Double-parton scattering studies in four-jet events with the CMS detector

Paolo Gunnellini

on behalf of CMS collaboration

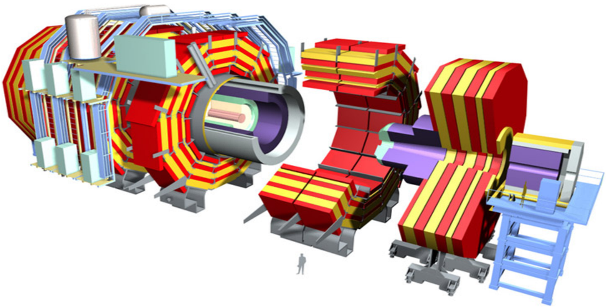
Deutsches Elektronen-Synchrotron

MPI@LHC 2013

Universiteit Antwerpen

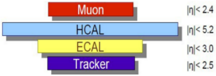
December, 2013

Introduction and outline

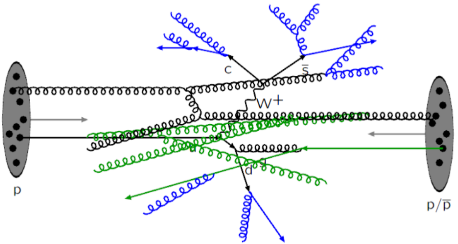


CMS detector:

- excellent energy resolution
- Particle Flow technique for jet reconstruction



- Hard MPI: where and how to measure a direct evidence
- The four-jet channel:
  - Preliminary sensitivity studies
  - Event selection
  - Results
    - Jet kinematical spectra
    - Correlation observables
- Summary and outlook



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

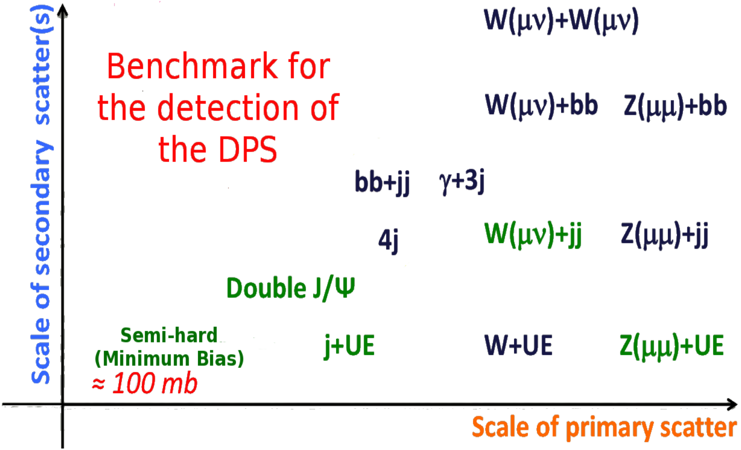
In general the UE is a softer contribution but... some MPIs can be even hard!

→ Double Parton Scattering (DPS)

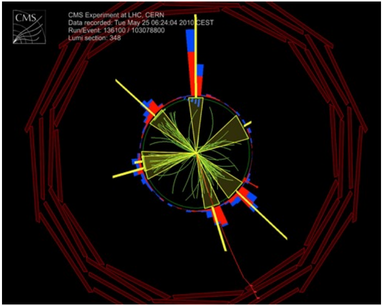
Is the DPS signal accessible?

Several channels are available to extract the DPS signal

Credits: Paolo Bartalini



Four-jet channel already measured by CDF (**Phys. Rev. D 56, 38113832 (1997)**)



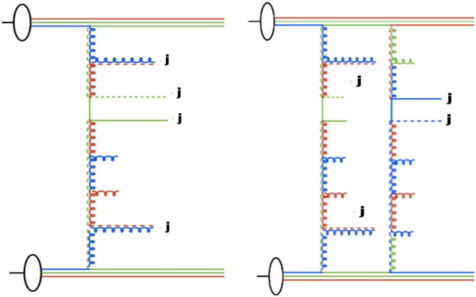
Measurement of observables in the four-jet channel

NEW!

Physics of a four-jet scenario (I)

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

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

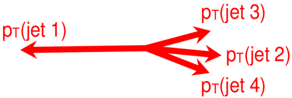


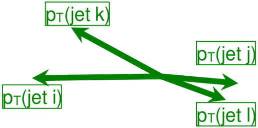
The different kinematical configuration can be used to discriminate the two processes through some observables:

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

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

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





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

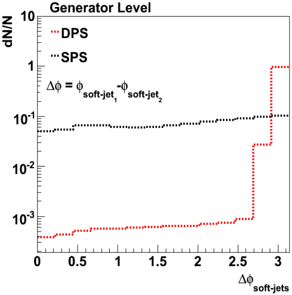
Which regions of the phase space are interesting for DPS detection?

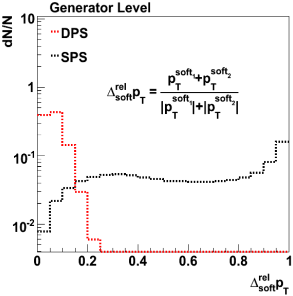
Studies of SPS and DPS contributions performed with PYTHIA8 generator tune 4C:

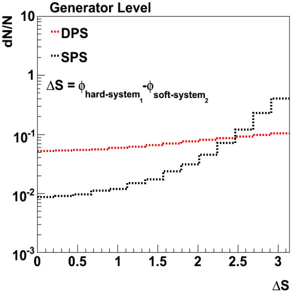
Selection of a four-jet final state in $|\eta| < 4.7$ at two different p_T thresholds (20 and 50 GeV)

A SIMPLE scenario:

- SPS: MPI contribution switched off
- DPS: Two hard scatterings at the parton level forced to happen w/o parton shower







- Discriminating power: The two processes exhibit different shapes and specific regions of the phase space can be exploited to extract the DPS contribution

Event selection

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

Data samples

- pp collisions @ 7 TeV
- Integrated luminosity: 36 pb^{-1}
- very 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 four jets in $|\eta| < 4.7$:
  - two jets with $p_T > 50$ GeV
  - two jets with $p_T > 20$ GeV
- Tight selection applied for the selected jets

The jets are associated in pairs:

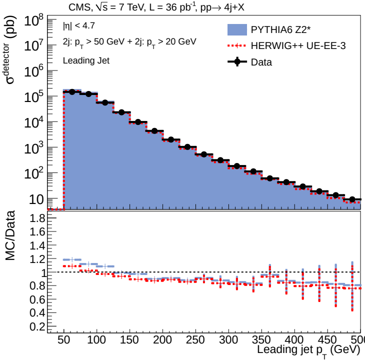
- **hard-jet pair**: the two leading jets above 50 GeV
- **soft-jet pair**: the other two selected jets above 20 GeV

CMS-PAS-FSQ-12-013 $\rightarrow$ To be submitted soon to PRD

NEW!

Unfolding and systematic effects

- Low migration effects inside and outside the phase space
- Detector effects well under control
- Bayes unfolding



Measured observable	Model	Jet Energy Scale	Jet Energy Resolution	Luminosity	Total
Jet p_T	2%	13-14%	1%	4%	**15%**
Jet η	2%	13-14%	1%	4%	**15%**
$\Delta\phi_{\text{soft}}$	3% (3%)	14% (3%)	2% (2%)	4% (-)	**15% (5%)**
$\Delta^{\text{rel}}_{\text{soft}} p_T$	3% (3%)	13% (3%)	1% (2%)	4% (-)	**14% (5%)**
ΔS	5% (4%)	15% (3%)	4% (3%)	4% (-)	**16% (5%)**

CMS-PAS-FSQ-12-013 → To be submitted soon to PRD

NEW!

Cross section measurement and theory comparison

AIM: Comparison between data and different MC generators

- PYTHIA8 and HERWIG++: LO MC generators with extra jets from PS & MPI
- POWHEG: matrix element with a hard emission @ NLO (real & virtual)
- SHERPA, MADGRAPH: matrix element with N-jets (extra real emission)

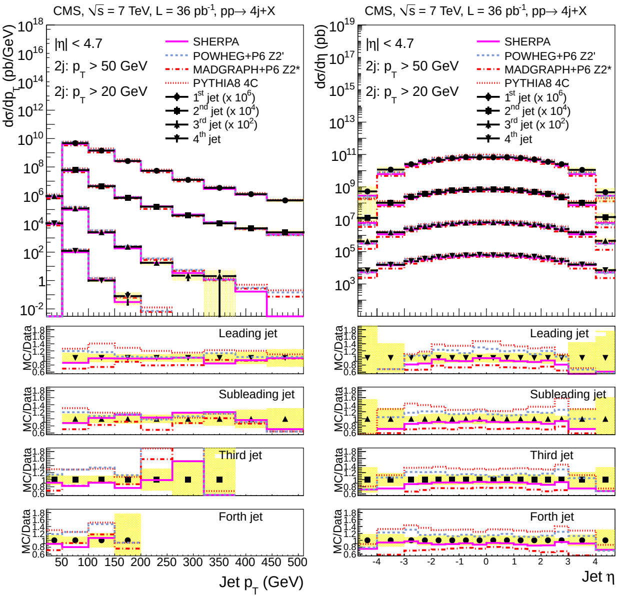
Sample	Cross section (nb)
PYTHIA8, tune 4C	423
POWHEG + PYTHIA6, tune Z2'	378
MADGRAPH + PYTHIA6, tune Z2*	234
SHERPA	293
HERWIG++, tune UE-EE-3	343
Data	327 $\pm$ 5 (stat.) $\pm$ 45 (syst.)

- PYTHIA8 and POWHEG+PYTHIA6 overshoot the cross section value
- MADGRAPH+PYTHIA6 underestimates the measurement
- SHERPA and HERWIG++ are in good agreement with the data

CMS-PAS-FSQ-12-013 $\rightarrow$ To be submitted soon to PRD

NEW!

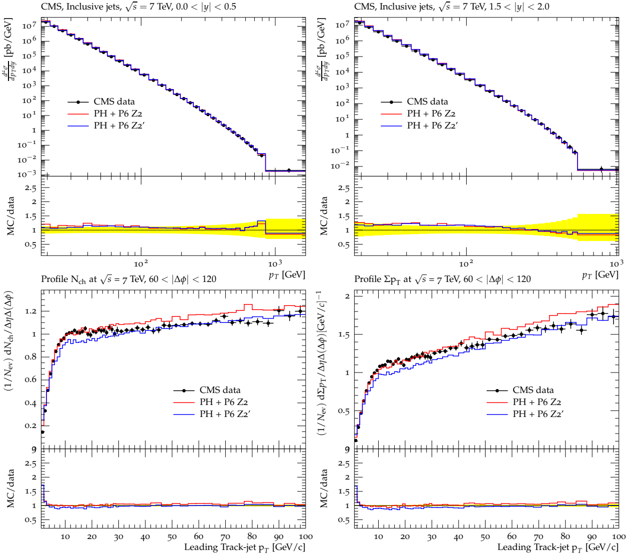
A comparison between data and predictions from different generators is provided



- PYTHIA8 overestimates the low-p_T region
- POWHEG is closer to the data but it does not describe optimally the soft-jet spectra
- MADGRAPH underestimates the low-p_T region
- SHERPA offers an overall agreement for all the jet cross sections
- HERWIG++ (not shown) is not able to reproduce the high-p_T region

Do the used tunes remain meaningful when a different matrix element is used?

Checking the validity of the tunes... (I)



POWHEG is interfaced with PYTHIA6 for PS and UE:

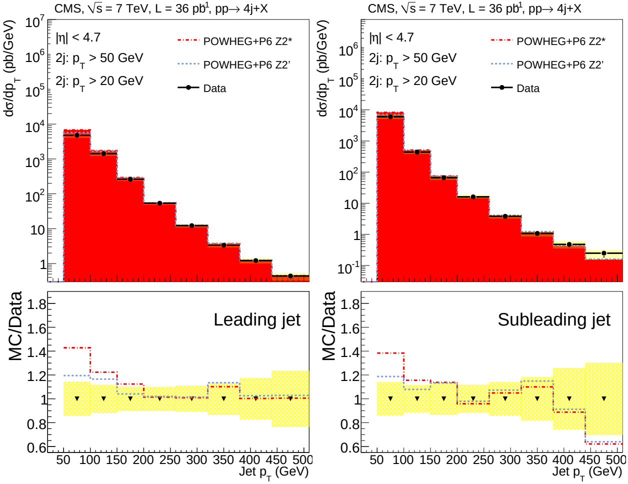
→ Z2': ad-hoc tune where the ISR and FSR phase space is reduced

- Good description for inclusive jet distributions and UE data
- Little tune dependence

CMS Collaboration, *Measurement of the Inclusive Jet Cross Section in pp collisions at $\sqrt{s} = 7$ TeV*, **10.1103/PhysRevLett.107.132001**
CMS Collaboration, *Measurement of the Underlying Event Activity at the LHC with $\sqrt{s} = 7$ TeV*, **10.1007/JHEP09(2011)109**

Checking the validity of the tunes...(II)

What happens in high jet multiplicity selections?



→ Z2' is obtained by changing:

- PARP(67) = 1
- PARP(71) = 1

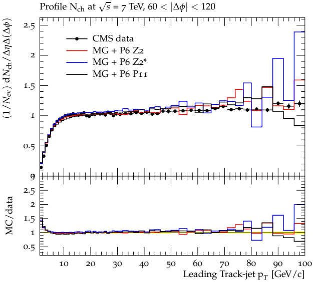
→ They set the upper scale for the ISR and FSR phase space → Default value in Z2* is 4

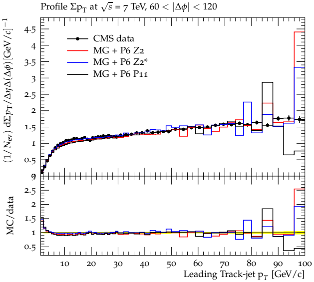
→ Effect in the four-jet scenario

- lower contribution at low p_T
- better agreement with the data

Strong tune dependence in the four-jet scenario → choice of Z2' tune

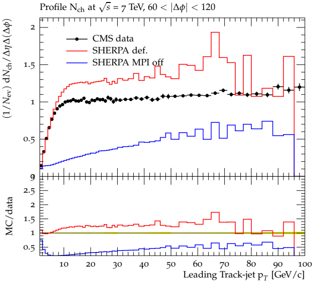
LEFT: 1^{st}, RIGHT: 2^{nd} jet p_T

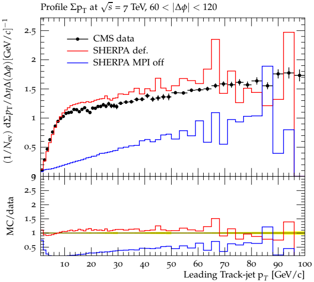




MADGRAPH is interfaced with existing PYTHIA6 tunes

- MADGRAPH reproduces well the UE CMS data and inclusive jet distributions
- Little tune dependence





SHERPA contains its own PS model

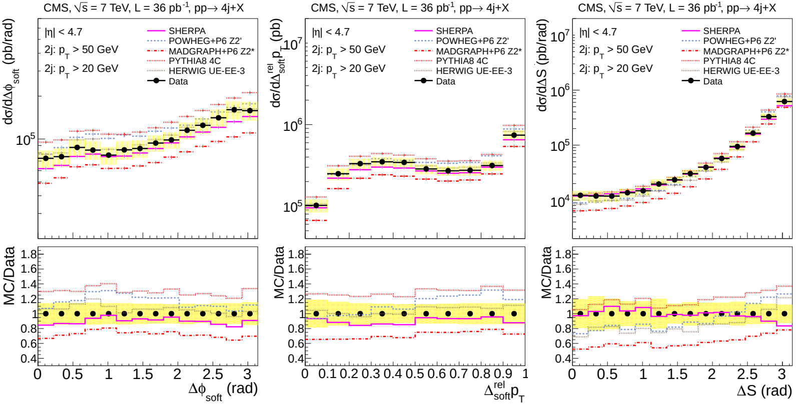
- SHERPA predicts a higher particle multiplicity and p_T sum but reproduces inclusive jet distributions

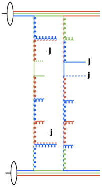
CMS Collaboration, *Measurement of the Underlying Event Activity at the LHC with $\sqrt{s}$ = 7 TeV*, **10.1007/JHEP09(2011)109**

Correlation observables: cross section measurements

Kinematical topology of the jets of the final state in the transverse plane:

$$\Delta\phi(j_i, j_k) = \phi_i - \phi_k \qquad \Delta^{rel}_{soft} p_T = \frac{|p_T(j_i, j_k)|}{|p_T(j_i)| + |p_T(j_k)|} \qquad \Delta S = \arccos\left(\frac{\vec{p}_T(j^i, j^k) \cdot \vec{p}_T(j^l, j^m)}{|\vec{p}_T(j^i, j^k)| \cdot |\vec{p}_T(j^l, j^m)|}\right)$$





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

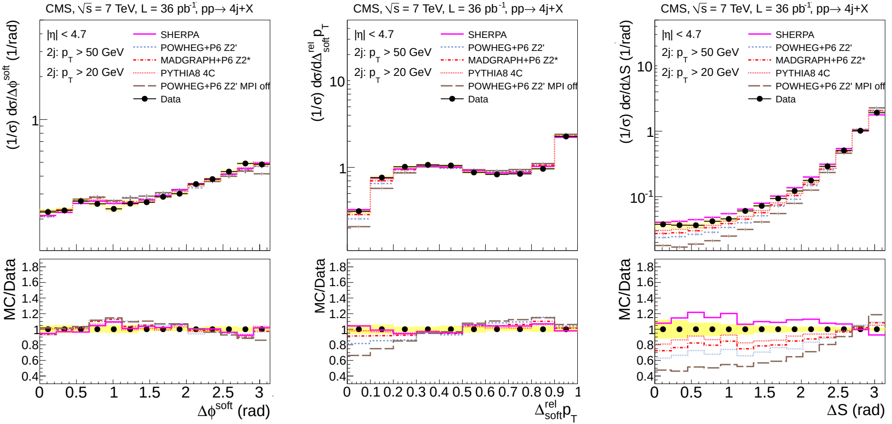
- PYTHIA8 and POWHEG overshoot the measurements
- HERWIG++ reproduces $\Delta\phi$ and $\Delta^{rel}_{soft} p_T$, but not ΔS
- MADGRAPH is below the data in the whole phase space
- SHERPA gives the best description for all the observables

Normalized distributions are useful to constrain systematics

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

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

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



- No significant differences in $\Delta\phi$ and $\Delta^{rel}_{soft} p_T$ among generators
- POWHEG w/o MPI is far below for $\Delta^{rel}_{soft} p_T$ and ΔS
- SHERPA and PYTHIA8 perform best for ΔS
- ΔS and $\Delta^{rel}_{soft} p_T$ sensitive to MPI contribution: ROOM for DPS!

Outlook: how to extract σ_{eff} from these distributions

IDEA: tune the parameters corresponding to the amount of DPS contribution in the available MCs

WHICH PARAMETERS:

- Transverse parton density profile in proton
- Other MPI-related parameters (e.g. p_T^0, ..)

$\rightarrow$ ..After the tune:

- plug-in the obtained parameters and check if the MC description improves w/o spoiling agreement with other UE, MB measurements
- extract the effective cross section corresponding to the choice of the parameter from the MC output
- study systematic effects of this method and assign an uncertainty to the σ_{eff} result

More in the discussion session:

"Determination of σ_{eff} from DPS-sensitive observables (Wednesday 12.40h)"

Summary and conclusions

Four-jet final state has been measured in CMS

- The four-jet measurements are sensitive to the hard matrix element and to multiparton interactions
  - need for a proper admixture of ME and UE contributions
- Correlation observable measurements have been performed in a four-jet scenario
  - Need for a four-jet NLO calculation
  - Useful baseline for further DPS studies
- SHERPA gives the best description of the measurement but with the same tune fails to reproduce the UE data

THANKS FOR YOUR ATTENTION

BACK-UP SLIDES

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

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:

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

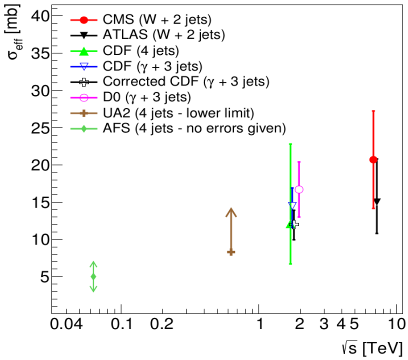
where σ_{eff} is the effective area parameter for the DPS

$$\boxed{\sigma_{eff} \approx 20 \text{ mb}}$$

How to measure it?

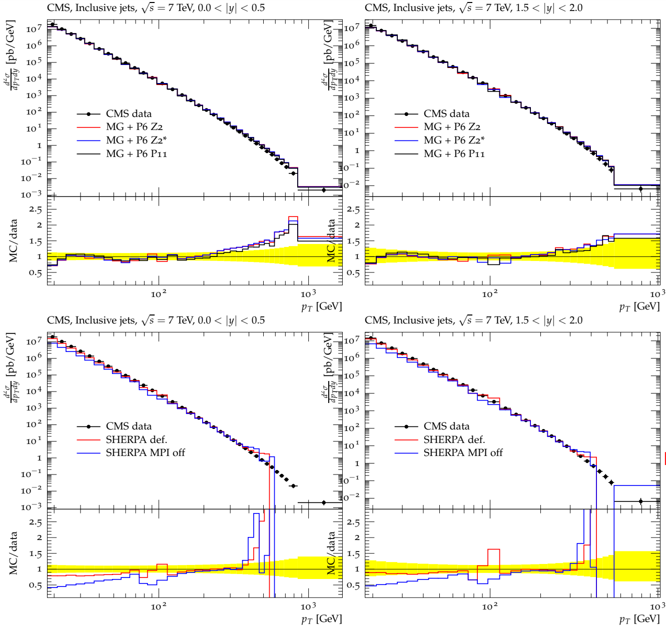
Evaluating the fraction of DPS events that occur in a given physics channel wrt the single chain processes

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

Checking the validity of the tunes... (BACKUP)

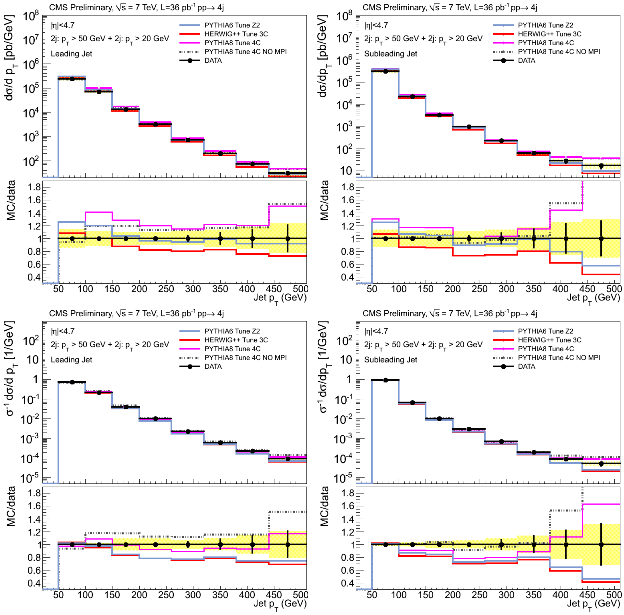


Nice description for MADGRAPH and SHERPA for inclusive jet p_T distributions

- low statistics for MG at high p_T
- low statistics at central p_T for SHERPA (merging region between two samples)

TOP: MADGRAPH
BOTTOM: SHERPA

Further MC-data comparisons



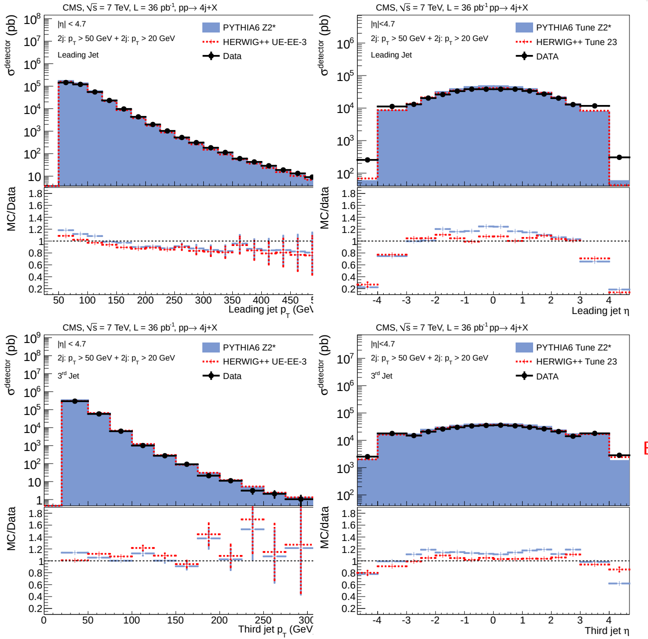
HERWIG++ description is not optimal for jet p_T

- overestimation of the low p_T region
- underestimation of the high p_T region

→ The cross section is well in agreement with the data but the differential distributions are not well described

TOP: 1^{st}, 2^{nd} jet p_T cross section
BOTTOM: 1^{st}, 2^{nd} jet p_T shapes

Control distributions at the detector level



- Good agreement at detector level for PYTHIA6 and HERWIG++
- Discrepancy in the forward region:
  - generator dependence
  - big energy scale uncertainty

TOP: 1^{st} jet p_T, η
BOTTOM: 3^{rd} jet p_T, η

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..

Physics of a four-jet scenario (III)

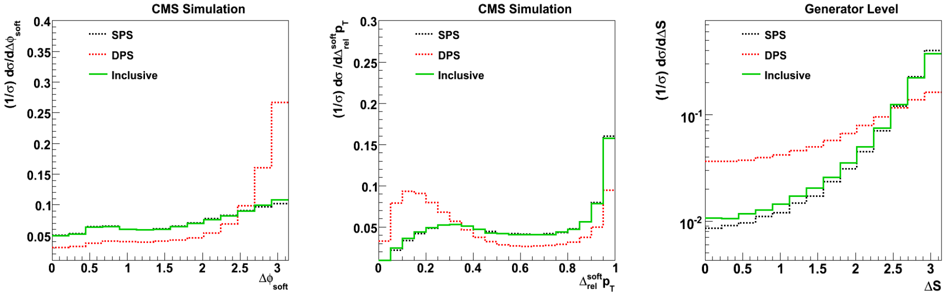
Which regions of the phase space are interested for DPS detection?

Studies of SPS and DPS contributions performed with PYTHIA8 generator tune 4C:

Selection of a four-jet final state in $|\eta| < 4.7$ at two different p_T thresholds (20 and 50 GeV)

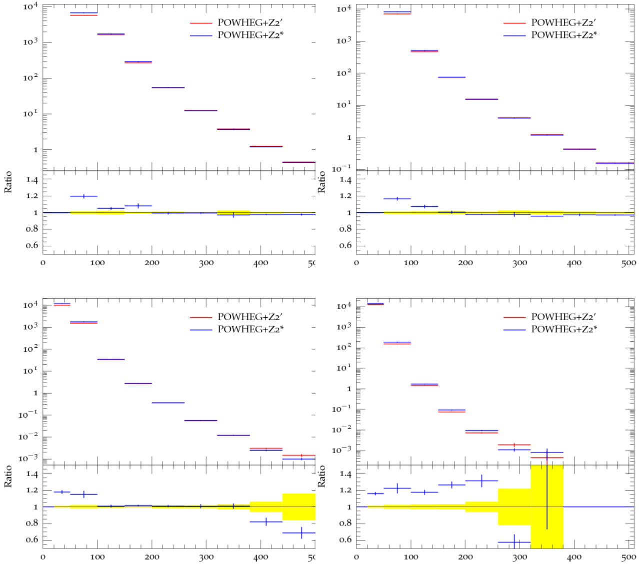
A preliminary (MORE REALISTIC) scenario:

- Inclusive: nominal PYTHIA8 sample
- SPS: MPI switched off
- DPS: two hard scatterings at the parton level with parton shower



- Still differences between SPS and DPS distributions
- Small difference between inclusive and SPS samples

Checking the validity of the tunes...(II)



→ Z2' is obtained by changing:

- PARP(67) = 1
- PARP(71) = 1

→ They set the upper scale for the ISR and FSR phase space
→ Default value in Z2* is 4

→ Effect in the four-jet scenario

- lower contribution at low p_T
- better agreement with the data

TOP: 1^{st}, 2^{nd} jet p_T
BOTTOM: 3^{rd}, 4^{th} jet p_T

Strong tune dependence in the four-jet scenario → choice of Z2' tune