QCD Results with Jets and Photons
On Behalf of the CMS Collaboration

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23rd Rencontres de Blois Particle Physics and Cosmology
May 28 – June 3 2011
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Introduction

• QCD measurements with Jets and Photons are of great important in order to:
  
  – Test pQCD in a new energy regime, in a totally unexplored kinematic region.

  – Tune Monte Carlo generators in order to better describe the data.

  – Commission and understand basic physics objects (photons and jets) used in all analysis looking for New Physics (NP)

  – Measure and understand the main background to most NP physics searches, or get a chance to have a first glimpse of something new and unexpected.
Results presented here make use of the 2010 Data Run with a total integrated luminosity of 36 pb$^{-1}$ out of the 47 pb$^{-1}$ delivered and 43 pb$^{-1}$ recorded.
Jet Reconstruction

• **Anti-kt clustering algorithm**: with a cone $R = 0.5$, which is infrared and collinear safe, geometrically well defined, and tends to cluster around the hard energy deposits.

• **Calorimeter Jets**: Clustering of Calorimeter Towers composed of ECAL and HCAL energy deposits

• **Particle Flow Jets**: Clustering of Particle Flow candidates constructed combining information from all sub-detector systems.
Jet Energy Scale and Resolution

Data driven methods used

- Dijet Asymmetry

- Photon plus Jet Balance

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Inclusive Jet Cross Section

\[ \frac{d^2 \sigma}{dp_T d|y|} = \frac{C_{\text{unsm}}}{\epsilon \cdot \mathcal{L}} \cdot \frac{N_{\text{jets}}}{\Delta p_T \Delta |y|} \]

- Experimental uncertainties dominated by JES.

- Theoretical uncertainties dominated by non-perturbative corrections at low pT, and PDFs at high pT.

- Good agreement between data and theory.
Inclusive Jet Cross Section

CMS, 34 pb$^{-1}$

Anti-$k_T$ R=0.5

$\sqrt{s} = 7$ TeV

- Good agreement between data and theory.
Dijet Cross Section

\[ \frac{d^2\sigma}{dM_{jj}d|y|_{max}} = \frac{C}{\epsilon \cdot \mathcal{L}_{\text{equiv}}} \cdot \frac{N}{\Delta M_{jj} \Delta |y|_{max}} \]

- Experimental uncertainties dominated by JES.

- Theoretical uncertainties dominated by non-perturbative corrections at low masses, and PDFs at high masses.

- Good agreement between data and theory.

Arxiv1104.1693
Accepted in PLB
Good agreement between pQCD@NLO and Data.

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Dijet Angular Distributions

- Parton-parton scattering in QCD is t-channel dominated.
- Stringent test of pQCD with no dependence on PDFs.
- New physics would show deviations from expectation at large scattering angles.
Dijet Angular Distributions

\[ \chi = e^{y_1 - y_2} \approx \frac{1 + |\cos \theta^*|}{1 - |\cos \theta^*|} \]

- \( X \) chosen since QCD flat as a function of \( x \).

- Experimental uncertainties dominated by jet resolution and relative (vs \( \eta \)) JES (absolute cancels)

- Theoretical uncertainties dominated by non perturbative corrections and renormalization scale.

- Good agreement between data and theory. Highest mass bins sensitive to contact interactions.

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Dijet Azimuthal Decorrelations

- Normalized Dijet cross section as a function of $\Delta \phi$ and indirect probe of multijet topologies

- NLO pQCD describes the data well up to $\sim 2\pi/3$, NNLO needed for higher jet multiplicities

Dijet Azimuthal Decorrelations

- Pythia6 and Herwig++ in good agreement with the Data
- Madgraph predicts less multijet events and Pythia8 more.
- Results are sensitive to ISR effects

Photon Reconstruction

Photons are key objects for both calibration and major discoveries. (H-\(\rightarrow\gamma\gamma\) and BMS searches)

- Photons are isolated energy deposits in the ECAL, with no charged track pointing to them, and with a shape compatible with a photon electromagnetic Shower.

\[
\mathcal{L} = -\ln L = -(N_S + N_B) + \sum_i N_i \ln(N_S S_i + N_B B_i)
\]
Inclusive Photon Cross Section

\[ \frac{d^2\sigma}{dE_T^\gamma d\eta^\gamma} = N^\gamma / (L \cdot \mathcal{U} \cdot e \cdot \Delta E_T^\gamma \cdot \Delta \eta^\gamma) \]

- Good agreement with NLO prediction.
- Experimental systematic uncertainty varies from 10% to 16% with the dominant source being from the background template shape.
- Dominant theoretical systematic uncertainty is the scale dependence.

Inclusive Photon Cross Section


Good agreement of data with pQCD at NLO

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Summary - Conclusions

• CMS has very good understanding of jet reconstruction and calibration as well as photon reconstruction and identification.

• Using these physics objects many important as well as challenging QCD measurements have been performed and published.

• The agreement between data and pQCD at NLO has been surprisingly good.

• With the 2011 data, CMS plans to perform precision studies and differentiate between the various PDFs, and perhaps gets a glimpse of the “unexpected”.

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BACKUP
Jet Calibration

- Dijet asymmetry

Raw Jet \times \frac{\text{Offset Correction (pile up)}}{\text{Relative Response (vs. } \eta)} \times \frac{\text{Absolute Response (vs. } p_T)}{\text{Physics Object}} = \text{Calibrated Jet}

- Photon+Jet Balance

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Photon Shower Shape

Signal shape : Pythia MC

Background Shape: Track Isolation Sideband

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Theory Predictions

- **QCD Monte-Carlo generators:**
  - PYTHIA6
  - PYTHIA8
  - HERWIG++
  - ALPGEN
  - MADGRAPH

- **Proton PDFs**
  - CT10: $\alpha_S(M_Z) = 0.1180$
  - MSTW2008: $\alpha_S(M_Z) = 0.1202$
  - NNPDF2.0: $\alpha_S(M_Z) = 0.1190$

- **Perturbative QCD Calculations**
  - Next to leading order using NLOJet++ program at the fastNLO package

- **Non Perturbative Corrections**
  - MPI
  - Hadronization
The PDF4LHC prescription describes the way to combine the various PDFs:

- compute the observable of interest with each PDF set
- construct the 1-sigma (68% CL) band from each PDF set
- at every point, define the global envelope from the 1-sigma bands
- the PDF4LHC prediction is the center of the global envelope
Non perturbative corrections

- Non perturbative corrections needed to go from parton to particle level, and hence be able to compare theory with data.

- Non perturbative corrections account for:
  - Multi-parton interactions
  - Hadronization effects

- Use different MC generators to estimate, and take spread as systematic uncertainty.
JetPhox Predictions

• NLO pQCD
  – JETPHOX1.1, CT10 PDFs, BFG II FF
  – Renormalization, fragmentation, and factorization scales set to ET
  – Require “isolated” definition: $\Sigma ET < 5$ GeV within $R < 0.4$

• Scale uncertainty
  – 30 to 11% with ET, change all scales to ET/2 and 2ET

• PDF uncertainty
  - 6% over full ET range

• Envelope of CT10, MSTW08 and NNPDF2.0 (PDF4LHC recommendation)
• CTEQ6M instead of CT10: 3%
• BFG I instead of BFG II: <1%
Non Perturbative Corrections

- Non-perturbative effects increase energy in isolation cone

- Correction is obtained by comparing the efficiency of isolation cut of 5GeV in a cone of radius 0.4 with and without:
  - Multi-parton interaction
  - Hadronization

- Final correction is the mean of the four different tunes considered
  - D6T
  - Z2
  - DWT
  - P0

- ~3% overall correction applied to the NLO calculation
Unfolding correction through forward smearing: Generate true jet mass according to the NLO spectrum and smear using the MC mass resolution (bin by bin correction)

- Straightforward to study the systematics by varying the spectrum slope and the Dijet mass resolution
- The result agrees with the more advanced SVD and Bayes Unfolding methods
- The unfolding correction is small (between 0.94 and 0.98) for all rapidity bins

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The JES uncertainty is mapped on the dijet mass variable through “jet-by-jet” shifting and taking the average over all jets in each rapidity bin.

For outer rapidity bins, the mass scale uncertainty is lower because it probes smaller jet $p_T$. 

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Experimental Uncertainties

- The total experimental uncertainty ranges from ~15% at low mass values to ~60% at high mass values.

- This is almost the same for all rapidity bins.

- The major contribution to the total experimental uncertainty comes from the JES uncertainty.

- The unsmearing uncertainty is of order ~2 -3%.
Theoretical Uncertainties

- The PDF uncertainty is estimated according to the PDF4LHC prescription through the variation of the PDF sets.

- Maximal deviation of the six point variation is used to estimate the renormalization and factorization scale uncertainties $(\mu_R/pT_{ave}, \mu_F/pT_{ave}) = (1/2, 1/2), (2, 2), (1, 1/2), (1, 2), (1/2, 1), (2, 1)$

- The non-perturbation correction uncertainty is estimated as half of the NP correction deviation from unity