Multiparton and double parton scatterings in CMS

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on behalf of CMS collaboration

Deutsches Elektronen-Synchrotron

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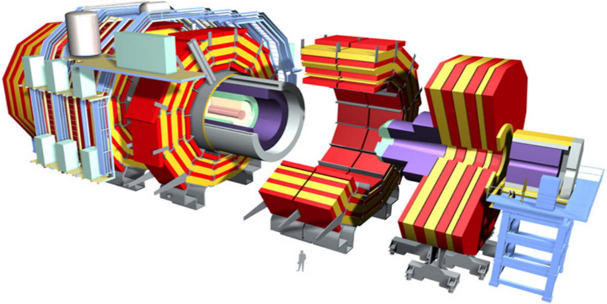
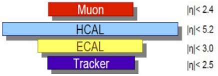
Introduction and outline



CMS detector:

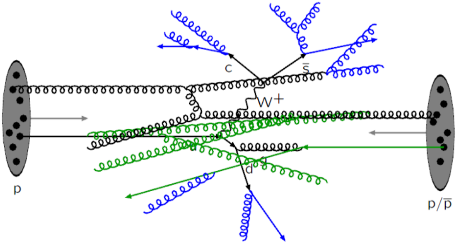
- excellent energy resolution
- Particle Flow technique for jet reconstruction



- Soft MPI: role in the underlying event
- Hard MPI: where and how to measure a direct evidence
  - W+dijet channel
  - 4 light-jet channel
- Summary and outlook

This is just a small selection of topics due to the speaker taste.
More information can be found in the backup slides.

The underlying event at the LHC



Lecture by Torbjörn Sjöstrand, April 2005

A hard *pp*-collision at the LHC can be interpreted as a hard scattering between partons accompanied by the underlying event (UE) consisting of:

- Initial and final state radiation
- Multiple Parton Interactions (MPIs)
- Beam Remnants

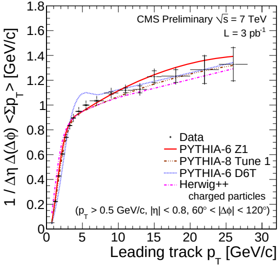
In general the UE is a softer contribution but... some MPIs can be even hard!

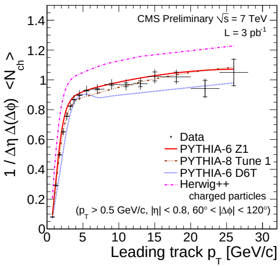
Double Parton Scattering (DPS)

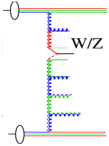
The UE in different types of events

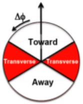
Measurement of the Underlying Event activity as a function of the scale of the hard process

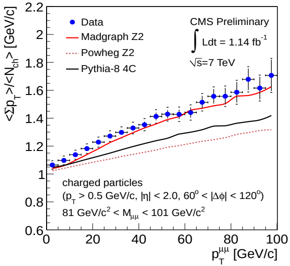
- MB as a function of the leading track-jet p_T CMS-PAS-FSQ-12-020
- Drell-Yan as a function of the di-lepton p_T ($81 < M_{\mu\mu} < 120$ GeV) CMS-PAS-QCD-11-012

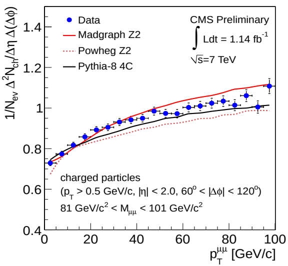












Observables: N_{ch}, $< \Sigma p_T >$:
→ Transverse region

MB events, two regimes:

- rapid increase at low p_T due to MPI;
- plateaux due to radiation;

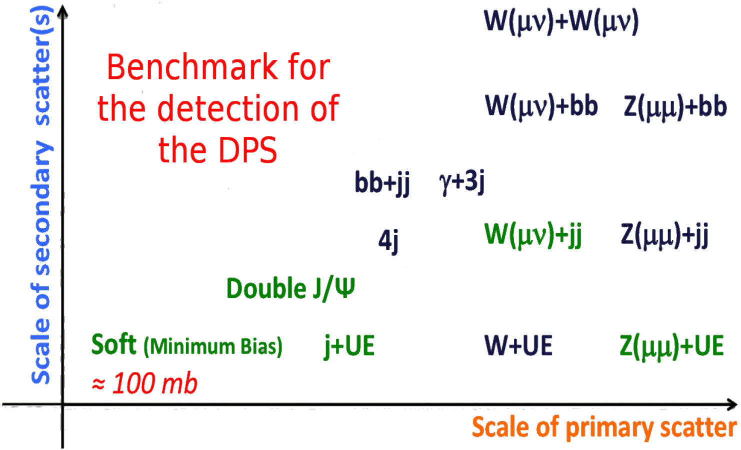
DY events, different behaviour:

- the MPI effect is already saturated;
- increase only due to the radiative component.

Investigation of DPS direct evidences (additional jets)

Is the DPS signal accessible?

Several channels are available to extract the DPS signal



Large physics program → *scan over 15 orders of magnitude for* σ

CMS strategy for the DPS measurement

1st step

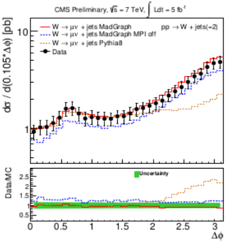
Corrected distributions DPS-sensitive variables

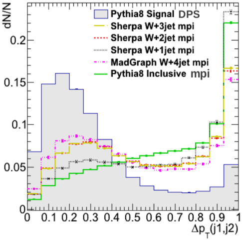
2nd step

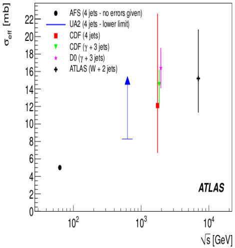
Data interpretation and unambigous definition of signal and background templates

3rd step

Extraction of the DPS fraction and study of the process dependence



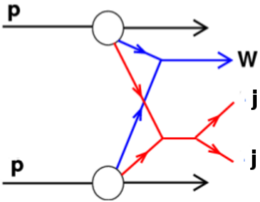


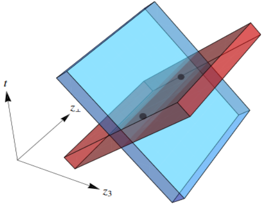


- Compare the data to your own favourite predictions!

4th (future) step: differential distributions with high luminosities..

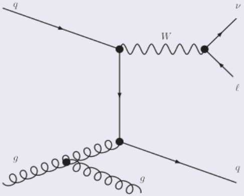
Measurement of correlation observables in the W+dijet channel

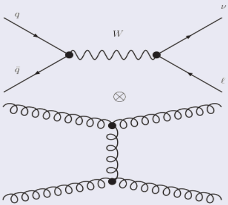




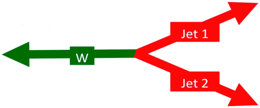
Phenomenology of a W+dijet final state

Two diagrams contribute..

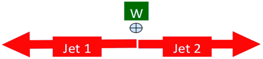




SPS process: the momentum of the W+jets system is overall balanced



DPS process: the jets balance each other in the transverse plane



Different kinematical topology of the two types of processes

- by using simple correlation observables, possibility to discriminate them

Event selection

Data samples

- Full 2011 collision data at $\sqrt{s} = 7$ TeV
- Single muon datastreams:
  - integrated luminosity 5 fb^{-1}

W selection

- Request for exactly one muon:
  - with $p_T > 35$ GeV in $|\eta| < 2.1$
  - isolated and passing tight selection criteria
- 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 jet configurations in the final state:

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

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The correlation observables

Different categories of jet configurations in the final state:

- difference in azimuthal angle between the two jets

$$\Delta\phi = \phi^{jet1} - \phi^{jet2}$$

- normalized balance of the transverse momenta between the two jets

$$\Delta^{rel} p_T = \frac{|\vec{p_T}^{jet1} + \vec{p_T}^{jet2}|}{|\vec{p_T}^{jet1}| + |\vec{p_T}^{jet2}|}$$

- balance in transverse momenta between the two jets

$$\Delta p_T = |\vec{p_T}^{jet1} + \vec{p_T}^{jet2}|$$

- angular difference between the planes of the W- and dijet-systems

$$\Delta S = arccos\left(\frac{\vec{p_T}^{W} \cdot \vec{p_T}^{dijet}}{|\vec{p_T}^{W}| \cdot |\vec{p_T}^{dijet}|}\right)$$

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

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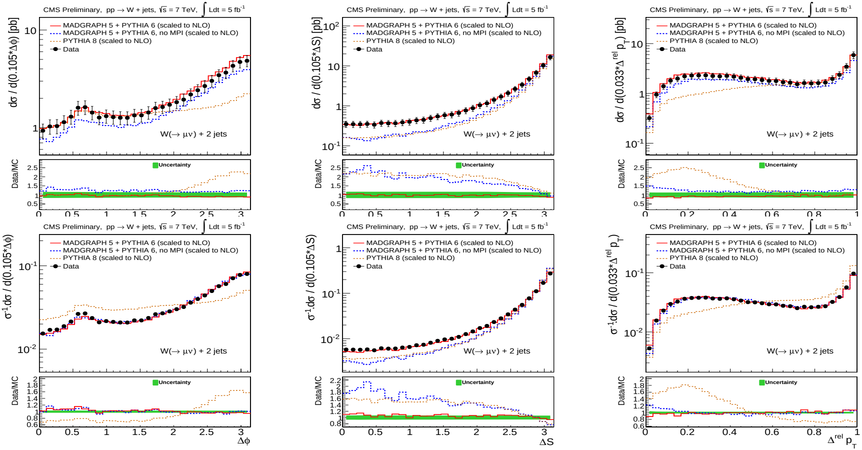
DPS Observables: exclusive 2-jet scenario

→ Fully corrected data with background already subtracted



- MADGRAPH with MPI provides a very good description of the data
- High-order diagrams with MG fill the phase space that PYTHIA8 assigns to MPI
- Need to understand better the contribution of the SPS

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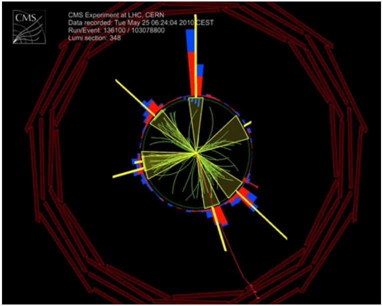
$\sigma = 60.6 \pm 8.7$ pb



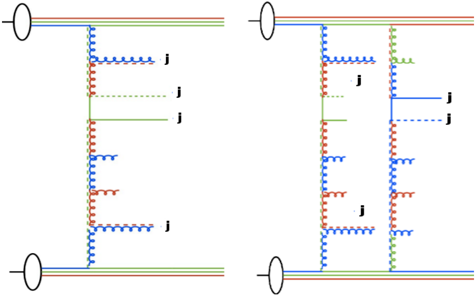
Measurement of correlation observables in the 4-jet channel

NEW!

Physics of a 4-jet scenario

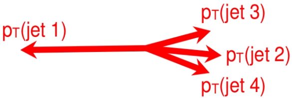
A 4-jet final state may arise from one or two chains:

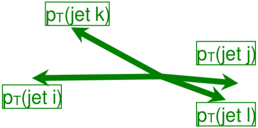
- the two additional jets may be produced via PS or a 2nd hard scattering



The different kinematical configuration can be exploited to discriminate the two processes through some observables:

$$\Delta\phi(j_i, j_k) = \phi_i - \phi_k$$
$$\Delta\eta(j_i, j_k) = \eta_i - \eta_k$$
$$\Delta^{rel}_{pair} p_T = \frac{|p_T(j_i, j_k)|}{|p_T(j_i)| + |p_T(j_k)|}$$





! Selection of jet pairs at different scales helps the jet association !

Event selection

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

Data samples

- pp collisions @ 7 TeV
- 2010 data (36 pb^{-1})
- low pile-up conditions
- single jet triggers

- Request for at least one good reconstructed primary vertex
- Particle Flow Jets clustered with the 0.5 anti-k_T algorithm
- Selection of exactly 4 jets in $|\eta| < 2.5$:
  - 2 jets with $p_T > 50$ GeV
  - 2 jets with $p_T > 20$ GeV
- Tight selection applied for the selected jets

The jets are associated in pairs:

- **hard-jet pair**: the two leading jets above 50 GeV
- **soft-jet pair**: the other two selected jets above 20 GeV

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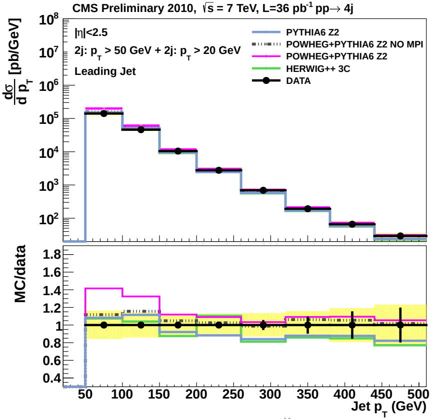
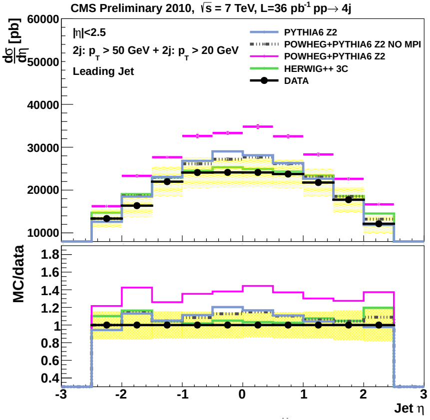
NEW!

Leading jet: cross section measurements (I)

A comparison between data and predictions from different generators is provided





- POWHEG fails in the low p_T region but it performs very well from 150 GeV on
- The best agreement is achieved by HERWIG++ and PYTHIA6

→ A NLO calculation does not perform necessarily well with the best tune at LO

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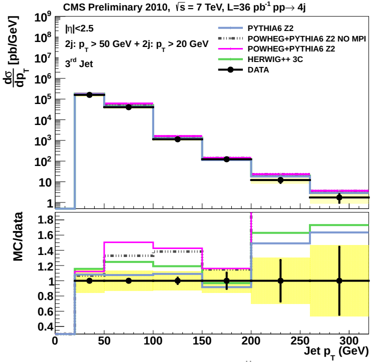
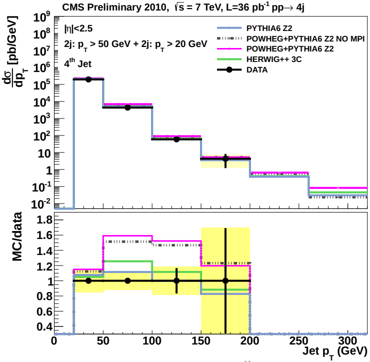
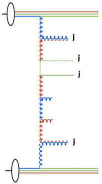
NEW!

We can measure a final state with 4 jets down to 20 GeV!







3^{rd} and 4^{th} jet come from hard radiation

- POWHEG fails in the description of the high p_T region
- The best agreement is achieved by HERWIG++ and PYTHIA6

→ The LO event generators performs well even for the soft jets!

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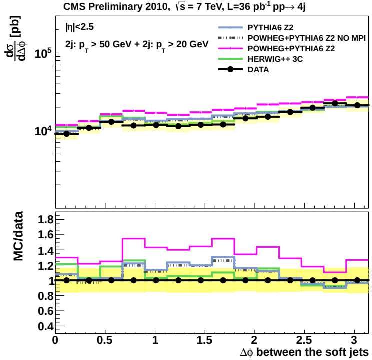
NEW!

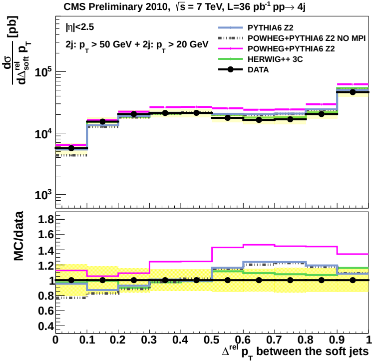
Correlation observables: cross section measurements (III)

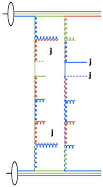
A look at the kinematical topology of the jets in the final state:

$$\Delta\phi(j_i, j_k) = \phi_i - \phi_k \qquad \Delta^{rel}_{pair} p_T = \frac{|p_T(j_i, j_k)|}{|p_T(j_i)| + |p_T(j_k)|}$$

i,k = soft jets







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

- POWHEG interfaced with PYTHIA6 tune Z2 overshoots the data
- PYTHIA6 and HERWIG++ describe the data quite well

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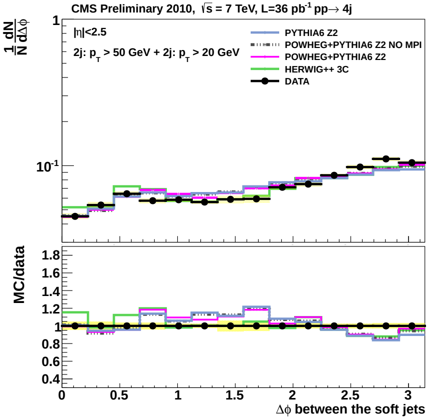
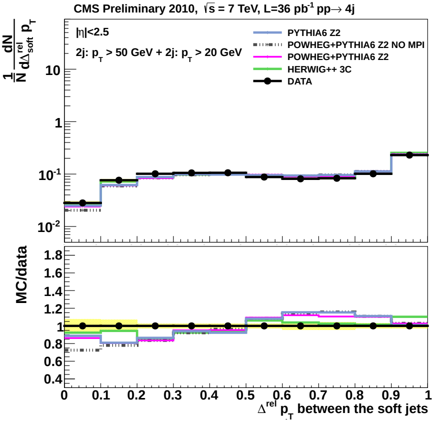
NEW!

Correlation observables: normalized distributions

Normalized distributions of the correlation observables are more sensitive to the DPS

Very useful to constrain the systematics





- Herwig++ and Powheg succeed to describe reasonably well the data
- The p_T-based observables seem to show bigger differences between samples with and w/o MPI

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Summary and conclusions

→ Soft Multiple Parton Interactions

..MPIs can explain the KNO scaling violation, the "ridge" effect and the large multiplicity tails...

- The UE activity has been measured in hadronic and Drell-Yan events
- Different behaviours as a function of the hard scale can be described mainly by MPI and radiation models
- Interesting is to measure hard scales produced by MPIs

→ Hard Multiple Parton Interactions

- The 4-jet measurement is sensitive to the hard matrix element and to the underlying event
  - tune dependence observed and need for tuning NLO generators
- 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

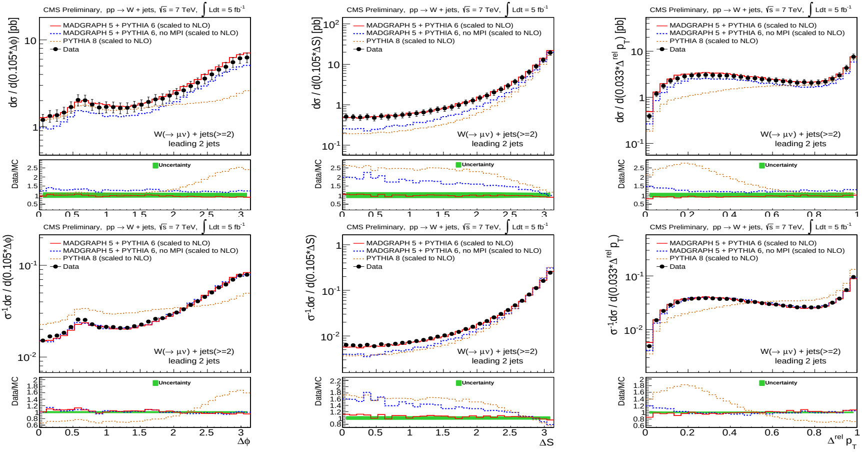
...many more analyses will come...

(γ+3jet, 2 b-+2 light-jets, Z+dijet, same-sign WW...)

THANKS FOR YOUR ATTENTION

BACK-UP SLIDES

→ Fully corrected data with background already subtracted



- MADGRAPH+PYTHIA6 with MPI provides a very good description of the data
- MADGRAPH+PYTHIA6 w/o MPI undershoots the data of around 20%
- PYTHIA8 is below the data of a factor 1.5-2

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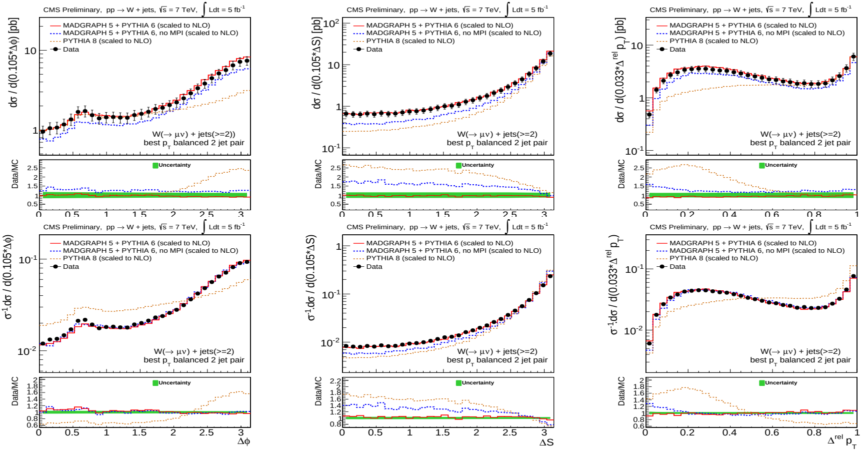
$\sigma = 79.4 \pm 10.8$ pb

DPS Observables: inclusive 2-jet scenario

$\rightarrow$ Best balanced jets are associated in the final state



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Correction to stable particle level and systematic effects

Unfolding technique

- Bayes method in the RooUnfold package
- Generator-detector level correction up to 40%

Systematic effects: total uncertainty $\sim$ 13-17%

- Trigger: $\sim$ 1%
- Muon ID: $\sim$ 2%
- Luminosity: 2.2%
- Pile-up: $\sim$ 2-3%
- MET Resolution: $\sim$ 5-7%
- Jet energy scale: $\sim$ 5-13%

The systematics have been re-calculated for the normalized distributions and the total effect is around 2-6%

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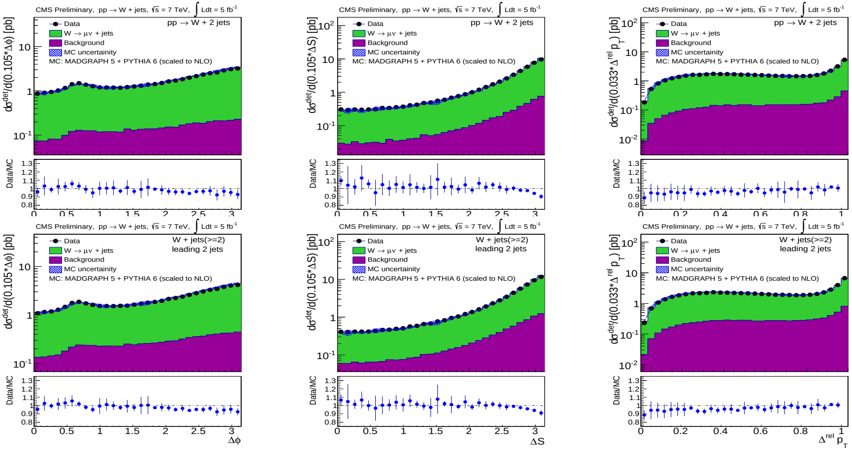
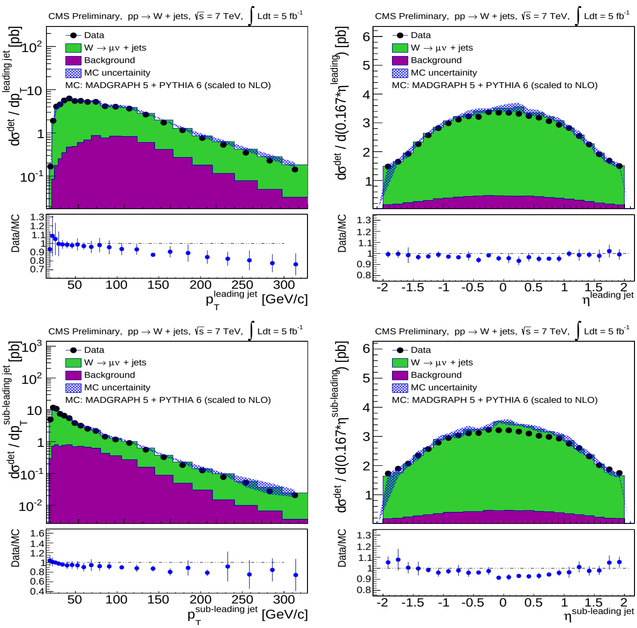
→ Validation plots for the correlation observables in two scenarios



- MADGRAPH+PYTHIA6 describes the data very well in all the scenarios

CMS-PAS-FSQ-12-028



→ Validation plots for the kinematical single jet distributions

- MADGRAPH+PYTHIA6 describes the data very well in all the scenarios

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FSQ-12-028: Number of selected events

Sample	Exclusive selection (exactly 2 jets)		Inclusive selection (at least 2 jets)	
	Events	Relative contribution(%)	Events	Relative contribution(%)
Data	243803	-	315096	-
W→μ+ν	228761	91.5	284439	87.6
W→τ+ν	3723	1.48	4736	1.46
DY	5301	2.12	6564	2.02
QCD	350	0.14	467	0.14
WW/WZ	2564	1.02	3463	1.07
top	**9360**	**3.74**	**25210**	**7.76**

- Highest contribution from the top background
- Very little contamination from QCD events

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FSQ-12-028: Systematic effects

source	$\Delta\phi$	$\Delta^{rel}p_T$	ΔS
Exclusive W + 2 jets selection			
Model dependency	11 (1.5)	11 (1.5)	11 (1.5)
Muon ID and trigger	2.2 (–)	2.2 (–)	2.2 (–)
Background normalization	0.7 (0.2)	0.6 (0.2)	1 (0.3)
JES	5.3–12 (2.3)	4.5–10 (1.4)	5–11 (2.9)
JER	1.1 (0.3)	1.1 (0.5)	1.7 (0.7)
E_T scale	3.3 (0.6)	3.2 (0.5)	0.5–6.8 (3.7)
Pileup	2.2 (1)	2.4 (0.8)	1.4–7 (3.7)
Luminosity	2.2 (–)	2.2 (–)	2.2 (–)
Total	13–17 (3)	13–16 (2.3)	14–17 (6.2)
Inclusive W + 2 jets selection, leading two jets			
Model dependency	11 (1.5)	11 (1.5)	11 (1.5)
Muon ID and trigger	2.2 (–)	2.2 (–)	2.2 (–)
Background normalization	1.1 (0.3)	1 (0.3)	1.5 (0.4)
JES	3.7–9.7 (2.1)	3–8.4 (1.5)	3.2–9.5 (3.3)
JER	0.9 (0.4)	0.9 (0.4)	1.3 (0.4)
E_T scale	3.3 (0.5)	3.3 (0.4)	0.5–6.1 (2.8)
Pileup	2.4 (0.8)	2.5 (0.7)	0.8–5 (2.7)
Luminosity	2.2 (–)	2.2 (–)	2.2 (–)
Total	13–16 (2.8)	13–15 (2.3)	14–16 (5.3)
Inclusive W + 2 jets selection, best p_T-balanced 2 jet pair			
Model dependency	11 (1.5)	11 (1.5)	11 (1.5)
Muon ID and trigger	2.2 (–)	2.2 (–)	2.2 (–)
Background normalization	1.1 (0.3)	1.2 (0.2)	1.6 (0.5)
JES	2.6–13 (2.2–3.8)	1.3–10 (2)	4–8 (1.4)
JER	0.9 (0.4)	0.8 (0.4)	1.1 (0.2)
E_T scale	3.3 (0.5)	3.2 (0.4)	0.5–5.6 (1.7)
Pileup	2.4 (0.8)	2.5 (0.7)	0.8–5 (1.0)
Luminosity	2.2 (–)	2.2 (–)	2.2 (–)
Total	13–18 (2.9–4.2)	12–16 (2.7)	14–15 (2.9)

- Jet Energy scale and model dependency affect the measurements with the biggest uncertainty

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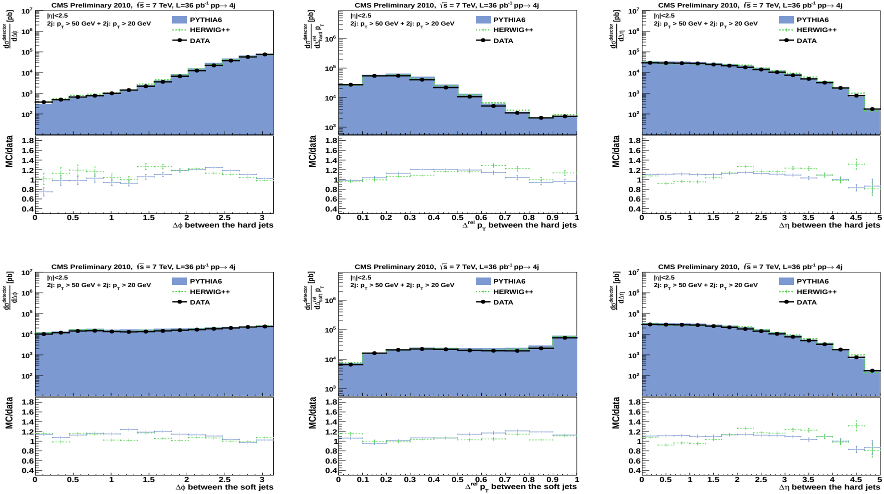
FSQ-12-013: Control distributions at detector level (I)

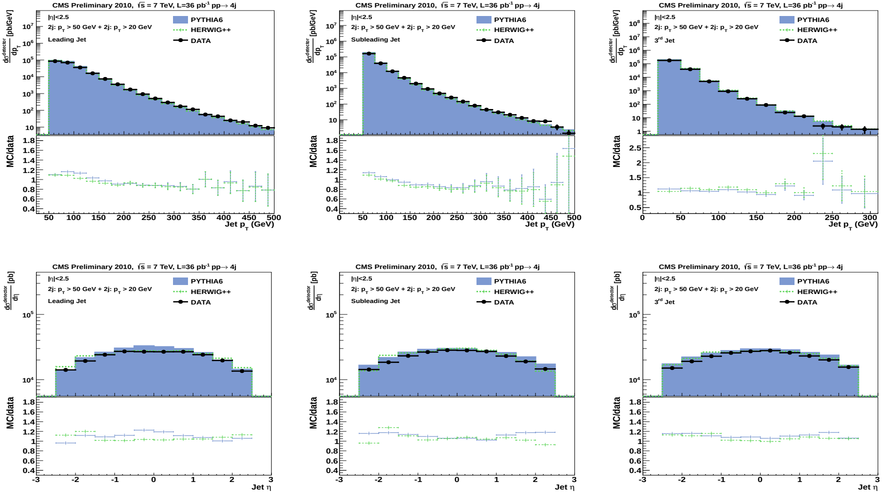
→ Validation plots for the correlation observables



- LO generators describe the data very well

CMS-PAS-FSQ-12-013

→ Validation plots for the basic kinematical jet distributions



- LO generators describe the data very well

CMS-PAS-FSQ-12-013

DATA Sample	Total Number of Events	Trigger region	Good Vertex requirement	Number of events in trigger region	Number of Selected Events
JETMET	20350952	50-80	6730757	1168570	17125
	20350952	80-140	6730757	232628	19198
	20350952	>140	6730757	283420	57318
JETMETTAU	4887422	50-80	1728630	722490	10647
	4887422	80-140	1728630	143640	5431
	4887422	>140	1728630	27606	11785
JET2010B	11234922	50-80	408361	165592	2624
	11234922	80-140	408361	33016	4958
	11234922	>140	408361	24902	2784

Table 4: Number of events passing the applied selections for each data sample and each trigger region.

Montecarlo Sample	Total Number of Events	Number of Triggered Events	Good Vertex requirement	Number of Selected Events
PYTHIA6	9982400	7128229	7127080	1130589
HERWIG++	9971200	6732445	6731530	1125835

Table 5: Number of events passing the applied selections for each MC sample.

CMS-PAS-FSQ-12-013

Correction to stable particle level and systematic effects

Unfolding technique

- Different methods used for cross-check:
  - Bin-by-bin correction
  - Bayes unfolding
- Low migration effects inside the phase space
- Detector effects well under control

Systematic effects: total uncertainty $\sim$ 15-18%

- Jet energy scale: $\sim$ 13-15%
- Model dependence: $\sim$ 3-6%
- Jet energy resolution: $\sim$ 2-3%
- Pile-up reweighting: $\lesssim$ 0.1%
- Trigger efficiency: $\lesssim$ 0.4%

Systematic uncertainties assigned to the normalized distributions: $\sim$ 5-8%

CMS-PAS-FSQ-12-013

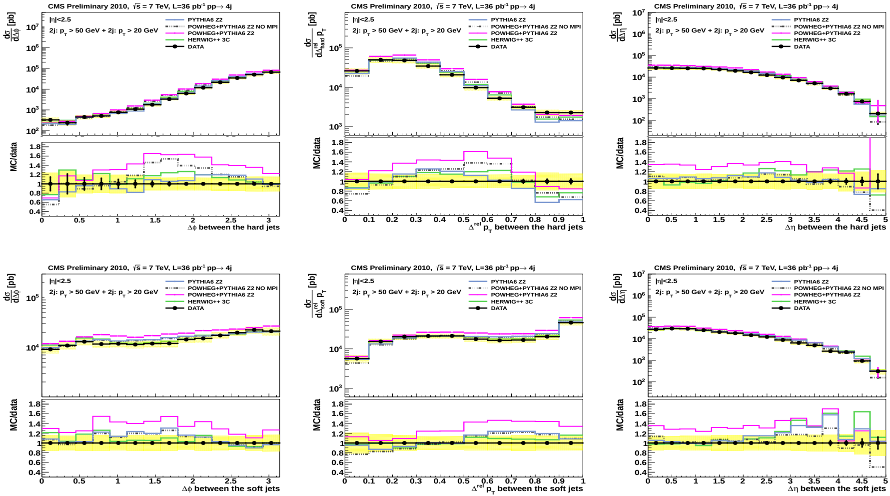
FSQ-12-013: Systematic effects

Measured Observable	Model dependence	Jet Energy Scale	Jet Energy Resolution	Pileup reweighting	Luminosity	Total Uncertainty
$\Delta\phi^{hard}$	6%	15%	1%	<0.1%	4%	**16%**
$\Delta\phi^{soft}$	3%	14%	1%	<0.1%	4%	**15%**
$\Delta\eta^{hard}$	3%	13%	1%	<0.1%	4%	**16%**
$\Delta\eta^{soft}$	3%	13%	2%	<0.1%	4%	**16%**
$\Delta^{rel}_{hard} p_T$	3%	13%	1%	<0.1%	4%	**16%**
$\Delta^{rel}_{soft} p_T$	3%	13%	1%	<0.1%	4%	**17%**
1^{st} jet p_T	2%	14%	0.5%	<0.1%	4%	**15%**
2^{nd} jet p_T	2%	14%	0.5%	<0.1%	4%	**15%**
3^{rd} jet p_T	2%	14%	0.5%	<0.1%	4%	**15%**
4^{th} jet p_T	2%	14%	0.5%	<0.1%	4%	**15%**
1^{st} jet η	2%	13%	0.5%	<0.1%	4%	**15%**
2^{nd} jet η	3%	13%	0.5%	<0.1%	4%	**15%**
3^{rd} jet η	3%	13%	0.5%	<0.1%	4%	**15%**
4^{th} jet η	2%	13%	0.5%	<0.1%	4%	**15%**

- Jet Energy scale affects the measurements with the biggest uncertainty

CMS-PAS-FSQ-12-013

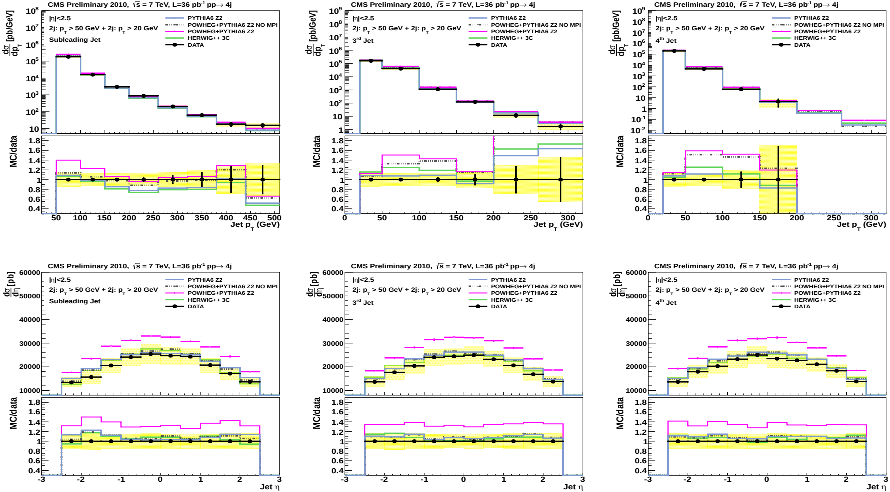
→ Cross section measurements



- LO and NLO generators describe the data very well

CMS-PAS-FSQ-12-013

→ Cross section measurements

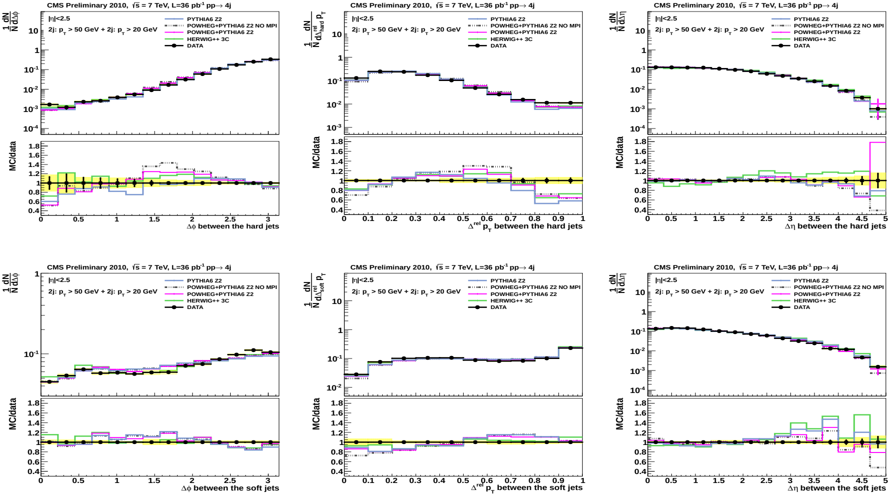


- LO and NLO generators describe the data very well

CMS-PAS-FSQ-12-013

FSQ-12-013: Corrected distributions at particle level (III)

→ Normalized shape measurements

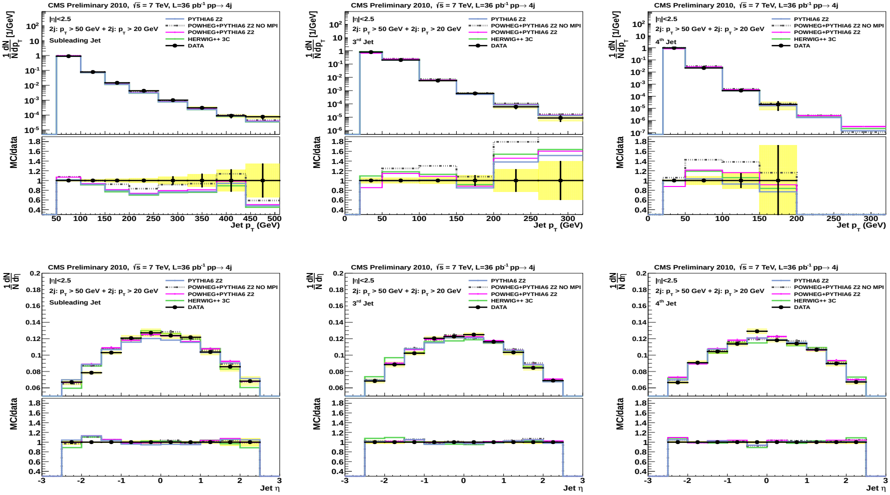


- LO and NLO generators describe the data very well

CMS-PAS-FSQ-12-013

FSQ-12-013: Corrected distributions at particle level (IV)

→ Normalized shape measurements



- LO and NLO generators describe the data very well

CMS-PAS-FSQ-12-013

References (I)

1^{st} part: the basic soft QCD measurements

Focusing on Kinematics:

QCD-09-010: "Transverse momentum and pseudorapidity distributions of charged hadrons in pp collisions at $\sqrt{s} = 0.9$ and 2.36 TeV". J. High Energy Phys. 02 (2010) 041

QCD-10-006: "Transverse-momentum and pseudorapidity distributions of charged hadrons in pp collisions at $\sqrt{s} = 7$ TeV". Phys. Rev. Lett. 105 (2010) 022002

QCD-10-004: "Charged particle multiplicities in pp interactions at $\sqrt{s}$ = 0.9, 2.36, and 7.0 TeV". J. High Energy Phys. 01 (2011) 079

QCD-10-007: "Strange particle production in pp collisions at $\sqrt{s}$ = 0.9 and 7 TeV". J. High Energy Phys. 1105:064, 2011, 1102.4282

Using also high p_T triggers to explore the tails:

QCD-10-008: "Charged particle transverse momentum spectra in pp collisions at $\sqrt{s}$ = 0.9 and 7 TeV". J. High Energy Phys. 1108:086,2011

≈ *measuring low p_T tracks and identifying hadrons in pp interactions*

QCD-XX-YYY: ....

Impact on detector occupancies, pT spectra, PU features etc.

Access to deep information of the hadron structure

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[QCD-XX-YYY]

2^{nd} part: soft particle correlations

p-p

QCD-10-003: "First measurement of Bose–Einstein correlations in proton-proton collisions at $\sqrt{s}$ = 0.9 and 2.36 TeV at the LHC ". Phys. Rev. Lett. 105 (2010) 032001

QCD-10-023: "Measurement of Bose–Einstein Correlations in pp Collisions at $\sqrt{s}$ = 0.9 and 7 TeV at the LHC".J. High Energy Phys. 1105:029, 2011, 1101.3518

Using also large multiplicity triggers to avoid jet bias:

QCD-10-002: "Observation of Long-Range, Near-Side Angular Correlations in Proton-Proton Collisions at the LHC ". J. High Energy Phys. 09 (2010) 091

Pb-Pb

HIN-11-001: "Long-range and short-range di-hadron angular correlations in central PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV". J. High Energy Phys. 1107:076,2011

HIN-11-006: "Centrality and multiplicity dependence of di-hadron correlations in PbPb and pp collisions". J. High Energy Phys. 1107 (2011) 076

p-Pb…

HIN-12-005: "Observation of long-range, near-side angular correlations in pPb collisions at the LHC". CERN-PH-EP-2012-320

≈ measuring correlations of low p_T tracks and identifying hadrons in pp interactions

QCD- or HIN- XX-YYY: ….

[QCD-XX-YYY]

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3rd part: the underlying event measurements

Central Region (Tracks)

QCD-10-001: "First Measurement of the Underlying Event Activity at the LHC with $\sqrt{s}$ = 0.9 TeV". Eur. Phys. J. C 70 (2010) 555-572.

QCD-10-010: "Measurement of the Underlying Event Activity at the LHC with $\sqrt{s}$ = 7 TeV and Comparison with $\sqrt{s}$ = 0.9 TeV". JHEP 1109, 109 (2011).

QCD-10-021: "Measurement of the Underlying Event Activity with the Jet Area/Median Approach at 7 TeV and comparison to 0.9 TeV". CERN-PH-EP-2012-152, arXiv (2012), 1207.2392, submitted to JHEP.

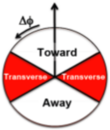
QCD-11-012: "Measurement of the Underlying Event Activity in the Drell-Yan process in proton-proton collisions at $\sqrt{s}$ = 7 TeV". CERN-PH-EP-2012-085, arXiv:1204.1411v1, submitted to Eur. Phys. J. C.

Forward Region (E-Flow)

FWD-10-008: "Forward Energy Flow, Central Charged-Particle Multiplicities, and Pseudorapidity Gaps in W and Z Boson Events from pp Collisions at 7 TeV. ". Eur.Phys.J. C72 (2012) 1839.

FWD-10-011: "Measurement of energy flow at large pseudorapidities in pp collisions at $\sqrt{s}$ = 0.9 and 7 TeV". JHEP 1111 (2011) 148, Erratum-ibid. 1202 (2012) 055.

FWD-11-003: "Study of the Underlying Event at Forward Rapidity in Proton-Proton Collisions at the LHC". CDS Record: 1434458.



≈ Measuring low p_T tracks
in phase space regions
not affected by the leading interaction

Impact on isolations, jet pedestals, vertex reco etc.
"There would not be a vertex in H → γγ events without the Underlying Event." [QCD-10-010]
Actually UE is interesting per se!
Handle on soft MPI and beam remnants.

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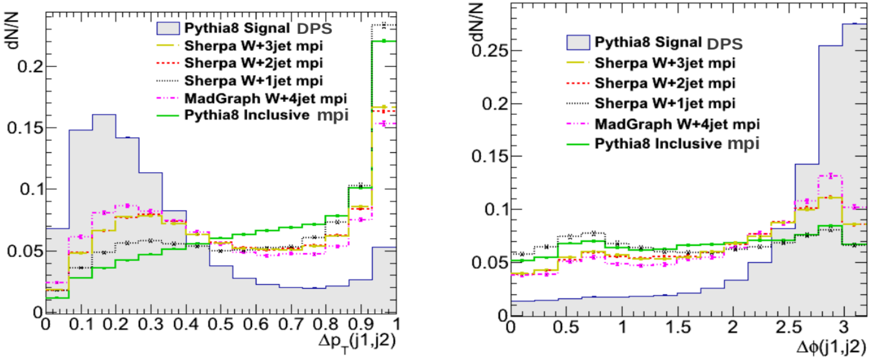
Definition of templates for signal and background

→ Using SHERPA for $\Delta\phi$ and Δp_T of the jets in a W+dijet final state

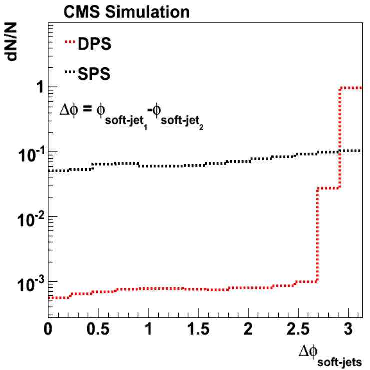


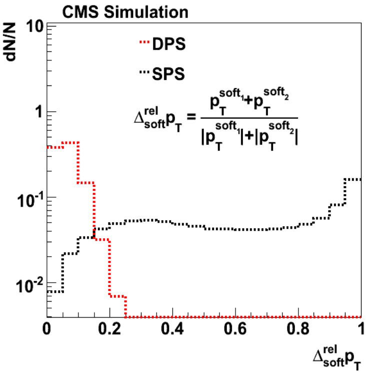
- By adding an increasing number of additional partons in SHERPA, the background shape changes and it tends to fill the phase space of the signal

Phenomenology of the DPS in a 4-jet scenario

Preliminary MC study
performed with PYTHIA8 4C

- SPS: MPI switched off + PS switched on
- DPS: MPI switched on + PS switched off





The two processes involve different regions of the phase space:

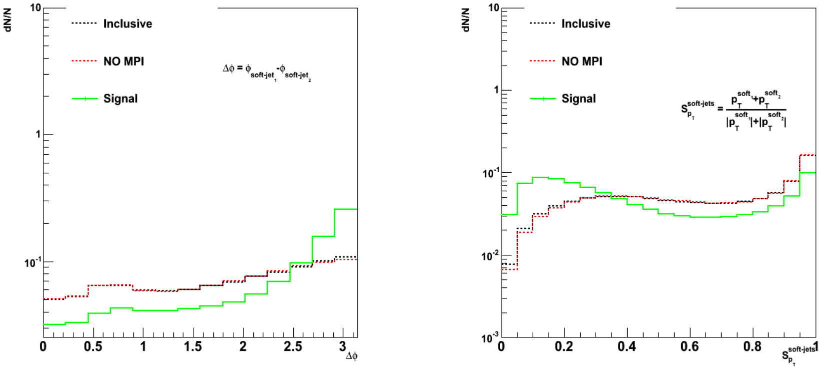
- SPS is broad throughout the whole phase space
- DPS populates high values of $\Delta\phi$ and low values of $\Delta^{rel} p_T$

This is indeed an idealistic picture but helps to identify the "hot" regions
→ The PS in the DPS only smears the distribution but differences with SPS survive

Phenomenology of the DPS in a 4-jet scenario

Inclusive QCD sample production comparing:

- Inclusive: nominal PYTHIA8 sample
- NO MPI: MPI switched off + PS switched on
- Signal: two hard scatterings at the parton level



- Discriminating power: The two processes exhibit different shapes and specific regions of the phase space can be exploited to extract the DPS contribution
- BUT..little difference between MPI switched on and off

Formalism of the double parton scattering

A bit of (simplified) theory of the double parton scattering..

The cross section for a generic process that involve DPS can be written:

$$\boxed{\sigma_{AB} = \frac{m}{2}\frac{\sigma_A\sigma_B}{\sigma_{eff}}}$$

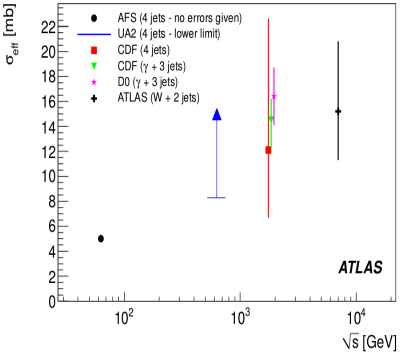
where σ_{eff} is the effective area parameter for the DPS

$$\boxed{\sigma_{eff} \approx 15 \text{ mb}}$$

How to measure it?

Evaluating the fraction of DPS events that occur in a given physics channel wrt the single chain processes

Theory says that it's independent on the collision energy and the process type

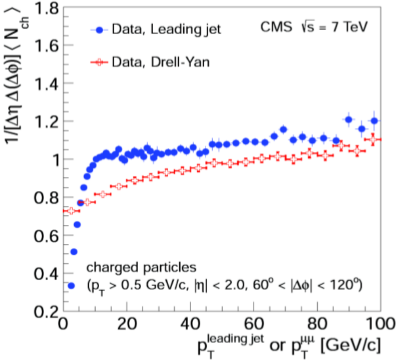


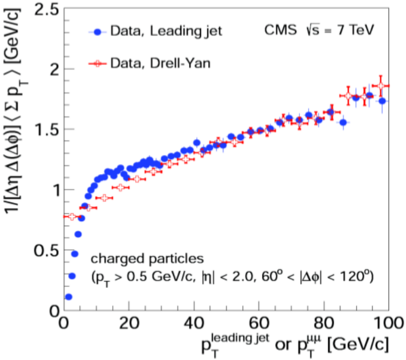
- a high energy phase for the LHC extends the study of the energy dependence
- with increasing energy, partons with lower x start to be relevant and detectable

The UE in different types of events

Measurement of the Underlying Event activity as a function of the scale of the hard process

- MB as a function of the leading track-jet p_T CMS-PAS-FSQ-12-020
- Drell-Yan as a function of the di-lepton p_T ($81 < M_{\mu\mu} < 120$ GeV) CMS-PAS-FSQ-11-012





- The differences in spectrum at scales above 10 GeV are due to the hadronic radiation of the two processes:
  - Hadronic events have ISR and FSR from gluons
  - DY events have only ISR initiated by quarks

$\rightarrow$ The UE (and the MPI) depends on the first hard scattering

$\rightarrow$ Investigation of direct evidence of double hard scatterings (additional jets)