Underlying event and jet measurements at high multiplicity in pp collisions in CMS

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on behalf of CMS collaboration

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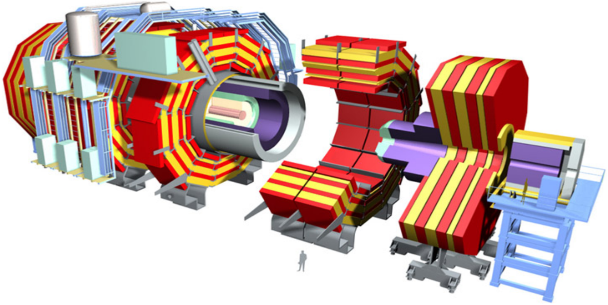
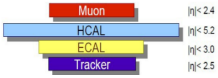
Introduction and outline

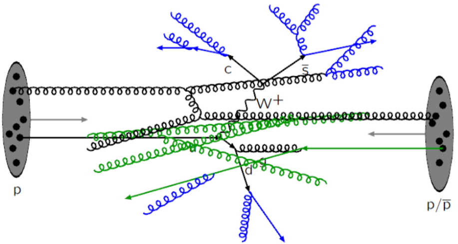


CMS detector:

- high tracking efficiency down to low p_T
- excellent jet energy resolution
- Particle Flow technique for jet reconstruction



- Physics motivation
- UE tunes: study of energy dependence
- Tuning DPS-sensitive observables
- Compatibility studies among UE- and DPS-based tunes
- Validation of the new tunes in high multiplicity environments
- 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)

$$\sigma_{AB} = \frac{m}{2}\frac{\sigma_A \sigma_B}{\sigma_{eff}} \rightarrow \sigma_{eff} \approx \text{15-20 mb}$$

Physics motivation (I)

Large collection of Underlying Event data at several collision energies in a very complete way

$\rightarrow$ Charged particle multiplicity and p_T sum as a function of the leading charged particle

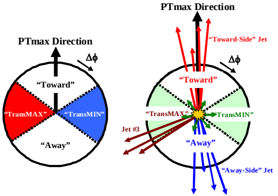
$$|\Delta\phi| = |\Delta\phi^{part} - \Delta\phi^{lead}| \rightarrow$$

if $|\Delta\phi| < \pi/3 \rightarrow$ TOWARD region

if $\pi/3 < |\Delta\phi| < 2\pi/3 \rightarrow$ TRANSVERSE region

if $|\Delta\phi| > 2\pi/3 \rightarrow$ AWAY region

- TRANS MIN: sensitive to MPI
- TRANS MAX: sensitive to MPI and PS
- TRANS DIF: sensitive to PS
- TRANS AVE: sensitive to MPI and PS

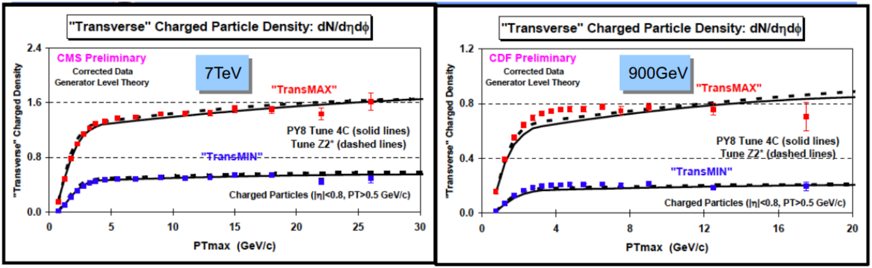


MIN and MAX regions are defined by the activity in each of the two transverse regions

Charged particles in $|\eta| < 0.8$ with $p_T > 0.5$ GeV are counted

Physics motivation (II)

→ Understanding of the Underlying Event data is crucial for every analysis using MC predictions



Comparison of charged particle multiplicity data in TRANS MIN and MAX with P6 Z2* and P8 4C predictions at 7000 and 900 GeV

→ The energy dependence of the UE data is not well described by the current tunes

- → Spectrum well followed by the predictions at 7 TeV
- → Not optimal description at 900 GeV

→ How to make reliable predictions for the new LHC runs at 13 TeV?

Need for a better tune by looking at the energy dependence

CDF energy scans (300, 900, 1960 GeV) and CMS (7000 GeV) data

R.Field, The Tevatron Energy Scan: Findings & Surprises, (September 17,2013)

CMS Collaboration, Measurement of the UE Activity at the LHC at 7 TeV and Comparison with 0.9 TeV, CMS-PAS-FSQ-12-020

The software used for the tunes

RIVET (A. Buckley et al, doi:10.1016/j.cpc.2013.05.021)
PROFESSOR (A. Buckley et al. , Eur.Phys.J.C65(2010) 331357)

- Run predictions of several analyses for different choice of UE parameters
- Tune the MC response according to best data description

The parameters have been varied within these ranges:
→ Each MC sample uses a random choice of the parameters

PYTHIA 6:
CUETP6S1
(CMS Underlying Event Tune Pythia6 Set 1)

- Tune reference Z2* lep
  (CMS Coll. JHEP04(2013)072)
- PDF set: CTEQ6L1
  J. Pumplin et al., JHEP0207(2002)012

Parameter	Tuning Range
PARP(82): MPI cut-off	1.6-2.2
PARP(77): CR suppression	0.25-1.2
PARP(78): CR strength	0.2-0.6
PARP(90): MPI energy extrapolation	0.18-0.28
PARP(83): Matter fraction in core	0.1-1.0

PYTHIA 8:
CUETP8S1-CTEQ6L1,
CUEPT8S1-HERAPDF1.5LO

- Tune reference 4C
  R. Corke et al., JHEP03(2011)032
- PDF set: CTEQ6L1
  J. Pumplin et al., JHEP0207(2002)012
- Additional tune with HERAPDF1.5LO
  H1 and ZEUS Coll., H1prelim-13-141, ZEUS-prel-13-003

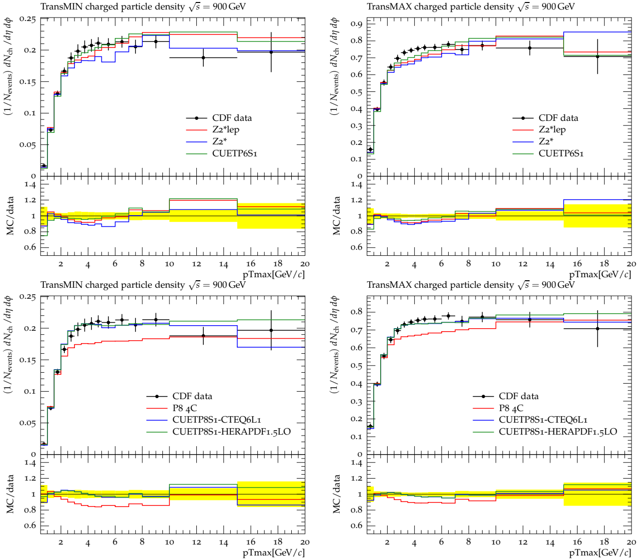
Parameter	Tuning Range
MultipleInteractions:pT0Ref	1.0-3.0
MultipleInteractions:ecmPow	0.0-0.4
MultipleInteractions:expPow	0.4-10.0
BeamRemnants:reconnectRange	0.0-9.0

By using the output from PYTHIA 8:

- it is possible to predict the σ_{eff} value in the tune, defined by the UE parameters
- Professor gives the eigentunes in order to get the uncertainties of the parameters

Tuning results at 900 GeV

Charged particle multiplicity, $\Sigma\ p_T$ in TransMIN, TransMAX at 900 GeV



Significant improvement in the description of TransMIN and TransMAX regions for the new tunes

Both the rising part and the plateaux region are very well predicted by CUETP6S1, CUETP8S1-CTEQ6L1, CUETP8S1-HERAPDF1.5LO

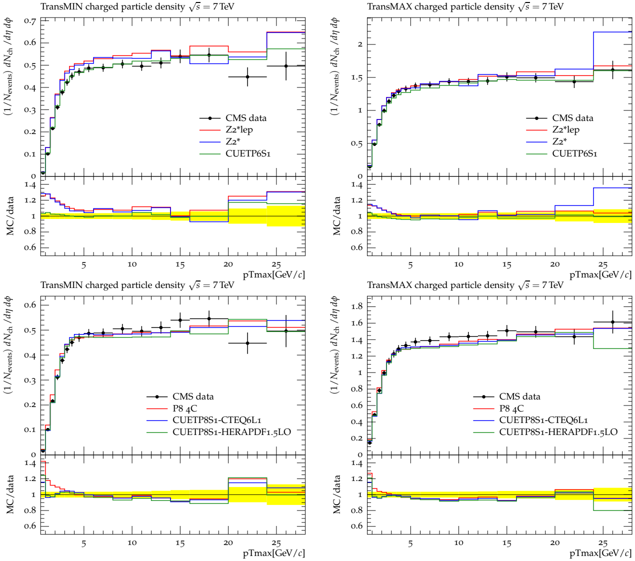
Same behaviour for p_T sum

PYTHIA 6 (top)
PYTHIA 8 (bottom)

CMS-GEN-14-001

Tuning results at 7000 GeV

Charged particle multiplicity, $\Sigma\ p_T$ in TransMIN, TransMAX at 7 TeV



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Same behaviour for p_T sum

PYTHIA 6 (top)
PYTHIA 8 (bottom)

CMS-GEN-14-001 NEW!

Data points from CMS-FSQ-12-020

Are the tunes able to predict hard MPI contribution?

- PYTHIA6 and PYTHIA8 seem to add the right MPI contribution for the description of average quantities
- Differential distributions in high multiplicity scenarios are not well described
- New tunes do not help much to improve the situation
- A look at the predicted DPS-related parameter, σ_{eff}, in the extracted UE tunes
  - Tune 4C $\sigma_{eff} = 30.3$ mb
  - CUETP8S1-CTEQ6L1 $\sigma_{eff} = 27.8^{+1.2}_{-1.3}$ mb
  - CUETP8S1-HERAPDF $\sigma_{eff} = 29.1^{+2.3}_{-2.0}$ mb
- It stays stable with respect to the old tune 4C, at a quite high value
- CMS result: $\sigma_{eff} = 20.7 \pm 0.8$ (stat) $\pm$ 6.6 (syst) mb (W+dijet @ 7 TeV)
- What is σ_{eff} value which would describe best DPS-sensitive data? $\rightarrow$ TUNING

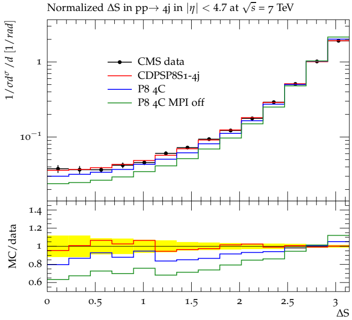
Effective cross section in the four-jets channel

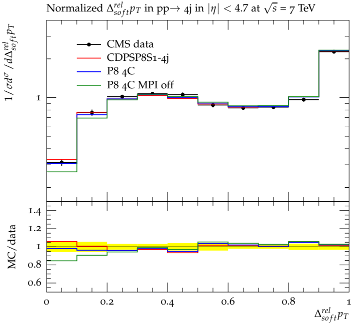
Tuning the four-jet distributions in the tuning range [0.8,2.5]

Parameter	New Tune	4C
MultipleInteractions:expPow	1.160	2.0
+Unc	1.2096	-
-Unc	1.1109	-
Goodness of fit	0.751	-

$$\sigma_{eff} = 21.3^{+1.2}_{-1.6}\ \text{mb}$$

$\rightarrow \sigma_{eff}$ (Tune 4C) $\sim$ 30.2 mb





Improved agreement with the new tune

New set of parameters: CDPSP8S1-4j

LEFT: ΔS

RIGHT: $\Delta^{rel}_{soft}p_T$

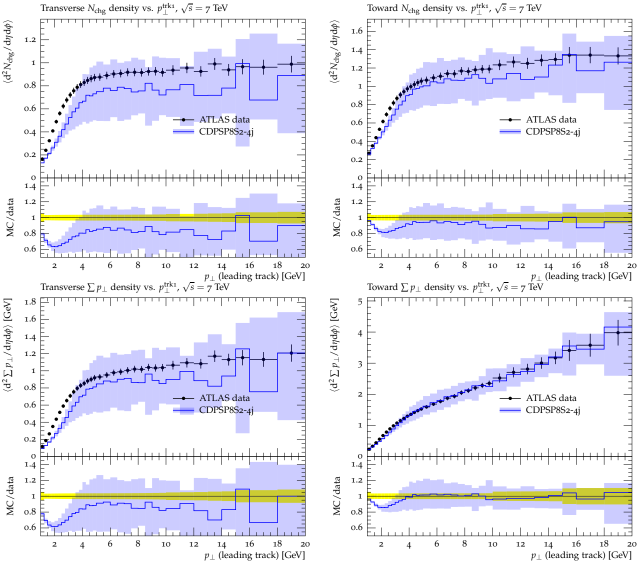
CMS-GEN-14-001

Data points from CMS-FSQ-12-013
See Talk by Greg (Friday morning)

How does the new tune perform in the UE description?

ATLAS_2010_S8894728: charged particle multiplicity and p_T sum

$\rightarrow$ Samples obtained by changing the parameters given by Professor's eigentunes



Testing CDPSTP8S2-4j:

- nominal tune: blue continuous line
- set of four eigentunes: uncertainties represented by the blue band

Not optimal description of the nominal tune
$\rightarrow$ lower activity predicted

Measurement well contained within the tune uncertainties only in some regions of the phase space

Charged particle multiplicity (top) and p_T sum (bottom) for transverse (left) and toward (right) regions

CMS-GEN-14-001

NEW!

Summary of σ_{eff} values

Are σ_{eff} values compatible among the different tunes?

Tune name	σ_{eff} value (mb)
P8 4C	30.3
CDPSTP8S1	$21.3^{+1.2}_{-1.6}$
CDPSTP8S2	$19.0^{+4.7}_{-3.0}$
CUETP8S1-CTEQ6L1	$27.8^{+1.2}_{-1.3}$
CUETP8S1-HERAPDF	$29.1^{+2.3}_{-2.0}$

- UE tunes tend to have high σ_{eff} values $\rightarrow$ Lower DPS contribution
- DPS tunes predict lower σ_{eff} values $\rightarrow$ Higher DPS contribution

A tension appears between the description of "softer" and "harder" MPI within the same framework

Jet properties in low and high multiplicity events in pp collisions at 7 TeV

- Search for collective effects and hints of jet quenching
- Measurement divided into subspaces of charged particle multiplicity
  $\rightarrow$ they give indication of the "centrality" of the collision

Low multiplicities $\rightarrow$ mainly softer MPI components
High multiplicities $\rightarrow$ contribution of harder MPI

CMS-FSQ-12-022

Published in Eur.Phys.J. C73 (2013) 2674

Details of the experimental measurement

Measurement decomposed in five multiplicity domains

→ Low pile-up 2010 data (3 pb^{-1}) with MB triggers

- UE measurements
  - Charged particles with $p_T > 0.25$ GeV in $|\eta| < 2.4$
- Jet measurements
  - Track jets with $p_T^{jet} > 5$ GeV in $|\eta| < 1.9$
  - Built with high purity tracks with $p_T > 0.25$ GeV in $|\eta| < 2.4$

Source	UE	Jet
Track Selection	$< 0.2\%$	$< 2\%$
Tracking Performance	$< 0.3\%$	2%
Model Dependence	$< 0.5\%$	2%
Unfolding	-	$< 2\%$
Statistical	$< 0.1\%$	$< 1\%$
Total	$< 0.6\%$	$< 5\%$

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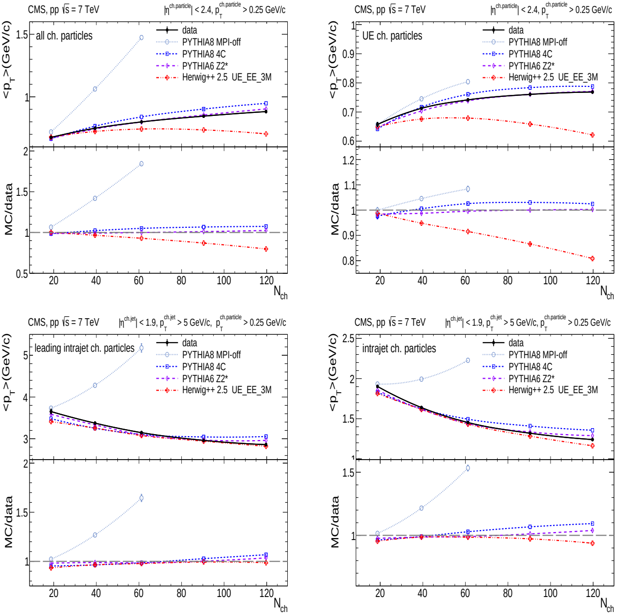
UE measurements in different multiplicity domains



Nice collection of measurements of charged particles inside and outside jets

PYTHIA nicely follows the average p_T spectra at different particle multiplicities

BUT..increasing disagreement appears for higher multiplicities

→ Clear need for MPI

Charged particle spectra p_T as a function of multiplicity

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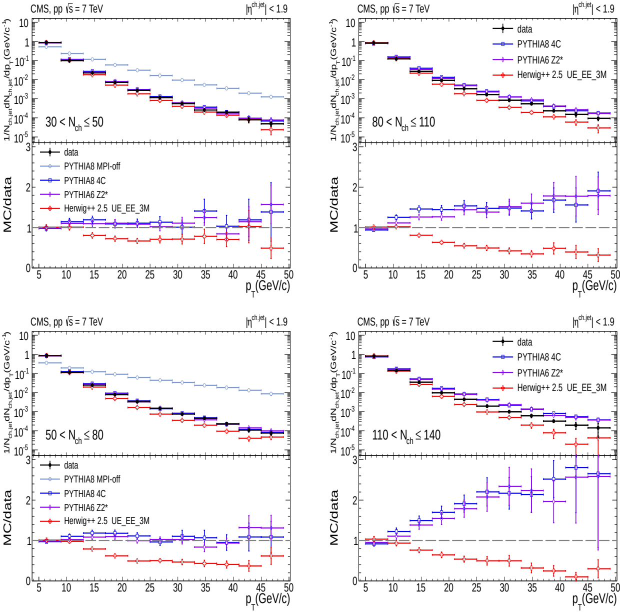
Jet measurements in different multiplicity domains



Good description for jet rates as a function of p_T for PYTHIA but not for HERWIG

BUT..the jet p_T spectra are not well described by any generator for increasing multiplicities

→ Clear need for MPI

Normalized jet p_T spectrum at different multiplicities

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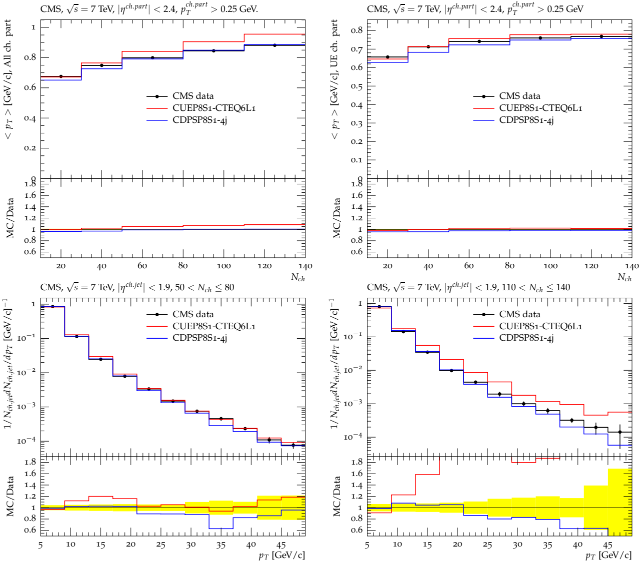
How do the new tunes perform in high multiplicities?



Reasonable agreement for average p_T as a function of particle multiplicity for the new tunes

BUT..the agreement does not improve with UE tunes when going to increasing multiplicities

→ Better description at high multiplicities for the DPS tunes!

Charged particle spectra p_T as a function of multiplicity (top)
Normalized jet p_T spectrum at different multiplicities (bottom)

CMS-FSQ-12-022

Eur.Phys.J. C73 (2013) 2674

Summary and conclusions

- New UE tunes have been obtained by looking at the energy dependence of charged particle content in the separated TRANSVERSE regions
  - PYTHIA6: CUETP6S1
  - PYTHIA8: CUETP8S1-CTEQ6L1, CUETP8S1-HERAPDF
- Significant improvement for the new tunes in the description of all regions of the UE at a wide range of collision energy
- Good description of most of the validation measurements related to particle densities, UE data and energy flow
  - The UE tunes are still not able to describe high multiplicity environments
- A Professor method for σ_{eff} extraction is available and has been tested in two different analyses (W+dijet, four-jets)
- FOUR-JETS: two different tunes have been performed:
  - Four-jet σ_{eff} estimation: the two tunes give compatible results
  - The UE description with the new tune agrees only in some regions
  - σ_{eff} from UE tunes tend to be higher than σ_{eff} from DPS tunes
  - DPS-based tunes describe better events with high particle multiplicity

THANKS FOR
YOUR ATTENTION

BACK-UP SLIDES

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:

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

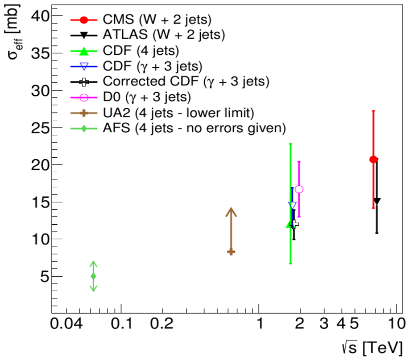
where σ_{eff} is the effective area parameter for the DPS

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

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



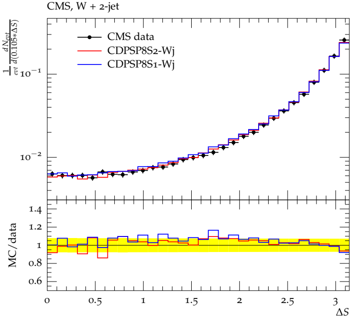
- a high energy phase for the LHC extends the study of the energy dependence
- with increasing energy, partons with lower x start to be relevant and detectable

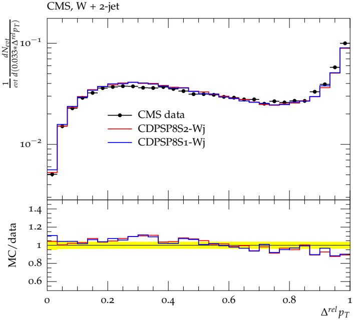
Effective cross section in the W-jets channel

Tuning the W-jet distributions for the usual UE tuning range

Parameter	CDPSTP8S1-Wj	CDPSTP8S2-Wj	4C
MultipleInteractions:expPow	1.523371	1.1197	2.0
MultipleInteractions:ecmPow	0.19	0.179	0.19
MultipleInteractions:pT0ref	2.09	2.5014	2.09
BeamRemnants:reconnectRange	1.5	2.5862	1.5
Goodness of fit	0.118	0.09	-
σ_{eff} (mb)	$25.9^{+2.4}_{-2.9}$	$25.8^{+8.2}_{-4.2}$	30.3

$\rightarrow$ CMS result $\sigma_{eff} = 20.7 \pm 0.8 \pm 6.6$ mb





Compatible results between the two tunes and in agreement with the published result

LEFT: ΔS
RIGHT: $\Delta^{rel}_{soft} p_T$

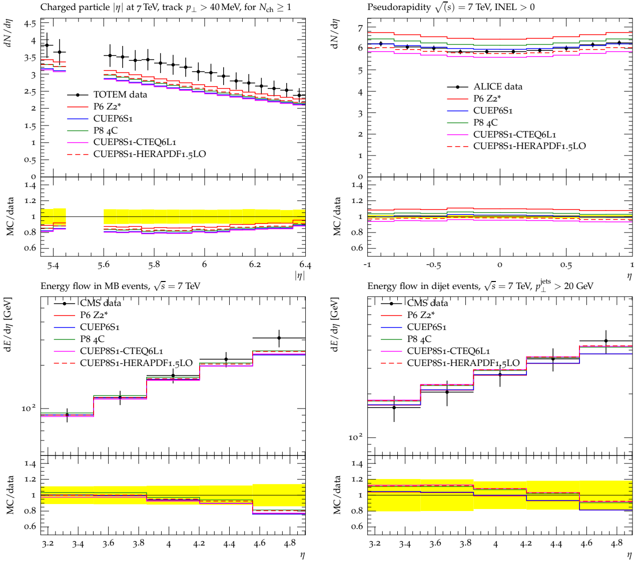
Tuned parameters

PYTHIA6 Parameter	Z2*lep	CUETP6S1
PARP(82) - MPI Cut-off	1.921	1.9096
PARP(90) - MPI Energy Extrapolation	0.227	0.2479
PARP(77) - CR Suppression	1.016	0.6646
PARP(78) - CR Strength	0.538	0.5454
PARP(83) - Matter fraction in core	0.356	0.8217
Reduced χ^2	-	0.915

PYTHIA8 Parameter	4C	CUETP8S1-CTEQ6L	CUETP8S1-HERAPDF1.5LO
MultipleInteractions:pT0Ref	2.085	2.1006	2.0001
MultipleInteractions:ecmPow	0.19	0.2106	0.2499
MultipleInteractions:expPow	2.0	1.6089	1.6905
BeamRemnants:reconnectRange	1.5	3.3126	6.0964
Reduced χ^2	-	0.952	1.13

Validation plots

How well do the new tunes perform in different observables
(and compared to the old ones)?



Charged particle multiplicity at forward and central region

TOTEM Coll., Europhys.Lett.98(2012) 31002
ALICE Coll., Eur.Phys.J. C68 (2010)

Forward Energy Flow in MB and dijet events

CMS Coll., JHEP 1111 (2011) 148

Good data description from predictions of all new tunes except in the very fwd region

CMS-GEN-14-001

NEW!

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: arXiv 1312.6440 → Submitted to PRD

Physics of a four-jet scenario (II)

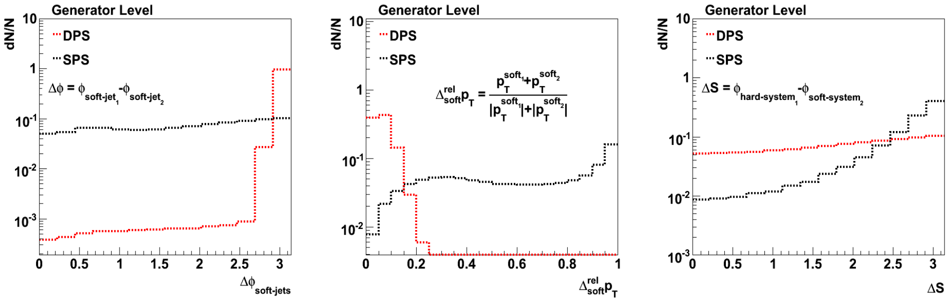
Which regions of the phase space are interesting for DPS detection?

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

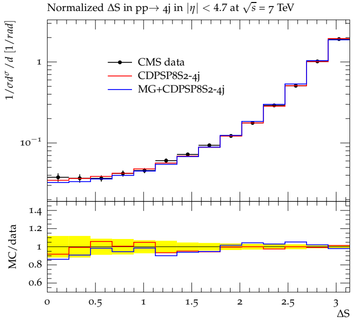
Effective cross section in the four-jets channel

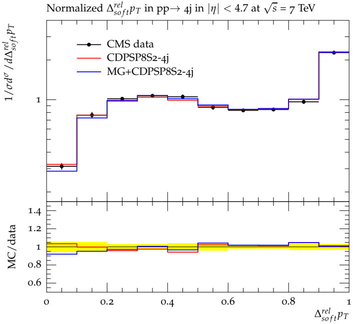
Tuning the four-jet distributions for the usual UE tuning range

Parameter	New Tune	4C
MultipleInteractions:expPow	0.6921	2.0
MultipleInteractions:ecmPow	0.345	0.19
MultipleInteractions:pT0ref	2.125	2.09
BeamRemnants:reconnectRange	6.526	1.5
Goodness of fit	0.42	-

$$\sigma_{eff} = 19.0^{+4.7}_{-3.0} \text{ mb}$$

$\rightarrow \sigma_{eff}$ (Tune 4C) $\sim$ 30.2 mb





Compatible results obtained with W-jet measurement

New set of parameters: CDPSP8S2-4j

LEFT: ΔS

RIGHT: $\Delta^{rel}_{soft} p_T$

CMS-GEN-14-001