Measurements of the production of prompt photons, jets and vector bosons + jets in pp collisions with the ATLAS detector

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on behalf of the ATLAS collaboration

QCD@LHC2016

Zurich - 23 August 2016

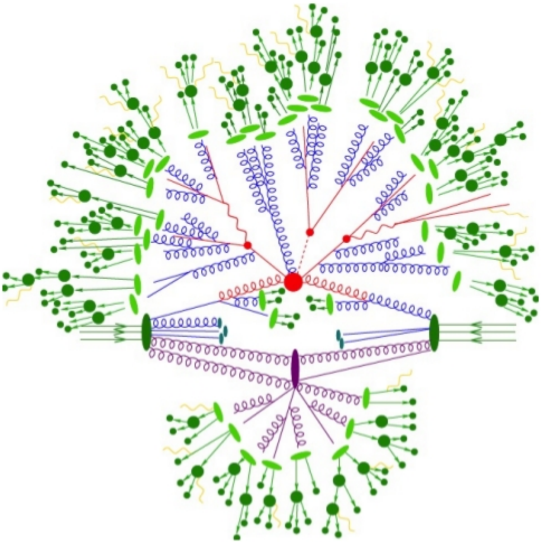
With SM measurements we essentially study the base of LHC physics

Perturbative QCD:

- **Hard interaction**
- **Radiative corrections**

Non-perturbative QCD:

- **Multiple interactions / Underlying event**
- **Hadronization**
- **Hadron decays**



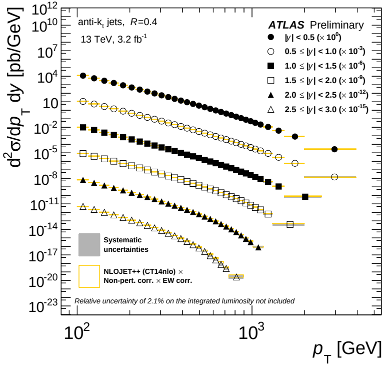
Often SM measurements are very high profile analysis and also the basis of Higgs measurements or BSM searches

Overview of most recent ATLAS cross-section measurements:

- Inclusive-jet at 13 TeV (NEW)
- $Z+$ jets at 13 TeV
- Inclusive photons at 8 TeV
- W boson angular distributions at 8 TeV
- $b\bar{b}$ dijet at 7 TeV

Inclusive-jet cross-sections at $\sqrt{s} = 13$ TeV (NEW) (ATLAS-CONF-2016-092)

Data set:	$\mathcal{L} = 3.2\,\text{fb}^{-1}$ recorded in 2015
Event selection:	Single jet triggers
Jet selection:	Anti-k_t, R $= 0.4$ jets
	$p_T > 100$ GeV
	$\lvert y \rvert < 3$

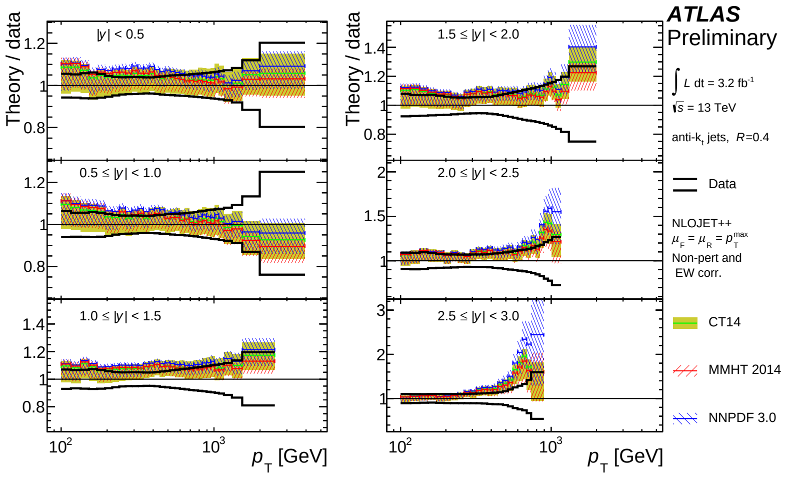


Unfolded measured inclusive-jet cross-sections are compared to NLO QCD calculations corrected for non-perturbative and electroweak effects

The dominant systematic uncertainty of data arises from the jet energy scale calibration

Inclusive-jet cross-sections at $\sqrt{s} = 13$ TeV (NEW) (ATLAS-CONF-2016-092)

Ratio of NLO pQCD predictions to the unfolded inclusive-jet cross-sections



The predictions are in **good agreement** with the Data at $\sqrt{s} = 13$ TeV in the measured kinematic regions

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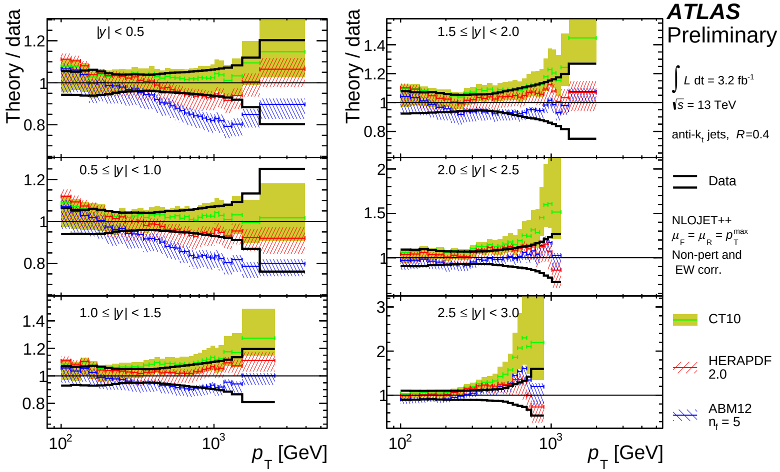


The predictions are in **good agreement** with the Data at $\sqrt{s} = 13$ TeV in the measured kinematic regions

$Z + \text{jets}$ cross-section at $\sqrt{s} = 13$ TeV (ATLAS-CONF-2016-046)

Data set: $\mathcal{L} = 3.16\,\text{fb}^{-1}$ recorded in 2015

Selection of $Z(ee/\mu\mu)$ candidates:

- Single lepton triggers used for online selection
- Reconstruction of isolated charged leptons of $p_{\text{T}} > 25$ GeV in detector acceptance
  - Electrons up to $|\eta| = 2.47$
  - Muons up to $|\eta| = 2.4$

Reconstruct and select jets:

- Anti-k_t $\Delta R = 0.4$
- $p_{\text{T}} > 30$ GeV
- Acceptance up to $|y| < 2.5$

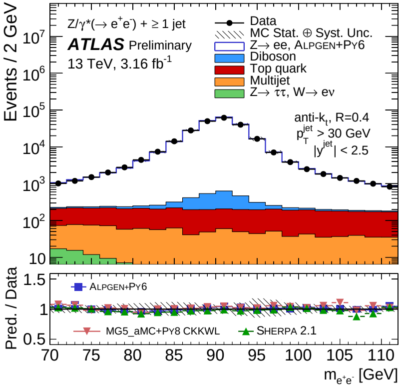
Z boson:

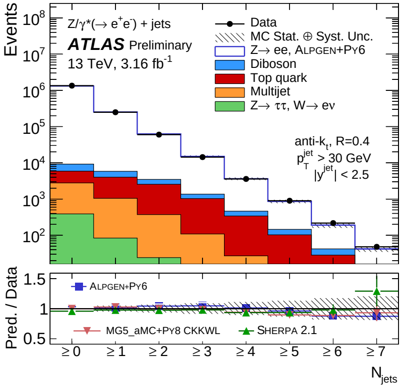
- Two opposite-sign same-flavour leptons within $M_{\ell\ell}$ window around M_Z
- Small backgrounds:
  - Irreducible backgrounds (top-quark, diboson) (% level contamination, estimated w/MC)
  - Multi-jet contamination often negligible, extracted with data-driven methods

$Z+$ jets cross-section at $\sqrt{s}=13$ TeV (ATLAS-CONF-2016-046)

Unfolded data compared to MC simulations or to fixed-order calculations (corrected for non-perturbative effects as fragmentation and underlying event)

Measurement extends up to $Z+7$ jets!





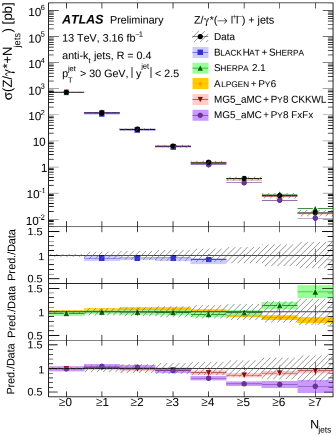
Data uncertainties:

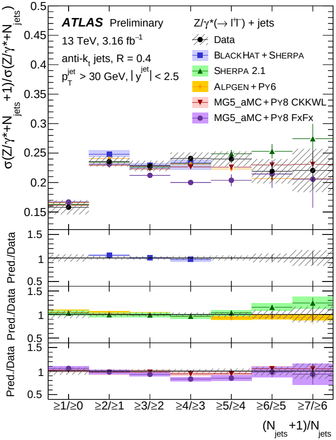
- Main systematic uncertainty comes from jet energy scale calibration and resolution
- Statistical uncertainty negligible with 3.16 fb^{-1} of data

$Z+$ jets cross-section at $\sqrt{s} = 13$ TeV (ATLAS-CONF-2016-046)

Jet multiplicity and ratio of jet multiplicities

- Important test of perturbative QCD predictions
- Discriminating variable for Higgs boson and BSM searches



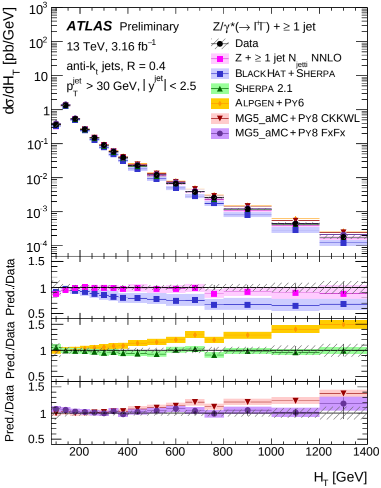


Well reproduced by most of available predictions

$Z + \text{jets}$ cross-section at $\sqrt{s} = 13$ TeV (ATLAS-CONF-2016-046)

$$H_T = \sum_{\ell,\text{jets}} |p_T| :$$

- Used as QCD scale in NLO calculations
- Used in searches for BSM topologies with large jet activity



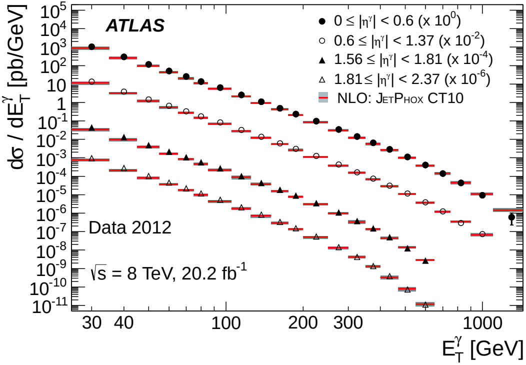
Very good agreement from New NNLO predictions in the full range of H_T!

Very good agreement from NLO predictions (except BLACKHAT+SHERPA) in full H_T range

LO predictions overestimate the cross-section at large values of H_T

Inclusive isolated prompt photon cross-section at $\sqrt{s} = 8$ TeV (arXiv:1605.03495v1)

Data set:	$\mathcal{L} = 20.2\,\text{fb}^{-1}$ recorded in 2012
Event selection:	Single photon triggers
Kinematic region:	$E_T^\gamma > 25\,\text{GeV}$
	$\lvert\eta^\gamma\rvert < 1.37$ and $1.56 \leq \lvert\eta^\gamma\rvert < 2.37$
Isolation:	$E_T^{\text{iso}} < 4.8 + 4.2 \times 10^{-3} \times E_T^\gamma$ GeV

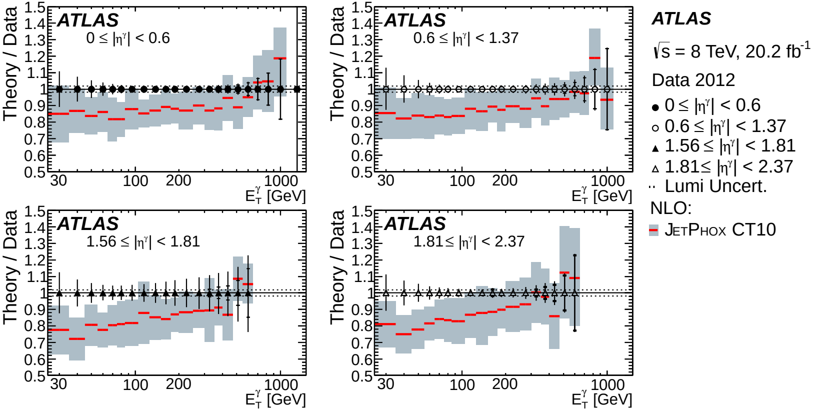


Unfolded data

NLO JetPhox with CT10 PDF set prediction

Inclusive isolated prompt photon cross-section at $\sqrt{s} = 8$ TeV (arXiv:1605.03495v1)

Ratio of theory to data for the differential cross-sections vs E_T^{γ}



The NLO JetPhox calculation for most of the $|\eta^{\gamma}|$ ranges has similar shape but lies below data.

Inclusive isolated prompt photon cross-section at $\sqrt{s} = 8$ TeV (arXiv:1605.03495v1)

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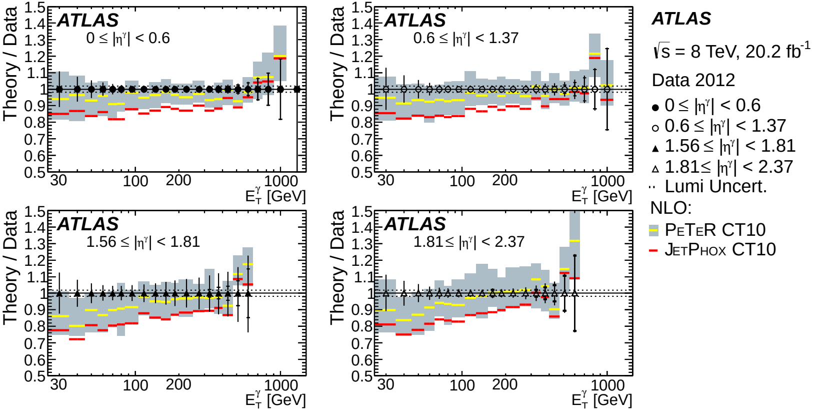


The PeTeR calculation for most of the $|\eta^\gamma|$ ranges has similar shape, lying below data but closer than JetPhox

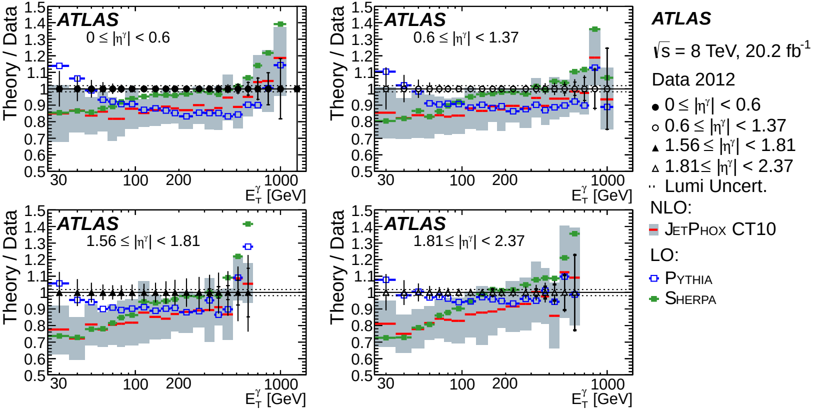
PeTeR: NLO calculation including the resummation of threshold logarithms at the NNNLL level.

PeTeR is roughly equivalent to a fixed-order calculation at NNLO.

Inclusive isolated prompt photon cross-section at $\sqrt{s} = 8$ TeV (arXiv:1605.03495v1)

Ratio of theory to data for the differential cross-sections vs E_T^γ

In addition to JetPhox, LO Pythia8 (CTEQ6L1) and NLO SHERPA (CT10) are shown



LO SHERPA consistent with JetPhox across all the E_T^γ bins

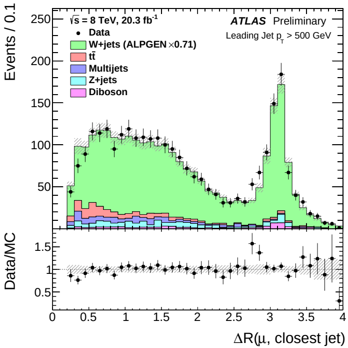
LO Pythia8 consistent with JetPhox except at low E_T^γ

W boson angular distributions in events w/ high p_T jets at 8 TeV (STDM-2015-16)

Collinear W boson emission:

- Will play a significant role in:
  - W+jets measurements at hight p_{T}
  - Searches for BSM physics involving Lorentz-boosted top quarks
  - QCD multijet measurements at very large dijet invariant masses
- At high energies, real emission of weak bosons in dijet events can contribute significantly to inclusive W+jets measurements
- Dominant process for events with $\Delta R = \Delta R(\mu, \text{jet}) = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 2.4$
- This measurement has implications for MC programs incorporating real W boson emission

W boson angular distributions in events w/ high p_T jets at 8 TeV (STDM-2015-16)



In this kinematic regime, contributions to W+jets processes from real W boson emission are enhanced for small ΔR

Data set: $\mathcal{L} = 20.3\,\text{fb}^{-1}$ (2012)

Event selection:

- Studying only $W \to \mu\nu$
- Single muon triggers
- At least one jet with $p_T > 500$ GeV

Muon selection:

- $p_T > 25$ GeV, $|\eta| < 2.4$

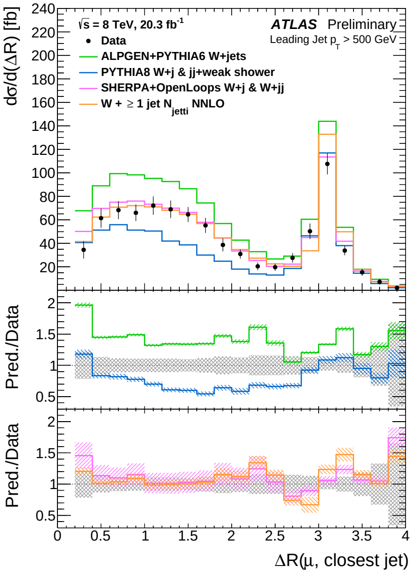
Jet selection:

- Anti-k_t $R = 0.4$
- $p_T > 100$ GeV, $|\eta| < 2.1$

Signal region:

- Isolated muon
  - Reduces significantly dijet background
- Zero b-jets
  - Reduces significantly $t\bar{t}$ background

W boson angular distributions in events w/ high p_T jets at 8 TeV (STDM-2015-16)

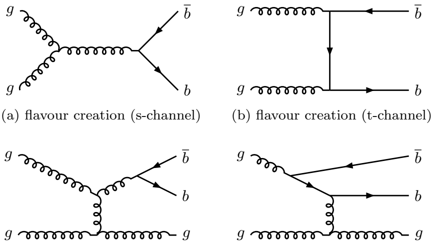


- Unfolded data
- Reasonably small data uncertainties:
  - Dominant systematic uncertainties: jet energy scale (5%) and b-tagging efficiency (3%)
- Substantial differences between theory predictions
- New theory calculations (SHERPA+OpenLoops and NNLO) perform well

b-quark pair production:

- Mixture of production diagrams
- Test heavy flavour pQCD calculations

LO Feynmann diagrams for $b\bar{b}$ production



(a) flavour creation (s-channel) (b) flavour creation (t-channel) (c) gluon splitting (d) flavour excitation

- $\mathcal{L} = 4.2\,\mathrm{fb}^{-1}$ recorded in 2011
- Single-jet triggers
- Two b-jets $p_T > 20$ GeV, $|\eta| < 2.5$
- $p_T^{\text{leading jet}} > 270$ GeV
- Several observables:
  - m_{bb}, p_{Tbb}, $\Delta\phi$, ΔR, $y_B = \frac{1}{2}|y_1 + y_2|$, $y^* = \frac{1}{2}|y_1 - y_2|$
- Different ranges of observables probe different production mechanisms
- For instance:

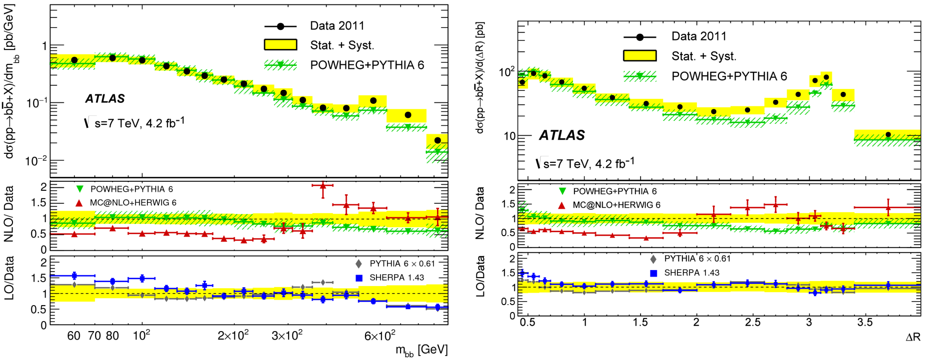
Observable	Dominates
Large m_{bb} Small p_{Tbb}	Flavour creation
Small m_{bb} Large p_{Tbb}	Gluon splitting Flavour excitation

(see also talk “Measurements of heavy flavour production directly or in association with W and Z bosons with ATLAS”, Gabriele Chiodini)

Measurement of the $b\bar{b}$ dijet cross-section at 7 TeV (arXiv:1607.08430v1)

Ratio of the theory predictions to the unfolded data

- Reasonable agreement with POWHEG+PYTHIA 6
- MC@NLO+HERWIG 6 shows significant deviations in all variables
- LO MCs generally reproduce shape of data for most observables (though some bins deviate)



The dominant systematic uncertainties of data arises from the b-tagging (10-30%) and the jet energy scale calibration (10-20%)

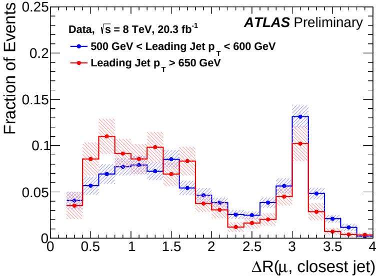
Summary

- Several precision ATLAS measurements have been performed for different observables at various collision energies
- The very new inclusive-jet cross-section measurement at $\sqrt{s} = 13\,\text{TeV}$ was presented
- Cross-section measurements are important to test pQCD calculations
- State-of-the-art theory predictions provide decent description of measured cross-sections, even for the new measurements at centre-of-mass energy of 13 TeV

(If you found Waldo  clap loud!)

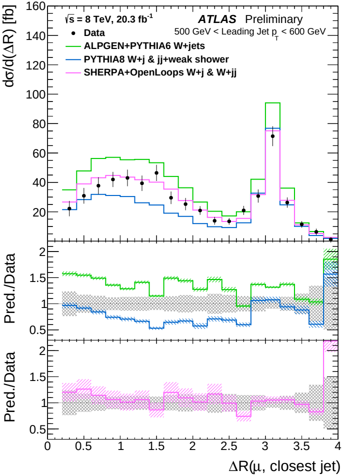
Back-up slides

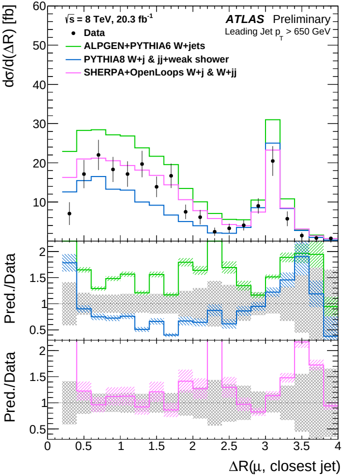
W boson angular distributions in events w/ high p_T jets at 8 TeV (STDM-2015-16)



- Further event selection:
  - 500 GeV $< p_T^{\text{leading jet}} <$ 600 GeV
  - $p_T^{\text{leading jet}} >$ 600 GeV
- Not enough stats to do more p_T ranges
- At high-p_T:
  - Collinear fraction increases
  - Collinear peak also shifts slightly lower in ΔR

W boson angular distributions in events w/ high p_T jets at 8 TeV (STDM-2015-16)

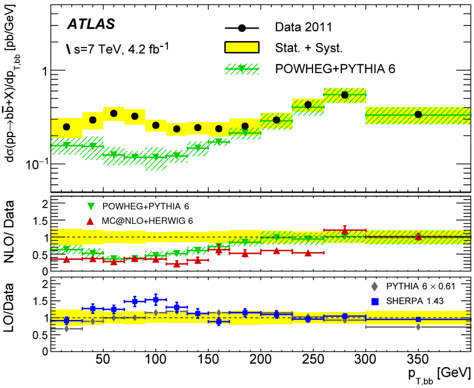


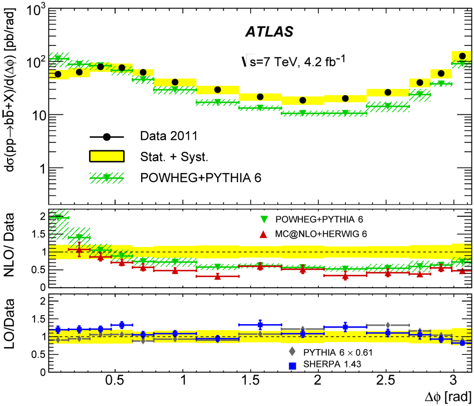


Measurement of the $b\bar{b}$ dijet cross-section at 7 TeV (arXiv:1607.08430v1)

Ratio of the theory predictions to the unfolded data

- Reasonable agreement with Powheg+PYTHIA6 except for low p_{Tbb} and for $\Delta\phi$
- MC@NLO shows significant deviations in all variables
- LO MCs generally reproduce shape of data (though some bins deviate)





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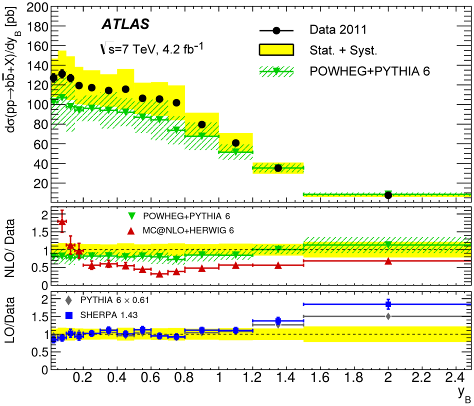
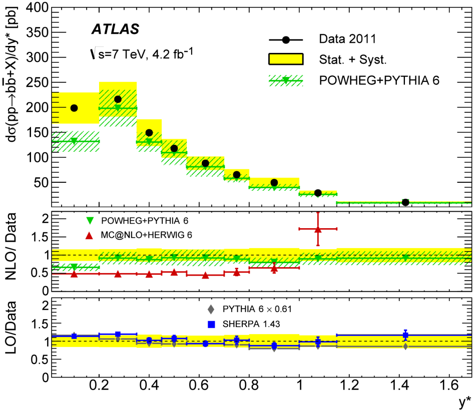




Measurement of the $b\bar{b}$ dijet cross-section at 7 TeV (arXiv:1607.08430v1)

Source	Cross-section relative uncertainty
b-tagging efficiency	10-30%
b-jet template fit	3-8%
Jet energy scale	10-20%
Jet energy resolution	2-8%
Jet angular resolution	1-5%
Unfolding	5-10%
Luminosity	1.8%

Inclusive-jet cross-sections at $\sqrt{s} = 13$ TeV (NEW) (ATLAS-CONF-2016-092)

Non-Perturbative correction:

Considers effects from underlying-event and hadronisation.

- $C_{NP} = \frac{MC(UE\_ON, HAD\_ON)}{MC(UE\_OFF, HAD\_OFF)}$

Electroweak correction:

- NLO pQCD predictions are corrected for the effects of γ and $W^{\pm}/Z$ interactions at the tree and one-loop level
- The correction is defined as the ratio

$$\frac{\sigma\left(2\to 2, \mathrm{LO}^{(\mathrm{QCD})} + \mathrm{NLO}^{(\mathrm{EW})}\right)}{\sigma\left(2\to 2, \mathrm{LO}^{(\mathrm{QCD})}\right)}$$

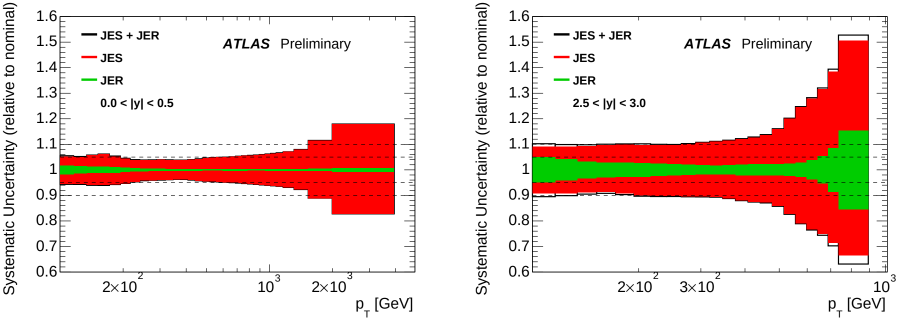
Systematic uncertainty on the unfolding (closure test):

- A data-driven method is used to estimate the bias of the unfolding coming from mismodelling of the truth MC spectrum.

1. Reweight the MC truth spectrum by multipliying each bin with a function chosen to improve the agreement between detector level data/MC.
2. Unfold the modified reco MC spectrum with the original transfer matrix.
3. The difference between the unfolded modified reco MC spectrum and the modified truth MC spectrum is taken as a systematic.

Inclusive-jet cross-sections at $\sqrt{s} = 13$ TeV (NEW) (ATLAS-CONF-2016-092)

Effects of the JES and JER uncertainties on the measured cross-sections propagated through the unfolding



Inclusive-jet cross-sections at $\sqrt{s} = 7$ TeV (arXiv:1410.8857)

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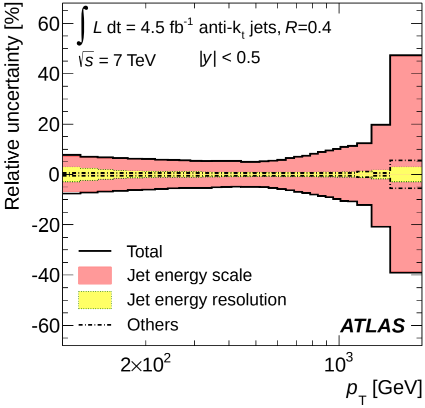
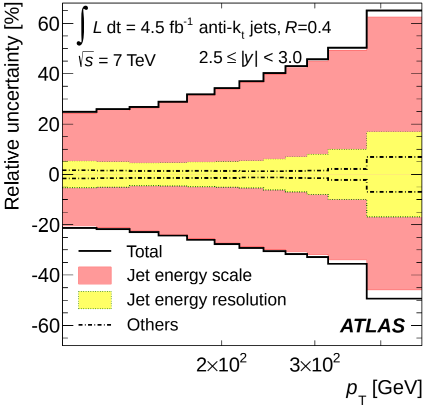
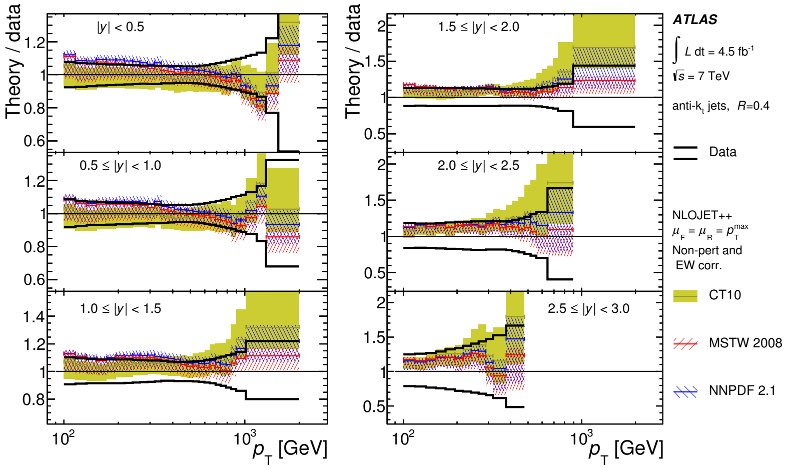




Inclusive-jet cross-sections at $\sqrt{s} = 7$ TeV (arXiv:1410.8857)

Ratio of NLO pQCD predictions to the unfolded inclusive-jet cross-sections



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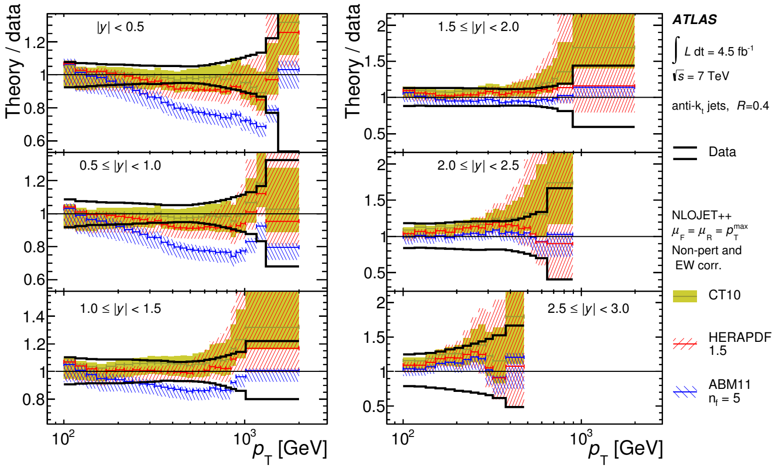
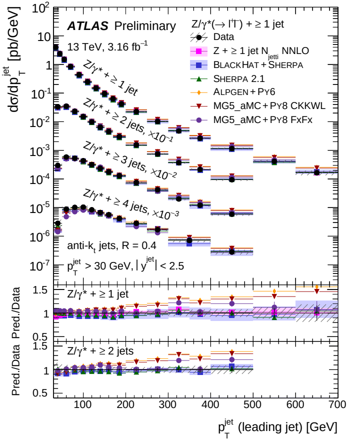
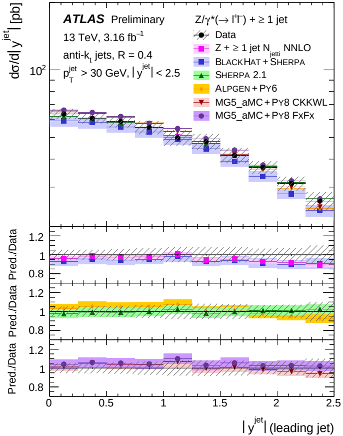


$Z+$ jets cross-section at $\sqrt{s}=13$ TeV (ATLAS-CONF-2016-046)





- Leading jet p_T in $\geq$ 1,2 jets too hard for LO generators at high p_T (large scale uncertainty also expected)
- Leading jet rapidity (sensitive to PDFs) well modeled within uncertainties by all predictions
- NLO and NNLO calculations show very good modelling!

The overlap between leptons and jets is removed in a two-step process:

- Remove jets closer than $\Delta R = 0.2$ to a selected electron, and jets closer than $\Delta R = 0.2$ to a selected muon, if they are likely to be reconstructed from photons radiated by the muon.
- Electrons and muons are discarded if they are located closer that $\Delta R = 0.4$ to a remaining selected jet

$W+ \geq 1$jet at NNLO

- Predictions for the ΔR variable for $W+ \geq 1$jet have been recent calculated
  - see for instance arXiv:1602:06965
- The calculation has been carried out with a new technique for subtraction (n-jettiness) at NNLO. The technique relies on splitting the phase space for the real emission according to the jettiness variable. It also relies heavily on the theoretical machinery of soft-collinear effective theory.

- The calculation uses CT14 NNLO PDFs and a central scale of

$$\mu_0 = \sqrt{\mathrm{M}^2_{l\nu} + \sum_i \left(p_T^{J_i}\right)^2}$$

  has been chosen for both the renormalization and factorization scales
- The calculation is only at the parton level; those partons are clustered with the Anti-k_t jet algorithm. The same p_T and rapidity cut are applied to the partonic jets as to the jets in the data. Similar cuts as applied to the data are applied to the W decay products.

Iterative Bayesian unfolding technique

The iterative unfolding techniue updates the initial estimators for the generated (“truth”) distributions in consecutive steps, using the Bayes theorem in each iteration to derive an unfolding matrix from the initial response matrix (which relates truth and reconstructed distributions of given observables) and the current truth estimator.

A given bin in the response matrix corresponds to the probability that a true jet object is reconstructed in the same or in another bin of the distribution.

The data is corrected for the fraction of events unmatched to any generator object before entering the iterative unfolding.

Inclusive isolated prompt photon cross-section at $\sqrt{s} = 8$ TeV (arXiv:1605.03495v1)

Cross-section:

$$\frac{d\sigma}{d\mathrm{E}_\mathrm{T}^\gamma} = \frac{1}{\int \mathcal{L}\mathrm{dt}\left(\cdot \mathrm{E}_\mathrm{T}^\gamma\right)} \cdot \left(N^{\gamma,\mathrm{data}} \cdot P_\mathrm{signal} - N_{e\to\gamma}\right) \cdot \frac{1}{\epsilon_\mathrm{trig}} \cdot \frac{1}{\epsilon_\mathrm{corr}}$$

Where:

$\epsilon_\mathrm{corr} = \frac{N^\mathrm{MC}_\mathrm{signal}}{N^\mathrm{MC}_\mathrm{particle}}$: unfolding correction factor

$N_{e\to\gamma}$: number of fake photons

ϵ_trig: trigger efficiency

P_signal: signal purity