Study of inclusive Higgs-boson production at high transverse momentum in the *H->bb* decay mode with the ATLAS detector

ATLAS-CONF-2021-010

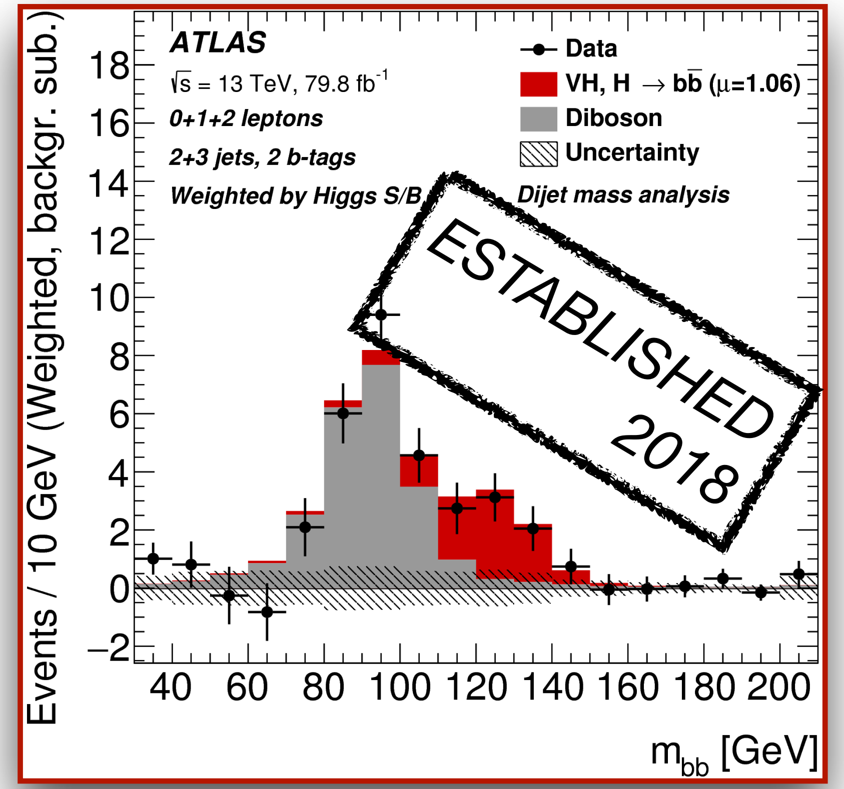
DPF21

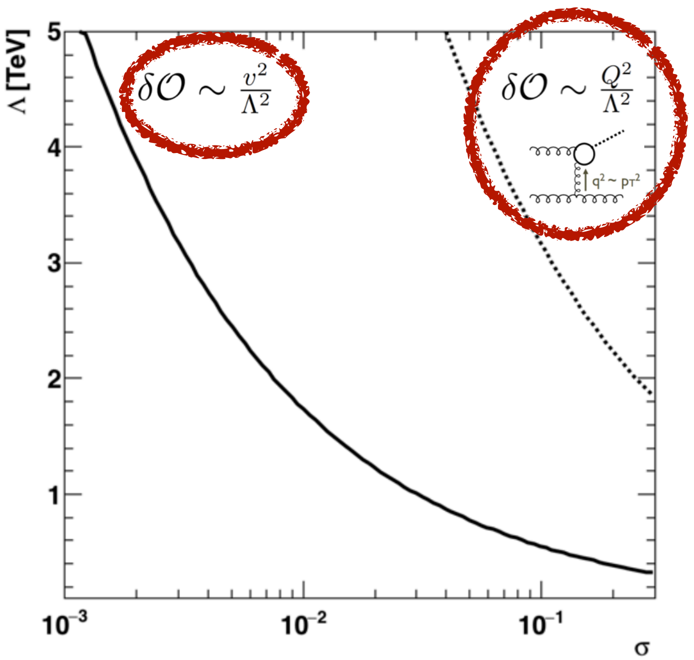
Andrea Sciandra

July, 12th 2021

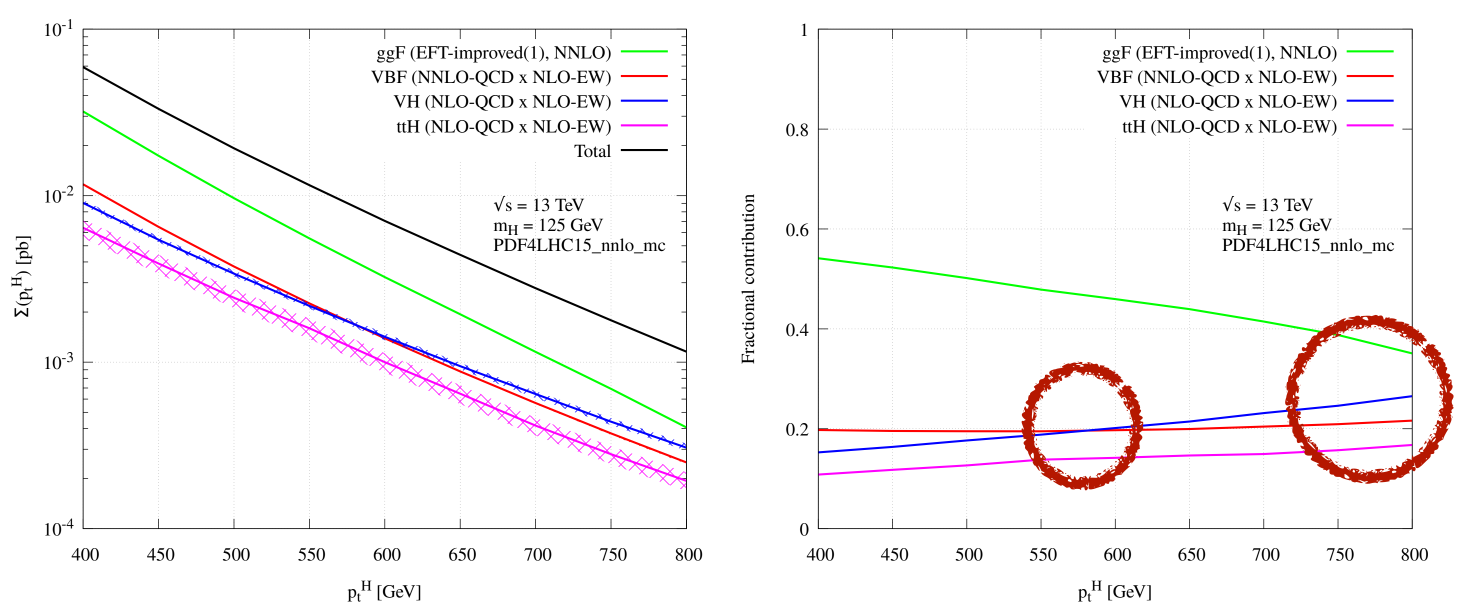
Towards Dynamics of the Higgs Boson

- Shifting interest from static (inclusive cross section, couplings, …) to ***dynamic*** properties of the Higgs boson
- Large dynamic range yet to explore for Higgs production in $\boldsymbol{p_T^H}$, $m(H+X)$, …
  - New opportunities for reduction of systematic uncertainties (e.g. the higher p_T^H, the smaller the n. of events produced)
  - **Different hierarchy** of production modes
  - All **production modes contribute ~equally**, close to **TeV scale**
- Indirect sensitivity to Beyond-Standard-Model effects at **large Q²**
  - **Complementary to Q~$\boldsymbol{m_H}$** precision studies
  - **Sensitivity to New Physics (NP) enhanced approximately** $\propto \boldsymbol{p_T^H/v}$

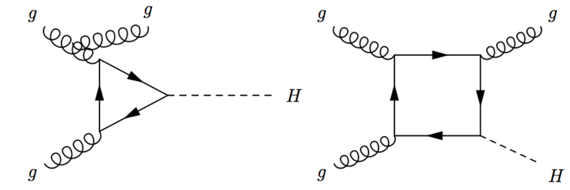




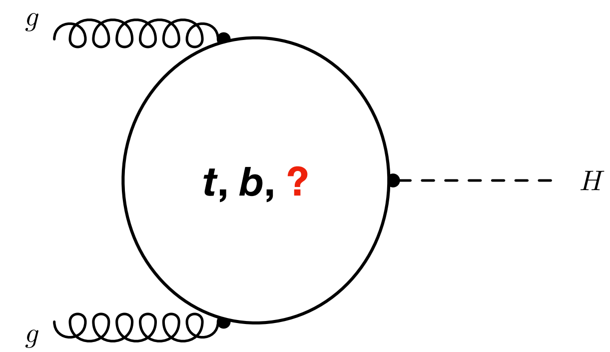
arXiv:2005.07762



Production at High p_T^H & New Physics

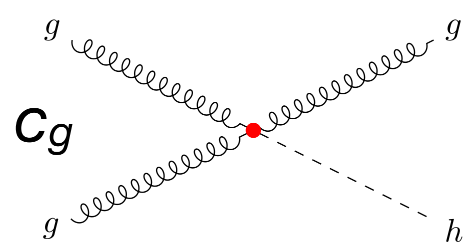


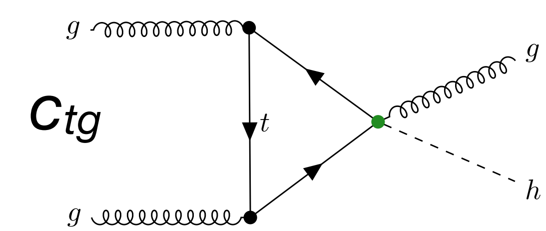
- Decay channels other than *bb*(BR~58%) and specific production modes signatures (e.g. *V(->ll,lv,vv)H)* are pure
  - But limited p_T^H reach -> **inclusive *H->bb*** to access **higher portion of the p_T^H spectrum**
- At high p_T^H, can **resolve loop-induced contributions to *ggF*** from new particles
  - Effective *ggH* vertex at low energy
- **EFT**: effects at high p_T^H enhanced by **powers of E/Λ**

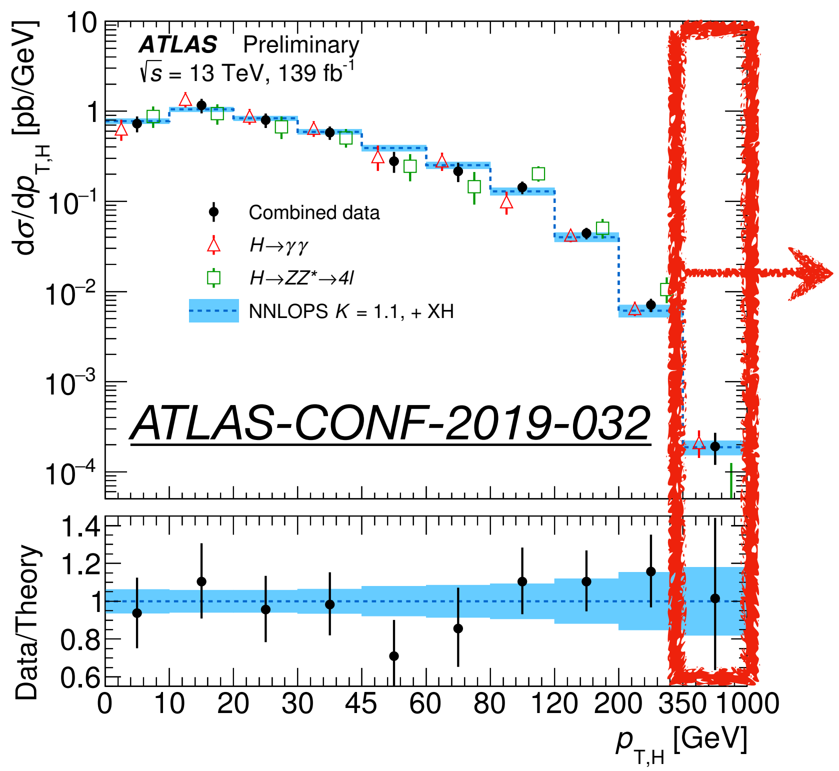


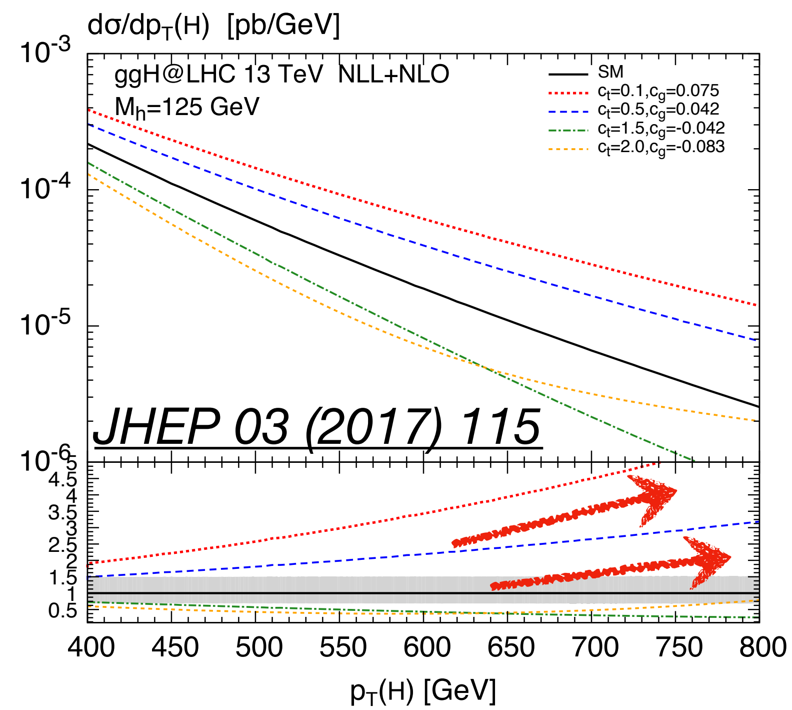
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \text{higher dimensional operators}$$

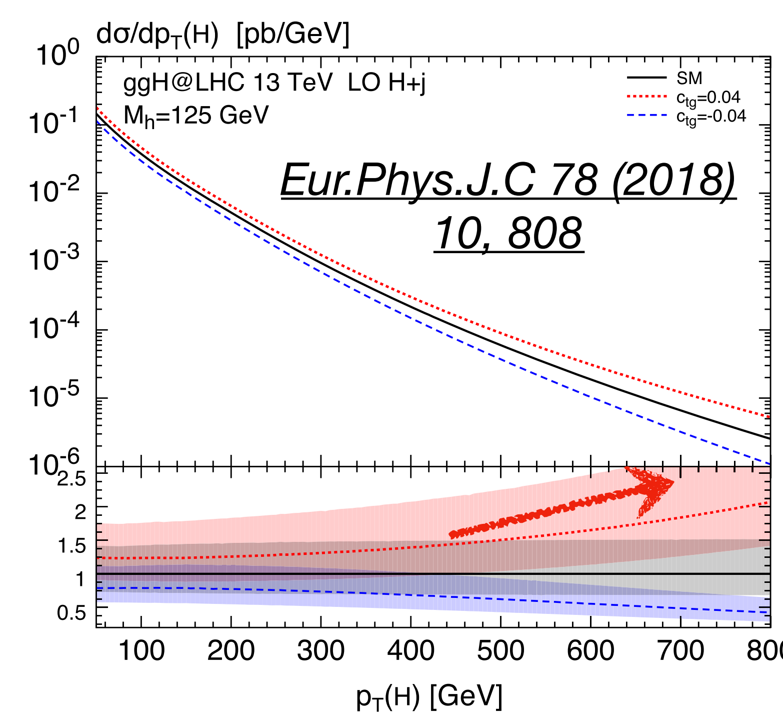
Scale of NP





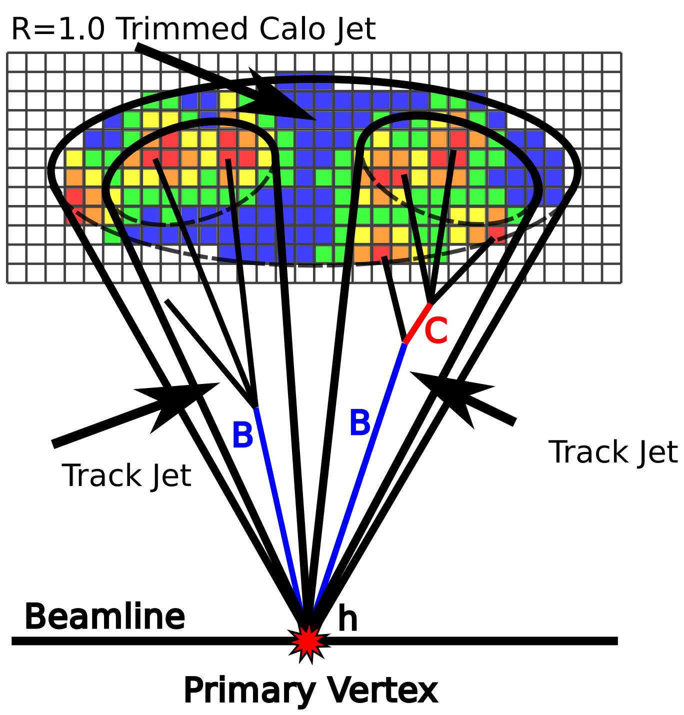






Experimental Toolkit

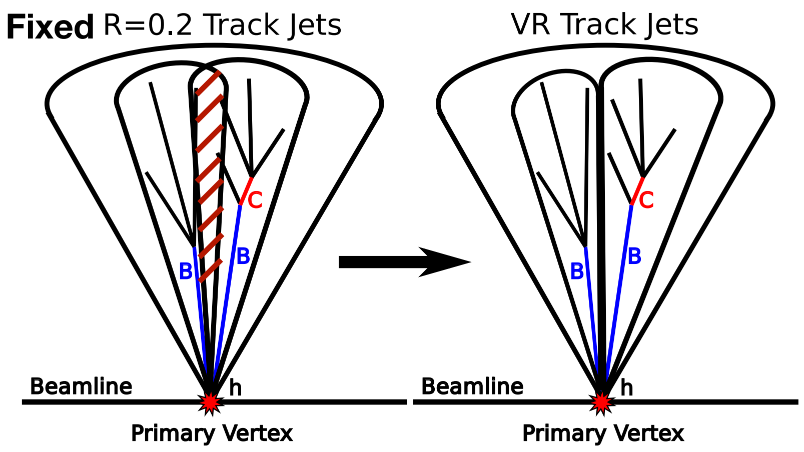
- Looking into hadronic, i.e. ***H->bb***, Higgs **decay dynamics**
- **Angular separation** of decay products can be expressed as:



$$\Delta R = \frac{1}{\sqrt{x(1-x)}} \frac{m_H}{p_{T_H}}$$

momentum fraction carried by decay products

- For Higgs decay x~0.5 ⟶ $\Delta R \approx 2\frac{m_H}{p_{T_H}}$
- At high p_T^H (>250 GeV), Higgs decay products start being fully contained within ΔR=1 -> **m_J~m_H!**
  - **-> Natural to use large-R calorimetric jets for high energetic *H->bb* production**
- Identification of **decay products** performed through **track jets within large-R calo jet**
  - Collimation depends on p_T -> **Variable-Radius track jets**

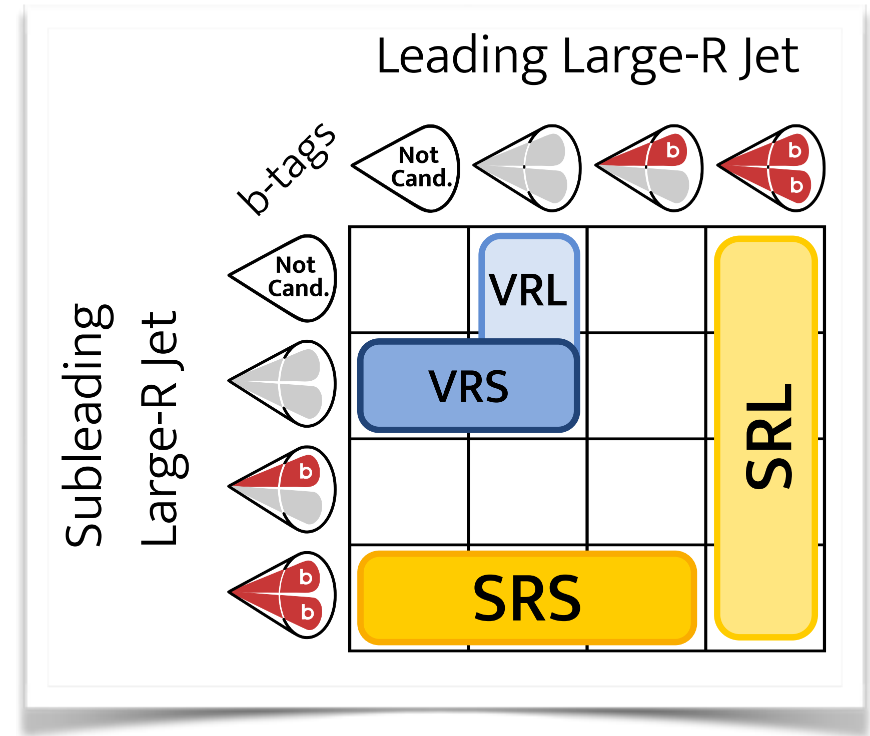


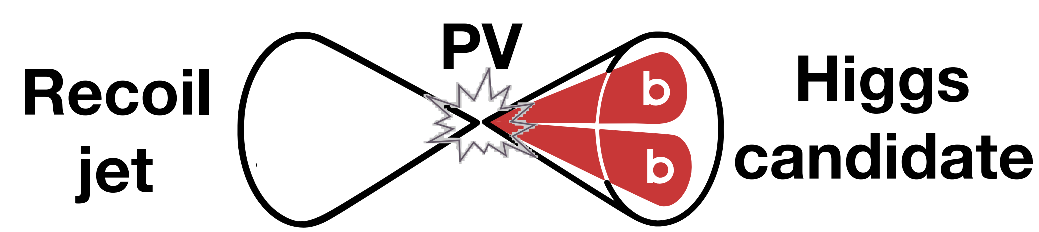
- ***b*-tagging** applied to **2 leading track-jets** (2-prong decay structure)
  - Identify *bb* exploiting products of *b*-hadronization/fragmentation
- **Correct large-R jet reconstructed mass and p_T** by including **muons** from semi-leptonic *b*-decays

Event **Selection** & Analysis **Strategy**

Event selection

- **Large-R jet** trigger with mass cut
    - $m_J \sim m_{X\to bb}$ and Higgs is massive!
- At least one large-R jet with p_T **>450** & m_J **>60 GeV**
- At least **2 large-R jets** with p_T **>200 GeV**
    - High-p_T back-to-back topology requires **recoil** jet
- Categorization into **signal regions (SR)** based on *b*-tagging and large-R jet (reconstructed) p_T **requirements**

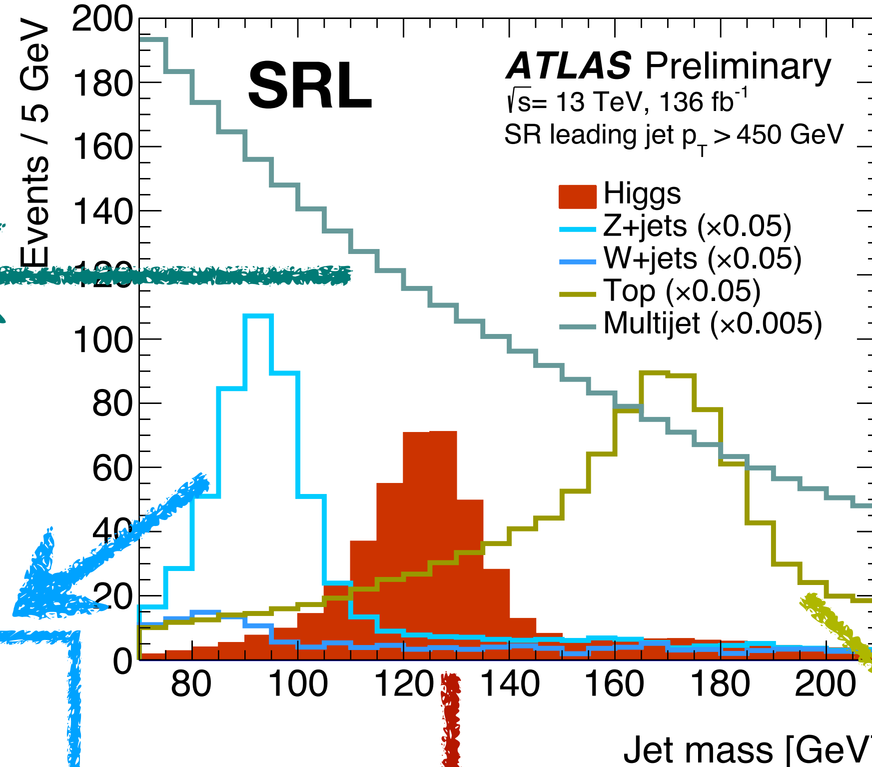


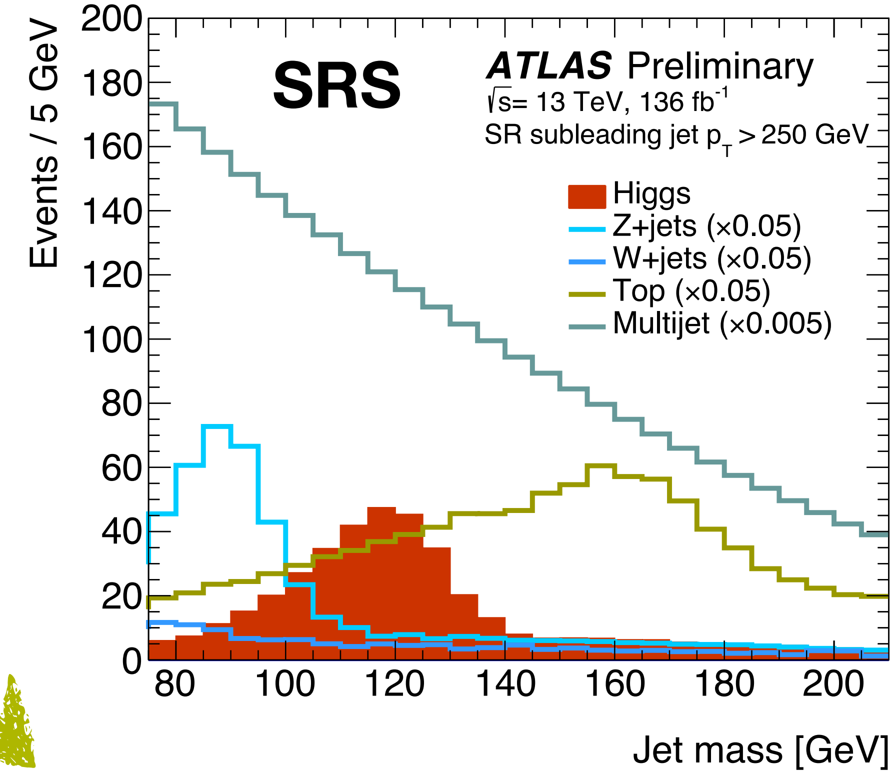


Signal region definitions and reco-p_T range

Considered Jet			Inclusive	Fiducial		Differential		
Type	N *b*-tags	Order*	p_T Range [GeV] >250/450	>450	>1000	250–450	450–650	650–1000
Signal Regions								
Candidate	2	Lead	SRL	SRL	SRL	–	SRL1	SRL2
	2	Sublead	SRS	SRS	–	SRS0	SRS1	SRS2

Background Composition & Modeling





QCD Multijet modeled with fully data-driven smooth analytical model

W/Z+jets

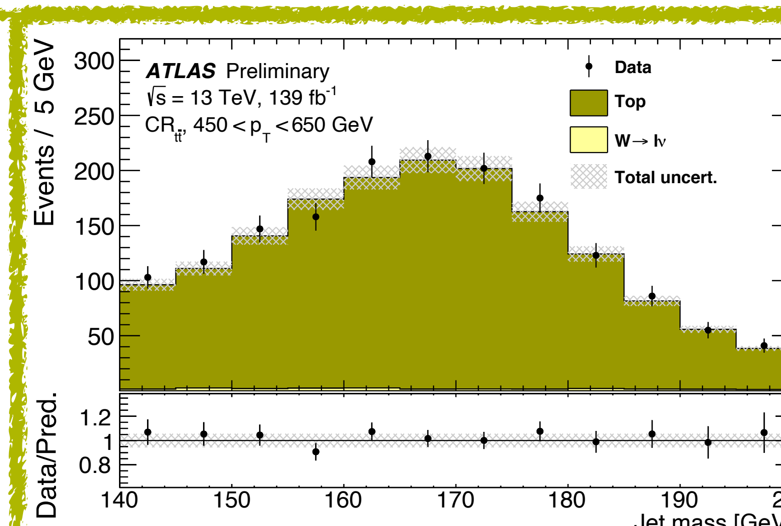
- Modeled by **simulation**
- "**Standard candle**" for Higgs extraction
  - "**Conspiracy**" together with *H* (positively correlated)
- Mostly *Z*+jets (double *b*-tagging)
- **Width extracted** from dedicated *W*-enriched region

Full control of peak position and width is key to resonances fitted on top of free-shape large background

Higgs signal = *ggF + VBF + VH + ttH*

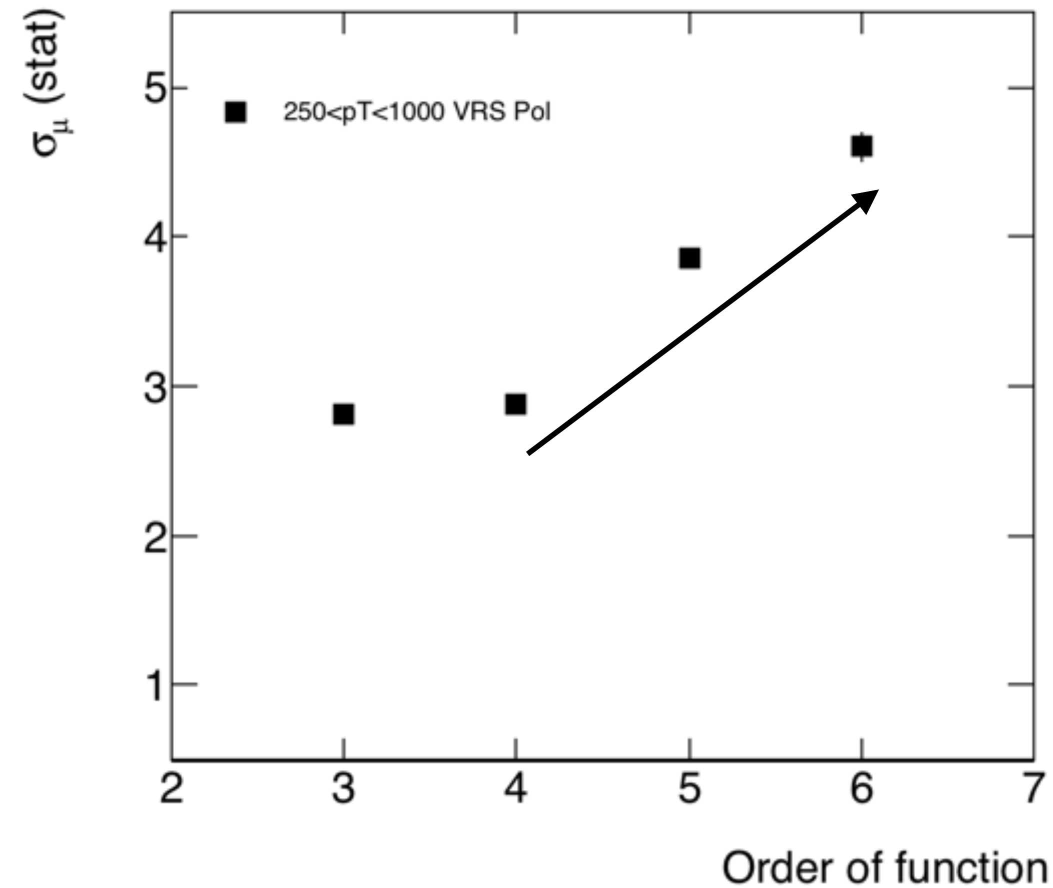
Top

- Described by **simulation**
- **Normalization and shape** extracted from **semi-leptonic ttbar dedicated region (>95% pure)**



QCD Multijet Modeling

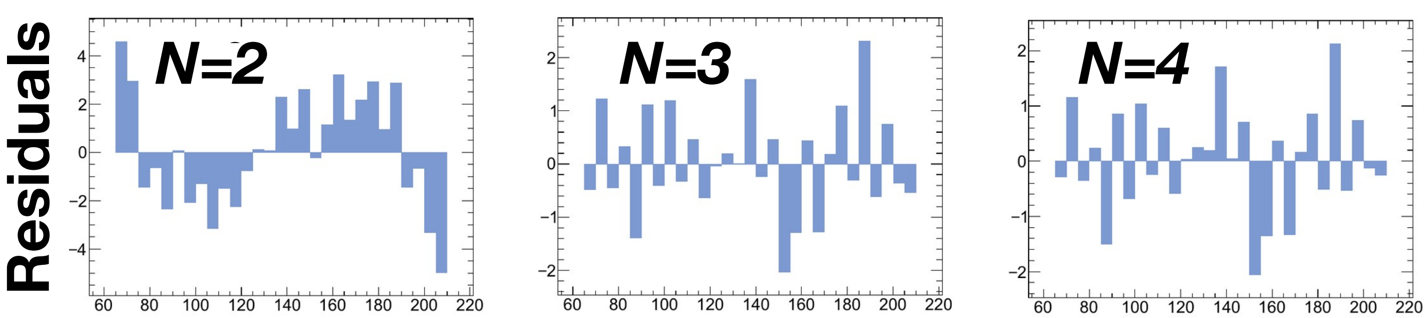
- Do not rely on simulation for the modeling of **Multijet mass shape and normalization**
- Main background estimated by means of a **functional-form** fit to data in the region of interest
- **How many parameters?** The choice depends on luminosity and it is a trade-off
  - Too few: not a good description of QCD
  - Too many: 'eat' resonances and significance
- **Fix and validate QCD modeling by means of studies in dedicated anti-tagged regions, fairly representing SRL/S statistics, m_J & p_T spectra** (~x50-60)



N = 4, 5

$$f_N\left(x \,\middle|\, \vec{\theta}\right) = \theta_0 \exp\left(\sum_{i=1}^{N} \theta_i x^i\right)$$

$$x = (m_J - 140\ \text{GeV})/70\ \text{GeV}$$



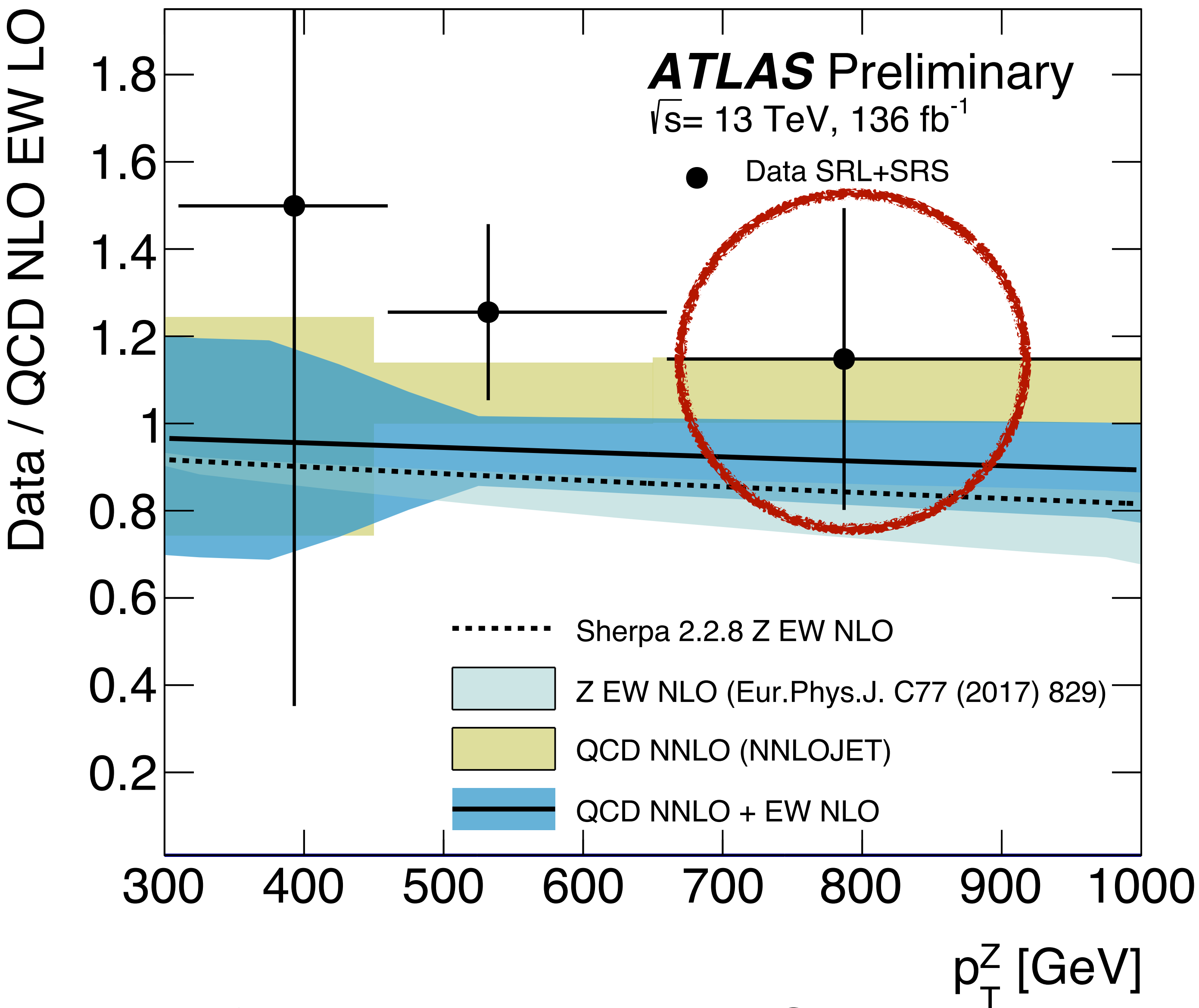
Boosted *H->bb* Analysis Results

- **Fiducial p_T^H > 450 GeV *H->bb*** extraction
  - ***H*** cross section in a well-defined phase-space volume (**p_T^H >450 GeV & |η|<2**)
  - Fairly **flat A x ε**, useful to theory community
- **Fiducial p_T^H > 1 TeV *H->bb*** extraction
  - Probe **Higgs production** & potential large **cross-section enhancement** at ***very* high p_T^H**
- **Differential (p_T) *H->bb*** extraction
  - Extraction of ***H*** yield in bins of p_T^H from reco-p_T-binned SRs
    - Accounting for **p_T^H vs. p_T migrations** due to limited resolution
    - Sensitivity to **EFT** operators at high p_T
- **Differential (p_T) *Z->bb*** measurement
  - Unique sensitivity to boosted production of hadronically-decaying *Z*
  - Combined extraction of ***Z*** p_T spectrum using same machinery as for *H*
  - Predictions at NNLO QCD + NLO EW

95% CL limits on Higgs production rates

Cross-section results

Z(->bb)+j Differential Extraction



3.3σ -> evidence for the production of *Z->bb* with p_T^Z>650 GeV

- Results fully **compatible with SM**
- Trend following negative p_T-dependent NLO EW corrections?
- Interesting excess overall, not observed in *W*-dominated anti-tagged region: something to learn with *b*-tagging efficiency in boosted environment?

Fiducial p_T^H > 450 GeV & 1 TeV Fit - Results

The two fiducial regions determine the Higgs boson yield and cross section in the phase space defined by the Higgs boson pseudo-rapidity range $|\eta_H| < 2.0$ and transverse momentum $p_T^H > 450$ GeV and $p_T^H > 1$ TeV

Signal-strength results

p_T^H/Jet p_T	μ_H Exp.	μ_H Obs.	μ_Z Exp.	μ_Z Obs.	$\mu_{t\bar{t}}$ Exp.	$\mu_{t\bar{t}}$ Obs.
> 450 GeV	1.0 ± 3.3	0.7 ± 3.3	1.00 ± 0.18	1.27 ± 0.22	1.00 ± 0.07	0.81 ± 0.06
> 1 TeV	1.0 ± 29.0	26 ± 31	1.0 ± 1.6	2.4 ± 1.7	1.0 ± 0.3	0.51 ± 0.19

Signal acceptance x efficiency for fiducial extractions

Process	$p_T^H > 450$ GeV	$p_T^H > 1$ TeV
All	0.25	0.18
ggF	0.26	0.22
VH	0.27	0.19
VBF	0.22	0.15
ttH	0.20	0.16

Cross-section results

$$\sigma_H(p_T^H > 450\ \text{GeV}) = 13 \pm 52\ (\text{stat.}) \pm 32\ (\text{syst.}) \pm 3\ (\text{theory})\ \text{fb} \quad \textbf{(\sim 0.2\sigma)}$$

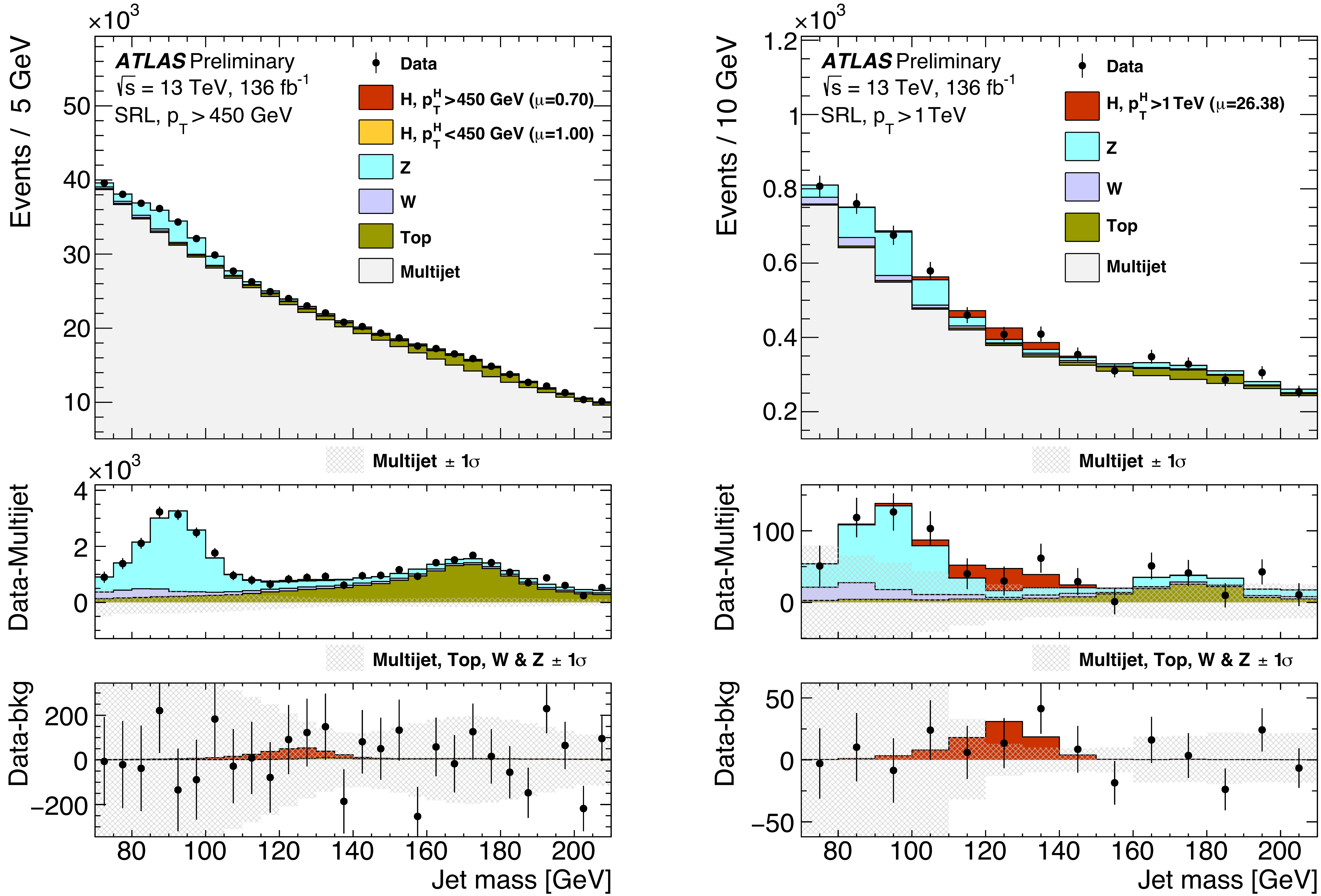
$$\sigma_H(p_T^H > 1\ \text{TeV}) = 3.4 \pm 3.9\ (\text{stat.}) \pm 1.0\ (\text{syst.}) \pm 0.8\ (\text{theory})\ \text{fb} \quad \textbf{(\sim 0.9\sigma)}$$

95% CL_s limits on production cross-sections

$$\sigma_H(p_T^H > 450\ \text{GeV}) < 144\ \text{fb} \quad \textbf{(\sim 8x SM)}$$

$$\sigma_H(p_T^H > 1\ \text{TeV}) < 10.3\ \text{fb} \quad \textbf{(\sim 80x SM)}$$

Fiducial p_T^H > 450 GeV & 1 TeV - Post-Fit Plots



H->bb Differential Fit Results

- Higgs boson signal strength from **8 differential SR and CR regions**
- **Small correlations amongst strength** parameters, **positive correlations with *Z*** signal strengths
- ***p_T^H* > 650 GeV fiducial cross-section & 3 upper limits extracted**

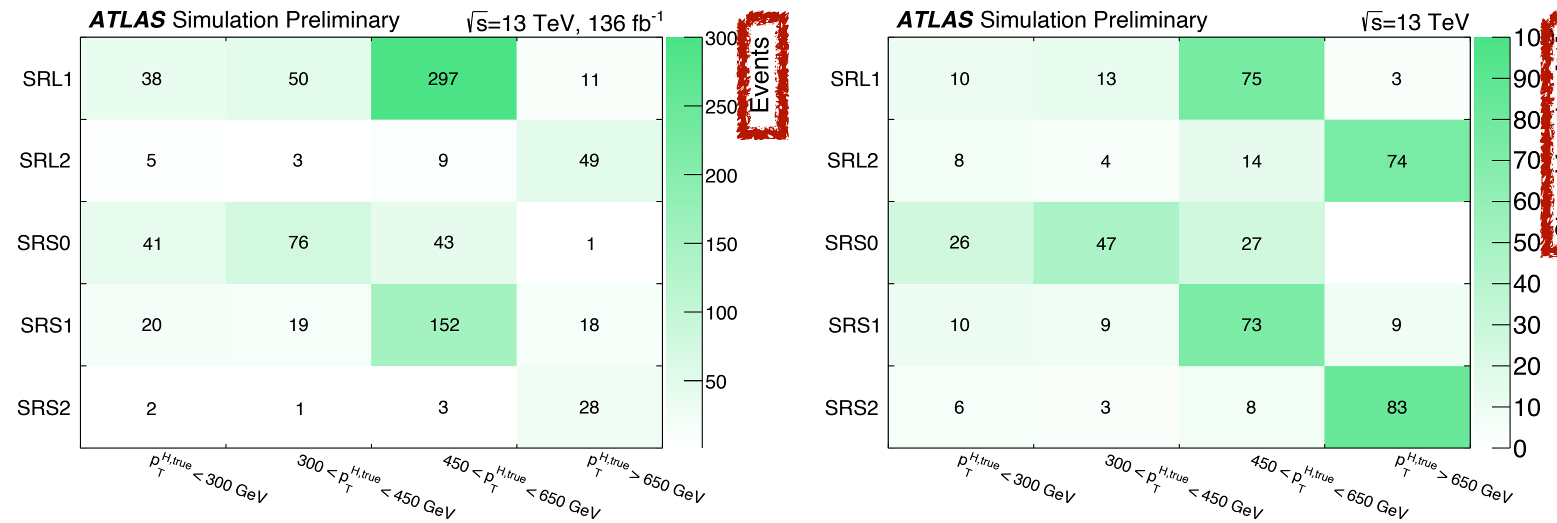


Figure 7: For each of the differential regions, the expected signal event yield for all Higgs boson events (a) and the fraction of signal in percent (b) in each reconstructed region vs. the differential fiducial volumes.

Correlations

	$\mu_H^{300-450}$	$\mu_H^{450-650}$	$\mu_H^{>650}$
$\mu_H^{300-450}$	1.00	−0.18	0.07
$\mu_H^{450-650}$	−0.18	1.00	−0.05
$\mu_H^{>650}$	0.07	−0.05	1.00

	μ_Z^{SRS0}	μ_Z^{SR1}	μ_Z^{SR2}
$\mu_H^{300-450}$	−0.07	−0.02	−0.03
$\mu_H^{450-650}$	0.04	0.51	−0.21
$\mu_H^{>650}$	0.03	−0.05	0.54

Signal-strength results

p_T^H [GeV]	μ_H Exp.	μ_H Obs.
300–450	1 ± 18	−7 ± 17
450–650	1.0 ± 3.3	−2.9 ± 4.7
>650	1.0 ± 6.3	4.8 ± 6.4

Cross-section result

$$p_T^H > 650 \text{ GeV} = 13 \pm 16 \text{ (stat.)} \pm 7 \text{ (syst.)} \pm 3 \text{ (theory) fb}$$

(~0.75σ)

Signal acc. x eff.

Process	$300 < p_T^H < 450$ GeV	$450 < p_T^H < 650$ GeV	$p_T^H > 650$ GeV
All	1.4×10^{-2}	0.25	0.33
ggF	0.7×10^{-2}	0.26	0.37
VH	1.8×10^{-2}	0.28	0.31
VBF	0.2×10^{-2}	0.14	0.18
$t\bar{t}H$	4.9×10^{-2}	0.20	0.25

95% CLs limits

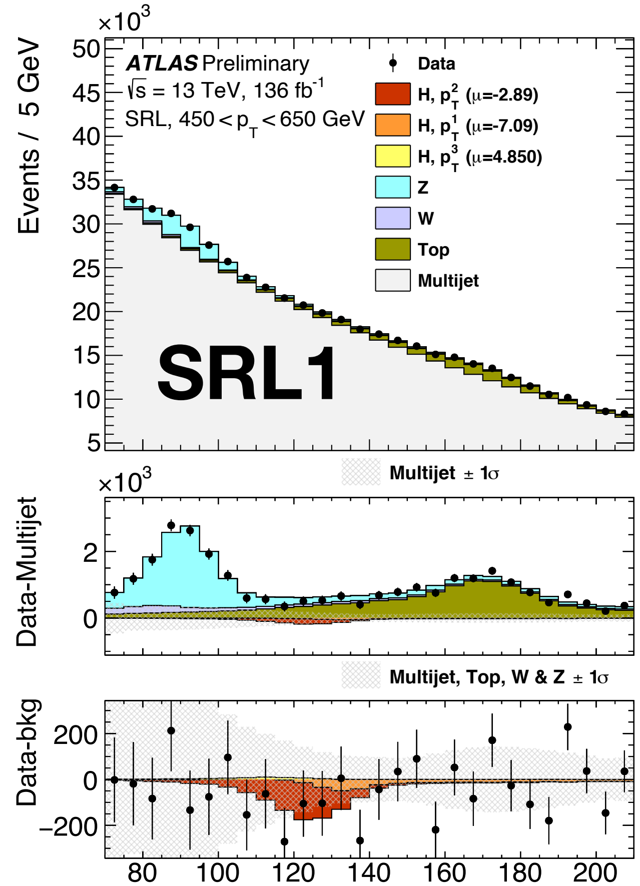
$$\sigma_H(300 < p_T^H < 450 \text{ GeV}) < 2.8 \text{ pb}$$ **(~30x SM)**

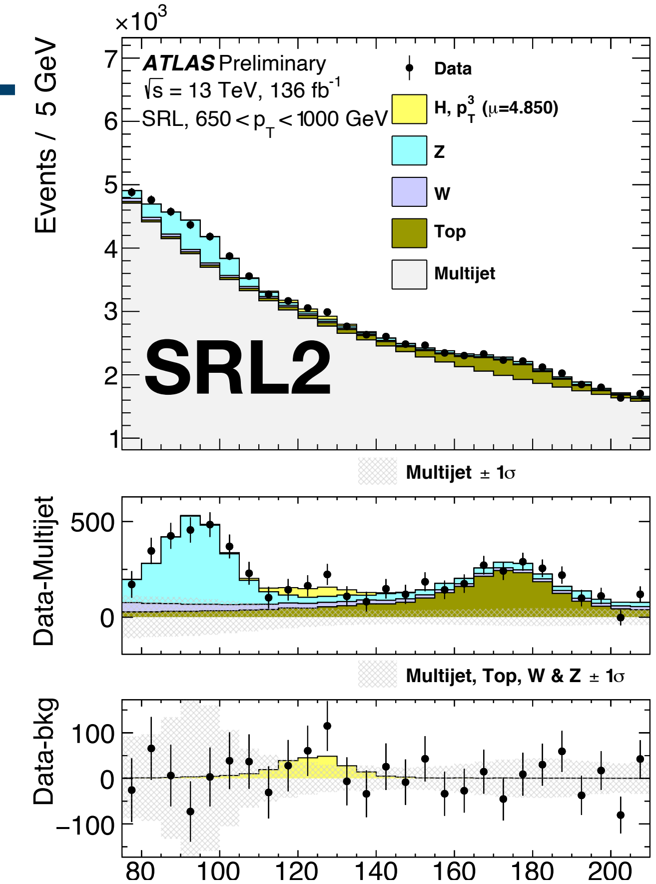
$$\sigma_H(450 < p_T^H < 650 \text{ GeV}) < 91 \text{ fb}$$ **(~5.8x SM)**

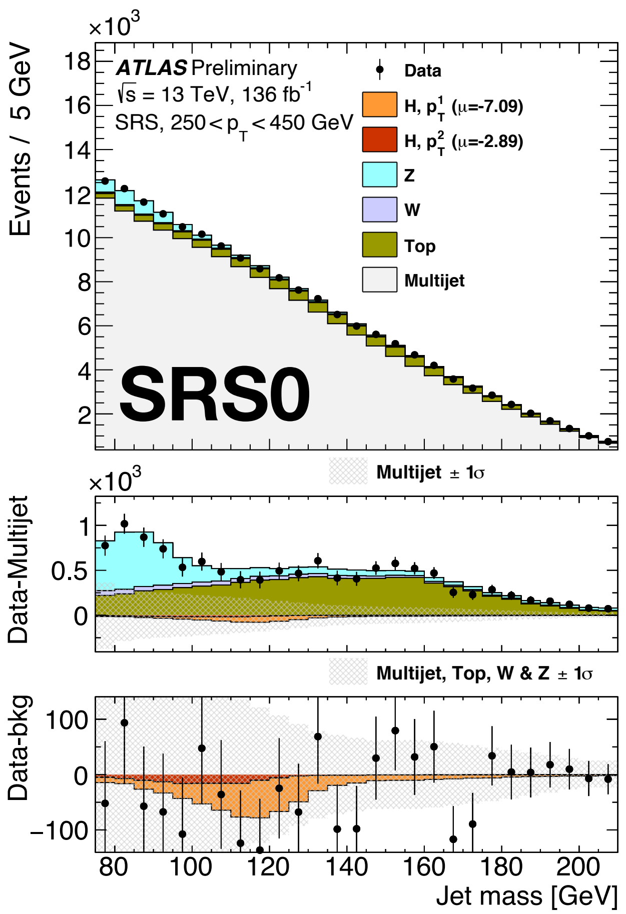
$$\sigma_H(p_T^H > 650 \text{ GeV}) < 40.5 \text{ fb}$$ **(~15x SM)**

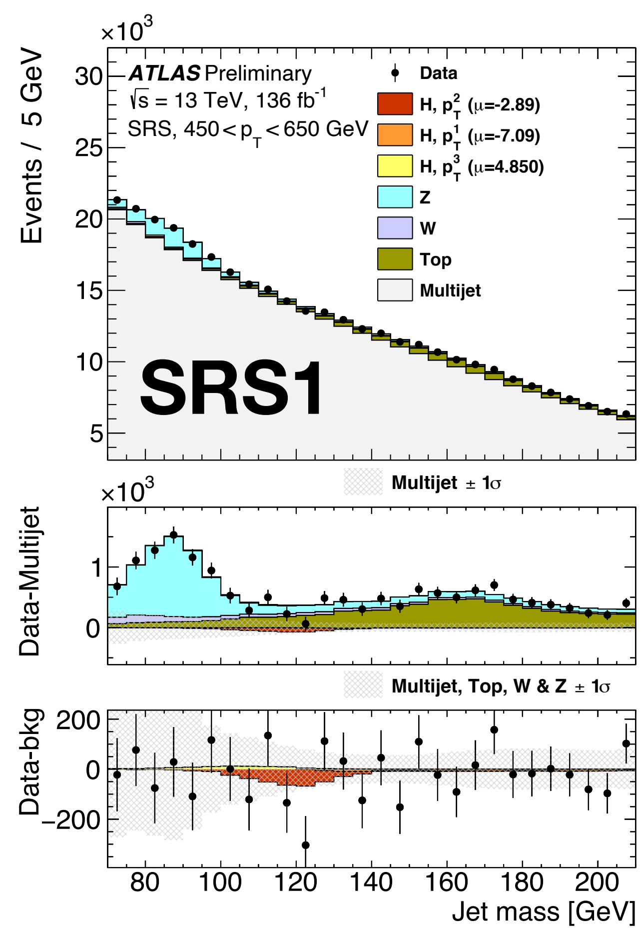
Exp. sensitivity ↑ Exp. enhancement ↓

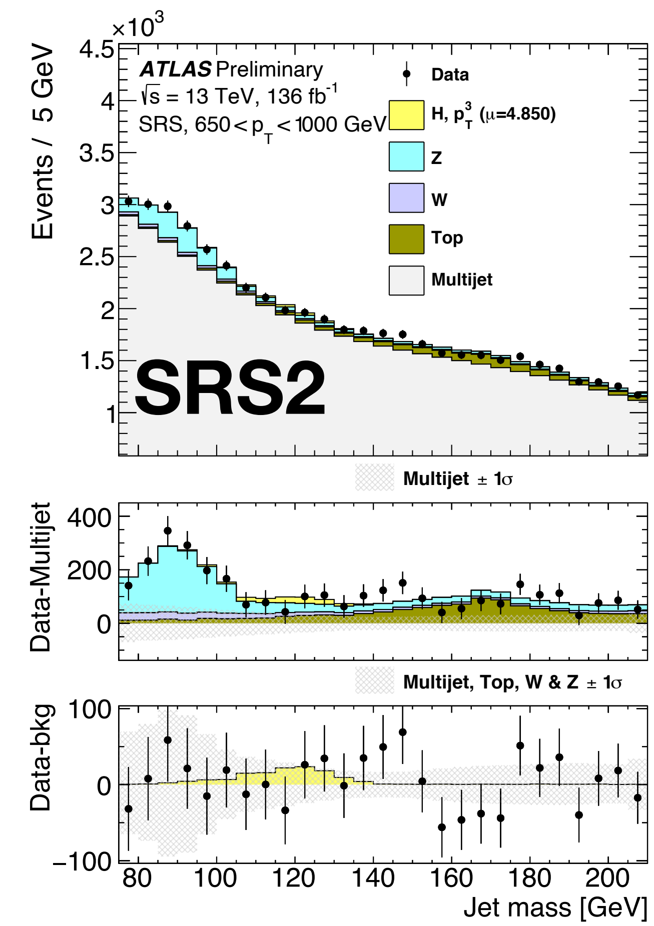
H->bb Differential - Post-Fit Plots





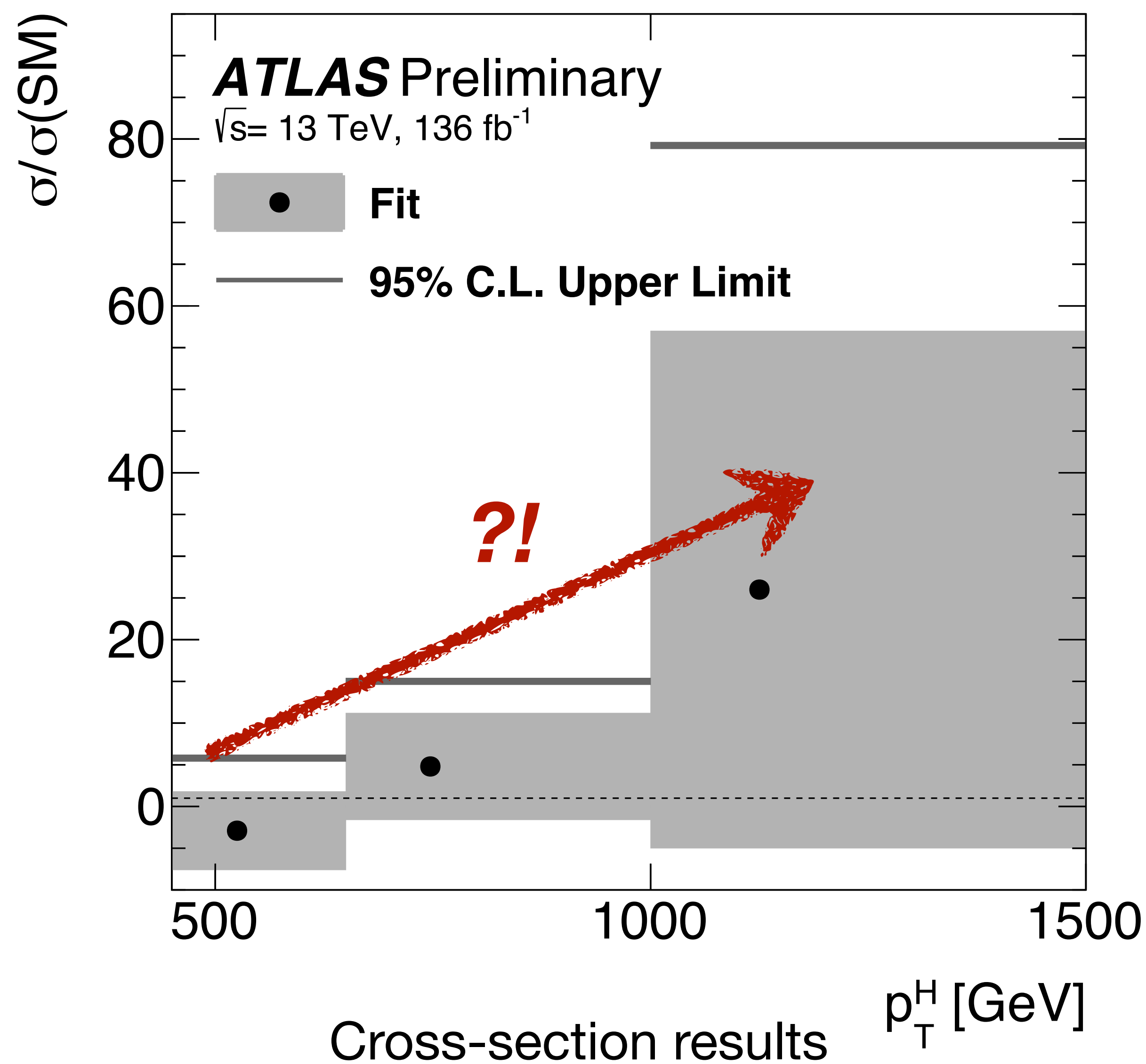






Overview, Conclusions & Plans

- First ATLAS studies of **Higgs** boson produced at very **high p_T** with ***H->bb***
- Cross-section extracted in multiple regions of increasing p_T^H
  - Within same kinematic ranges ***Z->bb*** **production rates agree with SM**
- First attempt to access **Higgs production at p_T^H > 1 TeV**
- Several ideas to **improve sensitivity and understanding of boosted Higgs production**
  - **Mode categorization** based on recoil jet (vs. *VH* and *ttH*)
  - **Classifier(s)** to reduce QCD Multijet background



Cross-section results

$$\sigma_H(p_T^H > 450\ \text{GeV}) = 13 \pm 57\ (\text{stat.}) \pm 22\ (\text{syst.}) \pm 3\ (\text{theory})\ \text{fb}$$
$$\sigma_H(p_T^H > 650\ \text{GeV}) = 13 \pm 16\ (\text{stat.}) \pm 7\ (\text{syst.}) \pm 3\ (\text{theory})\ \text{fb}$$
$$\sigma_H(p_T^H > 1\ \text{TeV}) = 3.4 \pm 3.9\ (\text{stat.}) \pm 1.0\ (\text{syst.}) \pm 0.8\ (\text{theory})\ \text{fb}$$

BACKUP

Higgs-Signal Description & Composition

- Assume **state-of-the-art predictions for Higgs boosted production** (LHCXSWG)
  - Expected cross sections **@NLO in QCD**, *ggF* includes finite top mass effects
- p_T^H-dependent **NLO EW corrections** applied to *VBF, VH & ttH*
  - EW corrections not known for *ggF*
- Our **phase space** is, in fact, **fully inclusive in Higgs production modes**
- **Acceptance varies with p_T**, reflecting changes in hierarchy of production modes
  - *ttH* acceptance favored at low p_T, where two massive top quarks trigger
  - **No attempt to disentangle modes**

Fractional contribution of each prod mode to SRs within [105,140] GeV

Process	p_T Range [GeV] 250–450	450–650	650–1000	> 1000
SRL				
ggF	–	0.56	0.50	0.39
VBF	–	0.17	0.16	0.17
VH	–	0.14	0.18	0.25
$t\bar{t}H$	–	0.13	0.16	0.19
SRS				
ggF	0.28	0.46	0.43	–
VBF	0.07	0.19	0.21	–
VH	0.26	0.24	0.26	–
$t\bar{t}H$	0.39	0.11	0.10	–

LHCXSWG

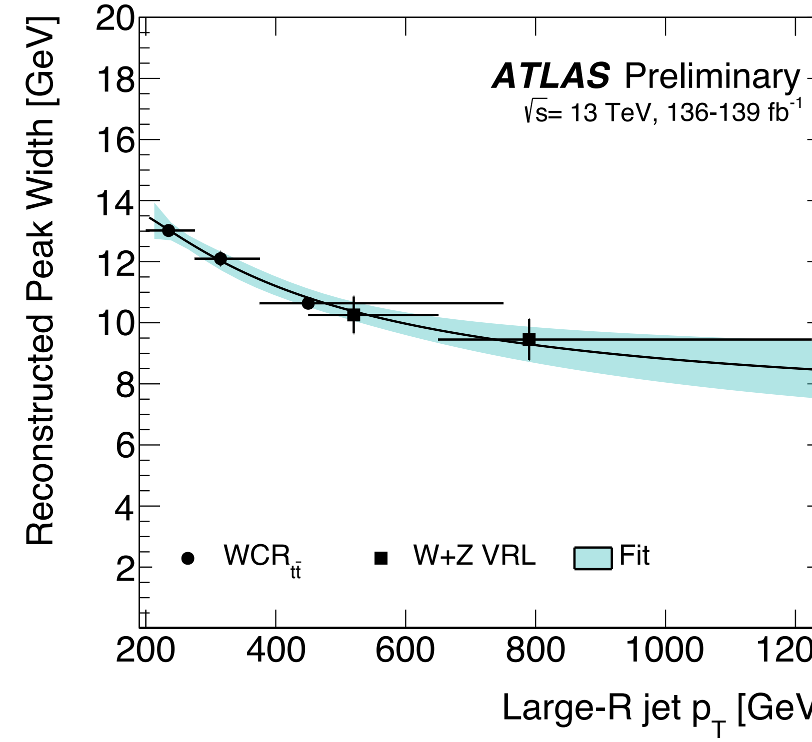
p_T^{cut} [GeV]	ggF [fb]	VBF [fb]	VH [fb]	ttH [fb]
400	$32.30^{+10.89\%}_{-12.91\%}$	$14.23^{+0.15\%}_{-0.19\%}$	$11.16^{+4.12\%}_{-3.68\%}$	$6.89^{+12.62\%}_{-12.97\%}$
450	$18.08^{+10.78}_{-12.79}$	$8.06^{+0.24}_{-0.23}$	$6.87^{+4.6}_{-3.49}$	$4.24^{+12.84}_{-13.15}$
500	$10.17^{+10.67}_{-12.74}$	$4.75^{+0.33}_{-0.29}$	$4.39^{+4.43}_{-4.04}$	$2.66^{+12.85}_{-13.22}$
550	$5.87^{+10.54}_{-12.60}$	$2.90^{+0.34}_{-0.36}$	$2.87^{+4.44}_{-3.74}$	$1.76^{+14.23}_{-13.93}$
600	$3.48^{+10.35}_{-12.49}$	$1.82^{+0.41}_{-0.39}$	$1.91^{+5.22}_{-4.71}$	$1.11^{+12.99}_{-13.4}$
650	$2.13^{+10.23}_{-12.45}$	$1.17^{+0.49}_{-0.39}$	$1.30^{+4.67}_{-4.28}$	$0.72^{+12.6}_{-13.26}$
700	$1.32^{+10.03}_{-12.32}$	$0.77^{+0.57}_{-0.45}$	$0.90^{+4.15}_{-5.4}$	$0.47^{+11.42}_{-12.74}$
750	$0.84^{+10.05}_{-12.31}$	$0.51^{+0.69}_{-0.56}$	$0.62^{+5.15}_{-4.66}$	$0.32^{+11.53}_{-12.84}$
800	$0.54^{+9.91}_{-12.24}$	$0.35^{+0.71}_{-0.6}$	$0.44^{+5.64}_{-4.13}$	$0.22^{+11.42}_{-13.3}$

V+j Modelling & Mass Resolution (JMR) vs. p_T

Interaction between V+j template & QCD flexible model makes it impossible to simultaneously extract V+j width and normalization -> extraction of dedicated W/Z Jet Mass Resolution constraints in dedicated regions

JMR constraints obtained from Sherpa JMR fit results via folding with SR p_T Spectrum

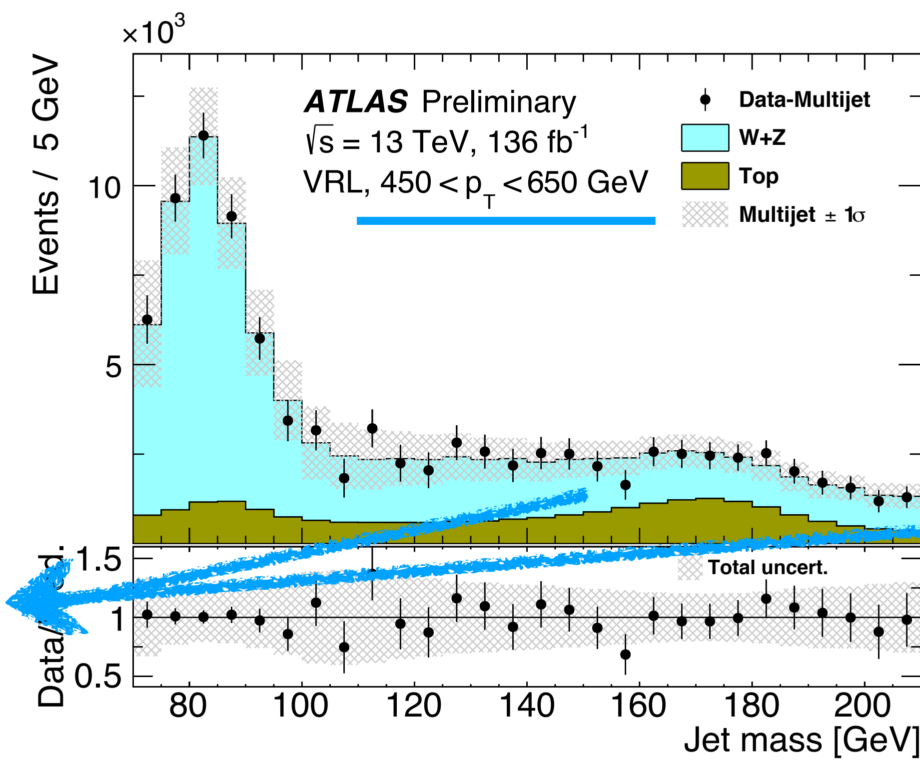
Region	Average p_T [GeV]	Fit value	p_T-Folded	μ_{ext}	σ_{ext}
Inclusive SRL	562	0.051 ± 0.108	0.056 ± 0.122	0.056	0.158
SRL1	520	0.070 ± 0.104	0.071 ± 0.107	0.071	0.146
SRL2	775	-0.014 ± 0.185	-0.018 ± 0.198	-0.018	0.222
Inclusive SRS	516	0.070 ± 0.104	0.074 ± 0.116	0.074	0.153
SRS0	381	0.127 ± 0.105	0.127 ± 0.100	0.127	0.141
SRS1	520	0.070 ± 0.104	0.071 ± 0.107	0.071	0.146
SRS2	775	-0.014 ± 0.185	-0.018 ± 0.198	-0.018	0.212

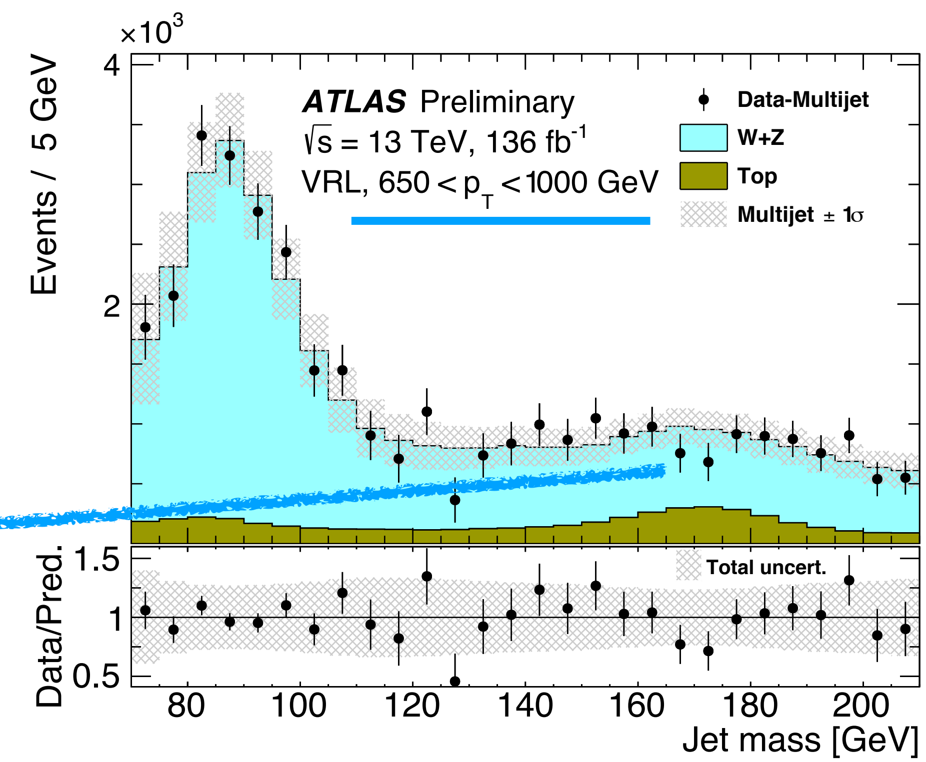


Additional **±0.10 syst** uncertainty for **transfer from V->qq to Z->bb**

Good description of V+jets mass distributions in VRL

Tails from recoiling (QCD-like) jet in V+jets, higher acceptance with anti-b-tags

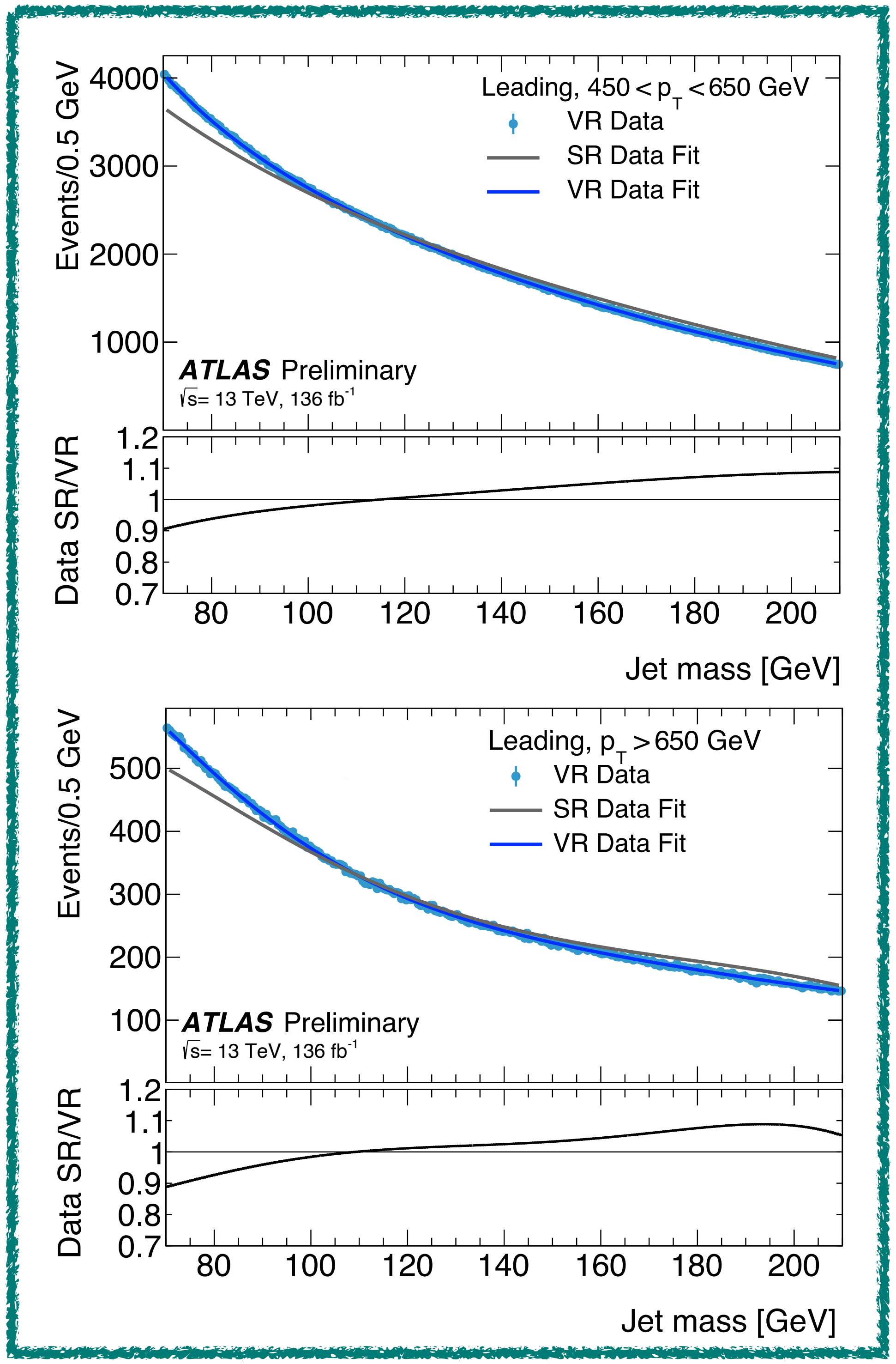




QCD Multijet Background Modeling

$$\mathrm{VR}^i_{\mathrm{hyb}} = (\mathrm{VR}^i - V_{\mathrm{VR}} - t\bar{t}_{\mathrm{VR}}) \times \left(\frac{\mathrm{MJ}_{\mathrm{SR}}}{\mathrm{MJ}_{\mathrm{VR}}}\right) + V_{\mathrm{SR}} + t\bar{t}_{\mathrm{SR}} + H_{\mathrm{SR}}$$

- **Hybrid VR as best available proxy for SR**
  - 'Ensemble tests' using modified VR subsets with roughly the same number of events as the corresponding SR
  - VR resonance peaks replaced with the SM prediction from the SR and **correcting the underlying Multijet shape for SR acceptance effects**
- A procedure to choose the **optimal *N*** for each region by means of three metrics: **LLR** test (N vs. N+1), **2σ outliers** & **average μ/σ_{stat}**
- **Spurious signal systematic uncertainty** and ranges from **0.01–0.33 for *H*** & **0.15–0.65 for *Z*** in average μ/σ_{stat} units
- Minor impact on the sensitivity



Statistical Analysis (Details)

- Signal yields extracted minimising NLL with RooStats
  - Fits performed to **full large-R jet mass range** [70/5,210] GeV & with **5-GeV bin width** (RooFit developments to fix NLL bias)
  - **Limits** on the Higgs production rate derived using the **CL_s** method
- ***H/Z->bb* STXS: *H/Z*+j** contribution binned in **truth-p_T bins**: [300,450], [450,650], [650,inf] GeV , [0,300] GeV fixed to SM
- **Systematic** uncertainties included as **constrained** parameters; **normalisation of MC** templates within each reco-pT region or fiducial volume & **QCD parameters floating**
  - ***W*+j contribution fixed to SM** prediction within uncertainties (+/-10% Gaussian prior)
- Table: systematic variations included in fits

Description	Processes	Category	Effect
Experimental Systematic Uncertainties			
JMR	$t\bar{t}$, V+jets, H	p_T bins	N+S
JMS (dominant)	$t\bar{t}$, V+jets, H	p_T bins	N+S
JMS (rest)	$t\bar{t}$, V+jets +H	all	N+S
Jet energy scale	all$^{(*)}$	all	N+S
Jet energy resolution	all	all	N+S
b-tag efficiency b-jets	all	all	N+S
b-tag efficiency c-jets	all	all	N+S
b-tag efficiency l-jets	all	all	N+S
Modeling Systematic Uncertainties			
Cross-section and acceptance	W+jets	all	N
Renormalization and factorization scale	V+jets	all	N+S
Parton shower model	$t\bar{t}$	all	N+S
Matrix element calculation	$t\bar{t}$	all	N+S
Initial-/Final-state radiation	$t\bar{t}$	all	N+S
Acceptance	H	all	N
NLO EW corrections	VBF+VH+$t\bar{t}H$	all	N
	V+jets	all	N
Spurious signal	H	p_T^H bins $\times$ LS	N
	Z + jets $^{(\bullet)}$	p_T^Z bins $\times$ LS	N

V+j NNLO QCD k-Factors

- Sherpa 2.2.8 V+j is generated @NLO in QCD, on-the-fly NLO EW corrections applied
- NNLOJET calculations, @NNLO in QCD, limited to 8 TeV
- Help from Alexander Huss & the NNLOJET group to get **NNLO QCD k-factors in our fiducial region**
  - NNLO k-factor computed for the **three kinematical bins** of the analysis
  - **p_T-averaged** k-factors, rather **flat**

p_T^Z Range [GeV]	NNLO k-factor	stat	scale unc.
250-450	1.013	±0.0016	$^{+0.23}_{-0.27}$
450-650	1.076	±0.0011	$^{+0.06}_{-0.07}$
650-3000	1.081	±0.0010	$^{+0.07}_{-0.08}$

NNLOJET results sampled with the p_T spectrum for each analysis region

Region	$< p_T >$	$<$ NNLOk – factor $>$
SRL [450-3000]	562	1.071
SRL [450-650]	520	1.069
SRL [650-3000]	775	1.084
SRS [250-3000]	516	1.068
SRS [250-450]	381	1.059
SRS [450-450]	520	1.069
SRS [650-3000]	775	1.083