Deutsches Elektronen-Synchrotron
(DESY), Hamburg

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

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on behalf of the CMS Collaboration

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Outline

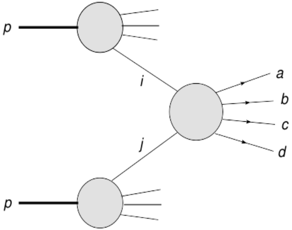
- Motivation
- Sensitivity studies to double parton scattering
- Detector level distributions
- Unfolding procedure
- Evaluation of systematics
- Results and MC comparisons
- Method for DPS signal extraction
- Summary and Conclusion

arXiv 1609.03489

Accepted by PRD

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 additional 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.

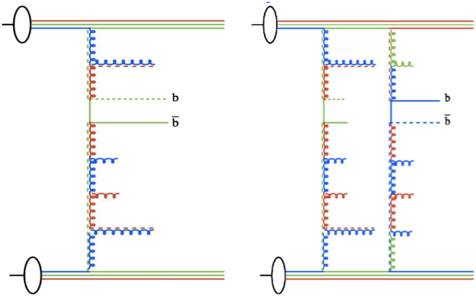
$\rightarrow$ extension of the four-jet analysis CMS Collaboration, Phys.Rev.D89(2014)092010

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:

($\rightarrow$ natural way thanks to the different flavour $\rightarrow$ light and bottom pair)



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

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

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

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

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

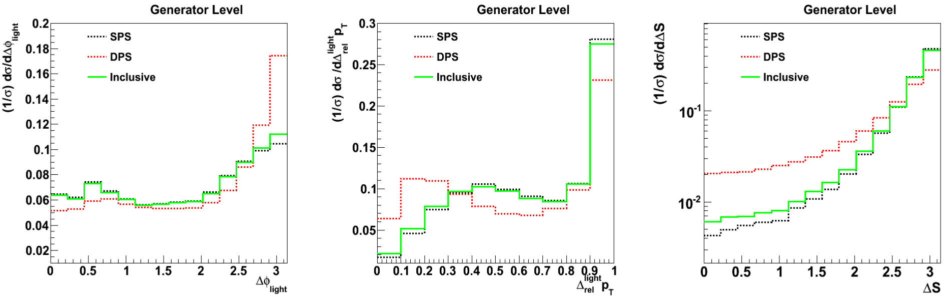
DPS Phenomenology in a two b- and two other-jet scenario

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

Inclusive QCD sample to compare:

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

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



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

DESY-THESIS-15-010

Event selection

- Use of low p_T jet trigger data recorded in 2010 (~ 3 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 $p_T > 20$ 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

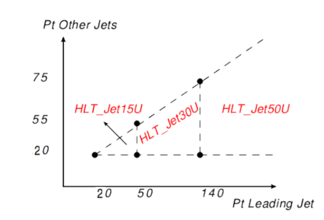
Absolute cross sections as a function of jet p_T and η,
normalized cross sections as a function of jet p_T, η and correlation obs.

Detector corrections applied

Trigger strategy

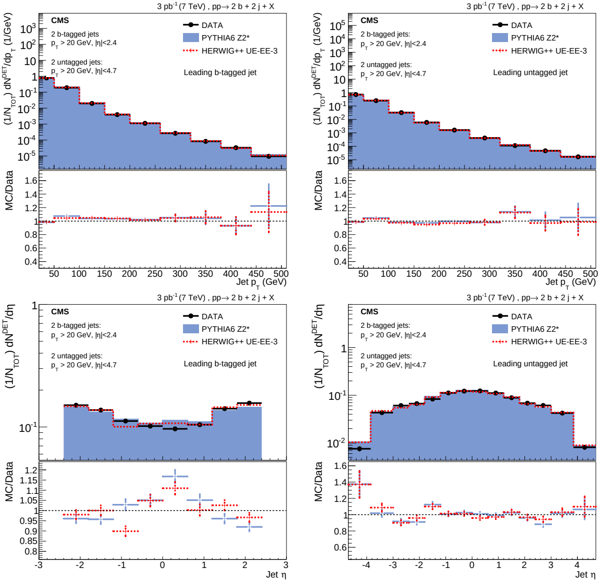
Exclusive division method

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

arXiv 1609.03489

NEW!

→ UNFOLDING THE DATA:

→ D'AGOSTINI METHOD:

How to decide the optimal number of iterations?

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

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

The quality of the backfolding is estimated by evaluating:

$$\chi^2 = \sum_{i=1}^{Nbins} \left(\frac{X_{det} - X_{fold}}{\sqrt{\sigma^2_{det} + \sigma^2_{fold}}} \right)^2$$

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

Phase space of the applied selection:

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

Systematics for absolute and normalized cross sections

Systematical uncertainties quantified for the different observables

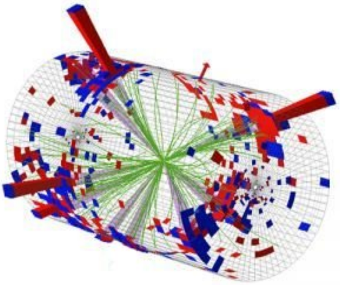
Measured observable	Model	JES	JER	B-tag	Pur.	Trig.	Stat.	Total
Absolute cross sections								
b-tagged jet p_T	20%	25%	4%	15%	12%	6%	4%	38%
light-jet p_T	10%	25%	4%	15%	12%	6%	4%	34%
Jet $\|\eta\| \leq 3$	10%	25%	4%	15%	12%	5%	4%	34%
Jet $\|\eta\| > 3$	20%	35%	4%	15%	12%	5%	4%	45%
Normalized cross sections								
$\Delta\phi^{\mathrm{light}}$	13%	5%	1%	2%	1%	1%	4%	15%
ΔS	20%	5%	10%	2%	2%	1%	4%	23%
$\Delta^{\mathrm{rel}}_{\mathrm{light}} p_{\mathrm{T}}$	13%	5%	7%	2%	1%	1%	4%	16%

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

THEORY UNCERTAINTY: evaluated for POWHEG+PYTHIA 8
(with consistent use of PDF for matrix element and UE tune)

PDF: $\sim$ 10-50%, Scale: $\sim$ 10-15%

Future: need for consistent variations of PDF and scales between ME and UE tunes



Measurement of correlation observables in the four-jet channel

NEW!

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)

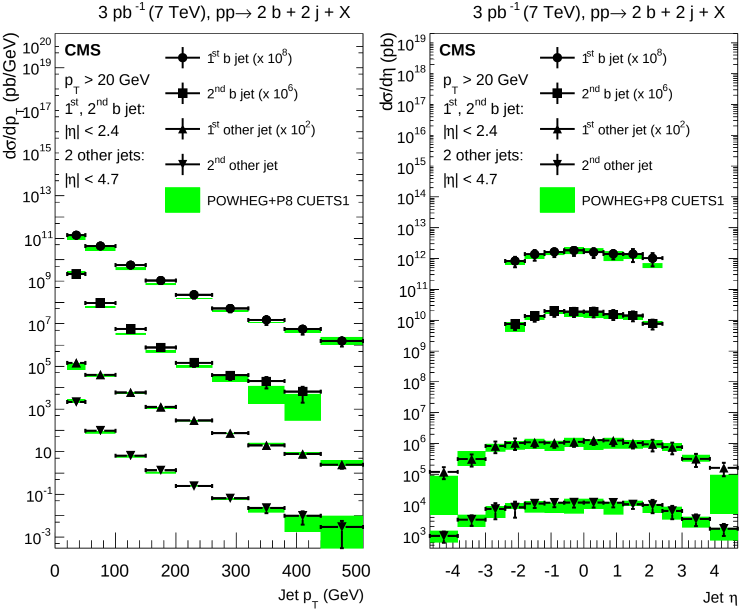
Sample	PDF	Cross section (nb)
PYTHIA 6 Tune Z2*	CTEQ6L1	77
PYTHIA 6 Tune CUETP6S1	CTEQ6L1	77
HERWIG ++ Tune UE-EE-3	MRST2008**	44
HERWIG ++ Tune UE-EE-5-CTEQ6L1	CTEQ6L1	47
PYTHIA 8 Tune CUETP8S1-CTEQ6L1	CTEQ6L1	96
POWHEG+PYTHIA 8 CUETS1	CT10	65 ± 12
POWHEG+PYTHIA 8 CUETS1 MPI off	CT10	31 ± 6
MADGRAPH+PYTHIA 8 Tune CUETM1	CTEQ6L1	39
DATA	-	69 ± 3 (stat.) ± 24 (syst.)

PYTHIA 8 overshoots a bit the measurement
P6, POWHEG+P8 and H++ predict the correct cross section
MADGRAPH+P8 slightly underestimates the measurement

arXiv 1609.03489

NEW!

Results: differential measurements and MC comparison



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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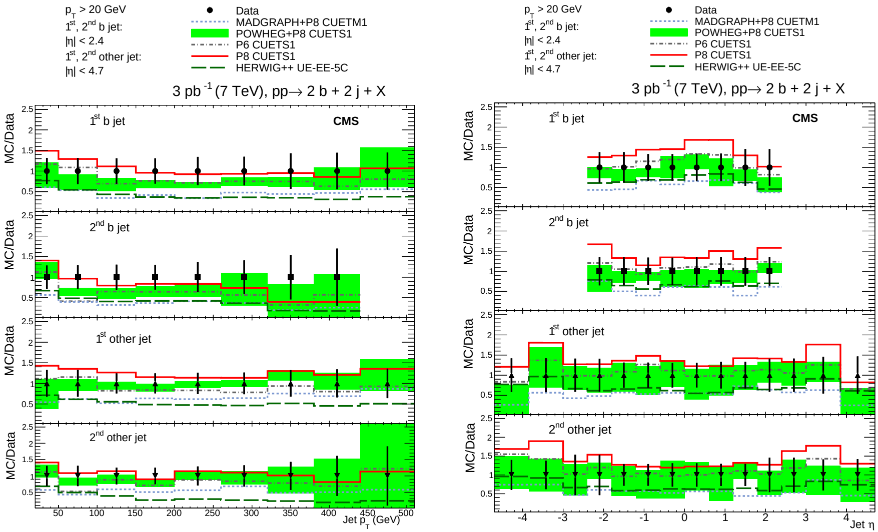
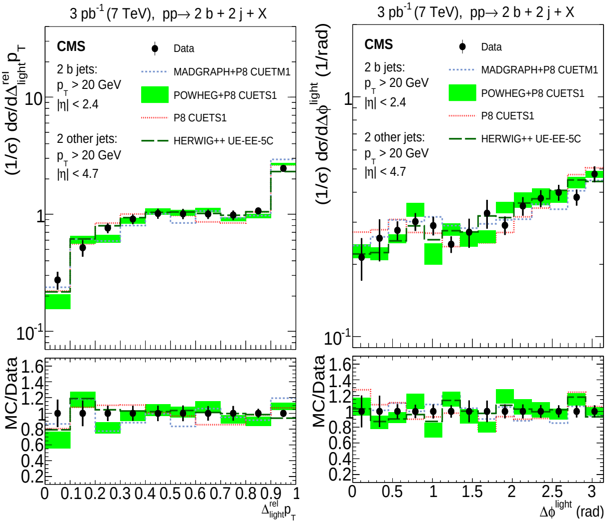
NEW!

Results: differential measurements and MC comparison (II)



- PYTHIA 8 CUETP8S1-CTEQ6L1 overestimates the low p_T region of leading jets
- HERWIG++ and MADGRAPH tend to underestimate the high p_T region
- Good description achieved by PYTHIA 6 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 jets

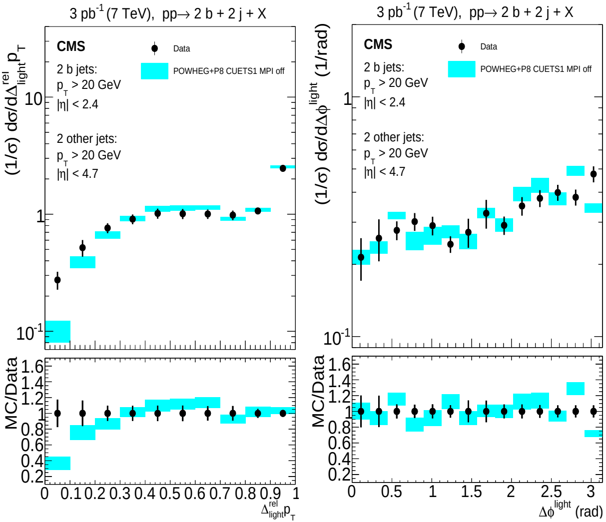
LEFT: $\Delta^{rel} p_T$
RIGHT: $\Delta\phi$

- All nominal predictions give a reasonable description of the shapes
- POWHEG+P8 CUETS1 has a small deficit at low $\Delta^{rel} p_T$
- Theory uncertainty comparable to experimental one

arXiv 1609.03489

NEW!

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 jets

LEFT: $\Delta^{rel} p_T$

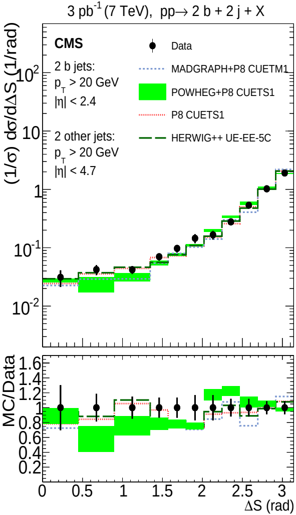
RIGHT: $\Delta\phi$

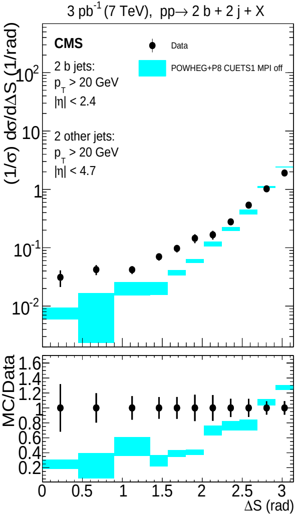
- Absolute cross sections are not well described by predictions without MPI
- POWHEG+P8 CUETS1 has a big deficit at low $\Delta^{rel} p_T$
- $\Delta\phi$ is not very sensitive to DPS contributions

arXiv 1609.03489

NEW!

Results: normalized measurements and MC comparison





Most DPS-sensitive observable!

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

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

arXiv 1609.03489

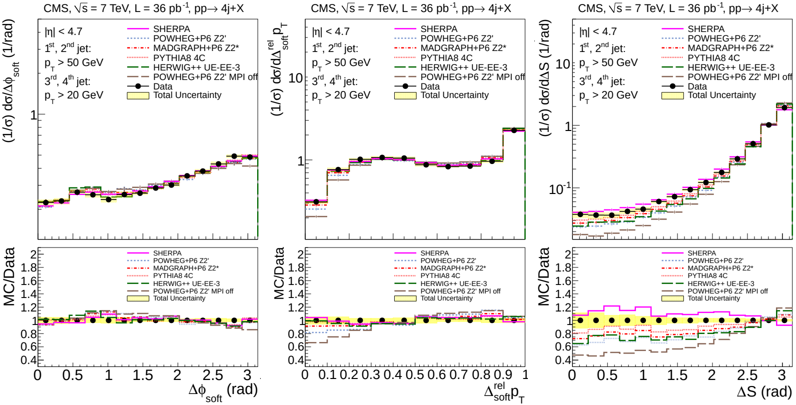
Phys.Rev.D89(2014)092010

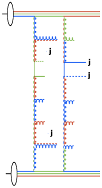
Eur. Phys. J C 76 (2016) 155

Measurement of correlation observables in the four-jet channel (light sector)

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

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



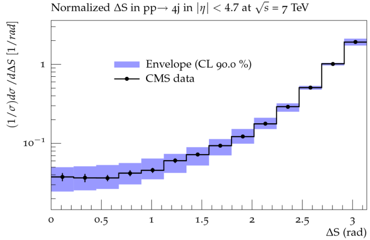


Soft jets are expected to be produced also by a 2^{nd} scattering

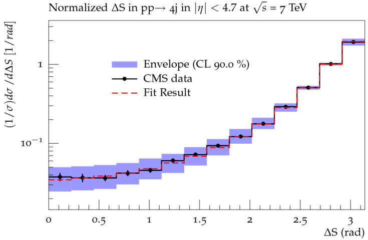
- No significant differences in $\Delta\phi$ and $\Delta^{rel}_{soft} p_T$ among generators
- POWHEG w/o MPI is far below for $\Delta^{rel}_{soft} p_T$ and ΔS
- SHERPA and PYTHIA8 perform best for ΔS
- ΔS and $\Delta^{rel}_{soft} p_T$ sensitive to MPI contribution: ROOM for DPS!

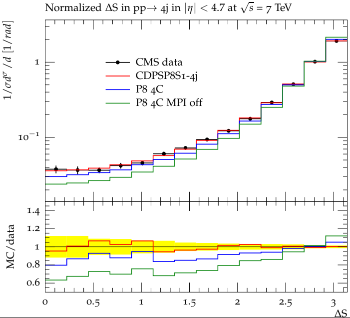
Extraction of DPS signal

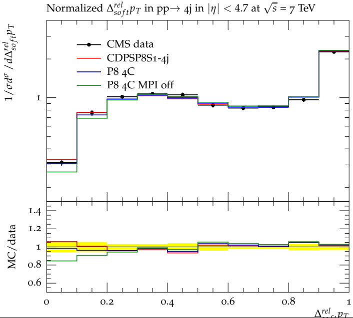
Minimization of the binned $\chi^2 = \sum_O \sum_{b \in O} \frac{(MC^b - DATA^b)^2}{\Delta_b^2}$



MINIMIZ.







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

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

Preliminary results from tuning

Four-parameter tune of the separate measurements:

- PDF: CTEQ6L1 set

Fitted measurement	σ_{eff} value (mb)	Reference
4j	$\mathbf{19.0}^{+4.7}_{-3.0}$	Eur. Phys. J. C (2016) 76 155
Wj	$\mathbf{25.8}^{+8.2}_{-4.2}$	Eur. Phys. J. C (2016) 76 155
2b2j	$\mathbf{23.2}^{+3.3}_{-2.5}$	DESY-THESIS-15-010

Two-parameter tunes of the separate measurements and common fits:

- PDF: CTEQ6L1 set

N.B. PRIVATE WORK!

Fitted measurements	σ_{eff} value	χ^2/Ndf
4j	**21.49 mb**	0.521
Wj	**27.49 mb**	0.823
2b2j	**23.96 mb**	0.543
4j+2b2j	**24.37 mb**	0.631
Wj+2b2j	**25.32 mb**	0.807
Wj+4j	**23.20 mb**	0.948
2b2j+Wj+4j	**22.57 mb**	0.876

All fitted σ_{eff} values are very close between each other

It is possible to fit all measurements at the same time, with good fit quality

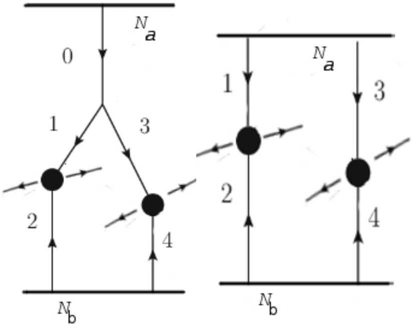
No uncertainties provided..still work ongoing from MC tuning side!

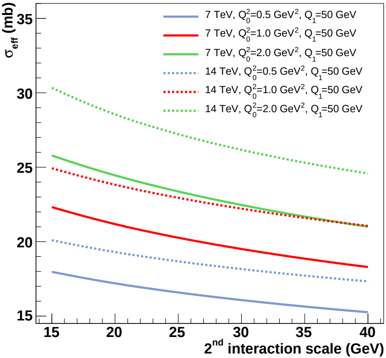
Interpretation of the results

- CUETP8M1: UE-based tune, describes overall measur. at 7 TeV ($\sigma_{eff} \sim 28$ mb)
- CDPSTP8S1: DPS-based tune, describes 4j observables at 7 TeV ($\sigma_{eff} \sim 19$ mb)
- EPJC.75.282: UE-based tune with dynamic σ_{eff} values

The so-called 1×2 and 2×2 mechanisms also contribute to MPI processes

The 1×2 mechanisms lead to transverse-scale dependence of MPI cross sections





Dynamic dependence of σ_{eff} is performed
by reweighting plain PYTHIA 8 simulation (EPJC.75.282)

Interpretation of the results

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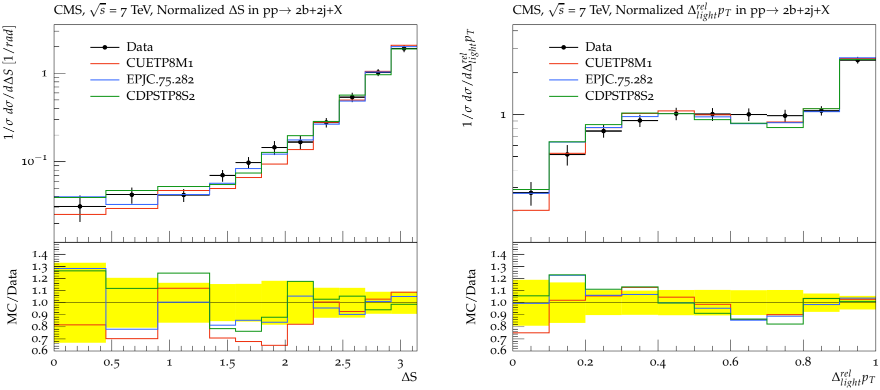

- UE tune description is good but not optimal
- Description from DPS tune or simulation with dynamic σ_{eff} is better

Conclusion

- 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 whose amount is crucial for ΔS
- Useful baseline for future DPS extraction (ongoing work)

Conclusion

- 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
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Thanks for your attention

BACKUP SLIDES

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)

Extraction of DPS signal (I)

- Run predictions of the considered analysis for different choices of UE parameters
- Interpolate the generator response in a multidimensional parameter grid
- Tune the MC response in order to obtain the best data description

CMS-GEN-14-001

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

I No separation between signal and background;

II Possibility to use any MC generator;

III Possibility to extract σ_{eff} from any model;

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)

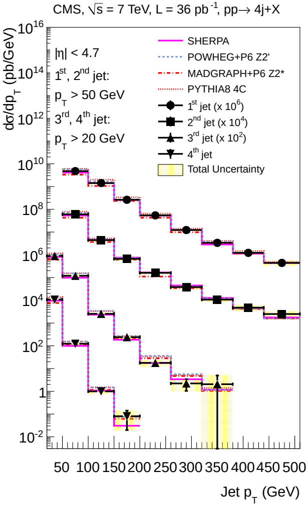
Sample	Cross section (nb)
PYTHIA8, tune 4C	423
POWHEG + PYTHIA6, tune Z2'	378
MADGRAPH + PYTHIA6, tune Z2*	234
SHERPA	293
HERWIG++, tune UE-EE-3	343
Data	330 ± 5 (stat.) ± 45 (syst.)

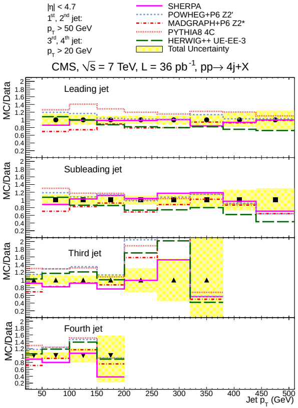
- PYTHIA8 and POWHEG+PYTHIA6 overshoot the cross section value
- MADGRAPH+PYTHIA6 underestimates the measurement
- SHERPA and HERWIG++ are in good agreement with the data

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

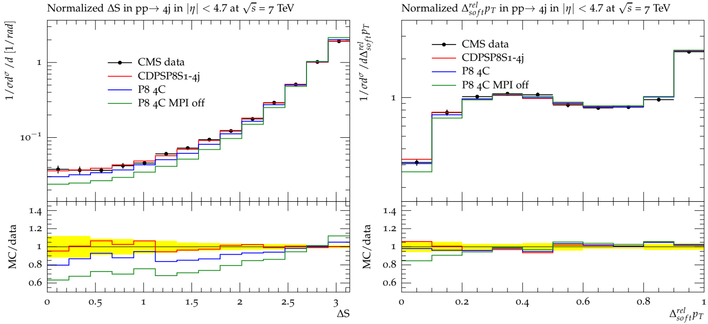
Effective cross section in the four-jets channel (I)

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	-

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

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



Improved agreement with the new tune

New set of parameters: CDPSP8S1-4j

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

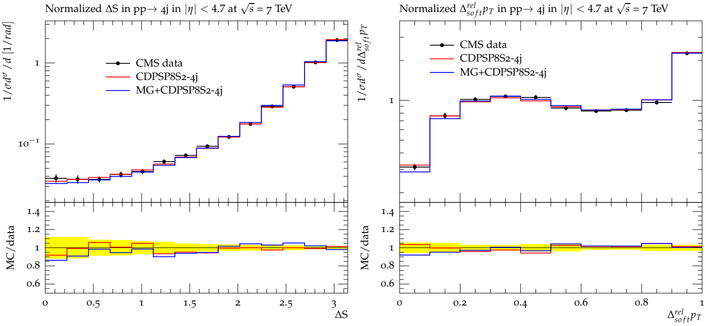
CMS-GEN-14-001

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	-

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



Compatible results obtained with W-jet measurement

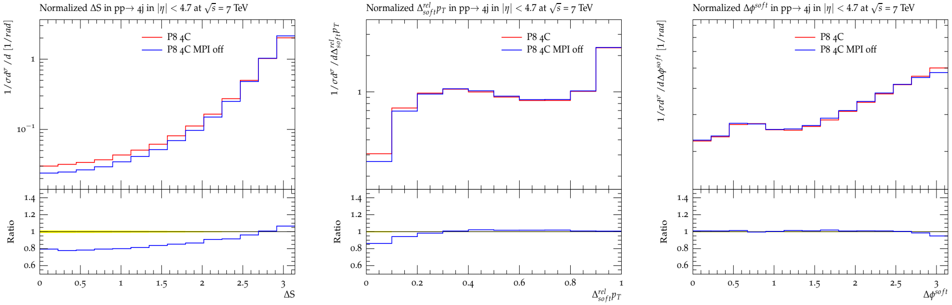
New set of parameters: CDPSP8S2-4j

LEFT: ΔS

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

CMS-GEN-14-001

DPS sensitivity of the two four-jet scenarios



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