Forward production of particles and jets at the CMS

Anastasia Grebenyuk

on behalf of the CMS Collaboration

QCD @ LHC
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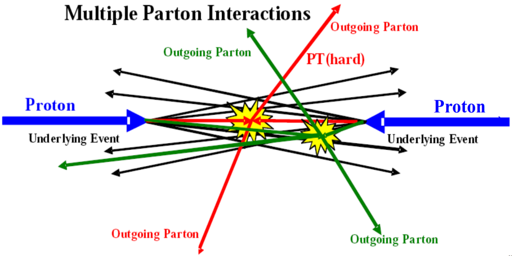
Outline

- Semi-hard processes
  - Pseudorapidity distribution of charged particles (CMS-PAS-FSQ-12-026)
  - Leading charged particle (CMS-PAS-FSQ-12-026)
- Double parton scattering
  - W + dijet channel (CMS-PAS-FSQ-12-028)
  - 4 light-jet channel (CMS-PAS-FSQ-12-013)

Sources of hadron hadron production in *pp*



(Rick Field)

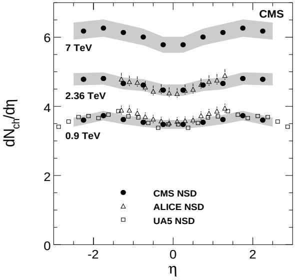
In addition to the single hard interaction with large p_T:

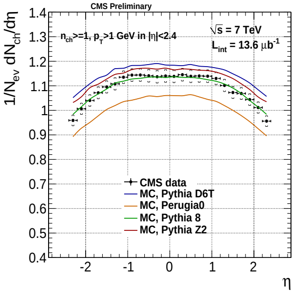
- Interactions with low p_T
- Parton showers
- Multi-parton interactions (MPI): additional parton interaction from the remnants

Pseudorapidity distribution of charged particles

Motivation:

- Particle yields and kinematic distributions are essential for understanding of the physics of hadron production including the relative roles of soft and hard scattering contributions
- The bulk of particles produced in pp collisions arise from semi-hard (multi)parton interactions → phenomenological models → tuning based on experimental data





Analysis details (CMS-PAS-FSQ-12-026)

Measurement of $dN_{ch}/d\eta$ performed in common with TOTEM

- test of model predictions from central to forward pseudorapidities in a previously unexplored phase-space region
- role of diffractive components

Data

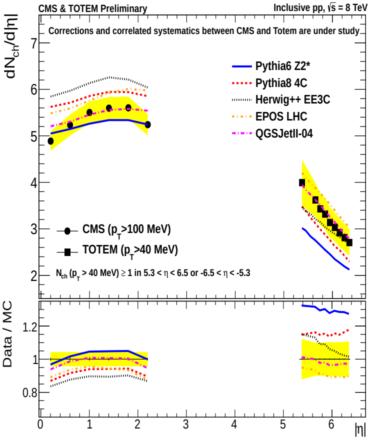
- Common CMS+TOTEM low pile up run with non-standard β*=90m optics configuration (L=17.4 nb^{-1})
- Minimum bias trigger provided by TOTEM (T2 track in either side)
- Track selection:
  - Good quality tracks in $|\eta|^{\mathrm{track}}$ <2.4
  - for the $dN_{\mathrm{ch}}/d\eta$ analysis: $p_T > 0.1$ or 1 GeV

Stable particle level definition

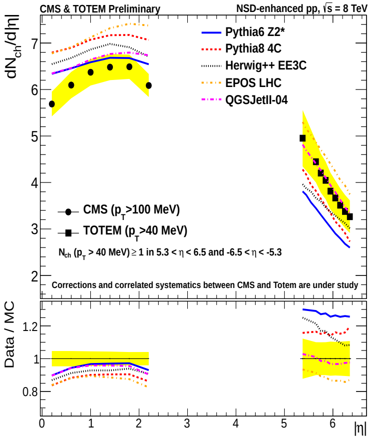
- Defined as primary charged particles or decay products with proper lifetimes $c\tau$ <1 cm
- Two different event samples defined:
  - Inclusive: at least one charged particle in 5.3< η <6.5 OR -6.5< η <-5.3 with p_T >40 MeV
  - NSD-enhanced: at least one charged particle in 5.3< η <6.5 and -6.5< η <-5.3 with p_T >40 MeV (double-sided events)

Combined CMS-TOTEM results (CMS-PAS-FSQ-12-026)

Inclusive:



NSD-enhanced:



- Data are well described by cosmic-ray MC QGSJETII-04
- All models overestimate the data by up to 20% in the central region and most of them underestimate the data in the forward region

Leading charged particle; Motivation

Integrated cross section for hard $2 \to 2$ process above some $p_{T,min}$:

$$\sigma_{int}(p_{T,min}) = \int_{p_{T,min}} dp_T \frac{d\sigma}{dp_T}$$

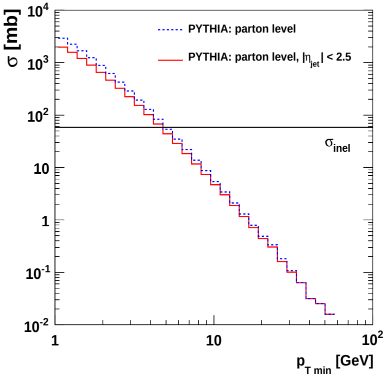
- divergency: $d\sigma \propto \frac{dp_T^2}{p_T^4}$
  $\sigma_{int}(p_{T,min}) \propto \frac{1}{p_{Tmin}^2}$ for $p_{T,min} \to 0$
- $\sigma_{int} > \sigma_{inel}$

Proposal for a measurement:

- Visible leading minijet (charged particle) cross section integrated over transverse momentum
- Event cross section (rather than inclusive jet cross section)
  - Sensitivity to the unitarity bound set by the $\sigma_{inel}(pp)$
- Comparison with inelastic σ(pp) within acceptance - no extrapolation needed

A. Grebenyuk, F. Hautmann, H. Jung, P. Katsas, and A. Knutsson
Phys. Rev. D 86, 117501 (2012)

Integrated leading minijet cross section:



$\sigma_{jet} > \sigma_{inel}$ in η range accessible by experiments

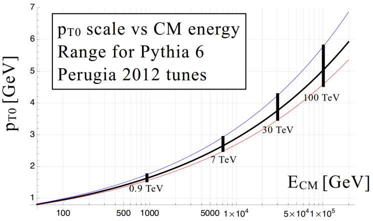
Regulator p_{T0}

In PYTHIA the rise of σ_{int} is tamed by:

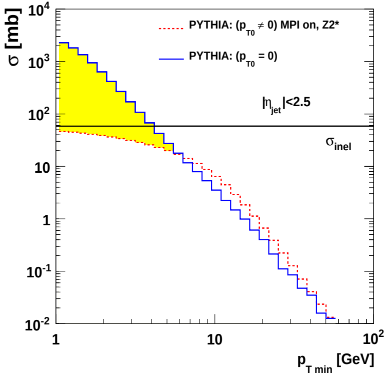
$$\sigma \to \sigma \times \frac{\alpha_s^2(p_{T0}^2+p_T^2)}{\alpha_s^2(p_T^2)} \frac{p_T^4}{(p_{T0}^2+p_T^2)^2}$$

Energy-dependent p_{T0} is determined by tuning to data (PARP(82) $\sim$ few GeV)

from P. Skands talk:



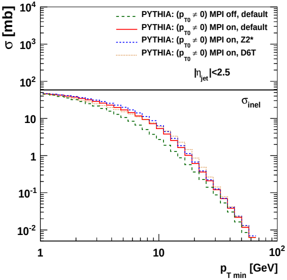
$$p_{T0}^2 \sim s^n, n \sim 0.1$$



PYTHIA with $p_{T0} = 0$

PYTHIA with $p_{T0} \neq 0$

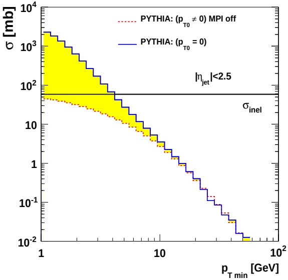
Effect on MPI



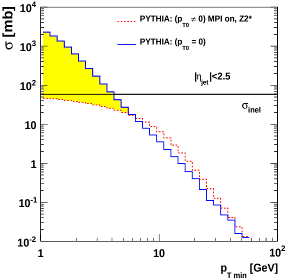
⟵ PYTHIA with $p_{T0} \neq 0$ and MPI with different UE tunes

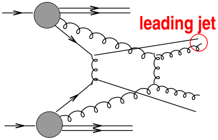
- Taming does not totally depend on MPI

PYTHIA ($p_{T0} \neq 0$), MPI off



PYTHIA ($p_{T0} \neq 0$), MPI on

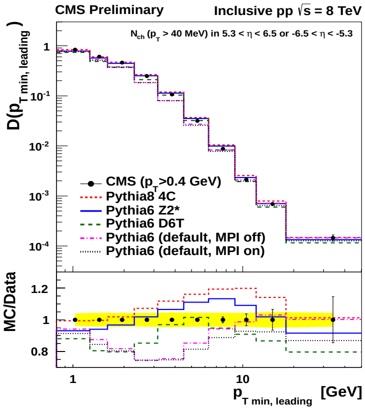


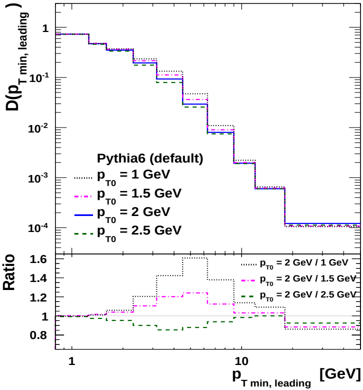


Measurement of the integrated leading charged particle (CMS-PAS-FSQ-12-026)

Normalised distribution: $D(p_{T,min\ leading}) = \frac{1}{N}\int_{p_{T,min\ leading}} dp_{T,leading} \left(\frac{dn}{dp_{T,leading}}\right)$

Measurement of the integrated leading charged particle together with PYTHIA predictions:

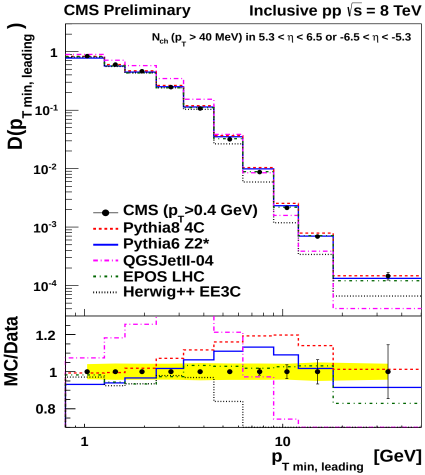




- Shape of the data not well described
- Deviations between different PYTHIA tunes

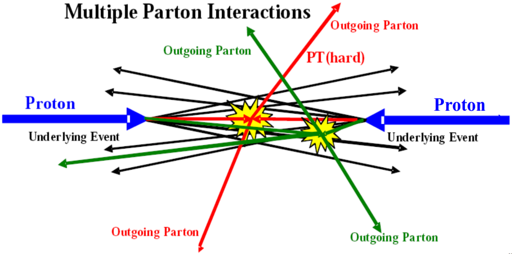
- Sensitivity to p_{T0}

Data vs cosmic ray MC



- The best description of the data is achieved by the EPOS MC

Sources of hadron production in *pp*



(Rick Field)

In addition to the single hard interaction with large p_T:

- Interactions with low p_T
- Parton showers
- Multi-parton interactions (MPI): additional parton interaction from the remnants

  ⟶ Double Parton Scattering (DPS)

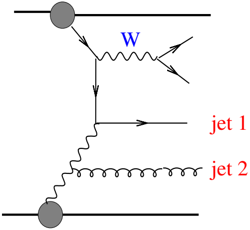
  - W + dijet channel (CMS-PAS-FSQ-12-028)
  - 4 light-jet channel (CMS-PAS-FSQ-12-013)

W + dijets

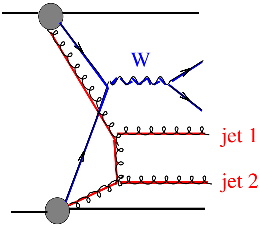
Motivation:

- Study DPS events (DPS fraction, process dependence, ...)
- Test for higher order calculations

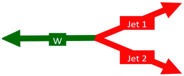
Single parton scattering (SPS)



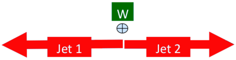
Double parton scattering (DPS)



The momentum of the W+jets system is overall balanced



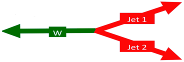
The jets balance each other in the transverse plane



MC generators:

MADGRAPH: W+jets are from matrix element (ME); underlying events - from PYTHIA6 (Z2)
PYTHIA8: W+jets are from LO matrix element and MPI

DPS-sensitive observables

Observables:	SPS	DPS
		
Difference in azimuthal angle between the two jets: $\Delta\varphi = \varphi^{jet1} - \varphi^{jet2}$	$\Delta\varphi \neq \pi$	$\Delta\varphi = \pi$
Normalised balance of the transverse momenta between the two jets: $\Delta^{rel} p_T = \frac{\lvert \vec{p_T}^{jet1} + \vec{p_T}^{jet1} \rvert}{\lvert \vec{p_T}^{jet1} \rvert + \lvert \vec{p_T}^{jet1} \rvert}$	$\Delta^{rel} p_T$ is not small	$\Delta^{rel} p_T$ is small
Angular difference between the planes of the W- and dijet-systems: $\Delta S = arccos(\frac{\vec{p_T}^{W} \cdot \vec{p_T}^{dijet}}{\lvert \vec{p_T}^{W} \rvert \cdot \lvert \vec{p_T}^{dijet} \rvert})$	$\Delta S = \pi$	$\Delta S \neq \pi$

Measurements of the cross section and the normalized distributions for the three different jet scenarios

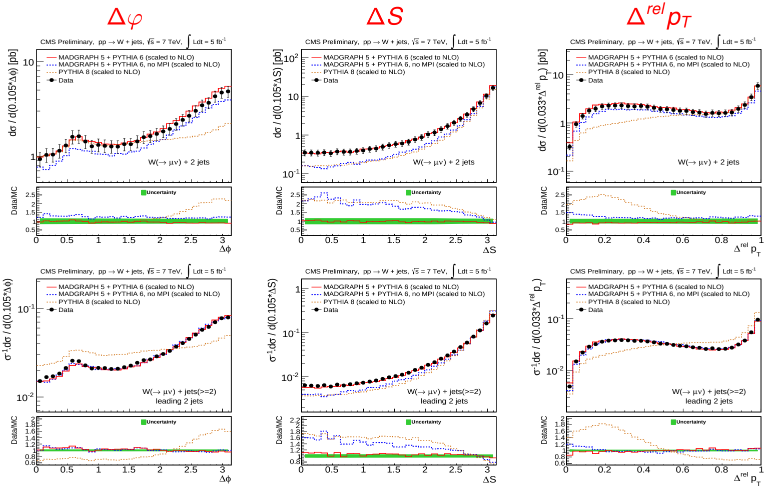
Analysis details

- Full 2011 collision data at $\sqrt{s}$ =7 TeV
- Single muon datastreams, $L = 5$ fb^{-1}
- W selection:
  - Request for exactly one muon with $p_T > 35$ GeV in $|\eta| < 2.1$
  - PF Missing Transverse Energy (MET) > 30 GeV
  - Transverse mass between muon and MET > 50 GeV
- Jet selection
  - Particle flow information
  - Anti-k_t jet cluster algorithm
  - $|\eta| < 2.5$

Different categories of the jet configurations in the final state:

- exclusively two jets with $p_T > 20$ GeV
- two leading jets with $p_T > 20$ GeV
- two best-balanced jets with $p_T > 20$ GeV

DPS-sensitive observables; exclusively two jets scenario



- MADGRAPH (ME + PYTHIA PS and MPI) provides a very good description of the data
- PYTHIA fails to describe the data
- Need to understand the contribution of the Single Parton Scattering (SPS)

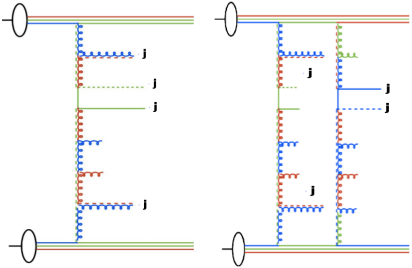
CMS-PAS-FSQ-12-028

4 light-jet channel

4-jet final state may arise from one or two chains
Pair of jets at different thresholds in p_T are selected:

- pair at high p_T (from hard scattering)
- pair at low p_T (from parton shower or DPS)

Single parton scattering (SPS) Double parton scattering (DPS)



Observables to discriminate two processes (i,k= soft or i,k= hard):

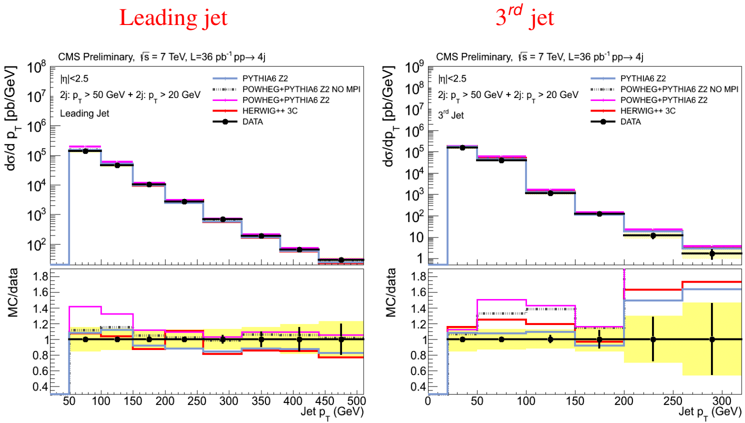
$$\Delta\varphi(j_i, j_k) = \varphi_i - \varphi_k$$
$$\Delta\eta(j_i, j_k) = \eta_i - \eta_k$$
$$\Delta^{\text{rel}}_{\text{pair}} p_T = \frac{|p_T(j_i, j_k)|}{|p_T(j_i)| + |p_T(j_k)|}$$

Analysis details

- 2010 collision data at $\sqrt{s}$ =7 TeV, $L = 36$ pb^{-1}
- low pile-up conditions
- single jet trigger
- Jets selection:
  - selection of exactly 4 jets in $|\eta| < 2.5$
    - hard-jet pair: 2 jets with $p_T > 50$ GeV
    - soft-jet pair: 2 jets with $p_T > 20$ GeV

Measurement of cross sections and normalized distributions of jet spectra and correlation observables

Leading and soft jets; cross section measurements

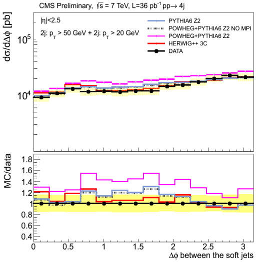


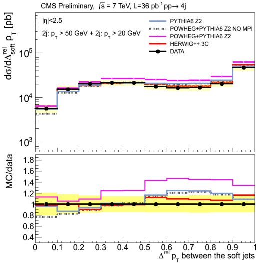
- Best description of the data is achieved by Herwig++ and PYTHIA6
- POWHEG (NLO + PYTHIA PS and MPI) fails to describe low p_T region for leading jet and high p_T for 3^{rd} jet
  - NLO calculation does not perform necessary well with the best tune at LO!

CMS-PAS-FSQ-12-013

Correlation observables

Cross section:





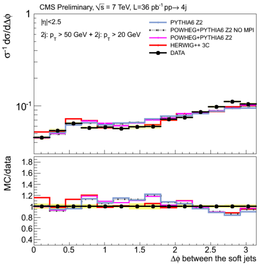
$$\Delta\varphi(j_i, j_k) = \varphi_i - \varphi_k$$

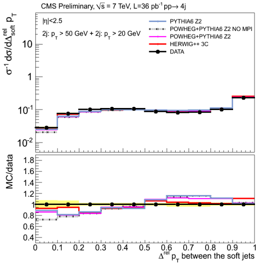
$$\Delta^{\text{rel}}_{\text{pair}} p_T = \frac{|p_T(j_i, j_k)|}{|p_T(j_i)| + |p_T(j_k)|}$$

i,k = soft jets

- Best description of the data is achieved by Herwig++
- POWHEG overshoots the data

Normalised distributions:





- All models provide reasonable description of the shape of the data
- $\Delta^{\text{rel}}_{\text{soft}} p_T$ shows bigger sensitivity to MPI

CMS-PAS-FSQ-12-013

Summary

- Semi-hard processes
  - $dN_{ch}/d\eta$ measurement
    - role of semi-hard scattering and diffractive components
    - tuning of the models
  - Measurement of the leading charged particle distribution
    - sensitivity to the unitarity bound set by the total inelastic proton-proton cross section
    - transition from the perturbative to the non-perturbative region $\longrightarrow$ test of the models in this region
- Double parton scattering
  - 4-jet measurement is sensitive to the hard matrix element and to the underlying event
  - correlation observable measurements have been performed in the W+dijet channel and in a 4-jet scenario
    - need for a proper tune of POWHEG and MADGRAPH
    - need for a 4-jet NLO calculation
    - need to compare the W+2 jet with a NLO calculation