Measurement of Double Parton Scattering at LHC with the CMS experiment

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EPS HEP 2015, Vienna

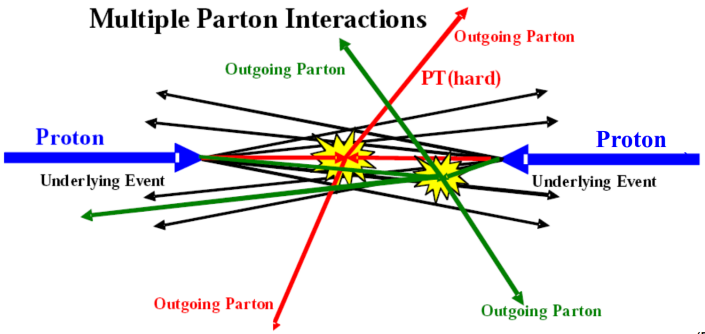
23 July 2015

Outline

- Multiparton interactions and double parton scattering (DPS)
- Effective cross section (σ_{eff})
- Looking for MPI
- DPS using processes:
  - W + 2jets
  - 4jets
  - 2b + 2jets
  - photon + 3jets
- Results and Summary

Multi-parton interactions

- A hadron−hadron collision is described in terms of one single hard scattering between the partons of the colliding hadrons
- Large parton densities and small x→ probability to have more than one scattering between partons: **Multi-parton interactions (MPI)**



(Rick Field)

- MPI are accompained by large hadronic activity and are usually soft
- Underlying event measurements show evidence of MPI presence
- Two simultaneous hard parton-parton interactions in a single proton-proton collision: **Double Parton Scattering**
  - W + 2jets (CMS Collaboration; JHEP 1403(2014)032)
  - 4jets (CMS Collaboration; Phys.Rev.D 89(2014)092010)
  - 2light + 2bjets (CMS-PAS-FSQ-13-010)
  - photon + 3jets (CMS-PAS-FSQ-12-017)

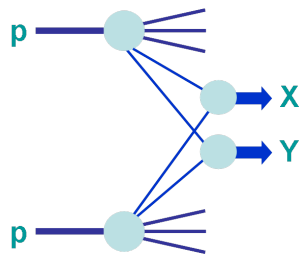
Effective cross section

Cross section of two processes "X" and "Y" occuring simultaneously can be written as:

(Inclusive formalism, no parton correlation)

$$\sigma(X+Y) = \frac{m*\sigma(X)*\sigma(Y)}{\sigma_{eff}}$$

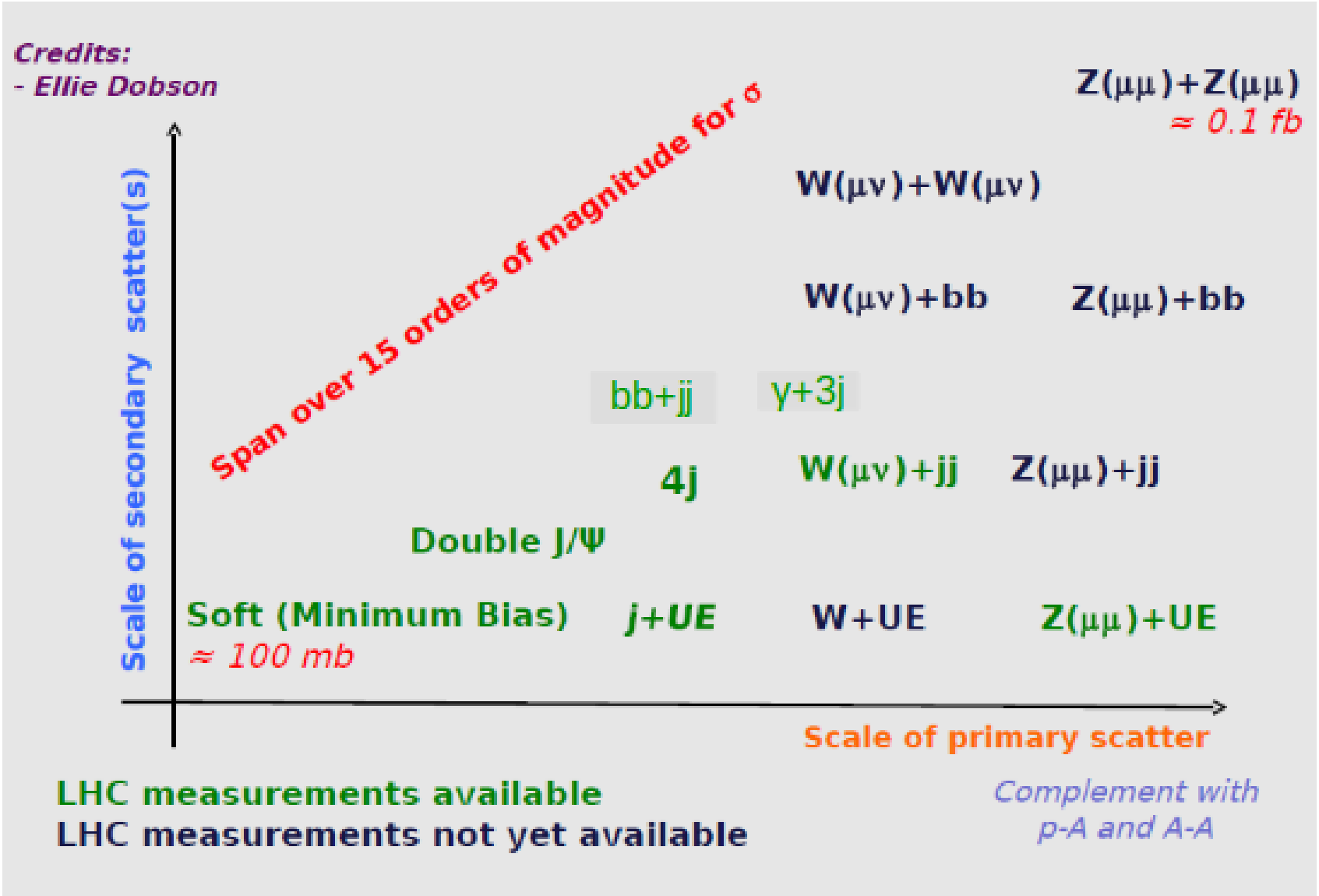
where $\sigma(X)$ and $\sigma(Y)$ are cross section for processes X and Y, "m" is the symmetry factor $m = \frac{1}{2}$, if processes "X" and "Y" are identical otherwise one.



- σ_{eff}**: Effective area parameter for double-parton interactions**
- Input for theoretical models
- Is expected to be independent of process type and collision energy

Measurement of σ_{eff} provides access to information about hadron structure in transverse plane, understanding of background to the new Physics searches

Where to look for MPI !!



DPS using W + 2jets

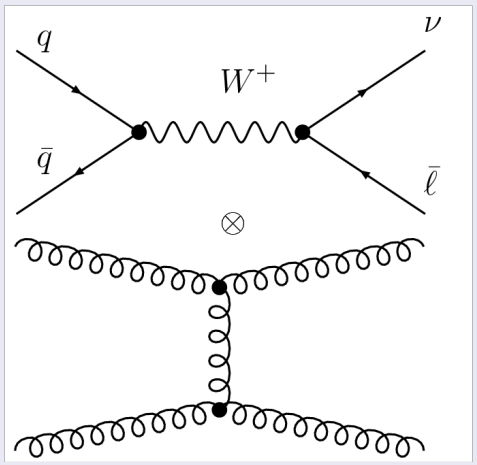
Signal

- W from first hard parton-parton interaction
- Exactly two jets from the second hard interaction
- Only muoninc decay of W is considered for the analysis

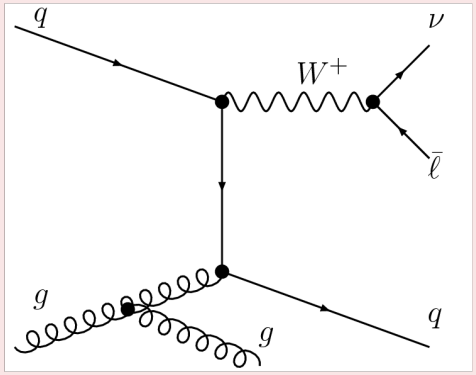
Background

- Both W and two jets coming from single hard interaction (SPS)

DPS



SPS



Event selection and effective cross section

- Full 2011 pp collision data collected with CMS detector at $\sqrt{s} = 7$ TeV
- Integrated luminosity 5 fb^{-1}
- Simulated Samples
  - MADGRAPH5+PYTHIA8 4C, PYTHIA6 Z2*
  - POWHEG (MiNLO) + PYTHIA6 Z2*, HERWIG6
  - Various background samples: VV, top, QCD multijets, Drell-Yan

W selection

- Single muon trigger,with only one well reconstructed and isolated muon
- $p_T(\mu) > 35$ GeV, $|\eta|(\mu) < 2.1$
- Missing transverse energy > 35 GeV/c
- W transverse mass > 50 GeV$/c^2$

Jets selection

- Particle flow jets reconstructed with anti-kT jet clustering algorithm, with cone size of 0.5
- $p_T > 20$ GeV/c, $|\eta| < 2.0$
- No muon within $\Delta R = 0.5$

Effective cross section

$$\sigma_{\text{eff}} = \frac{\sigma'_{\text{W+0jet}}}{\sigma'^{\text{DPS}}_{\text{W+2j}}} \cdot \sigma'_{\text{2j}} \longrightarrow \sigma_{\text{eff}} = \frac{R}{f^{\text{DPS}}} \cdot \sigma'_{2j}$$

R - fraction of W+0-jet events with respect to W+2-jet events (from data)

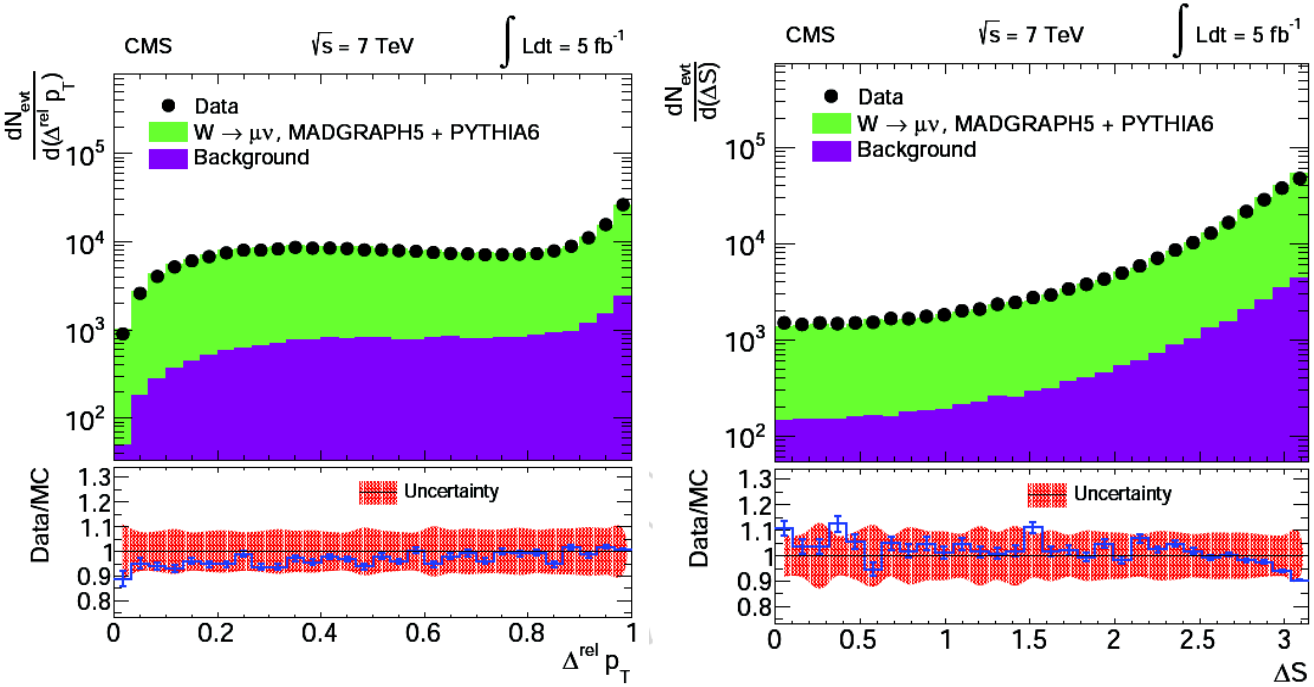
f^{DPS} - fraction of (W+2-jet)$^{\text{DPS}}$ events with respect to total W+2-jet events (from data and MC)

σ'_{2j} - dijet cross section at particle level (from data)

DPS sensitive observables in W + 2jets events

- Relative transverse momentum balance between selected jets ($\Delta^{rel} p_T$)
- Azimuthal angle between W and dijet system (ΔS)

$$\Delta^{\text{rel}}\, p_T = \frac{|\vec{p}_T(\text{j}_1) + \vec{p}_T(\text{j}_2)|}{|\vec{p}_T(\text{j}_1)| + |\vec{p}_T(\text{j}_2)|}. \qquad \Delta\text{S} = \arccos\left(\frac{\vec{p}_T(\mu, \not{E}_T).\vec{p}_T(\text{j}_1, \text{j}_2)}{|\vec{p}_T(\mu, \not{E}_T)|.|\vec{p}_T(\text{j}_1, \text{j}_2)|}\right),$$



- Nice agreement between data and MC predictions
- No DPS extraction at detector level, unfold distributions at particle level

Unfolding and systematic uncertainities

- Background contribution is subtracted before unfolding
- Method: Bayesian approach (cross checked with SVD method), consistent within 1-2%
- W + 2jets cross section also unfolded to particle level

Particle level selection

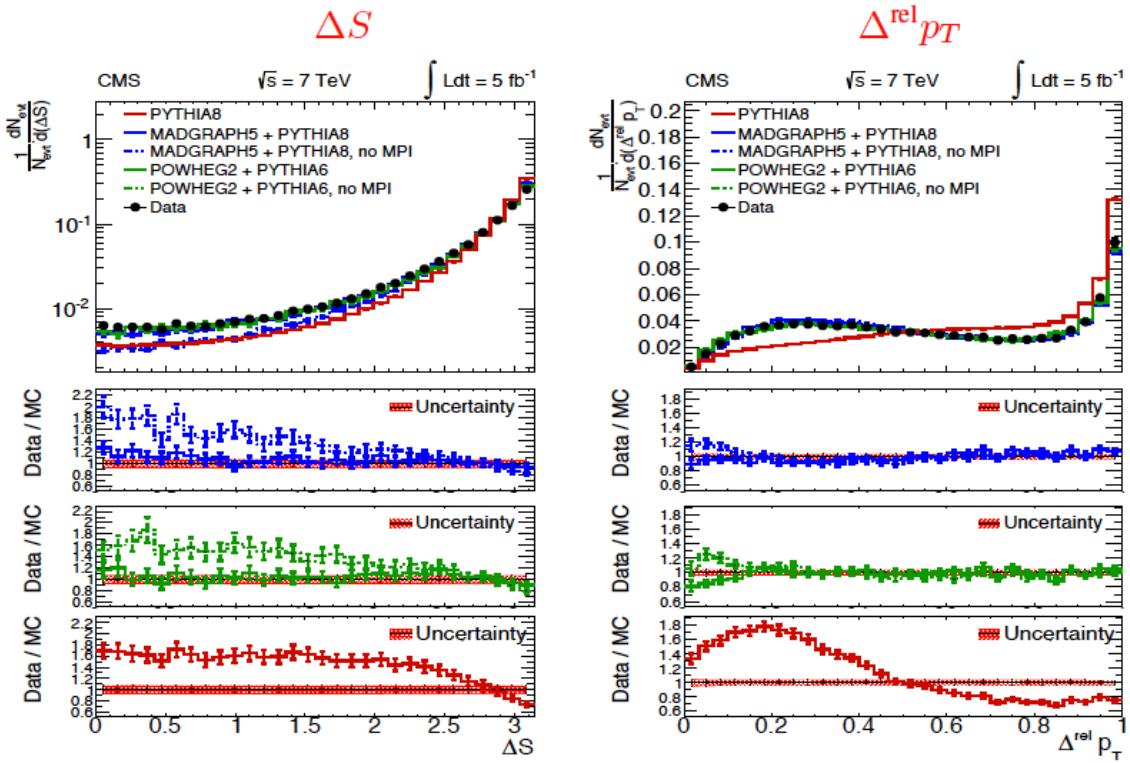
- μ: p_T > 35 GeV/c and $|\eta|$ < 2.1
- Missing transverse energy > 30 GeV/c and M_T > 50 GeVc^2
- Exactly 2 jets: p_T > 20 GeV/c and $|\eta|$ < 2.0

Systematic uncertainities

Source	$\Delta^{\text{rel}} p_{\text{T}}$	ΔS	Cross section
Model dependence	≤ 3.2	≤ 3.9	11
Background normalization	≤ 0.2	≤ 0.3	1.0
JES	≤ 1.4	≤ 2.9	7.4
JER	≤ 0.5	≤ 0.7	1.3
$\not{E}_{\text{T}}$ scale	≤ 0.5	≤ 3.7	3.3
Pileup	≤ 0.8	≤ 3.7	2.3
Muon ID and trigger	—	—	2.2
Luminosity	—	—	2.2
Total	≤ 3.7	≤ 7.2	14

Particle level distributions

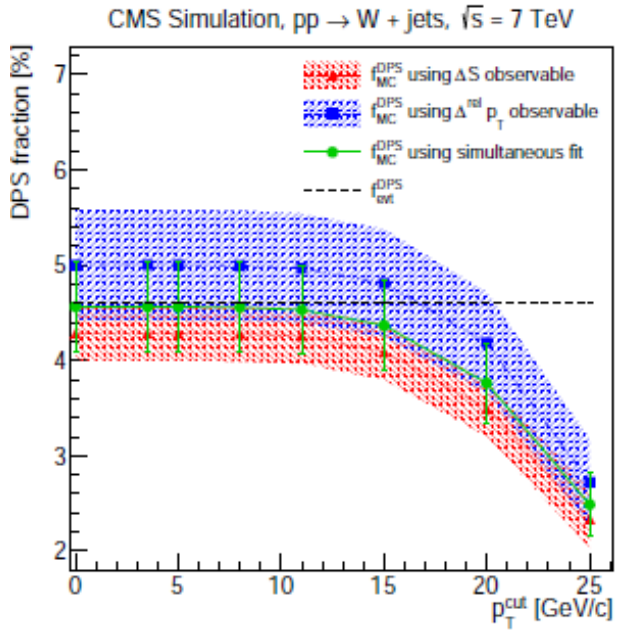
- W + 2jets cross section; 53.4 ± 0.11 (stat.) ± 7.6 (syst.)pb, consistent with MC

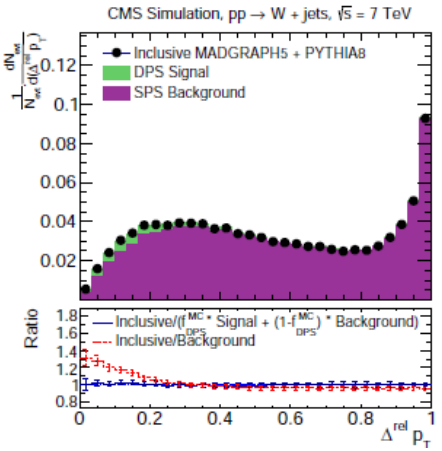


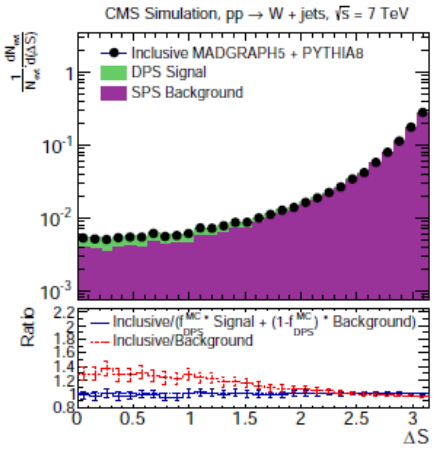
- PYTHIA8 fails; due to missing contribution of higher order processes
- LO (MADGRAPH + PYTHIA) and NLO (POWHEG + PYTHIA/HERWIG6) provide same level of agreement with measurement
- POWHEG + PYTHIA and MADGRAPH + PYTHIA fail in absence of MPI

DPS fraction extraction

- **Signal templates:** Random of W+0-jet and dijet events from MCs, templates are validated with data
- **Background templates:**
  - MADGRAPH + PYTHIA; MPI parton tagged with status code
  - Remove events which can be identified as signal at particle level i.e. two MPI partons should not be in η acceptance ($|\eta| < 2$)
  - NO jet-parton matching
  - NO overlap and/or missing phase space
  - NO p_T dependence for < 12-15 GeV
- Fractions with two observables are consistent within uncertainties
- Simultaneous fit of observables; close with f_{evt}^{DPS} (DPS fraction by default MPI model)



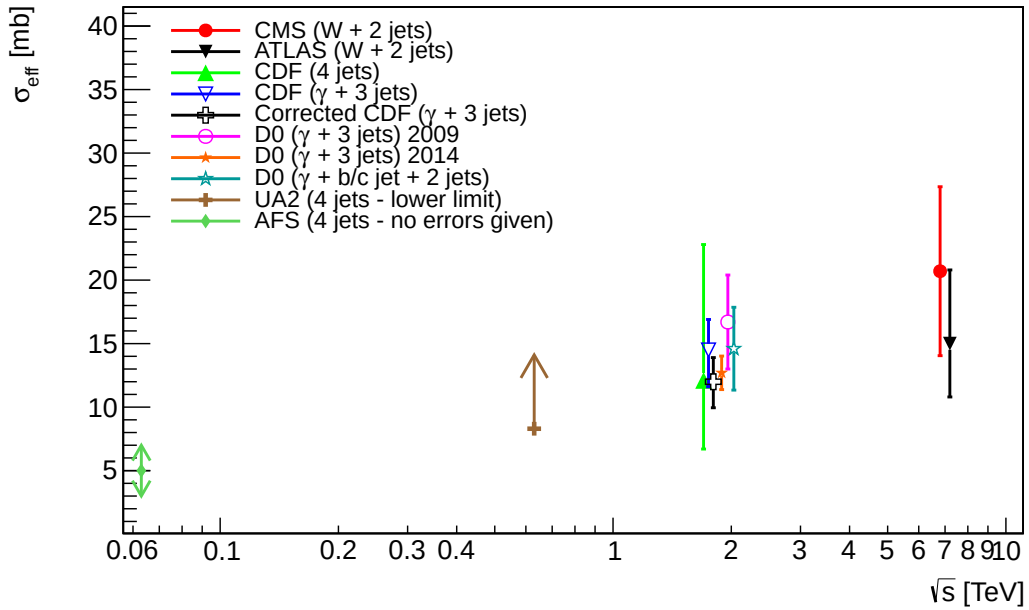




Results: DPS via W + 2jets - II

$$\sigma_{\text{eff}} = \frac{\text{R}}{f_{\text{DPS}}} \cdot \sigma'_{\text{2j}}$$

- Measured R, ratio between W + 2jets and W + 0jet events, corrected to particle level using MADGRAPH + PYTHIA6
- Measured dijet production cross section
- Combining all inputs, $\sigma_{eff} = \mathbf{20.7 \pm 0.8\ (stat.) \pm 6.65\ (syst.)\ mb}$
- **Consistent within uncertainties with ATLAS, CDF and D0 measurements**
- **No conclusion can be made about the independence on the process and collision energy due to large uncertainities**

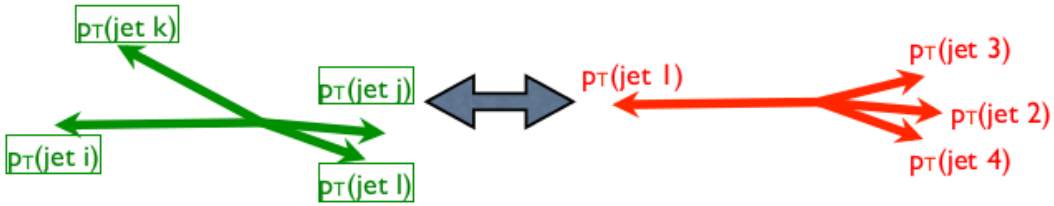


DPS via 4jets - I

4-jet final state may arise from:

- **Parton Shower (PS)**
- **Second hard scattering**

Disentangle double parton scattering from single parton scatering



- **4jets measurements are sensitive to hard matrix element and underlying events: A proper admixture of ME and UE contributions is needed**

Event selection

- pp collisions at 7 TeV with itegrated luminosity: 36 pb^{-1}
- Low PileUp and single jet triggers
- Two jets with p_T > 50 GeV (20 for others) respectively hard pair (soft pair)

Observables

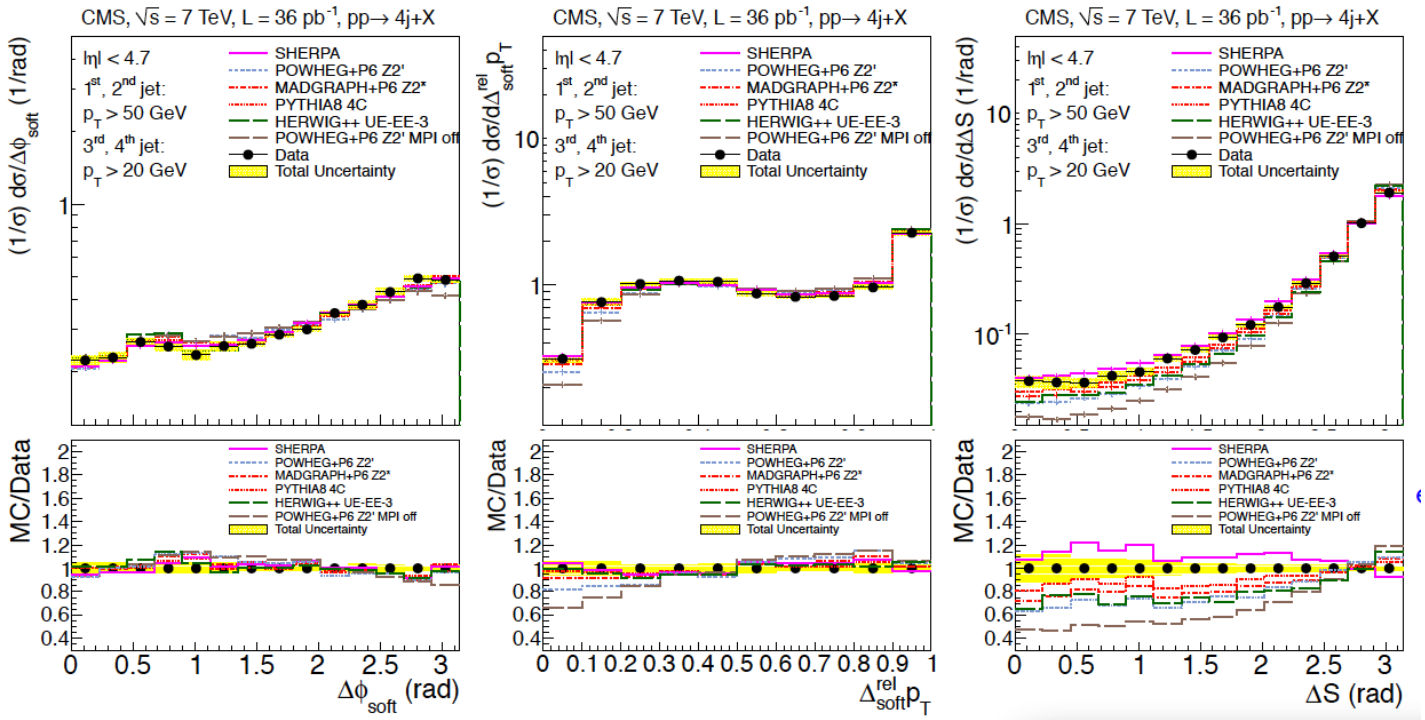
The different kinematical configuration can be used to discriminate the two processes through some observables:

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

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

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

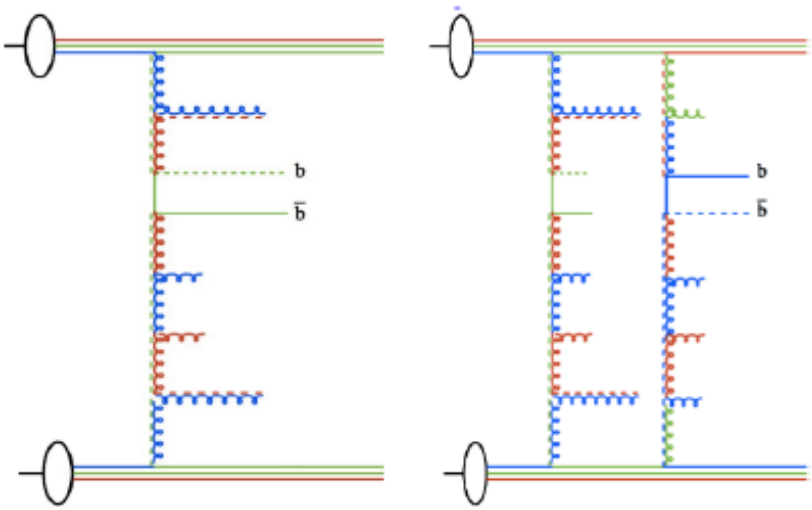
DPS via 4jets: Kinematical topology of jets of the final state in the transverse plane



- No significant difference in $\Delta\phi$ and $\Delta^{rel}_{soft}p_T$ for different generators
- SHERPA and PYTHIA8 perform best for ΔS
- POWHEG + PYTHIA with MPI off underestimates the data for ΔS and $\Delta^{rel}_{soft}p_T$
- $\Delta^{rel}_{soft}p_T$ and ΔS are sensitive to MPI

DPS via 2b-jets + 2jets - I

- Study of QCD evolution in a heavy flavour scenario
- Comparison with different MC models and test of their performance
- Study and separate the different topologies for events coming from single chain and double chain processes



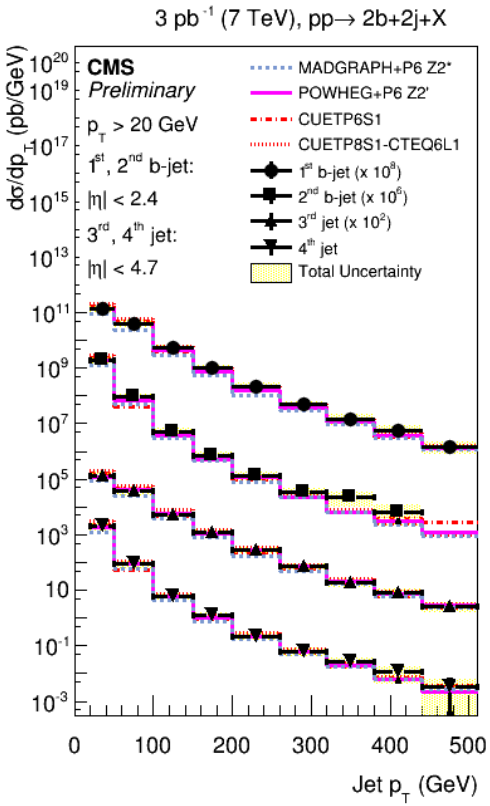
$$\Delta\phi(j_i, j_k) = |\phi_i - \phi_k|$$

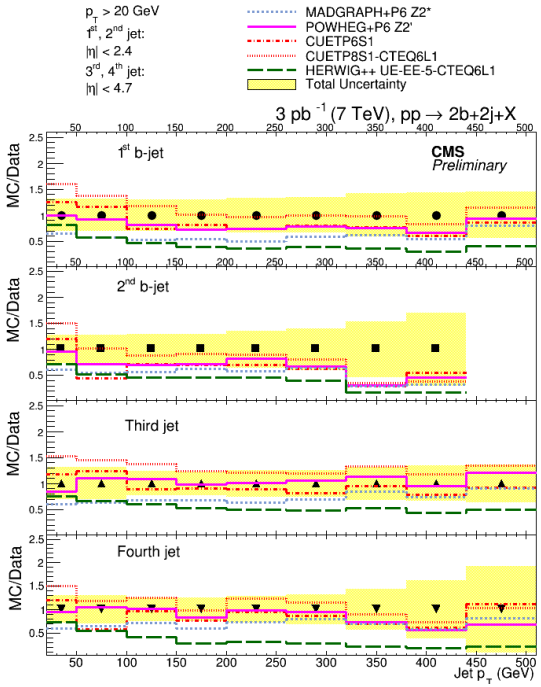
$$\Delta S = arccos\left(\frac{\vec{p}_T^{\,b} \cdot \vec{p}_T^{\,l}}{|p_T^b| \cdot |p_T^l|}\right)$$

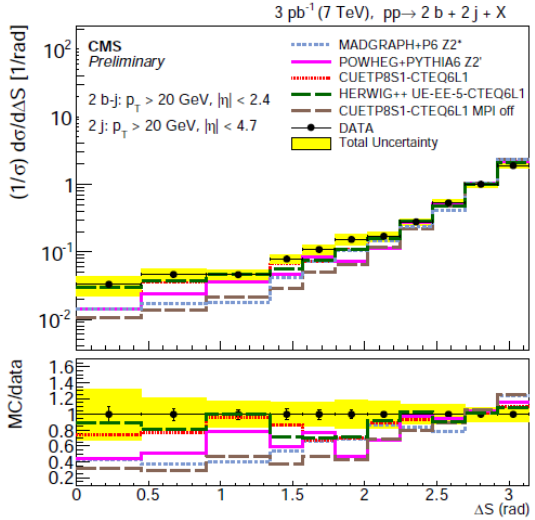
$$\Delta^{rel}_{pair} p_T = \frac{|p_T(j_i, j_k)|}{|p_T(j_i)| + |p_T(j_k)|}$$

- The jets need to be associated in pairs: ($\rightarrow$ natural way thanks to the different flavour)
- The equal scale of the two jet pairs should suppress the SPS contribution (at least 4 jets with $p_T > 20$ GeV)

DPS via 2b-jets + 2jets - II

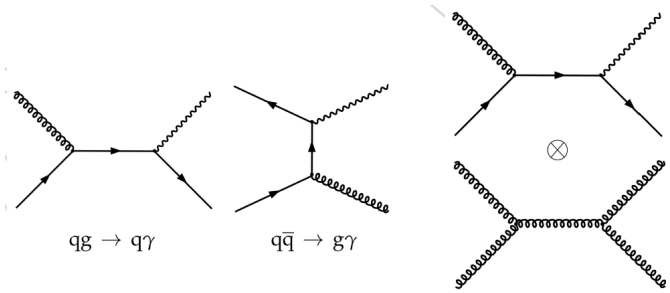






- MADGRAPH, PYTHIA6 and POWHEG are able to reproduce quite well jet p_T spectra
- HERWIG++ tends to underestimate data at low p_T region
- ΔS distributions best described by PYTHIA8 and HERWIG++
- Description of correlation observables depends on DPS contribution

DPS via photon + 3jets



- Photon-jet from first hard interaction
- Dijet from second hard interaction

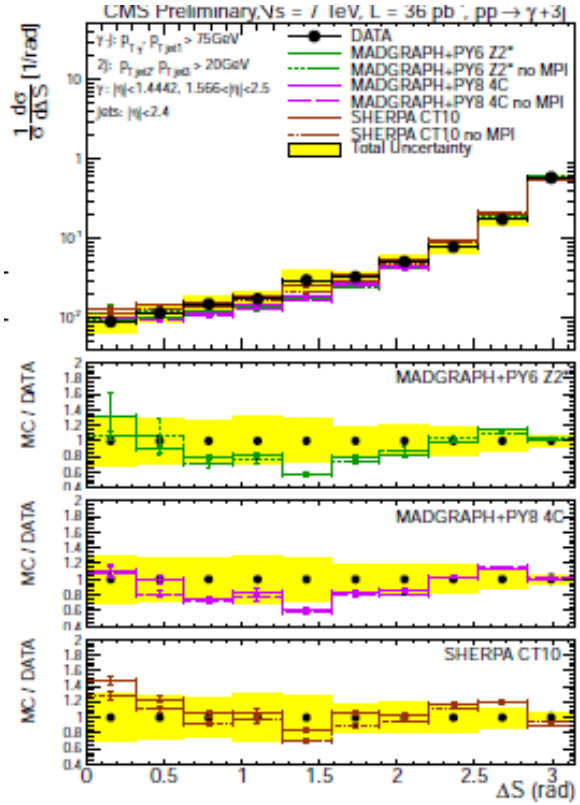
Selections:

γ and one jet in the central region with $p_T > 75$ GeV
pair of "soft" jets with $p_T > 20$ GeV in $\lvert\eta\rvert < 2.4$

- Data is reasonably well described by all MCs
- Measurement is not yet sensitive to MPI

Three kind of contributions are considered:

- direct photon + 3 jets events
- fragmentation photon + 3 jets events
- misidentified (fake) photon + 3 jets events



Summary

- DPS measurements are quite important for understanding partonic structure of hadrons as well as for New Physics searches at LHC
- Various channels are being probed to perform DPS measurement at LHC
- Presented results for: W + 2jets, 4jets, 2b + 2jets, γ + 3jets
- Measurements are reasonably well described by different generator tunes
- Large systematics on σ_{eff} measurements due to model dependence
- To conclude on process, scale, and energy dependence, important to reduce systematic uncertainties
- More integrated luminosity is needed for new channels
- Higher center of mass energy would increase DPS contribution