ATLAS and CMS Perspectives on MC for SM Higgs Physics

ATLAS-CMS MC Generators Worksohp
3rd May 2016

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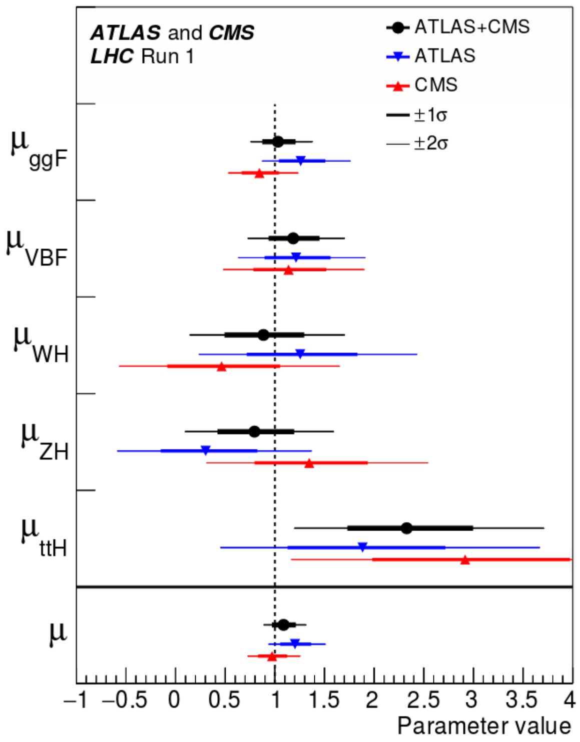
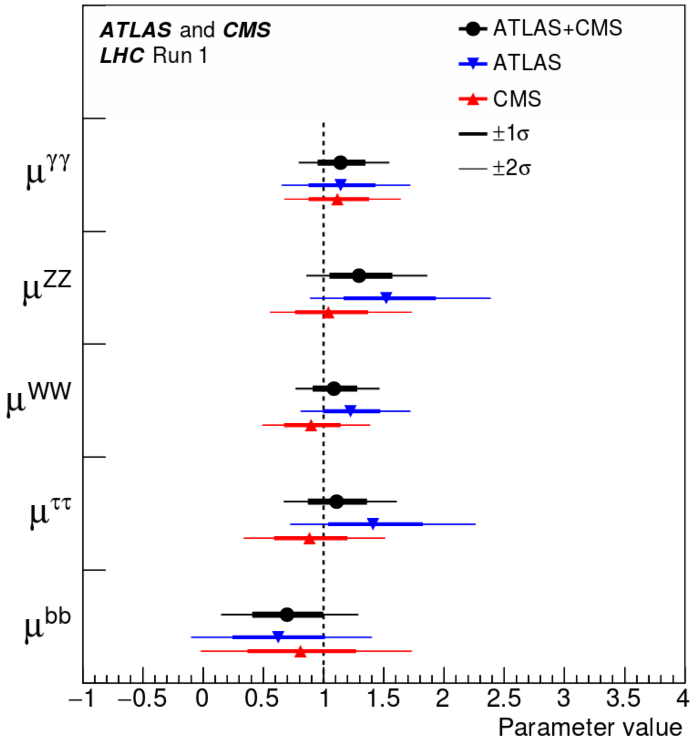
University of Florida

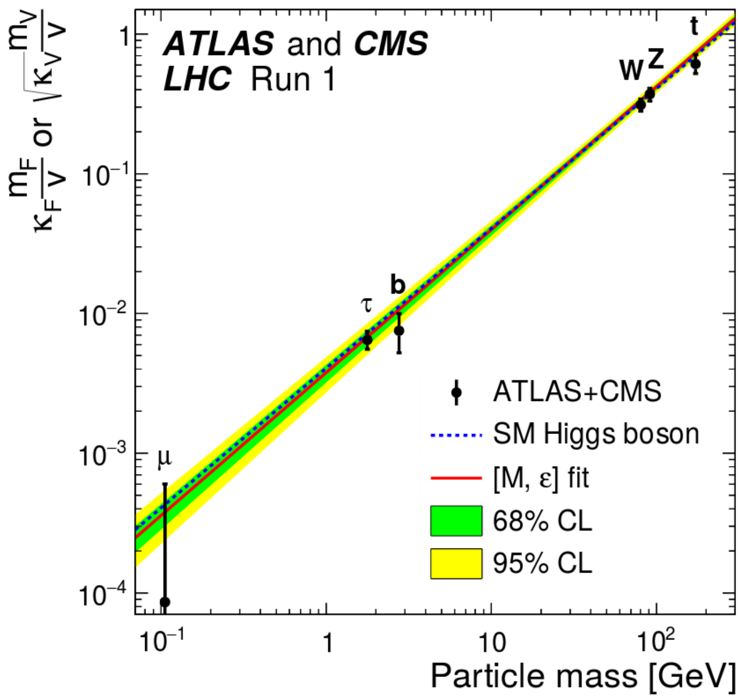
On Behalf of the ATLAS and CMS Collaborations

Where We Stood Before Run 2

- The discovery of the 125 GeV Higgs boson was the triumph of LHC Run 1
- No evidence for deviations from the SM, but large uncertainties

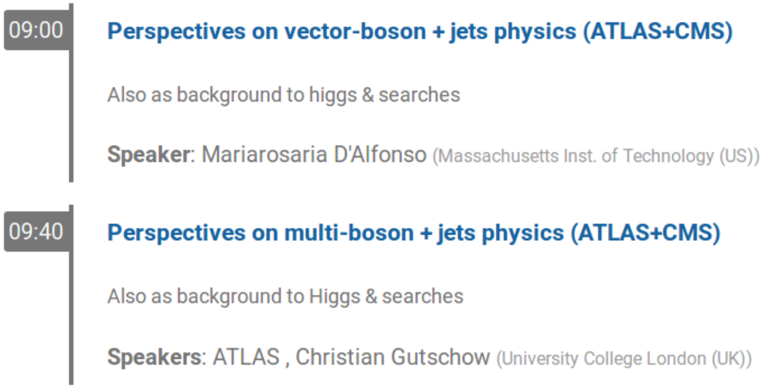






- The experiments continue to test the Higgs sector at 13 TeV
  - Precise measurements of gluon fusion production, including differentially
  - Approaching discovery for of sub-leading production modes
  - Eventually, combined fits of couplings/cross sections using Run 2 data

Background Modeling



09:00 **Perspectives on vector-boson + jets physics (ATLAS+CMS)**

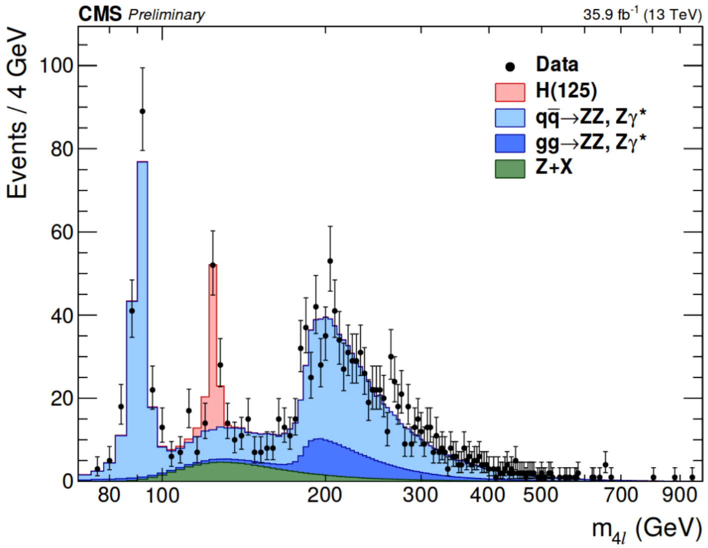
Also as background to higgs & searches

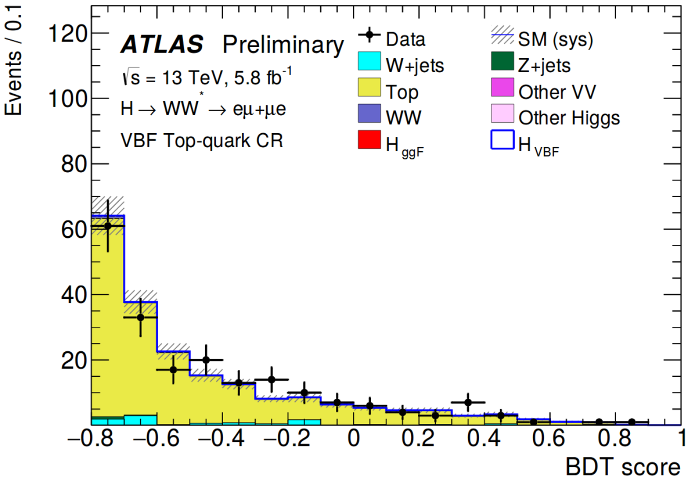
Speaker: Mariarosaria D'Alfonso (Massachusetts Inst. of Technology (US))

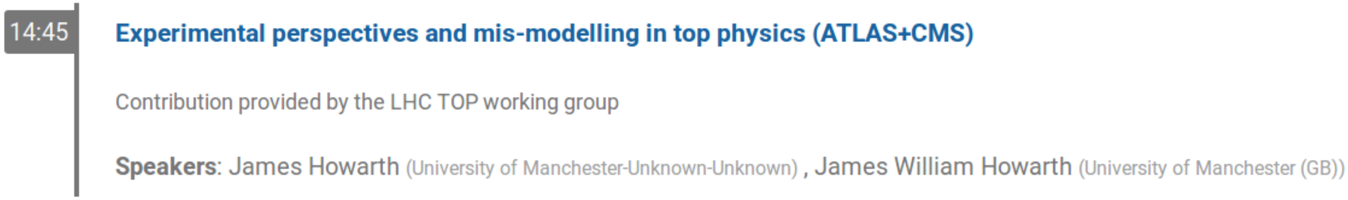
09:40 **Perspectives on multi-boson + jets physics (ATLAS+CMS)**

Also as background to Higgs & searches

Speakers: ATLAS , Christian Gutschow (University College London (UK))



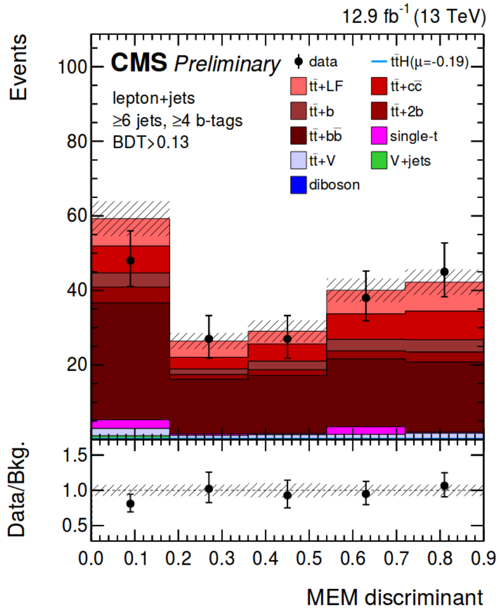


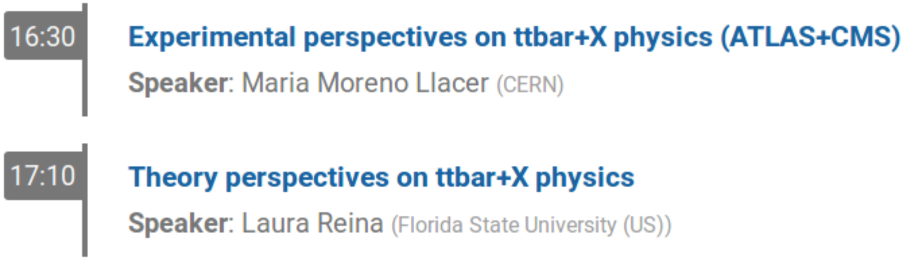


14:45 **Experimental perspectives and mis-modelling in top physics (ATLAS+CMS)**

Contribution provided by the LHC TOP working group

Speakers: James Howarth (University of Manchester-Unknown-Unknown) , James William Howarth (University of Manchester (GB))





16:30 **Experimental perspectives on ttbar+X physics (ATLAS+CMS)**

Speaker: Maria Moreno Llacer (CERN)

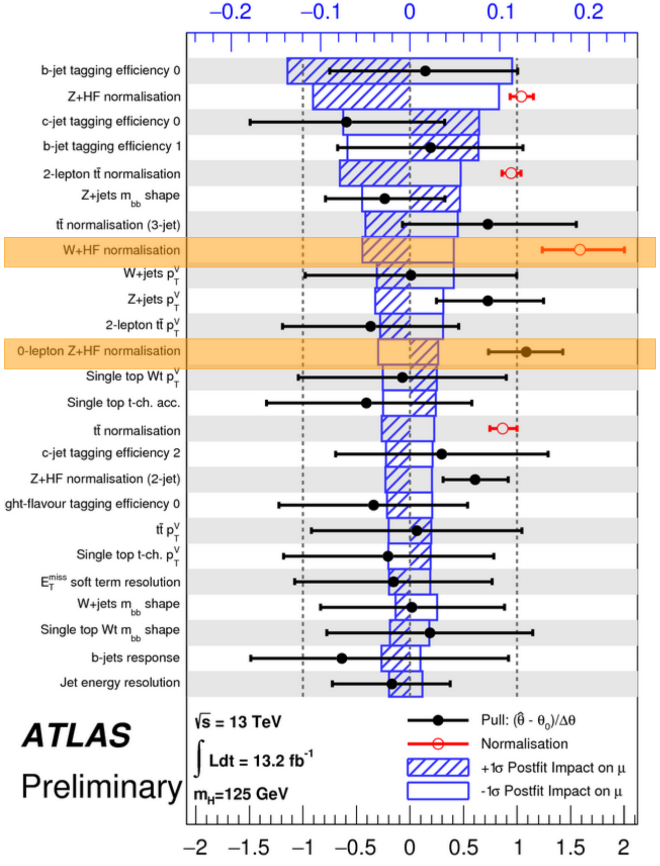
17:10 **Theory perspectives on ttbar+X physics**

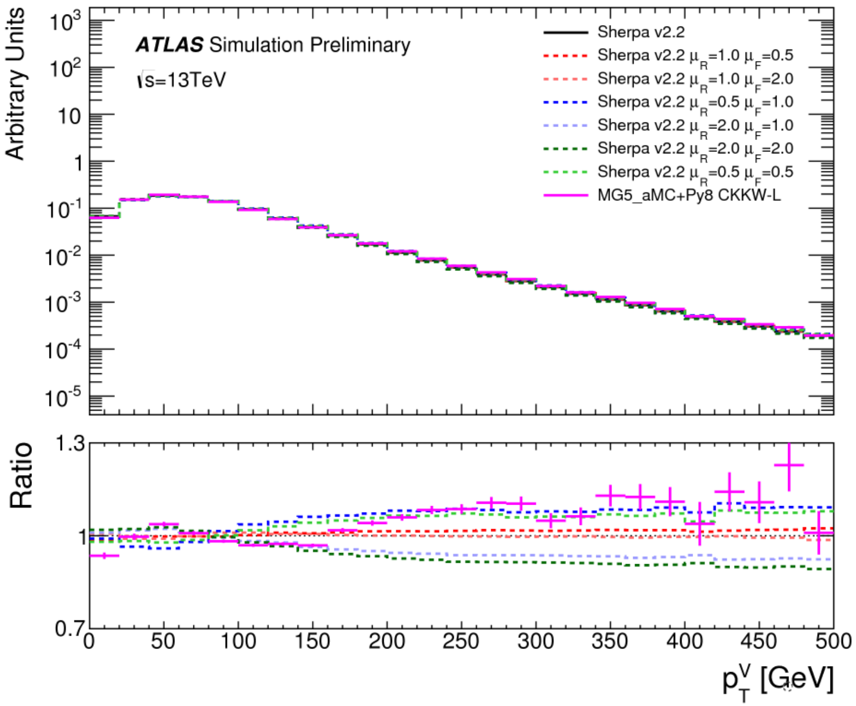
Speaker: Laura Reina (Florida State University (US))

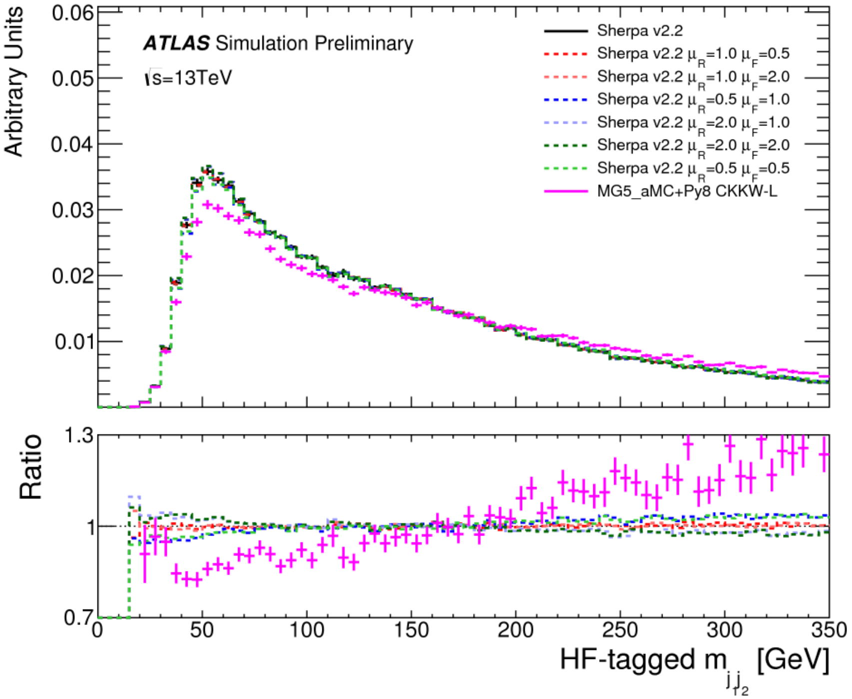
V+heavy flavour Background Modeling

- Modeling of V+HF critical for VH(bb) analyses, some tension observed in most recent ATLAS results
- Differences observed between aMC@NLO+Pythia8 and Sherpa, not covered by scale variations

ATLAS-CONF-2016-091







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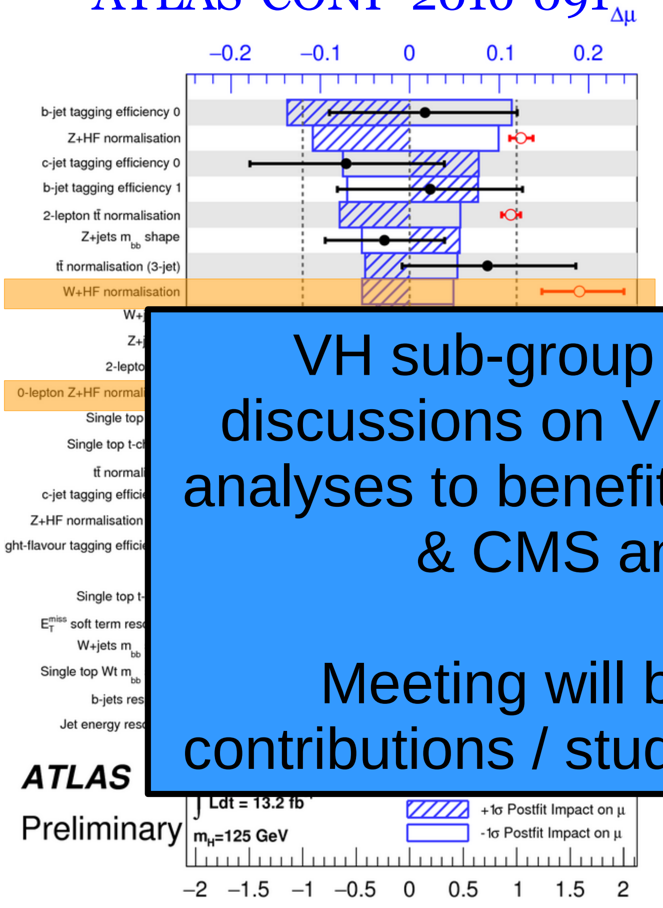
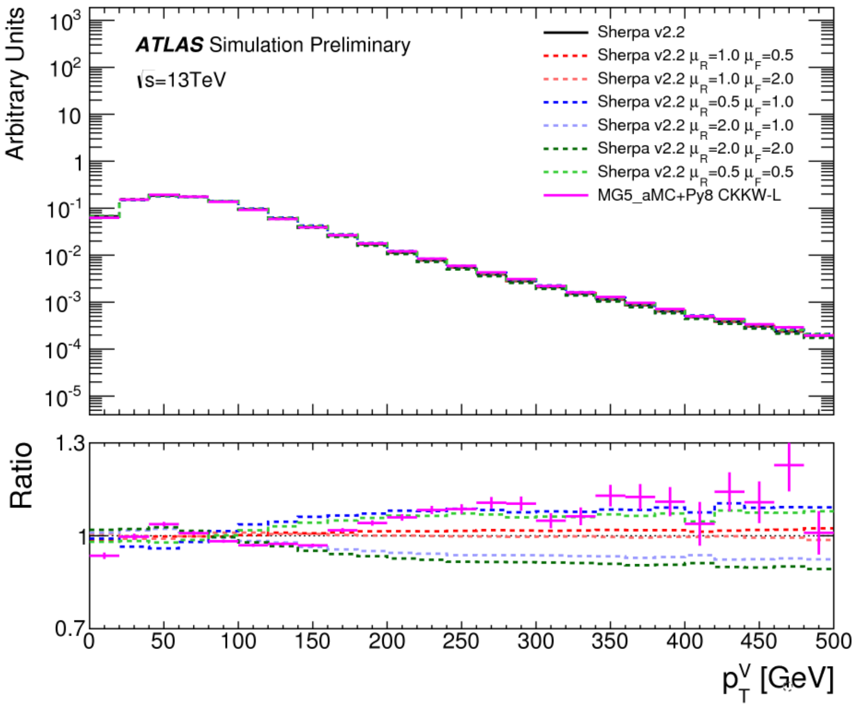
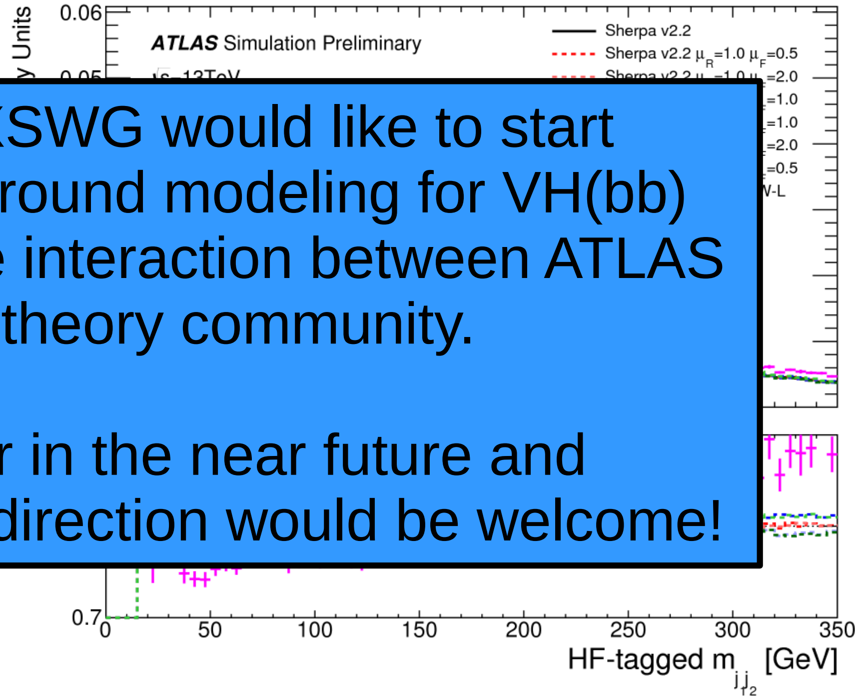




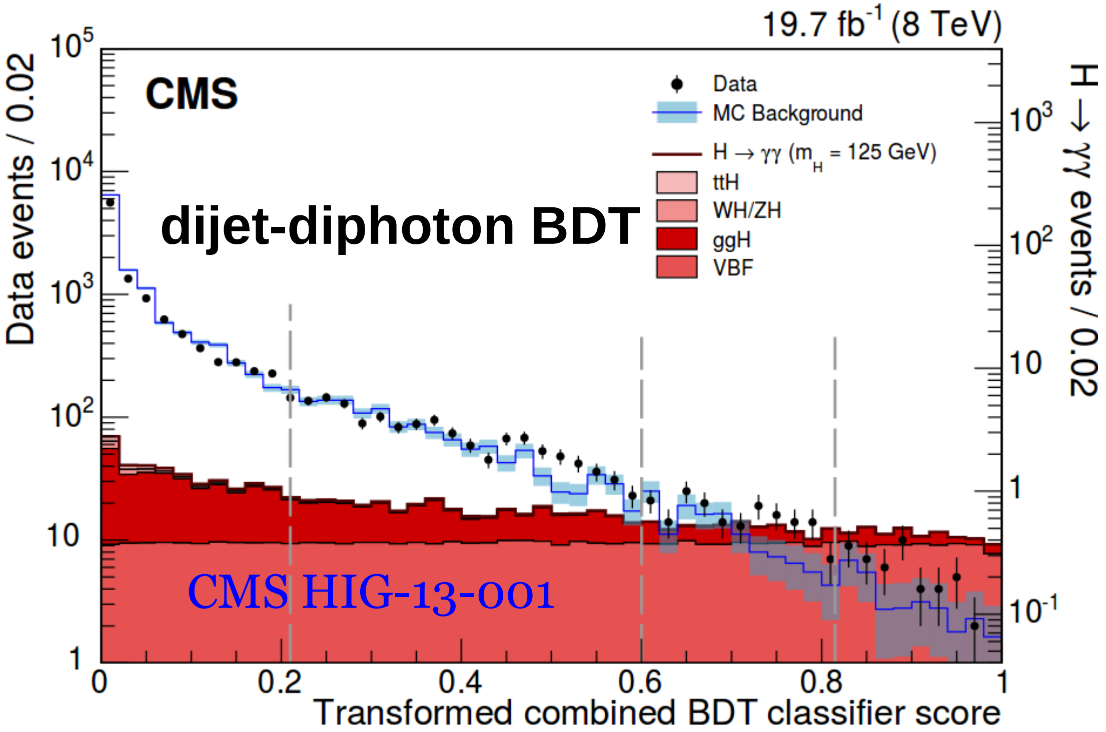


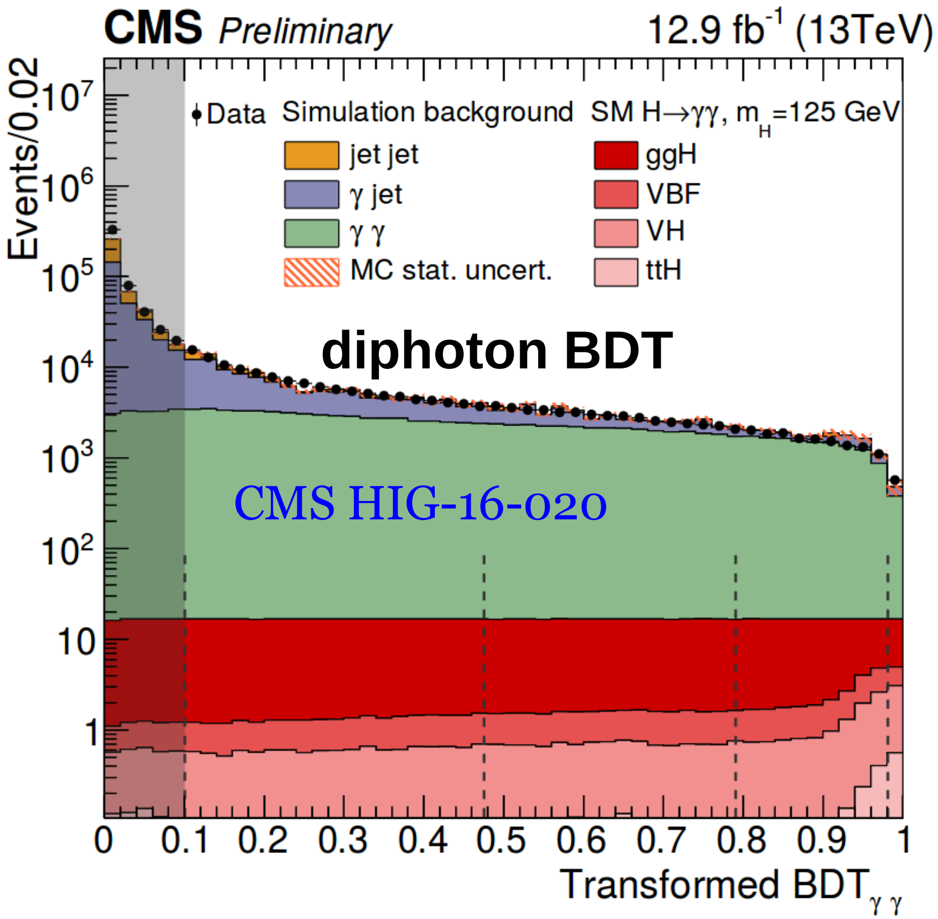
VH sub-group of LHC-HXSWG would like to start discussions on V+HF background modeling for VH(bb) analyses to benefit from more interaction between ATLAS & CMS and with the theory community.

Meeting will be called for in the near future and contributions / studies in this direction would be welcome!

γ+jet / dijet Background Modeling

- Important for MVA training in H→γγ analysis (diphoton BDT and dijet BDT)
- Most challenging in VBF phase space to obtain sufficient statistics
- CMS currently uses Pythia8, filtered at for jets with excess of EM particles

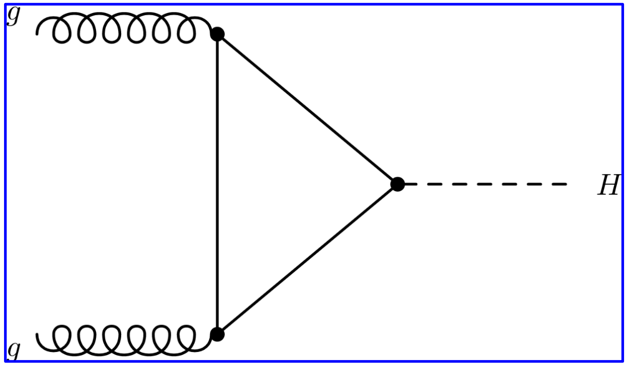




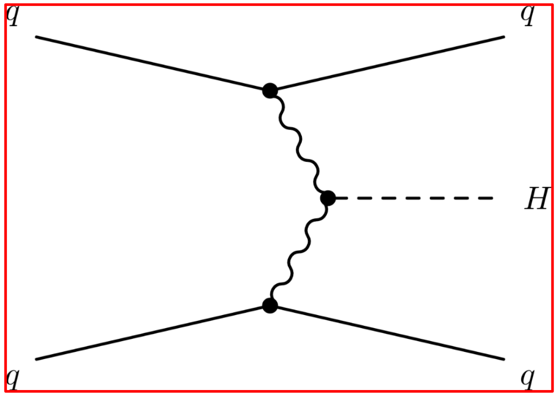
- Interested in γ+jet aMC@NLO with FxFx matching if/when it becomes available
- Sherpa+OpenLoops also an option

Higgs Boson Production Modes

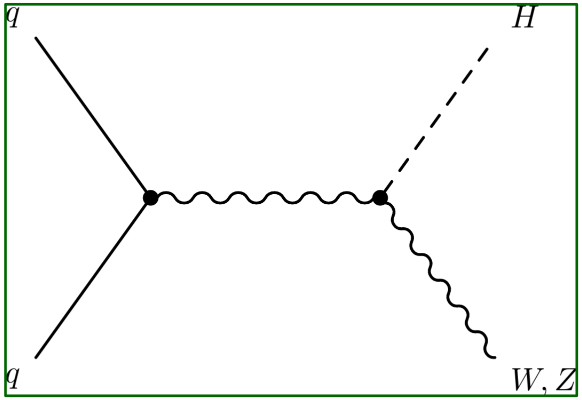
- Monte Carlo samples are normalized to best available theory calculations:



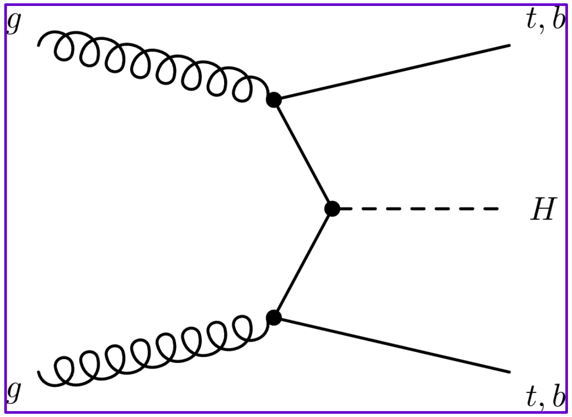
σ(gg→H) = 48.52 pb ±3.9% (th.) ±3.2% (pdf)
(N^3LO QCD + NLO EW)



σ(VBF) = 3.779 pb ±0.4% (th.) ±2.1% (pdf)
(NNLO QCD + NLO EW)



σ(pp→WH) = 1.369 pb ±0.7% (th.) ±1.9% (pdf)
σ(pp→ZH) = 0.8824 pb ±3.8% (th.) ±1.9% (pdf)
(NNLO QCD + NLO EW)



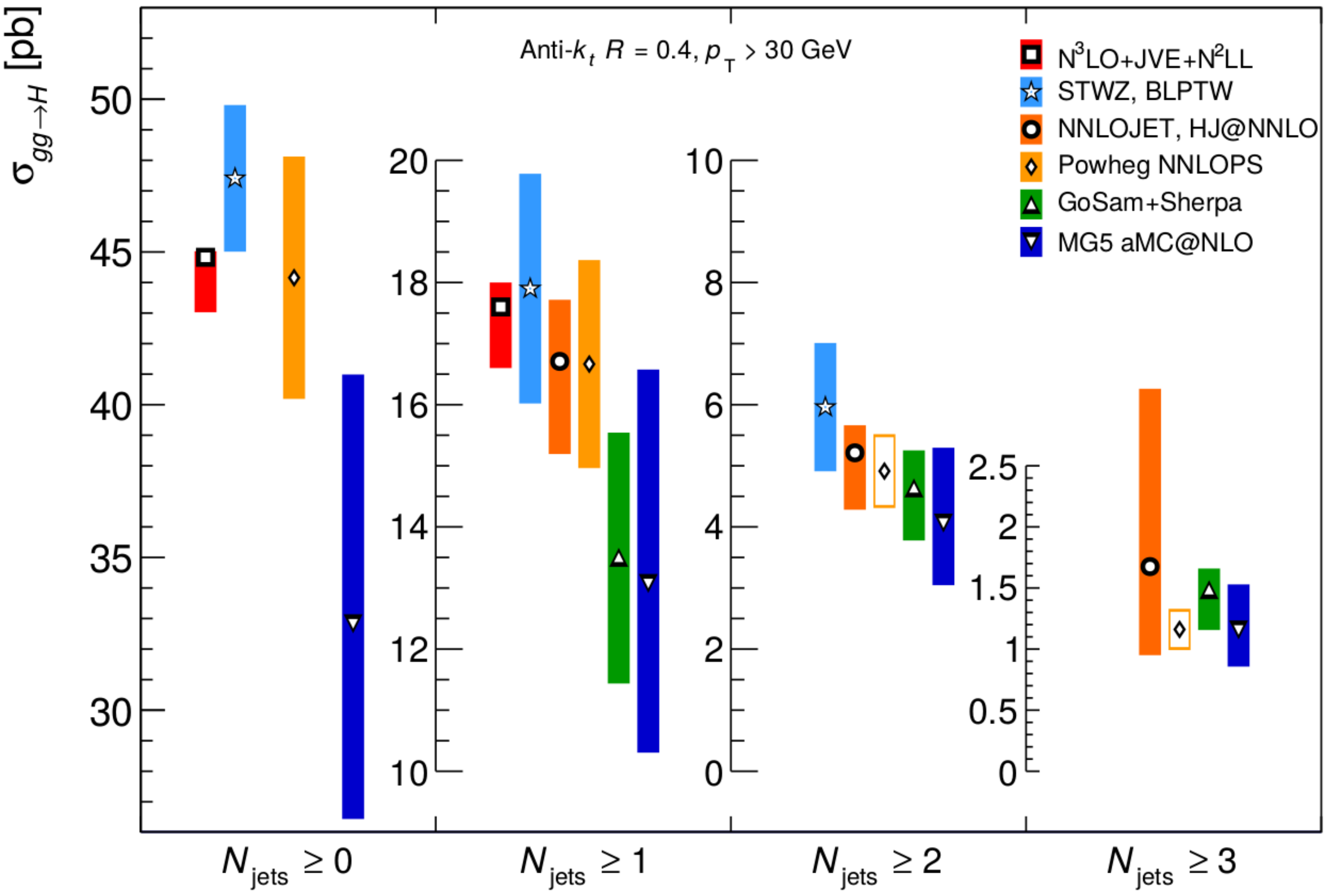
σ(ttH) =0.5065 pb $\pm^{5.8}_{9.2}$% (th.) ±3.6% (pdf)
(NLO QCD + NLO EW)

Gluon Fusion Signal Modeling

- Several generators are used in ATLAS and CMS for simulating gluon fusion production
  - Powheg (0-jet @ NLO): first jet at LO, additional jets from parton shower. Imperfect modeling of jet activity and $p_T(H)$, but can be tuned using generator parameters (e.g. hfact) to try and match e.g. HRes
  - ➔ aMC@NLO (NLO merged (FxFx) 0,1,2 jets @NLO)
  - ➔ Powheg NNLOPS: (inclusive NNLO, 1j @NLO)
- In Run 1, distributions were reweighted: $p_T(H)$ to match HRes 2.3 (dynamic scale) and N(jets) to match higher order calculations
  - ➔ In Run-2 goal is to not have to apply any reweighting
- MC Generators have been compared to state of the art parton level / analytical predictions to ensure their accuracy

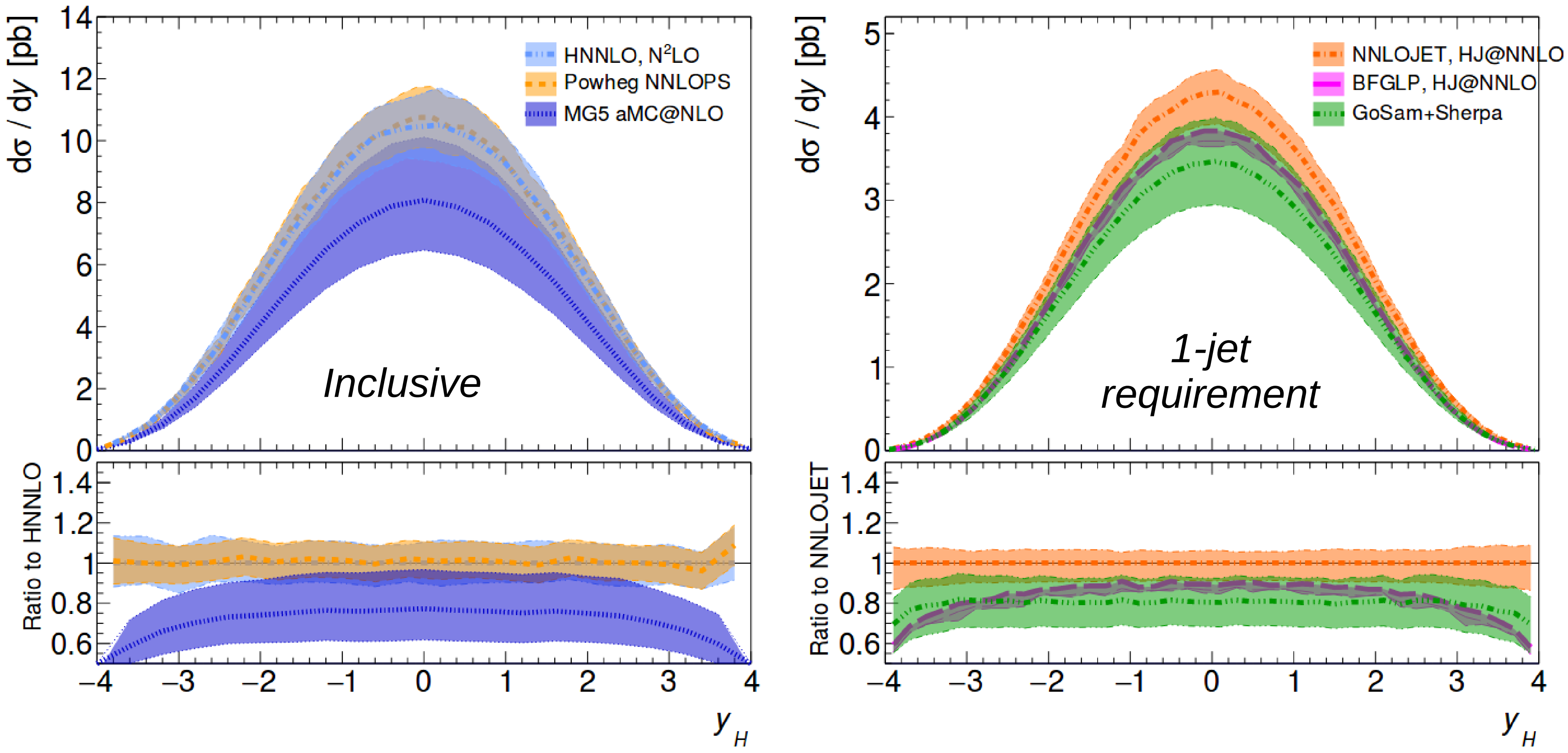
Gluon Fusion Signal Modeling

- Inclusive cross sections for different jet multiplicities computed by hadron level event generators compared to parton level calculations
  - ➔ NNLOPS agrees well with higher order calculations for all jet multiplicity
  - ➔ aMC@NLO prediction is low for lower jet multiplicity (only NLO)
  - ➔ Pretty good agreement for both generators when N(jets) ≥ 2



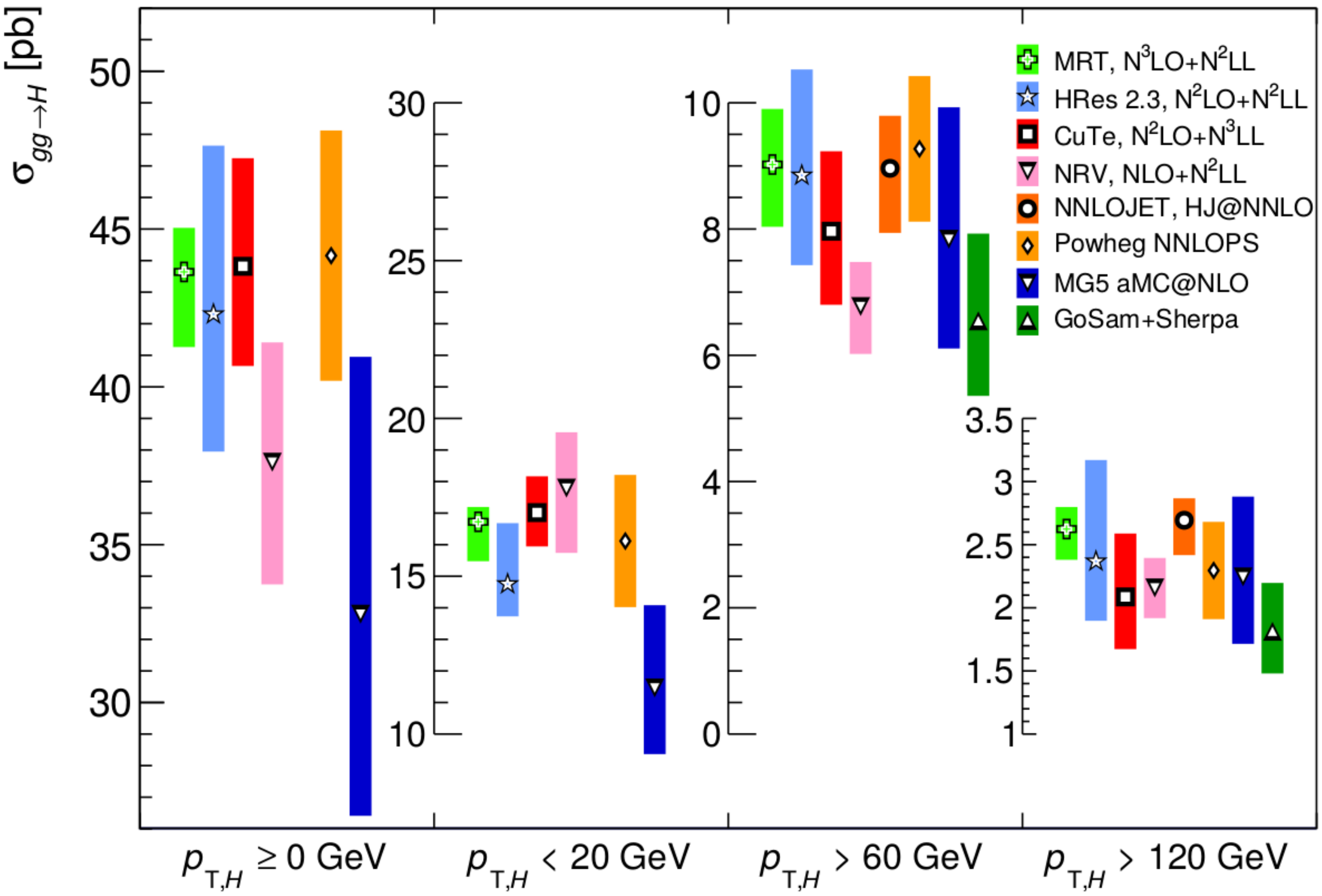
Gluon Fusion Signal Modeling

- Higgs rapidity spectrum important for estimating experimental acceptance
- NNLOPS matches HNNLO prediction by construction, aMC@NLO has a different shape especially at large y, where NNLO corrections are larger
  - ➔ Only matters for extrapolation to full phase space (i.e. total cross section)



Gluon Fusion Signal Modeling: $p_T(H)$

- $p_T(H)$ spectrum also important for determining acceptance, as well as testing for presence of BSM particles in the loop
- NNLOPS agrees well with higher order calculations, even at low p_T where it is not formally NNLL and at high p_T where it is only NLO for H+1jet



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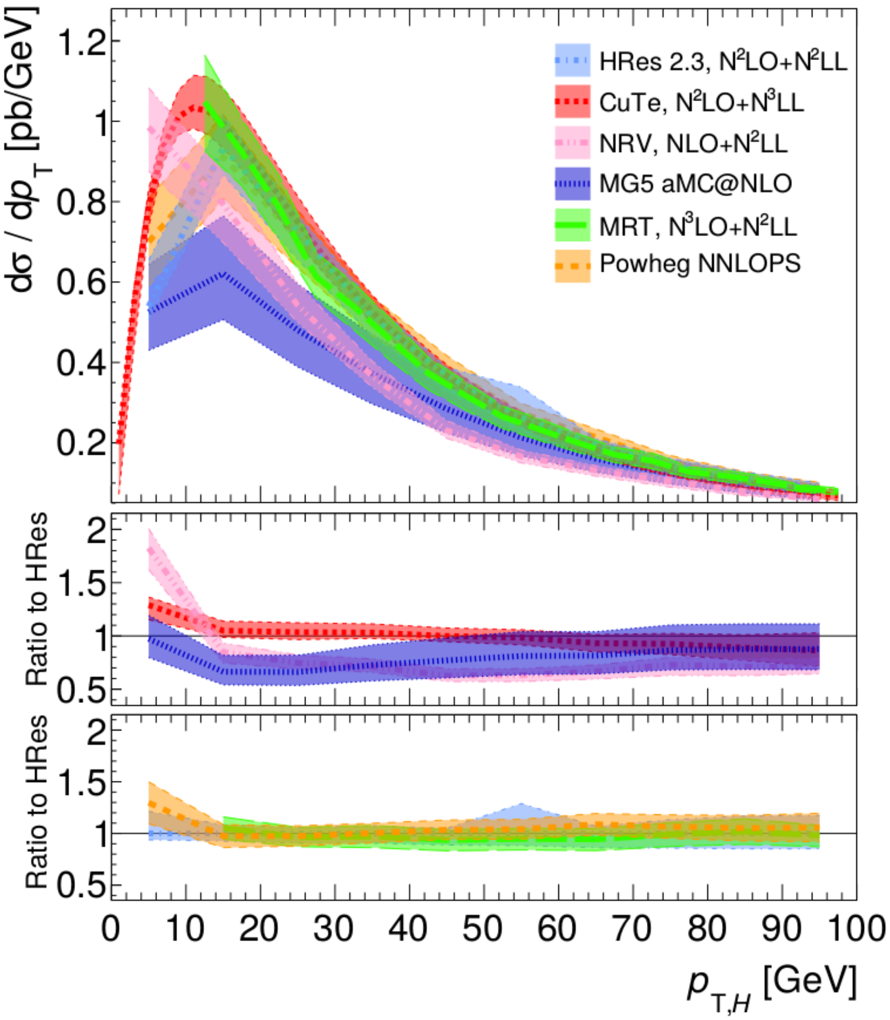
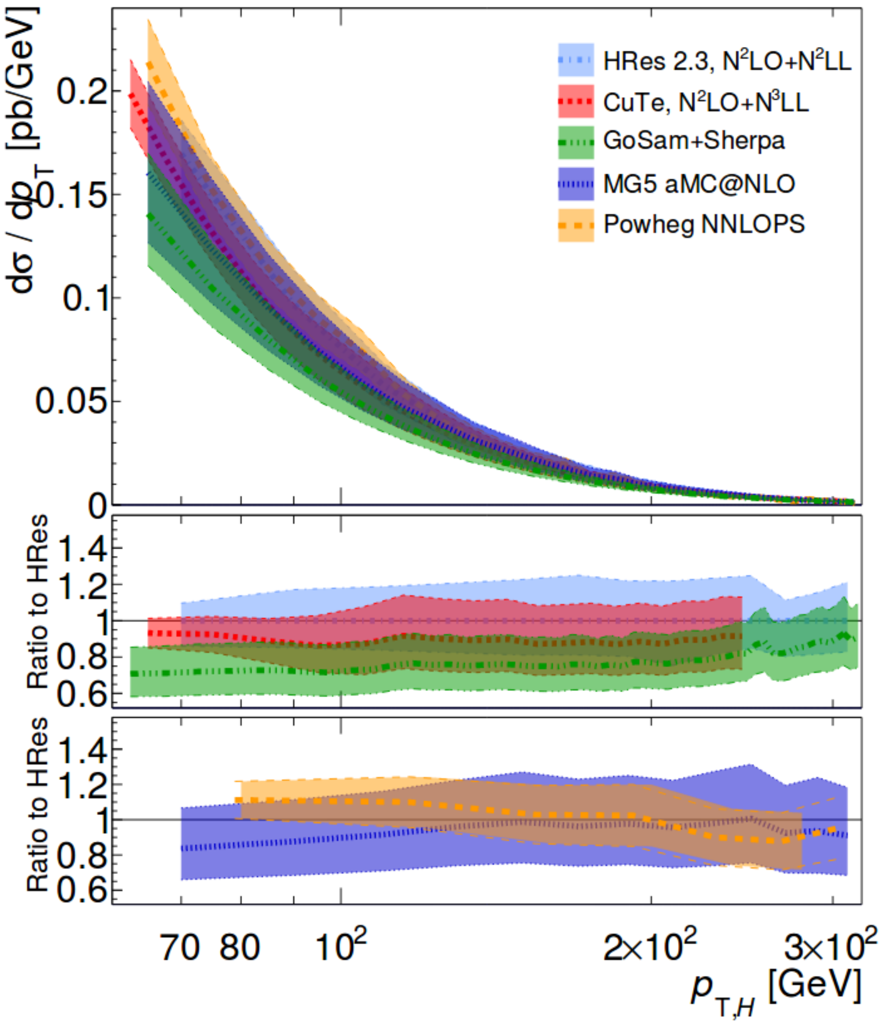
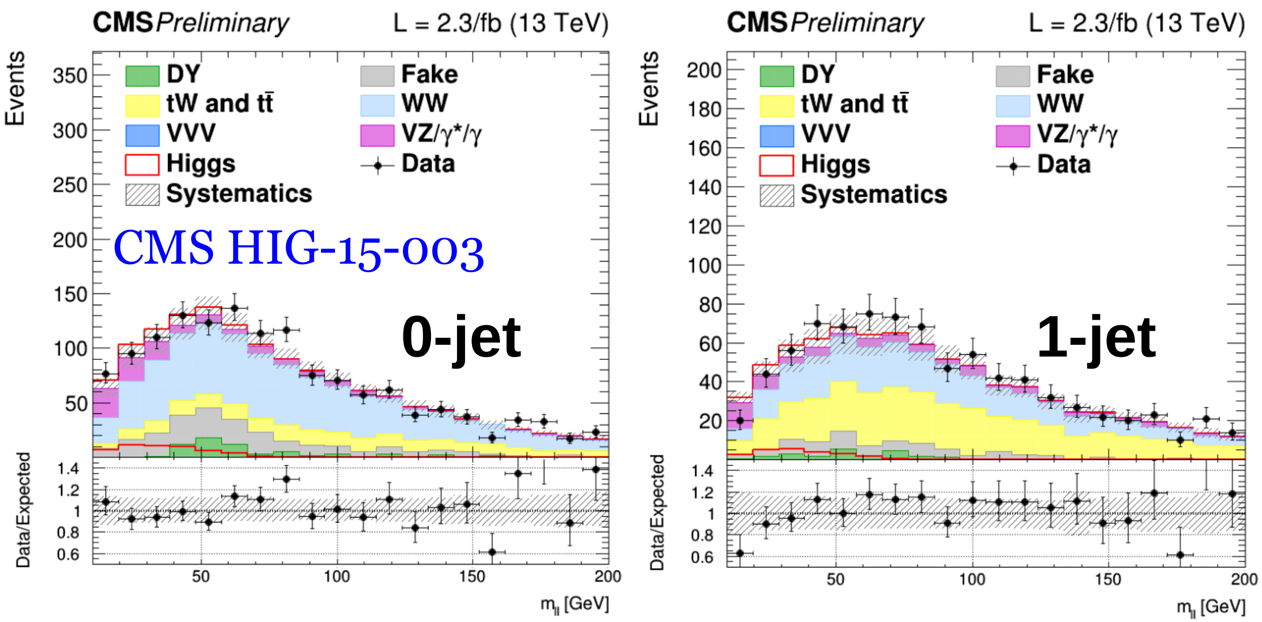




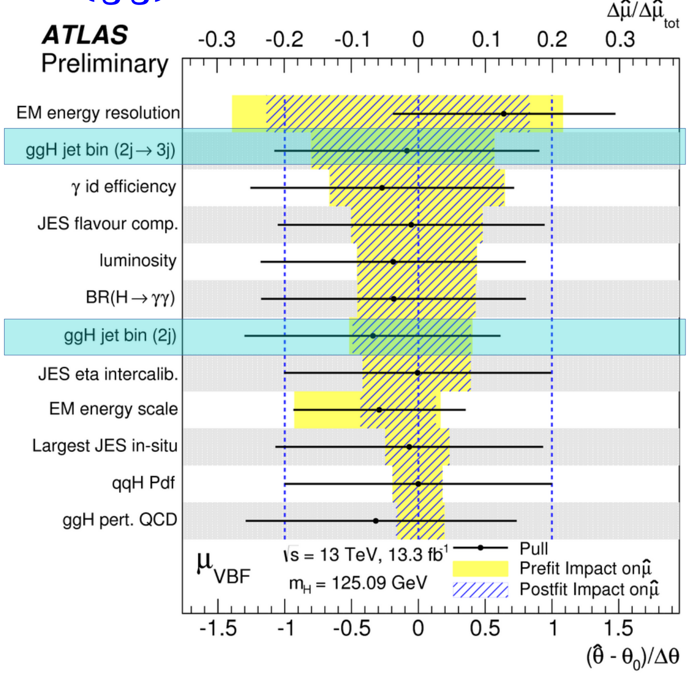
Gluon Fusion in Exclusive Jet Bins

- Exclusive jet bin predictions and uncertainties are important for channels which categorize events based on jet multiplicity (e.g. WW, ττ)
- Predictions for higher jet multiplicities also extremely important for measurement of VBF production (ggH is an irreducible background)

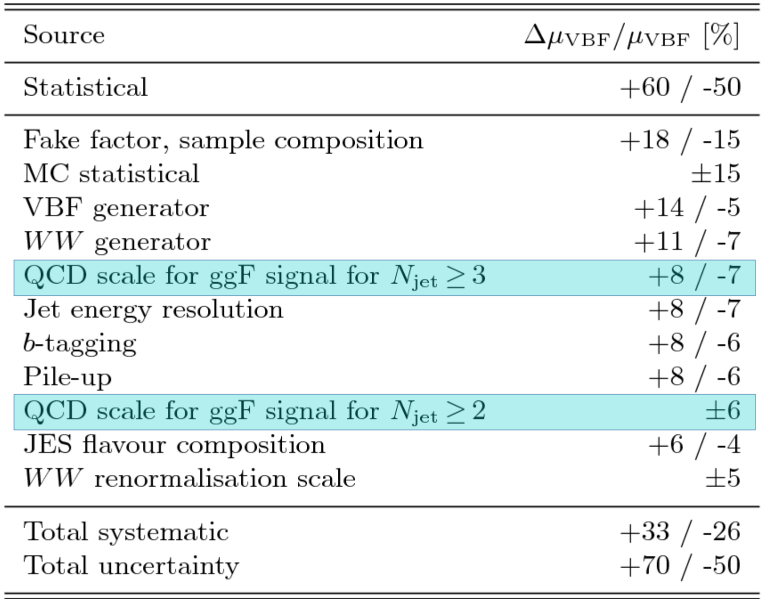


CMS HIG-15-003

H(γγ): ATLAS-CONF-2016-067



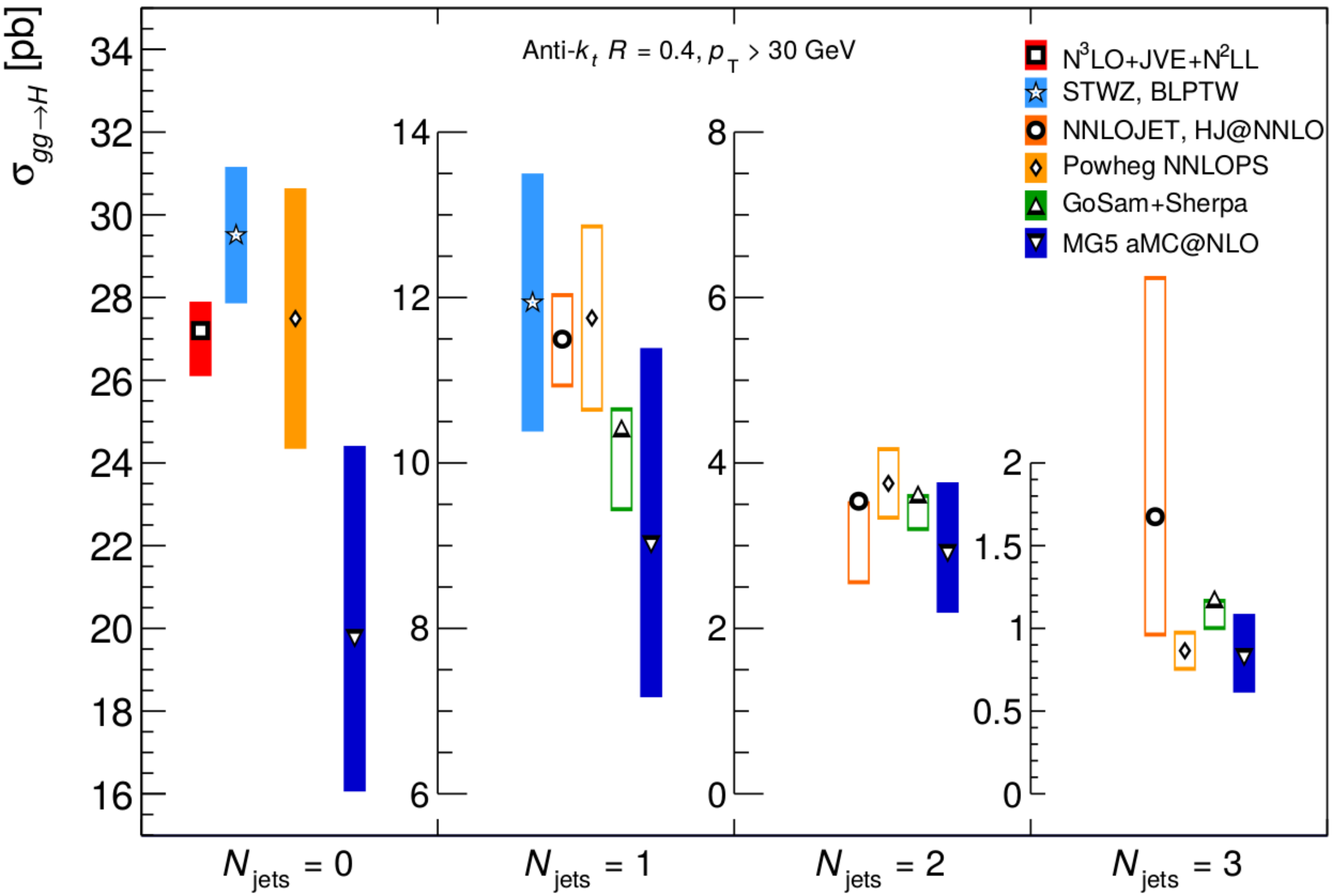
H(WW): ATLAS-CONF-2016-112



Source	$\Delta\mu_{\mathrm{VBF}}/\mu_{\mathrm{VBF}}$ [%]
Statistical	+60 / -50
Fake factor, sample composition	+18 / -15
MC statistical	±15
VBF generator	+14 / -5
WW generator	+11 / -7
QCD scale for ggF signal for $N_{\mathrm{jet}} \geq 3$	+8 / -7
Jet energy resolution	+8 / -7
b-tagging	+8 / -6
Pile-up	+8 / -6
QCD scale for ggF signal for $N_{\mathrm{jet}} \geq 2$	±6
JES flavour composition	+6 / -4
WW renormalisation scale	±5
Total systematic	+33 / -26
Total uncertainty	+70 / -50

Gluon Fusion in Exclusive Jet Bins

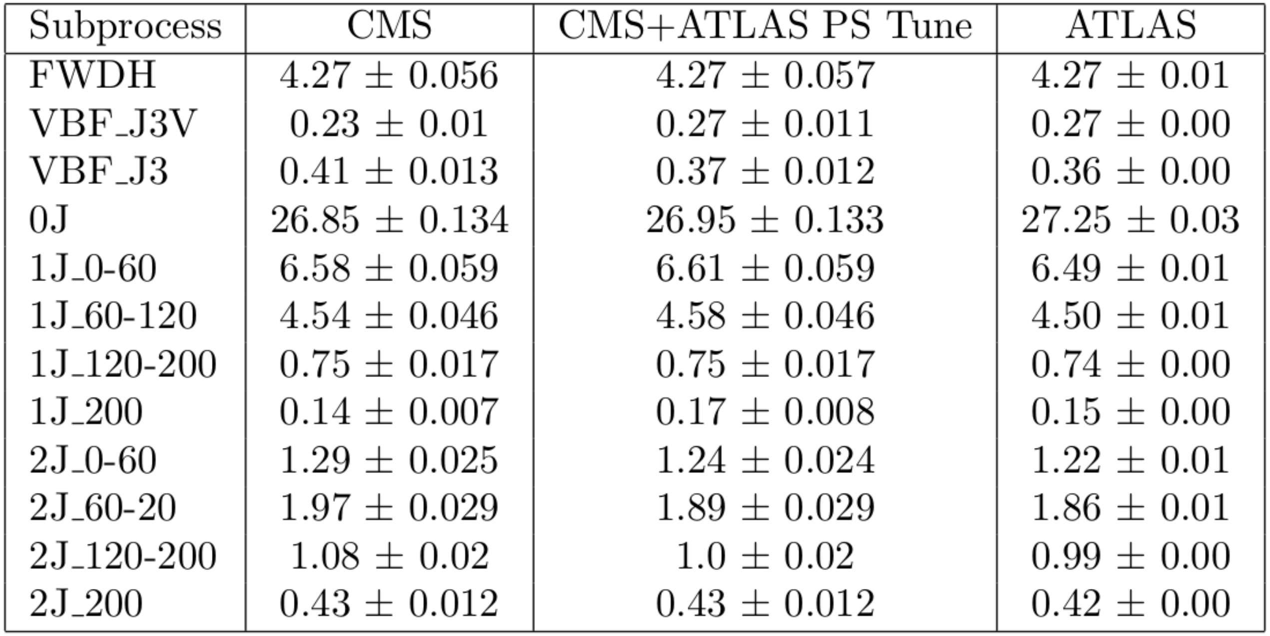
- Again, pretty good agreement with higher order calculations even for larger jet multiplicities, while aMC @NLO is a bit low for lower jet multiplicities
- Estimation of migration uncertainties is important, e.g. using JVE or ST approaches, standard uncertainties from scale variations unreliable
- More studies welcome on modeling of kinematic distributions in jet bins



Discussion items on NNLOPS

- We have seen that NNLOPS agrees well with state of the art calculations, and ATLAS and CMS plan to use it as the baseline for future measurements
- Comparison between the experiments have achieved good synchronization

Stage-1 subprocess cross sections from NNLOPS (pb). Uncertainties are statistical uncertainties only.

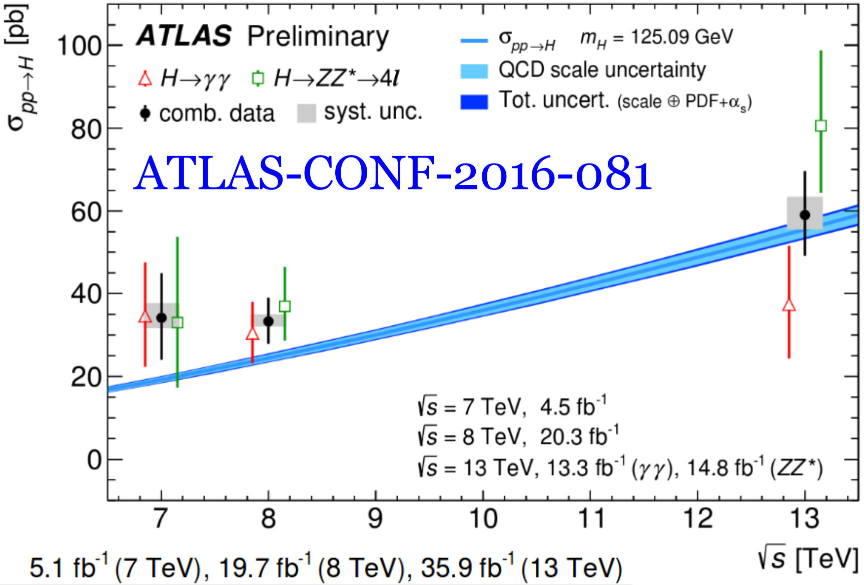


Subprocess	CMS	CMS+ATLAS PS Tune	ATLAS
FWDH	4.27 ± 0.056	4.27 ± 0.057	4.27 ± 0.01
VBF_J3V	0.23 ± 0.01	0.27 ± 0.011	0.27 ± 0.00
VBF_J3	0.41 ± 0.013	0.37 ± 0.012	0.36 ± 0.00
0J	26.85 ± 0.134	26.95 ± 0.133	27.25 ± 0.03
1J_0-60	6.58 ± 0.059	6.61 ± 0.059	6.49 ± 0.01
1J_60-120	4.54 ± 0.046	4.58 ± 0.046	4.50 ± 0.01
1J_120-200	0.75 ± 0.017	0.75 ± 0.017	0.74 ± 0.00
1J_200	0.14 ± 0.007	0.17 ± 0.008	0.15 ± 0.00
2J_0-60	1.29 ± 0.025	1.24 ± 0.024	1.22 ± 0.01
2J_60-20	1.97 ± 0.029	1.89 ± 0.029	1.86 ± 0.01
2J_120-200	1.08 ± 0.02	1.0 ± 0.02	0.99 ± 0.00
2J_200	0.43 ± 0.012	0.43 ± 0.012	0.42 ± 0.00

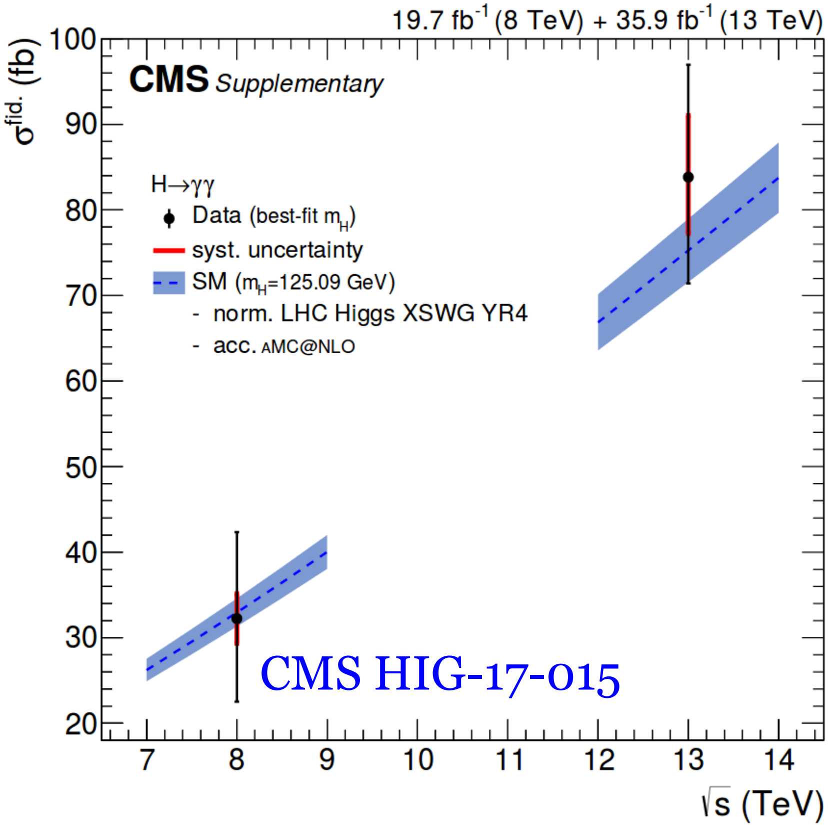
- Parton shower tune differences lead to significant differences in VBF phase space, should be investigated further
- Technical point: good agreement only when generating large number of events per job, a challenge for production of high statistics samples

Fiducial Cross Section Measurements

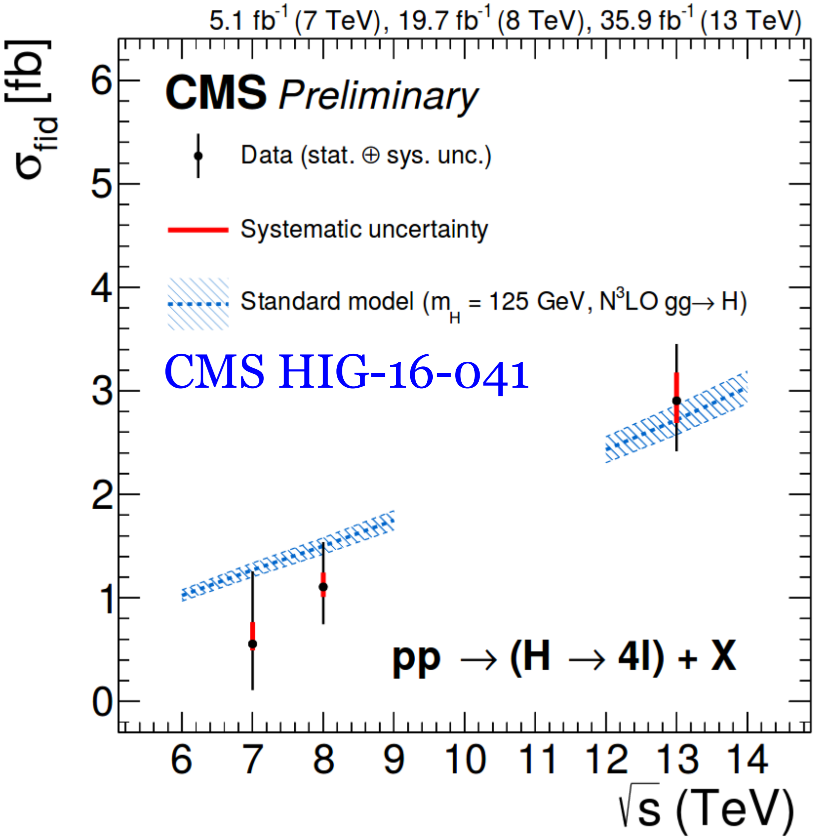
- Measurements of model independent fiducial cross sections, fiducial volume closely matching experimental acceptance
  - ➔ Not sensitive to production mechanism, but expected to be dominated by gluon fusion
  - ➔ Decouple uncertainties on the signal cross section from the measurement uncs.



ATLAS-CONF-2016-081



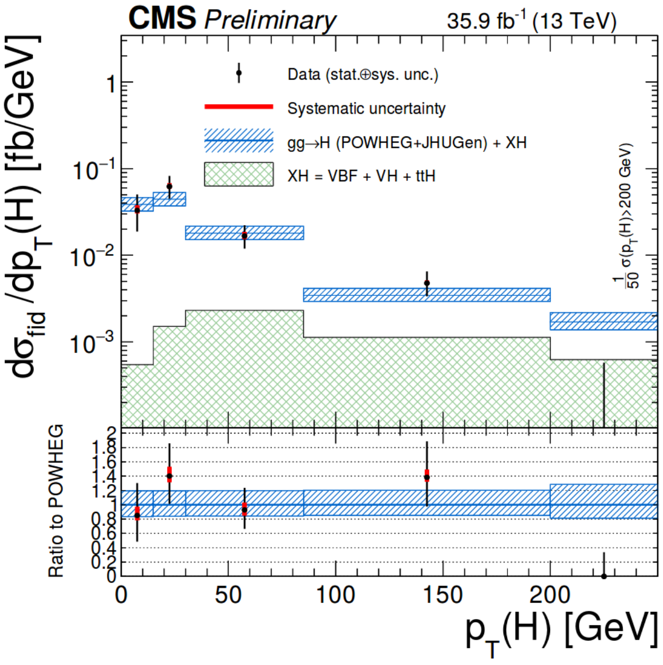
CMS HIG-17-015

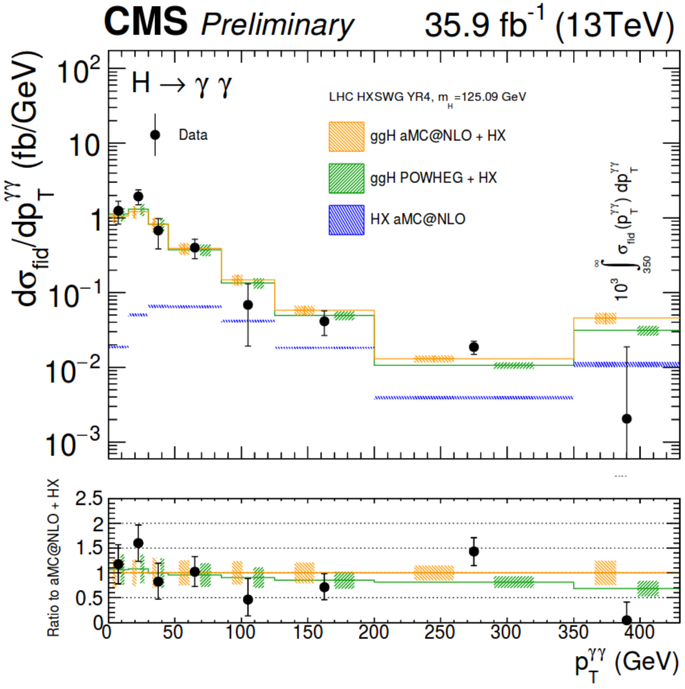


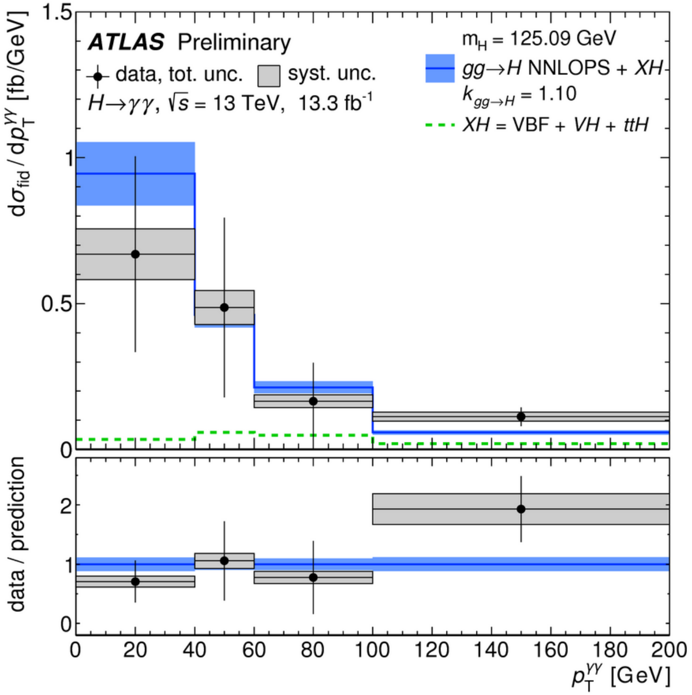
CMS HIG-16-041

Differential Cross Sections

- We have seen new results on differential cross section measurements at 13 TeV in ZZ (CMS) and γγ (CMS and ATLAS)
- Comparisons to Powheg and aMC@NLO (CMS) and NNLOPS (ATLAS) show no significant deviations so far
- Combinations between the channels and experiments are possible assuming acceptance factors from theoretical calculations

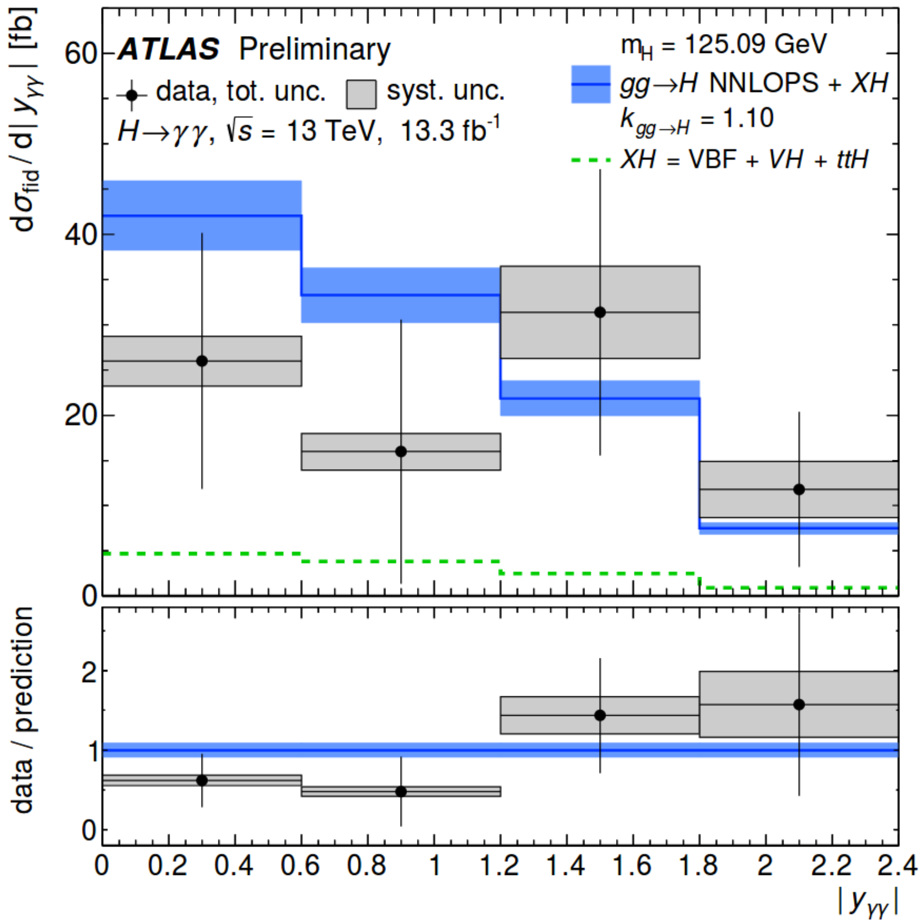


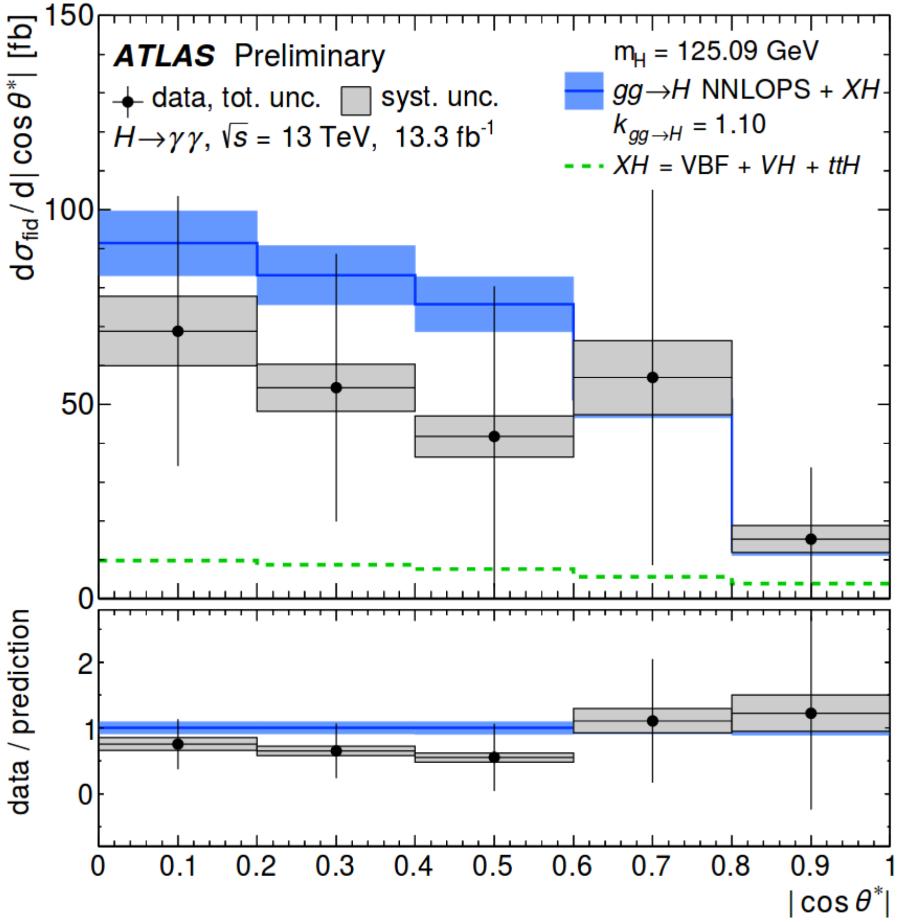




Differential Cross Sections

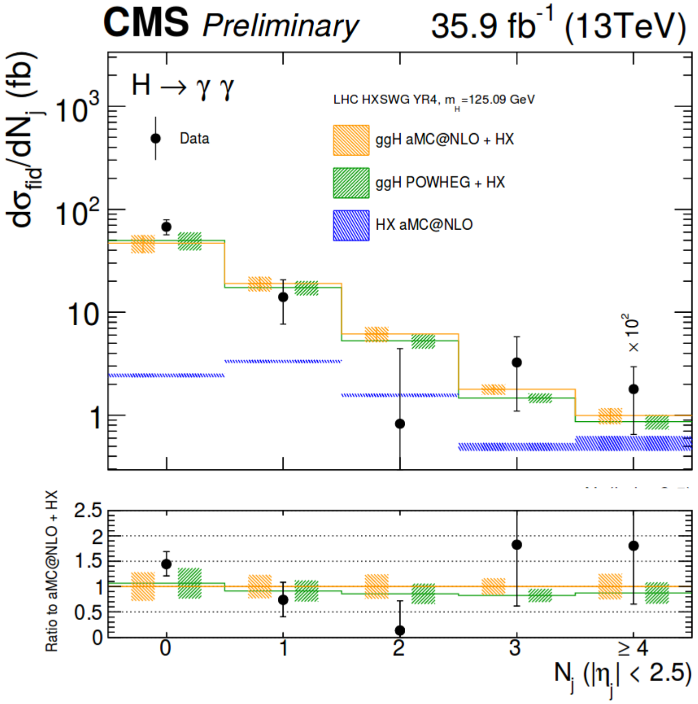
- ATLAS has also measured differential cross sections vs y(H) and cosθ*
  - ➔ Sensitive to the parton distribution functions of the colliding protons, production mechanism, and anomalous couplings of the Higgs
- No significant deviations observed so far

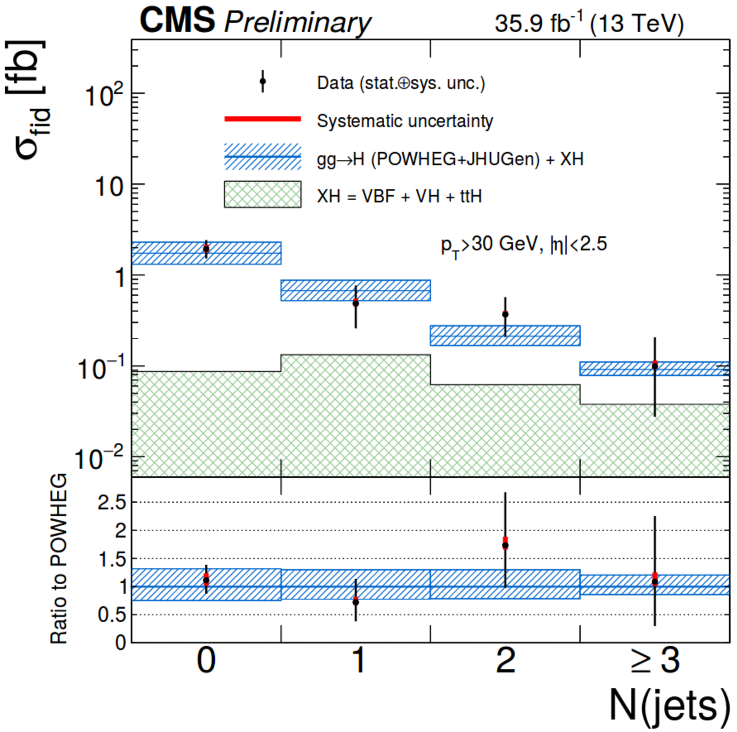


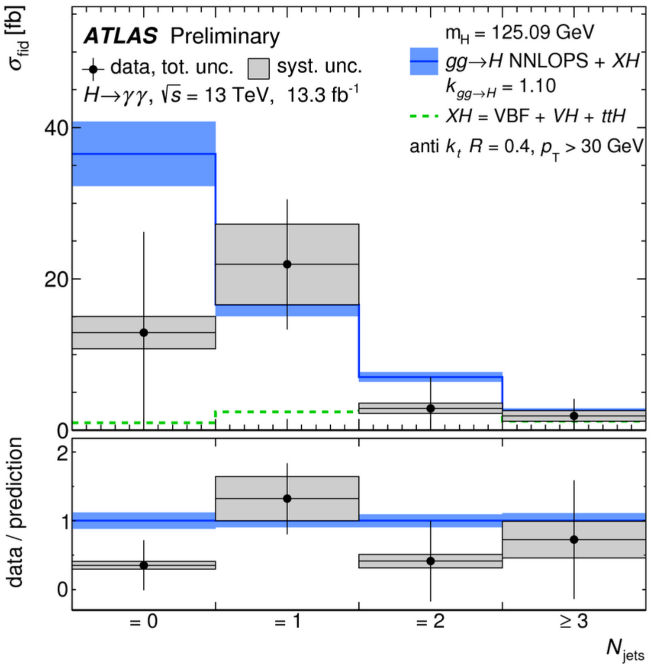


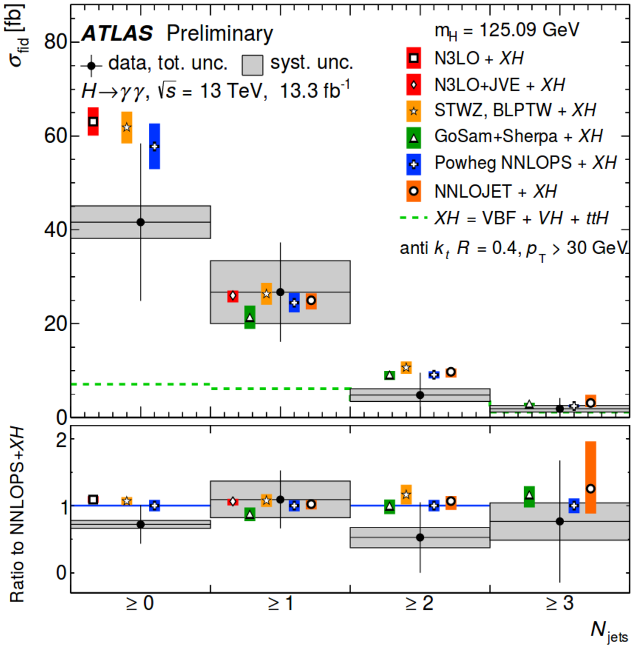
Differential Cross Sections

- Exclusive jet cross sections measured by both ATLAS and CMS, ATLAS also measured inclusive cross sections for different jet multiplicity requirements
- ATLAS observes slight deficit in 0-jet bin (still compatible with SM prediction), not seen by CMS
- Experimental uncertainties surpassing NLO theoretical unc., especially for 0-jet bin
  - ➔ NNLO needed



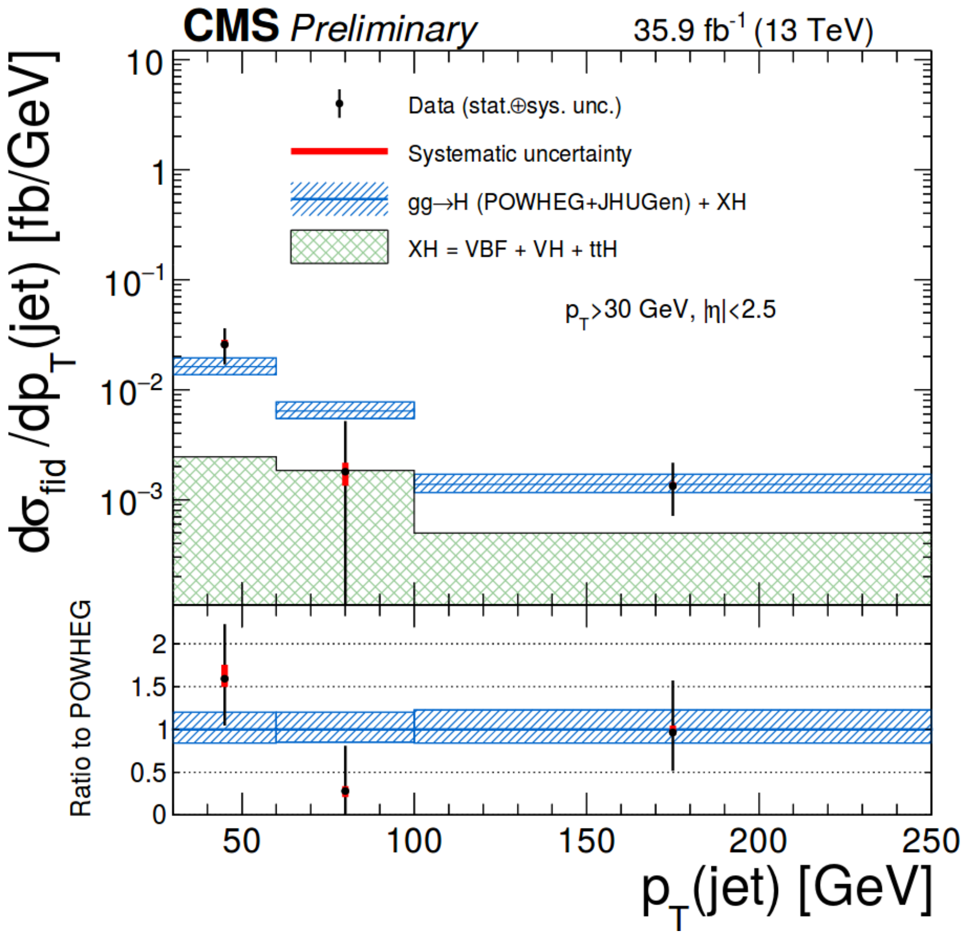


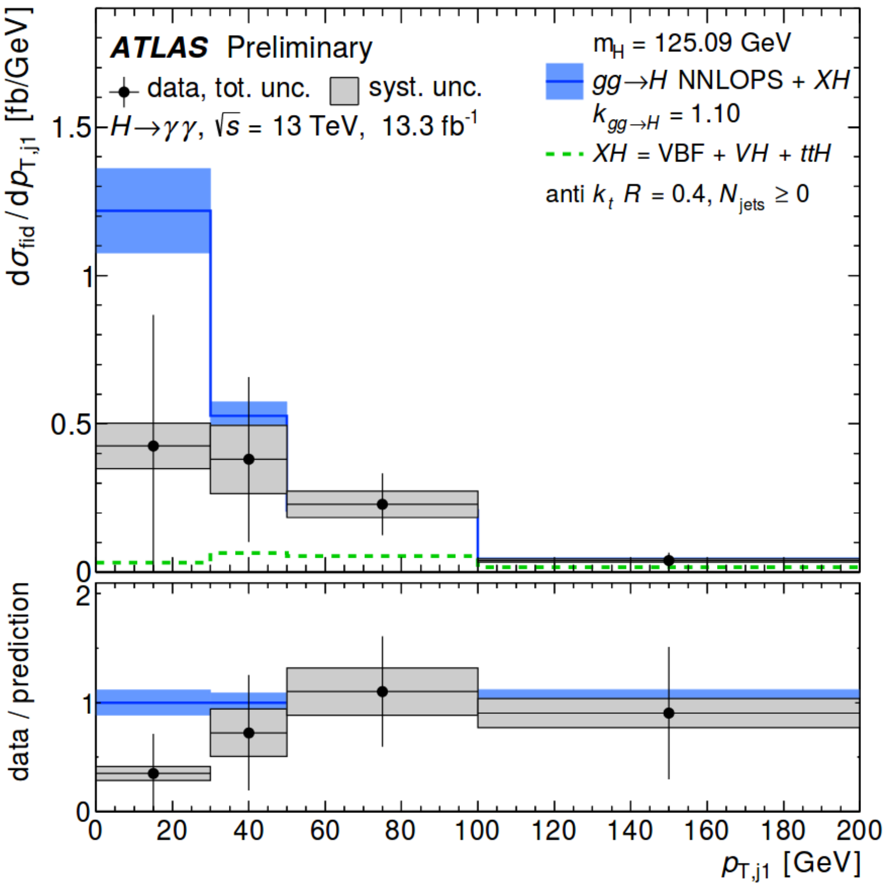




Differential Cross Sections

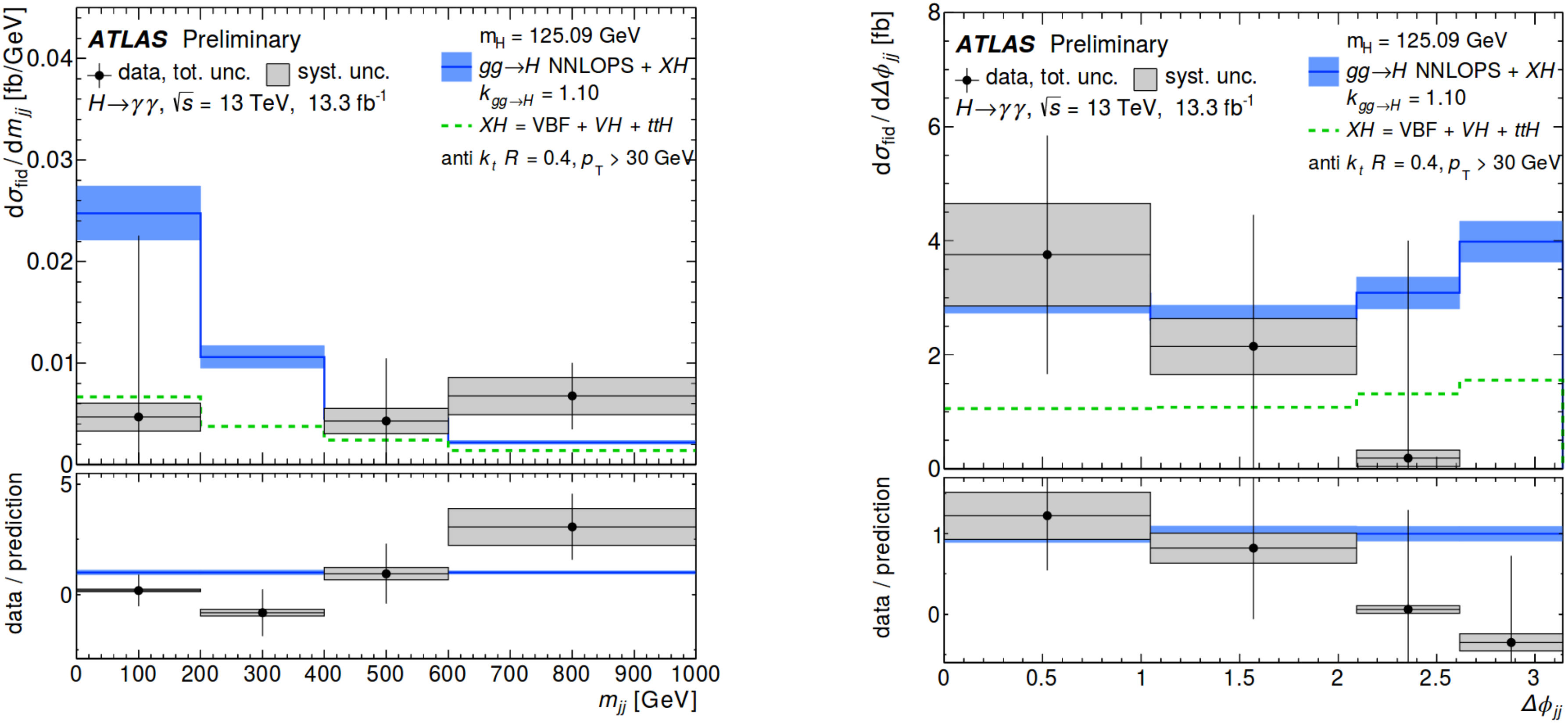
- ATLAS and CMS also measure the differential cross section vs. p_T of the leading jet, sensitive to higher order QCD effects, potential BSM
- No significant deviations observed so far





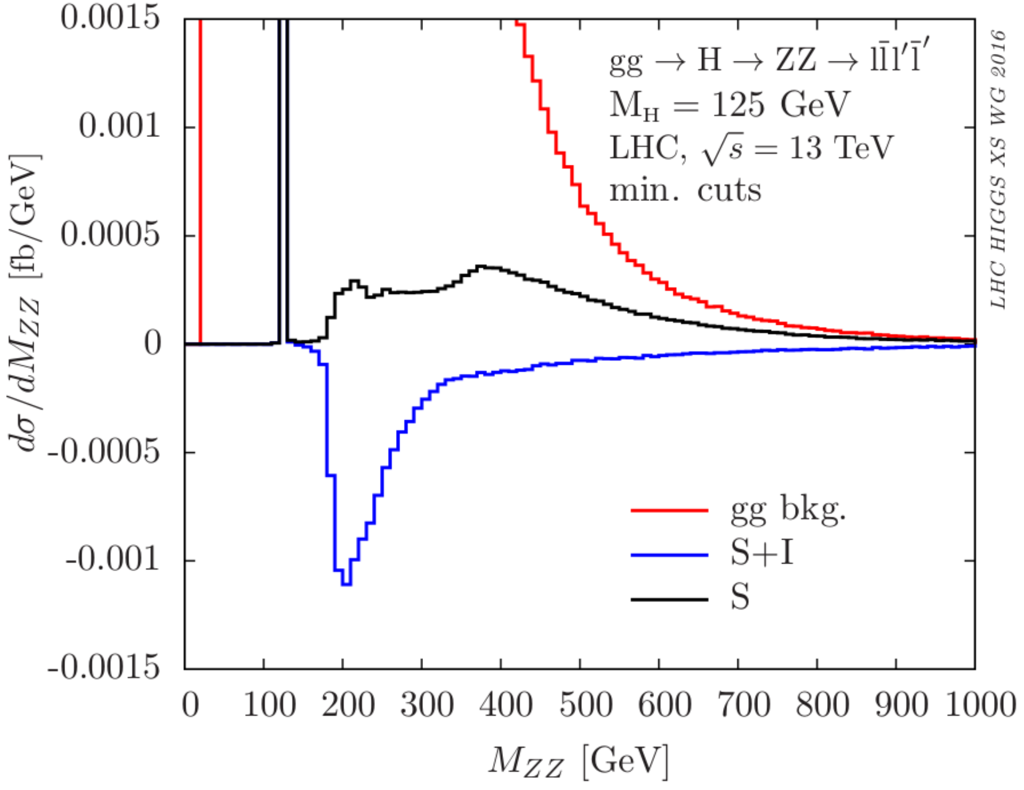
Differential Cross Sections

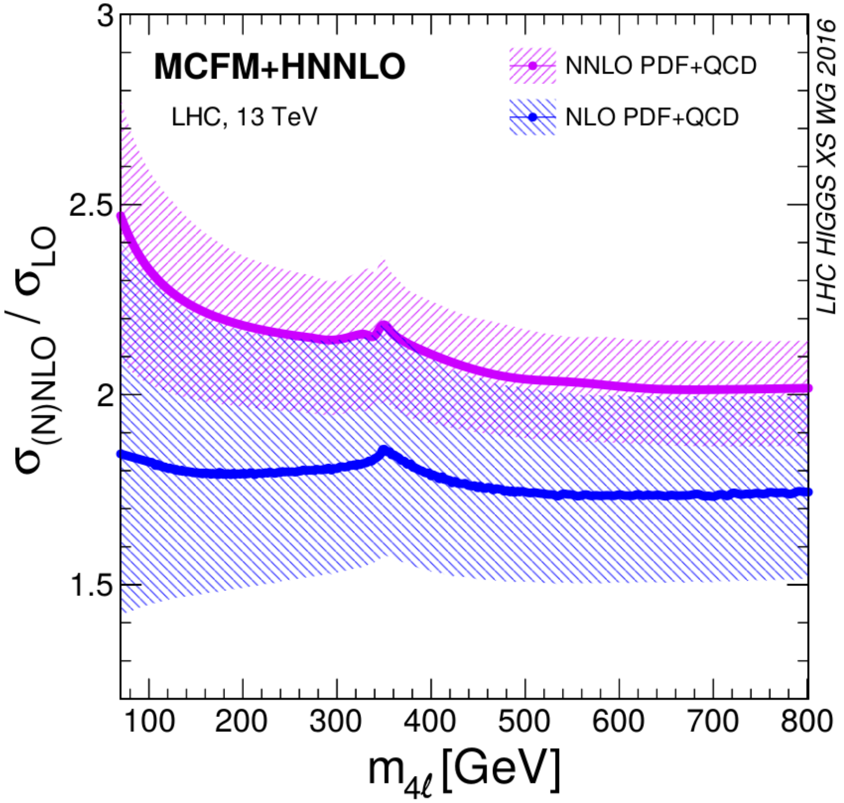
- ATLAS has also measured differential cross sections in H+2 jet phase space for m_{jj} and azimuthal difference between the two jets $\Delta\Phi_{jj}$
  - ➔ SM cross section starts to be dominated by VBF at high m_{jj}
- Some difference in shapes, but compatible within current uncertainty



Interference Effects in Gluon Fusion

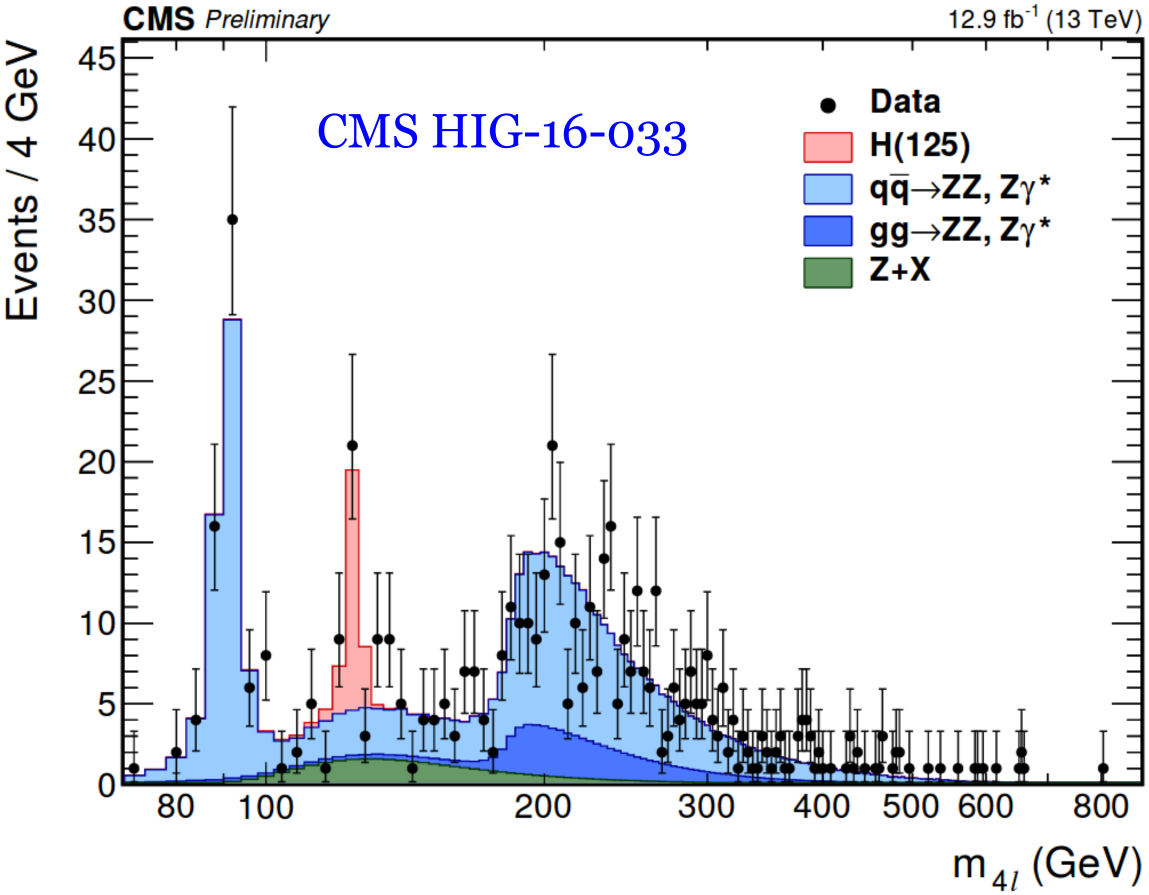
- The Higgs boson production cross section has a significant off-shell component in the diboson decay channels
- Furthermore there is interference with the gg → ZZ continuum background, which provides sensitivity to the Higgs boson width
- Interference effects are simulated at α_S^2, lower than signal only
  - ➔ Large K-factors applied to background and interference terms



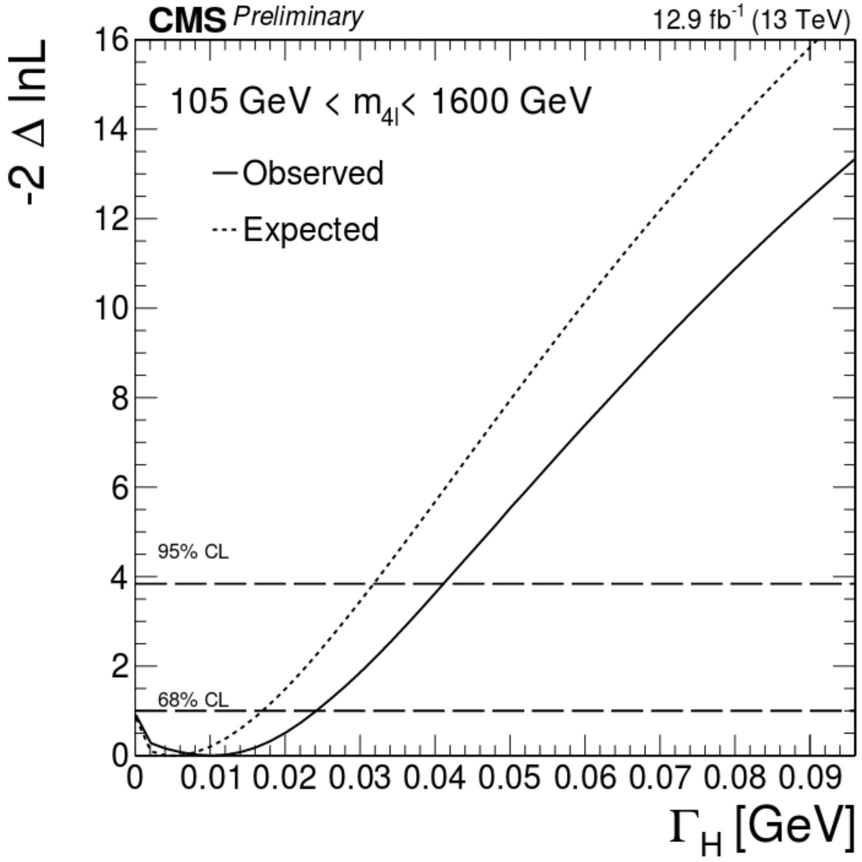


Width Measurement from Off-Shell Region

- The Higgs width has been remeasured at 13 TeV by CMS using the 12.9 fb^{-1} in the $ZZ \rightarrow 4\ell$ decay channel using combination of on-shell and off-shell tail
- Best fit of width slightly broader than expected, opposite to Run 1 result



CMS HIG-16-033

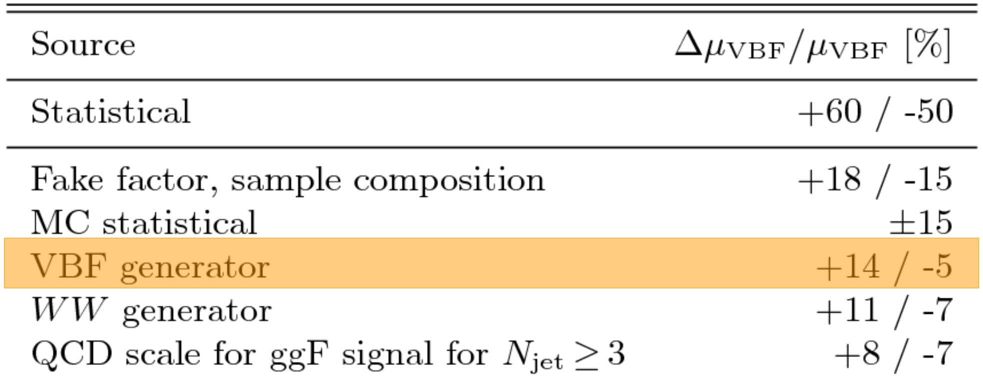


Γ_H < 41 MeV (95% CL)

VBF Signal Modeling

- Both ATLAS and CMS use Powheg+Pythia8 (aMC@NLO for cross checks)
- VBF in H(WW) ATLAS ICHEP results:

ATLAS-CONF-2016-112



Source	$\Delta\mu_{\mathrm{VBF}}/\mu_{\mathrm{VBF}}$ [%]
Statistical	+60 / -50
Fake factor, sample composition	+18 / -15
MC statistical	±15
VBF generator	+14 / -5
WW generator	+11 / -7
QCD scale for ggF signal for $N_{\mathrm{jet}} \geq 3$	+8 / -7

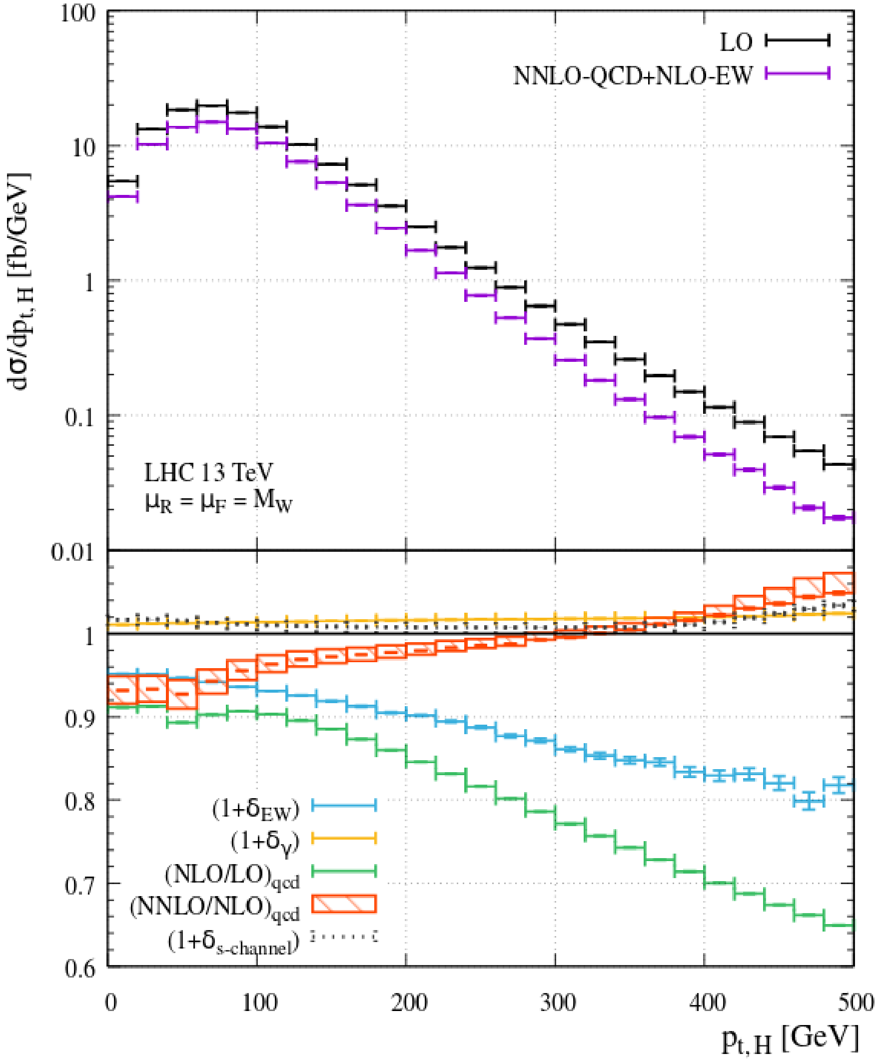
- VBF modeling uncertainty rather important for H→WW systematic model:
  - ➔ Mainly coming from “ME” uncertainty - estimated from generator comparison (Powheg vs aMC@NLO, matched to the same parton-shower)

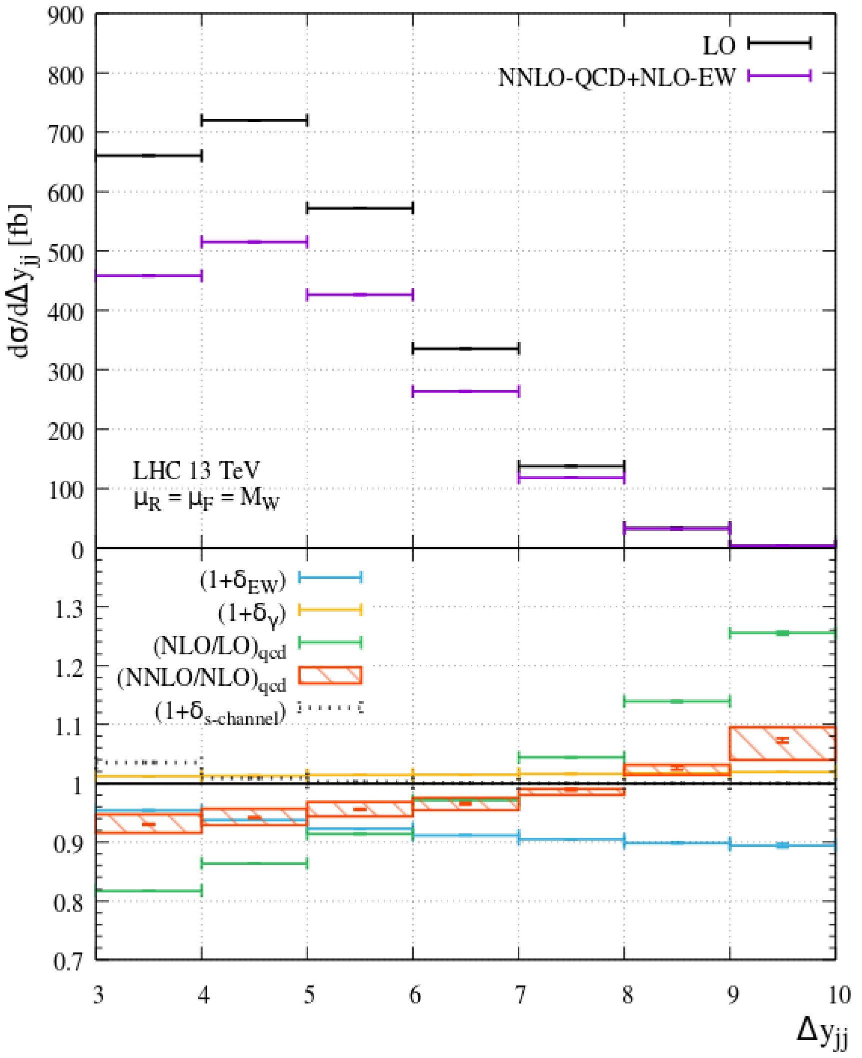
- Full understanding of this source of uncertainties not trivial (different effects encoded in the comparison): not trivial treatment of 2-point systematics

- From Run-1 analyses (H→ττ, H→WW) we also know that PS systematics play an important role in VBF selections

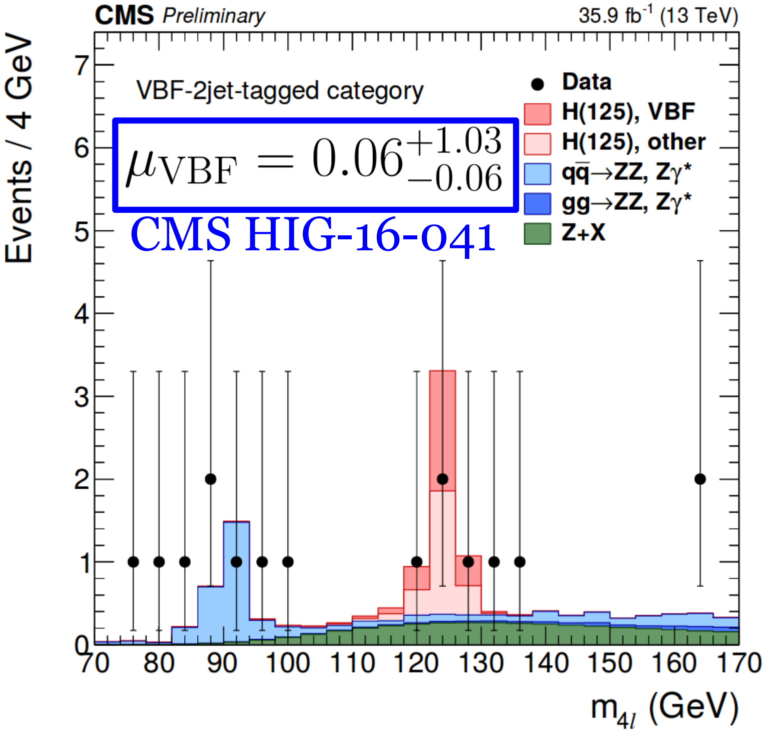
VBF NNLO Corrections

- Experiments would like to profit from computations of fully differential NNLO QCD + NLO EWK cross sections, likely via 1D reweighting of NLO samples
- Discussions ongoing to determine the appropriate variable and phase space





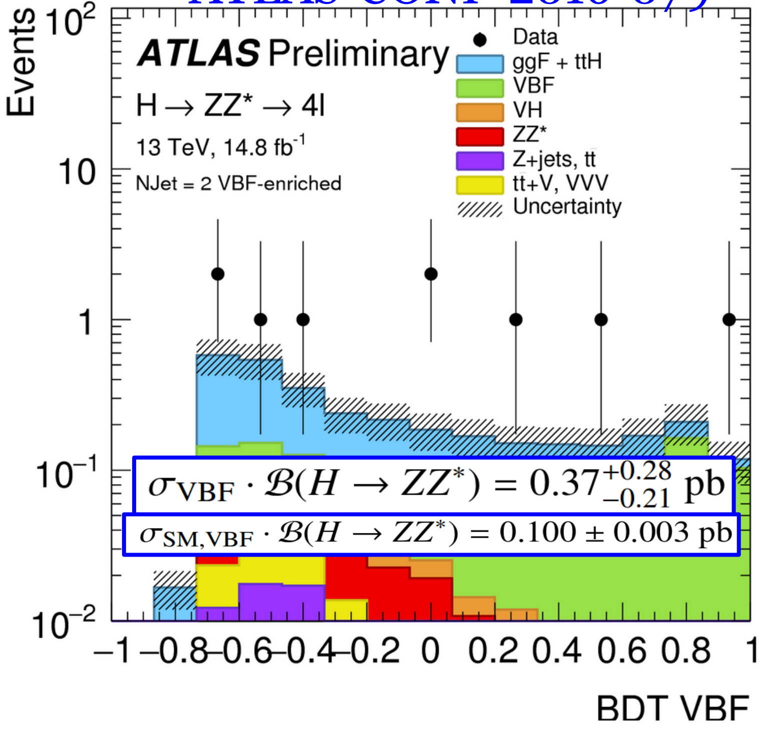
VBF Measurements at 13 TeV



$\mu_{\text{VBF}} = 0.06^{+1.03}_{-0.06}$

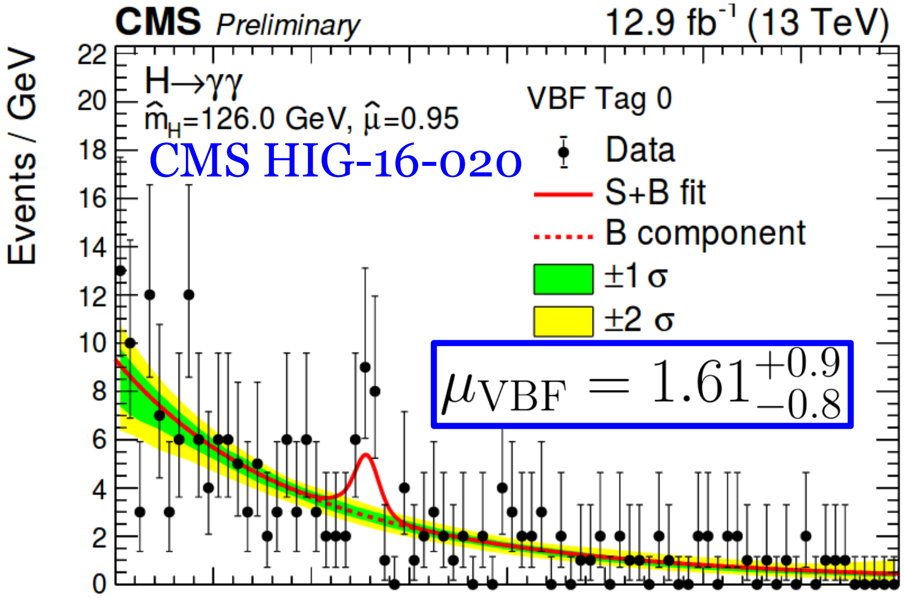
CMS HIG-16-041

ATLAS-CONF-2016-079



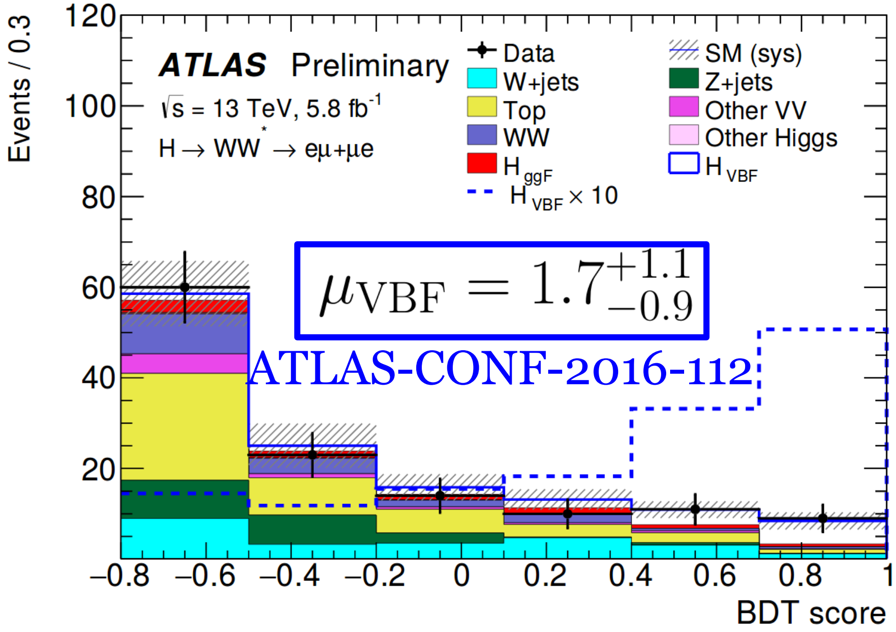
$\sigma_{\text{VBF}} \cdot \mathcal{B}(H \to ZZ^*) = 0.37^{+0.28}_{-0.21}$ pb

$\sigma_{\text{SM,VBF}} \cdot \mathcal{B}(H \to ZZ^*) = 0.100 \pm 0.003$ pb



CMS HIG-16-020

$\mu_{\text{VBF}} = 1.61^{+0.9}_{-0.8}$

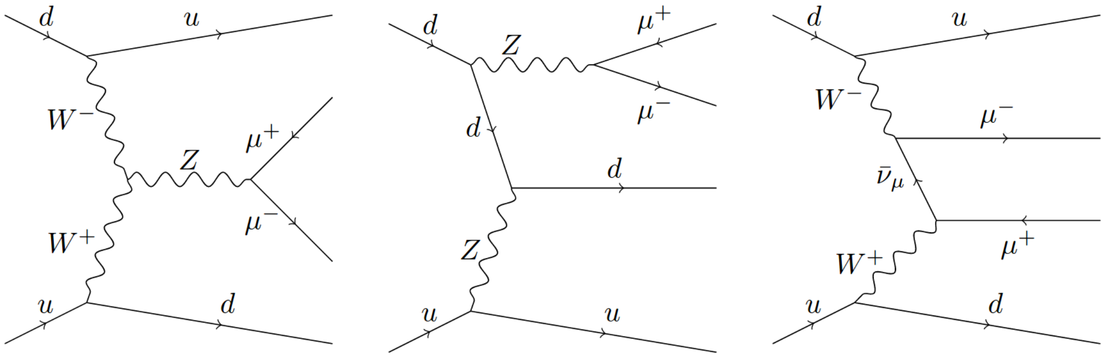


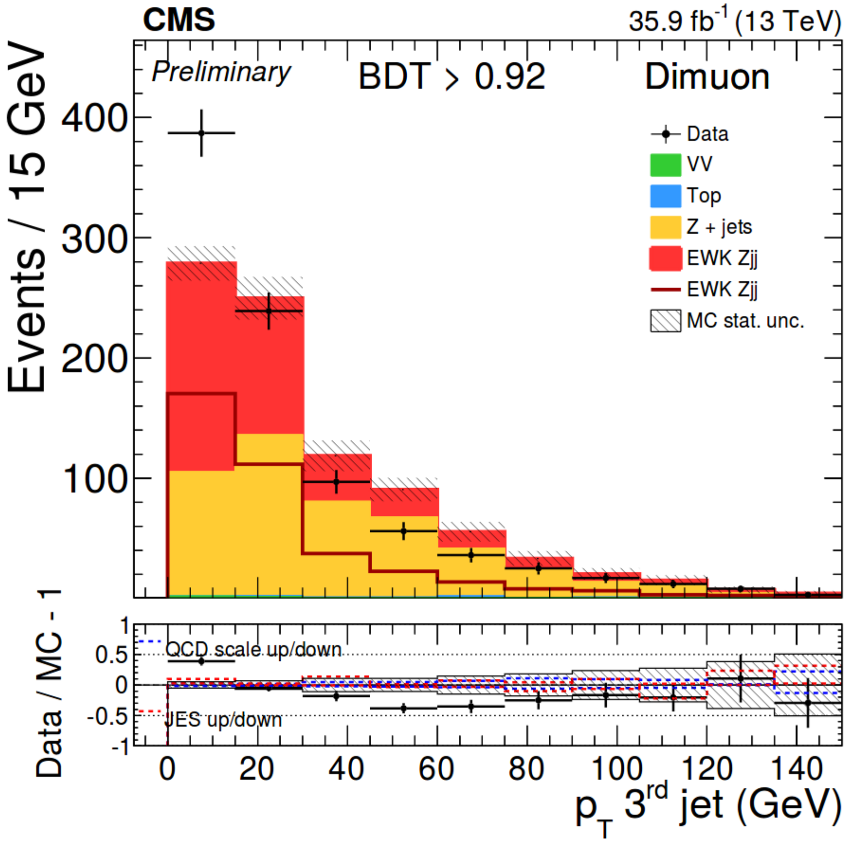
$\mu_{\text{VBF}} = 1.7^{+1.1}_{-0.9}$

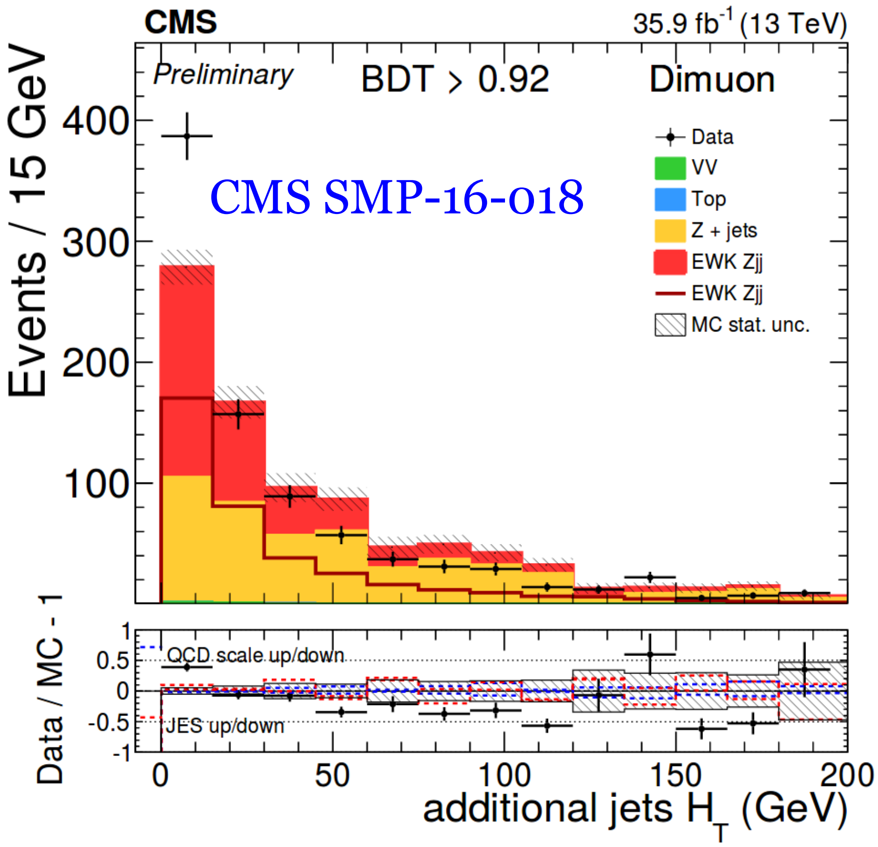
ATLAS-CONF-2016-112

Vjj Measurements at 13 TeV

- LO Madgraph generation of EW Zjj
  - ~5% agreement with VBFNLO
- Suppression of additional jet activity in the signal enhanced region observed
  - Additional jets provided by the Parton Shower





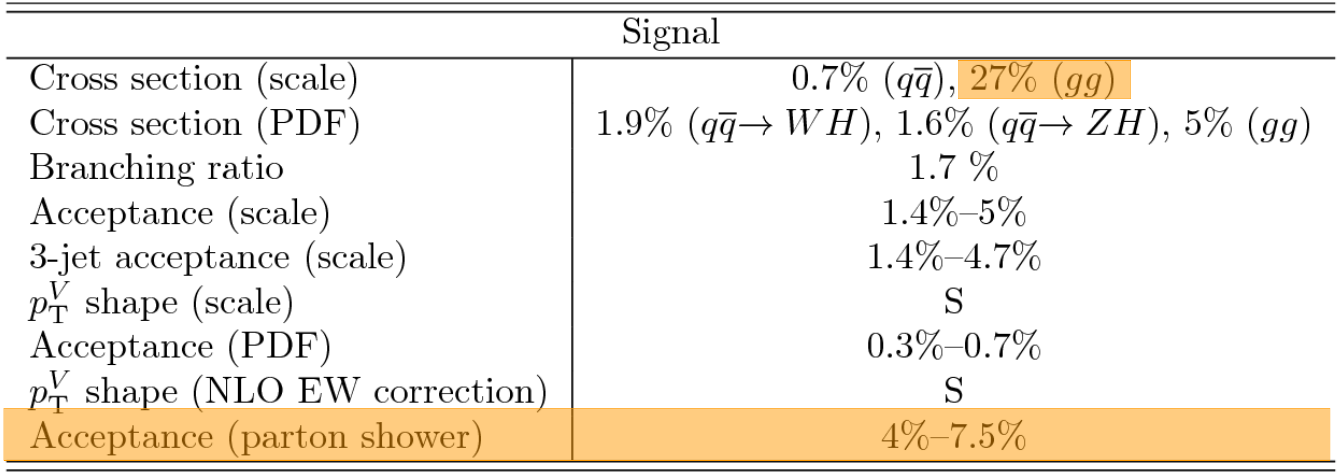


CMS SMP-16-018

VH Signal Modeling

- Both ATLAS and CMS use Powheg(MiNLO)+Pythia8
- VH modeling unc. smaller than experimental unc., but interesting to note:
  - EWK corrections not simulated in the MC, applied by reweighting
  - gg → ZH has a large uncertainty, improvement would be nice
  - Parton-shower modeling already has sizable impact on signal uncertainties

VH(bb): ATLAS-CONF-2016-091

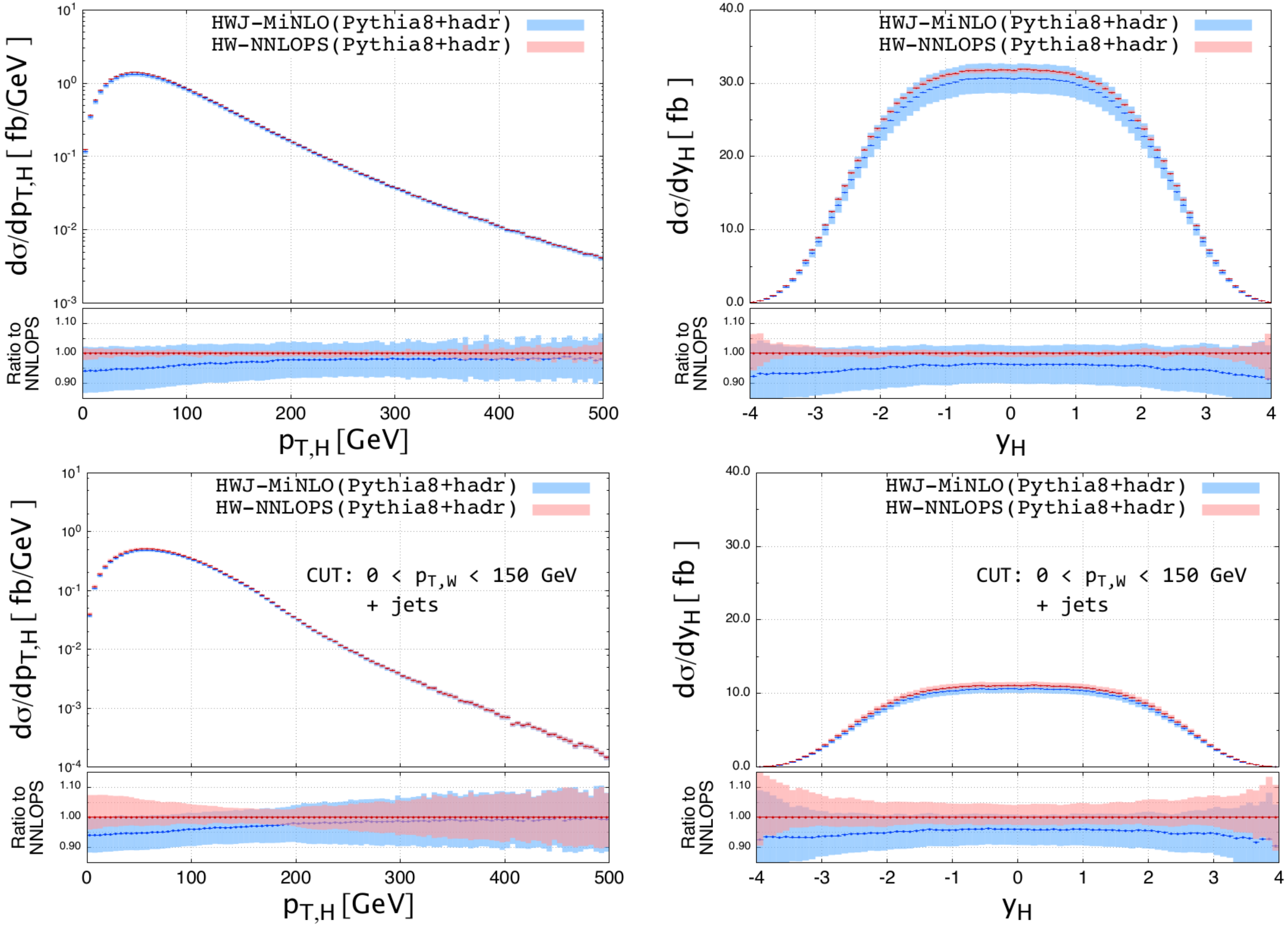


	Signal
Cross section (scale)	0.7% ($q\bar{q}$), 27% (gg)
Cross section (PDF)	1.9% ($q\bar{q} \to WH$), 1.6% ($q\bar{q} \to ZH$), 5% (gg)
Branching ratio	1.7 %
Acceptance (scale)	1.4%–5%
3-jet acceptance (scale)	1.4%–4.7%
p_T^V shape (scale)	S
Acceptance (PDF)	0.3%–0.7%
p_T^V shape (NLO EW correction)	S
Acceptance (parton shower)	4%–7.5%

- Dealing with this source of uncertainty is not trivial:
  - Variations in dedicated experimental tune parameters
  - 2-point comparison among PS (e.g. Pythia vs Herwig)
  - New possibility: internal weights for PS parameter variations 1605.08352
- Discussion: How to accurately determine these uncs./properly use new tools?

VH Signal Modeling

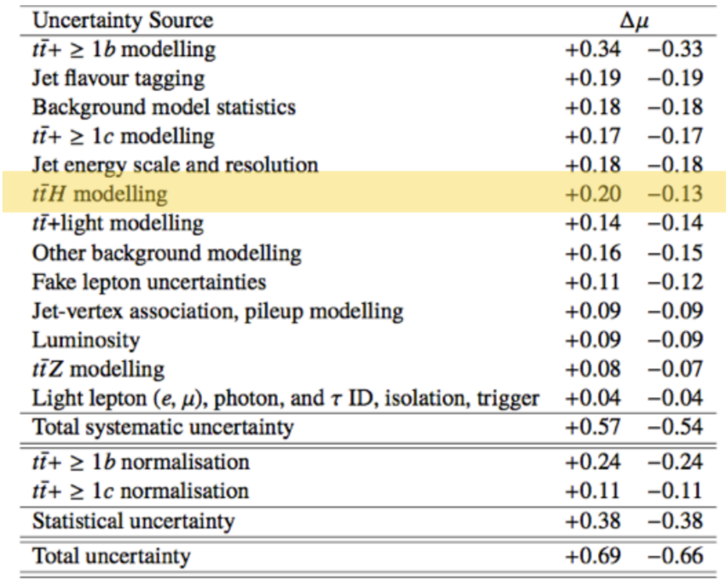
- NNLOPS simulation of VH also available, not yet used by the experiments
  - ➔ Some difference in shapes of relevant distributions, smaller uncertainties



ttH Signal Modeling

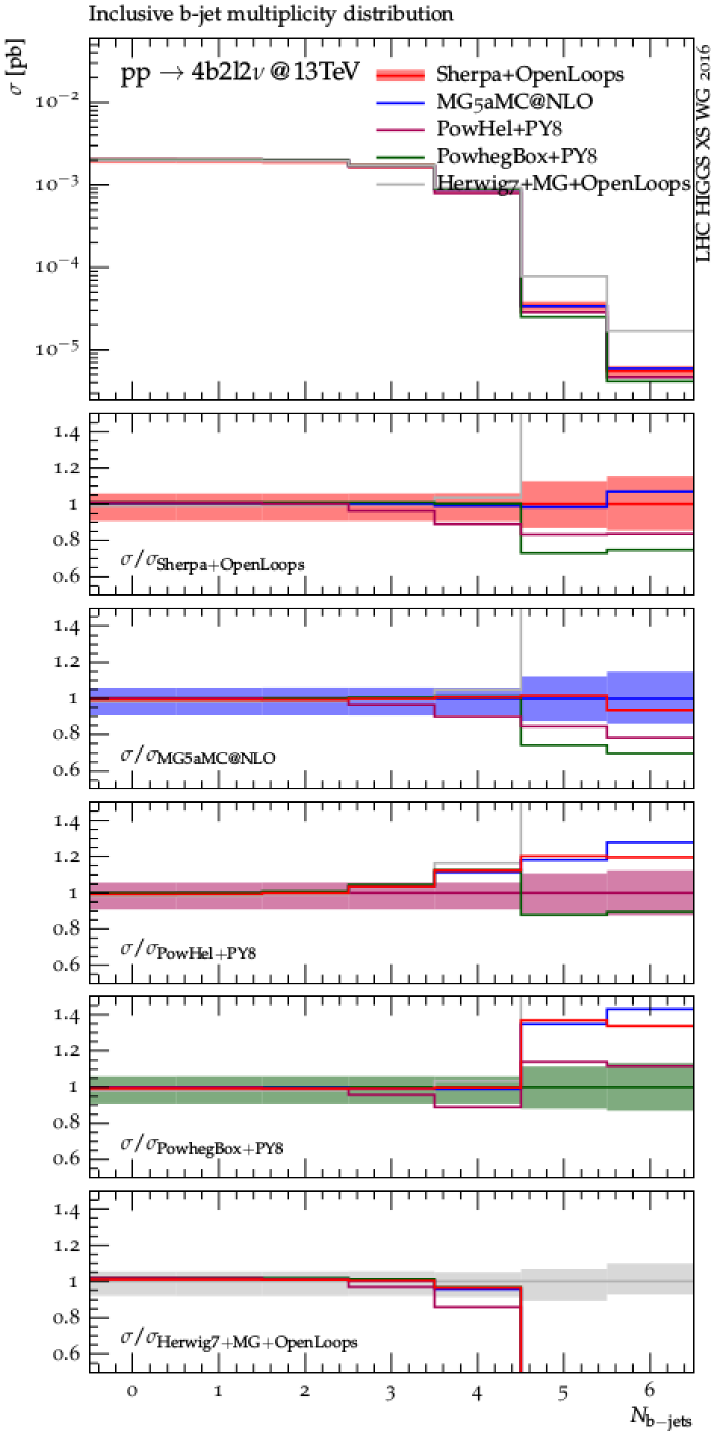
- ATLAS uses aMC@NLO+Pythia8, CMS uses aMC@NLO and Powheg + Pythia8, depending on the channel
- Currently background modeling dominates, but signal modeling is also important:

ttH(combination): ATLAS-CONF-2016-088



Uncertainty Source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modelling	+0.34	−0.33
Jet flavour tagging	+0.19	−0.19
Background model statistics	+0.18	−0.18
$t\bar{t}+\geq 1c$ modelling	+0.17	−0.17
Jet energy scale and resolution	+0.18	−0.18
$t\bar{t}H$ modelling	+0.20	−0.13
$t\bar{t}$+light modelling	+0.14	−0.14
Other background modelling	+0.16	−0.15
Fake lepton uncertainties	+0.11	−0.12
Jet-vertex association, pileup modelling	+0.09	−0.09
Luminosity	+0.09	−0.09
$t\bar{t}Z$ modelling	+0.08	−0.07
Light lepton (e, μ), photon, and τ ID, isolation, trigger	+0.04	−0.04
Total systematic uncertainty	+0.57	−0.54
$t\bar{t}+\geq 1b$ normalisation	+0.24	−0.24
$t\bar{t}+\geq 1c$ normalisation	+0.11	−0.11
Statistical uncertainty	+0.38	−0.38
Total uncertainty	+0.69	−0.66

- MC studies (ATLAS-CONF-2016-005 and YR4) show that PS variations have a sizable effects on the shape of relevant ttH variables.
  - ➔ Difference between Pythia8 and Herwig++ larger than tune variations



Conclusions

- **MC Tools used by ATLAS and CMS have progressed greatly since Run 1**
  - NLO generators for all production modes
  - NNLO generation for gluon fusion

- **Experimental accuracy for differential cross sections approaching theoretical uncertainty**
  - Dominated by gluon fusion
  - Subleading production modes are next

- **Previously sub-dominant uncertainties may soon become dominant (e.g. PS variations)**

- **Experiments are always interested in more accurate predictions!**