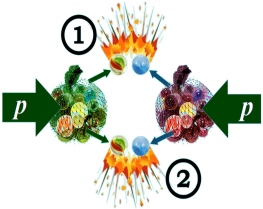
Deutsches Elektronen-Synchrotron
(DESY), Hamburg

Study of high p_T particle production from Double Parton Scatterings

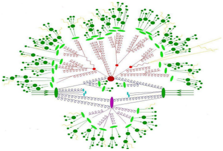
Paolo Gunnellini on behalf of the CMS collaboration

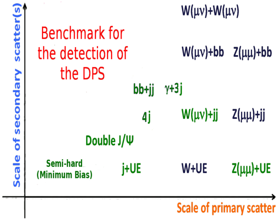


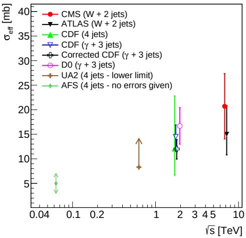
MPI@LHC 2015
Trieste (Italy)
November 2015

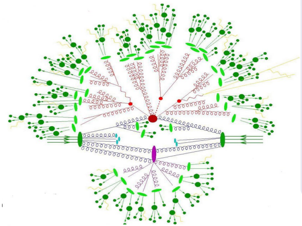
Outline

1. Introduction
2. Choice of sensitive observables
3. Choice of physics channels
4. Summary of recent DPS measurements
5. Extraction of the DPS contribution
6. Other DPS-sensitive measurements
7. Summary and conclusion









Hard scattering

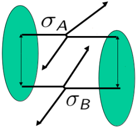
Initial and Final State Radiation

Multiple Parton Interaction (MPI)

Beam-beam remnants

In general, the UE is a softer contribution but.. some MPI can be hard!

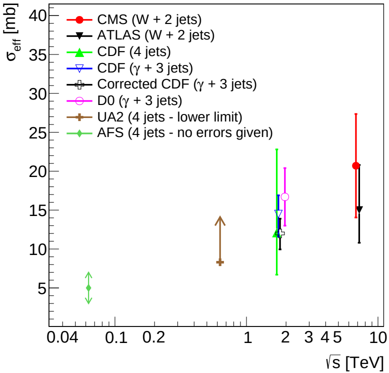
Double Parton Scattering



$$P_A = \frac{\sigma_A}{\sigma^{pp}_{tot}}$$

$$P_B = \frac{\sigma_B}{\sigma^{pp}_{tot}}$$

$$\sigma^{DPS}_{AB} \propto \frac{m}{2} P_A P_B \sigma^{pp}_{tot}$$



$$\sigma^{DPS}_{AB} = \frac{m}{2}\frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

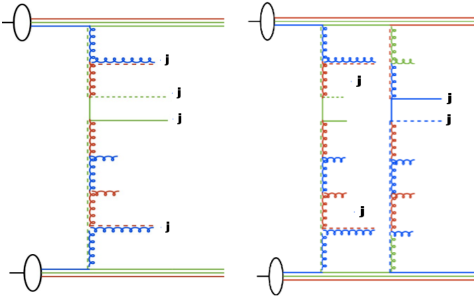
$$\sigma_{eff} \ll \sigma^{pp}_{tot}$$

Need for correlations!

Choice of sensitive observables (I): a four-jet scenario

A four-jet final state may arise from one or two chains:

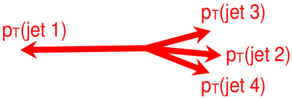
- the two additional jets may be produced via PS or a 2nd hard scattering

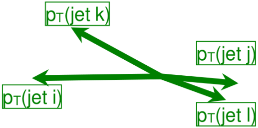


Various kinematical observables can discriminate the two processes:

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

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





! Selection of jet pairs at different scales helps the jet association !

Choice of sensitive observables (II): a four-jet scenario

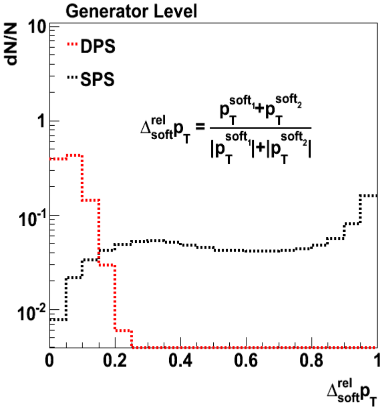
Which regions of the phase space are interesting for DPS detection?

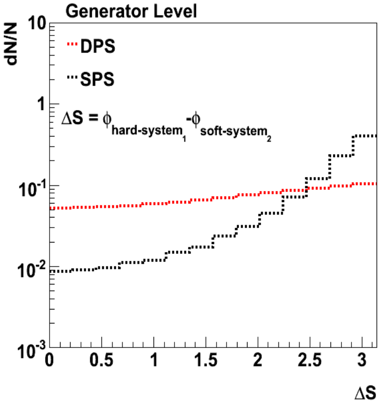
Studies of SPS and DPS contributions performed with PYTHIA8:

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





Different regions of the phase space are filled by the two processes

Discriminating power

Choice of physics channels

See Diego's talk

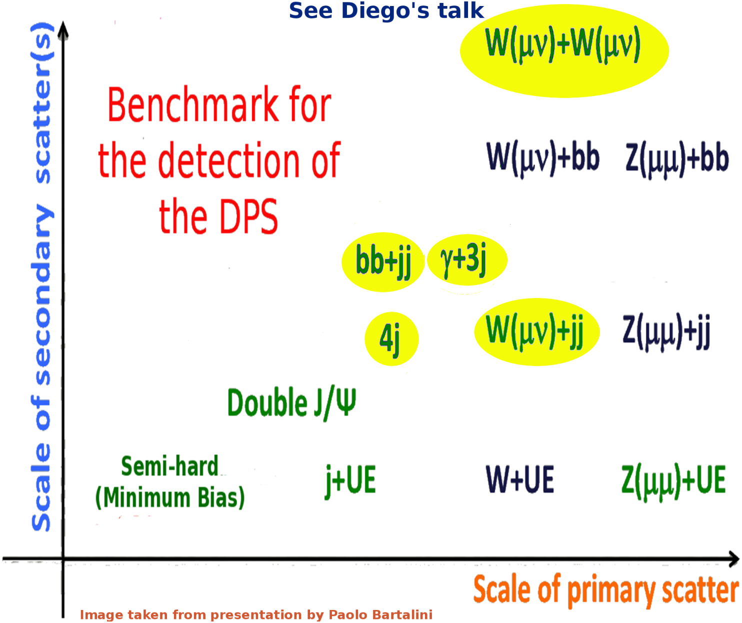
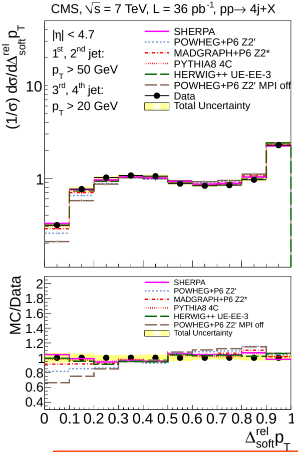


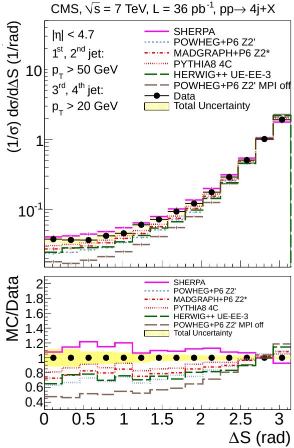
Image taken from presentation by Paolo Bartalini

Measurement of a four-jet final state

Event selection

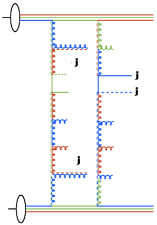
Exactly four jets in the final state in $|\eta| < 4.7$:
2 jets: $p_T > 50$ GeV (hard), 2 jets: $p_T > 20$ GeV (soft)





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

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



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

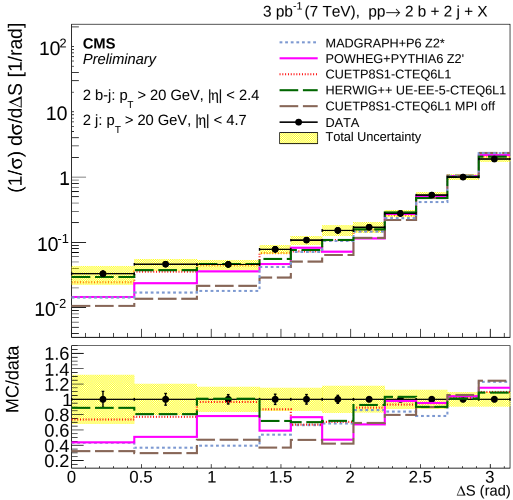
PRD 89 (2014) 092010

ΔS and $\Delta^{rel}_{soft} p_T$ sensitive to MPI contribution: → ROOM for DPS!

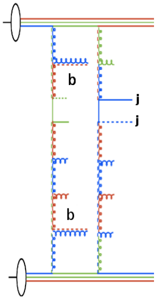
Measurement of a four-jet final state with b-jets

Event selection

Selection of at least four jets with $p_T > 20$ GeV:
2 b-jets: $|\eta| < 2.4$, 2 other jets: $|\eta| < 4.7$



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



Additional jets may be produced also by DPS

CMS-FSQ-13-010

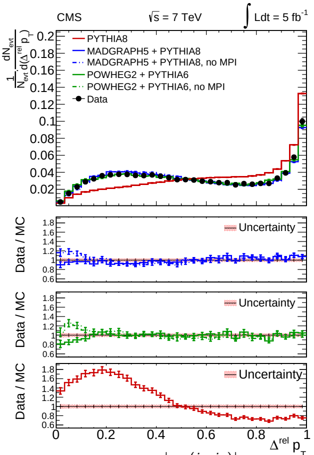
Sensitivity to higher orders..

..but also to MPI!

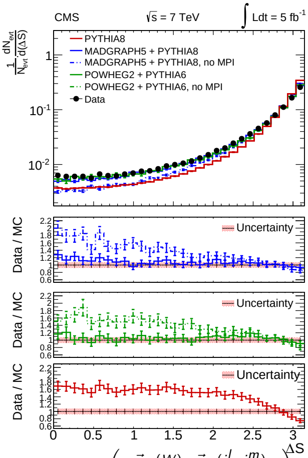
Measurement of a W+dijet final state

Event selection

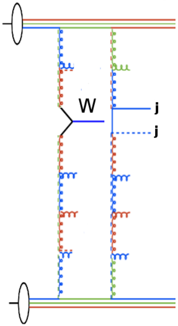
Presence of a muon with $p_T > 35$ GeV in $|\eta| < 2.1$ and $E_T^{miss} > 50$ GeV
+ at least 2 jets: $p_T > 20$ GeV in $|\eta| < 2.0$



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



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



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

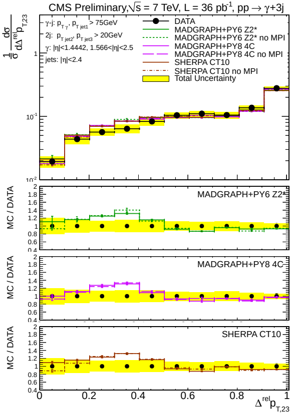
JHEP 03 (2014) 032

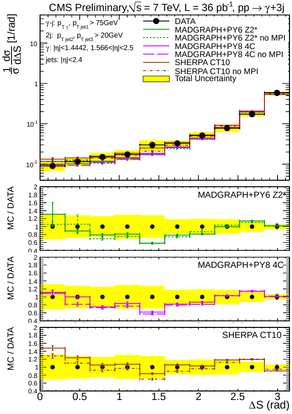
Sensitivity to DPS!

Measurement of a final state with γ+ 3 jets

Event selection

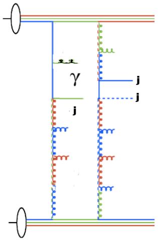
Selection of a photon and at least three jets in $|\eta| < 2.5$:
γ+1 jet: $p_T > 75$ GeV, 2 jets: $p_T > 20$ GeV





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

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

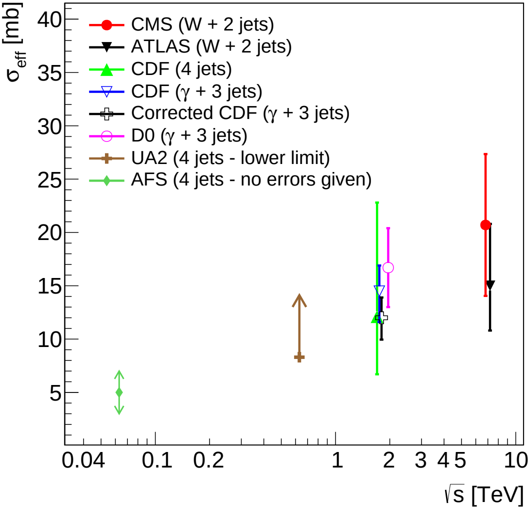


Soft jets are expected to be produced also by a 2^{nd} scattering

No difference between predictions with and w/o MPI

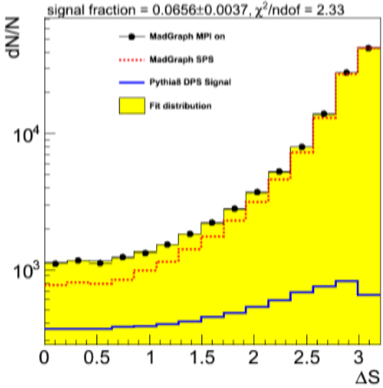
Need for improving sensitivity!

How can one extract the DPS contribution from the measured observables?



How to extract σ_{eff}: the template method

- Measurement of DPS-sensitive observables
- Definition of signal and background
- Fit the relative fraction of signal and background
- The signal fraction translates into a value for σ_{eff}



Plot from Ramandeep Kumar

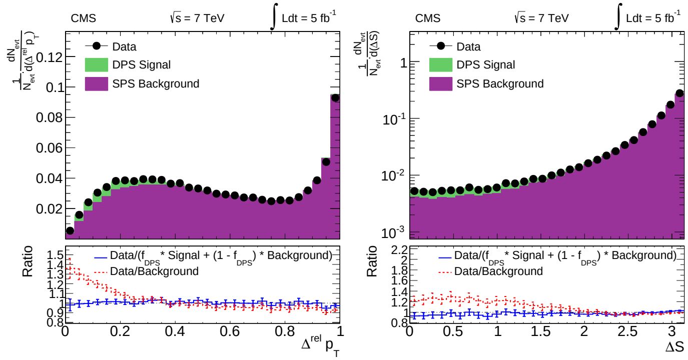
W + jets channel

$$\sigma_{eff} = \frac{\sigma_A \cdot \sigma_B}{\sigma_{DPS}}$$

$$\sigma_{eff} = \frac{N_A^{ev}}{N_{A+B(DPS)}^{ev}} \cdot \sigma_B$$

$$\sigma_{eff} = \frac{N_A^{ev}}{f_{DPS} \cdot N_{A+B}^{ev}} \cdot \sigma_B$$

CONSIDERED OBSERVABLES: normalized ΔS and $\Delta^{rel} p_T$
BACKGROUND: MADGRAPH+P8 with hard MPI above 15 GeV excluded
SIGNAL: Two mixed independent scatterings generated with P8 and MG+P8
DRIVING UNCERTAINTY: model dependence



$$\sigma_{eff} = \frac{N_{W+0j}}{f_{DPS} \cdot N_{W+2j}} \cdot \sigma_{2j}$$

$$f_{DPS} = 5.5\%,$$

$$\frac{N_{W+0j}}{N_{W+2j}} = 27.8$$

JHEP 03 (2014) 032

$$\sigma_{eff} = 20.7 \pm 0.8 \text{ (stat.) } \pm 6.6 \text{ (syst.) mb}$$

Experimental difficulties of the template method

→ **How to define the background?**

- Good to exclude hard MPI..but no such possibility in some generators

→ **How to define exclusive and inclusive events?**

- N_{W+0j} and N_{W+2j} are sensitive to the jet scales

→ These issues have an impact on the systematic uncertainty!

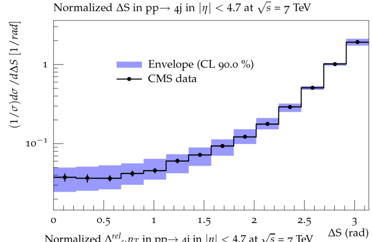
Is there a way out?

The inclusive fit method

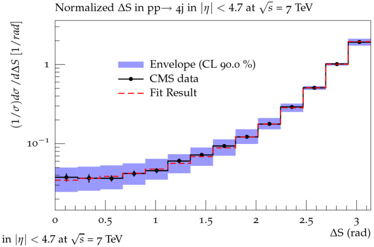
- Run predictions for different choices of UE parameters
- Fit the MC predictions to the considered observables
- Improve the data description with the examined model
- (..look at the corresponding σ_{eff}..)

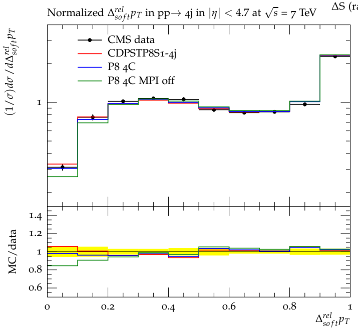
Extraction of σ_{eff} in four-jet final states

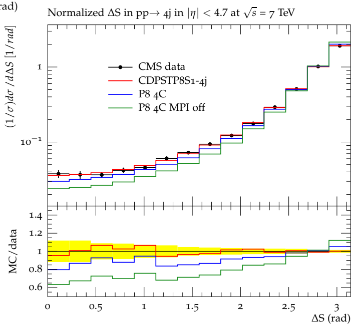
Minimization of the binned $\chi^2 = \sum_O \sum_{b \in O} \frac{(MC^b - DATA^b)^2}{\Delta_b^2}$



MINIMIZ.







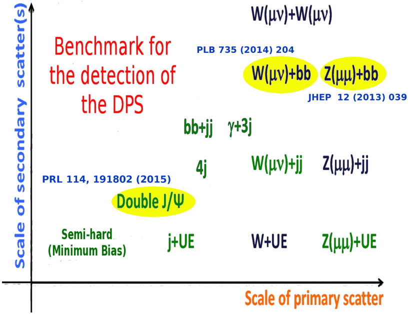
$\sigma_{eff} = 19.0^{+4.7}_{-3.0}$ mb

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

CMS-GEN-14-001

Where do we stand now?

- Observables sensitive to DPS measured in various final states
- Values of σ_{eff} extracted in W+dijet, four-jet and WW
- Ongoing extraction for the other channels



Channel dependence
Scale dependence
Flavour dependence

Investigation of various models

Large uncertainties

STILL MUCH TO DO!

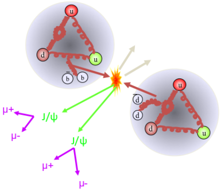
..and it's not all!

No extraction of a value of σ_{eff} but indication of need for DPS !

Inclusive double J/ψ production

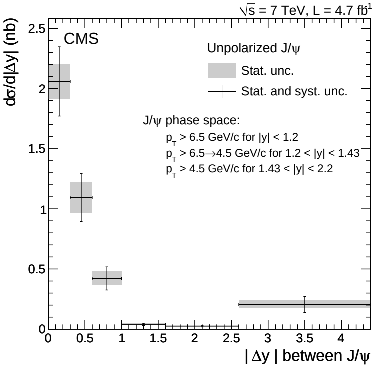
Event selection

Presence of two pairs of opposite-charge muons in $|\eta| < 2.2$; the two pairs must have invariant mass close to J/ψ



$\sigma(J/\psi J/\psi + X)$

1.49±0.07±0.13 nb



Correction and phase-space extrapolation assuming unpolarized production

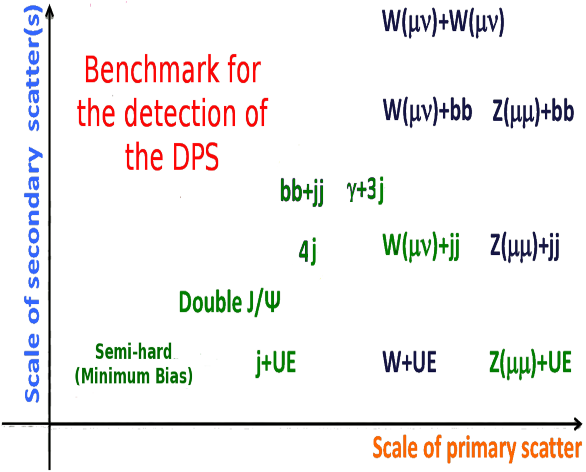
SPS background should dominate the fall at low Δy

DPS expected to fill the high Δy region

Useful baseline for building reliable models of J/ψ production before extracting DPS signal

What to do next?

→ Measurements for LHC Run 2



Energy dependence

Channel dependence
Scale dependence
Flavour dependence

→ **more statistics**
→ **double differential distributions**
→ **access to diboson final states**
→ **DPS with Higgs**

Joined effort between phenomenological and experimental community

Personal remarks and summary

- **Important to study first the sensitivity of the physics channel and the considered observables**
- **Important to produce unfolded results in order to be able to compare predictions from any model**

- Double parton scattering is essential for proton structure as well as for background to physics searches
- Several final states can be used for DPS detection
  - W+jets, four-jets, two b- + two other jets...
- **The measured final states clearly indicate the need for DPS for describing the experimental results**
- **Future: measure energy dependence**
  get a unified picture of DPS with UE- and MB-sensitive measurements

Personal remarks and summary

- **Important to study first the sensitivity of the physics channel and the considered observables**
- **Important to produce unfolded results in order to be able to compare predictions from any model**

- Double parton scattering is essential for proton structure as well as for background to physics searches
- Several final states can be used for DPS detection
  - W+jets, four-jets, two b- + two other jets, γ+three jets, WW...
- **The measured final states clearly indicate the need for DPS for describing the experimental results**
- **Future: measure energy dependence**
  get a unified picture of DPS with UE- and MB-sensitive measurements

THANK YOU!

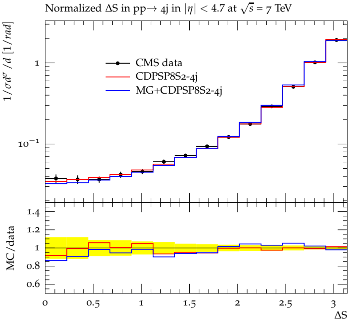
BACK-UP SLIDES

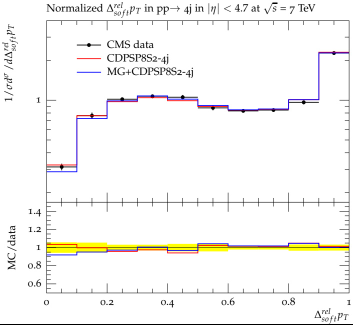
Determination of σ_{eff} in the four-jet channel

Tuning the four-jet observables (Phys.Rev., D89, 2014) with PYTHIA8

Parameter	CDPSTP8S1-4j	CDPSTP8S2-4j	4C
MultipleInteractions:expPow	1.16	0.6921	2.0
MultipleInteractions:ecmPow	**0.19***	0.345	0.19
MultipleInteractions:pT0ref	**2.09***	2.125	2.09
BeamRemnants:reconnectRange	**1.5*** *=unchanged wrt 4C	6.526	1.5
χ^2/NdF	0.75	0.42	-
σ_{eff} (mb)	$21.3^{+1.7}_{-1.3}$	$19.0^{+4.7}_{-3.0}$	30.3

$$\sigma_{eff} = 19.0^{+4.7}_{-3.0} \text{ mb}$$ $\rightarrow \sigma_{eff}$ (Tune 4C) $\sim$ 30.3 mb





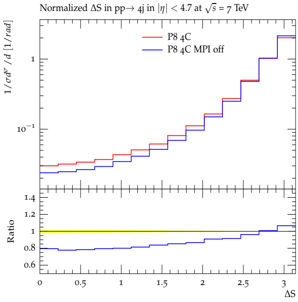
DPS-based tune propagated to MADGRAPH ME

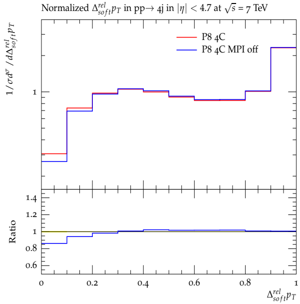
Simulation of UE independent on the used matrix element

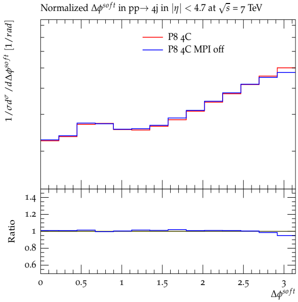
LEFT: ΔS
RIGHT: $\Delta^{rel}_{soft}p_T$

CMS-GEN-14-001

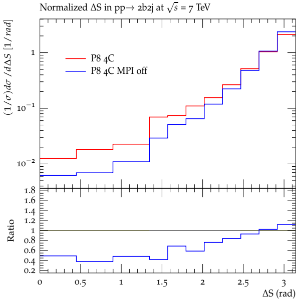
Choice of sensitive observables







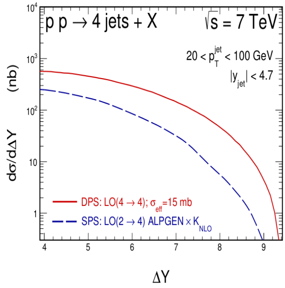
...but also the phase space thresholds matter!!



LEFT: four jets selected applying the same p_T

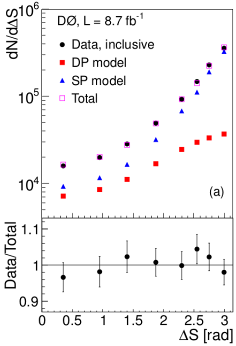
RIGHT: four jets with a rapidity cut applied between the most remote jets

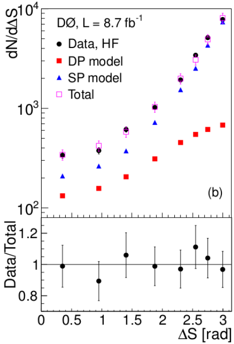
arXiv 1503.08022



D0 DPS analysis: γ+3jets and γ+b/c jet+2jets

SELECTION 1: $p_T^\gamma > 26$ GeV, $p_T^{lead} > 35$ GeV, $15 < p_T^{oth.} < 35$ GeV in $|\eta| < 2.5$
SELECTION 2: $p_T^\gamma > 26$ GeV, $p_T^b > 35$ GeV, $15 < p_T^{oth.} < 35$ GeV in $|\eta| < 2.5$
CONSIDERED OBSERVABLES: normalized ΔS btw γ-j and dijet systems
BACKGROUND: SHERPA sample with MPI simulation off
SIGNAL: Two independent events recorded from data
DRIVING UNCERTAINTY: model dependence (only samples with MPI off!)





$$\sigma_{eff} \propto \frac{N_{DI}}{N_{DP}} \cdot \frac{\epsilon_{DP}}{\epsilon_{DI}} \cdot \sigma_{hard}$$

with $f^{DP}_{\gamma+3j} = 21\%$ and $f^{DP}_{\gamma+b/cj+2j} = 17\%$

γ+3jets

$\sigma_{eff} = 12.7 \pm 0.2 \pm 1.3$ mb

γ+b/c jet+2jets

$\sigma_{eff} = 14.6 \pm 0.6 \pm 3.2$ mb

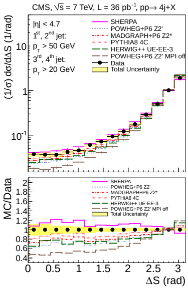
Phys. Rev. D 89, 072006 (2014)

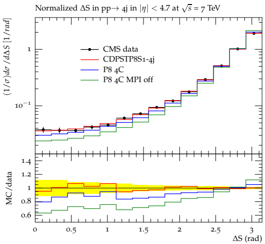
Recommendations for DPS extraction

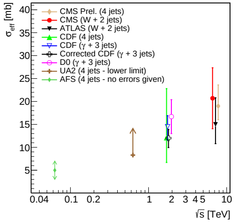
	CMS	ATLAS	D0/CDF
Background and signal should cover the full phase space	✓	✓	x
Use more than one MC event generator to correctly evaluate the model dependence and the systematic uncertainty	✓	✓	✓
Use more than one variable for the DPS determination	✓	x	x

BUT..difficult to define the background template in the same way with different generators!

The proposed new approach







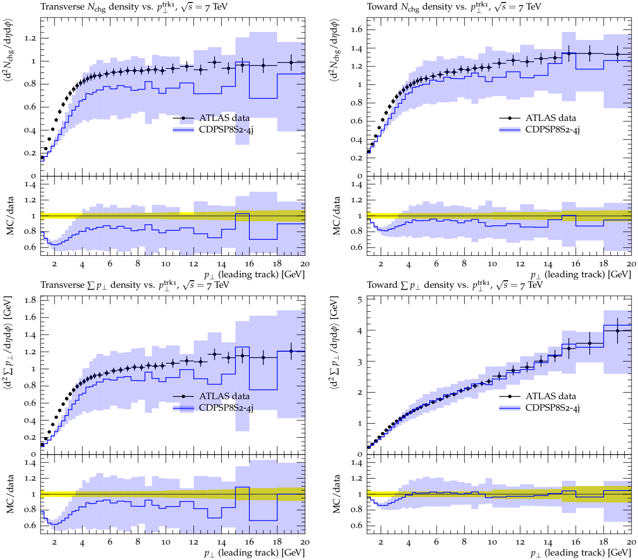
A FEW REMARKS WHEN USING THE TUNING METHOD:

1. Investigation of the contribution of different matrix elements used with the same UE simulation
2. Use more than one MC event generator to study the DPS contribution needed in different models
3. Use more than one variable for the DPS determination
4. Check if the new set of parameters spoil description of more inclusive distribution

How does the new tune perform in the UE description?

Measurement of charged particle mult. and p_T sum in hadronic events

ATLAS Coll. Phys.Rev. D83 (2011) 112001



Tune	σ_{eff} (mb)
P8 4C	30.3
CDPSTP8S2	$19.0^{+4.7}_{-3.0}$

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

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

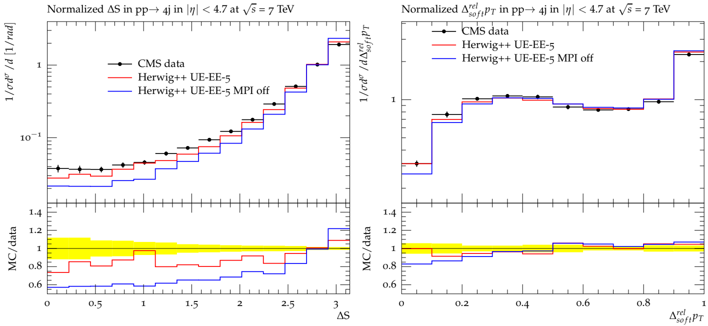
CMS-GEN-14-001

How to fix this?

→ Attempt to implement in a tune a value of σ_{eff} compatible with experimental measurements

HERWIG++ case: $\sigma_{eff} = \frac{28\pi}{\mu}$, with μ inverse proton radius

Tune UE-EE-5C (arXiv:1307.5015) : σ_{eff} = 15 mb (CDF)



Slight underestimation of the low ΔS region

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

Another approach:
Dynamical approach to MPI contribution
(arXiv:1503.08246)

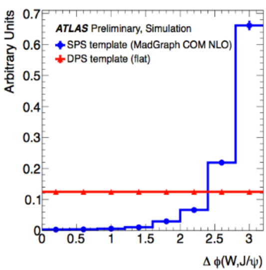
- Introduction of x- and scale-dependence for values of σ_{eff}
- Inclusion of 1×2 mechanisms

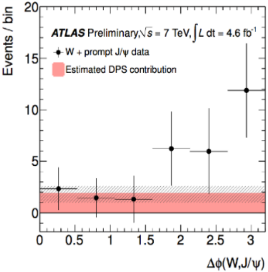
It is not all..

- ATLAS Coll. *Associated production of prompt J/ψ mesons and W boson* JHEP 04 (2014) 172
- LHCb Coll. *Prompt charm production in pp collisions* HEP 1206 (2012) 141
- ATLAS Coll. *Measurement of the cross-section for W boson production in association with b-jets* New J. Phys. 15 (2013) 033038
- LHCb Coll. *Study of forward Z+jet production in pp collisions* JHEP 01 (2014) 033
- CMS Coll. *Measurement of the cross section and angular correlations for associated production of a Z boson with b hadrons* JHEP 12 (2013) 039
- CMS Coll. *Measurement of Prompt Double J/psi Production in pp Collisions* JHEP 1409 (2014) 094
- ALICE Coll. *J/psi production as a function of charged particle multiplicity in pp collisions at 7 TeV* Phys.Lett.B 712, 165 (2012)

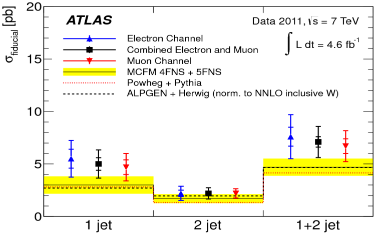
No extraction of a value of σ_{eff} but clear indication of need for DPS !

ATLAS Collaboration:
"Measurements of W+prompt J/ψ in *pp* collisions at 7 TeV"
JHEP 04 (2014) 172





ATLAS Collaboration:
"Measurement of the cross-section for W boson production in association with b-jets"
New J. Phys. 15 (2013) 033038



Measurements compatible with a DPS contribution with σ_{eff} ~15-20 mb

Short summary

Keypoints of the choice of variables

- Observables which consider the whole final state are more sensitive to DPS
  - ΔS, sum of transverse momenta, energy of the four objects
- A large phase space for additional radiation reduces the DPS sensitivity
  - Better selection with objects close in transverse momentum
  - BUT..more complicated migration effects (and unfolding procedure)

CMS strategy for the DPS measurement

1st step

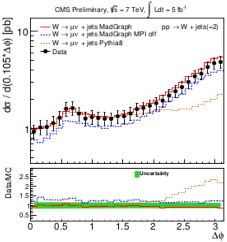
Corrected distributions DPS-sensitive variables

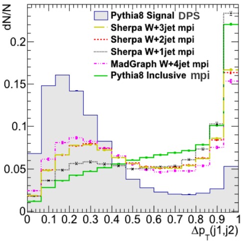
2nd step

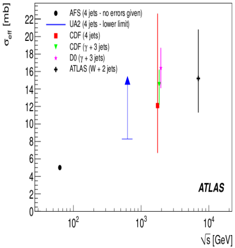
Data interpretation and unambigous definition of signal and background templates

3rd step

Extraction of the DPS fraction and study of the process dependence







- Compare the data to your own favourite predictions!

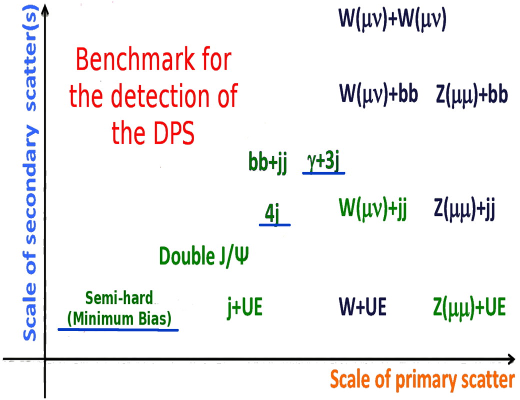
4th (future) step: differential distributions with high luminosities..

Choice of the physics channel

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

Internal structure of the proton
DPS background for any physics channel

→ Which channels can be used to look for DPS signals?

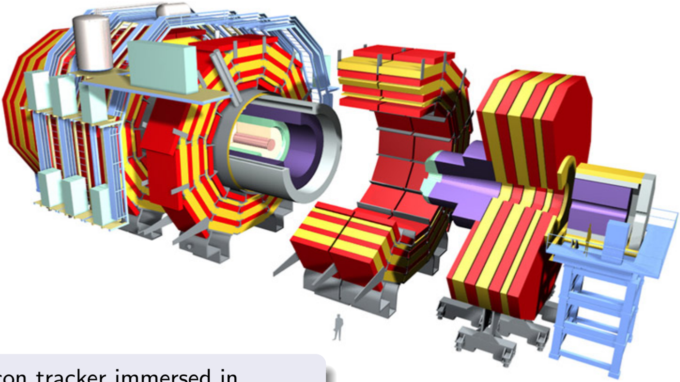


Published by
CMS and/or ATLAS

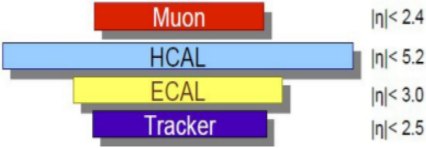
Published by
D0 and/or CDF

How can DPS be detected?

The Compact Muon Solenoid experiment



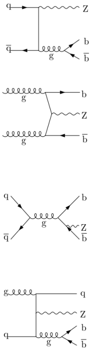
- Silicon tracker immersed in a 3.8 T magnetic field
- Wide calorimeter coverage
- Excellent jet energy resolution and muon detection efficiency
- Particle Flow technique for jet reconstruction



Angular correlations in Z+b-hadrons final states

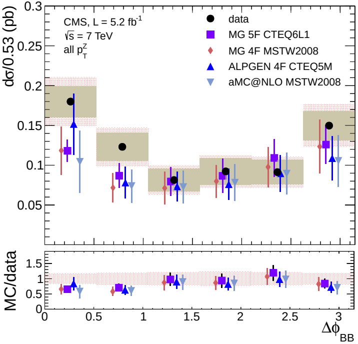
Event selection

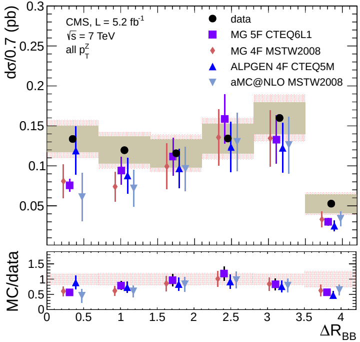
Presence of two leptons with $p_T > 20$ GeV in $|\eta| < 2.4$ with invariant mass close to the Z peak and two b-hadrons with $p_T > 15$ GeV in $|\eta| < 2$



$$\Delta\phi = |\Delta\phi_{b1} - \Delta\phi_{b2}|$$

$$\Delta R = \sqrt{\Delta\phi_{b1}^2 + \Delta\eta_{b2}^2}$$





JHEP 12 (2013) 039

Data compatible with predictions at parton level with DPS contribution ($\sigma_{eff} \sim$ 25-30 mb) included