Forward and small-x QCD

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on behalf of the CMS Collaboration
1. Introduction
2. Inclusive jet measurements
3. Müller-Navelet jet measurements
4. Studies of behaviour of gluon distribution
5. Double parton scattering
6. Summary and conclusion
\[ \sigma_{ab \to F}(Q^2) = \int dx_1 dx'_1 f_a^1(x_1, Q^2) f_b^2(x'_1, Q^2) \hat{\sigma}_{ab}(x_1, x'_1, Q^2) \]

- Partonic cross section
- Parton Distribution Functions

Different final states access different scales and \( x \) values

Small-\( x \): BFKL evolution equation

High \( Q^2 \) and high-\( x \):
DGLAP evolution equation

CCFM equation bridges between DGLAP and BFKL

Saturation effects appearing at very small-\( x \)

At the LHC, huge opportunity to study the different regimes
Double differential cross section measurement in rapidity bins as a function of jet $p_T$

Inclusive jet measurements - Event selection

7 TeV: ak5 - first measurement of inclusive jet cross section at CMS
8 TeV: ak7 - large increase of the phase space in $p_T$ and inclusion of the forward region

CMS L = 34 pb$^{-1}$

\[ \frac{d^2\sigma}{dp_T^2 dy} \] for different rapidity bins:
- $|y| < 0.5$ ($\times 3125$)
- $0.5 \leq |y| < 1$ ($\times 625$)
- $1 \leq |y| < 1.5$ ($\times 125$)
- $1.5 \leq |y| < 2$ ($\times 25$)
- $2 \leq |y| < 2.5$ ($\times 5$)
- $2.5 \leq |y| < 3$

CMS Preliminary

pp $\sqrt{s} = 8$ TeV

- open: $L_{int} = 5.8$ pb$^{-1}$ (low PU runs)
- filled: $L_{int} = 10.71$ fb$^{-1}$ (high PU runs)

- NNPDF 2.1 NLO $\otimes$ NP


CMS-SMP-12-012 + CMS-FSQ-12-031
Comparisons with theory predictions from NLO calculations with NP corrections

Good agreement in central region but progressive worsening towards forward region

- Effect of pert. corrections (PhysRevD.87.094009)
- Higher sensitivity to dynamics in low-\(x\) region

Same trend at 8 TeV

Soon results at 13 TeV!
Searching for BFKL (I)

Going more forward..

Forward-central measurements - Event selection

Proton-proton collisions at 7 TeV: leading central ($|\eta| < 2.8$) jet and leading forward ($3.2 < |\eta| < 4.7$) jet with $p_T > 35$ GeV

General agreement with (most of) predictions based on different evolution equations

Little sensitivity to BFKL effects
Searching for BFKL (II)

Going more forward..

Müller-Navelet jets - Event selection

Proton-proton collisions at 7 TeV:
most forward and most backward jets in $|y| < 4.7$ with $p_T > 35$ GeV

Good agreement with DGLAP-based predictions in every bin of jet rapidity separation

Same conclusion for measurements of terms of Fourier expansion (Nucl.Phys.B776 (2007))

No clear evidence for non-DGLAP behaviour!
Sensitivity to low-x gluon

Low-x gluon distribution affects the forward region!

New tunes available:

**CUETP8S1 - CTEQ6L1**

**CUETP8M1 - NNPDF2.3LO**

Very different behaviour at low-\(x\) for the two PDFs

\(N_{ch}\) in fwd region better described by NNPDF tunes

What happens if one modifies by hand the low-x gluon distribution with an increasing density in e.g. HERAPDF?

We do improve the description at large \(\eta\)!

What happens with saturation?
Sensitivity to saturation scale

Total partonic $2 \to 2$ cross section given by:

$$\sigma(p_{T_{\text{min}}}) = \int_{p_{T_{\text{min}}}}^{\infty} dp_T^2 \int_{-\infty}^{\infty} dy \frac{d^2\sigma}{dp_T^2 dy}$$

- Divergent at low $p_T$
- Behaviour tamed in the MC

Measurement of the integrated cross section as a function of the charged mini-jet $p_T$

**Saturation effects are shown towards low $p_{T_{\text{min}}}$ where the cross section converges**

**Sensitivity to MC models and tunes:**
- standard HEP MC fails to describe the convergence
- Cosmic Ray MC EPOS describes the data best

CMS-PAS-FSQ-12-032 (submitted to PRD)
Hard multiple scatterings become relevant!

- Increasing contribution at the LHC when going to higher energy
- Sizeable background for LHC processes (SM and searches), e.g. Higgsstrahlung
- Information about the structure of the proton, i.e. parton correlations

And...increasing interest and number of entries in Spires!
Choice of physics channels

*COMING SOON!*

**Benchmark for the detection of the DPS**

- **Double J/Ψ**
  - $W(\mu\nu)+W(\mu\nu)$
  - $W(\mu\nu)+bb$
  - $Z(\mu\mu)+bb$
  - $bb+jj$
  - $\gamma+3j$
  - $4j$
  - $W(\mu\nu)+jj$
  - $Z(\mu\mu)+jj$
  - $j+UE$
  - $W+UE$
  - $Z(\mu\mu)+UE$

**Scale of primary scatter**

**Scale of secondary scatter(s)**

- Semi-hard (Minimum Bias)
- $j+UE$
- $W+UE$
- $Z(\mu\mu)+UE$
Measurement of a four-jet final state

Event selection

Exactly four jets in the final state in $|\eta| < 4.7$:
2 jets: $p_T > 50$ GeV (hard), 2 jets: $p_T > 20$ GeV (soft)

$\Delta_{soft} p_T = \frac{|p_T(i,j,k)|}{|p_T(i,j)| + |p_T(j,k)|}$

$\Delta S = \arccos \left( \frac{\vec{p}_T(i,j,k) \cdot \vec{p}_T(j,l,m)}{|\vec{p}_T(i,j,k)| \cdot |\vec{p}_T(j,l,m)|} \right)$

Soft jets are expected to be produced also by a 2nd scattering

$\Delta S$ and $\Delta_{soft} p_T$ sensitive to MPI contribution: $\rightarrow$ ROOM for DPS!

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Measurement of a four-jet final state with b-jets

**Event selection**

Selection of at least four jets with $p_T > 20$ GeV:
- 2 b-jets: $|\eta| < 2.4$
- 2 other jets: $|\eta| < 4.7$

$3 \text{ pb}^{-1}$ (7 TeV), $pp \rightarrow 2\ b + 2\ j + X$

$\Delta S = \arccos \left( \frac{\vec{p}_T(j^i,j^k) \cdot \vec{p}_T(j^l,j^m)}{|\vec{p}_T(j^i,j^k)| \cdot |\vec{p}_T(j^l,j^m)|} \right)$

Additional jets may be produced also by DPS

CMS-FSQ-13-010

Sensitivity to higher orders..

..but also to MPI!
Measurement of a final state with $\gamma + 3$ jets

**Event selection**

Selection of a photon and at least three jets in $|\eta| < 2.5$:

- $\gamma + 1$ jet: $p_T > 75$ GeV
- $2$ jets: $p_T > 20$ GeV

No difference between predictions with and w/o MPI

Soft jets may also be produced also by a $2^{nd}$ scattering

CMS-FSQ-12-017

$$\Delta \phi(j_i, j_k) = \phi_i - \phi_k$$

$$\Delta_{soft}^{rel}p_T = \frac{|p_T(j_i, j_k)|}{|p_T(j_i)| + |p_T(j_k)|}$$

$$\Delta S = \arccos\left(\frac{\vec{p}_T(\gamma, j^k) \cdot \vec{p}_T(j^l, j^m)}{|\vec{p}_T(\gamma, j^k)| \cdot |\vec{p}_T(j^l, j^m)|}\right)$$
Measurement of a $W$+dijet final state

Event selection

Presence of a muon with $p_T > 35$ GeV in $|\eta| < 2.1$ and $E_{T}^{\text{miss}} > 50$ GeV + at least 2 jets: $p_T > 20$ GeV in $|\eta| < 2.0$

The jets are expected to be produced also by a 2$^{nd}$ scattering

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Sensitivity to DPS!

$\Delta_{\text{soft}}p_T = \frac{|p_T(j_i, j_k)|}{|p_T(j_i)| + |p_T(j_k)|}$

$\Delta S = \arccos \left( \frac{\vec{p}_T(W) \cdot \vec{p}_T(j^l, j^m)}{|\vec{p}_T(W)| \cdot |\vec{p}_T(j^l, j^m)|} \right)$
Extraction of $\sigma_{\text{eff}}$ from W+dijet final state

CONSIDERED OBSERVABLES: normalized $\Delta S$ and $\Delta^{rel} p_T$  
BACKGROUND: MADGRAPH+P8 with hard MPI above 15 GeV excluded  
SIGNAL: Two mixed independent scatterings generated with P8 and MG+P8  
DRIVING UNCERTAINTY: model dependence

$$\sigma_{\text{eff}} = \frac{N_{W+0j}}{f_{DPS} \cdot N_{W+2j}} \cdot \sigma_{2j}$$

$$f_{DPS} = 5.5\%,$$

$$\frac{N_{W+0j}}{N_{W+2j}} = 27.8$$

$$\sigma_{\text{eff}} = 20.7 \pm 0.8 \text{ (stat.)} \pm 6.6 \text{ (syst.) \, mb}$$
Extraction of $\sigma_{\text{eff}}$ in four-jet final states

CONSIDERED OBSERVABLES: normalized $\Delta S$ and $\Delta^{\text{rel}} p_T$

NEW METHOD USED: inclusive fits to observables

DRIVING UNCERTAINTY: fit uncertainty (no model dependence included)

Minimization of the binned $\chi^2 = \sum O \sum b \in O \frac{(MC^b - DATA^b)^2}{\Delta^2 b}$

A lower value of $\sigma_{\text{eff}}$ improves the description of the measurement

Values of $\sigma_{\text{eff}}$ are compatible between four-jet and W+dijet final states

$\sigma_{\text{eff}} = 19.0^{+4.7}_{-3.0}$ mb
CMS has a very rich QCD program investigating processes at different scales, final states, and phase space sensitive to low-$x$ dynamics

- Good description of QCD processes in central and forward region
- No clear evidence of behaviour disagreeing with DGLAP eq. (yet)
- Saturation of the cross section measured when going to low $p_T$
- Many DPS-sensitive measurements performed with different final states ($W$+jets, four-jets, two b- + two other jets...)
  - Need for DPS contribution for better data description

**Future:** New energy, sensitivity to lower $x$ values, new phase space!
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THANK YOU!
BACK-UP SLIDES
Choice of the physics channel

\[ \sigma_{DPS}^{AB} = \frac{m}{2} \frac{\sigma_A \sigma_B}{\sigma_{\text{eff}}} \]

Internal structure of the proton DPS background for any physics channel

→ Which channels can be used to look for DPS signals?

Published by CMS and/or ATLAS

Published by D0 and/or CDF

How can DPS be detected?
The Compact Muon Solenoid experiment

- Silicon tracker immersed in a 3.8 T magnetic field
- Wide calorimeter coverage
- Excellent jet energy resolution and muon detection efficiency
- Particle Flow technique for jet reconstruction
Introduction: the Underlying Event

- **Hard scattering**
- **Initial and Final State Radiation**
- **Multiple Parton Interaction (MPI)**
- **Beam-beam remnants**

In general, the UE is a softer contribution but.. some MPI can be hard!

**Double Parton Scattering**

\[
P_A = \frac{\sigma_A}{\sigma_{tot}}
\]

\[
P_B = \frac{\sigma_B}{\sigma_{tot}}
\]

\[
\sigma_{DPS} \propto m^2 P_A P_B \sigma_{tot}^{pp}
\]

\[
\sigma_{DPS}^{AB} = \frac{m \sigma_A \sigma_B}{2 \sigma_{eff}}
\]

\[
\sigma_{eff} \ll \sigma_{tot}^{pp}
\]

Need for correlations!
The inclusive fit method

Experimental difficulties of the template method

→ **How to define the background?**
  - Good to exclude hard MPI..but no such possibility in some generators

→ **How to define exclusive and inclusive events?**
  - \( N_{W+0j} \) and \( N_{W+2j} \) are sensitive to the jet scales

→ **These issues have an impact on the systematic uncertainty!**
  
  *Is there a way out?*

The inclusive fit method

- Run predictions for different choices of UE parameters
- Fit the MC predictions to the considered observables
- Improve the data description with the examined model
- (..look at the corresponding \( \sigma_{\text{eff}} \)...)