

Deutsches Elektronen-Synchrotron
(DESY), Hamburg



Measurement of four-jet production including two heavy-flavour jets in pp collisions at CMS

Paolo Gunnellini

on behalf of the CMS Collaboration



Deep Inelastic Scattering 2015
Dallas (TX)
USA

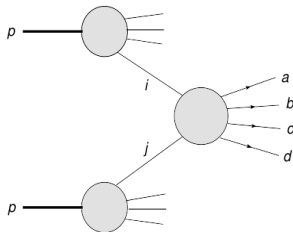
- Motivation
- Sensitivity studies to double parton scattering
- Detector level distributions
- Unfolding procedure
- Evaluation of systematics
- Results and MC comparisons
- Summary and Conclusion



CMS-PAS-FSQ-13-010

Physics of a four-jet scenario (I)

- Study of QCD evolution in a heavy flavour scenario



- One of the two jet pairs is emitted by the hard scattering
- Hard radiation can produce softer jets

Further measurement of a 4-jet final state:
multijet scenario with $b\bar{b}$ production

Comparison with different Monte Carlo models and test of their performance:

- in Leading Order (LO) MCs, the additional jets come from the parton shower;
- in POWHEG, a third parton is already in the matrix element while the forth comes from the parton shower;
- in other generators, like MADGRAPH, all the jets can be produced by partons in the matrix element.

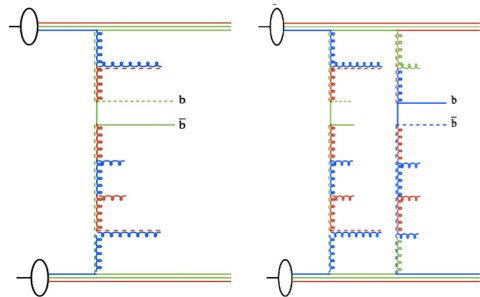
→ extension of the four-jet analysis [CMS Collaboration, Phys.Rev.D89\(2014\)092010](#)

Physics of a four-jet scenario (II)

- Study and separate the different topologies for events coming from single chain and double chain processes

The jets need to be associated in pairs:

(→ natural way thanks to the different flavour → light and bottom pair)



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

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

$$\Delta S = \arccos \left(\frac{\vec{p}_T^b \cdot \vec{p}_T^l}{|\vec{p}_T^b| \cdot |\vec{p}_T^l|} \right)$$

$$\Delta_{pair}^{rel} p_T = \frac{|p_T(j_i^l, j_k^l)|}{|p_T(j_i^l)| + |p_T(j_k^l)|}$$

The equal scale of the two jet pairs should suppress the SPS contribution

- DPS sensitivity expected mainly from ΔS and $\Delta_{pair}^{rel} p_T$
- Useful baseline for estimation of DPS contribution

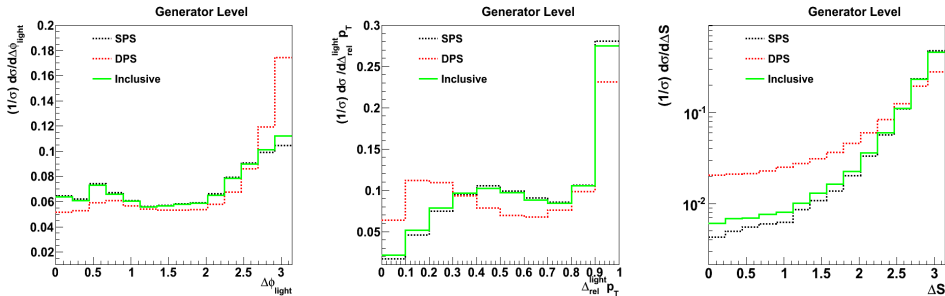
DPS Phenomenology in a two b- and two other-jet scenario

Preliminary studies of SPS and DPS contributions performed with PYTHIA8 4C:
→ jet $p_T > 20$ GeV for both pairs (mimicking the experimental measurement)

Inclusive QCD sample to compare:

- Inclusive: Standard Pythia8 sample
- DPS: Two hard scattering above threshold
- SPS: Standard Pythia8 sample with hard MPI vetoed

Left: $\Delta\phi_{light}$, Center: $\Delta_{light}^{rel} p_T$, Right: ΔS



Discriminating power: The two processes fill different regions of the phase space

- Use of low p_T jet trigger data recorded in 2010 ($\sim 3 \text{ pb}^{-1}$)
- Request for at least one good reconstructed primary vertex
- Particle Flow Jets clustered with the 0.5 anti- k_T algorithm
- B-tag algorithm: Combined secondary vertex
 - Tagging efficiency
 - Misidentification efficiency
- Jet selection:
 - at least 4 jets with $p_T > 20 \text{ GeV}$;
 - 2 leading b-jets in $|\eta| < 2.4$
 - 2 leading light-jets in $|\eta| < 4.7$

The jets are associated in pairs:

- **b-jet pair**: the two leading b-tagged jets above 20 GeV
- **light-jet pair**: the other two selected jets above 20 GeV

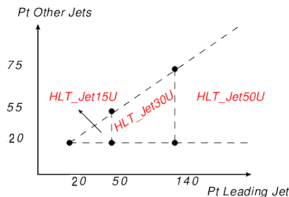
Absolute cross sections as a function of jet p_T and η ,
normalized cross sections as a function of jet p_T , η and correlation obs.

Detector corrections applied

Trigger strategy

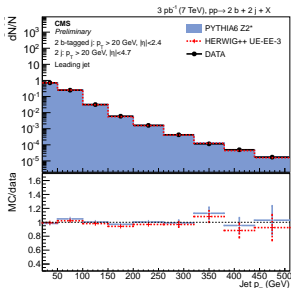
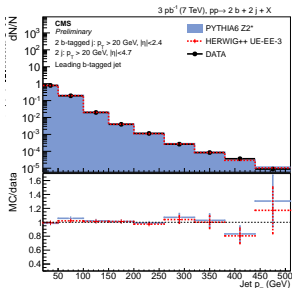
Exclusive division method

doi:10.1016/j.nima.2009.03.173



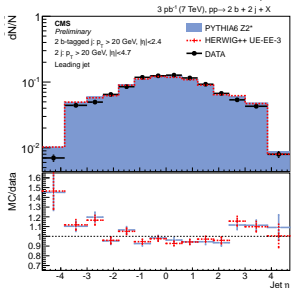
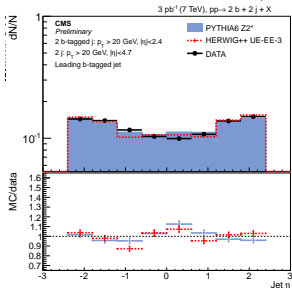
- Pile-up reweighting
- Trigger efficiency correction
- B-tag performance: Scale factors for matching the tagging performance in data and simulation
- Purity: Scale factors for matching the flavour composition of the tagged sample
- Reweighting as a function of \hat{p}_T : additional correction due to non optimal description of the jet transverse momentum spectra

Control distributions at detector level



Good agreement
between data and
simulation
at detector level

Slight differences only in
the very forward region



LEFT: Leading b-tagged jet
RIGHT: Leading other jet

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Unfolding to stable particle level

→ UNFOLDING THE DATA:

→ D'AGOSTINI METHOD:

How to decide the optimal number of iterations?

- Correction with different generators (PYTHIA, HERWIG) and comparison with generator level
- Backfolding → The detector effects are added back to the unfolded distributions and compared to the detector level

$$N_{det}^i = \sum_{j=1}^{N_{bins}} \frac{P_{ij} \cdot N_{unfold}^j \cdot (1 - Miss^i)}{1 - Fake^i}$$

The quality of the backfolding is estimated by evaluating:

$$\chi^2 = \sum_{i=1}^{N_{bins}} \left(\frac{X_{det} - X_{fold}}{\sqrt{\sigma_{det}^2 + \sigma_{fold}^2}} \right)^2$$

Phase space of the applied selection:

At least four jets	$p_T > 20 \text{ GeV}$
two leading b-jets	$ \eta < 2.4$
two leading additional jets	$ \eta < 4.7$

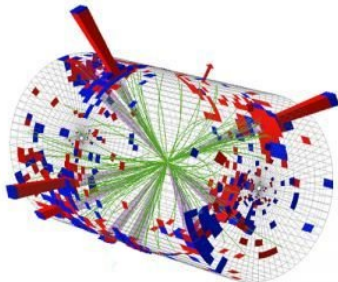
The minimum of the χ^2 has been chosen as optimal number of iteration

Systematics for absolute and normalized cross sections

Systematics uncertainties quantified for the different observables

Measured observable	Model	JES	JER	PU	B-tag	Pur.	Trig.	Stat.	Total
Absolute cross sections									
b-tagged jet p_T	20%	25%	4%	$< 0.1\%$	15%	4%	6%	4%	35%
light-jet p_T	10%	25%	4%	$< 0.1\%$	15%	4%	6%	4%	32%
Jet $ \eta \leq 3$	10%	25%	4%	$< 0.1\%$	15%	4%	5%	4%	32%
Jet $ \eta > 3$	20%	35%	4%	$< 0.1\%$	15%	4%	5%	4%	44%
Normalized cross sections									
b-tagged jet p_T	15%	15%	10%	$< 0.1\%$	2%	1%	5%	4%	24%
light-jet p_T	10%	15%	10%	$< 0.1\%$	2%	1%	5%	4%	22%
Jet $ \eta \leq 3$	5%	8%	1%	$< 0.1\%$	1%	1%	1%	4%	10%
Jet $ \eta > 3$	10%	15%	1%	$< 0.1\%$	2%	2%	1%	4%	19%
S'_{pT}	10%	5%	1%	$< 0.1\%$	2%	1%	1%	4%	12%
S_ϕ	10%	5%	1%	$< 0.1\%$	2%	1%	1%	4%	12%
$\Delta\phi^{\text{bottom}}$	13%	5%	1%	$< 0.1\%$	2%	1%	1%	4%	15%
$\Delta\phi^{\text{light}}$	13%	5%	1%	$< 0.1\%$	2%	1%	1%	4%	15%
ΔS	20%	5%	10%	$< 0.1\%$	2%	2%	1%	4%	23%
$\Delta\eta^{\text{bottom}}$	15%	5%	1%	$< 0.1\%$	2%	1%	1%	4%	16%
$\Delta\eta^{\text{light}}$	15%	5%	1%	$< 0.1\%$	2%	1%	1%	4%	16%
$\Delta_{\text{bottom}}^{\text{rel}} p_T$	9%	5%	7%	$< 0.1\%$	2%	1%	1%	4%	13%
$\Delta_{\text{light}}^{\text{rel}} p_T$	13%	5%	7%	$< 0.1\%$	2%	1%	1%	4%	16%

Dominant contribution: jet energy scale (abs.) and model dependence (norm.)



Measurement of correlation observables in the four-jet channel



Results: cross section measurements and MC comparison

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

Sample	PDF	Cross section (nb)
PYTHIA 6 Tune Z2*	CTEQ6L1	76.84
PYTHIA 6 Tune CUETP6S1	CTEQ6L1	76.66
HERWIG ++ Tune UE-EE-3	MRST2008**	43.78
HERWIG ++ Tune UE-EE-5-CTEQ6L1	CTEQ6L1	47.39
PYTHIA 8 Tune CUETP8S1-CTEQ6L1	CTEQ6L1	95.58
POWHEG+PYTHIA 6 Tune Z2*	CT10	77.96
POWHEG+PYTHIA 6 Tune Z2'	CT10	54.91
MADGRAPH+PYTHIA 6 Tune Z2*	CTEQ6L1	39.33
DATA	-	64.6 ± 2.4 (stat.) ± 21.6 (syst.)

PYTHIA 8 overshoots a bit the measurement

P6, POWHEG+P6 tune Z2' and H++ predict the correct cross section

MADGRAPH+P6 Z2* slightly underestimates the measurement

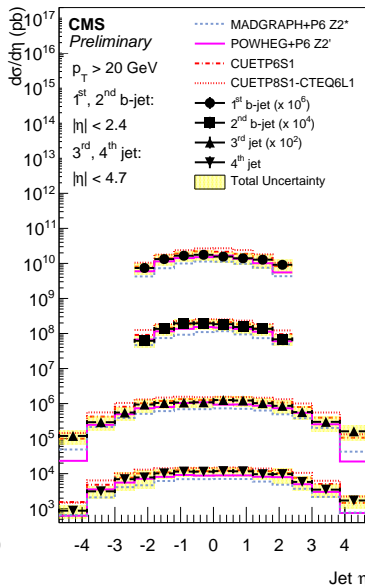
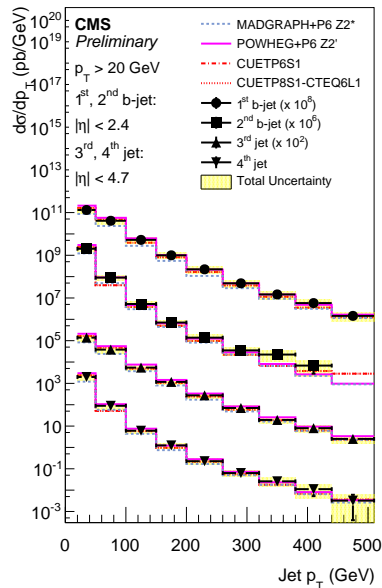
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Results: differential measurements and MC comparison

3 pb⁻¹ (7 TeV), pp → 2b+2j+X

3 pb⁻¹ (7 TeV), pp → 2b+2j+X



Jet p_T and η
spectra

- Enough statistics to have this measurement also at high p_T !
- Different η spectrum depends on the selected phase space

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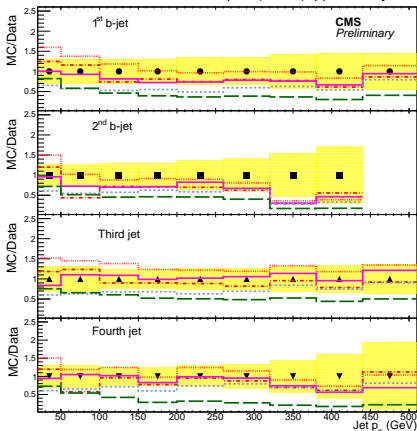


Results: differential measurements and MC comparison (II)

$p_T > 20$ GeV
 $1^{st}, 2^{nd}$ jet:
 $|\eta| < 2.4$
 $3^{rd}, 4^{th}$ jet:
 $|\eta| < 4.7$

..... MADGRAPH+P6 ZZ*
 POWHEG+P6 ZZ*
 CUETP6S1
 CUETP8S1-CTEQ6L1
 HERWIG++ UE-EE-5-CTEQ6L1
 Total Uncertainty

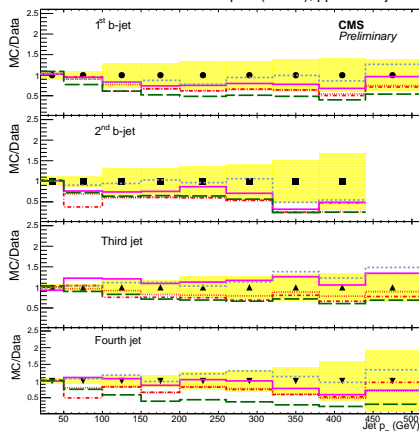
3 pb^{-1} (7 TeV), $pp \rightarrow 2b+2j+X$



$p_T > 20$ GeV
 $1^{st}, 2^{nd}$ jet:
 $|\eta| < 2.4$
 $3^{rd}, 4^{th}$ jet:
 $|\eta| < 4.7$

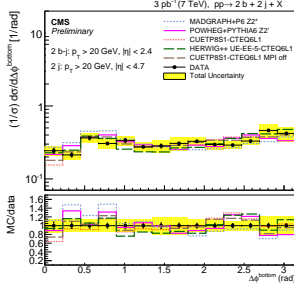
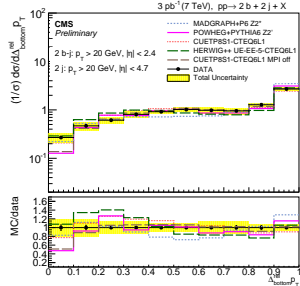
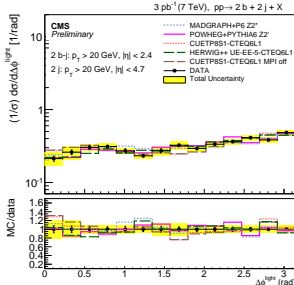
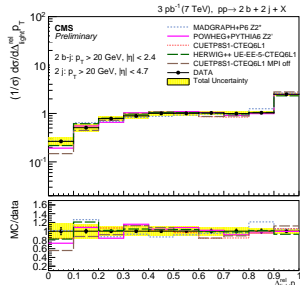
..... MADGRAPH+P6 ZZ*
 POWHEG+P6 ZZ*
 CUETP6S1
 CUETP8S1-CTEQ6L1
 HERWIG++ UE-EE-5-CTEQ6L1
 Total Uncertainty

3 pb^{-1} (7 TeV), $pp \rightarrow 2b+2j+X$



- PYTHIA 8 CUETP8S1-CTEQ6L1 overestimates the low p_T region of leading jets
- HERWIG++ tends to underestimate the high p_T region
- Good description achieved by MADGRAPH, PYTHIA 6 and POWHEG
- Normalized cross sections are best described by MADGRAPH and POWHEG

Results: normalized measurements and MC comparison



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

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

with i, k = light/bottom jets

TOP: light jets,
BOTTOM: bottom jets

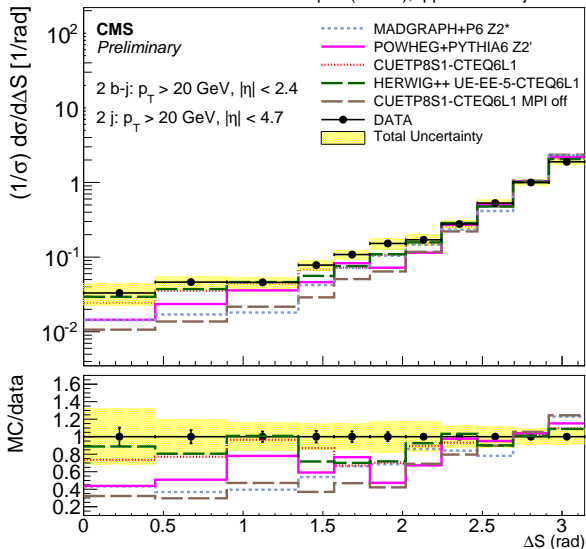
- All nominal predictions give a reasonable description of the shapes
- POWHEG+PYTHIA6 Z2' has a small deficit at low $\Delta^{rel} p_T$
- PYTHIA 8 w/o MPI also underestimates the low $\Delta^{rel} p_T$ region

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Results: normalized measurements and MC comparison

3 pb⁻¹ (7 TeV), pp → 2 b + 2 j + X



Most DPS-sensitive observable!

$$\Delta S = \arccos \left(\frac{\vec{p}_T^b \cdot \vec{p}_T^l}{|\vec{p}_T^b| \cdot |\vec{p}_T^l|} \right)$$

Predictions without MPI badly fail to describe the data

Best description provided by PYTHIA 8 and HERWIG++..
but not optimal!

The DPS contribution is crucial for describing this observable

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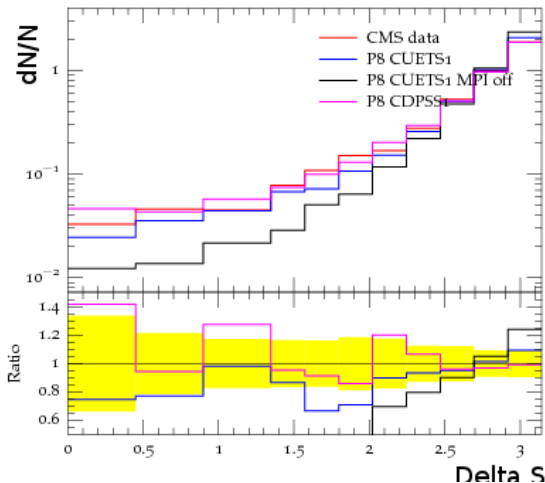


- A scenario with four-jets in the final state in the heavy flavour sector has been measured at 7 TeV with the CMS experiment
- Differential absolute and normalized distributions as a function of jet p_T , η and correlation observables have been presented
- Fixed-order ME calculations interfaced with PS are able to reproduce quite well single jet spectra
- Description of correlation observables depends on DPS contribution and is not optimal in some regions of the phase space
- Useful baseline for future DPS extraction

Thanks for your attention

Interpretation of the results

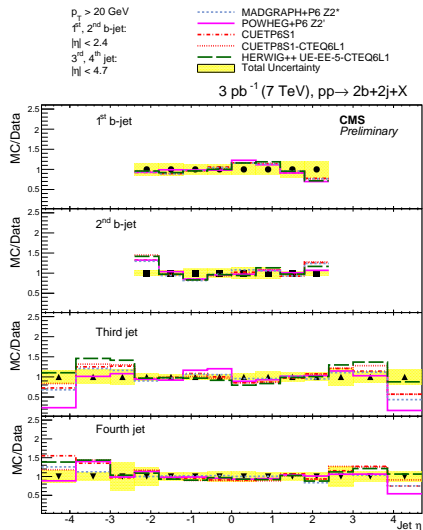
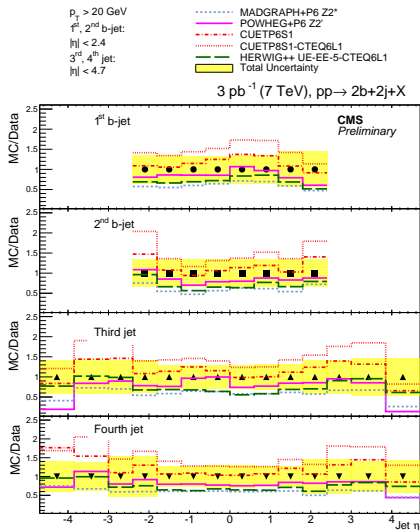
Comparison among predictions of UE- and DPS-tunes



RED: data
BLUE: UE tune
BLACK: UE tune w/o
MPI
PINK: DPS tune
(GEN-14-001)

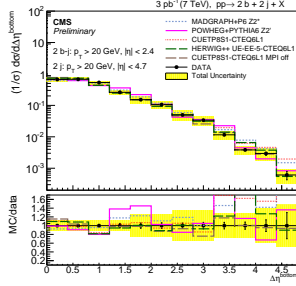
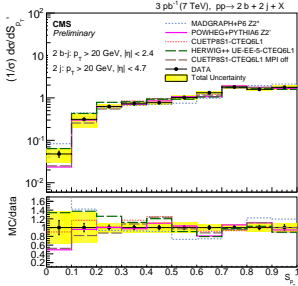
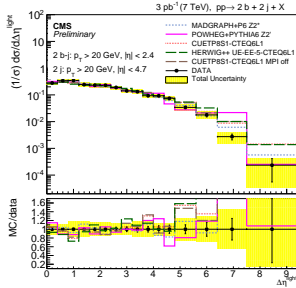
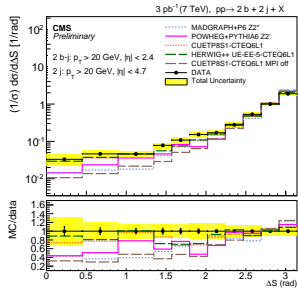
The DPS tune obtained by tuning the four-jet channel is improving the description!

Results: normalized measurements and MC comparison



- p_T shapes well described by POWHEG+PYTHIA 6 tune Z2' and MADGRAPH
- HERWIG ++ tends to underestimate the high p_T region
- η dependence well reproduced by all predictions except in the forward region

Results: normalized measurements and MC comparison



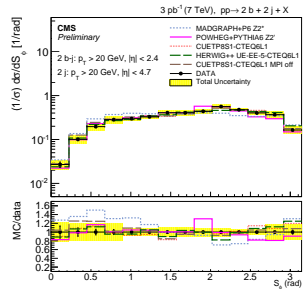
$$\Delta S = \arccos \left(\frac{\vec{p}_T^b \cdot \vec{p}_T^l}{|\vec{p}_T^b| \cdot |\vec{p}_T^l|} \right)$$

$$\Delta\eta(j_i, j_k) = |\eta_i - \eta_k|$$

$$S'_{p_T} = \sqrt{\Delta_b^{rel} p_T^2 + \Delta_l^{rel} p_T^2}$$

$$S'_\phi = \sqrt{\Delta\phi_b^2 + \Delta\phi_l^2}$$

with i, k = light/bottom jets



Definition of the stable-particle level

The stable-particle level is defined as:

- at least 4 jets with $p_T > 20$ GeV
- two b-jets in $|\eta| < 2.4$
- b-jet definition: presence of a b-quark inside the jet cone
- two additional jets in $|\eta| < 4.7$
- no flavour requirements for the additional jets

It loops over the quarks and if there is evidence of a b-quark inside a cone around the jet axis, the jet is identified as a b-jet
(Different definitions checked, no visible dependence)

Measurement of a
four light-jet scenario in
proton-proton collisions
at 7 TeV with the CMS experiment

Measurement of a four light-jet scenario at 7 TeV

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)

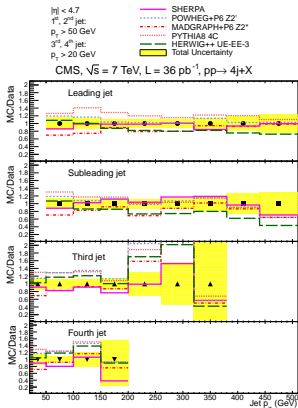
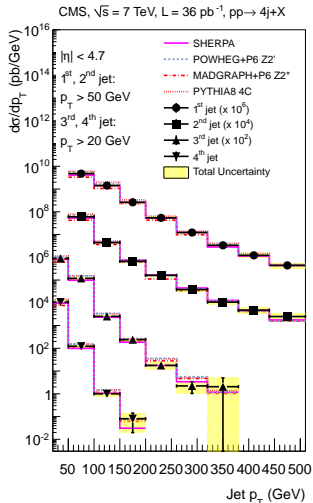
Sample	Cross section (nb)
PYTHIA8, tune 4C	423
POWHEG + PYTHIA6, tune Z2'	378
MADGRAPH + PYTHIA6, tune Z2*	234
SHERPA	293
HERWIG++, tune UE-EE-3	343
Data	330 ± 5 (stat.) ± 45 (syst.)

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

Phys.Rev.D89(2014)092010

Jet spectra: differential p_T cross sections

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++ is not able to reproduce the high- p_T region

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

Yes, checked with UE and inclusive jet cross section data

LEFT: Absolute differential cross section as a function of p_T

RIGHT: Ratios of predictions over data for the four jets

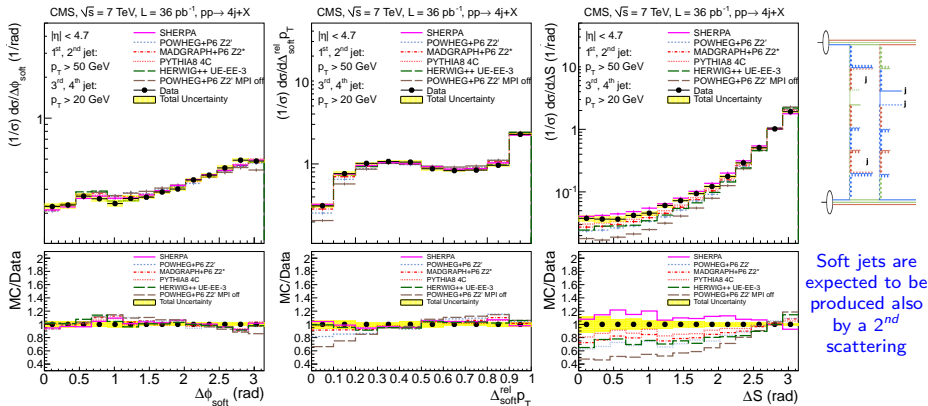
Correlation observables: normalized cross sections

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

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

$$\Delta_{\text{soft}}^{\text{rel}} p_T = \frac{|\vec{p}_T(j_i, j_k)|}{|\vec{p}_T(j_i)| + |\vec{p}_T(j_k)|}$$

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



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

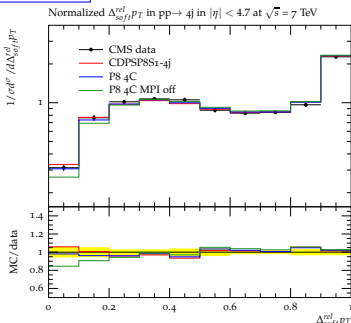
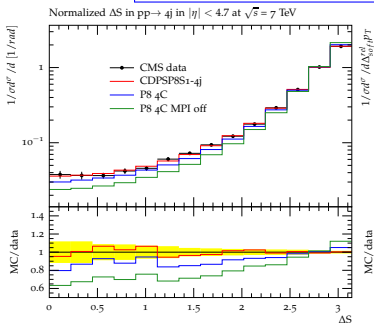
- No significant differences in $\Delta\phi$ and $\Delta_{\text{soft}}^{\text{rel}} p_T$ among generators
- POWHEG w/o MPI is far below for $\Delta_{\text{soft}}^{\text{rel}} p_T$ and ΔS
- SHERPA and PYTHIA8 perform best for ΔS
- ΔS and $\Delta_{\text{soft}}^{\text{rel}} p_T$ sensitive to MPI contribution: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

Effective cross section in the four-jets channel (I)

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	-

$$\sigma_{eff} = 21.3^{+1.2}_{-1.6} \text{ mb} \rightarrow \sigma_{eff} (\text{Tune 4C}) \sim 30.2 \text{ mb}$$



Improved agreement with the new tune

New set of parameters:
CDPSP8S1-4j

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

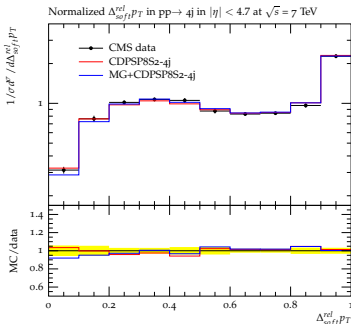
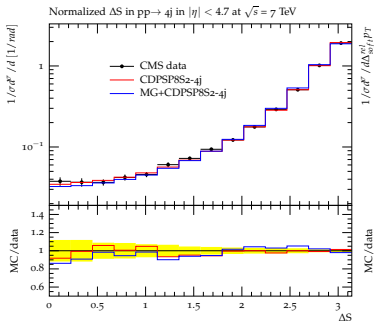
CMS-GEN-14-001

Effective cross section in the four-jets channel (II)

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	-

$$\sigma_{eff} = 19.0^{+4.7}_{-3.0} \text{ mb} \rightarrow \sigma_{eff} (\text{Tune 4C}) \sim 30.2 \text{ mb}$$



Compatible results
obtained with W-jet
measurement

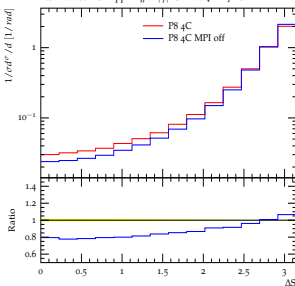
New set of parameters:
CDPSP8S2-4j

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

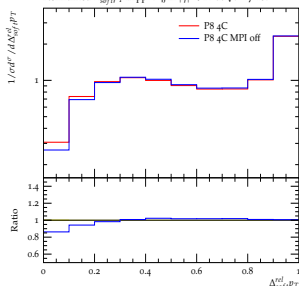
CMS-GEN-14-001

DPS sensitivity of the two four-jet scenarios

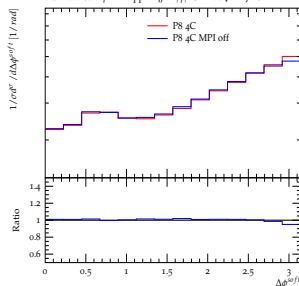
Normalized ΔS in $pp \rightarrow 4j$ in $|\eta| < 4.7$ at $\sqrt{s} = 7$ TeV



Normalized $\Delta_{soft}^{rel} p_T$ in $pp \rightarrow 4j$ in $|\eta| < 4.7$ at $\sqrt{s} = 7$ TeV

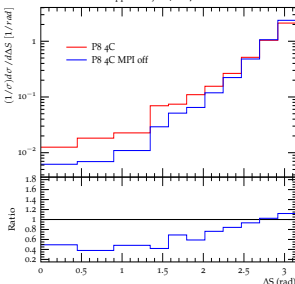


Normalized $\Delta\phi^{soft}$ in $pp \rightarrow 4j$ in $|\eta| < 4.7$ at $\sqrt{s} = 7$ TeV

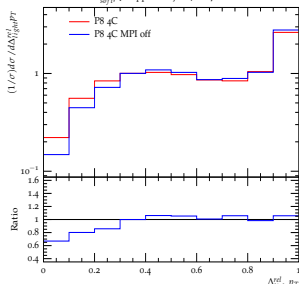


TOP: light-jet scenario, BOTTOM: heavy flavour scenario

Normalized ΔS in $pp \rightarrow 2b2j$ at $\sqrt{s} = 7$ TeV



Normalized $\Delta_{soft}^{rel} p_T$ in $pp \rightarrow 2b2j$ at $\sqrt{s} = 7$ TeV



Normalized $\Delta\phi^{light}$ in $pp \rightarrow 2b2j$ at $\sqrt{s} = 7$ TeV

