Jet and photon physics

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on behalf of the ATLAS and CMS collaborations

LHCP 2014
New York, June 3rd, 2014
A great success!

- Differential jet cross section predicted over many orders of magnitude
  - NLO fixed-order calculation + NP and EW corrections

Jet energy scale is the main experimental uncertainty (10-30% of the cross section)

- Theory: main uncertainties PDF / scale
Non-perturbative corrections: from fixed-order parton-level to particle-level predictions

- Non-perturbative corrections
- Low-\(p_T\) leading jet sensitive to UE, MPI model and saturation effects
PDF sensitivity

- High-$p_T$ cross section sensitive to PDFs
- Probing gluon content at high $x$
  - uncertainties reduced including LHC data
  - data favour larger contribution

JHEP 05 (2014) 059

**ATLAS**

$\int L \, dt = 4.5 \, fb^{-1}$

$\sqrt{s} = 7 \, TeV$

anti-$k_T$, jets, $R = 0.4$

![Graphs showing PDF sensitivity](image)

CMS Preliminary

 gluon, $Q^2 = 1.9 GeV^2$
Strong coupling constant

- $R_{3/2}$ and three-jet mass constrain $\alpha_s$ up to the TeV scale
- Energy scale dependence nicely in agreement with RGE evolution
Event shapes

- **Multi-jet events**: more than a 2 \( \rightarrow \) 2 process!
- **Topological variables sensitive to approximate treatment of higher-order effects**
- **Madgraph describes well event shapes** (ME includes multi-parton final states)

Jet broadening = spread of jets around transverse thrust axis
Insensitive to hadronization

\[ 1/N \frac{dN}{d\ln(B_{T,C})} \]

\[ 10 < p_T < 170 \text{ GeV/c} \]

\[ 0 < y < 2.5 \]

Leading Jet \( p_T \): 190-300 GeV

CMS Preliminary 7 TeV

CMS-PAS-QCD-11-006
Event shapes

- **Color coherence**: soft radiation between color-connected final-state partons
- third jet emitted close to di-jet event plane
- data support larger effect than in MC

![Graphs showing distributions of jet shapes](image)

- **Soft jets from parton splitting**
- **Angular distributions** probe parton shower

**Equation**: \( \beta = \Delta \phi / \Delta \eta \) between third and second jet

*arXiv:1311.5815*
Jet size choice is a trade-off:

- collinear radiation losses
- non-perturbative effects
- pileup and UE energy

Jet measurements with different size parameters

- AK5/AK7 ratio sensitive to collinear radiation
  - PYTHIA does well in low-p_T region (NP effects)
  - HERWIG describes high-p_T substructure
Pileup effect on jets

- Pileup energy contribution to jets subtracted using jet area methods
- Intense research activity on substructure quantities: e.g. mass

Solution: apply cleaning on jet constituents
- Pileup dependency strongly reduced
Jet grooming techniques

- **Filtering:**
  - keep only the 3 leading sub-jets

- **Trimming:**
  - remove soft sub-jets

- **Pruning:**
  - reject soft and wide-angle radiation at each clustering step

- Separation of hard-core jets from symmetric gluon splittings

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filtered data RECO
filtered PYTHIA6, Z2 RECO
filtered PYTHIA6, Z2 GEN
trimmed data RECO
trimmed PYTHIA6, Z2 RECO
trimmed PYTHIA6, Z2 GEN
pruned data RECO
pruned PYTHIA6, Z2 RECO
pruned PYTHIA6, Z2 GEN

JHEP 05 (2013) 090
JHEP 09 (2013) 076
Tagging boosted decays

- Pruned mass used for tagging boosted W/top
- More sub-jet and clustering-history variables improve discrimination

Shower deconstruction method
- Probability-weighting shower histories compatible with reconstructed sub-jets
Photon production tests directly the hard scattering in pQCD

$qg$ channel dominates at the LHC

Parton fragmentation to photon contributes in some regions

Strong sensitivity to NNLO phenomenology from diphoton differential cross section

Background in searches for new physics
Photon reconstruction

- Electromagnetic shower
- High-granularity calorimeter cells clustered to reconstruct energy deposit
- Background from boosted neutral mesons collimated diphoton decays, reconstructed as single photon

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Jet and photon physics - LHCP 2014
Background subtraction

- Key concepts:
  - shape of em shower
  - isolation energy
  - Variables de-correlated ➔ sideband methods
  - Background subtracted on statistical basis
PDF sensitivity

- Inclusive photon cross section in agreement with NLO prediction
- Sensitivity to PDF investigated, limited by scale uncertainty

ATLAS Preliminary

- Data 2011 $\sqrt{s}$=7 TeV
- PYTHIA (MRST 2007 LO*)
- HERWIG (MRST 2007 LO*)
- NLO (Jetphox) CT10
- Total uncertainty
- Scale uncertainty
- NLO (Jetphox) MSTW2008nlo

Data $|\eta|<1.37$ $|<1.37$

$\gamma T$ d$E$/$\sigma d\gamma$

$\gamma T$ [pb/GeV]

$E_T$ [GeV]

Theory/Data pulls

ATL-PHYS-PUB-2013-018
Photon + jet production

CMS, $L = 2.14 \text{fb}^{-1}$ \(\sqrt{s} = 7 \text{ TeV}\)

- 50 < $E_T^\gamma$ < 60 GeV
- 0 < $|\eta^\gamma|$ < 0.9
- 0 < $|\eta^{\text{jet}}|$ < 1.5

- Data
- Signal Component
- Background Component
- Fitting Result

- Isolation template fit to extract signal
- Purity is increasing with $p_T$
- Very good agreement with NLO calculation

\[\frac{d\sigma}{dp_T^\gamma d\eta^\gamma}dT_{\text{jet}}\]

\[\text{CMS, } L = 2.14 \text{ fb}^{-1} \quad \sqrt{s} = 7 \text{ TeV}\]

- JETPHOX
- SHERPA
  - $h_{|\eta^\gamma| < 0.9}$ (X8000)
  - $0.9 < h_{|\eta^\gamma| < 1.4442}$ (X400)
  - $1.566 < h_{|\eta^\gamma| < 2.1}$ (X20)
  - $2.1 < h_{|\eta^\gamma| < 2.5}$

Total uncertainty

1.5 < $h_{|\eta^{\text{jet}}| < 2.5}$

arXiv:1311.6141
Angular distributions probe pQCD production diagrams

Relative enhancement of fragmentation in corners of the phase space

Small uncertainties, very good agreement with NLO theory
Diphoton measurement

- Separate prompt diphoton component from photon+jet, di-jet
- **Two-dimensional template fit**: isolation as discriminating variable
- Robust **data-driven template building** methods
- Correlation between isolation sums taken into account

[Graphs showing diphoton measurements in CMS with different isolation regions and event distributions.]

arXiv:1405.7225
Isolation templates in data

- Isolation templates built from data:
  - random-cone technique for signal (isolated photons)
  - shower shape sideband for background
- Very successful closure of the method, leading to small uncertainties

![Isolation template diagram](image)

- Signal template EB
- Rand. cone in data
- Prompt photon in MC
- Rand. cone in MC
- Background template EB
- Sideband photon in data
- Non-prompt photon in MC
- Sideband photon in MC

Prompt photon

Photon footprint excluded from isolation sum

arXiv:1405.7225
NNLO pQCD sensitivity

❖ NNLO calculation is needed to describe low-\(m_{\gamma\gamma}\), low-\(\Delta\phi_{\gamma\gamma}\) region

❖ SHERPA also in good agreement with the data
Conclusions

- Jet production is predicted very successfully in QCD
- ATLAS and CMS achieve strong performance in jet and photon reconstruction, even in challenging pileup conditions
- Valuable physics input to $\alpha_S$ and PDF fits
- Multi-jet observables probe various aspects of QCD radiation
- Jet substructure methods useful to withstand pileup and tag boosted heavy object decays
- Diphoton measurements stringently test NNLO phenomenology
Backup slides
Measurement of $k_T$ splitting scales
- value of $k_T$ metric at k-th last clustering
- hard tail described by ME generators
- soft region sensitive to hadronization and MPI
- ratio $\sim 1$ = subsequent emissions at the same scale
Random cone method

Procedure (event-by-event):
- rotate the isolation cone in $\phi$ by a random angle
- check that no other photon or jet is nearby
- underlying activity does not change (same $\eta$)
- build the template from this isolation sum away from the photon candidate