Overview of Forward, Soft and Small-x QCD Physics from CMS

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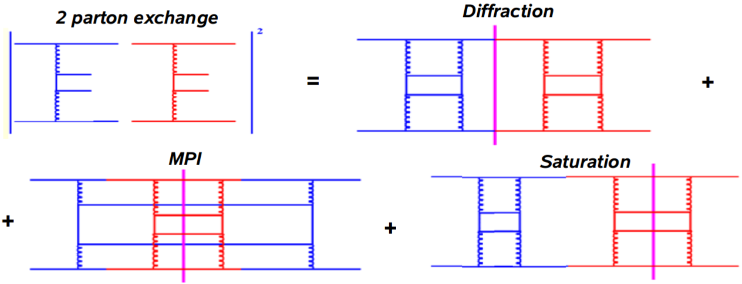
Open Questions in QCD

- All processes at the LHC are QCD ones, whether signal or background is considered
- Description of hadron scattering in the high energy limit - Saturation?
- Nature of Multiple Parton Interactions?
- Hadron production - Description of the Underlying Event?
- Search for Double Parton Scattering?
- Description of the Rapidity Gap Survival Probability in Diffraction?
- MPI, Saturation and Diffraction are related by the AGK cutting rules



Description of hadron scattering in QCD

- Collinear Factorization and fixed-order QCD calculation
  - Factorization of short and long distance dynamics:

    $$\sigma_{pp} = f_i(x_1, \mu^2) \otimes \hat{\sigma}_{ij}(x_1, x_2, Q^2) \otimes f_j(x_2, \mu^2)$$

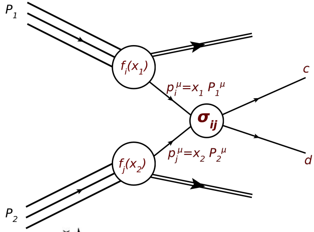
    $\hat{\sigma}_{ij}(x, Q^2)$: Matrix Element (ME) at LO,NLO,...

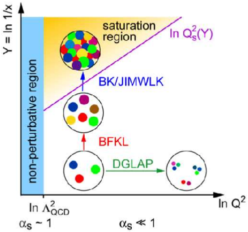
    $f_i(x, \mu^2)$: parton density functions (pdfs)
  - pdf evolution driven by DGLAP equations:

    $f(x, Q^2)$ from $f(x_0 > x, Q_0^2 < Q^2)$
  - pdfs do not depend on parton transverse momentum k_T:

    initial state collinear with the incoming hadrons at LO

    final state p_T can only be produced from ME
  - Leading Twist: single parton scattering
  - Validity: presence of hard scale - dilute system of partons



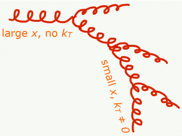


Implementation in Monte Carlo Models

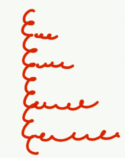
- Fixed-order Matrix Elements matched with Parton Showers

  Initial state shower:

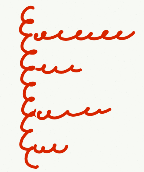
  - high-x parton at the starting scale radiates secondary partons
  - loss of longitudinal momentum and gain of k_T
  - parton with $k_T \neq 0$ enters hard scattering



- Evolution according to DGLAP
  - Validity: $\sqrt{s} > p_T \gg \Lambda_{QCD}$
  - Resum leading contributions in $\log(Q^2)$
  - Strong ordering of the parton shower in k_T



- Evolution according to BFKL (k_T factorization)
  - Validity: $\sqrt{s} \gg p_T \gg \Lambda_{QCD}$
  - Resum leading contributions in $\log(1/x)$
  - Strong ordering in x - random walk in k_T
  - Number of emitted gluons increases with available phase space in y



Alternative approach

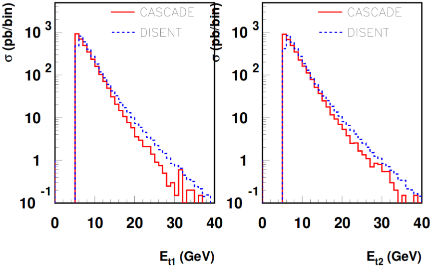
- High Energy Factorization

$$\sigma_{pp} = \mathcal{A}_i(x_1, k_{T1}, \mu^2) \otimes \hat{\sigma}_{ij}(x_1, x_2, k_{T1}, k_{T2}) \otimes \mathcal{A}_j(x_2, k_{T2}, \mu^2)$$

$\hat{\sigma}_{ij}(x, k_T)$: off-shell Matrix Element

$\mathcal{A}_i(x, k_T, \mu^2)$: unintegrated parton density functions (updfs)

- Evolution according to CCFM
  - Resum leading contributions in both $\log(Q^2)$ and $\log(1/x)$
  - unintegrated (k_T dependent) pdfs contain already at leading order some effects which are only achieved at higher order in the collinear factorization scheme

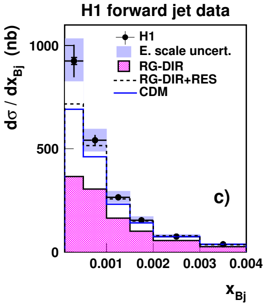


- CASCADE: predictions from CCFM and k_T factorization
- DISENT: NLO calculations in collinear approximation

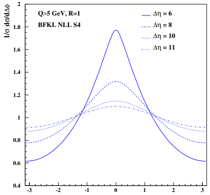
AIP Conf. Proc. **1056** (2008) 79 F. Hautmann and H. Jung

Forward jets - jets at large $\Delta\eta$

- Forward jets $\rightarrow$ Distinguish between parton shower models
- Difference more prominent in the forward region
- DGLAP: k_T ordering: softest emissions are forward
- BFKL: no k_T ordering: forward emissions “arbitrarily” large

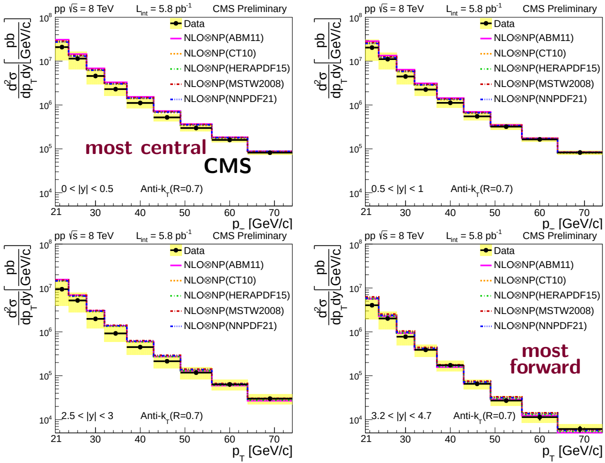


- Jets at large $\Delta\eta$ $\rightarrow$ Open phase-space for BFKL-type radiations
- Wider separation $\Delta\eta$ $\rightarrow$ larger azimuthal decorrelation $\Delta\varphi$
- DGLAP: jets more balanced in p_T, more correlation
- BFKL: higher order emissions, flatter $\Delta\varphi$



Forward & low p_T jets at 8 TeV

CMS-PAS-FSQ-12-031

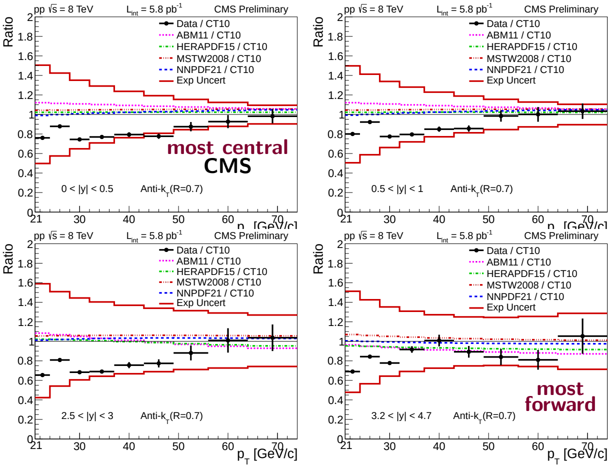


Events with at least one jet with $|y| < 4.7$ and $21 < p_T < 74$ GeV

- NLO predictions too high especially in the forward region $2.5 < |y| < 4.7$
  Global agreement with the data within the experimental and theoretical uncertainties

Forward & low p_T jets at 8 TeV

CMS-PAS-FSQ-12-031



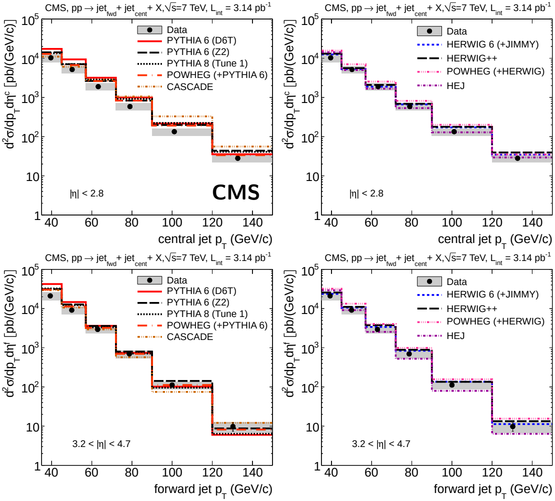
- NLO predictions using different PDF sets (ratios to CT10) describe data within uncertainties
- Use these jet cross sections to further constrain the proton pdfs ?

Forward + Central Jets at 7 TeV

JHEP 1206 (2012) 036

Events with at least one forward jet with $3.5 < |\eta| < 4.7$ and $p_T > 35$ GeV
one central jet with $|\eta| < 2.8$ and $p_T > 35$ GeV

- Central jet p_T spectrum
  Pythia6, Pythia8 & CASCADE
  miss the normalization
  Herwig6, Herwig++ and HEJ
  give the best description
- Forward jet p_T spectrum
  Pythia6, Pythia8 & CASCADE
  miss the shape
  Herwig6, Herwig++ and HEJ
  give the best description



MN to exclusive dijet cross section ratio at 7 TeV

Eur.Phys.J. C72 (2012) 2216

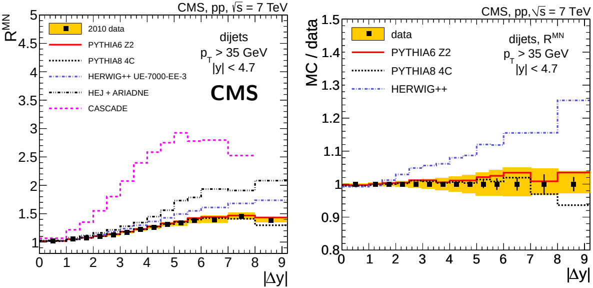
Events with at least 2 jets with $|\eta| < 4.7$ and $p_T > 35$ GeV

Observable: Rapidity separation Δy between the pairs of jets

Exclusive sample: exactly 2 jets in the event

MN sample: at least 2 jets in the event, Δy between the most forward and most backward jets

- $R = \frac{\sigma_{dijet}(\mathrm{MN})}{\sigma_{dijet}(\mathrm{exclusive})}$



- Increasing Δy $\rightarrow$ larger phase space for extra radiation $\rightarrow$ increasing ratio
- Pythia6 Z2 and Pythia8 4C describe the data
- Herwig++ and HEJ+Ariadne are too high at high Δy
- No visible effects beyond collinear factorization + LL parton shower

Dijet azimuthal decorrelations at 7 TeV

CMS-PAS-FSQ-12-002

Events with at least two jets with $|\eta| < 4.7$ and $p_T > 35$ GeV

Observables:

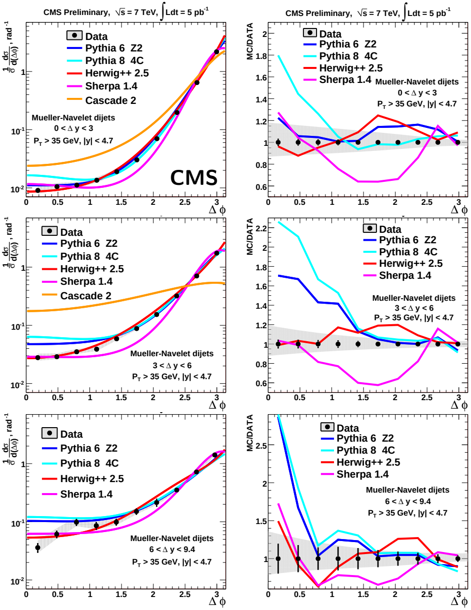
- azimuthal decorrelation $\Delta\varphi$ between the most forward and the most backward jets
- Fourier coefficients C_n of the Fourier expansion of the differential cross section in $\Delta\varphi$

$$\frac{1}{\sigma}\frac{d\sigma}{d\Delta\varphi} \sim \sum_n C_n \cos\left(n\left(\pi - \Delta\varphi\right)\right)$$

$$C_n = \langle \cos\left(n\left(\pi - \Delta\varphi\right)\right)\rangle$$

- Measure $C_1 = \langle \cos\left(\pi - \Delta\varphi\right)\rangle$, $C_2 = \langle \cos\left(2\left(\pi - \Delta\varphi\right)\right)\rangle$ and $C_3 = \langle \cos\left(3\left(\pi - \Delta\varphi\right)\right)\rangle$
- Ratios of coefficients: DGLAP suppressed $\rightarrow$ more sensitivity to BFKL effects
- Measure ratios C_2/C_1 and C_3/C_2
- Measurement for increasing rapidity separation between jets: $0 < \Delta y < 3$
  $\rightarrow$ open phase-space for extra radiations $3 < \Delta y < 6$
  $\rightarrow$ more decorrelation expected $6 < \Delta y < 9.4$

Azimuthal decorrelation in bins of Δy

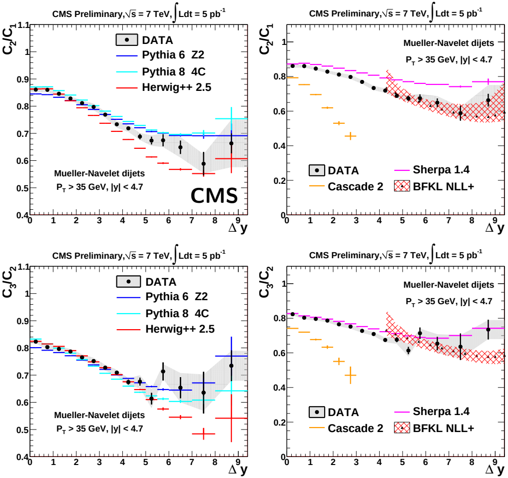


- azimuthal decorrelation $\Delta\varphi$ in 3 bins of rapidity separation Δy
- Increasing azimuthal decorrelation with increasing rapidity separation Δy
- Herwig++: best description of the data
- PYTHIA6/PYTHIA8: too large decorrelation

  $\rightarrow$ in contrast to dijet ratio measurement, where Pythia6/Pythia8 provide better description of data than Herwig++
- Sherpa with 4 final state partons: too much correlation
- CASCADE (CCFM): too much decorrelation

Ratios C_2/C_1 and C_3/C_2

Ratios C_{n+1}/C_n → DGLAP contributions suppressed → more sensitivity to BFKL effects



- At low Δy, C_{n+1}/C_n are described by LL DGLAP based generators
- At larger Δy, LL DGLAP fails (PYTHIA6/8 and Herwig++)
- Sherpa overestimates both ratios
- CASCADE predicts too small ratios
- At $\Delta y > 4$, BFKL NLL prediction describes the ratios within uncertainties (in particular C_2/C_1)

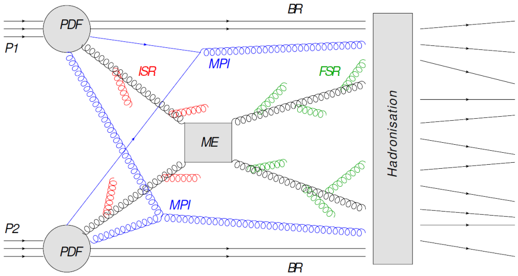
Multiple Parton Interactions - Motivation

- MPI introduced to describe large multiplicity tails and KNO scaling violation
- MPI has become a key ingredient to describe Underlying Event measurements
- Underlying Event: activity not attributed to the hard scattering between partons

  Initial State Radiation and Final State Radiation

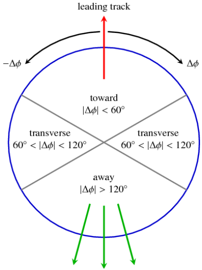
  Beam Remnants

  Multiple Parton Interactions (with its own ISR and FSR)



- The Underlying Event is characterized by a smaller scale than the hard scattering
- Increase of MPI activity happens at the transition between soft and hard collision
- Some MPI can be harder → Double Parton Scattering

Measurement of the Underlying Event



Divide phase space in φ to separate the UE from the hard scatter

3 regions in φ with respect to the leading object direction

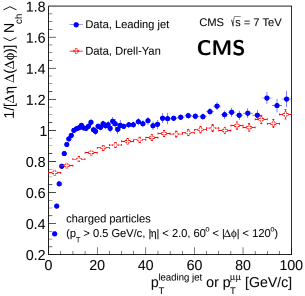
Transverse region most sensitive to the UE activity

Look at particle and energy densities in the transverse region

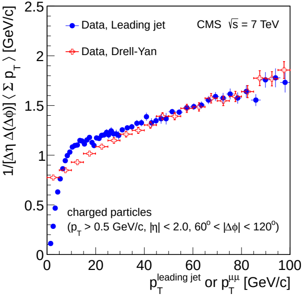
Underlying Event in Jets and Drell-Yan events

Eur.Phys.J. C72 (2012) 2080

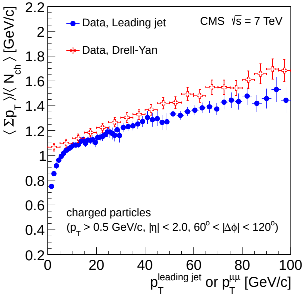
particle density



energy density



average energy / average density



UE activity in hadronic events as a function of the leading jet p_T: two different regimes

At low p_T: fast rise due to the increase of MPI activity

At higher p_T: constant particle density, slow radiative increase of the energy density (ISR/FSR)

UE activity in DY events as a function of $p_T^{\mu\mu}$: one regime

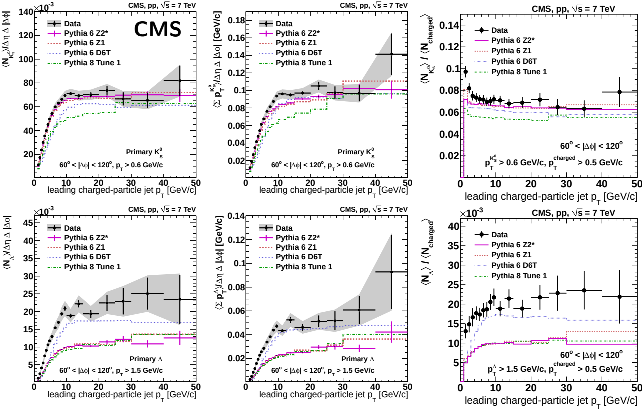
At low p_T: no fast rise , MPI activity saturated (hard scale $81 < M_{\mu\mu} < 101$ GeV)

Slow radiative increase of the UE activity with p_T (ISR)

Strangeness production in the UE at 7 TeV

CMS-PAS-QCD-11-010

particle density | **energy density** | **strange/charged densities**



PYTHIA underestimates data

Deficit similar to inclusive strange particle production

Strange to charged particle activity ratios flat with p_T

$\rightarrow$ MPI decoupled from hadronization

Direction defined by the leading charged-particle jet, with $p_T > 1$ GeV and $|\eta| < 2$

Production of primary K_S^0 and Λ in transverse region

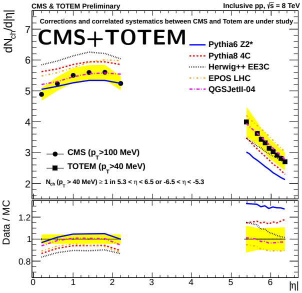
Behaviour similar to inclusive charged particles $\rightarrow$ universal impact parameter picture of MPI

At low p_T: fast rise of the densities - At higher p_T: saturation

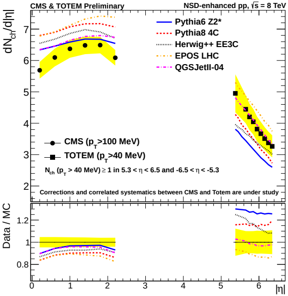
Pseudorapidity distribution of particles at 8 TeV

CMS-PAS-FSQ-12-026

Inclusive



NSD-enhanced



CMS-TOTEM measurement

Predictions vary within 10-20%

Inclusive well described by Pythia6 Z2* and QGSJetII-04

NSD overestimated by all models

Events triggered by the TOTEM T2 telescopes ($5.3 < |\eta| < 6.5$)

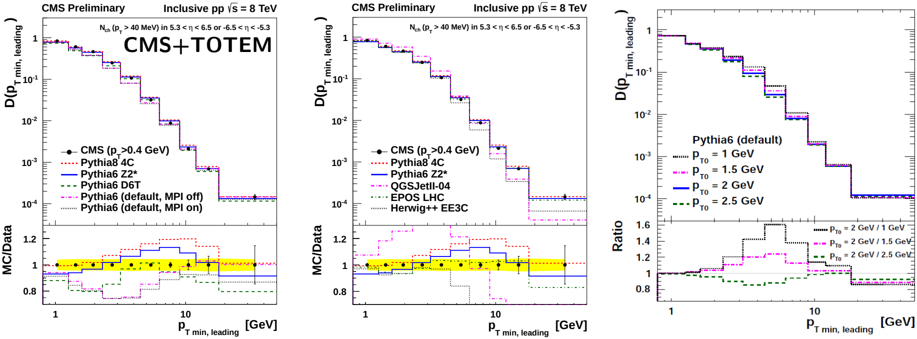
Pseudorapidity distribution of charged particles in $|\eta| < 2.3$ with $p_T > 100$ MeV (CMS)
in $5.3 < |\eta| < 6.4$ with $p_T > 40$ MeV (TOTEM)

Inclusive: at least one charged particle with $p_T > 40$ MeV in either T2 telescope

NSD-enhanced: at least one charged particle with $p_T > 40$ MeV in both T2 telescopes

No consistent description of the distributions by MC predictions

Leading track p_T distribution at 8 TeV



Events triggered by the TOTEM T2 telescopes - Inclusive selection

Leading track p_T distribution for tracks in $|\eta| < 2.4$ with $p_T > 0.8$ GeV

Integrated leading track p_T distribution above p_{Tmin} : $D(p_{Tmin}) = \frac{1}{N} \int_{p_{Tmin}} dp_{T,leading} \frac{dn}{dp_{T,leading}}$

Sensitivity to p_{T0} - probes transition from perturbative to non-perturbative region

Tamed behaviour of the cross section not well described by models - Epos LHC closest to data

Switching on/off MPI does not improve agreement

Double Parton Scattering - Motivation

General expression for DPS cross section leading to A and B plus anything:

$$\sigma(A+B) \propto \int d^2\mathbf{b}\, dx_1\, dx_2\, d\bar{x}_1\, d\bar{x}_2\, D_{ik}(x_1, \bar{x}_1, \mathbf{b})\, D_{jl}(x_2, \bar{x}_2, \mathbf{b})\, \hat{\sigma}_{ij}\, \hat{\sigma}_{kl}$$

Assume $D_{ik}(x_1, \bar{x}_1, \mathbf{b}) = f_i(x_1)\, f_k(\bar{x}_1)\, G(\mathbf{b})$, DPS cross section given by:

$$\sigma(A+B) = m\frac{\sigma(A)\,\sigma(B)}{\sigma_{eff}} \;\text{ with }\; \sigma_{eff} = \left[\int d^2\mathbf{b}\, G^2(\mathbf{b})\right]^{-1}$$

(m = 1/2 for identical interactions, m = 1 otherwise)

Using conditional probability and $\sigma(A) = P(A)\,\sigma_{ND}$, one can write:

$$P(B|A) = P(B)\,\frac{\sigma_{ND}}{\sigma_{eff}}$$

σ_{eff} mostly depends on geometry - supposed to be process, scale and $\sqrt{s}$ independent

$\sigma_{eff} \sim 10 - 15$ mb from CDF and D0 $\gamma + 3$ jets, confirmed by ATLAS W + 2 jets

Experimental picture: measure DPS for different processes, at different scales and $\sqrt{s}$

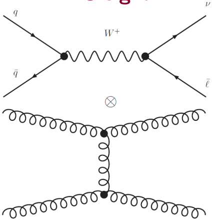
DPS via W + 2 jets

CMS-PAS-FSQ-12-028

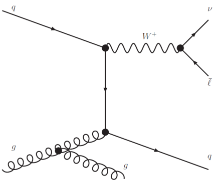
DPS Signal: W from first hard parton scattering, at least two jets from a second one

SPS Background: W + at least 2 jets from a single parton scattering

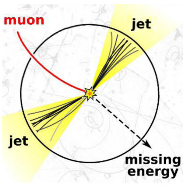
DPS signal

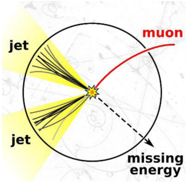


SPS background



Transverse plane view





Discriminating variables:

Azimuthal separation between 2 jets:

$$\Delta\varphi = |\varphi^{j1} - \varphi^{j2}|$$

Relative p_T balance between 2 jets :

$$\Delta^{rel}_{p_T} = \frac{|\mathbf{p_T}^{j1} + \mathbf{p_T}^{j2}|}{|\mathbf{p_T}^{j1}| + |\mathbf{p_T}^{j2}|}$$

Angle ΔS between $W(\mu\nu)$ and dijet vector:

$$\Delta S = \arccos\left(\frac{\mathbf{p_T}(\mu, \not{E}_T) \cdot \mathbf{p_T}(j1, j2)}{|\mathbf{p_T}(\mu, \not{E}_T)|\,|\mathbf{p_T}(j1, j2)|}\right)$$

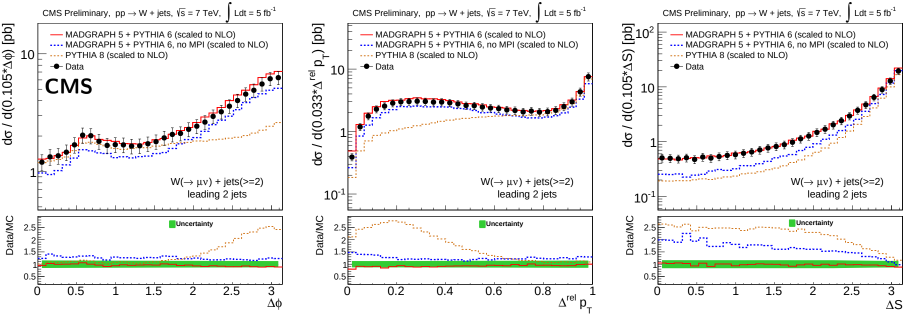
DPS via W + 2 jets

CMS-PAS-FSQ-12-028

Inclusive sample: W + at least 2 jets

Leading two jets considered for calculation of DPS observables

$\Delta\varphi$, $\Delta^{rel}_{p_T}$ and ΔS cross sections



MadGraph with MPI on in good agreement with data

MadGraph with MPI off underestimates data by 20%

Pythia8 underestimates data by a factor ~ 2 in the DPS sensitive regions

Mostly due to missing higher order processes faking DPS

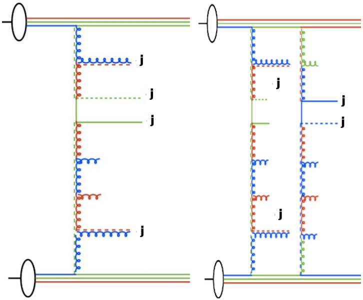
CMS-PAS-FSQ-12-013

DPS via 4 jets

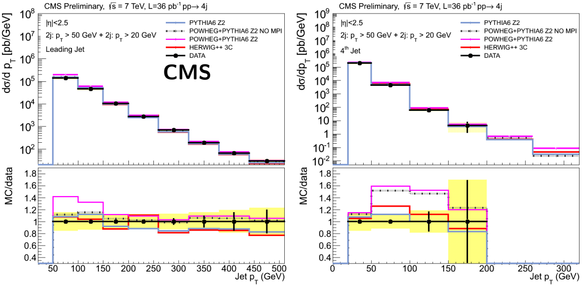
Four jets final state can arise from one or two chains

The two additional jets can be produced via parton shower or a second hard scattering

SPS background **DPS signal**



leading jet **4th jet**



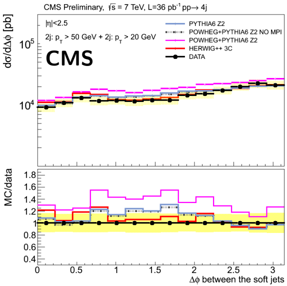
Selection: exactly 4 jets in $|\eta| < 2.5$ - 2 jets with $p_T > 50$ GeV - 2 jets with $p_T > 20$ GeV

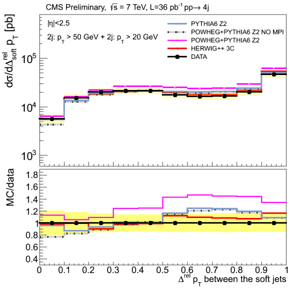
Jets associated in pairs: hard-jet pair: the two leading jets above 50 GeV

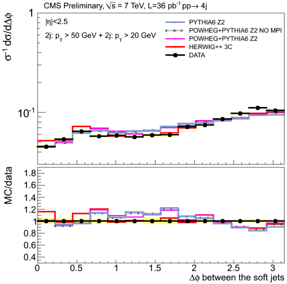
soft-jet pair: the two other jets above 20 GeV

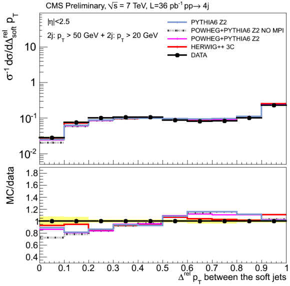
Discriminate the two processes via $\Delta\varphi$ and $\Delta^{rel}_{p_T}$ for each pair

DPS via 4 jets - $\Delta\varphi$ and $\Delta^{rel}_{p_T}$ soft-jet pair









- **Absolute normalization**

  POWHEG overshoots the data

  PYTHIA6 and HERWIG++ describe the data quite well

- **Normalized to unit area**

  Herwig++ and POWHEG describe well the data

  $\Delta^{rel}_{p_T}$ more suited to distinguish MPI on versus MPI off in the normalized distributions

Diffraction and exclusive processes - Motivation

- Diffraction represents a sizeable fraction of σ_{tot} - of the order of 25-35 %

  Important ingredient for the description of the Underlying Event

- Rapidity gap survival probability S^2 poorly known theoretically

  Absence of description in the MPI framework

  Not a simple number - dependence on the diffractive kinematic variables

- Central Exclusive Production

  CEP WW: precise test of the SM - Search for aQGCs

Rapidity Gap cross section

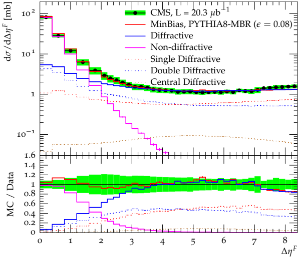
CMS-PAS-FSQ-12-005

Forward rapidity gap $\Delta\eta^F$: largest empty η region, starting at the edge of the detector

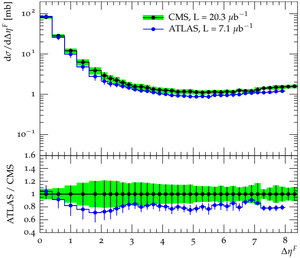
Inclusive measurement - no separation of diffraction

Hadron level definition: gap defined by absence of particle with $p_T > 200$ MeV

CMS



Comparison



Evidence for diffraction at high $\Delta\eta^F$: ND exponentially suppressed - plateau from SD and DD

Diffractive plateau ~ 1 mb / unit of gap size

Sensitivity to diffractive models: PYTHIA8-MBR with $\alpha_P(0) = 1.08$ gives the best description

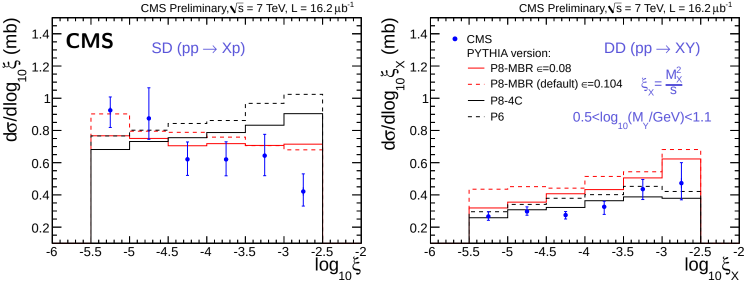
Phojet in good agreement at high $\Delta\eta^F$ but overestimates data at low $\Delta\eta^F$

Agreement ATLAS-CMS within uncertainties - CMS extends ATLAS by 0.4 unit of gap size

Soft diffractive cross sections

CMS-PAS-FSQ-12-005

SD and DD cross sections as a function of ξ



MBR model presented for 2 values of the Pomeron intercept $\alpha_P(0) = 1.08$ & 1.104

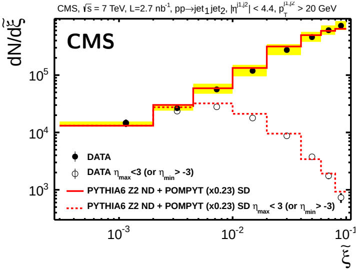
Both describe well the SD cross section - DD better described with smaller $\alpha_P(0)$ value

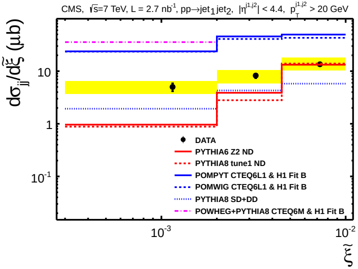
Schuler & Sjostrand model implemented in PYTHIA8-4C and PYTHIA6

Can describe the DD cross section - But not the SD falling behavior

SD cross section integrated over $-5.5 < \log\xi < -2.5$:
$\sigma^{SD}_{vis} = 4.27 \pm 0.04$ (stat.) $+0.65/-0.58$ (syst.) mb for $1.1 \lesssim \log(M_X/\mathrm{GeV}) \lesssim 2.6$

Phys.Rev. D87 (2013) 012006





At least 2 jets with $p_T > 20$ GeV and $|\eta| < 4.4$

Most forward particle should have $\eta_{max} < 3$ or $\eta_{min} > -3$

LRG data described by a combination of ND (PYTHIA6 Z2) and SD (POMPYT) predictions

Relative fraction of SD obtained from a fit to the data

Excess of events at low ξ wrt ND predictions (PYTHIA6 and PYTHIA8)

SD predictions overestimate data by a factor ~ 5 in the lowest ξ bin

Estimate of the rapidity gap survival probability: 0.12 ± 0.05 from LO POMPYT and POMWIG

0.08 ± 0.04 from NLO POWHEG

Exclusive W W production

JHEP 07 (2013) 116

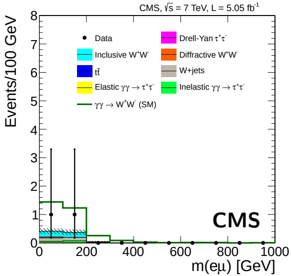
Search for exclusive $\gamma\gamma \to W^+W^-$ and anomalous quartic gauge couplings

In the unlike-flavor dilepton decay channel: $\gamma\gamma \to W^+W^- \to \mu^\pm e^\mp \nu\bar{\nu}$

Exclusivity: No extra tracks associated to the dilepton vertex

SM signal region: $p_T(\mu^\pm e^\mp) > 30$ GeV

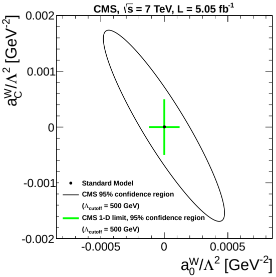
aQGCs search: $p_T(\mu^\pm e^\mp) > 100$ GeV



2 events passing all selection criteria

expected bkg: 0.84 ± 0.15 events

expected signal: 2.2 ± 0.4 events



No events observed in data

Consistent with SM expectation of 0.14

Limits on aQGCs with $\Lambda_{\rm cutoff} = 500$ GeV

New limits $\sim$ 1 (2) order(s) of magnitude more stringent than Tevatron (LEP)

Summary

- Forward and low p_T jets carry information about parton radiation and pdfs at low x

  Simultaneous forward and central production increases the sensitivity

  Dijet production widely separated in η

  Increase sensitivity even more - Probe BFKL-like effects

  None of the MCs can reproduce consistently all the measured observables

  Constraints limited by the uncertainty on the jet energy scale

- Understanding of UE needed for a full understanding of (semi-hard) QCD dynamics, for precision measurements of SM processes, search for new physics

  Improvement of our knowledge: UE in DY and hadronic events

  Strangeness in UE $\sim$ inclusive production

- DPS: Look for dsicriminating variables - More to come
- Diffraction & Exclusive processes: New constraints from soft & hard diffractive measurements

  Exclusive measurements give precise test of SM and constraints on its extensions (e.g. aQGC)

Forward + Central Jets at 7 TeV

- Central jet p_T spectrum

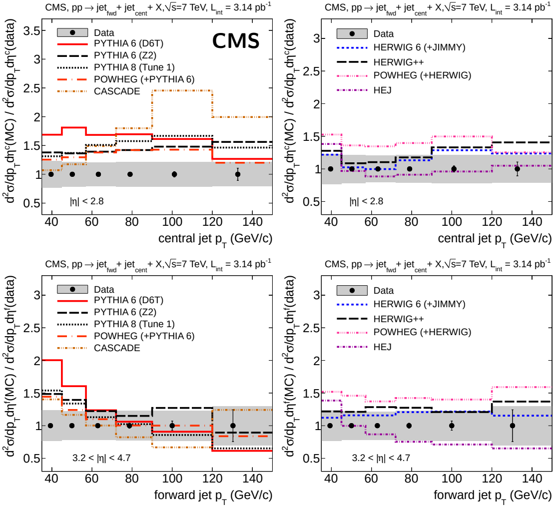
  Pythia6, Pythia8 and CASCADE miss the normalization

  Herwig6, Herwig++ and HEJ give the best description

- Forward jet p_T spectrum

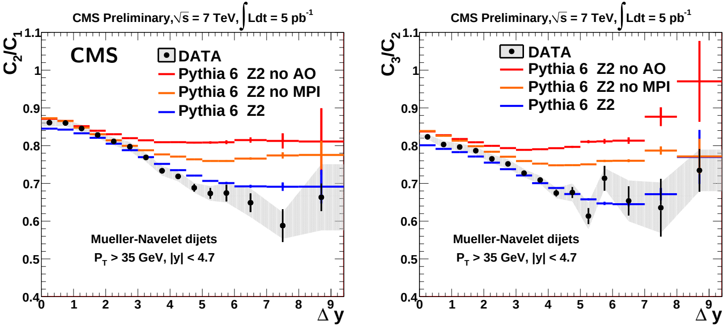
  Pythia6, Pythia8 and CASCADE miss the shape

  Herwig6, Herwig++ and HEJ give the best description



- Different level of agreement between data and MC for the central jet and the forward jet
- Largest shape difference for the forward jet

Effect of Angular Ordering & MPI

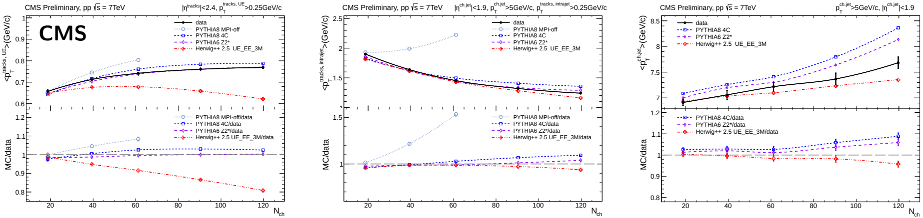


- PYTHIA6 Z2 with and without angular ordering or MPI
- Angular ordering and MPI improve the description of the data, in particular at high Δy

Jets and UE properties versus particle multiplicity

CMS-PAS-FSQ-12-022

p_T tracks UE | **p_T tracks intra jet** | **p_T jet**



Charged particles with $p_T > 0.25$ GeV and $|\eta| < 2.4$

Charged-particle jets with $p_T > 5$ GeV and $|\eta| < 1.9$

Charged particles divided into 2 classes: those belonging to jets and those belonging to the UE

UE and jet properties as a function of charged-particle multiplicity

PYTHIA predicts harder p_T spectra than seen in data

Herwig++ shows the opposite behaviour

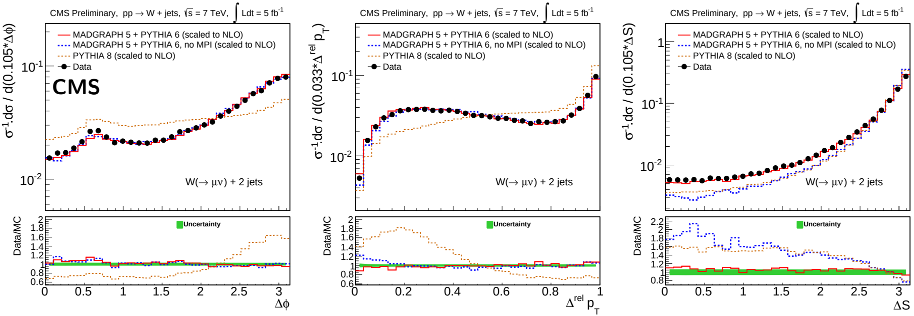
Predictions without MPI fail to describe the data

DPS via W + exactly 2 jets

Exclusive sample: W + exactly 2 jets

Integrated cross section $= 60.6 \pm 8.7$ pb - consistent with NLO scaled MADGRAPH prediction

Distributions $\Delta\varphi$, $\Delta^{rel}_{p_T}$ and ΔS normalized to unit area



MadGraph with and without MPI in good agreement with data except for ΔS

ΔS is the only observable able to distinguish MPI on versus MPI off for the normalized distributions

Bibliography Forward jets

1. Forward and low p_T jets (FSQ-12-031)

Measurement of jet cross sections at low transverse momentum in pp collisions at 8 TeV

2. Forward + Central Jets (FWD-11-002)

Measurement of the inclusive production cross sections for forward jets and for dijet events with one forward and one central jet in pp collisions at 7 TeV

3. Dijet K-factor (FWD-10-014)

Measurement of inclusive and exclusive dijet production ratio at large rapidity intervals at 7 TeV

4. Azimuthal decorrelation (FSQ-12-002)

Azimuthal angle decorrelations of jets widely separated in rapidity in pp collisions at 7 TeV

Bibliography MPI

1. UE DY (QCD-11-012)

Measurement of the UE in the Drell-Yan process in pp collisions at 7 TeV

2. UE Strangeness (QCD-11-010)

Measurement of neutral strange particle production in the UE in pp collisions at 7 TeV

3. Jets and UE properties versus particle multiplicity (FSQ-12-022)

Jet and UE properties as a function of particle multiplicity in pp collisions at 7 TeV

4. dN/deta - Leading tracks p_T CMS-TOTEM (FSQ-12-026)

Pseudorapidity and leading transverse momentum distributions of charged particles in pp collisions at 8 TeV

Bibliography DPS

1. DPS via W + 2 jets (FSQ-12-028)

Study of observables sensitive to double parton scattering in W + 2 jets process in pp collisions at 7 TeV

2. DPS via 4 jets (FSQ-12-013)

Studies of 4-jet production in pp collisions at 7 TeV

Bibliography Diffraction and exclusive processes

1. Rapidity Gap cross section (FSQ-12-006)

Measurement of pp diffractive dissociation cross sections at 7 TeV at the LHC

2. Soft diffractive cross sections (FSQ-12-005)

Measurement of pp diffractive dissociation cross sections at 7 TeV at the LHC

3. Diffractive dijet production at 7 TeV (FWD-10-004)

Observation of a diffractive contribution to dijet production in pp collisions at 7 TeV

4. Exclusive W W production at 7 TeV (FSQ-12-010)

Study of exclusive two-photon production of W^+W^- in pp collisions at 7 TeV and constraints on anomalous quartic gauge couplings