Study of double parton scattering using W + 2-jet events

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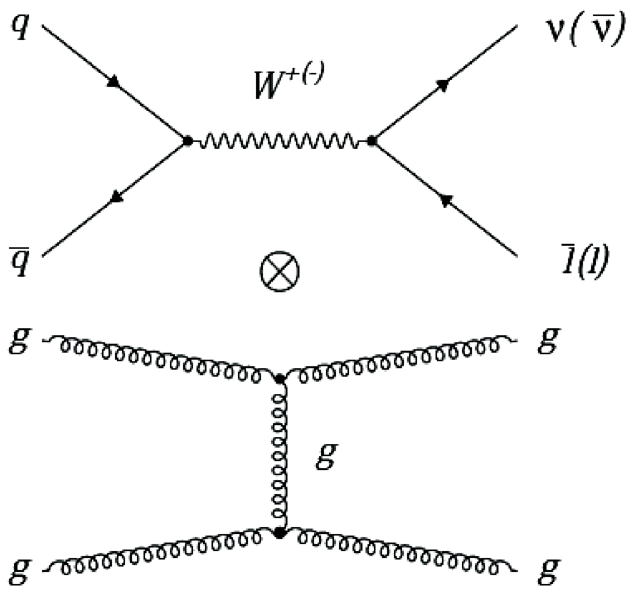
on behalf of
CMS collaboration



MPI @ LHC 2013, Workshop on Multi-Parton Interactions at the LHC

2-6 December 2013, Antwerp, Belgium

Outline

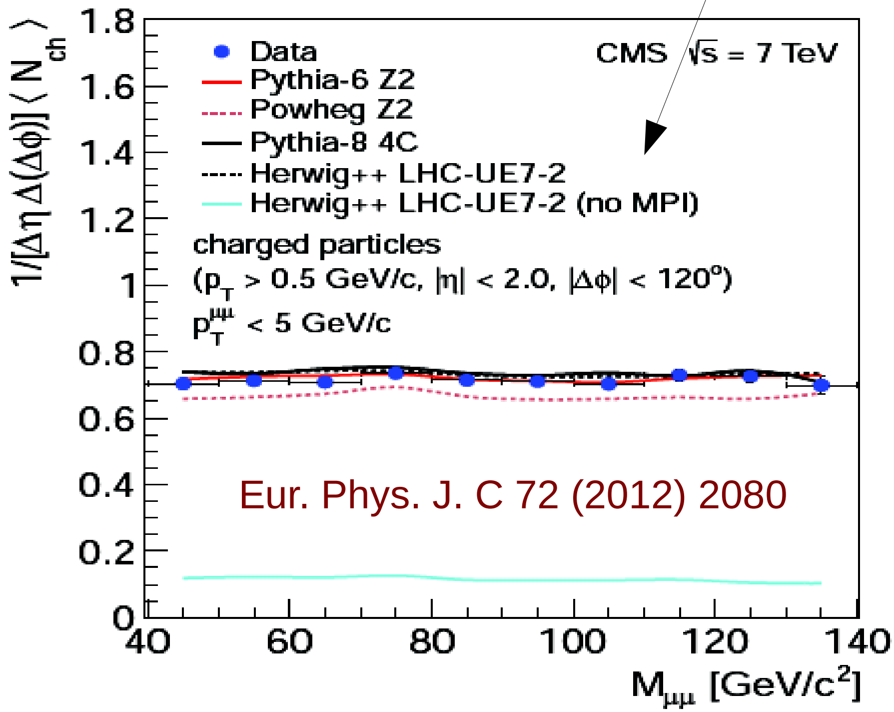
- DPS, effective cross section, and observables
- W + jets selection and validation
- Unfolding and systematic
- Results on DPS fraction and effective cross section
- Summary

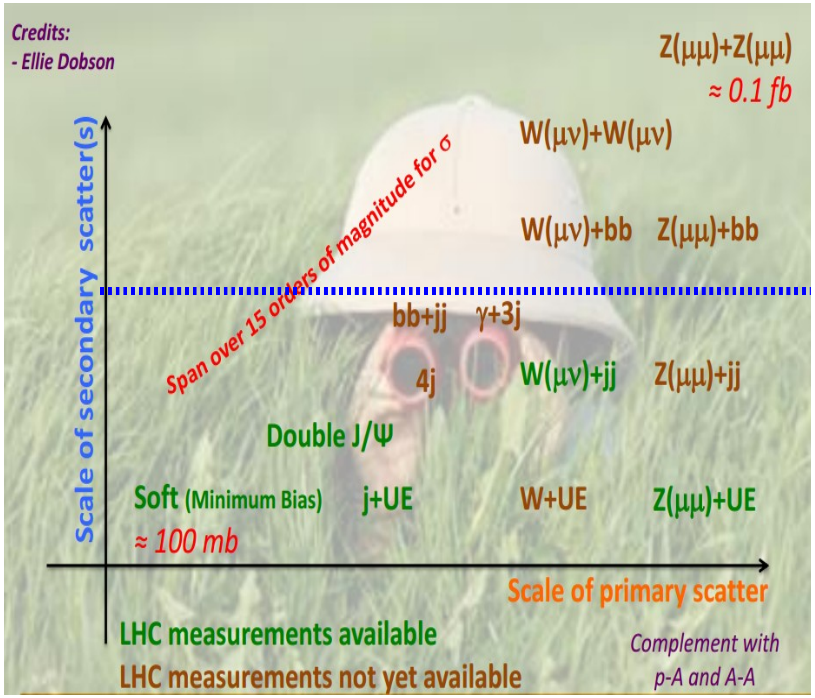
Double parton scattering

- Large parton densities and small x → large probability to have more than one parton-parton interaction in single pp collision.

- Presence of soft MPI is evident from UE measurements.

particle density





- What about large p_T/ mass particle from second interaction?
- Model tuned with UE data is OK with describing hard MPI?

Effective cross section (I/II)

→ Measure of the matter overlap in hadron-hadron interactions, input for theoretical models.

$$\sigma_{eff} = \frac{1}{m} \frac{\sigma_A \cdot \sigma_B}{\sigma_{A+B}^{DPS}}$$

m = 1 when A ≠ B
m = 2 when A = B

→ Cross section should be inclusive to have process independent measurements.

→ Exclusive selection: important to identify DPS jets and define DPS discriminating observables.

$$\sigma_{\mathrm{eff}} = \frac{\sigma'_{\mathrm{W+0j}}}{\sigma'^{\mathrm{DPS}}_{\mathrm{W+2j}}} \cdot \sigma'_{\mathrm{2j}}$$

→ No bias due to exclusive event selection (For kinematic selection in present analysis).

Effective cross section (II/II)

$$\sigma_{\rm eff} = \frac{\sigma'_{\rm W+0j}}{\sigma'^{\rm DPS}_{\rm W+2j}} \cdot \sigma'_{\rm 2j} \xrightarrow{\text{With simple assumptions}} \sigma_{\rm eff} = \frac{\rm R}{f_{\rm DPS}} \cdot \sigma'_{\rm 2j}$$

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

f^{DPS} = fraction of (W+2-jet)^{DPS} events with respect to total W + 2-jet events (from data and MCs)

σ_{2j}' = dijet cross section at particle level (from data)

- DPS sensitive observables:
  - p_T-balance between two jets $\Delta^{rel} p_T$
  - azimuthal angle between W and dijet system ΔS

} Uncorrelated for DPS events

W + jet selection

- pp @ 7 TeV, integrated luminosity 5 fb^{-1}
- Simulated samples:
  - MadGraph + Pythia8 4C, Pythia6 Z2*
  - Powheg (MiNLO) + Pythia6 Z2*, Herwig6
  - various simulations for backgrounds i.e. top, DY, VV

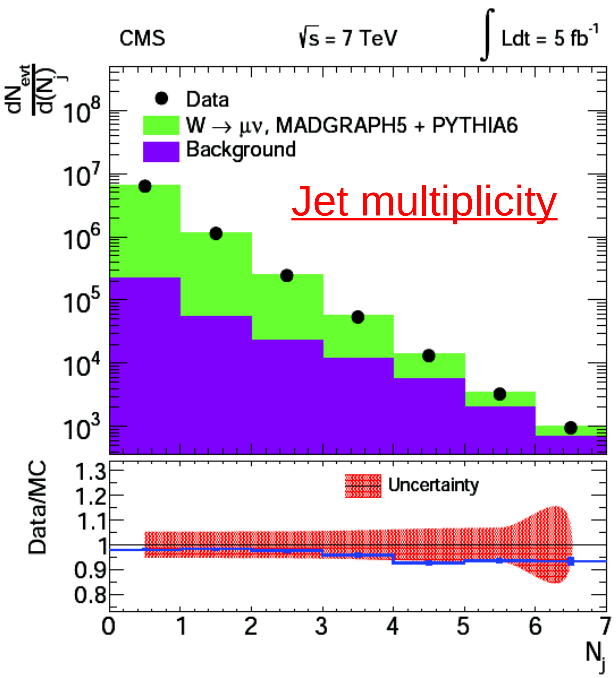
- W selection:
  - single muon trigger
  - well reconstructed and isolated muon (combined isolation, corrected for pileup)
  - $p_T > 35$ GeV, $|\eta| < 2.1$
  - missing transverse energy > 35 GeV
  - transverse mass > 50 GeV
- Jet selection:
  - anti-k_T, R = 0.5
  - $p_T > 20$ GeV, $|\eta| < 2$
  - no muon overlap
  - PU rejection

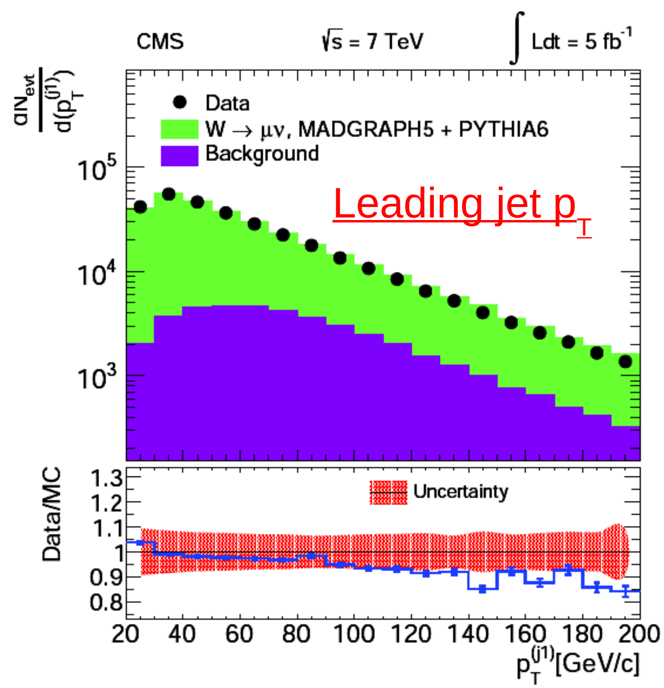
$$\beta = \frac{\Sigma(p_T^{\text{signal vertex}})}{\Sigma(p_T^{\text{all}})}$$

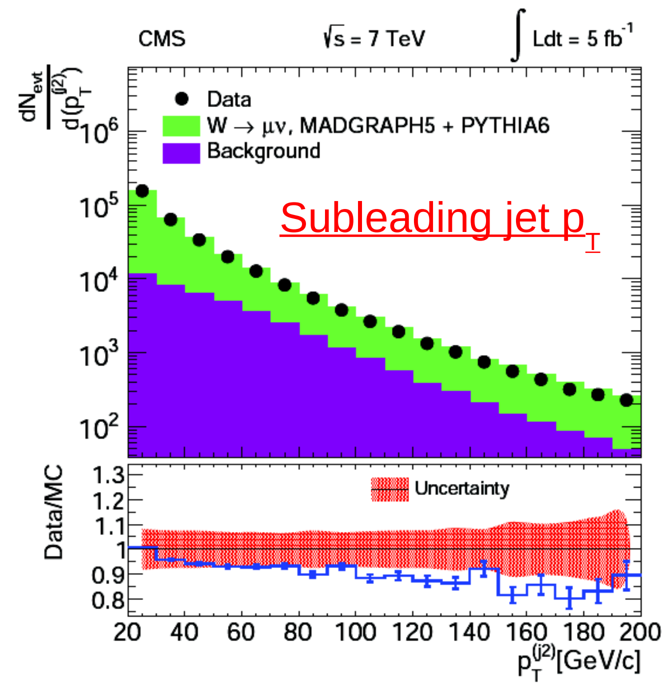
- Vertex selection:
  - $|z| < 24$ cm, $\rho < 2$ cm
  - muon should be associated to selected vertex

Validation at detector level

→ Nice agreement between data and MCs; trend in jet pT but not a concern as measurement is inclusive in p_T.





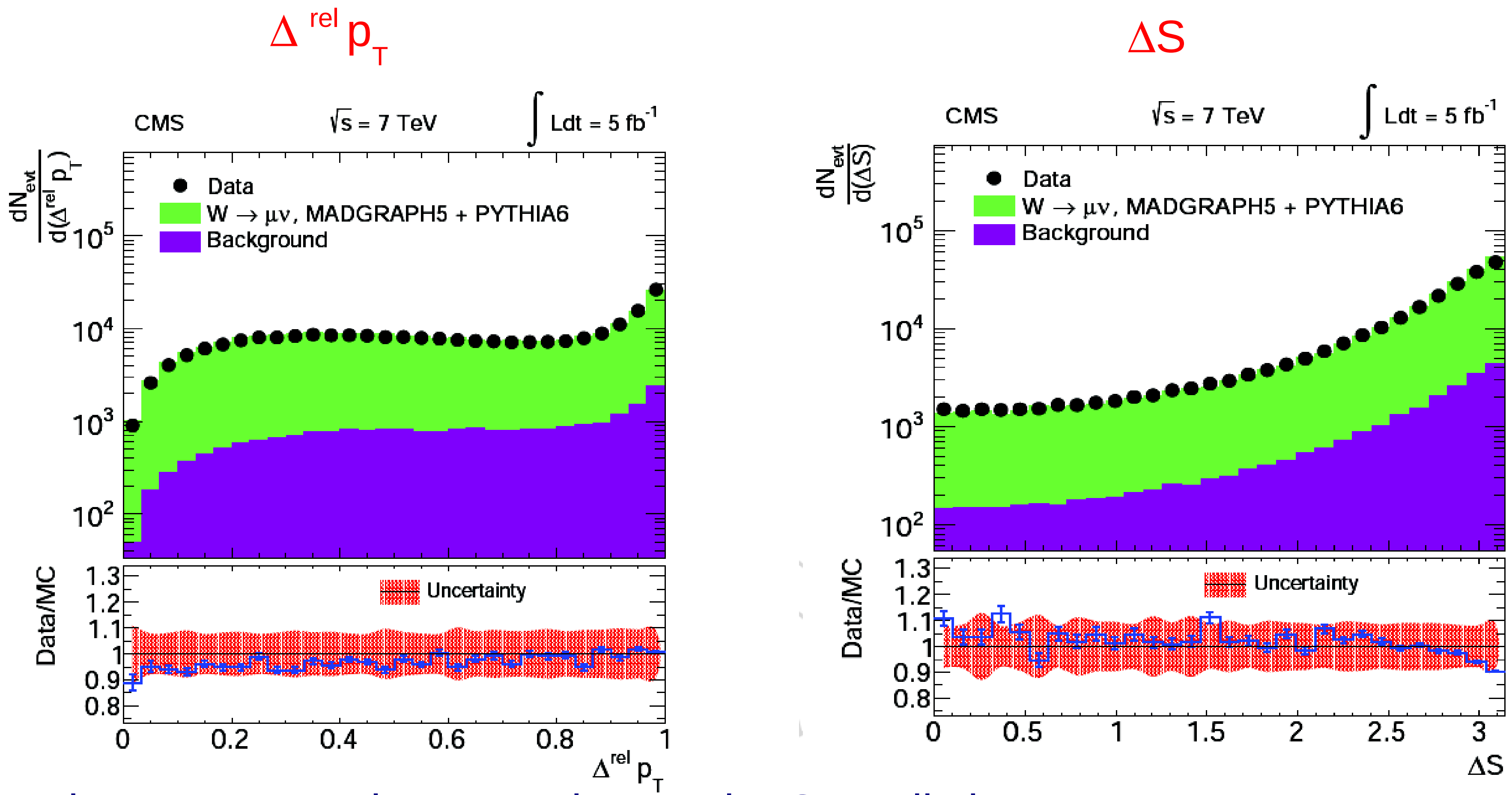


→ Select events with exactly two jets

→ Nice agreement between expected and observed number of W + 2-jet events

Process	Number of events
$W\rightarrow \mu\nu$	$2.3\times10^5 \pm 1.2\times10^4$
$W\rightarrow \tau\nu$	$3.7\times10^3 \pm 2.0\times10^2$
Top quark	$9.4\times10^3 \pm 6.9\times10^2$
Drell-Yan	$5.3\times10^3 \pm 2.6\times10^2$
Diboson	$2.6\times10^3 \pm 2.6\times10^2$
Multijet	$1.1\times10^3 \pm 3.4\times10^2$
Total expected events	$2.5\times10^5 \pm 1.4\times10^4$
Data	$2.4\times10^5 \pm 4.9\times10^2$

DPS sensitive observables (detector level)



→ Nice agreement between data and MC predictions.

→ No DPS extraction at detector level, unfold distributions to stable particle level

Unfolding and systematic uncertainties

- Background contribution is subtracted before unfolding
- Method: Bayesian approach (cross checked with SVD method), consistent with 1-2%

particle level selection

$$1\ \mu : p_T > 35\,\mathrm{GeV}/c \text{ and } |\eta| < 2.1$$
$$\not{E}_T > 30\,\mathrm{GeV} \text{ and } M_T > 50\,\mathrm{GeV}/c^2$$
$$2 \text{ jets} : p_T > 20\,\mathrm{GeV}/c \text{ and } |\eta| < 2.0$$

- Systematic:
  - – background; < 0.5%
  - – jet energy scale; 1-3%
  - – jet energy resolution; < 1%
  - – missing energy resolution;1-4%
  - – pile; 1-4%

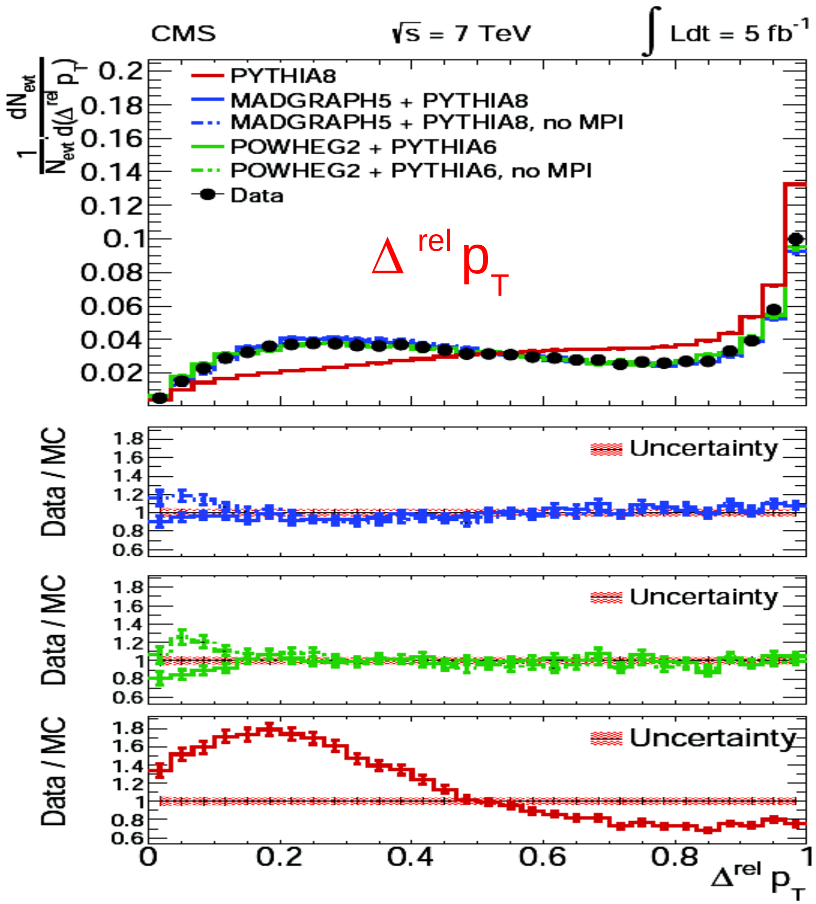
Systematic uncertainties (%)

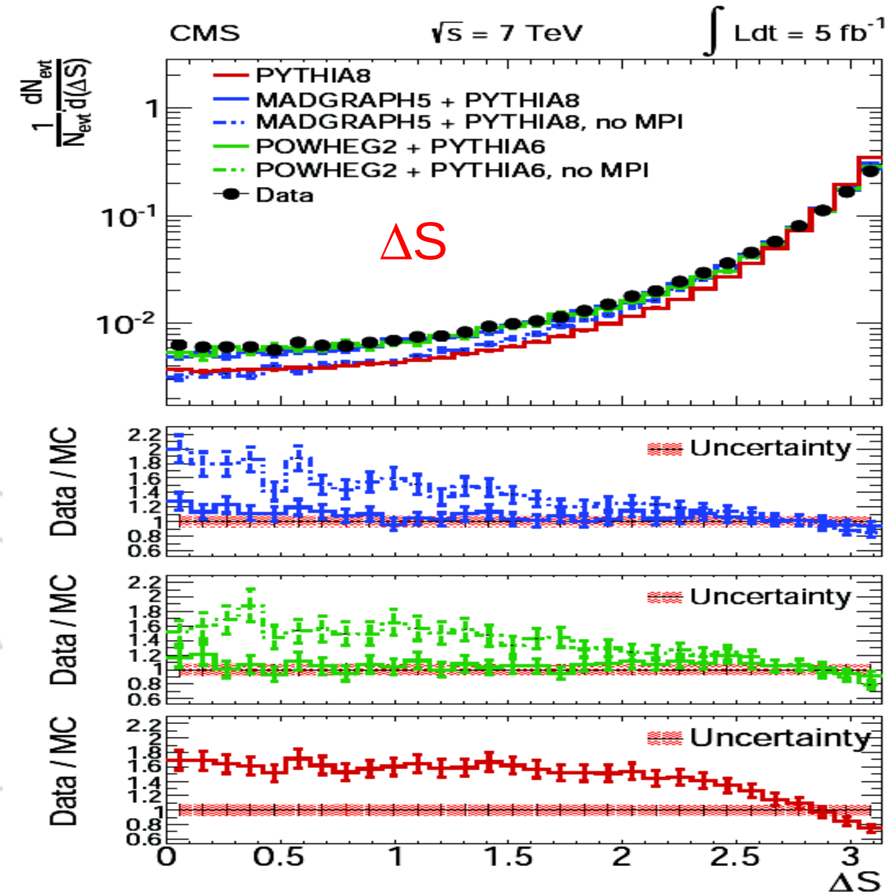
Source	$\Delta^{rel} p_T$	ΔS	Cross section
Model dependence	≤ 3.2	≤ 3.9	11
Background normalization	≤ 0.2	≤ 0.3	1.0
JES	≤ 1.4	≤ 2.9	7.4
JER	≤ 0.5	≤ 0.7	1.3
$\not{E}_T$ scale	≤ 0.5	≤ 3.7	3.3
Pileup	≤ 0.8	≤ 3.7	2.3
Muon ID and trigger	–	–	2.2
Luminosity	–	–	2.2
Total	≤ 3.7	≤ 7.2	14.3

- W + 2-jet cross section also unfolded to particle level
  - – above sources +
  - – luminosity; 2.2%
  - – muon ID and trigger; 2.2%

Results at particle level

- W + 2-jet cross section; 53.4 ± 0.1 (stat.) ± 7.6 (syst.), consistent with MC





- Pythia8 fails; due to missing contribution of higher order processes.
- LO (MG + Pythia) and NLO (Powheg + Pythia/Herwig6) MCs provide same level of agreement with the measurement.
- Both LO and NLO calculations fails in absence of MPI. *Next step is to extract contribution of hard MPI*

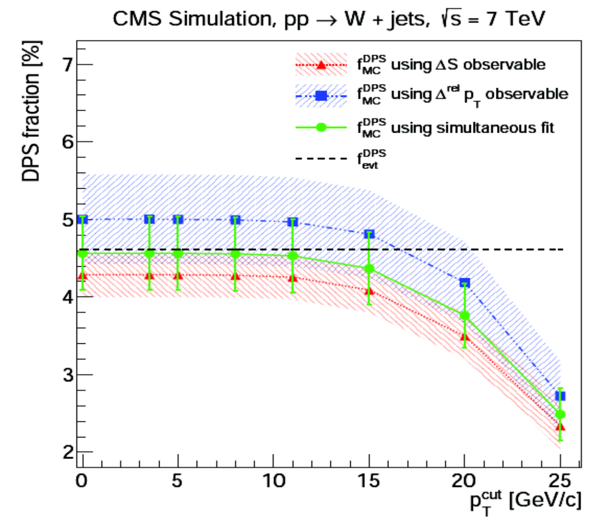
Strategy to extract DPS fraction

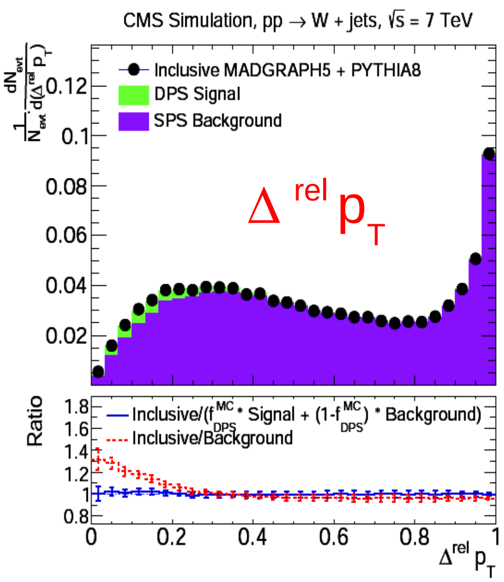
- Binned likelihood fit

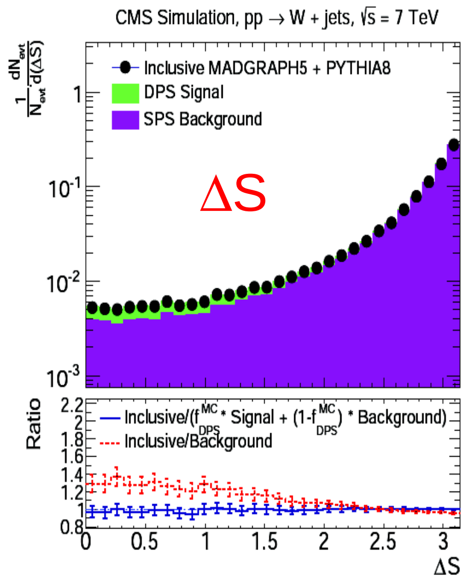
- Signal templates: Random of W + 0-jet and dijet events from MCs, ***templates are validated with data.***
-
- Background templates:
  – MadGraph + Pythia8; MPI parton tagged with status code
  – NO jet-parton matching,

  – NO overlap and/or missing phase space.
  – Remove events which can be identified as signal events at particle level i.e. two MPI partons should not be in η acceptance ($|\eta| < 2$)

  – NO p_T dependence for < 12-15 GeV







- Fractions with two observables are consistent within uncertainties.
- Simultaneous fit of observables; close with f^{DPS}_{evt} (DPS fraction by default MPI model)

DPS fraction in data

→ Background templates; remove events which have leading MPI partons $|\eta| < 2$.

→ Simultaneous fit of $\Delta^{rel} p_T$ and ΔS, effect of correlation is small (less than 5%).

→ DPS fraction in data is measured to be:

$$f_{DPS} = 0.055 \pm 0.002\ \text{(stat.)} \pm 0.014\ \text{(syst.)}$$

→ Dominated by systematic uncertainties (next slide).

Uncertainties on DPS fraction

- Signal templates:
  - different MCs for dijet events.
  - template with Pythia8, to see effect of momentum conservation and color reconnection.

- Background templates:
  - different MCs i.e. MadGraph + Pythia6 Z2*, Powheg + Pythia6 Z2*, and Powheg + Herwig6
  - renormalization and factorization scale (by a factor 2)
  - matching scale (15-25 GeV)

- Limited MC stat.

- Systematic on the corrected distributions

- PDFs

Systematic uncertainties

Source	Uncertainty (%)
Signal template	9
Background template	20
PDFs	5
Limited MC statistics	5
Uncertainty in corrected data	10
Total	25

Measurement of dijet cross section

- pp @ 7 TeV, 2010 run, integrated luminosity ~35 pb-1

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

- Minimum bias + single jet triggers
- Exactly two jets; $p_T > 20$ and $|\eta| < 2$
- Pythia6 and Herwig++ for efficiency corrections and model dependency
- Uncertainties due to JES and JER
- Dijet production cross section measured to be:

0.0409 ± 0.0004 (stat.) ± 0.0061 (syst.) mb

Systematic uncertainties (%)

Source	Uncertainty (%)
Model dependence	8
JES	13
JER	2
Total	15

Measurement of R

- pp @ 7 TeV, integrated luminosity 5 fb^{-1}
- R, ratio of W + 0-jet and W + 2-jet events
- Corrected to particle level using MadGraph + Pythia6
- Measured value of R (at particle level) is:

  27.8 ± 0.2 (stat.) ± 3.3 (syst.)

- Consistent with MC predictions.

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

Systematic uncertainties (%)

Source	Uncertainty (%)
Model dependence	9
JES	7
JER	2
Background	2
Pileup	1
Total	12

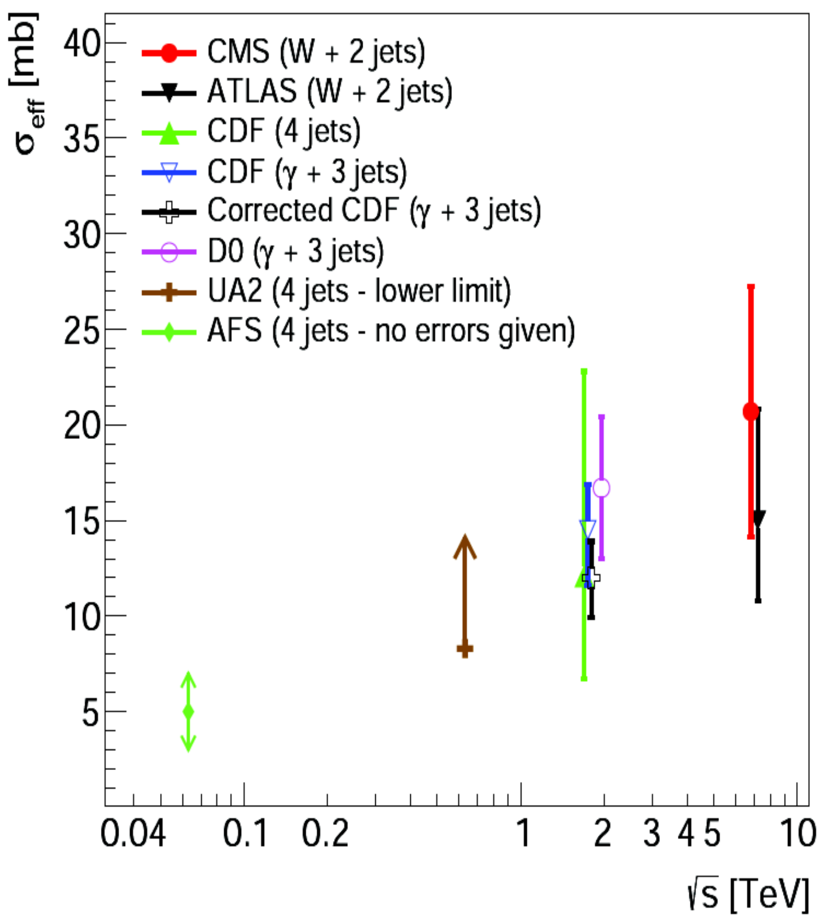
Determination of σ_{eff}

- Combining all inputs, σ_{eff} calculated to be:

  20.7 ± 0.8 (stat.) ± 6.5 (syst.) mb

- Measured value is consistent (within uncertainties) with the previous results by ATLAS, CDF, and D0.
- Large uncertainties: can not conclude dependence on collision energy.
- Consistent with value obtained for Herwig++ by fitting UE data from LHC and Tevatron.
- Pythia ~ 20-30 mb (tune dependent).

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



Summary

- Study of double parton scattering using W + 2-jet events at sqrt(s) = 7 TeV
  - CMS-PAS-FSQ-12-028 (preliminary results with corrected distributions)
  - Soon to be submitted in JHEP
- Two uncorrelated DPS-sensitive observables are fully corrected for detector effect.
- LO and NLO calculation give same level of agreement with measurement but fail without MPI.
- Effective cross section is measured to be;

20.7 ± 0.8 (stat.) ± 6.5 (syst.) mb

- Consistent with previous measurements and model predictions.
- To conclude on process, scale, and energy dependence, it is important to reduce systematic uncertainties.