Top production with N jets and jet vetoes at ATLAS

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On behalf of the ATLAS collaboration

Workshop on Jet Vetoes and Jet Multiplicity Observables at the LHC
IPPP, Durham, 17$^{\text{th}}$ Jul, 2013

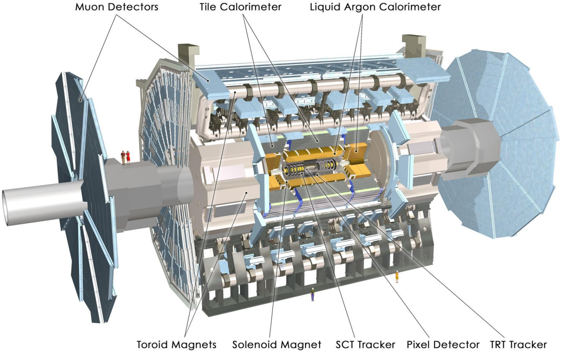
Outline

- Introduction
- Jet vetoes
- Jet multiplicity
- Conclusion and outlook

The ATLAS detector at the LHC:

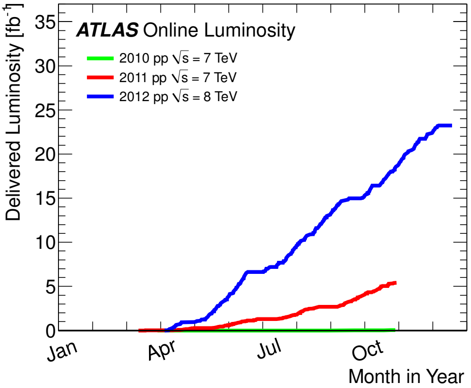
- precise calorimetry:
  - Hadronic jets
  - electrons
- Precise tracking:
  - Muons
  - b-jet tagging
- Excellent solid-angle coverage:
  - E_T^{miss}

Versatile detector well suited to measurements in $t\bar{t}$ final states



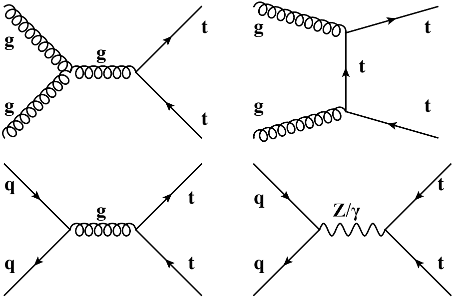
The LHC has been performing excellently since 2010:

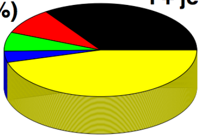
- $\sim 35\,\mathrm{pb}^{-1}$ of 7 TeV *pp* collisions/experiment 2010
- $\sim 5\,\mathrm{fb}^{-1}$ of 7 TeV *pp* collisions/experiment 2011
- $\sim 20\,\mathrm{fb}^{-1}$ of 8 TeV *pp* collisions/experiment 2012



Results shown today use 2011 data:

- Jet Vetoes: Eur.Phys.J. C72 (2012) 2043
- Jet Multiplicities: ATLAS-CONF-2012-155





- $t\bar{t}$ pairs copiously produced at the LHC
- A good environment to study QCD

- Top decays approximately 100% $t \to Wb$

The measurement of $t\bar{t}$ production with a veto on central jet production is an extremely important one.

	Relative cross-section uncertainty [%]	
Source	e+jets	μ+jets
Statistical uncertainty	±43	±29
Object selection		
Lepton reconstruction, identification, trigger	±3	±2
Jet energy reconstruction	±13	±11
b-tagging	-10 / +15	-10 / +14
Background rates		
QCD normalisation	±30	±2
W+jets normalisation	±11	±11
Other backgrounds normalisation	±1	±1
Signal simulation		
Initial/final state radiation	-6 / +13	±8
Parton distribution functions	±2	±2
Parton shower and hadronisation	±1	±3
Next-to-leading-order generator	±4	±6
Integrated luminosity	-11 / +14	-10 / +13
Total systematic uncertainty	-38 / +43	-23 / +27
Statistical + systematic uncertainty	-58 / +61	-37 / +40

(Eur.Phys.J.C71 (2011) 1577)

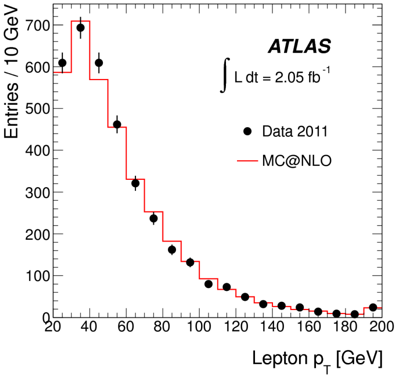
- Many $t\bar{t}$ analyses (especially $t\bar{t}+X$) have large uncertainties from MC QCD I/FSR
- Fraction of events with/without extra jets tests how well MC describes this radiation
- This measurement focusses on the fraction of events with no-additional central jet (beyond the $t\bar{t}$ system) above a certain threshold (a jet veto)

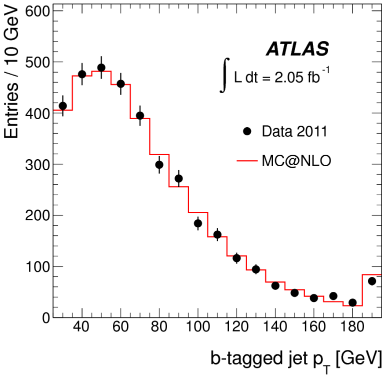
This measurement well suited to the **dileptonic** channel, requiring:

- Two opposite-sign isolated leptons
  - $m_{ll} > 15\,\mathrm{GeV}$
  - $|m_{ll} - m_Z| < 10\,\mathrm{GeV}$
- Two b-tagged jets $p_T > 25\,\mathrm{GeV}$,
  - anti-k_t $R = 0.4$
  - $|\eta| < 2.4$

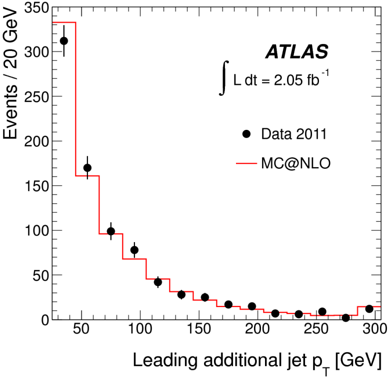
This gives a very pure $t\bar{t}$ sample
Additional $R = 0.4$ anti-k_t jets are ascribed to QCD I/FSR

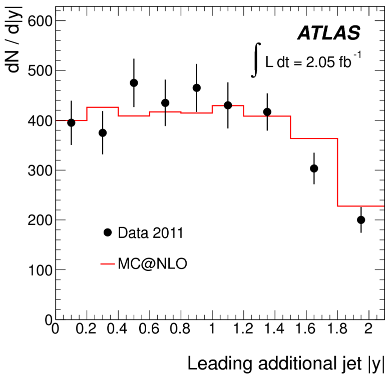
Data Description





Data Description



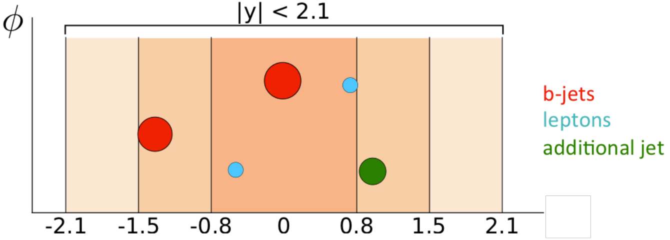


Gap Fraction

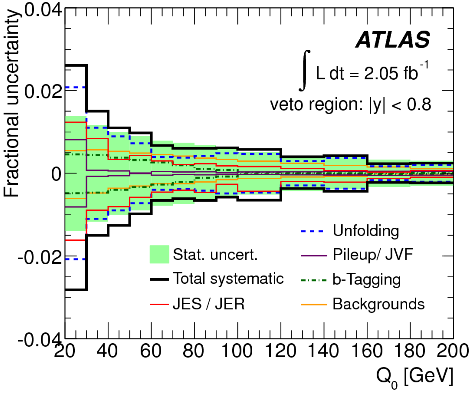
Absence of activity quantified in terms of the *gap fraction*, $f(Q_0)$:

$$f(Q_0) = \sigma(Q_0)/\sigma$$

- σ is the fiducial cross section for inclusive $t\bar{t}$ production
- $\sigma(Q_0)$ is the fiducial cross section for $t\bar{t}$ events produced without any jet with $p_T > Q_0$
- Various rapidity (y) ranges used for the additional jet



Unfolding

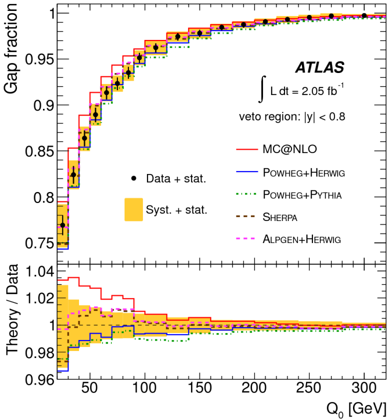


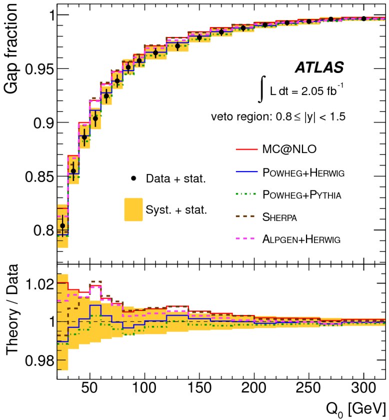
- Simple bin-by-bin unfolding

$$C(x) = \frac{f_{\mathrm{truth}}(x)}{f_{\mathrm{reco}}(x)}$$

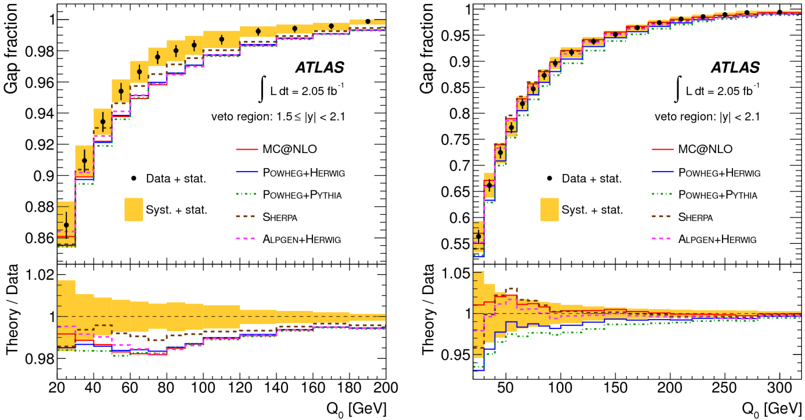
- justified: high purity

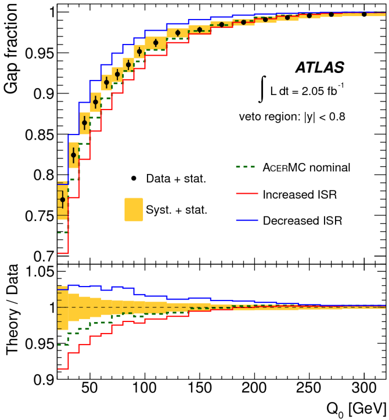
Results: $f(Q_0)$

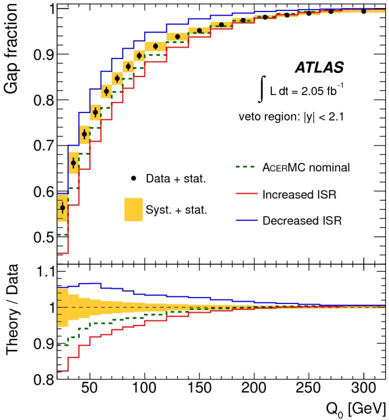

Gap fraction
Theory / Data
ATLAS
$\int$ L dt = 2.05 fb^{-1}
veto region: |y| < 0.8
Data + stat.
Syst. + stat.
MC@NLO
POWHEG+HERWIG
POWHEG+PYTHIA
SHERPA
ALPGEN+HERWIG
Q_0 [GeV]


Gap fraction
Theory / Data
ATLAS
$\int$ L dt = 2.05 fb^{-1}
veto region: 0.8≤ |y| < 1.5
Data + stat.
Syst. + stat.
MC@NLO
POWHEG+HERWIG
POWHEG+PYTHIA
SHERPA
ALPGEN+HERWIG
Q_0 [GeV]

Results: $f(Q_0)$


Gap fraction
Theory / Data
ATLAS
$\int$ L dt = 2.05 fb^{-1}
veto region: 1.5 ≤ |y| < 2.1
Data + stat.
Syst. + stat.
MC@NLO
POWHEG+HERWIG
POWHEG+PYTHIA
SHERPA
ALPGEN+HERWIG
Q_0 [GeV]
veto region: |y| < 2.1


Gap fraction
Theory / Data
ATLAS
$\int$ L dt = 2.05 fb^{-1}
veto region: |y| < 0.8
Data + stat.
Syst. + stat.
AcerMC nominal
Increased ISR
Decreased ISR
Q_0 [GeV]

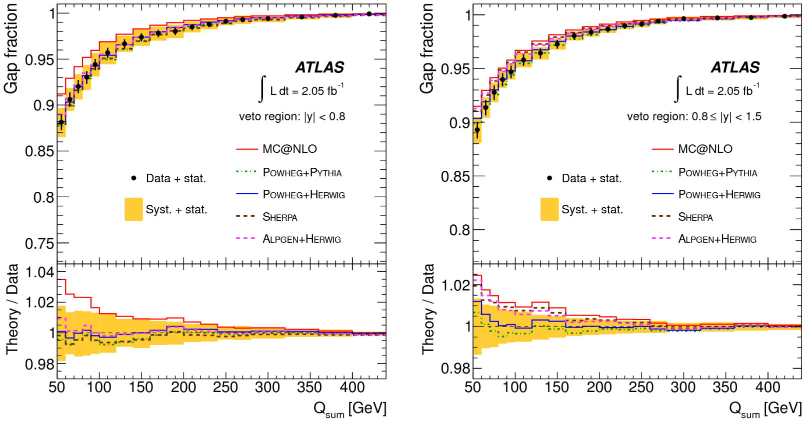

Gap fraction
Theory / Data
ATLAS
$\int$ L dt = 2.05 fb^{-1}
veto region: |y| < 2.1
Data + stat.
Syst. + stat.
AcerMC nominal
Increased ISR
Decreased ISR
Q_0 [GeV]

Alternative *gap fraction*, $f(Q_{\rm sum})$ probes activity beyond the leading jet:

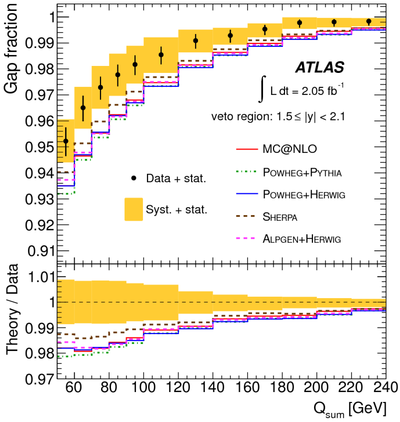
$$f(Q_{\rm sum}) = \sigma(Q_{\rm sum})/\sigma$$

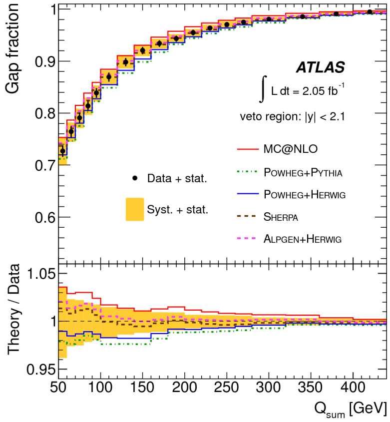
- σ is the fiducial cross section for inclusive $t\bar{t}$ production
- $\sigma(Q_{\rm sum})$ is the fiducial cross section for $t\bar{t}$ events produced where the scalar p_T sum of all jets within the rapidity region is $< Q_{\rm sum}$

Results: $f(Q_{\mathrm{sum}})$



Results: $f(Q_{\mathrm{sum}})$



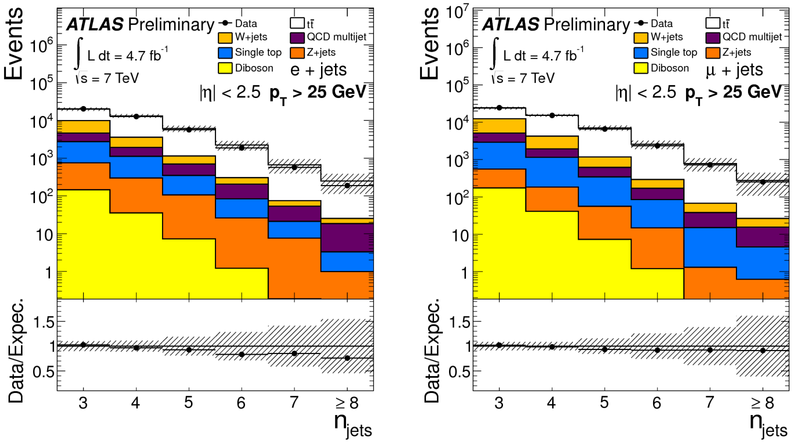


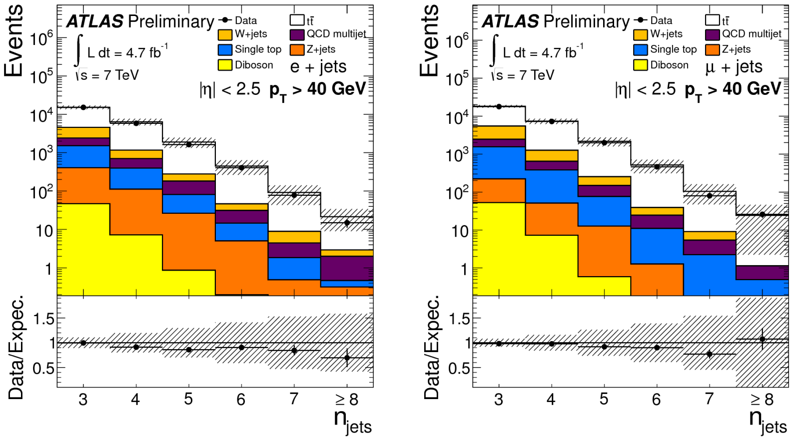
Another probe of extra QCD activity in $t\bar{t}$ is the measurement of the jet multiplicity

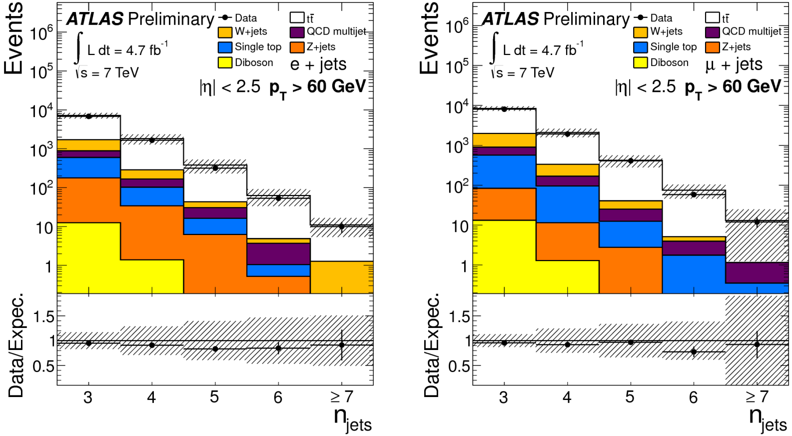
- Measure the rate of production of events with different numbers of jets
- Excellent test of the performance of different MCs for $t\bar{t}$ production
    - Expect NLO MCs to do well for up to 1 extra jet in the ME
    - expect multi-leg to do better for > 1 extra jet
- Complementary information to gap fraction for understanding QCD I/FSR in $t\bar{t}$ events

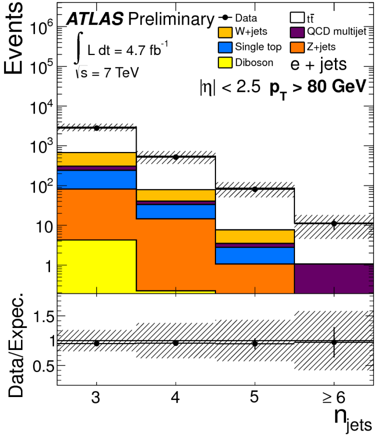
This CONF note used the l+jets channel:

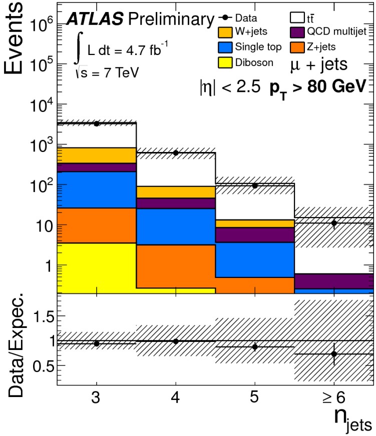
- require: isolated lepton, E_T^{miss}, at least one b-tagged jet, > 2 jets, $m_T(W)$
- Large branching ratio
- Significant backgrounds:
  - **W+jets**: Shape mainly from ALPGEN MC, overall normalisation extracted using W charge asymmetry, Heavy flavour fraction from fits in 2 jet multiplicity bins
  - **QCD multijet events**: Extracted from data using the *matrix method*, employing loose and tight lepton selections to determine the shape and normalisation
  - **VV, single-top, Z+jets**: are small and estimated using MC


ATLAS Preliminary
∫ L dt = 4.7 fb^-1
√s = 7 TeV
Data
tt̄
W+jets
QCD multijet
Single top
Z+jets
Diboson
e + jets
μ + jets
|η| < 2.5 p_T > 25 GeV
Events
Data/Expec.
n_jets
3
4
5
6
7
≥ 8


ATLAS Preliminary
∫ L dt = 4.7 fb^{-1}
√s = 7 TeV
Data
tt̄
W+jets
QCD multijet
Single top
Z+jets
Diboson
e + jets
μ + jets
|η| < 2.5 p$_T$ > 40 GeV
Events
Data/Expec.
n$_{jets}$


ATLAS Preliminary
∫ L dt = 4.7 fb^-1
√s = 7 TeV
Data
tt̄
W+jets
QCD multijet
Single top
Z+jets
Diboson
e + jets
|η| < 2.5 p_T > 60 GeV
Events
Data/Expec.
n_jets
3
4
5
6
≥ 7
ATLAS Preliminary
∫ L dt = 4.7 fb^-1
√s = 7 TeV
μ + jets
|η| < 2.5 p_T > 60 GeV


ATLAS Preliminary
∫ L dt = 4.7 fb^{-1}
√s = 7 TeV
Data
W+jets
Single top
Diboson
$t\bar{t}$
QCD multijet
Z+jets
e + jets
|η| < 2.5 p_T > 80 GeV
Events
Data/Expec.
n_{jets}


ATLAS Preliminary
∫ L dt = 4.7 fb^{-1}
√s = 7 TeV
Data
W+jets
Single top
Diboson
$t\bar{t}$
QCD multijet
Z+jets
μ + jets
|η| < 2.5 p_T > 80 GeV
Events
Data/Expec.
n_{jets}

Reco distribution ($\overrightarrow{N}_{\text{reco}}$) unfolded to particle level ($\overrightarrow{N}_{\text{part}}$) using:

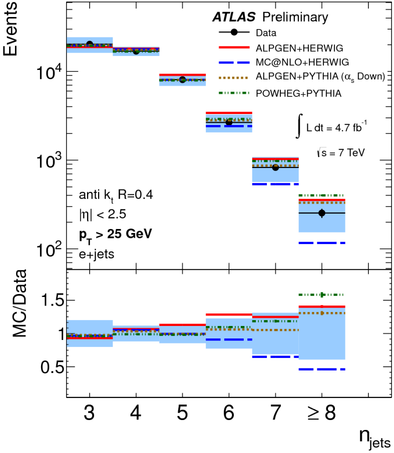
$$\overrightarrow{N}_{\text{part}} = \overrightarrow{f}_{\text{part!reco}} \cdot \mathbf{M}^{\text{reco}}_{\text{part}} \cdot \overrightarrow{f}_{\text{reco!part}} \cdot \overrightarrow{f}_{\text{accpt}} \cdot (\overrightarrow{N}_{\text{reco}} - \overrightarrow{f}_{\text{bgnd}})$$

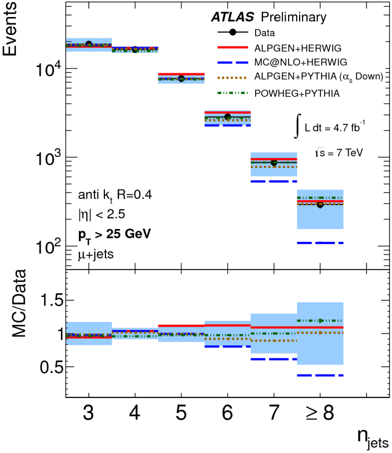
- $\overrightarrow{f}_{\text{accpt}}$: acceptance correction for all selection efficiencies except jet multiplicity (1.8-1.9 e, 1.4-1.5 μ)
- $\mathbf{M}^{\text{reco}}_{\text{part}}$: response matrix applied iteratively using Bayesian unfolding (on diagonal: 0.5-0.7)
- $\overrightarrow{f}_{\text{part!reco}}$: efficiency correction factor for events passing at particle level but not reconstructed level (0.9-0.75)
- $\overrightarrow{f}_{\text{reco!part}}$: efficiency correction factor for events passing at reconstructed level but not particle level (0.9-0.75, for 3 jets, consistent with 1 elsewhere)
- $\overrightarrow{f}_{\text{bgnd}}$: non-$t\bar{t}$ background

Dominant uncertainties:

- Low multiplicity: Backgrounds (18%)
- High multiplicity: JES (40%)
- Other uncertainties at around the (6%) or smaller level
- MC statistical uncertainy is never dominant, only significant at largest multiplicities with high p_T thresholds

Results


ATLAS Preliminary
Data
ALPGEN+HERWIG
MC@NLO+HERWIG
ALPGEN+PYTHIA (α_s Down)
POWHEG+PYTHIA
$\int L\,dt = 4.7\ \mathrm{fb}^{-1}$
$\sqrt{s} = 7$ TeV
anti k_t R=0.4
$|\eta| < 2.5$
$p_T > 25$ GeV
e+jets
Events
10^2
10^3
10^4
MC/Data
0.5
1
1.5
3
4
5
6
7
≥ 8
n_{jets}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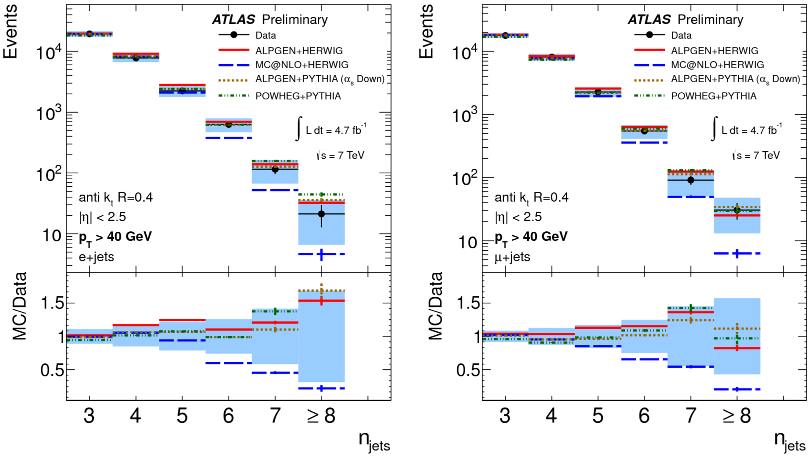
MC@NLO+HERWIG
ALPGEN+PYTHIA (α_s Down)
POWHEG+PYTHIA
$\int L\,dt = 4.7\ \mathrm{fb}^{-1}$
$\sqrt{s} = 7$ TeV
anti k_t R=0.4
$|\eta| < 2.5$
$p_T > 25$ GeV
μ+jets
Events
10^2
10^3
10^4
MC/Data
0.5
1
1.5
3
4
5
6
7
≥ 8
n_{jets}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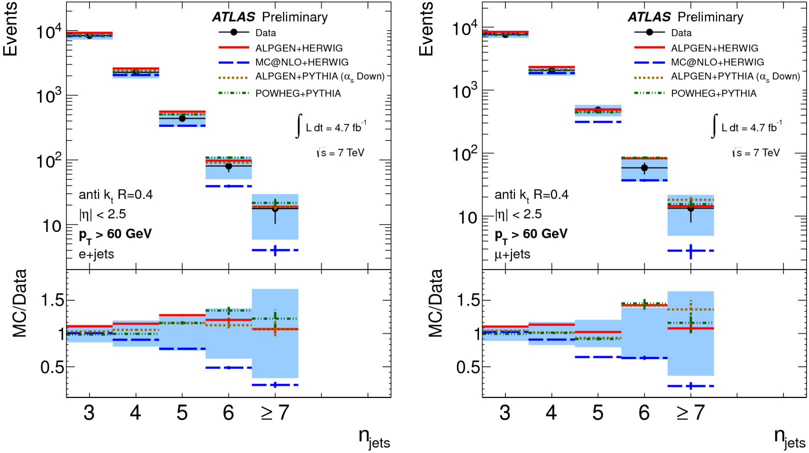
$\sqrt{s} = 7$ TeV
anti k_t R=0.4
$|\eta| < 2.5$
$p_T > 40$ GeV
e+jets
μ+jets
Events
MC/Data
n_{jets}
3
4
5
6
7
≥ 8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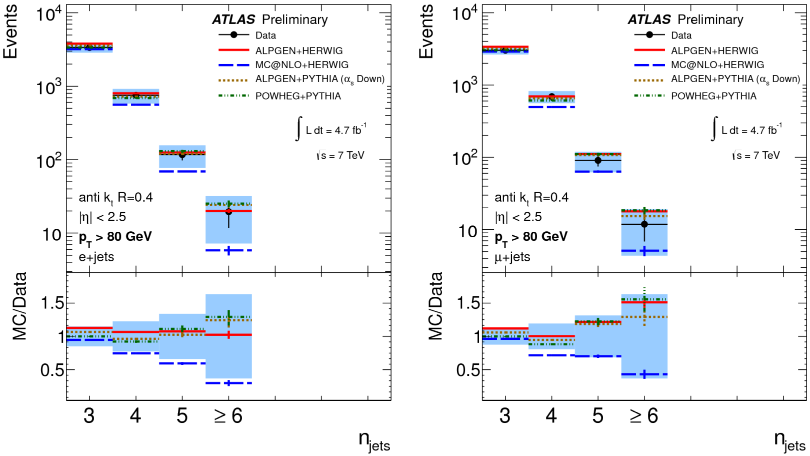
ALPGEN+HERWIG
MC@NLO+HERWIG
ALPGEN+PYTHIA (αs Down)
POWHEG+PYTHIA
∫ L dt = 4.7 fb-1
√s = 7 TeV
anti kt R=0.4
|η| < 2.5
pT > 60 GeV
e+jets
μ+jets
Events
MC/Data
njets
3
4
5
6
≥ 7

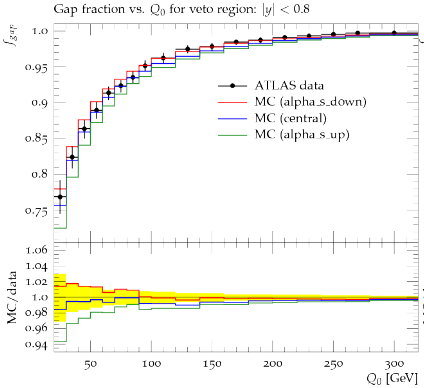
Results

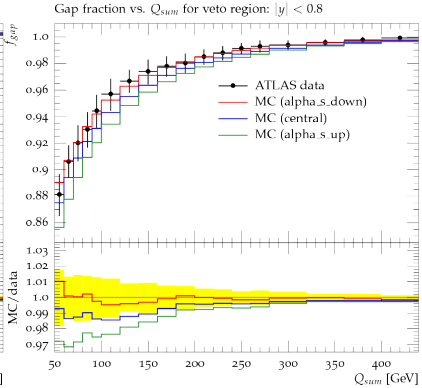

Events
ATLAS Preliminary
Data
ALPGEN+HERWIG
MC@NLO+HERWIG
ALPGEN+PYTHIA (α_s Down)
POWHEG+PYTHIA
$\int$ L dt = 4.7 fb^{-1}
$\sqrt{s}$ = 7 TeV
anti k_t R=0.4
$|\eta| < 2.5$
p_T > 80 GeV
e+jets
μ+jets
MC/Data
3
4
5
≥ 6
n_{jets}

Vs Jet Veto

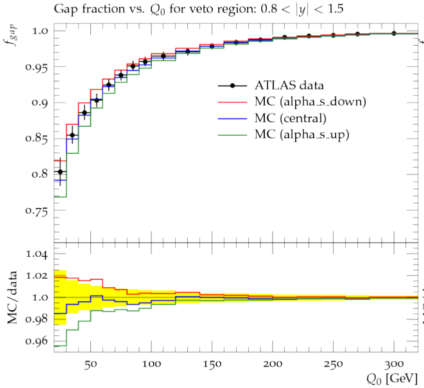
- ALPGEN+PYTHIA performs well for the jet multiplicity measurement
- Was not used in the original jet veto measurement
- Can be compared to the data using the `Rivet` implementation of that analysis

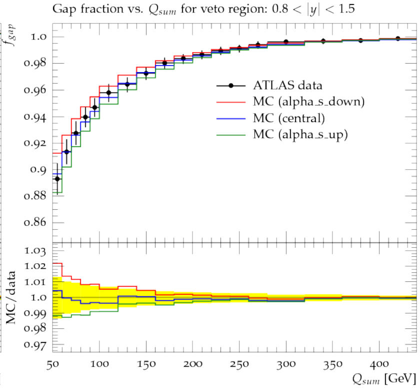
Vs Jet Veto

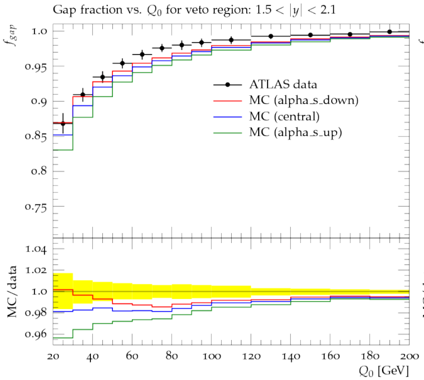

Gap fraction vs. Q_0 for veto region: $|y| < 0.8$
f_{gap}
ATLAS data
MC (alpha_s_down)
MC (central)
MC (alpha_s_up)
MC/data
Q_0 [GeV]

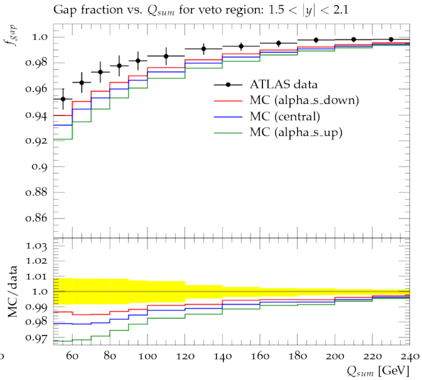

Gap fraction vs. Q_{sum} for veto region: $|y| < 0.8$
f_{gap}
ATLAS data
MC (alpha_s_down)
MC (central)
MC (alpha_s_up)
MC/data
Q_{sum} [GeV]

Vs Jet Veto


Gap fraction vs. Q_0 for veto region: $0.8 < |y| < 1.5$
f_{gap}
1.0
0.95
0.9
0.85
0.8
0.75
ATLAS data
MC (alpha_s_down)
MC (central)
MC (alpha_s_up)
MC/data
1.04
1.02
1.0
0.98
0.96
50
100
150
200
250
300
Q_0 [GeV]


Gap fraction vs. Q_{sum} for veto region: $0.8 < |y| < 1.5$
f_{gap}
1.0
0.98
0.96
0.94
0.92
0.9
0.88
0.86
ATLAS data
MC (alpha_s_down)
MC (central)
MC (alpha_s_up)
MC/data
1.03
1.02
1.01
1.0
0.99
0.98
0.97
50
100
150
200
250
300
350
400
Q_{sum} [GeV]

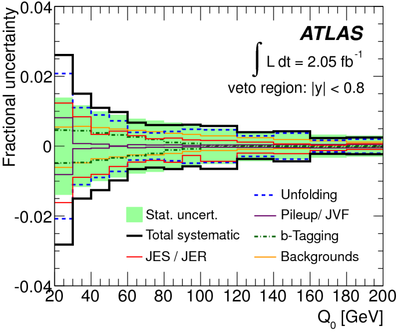

Gap fraction vs. Q_0 for veto region: $1.5 < |y| < 2.1$
f_{gap}
ATLAS data
MC (alpha_s_down)
MC (central)
MC (alpha_s_up)
MC / data
Q_0 [GeV]

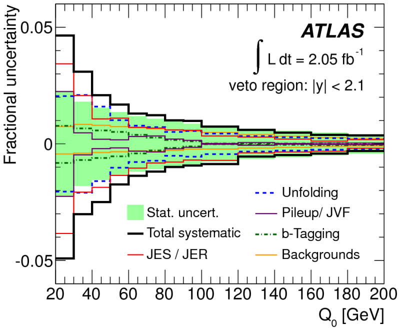

Gap fraction vs. Q_{sum} for veto region: $1.5 < |y| < 2.1$
f_{gap}
ATLAS data
MC (alpha_s_down)
MC (central)
MC (alpha_s_up)
MC / data
Q_{sum} [GeV]

Top production with extra jets and with a veto on central jets have been measured in 7 TeV ATLAS data.

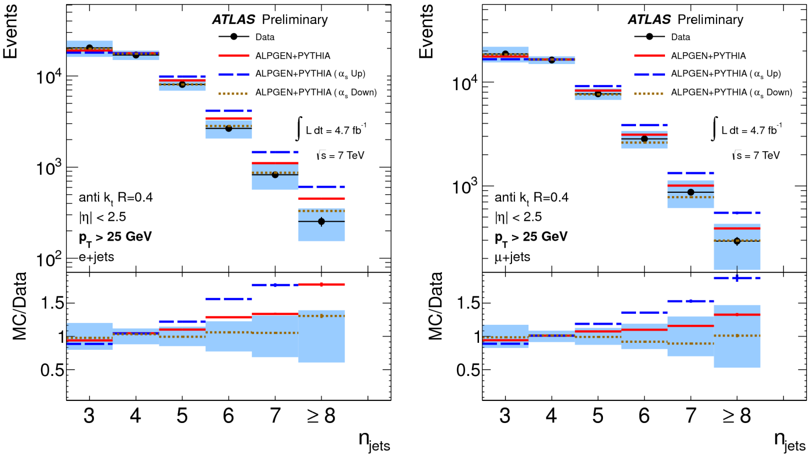
- MC models can describe the data well - jet veto data in the forward region is the least well described region
- Jet veto measurement has been used to define MC samples for QCD I/FSR uncertainty in other ATLAS analyses - `Rivet` analysis available for comparison with any prediction
- Jet multiplicity measurement reaches ≥ 8 jets, currently refining definition of fiducial regions before publication

Extra slides and goodies follow...

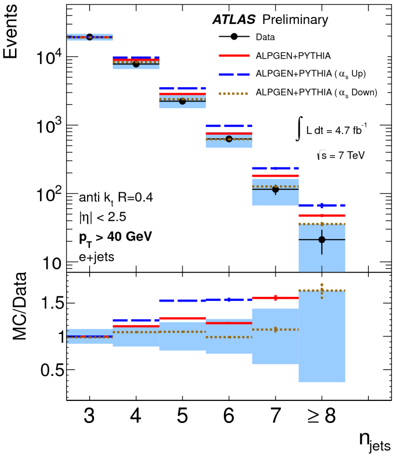

ATLAS
$\int$ L dt = 2.05 fb^{-1}
veto region: |y| < 0.8
Fractional uncertainty
0.04
0.02
0
-0.02
-0.04
20 40 60 80 100 120 140 160 180 200
Q_0 [GeV]
Unfolding
Stat. uncert.
Pileup/ JVF
Total systematic
b-Tagging
JES / JER
Backgrounds

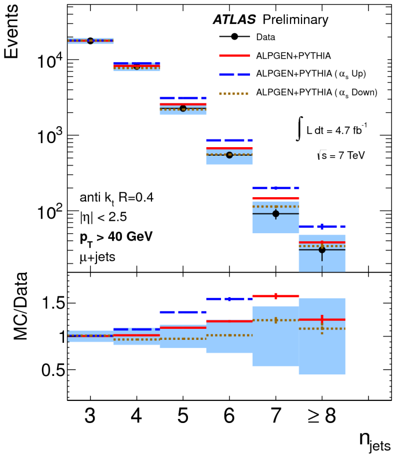

ATLAS
$\int$ L dt = 2.05 fb^{-1}
veto region: |y| < 2.1
Fractional uncertainty
0.05
0
-0.05
20 40 60 80 100 120 140 160 180 200
Q_0 [GeV]
Unfolding
Stat. uncert.
Pileup/ JVF
Total systematic
b-Tagging
JES / JER
Backgrounds

Jet Multiplicity vs Alpgen

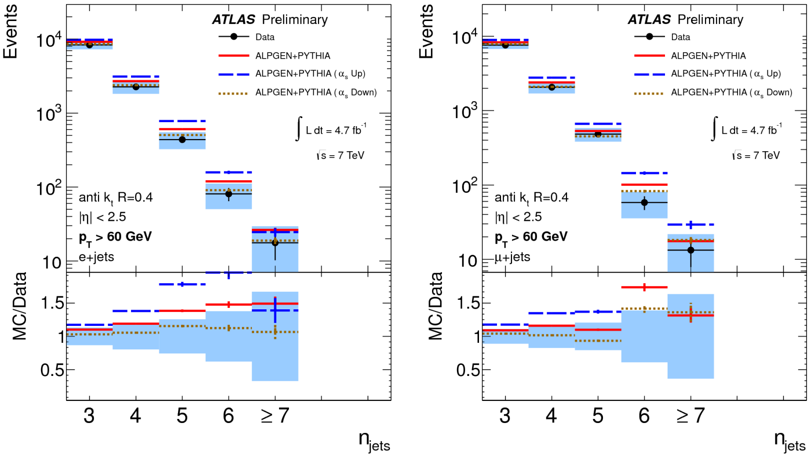


Jet Multiplicity vs Alpgen

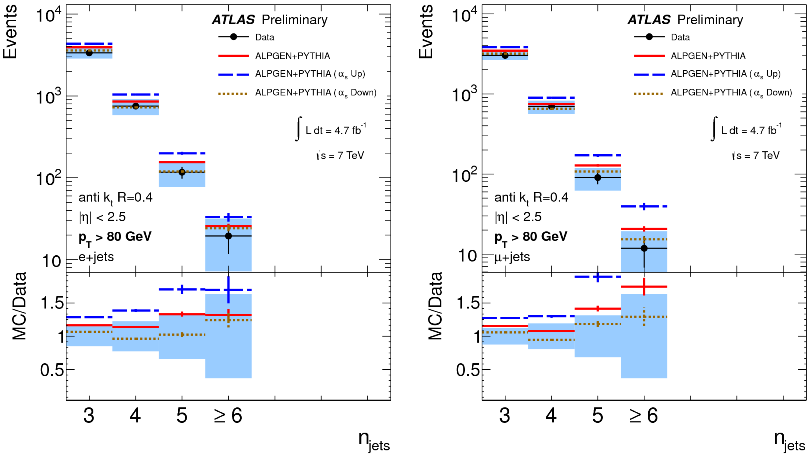




Jet Multiplicity vs Alpgen

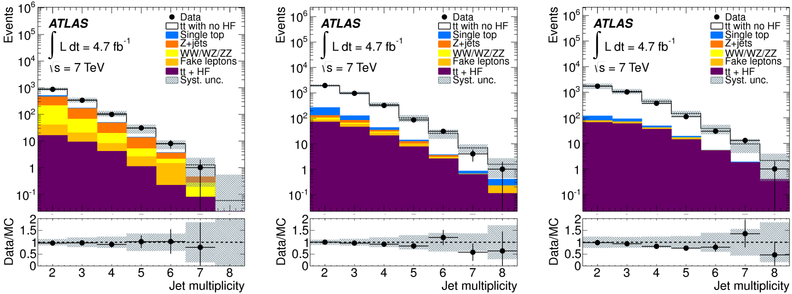


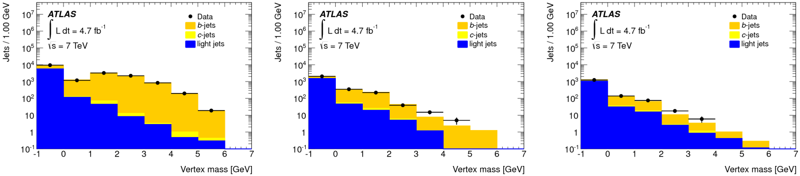
Jet Multiplicity vs Alpgen



A related study of heavy flavor quarks produced in association with top quark pairs: arXiv:1304.6386.

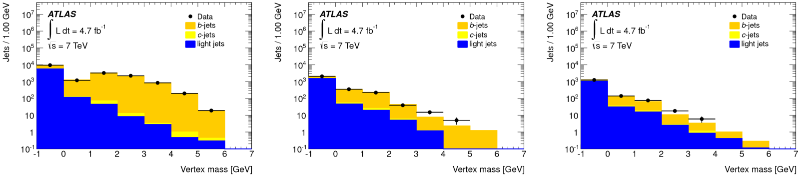
- Dilepton selection
- Fit to secondary vertex mass distribution to obtain fraction of events with extra heavy flavour


ATLAS
$\int$ L dt = 4.7 fb^{-1}
$\sqrt{s}$ = 7 TeV
Data
tt with no HF
Single top
Z+jets
WW/WZ/ZZ
Fake leptons
tt + HF
Syst. unc.
Events
Data/MC
Jet multiplicity

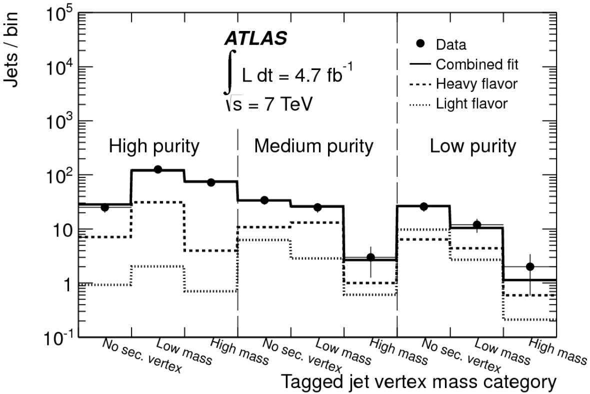


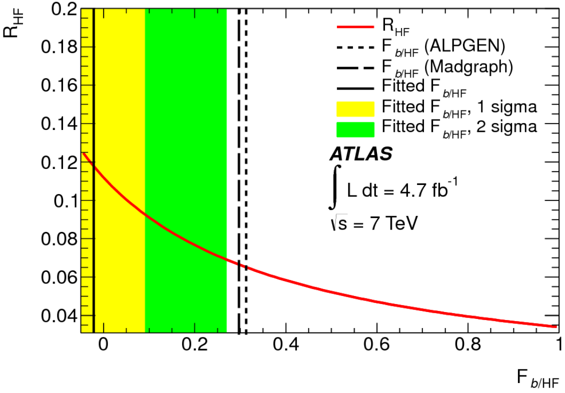
(tight, medium, loose purity b-jets)

$t\bar{t}$+HF



(tight, medium, loose purity *b*-jets)


ATLAS
∫ L dt = 4.7 fb^-1
√s = 7 TeV
Data
Combined fit
Heavy flavor
Light flavor
High purity
Medium purity
Low purity
Jets / bin
No sec. vertex
Low mass
High mass
Tagged jet vertex mass category



$R_{\mathrm{HF}} = 7.1 \pm 1.3$ (stat.) $+5.3$ (syst.) % (ALPGEN: 3.4 ± 1.1 %, POWHEG+PYTHIA: 5.2 ± 1.7 (syst.) %)