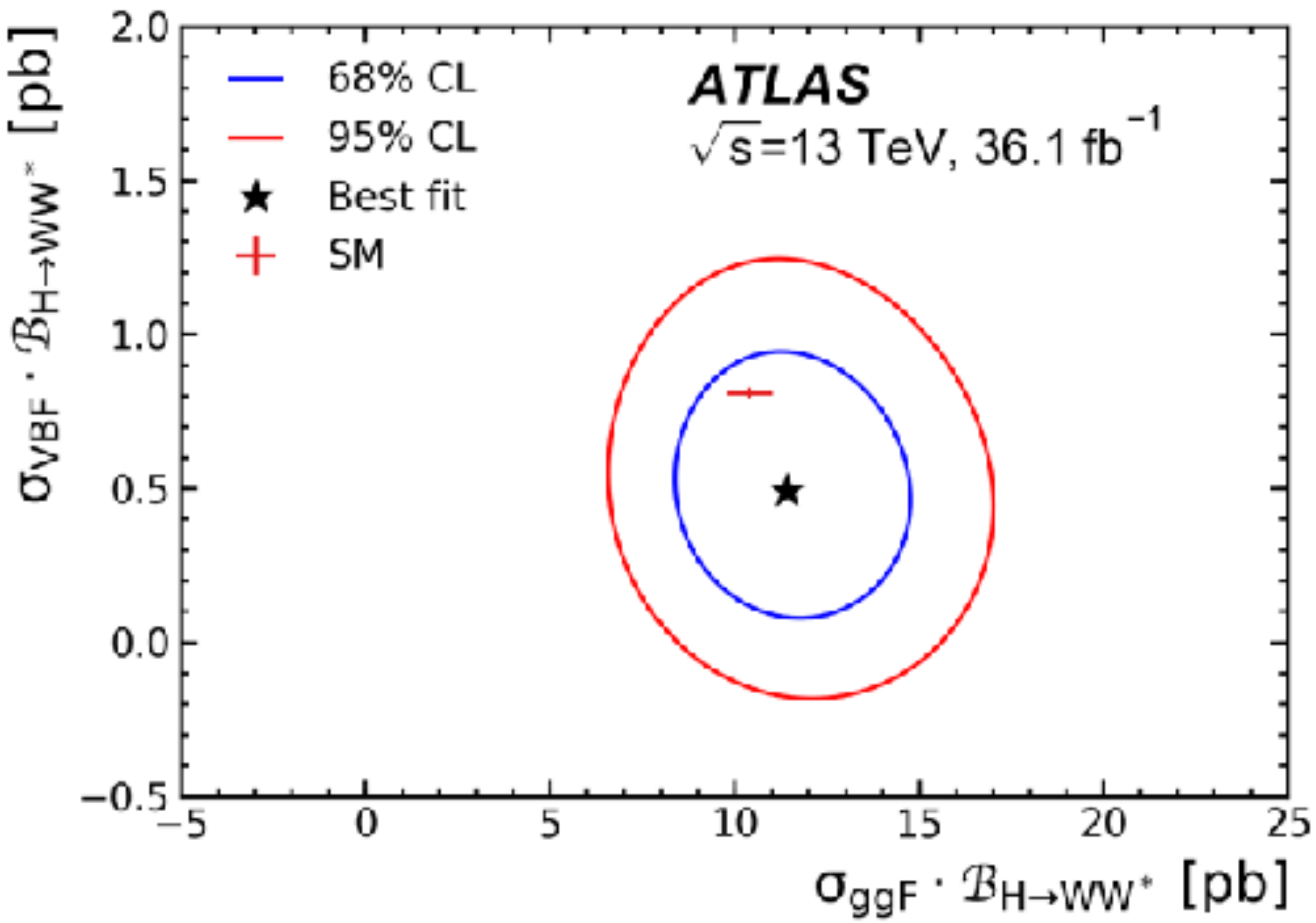
- 3D likelihood includes mass, mass resolution, kinematic discriminant
    - Discriminant to separate signal and background
    - Final result uses mass and resolution with Z-mass constraint applied to leading lepton pair

STXS Correlation Matrices





ATLAS H→WW Measurements



arXiv:2004.03447

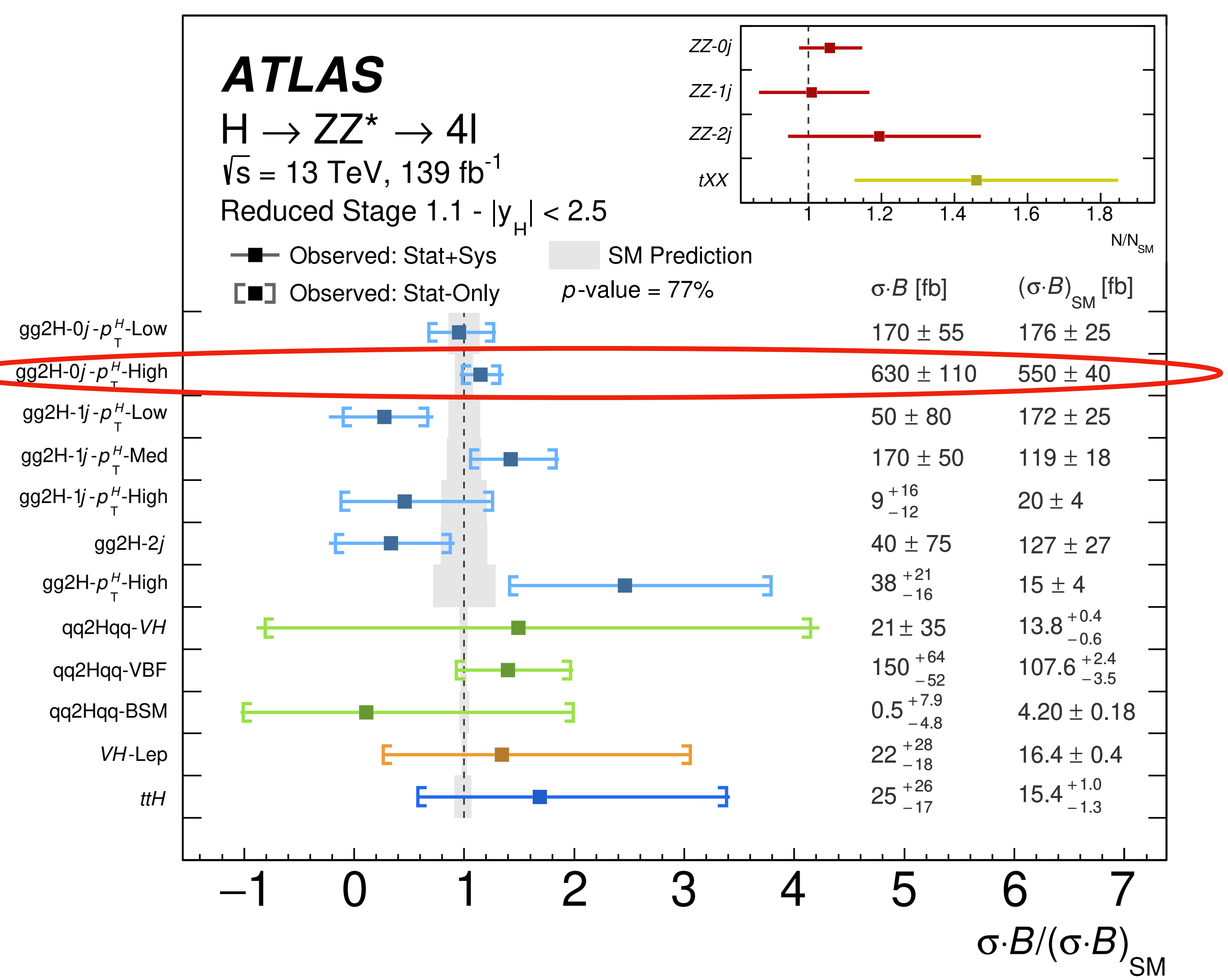
Effective Field Theory Interpretations

$$\mathcal{L} = \mathcal{L}^{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{d=6} + (\text{dim } > 6)$$

- Add new physics to the Lagrangian without committing to specific model
- Wilson coefficients for generic interactions

$O_{HG} \sim c_{HG}\, HH^\dagger G^A_{\mu\nu} G^{\mu\nu A}$ CP-even interaction between Higgs and gluons

ggH STXS: split by N_{jets} and p_T^H



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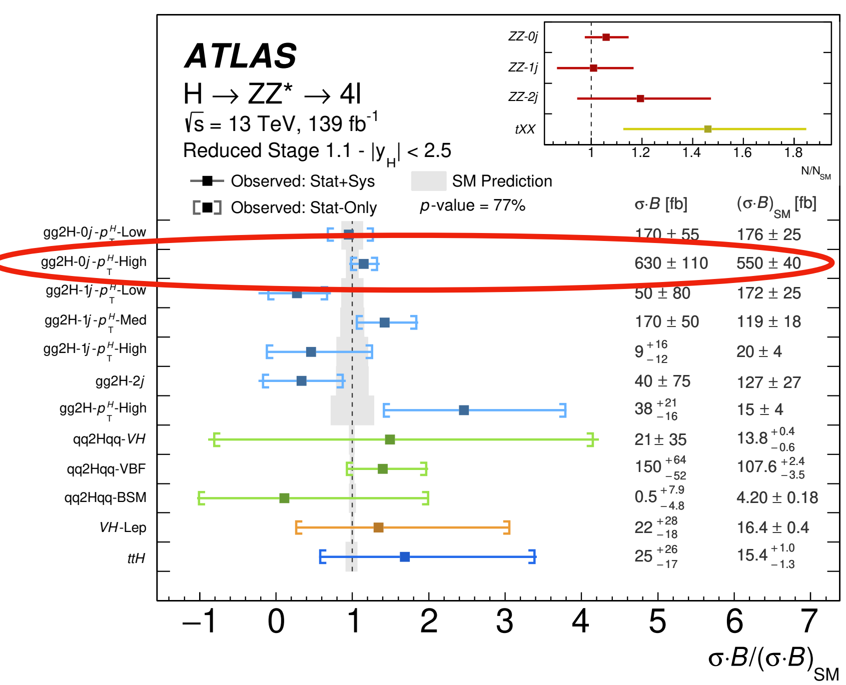

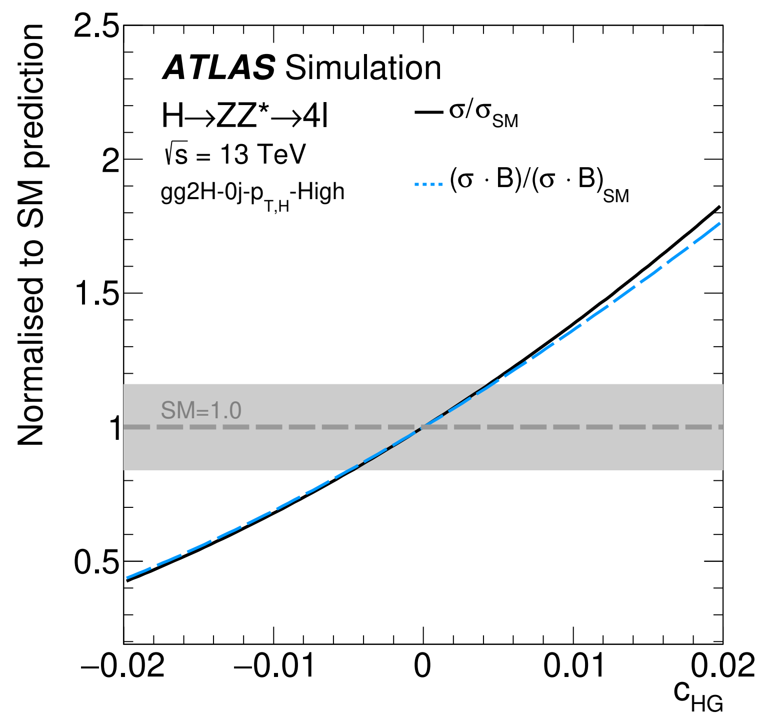

- Add new physics to the Lagrangian without committing to specific model
- Wilson coefficients for generic interactions
- Parametrize predictions in STXS bins
    - Include effects on cross sections, branching fractions, in some cases acceptances

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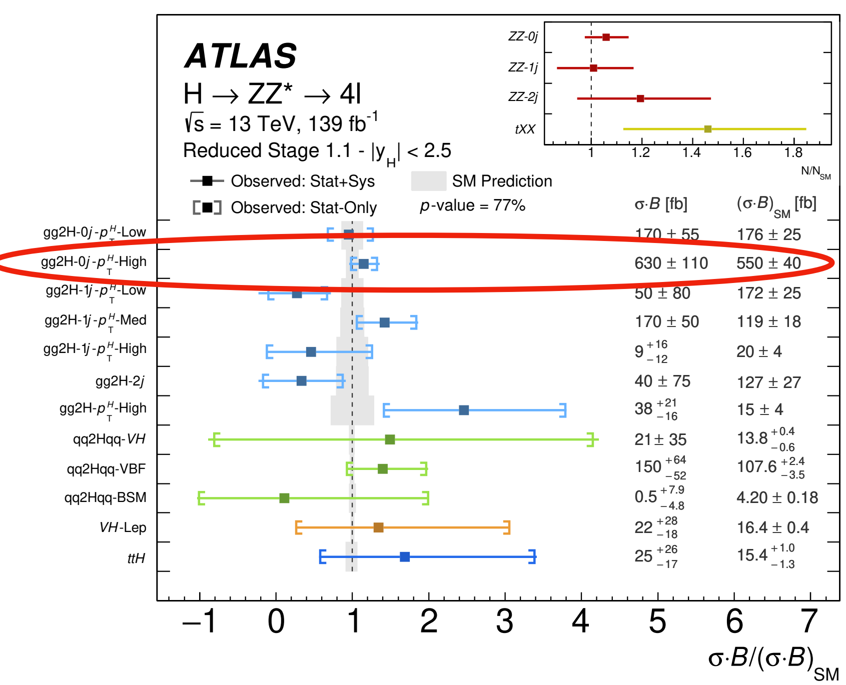

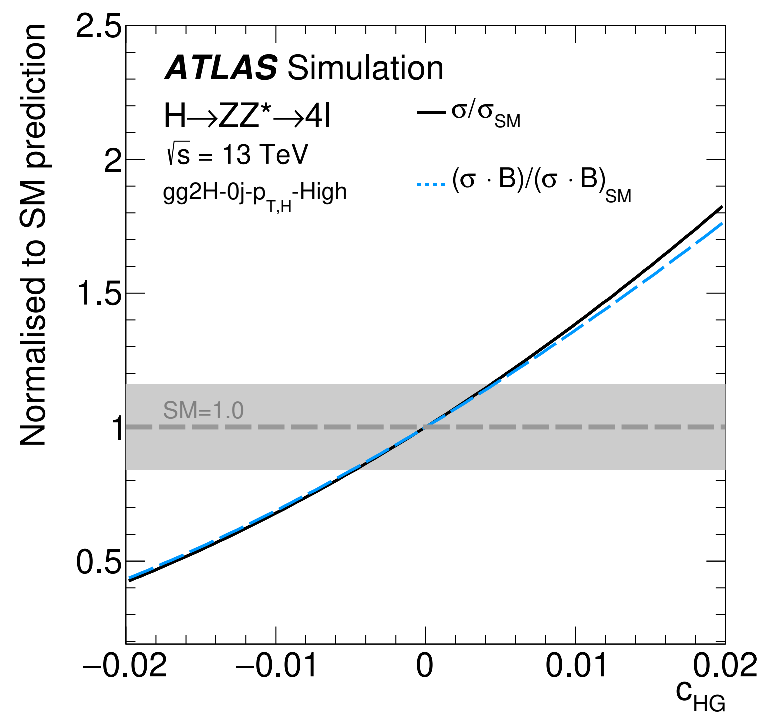

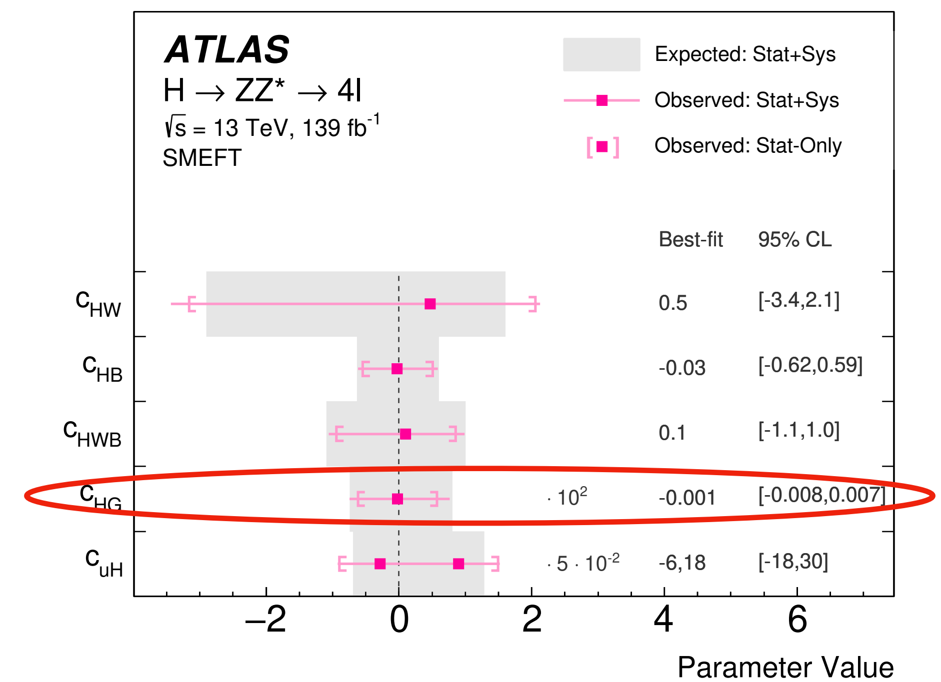

- Fit to STXS results to constrain values of Wilson coefficients
- Best-fit values are all consistent with 0

CP-Odd Wilson Coefficients