Hard QCD Results on Jets and Photons at CMS

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for the CMS collaboration
Jet physics

- Main goal is to improve our detailed description of **Standard Model physics**
  - hard QCD: proton parton distribution functions (PDFs), perturbation theory, initial and final state radiation, parton showers
  - soft QCD: multiparton scattering, fragmentation, underlying event, etc.
- Collaboration with Exotica group on searches of **New Physics at high p_T**
- QCD jets are **background** for searches and high statistics calibration source
Compact Muon Solenoid

- Precise silicon pixel and silicon strip tracking at $|\eta| < 2.4$
- Fine-grained lead tungstate crystal ECAL at $|\eta| < 3.0$
- Brass+scintillator HCAL at $|\eta| < 3.0$
- Tracking, ECAL and HCAL embedded inside 3.8 T solenoid magnet
- Muon chambers outside magnet, interleaved with iron return yoke

Calorimeter granularity:
ECAL $5 \times 5$ vs HCAL $1 \times 1$
Compact Muon Solenoid

Standard Model re-discovered within months!

CMS Preliminary

$\sqrt{s} = 7\, \text{TeV}$, $L_{\text{int}} = 40\, \text{pb}^{-1}$
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Particle Flow is a novelty at hadron colliders, but used before at LEP (Aleph).

- Very precise tracker, highly granular ECAL and strong magnetic field are CMS specialities.
  - Magnetic field separates charged particles.
  - Small fraction of $p_T$ measured with HCAL only.
  - Linking stage optimizes subdetector consistency.

- 2 charged hadrons, 3 photons.

- 10% of jet $p_T$, $\sigma(p_T)/p_T \sim 120%/\sqrt{E}$
- 25% of jet $p_T$, $\sigma(p_T)/p_T \sim 1%/\sqrt{E}$
- 65% of jet $p_T$, $\sigma(p_T)/p_T \sim 10%$
Jet reconstruction

Particle Flow algorithm

Combining detector inputs optimally before jet clustering allows CMS to tackle bent tracks, non-linear calorimeter response and overlapping collisions in an ideal way.
Jet energy correction

- JEC corrects sum of tracks and calorimeter deposits on average back to particle level
- $\eta$-dependent correction relative to $|\eta|<1.3$ is done with high statistics **dijet events**
- Absolute correction is fixed with $Z/\gamma$+jet events to precise ECAL and tracker scales
- Detector simulation has already very good (~1.5%) precision in barrel region
**JEC uncertainty**

- JEC dominant uncertainty in most jet analyses
- Big improvement in going from early 2010 (3/pb) to final 2010 (36/pb) data; however, due to time constraints most analyses used 3/pb uncertainty
- Uncertainties between 1-2% over much of the kinematic range at $p_T > 50$ GeV and $|y| < 3$
- Already competitive with Tevatron; improvements and uncertainty correlations expected with 5/fb

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**Jet Energy Correction Factor**

- CALO jets
- JPT jets
- PF jets

**Relative JES Uncertainty [%]**

- CALO jets
- JPT jets
- PF jets

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**Jet Energy Correction Factor**

- Anti-$k_T$ $R = 0.5$
- $p_T = 200$ GeV

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**Absolute scale uncertainty [%]**

- Total uncertainty
- Total MPF
- Photon scale
- Extrapolation
- Offset (+1PU)
- Residuals

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**CMS, L = 36 pb$^{-1}$**

- $\sqrt{s} = 7$ TeV
- Anti-$k_T$ $R = 0.5$
- $p_T = 200$ GeV
- $\eta$ (Jet)

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**CMS, L = 36 pb$^{-1}$**

- $\sqrt{s} = 7$ TeV
- $p_T$ (GeV)
- $\eta$ (Jet)

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**CMS preliminary, 2.9 pb$^{-1}$**

- $\sqrt{s} = 7$ TeV
- JME-10-010
- particle flow jets
- Anti-$k_T$ 0.5 & 0.7

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**CMS, 36 pb$^{-1}$**

- $\sqrt{s} = 7$ TeV
- $p_T$ (GeV)
- $\eta$ (Jet)
Jet $p_T$ resolution

- Jet $p_T$ resolution measured from data using dijet asymmetry, $A = (p_T - p_T^{\text{ref}}) / (p_T + p_T^{\text{ref}})$, $|\eta_{\text{ref}}| < 1.3$

- Main bias are additional soft jets in the event; corrected by extrapolating jet activity to $p_T^{3,\text{rel}} = 0$

- Remaining biases from out-of-cone radiation and underlying event estimated using simulation

- Data and MC agree to about 10% at central rapidities, with 5-10% systematic uncertainty
Inclusive jets

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Good agreement between data and theory (perturbative QCD with world average PDF), on a challenging measurement that took years at Tevatron

Not yet sensitive enough to discriminate PDFs, but this is the long term goal
Prompt photons

- Isolated prompt photons produced in association with jets give a direct handle on the interaction at parton level.

- Main background \( \pi^0 \)-jets:
  - isolation, conversion methods
  - final result combination of both

\[ \text{Prompt photons} \]

\[ \text{Phys. Rev. D 84, 052011 (2011)} \]
Prompt photons

- Photon+jet data long advertised to constrain PDFs, but never used by global fitters due to data/theory disagreements at Tevatron.
- NLO predictions in agreement with data at CMS, although experimental and theory uncertainties still large.
- With 5/fb can extend to higher $p_T$ and to triple differential distributions.

Phys. Rev. D 84, 052011 (2011)
B-tagged jets

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- B-jet purity determined from data with template fits
- Efficiency checked with μ-tags

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B-tagged jets with muons

- Complementary b-jet sample with muon triggers
- Double-tagged jets (muon and secondary vertex) => both efficiency and purity with fits to muon $p_T,_{rel}$
- Consistent results with jet triggered analysis:
  - Pythia models shape vs $\eta$ better than MC@NLO, but is off on the overall cross section for both inclusive b-jets and inclusive jets (ratio ok)
  - MC@NLO agreement better before extrapolation

Extrapolated to full phase space

Original phase space

CMS PAS BPH-10-008
Dijet topologies probe specifics of QCD
Dijet $\Delta \Phi$ is a good probe of initial state radiation (ISR)
Good agreement with NLO predictions, within range of pQCD applicability
Comparing to different MC models, Pythia 6 (Z2 and D6T) and Herwig++ do well, while Pythia 8 and MadGraph struggle to model the azimuthal decorrelation correctly.
Hadronic event shapes

- Geometric shape of the hadronic final state sensitive to details of QCD multijet production, but robust against experimental systematics, e.g. jet energy scale
- Pythia 6 (D6T), Pythia 8 (2C) and Herwig++ (2.3) agree with data, while MadGraph and Alpgen do not

Central transverse thrust:

\[ \tau_{\perp,c} \equiv 1 - \max \frac{\sum_i |p_{\perp,i} \cdot \hat{n}_T|}{\sum_i p_{\perp,i}} \]

125 GeV/c < \( p_T \), x 200 GeV/c anti-k_{\perp}, R=0.5, \( p_T > 30 \text{ GeV/c} \)

![Diagram showing Dijet and Multijet event shapes](image)
3-jet/2-jet ratio

- Jets with $p_T > 50 \text{ GeV}, |y| < 2.5$:
  - $R_{32} = (d\sigma_3/dH_T) / (d\sigma_2/dH_T)$
  - $H_T = \Sigma_i p_{T,i}$
- Ratio rises as phase space open up, plateau sensitive to strong coupling $\alpha_s$
- MadGraph, Alpgen differences from parton matching, both use tree-level helicity amplitudes
- Although MadGraph struggled with event shapes and angular decorrelations, probability of 3rd parton emission correct

Dijet angular distributions

- Isotropic new physics peaks at low $\chi (y_1 \sim y_2)$, e.g. contact interactions
- QCD mostly t-channel $\Rightarrow$ flat in $X_{dijet} = \exp(|y_1 - y_2|)$
- Sensitivity up to $\Lambda = 5$ TeV with few pb$^{-1}$; Tevatron limits $\Lambda > 2.8-3$ TeV
- No evidence of new physics, but can confirm QCD over Rutherford scattering

Bump hunts with dijets

- Dijet mass spectrum doubles as a bump hunt for new resonances
- Consistent results with NLO predictions and with inclusive jets (smaller cone); no bumps found in 2010 data set
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Heavy particle decaying? No.


QCD-10-025

EXO-10-010

Heavy particle decaying?

No.
Conclusions and outlook

- Wealth of precise Standard Model results coming out from CMS
  - Good agreement between data and theory predictions so far
- First interesting new phenomena observed in heavy ions, more hoped for from 2011 pp collisions
- Looking forward to 2011 results, with x100 statistics
  - expecting to confront SM with high precision
  - starting to probe high-x regime at the LHC

For CMS results on heavy ions, see talk by M. Nguyen on Tuesday 10:40

Phys. Rev. C 84, 024906 (2011); CMS PAS HIN-11-004
Backup slides
LHC re-start

LHC re-start November 23, 2009

7 TeV physics run started on March 30, 2010 at 12:57
The Large Hadron Collider

- 27 km of tunnel across franco-swiss border
- 3.5+3.5 trillion electronvolt (TeV) proton beams
- 287+287 TeV lead ion beams
- 1.9K superconducting magnets

Geneva (airport)

CMS
Unfolding

- Inclusive jet cross section uses ansatz unfolding to get to the particle level
- Phenomenological power law motivated by parton model (Feynman/Field/Fox), extended at the Tevatron, and updated at CMS for low $p_T$ and $b$-jets

$$f(p_T) = N_0 p_T^{-\alpha} \left( 1 - \frac{2p_T \cosh(y_{\text{min}})}{\sqrt{s}} \right)^\beta \exp\left(-\gamma/p_T\right)$$

low $p_T$ and $b$-jets

new

$$C_{\text{smear}}(p_T) = \frac{f(p_T)}{F(p_T)}, \quad F(p_T) = \int_{x=0}^{x=\infty} f(x)g(p_T - x)dx,$$