Results on QCD jet production at the LHC (incl. Heavy flavours)

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“Windows on the Universe”
Outline

- Introduction
- Jet Reconstruction and Calibration
- Jet Cross Sections
- Determination of $\alpha_s$
- Colour Coherence
- Heavy Flavours
- Summary and Conclusions
Introduction - QCD

- LHC is a discovery machine (→ Higgs 1st anniversary)
- Why doing QCD measurements?
  - dominant process at LHC
  - LHC provides previously inaccessible energy regime
  - provides wealth of new measurements
  - constrain PDFs – parton density functions
  - last but not least: main background for many searches
- Why measuring (QCD) Jets?
  - manifest confinement i.e. no free quarks
  - reflect approximately interactions of partons
Introduction - LHC

- excellent performance of LHC over last years
  → huge datasets to analyse
    ATLAS 2012: ~21 fb⁻¹
    2011: ~5 fb⁻¹
    2010: ~50 pb⁻¹

- varying levels of pileup during run 1, from ~zero up to almost 40 coll./xing!

- requires new techniques to deal with pileup
  → in active development
  → some QCD measurements done with low pileup data from (mostly) 2011
  some even from 2010
Jet Reconstruction + calibration

Jet Algorithm: iterative procedure to cluster particles to new pseudo particles based on a measure of distance until a cut-off $R$ is reached.

now anti-$k_T$ recombination scheme commonly used

both ATLAS and CMS have non-compensating calorimeters for hadrons requires dedicated jet energy calibration (JES)

Jet Recontruction + calibration

- Jets reconstructed from electromagnetic clusters of calorimeter cells using Anti-$k_T$ algorithm with $R = 0.4$ and $R = 0.6$
- Jet Energy Scale calibration applied:
  - Jet Energy Scale (JES) dominant experimental uncertainty
  - For the jet energy scale calibration CMS adopted a Factorized approach.

for 2012 new calibration and new pileup subtraction schemes are being developed
Inclusive Jet Cross Section at 8 TeV

CMS Preliminary

JES dominating experimental systematic uncertainty

$\sqrt{s} = 8\text{ TeV}$  anti-$k_T$ $R=0.7$  $L = 10.71\text{ fb}^{-1}$

→ good agreement over several orders of magnitude!

- differences data – MC mostly smaller than systematic uncertainties
- NLO PDF sets agree well with data (except ABM11 – not shown here)
Ratio of Jet Cross Sections at 2.76 TeV and 7 TeV

ATLAS arXiv: 1304.4739

correlations reduce systematic uncertainties such that PDF can be constrained
√s=2.76 TeV, L=0.20 pb⁻¹, anti-k_T with R=0.4 and R=0.6

\[ x_T = 2 \frac{p_T}{\sqrt{s}} \]

\( x_T \) and \( p_T \) have both advantages, \( p_T \) lower experimental systematics due to common uncertainty on JES \( \rightarrow p_T \) preferred observable

this ratio becomes sensitive to constrain PDF \( \rightarrow \) next slide
Gluon contribution to PDF

in general well constrained by PDF fits from HERA data

in this analysis due to large NP uncertainties, jets below 45 GeV excluded in fits

2.76 TeV and 7 TeV considered fully correlated in jet calibration

→ Harder gluon spectrum after including ATLAS data

As a result, sea quark momentum spectrum softer
Ratio of Jet X Sections – different R

CMS PAS SMP-13-002

$$R(0.5,0.7) = \frac{\sigma(R=0.5)}{\sigma(R=0.7)}$$

ratio of unfolded cross sections

R=0.5 jets show bigger deviations (not shown here) → non-perturbative corrections needed to improve description of jets with small radii paronshowers in modern Monte Carlo generators mimick the NP corrections well
Ratio of Jet X Sections – different $N_{\text{jet}}$

ATLAS CONF-2013-041

both $R_{3/2}$ and $N_{3/2}$ have sensitivity to $\alpha_s$

$$R_{3/2}(p_T^{\text{lead}}) = \frac{d\sigma_{N_{\text{jet}}\geq 3}/dp_T^{\text{lead}}}{d\sigma_{N_{\text{jet}}\geq 2}/dp_T^{\text{lead}}}$$

$$N_{3/2}(p_T^{\text{all jets}}) = \frac{\sum_i (d\sigma_{N_{\text{jet}}\geq 3}/dp_T,i)}{\sum_i (d\sigma_{N_{\text{jet}}\geq 2}/dp_T,i)}$$

$N_{3/2}$ has lower sensitivity to variations in scales
→ used to determine $\alpha_s$ shown on next slide
Determination of Running of $\alpha_s$

ATLAS CONF-2013-041

$\alpha_s(M_Z) = 0.111 \pm 0.006 \text{ (exp)} ^{+0.016}_{-0.003} \text{ (theory)}$

previous measurement from CMS with similar technique:

$\alpha_s(M_Z) = 0.1148 \pm 0.0014 \text{ (exp)} \pm 0.0018 \text{ (PDF)} ^{+0.0050}_{-0.0000} \text{ (scale)}$
\(\alpha_s\) measurement from Jet Masses

\[ m_3^2 = (p_1 + p_2 + p_3)^2 \]

\[ y_{\text{max}} = \text{sign} (\max (y_1, y_2, y_3) - \min (y_1, y_2, y_3)) \cdot \max (|y_1|, |y_2|, |y_3|) \]

unfolded spectra agree well with theory over five orders of magnitude and up to \(m_3\) of 3 TeV

running of \(\alpha_s\) agrees well with prediction up to \(Q \sim 1.4\) TeV

initial studies show sensitivity of \(m_3\) to gluon distribution between \(0.05 < x < 0.5\)

\[ \alpha_s(M_Z) = 0.1160^{+0.0025}_{-0.0023} (\text{exp,PDF,NP}) +0.0068_{-0.0021} (\text{scale}) \]
**k_T splitting scales in W->lv**


**k_T jet algorithm:**

\[ d_{ij} = \min \left( p_{T,i}^2, p_{T,j}^2 \right) \frac{\Delta R_{ij}^2}{R^2} \]

\[ \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2 \]

\[ d_{IB} = p_{T_i}^2 \]

**k_T recombination approximates QCD evolution**

Partial cancelation of systematic uncertainties in ratio of splitting scales

Hard QCD regime better described by multi-leg generators ALPGEN+HERWIG / SHERPA

HERWIG PS gives better description for \( \sqrt{d_1/d_0} \) (two hardest branchings)
Colour Coherence

\[ \beta = |\text{atan2} (\Delta \Phi_{23}, \Delta \eta_{23})| \]

anti-kT with R=0.5

colour coherence suppresses particle emission around \( \pi/2 \) and enhances emission at 0, \( \pi \)

\[ \beta = \left| \text{atan2} (\Delta \Phi_{23}, \Delta \eta_{23}) \right| \]

→ colour coherence in MC improves description, but still does not describe it fully can be used for new tuning of MC to further improve description
classify jets according to initial flavour: light quarks (U) and heavy quarks (C) and (B)
6 combinations for di-jets BB, CC, UU and mixed CU, BU, BC
create 2D templates in two kinematic variables for found vertices in jets and fit simultaniously all 6 combinations

good agreement between data and MC prediction for all 6 combinations except BU which is higher for $p_T>100\text{GeV}$ than LO and NLO MC predictions
Jet Shapes in Light & b Quark Jets

ATLAS arXiv: 1307.5749

1.8 fb$^{-1}$ collected beginning of 2011
use $t\bar{t}$ events as source of clean b (from t) and light (from W) jets; di-lepton and single-lepton channels show compatible results and were combined
mild dependence on pseudorapidity of jet; strong dependence on $p_T$ of jet

calculate differential jet shape:

$$\rho(r) = \frac{1}{\Delta r} \cdot \frac{p_T(r - \Delta r/2, r + \Delta r/2)}{p_T(0, R)}$$

$\rightarrow$ light jets are narrower than b-jets and is more pronounced at low jet $p_T$
well MC description of the measurement
Other, New Results not shown

• Jet Substructure
  - grooming, trimming, more aimed pileup suppression as well as searches and investigating heavy particles
    CMS: JHEP 05 (2013) 090

• other Vector Boson + Jets

• complete list of (all) publications available at:
  ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults#Jet_Physics
  CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP
Summary and Conclusions

- many interesting new results in QCD
- in general good agreement with theory predictions
  - few exceptions e.g. heavy and light flavour QCD production
- running of strong coupling constant confirmed well above 1 TeV scale
- QCD well understood at LHC!