Studies of jet cross-sections and production properties with the ATLAS and CMS detectors

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Motivation

- Jets: narrow collimated clusters of stable particles (mainly hadrons) produced by the fragmentation of a hard parton → experimental signature of quarks and gluons.

Jets: signatures and also background for (B)SM processes.
Understanding jet production: pre-condition for many measurements and searches.

- Probe parton substructure: test QCD through wide energy range.
- Probe highest p_T transfers: best handles on searches for new physics.

In this talk: focus on experimental insights onto modeling parton showers and hadronization.

Parton fragmentation:
- Phenomenological models (PYTHIA, HERWIG).
- Matching to fixed order.

Parton shower:
- Soft- and collinear approximations.
- Mismatch between kinematics of virtual and real corrections: soft-gluon resummation.

Hard acattering: pQCD predictions at fixed orders, LO, NLO, NNLO.

Initial State: PDFs.
Jet Performance

- Jets: extended objects, reconstructed using algorithms.
- Require **calibration**, corrections for **pile-up** and **detector effects**.
  - **Anti-\( k_T \)** recombination jet algorithm: collinear and infrared safe (ATLAS and CMS).
- Inputs for jet building: **topological** calorimeter **clusters** (ALTAS), particle candidates identified with **particle flow** algorithm (CMS).
- Distance parameter \( R \): 0.4 and 0.6 (ATLAS); 0.5 and 0.7 (CMS)
- Jet calibration; Factorized, with corrections for **pile-up** and **jet energy scale** (ATLAS and CMS).

\[
d_{ij} = \min\left(k_{\text{ij}}^{2p}, k_{\text{ij}}^{2p}\right) \frac{\delta_{ij}^2}{R^2}
\]

- Both ATLAS and CMS correct to “**particle level**”: remove detector effects, allow **comparison with theory**.
- Measurements are **unfolded** to particle level with a variety of methods (Bayesian, IDS, SVD, bin-by-bin).
- \( p\text{QCD} \) predictions corrected for non-perturbative effects such as fragmentation and hadronization, underlying event.

Jet energy scale: calibrated to about 1% (in the most precise region) in Run-1.
Event Shapes: combinations of hadron momenta in a number related to event geometry → indirect probes of multi-jet topology

\[
T_{\perp,C} \equiv \max_{\hat{n}_T} \frac{\sum_i |\vec{p}_{\perp i} \cdot \hat{n}_T|}{\sum_i p_{\perp i}} , \quad \tau_{\perp,C} \equiv 1 - T_{\perp,C}
\]

Central Transverse Thrust
Sensitive to modelling of two-jet and multijet topologies. For a perfectly balanced two jet event it is zero, while in isotropic multi-jet events it is \((1-2/\pi)\).

Jet Broadenings
Insensitive to contributions from underlying event and hadronization. Sensitive to color coherence effects.

\[
B_{X,C} \equiv \frac{1}{2} \frac{1}{P_{\perp}} \sum_{i \in C_X} p_{\perp i} \sqrt{(\eta_i - \eta_X)^2 + (\phi_i - \phi_X)^2}
\]

Jet Masses
Q: scalar sum of momenta of all jet constituents. Same behavior and dependence as jet broadenings but more sensitive to (initial state) forward radiation.

\[
\rho_X \equiv \frac{1}{Q^2} \left( \sum_{i \in C_X} q_i \right)^2
\]

Third-jet Resolution Parameter
Estimates relative strength of a third jet \(p_T\) with respect to other two jets. Zero for two-jet events, non-zero value indicates presence of hard parton emission. Sensitive to parton showering modelling.
Event Shapes

- Central thrust: generators show overall agreement with data to within 20%.
- Variables sensitive to longitudinal energy flow show larger disagreement between data and theory.

CMS, 5/ fb @ 7TeV, 2011 data, JHEP 10 (2014) 087
Jet Vetoes and Azimuthal Decorrelations in Dijet Events
ATLAS, 36/pb+4.5/fb @ 7TeV, 2010+2011 data, EPJ C74 (2014) 3117

- **Probe** parton evolution using large-$y$ separated di-jets along with veto on a third in-between jet.
- The ratio of the 1st and 2nd moments of the cosine of the $\phi$ separation of the di-jets is particularly sensitive to BFKL effects.
- POWHEG+PYTHIA 8 and HEJ+ARIADNE provide best agreement with data
- POWHEG (BFKL-like) underestimates whereas HEJ (DGLAP-like) overestimates $\phi$ correlation.

**Gap fraction:** $f(Q_0) = \sigma_{jj}(Q_0) / \sigma_{jj}$

**Angular moments:** $<\cos(n(\pi-\Delta\varphi))>, n = 1, 2$
$\Delta\phi$:  
- sensitive to radiation of additional jets,  
- probes dynamics of multi-jet production.

Two leading jets $\Delta\phi$ for 7 regions of jet $p_T$ up to 2.2 TeV.

- Multi-jet 2→4 MC (Madgraph + Pythia6) agrees with data throughout whole $\Delta\phi_{Dijet}$ region.
- LO MCs HERWIG++, PYTHIA8 and POWHEG overestimate data for $\pi/2 < \Delta\phi_{Dijet} < \pi$.
- PYTHIA6 and HERWIG++ systematically overshoot data, in particular around $\Delta\phi_{Dijet} = 5\pi/6$. 

Measurement of dijet azimuthal decorrelations 
CMS, 19.7/fb @ 8TeV, 2012 data, CMS-PAS-SMP-14-015
Measurement of double differential cross section:

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

\[ |y|_{\text{max}} = \max(|y_1|, |y_2|, |y_3|) \]

- Sensitive to PDFs and \( \alpha_s \) (see dedicated talks)
- Require jet \( p_T > 100 \) GeV
- Two rapidity bins: \( |y|_{\text{max}} < 1 \) and \( 1 < |y|_{\text{max}} < 2 \)
- Scale choice: \( \mu_R = \mu_F = m_3/2 \)
- Good agreement with pQCD at NLO.

Best agreement with CT10-NLO PDF.

CT10-NLO

\[ \text{Anti-} k_t \ R = 0.7 \]

\[ 5.0 \text{ fb}^{-1} \ (7 \text{ TeV}) \]
3-Jet cross-section

Measurement of Three-jet Production Cross-sections
ATLAS, 4.5/fb @ 7TeV, 2011 data, EPJ C75 (2015) 228

- 3 leading jets with pT>150, 100, 50 GeV respectively in rapidity region |y|<3.
- Double differential cross section as function of $m_{jjj} = \sqrt{((p_1 + p_2 + p_3)^2)}$ in slices of $|Y^*| = |y_1 - y_2| + |y_2 - y_3| + |y_1 - y_3|$
- Scale: $\mu_R = \mu_F = m_{jjj}$.
- Two distinct jet radius parameters.

- Good agreement for R=0.4.
- ABM11 PDF yield systematically lower predictions, in particular in low rapidity region.

- Prediction/data ratio for R=0.6 is shifted towards lower values.
Measurement of Four-jet Differential Cross-sections

- Detailed study of **four-jet topologies**: differential measurements in several variables depending on the jet momenta and angular distributions.
- Unfolded measurements compared to various MC generators and fixed order predictions.
- Measurements test QCD predictions up to scale $H_T \sim 7$ TeV with $p_{T1}$ reaching 3 TeV, $p_{T2} \sim 2.5$ TeV, $p_{T3} \sim 2$ TeV, $p_{T4} \sim 1.5$ TeV.

- $\Delta \phi$ very sensitive to soft emissions.
- Good overall agreement between data and MC.

Total experimental uncertainty $\sim 8\% – 12\%$
4-Jet cross-section


Jets are reconstructed with anti-$k_t$ $R=0.4$.

- **LO MC**: PYTHIA, HERWIG and MADGRAPH+PYTHIA.
- **NLO pQCD**: Blackhat/Sherpa and NJet/Sherpa.
- **HEJ** also used: Fully exclusive MC generator. Approximates matrix element to all orders for jet multiplicities of two or greater. Approximation exact for large separation in rapidity between partons.

- $m_{4j}$ well described by NLO up to 3 TeV and by HEJ at high masses.
- NLO uncertainties relatively large, $O(30\%)$ at low momenta.
Topological variables sensitive to QCD color factors, gluon spin structure, and hadronization models.

- Best descriptions: Pythia8 (3-jet mass), Madgraph ($x_3$, $x_4$).
- Data-MC differences possibly due to missing higher multiplicities.
Multi-Jet Topologies

CMS, 5/fb @ 7TeV, 2011 data, EPJ C75 (2015) 302

Four-jet Variables

- four-jet mass

\[ E_{CM} = \sqrt{s} \]

Bengtsson–Zerwas angle

\[ \cos \chi_{BZ} = \frac{\vec{p}_3 \times \vec{p}_4 \cdot (\vec{p}_5 \times \vec{p}_6)}{|\vec{p}_3 \times \vec{p}_4||\vec{p}_5 \times \vec{p}_6|} \]

Nachtmann–Reiter angle

\[ \cos \theta_{NR} = \frac{(\vec{p}_3 - \vec{p}_4) \cdot (\vec{p}_5 - \vec{p}_6)}{|\vec{p}_3 - \vec{p}_4||\vec{p}_5 - \vec{p}_6|} \]

- Good overall data-MC agreement.
- Specific regions have less good agreement or large uncertainties.
Jet charge: momentum-weighted sum of the charges of tracks associated to a jet.

- sensitive to charge of initiating quark or gluon.
- depends on jet flavor, energy-dependence of PDFs and fragmentation functions.
- can provide constraint on models of jet formation.

Average charge expected to increase with jet $p_T$ (increase in up-flavor jets).

**Dijets events:**
- Jet $p_T > 50$ GeV,
  $p_{T1}/p_{T2} < 1.5$,
- $|\eta_{jet}| < 2.1$
- Tracks for reco-jet + charged particles for particle-jets.
- Track multiplicity and JES are the major systematics.

**Comparison with NLO/LO MCs for more central (left) and forward (right) jets.**
- Data consistently above predictions, possibly due to fragmentation modelling (not PDFs alone).

$Q_J = \frac{1}{(p_{TJ})^\kappa} \sum_{i \in \text{Tracks}} q_i \times (p_{T,i})^\kappa$

$k$ regulates sensitivity to soft radiation (0.3, 0.5 and 0.7 considered)
Using fractions of up/down quarks information computed in the MC, the charge of up/down quark initiated jets is extracted from data.

\[ \frac{p_T}{dQ_{\kappa}} < Q_{\kappa} > = \frac{\alpha_s}{\pi} P_{qq}(\kappa) = c_{\kappa} \]

\[ \langle Q_i \rangle \approx \sum_f \alpha_{f,i} \tilde{Q}_f \left( 1 + c_{\kappa} \log p_T / \bar{p}_T \right) \]

\[ \alpha_{f,i} \text{ : flavour fraction in the } i\text{-th } p_T \text{ bin} \]

\[ Q_f \text{ : mean charge at fixed } p_T = 700 \text{GeV} \]

Data supports prediction that \( c_{\kappa} < 0 \) and \( \frac{\partial c_{\kappa}}{\partial \kappa} < 0 \).
Transverse energy-energy correlation (TEEC):

- Event shape used in $e^+e^-$, adapted to pp.
- Exhibits quadratic dependence on $\alpha_s$.

Measures angular distributions of jet pairs weighted by $E_T^1 E_T^2 / (\Sigma E_T)^2$

- Its asymmetry (ATEEC) is also studied.

- At least two jets with $p_T > 50$ GeV
- $p_{T1} + p_{T2} > 500$ GeV
- $|y_{\text{jet}}| < 2.5$

Total uncertainty $\sim 5\%$, dominated by jet energy scale, pileup and MC parton-shower modelling.

Comparisons with LO MCs: Pythia/Alpgen predictions agree reasonably well with data, Herwig++ deviates from data by up to 20%.
Transverse Energy-energy Correlations

Good agreement with NLO pQCD calculations including non-perturbative corrections.

- Small sensitivity to non-perturbative effects.
- Very good experimental precision.
- Theoretical scale uncertainty dominate over experimental uncertainties.

\[ \alpha_s(m_Z) \] extraction: \( \chi^2 \) fit of NLO predictions to data.

\[ \alpha_s(m_Z) = 0.1173 \pm 0.0010 \, (\text{exp.}) \pm 0.0006^3 \cdot 0.0020 \, (\text{scale}) \pm 0.0017 \, (\text{PDF}) \pm 0.0002 \, (\text{NPC}) \]

**ATLAS**

Experimental Uncertainty
Total Uncertainty
PDG Total Uncertainty

ATLAS Energy Energy Correlations
ATLAS \( N_L \)
Malaeuscu & Starovoitov ATLAS Inclusive jet
CMS \( R_{\text{Z}} \)
CMS inclusive jet cross section
CMS 3-jet mass
CDF Inclusive jet cross sections
D0 Inclusive jet cross sections
D0 Jet angular correlations
ZEUS Inclusive jet cross sections in \( \gamma p \)
H1 Multijet production at high \( Q^2 \) in \( ep \) collisions
H1 + ZEUS Inclusive jet cross sections in \( ep \) collisions
H1prelim-07-132, ZEUS-prel-07-025
World average 2014

Excellent compatibility with World average.
Conclusion

- Jets are the most abundant high $p_T$ final state in hadron colliders.
- Understanding jet production essential to physics at the LHC.
- Perturbative QCD predictions, parton shower approximations and hadronization models need to be extensively tested.
- Performance of LHC detectors allows for precision jet physics.

- Studies of event shapes, 3- and 4-jet cross sections and topological distributions in multijet events allow extensive testing of MC simulation.
- Overall good data-MC agreement, Pythia8 does well at LO.
- NLO simulation: generally best performance, but scale uncertainties an issue.

- Azimuthal Decorrelations with Jet Vetoes show potential to probe BFKL effects.
- Jet charge measurements can correlate to charge of original partons.
- TEEC allow precise extraction of strong coupling constant.

- Run 1 analysis still ongoing, Run 2 data arriving fast.
- Meanwhile, look for more QCD results in other talks:
  - Overview of QCD measurements at high $p_T$
  - The 2015 World Summary of $\alpha_s$
  - Early Run 2 Hard QCD Results from the ATLAS Collaboration