Past, present, and future of VBF, 19th-21st October 2022, CERN

Limiting components of theoretical uncertainties in current VBF ATLAS measurements

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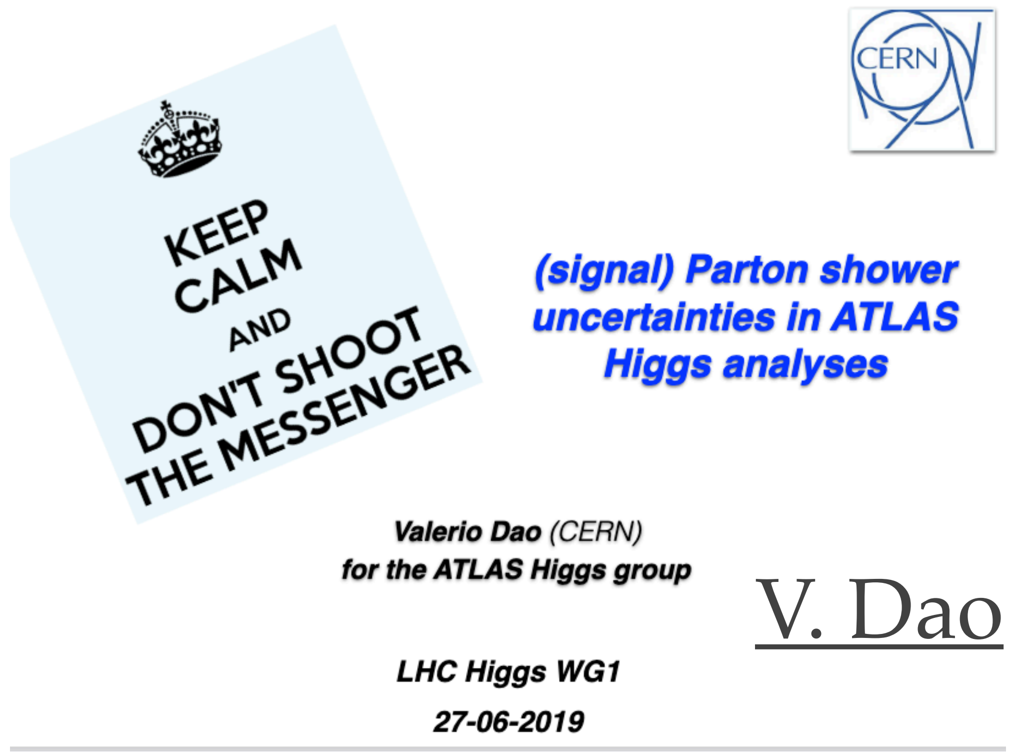
Introduction

- **Long-standing discussion about theory uncertainties in VBF**
  - Parton shower uncertainties (not only in VBF) has played a dominant role in these discussions
  - Several studies to understand differences between parton showers and generators from the theory side (see Silvia's talk from yesterday)



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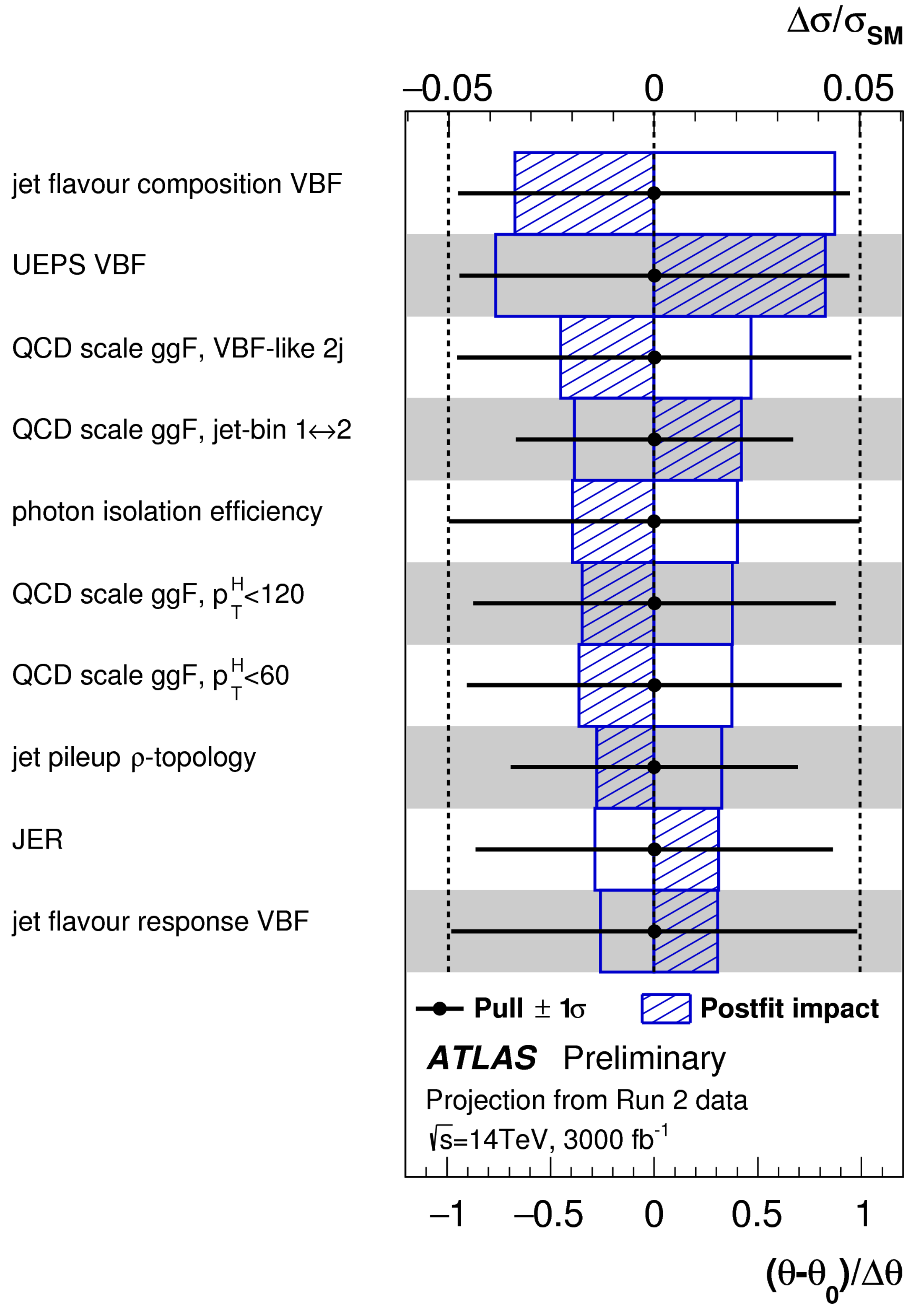
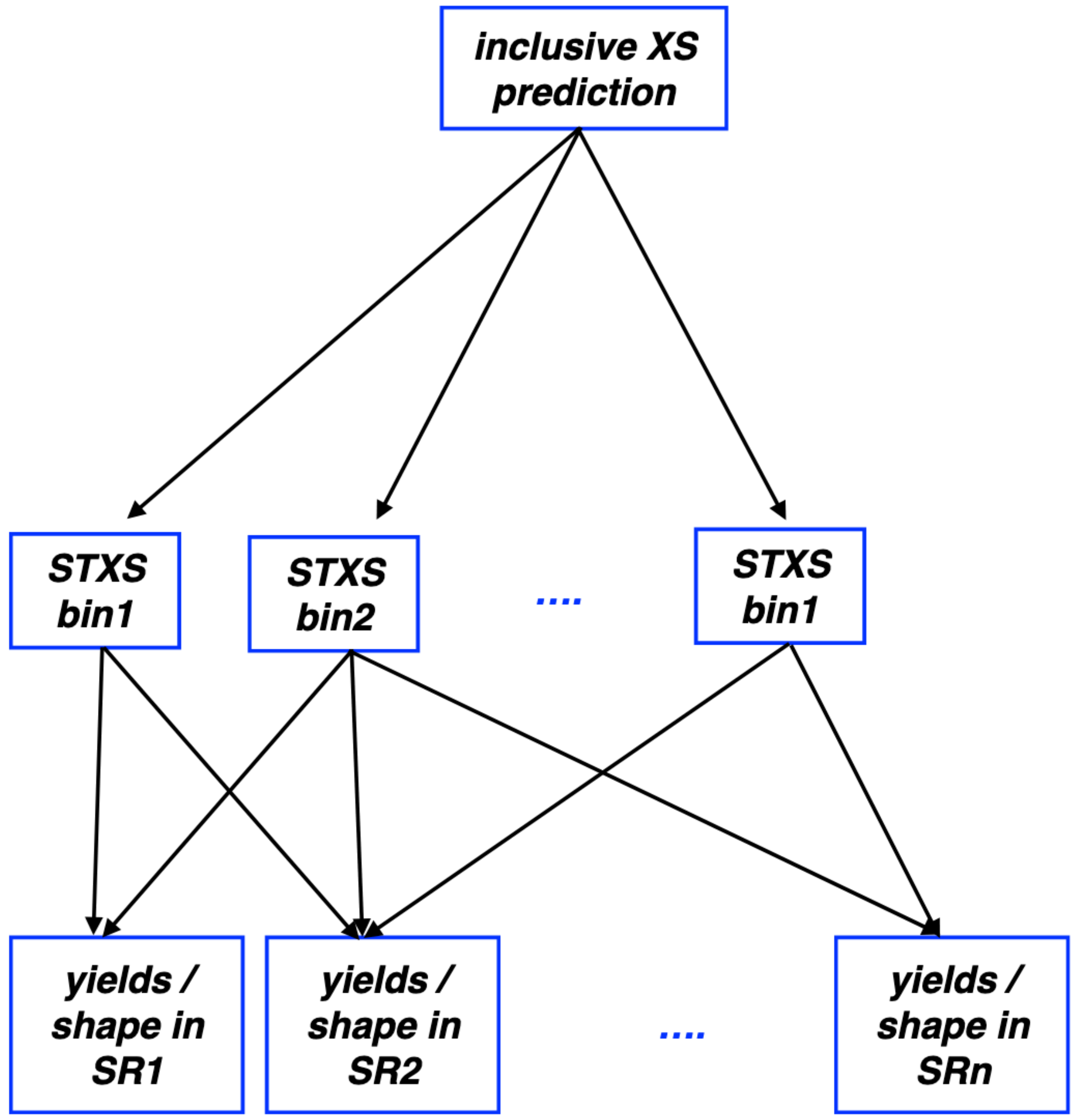


Projections of Higgs measurements

- **Effects on Higgs analysis**
  - Also dominated by PS uncertainties
  - And expected to be a leading uncertainty in HL-LHC
  - Convolution of different ingredients:
    - Variables used for classifying events, relevance of categories with larger differences in yields/shapes arising from theory uncertainties, …

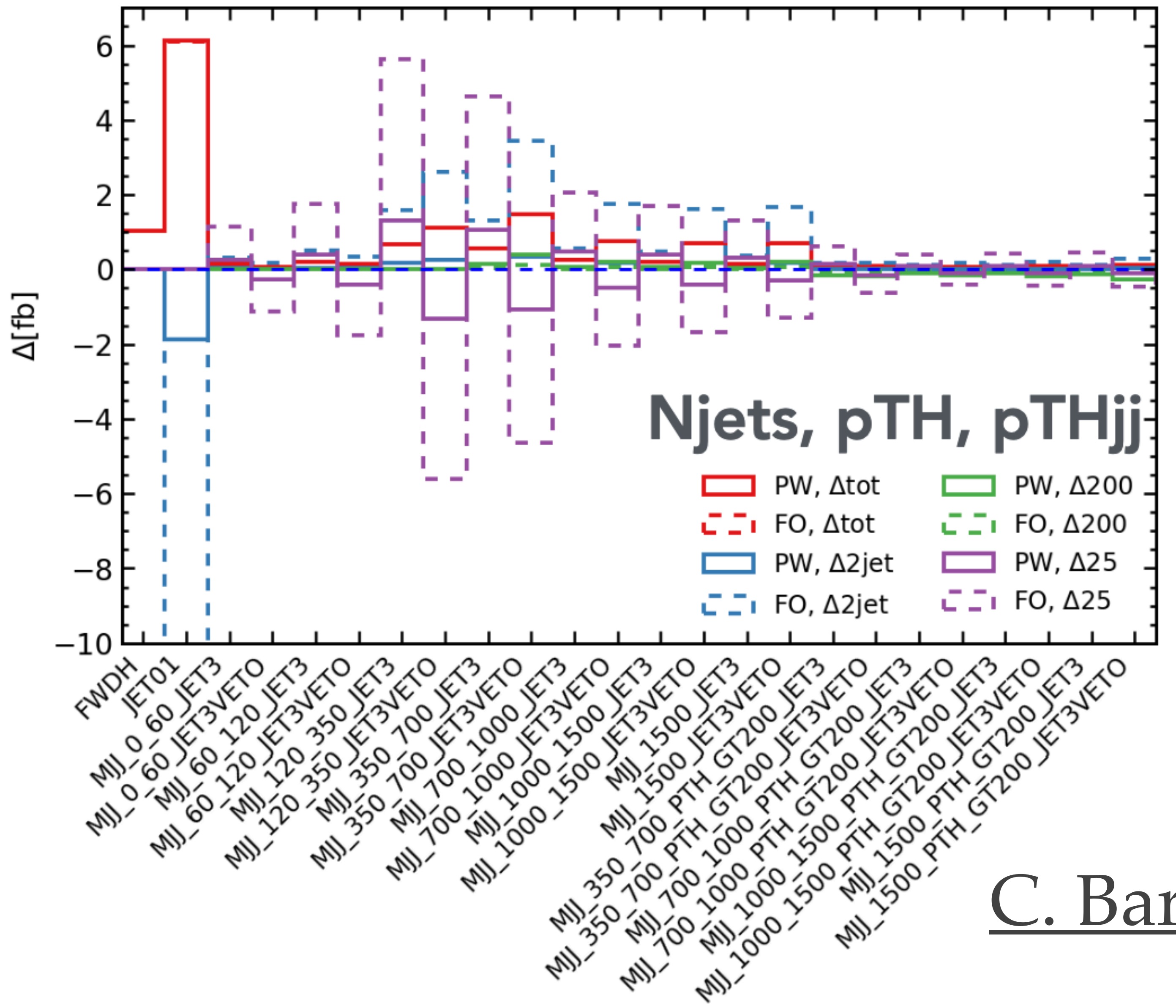


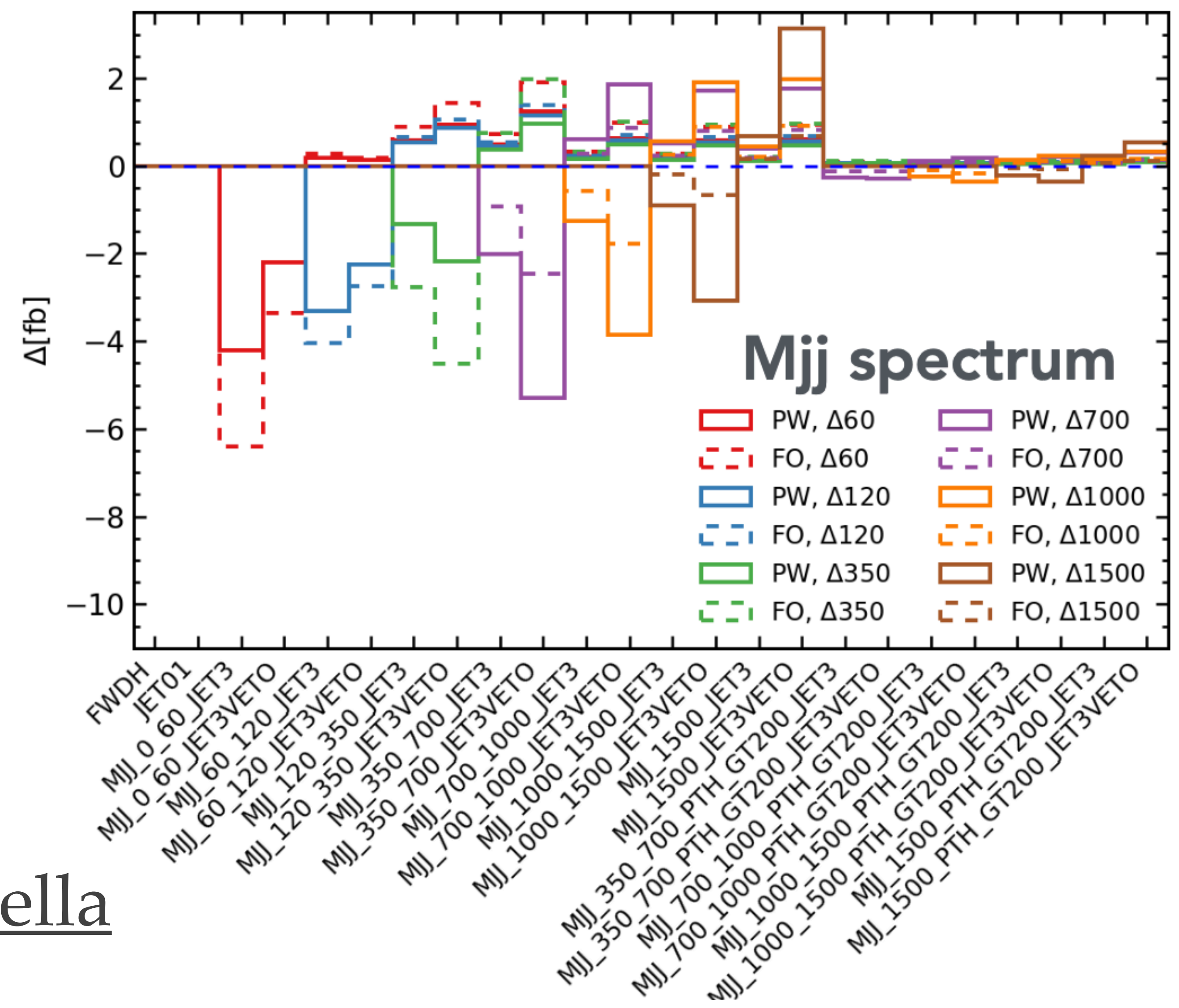
Outline

- **Uncertainties considered in ATLAS analyses**
- **VBF theory uncertainties effects considered in ATLAS analyses**
- **VBF simulation in ATLAS**
- **Conclusions**

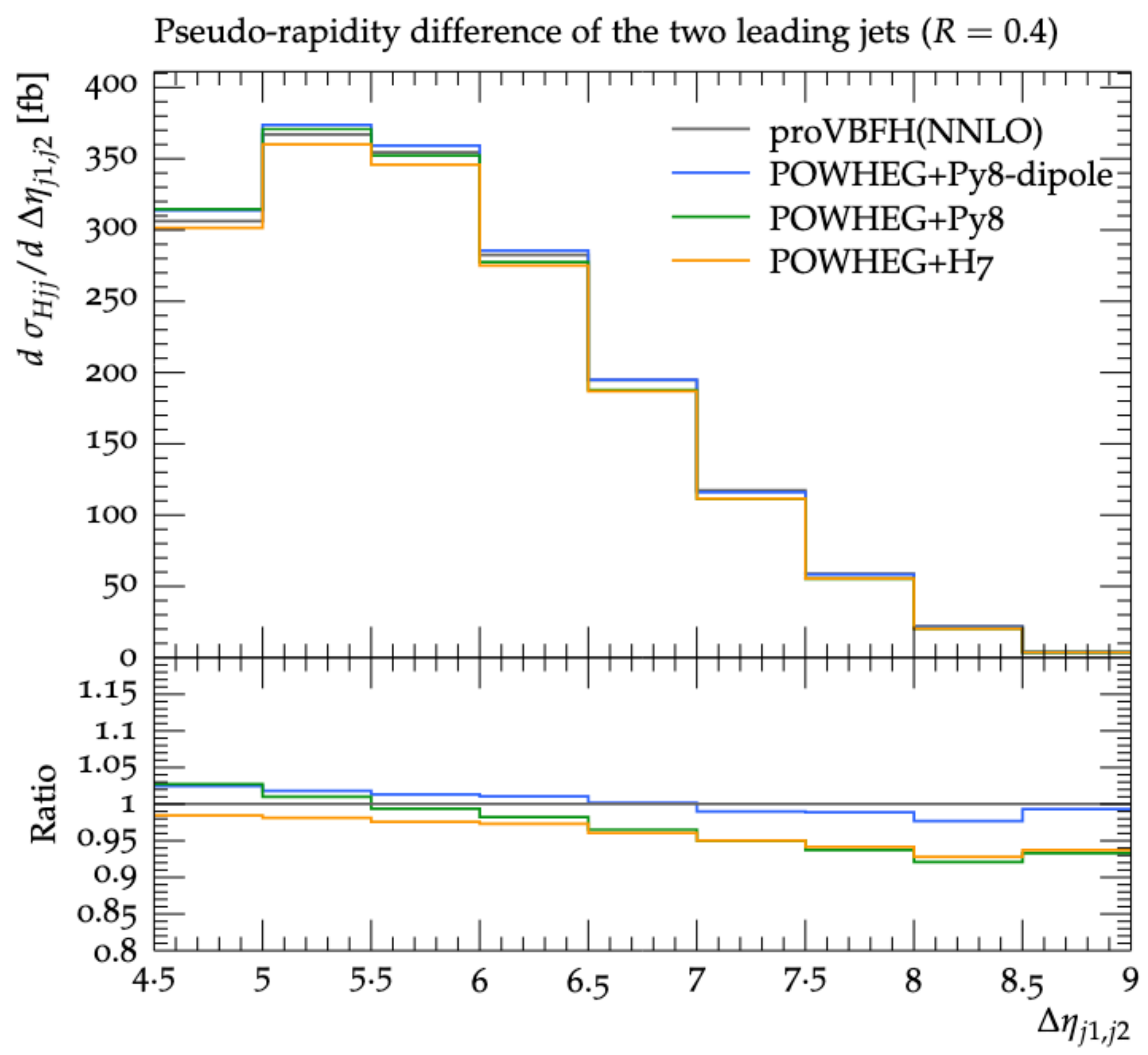
Uncertainties considered in ATLAS analyses

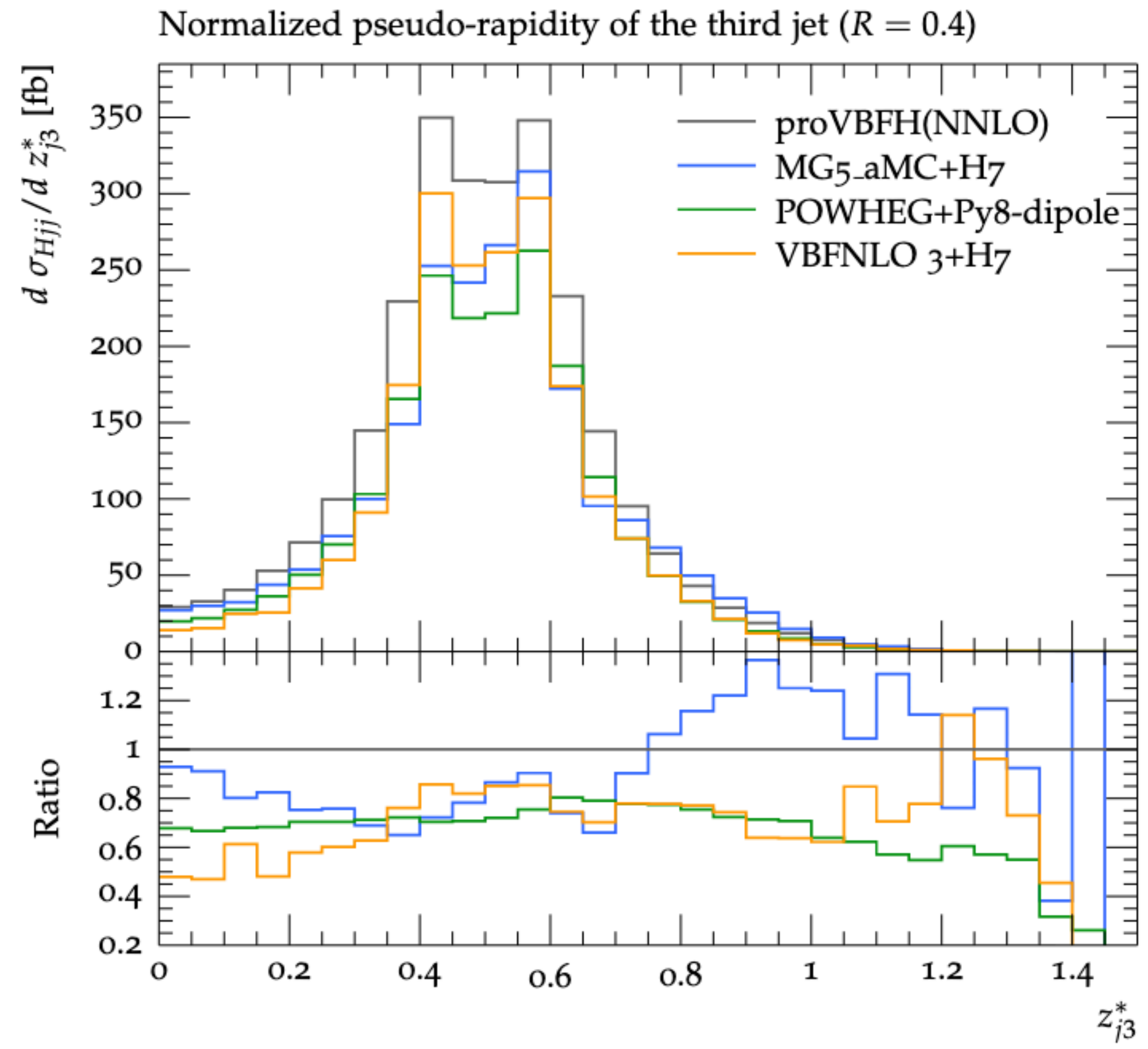
- **STXS uncertainties:**
  - As determined for the STXS Stage 1.2 scheme for all productions modes.
  - Sizeable contamination of ggF uncertainties in VBF regions
- **PDF and αs uncertainties**
- **Parton shower uncertainties:**
  - All analyses: 2-point uncertainty comparing Powheg+Pythia8 (dipole) vs Powheg+Herwig7
  - Some analyses: Also include AZNLO tune variations
  - Parton shower weights in Pythia internally checked but not used in publications.
- **Matrix element and matching scheme:**
  - Some analyses: 2-point uncertainty comparing Powheg+Herwig7 vs MadGraph+Herwig7
- **Theory uncertainties affecting background processes:**
  - No further covered in this talk





C. Bartella

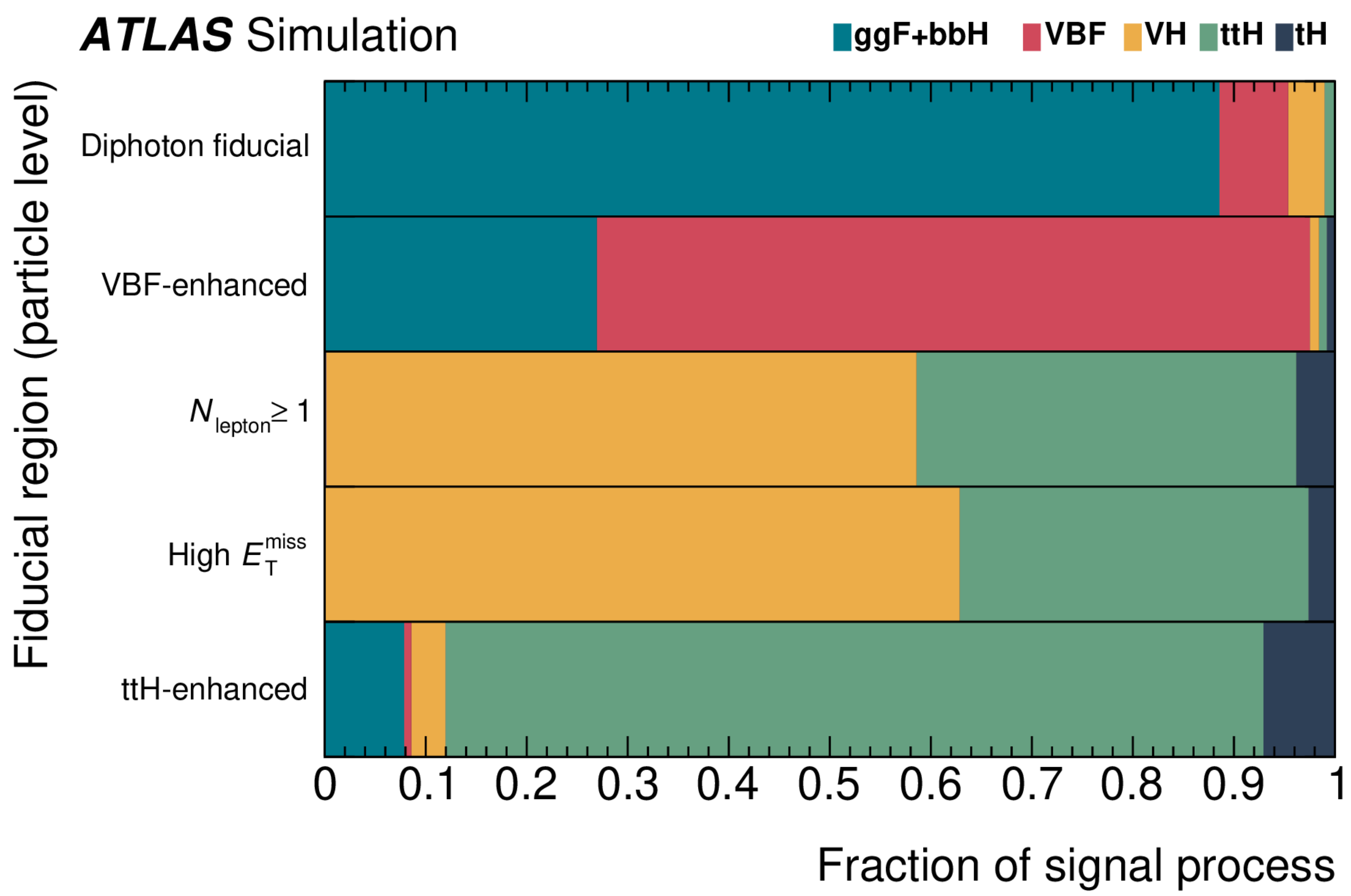




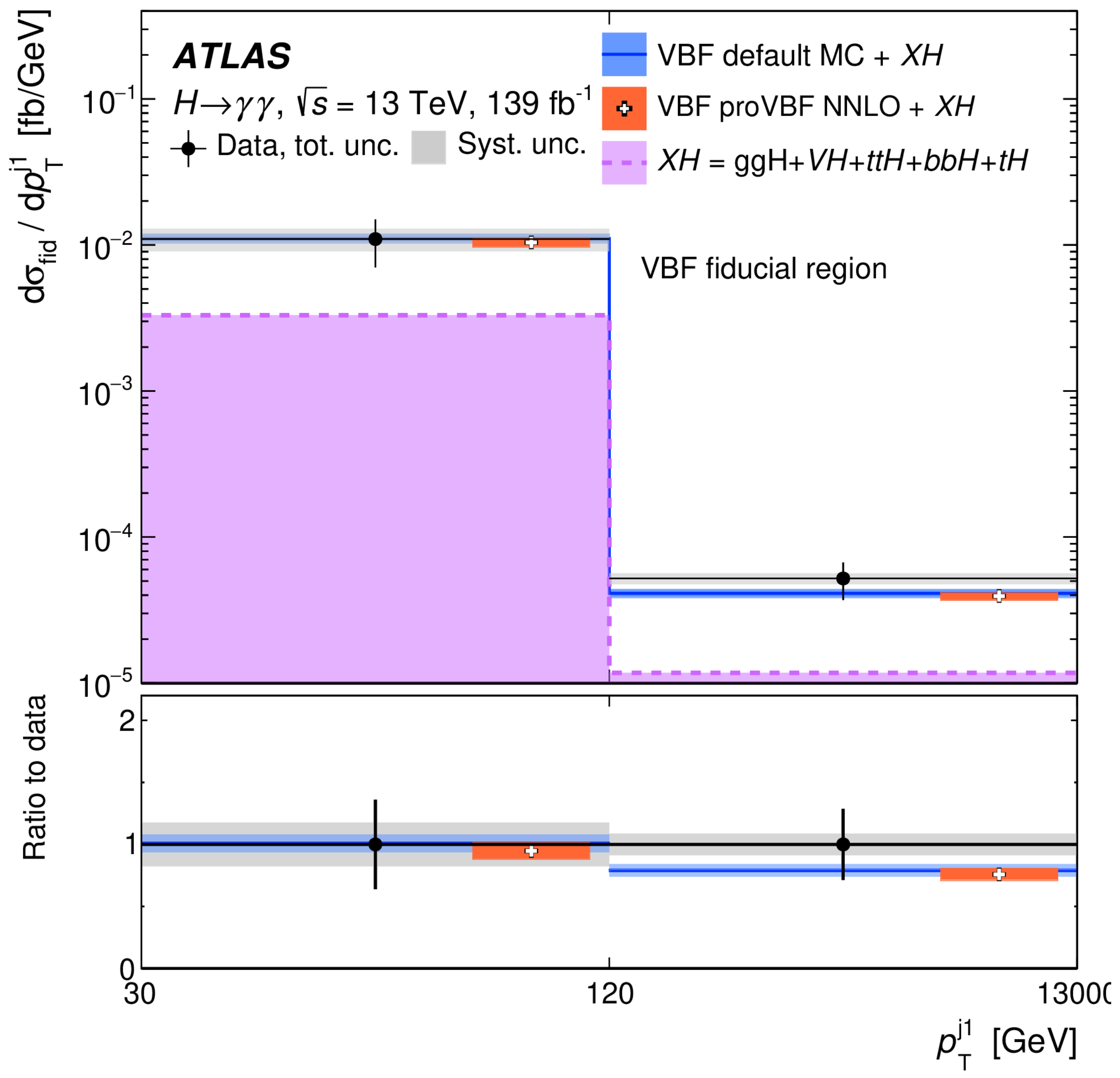
arXiv:2003.12435

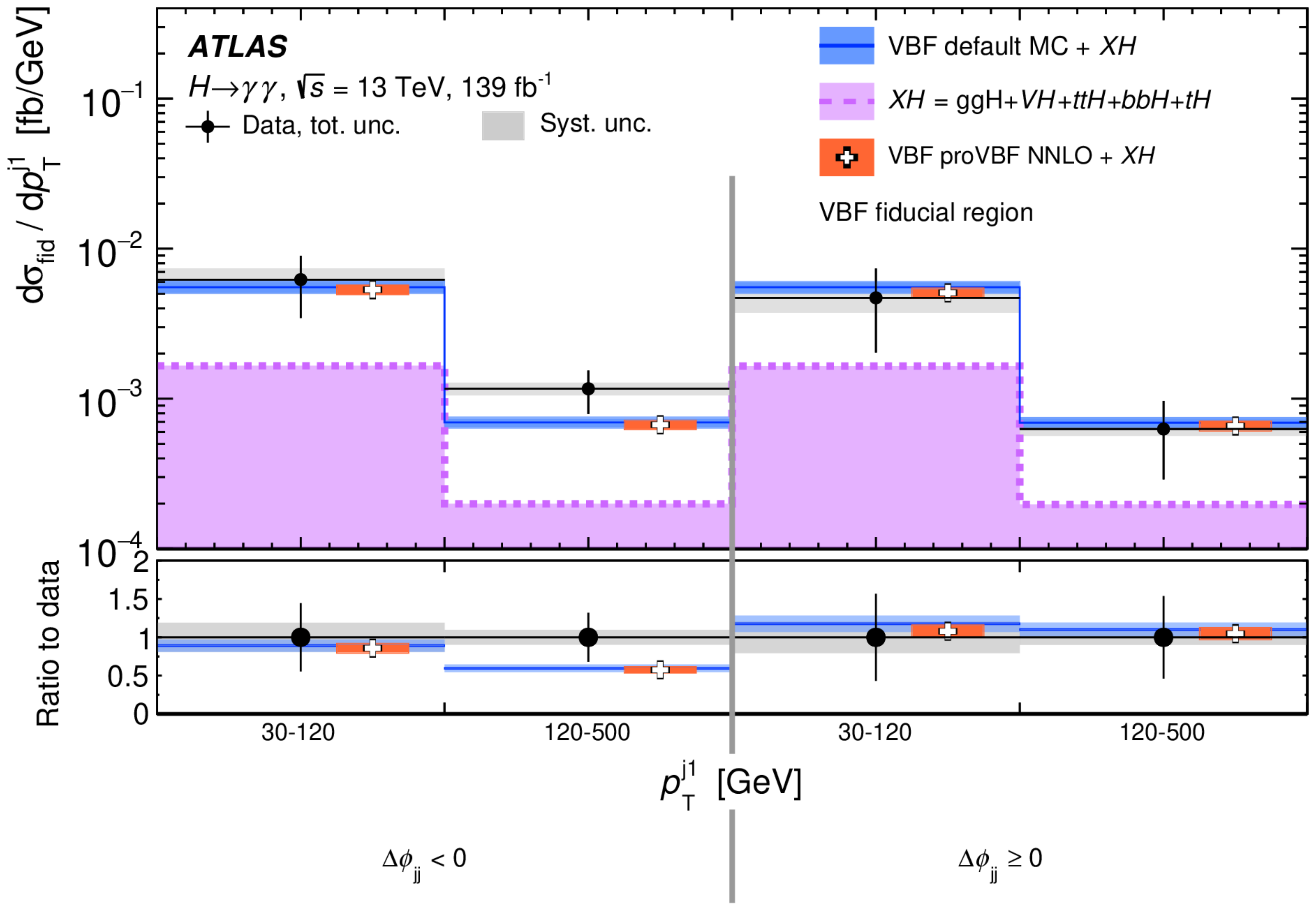
Theory uncertainties effects: H→γγ

- **Differential cross sections**
  - Measurements in VBF-enhanced regions: $m_{jj} > 600$ GeV, $|\Delta\eta_{jj}| > 3.5$
- Theory uncertainties are associated either only to the predictions (e.g missing higher-orders) or included as an uncertainty of the response matrix used for unfolding.



- Signal composition
  - Varying XS of the different processes within their uncertainties → at most 1%
- Parton shower uncertainty:
  - Pythia8 vs Herwig7: typically small, reaches 1.6% in high jet multiplicities
- Matrix element:
  - Powheg vs MadGraph: small: 1-2%

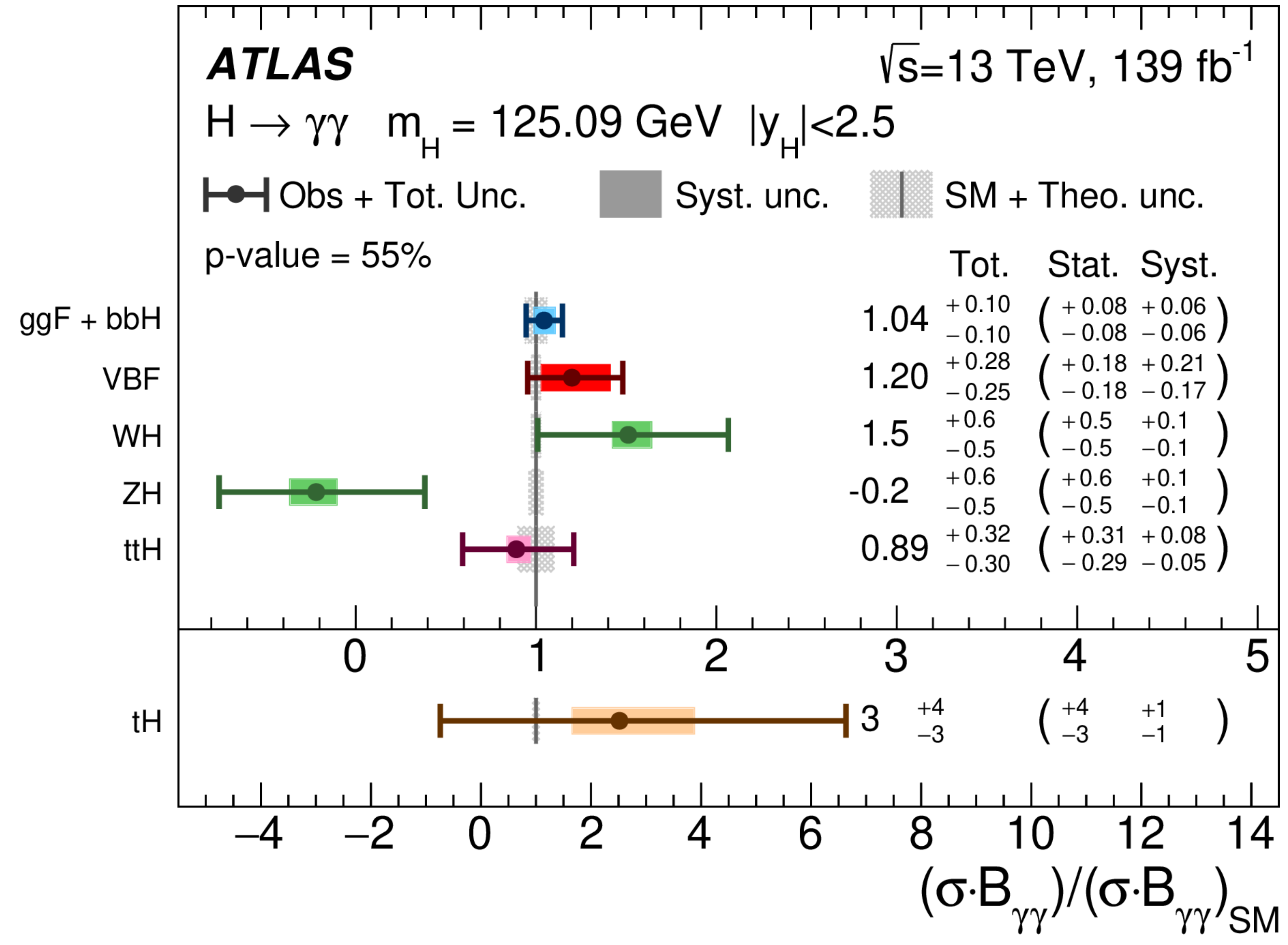




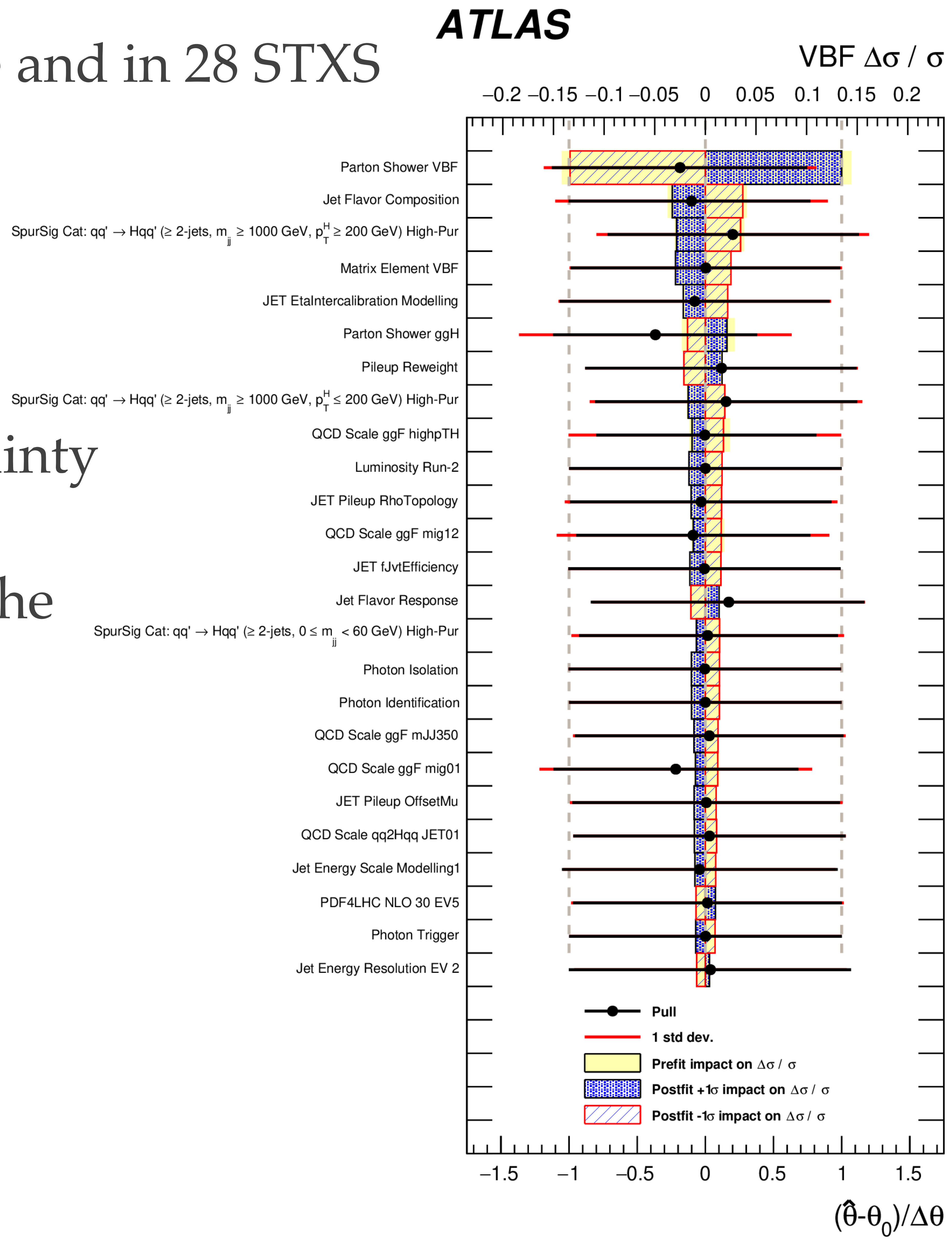
Numbers describe effects in general, not only in VBF regions

Theory uncertainties effects: H→γγ

- **Couplings analysis**
  - Measures cross-sections inclusively, per production mode and in 28 STXS regions.



- Parton shower uncertainty is by far the dominant theory uncertainty in the VBF production mode



	ggF + $b\bar{b}H$	VBF	WH	ZH	$t\bar{t}H$	tH
Uncertainty source	$\Delta\sigma$[%]	$\Delta\sigma$[%]	$\Delta\sigma$[%]	$\Delta\sigma$[%]	$\Delta\sigma$[%]	$\Delta\sigma$[%]
Theory uncertainties						
Higher-order QCD terms	±1.4	±4.1	±4.1	±12	±2.8	±16
Underlying event and parton shower	±2.5	±16	±2.5	±4.0	±3.6	±48
PDF and α_s	< ±1	±2.0	±1.4	±2.3	< ±1	±5.8
Matrix element	< ±1	±3.2	< ±1	±1.2	±2.5	±8.2
Heavy-flavour jet modelling in non-$t\bar{t}H$ processes	< ±1	< ±1	< ±1	< ±1	< ±1	±13

Theory uncertainties effects: H→γγ

- H→γγ couplings analysis categorises events globally (no staged classification per production mode) using BDTs
  - Many different variables are used in the categorisation: to characterise diphoton or diphoton plus jet(s) system, number of the different objects and its kinematics (jets, leptons, muons, top quarks), etc…
- The number of signal events in a category (c) is modelled as

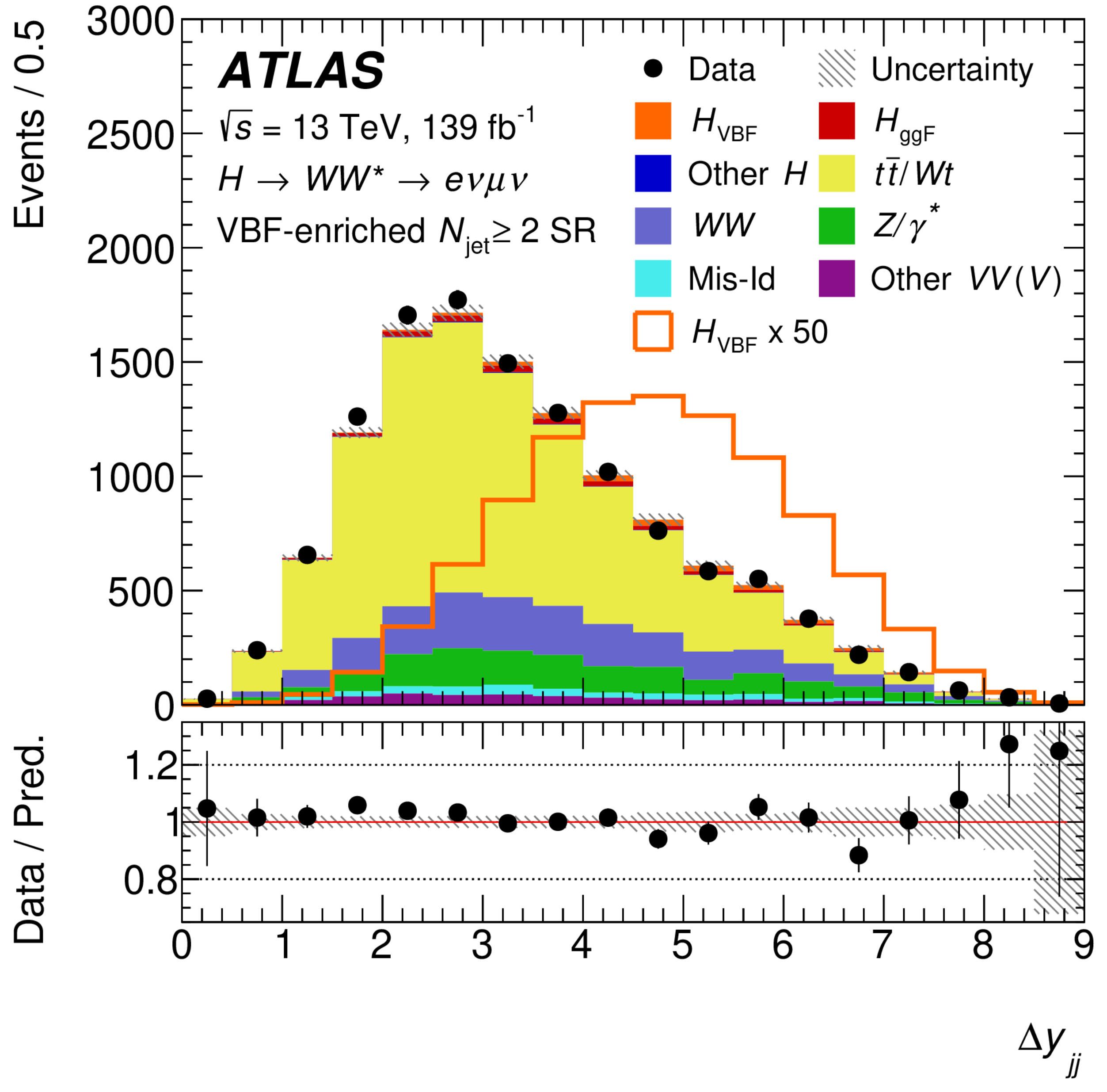
$$s_c(\boldsymbol{\mu},\boldsymbol{\theta}) = \sum_t \mu_t \cdot s_{tc}(\boldsymbol{\theta}) = \sum_t \mu_t \cdot L(\theta_{lumi}) \cdot \sigma_t^{\gamma\gamma}(\boldsymbol{\theta}_{sig}, \theta_{BR}) \cdot \epsilon_{ct}(\boldsymbol{\theta}_{sig})$$

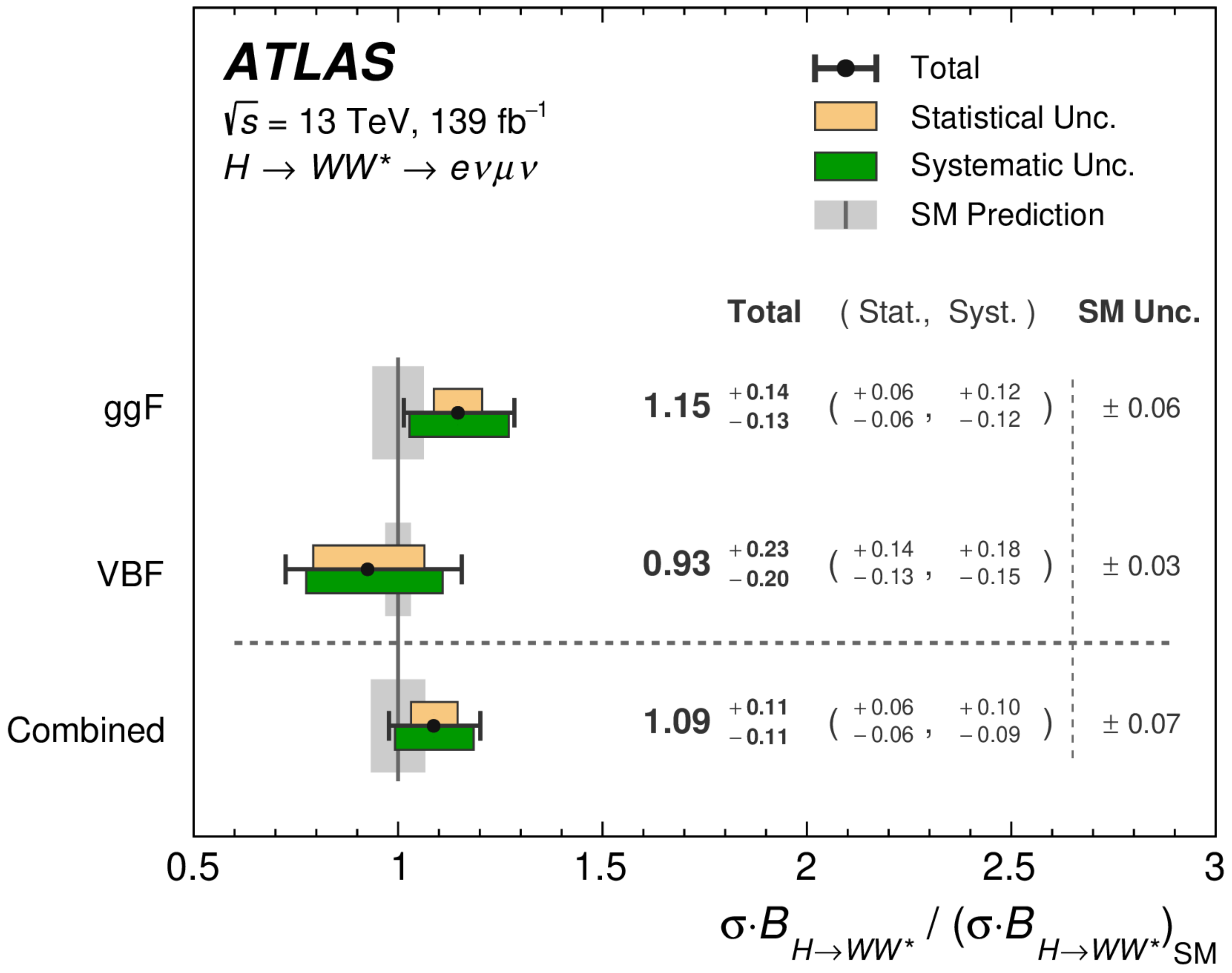
- The only part that is varied for the parton shower uncertainty is ϵ_{tc} with both generators normalised to the same cross section.
- For each STXS bin $\sigma^{\gamma\gamma}{}_t$ is computed using the STXS bin acceptances from Powheg+Pythia8 considering EW corrections provided by this group.
- Categories are merged statistically in the likelihood and their weight in the final result depend on signal to background ratio

Having reco categories split by variables with different PS modelling and with different S/B ratio increase the PS uncertainty in inclusive VBF measurement

Theory uncertainties effects: H→WW

- **Measurements of ggF and VBF in H→WW**
  - Higgs boson cross sections in ggF and VBF and in 11 STXS bins
  - Analysis performed in 4 channels depending of N_{jet}
  - Deep NN to identify VBF topology in events with central jet veto, outside (the jet rapidity gap) lepton veto, and m_{jj}>120 GeV
- For VBF signals, the comparison of the different generators for the matrix-element matching and for the PS result in the largest uncertainties in the measurement



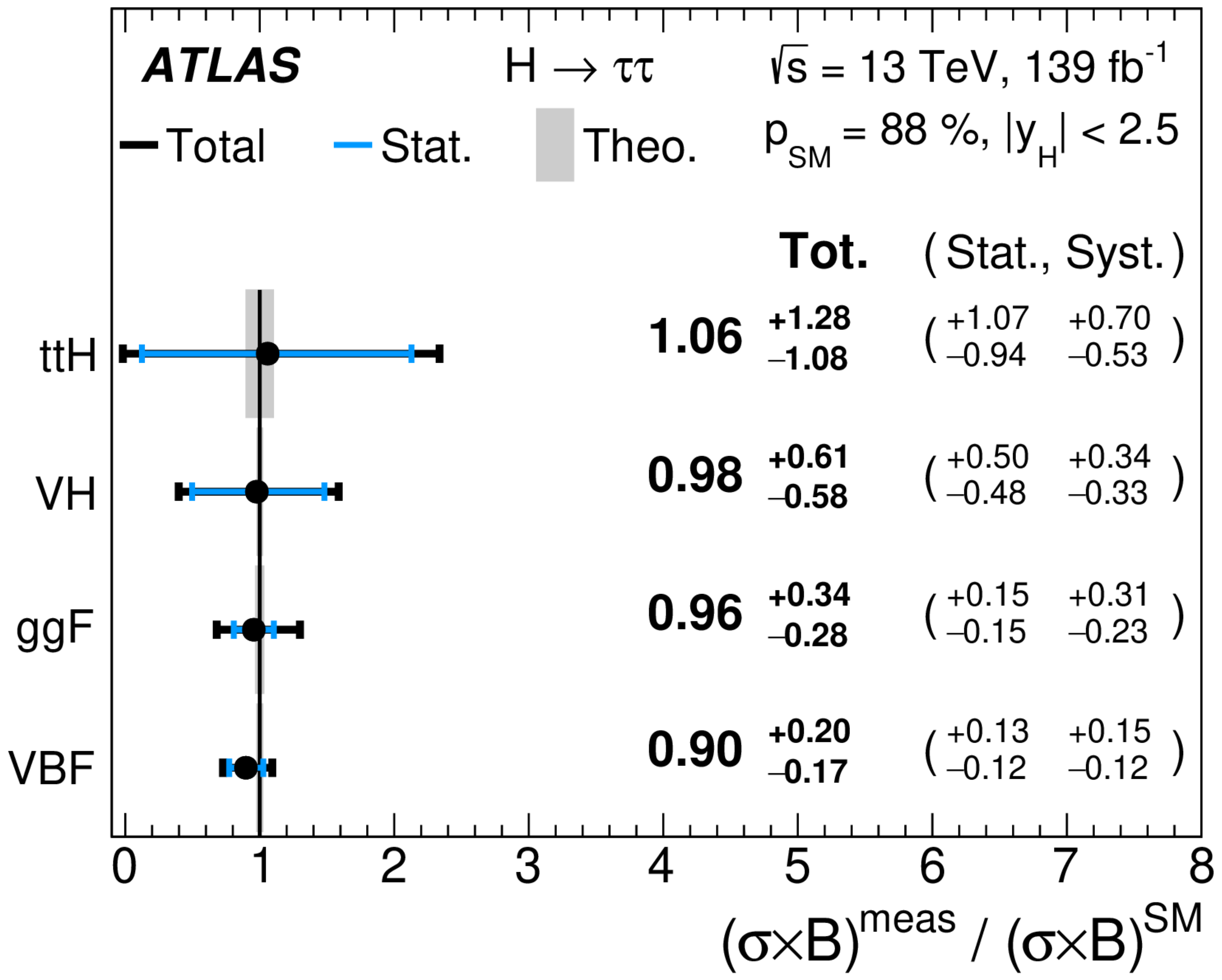


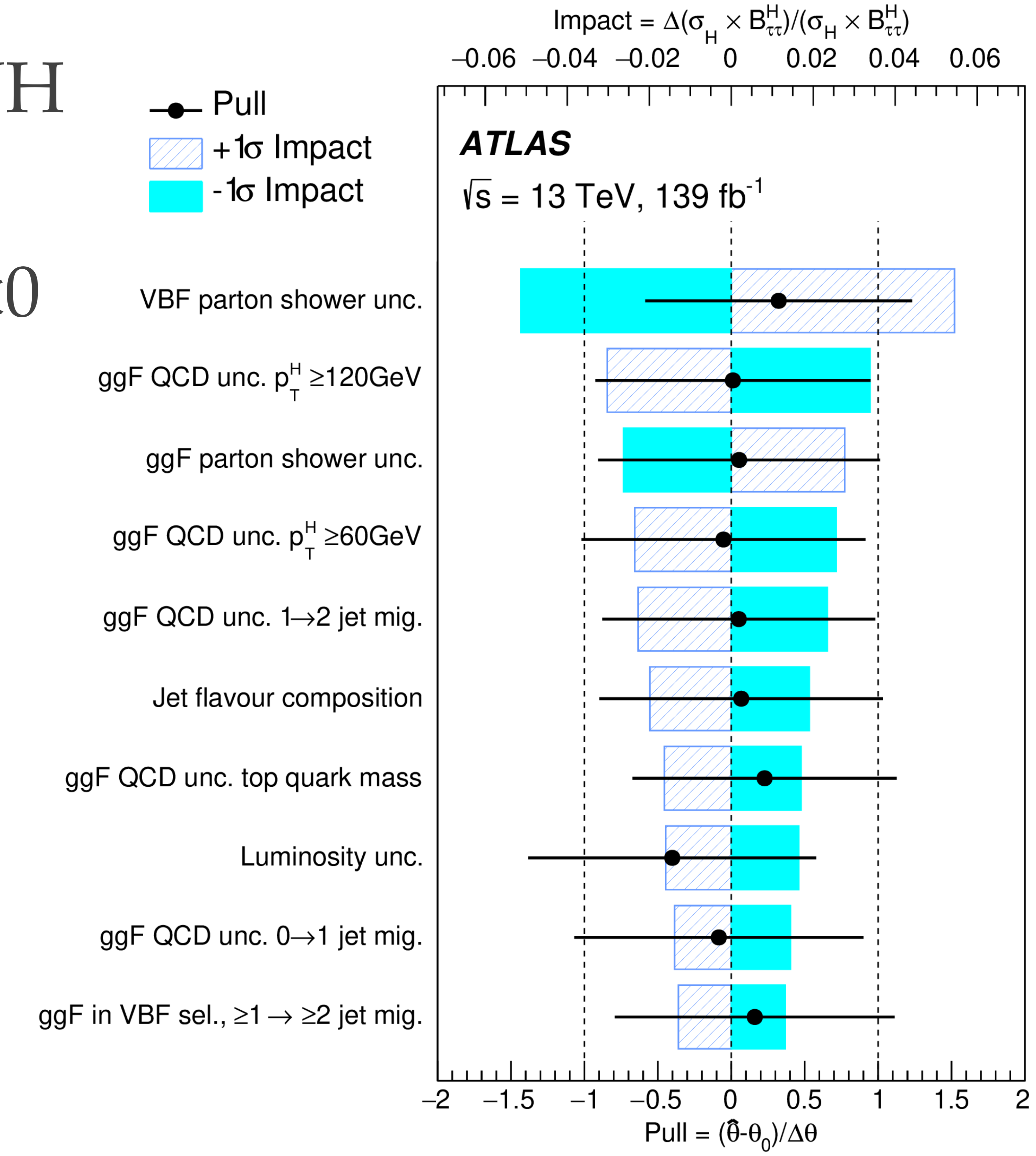
Source	$\frac{\Delta\sigma_{\text{ggF+VBF}}\cdot\mathcal{B}_{H\to WW^*}}{\sigma_{\text{ggF+VBF}}\cdot\mathcal{B}_{H\to WW^*}}$ [%]	$\frac{\Delta\sigma_{\text{ggF}}\cdot\mathcal{B}_{H\to WW^*}}{\sigma_{\text{ggF}}\cdot\mathcal{B}_{H\to WW^*}}$ [%]	$\frac{\Delta\sigma_{\text{VBF}}\cdot\mathcal{B}_{H\to WW^*}}{\sigma_{\text{VBF}}\cdot\mathcal{B}_{H\to WW^*}}$ [%]
Data statistical uncertainties	4.6	5.1	15
Total systematic uncertainties	9.5	11	18
Theoretical uncertainties	6.8	7.8	16
ggF	3.8	4.3	4.6
VBF	3.2	0.7	12

Theory uncertainties effects: H→ττ

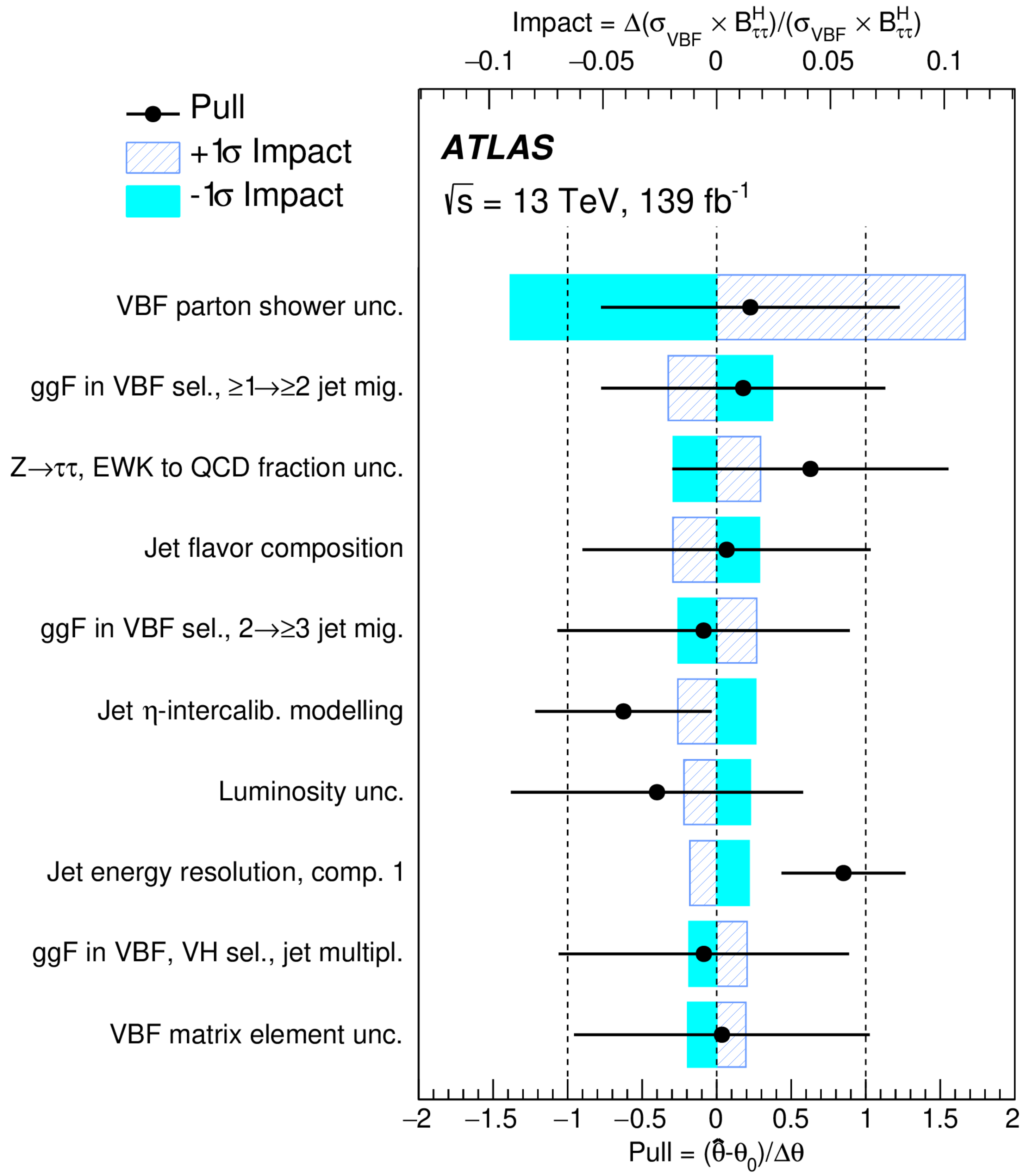
Measurements of cross sections in H→ττ

- pp→H→ττ cross sections in ggF, VBF, WH and ttH and in 9 STXS bins
- VBF selection with m_{jj}>350 GeV, $\eta_{j1} \times \eta_{j2}<0$ and $|\Delta\eta_{jj}|>3.5$
- BDT to select VBF (pure category) and other category for the rest of events





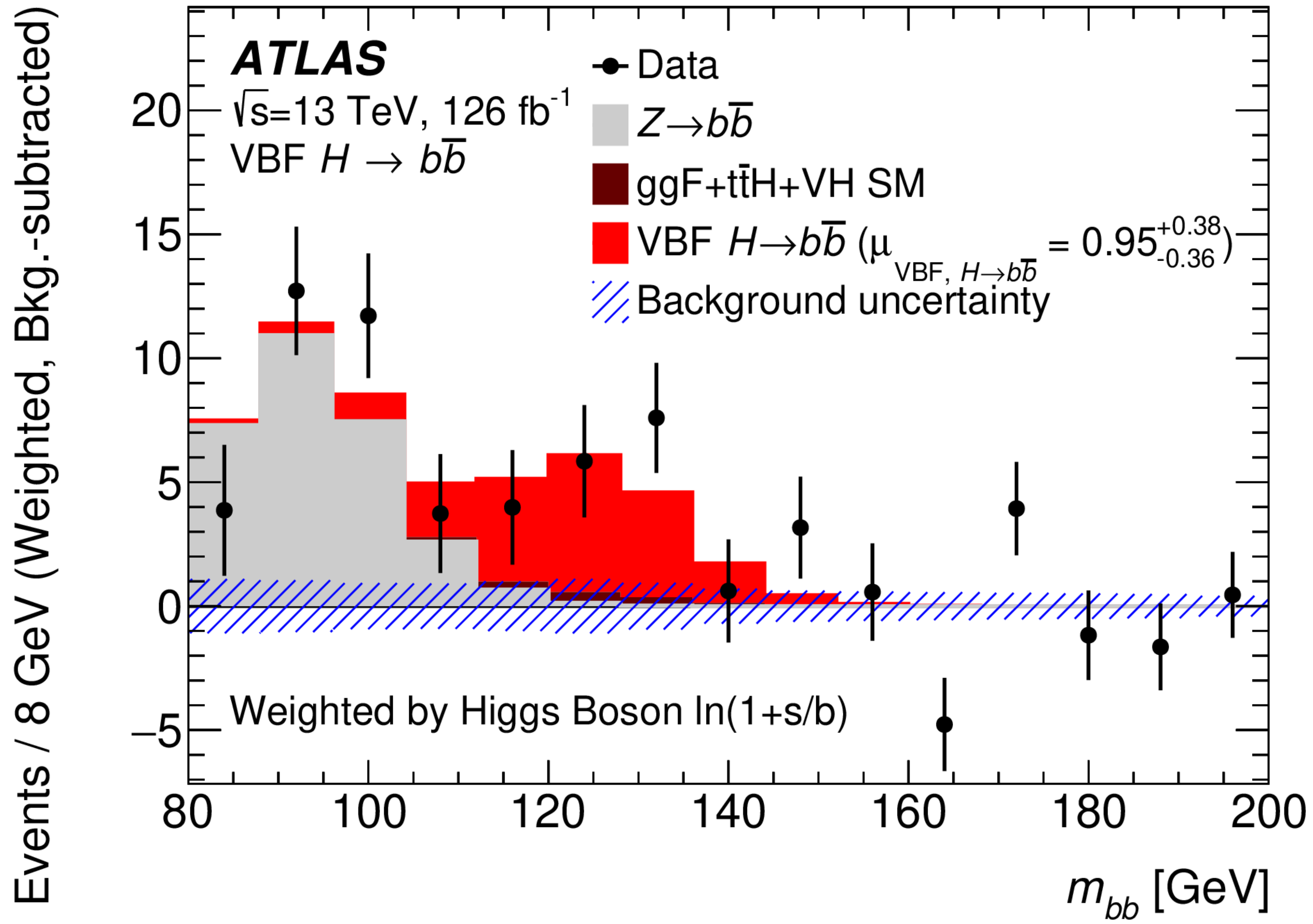
Ranking of uncertainties for the total production cross sections: Most of the leading ones are of theoretical nature



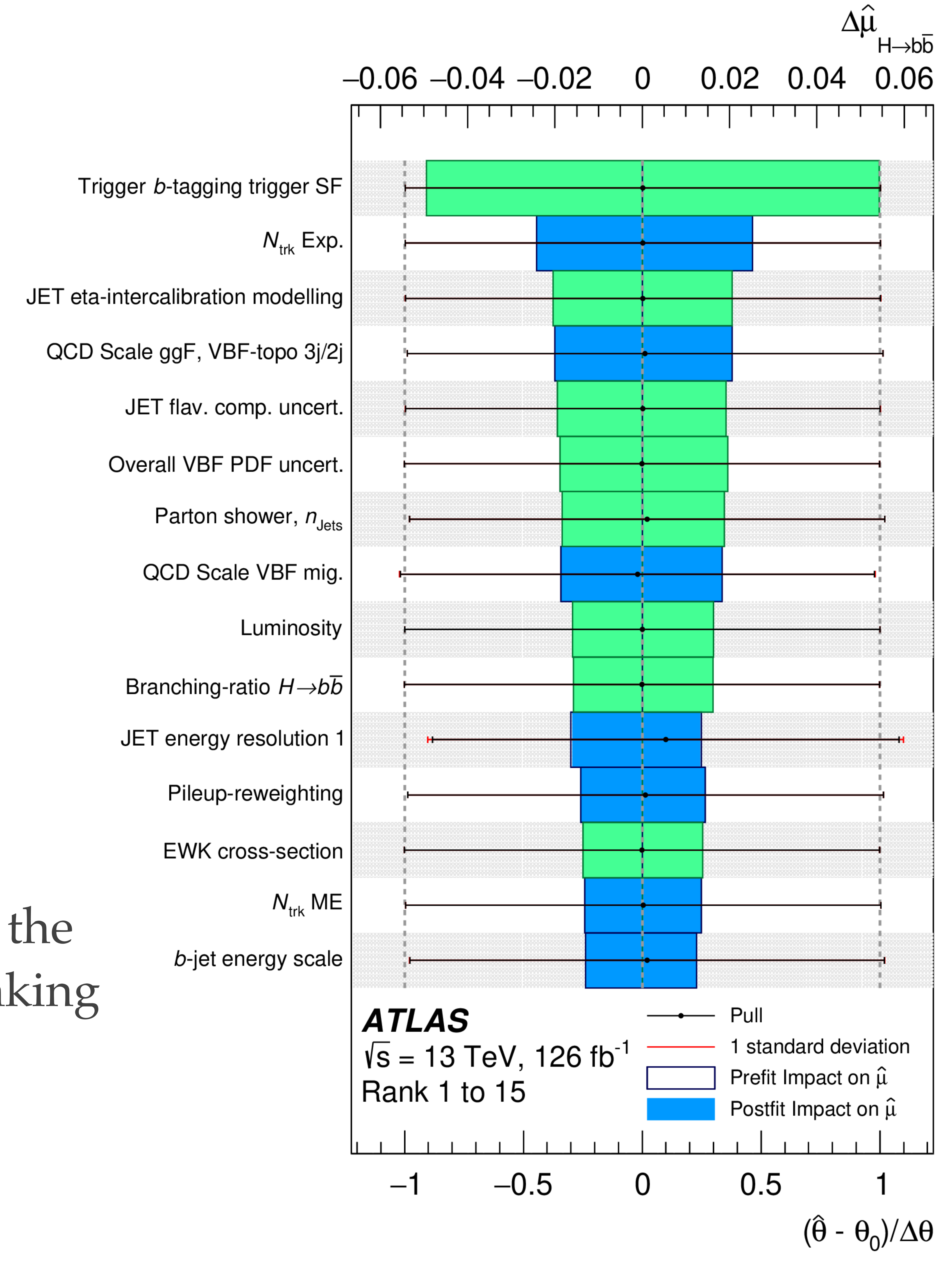
Ranking of uncertainties for the VBF production cross sections: Clear lead of the VBF PS uncertainty

Theory uncertainties effects: H→bb

- **VBF H→bb measurement**
  - Two channels: forward (one high pT jet in 3.2<|η_j|<4.5) and central (no forward and m_{jj} > 600 GeV)
  - 5 signal regions in each channel determined by ANN output
  - Pythia8 vs Herwig7 uncertainties propagated through the analysis with weights determined from the ratios of mbb and Njet variables at particle level (Njet enters the ANN while the signal is extracted from a binned likelihood fit to mbb)

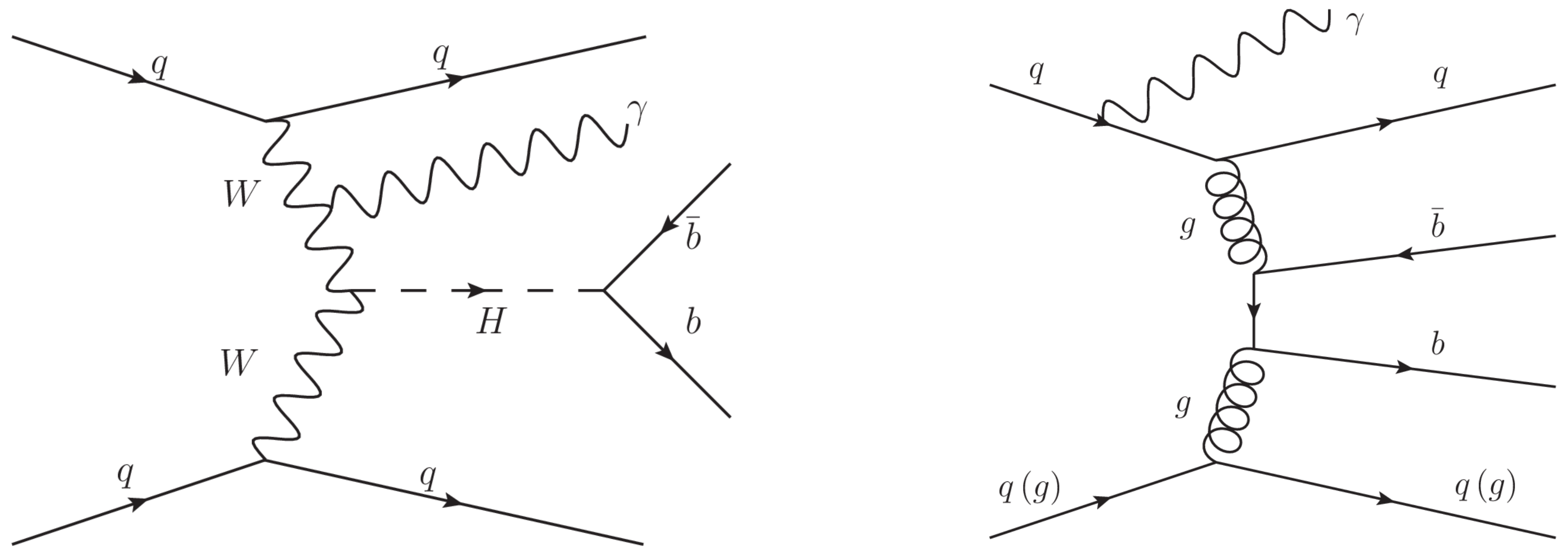


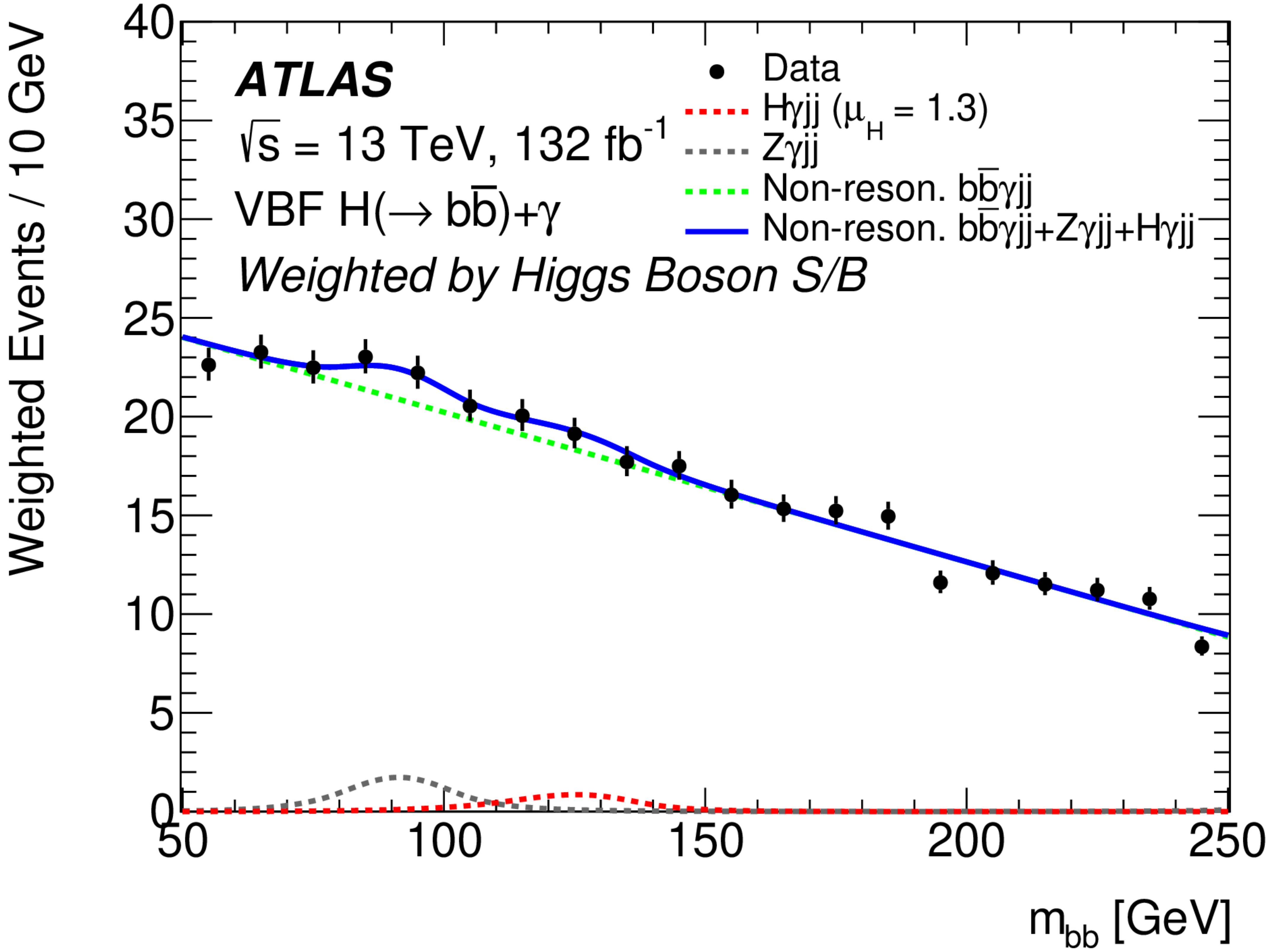
No theory uncertainty in the top 3 of the ranking



Theory uncertainties effects: H→bb

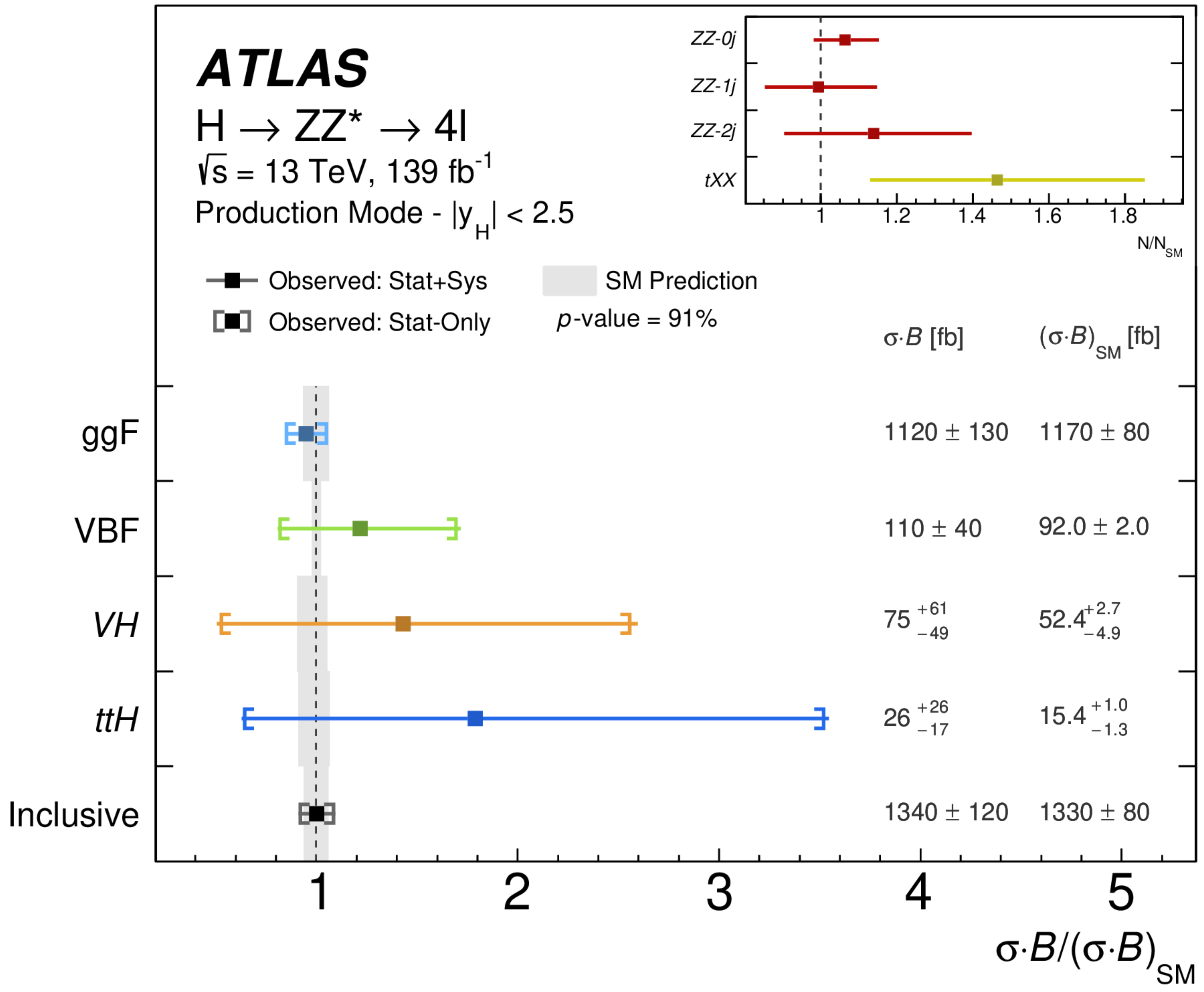
- **Search for VBF + γ in H->bb**
  - VBF is the main production mode in Hγ
  - Z-boson fusion and multi jet non-resonant background suppressed due to interference effects.
  - $m_{jj} > 800$ GeV to select VBF phase space.
  - Categorisation using BDT with variables not correlated to mbb
  - Theory uncertainties from scale, PDF, α_s variations and variations of 'HardScaleFactor' in Herwig 7.1
  - Uncertainties dominated by spurious signal
  - No theory limiting factor, but better sensitivity expected at the end of Run3 in which several STXS-like bins could be potentially measured
  - Could be the STXS scheme adapted for these type of signals?
    - More Hγ measurements can potentially be searched in other channels in HL-LHC

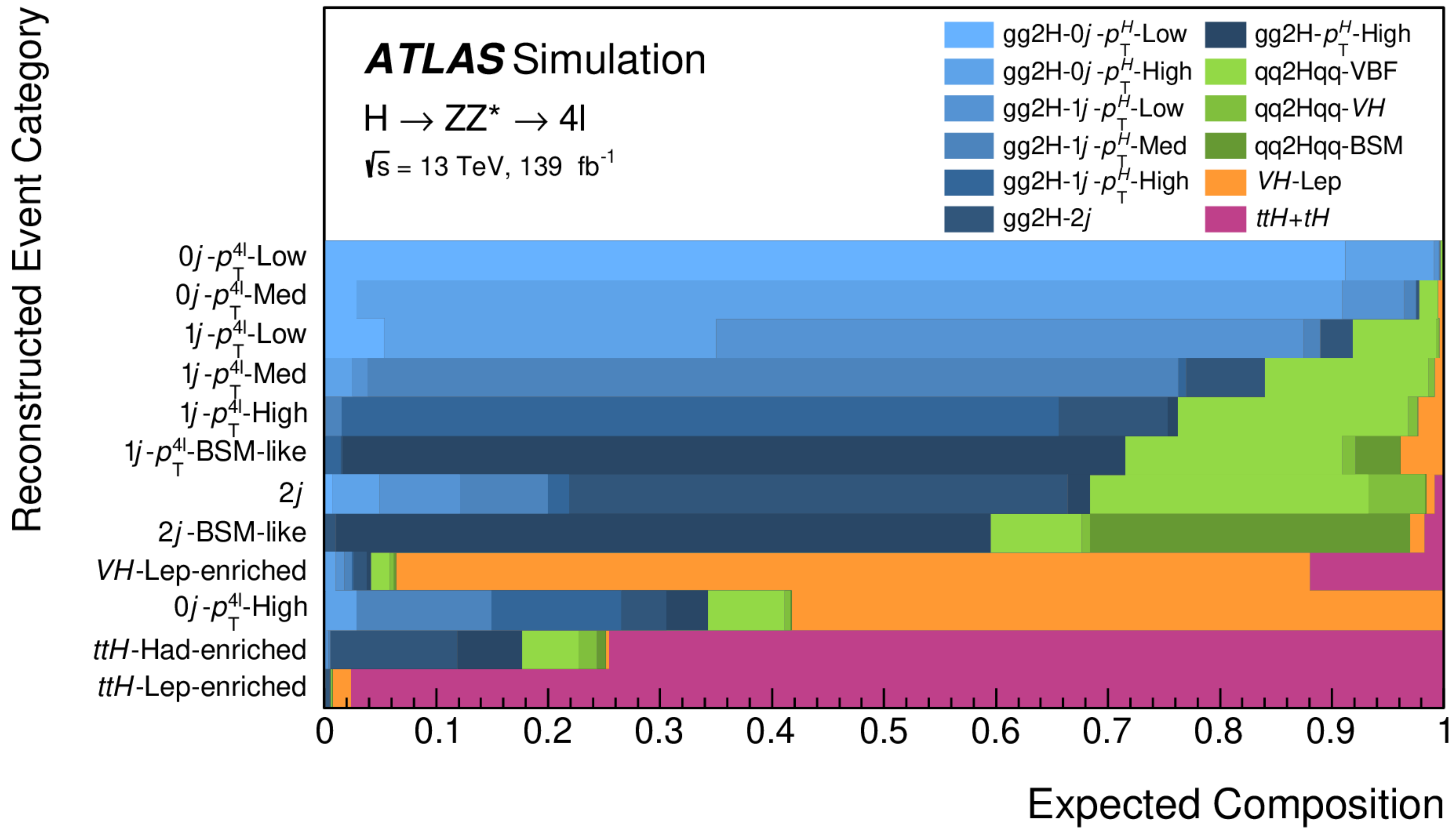




Theory uncertainties effects: H→4l

- **Couplings measurement in H→4l**
  - Measurement of inclusive, production mode and 12 exclusive fiducial volumes cross sections
  - Staged categorisation starting from ttH, then VH and then separated according to number of jets. NN inside the categories to improved sensitivity
  - PS uncertainties with Pythia8 vs Herwig7 and AZNLO tune variations





- For the VBF production bin, the dominant uncertainties are related to the parton shower modelling and the jet energy scale and resolution

VBF simulation in ATLAS

- Baseline generation is done with Powheg+Pythia8
  - Default Powheg configuration + complex pole scheme activated
  - LHE files produced for all Higgs groups
  - Higgs decayed thought the Pythia8 parton shower. In all of them dipole recoil in Pythia is turned on
  - As alternative shower, the same LHE files are showered with Herwig7 angular shower

- Alternative samples done with MG5_aMC@NLO+Herwig7
  - Using either HC_NLO_X0_UFO-no_b_mass or loop_qcd_qed_sm_Gmu models (no significant differences observed). pTj>15 GeV at ME level
  - Only Herwig7 shower since shower counter-terms assuming dipole recoil not available at the time of the samples generation

- ATLAS-like setup used to check comparisons at particle level using the Rivet routine from: arXiv:2003.12435
  - Powheg setups only showing statistical uncertainty, MG5_aMC showing envelope of muR,muF variations

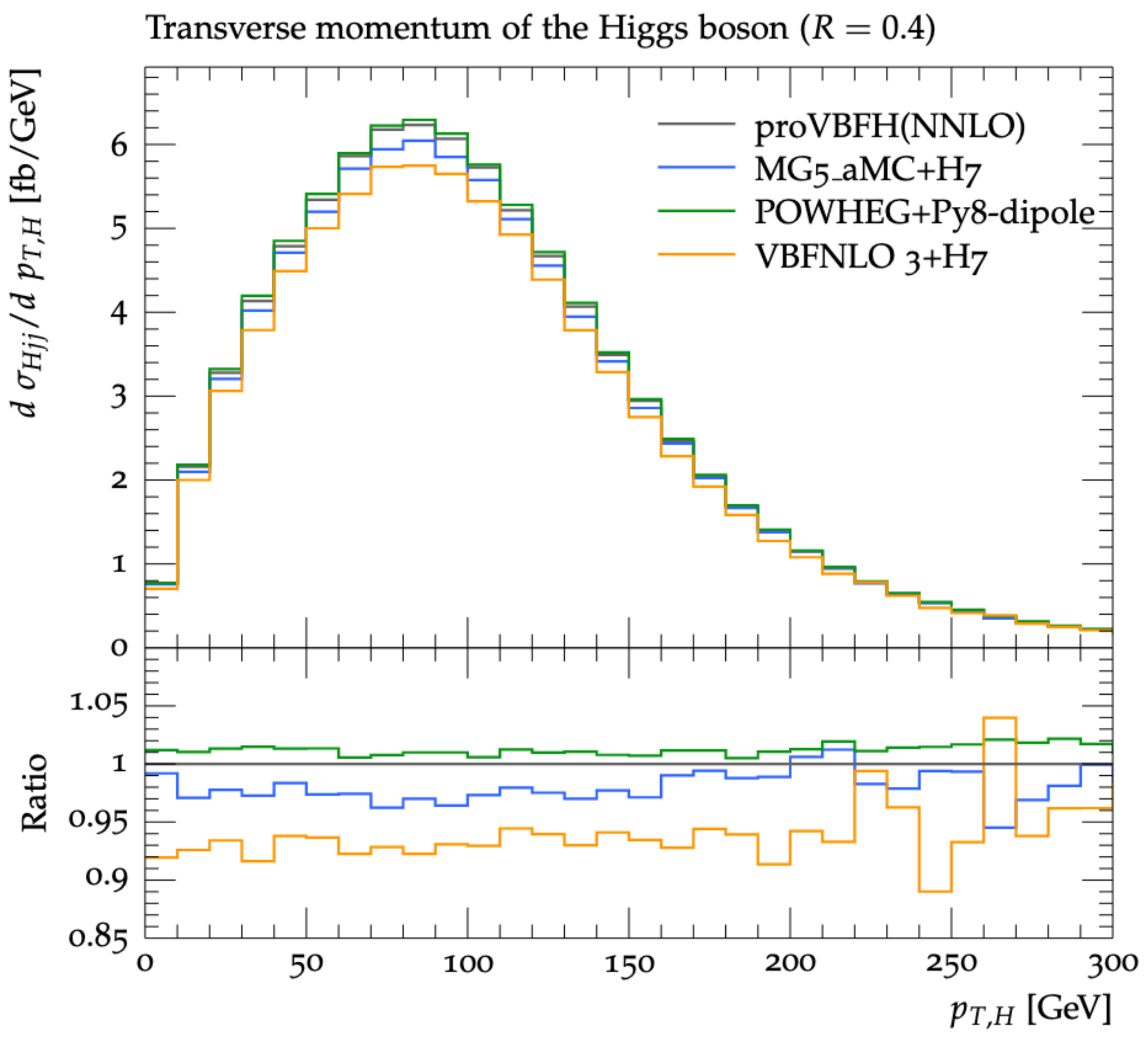
VBF simulation in ATLAS

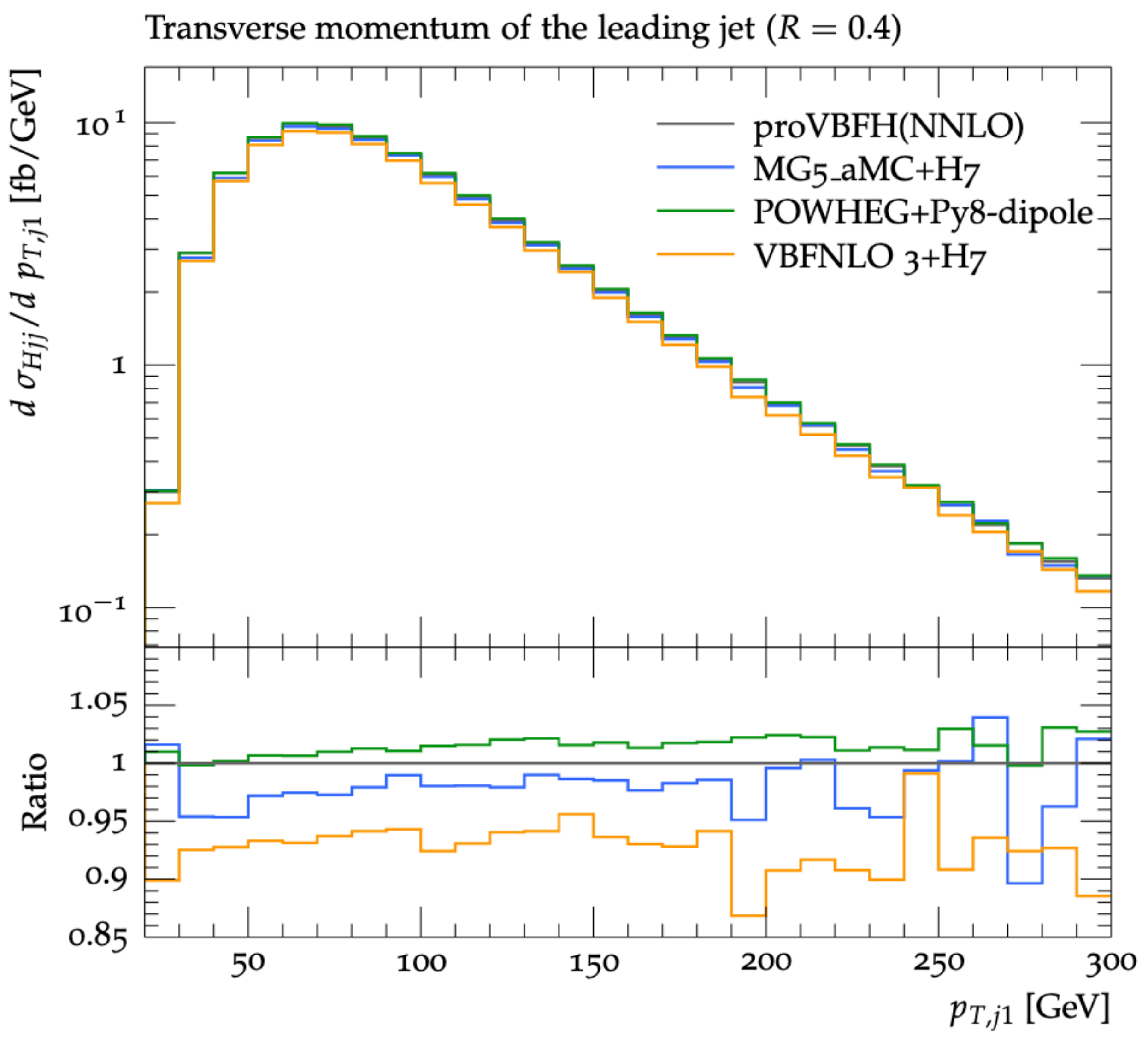
Observations in ATLAS-like setups:

Similar shape in pTH between all generators in VBF region. Differences for pTH<100 GeV in MG5_aMC

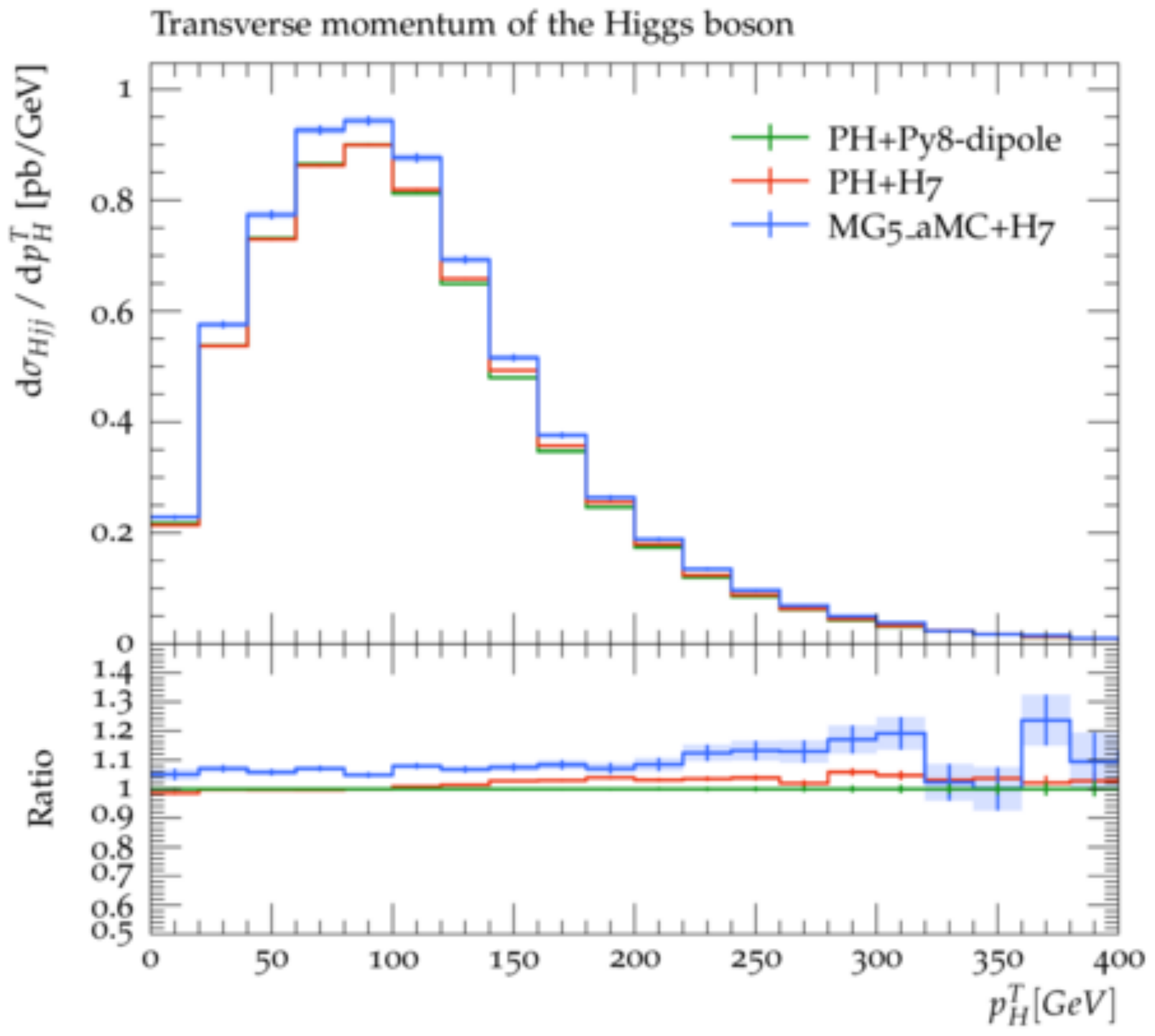
Discrepancies (10-20%) at low pT_j1 between different showers

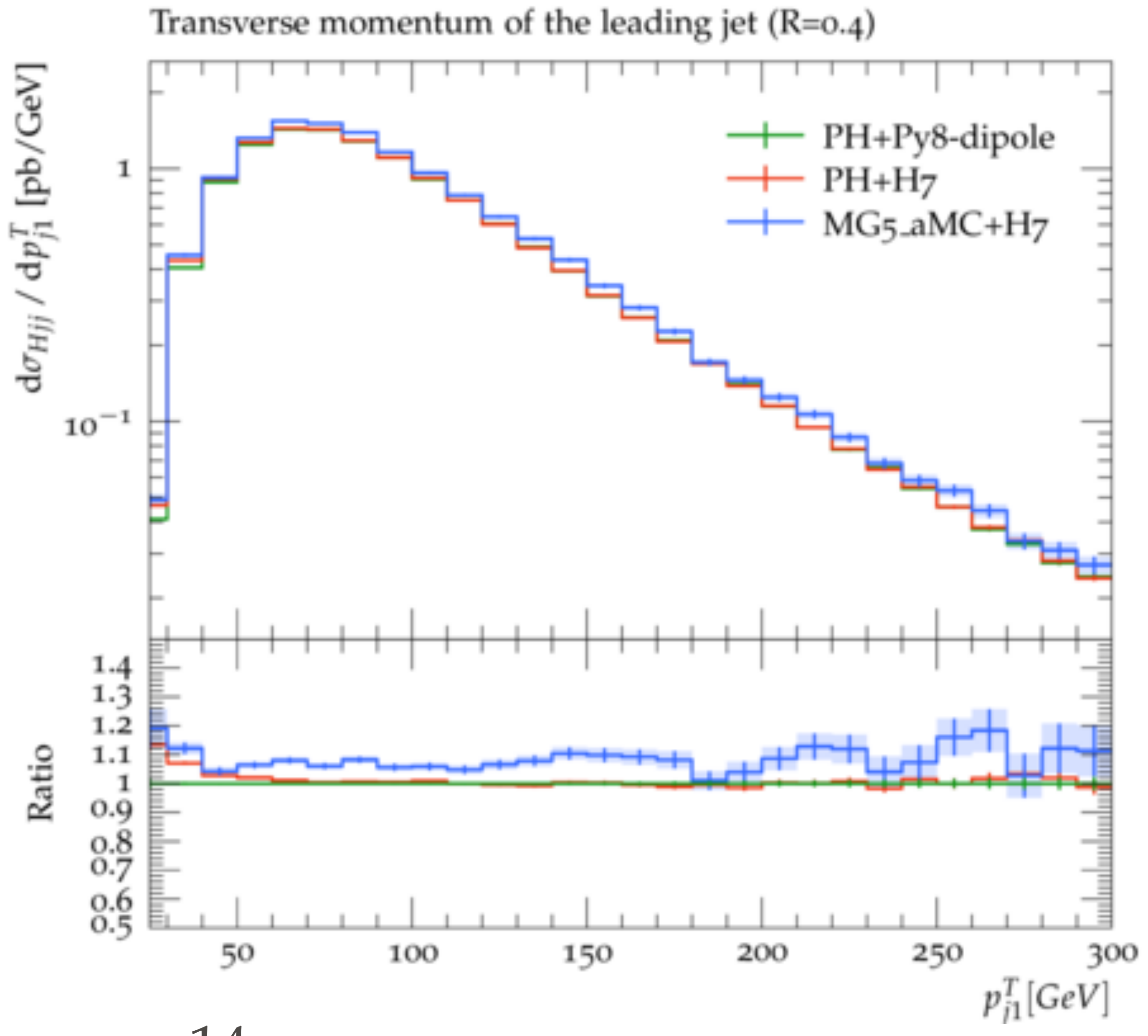
arXiv:2003.12435



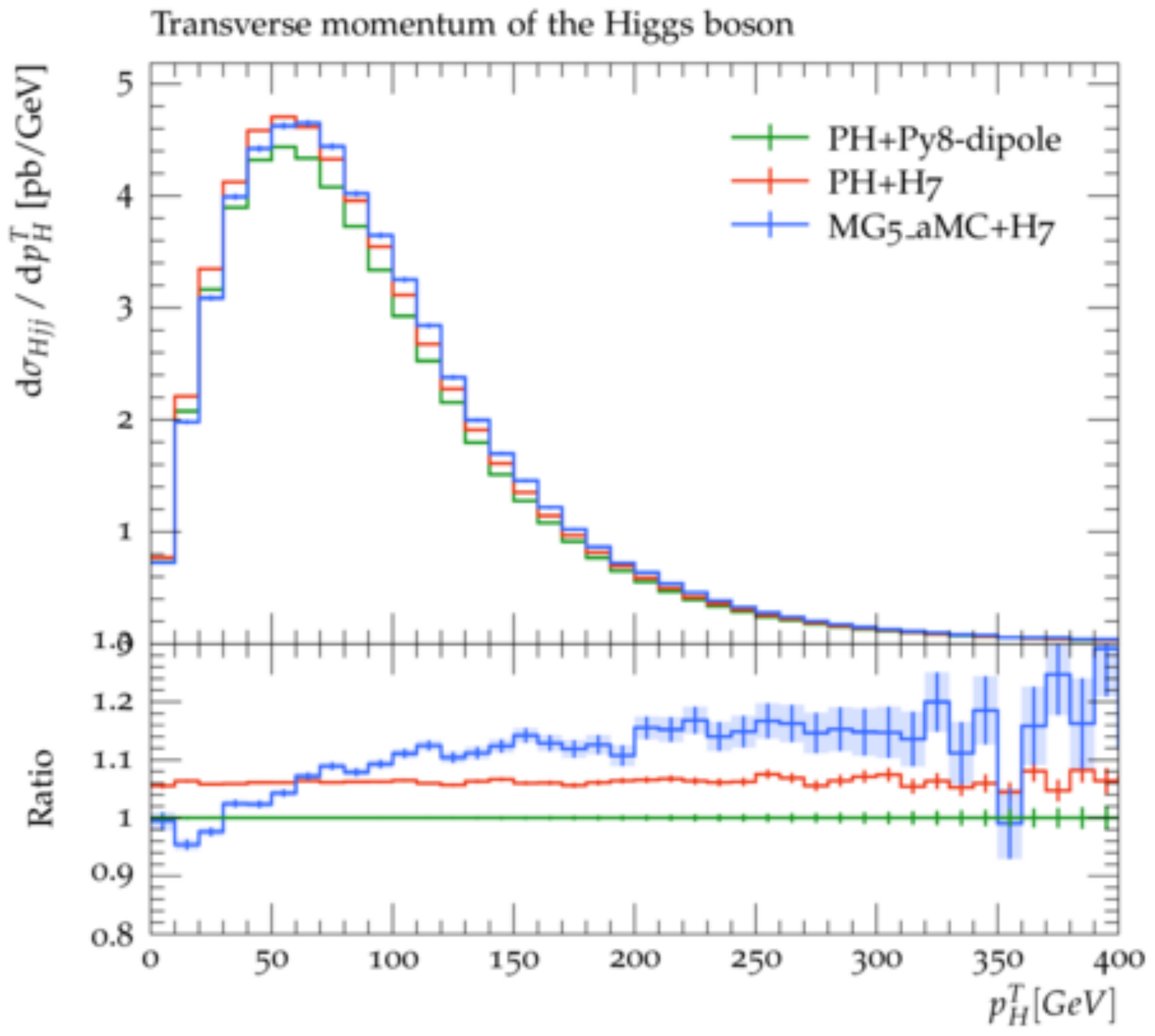


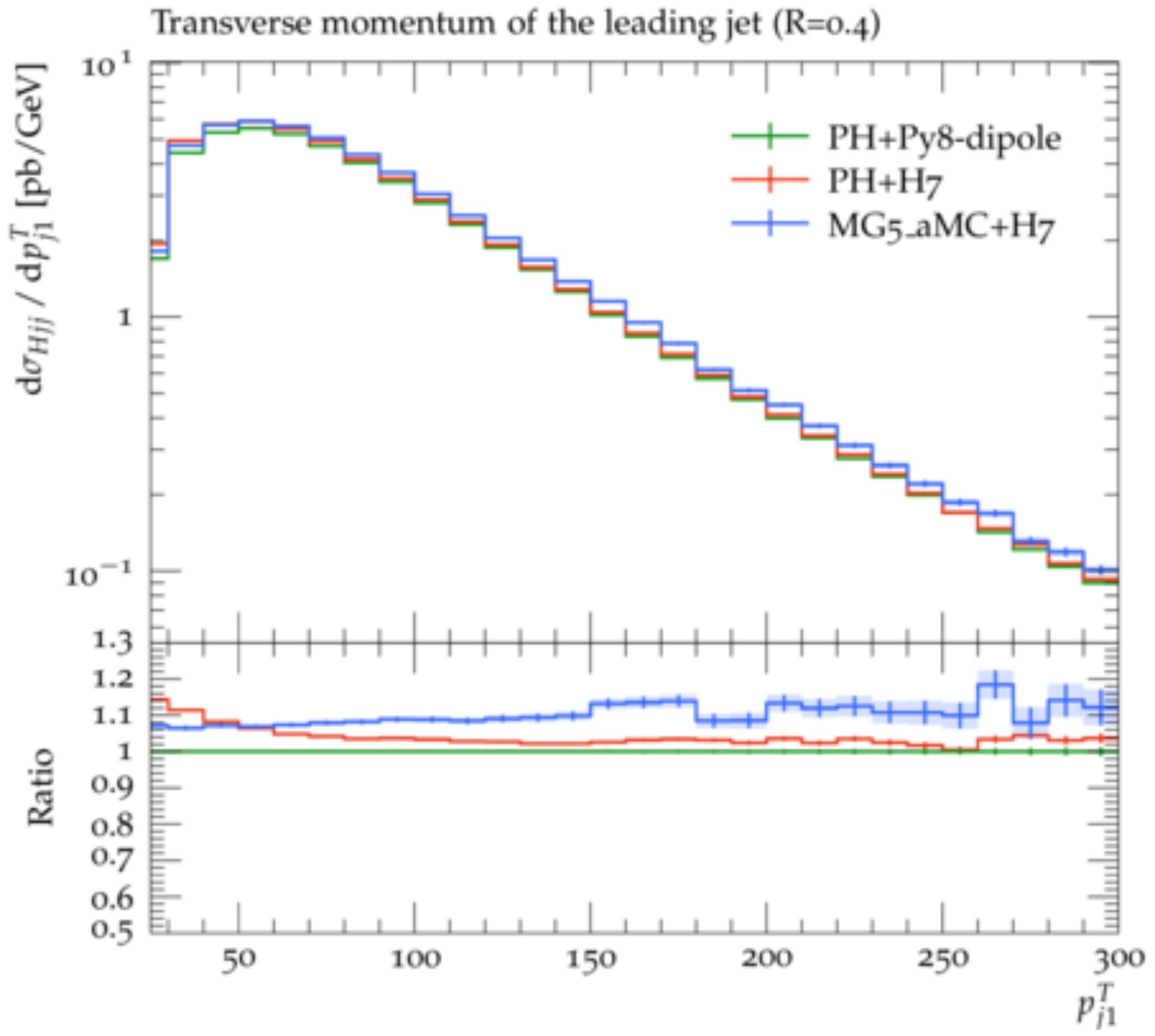
ATLAS (VBF sel.)





ATLAS (no VBF sel.)

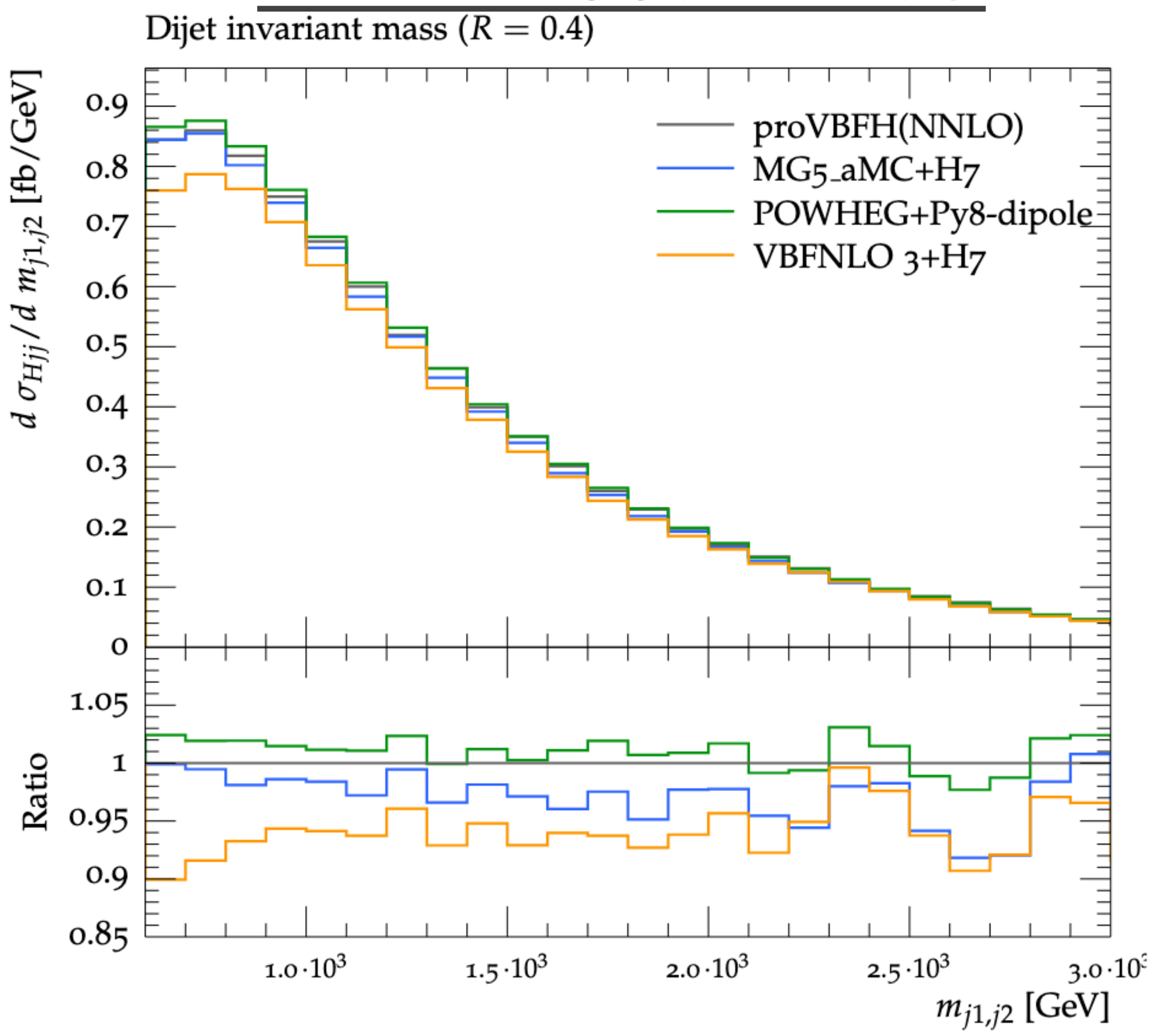




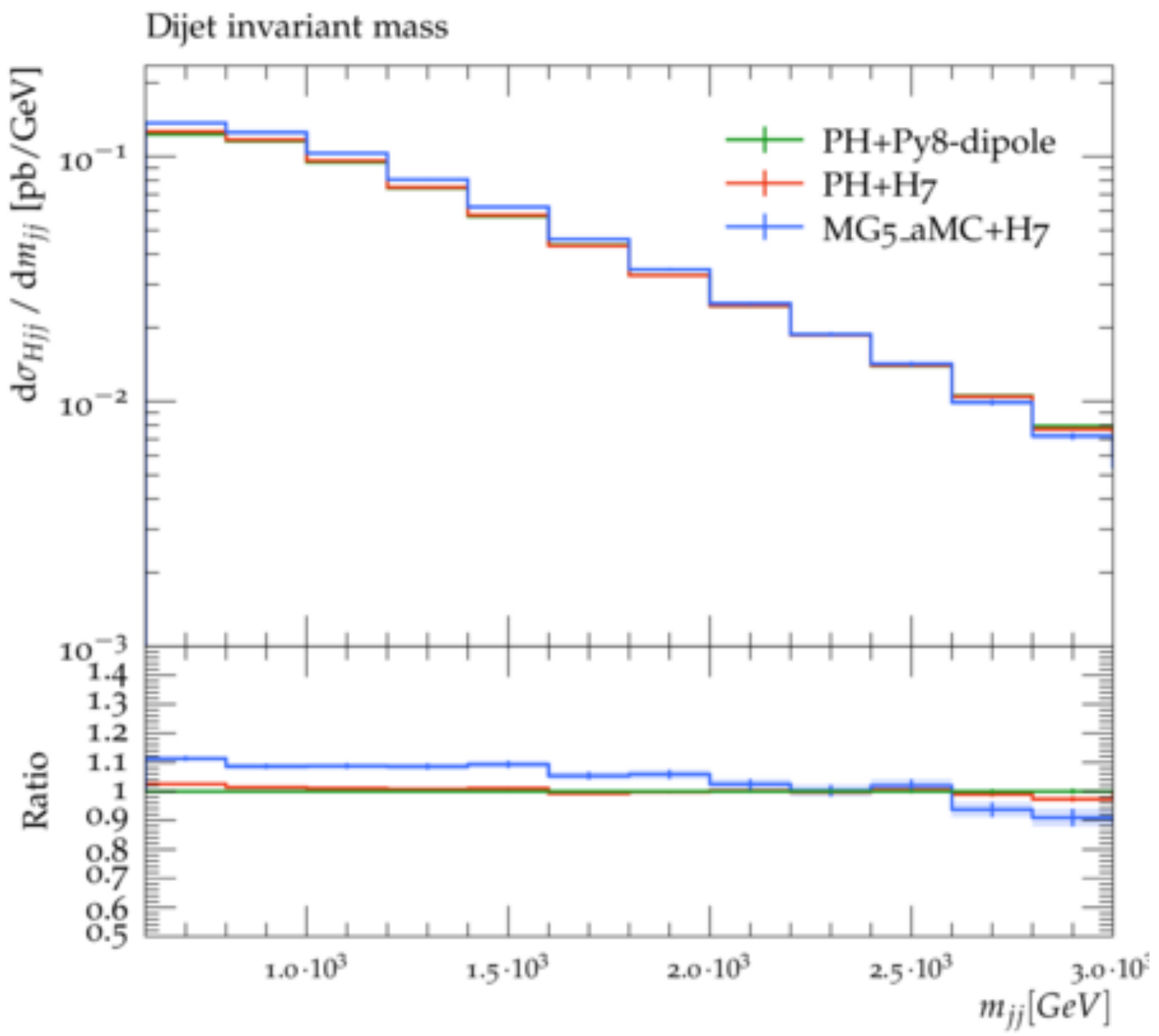
VBF simulation in ATLAS

Discrepancies (up to 10%) at low mjj between different showers, but very good agreement in VBF phase-space. Differences in shape between PH and MG5

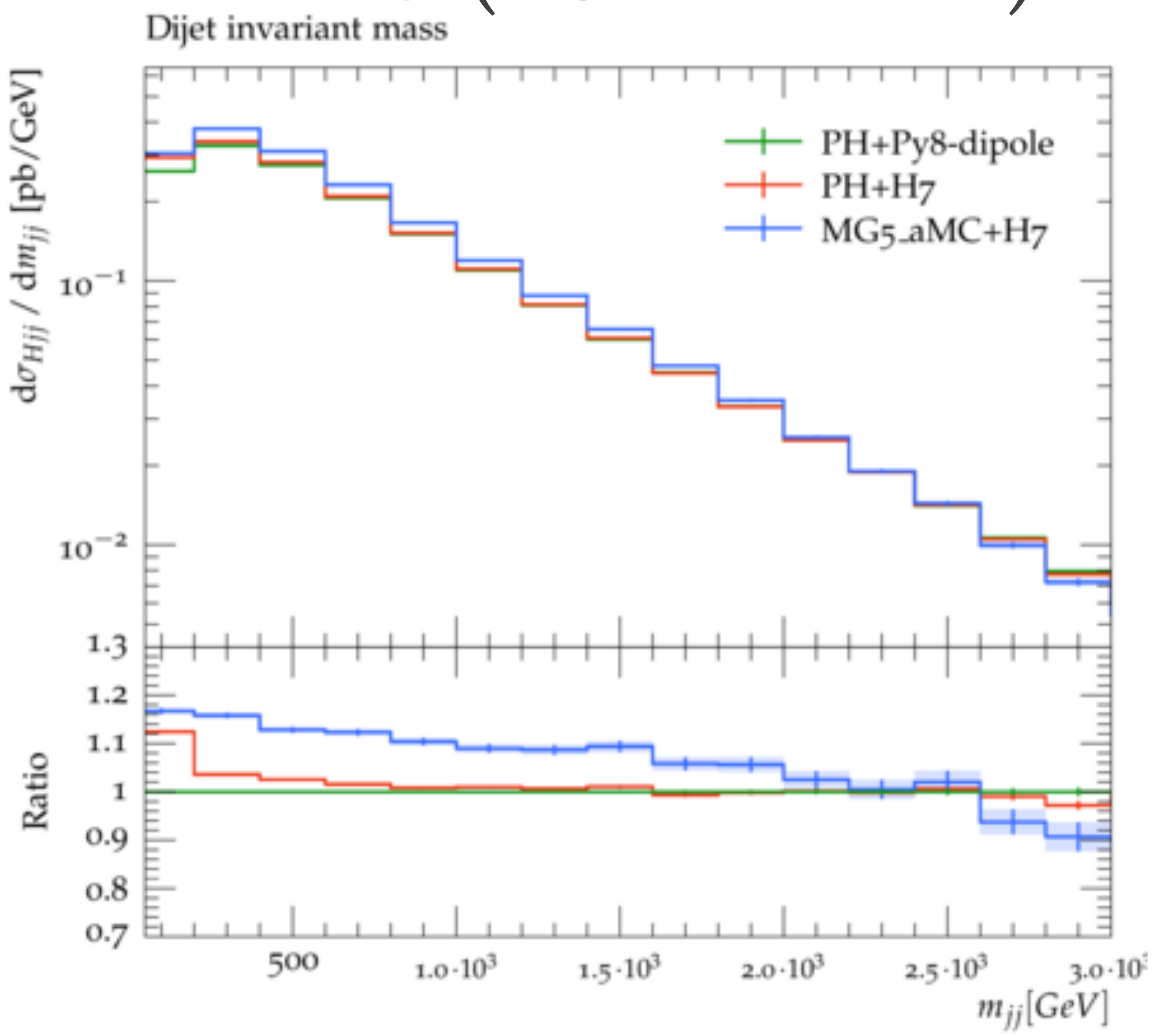
arXiv:2003.12435



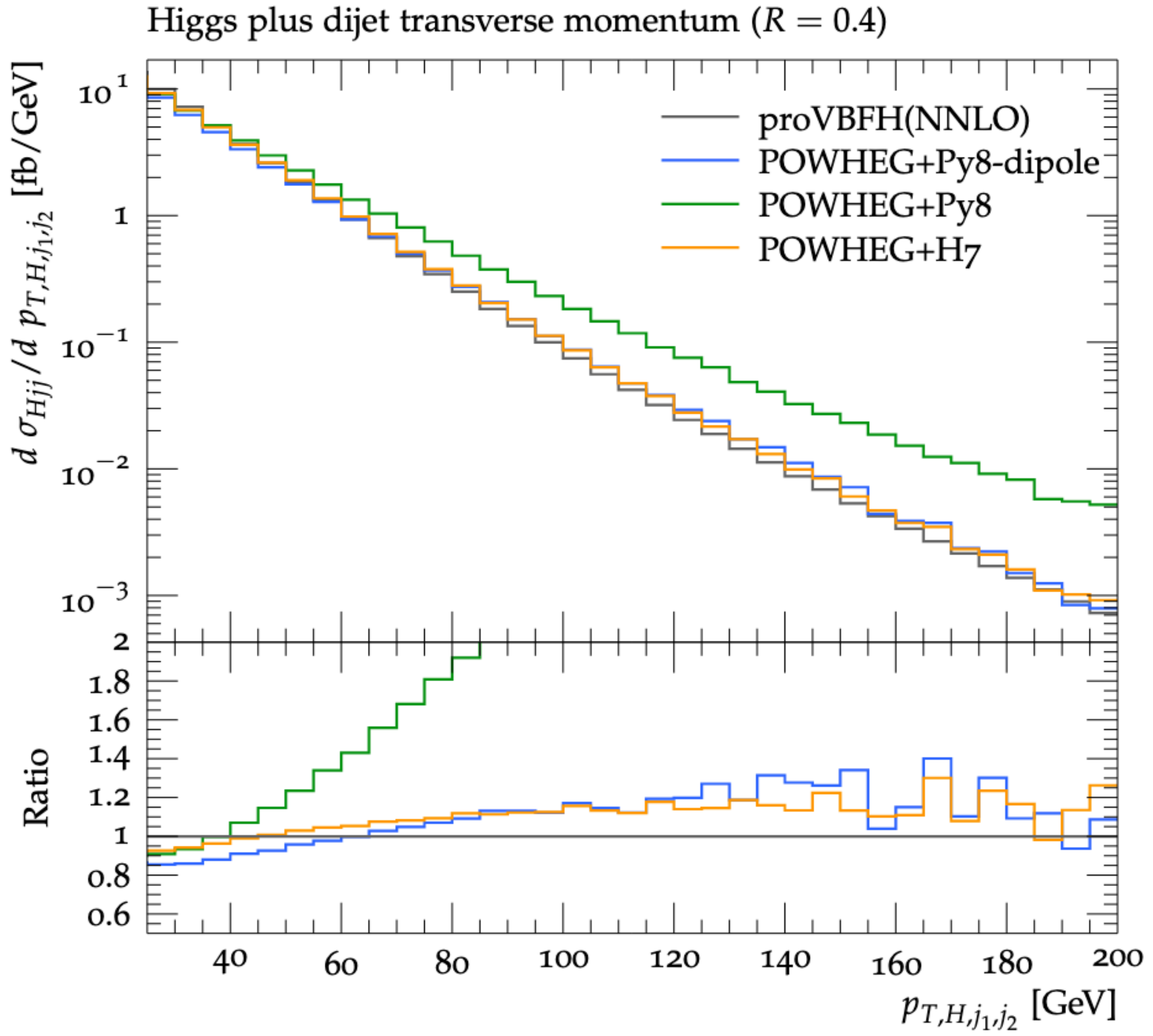
ATLAS (VBF sel.)

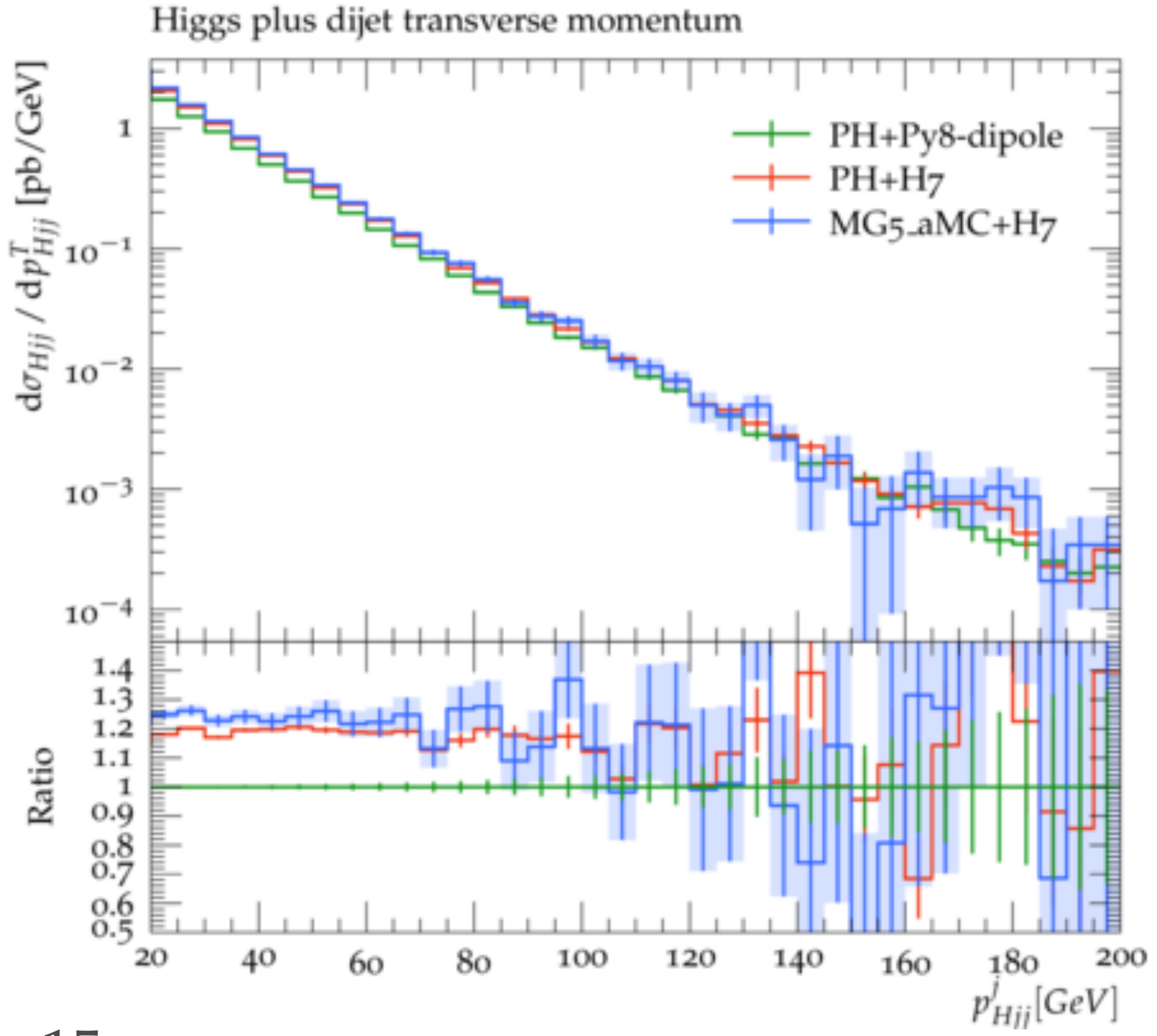


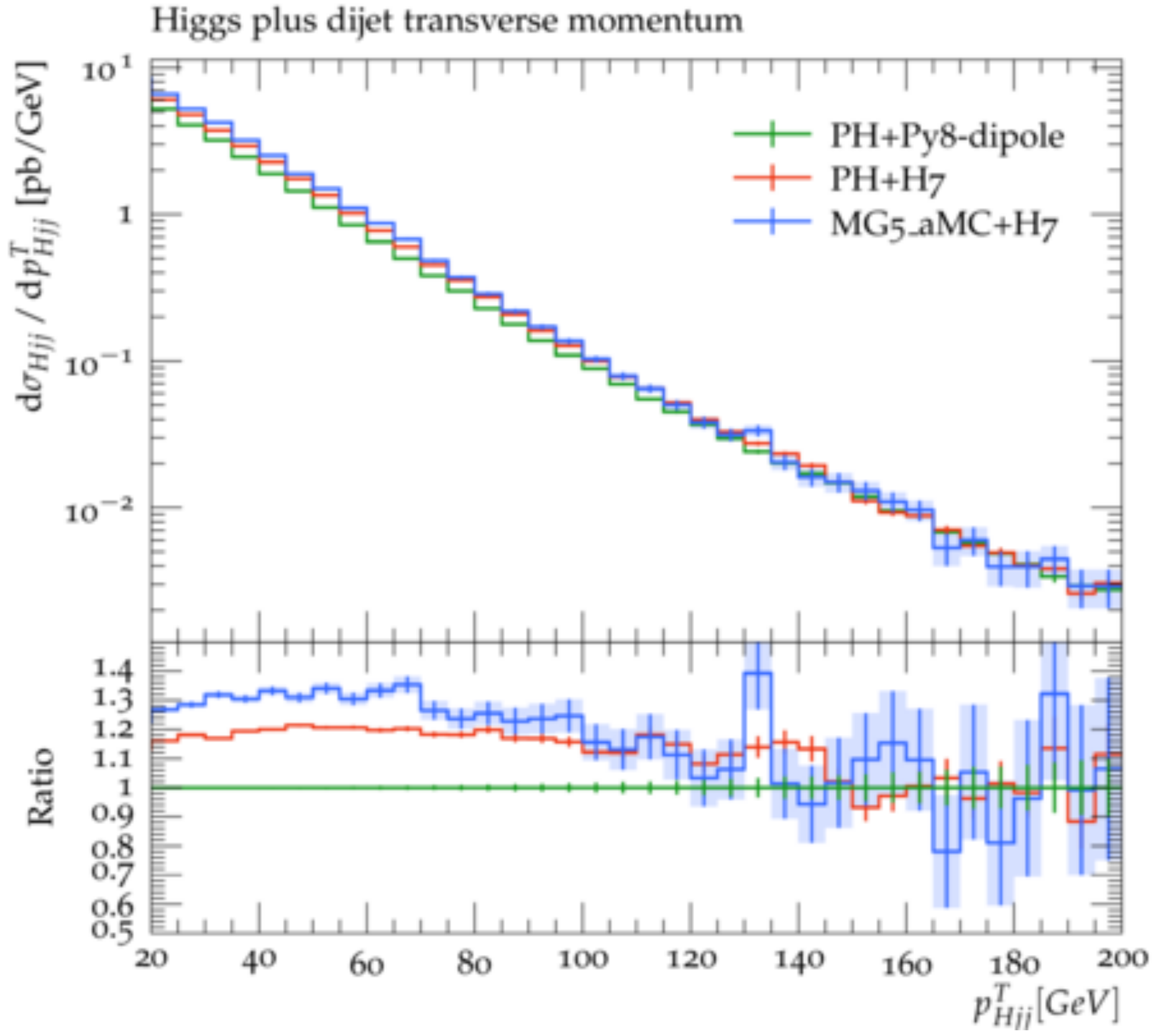
ATLAS (no VBF sel.)



Larger number of events with 3 jets passing the cuts in Herwig7 than in Pythia8. Difference in shape when no VBF selection is applied







Conclusions

- **Missing higher-order VBF uncertainties play a subdominant role in Higgs analyses**
- **Parton shower uncertainties are by far the most limiting uncertainty when measuring VBF:**
  - Leading uncertainty in most of the analyses with the only exception of H->bb
  - Largest uncertainty in $H\to\gamma\gamma$ (is the only one targeting the full VBF phase space at reco level without requirements in Njets, mjj or other variables)
  - No large pulls observed
- **Impact of each analysis can depend on analysis strategy and categorisation, but an overall >~10% observed**
  - Important to have a consistent modelling in the PS in variables that are used to improve the sensitivity of the analyses
  - Full correlation in combinations
- **Experiments behind theory developments**
  - We are happy to explore different venues in synergy with theorists (and apply it to analyses once recommendations are provided)

Back up

AZNLO tune variations

AZNLO: *designed for the Powheg+Pythia8 NLO+PS generator, and provide a very good description of ISR in the low and medium p_T region*

Measurements of the Z/γ_* boson transverse momentum distribution (and ϕ^*_η angular correlation) in pp collisions at $\sqrt{s}$ = 7 TeV

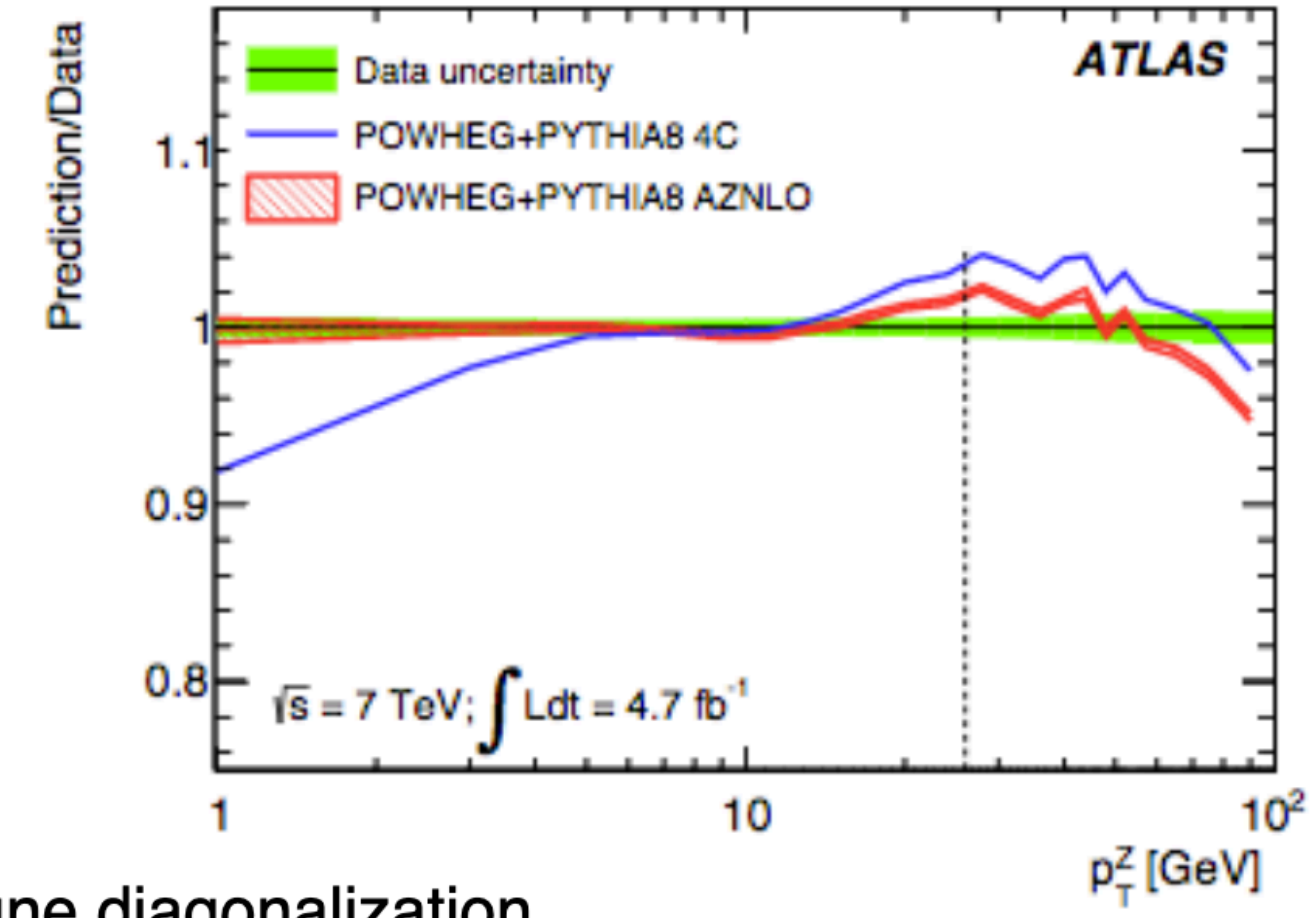
JHEP, 09:145, 2014

1211.6899

Strategy for the Powheg+Pythia8 tune → tunes performed for **$p_T(Z)<26$GeV** and $\phi^*_\eta<0.29$ (best description of the tuning parameters)

The tuning only varies the ISR shower cut-off and the primordial k_T in Pythia8: essentially constrained by data $p_T(Z)<12$GeV - not affected by tuning upper bound (plus MPI parameters)

Tuned predictions agree with the measured XS within 2% for $p_T(Z)<50$GeV



C. Pandini

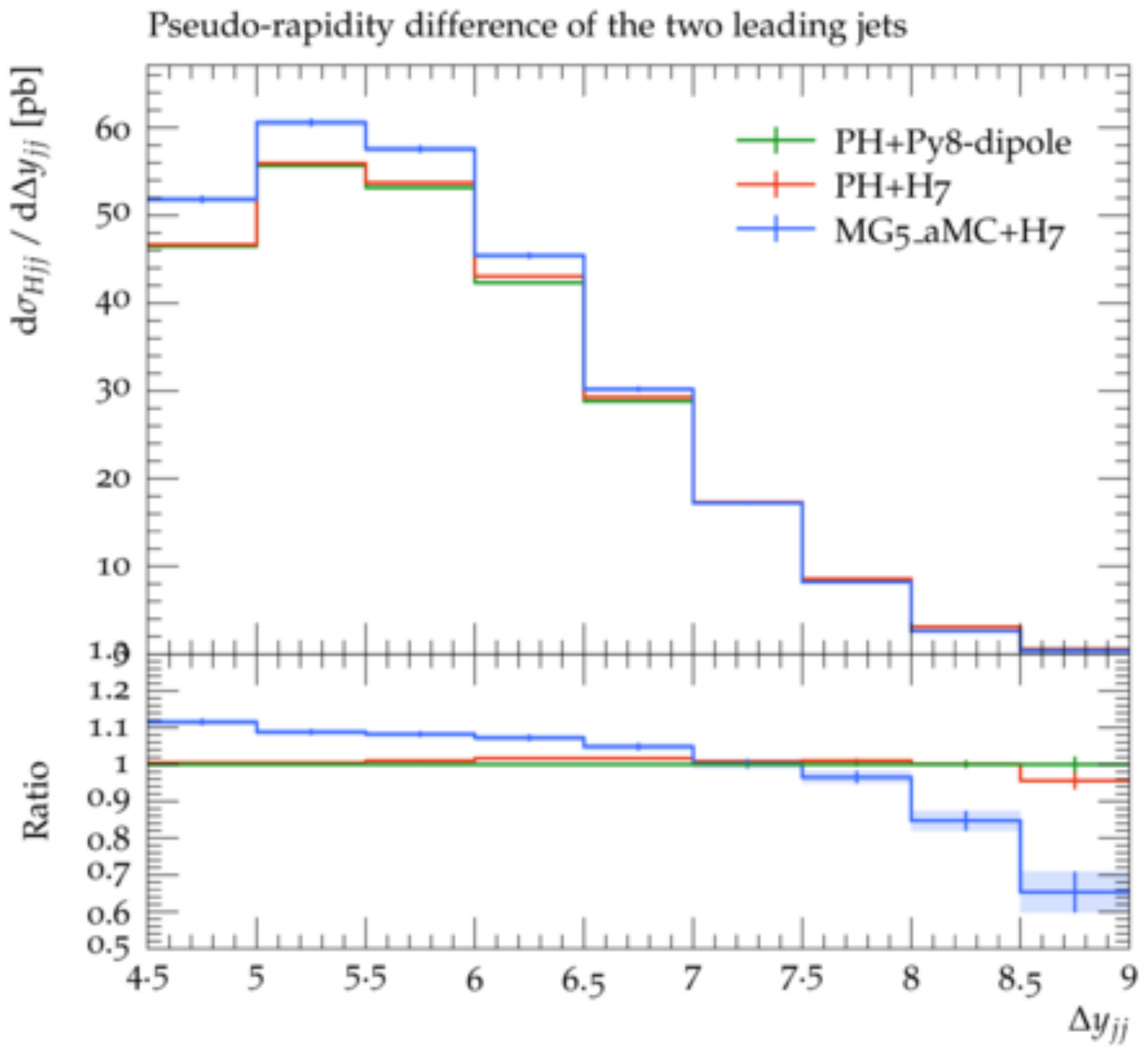
"Eigentune variations":

only covering ISR/primordial-k_T variations;
ren. scale variations for FSR, and MPI cut-off paramaters are recommended to cover the full range of UE/PS/MPI uncertainties

- VAR1,VAR2: eigentune diagonalization
- MPIUp, MPIDown
- FSRUp, FSRDown

VBF simulation in ATLAS

ATLAS (VBF sel.)



ATLAS (no VBF sel.)