Searches for boosted low mass resonances decaying to b-quarks with the ATLAS detector

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Higgs Couplings
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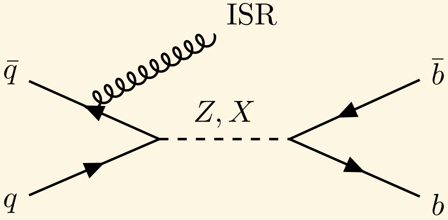
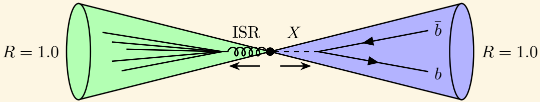
Introduction: Exotics search

Search for low-mass resonances in 2015 - 2017 data

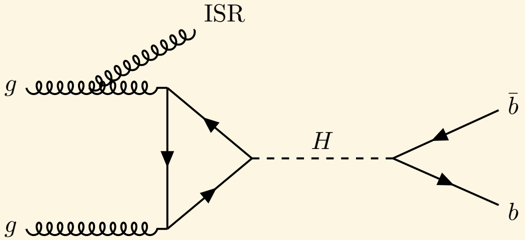
- Search for dark matter (DM) mediator, X, with $100\ \mathrm{GeV} < m_X < 200\ \mathrm{GeV}$ [CERN-PH-TH-2015-139] through boosted decays to $b\bar{b}$ + ISR jet
  - Complements other low-mass DM mediator dijet searches [ATLAS-CONF-2016-070]
- More sensitive to new mediators with Higgs-like couplings through preferential decays $X \to b\bar{b}$ ($g \propto m$)
  - QCD background suppression improves sensitivity
  - Benchmark leptophobic Z' model considered has democratic couplings
- Measuring the Z validates our results
- Analysis signature: Two large-R jets, 1 boosted and double b-tagged

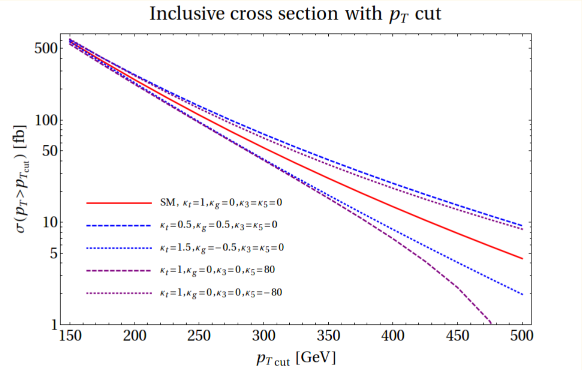




Introduction: Boosted Higgs

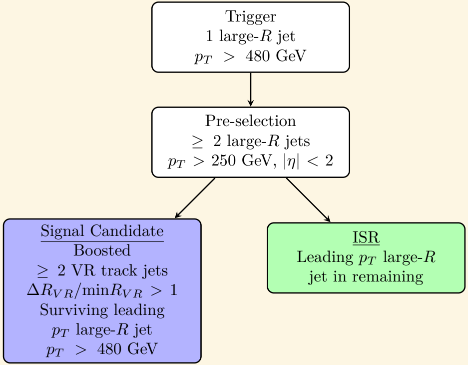
- Search for boosted $H \to b\bar{b}$
  - Production is dominated by gluon-gluon fusion ($\sigma_{p_T > 400\ \mathrm{GeV}} = 29$ fb)
  - High-p_T production cross-section could be enhanced by couplings to new heavy resonances running in the ggF loop [Eur.Phys.J. C74 (2014) no.10, 3120]
  - Review from earlier: Jonas Lindert, Higgs Couplings 2018

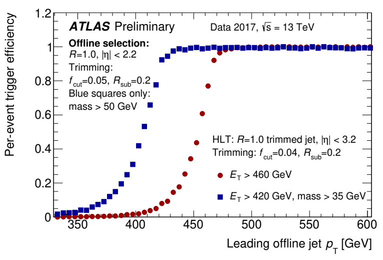




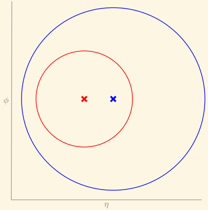
BSM model with sizeable deviations from SM cross-section in high p_T tail [Phys.Rev. D91 (2015) 074012]

Event Selection





Trimming $(\mathrm{f_{cut}} = 0.05, R_{\mathrm{sub}=0.2})$ suppresses gluon radiation and pile-up

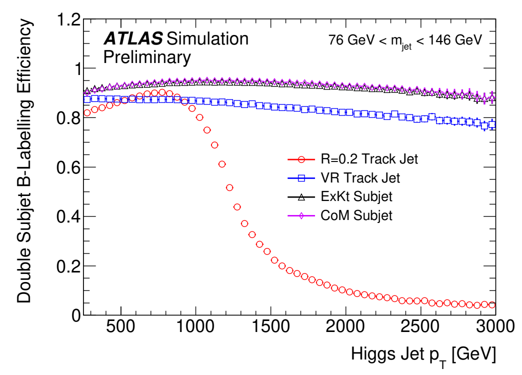


$(\Delta R_{\mathrm{lead,sub}}/R_{\mathrm{lead}}) < 1$ implies both VR jet axes are inside both VR cones. Typical of $g \to b\bar{b}$ splitting.

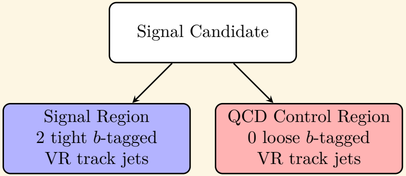
Event Classification

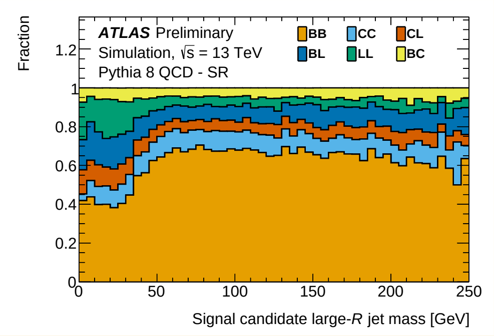
***b*-tagging operating points for `MV2c10`**
(corresponding to fixed efficiencies for *b*-quarks in $t\bar{t}$ events)

- **Loose**: *b*-tagging cut at 85% efficient operating point
- **Tight**: *b*-tagging cut at 77% efficient operating point



VR track jets give flat high $H \to b\bar{b}$ tagging efficiency [ATL-PHYS-PUB-2017-010]





Light-flavour component of dijet background in Signal Region small after tagging

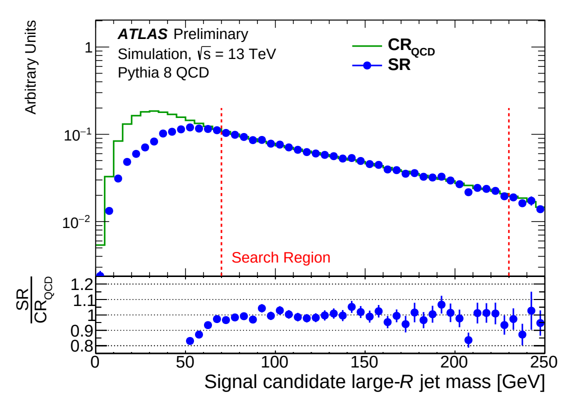
Modeling the multijet background

- Multijet background modeled with exponential polynomial with 5 parameters of form

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

$$x = \frac{m_J - 150\ \mathrm{GeV}}{80\ \mathrm{GeV}}$$

- parameterization maps fit range of $m_J \in [70, 230]\ \mathrm{GeV}$ to $x \in [-1, 1]$
- Model unbiased and not susceptible to fitting statistical fluctuations in data (signal injection and spurious signal tests done in $\mathrm{CR_{QCD}}$)



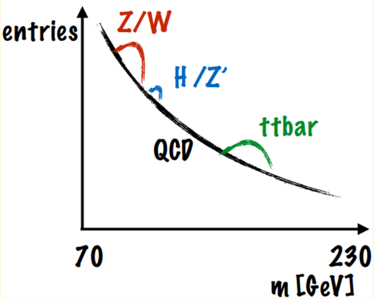
Multijet shapes in Signal Region and QCD Control Region very similar

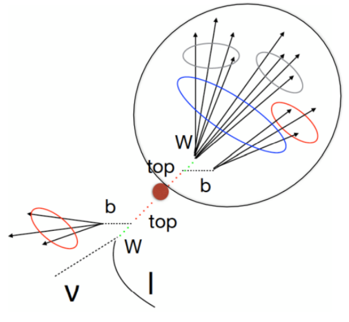
Modeling the resonant backgrounds: V+jets, $t\bar{t}$

- V+jets modeled with Monte Carlo templates
- $t\bar{t}$ modeled with Monte Carlo template but constrained
  - Fit template to $t\bar{t}$ Control Region
  - Resulting k-factor defines Gaussian prior in Signal Region

Opposite hemisphere

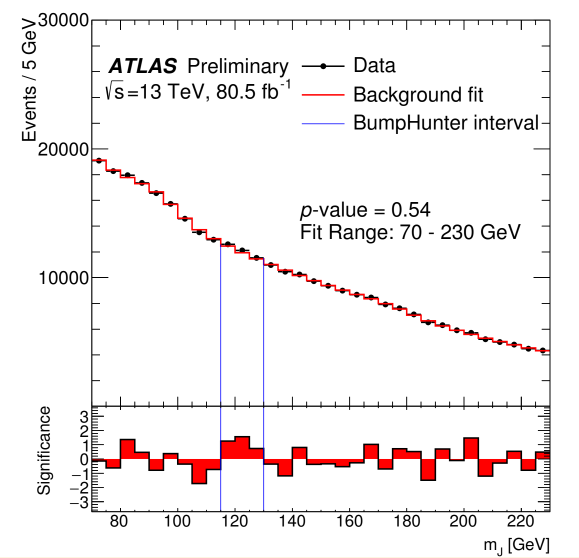
μ only semi-leptonic $t\bar{t}$ → Signal jet: exactly 1 tight b-tag → muon: $p_T > 40$ GeV, $\Delta\phi\,(\mu, \text{signal}) > 2/3\pi$ → large-R jet: 1 loose b-tagged VR track jet





BumpHunter Search for new Physics

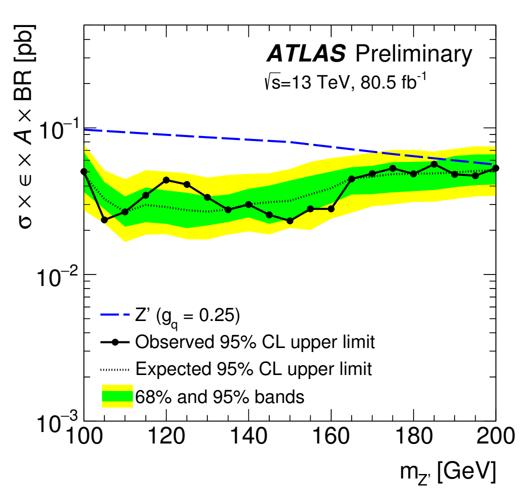
- Perform fit with model of QCD, $V + jets$, $t\bar{t}$ to $80.5\ \mathrm{fb}^{-1}$ of data with systematic uncertainties and extract best fit values for the nuisance parameters
  - Higgs template neglected as at $\mu_H = 1$ is smaller than uncertainties
- With postfit shapes perform BumpHunter scan [PHYSTAT2011, arXiv:1101.0390]
  - BumpHunter: fit in varying width window to find region of data most discrepant with model and calculates global p-value (accounts for "look elsewhere effect")
- Observe no significant excess in data
  - Most significant deviation between data and model is interval of $[115, 130]$ GeV (good sign for our Higgs search)
  - Though BumpHunter global p-value $= 0.54$ (model is quite consistent with data)



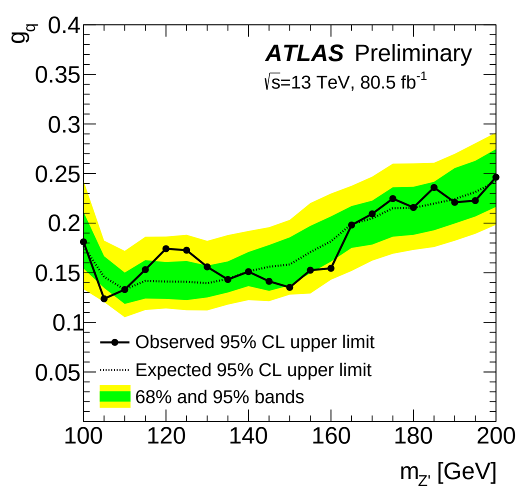
Set Limits on Z' couplings to Standard Model quarks

Exclude Z' with $g_q = 0.25$ for $m_{Z'} < 200$ GeV at the 95% CL

$$\sigma\left(pp \to Z' \to q\bar{q}\right) \propto g_q^2$$



95% CL upper limits on $\sigma \times \epsilon \times A \times BR$ from the Z' invariant mass

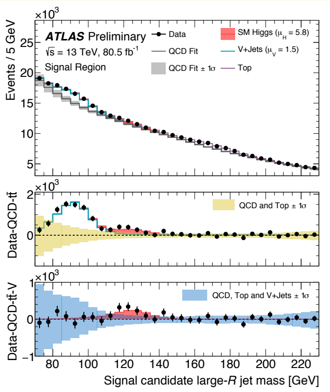


95% CL upper limits on g_q from the Z' invariant mass

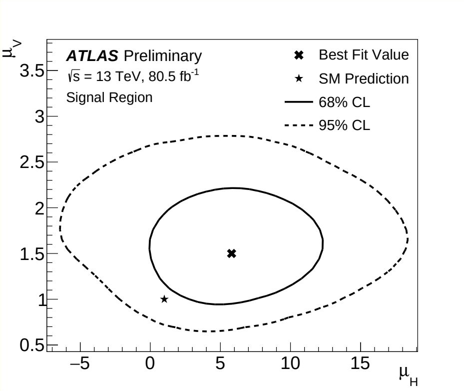
Boosted Higgs Search

Model fit with Bayesian Analysis Toolkit results in $\mu_V = 1.5 \pm 0.22\,(\text{stat.})^{+0.29}_{-0.25}\,(\text{syst.}) \pm 0.18\,(\text{th.})$ and $\mu_H = 5.8 \pm 3.1\,(\text{stat.}) \pm 1.9\,(\text{syst.}) \pm 0.17\,(\text{th.})$

- μ_V consistent with Standard Model expectation given uncertainties. Significance: 5σ (Expected: 4.8σ) (Methodology validated!)
- μ_H consistent with background-only hypothesis given uncertainties at 1.6σ (Expected: 0.28σ) (A nice hint to improve on!)



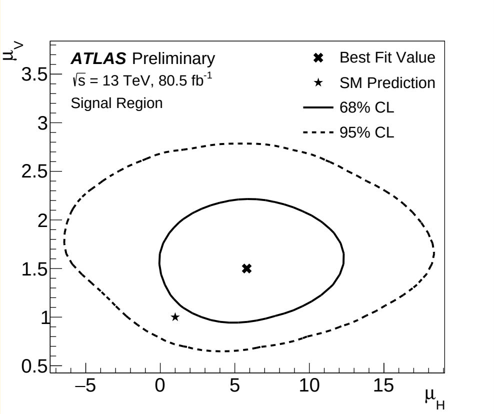
Fit of model comprised of QCD, $V+$ jets, $t\bar{t}$, and SM Higgs to 80.5 fb^{-1} of data

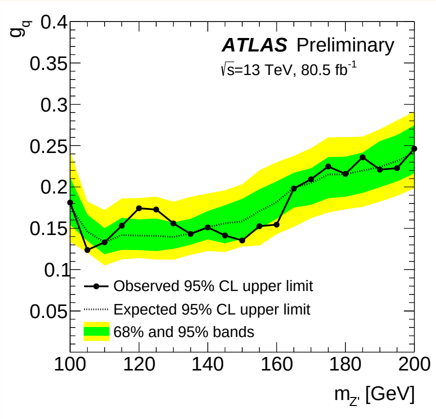


Best fit contours for observed Higgs signal strength and $V+$jets signal strength

Summary

- First ATLAS search for boosted $X \to b\bar{b}$ with an ISR jet in 80.5 fb^{-1} of data [ATLAS-CONF-2018-052] (Looking forward to **full Run2 dataset**!)
- **Dark Matter mediator search:** Exclude leptophobic Z' with $g_q = 0.25$ for $m_{Z'} < 200$ GeV at 95% CL
- $V+$ **jets:** 5σ observation with $\mu_V = 1.5 \pm 0.22\,(\text{stat.})^{+0.29}_{-0.25}\,(\text{syst.}) \pm 0.18\,(\text{th.})$ (Methodology validated!)
- **Boosted Higgs:** $\mu_H = 5.8 \pm 3.1\,(\text{stat.}) \pm 1.9\,(\text{syst.}) \pm 0.17\,(\text{th.})$ (Look forward to **analysis improvements**!)





Backup

Event Selection

Trigger

- Leading large-R jet with $p_T > 480$ GeV (inclusive for 2015/16/17)

Analysis ntuples

- EXOT8 derivation: at least 2 large-R jets with $p_T > 200$ GeV

Pre-selection on large-R jets (calibrated jet cut [ATLAS-CONF-2016-035])

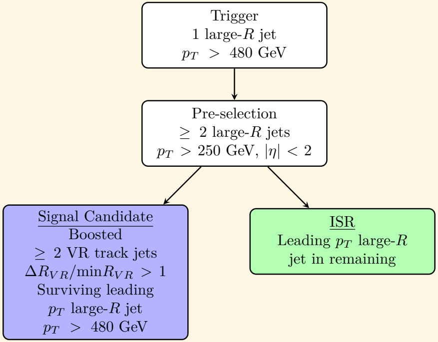
- At least 2 large-R jets with $p_T > 250$ GeV and $|\eta| < 2$

Selection for the signal candidate jet

- Boosted: $(2m_J/p_T) < 1$
- At least 2 VR track jets with $p_T > 10$ GeV
- VR jets must not be collinear: $\frac{\Delta R\,(\text{lead VR, sub-lead VR})}{R\,(\text{lead VR})} > 1$
  - $(\Delta R_{\text{lead,sub}}/R_{\text{lead}}) < 1$ implies both VR jet axes are inside both VR cones
- Remaining leading p_T large-R jet selected as the signal candidate
- Further require large-R jet $p_T > 480$ GeV to ensure a smooth p_T distribution and $m_J > 40$ GeV to be above m_J turn-on curve

Selection for the ISR jet

- Leading p_T jet in the pre-selected jets that is not the signal candidate



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- **Loose**: b-tagging cut at 85% efficient operating point
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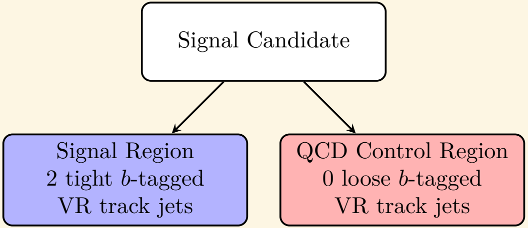
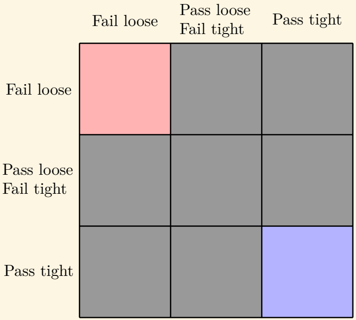
Signal Region (2-tag tight)

- Signal candidate jet has tight b-tagged leading and subleading p_T VR track jets

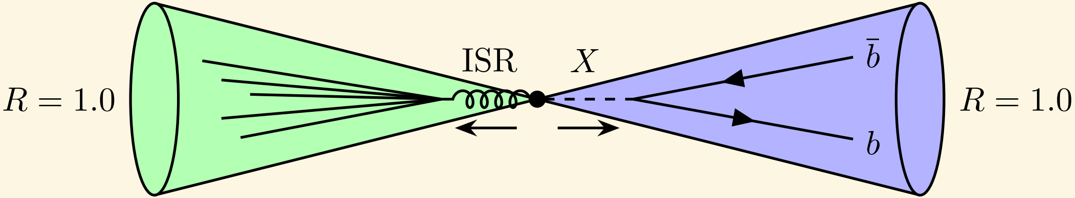
QCD Control Region (0-tag)

- Signal candidate jet has exactly 0 loose b-tagged VR track jets





Why is the ISR jet a large-R jet?



- Reduces issues with overlap removal
- Helps with $g \to b\bar{b}$ splitting
- Large-R jet triggers and resolved jet triggers have similar rate

VR Track Jets [JHEP 06 (2009) 059]

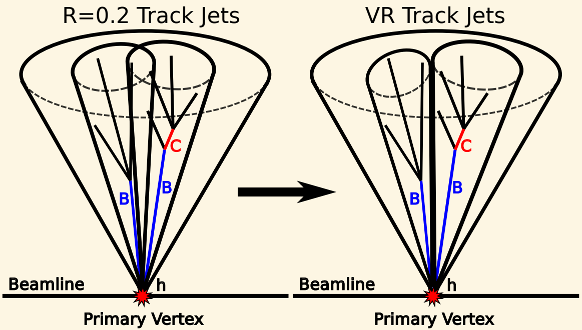
- Algorithm modifies the conventional iterative recombination algorithm by making the radius parameter a function of the jet p_T as

$$R \to R_{\mathrm{eff}}\left(p_T\right) = \frac{\rho}{p_T}$$

- Dimensionful constant ρ determines how fast the effective jet size decreases with the transverse momentum of the jet
  - $\rho \propto m_{\mathrm{resonance}}$ and should correctly reproduce the size of jets as long as $\rho \lesssim 2p_T$
- Additional parameters, R_{min} and R_{max}, to impose lower and upper cut-offs on the jet size

$$R_{\mathrm{eff}}\left(p_T\right) = \max\left[\min\left(\frac{\rho}{p_T}, R_{\mathrm{max}}\right), R_{\mathrm{min}}\right]$$

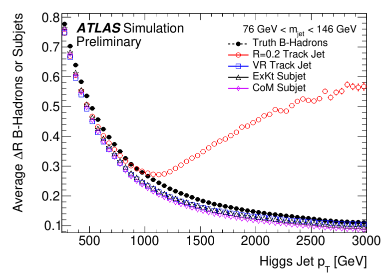
- This analysis [ATLAS-CONF-2018-052] uses $\rho = 30\ \mathrm{GeV},\ R_{\mathrm{min}} = 0.02,\ R_{\mathrm{max}} = 0.4$



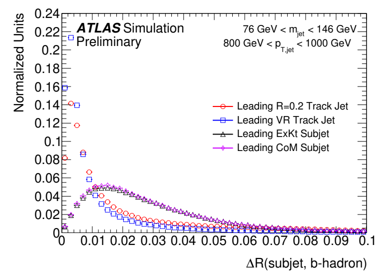
Subjet reconstruction using variable radius track jets [ATL-PHYS-PUB-2017-010]

$X \to b\bar{b}$ tagging with VR track jets [ATL-PHYS-PUB-2017-010]

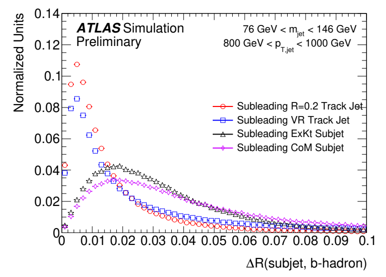
VR track jets accurately describe the topology of $H \to b\bar{b}$ events



The ΔR between the two leading truth b-hadrons or subjets associated to Higgs jets as a function of Higgs jet p_T. The error bars include statistical uncertainties only.



Distributions of the ΔR between leading subjets and matched truth b-hadrons for Higgs jet p_T between $[80, 200]$ GeV. The error bars include statistical uncertainties only.



Distributions of the ΔR between subleading subjets and matched truth b-hadrons for Higgs jet p_T between $[80, 200]$ GeV. The error bars include statistical uncertainties only.

Higgs production cross-section at high p_T

- Use HJ-MiNLO generator approach [JHEP 1505 (2015) 140] that agrees very well with fixed order given uncertainties for $p_T^{\text{cut}} = 400$ GeV
  - Inclusive cross-section of $29^{+24\%}_{-21\%}$ fb for matrix-element level Higgs bosons with $p_T > 400$ GeV
- Higgs + 1 jet implemented with finite top-mass correction
- NLO done with MiNLO [JHEP 1305 (2013) 082]

Monte-Carlo generators vs. Fixed Order [B. Mistlberger, 14th Workshop of LHCHXSWG]

p_T^{cut}	$\text{NNLO}^{\text{approximate}}_{\text{quad.unc.}}$ [fb]	HJ-MiNLO [fb]	MG5_MC@NNLO [fb]
400 GeV	$35.3^{+4.2\%}_{-9\%}$	$29^{+24\%}_{-21\%}$	$31.5^{+31\%}_{-25\%}$
430 GeV	$24.3^{+4\%}_{-8.9\%}$	-	$21.8^{+31\%}_{-25\%}$
450 GeV	$19.1^{+4\%}_{-8.9\%}$	$16.1^{+22\%}_{-21\%}$	$17.1^{+31\%}_{-25\%}$

cross-checked our samples against these values

Systematic Uncertainties

		Impact on Signals ($\sqrt{\Delta\sigma^2}/\mu$)			
Source	Type	V+jets	Higgs	Z' (100 GeV)	Z' (175 GeV)
Jet energy and mass scale	Norm. & Shape	15%	14%	23%	18%
Jet mass resolution	Norm. & Shape	20%	17%	30%	20%
$V + \text{jets}$ modeling	Shape	9%	4%	4%	$< 1\%$
$t\bar{t}$ modeling	Shape	$< 1\%$	1%	$< 1\%$	11%
b-tagging (b)	Normalisation	11%	12%	11%	15%
b-tagging (c)	Normalisation	3%	1%	3%	5%
b-tagging (l)	Normalisation	4%	1%	4%	7%
$t\bar{t}$ scale factor	Normalisation	2%	3%	2%	58%
Luminosity	Normalisation	2%	2%	2%	3%
Alternative QCD function	Norm. & Shape	4%	4%	3%	17%
W/Z and QCD (Theory)	Normalisation	14%	–	–	–
Higgs (Theory)	Normalisation	–	30%	–	–

Summary of the impact of the main systematic uncertainties on the uncertainty σ on the measurement of the signal strength μ for the $V + \text{jets}$, Higgs boson and Z' signals.

Limits: $\sigma \times \epsilon \times A \times BR$ vs. g_q

As

$$\sigma\left(pp \to Z' \to q\bar{q}\right) \propto g_q^2$$

and signal events simulated with $g_q = 0.25$, then for a limit of σ set a corresponding limit of

$$g_q = 0.25\sqrt{\frac{\sigma}{\sigma_{g_q=0.25}}}$$