ATLAS: Beyond Standard Model Jet Searches

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On behalf of the ATLAS Collaboration

JVMO Workshop
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Jet vetoes & multiplicity observables are crucial for many BSM searches with ATLAS

$\rightarrow$ Only a small selection of analyses will be highlighted here!

Analyses:

- **Dijet Angular**:

  15.7 fb^{-1}, $\sqrt{s} = 13$ TeV ATLAS-CONF-2016-069

- **ISR + Dijet**:

  15.5 fb^{-1}, $\sqrt{s} = 13$ TeV ATLAS-CONF-2016-070

- **Multi-jet**:

  3.6 fb^{-1}, $\sqrt{s} = 13$ TeV JHEP 03 (2016) 026

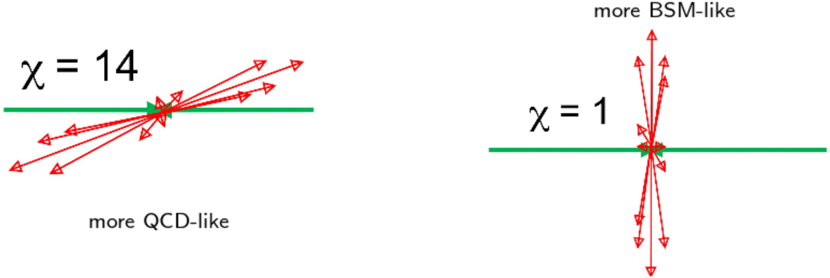
- **Single VLQ $\rightarrow$ Wb**:

  3.2 fb^{-1}, $\sqrt{s} = 13$ TeV ATLAS-CONF-2016-072

  20.3 fb^{-1}, $\sqrt{s} = 8$ TeV Eur. Phys. J. C76 (2016) 442

ATLAS-CONF-2016-069

Look for new non-resonant phenomena (e.g. contact interaction) through variations in dijet angular distribution



QCD dijet production mainly t-channel $\rightarrow$ small angle (forward) scattering

New particle or force $\rightarrow$ more isotropic production

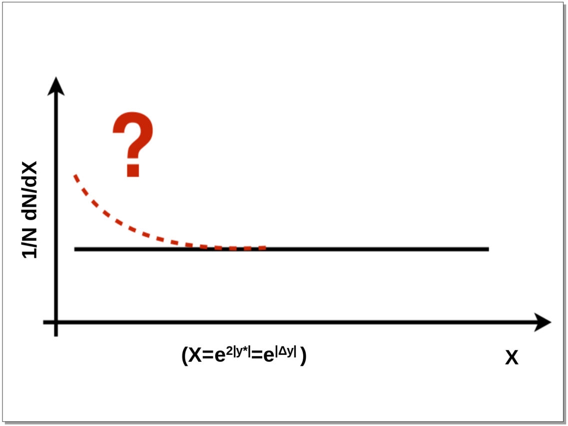
Discriminate using angular variable $\chi = e^{2|y^*|} \sim \frac{1}{1-|cos\theta^*|}$

$y^* = \frac{y_1 - y_2}{2}$, θ^* = polar angle in the dijet COM frame

Search: **Shape analysis (QCD $\sim$ flat)**

$\rightarrow$ Data-MC comparison of χ in different m_{jj} regions

$\rightarrow$ Look for rise at low χ, high m_{jj}

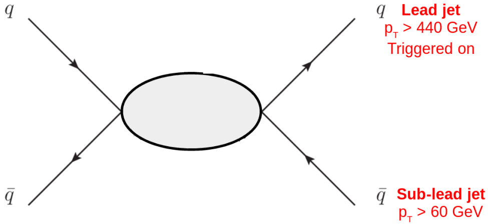


Dijet Angular - Strategy

Dataset: **15.7** fb^{-1}, $\sqrt{s} = 13$ **TeV**

Event Selection: Jets reconstructed using Anti-kT R = 0.4

Compositeness Scale $\Lambda >> \sqrt{s}$



- $m_{12} \geq 2.5$ TeV
- $|y^*_{12}| < 1.7$ (i.e. $\chi < 30$)
- $|y_{B_{12}}| < 1.1$ $\left(y_{B_{12}} = \frac{|y_{j1}+y_{j2}|}{2}\right)$

Bkg estimate: Pythia 8.186 MC, NLO Corrected (QCD and EW):

$\rightarrow$ Mass and χ-dependent correction factors

$\rightarrow$ QCD: Modify shape at level of 15% at low χ high m_{jj}, $\leq$ 5% at high χ

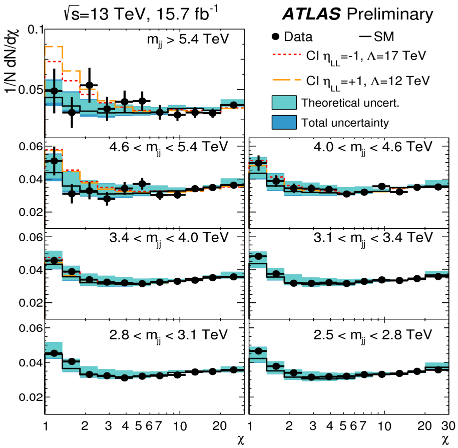
$\rightarrow$ EW: Unity at low m_{jj}, up to 3% in $m_{jj} > 3.4$ TeV region

Normalise to data in each mass bin

Use combined max-likelihood fit across 4 signal regions:
Coarse m_{jj} bins, covering $m_{jj} > 3.4$

$\rightarrow$ Low m_{jj} regions help to constrain nuisance parameters considered in the fit

p-value = 0.07



$\sqrt{8}$ TeV analysis used inclusive mass bin, not combined fit
$\rightarrow$ Combined fit introduces sensitivity to the evolution in m_{jj}

- **Dominant theory uncertainty at high m_{jj}:**

  Choice of renormalisation & factorisation scales (NLOJet++)

  - Scales set to average p_T of two leading jets
  - Vary each independently up & down by factor of 2 (excluding opposite variations)
  - **Uncertainty**: Envelope of variations in the normalised χ distributions
  - **Size**: Rises to 30% at smallest χ values at high m_{jj} values

- **Dominant experimental uncertainty:**

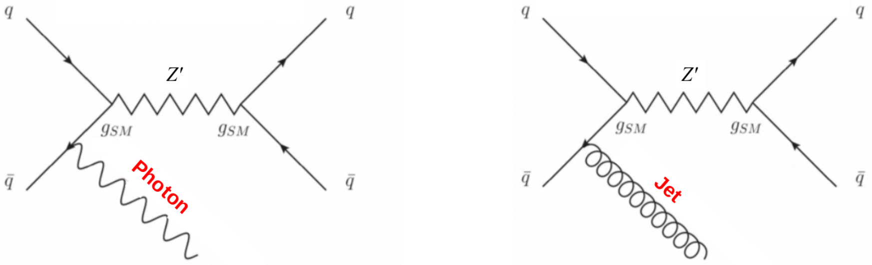
  Jet energy scale uncertainty

  - **Size**: At most 15% at high m_{jj} values

- Uncertainties which affect total cross-section rather than the shape of the χ distributions are very small e.g. PDF uncertainty $< 1\%$

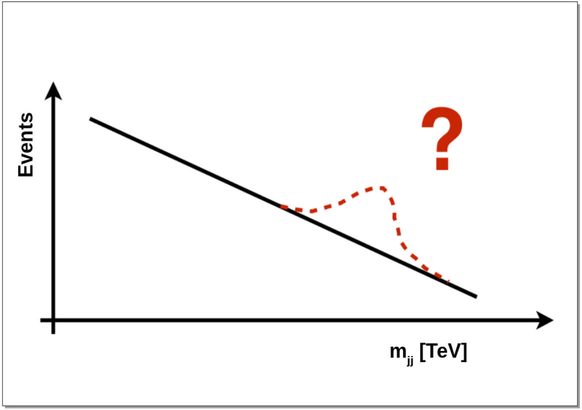
ATLAS-CONF-2016-070

Look for new resonance (e.g. Z') through its decay to quarks + trigger on ISR to reach low masses!



- γ **jet jet**: trigger on ISR photon and construct m_{12} (p_T Ordered)
- **3 jet**: trigger on ISR jet (leading jet) and construct m_{23} (p_T Ordered)

Search: Look for localised excess above smoothly falling bkg!

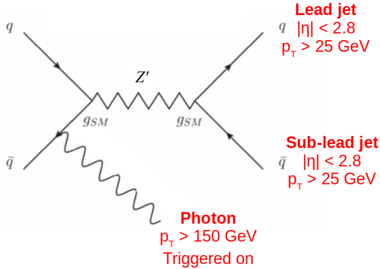


ISR + Dijet - Analysis Strategy

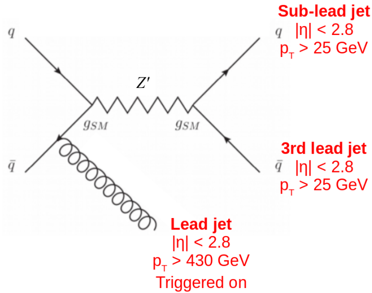
Dataset: **15.5** fb^{-1}, $\sqrt{s} = 13$ **TeV**

Event Selection: Jets reconstructed using Anti-kT R = 0.4 algorithm

γ **jet jet**



3 jet



- $|y^*_{12}| < 0.8$ ($y^*_{12} = \frac{|y_{j1} - y_{j2}|}{2}$)
- $\Delta R_{\gamma,\text{closest j}} > 0.85$

- $|y^*_{23}| < 0.6$ ($y^*_{23} = \frac{|y_{j2} - y_{j3}|}{2}$)

Bkg estimate: Fit m_{jj} with smooth function

- **Fit Range**:

  γ jet jet: 169 GeV - 1493 GeV

  3 jet: 303 GeV - 611 GeV

  Lower bound: To exclude inefficiencies due p_T requirements

  Upper bound: Lower for 3 jet analysis, at high mass ISR jet is not lead

- **Fit Function**: Use Wilk's test to choose between nested functions

  - Fit distributions using set of 3,4,5 parameter functions

$$p_0(1-x)^{p_1} x^{p_2 + p_3 ln x + p_4 ln x^2}, \; x = \frac{m_{jj}}{\sqrt{s}}$$

  - Test statistic: - $2log\,(\Lambda) = -2log\left(\frac{L(H_0|x)}{L(H_1|x)}\right)$ Nominal fit used as H_0

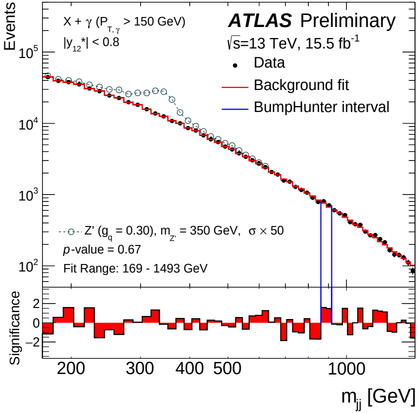
  $\rightarrow$ 3 parameter sufficient for 3 jet analysis

  $\rightarrow$ 4 parameter sufficient for γ jet jet

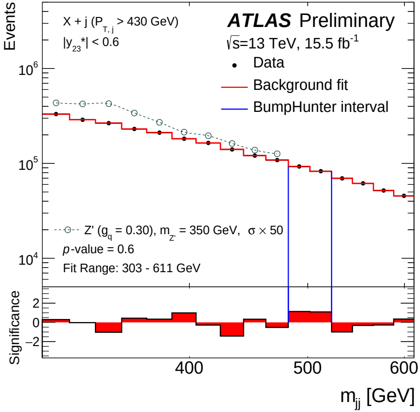
Use **BumpHunter** algorithm → Find most discrepant region

Use **Pseudo-Experiments (PEs)** → Quantify the global significance

γ jet jet



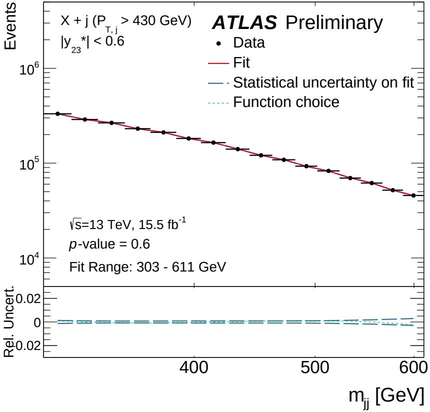
3 jet



3 jet

Fitting uncertainties:

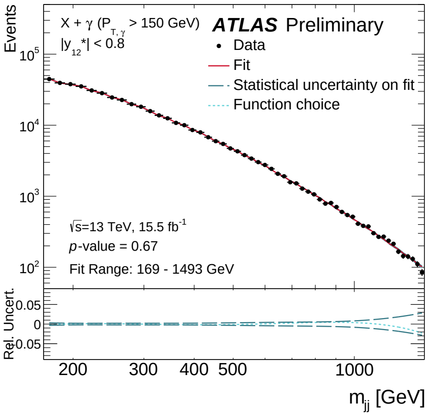
- Systematics in limit setting
- Used in spurious signal check (Fit MC not data)
  Sherpa 2.1.1 for γ jet jet
  Pythia 8.186 for 3 jet



Statistical uncertainty: Fit PEs (Poisson draws from bkg estimate) & in each m_{jj} bin take the std. dev. of the function value for all PEs in that bin

Function Choice: Difference between nominal & alternate fit (extra degree of freedom)

γ jet jet



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- Systematics in limit setting
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Function Choice: Difference between nominal & alternate fit (extra degree of freedom)

ISR + Dijet - Looking Ahead

The Present

- Global fit seems to be working well 🙂
- Good fits & uncertainties are relatively small, especially at lower mass

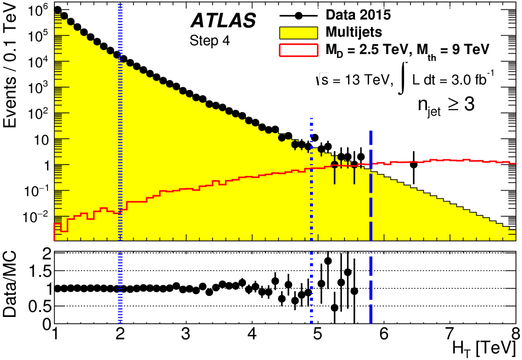
The Future

- Data becomes more precise with higher lumi
  $\rightarrow$ Need fit function that can accurately describe the data, while not fitting away bumps ... Or a new method!
- Need precise & trustworthy MC for cut optimisation, test fits & for spurious signal check

JHEP 03 (2016) 026

Search for new physics (e.g. micro black holes) in H_T distribution
H_T: scalar sum of jet transverse momenta

Bin in $N_{jets} \geq 3, 4, 5, 6, 7, 8 \rightarrow$ Look for excess of events at high H_T



$\geq$ 3 jet bin

Dataset: **3.6** fb^{-1}, $\sqrt{s} = 13$ **TeV**

Event Selection: Jets reconstructed using Anti-kT R = 0.4

- ≥ 3 jets
- Trigger: $H_T > 850$ GeV & ≥ 1 jet with $p_T > 200$ GeV
- Jets: $p_T > 50$ GeV & $|\eta|<2.8$
- $H_T > 1$ TeV

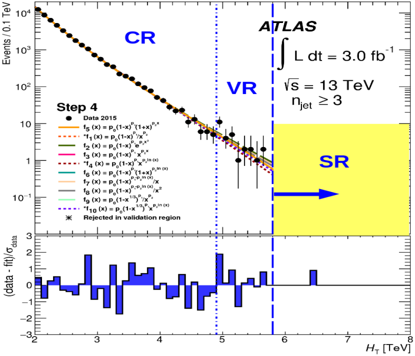
Bkg estimate:

Bin in $N_{jets} \geq 3, 4, 5, 6, 7, 8$

- Fit in low H_T control region CR

- Choose bkg parameterisation (from 10 functions) based on performance in validation region VR $\rightarrow$ nominal function

- Yield of nominal function in signal region SR gives bkg prediction



≥ 3 jet bin

Predictions made in all jet multiplicity bins

Bkg estimate:

Bin in $N_{jets} \geq 3, 4, 5, 6, 7, 8$

- Fit in low H_T control region CR

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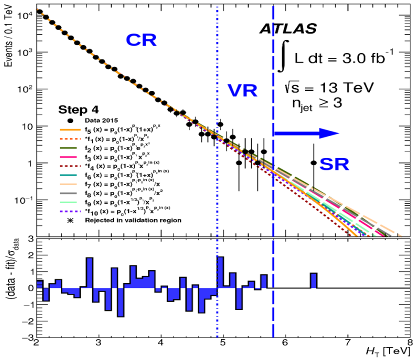

≥ 3 jet bin

Unblind SR + Search for excess at high H_T $\rightarrow$ **Counting experiment**

No excess seen in any jet multiplicity bin!

$n_{\text{jet}} \geq$	VR (obs)	VR (exp)	SR (obs)	SR (exp)
3	28	19.5 ± 3.6 (PE) $\pm$ 4.1 (DD)	1	2.10 ± 0.51 (PE) $\pm$ 1.78 (DD)
4	27	20.8 ± 2.3 (PE) $\pm$ 6.4 (DD)	2	2.36 ± 0.52 (PE) $\pm$ 2.12 (DD)
5	26	22.3 ± 2.6 (PE) $\pm$ 6.8 (DD)	2	1.95 ± 0.45 (PE) $^{+2.10}_{-1.95}$ (DD)
6	20	20.3 ± 2.9 (PE) $\pm$ 5.4 (DD)	3	1.82 ± 0.49 (PE) $^{+1.91}_{-1.82}$ (DD)
7	14	20.7 ± 4.1 (PE) $\pm$ 1.7 (DD)	0	0.53 ± 0.36 (PE) $\pm$ 0.22 (DD)
8	19	18.2 ± 4.9 (PE) $\pm$ 3.5 (DD)	0	0.43 ± 0.36 (PE) $\pm$ 0.26 (DD)

- **MC Based (PE)**: Pythia 8.186, NNPDF23, A14 tune

  Statistical: Data fluctuations in the CR

  Systematic: Extrapolation uncertainty

  - MC Normalised to data in region $1.5 < H_T < 2.9$ TeV

  - Fit PEs (drawn from MC) using nominal function

  - Calculate width & median value of the difference between VR & SR predictions & the actual values

$n_{\text{jet}} \geq$	VR (obs)	VR (exp)	SR (obs)	SR (exp)
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- **Data-driven (DD)**:

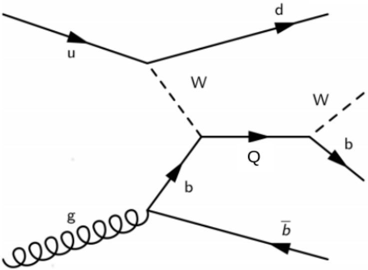
  Systematic: Fit function choice

  - Fit data with all qualified functions

  - Take max difference in SR prediction between nominal function & alternate

ATLAS-CONF-2016-072

Look for single production of Vector Like Quark (VLQ), through its decay to Wb, where W decays leptonically i.e. $Q \rightarrow Wb \rightarrow l\nu b$



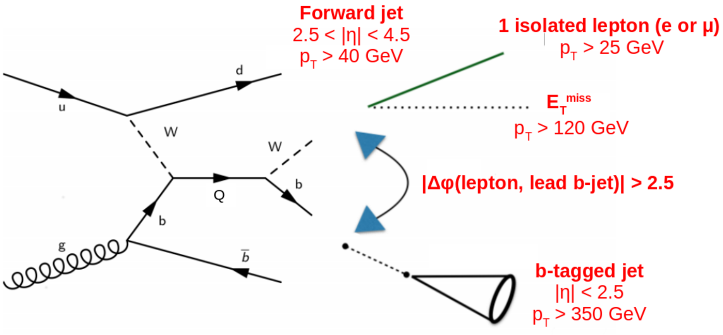
- Analysis focuses on interpretation where:

Q = T (charge $+\frac{2}{3}$)

Q = Y (charge $-\frac{4}{3}$)

Dataset: **3.2** fb^{-1}**,** $\sqrt{s} = 13$ **TeV**

Event Selection: Jets reconstructed using Anti-kT R = 0.4



Jet veto: Reject event if any central ($|\eta| < 2.5$) jets with $p_T > 75$ GeV around or opposite to the b-jet: ΔR (jet, lead b-jet) < 1.2 Or > 2.7
→ Suppresses $t\bar{t}$ bkg

Bkg Estimate:

- Backgrounds modelled using MC:

Process	Generator + parton showering/hadronisation	Tune	PDF set	Inclusive cross-section order in pQCD
Y **signal sample**	MADGRAPH5 + PYTHIA 8.186	A14	NNPDF2.3	NLO
$t\bar{t}$	POWHEG-BOX 2.0 + PYTHIA 6.428	P2012	CT10	NNLO+NNLL
Single top	POWHEG-BOX 2.0 + PYTHIA 6.428	P2012	CT10	NNLO+NNLL
Dibosons WW, WZ, ZZ	SHERPA 2.1.1	Default	CT10	NLO
W/Z + **jets**	SHERPA 2.2.0	Default	CT10	NNLO

W-boson p_T mismodelling at high p_T, corrected using re-weighting factors

- Backgrounds estimated using data-driven method: **Multijet**
  Contributes due to the mis-ID of a jet or γ as an electron, or presence of a non-prompt lepton. Suppressed by E_T^{miss} requirement

Bkg Estimate:

- **W/Z + jets, $t\bar{t}$ & single top**: Normalisation constrained by fitting predicted yields to data in Control Regions enriched in $t\bar{t}$ and W+jets events, with large number of events.

Selection changes for Control Regions (CRs) wrt Signal Region (SR) selection

Region	Selection cuts: Leading jet p_{T}	Leading jet is b-tagged	ΔR (jet, b-tagged jet))< 1.2 or ΔR (jet, b-tagged jet) > 2.7
SR	> 350 GeV	yes	0
$t\bar{t}$ CR	> 200 GeV	yes	≥ 1
W+jets CR	> 250 GeV	no	-

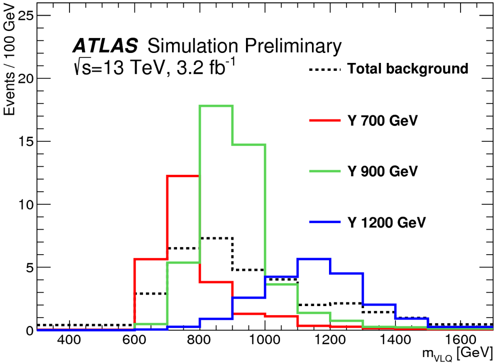
Search:

- Use invariant mass of the reconstructed VLQ candidate m_{VLQ} to discriminate signal from background

  m_{VLQ} calculated from lead b-jet & W decay products (e or μ & ν)

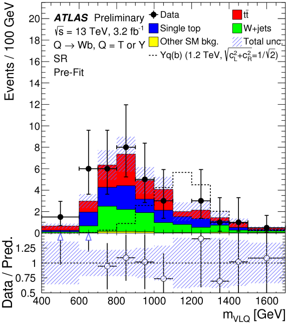
MC Signal Region Example: VLQ candidate mass for 3 signal masses & the total SM bkg

→ Good discrimination between signal and background events in SR

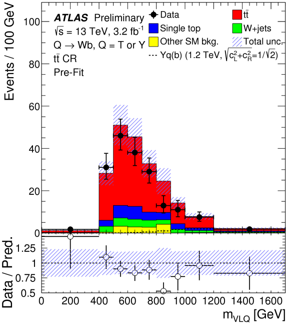


Pre-fit

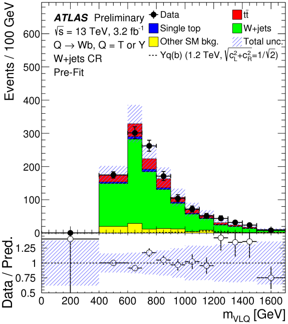
Signal Region



$t\bar{t}$ Control Region



W+Jets Control Region



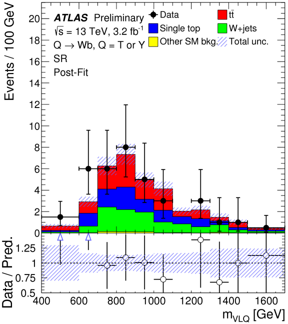
Perform combined max-likelihood fit of SR, $t\bar{t}$ CR & W+jets CR:

→ Allows for simultaneous determination of W+jets & top contribution from CRs

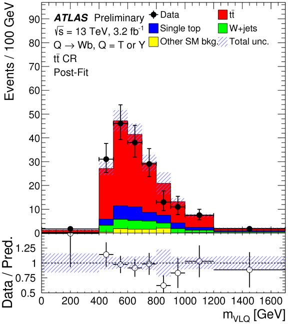
Single VLQ → Wb - Search Results (Post-fit

Post-fit

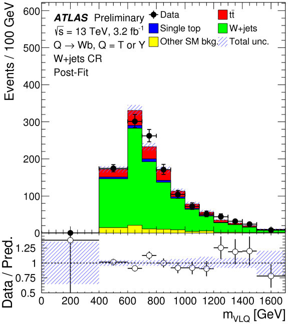
Signal Region



$t\bar{t}$ Control Region



W+Jets Control Region



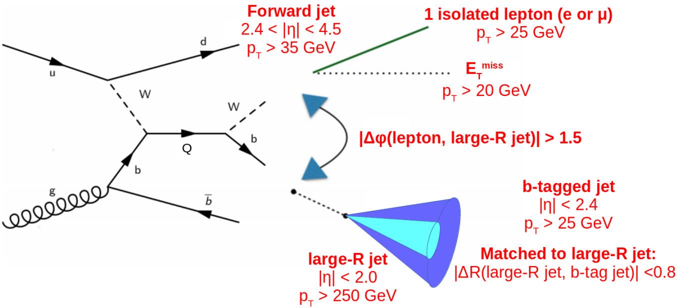
No significant excess over Standard Model backgrounds is observed, but:

→ Use of bkg enhanced CRs significantly reduces systematic uncerts on bkg estimate → Increases search sensitivity!

Eur. Phys. J. C76 (2016) 442

Event Selection:

Small-R jets Anti-kT R = 0.4 Large-R jets Anti-kT R = 0.1, trimmed



$m_T(W) + E_T^{miss} > 60$ GeV $\rightarrow$ Suppress multijet bkg

Jet vetoes: Reject event if large-R jet is massive (m > 70 GeV) or if any jet with $p_T > 75$ GeV and $|\eta| < 2.4$ outside the large-R jet $\rightarrow$ Suppresses $t\bar{t}$ bkg

Jet vetoes & multiplicity observables are crucial for many BSM searches with ATLAS

Various techniques being used to estimate and reduce bkgs & systematics in analyses that use these observables → Shown small selection, including:

Bkg estimation:

- Fits to data distributions (with & without extrapolation)

- MC based estimates

Reduction of backgrounds & systematics:

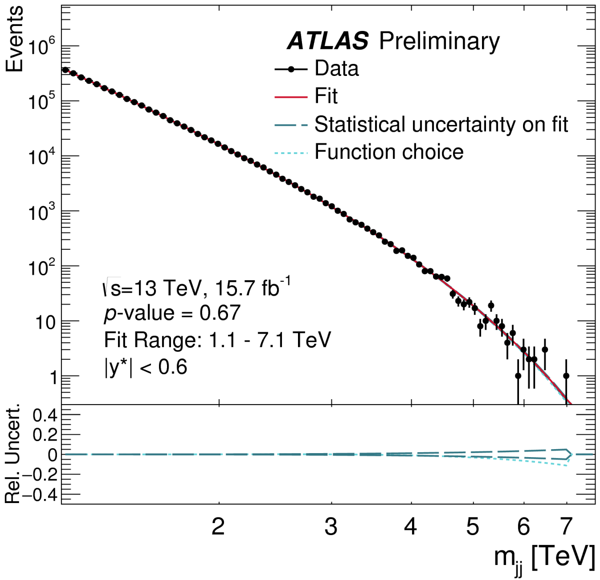
- Analysis cuts, including large + small R jet vetoes

- Bkg enhanced control regions

- Mass binned signal regions

BACKUP

High Mass Dijet Resonance - Fit Uncerts



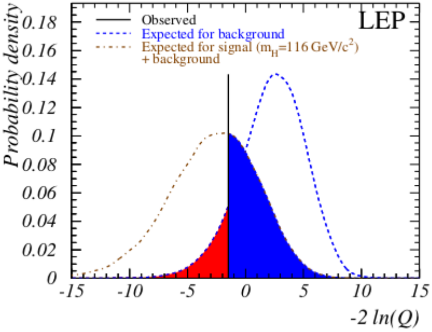
Pythia 8 calculations use matrix elements that are at leading order in the QCD coupling constant with simulation of higher-order contributions partially covered by the parton shower modelling. They also include modelling of hadronisation effects. The distributions of events predicted by Pythia 8 are reweighted to NLO predictions of NLOJET++ [42–44] using mass- and χ-dependent correction factors defined as in Ref. [19]. The correction factors modify the shape of the angular distributions at the level of 15% at low values of χ and high values of m_{jj}. The correction is 5% or less at the highest values of χ. The Pythia 8 predictions also omit electroweak effects. These are included as additional mass- and χ-dependent correction factors [45] that are unity at low m_{jj} and differ from unity by up to 3% in the $m_{jj} > 3.4$ TeV region.

Dijet Angular - NLO Corrections

PYTHIA 8 calculations use matrix elements that are at leading order in the QCD coupling constant with simulation of higher-order contributions partially covered by the parton shower modelling. They also include modelling of hadronisation effects. The distributions of events predicted by PYTHIA 8 are reweighted to NLO predictions of NLOJET++ [42–44] using mass- and χ-dependent correction factors defined as in Ref. [19]. The correction factors modify the shape of the angular distributions at the level of 15% at low values of χ and high values of m_{jj}. The correction is 5% or less at the highest values of χ. The PYTHIA 8 predictions also omit electroweak effects. These are included as additional mass- and χ-dependent correction factors [45] that are unity at low m_{jj} and differ from unity by up to 3% in the $m_{jj} > 3.4$ TeV region.

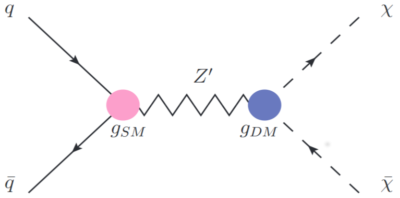
The test statistic q_μ is defined as the profile likelihood ratio: $q_\mu = -2\ln(\mathcal{L}(\mu,\hat{\hat{\theta}}_\mu)/\mathcal{L}(\hat{\mu},\hat{\theta}))$, where $\hat{\mu}$ and $\hat{\theta}$ are the values of the parameters that maximise the likelihood function (with the constraint $0 \le \hat{\mu} \le \mu$), and $\hat{\hat{\theta}}_\mu$ are the values of the nuisance parameters that maximise the likelihood function for a given value of μ. Statistical uncertainties in each bin of the discriminant distributions are also taken into account via dedicated parameters in the fit. The test statistic q_μ is implemented in the RooFit package [113, 114] and is used to measure the compatibility of the observed data with the background-only hypothesis (i.e. the discovery test) setting $\mu = 0$ in the profile likelihood ratio: $q_0 = -2\ln(\mathcal{L}(0,\hat{\hat{\theta}}_0)/\mathcal{L}(\hat{\mu},\hat{\theta}))$.

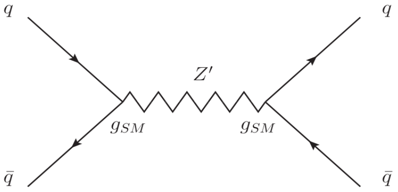
Shaded areas: $1 - CL_b$ and CL_{s+b}



Z' Dark Matter (DM) mediator

Link to paper





- MadGraph "dmA" model created by the Dark Matter Forum

Two new particles

Z' mediator of mass M_R

DM candidate χ of mass m_χ

Two new couplings

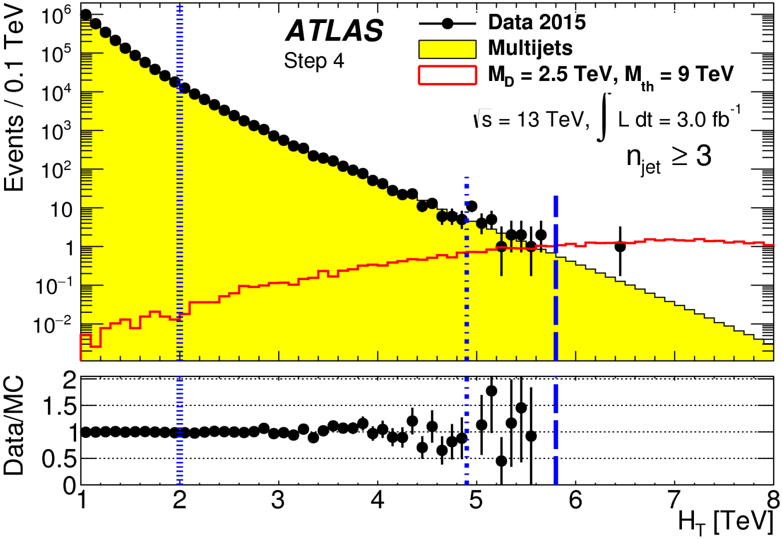
coupling g_{SM} of Z' to quarks

coupling g_{DM} of Z' to χ

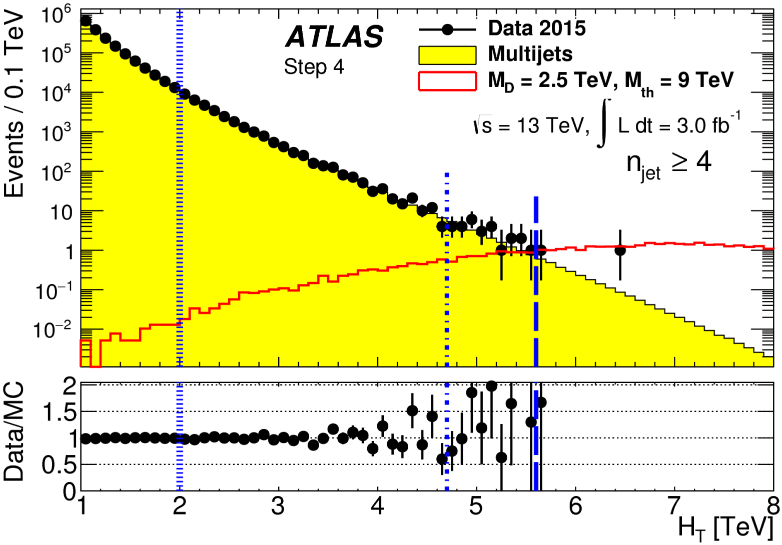
ISR + Dijet - Systematics in limit setting

- Statistical uncertainty on fit
- Fit function choice (N parameters + 1 as alternate)
- JES uncertainty
- Signal acceptance due to:
  - Luminosity 2.9%
  - Photon uncertainty 3% (No equivalent for 3 jet analysis yet)
  - JER: 2% for gjj, 1% for jjj
  - PDF: 1%

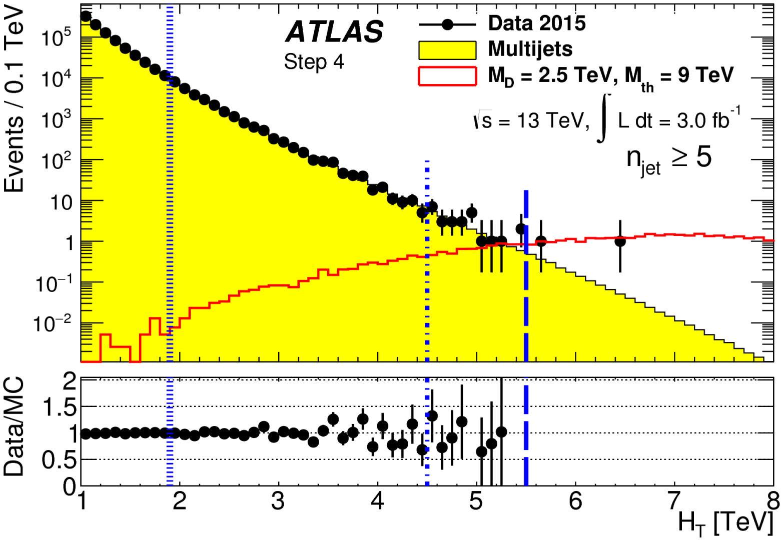
Multi-jet - Data MC agreement for H_T

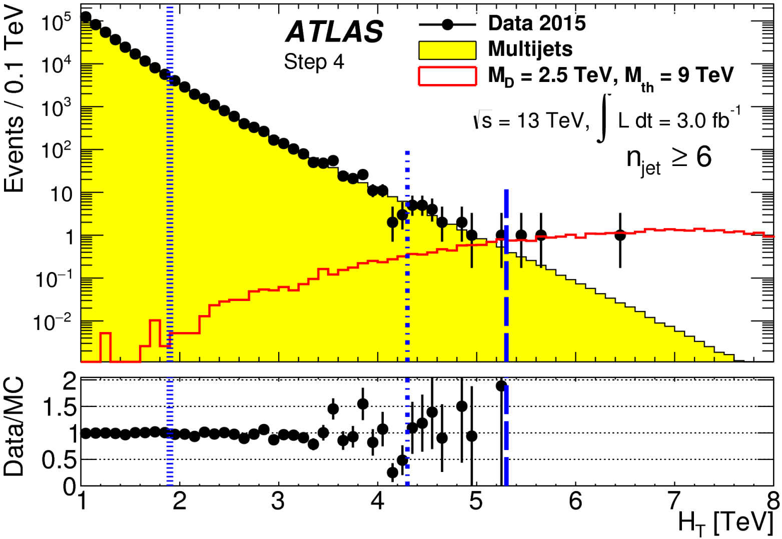


Multi-jet - Data MC agreement for H_T

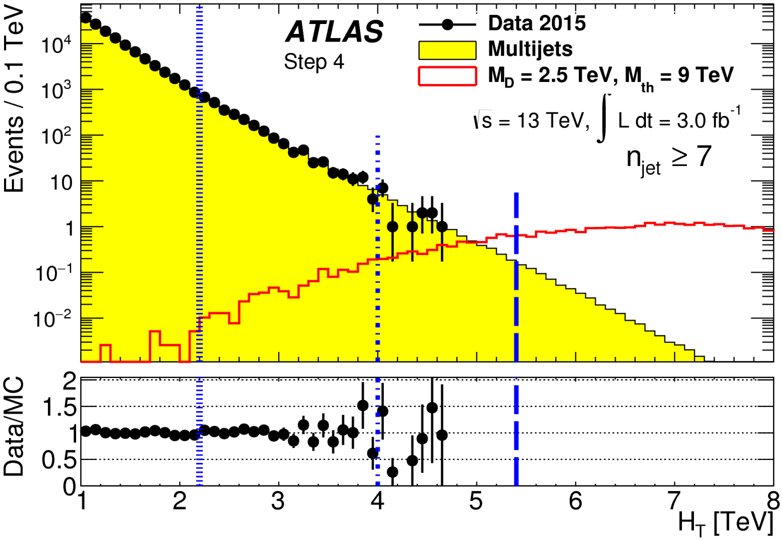


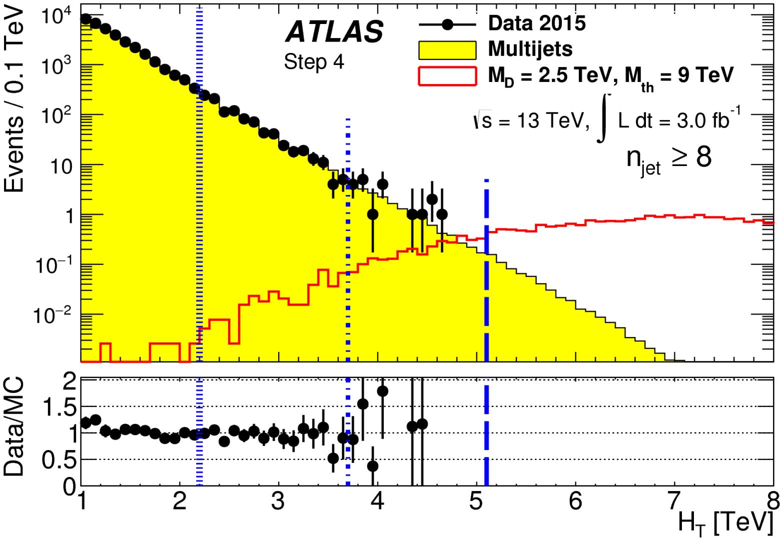
Multi-jet - Data MC agreement for H_T




ATLAS
Step 4
Data 2015
Multijets
M_D = 2.5 TeV, M_th = 9 TeV
√s = 13 TeV, ∫ L dt = 3.0 fb^-1
n_jet ≥ 6
Events / 0.1 TeV
Data/MC
H_T [TeV]

Multi-jet - Data MC agreement for H_T




ATLAS
Step 4
Data 2015
Multijets
M_D = 2.5 TeV, M_th = 9 TeV
√s = 13 TeV, ∫ L dt = 3.0 fb^-1
n_jet ≥ 8
Events / 0.1 TeV
Data/MC
H_T [TeV]

	Functional form	p_1	p_2
1	$f_1(x) = \frac{p_0(1-x)^{p_1}}{x^{p_2}}$	(0,+∞)	(0,+∞)
2	$f_2(x) = p_0(1-x)^{p_1} e^{p_2 x^2}$	(0,+∞)	(-∞ ,+∞)
3	$f_3(x) = p_0(1-x)^{p_1} x^{p_2 x}$	(0,+∞)	(-∞ ,+∞)
4	$f_4(x) = p_0(1-x)^{p_1} x^{p_2 \ln x}$	(0,+∞)	(-∞ ,+∞)
5	$f_5(x) = p_0(1-x)^{p_1}(1+x)^{p_2 x}$	(0,+∞)	(0,+∞)
6	$f_6(x) = p_0(1-x)^{p_1}(1+x)^{p_2 \ln x}$	(0,+∞)	(0,+∞)
7	$f_7(x) = \frac{p_0}{x}(1-x)^{[p_1 - p_2 \ln x]}$	(0,+∞)	(0,+∞)
8	$f_8(x) = \frac{p_0}{x^2}(1-x)^{[p_1 - p_2 \ln x]}$	(0,+∞)	(0,+∞)
9	$f_9(x) = \frac{p_0(1-x^{1/3})^{p_1}}{x^{p_2}}$	(0,+∞)	(0,+∞)
10	$f_{10}(x) = p_0(1-x^{1/3})^{p_1} x^{p_2 \ln x}$	(0,+∞)	(-∞ ,+∞)

Table 1. Analytic functions considered in this analysis where $x = H_T/\sqrt{s}$. p_0 is a normalization constant. p_1 and p_2 are free parameters in a fit, and their allowed floating ranges are shown in the last two columns.

Multi-jets - Region Definitions + VR Rank

Monte Carlo: Used for uncertainties + analysis decisions as VR blinded, normalised to data in region $1.5 < H_T < 2.9$ TeV

Region definitions:
Lower bound of VR chosen so that the normalised MC bkg predicts at least 20 events above this
Lower bound of CR chosen so the PE based uncertainty is minimised
Lower bound of SR chosen so that the extrapolation uncertainty is approximately 0.5 events in the SR

Function Ranking: 1000 PEs drawn from samples of MC bkg

Qualify if: Converge in CR, decrease monotonically with H_T in SR for $\geq$ 95% of PEs

Rank qualified functions based on goodness of extrapolation VR based on the statistical uncertainty and potential bias of their extrapolation.

Single VLQ $\rightarrow$ Wb - Vector like quarks

Vector-like Quarks (VLQ): hypothetical, spin 1/2 particles predicted by several BSM models

Vector like couplings, not chiral, left and right-handed components have same color and EW quantum numbers

Appear in different SU(2) multiplets:

Singlets: T, B
Doublets: (XT), (TB), (BY)
Triplets: (XTB), (TBY)

Single production $\sigma >$ pair-produced σ for large VLQ masses

Highest allowed singlet σ, T (singlet), Y (doublet) $\rightarrow$ Search for these!

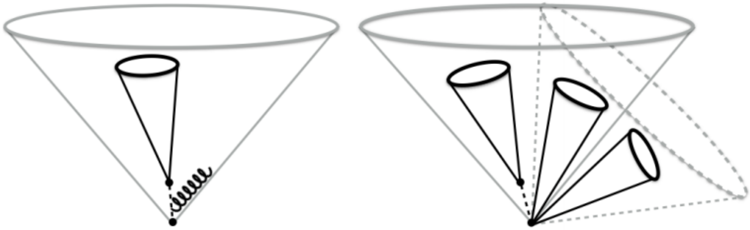


Figure 11: Illustration of the usage of large-radius jet mass to veto $t\bar{t}$ background. For the signal T→ Wb, the b-quark recoils against the W-boson. Thus the hardest large-R jet in the event typically contains a b-hadron plus additional soft and collinear radiation, and tends to have a low mass. For the semileptonic $t\bar{t}$ background, right, a mildly boosted hadronically decaying top quark produces large-R jets containing a significant fraction of the top decay products. The fraction of top decay products contained, and therefore the jet mass, increases with jet p_{T}. Hence, a cut based on the large-R jet p_{T} and mass can be optimised to distinguish between signal and $t\bar{t}$ background, whilst still retaining good signal efficiency. Figure from Ref [9].

4.3 Estimation of non-prompt and fake lepton backgrounds

Background processes involving non-prompt leptons, hadrons and photons may satisfy the selection criteria, giving rise to so called "non-prompt and fake" lepton backgrounds (fakes). The multijet background normalisation and shape are estimated with a data-driven method, referred to as Matrix Method [94, 95]. This method uses the efficiencies of loosely selected leptons (loose leptons) to pass the default tight lepton selection cuts. The efficiencies are obtained in dedicated control regions enriched with real or non-prompt leptons, respectively, and applied to events selected with either loose or tight lepton definition to obtain the fraction of multijet events. Systematic uncertainties on the estimate are assessed using alternative control samples, propagating systematic uncertainties associated to object reconstruction and MC simulation to the fake-lepton estimate as well as by comparing different parametrisations of the efficiencies.

Single VLQ $\rightarrow$ Wb - W Mismodelling

A mismodelling of the W-boson transverse momentum is observed at high p_T. To correct for this mismodelling, reweighting factors are obtained at preselection for W+jet events as a function of the W-boson p_T and applied to the W+jets background in all kinematic distributions. The correction factors are approximately between 0.9 and unity for W-boson p_T below 300 GeV, going to 0.7- 0.8 for higher p_T values.

To obtain the z-component of the neutrino momentum ($p_{z,\nu}$), the invariant mass of the lepton-neutrino system is set to the W-boson mass and the resulting quadratic equation is solved. If no real solution exists, the $\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$ vector is varied by the minimum amount required to produce exactly one real solution. If two real solutions are found, the one with the smallest $|p_{z,\nu}|$ is used. The W-boson candidate and the leading b-tagged jet are then used to reconstruct the Q candidate.