Small-$x$ QCD physics probed with jets in CMS

Pedro Cipriano$^1$ on behalf of the CMS collaboration

$^1$Deutsches Elektronen-Synchrotron

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Outline

1. Physics Motivation
2. Measurements
   - Inclusive forward jet production
   - Events with one forward and one central jet
   - Azimuthal correlations of jets widely separated in \( \eta \)
   - Fourier coefficients ratio of the average azimuthal correlation cosines
   - Ratios of dijet production
3. Summary
Physics Motivation

Forward Jets

- Excellent probe to low-\(x\) dynamics: high \(y\) \(\rightarrow\) low-\(x\)
- Classic final state for studies of higher order QCD, beyond-DGLAP and BFKL effects
- CMS has probed \(y\) (rapidity) up to 4.7 (blue area in the figure: LHC reach at \(\sqrt{s} = 7\) TeV)

Large rapidity separation

- Large rapidity range (\(\Delta y \leq 9.4\)) between jets open up phase space for more emissions and opportunity for detailed QCD tests
Physics Motivation

Azimuthal Correlations

- At leading order: $\Delta \phi = 180$
- Due to strong ordering in DGLAP the dijets are correlated, while in BFKL many emissions lead to strong decorrelations.
- Understanding the contribution of additional jets helps to distinguish between different parton evolution schemes.
- Sensitivity to MPI
Inclusive forward jet production at $\sqrt{s} = 7$ TeV

Events with at least one jet with $3.2 < |\eta| < 4.7$ and $p_T > 35$ GeV

- All predictions describe the data within the uncertainties
- NLO prediction (NLOJET++) too high, but agrees with the data within the large theoretical and experimental uncertainties
- NLO+PS (POWHEG+PYTHIA6) best

JHEP 1206 (2012) 036, arXiv:1202.0704
Events with one forward and one central jet at \( \sqrt{s} = 7 \text{ TeV} \)

Events with at least one jet with one forward jet \((3.5 < |\eta| < 4.7)\) \(p_T > 35 \text{ GeV}\) and one central jet \((|\eta| < 2.8)\) \(p_T > 35 \text{ GeV}\)

- Forward jet cross-section steeper than central jet.
- Difference in MC description of data between the forward and the central jet.
- Largest shape difference for forward jet.
- Pythia6 and Pythia8, as well as CCFM based CASCADE problem with normalization of the central jet and shape of the forward jet.
- Herwig6, Herwig++, and the BFKL inspired MC HEJ describe the data best.

JHEP 1206 (2012) 036, arXiv:1202.0704
Azimuthal angle decorrelations of jets widely separated in rapidity in pp collisions at $\sqrt{s} = 7$ TeV

Mueller-Navelet $\Delta \phi$ (azimuthal correlations) for dijets with $|y| < 4.7$ and $p_T > 35$ GeV, $0 < |\Delta y| < 3$

- Pythia 6 and Herwig++ describe the data within uncertainties
- Pythia 8 and Sherpa 1.4 with parton matrix elements matched show deviations at small and intermediate $\Delta \phi$

FSQ-12-002
Azimuthal angle decorrelations of jets widely separated in rapidity in pp collisions at $\sqrt{s} = 7$ TeV

Mueller-Navelet $\Delta \phi$ (azimuthal correlations) for dijets with $|y| < 4.7$ and $p_T > 35$ GeV, $3 < |\Delta y| < 6$

- All predictions show deviations beyond experimental uncertainties
- Herwig ++ provides the best description

FSQ-12-002
Azimuthal angle decorrelations of jets widely separated in rapidity in pp collisions at $\sqrt{s} = 7$ TeV

Mueller-Navelet $\Delta \phi$ (azimuthal correlations) for dijets with $|y| < 4.7$ and $p_T > 35$ GeV, $6 < |\Delta y| < 9.4$

- Dijets are strongly decorrelated
- Herwig is the best description
- Pythia 6 and Pythia 8 fail for the lower $\Delta \phi$ region

FSQ-12-002
Azimuthal angle decorrelations of jets widely separated in rapidity in pp collisions at $\sqrt{s} = 7$ TeV

Mueller-Navelet $\Delta \phi$ (azimuthal correlations) for dijets with $|y| < 4.7$ and $p_T > 35$ GeV

- Contributions of the angular ordering and multi-parton interactions are very similar
- No-MPI is better in the intermediate $\Delta y$ region
- Overall data better described with AO and MPI

FSQ-12-002
Fourier coefficients ratio of the average azimuthal correlation cosines

Mueller-Navelet $\Delta \phi$ (azimuthal correlations) for dijets with $|y| < 4.7$ and $p_T > 35$ GeV

Fourier coefficients, $C_n : d\sigma / d(\Delta \phi) \sim \sum C_n$

$C_n \equiv \langle \cos(n(\pi - \Delta \phi)) \rangle$

- DGLAP contributions are expected to partly cancel in the $C_{n+1}/C_n$
- $C_{n+1}/C_n$ described by LL DGLAP based generators towards low $\Delta y$
- Sherpa, Pythia8 and Pythia6 Z2 overestimate $C_2/C_1$
- Herwig++ underestimate $C_1/C_2$
- CCFM based CASCADE predicts too small $C_{n+1}/C_n$
- At $\Delta y > 4$ theoretical BFKL NLL describe in particular $C_2/C_1$ within uncertainties

FSQ-12-002
Ratios of dijet production as a function of the absolute difference in rapidity between jets at $\sqrt{s} = 7$ TeV

Jets with $p_T > 35$ GeV and $|\eta| < 4.7$

Observable: Rapidity difference between jets, $\Delta y$

Ratio $= \frac{\sigma_{dijet}(\text{inclusive})}{\sigma_{dijet}(\text{exclusive})}$

- Increasing $\Delta y \rightarrow$ Larger phase space for radiation
- Pythia6 and Pythia8 agrees well with data
- Herwig++ and HEJ+Ariadne too high at high $\Delta y$
- Small effect from MPI (not shown)
- Cascade off

Eur.Phys.J.C72(2012)2216; arXiv:1204.0696
Ratios of dijet production as a function of the absolute difference in rapidity between jets at $\sqrt{s} = 7$ TeV

Jets with $p_T > 35$ GeV and $|\eta| < 4.7$

Observable: Rapidity difference between jets, $\Delta y$

Ratio = $\frac{\sigma_{dijet}(MN)}{\sigma_{dijet}(exclusive)}$

- Low $\Delta y$: Ratio(MN/exc.) per definition smaller than Ratio/inc./exc.)
- High $\Delta y$: Ratio(MN/exc.) per definition same as Ratio/inc./exc.)
- MC data comparison: same as on previous slide
- Why only Pythia is describing the data while all others are far off?

Exclusive jets: Events with exactly two jets above the threshold
Mueller-Navelet jets: Most forward and backward jet in the inclusive sample

Eur.Phys.J.C72(2012)2216; arXiv:1204.0696
### Summary

CMS has probed the small-\(x\) region with jets in different measurements:

| Observable               | Pythia | Herwig | Sherpa | Cascade | HEJ |
|--------------------------|--------|--------|--------|---------|-----|
| Forward jet \(p_T\)      | ![Smiley](emoji) | ![Smiley](emoji) | -      | ![Sad](emoji) | ![Sad](emoji) |
| Central-forward jet \(p_T\) | ![Sad](emoji) | ![Sad](emoji) | -      | ![Sad](emoji) | ![Happy](emoji) |
| Azimutal correlations    | ![Sad](emoji) | ![Happy](emoji) | ![Sad](emoji) | ![Sad](emoji) | - |
| Fourier coefficients ratio | ![Sad](emoji) | ![Sad](emoji) | ![Sad](emoji) | ![Sad](emoji) | - |
| Dijet ratios             | ![Happy](emoji) | ![Sad](emoji) | -      | ![Sad](emoji) | ![Sad](emoji) |

- Inclusive measurements are reasonably well described
- In more exclusive measurements the description becomes more difficult

**New results comming soon:** Low \(p_T\) jets at \(\sqrt{8}\) TeV and Central-Forward jets correlations

Legend: ![Happy](emoji) → good agreement; ![Sad](emoji) → decent agreement; ![Sad](emoji) → bad agreement
Backup slides
**CMS DETECTOR**

- **Total weight**: 14,000 tonnes
- **Overall diameter**: 15.0 m
- **Overall length**: 28.7 m
- **Magnetic field**: 3.8 T

**STEEL RETURN YOKE**
12,500 tonnes

**SILICON TRACKERS**
- Pixel (100x150 μm) \(-16m^2 \sim 66M\) channels
- Microstrips (80x180 μm) \(-200m^2 \sim 9.6M\) channels

**SUPERCONDUCTING SOLENOID**
Niobium titanium coil carrying \(\sim 18,000A\)

**MUON CHAMBERS**
- Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
- Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

**PRESHOWER**
- Silicon strips \(-16m^2 \sim 137,000\) channels

**FORWARD CALORIMETER**
- Steel + Quartz fibres \(-2,000\) channels

**CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)**
- \(-76,000\) scintillating PbWO₄ crystals

**HADRON CALORIMETER (HCAL)**
- Brass + Plastic scintillator \(-7,000\) channels
Central-Forward Jets