Higgs Simplified Template and Differential Cross Sections

MoriondEW2021

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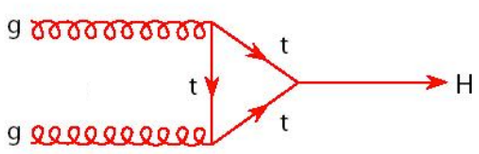
On behalf of
the ATLAS and CMS Collaborations

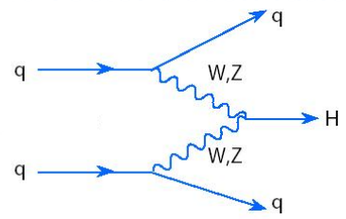
Overview

- The discovery of the Higgs boson has opened the door to a wealth of phenomenology available for study
  - Higgs couples directly to all massive particles
  - Variety of production / decay modes within reach at the LHC
- All leading Higgs production modes have by now been observed (some in multiple decay channels)

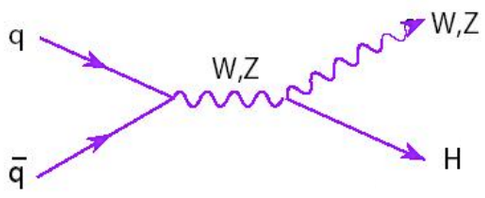
~88% Gluon fusion (ggF)



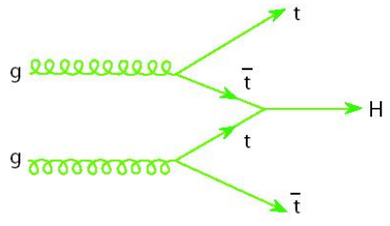
~7% Vector-boson-fusion (VBF)

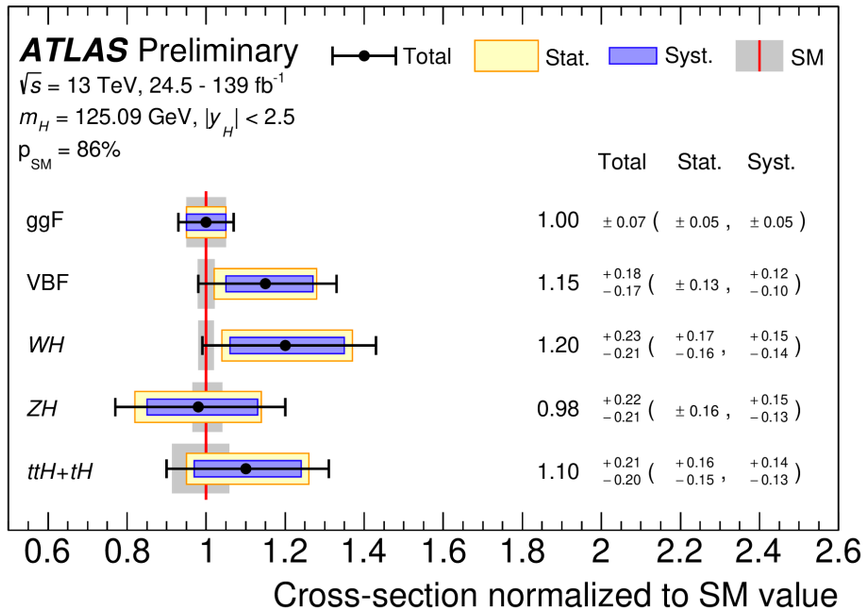


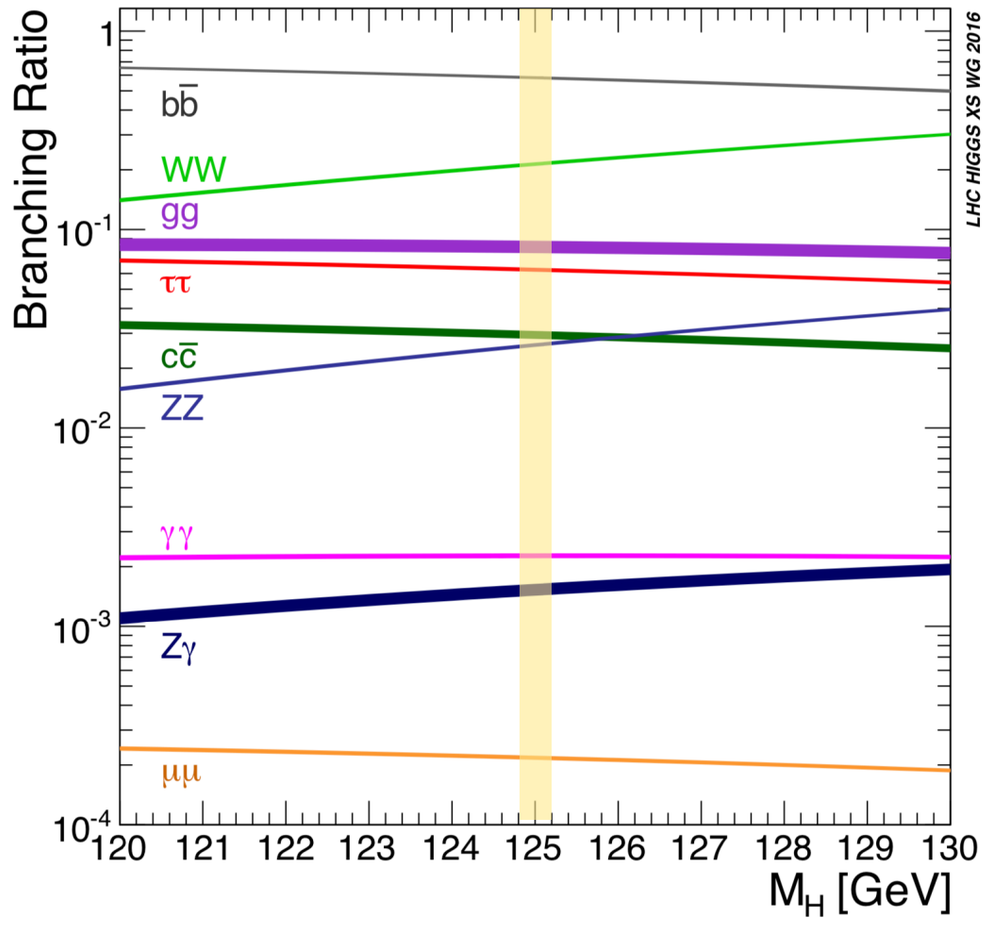
~4% Higgs-Strahlung (VH)



~1% Association with $t\bar{t}$ (ttH)



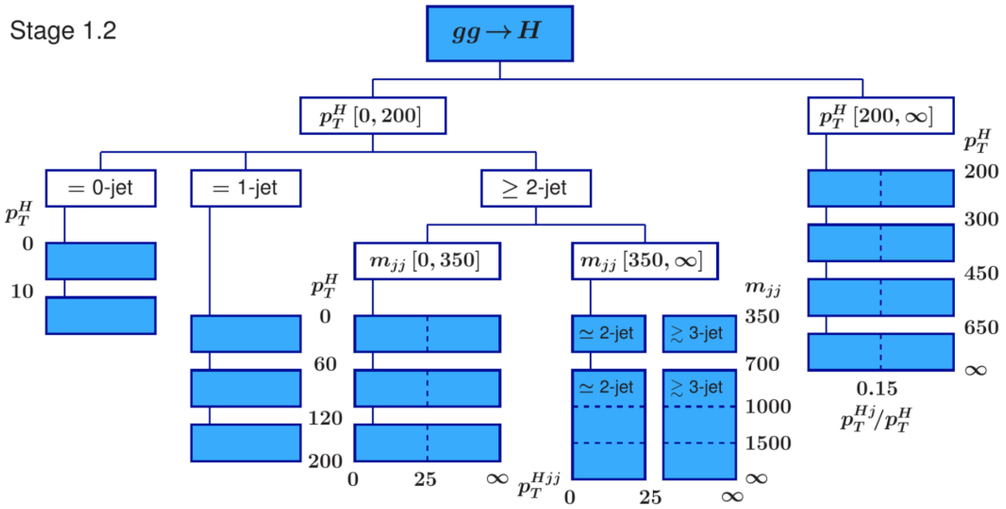




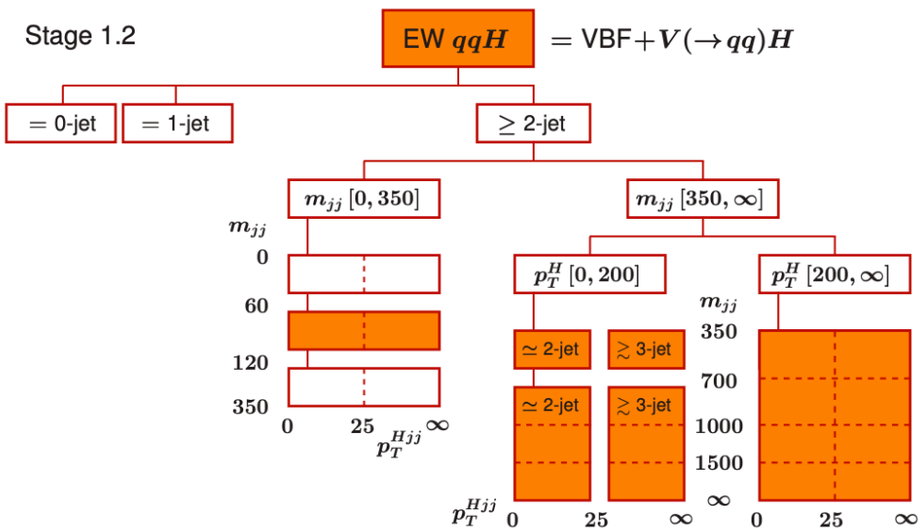
- One pathway to further scrutinise the Higgs is to perform cross section measurements within multiple phase space regions
- Two complementary approaches are being explored and the latest results are presented in this talk
  - Simplified template cross sections
  - Differential cross sections

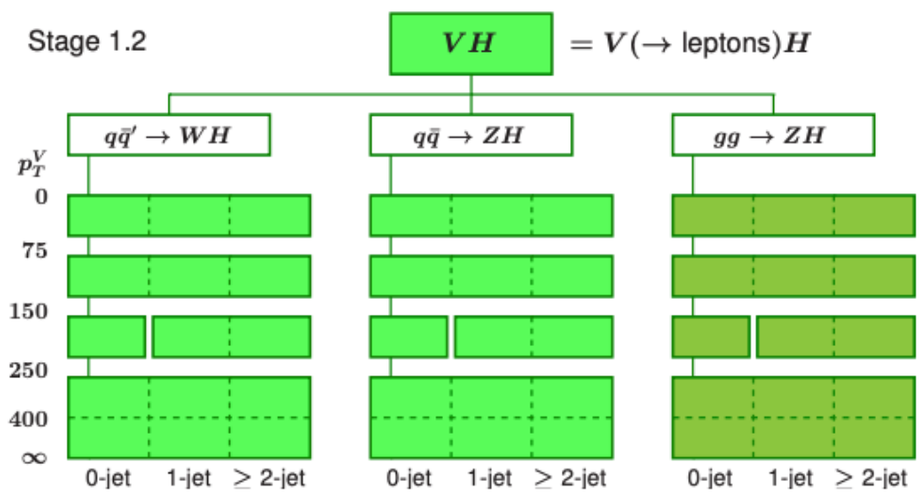
Simplified Template Cross Sections (STXS)

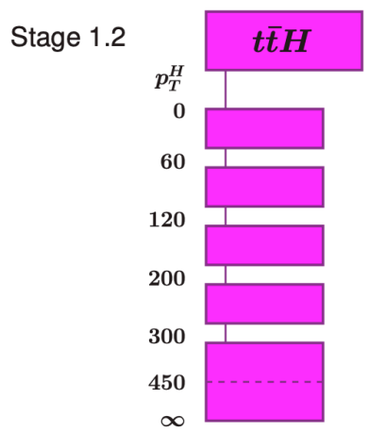
- Measure production modes separately, categorising each into bins of key (truth) quantities (p_T^H, N_{jets}, m_{jj})
  - Chosen as most sensitive variables for theory predictions / signal sensitivity / new physics
  - Framework provided in different stages (e.g. stage 0, stage 1, stage 1.2) with varying degrees of granularity
  - Decay mode agnostic: well-suited for combinations



- Degrees of freedom on analysis design:
  - How are events categorised into the bins?
    -> Reconstructed quantities as proxy for truth quantities or multivariate classifier
  - How many / which bins to target?
    -> Driven by analysis sensitivity

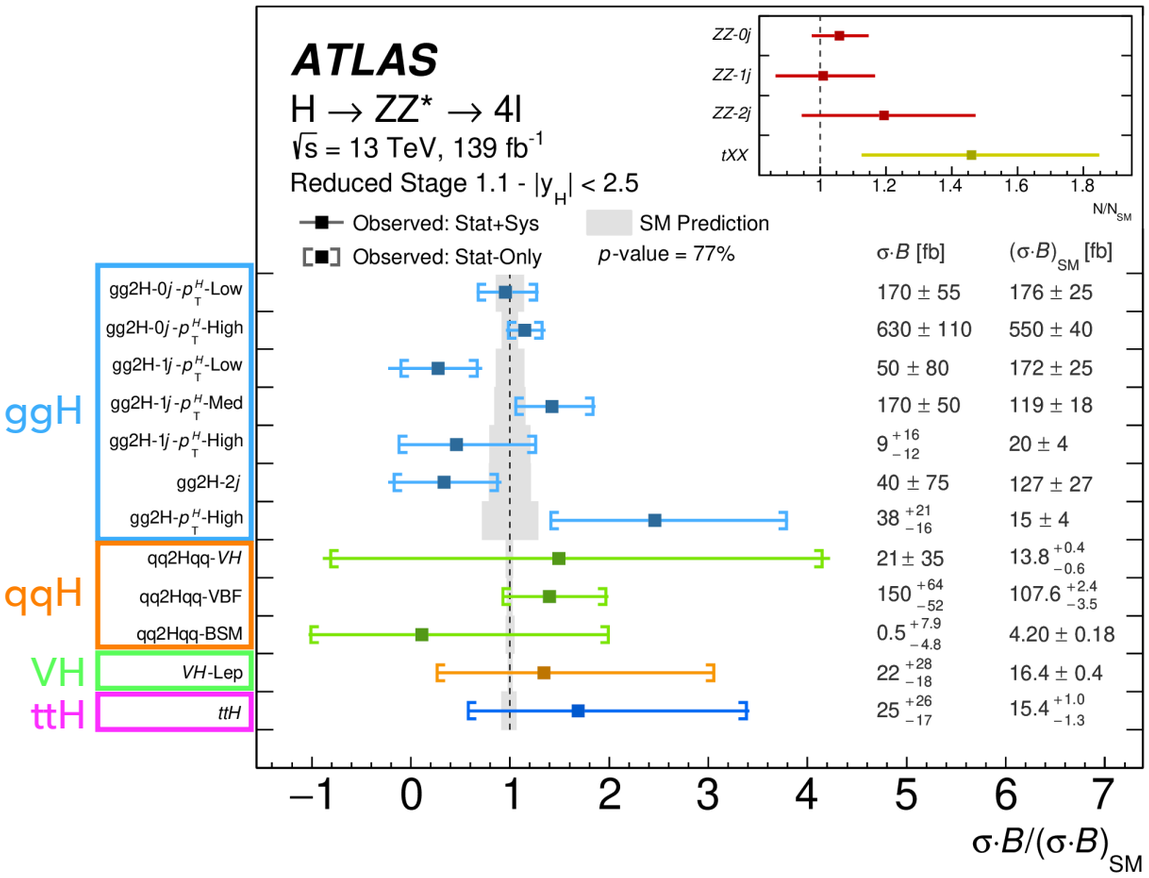




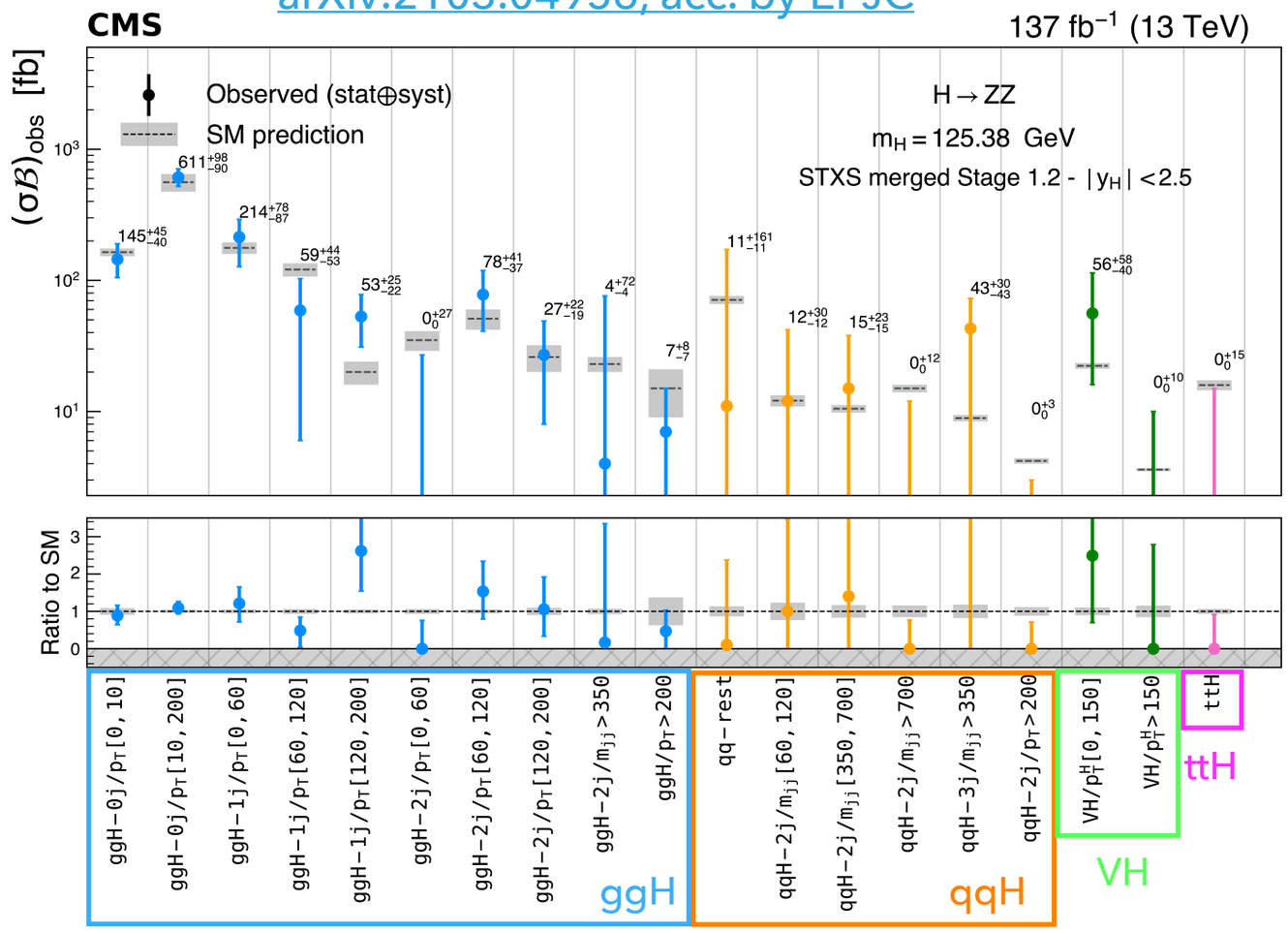


H->ZZ*->4l: STXS

arXiv:2004.03447, acc. by EPJC



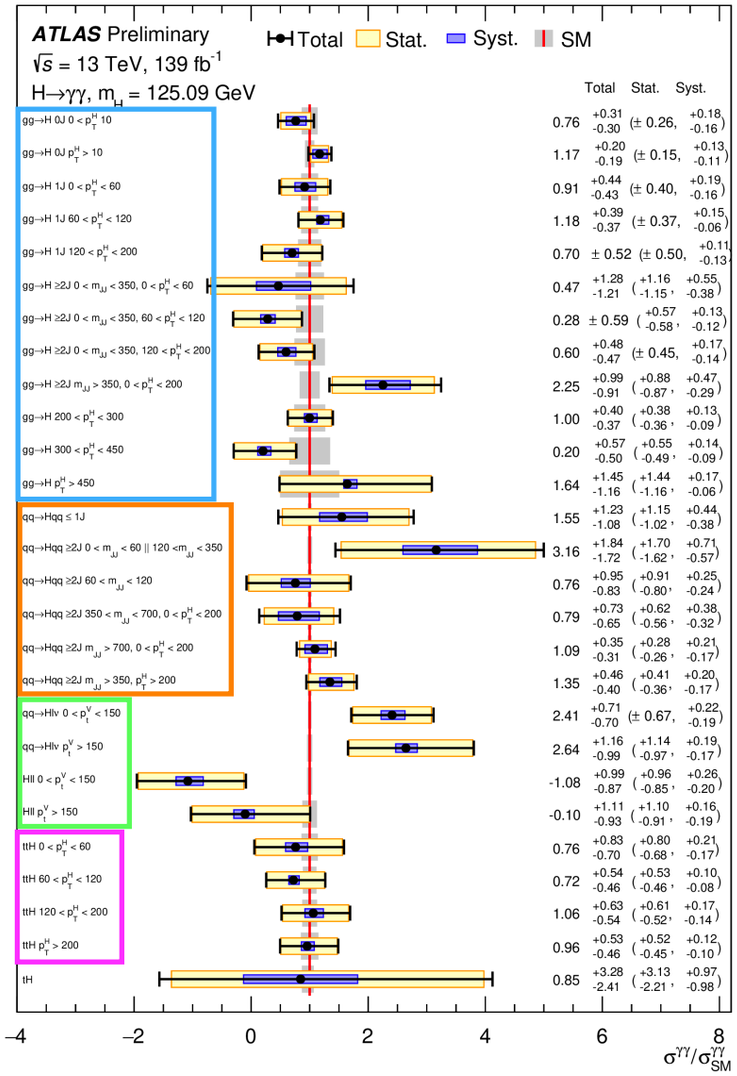
arXiv:2103.04956, acc. by EPJC

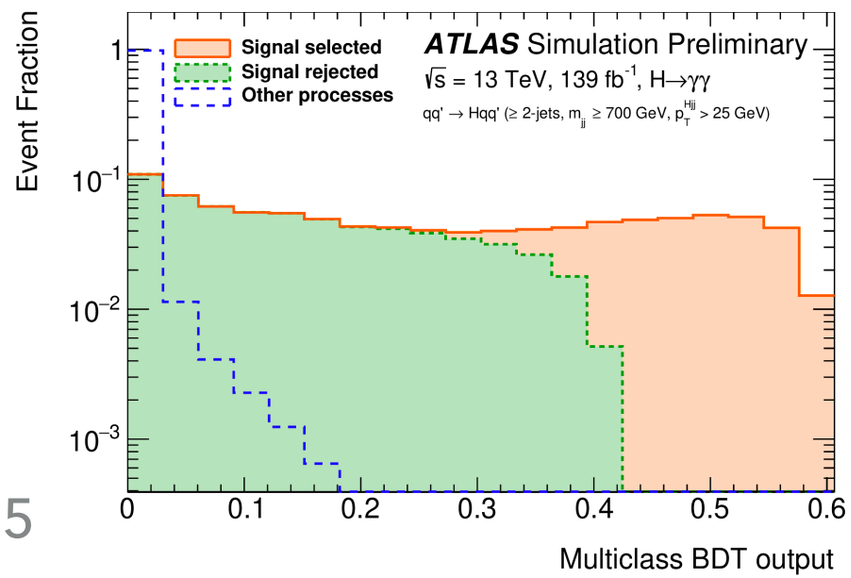


- ZZ*->4l decay mode provides a relatively high S/B and clean signature with fully reconstructed final state
  - -> Excellent resolution, great for more granular measurements of Higgs production
- Several bins measured for ggH and qqH, despite few statistics (low BR)
- Both analyses utilise NN-based categorisation either to define the categories (CMS) or as observable for fit (ATLAS)
- Good agreement with SM predictions (within large stat. uncertainty)

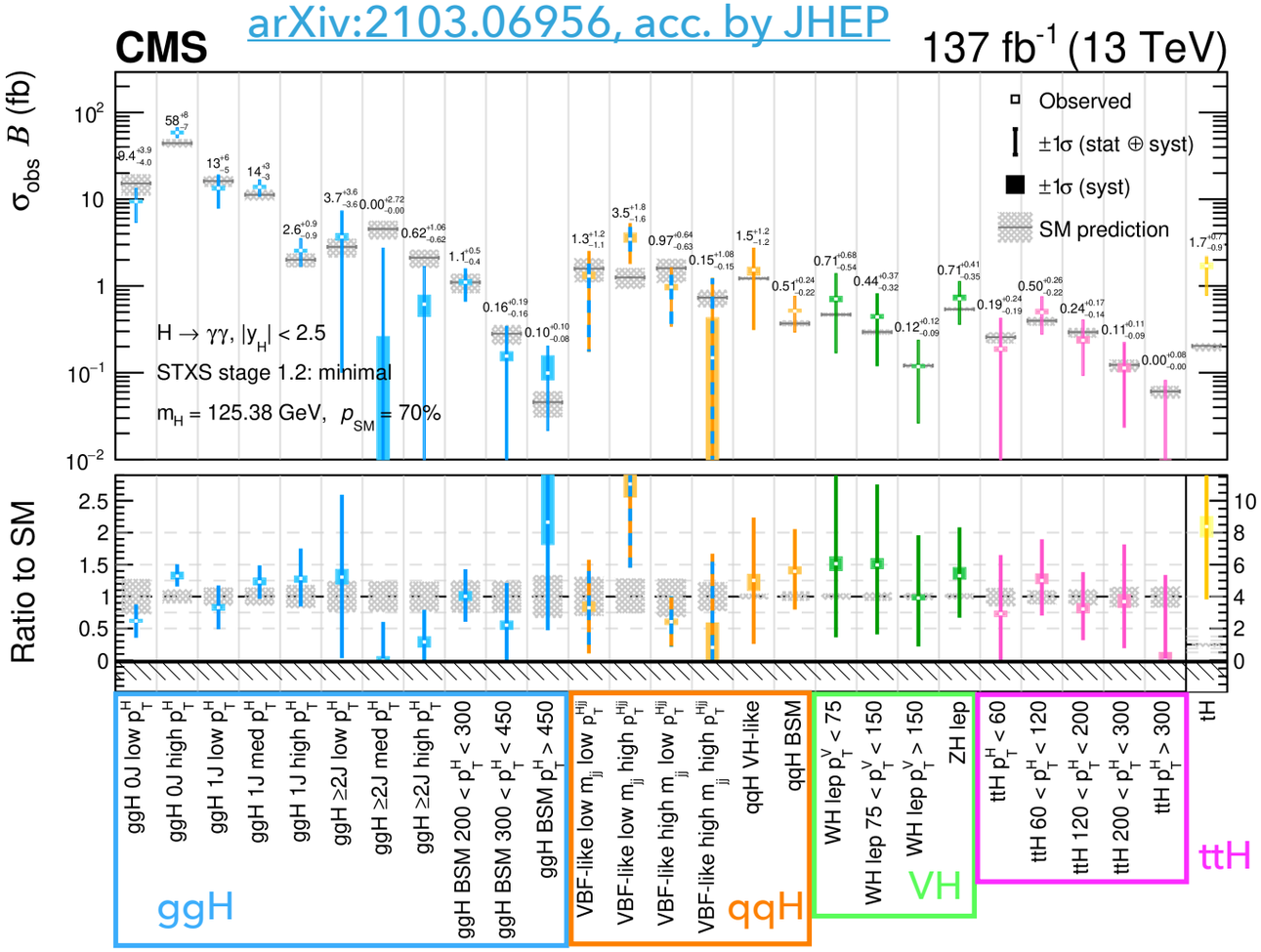
H->γγ: STXS

ATLAS-CONF-2020-026





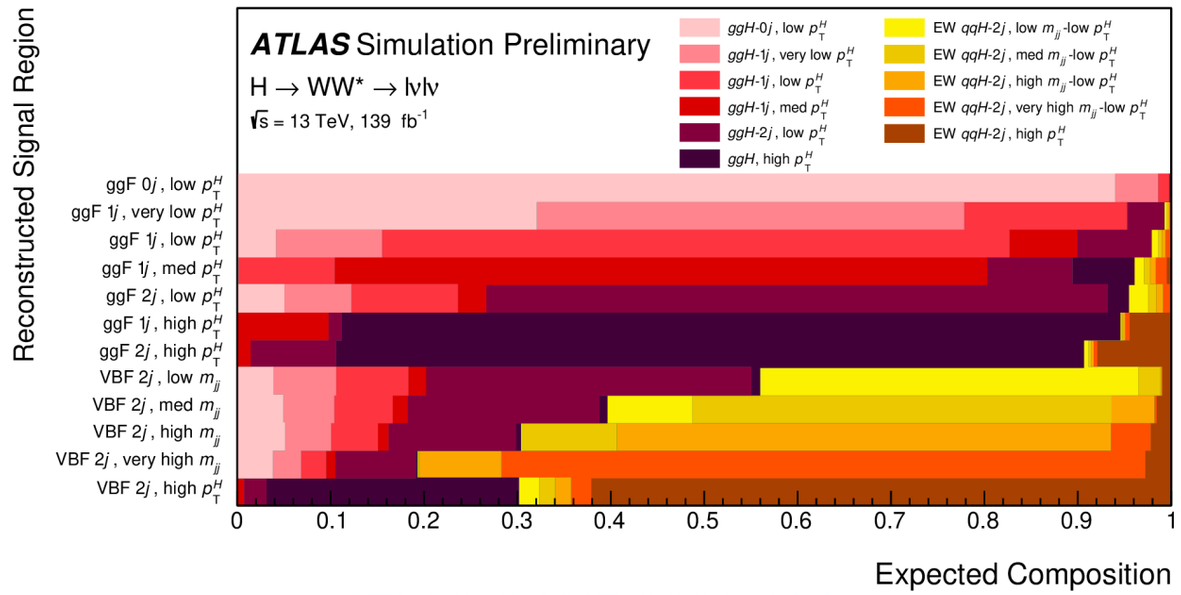
arXiv:2103.06956, acc. by JHEP



- More stats -> finer splitting, particularly for non-ggH production modes
  - First channel to perform ttH measurement differentially
- Event categorisation:
  - ATLAS - multiclass BDT targeting 44 STXS categories
  - CMS - mixture of multiclass BDT (ggH) and reco variables (other)
  - Multiclass BDT reduces correlations between measured parameters
- Dominated by stat. uncertainty due to fine splitting but overall compatible with SM predictions

H->WW*: STXS

- Targeting ggH+qqH STXS bins
  - WW* decay offers additional sensitivity due to relatively higher branching ratio compared with ZZ* / $\gamma\gamma$ channels
  - qqH-2j m_{jj} > 1500 GeV, p_T^H < 200 GeV measured with uncertainty below 40%!
- ggH uncertainties limited by both stat. + syst.
- qqH uncertainties limited by stat. at high m_{jj} / p_T^H
- Fit variables: m_T (ggH) and DNN (qqH)



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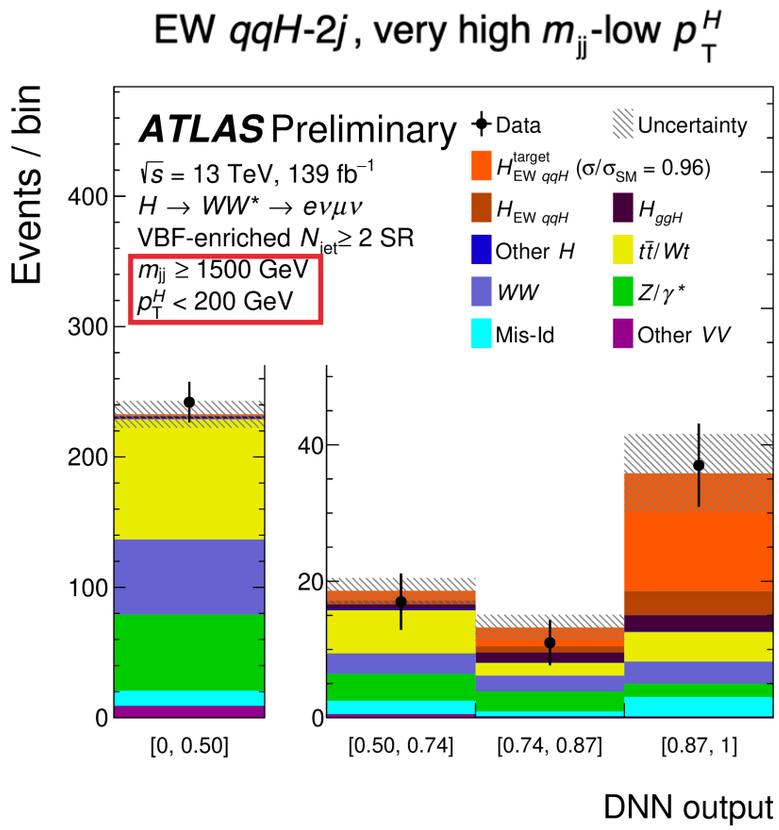
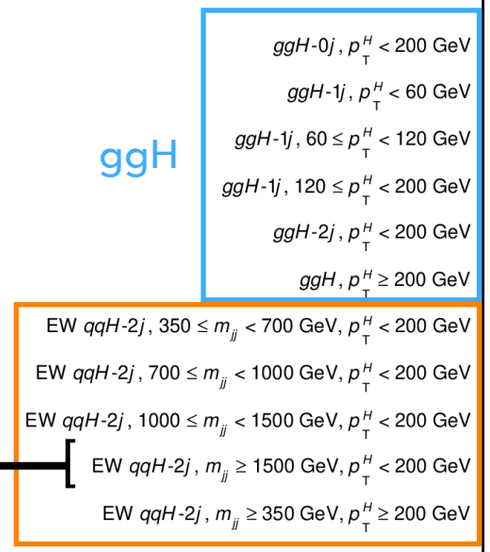
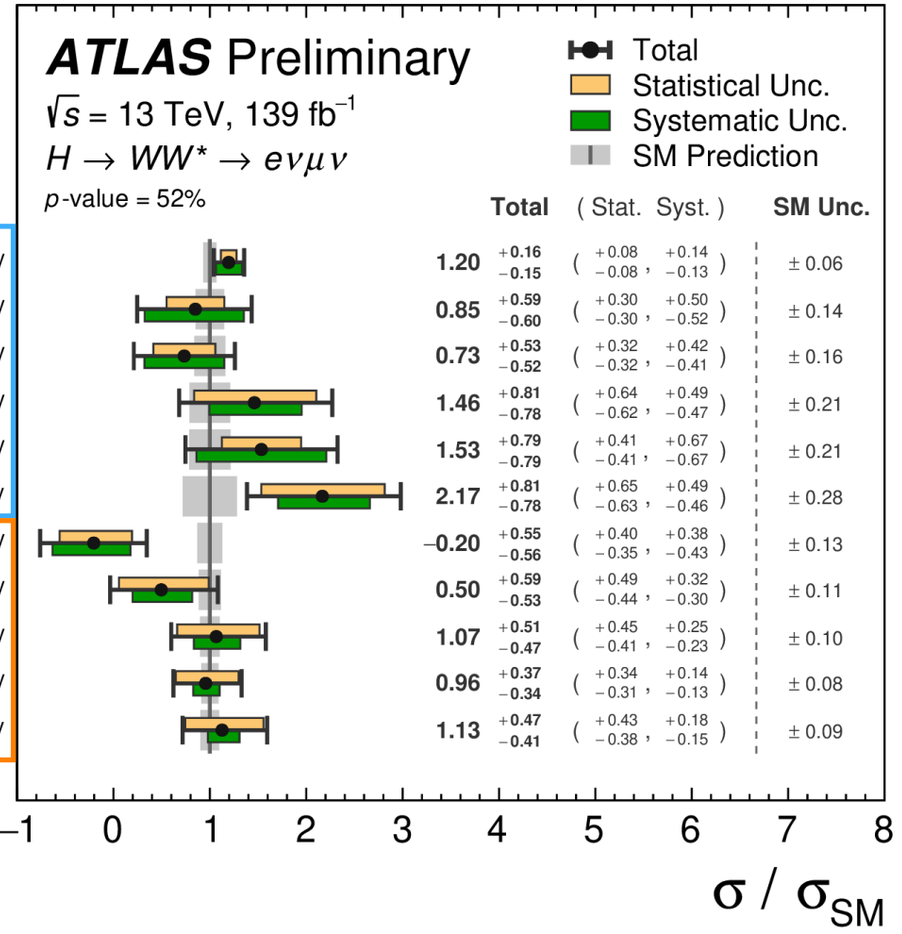
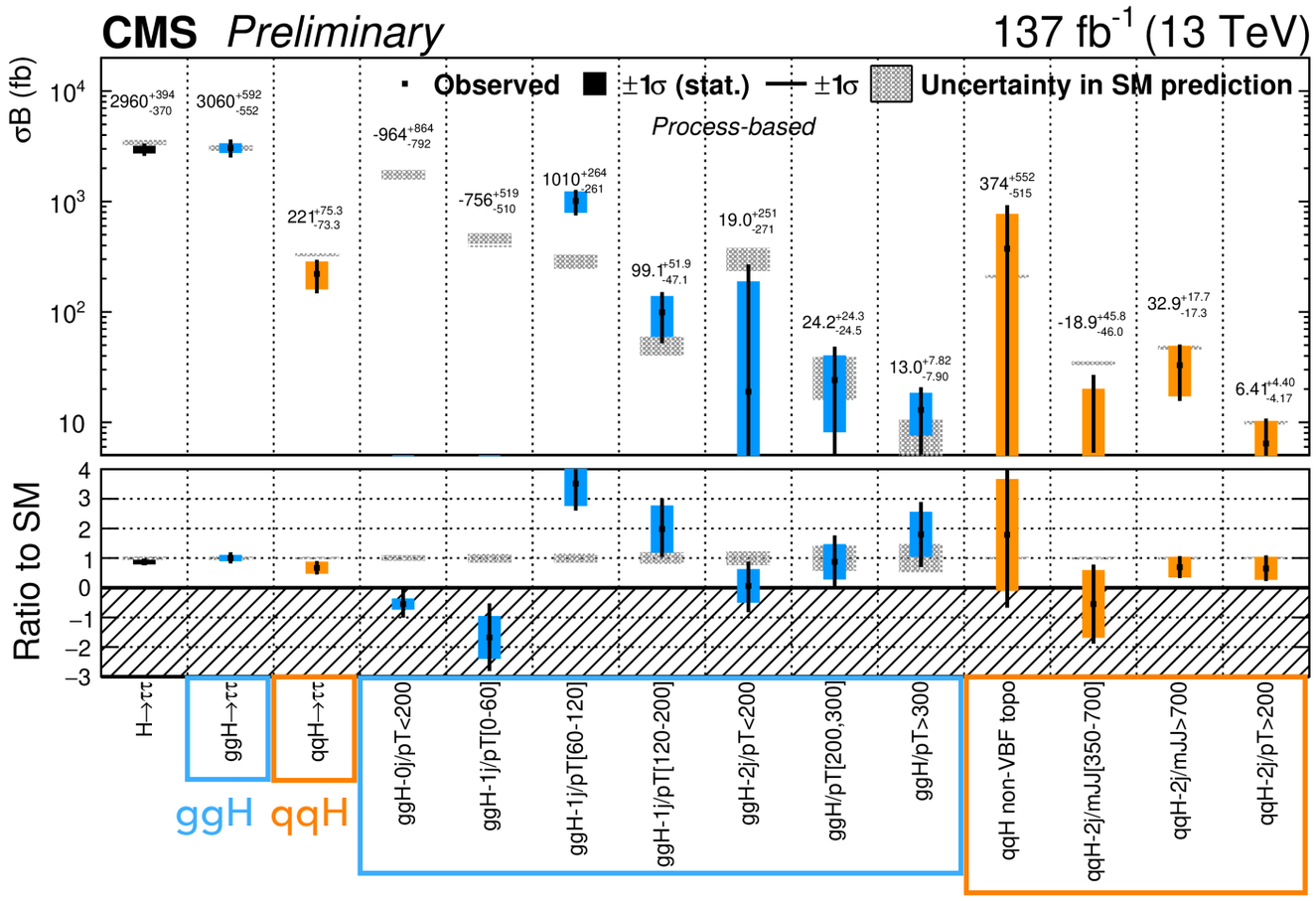
-> See talk by Ralf Gugel



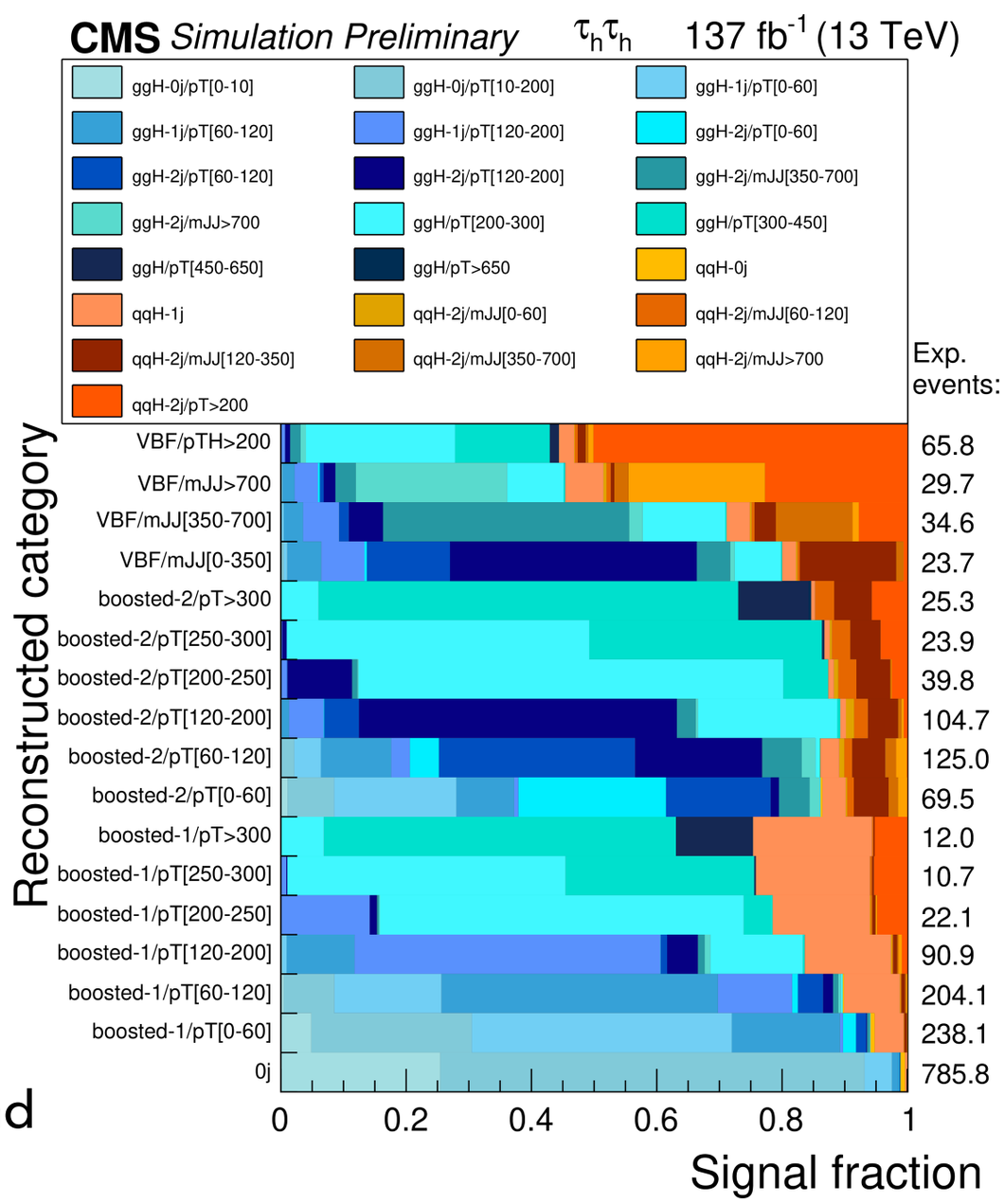




H->ττ: STXS



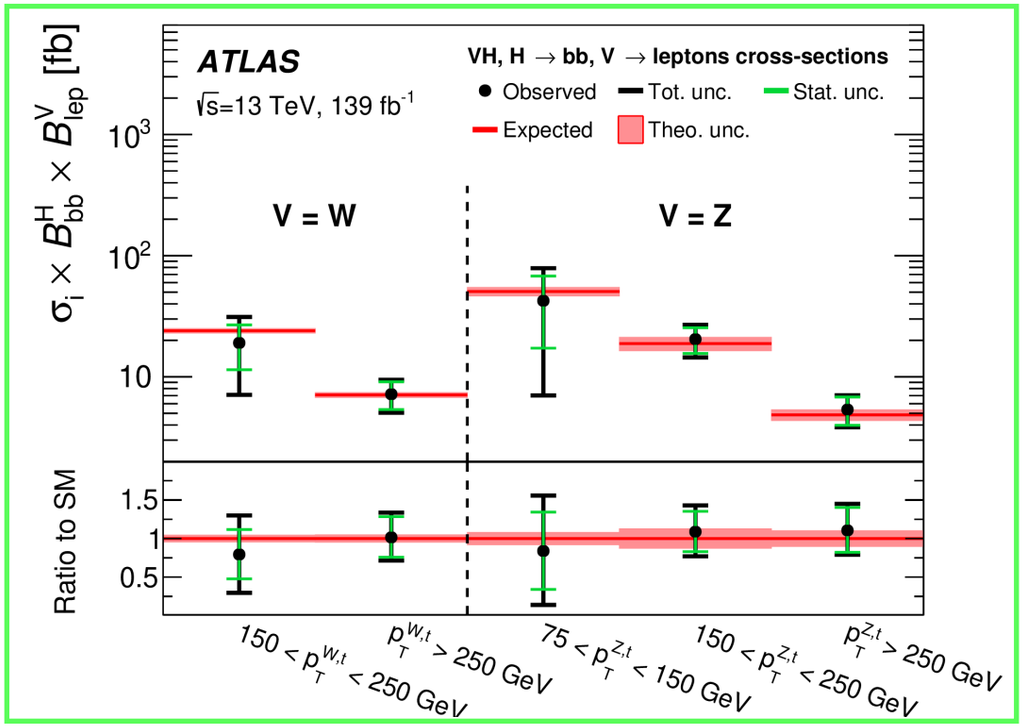
CMS-PAS-HIG-19-010

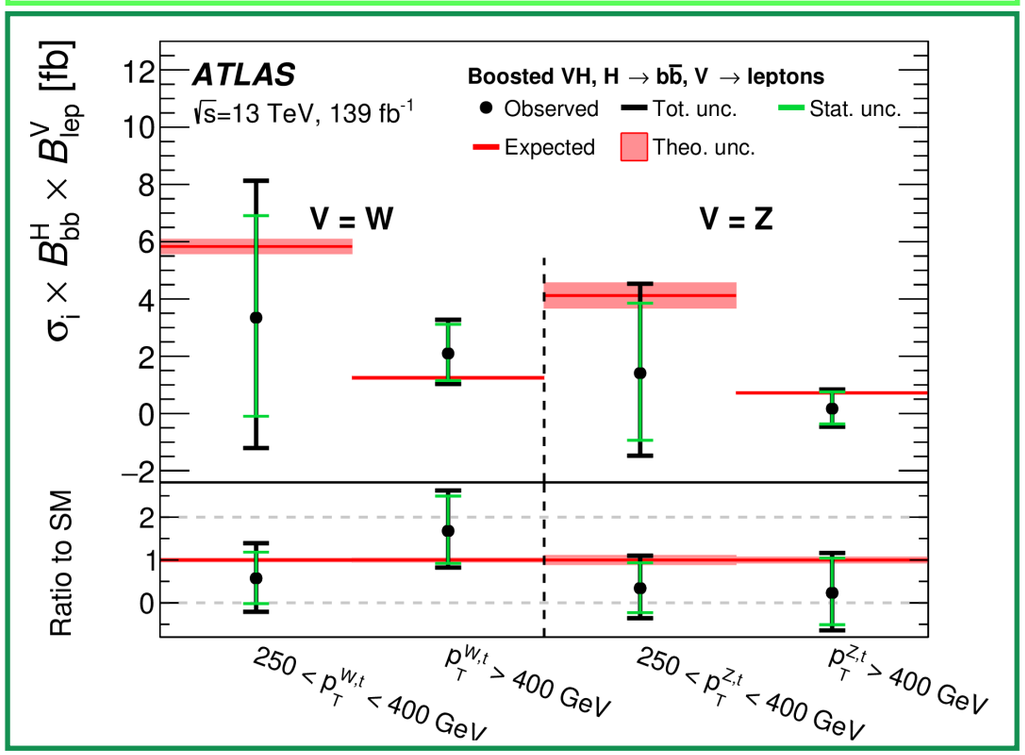


- Targeting ggH+qqH production modes
  - Particularly sensitive to ggH high p_T and to VBF topology
- Tau embedding for precise estimate of Z background
- 2D fit in each category: $m_{\tau\tau}$ and observable discriminating STXS process (e.g. p_T^H for ggH and m_{jj} for qqH)
- Results compatible with SM prediction within uncertainties

H->bb: STXS

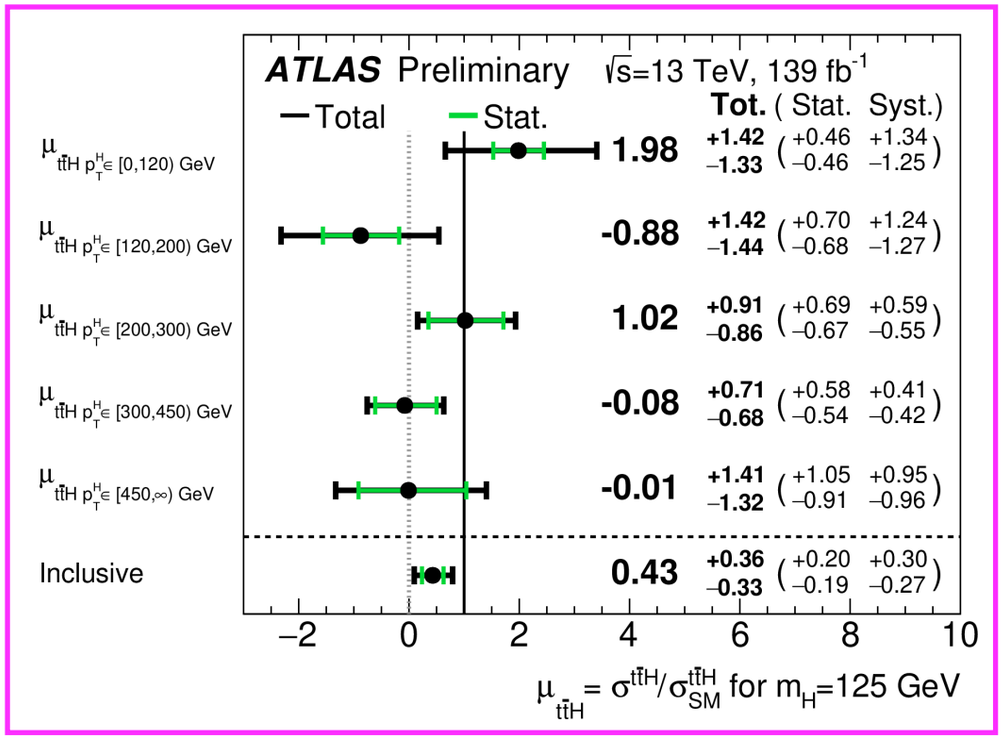
arXiv:2007.02873, acc. by EPJC





arXiv:2008.02508, acc. by Phys. Lett. B

- VH (resolved)
  - bb pair reconstructed as two separate jets
  - Single STXS bin for p_T^V > 250 GeV
  - Stat. limited at high p_T^V
- VH (boosted)
  - bb pair reconstructed as a single large-radius jet
  - Allows probing phase space p_T^V > 400 GeV
  - Dominated by statistical uncertainty
- ttH
  - First differential measurement of ttH production in H->bb
  - Compatible with SM prediction within large uncertainties



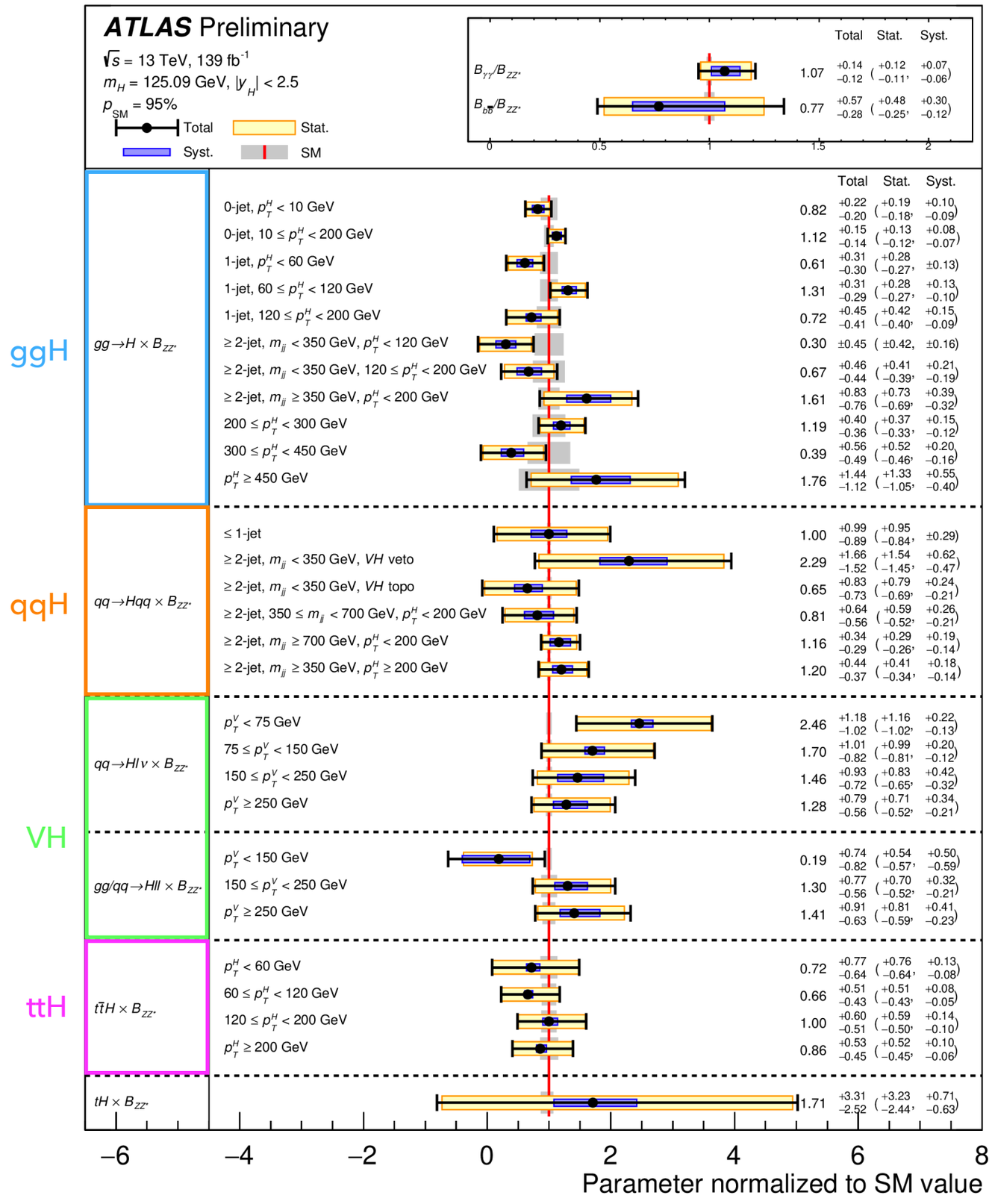
ATLAS-CONF-2020-058

STXS Combination

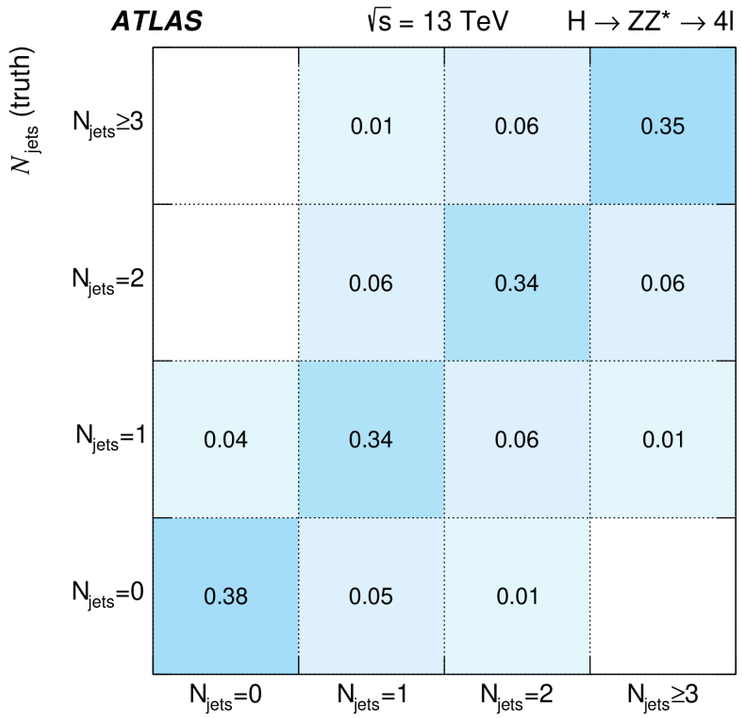
- Includes full Run 2 results from H->ZZ, H->γγ, VH(bb)
  - Further single channel results have more recently become available
- BR relative to H->ZZ channel:
  - 12% unc. on $BR_{\gamma\gamma}/BR_{ZZ}$
  - ~30% unc. on BR_{bb}/BR_{ZZ}
- 29 STXS bins measured
  - Uncertainty between 15% - 100% for most bins
  - Statistical uncertainties dominate
  - tH < 8.2*SM @ 95% CL
  - **Good agreement with SM predictions**

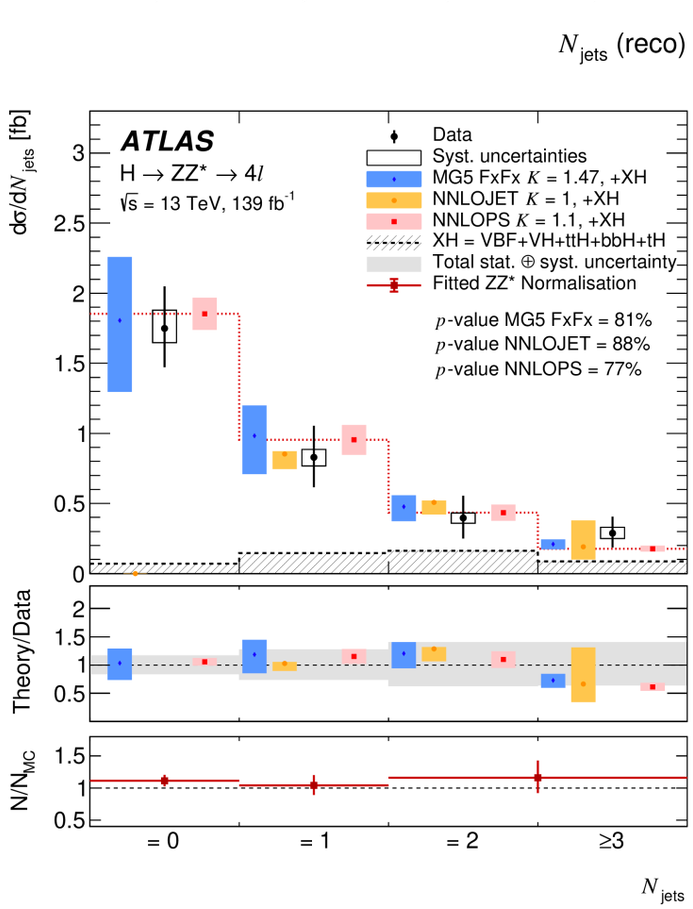
    p_{SM} = 95%

ATLAS-CONF-2020-027



Differential and Fiducial Cross Sections

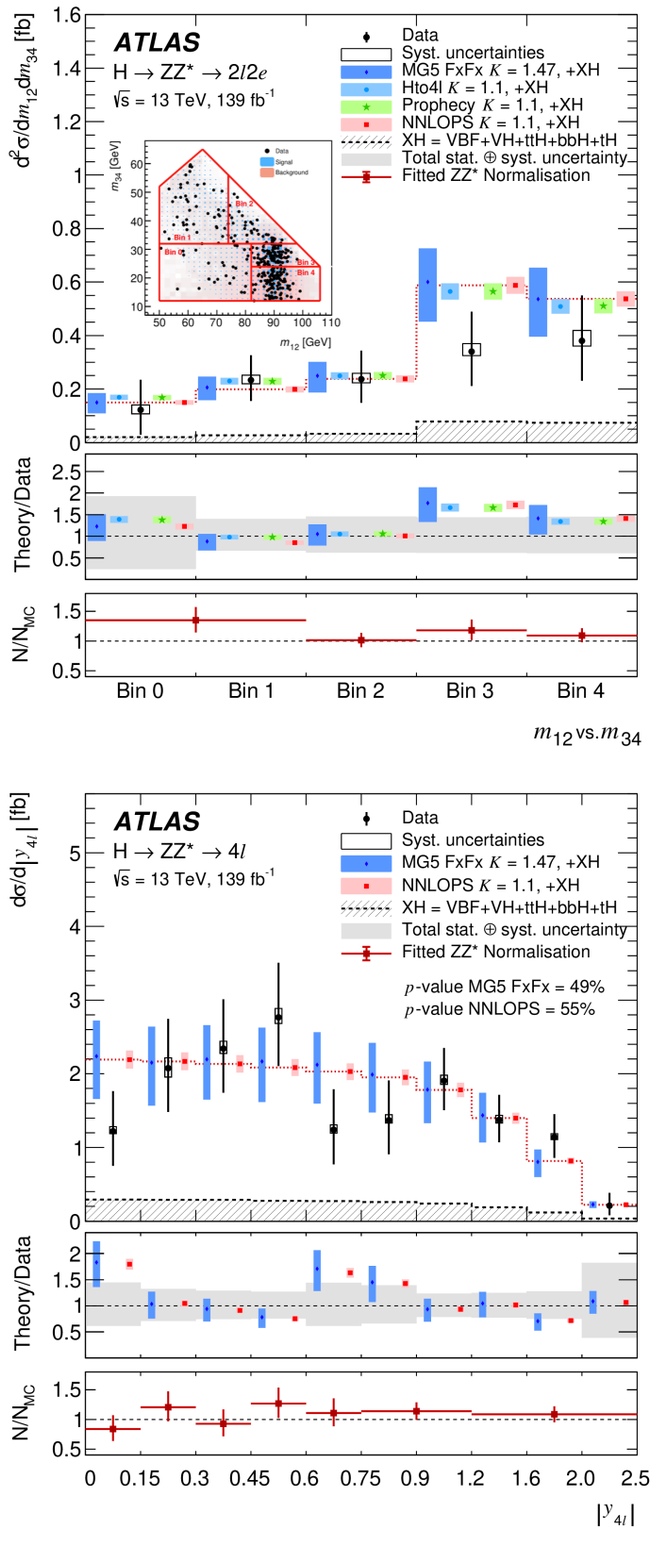




- Fiducial volume: a restricted truth phase space used for a cross section measurement
  - Defined closer to the experimental selection to reduce extrapolation into unmeasured regime
- Extract signal in each bin of the distribution
  - Typically using simple variables (m_{4l}, $m_{\gamma\gamma}$, m_{ll})
- Unfold to truth level:
  - Construct migration matrix, taking into account migration of events between bins at truth and reconstructed level
  - Methodology: bin-by-bin, matrix inversion, bayesian …
  - Correct for non-fiducial effects
- Differential distribution:
  - More model independent than STXS
  - Inclusive in production mode
  - Can be compared with latest theory predictions or reinterpreted under models with new physics

H->ZZ* Differential

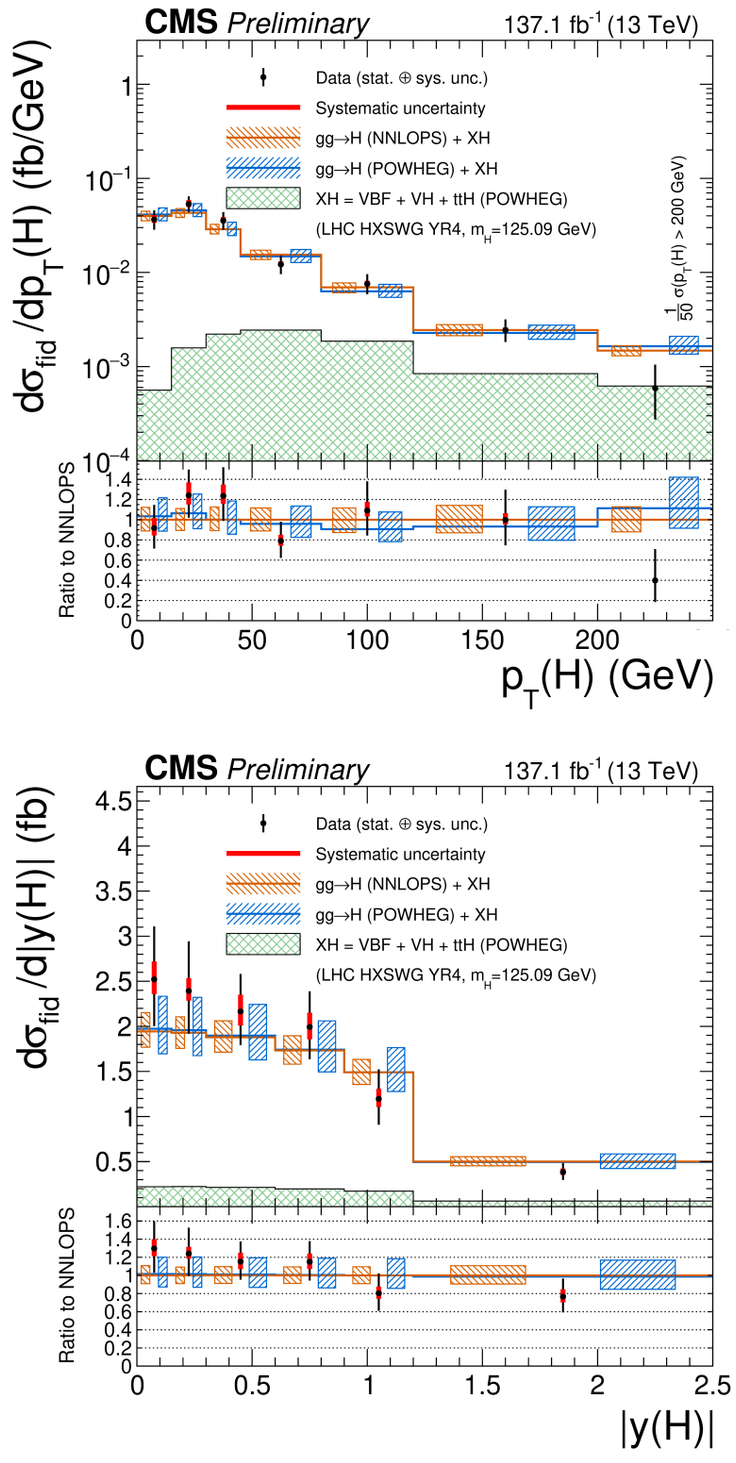
arXiv:2004.03969, acc. by EPJC



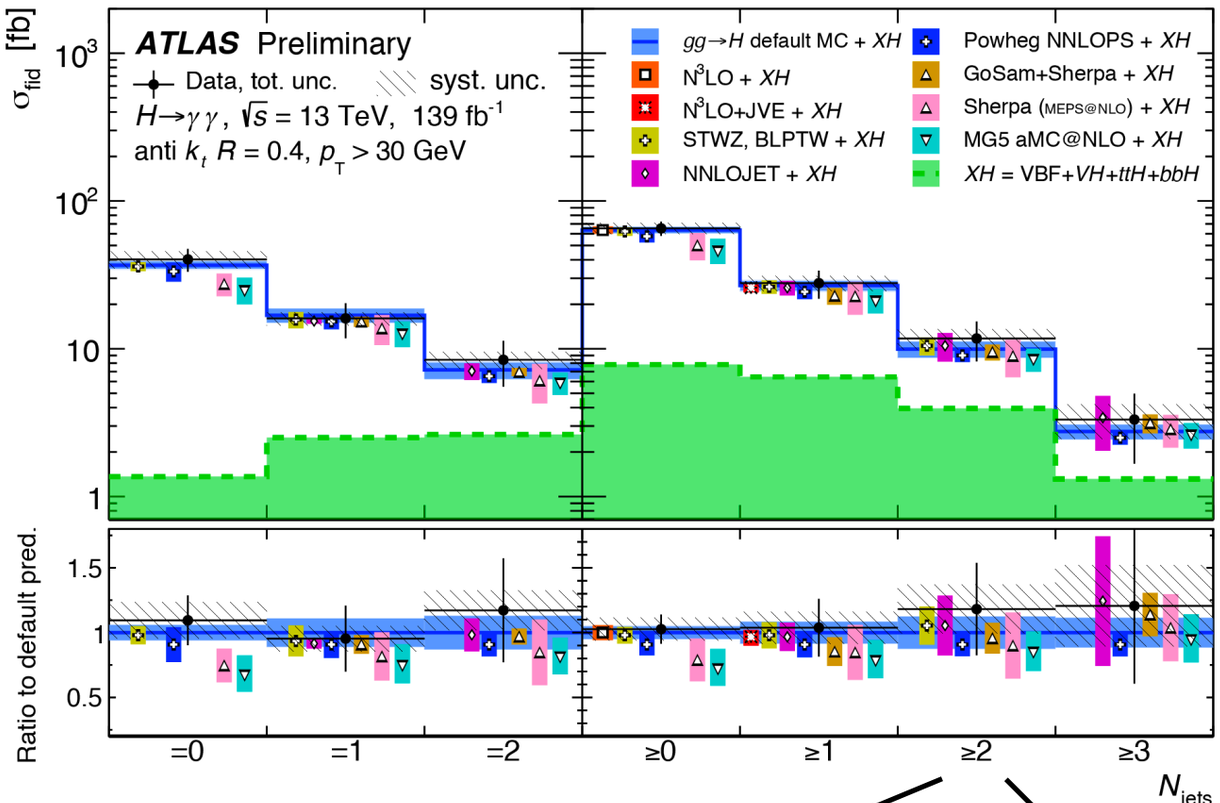
- ZZ*->4l decay mode provides excellent resolution for Higgs kinematic variables
- Measurements profit from very good S/B ratio
- Many distributions measured, including:
  - Higgs kinematics, including angular variables
  - Jet activities
  - m_{12} vs. m_{34} - specific to ZZ*->4l decays and offers good sensitivity to BSM physics
  - Double differential distributions

Limited by statistical uncertainties

CMS-PAS-HIG-19-001



H->γγ Differential



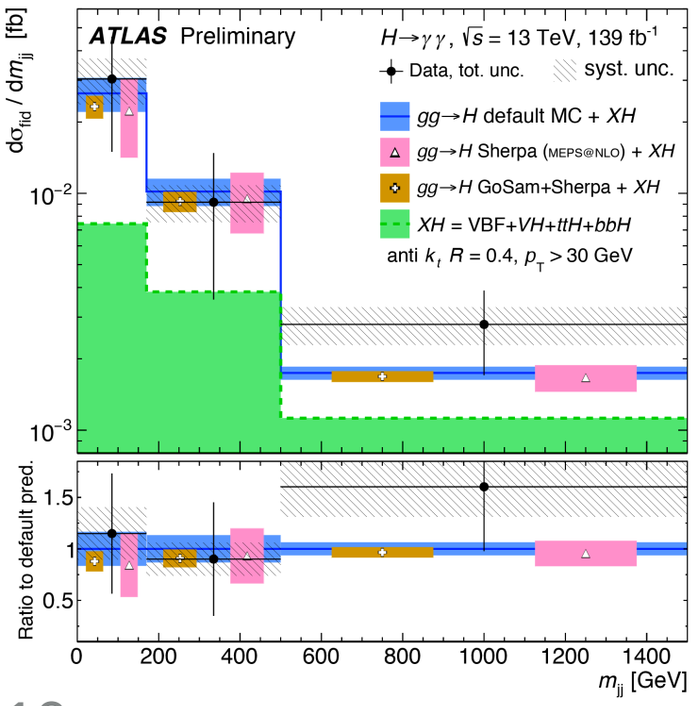
- Relatively easy to select and reconstruct Higgs candidate

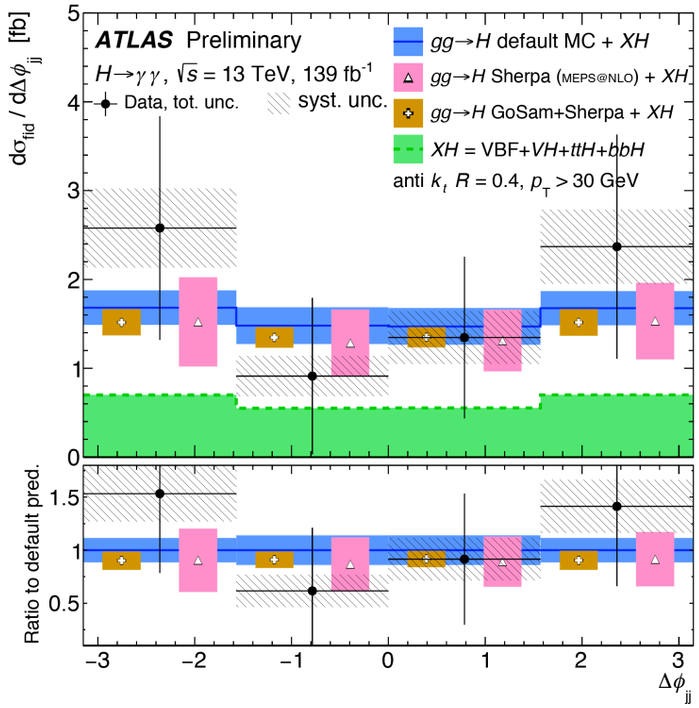
  -> good resolution for Higgs variables

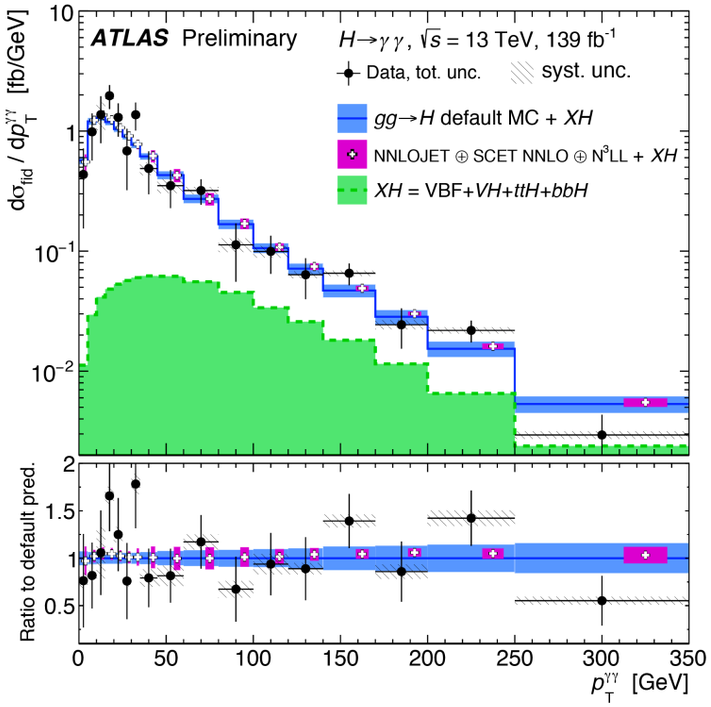
- N_{jets} sensitive to production modes and higher order QCD effects
- di-jet kinematics sensitive to anomalous operators including CP-odd

Limited by statistical uncertainties

ATLAS-CONF-2019-029

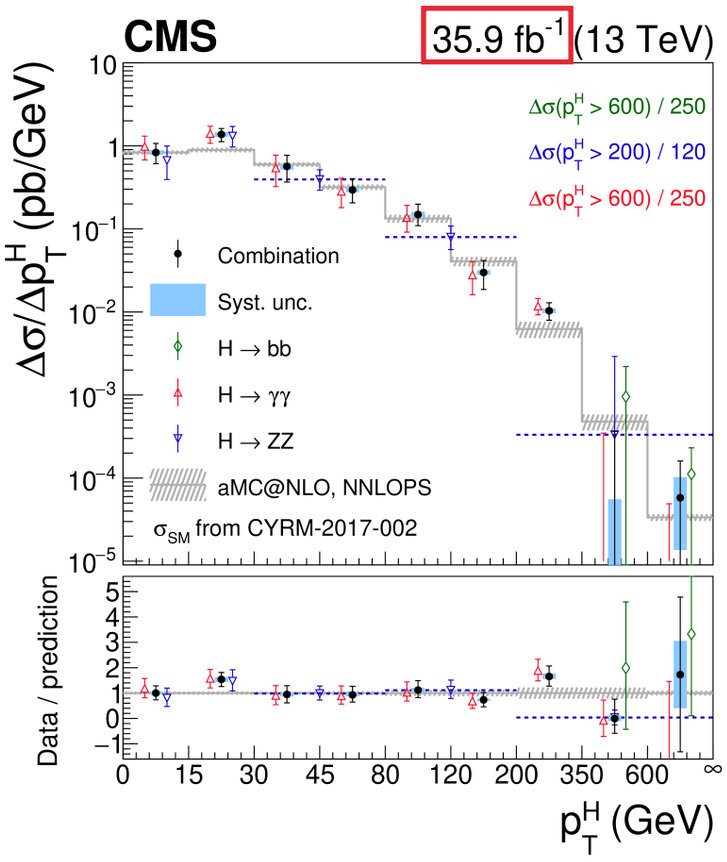






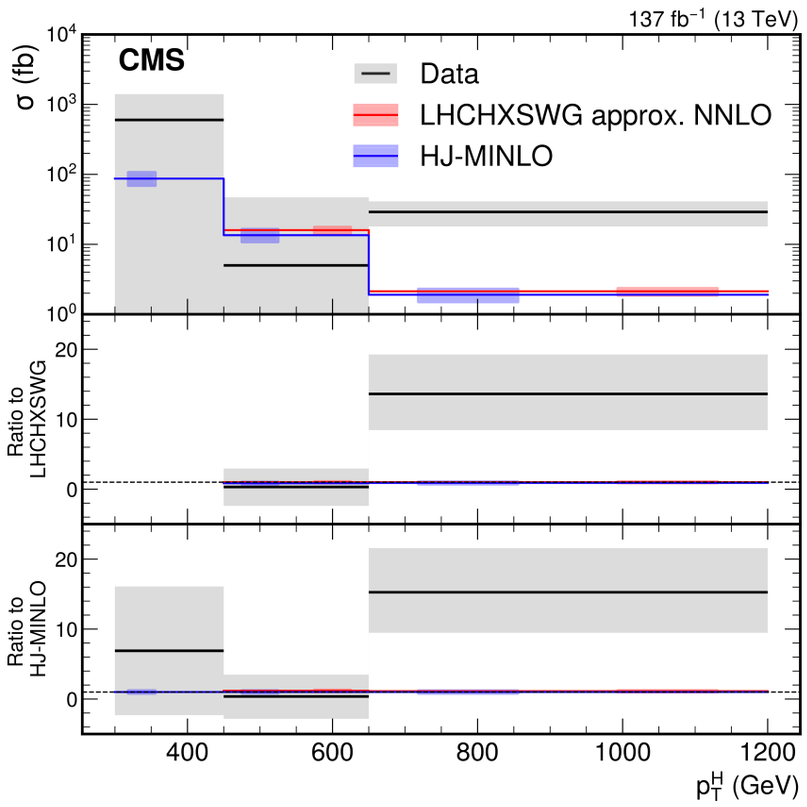
Differential: Higgs p_T

Phys. Lett. B 792 (2019) 369

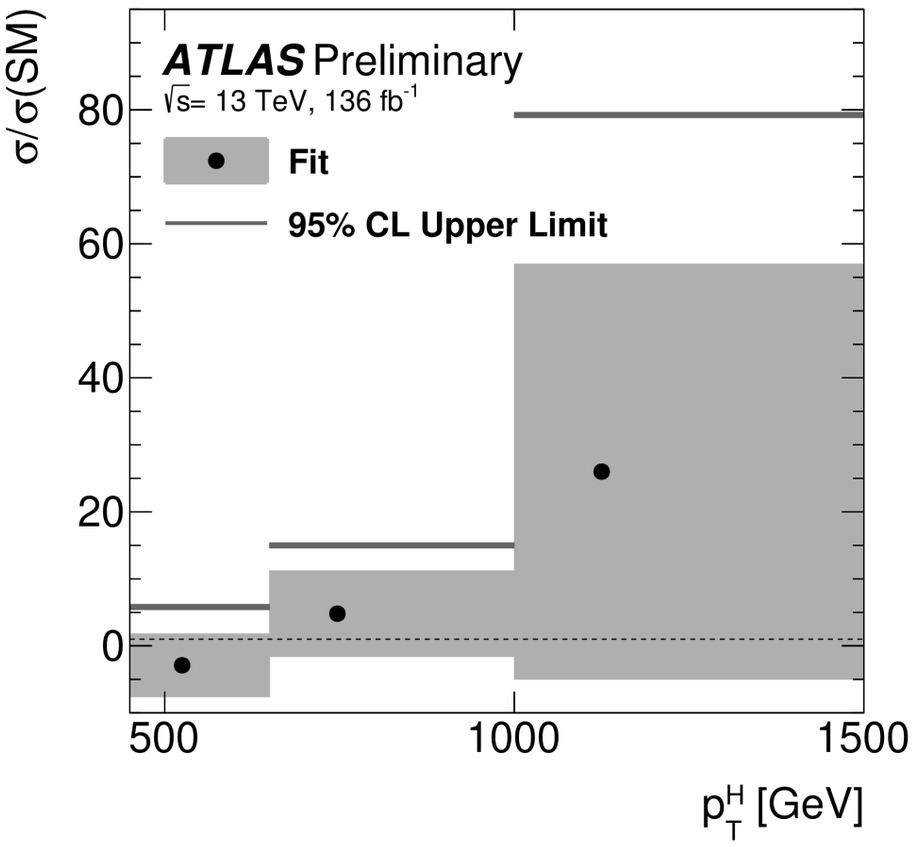


- Low p_T^H regime sensitive to c-quark contribution from loop modification and ccH
- High p_T^H regime sensitive to possible new particles in the loop

CMS-PAS-HIG-19-003, acc. by JHEP



ATLAS-CONF-2021-010

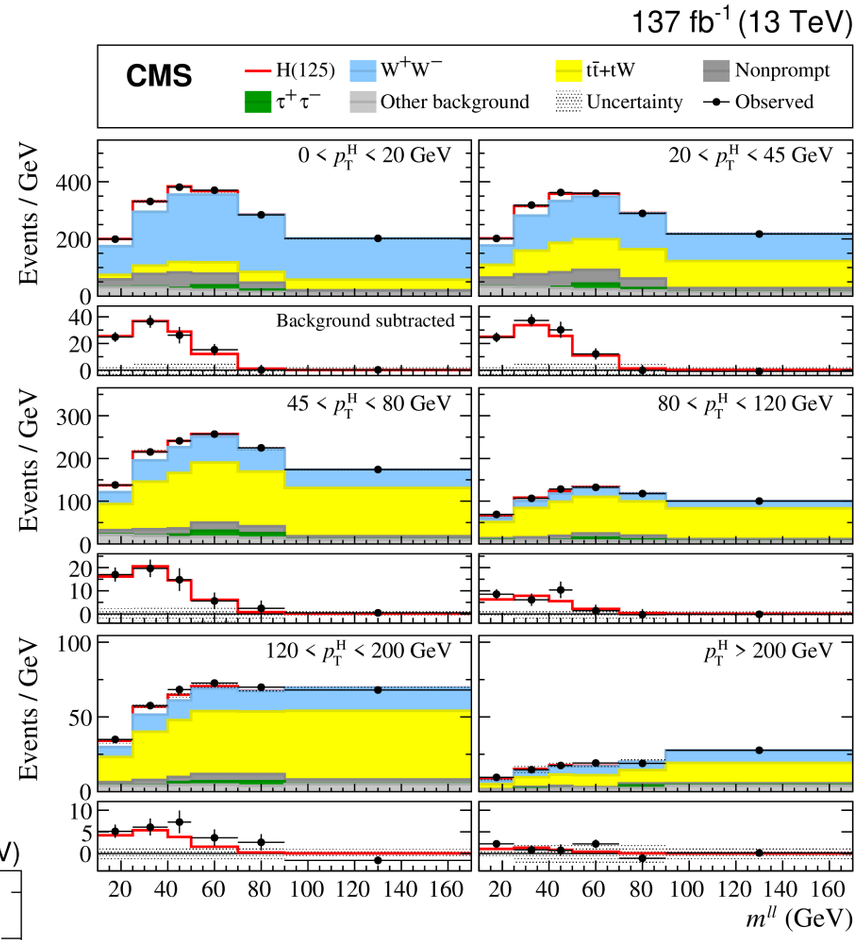


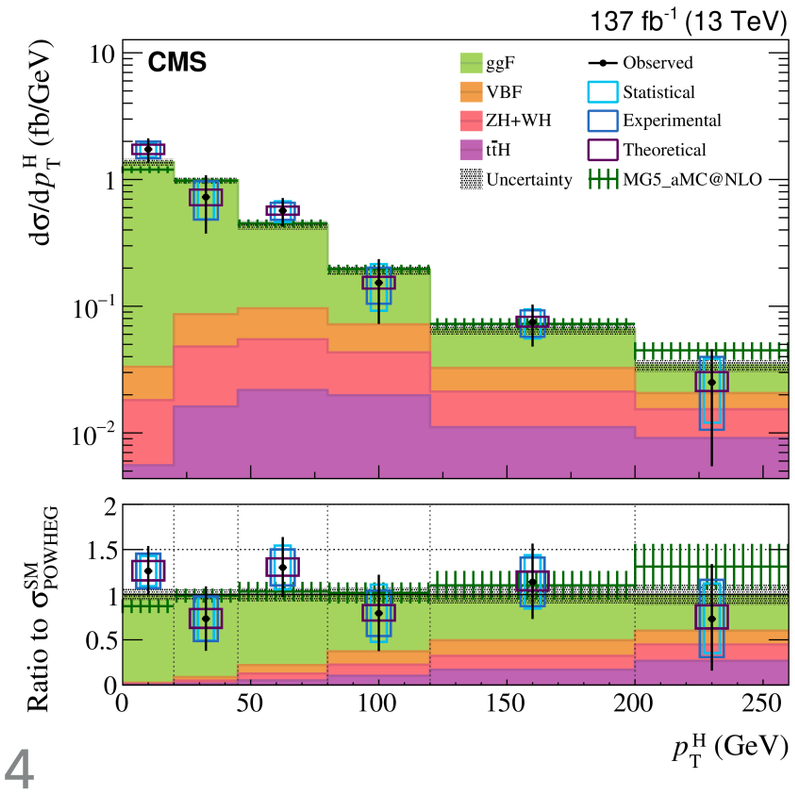
- Utilise boosted H->bb category to reach p_T^H regime
  - CMS - p_T^H > 650 GeV bin corresponds to a local significance of 2.6 σ w.r.t. SM (1.9 σ when considering all 3 bins simultaneously)
  - ATLAS - Now measuring Higgs cross section in a fiducial region corresponding to p_T^H > 1 TeV(!); Results compatible with SM expectation within uncertainties

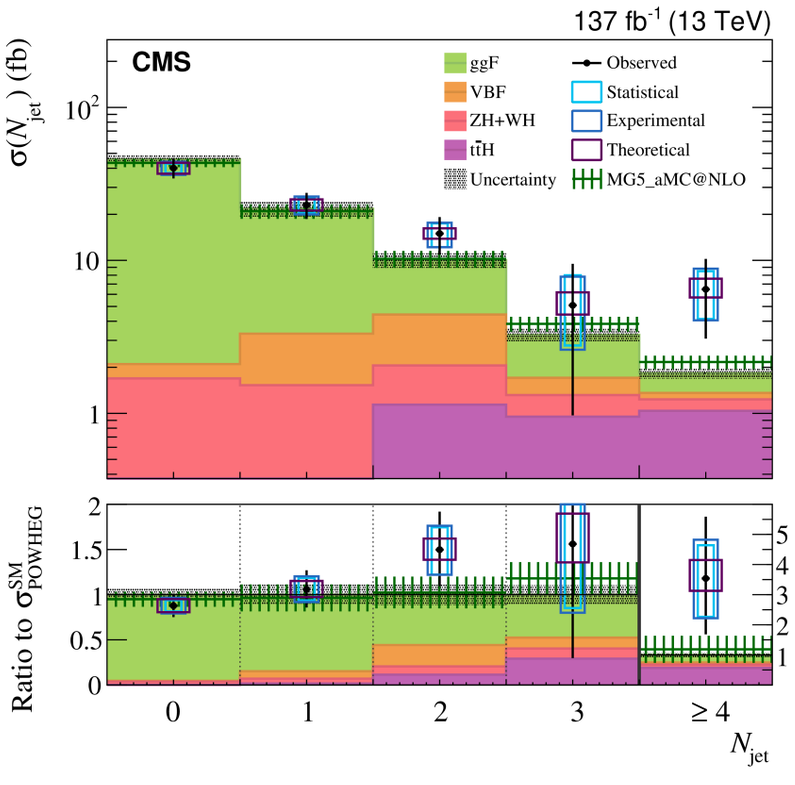
H->WW* Differential

- Events with different flavour / opposite sign leptons + MET
- Signal extracted from a 2D fit to m_{ll} vs. m_T in each category
- Differential p_T^H distribution:
  - Bin widths determined by detector resolution; large migration in p_T^H reconstruction due to MET
  - Uncertainty ranging from 20% at low p_T^H to 85% at high p_T^H
  - Comparable statistical and systematic uncertainties

CMS-PAS-HIG-19-002, acc. by JHEP

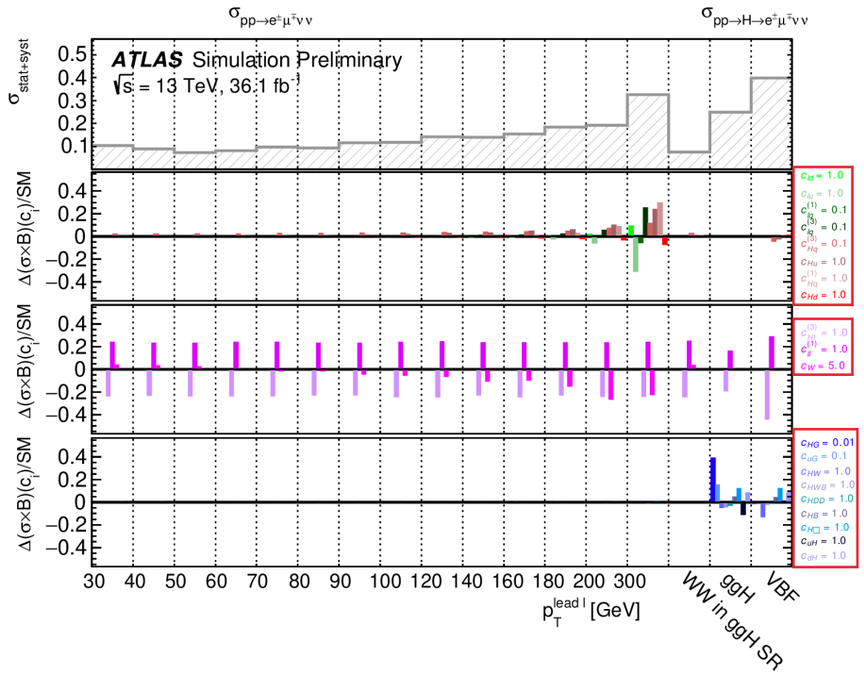






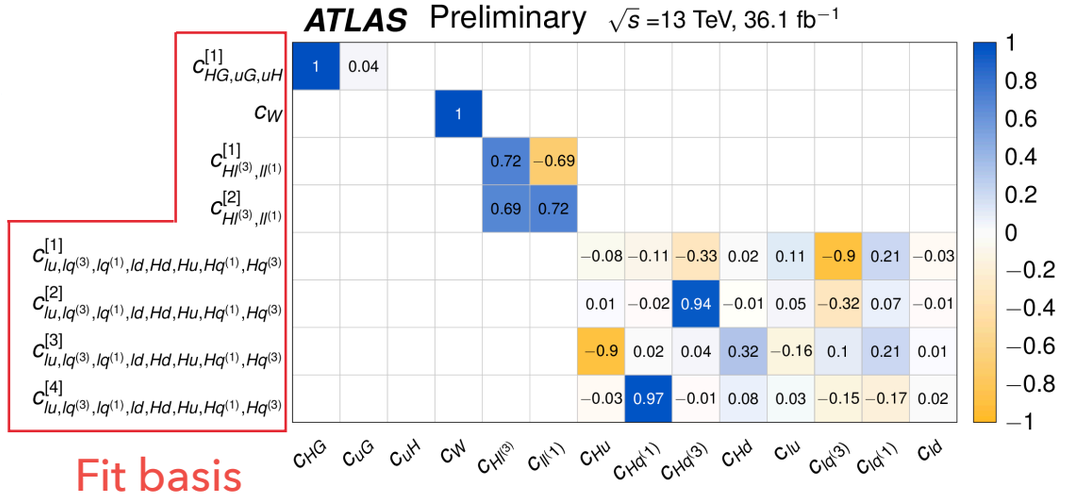
- Differential N_{jets} distribution:
  - Uncertainty ranging from 15% for N_{jet} = 0 to 80% - 90% at higher jet multiplicities
  - Comparable statistical and systematic uncertainties

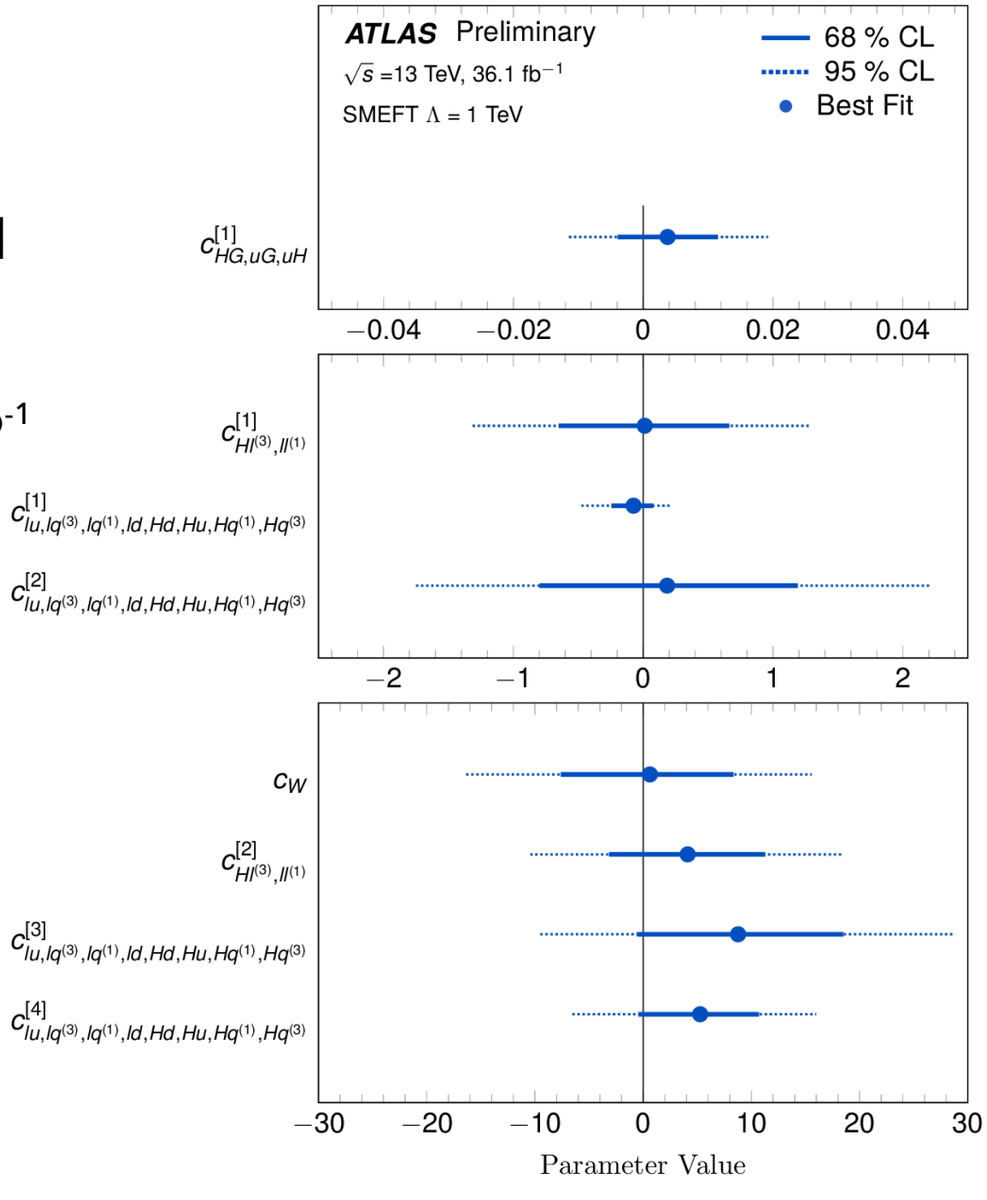
EFT Interpretation of Comb. H->WW* / WW



ATL-PHYS-PUB-2021-010

PCA on operator groups



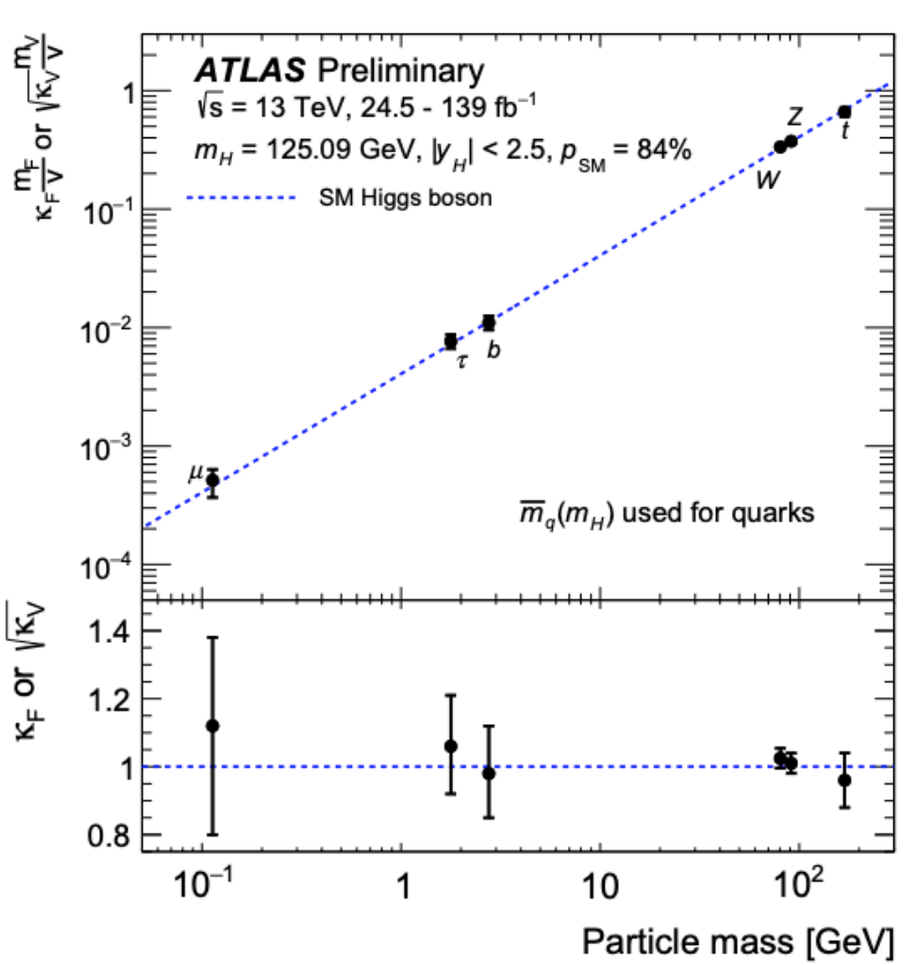


- Demonstrate how EFT parameters can be constrained through a combination of inputs:
  - H->WW* (signal strength) and SM WW (differential) with 36 fb^{-1}
  - Consider impact of 20 CP-even Wilson coefficients on combined analysis bins
  - Rotate space of operators such that flat directions in likelihood can be ignored (i.e. fixed to SM value of 0)
  - Simultaneous fit performed on 8 dimensions
- Stepping stone for more global EFT combinations
  - Additional measurements and larger datasets lead to probing more EFT parameters with higher sensitivity

Summary

- Simplified template and differential cross section measurements offer two complementary methods for further scrutinising the characteristics of the Higgs boson
- Full Run 2 dataset has so far delivered many new results across multiple Higgs production and decay modes
  - STXS stage 1.2 bins measured with uncertainty ranging from 15% to 100%
  - More finely-grained differential measurements, reaching more extreme kinematic regions
- Measurements continue to be consistent with the Standard Model, placing further constraints on new physics

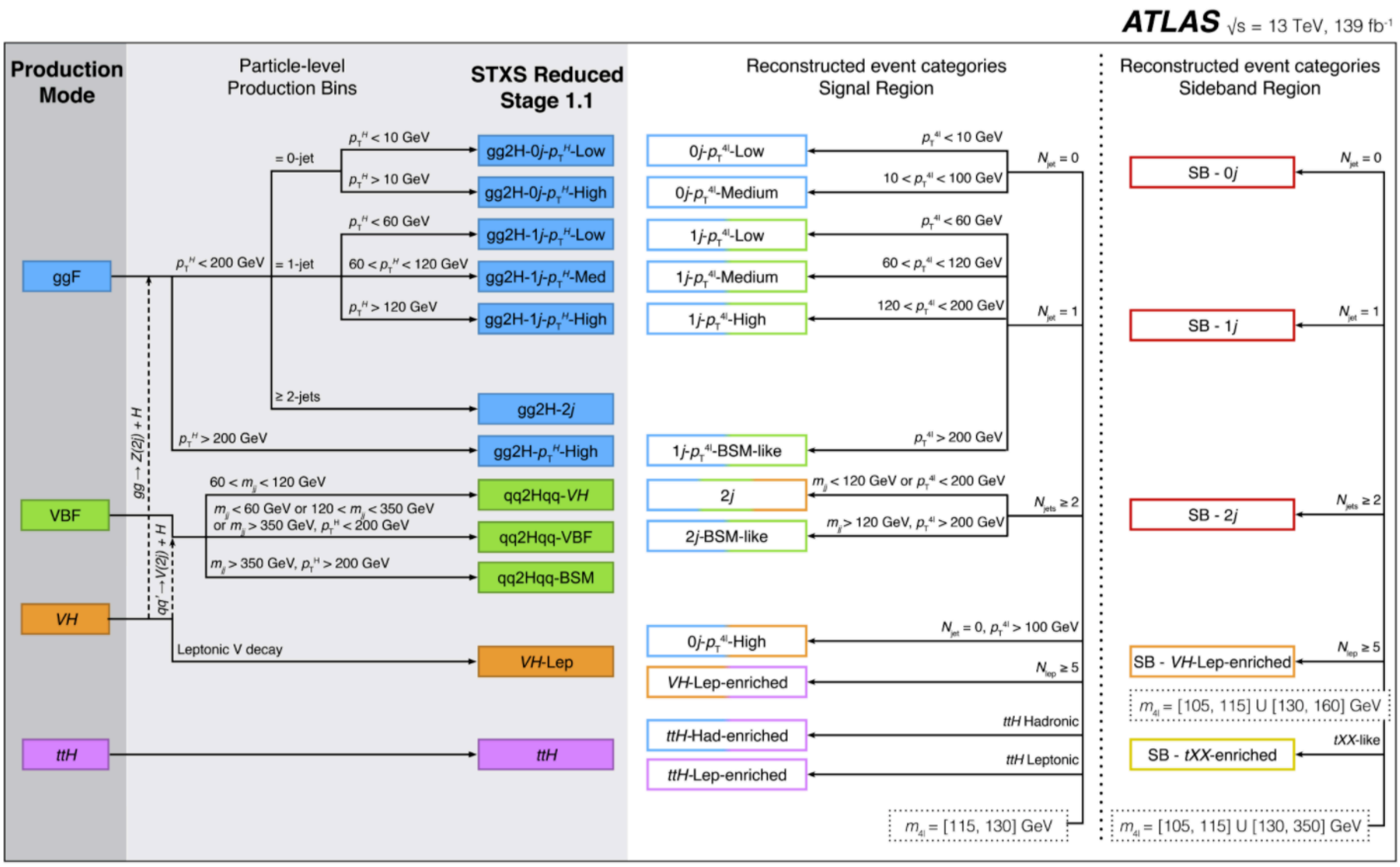
More results to come from Run 2, so stay tuned!



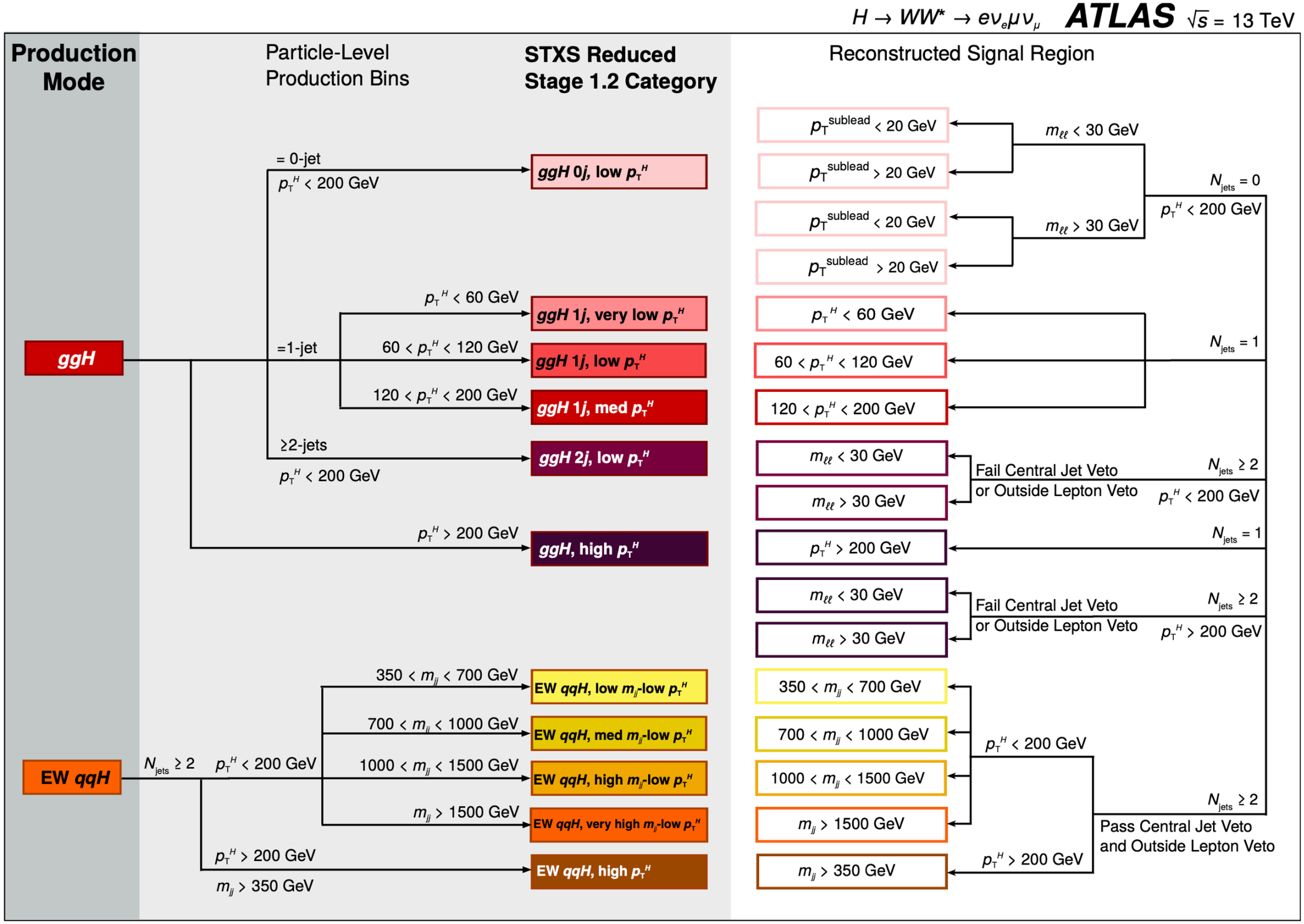
ATLAS EXPERIMENT

BACKUP

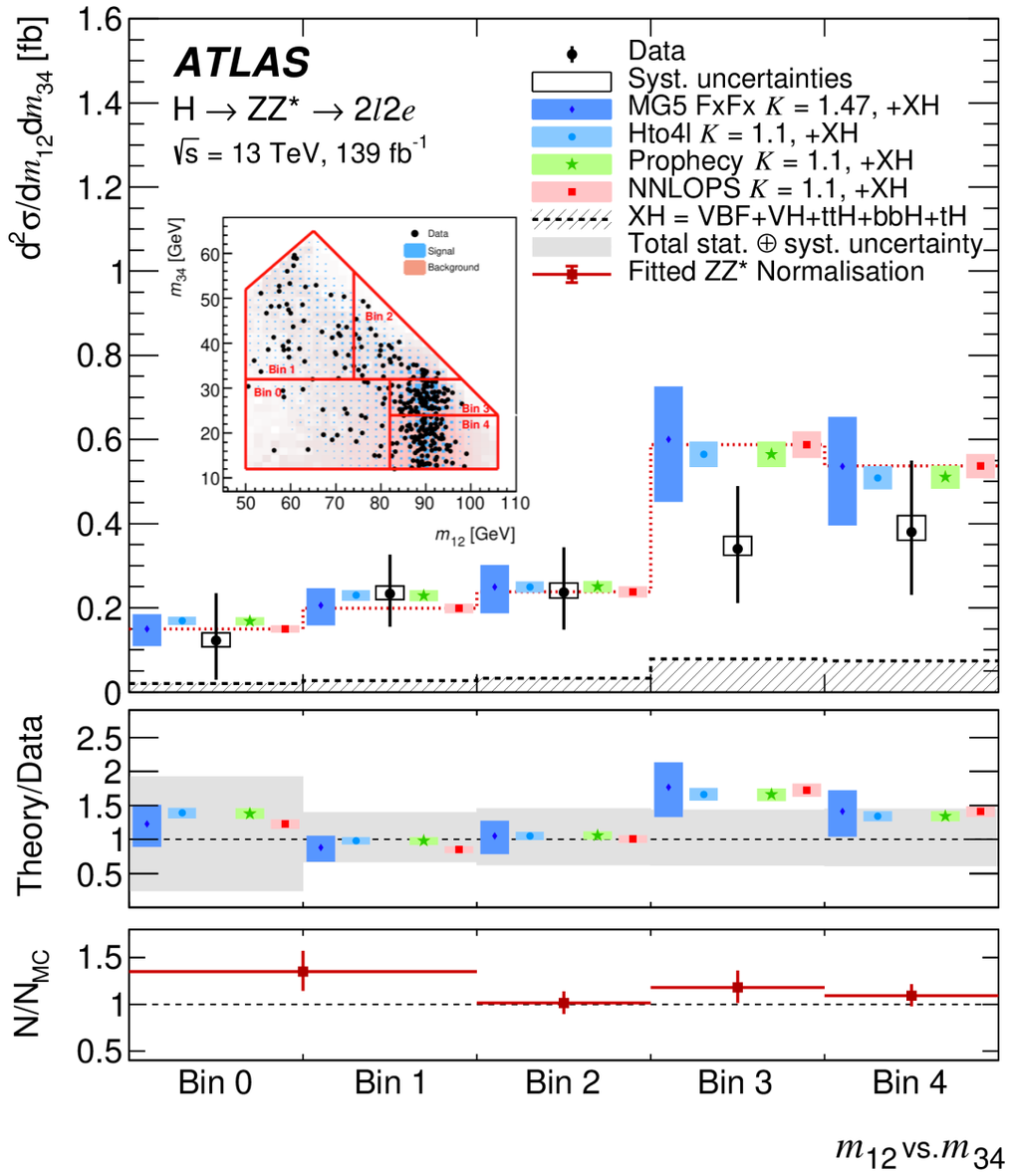
ATLAS H->ZZ*->4l STXS bin definitions



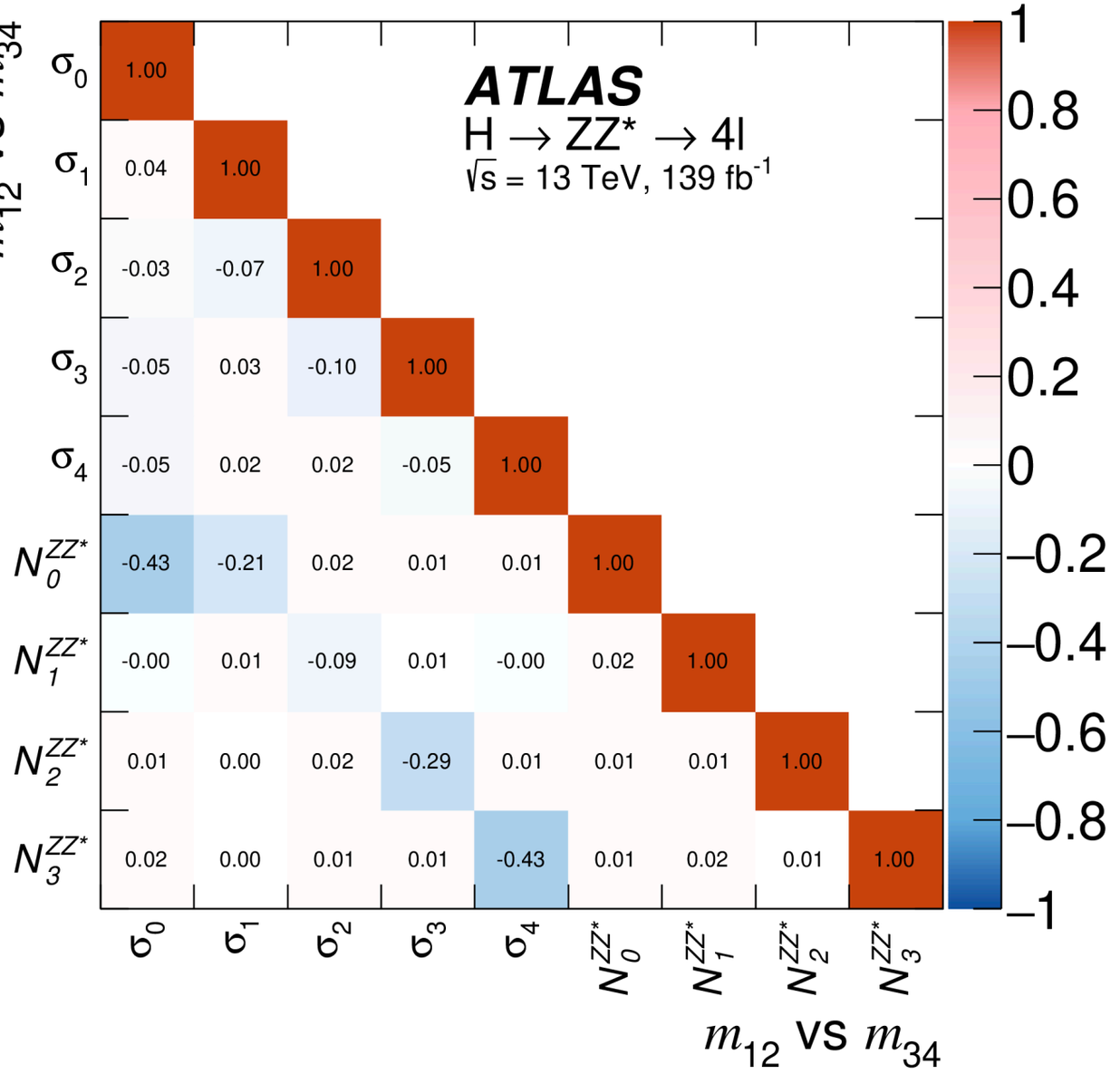
ATLAS H->WW* STXS bin definitions



H->ZZ* Differential (p_T^H) With Correlations



m_{12} vs. m_{34}



H->ZZ* Differential ($|y_{4l}|$) With Correlations