Searches of beyond-DGLAP dynamics with multi-jets at CMS

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pQCD resummation → parton showers (PS)

DGLAP PS regime:
\[ \sqrt{s} \sim p_T > \Lambda_{\text{QCD}} \]
Strong ordering of emissions in pT

BFKL PS regime (QCD high energy limit):
\[ \sqrt{s} \gg p_T > \Lambda_{\text{QCD}} \]
Strong ordering of emissions in \( y \)
Random walk of emissions in pT

BFKL prediction:
\[ \hat{\sigma} \approx e^{\Delta \Delta y} \approx \hat{s}^A \]

Experimental requirements for the beyond-DGLAP searches:
Large rapidity coverage
Capabilities for jet measurements at low pT
Introduction

Observables covered in this talk

**Forward jet differential cross-section**
An access to $x_1 << x_2$, sensitive to low-$x$ gluon densities

**Forward-central dijet production cross-section**
Jets with large rapidity separation cross-section

**Inclusive and exclusive dijet production ratio**
Higher order radiation at large rapidity intervals

**Mueller-Navelet dijet decorrelations**
Higher order radiation at large rapidity intervals

**All observables are corrected for the detector effects and compared to various Monte Carlo and analytic predictions**
CMS detector

- Tracker, $|\eta| < 2.4$
- Hadronic calorimeter, $|\eta| < 3.0$
- Weight: 12500T
- Diameter: 15m
- Length: 21m
- Hadronic Forward (HF) calorimeter, $2.9 < |\eta| < 5.2$
- Muon chambers

- Steel absorber
- Radiation-hard quartz fibers, Cherenkov light detection
- “Long” and “short” segments allow to distinguish between EM and HAD components of hadronic jet
Available data

LHC pp runs: $\sim 30 \text{ fb}^{-1}$ is collected in 2010 - 2013

pp data at 7, 8 and 2.76 TeV is available
Available data

Not all LHC data can be used for beyond-DGLAP searches

Huge pileup in 2011-2012 → Not possible to tag low-pT forward jets belonging to the same interaction

Analyses presented here use 2010 data
\(<\text{PU}> \sim 2.2\), integrated luminosity 44.2pb\(^{-1}\)

Much benefit from dedicated LHC pp runs @ low pileup (not covered here) 8 and 2.76 TeV datasets are available (O(10pb\(^{-1}\)) each)
Jet reconstruction

Several jet reconstruction techniques
- Calorimeter jets
- “Jet Plus Track” jets
- Particle Flow jets

MC and data driven jet energy scale (JES) calibration techniques
- Uncertainty of calibration < 10% for pT > 30 GeV
- Uncertainty grows as pT decreases

JES uncertainty - leading source of experimental uncertainty

Presented analyses use jets clustered from calorimeter energy
Anti-κT, R=0.5 clustering algorithm
Jet triggers are based on uncorrected calorimeter energy deposits.

- Lowest available trigger threshold $p_T > 15$ GeV
  - Turn-on point depends on $\eta$ and type of the jet
  - 100% efficiency in full acceptance for calojets with $p_T > 35$ GeV

Presented analyses use triggers requiring one or two jets with uncorrected ET > 15 GeV.
Measurements
Forward jet cross-section

At least one jet $3.2 < |\eta| < 4.7$
$35 < p_T < 150$

Sensitive to $x \sim 10^{-4}$

Experimental uncertainties:
JES: 20-30%
Unfolding: 3-6%
Luminosity: 4%

All predictions agree with the data within uncertainties

NLO prediction (NLOJET++) is above by $\sim 20\%$ but still within uncertainties

Best description – POWHEG (+ PYTHIA6)

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JetLHC2013 - IPPP Durham – July 13
Events with at least one jet with $p_T > 35$ GeV
In each of the regions:

- **forward**: $3.2 < |\eta| < 4.7$
- **central**: $|\eta| < 2.5$

Leading jet selection

Similar experimental systematics
PYTHIA6, PYTHIA8 and CASCADE problem with central normalization and forward shape

HERWIG6, HERWIG++ and HEJ best agreement with data

POWHEG matched to PYTHIA and HERWIG disagree with the data
Mueller-Navelet jets – pair above threshold with the largest rapidity separation in the event

→ Rapidity ordered selection defines the phase space for BFKL-type parton shower
→ No pT ordering

Observables sensitive to higher order QCD radiation between MN jets:

→ Inclusive to “exclusive” dijet production ratio
→ Azimuthal decorrelations
Common selections for both analyses:

- Require single primary vertex (~1/3 of 2010 data)

- Calorimeter jet $p_T > 35$ GeV, $|\eta| < 4.7$

- Rapidity separation coverage of the measurement: $\Delta y < 9.4$
  - Combination of inclusive and forward-backward jet triggers

Systematic uncertainties

- Dominated by JES and unfolding uncertainties

- Pileup influence is reduced (or even removed) by single vertex requirement
Dijet production ratios

Measurement of ratios of dijet production ratios as a function of rapidity separation

**Mueller-Navelet**

\[ R^{\text{MN}} = \frac{\sigma^{\text{MN}}}{\sigma^{\text{excl}}} \]

- \( \sigma^{\text{excl}} \) - veto on additional jets above the threshold in the event
- \( \sigma^{\text{MN}} \) - inclusive selection, no veto, MN pair
- \( \sigma^{\text{incl}} \) - inclusive selection, no veto, all pairwise combinations

\[ R^{\text{incl}} = \frac{\sigma^{\text{incl}}}{\sigma^{\text{excl}}} \]

\( R^{\text{incl}} \) is proposed in 10.1103/PhysRevD.53.6

**Properties of observables:**

- Ratio emphasize higher orders enhanced by \((\alpha_s \Delta y)^n\) in the BFKL limit
- Remove PDF contributions
- Experimental systematic uncertainties are decreased

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JetLHC2013 - IPPP Durham - July 13
Dijet production ratios

\[ R^{MN} = \frac{\sigma^{MN}}{\sigma^{excl}} \]

Best description of the data is given by PYTHIA6 and PYTHIA8

Herwig++ shows larger growth with increase of rapidity separation

BFKL inspired models CASCADE and HEJ overestimate data
Dijet production ratios

Similar quality of MC description

Conclusion: both ratios are well described by DGLAP-based PS models
MN azimuthal decorrelations

**Measurement at D0 in 1996**

[10.1103/PhysRevLett.77.595]

\[ \Delta \eta < 6.0, \ E_T > 50 \ (20) \]

LL BFKL overestimates decorrelation

**HERWIG** gives best description

**CMS measurement**

Extends to \( \Delta y < 9.4 \)

Symmetric \( p_T > 35 \) GeV

**Observables**

Azimuthal angle separation \( \Delta \phi \) in \( \Delta y \) bins

Average cosines \( C_1, C_2, C_3 \) as a function of \( \Delta y \)

Ratios \( C_2/C_1, C_3/C_2 \)

First presented at DIS13
Δφ shapes

Shapes of Δφ distributions

PYTHIA6 and PYTHIA8 show too strong decorrelation

SHERPA underestimates decorrelation

HERWIG++ is consistent with the data
Average cosines of $n(\pi-\Delta\phi)$

**First 3 coefficients of Fourrier transform of $\Delta\phi$ distribution**

Equal to average cosines: $C_n = \langle \cos(n(\pi - \Delta\phi)) \rangle$

**BFKL NLL predictions (valid from $\Delta y=4$) provided by**


Parton level predictions, negligible hadronization effect
CASCADE predicts too strong radiation

Correlation in SHERPA and NLL BFKL is stronger than in data

PYTHIA and HERWIG describe the data well

Average cosines of $n(\pi-\Delta\phi)$
Cosine ratios

Ratios of cosines as proposed in 10.1016/j.nuclphysb.2007.03.050

DGLAP contributions cancel

More stable calculations in NLL BFKL

PYTHIA6, 8 show better agreement than HERWIG++

SHERPA overestimate C2/C1, Consistent with C3/C2

NLL BFKL is consistent with ratios

CMS-PAS-FWD-12-002
AO and MPI were studied in PYTHIA6 (switched off and on)

Angular ordering in parton shower is essential for good data description
MN azimuthal decorrelations

SUMMARY

- For the first time decorrelations are measured up to $\Delta y = 9.4$
- Best description of all observables is given by HERWIG++
- PYTHIA6, PYTHIA8 and SHERPA do not describe all observables
- Cosine ratios are well described by NLL BFKL calculation
- **Angular ordering has large impact on decorrelation (in PYTHIA6)**

Conclusion: No clear evidence for BFKL dynamics
SUMMARY

**pT-ordered selections**

**Inclusive forward jet cross-section:**
- All theory predictions agree with the data (DGLAP-based MC, BFKL/CCFM-based MC, NLO DGLAP)

**Forward-central jet cross-sections**
- Best description is given by HERWIG++, HERWIG6, HEJ

**y-ordered selections**

**Inclusive to exclusive dijet production ratios**
- PYTHIA6 and PYTHIA8 predictions are with the experimental uncertainties
- HERWIG++, HEJ, CASCADE fail to describe

**Mueller-Navelet jets angular decorrelations**
- Best description is given by HERWIG++
- NLL BFKL predictions provide good description of cosines ratios

**General conclusion:**
No clear evidence for high energy limit asymptotics