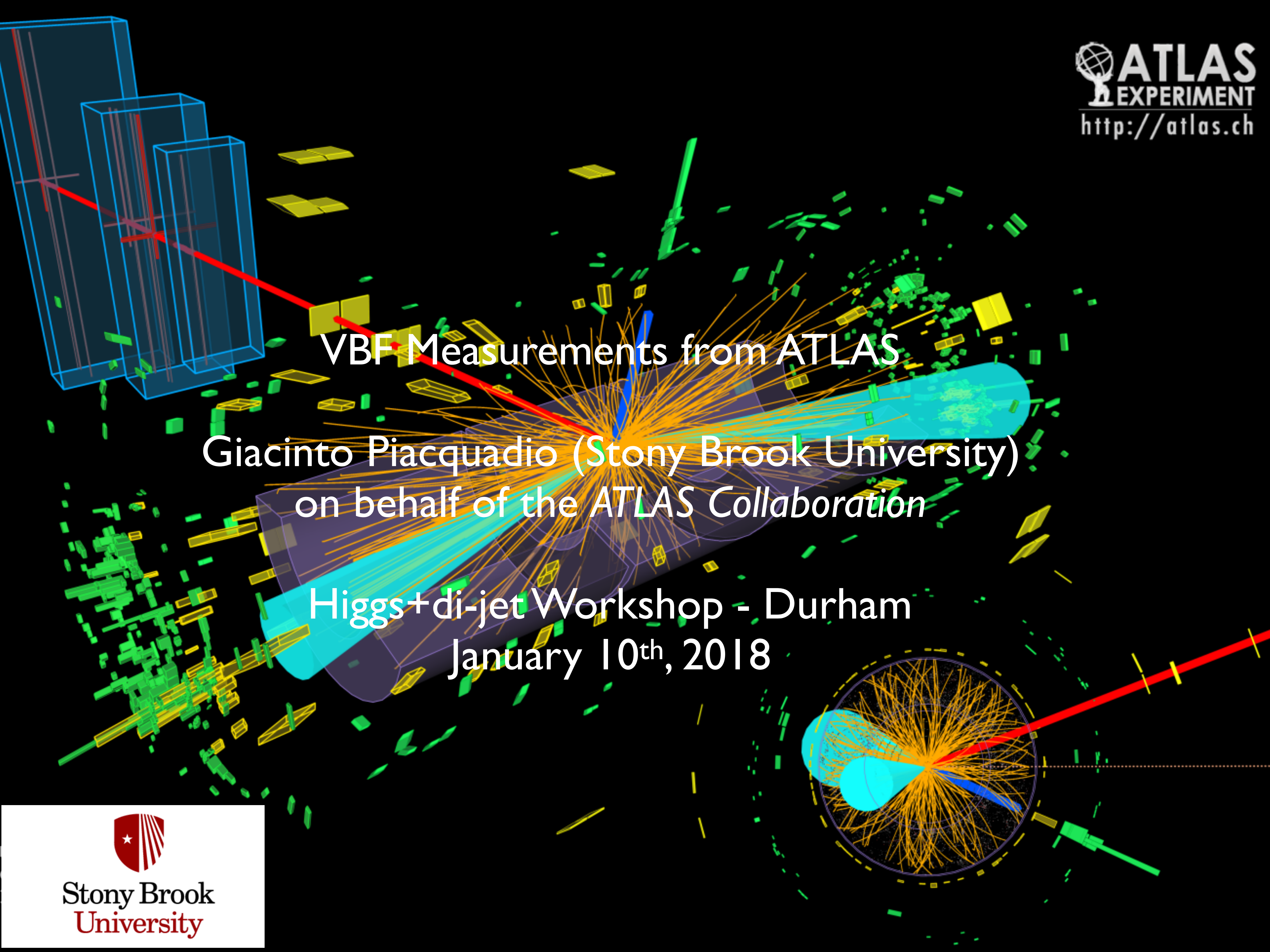


VBF Measurements from ATLAS

Giacinto Piacquadio (Stony Brook University)
on behalf of the *ATLAS Collaboration*

Higgs+di-jet Workshop - Durham
January 10th, 2018

Stony Brook University

Outline

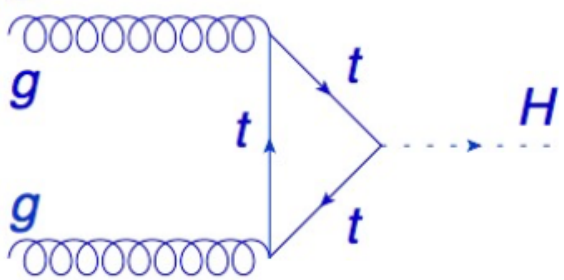
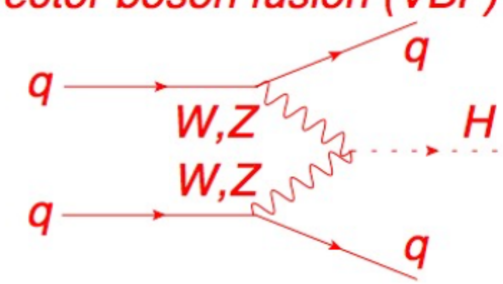
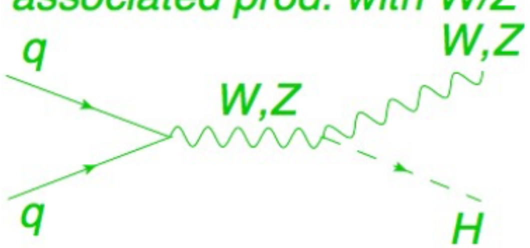
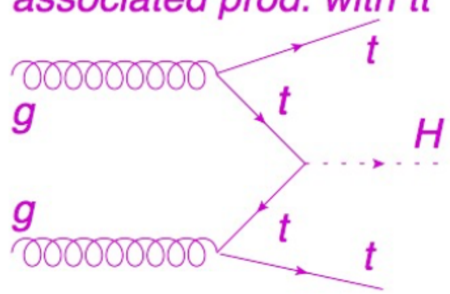
- New 13 TeV measurements
  - for Vector Boson Fusion (VBF) Higgs production
    - $H \to \gamma\gamma$
    - $H \to ZZ^*$
    - $H \to WW^*$ (partial 13 TeV dataset)
    - + comparison to 7+8 TeV results
  - for EW V+2-jets production (including VBF)
    - EW Z+2-jet production
    - + comparison to EW V+2-jets production @ 8 TeV
  - for VBF + γ production, with $H \to bb$
- Conclusions

Disclaimer(s)

- Because of limited time, I might need to skip the EW Z+jj and W+jj measurements
  - Nevertheless, this are the most precise measurements sensitive to VBF production we have today
- I have not worked myself on most of these analyses
  - This is a workshop: feel free to interrupt and comment
  - Several ATLAS long-time VBF experts in the audience that can help in the discussions
- Publications/conf notes, including links, are highlighted at the top right corner of the slides

Higgs boson production at LHC

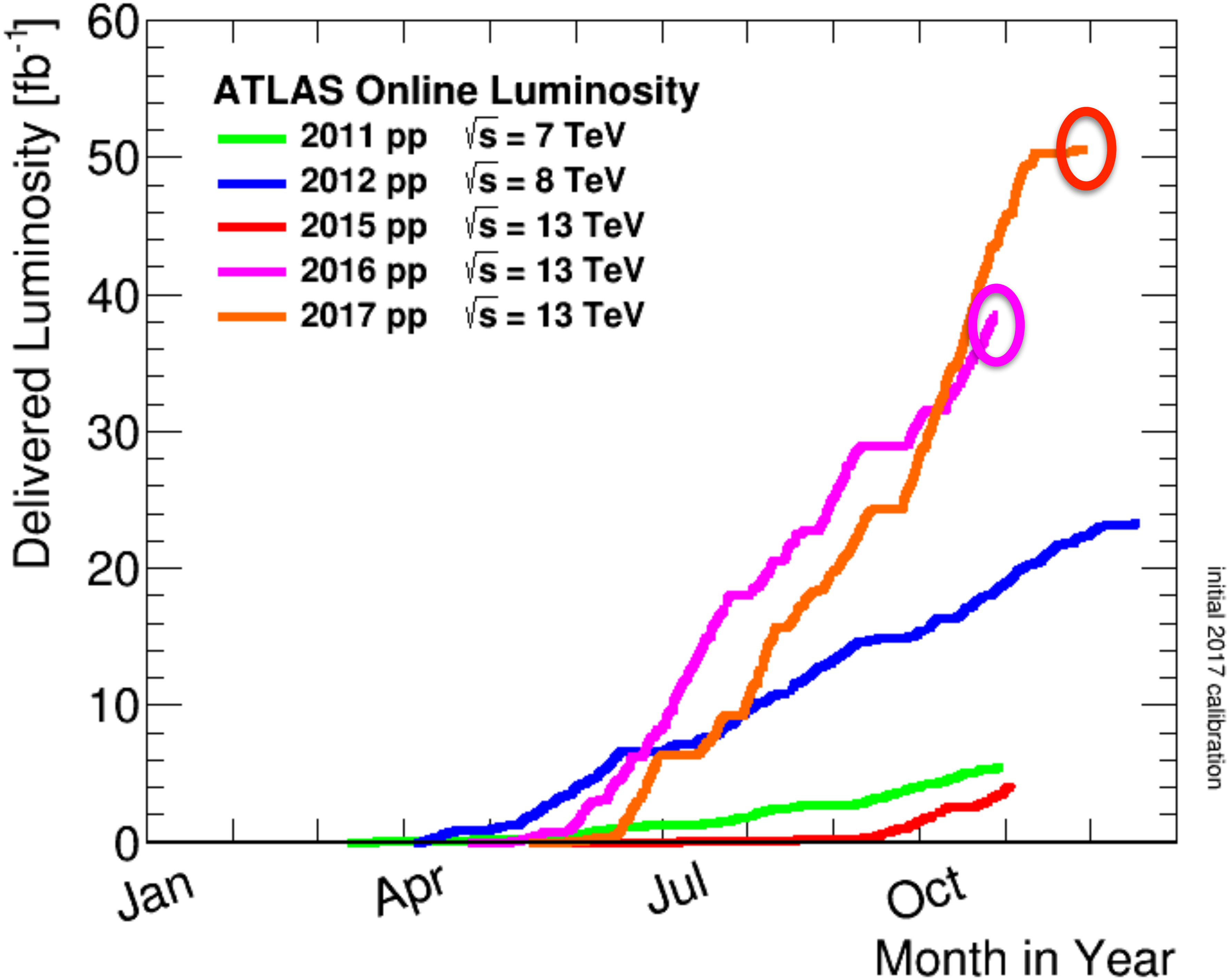
At the **LHC** there are many ways to **produce** the Higgs boson.

Production modes	σ(8 TeV)	σ(13 TeV)
gluon fusion 	21.4pb	48.5pb
vector boson fusion (VBF) 	1.6pb	3.8pb
associated prod. with W/Z 	1.1pb	2.25pb
associated prod. with tt 	0.13pb	0.5pb

- VBF is 12x-14x times smaller than inclusive production
- Higher cross section at 13 TeV helps making it accessible also in purer but rarer decay modes
  - $H \rightarrow ZZ^* \rightarrow$ 4 leptons
  - $H \rightarrow \gamma\gamma$

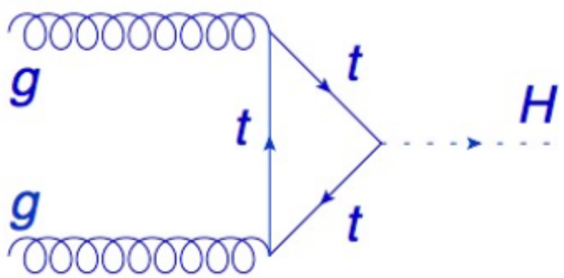
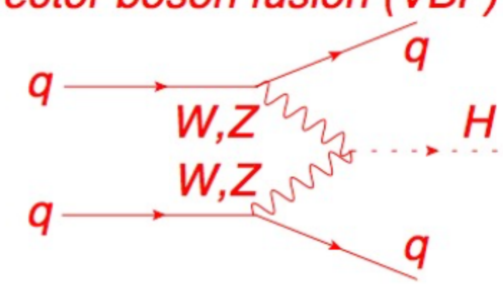
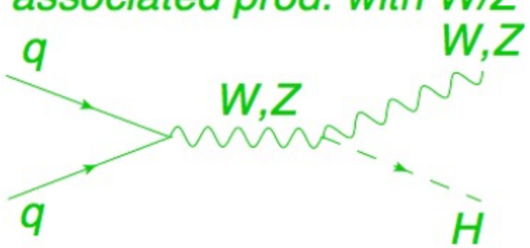
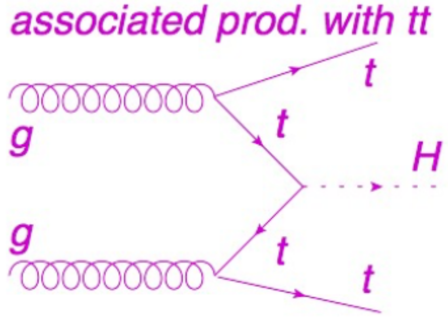
LHC & ATLAS performance

Two exciting years of data taking behind us! Lots of data for physics analysis!



Higgs boson production at LHC

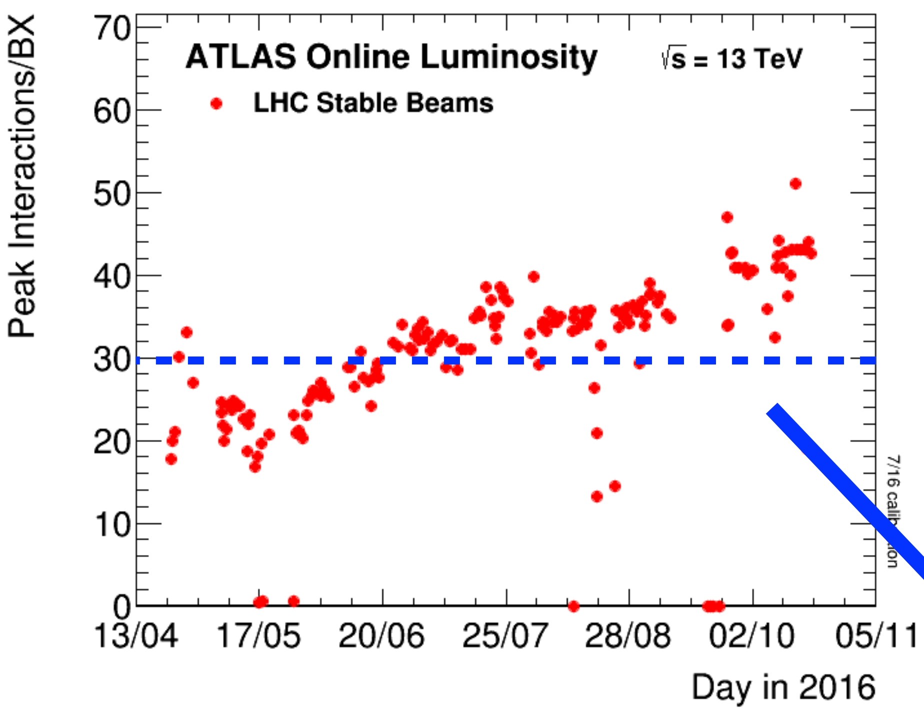
At the **LHC** there are many ways to **produce** the Higgs boson.

Production modes	σ(8 TeV)	σ(13 TeV)
gluon fusion 	21.4pb	48.5pb
vector boson fusion (VBF) 	1.6pb	3.8pb
associated prod. with W/Z 	1.1pb	2.25pb
associated prod. with tt 	0.13pb	0.5pb

N. events with 35 fb^{-1}

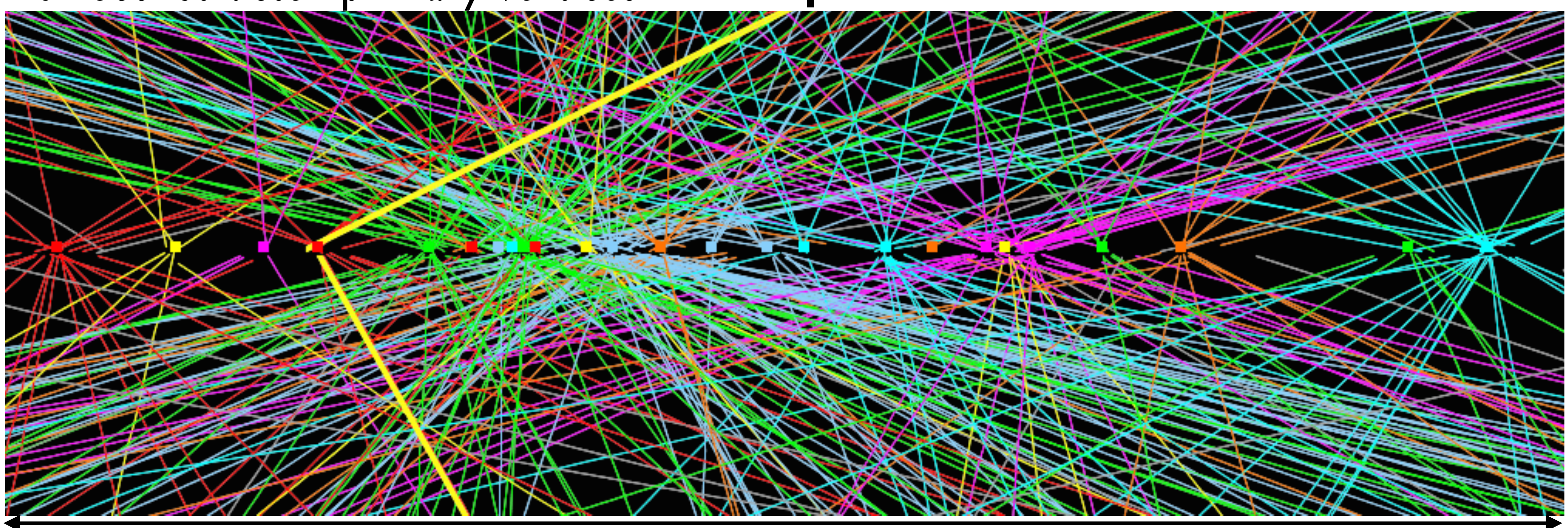
~130000 !

The luminosity challenge

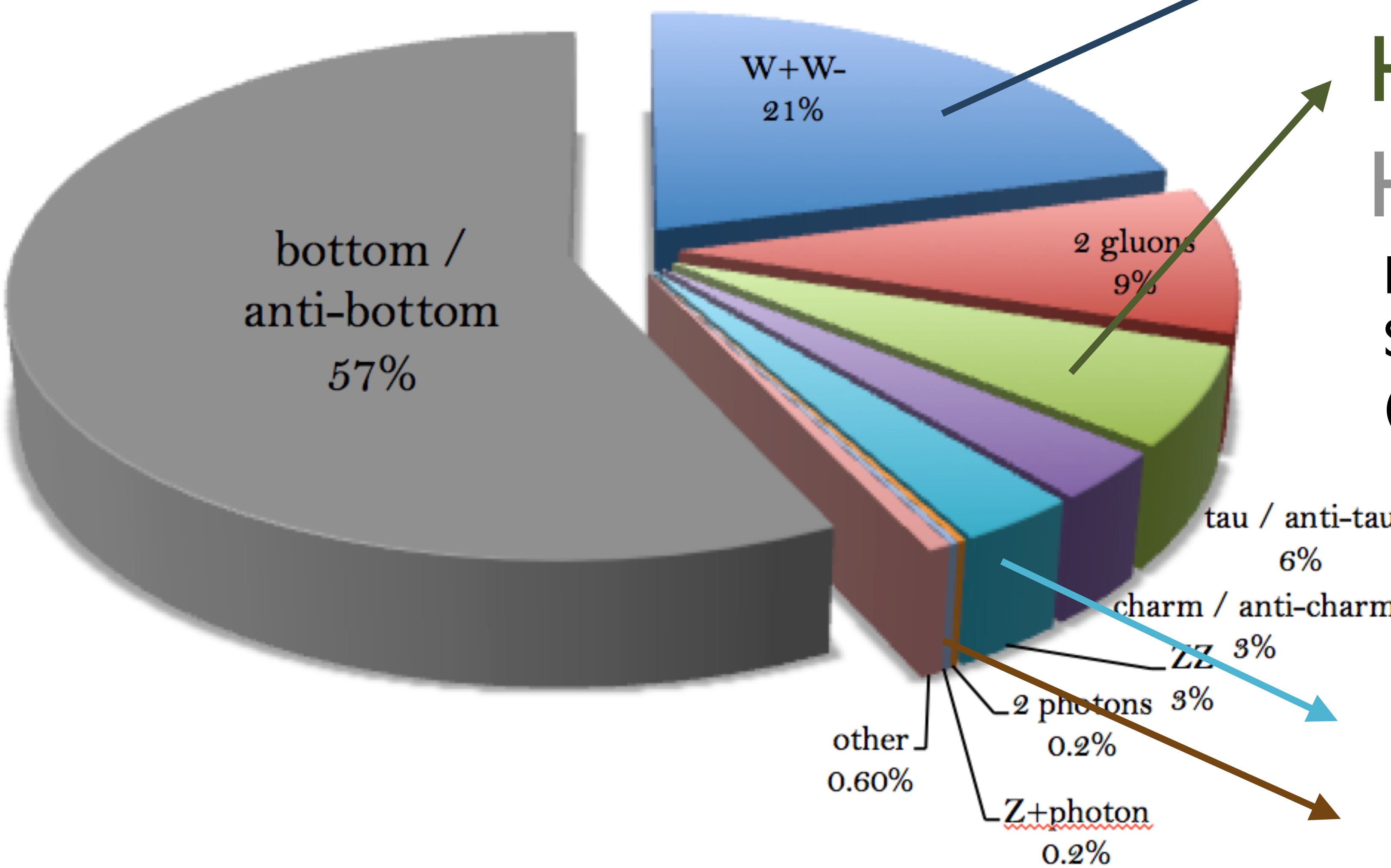


- This performance came at the cost of higher instantaneous luminosity!
- A lot of optimization performed in ATLAS to minimize performance degradation, or even improve the performance.
- Crucial for VBF signature: minimized impact of pile-up on **jet energy scale and resolution**

25 reconstructed primary vertices



Decay modes for VBF



$H \rightarrow WW^*$

$H \rightarrow \tau\tau$

$H \rightarrow bb$

High signal yield, but challenging S/B, 13 TeV analyses still ongoing (partial results for $H \rightarrow WW^*$)

$H \rightarrow ZZ^* \rightarrow 4l$

$H \rightarrow \gamma\gamma$

Small branching ratios, but high purity, first 13 TeV analysis ready, will describe next!

The path ahead?

Inclusive signal strength = N_{fit}/N_{exp}

Simplified template cross-section (sub-divide events in different phase space regions defined at particle level)

Unfolded distributions measured at particle level (in fiducial regions)

- The idea here is that comparison to specific models, or fits to EFTs, can be performed by interpreting these measurements.
- Experimentalists provide clear phase space definitions and full covariance matrices in addition to the measurements.

Signal samples in 13 TeV analyses

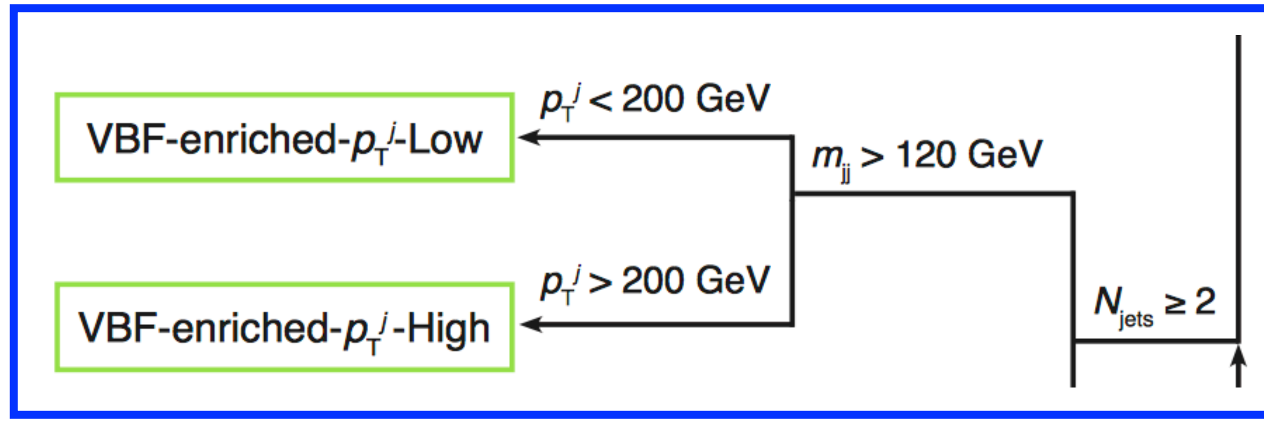
- Simulated signal samples
  - VBF Higgs Boson Signal generated with Powheg-Box v2 (NLO in QCD)
  - ggF Signal Powheg-Box v2 (NLO MiNLO H+0 and H+1 jet), reweighting of Higgs rapidity using HNNLO to reach NNLOPS accuracy [E. Re, arXiv:1401:2944]
    - pT(H) distribution compatible with NNLL+NLO prediction from HRes 2.3, so no reweighting applied
  - Pythia8 for shower / hadronisation / Higgs decay
- Cross-section
  - VBF: NLO QCD+EW, approx. NNLO
  - ggF: N3LO QCD + NLO EW
    - jet binning method based on combining 0-jet and 1-jet resummation [YR4 based on (STWZ) and (BLPTW) as input]

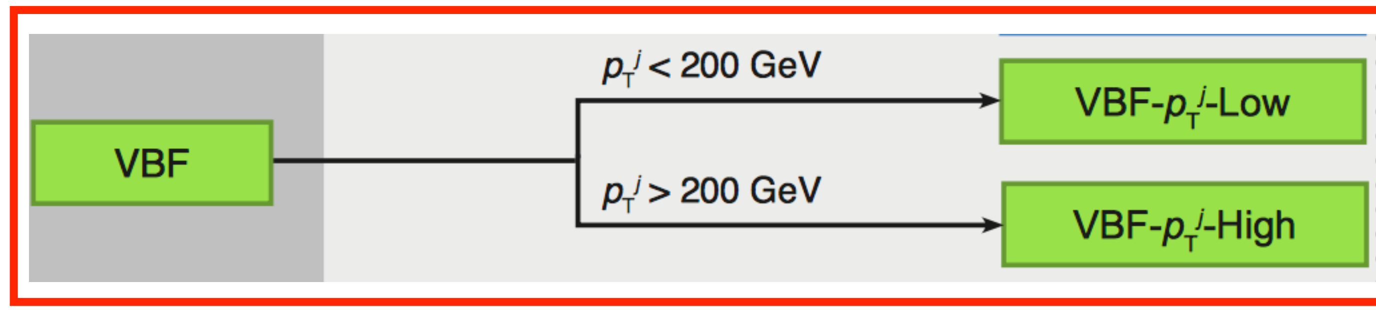
[arXiv:1712.02304]

H → 4 leptons

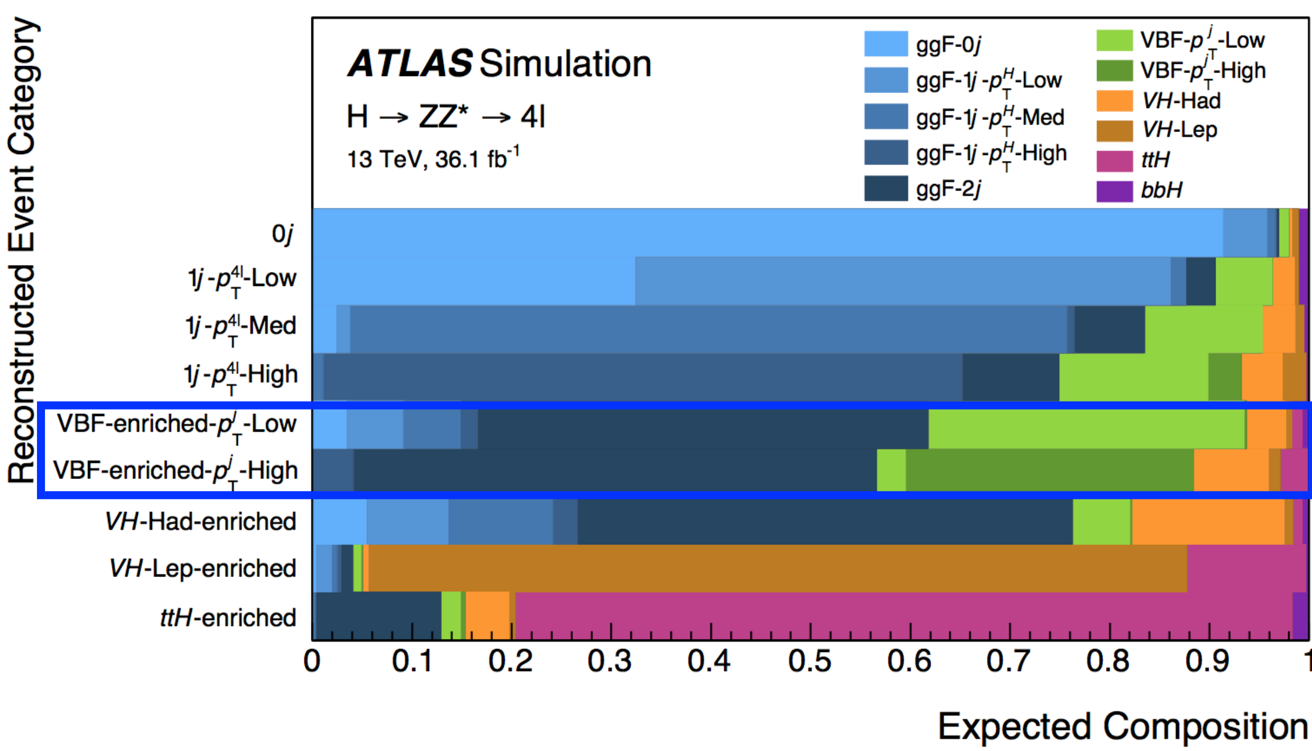
- Efficiency to reconstruct H to 4 lepton system: 31%, 21%, 17% and 16% for 4μ, 2e2μ, 2μ2e, 4e channels
- Jets selected with pT>30 GeV, |η|< 4.5 (jets from pile-up rejected)
- Dedicated **categories** for VBF production
- ..aiming at constraining Higgs production in different VBF phase space region defined by **“reduced stage 1” template cross sections method**

Selection level





Particle level



Significant ggF contamination in VBF categories

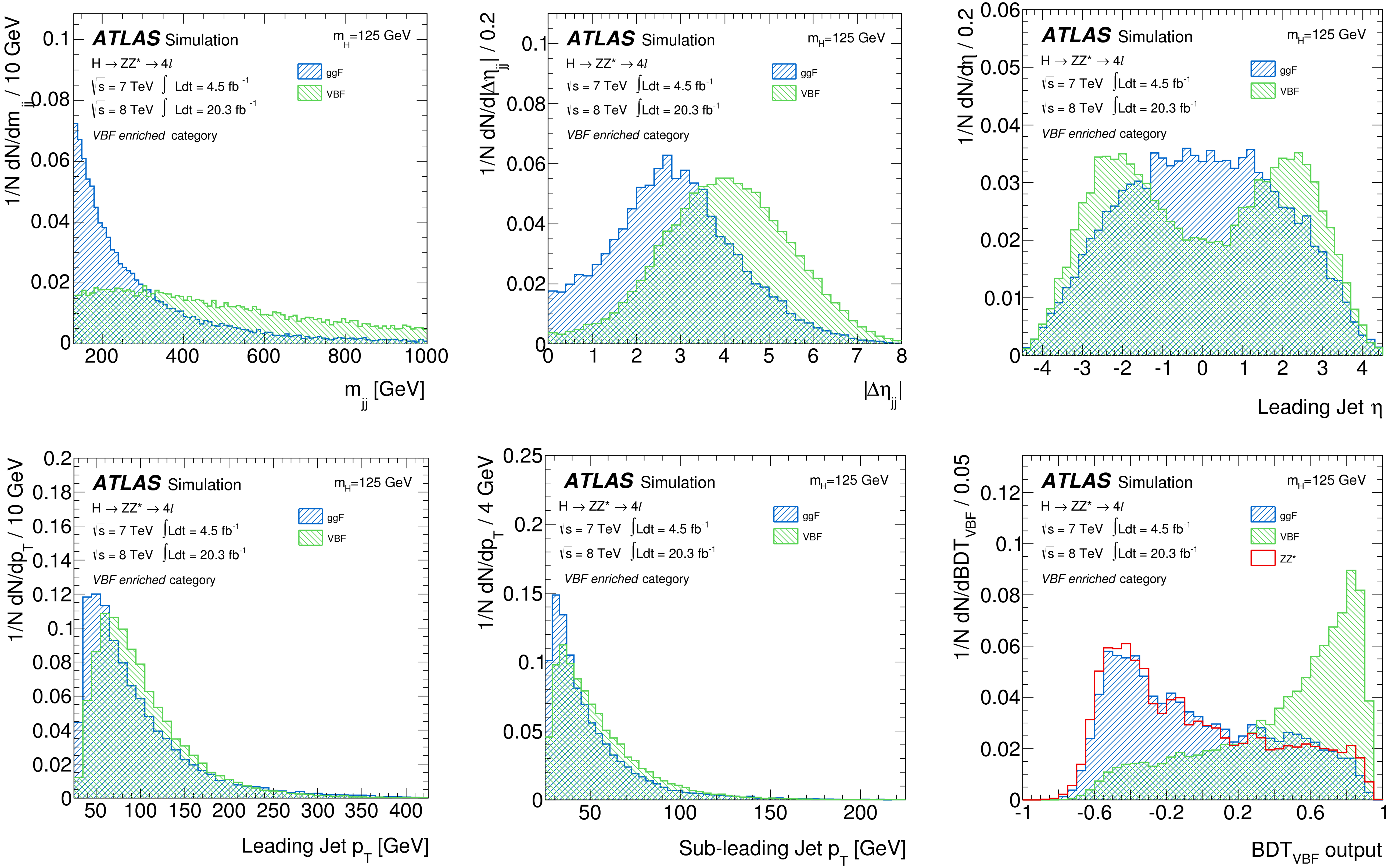
- Number of expected Higgs events in each signal category:

Reconstructed	SM Higgs boson production mode				
event category	ggF	VBF	VH	ttH	bbH
$0j$	25.9 ± 2.5	0.29 ± 0.09	0.253 ± 0.025	0.00025 ± 0.00019	0.29 ± 0.14
$1j$-$p_{\mathrm{T}}^{4\ell}$-Low	8.0 ± 1.1	0.514 ± 0.034	0.230 ± 0.018	0.0007 ± 0.0005	0.09 ± 0.05
$1j$-$p_{\mathrm{T}}^{4\ell}$-Med	4.5 ± 0.7	0.64 ± 0.09	0.227 ± 0.019	0.0010 ± 0.0005	0.026 ± 0.013
$1j$-$p_{\mathrm{T}}^{4\ell}$-High	1.10 ± 0.24	0.27 ± 0.04	0.095 ± 0.007	0.00080 ± 0.00024	0.0036 ± 0.0018
VBF-enriched-p_{T}^{j}-Low	3.9 ± 0.8	2.03 ± 0.19	0.285 ± 0.024	0.065 ± 0.009	0.045 ± 0.023
VBF-enriched-p_{T}^{j}-High	0.33 ± 0.09	0.185 ± 0.024	0.050 ± 0.004	0.0159 ± 0.0027	0.00058 ± 0.00029
VH-Had-enriched-$p_{\mathrm{T}}^{4\ell}$-Low	2.3 ± 0.5	0.169 ± 0.014	0.418 ± 0.023	0.022 ± 0.004	0.025 ± 0.013
VH-Had-enriched-$p_{\mathrm{T}}^{4\ell}$-High	0.42 ± 0.09	0.048 ± 0.008	0.162 ± 0.005	0.0090 ± 0.0015	< 0.0001
VH-Lep-enriched	0.0129 ± 0.0018	0.00310 ± 0.00021	0.263 ± 0.018	0.038 ± 0.005	0.0009 ± 0.0005
ttH-enriched	0.050 ± 0.016	0.010 ± 0.006	0.0196 ± 0.0031	0.301 ± 0.032	0.0064 ± 0.0035
Total	47 ± 4	4.16 ± 0.23	2.00 ± 0.11	0.45 ± 0.05	0.49 ± 0.24

- Additional separation between VBF and ggF thanks to specific BDT used in final fit:

Reconstructed event category	BDT discriminant	Input variables
VBF-enriched-p_{T}^{j}-Low	$\mathrm{BDT_{VBF}}$	m_{jj}, $\Delta\eta_{jj}$, p_{T}^{j1}, p_{T}^{j2}, $\eta^{*}_{4\ell}$, $\Delta R^{\mathrm{min}}_{jZ}$, $(p_{\mathrm{T}}^{4\ell jj})_{\mathrm{constrained}}$

- Here: η^*_{4l} is the difference in pseudo-rapidity between 4l system and average jet η, ΔR^{min}_{jZ} is between leading lepton pair and leading two jets, p_T^{4ljj} is the transverse momentum of H+di-jet system (only considered above 50 GeV to reduce impact of QCD scale uncertainties).

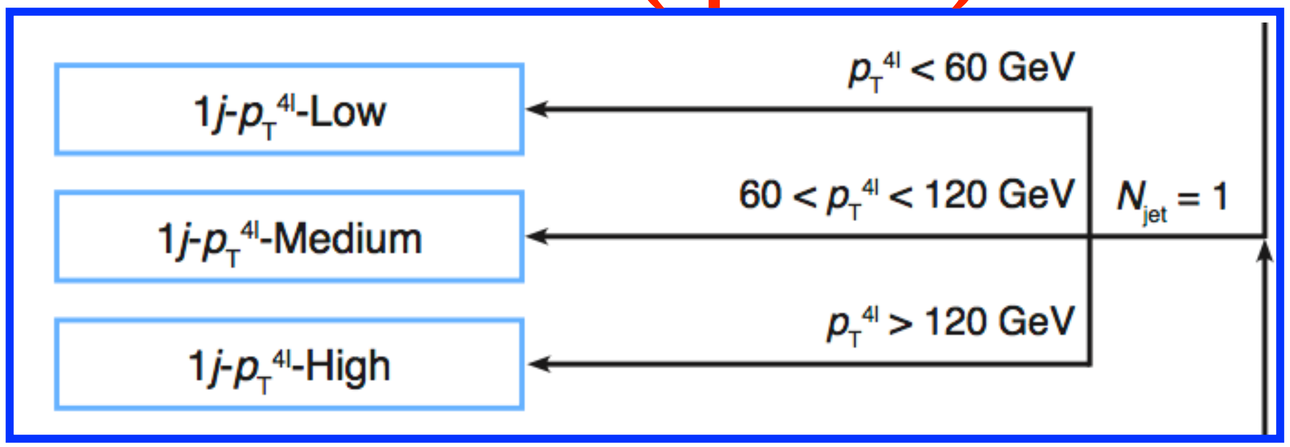


from 7 + 8 TeV analysis, differences: m_{jj}>130 GeV (55% signal efficiency), pT(jets) >25 GeV for |η|<2.5

[arXiv:1712.02304]

Additional 1-jet categories

Selection (+particle) level

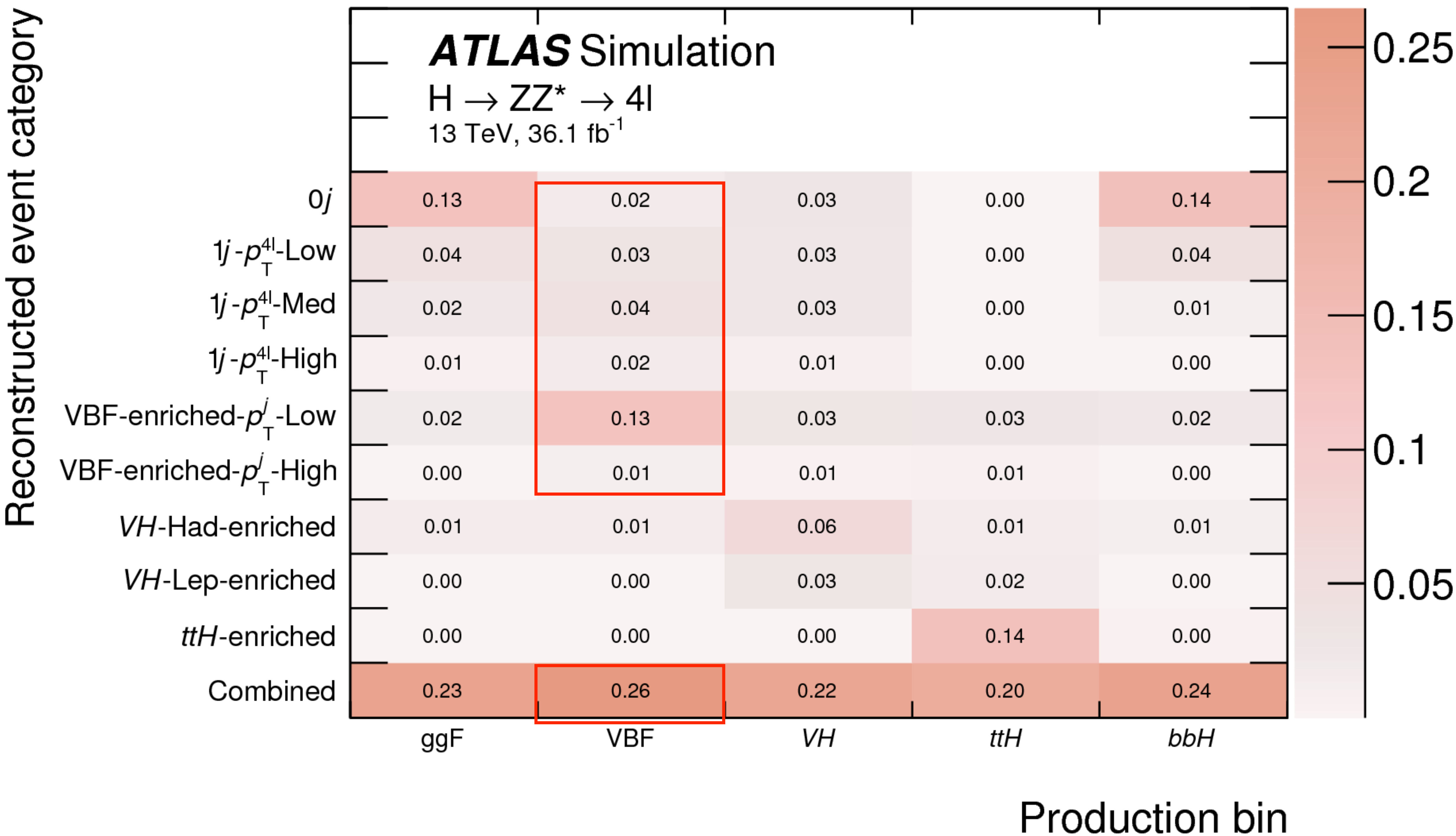


- Events in 1-jet have non-negligible VBF contribution, so BDT discriminant used in these categories to separate ggF from VBF production

Reconstructed event category	BDT discriminant	Input variables
$1j$-$p_{\mathrm{T}}^{4\ell}$-Low	$\mathrm{BDT}_{\mathrm{VBF}}^{1j\text{-}p_{\mathrm{T}}^{4\ell}\text{-Low}}$	p_{T}^{j}, η_j, $\Delta R(j, 4\ell)$
$1j$-$p_{\mathrm{T}}^{4\ell}$-Med	$\mathrm{BDT}_{\mathrm{VBF}}^{1j\text{-}p_{\mathrm{T}}^{4\ell}\text{-Med}}$	p_{T}^{j}, η_j, $\Delta R(j, 4\ell)$
$1j$-$p_{\mathrm{T}}^{4\ell}$-High	-	-

- BDTs employed in 1-jet and 2-jet VBF enriched categories reduce statistical uncertainty on mu(VBF) by 35%!

Higgs reconstruction efficiencies



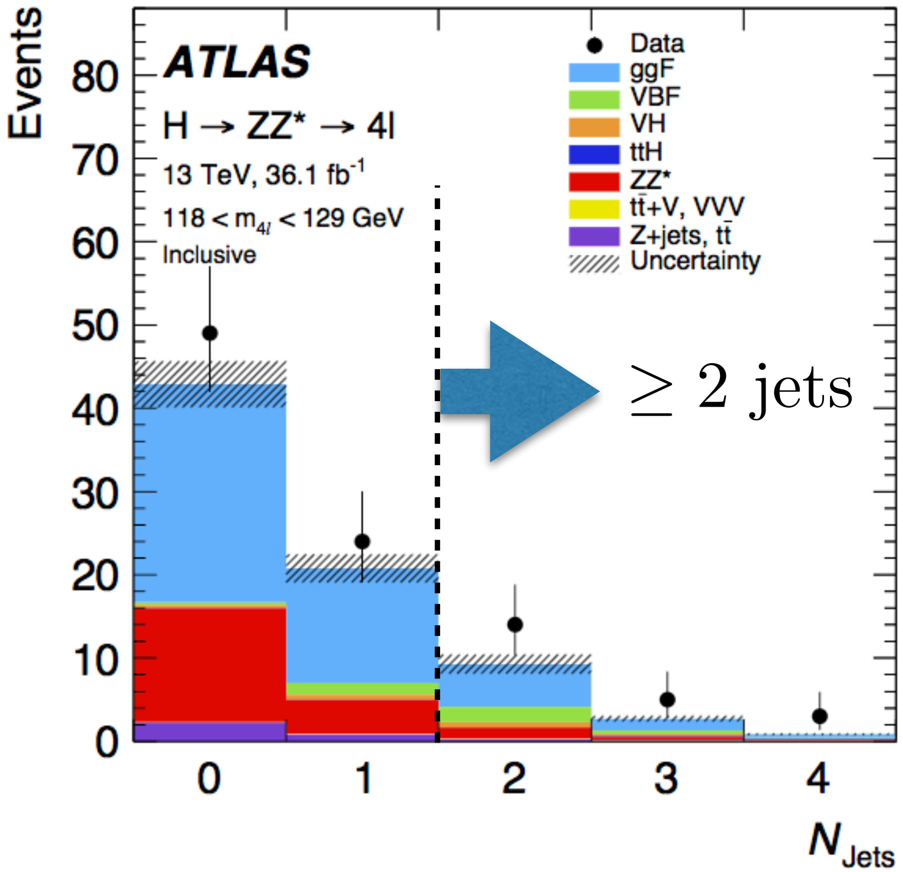
Uncertainties

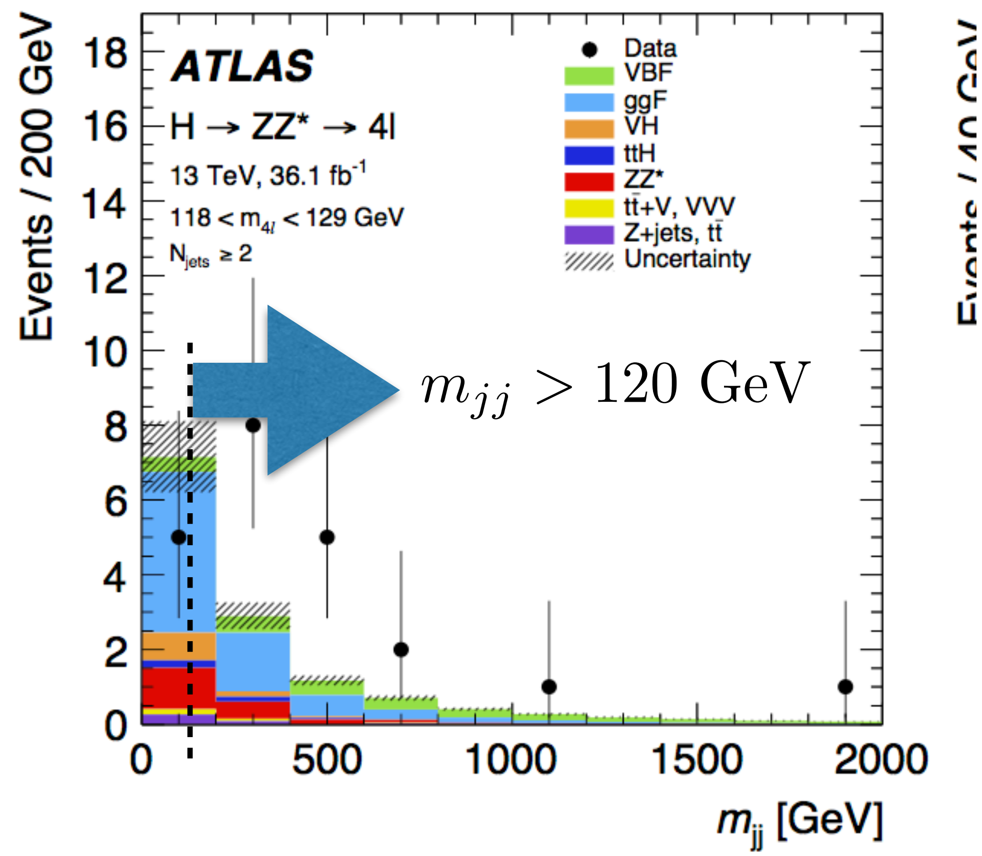
- Impact of dominant systematic uncertainties [%] on the overall signal strengths measured in the different production modes:

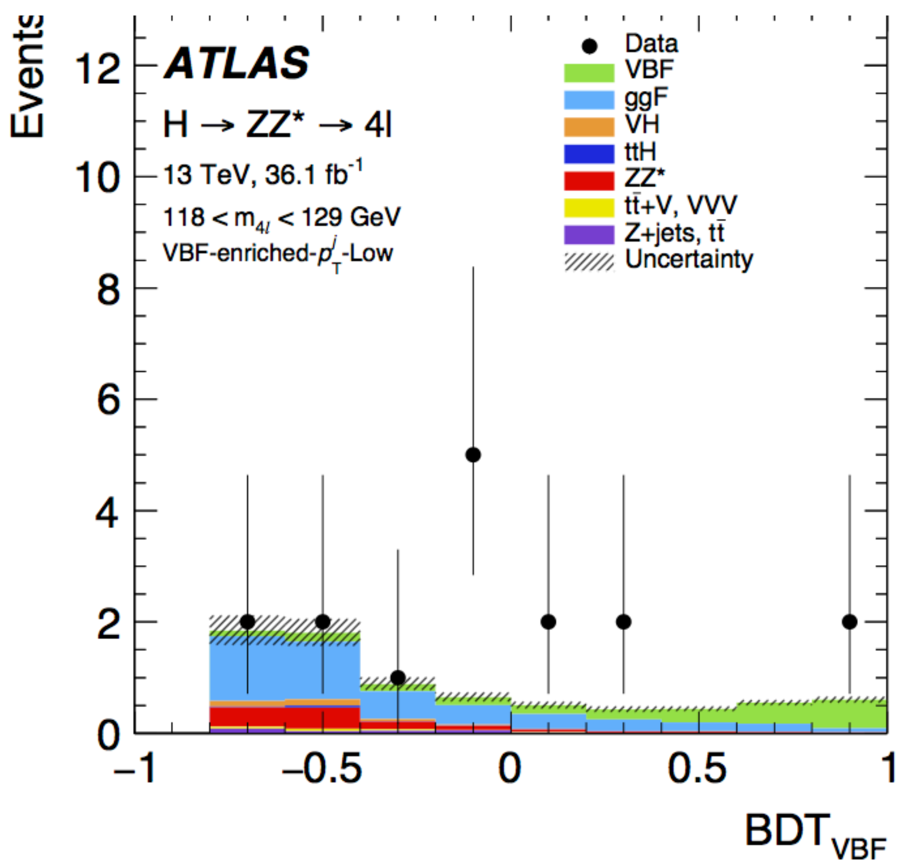
Production bin	Experimental uncertainties [%] Lumi	e, μ, pile-up	Jets, flavour tagging	Higgs mass	Reducible backgr.	Theory uncertainties [%] ZZ^* backgr.	PDF	Signal theory QCD scale	Shower
Inclusive cross section									
	4.1	3.1	0.7	0.8	0.9	1.9	0.3	0.8	1.2
Stage-0 production bin cross sections									
ggF	4.3	3.4	1.1	1.2	1.1	1.8	0.5	1.8	1.4
VBF	2.6	2.7	10	1.3	0.9	2.2	1.6	11	5.3
VH	3.0	2.7	11	1.6	1.7	5.9	2.1	12	3.7
ttH	3.6	2.9	19	< 0.1	2.4	1.9	3.3	7.9	2.1

- Leading uncertainty on VBF production yield is:
    - 11% from QCD scale variation (ggF: 3 NPs for scales in jet binning, 1 NP pT distribution, 1 NP infinite quark mass in loop, 1 NP VBF acceptance for ggF based on MCFM, VBF: μ_R, μ_F by x0.5/2)
    - 5% from shower (Pythia8 vs Herwig7 + AZNLO tune eigenvector variations)
- Compared to 10% for jet reconstruction (JES, JER, pile-up)

Results for H → 4 leptons







- Small excess seen in VBF production μ_{VBF} = 4.0 +/- 1.7 (stat. unc. dominated, theory <10%, 2.2σ from SM)

Production bin	Cross section $(\sigma \cdot B)$ [pb]		$(\sigma \cdot B)/(\sigma \cdot B)_{SM}$
	SM expected	Observed	Observed
Inclusive production, $\lvert y_H \rvert < 2.5$			
	1.34 ± 0.09	$1.73^{+0.24+0.10}_{-0.23-0.08} \pm 0.04$	$1.29^{+0.18+0.07}_{-0.17-0.06} \pm 0.03$
Stage-0 production bins, $\lvert y_H \rvert < 2.5$			
ggF	1.18 ± 0.08	$1.31^{+0.26+0.09}_{-0.24-0.07} \pm 0.05$	$1.11^{+0.22+0.07}_{-0.20-0.06} \pm 0.04$
VBF	0.0928 ± 0.0028	$0.37^{+0.15}_{-0.13} \pm 0.03 \pm 0.03$	$4.0^{+1.7}_{-1.4} \pm 0.3 \pm 0.3$

[ATLAS-CONF-2017-045]

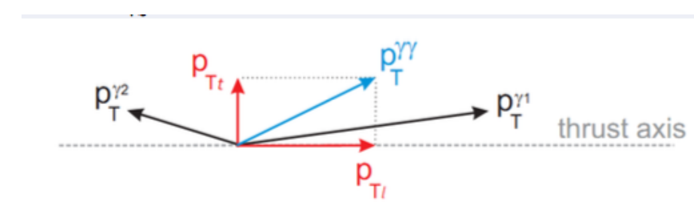
Categorization for H → γγ

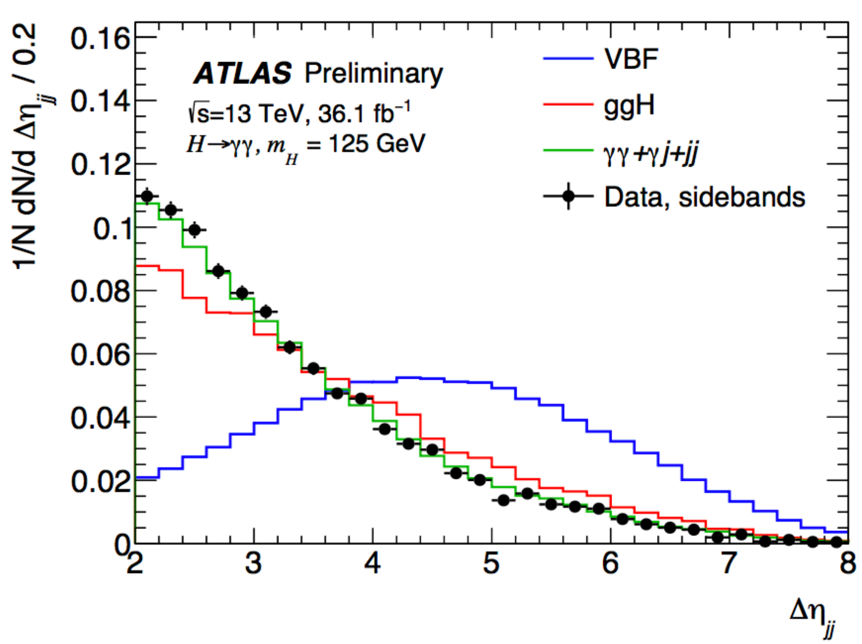
- Measurements regions slightly different than in H → 4 leptons.
- The typical efficiency to reconstruct a H → γγ signal is around ~42%.
- VBF-enhanced regions:

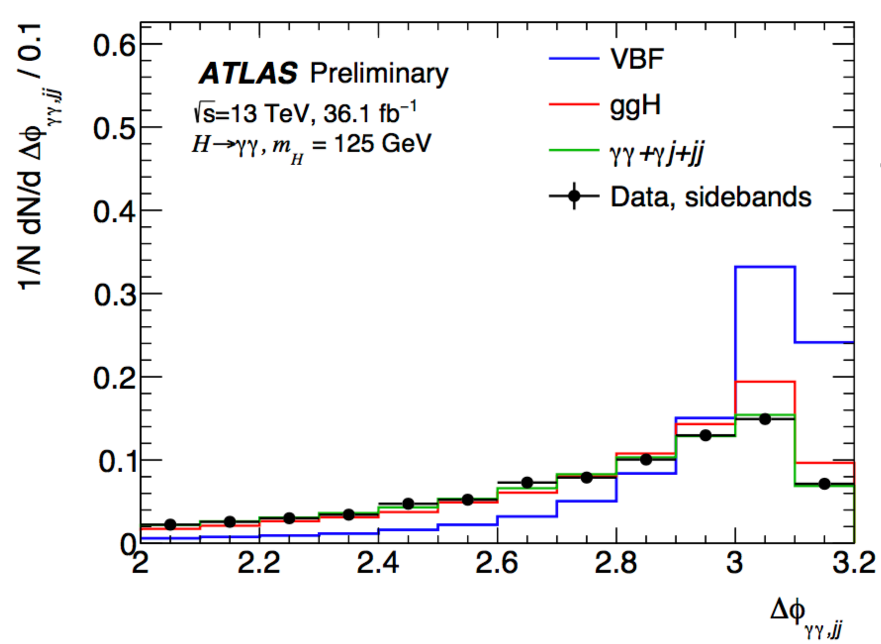
Category	Selection
jet BSM	$p_{\mathrm{T,j1}} > 200\,\mathrm{GeV}$
VBF tight, high p_T^{Hjj}	$\Delta\eta_{\mathrm{jj}} > 2$, $\lvert\eta_{\gamma\gamma} - 0.5(\eta_{\mathrm{j1}} + \eta_{\mathrm{j2}})\rvert < 5$, $p_T^{Hjj} > 25\,\mathrm{GeV}$, $\mathrm{BDT_{VBF}} > 0.47$
VBF loose, high p_T^{Hjj}	$\Delta\eta_{\mathrm{jj}} > 2$, $\lvert\eta_{\gamma\gamma} - 0.5(\eta_{\mathrm{j1}} + \eta_{\mathrm{j2}})\rvert < 5$, $p_T^{Hjj} > 25\,\mathrm{GeV}$, $-0.32 < \mathrm{BDT_{VBF}} < 0.47$
VBF tight, low p_T^{Hjj}	$\Delta\eta_{\mathrm{jj}} > 2$, $\lvert\eta_{\gamma\gamma} - 0.5(\eta_{\mathrm{j1}} + \eta_{\mathrm{j2}})\rvert < 5$, $p_T^{Hjj} < 25\,\mathrm{GeV}$, $\mathrm{BDT_{VBF}} > 0.87$
VBF loose, low p_T^{Hjj}	$\Delta\eta_{\mathrm{jj}} > 2$, $\lvert\eta_{\gamma\gamma} - 0.5(\eta_{\mathrm{j1}} + \eta_{\mathrm{j2}})\rvert < 5$, $p_T^{Hjj} < 25\,\mathrm{GeV}$, $0.26 < \mathrm{BDT_{VBF}} < 0.87$

- No cut on m_{jj}, but BDT that uses six kinematic variables:

$$m_{jj};\ \Delta\eta_{jj};\ \Delta\phi_{\gamma\gamma,jj};\ p_{\mathrm{Tt}}^{\gamma\gamma};\ \Delta R_{\gamma j}^{\min};\ |\eta_{\gamma\gamma} - 0.5(\eta_{j1}+\eta_{j2})|$$



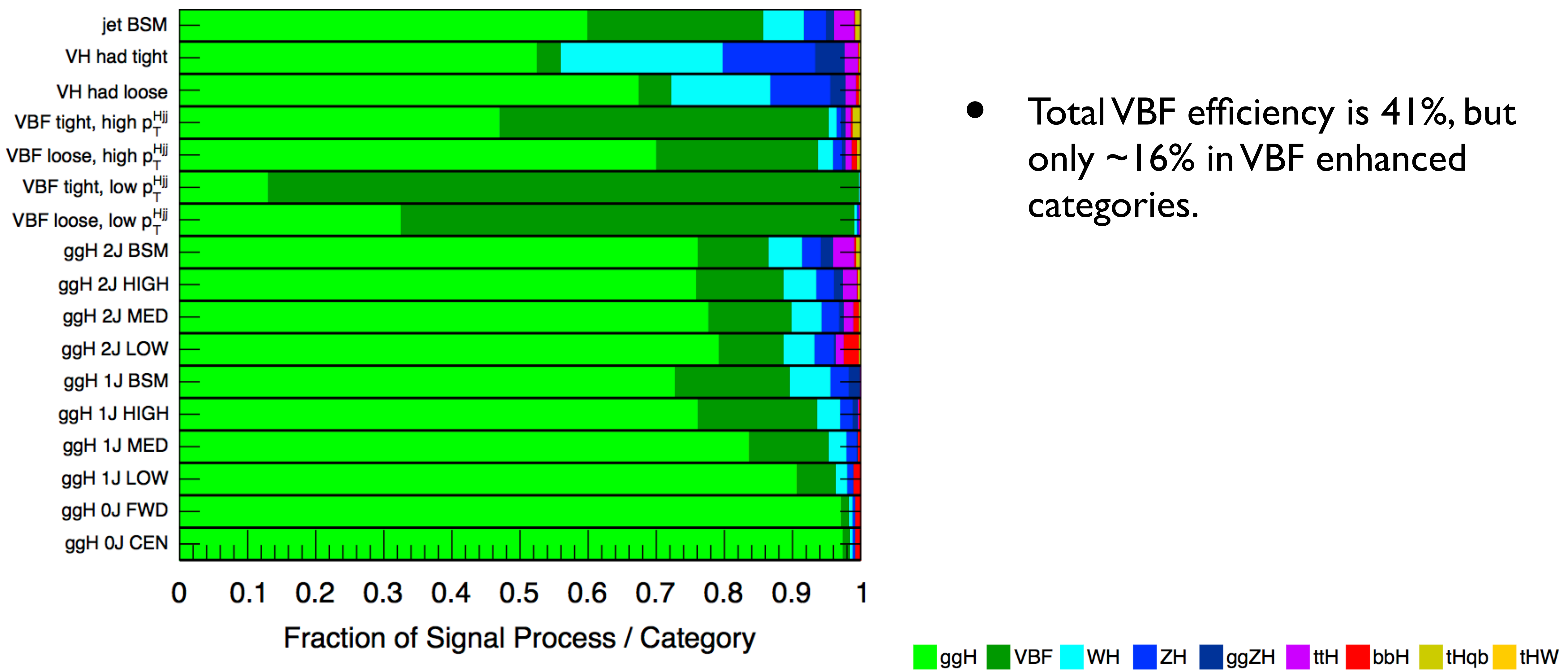




- No shape information used for $\Delta\phi_{\gamma\gamma} > 2.94$, to reduce theory dependence on n. jets

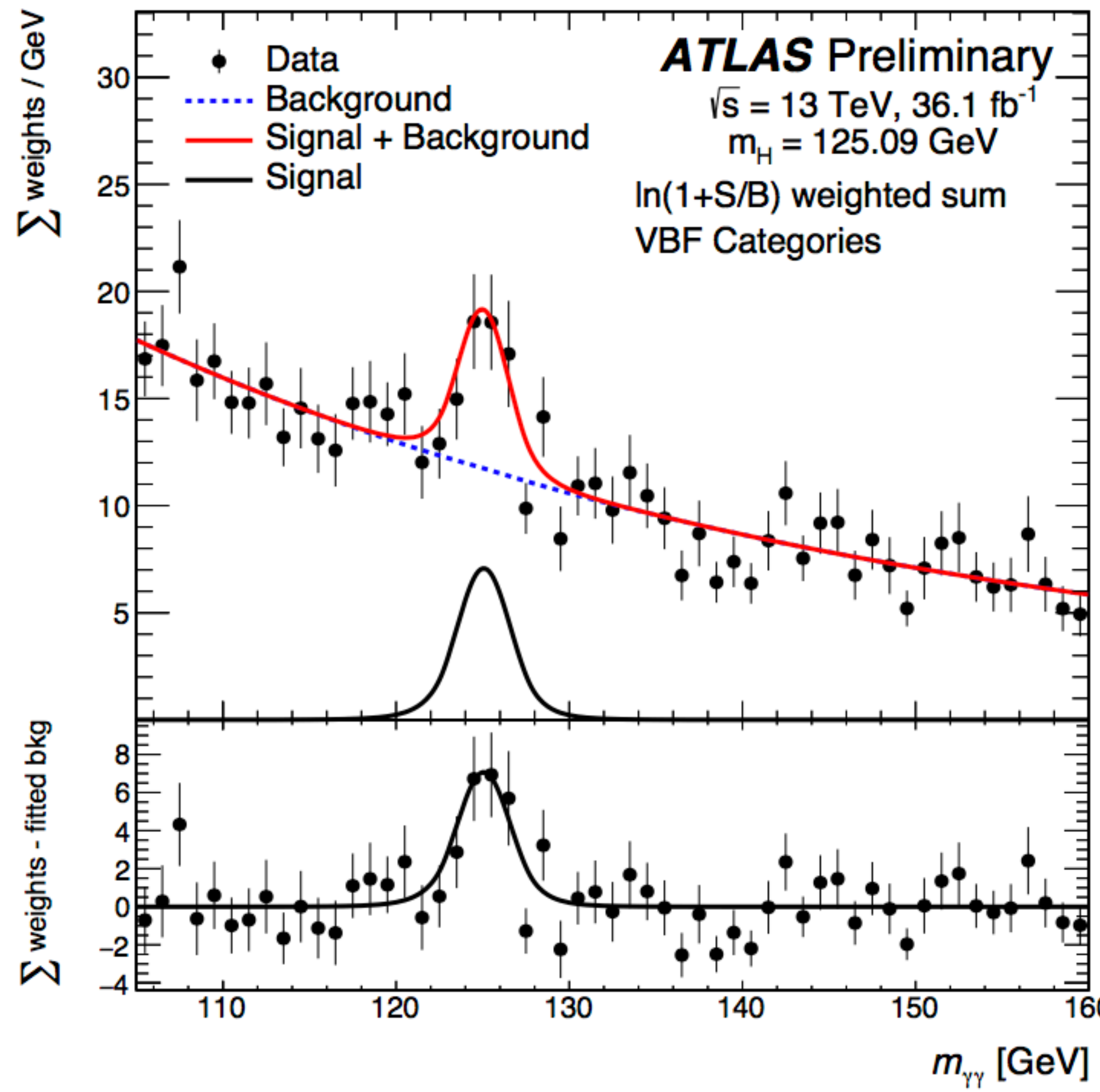
Categorization for H → γγ (II)

- Events that do not enter VBF (nor VH, ttH) categories, are split into 10 categories:
  - 0-jet events into 0J CEN (both photons |η|<0.95), or 0J FWD (otherwise)
  - 1-jet and 2-jet events into 1J/2J LOW, MED, HIGH, BSM for pTH [0,60], [60,120], [120,200], >200 GeV



- Total VBF efficiency is 41%, but only ~16% in VBF enhanced categories.

H to γγ signal in VBF categories



Measurement	Exp. Z_0	Obs. Z_0
μ_{VBF}	$2.6\,\sigma$	$4.9\,\sigma$

$$\mu_{\mathrm{VBF}} = 2.1\,^{+0.6}_{-0.6} = 2.1\,^{+0.5}_{-0.5}\,(\text{stat.})\,^{+0.3}_{-0.2}\,(\text{exp.})\,^{+0.3}_{-0.2}\,(\text{theory})$$

- VBF production measured ~2σ higher than SM prediction.
- Stat. unc. still dominant. Theory uncertainty as large as experimental systematics!

Theory uncertainties

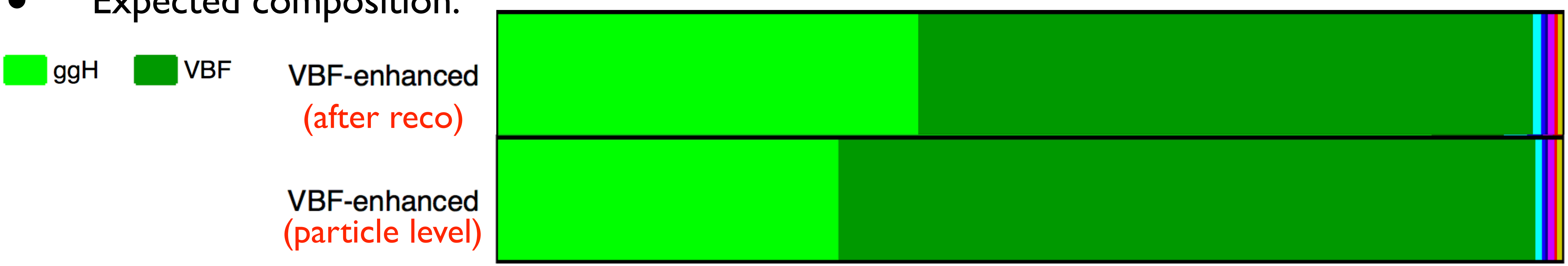
		Syst. source	N_{NP}	Implementation
Yield	Theo.	Missing higher orders	6	$N_S^p\, F_{\text{LN}}(\sigma_i, \theta_i)$
		PDF	30	$N_S^p\, F_{\text{LN}}(\sigma_i, \theta_i)$
		$B(H \to \gamma\gamma)$	1	$N_S^{\text{tot}}\, F_{\text{LN}}(\sigma_i, \theta_i)$
Migration	Theo.	ggH Theory	9	$N_S^{\text{ggH}}\, F_{\text{LN}}(\sigma_i, \theta_i)$
		UE/PS	3	$N_S^p\, F_{\text{LN}}(\sigma_i, \theta_i)$
		PDF	30	$N_S^p\, F_{\text{LN}}(\sigma_i, \theta_i)$
		α_S	1	$N_S^p\, F_{\text{LN}}(\sigma_i, \theta_i)$

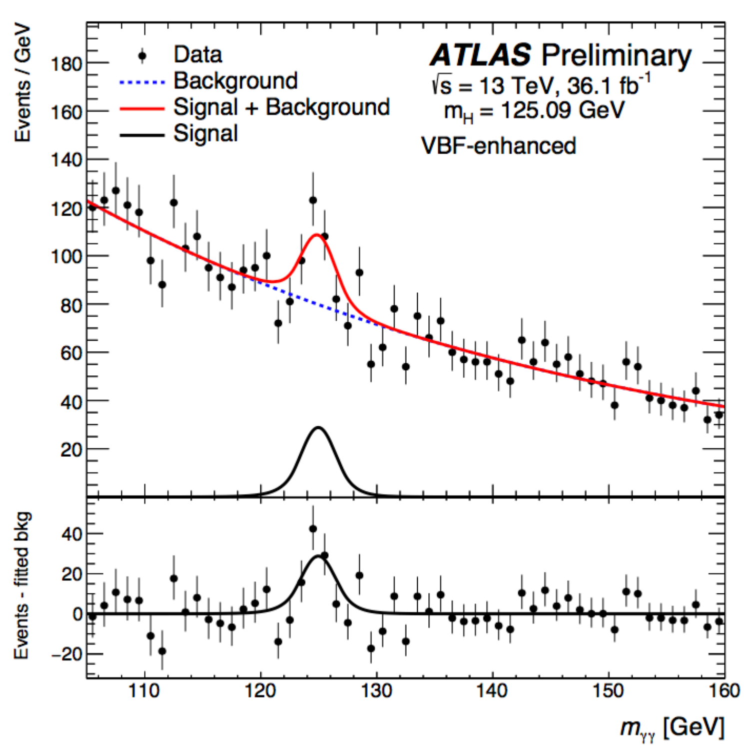
- UE/PS estimated by comparing Pythia8 to Herwig7
- PDF variations + α_S from PDF4LHC_nlo_30_as set

- More detailed uncertainties on ggF:
  - 4 NPs for variation of factorization, renormalization and resumption scales across 0-, 1- and 2-jet bins
  - 3 NPs parameterize uncertainty modeling uncertainty in Higgs boson pT (first two migration between 1-jet low and high pT(H), third difference between LO and NLO as "proxy" to estimate top quark mass effects in ggF loop, i.e. ~30% unc. pT>500 GeV)
  - 2 NPs to estimate VBF-like acceptance, based on MCFM (H+2, H+≥3 jets bins), incl. shape
- ggF uncertainties here presently leading source of systematics on μ_{VBF}

Fiducial VBF cross section

- Fiducial region definition:
  - Diphoton: $N_\gamma \geq 2, \quad p_{\mathrm{T}}^{\gamma_1} > 0.35\, m_{\gamma\gamma}, \quad p_{\mathrm{T}}^{\gamma_2} > 0.25\, m_{\gamma\gamma}$
  - VBF-enhanced: $N_j \geq 2, \quad m_{jj} > 400\ \mathrm{GeV}, \quad |\Delta y_{jj}| > 2.8, \quad |\Delta\phi_{\gamma\gamma,jj}| > 2.6$
- Expected composition:





- Fiducial cross section:

$$\sigma_{\mathrm{VBF-enhanced}} = 3.7 \pm 0.8\,(\mathrm{stat.}) \pm 0.5\,(\mathrm{syst.})\ \mathrm{fb}$$

- a bit high but compatible with expectation: 2.24 +/- 0.14 fb
- In addition to what previously highlighted, theory uncertainty goes also into unfolding correction factor: 1. relative contribution of Higgs production mechanisms (different acceptance) 2.uncertainty in Higgs p_T and η

Combination of H → γγ and H → ZZ*

- VBF+ggF categories in the two channels used in the combination:

$H \to \gamma\gamma$	$H \to ZZ^* \to 4\ell$
VBF, $p_T^{\gamma\gamma jj} \geq 25$ GeV(BDT tight and loose categories)	2-jet VBF, $p_T^{j1} \geq 200$ GeV
VBF, $p_T^{\gamma\gamma jj} < 25$ GeV(BDT tight and loose categories)	2-jet VBF, $p_T^{j1} < 200$ GeV
ggF 2-jet, $p_T^{\gamma\gamma} \geq 200$ GeV	1-jet ggF, $p_T^{4\ell} \geq 120$ GeV
ggF 2-jet, 120 GeV $\leq p_T^{\gamma\gamma} < 200$ GeV	1-jet ggF, 60 GeV $< p_T^{4\ell} < 120$ GeV
ggF 2-jet, 60 GeV $\leq p_T^{\gamma\gamma} < 120$ GeV	1-jet ggF, $p_T^{4\ell} < 60$ GeV
ggF 2-jet, $p_T^{\gamma\gamma} < 60$ GeV	0-jet ggF
ggF 1-jet, $p_T^{\gamma\gamma} \geq 200$ GeV	
ggF 1-jet, 120 GeV $\leq p_T^{\gamma\gamma} < 200$ GeV	
ggF 1-jet, 60 GeV $\leq p_T^{\gamma\gamma} < 120$ GeV	
ggF 1-jet, $p_T^{\gamma\gamma} < 60$ GeV	
ggF 0-jet (central and forward categories)	

- When fitting one inclusive cross-section for VBF:

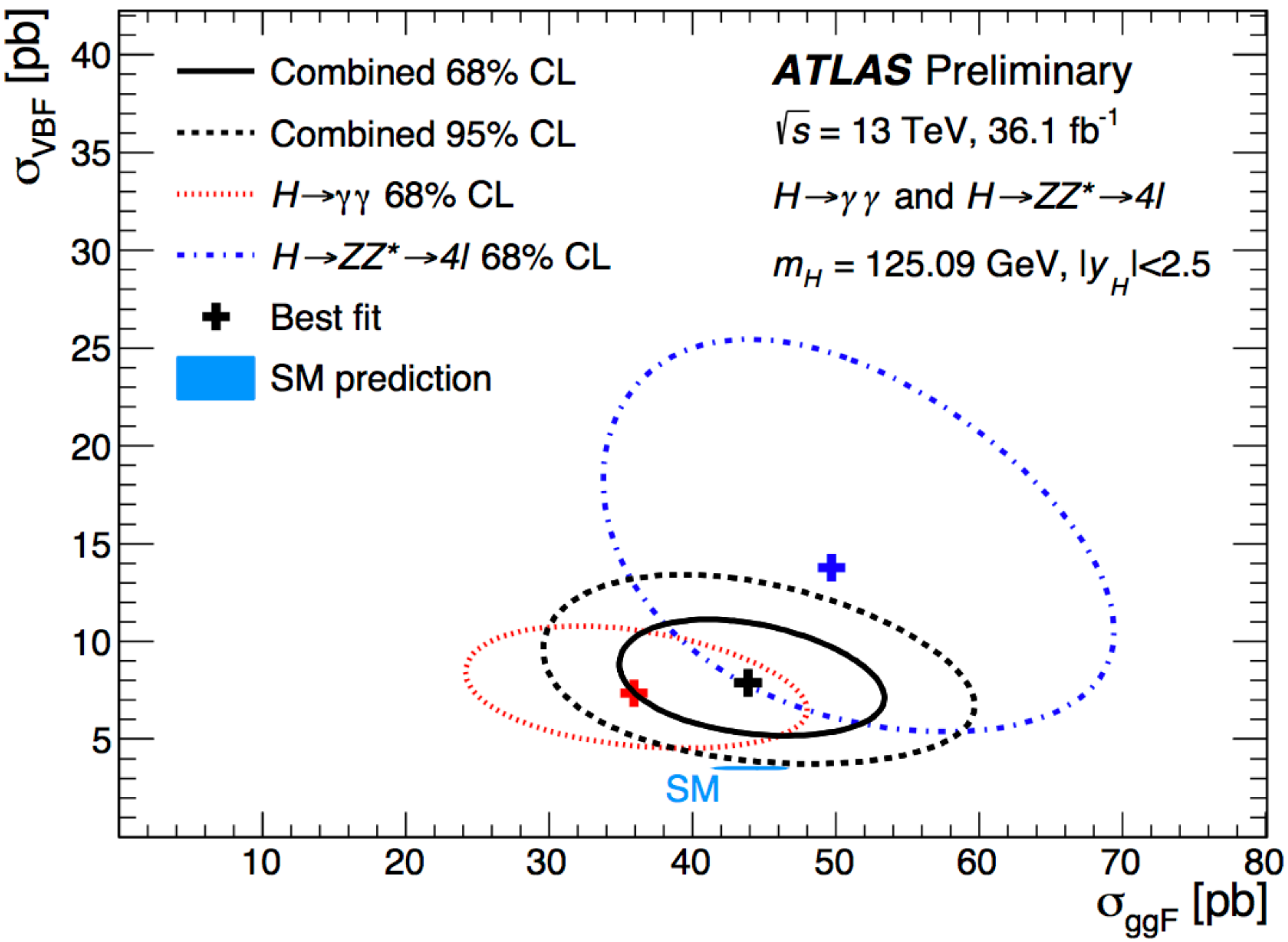
Process	Result	Uncertainty [pb]				SM prediction
($\|y_H\| < 2.5$)	[pb]	Total	Stat.	Exp.	Th.	[pb]
VBF	7.9	$^{+2.1}_{-1.8}$	$\left(^{+1.7}_{-1.6}\right.$	$^{+0.8}_{-0.6}$	$\left.^{+1.0}_{-0.7}\right)$	$3.52^{+0.08}_{-0.07}$

- -30% correlation with ggF (but ggF perfectly on expect.)
- μ_{VBF} = 2.2 +/- 0.6

- Theory uncertainty from subtraction of ggF contribution becomes leading systematic uncertainty in combination.

[ATLAS-CONF-2017-047]

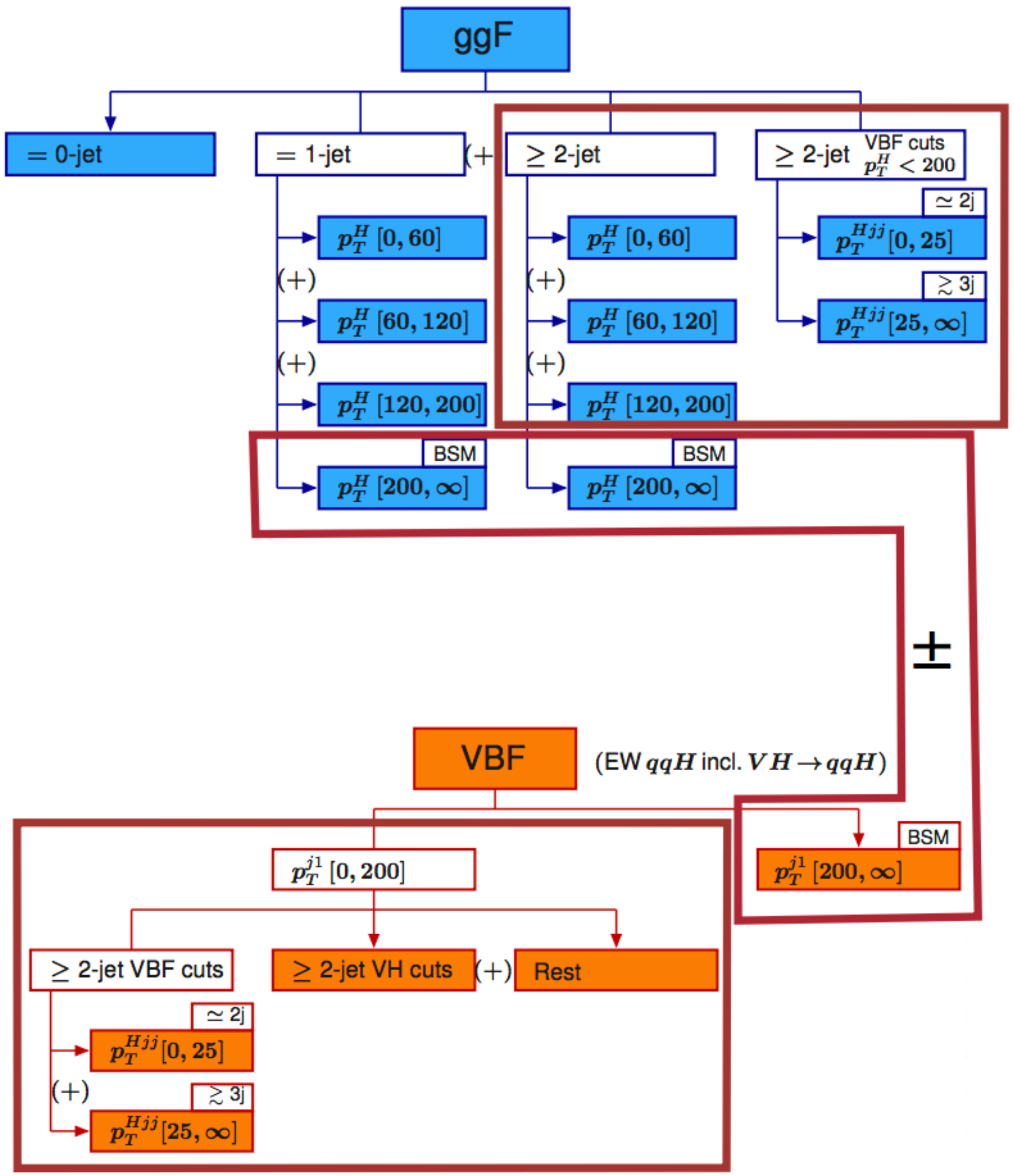
Combination of H → γγ and H → ZZ*



p_{SM} = 3%
(~1.9σ)

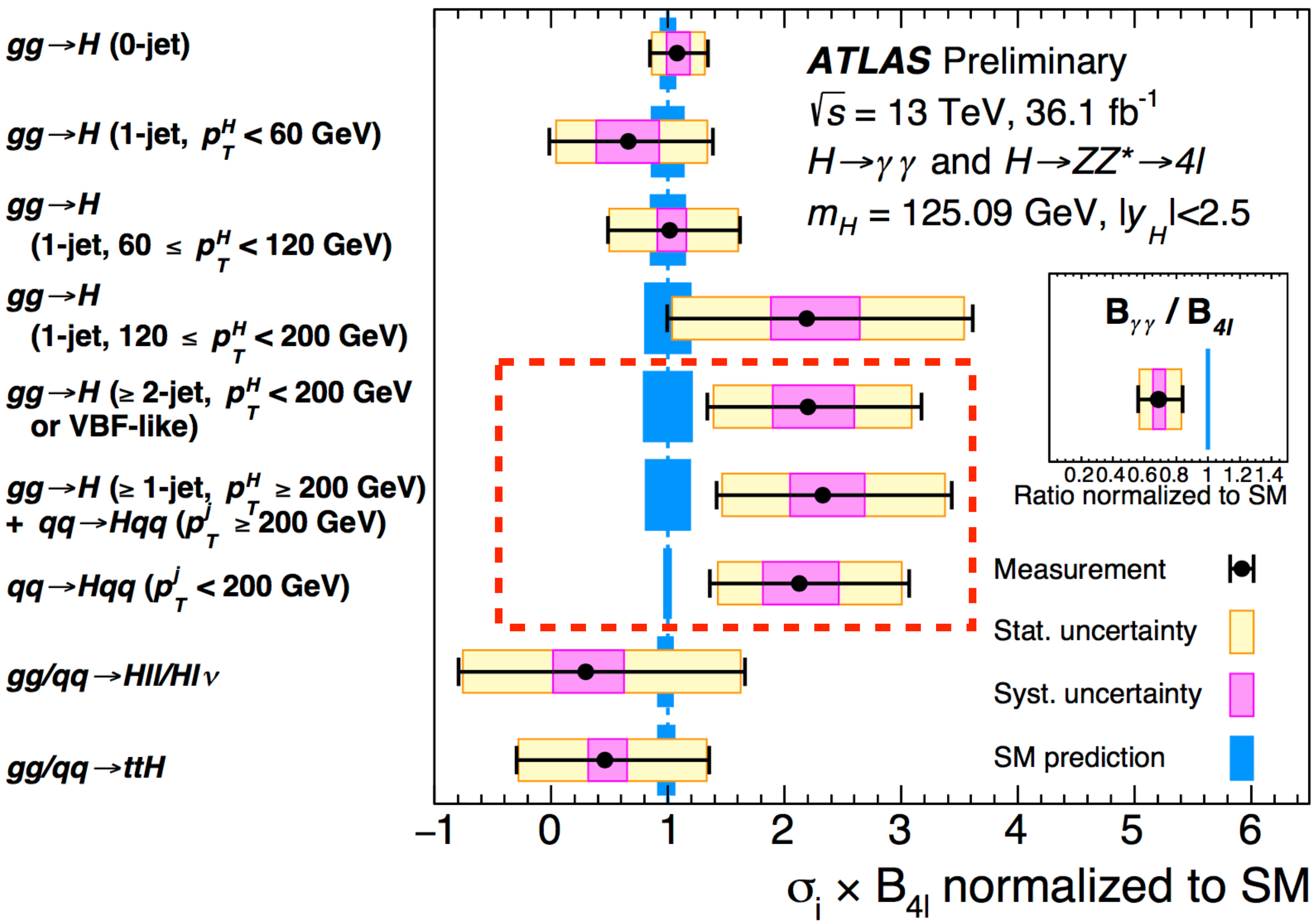
[ATLAS-CONF-2017-047]

Template cross section measurement



- Presently not sensitive to full stage-I processes, so need to merge bins to overcome limited statistics and anti-correlations between ggF and VBF
- A single measurement in ggF for ≥2 jets for pT_H<200 GeV → extrapolation from non-VBF to VBF region
- A single measurement for VBF with pT_H<200 GeV
- A single measurement for VBF+ggF for pTH/pTjet>200 GeV, especially sensitive to BSM physics [little sensitivity to difference between the two regions]

Template cross section measurement - results



- All 2-jet driven bins are measured a bit high, but well within 2σ from the SM expectation
- High pT region (potentially pointing to BSM physics) does not stick out

- More data, and combination with other channels (H → ττ, H → WW*) required to increase statistical precision of measurements!

H → WW* on partial 13 TeV dataset

- Most sensitive decay channel for VBF production
  - But experimentally difficult due to neutrinos in final state and no mass peak (σ_m ~ 20 %)
- Basic 2-lepton selection, Z/Y/JPsi veto + dedicated **BDT** to separate ggF from VBF
- + 3 VFB cuts: (1) outside-lepton-veto, (2) central-jet-veto (3) H → ττ veto ($m_{\tau\tau}$ < 66GeV)

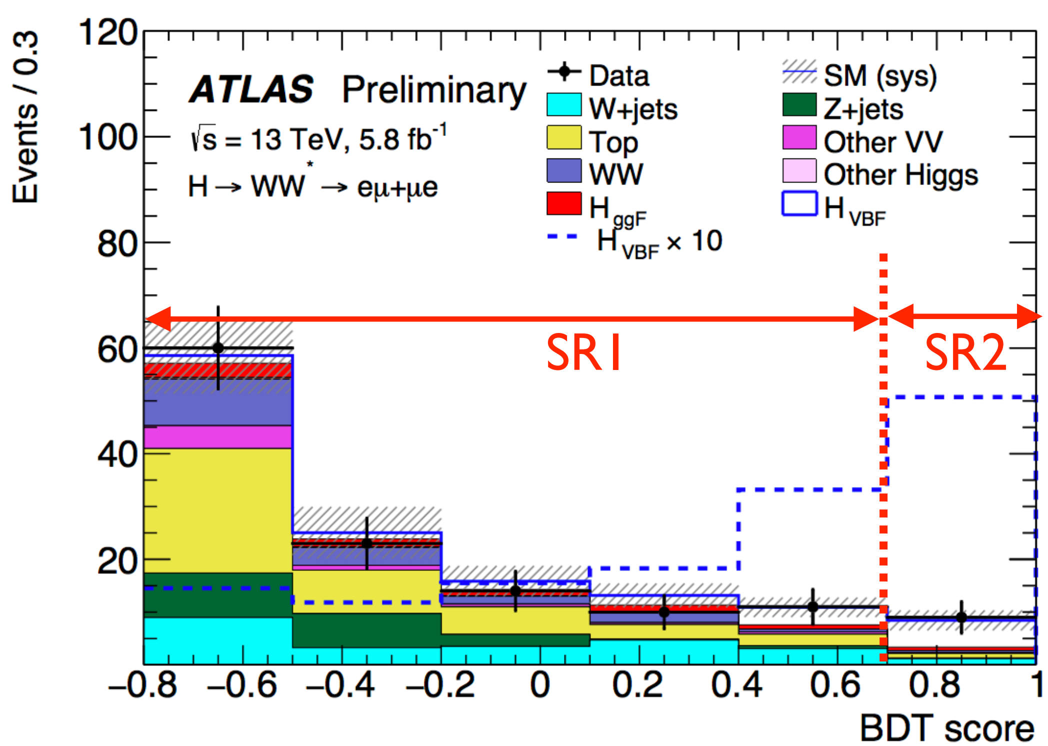
H → WW* related variables

$$\Delta\phi_{\ell\ell}, m_{\ell\ell}, m_{\mathrm{T}}$$

VBF related variables

$$\Delta y_{jj}, m_{jj}, p_{\mathrm{T}}^{\mathrm{tot}}, \sum_{\ell,j} m_{\ell j},$$

$$|\eta_\ell - 0.5\,(\eta_{j1} + \eta_{j2})\,|/(0.5\ \Delta\eta_{jj})$$



- Background normalizations through dedicated CRs

$$\mu_{\mathrm{VBF}} = 1.7^{+1.0}_{-0.8}(\mathrm{stat})^{+0.6}_{-0.4}(\mathrm{sys})$$

- ~100% exp. unc., 1.9σ (1.2σ) observed (expected)
- Statistical uncertainty dominates since analysis only based on 5.8 fb^{-1} of 13 TeV data, but measurement will be systematically limited already with full 2016 data (not published yet)

H → WW*: uncertainties

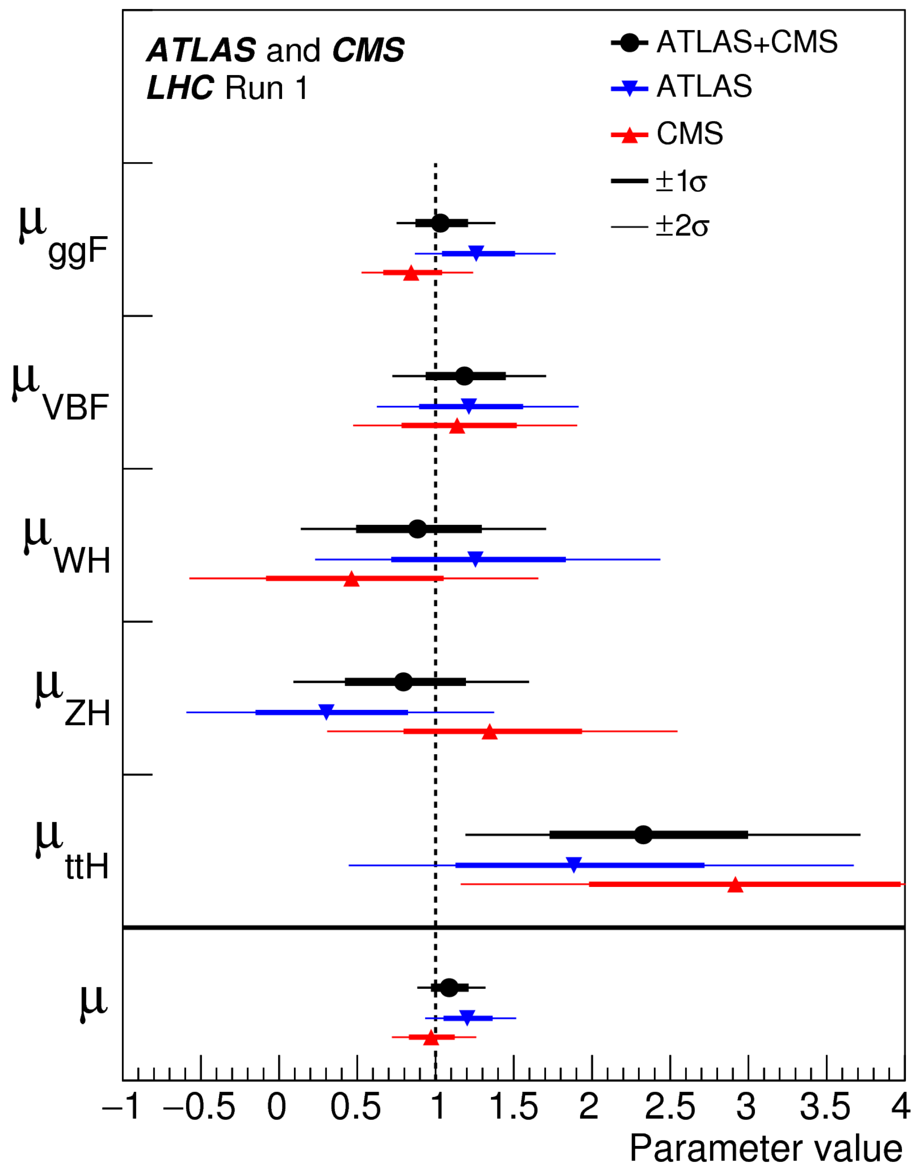
- Signal theory uncertainties in 4th, 6th and 10th position of most limiting systematics

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

- VBF:
  - Scale variations on top of signal VBF generator (Powheg+Pythia8), difference to MG5_aMC@NLO+Pythia8, difference between Pythia8 and Herwig 7
- ggF:
  - 1) Steward-Tackman method using scale variations for H+2 and H+3-jets based on MG5_aMC@NLO, incl. jet veto (28% unc. in 2-jets, 32% unc. in 3-jets
    2) Same for BDT shape (3% BDT SR1, 32% BDT SR2)
    3) Powheg+Pythia 8 vs MG5_aMC@NLO (NLO up to 2 jets)

[arXiv:1606.02266]

Comparison to Run-1



Production process	ATLAS+CMS	ATLAS	CMS
μ_{VBF}	$1.18^{+0.25}_{-0.23}$ $\left(^{+0.24}_{-0.23}\right)$	$1.21^{+0.33}_{-0.30}$ $\left(^{+0.32}_{-0.29}\right)$	$1.14^{+0.37}_{-0.34}$ $\left(^{+0.36}_{-0.34}\right)$

- In Run-1 each experiment alone measured overall VBF production cross section with a precision of ~35-40%
    - Combination with 25% precision (**5.4σ** (4.6σ) observed (exp.) significance)
- 13 TeV Run-2 ATLAS $H \rightarrow \tau\tau$ and $H \rightarrow WW$ analyses still in progress
    - Only the combination with $H \rightarrow \tau\tau$ and $H \rightarrow WW$ will clearly supersede the precision of the Run-1 results
    - Several interesting differential measurements relevant to cross-check modeling of ggF

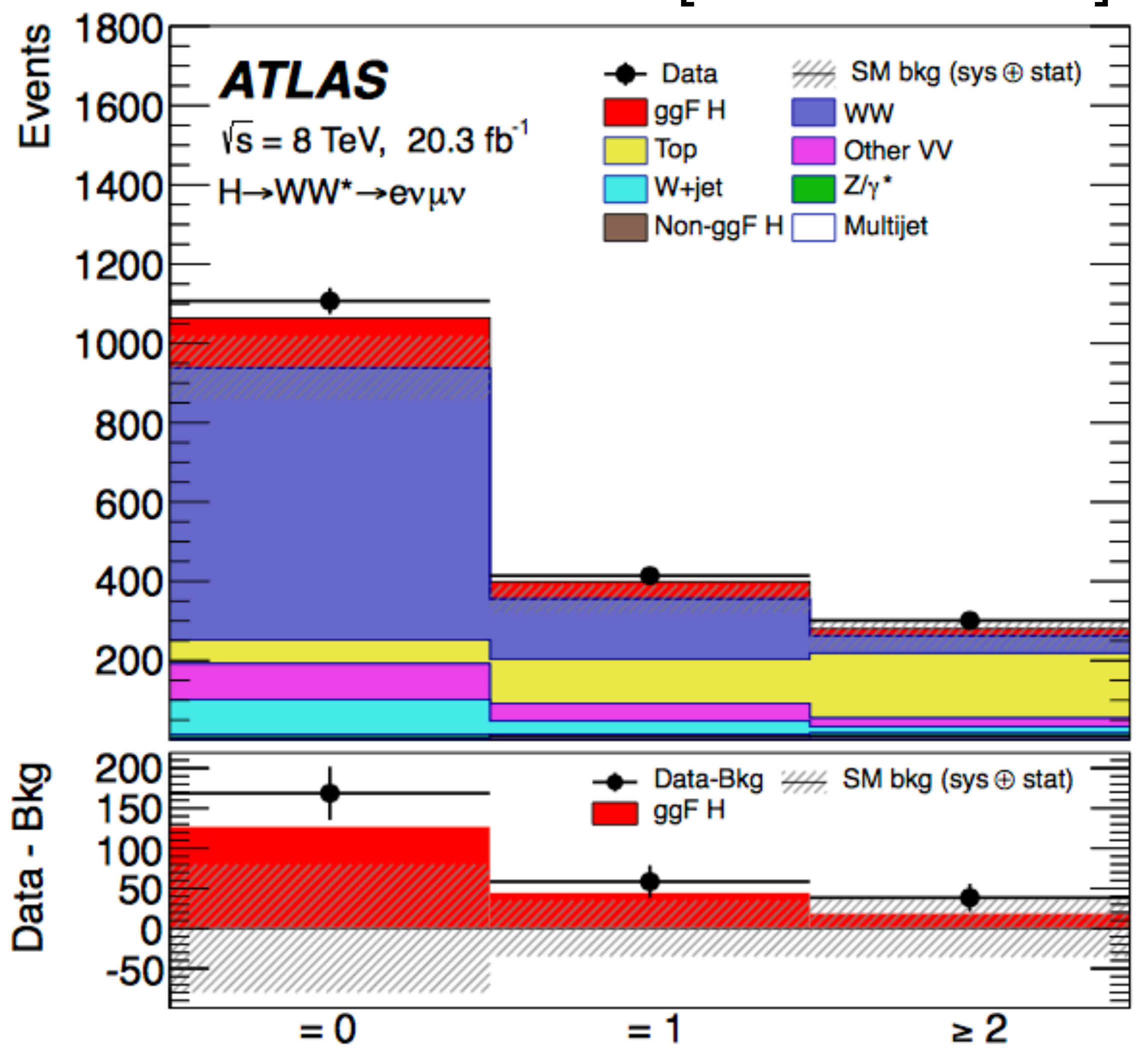
Main theory uncertainties to
VBF extraction:

1. *modeling of ggF Higgs production*
2. *modeling of VBF production*

ggF measurements in Run-1

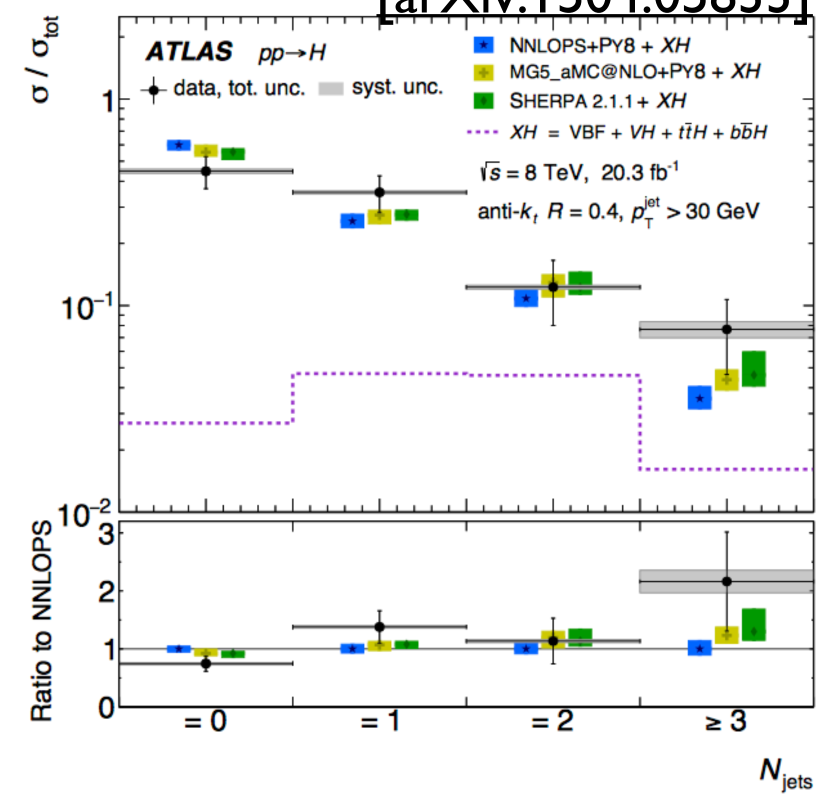
- In addition to differential measurements in $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^*$…
  - …most detailed measurement of ggF in $H \rightarrow WW^*$

[arXiv:1604.02997]



Jets p_T>25(30) GeV $|\eta|$<2.4(4.5)

[arXiv:1504.05833]



Jets
p_T>30 GeV
$|y|$<4.4

- $m_{jj} < 600$ GeV or $\Delta y_{jj} < 3.6$ (in 2-jet bin)
  VBF topologies vetoed in measurement
  (95% eff. ggF, 60% eff. for VBF)

	$N_{\rm jet}=0$	$N_{\rm jet}=1$	$N_{\rm jet}\geq 2$
Total background	936 ± 21 ± 41	355 ± 9 ± 12	263 ± 6 ± 9
Observed	1107	414	301
Observed − background	171 ± 39 ± 41	59 ± 22 ± 12	38 ± 18 ± 9
ggF H	125.9 ± 0.4 ± 5.7	43.4 ± 0.2 ± 1.7	17.6 ± 0.2 ± 1.4
Non-ggF H	2.2 ± 0.2 ± 0.2	7.1 ± 0.3 ± 0.5	8.2 ± 0.3 ± 0.4

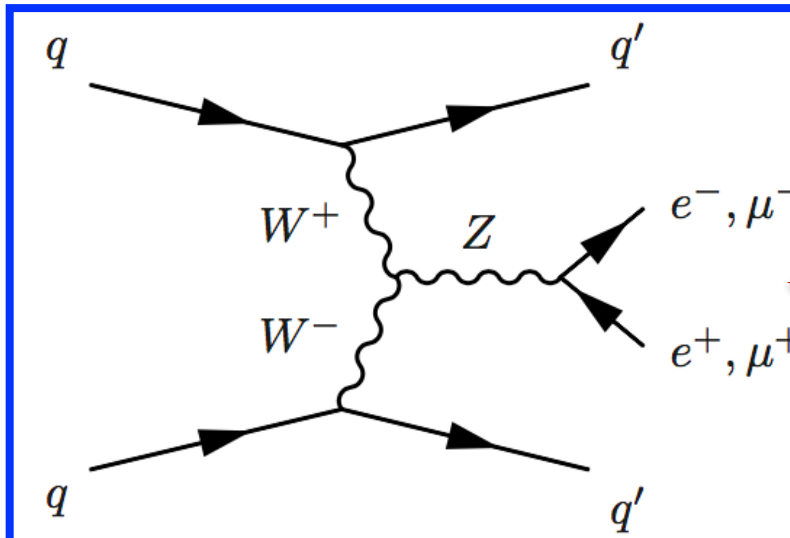
~50% unc.

- Statistically limited… Run-2 will help!

[arXiv:1709.10264]

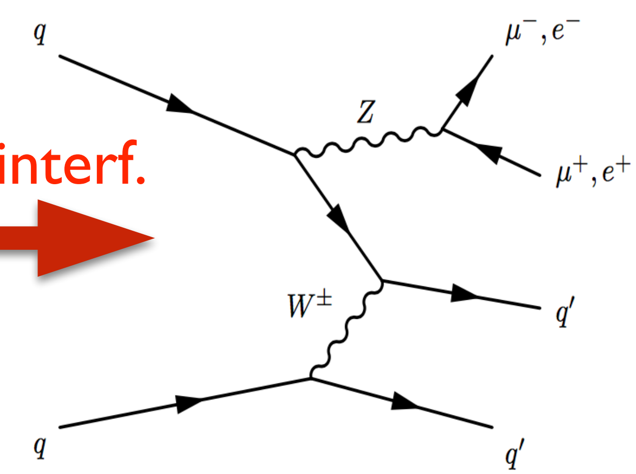
measurement of EW Z+2-jet production

- The modelling of VBF production can be also studied in non-Higgs related production processes, e.g. Z+2-jets
- EW Z+2-jet production made of tree components:

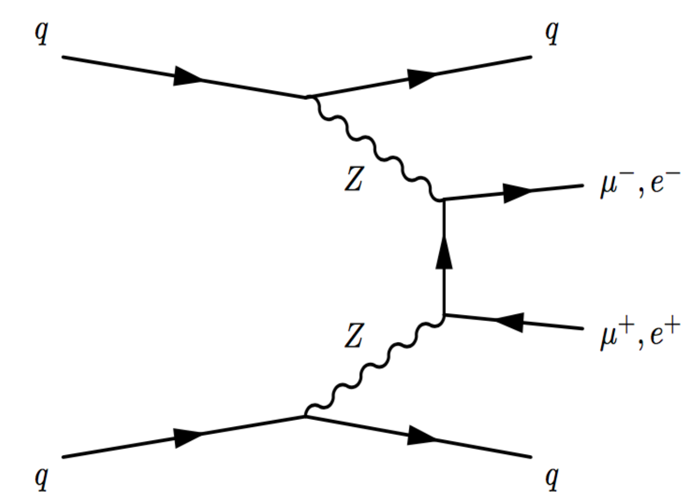


VBF production

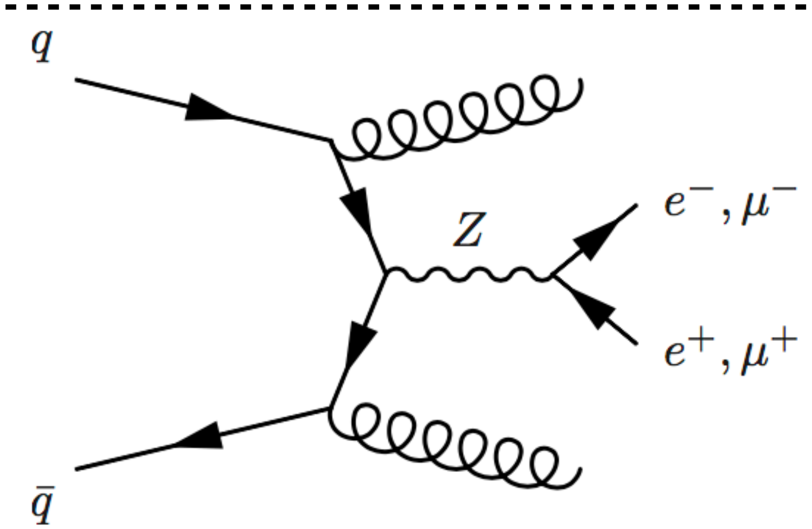
neg. interf.



Z-boson bremsstrahlung



non-resonant $\ell^+\ell^- qq$ (<1%)



QCD Z+2-jet bkg

Due to strong negative interference, VBF production can't be isolated

However, measurement of EW Z+2-jet production is still a stringent test for VBF modeling

Main background: QCD Z+2-jet production

[arXiv:1709.10264]

Selection in Z+2-jets analysis

Object	Fiducial region: EW-enriched	Fiducial region: EW-enriched, $m_{jj} > 1$ TeV	Fiducial region: QCD-enriched (CR)
Leptons	$\|\eta\| < 2.47$, $p_T > 25$ GeV, $\Delta R_{j,\ell} > 0.4$		
Dilepton pair	$81 < m_{\ell\ell} < 101$ GeV		
	$p_T^{\ell\ell} > 20$ GeV		
Jets	$\|y\| < 4.4$		
	$p_T^{j_1} > 55$ GeV		
	$p_T^{j_2} > 45$ GeV		
Dijet system	$m_{jj} > 250$ GeV	$m_{jj} > 1$ TeV	$m_{jj} > 250$ GeV
Interval jets	$N^{\text{interval}}_{\text{jet}\ (p_T>25\text{ GeV})} = 0$		$N^{\text{interval}}_{\text{jet}\ (p_T>25\text{ GeV})} \geq 1$
Zjj system	$p_T^{\text{balance}} < 0.15$		$p_T^{\text{balance,3}} < 0.15$

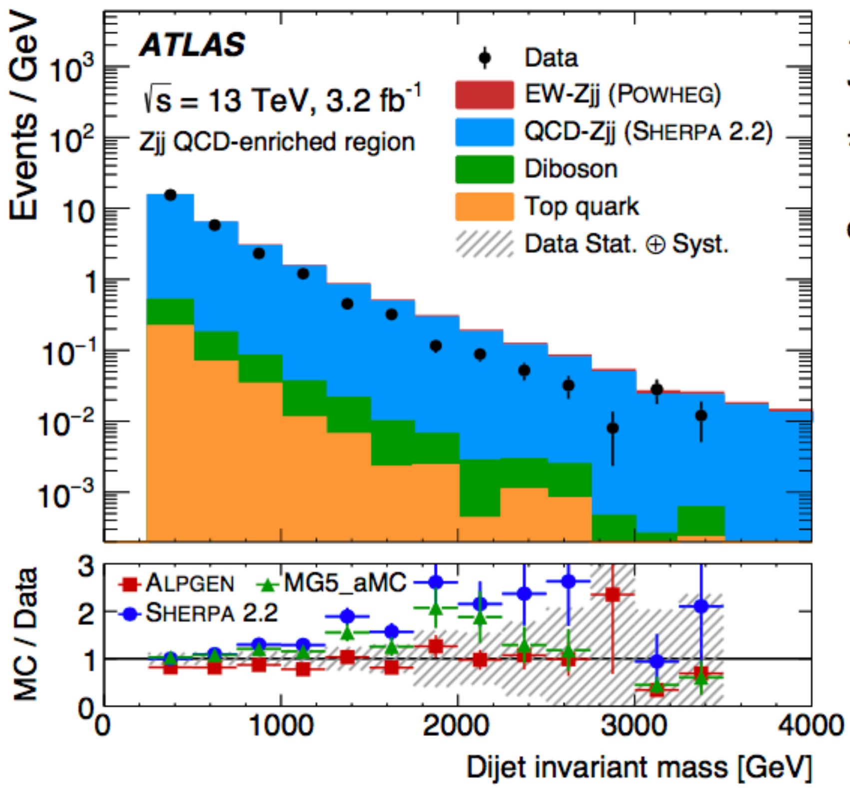
$$p_T^{\text{balance}} = \frac{\left|\vec{p}_T^{\,\ell_1} + \vec{p}_T^{\,\ell_2} + \vec{p}_T^{\,j_1} + \vec{p}_T^{\,j_2}\right|}{\left|\vec{p}_T^{\,\ell_1}\right| + \left|\vec{p}_T^{\,\ell_2}\right| + \left|\vec{p}_T^{\,j_1}\right| + \left|\vec{p}_T^{\,j_2}\right|}$$

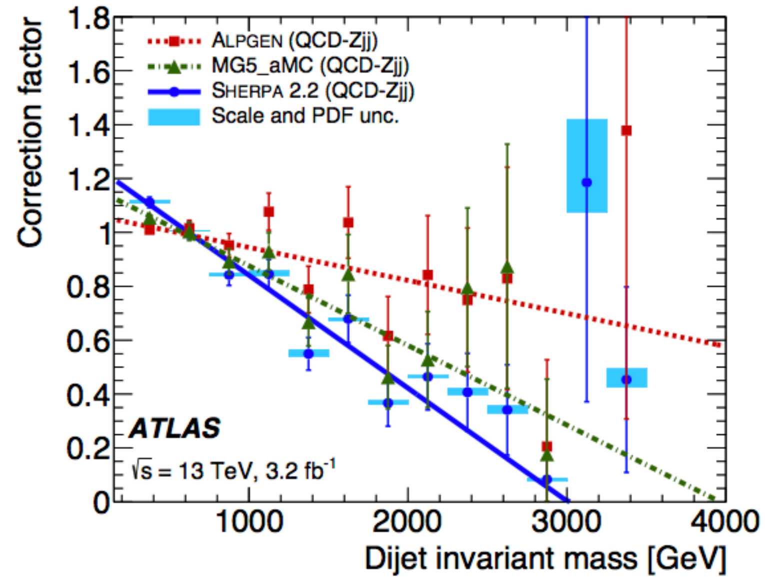
- Two signal regions that include central jet veto
  - $m_{jj} > 250$ GeV
  - $m_{jj} > 1$ TeV
- One QCD control region

Process	Composition [%]: EW-enriched	EW-enriched, $m_{jj} > 1$ TeV	QCD-enriched
QCD-Zjj	93.4 ± 0.9	72.9 ± 2.1	95.4 ± 0.8
EW-Zjj	4.8 ± <0.1	26.1 ± 0.5	1.6 ± <0.1
Diboson	1.0 ±0.5	0.8 ± 0.4	1.8 ±0.4
$t\bar{t}$	0.7 ± <0.1	0.1 ± 0.1	1.2 ± 0.1
Single-t	<0.1	<0.1	<0.1
Multijet	<0.3	<0.3	<0.3
Total expected	11100 ± 50 ± 520	640 ± 10 ± 40	7120 ± 30 ± 880
Total observed	11630	490	6453

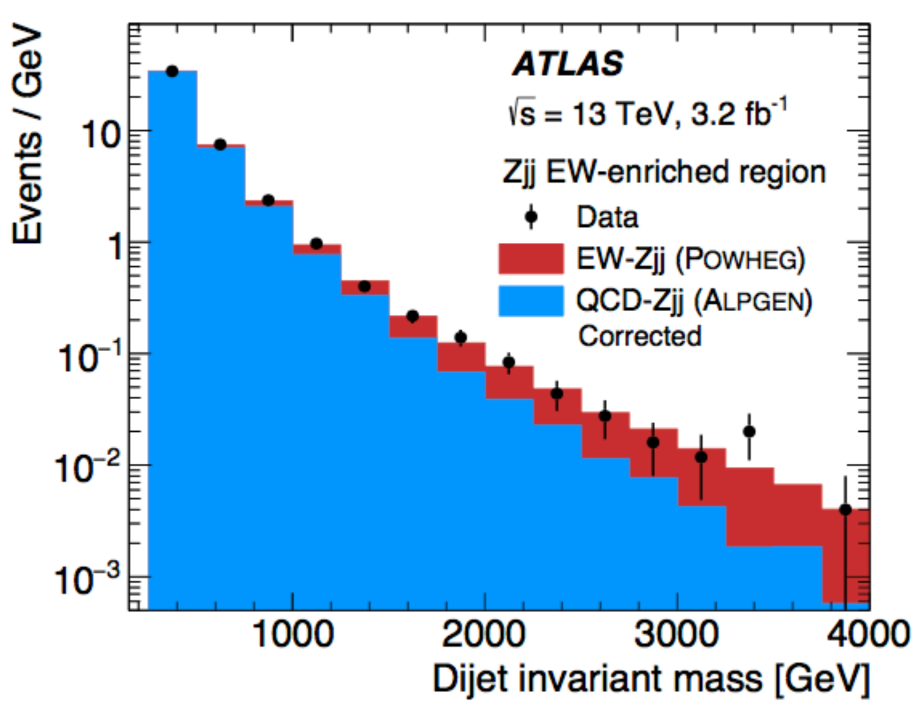
[arXiv:1709.10264]

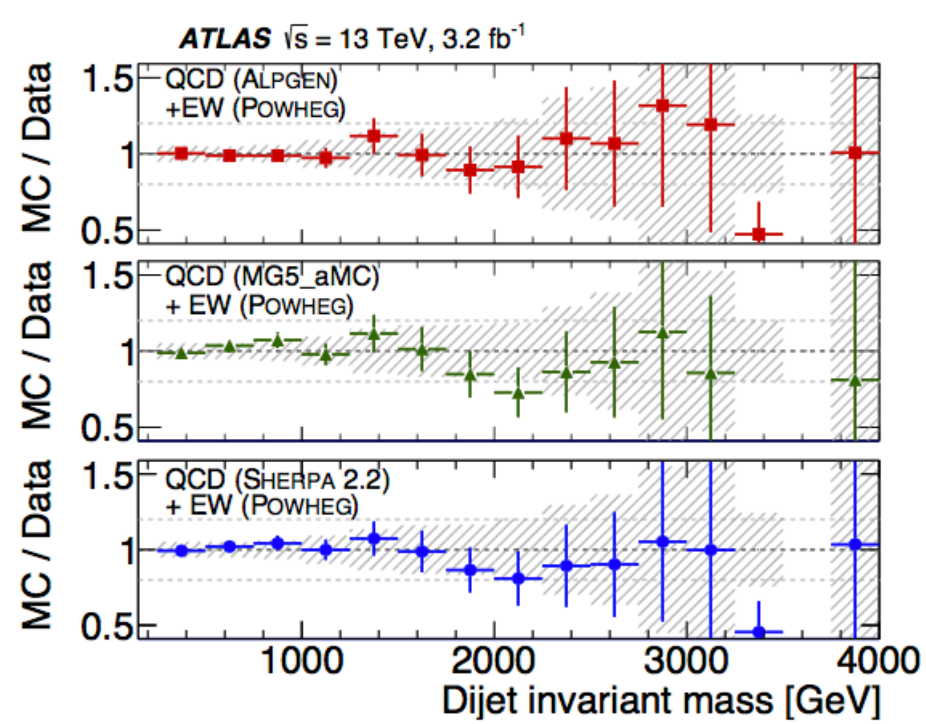
QCD background correction





- Mismodelling of QCD Z+2-jet background corrected with linear or second order polynomial re-weighting in m_{jj} (difference as systematic)
- Good agreement with data after correction





Results for EW Z+2-jets

- Likelihood fit in m_{jj} used to extract the EW Z+2-jets signal:

Fiducial region	EW-*Zjj* cross-sections [fb]	
	Measured	Powheg+Pythia
EW-enriched, $m_{jj} > 250$ GeV	119 ± 16 ± 20 ± 2	125.2 ± 3.4
EW-enriched, $m_{jj} > 1$ TeV	34.2 ± 5.8 ± 5.5 ± 0.7	38.5 ± 1.5

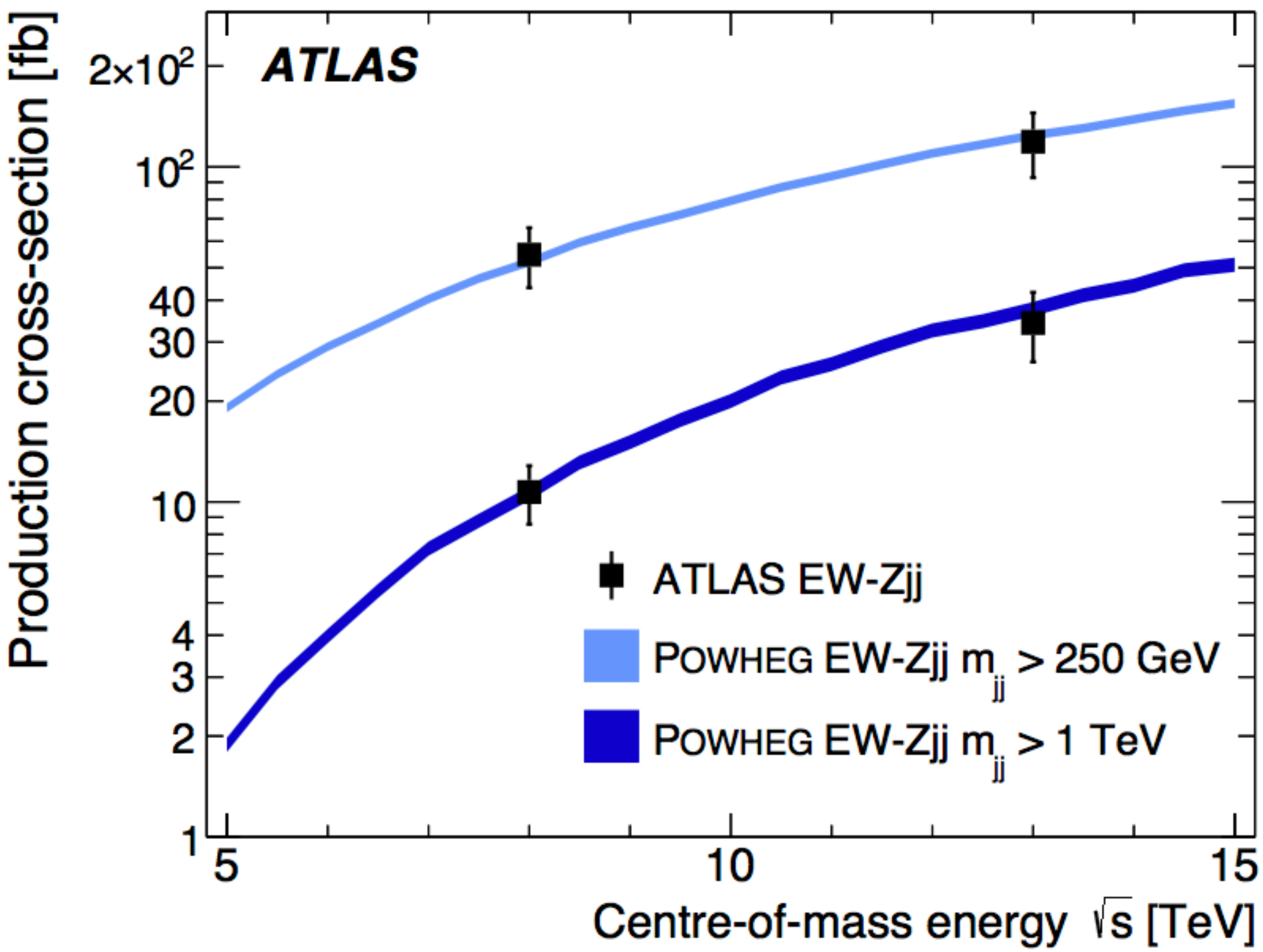
$$\sigma^f_{\mathrm{EW}} = \frac{N^f_{\mathrm{obs}} - N^f_{\mathrm{QCD-}Zjj} - N^f_{\mathrm{bkg}}}{L \cdot C^f_{\mathrm{EW}}}$$

- Good agreement with Powheg+Pythia8 (NLO, AZNLO tune,) predictions within ~20% to ~25% relative uncertainty. Based on only ~3 fb^{-1} of 13 TeV data.

Source	Relative systematic uncertainty [%] $\sigma^{m_{jj}>250\ \mathrm{GeV}}_{\mathrm{EW}}$	$\sigma^{m_{jj}>1\ \mathrm{TeV}}_{\mathrm{EW}}$
EW-*Zjj* signal modelling (QCD scales, PDF and UEPS)	± 7.4	± 1.7
EW-*Zjj* template statistical uncertainty	± 0.5	± 0.04
EW-*Zjj* contamination in QCD-enriched region	−0.1	−0.2
QCD-*Zjj* modelling (m_{jj} shape constraint / third-jet veto)	± 11	± 11
Stat. uncertainty in QCD control region constraint	± 6.2	± 6.4
QCD-*Zjj* signal modelling (QCD scales, PDF and UEPS)	± 4.5	± 6.5
QCD-*Zjj* template statistical uncertainty	± 2.5	± 3.5
QCD–EW interference	± 1.3	± 1.5
$t\bar{t}$ and single-top background modelling	± 1.0	± 1.2
Diboson background modelling	± 0.1	± 0.1
Jet energy resolution	± 2.3	± 1.1
Jet energy scale	+5.3/−4.1	+3.5/−4.2
Lepton identification, momentum scale, trigger, pile-up	+1.3/−2.5	+3.2/−1.5
Luminosity	± 2.1	± 2.1
Total	± 17	± 16

- This measurement would profit a lot from 10x more statistics.
- Already available on tape!

Results for EW Z+2-jets

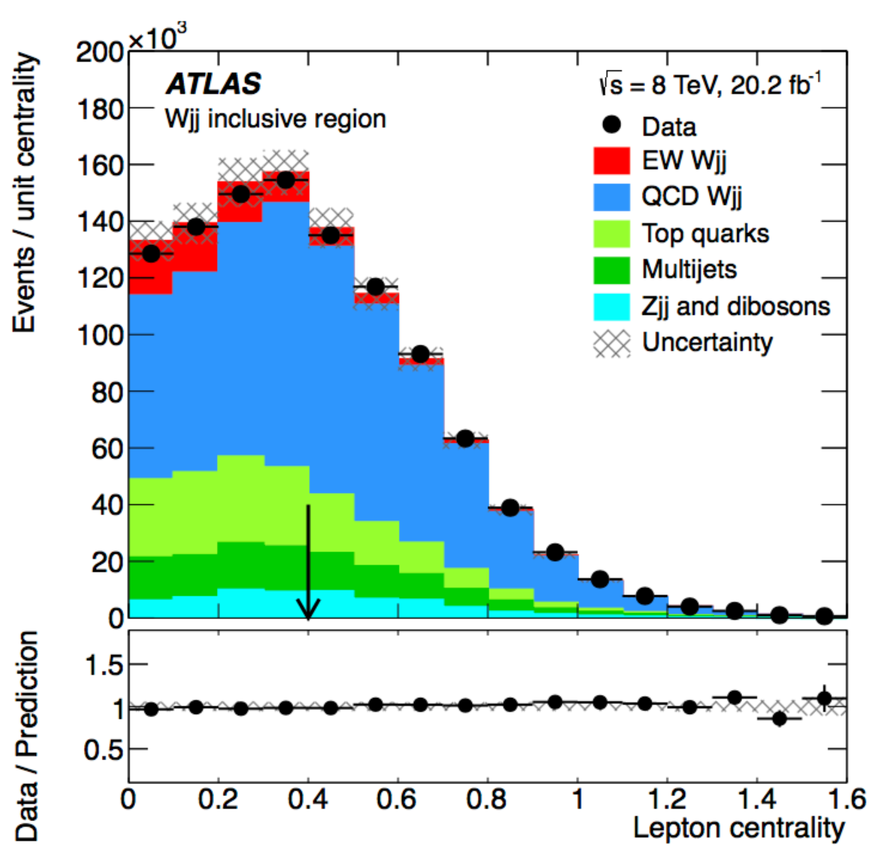


- Within uncertainties, good agreement both at 8 and at 13 TeV
- No sign of mismodelling of EW Z+2-jet contribution after VBF cuts and central jet veto

[arXiv:1703.04362]

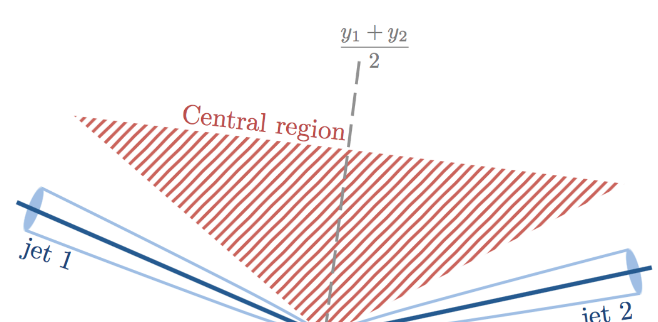
measurement of EW W+2-jet production

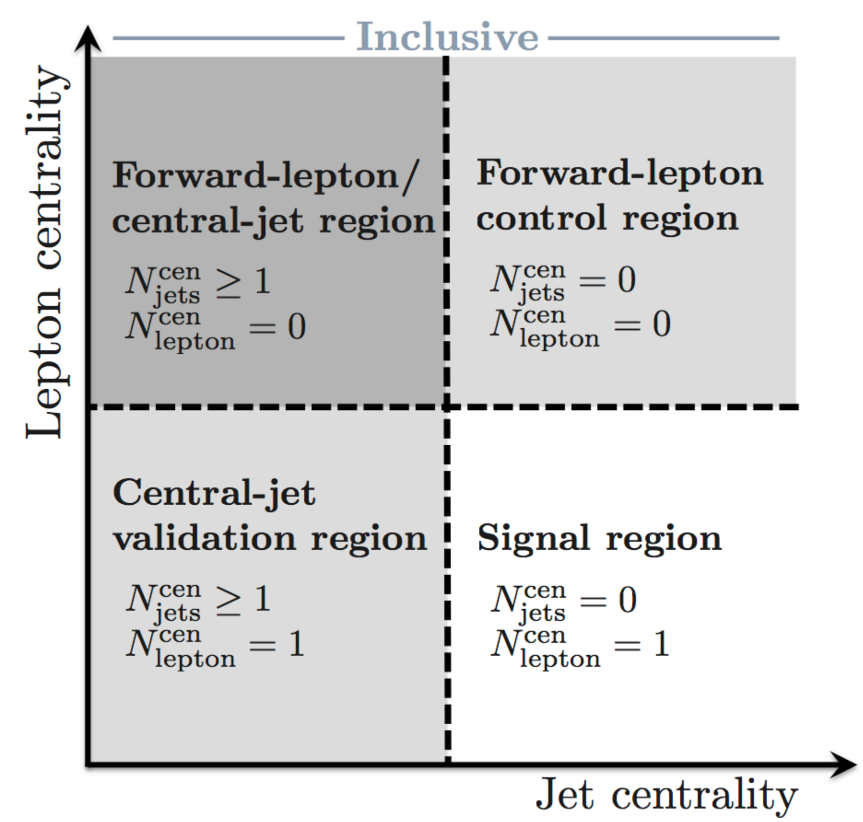
- Performed by ATLAS so far at $\sqrt{s}$ = 7 and 8 TeV.
- Same type of EW and QCD contributions as for Z+2-jets, but higher cross-sections allow for a more sensitive measurement.
- Basic signature is e or μ + MET + 2-jets
- Basic VBF selection: $pT_{1/2}$ > 80/60 GeV, jet $|y|<4.4$, $M_{jj}>500$ GeV, $\Delta y(j_1,j_2)>2$, $\Delta R(j,l)>0.3$
- Main backgrounds: top, Z+jets, dibosons (from MC) and multi-jets (data-driven)



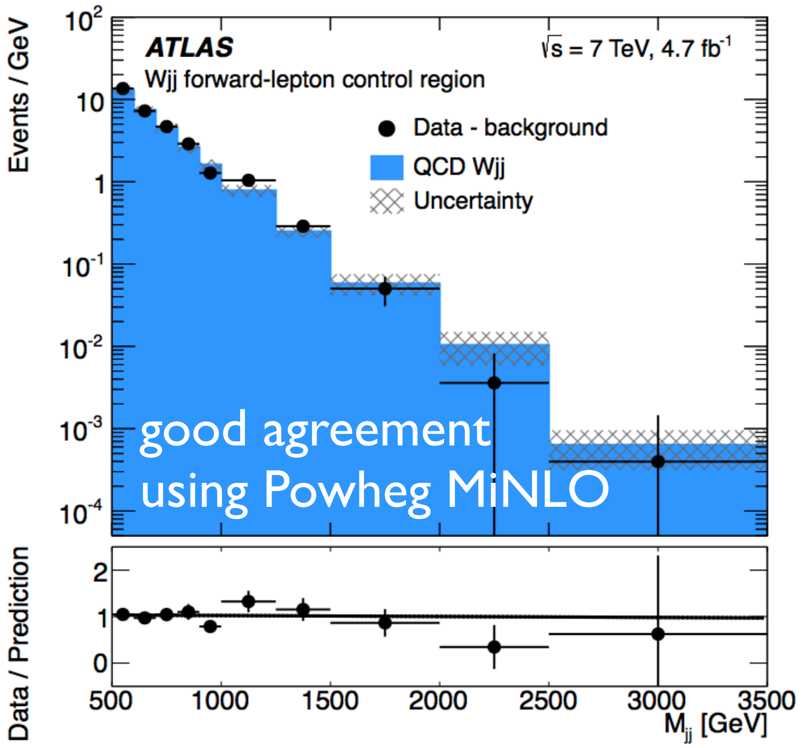
- Lepton/jet centrality used to define SR/CRs to constant begs

$$C_{\ell\,(j)} \equiv \left| \frac{y_{\ell\,(j)} - \frac{y_1+y_2}{2}}{y_1 - y_2} \right|$$



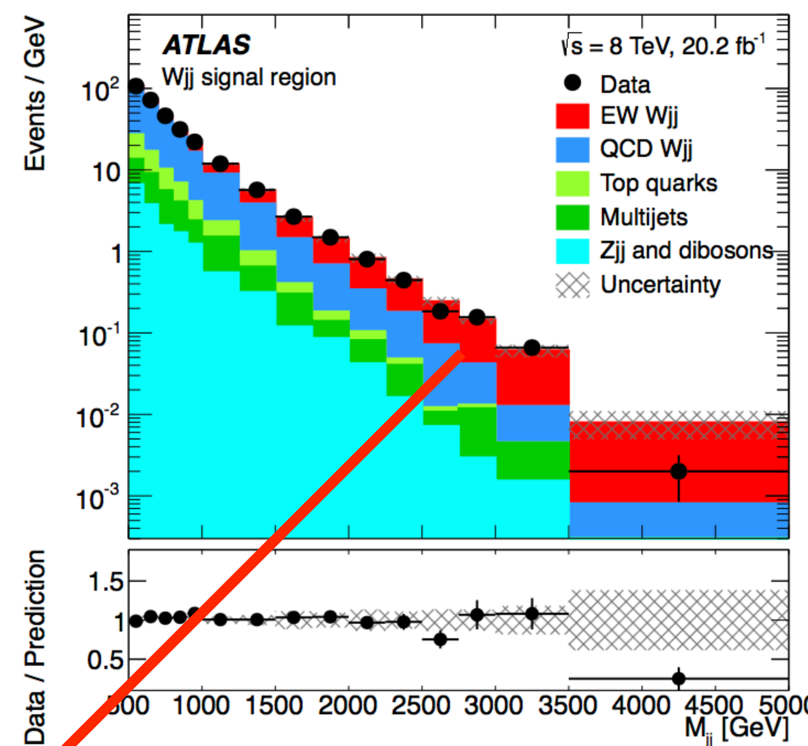


EW W+2-jet: fiducial cross section



Bkg constrained by linear fit to bkg subtract. data/pred. for QCD W+2jets in CR.

Constrain prediction in signal region



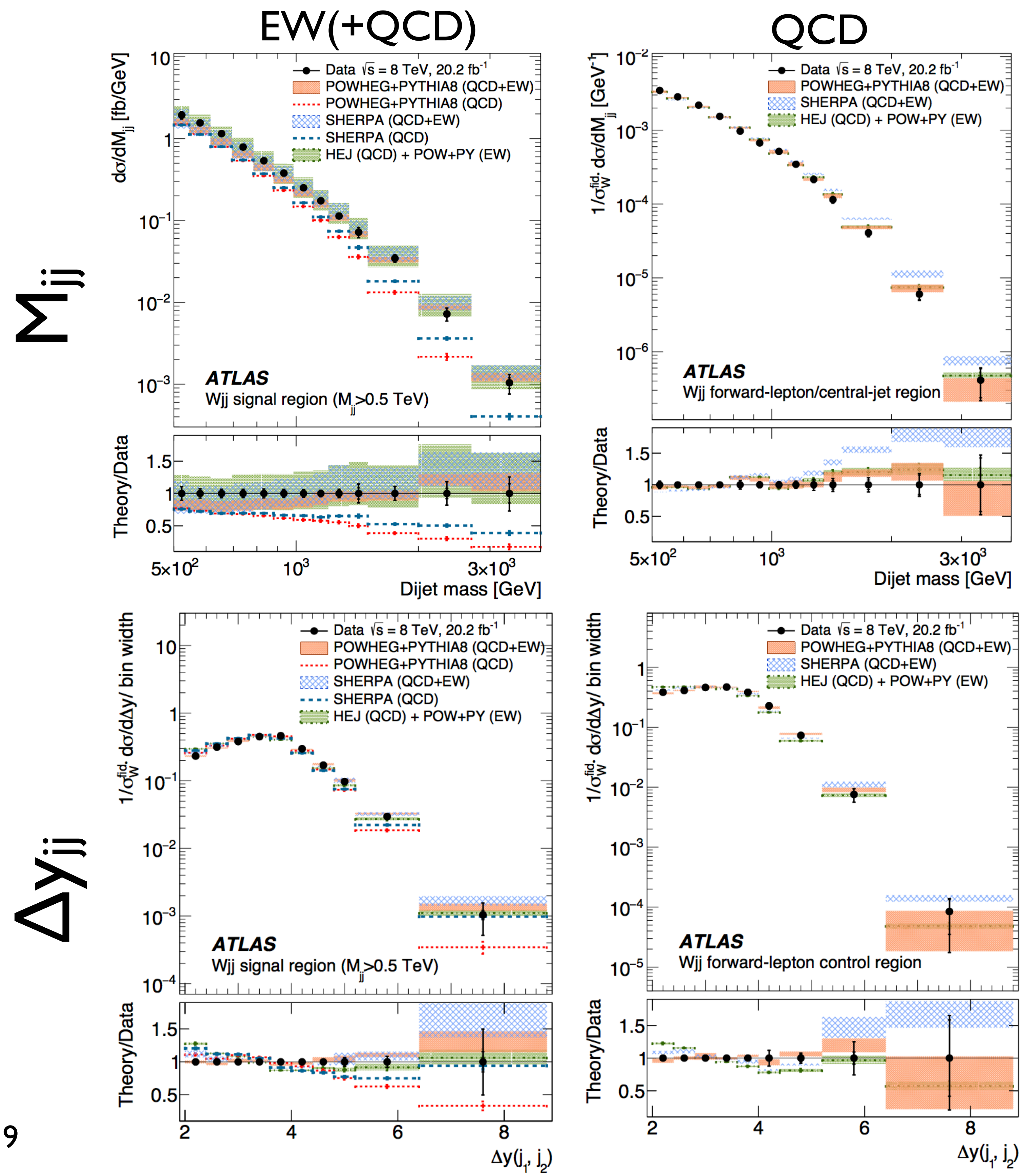
- $>5\sigma$ observation of electroweak W+2-jets production!

$\sqrt{s}$	$\sigma^{\text{fid}}_{\text{meas}}$ [fb]	$\sigma^{\text{fid}}_{\text{SM}}$ [fb]	Acceptance $\mathcal{A}$	$\sigma^{\text{inc}}_{\text{meas}}$ [fb]
7 TeV	144 ± 23 (stat) ± 23 (exp) ± 13 (th)	144 ± 11	0.053 ± 0.004	2760 ± 670
8 TeV	159 ± 10 (stat) ± 17 (exp) ± 15 (th)	198 ± 12	0.058 ± 0.003	2890 ± 510

- Measurement with ~15% precision. Good agreement within uncertainties.
- Leading uncertainties:
  - Exp: Jet Energy Scale, Theory: QCD W+jj scale unc. (Powheg MiNLO+Pythia8), PDFs, neglected interference between QCD and EW W+jj

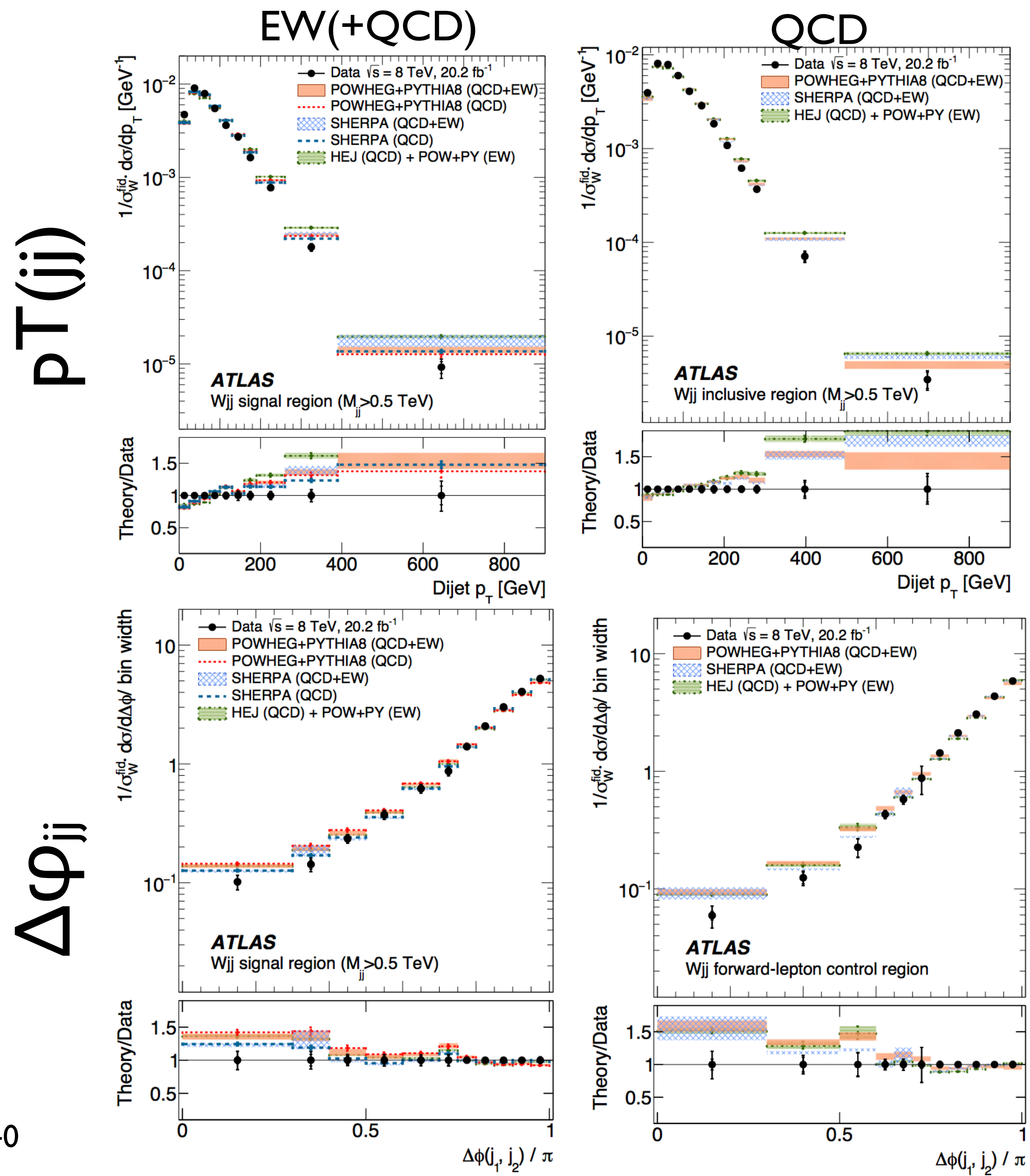
[arXiv:1703.04362]

EW W+2-jet: differential measurements



- In general:
  - Powheg+Pythia8 (NLO) and Sherpa v1.4 (LO) seem to reproduce EW W+2-jets reasonably well
  - Sherpa v1.4 (matched tree-level, including interference) does not correctly reproduce QCD W+2-jets shape, while Powheg+Pythia8 (MiNLO) gives the best description.

EW W+2-jet: differential measurements



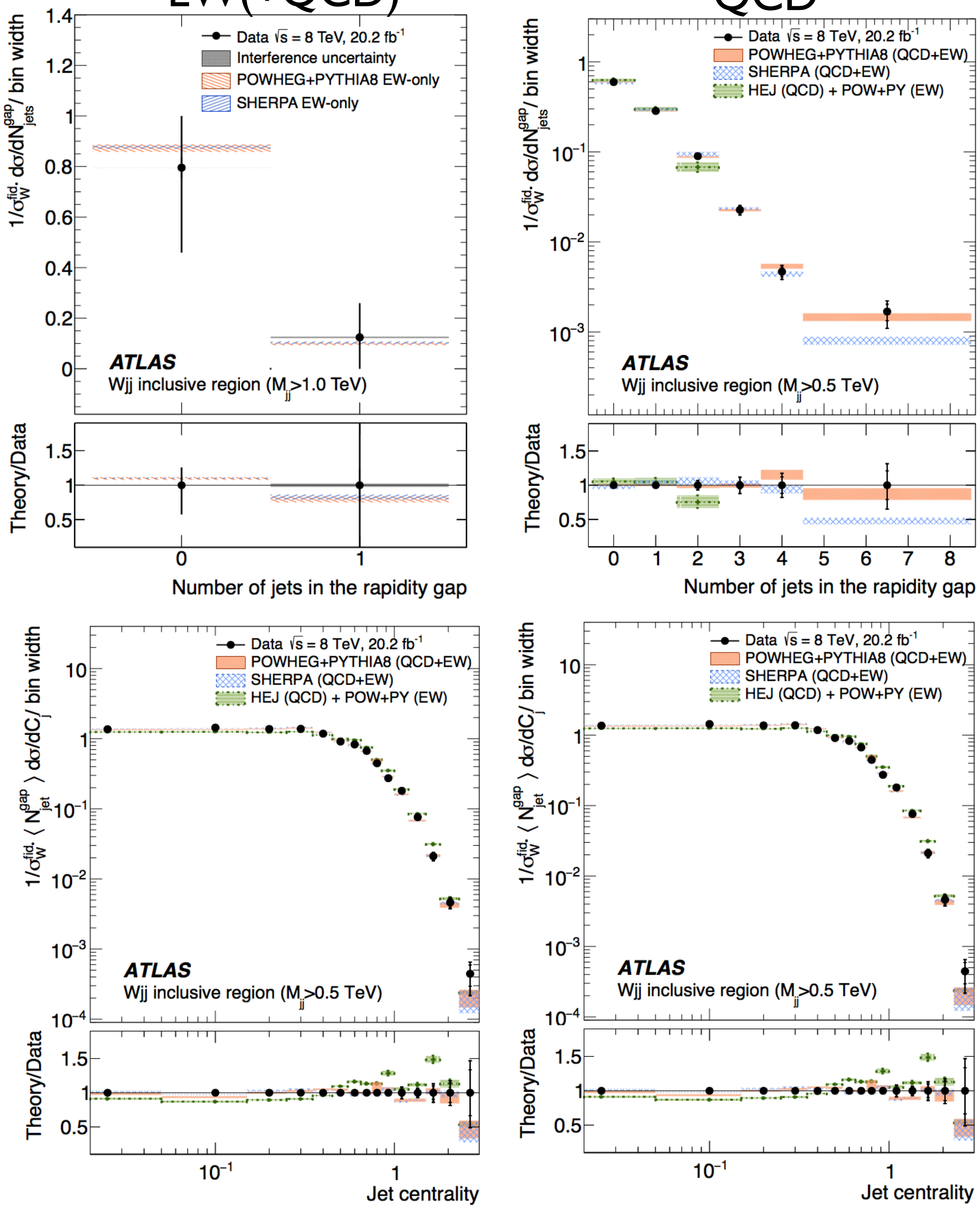
- However, both in EW and QCD enhanced W+2-jet regions, simulations overestimate rate at high pT(di-jet) and low DPhi(jj).
- Difference could be due to NLO EW corrections? (not included in simulations here)
- Integrated cross-section is also 15-20% higher than predictions in regions dominated by QCD

EW W+2-jet: differential measurements

EW(+QCD) QCD

pT(jj)

$\Delta\varphi_{jj}$

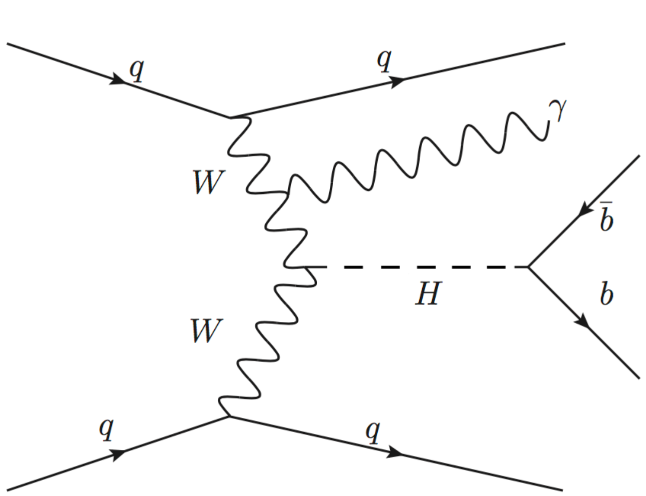


- Jet centrality and number of jets in the gap seems sufficiently well reproduced
- In this case, Sherpa v1.4 seems to have a small edge…

A slightly different production mode:
VBF + *high energy photon*

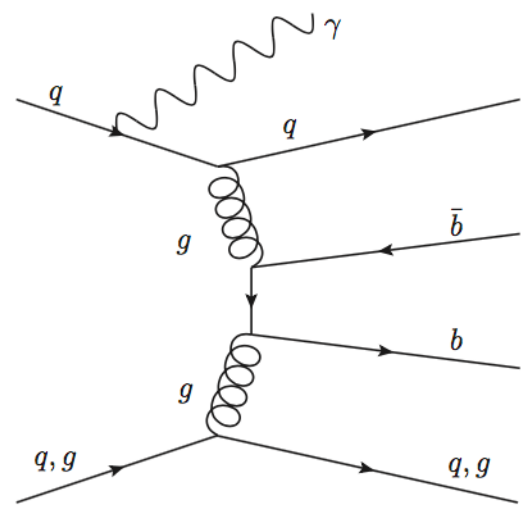
VBF+γ, with H → bb: selection

Tree-level signal diagram



+ many others…

Tree-level bkg diagram



+ many others…

- Despite reduction in S, destructive interference in background improves S/B [E. Gabrielli et al.]
- Photon provides trigger
  - Important to get enough low m(bb) side-bands to determine background properly!

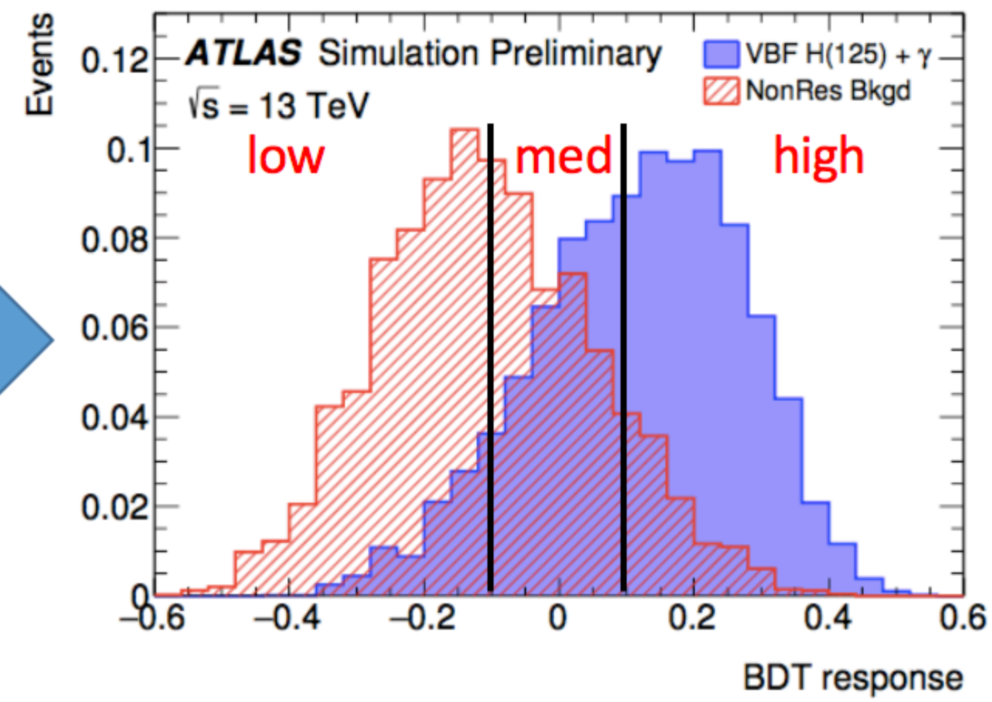
- Trigger given by pT(photon) > 25 GeV, 4 jets with pT > 35 GeV, m_{jj}(max) > 700 TeV
- Basic selection: photon pT > 30 GeV, 4 jets with pT > 40 GeV
  - 2 b-tagged jets (77% b-jet efficiency) with highest pT, pT(bb) > 80 GeV
  - 2 non-signal jets with highest m_{jj}, with m_{jj} > 800 GeV

VBF+γ, H → bb: BDT and data fits

- BDT used to improve separation of VBF from non-VBF topologies

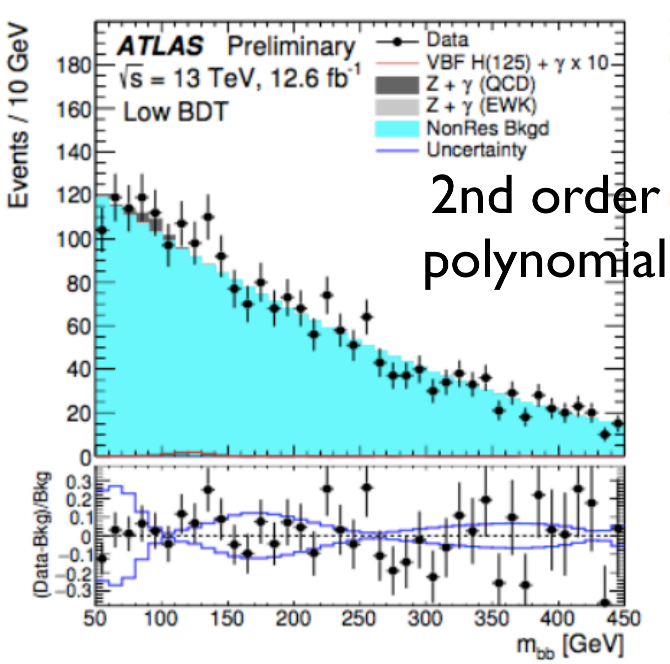
Input variables:

- $\Delta R(\text{jet},\gamma)$
- m_{jj}
- $\Delta\eta_{jj}$
- jet width for the VBF jets
- $p_T^{balance}$
- Centrality of the photon with respect to the VBF jets
- H_T^{soft}

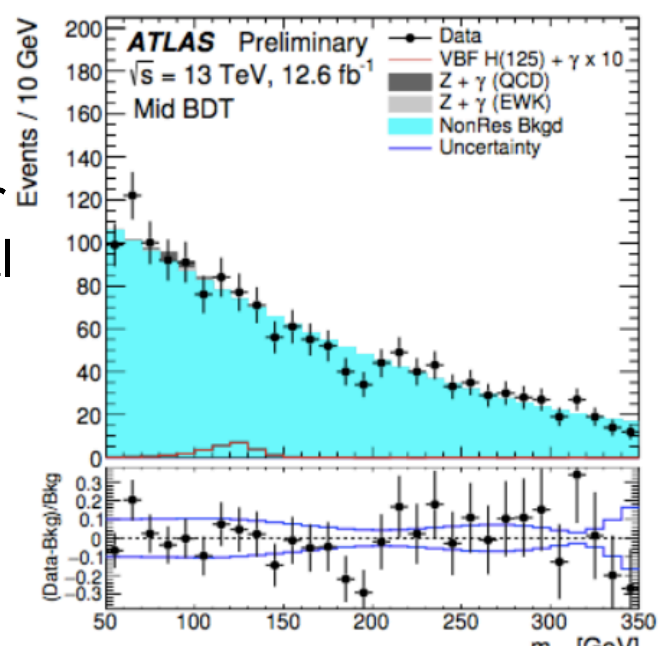


- different intervals of BDT give SRs, m_{bb} fit in each SR to extract signal

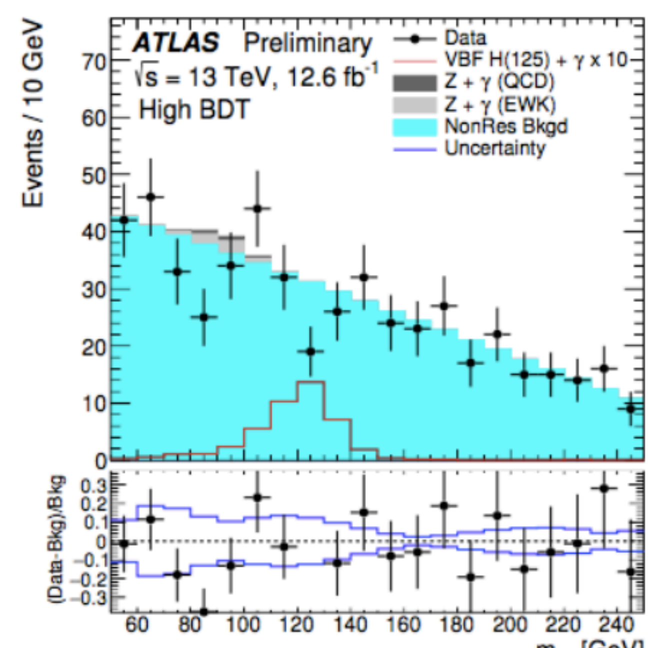
Low BDT region



Medium BDT region



High BDT region



$$\mu_{H+\gamma jj} = -3.9^{+2.8}_{-2.7}$$
$$\mu_{Z+\gamma jj} = 0.3 \pm 0.8$$

VBF+γ, H → bb: systematics

Uncertainty source	Uncertainty $\Delta\mu$
Non-resonant background uncertainty in medium-BDT region	0.22
Non-resonant background uncertainty in high-BDT region	0.21
Non-resonant background uncertainty in low-BDT region	0.17
Parton shower uncertainty on $H + \gamma$ acceptance	0.16
QCD scale uncertainty on $H + \gamma$ cross section	0.13
Jet energy uncertainty from calibration across η	0.10
Jet energy uncertainty from flavour composition in calibration	0.09
Integrated luminosity uncertainty	0.08

- Will go down with data statistics (here 13 fb^{-1} are used)

- Signal generation @ LO with MG5_aMC@NLO v2.3.3+Pythia8 (PDF4LHC, 5FNS)
  - NLO cross-section has only ~1% effect
  - Scale uncertainty from variation of μ_F and μ_R by a factor of 2.
  - Parton shower uncertainty comes from variations of the A14NNPDF23LO
- **Notice!** Signal μ is ~4, so all signal related uncertainties are overestimated by a factor of 4 here. For now signal uncertainties are subdominant here.

Summary

- With the increase in center of mass energy and in integrated luminosity delivered by LHC, ATLAS and CMS can know conduct stringent tests of the SM in the VBF production mode
  - VBF now measurable also in cleanest decay modes ($H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4l$)
  - In addition to inclusive signal strength measurements, now performing
    - (1) differential signal strength measurements (template cross-section method)
    - (2) fully unfolded measurement of distributions at particle level (for minimal model dependence, but typically largest uncertainty)
  - So far all measurements are compatible with the Standard Model
    - Already with the full LHC 2015+2016+2017 data statistics, expect many of these measurements to be limited by theory understanding of (1) VBF (2) ggF
    - Theory progress that went into YR4 for ggF already produced visible effects in measurement uncertainties
      - But need more of such theory progress in future to keep up with data… (+ can now use the Z/W+2-jets measurements to test SM predictions!)
      - … while experimentalists are busy understanding more difficult channels (e.g. $H \rightarrow WW^*$, $H \rightarrow \tau\tau$), and reducing experimental systematics as well!

VBF+γ, H → bb: systematics

Uncertainty source	Uncertainty $\Delta\mu$
Non-resonant background uncertainty in medium-BDT region	0.22
Non-resonant background uncertainty in high-BDT region	0.21
Non-resonant background uncertainty in low-BDT region	0.17
Parton shower uncertainty on $H + \gamma$ acceptance	0.16
QCD scale uncertainty on $H + \gamma$ cross section	0.13
Jet energy uncertainty from calibration across η	0.10
Jet energy uncertainty from flavour composition in calibration	0.09
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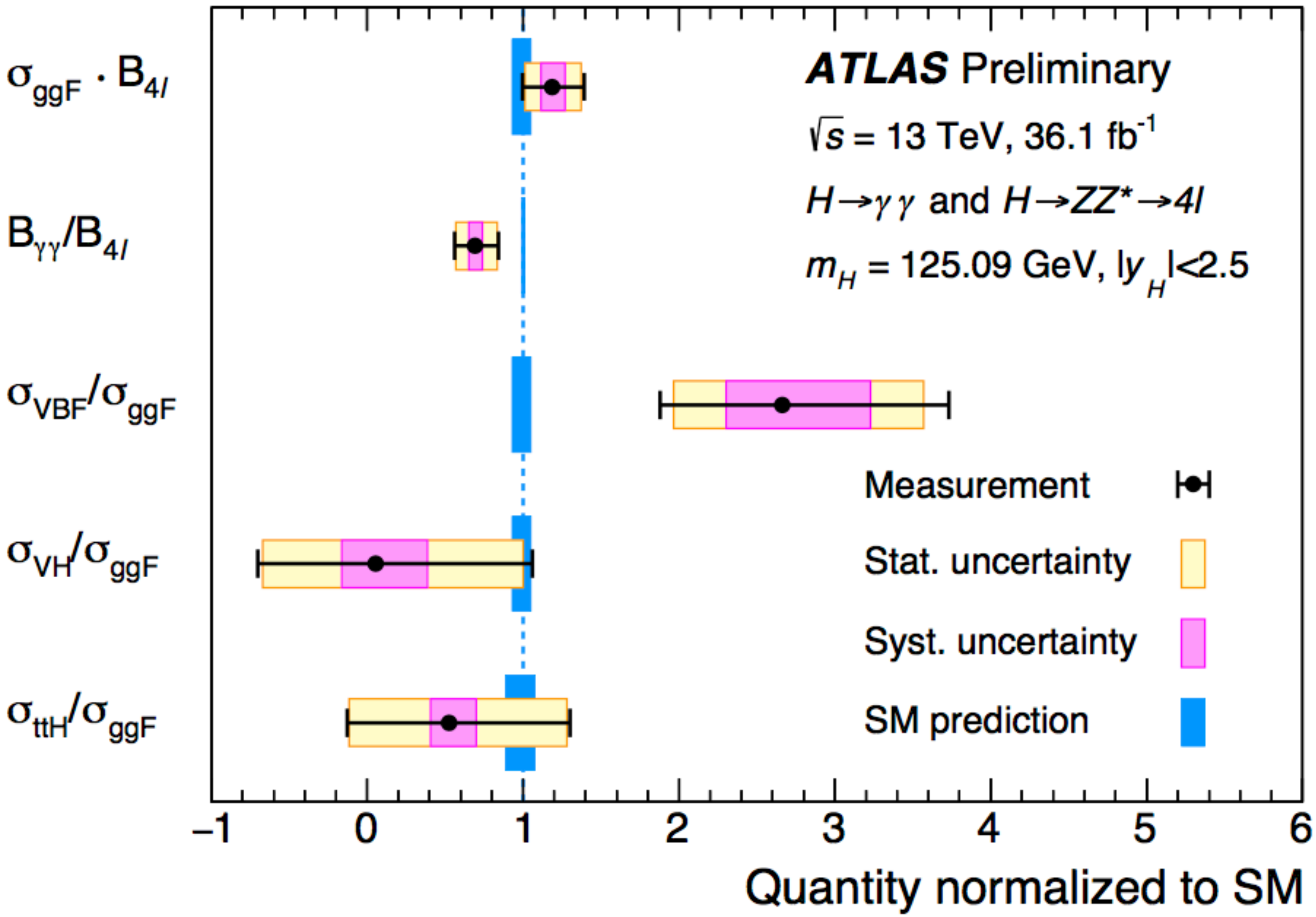
Backup slides

[ATLAS-CONF-2017-047]

$H \rightarrow \gamma\gamma + H \rightarrow ZZ^*$: Ratios of production modes



$H \rightarrow \gamma\gamma + H \rightarrow ZZ^*$: SM acceptance of each region

$gg \rightarrow H$ region	0-jet	1-jet	$\geq$ 2-jet
$p_T^H < 60$ GeV	0.562	0.134	0.025
60 GeV $\leq p_T^H < 120$ GeV	-	0.093	0.038
120 GeV $\leq p_T^H < 200$ GeV	-	0.015	0.020
$p_T^H \geq 200$ GeV	-	0.003	0.009
VBF-like			
$p_T^{Hjj} < 25$ GeV	-	-	0.006
$p_T^{Hjj} \geq 25$ GeV	-	-	0.007

$qq \rightarrow Hqq$ region	VBF	$q\bar{q}' \rightarrow WH$	$q\bar{q} \rightarrow ZH$
$p_T^j \geq 200$ GeV	0.043	0.027	0.029
$p_T^j < 200$ GeV			
VH-like	0.023	0.189	0.224
Rest	$\boxed{0.557}$	0.368	0.363
VBF-like			
$p_T^{Hjj} < 25$ GeV	0.234	0.002	0.002
$p_T^{Hjj} \geq 25$ GeV	0.074	0.007	0.008

H → γγ+H → ZZ*: absolute simplified template cross-section results

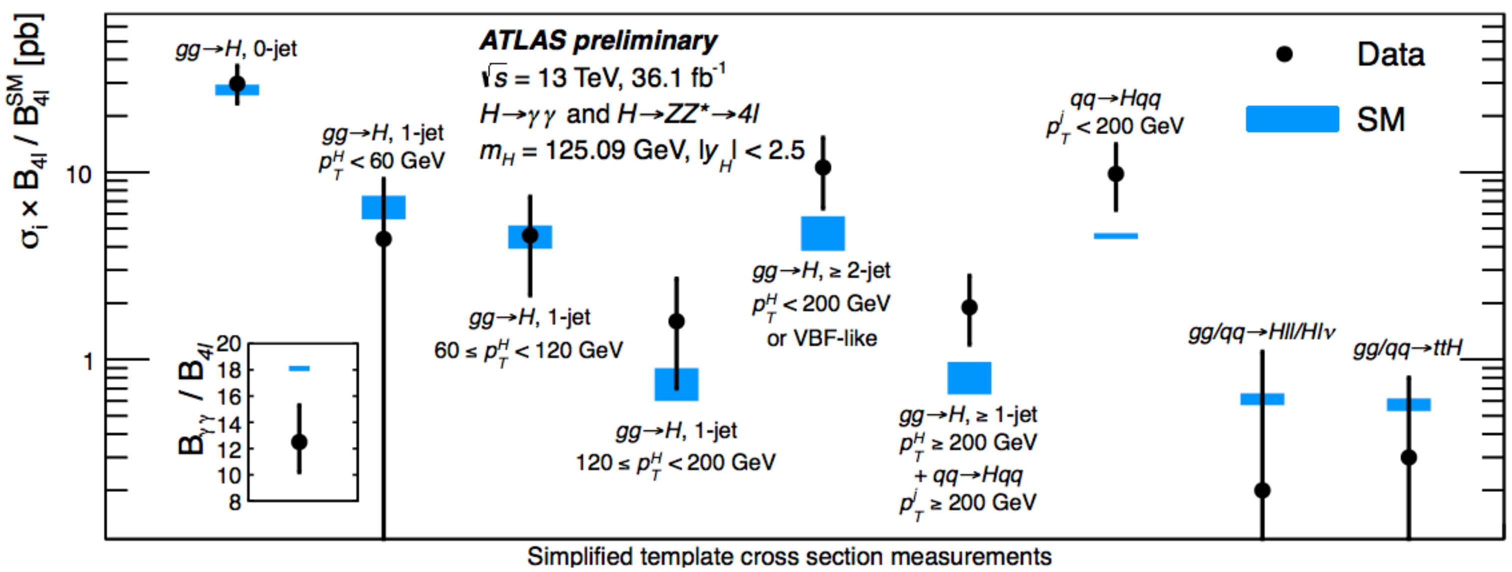


Figure 9: Best-fit results of STXS measurement regions given in Table 7. The fit results are shown normalized (top) and not normalized (bottom) to the SM predictions for the various parameters. The black error bar shows the total uncertainty on each measurement.