Recent QCD results from the LHC

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QCD interactions

Our knowledge of soft and hard QCD processes has a direct impact on the potential for precision measurements and discoveries.

We probe different aspects of QCD predictions to improve the understanding of SM physics and enhance our potential for new physics.

QCD interactions

Our knowledge of soft and hard QCD processes has a direct impact on the potential for precision measurements and discoveries.

How?
Measure jet production, in association or not with heavy objects (W/Z)

- test pQCD calculations and non-perturbative effects
- extract $\alpha_s$
- constraint PDF
- test MC generators

Outline

• Overview of recent (and selected) results of hard QCD from the 4 LHC experiments:
  – Jet production cross-sections
  – Measurement of $\alpha_S$
  – V+j studies

Complete list of public results:
  ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
  ALICE: https://twiki.cern.ch/twiki/bin/view/ALICEpublic/ALICEPublicResults

• Soft QCD → covered by Alessia Bruni's talk

Thanks to all physics coordination teams for their support
Jet production cross-sections

Jet production cross-sections are excellent probes of QCD and its modeling over many orders of magnitudes

LHC is (also) a jet-factory:
• Most typical high-p_T object
• Different jet clustering algorithm radii used to probe interplay between Hard and Soft QCD effect
• Perfect to measure jet rates, normalized cross sections, correlations between jets and multi-dimensional differential cross sections

with Hera, Tevatron and LHC → covering scales from few GeV to multi-TeV
Inclusive jet cross section, pp at 2.76 TeV

The double-differential inclusive jet cross section, 2013 data at 2.76 TeV
Six $|y|$ bins (0.0 - 3.0), $p_T$ range 74 - 592 GeV
Jets algorithm anti-$k_t$, $R=0.7$
Compared with theoretical predictions (NLOJET++) for five different sets of PDF

A theory-normalized cross section ratio is calculated using 2.76 TeV and 8 TeV measurements.

Precise test of QCD at different $\sqrt{s}$s and input to PDF fits [ATLAS 2.76TeV/7TeV[EPJC(2013)73 2509]

CMS 2.76 TeV / 8 TeV ratio → good agreement with NLO theory
Differential charged jet cross sections, jet fragmentation distributions, and jet shapes in minimum bias proton-proton collisions.

Jets reconstructed from charged particle momenta with three different jet finders: sequential recombination $k_t$, anti-$k_t$ and the SISCone jet finding algorithms (R=0.2 to 0.6).

Differential jet production cross-sections are in agreement in the 20-100 GeV $p_T$ range.

In the high $p_T$ range, PYTHIA Perugia-2011 describes the data best, while in the low $p_T$ range data is best described by HERWIG and PHOJET.
Two leading jets $\Delta \Phi$ for seven regions jet $p_T$ up to 2.2 TeV.

The di-jet azimuthal de-correlation is sensitive to the radiation of additional jets and probes the dynamics of multi-jet production.

Results are compared to perturbative QCD and to simulations using various Monte Carlo including NP corrections (parton showers, hadronization, and multi-parton interactions)

Good agreement with 3-jet NLO calculation (NLOJet++)

Multi-jet 2→4 MC (Madgraph +Pythia6) provides best description overall
4-jet cross section differential in several variables depending on jet momenta and angles

\[ \Delta \phi_{ijk}^{\text{min}} = \min_{i,j,k \in \{1,4\}} (|\Delta \phi_{ij}| + |\Delta \phi_{jk}|) \]

Jets are reconstructed with anti-\(k_\text{T}\) \(R=0.4\)

Differential cross sections compared to leading-order (Pythia8, Herwig++, MadGraph5) and next-to-leading order calculations.
Overall excellent description of Njet/Sherpa
MadGraph+Pythia: good description of the variables in most regions of phase space
Jet cross-sections at 13 TeV!

Inclusive-jet cross sections in $|y|<0.5$ for anti-$k_t$ jets with $R=0.4$, shown in a range of $350 < p_T < 840$ GeV

NLO pQCD predictions are compared to the data, where the predictions are calculated using NLOJET++ with the CT10 NLO PDF set, (non-perturbative corrections applied)
\[ \alpha_s \] measurements

\[ \alpha_s \] is a fundamental QCD quantity which can be extracted from many QCD measurements:

- Inclusive jet cross section, 3-jet mass, 3-jet to 2-jet cross section ratio (\( R_{32} \)), event shapes, tt cross-section etc.

LHC allows the evolution of the strong coupling in the TeV region to be explored.
Comparison of the $\alpha_s(Q)$ evolution as determined from the inclusive jet analysis (solid curve with yellow uncertainty band) to measurements from electron-proton, and proton-(anti)proton collider experiments. Covered range in $Q$ up to $\sim 1.4$ TeV.
MultiJet transverse energy–energy correlation and its asymmetry

arXiv:1508.01579

Transverse energy–energy correlation function and its asymmetry

\[
\frac{1}{\sigma} \frac{d\sigma^{\text{asy}}}{d\cos \phi} = \frac{1}{\sigma} \frac{d\sigma}{d\cos \phi} |_{\phi} - \frac{1}{\sigma} \frac{d\sigma}{d\cos \phi} |_{\phi - \pi}
\]

In good agreement with pQCD NLO calculations including non-perturbative corrections.

High energy jets \((<E_T>\text{ of 2 leading jets}> 250)\)

Fit at \(Q=M_Z\):

\[
\alpha_s(m_Z) = 0.1173 \pm 0.0010 \text{ (exp.)}^{+0.0063}_{-0.0020} \text{ (scale)} \pm 0.0017 \text{ (PDF)} \pm 0.0002 \text{ (NPC)}
\]
Excellent compatibility of latest results with the World Average and with jet-based measurements at hadron and e-p colliders.
Vector Boson production
Perfect benchmark measurement for QCD and EW processes.

Total cross sections
- $W \times \mathrm{BR}(W \to l\nu)$
- $Z \times \mathrm{BR}(Z \to ll)$

Dataset: 85 pb$^{-1}$

Theoretical predictions available up to NNLO in QCD, and include EW corrections at NLO accuracy: Fewz3.1 with 4 PDFs.
Vector Boson + jets production

V+jets probe different aspects of QCD calculations

Sensitivity to:
- soft physics description
- merging techniques in soft/mid-scales
- QCD/QED corrections at harder scales

Larger cross-sections at LHC and larger integrated luminosity, different Bjorken-x, parton densities and subprocesses

High experimental accuracy → RunI discrepancies observed have been used to improve calculations
- NLO calculations up to W+5 partons
- NNLO for W/Z+1 parton
- NLO MC matched to Parton Showering
W + jets differential cross-sections @7 TeV

In general good agreement with the predictions

Disagreement in:
• $p_T$ of the leading jets at high $p_T$
• $H_T$ at high-$H_T$ and low jet multiplicity
• difference in azimuthal angle between the leading jet and the muon
• $M_{jj}$ distributions (for $N_{jets} \geq 2$)
Double differential cross section vs. $p_T$ and $y$ of the leading jet at 8 TeV
$Z \rightarrow \mu\mu$. Jets reconstructed in an extended rapidity region, $|y| < 4.7$
Black lines: LO+PS MADGRAPH predictions normalized to the inclusive NNLO cross-section.
Blue band: NLO + PS SHERPA2 prediction shown with the statistical uncertainties

Discrepancies observed with MADGRAPH mainly for jet $p_T > 100$ GeV
Overall agreement with SHERPA 2, except some discrepancies in specific $p_T/y$ regions.
The agreement with theory improves in Rjets wrt single measurements, but significant discrepancies remain in some regions of phase space.

Differential cross-section ratio of $Z+$jets over $\gamma+$jets for central bosons @ 8 TeV ($Z \rightarrow \mu\mu$)

Theory tends to overshoot the data.

Differential cross-section ratio of $W+$jets and $Z+$jets (Rjets) @ 7 TeV (electron and muon channels combined)

The agreement with theory improves in Rjets wrt single measurements, but significant discrepancies remain in some regions of phase space.
**V + jets summary ATLAS**

**Vector Boson + X Cross Section Measurements**

- $\sigma^{\text{fid}}(Z \rightarrow \tau\tau)$
  - $[n_{\text{jet}} \geq 1]$,
  - $[n_{\text{jet}} \geq 2]$,
  - $[n_{\text{jet}} \geq 3]$,
  - $[n_{\text{jet}} \geq 4]$,
  - $[n_{b-\text{jet}} \geq 1]$,
  - $[n_{b-\text{jet}} \geq 2]$,
  - $\sigma^{\text{fid}}(Z \rightarrow \tau\tau)$

- $\sigma^{\text{fid}}(W \rightarrow ev, \mu\nu)$
  - $[n_{\text{jet}} \geq 1]$,
  - $[n_{\text{jet}} \geq 2]$,
  - $[n_{\text{jet}} \geq 3]$,
  - $[n_{\text{jet}} \geq 4]$,
  - $[n_{b-\text{jet}} \geq 1]$,
  - $[n_{b-\text{jet}} \geq 2]$,

- $\sigma^{\text{fid}}(W^{+}\rightarrow q\bar{q})$
  - $[n_{\text{jet}} \geq 1]$,
  - $[n_{\text{jet}} \geq 2]$,
  - $[n_{\text{jet}} \geq 3]$,
  - $[n_{b-\text{jet}} \geq 1]$,

**ATLAS Preliminary**
Run 1 $\sqrt{s} = 7, 8$ TeV

- **Observed/theory Ratio for several single-boson production cross section measurements**
  - theoretical expectations all calculated at NLO or higher
  - the dark-color error bar represents the statistical uncertainty.
  - the lighter-color error bar represents the full uncertainty (systematics and luminosity uncertainties)

**Observed**

<table>
<thead>
<tr>
<th>Observed stat</th>
<th>stat+syst</th>
</tr>
</thead>
<tbody>
<tr>
<td>[\sigma^{\text{ fid}}(Z \rightarrow \tau\tau, [n_{\text{jet}} \geq 1])]</td>
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**Theory**

- **LHC pp $\sqrt{s} = 7$ TeV**

- **LHC pp $\sqrt{s} = 8$ TeV**

- **MCM (MCFM)**

**QCD@LHC 2015 - London**

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V + jets summary CMS

Mar 2014

Production Cross Section, $\sigma$ [pb]

CMS Preliminary

- 7 TeV CMS measurement ($L \leq 5.0$ fb$^{-1}$)
- 8 TeV CMS measurement ($L \leq 19.6$ fb$^{-1}$)
- 7 TeV Theory prediction
- 8 TeV Theory prediction

Fiducial W and Z os with $W \rightarrow l\nu$, $Z \rightarrow ll$ and kinematic selection
**Z + jets @ 13TeV**

*Fresh from the press!*

Cross section for the production of a Z boson in association with jets (up to 4) at 13 TeV

**ATLAS-CONF-2015-041**

**Good agreement between data and MC predictions, i.e. Sherpa (ME+PS@NLO) and Madgraph (LO)**

MC events normalised to inclusive Z at NNLO.
Theoretical uncertainties on $W/Z+\text{heavy flavor}$ jets are larger than for light jets, because of:

- heavy-quark content in the proton
- modeling of gluon splitting (initial state, final state)
- massive vs massless $b$-quark in calculations

Important processes to be studied → background to Higgs and new physics searches

Allow the test of QCD predictions with various implementations (LO multileg+PS, NLO, NLO+PS)
W + jets (heavy flavor)

W + light-jet, W + b and W + c in forward region

LHCb

Events: W→ μν with 2.0<|ημ|<4.5 and 2.2<|ηjet|<4.2 and p_T^jet>20 GeV

7 TeV + 8 TeV

• W+c/W+j and W+b/W+j ratios consistent with NLO QCD (4-flavor scheme MCFM with CT10 PDF)

• Charge asymmetry for W + c lower than predicted:
  – larger strange-quark contribution or ss_{bar} asymmetry?

• All measurements in agreement with SM

\[ A(W_q) \equiv \frac{\sigma(W^q) - \sigma(W^{-q})}{\sigma(W^q) + \sigma(W^{-q})}. \]

\[
\begin{array}{cccccc}
\text{Results} & & & & \text{SM prediction} & \\
\text{7 TeV} & \text{8 TeV} & \text{7 TeV} & \text{8 TeV} & \\
\hline
\sigma(W_b) \times 10^2 & 0.66 \pm 0.13 \pm 0.13 & 0.78 \pm 0.08 \pm 0.16 & 0.74^{+0.17}_{-0.13} & 0.77^{+0.18}_{-0.13} \\
\sigma(W_c) \times 10^2 & 5.80 \pm 0.44 \pm 0.75 & 5.62 \pm 0.28 \pm 0.73 & 5.02^{+0.80}_{-0.69} & 5.31^{+0.87}_{-0.52} \\
\hline
A(W_b) & 0.51 \pm 0.20 \pm 0.09 & 0.27 \pm 0.13 \pm 0.09 & 0.27^{+0.03}_{-0.03} & 0.28^{+0.03}_{-0.03} \\
A(W_c) & -0.09 \pm 0.08 \pm 0.04 & -0.01 \pm 0.05 \pm 0.04 & -0.15^{+0.02}_{-0.04} & -0.14^{+0.02}_{-0.03} \\
\hline
\sigma(W_{+j})/\sigma(Z_j) & 10.49 \pm 0.28 \pm 0.53 & 9.44 \pm 0.19 \pm 0.47 & 9.90^{+0.28}_{-0.24} & 9.48^{+0.16}_{-0.33} \\
\sigma(W_{-j})/\sigma(Z_j) & 6.61 \pm 0.19 \pm 0.33 & 6.02 \pm 0.13 \pm 0.30 & 5.79^{+0.21}_{-0.18} & 5.52^{+0.13}_{-0.25} \\
\end{array}
\]
Production of a Z boson in association with at least one b-jet

\[ Z \rightarrow ee, \mu\mu \]

Studies of observables characterizing the b jet and Z boson kinematics

Cross section ratio R for the leading p_T jets between Z(1b) and Z+jets compared to MadGraph 5FS, MadGraph 4FS and POWHEG:
- MadGraph 4FS fails in reproducing the shape
- All other distributions of inclusive Z+jets (b included) are in good agreement
• RunI LHC data allowed our knowledge on QCD to be pushed forward on many fronts, exploring a wide kinematic range
  – scale dependence of $\alpha_s$ tested to the TeV energy scale
  – Jet production to multi-TeV scale
  – $V+$jets to high jet multiplicity
• New results continue to flow in from Hera, Tevatron and LHC, more and more precise, prompting further theoretical developments on QCD

• With the expected RunII data (statistics and energy range)
  – provide further insight on QCD dynamics (higher x PDFs, probe higher order pQCD corrections …)

Looking forward to LHC RunII full fledged results
Backup slides
Jet charge studies

Inclusive dijet events, average jet charge as a function of the more forward jet $p_T$ (for $\kappa=0.3, 0.5, \text{ and } 0.7$)

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

Jet charge: momentum-weighted sum of the charges of tracks associated to a jet

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

Average jet charge for the more forward jet compared with theory predictions with various PDF sets.
Prompt D meson and non-prompt $J/\psi$ yields studied as a function of the multiplicity of charged particles.

D-meson relative yield is found to increase with increasing charged-particle multiplicity.

The fraction of non-prompt $J/\psi$ in the inclusive $J/\psi$ yields shows no dependence on the charged-particle multiplicity at central rapidity.