Double Parton Scattering measurements at LHC

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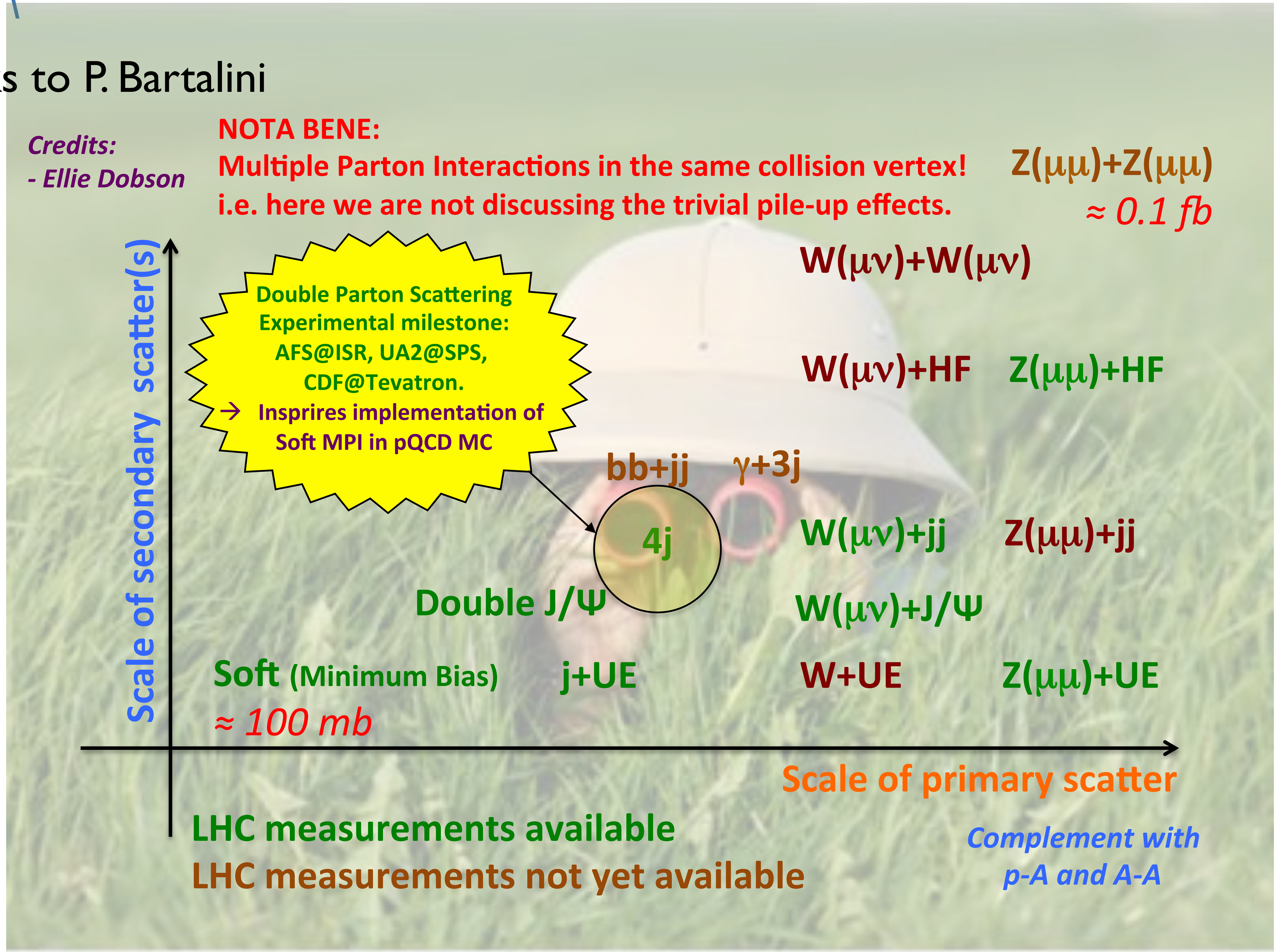
Where can we measure double parton scattering?

Thanks to P. Bartalini



How can we measure double parton scattering?

4 jets topology

AFS and UA2 (limit) observed double high pT interactions (~30 years)

3 jets + gamma

CDF and D0 observed double high pT interactions too (~20 years ago)

Inclusive measurement formalism

$$\sigma(A+B) = m * \sigma(A) * \sigma(B) / \sigma_{eff}$$

(m = ½ for identical interactions, m = 1 otherwise)

$$P(B|A) = P(B) * (\sigma_{Non\text{-}Diffractive}/\sigma_{eff})$$

$\sigma_{eff} \approx$ 10÷20 mb. Lowest figures at Tevatron (3jet+γ), higher figures from LHC (W+2jet etc.)

How can we measure double parton scattering?

By rough predictions, it was expected expected:

$\sigma_{eff} \approx 1/\pi R_{EM}^2 \approx$ **60 mb (3÷6 times higher than data!)**

In pythia 6/8 implementation:

$\sigma_{eff} = \sigma_{Non\text{-}Diffractive} / \langle f_{impact} \rangle$

$\langle f_{impact} \rangle$ is tune dependent

With soft MPI tune ↓

$\sigma_{eff} \approx$ **20÷30 mb**

Still 2 times higher than data

$\sigma_{eff} \approx$ **(process,) scale and √s independent**

[D. Treleani et al., rich bibliography]

Mainly dependent on geometry

σ_{eff} **≈ 34 mb considering 4->4 processes**

[M. Strikman et al.]

3->4 processes give significant contributions, rising with $x_{Bjorken}$

[B.Blok, MPI@LHC 2013]

Two main questions arose:

- **What is the relationship between soft and hard MPI?**
- **Is DPS really underestimated by models tuned on SoftQCD?**

What can we measure?

Rough estimations* of DPS processes cross section tell us what is possible to measure so far, and what not.

Avaible so far

σ_{DPS} (4jets@100 GeV)

σ_{DPS} (2γ+2jets@20 GeV)

→ $\sigma(A+B) = 1/2 * \sigma(A)^2 / \sigma_{eff}$ →

50 pb

0.5 pb

σ_{DPS} ($W^{\pm}\mu\nu$, $W^{\pm}\mu\nu$)

σ_{DPS} ($Z\mu\mu$, $Z\mu\mu$)

→ $\sigma(A+B) = 1/2 * \sigma(A)^2 / \sigma_{eff}$ →

20 fb

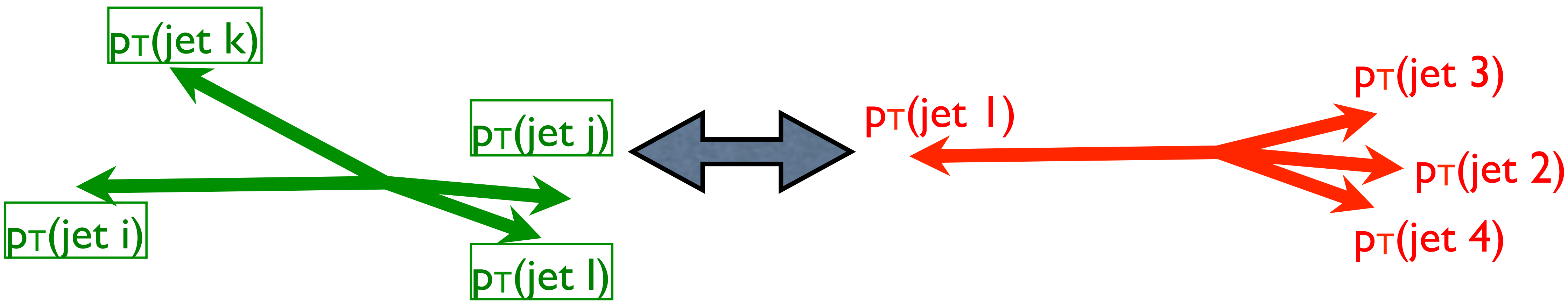
0.2 fb

Not yet possible/HL-LHC needed

*σ_{eff} = 10 mb is assumed

4 objects topology

Disentangle **double-parton-scattering** from **single-parton-scattering**



No correlation (DPS) vs Strong correlation (SPS)

- After PAIRING, one can define different correlation angles between jet pairs:
- AFS solution: Study $\Delta\varphi$ between p_{T1} - p_{T2} and p_{T3} - p_{T4}
- CDF solution: Study $\Delta\varphi$ between p_{T1} + p_{T2} and p_{T3} + p_{T4}

DPS measurements @ LHC

Double Parton Scattering @ LHC

ATLAS

W+2jets
W+ J/ψ

CMS

W+2jets
Double J/ψ

LHCb

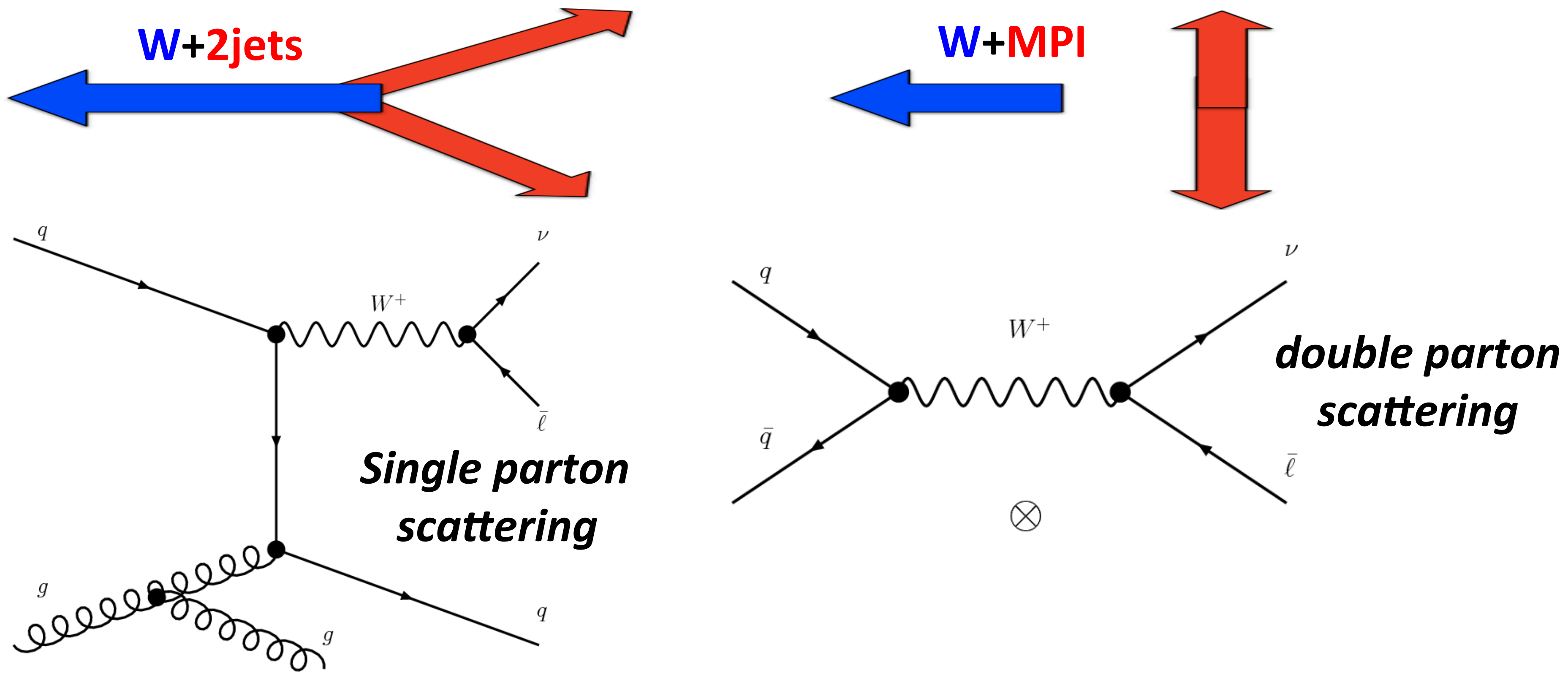
Double J/ψ
Z+D

ALICE

DPS yield vs charged multiplicity

Ongoing studies:
4jets, jj+bb
3jets+gamma
W+2jets in pA
DPS in open charm
Same sign W pair production

DPS in W+2jets



$$d\sigma^{(tot)}_{W+2j}(s) = d\sigma^{(dir)}_{W+2j}(s) + d\sigma^{(DPI)}_{W+2j}(s)$$

Measure fraction of W_0 + $2j_{DPI}$ in the W+2jet sample (f^R_{DP})

$$f^{R}_{DP} = \frac{N_{W_0+2j_{DPI}}}{N_{W+2j}}$$

$$\sigma_{eff} = \frac{1}{f^R_{DP}} \cdot \frac{N_{W_0} N_{2j}}{N_{W+2j}} \cdot \frac{1}{\varepsilon_{2j} L_{2j}}$$

DPS in W+2jets @ ATLAS

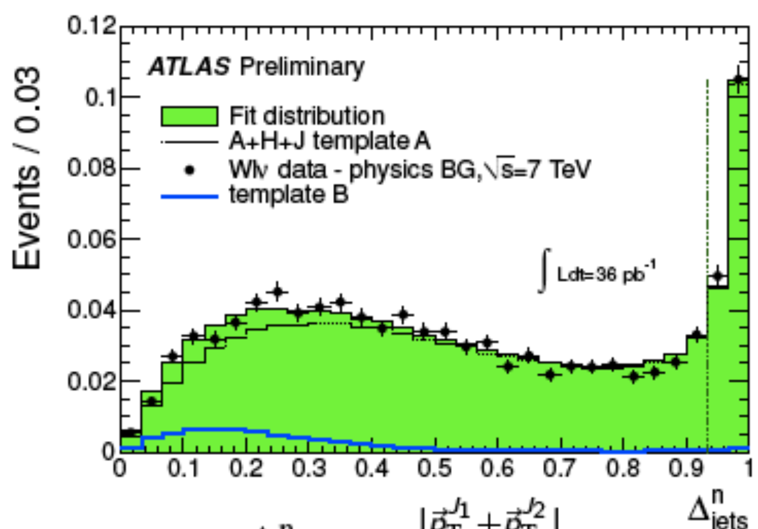
New J.Phys. 15 (2013) 033038.

Extraction of f^R_{DP} using fit to data with two templates
Template A (non DPS sample): both jets originate from the primary scatter
Template B (a DPS sample): both jets originate from the DPS scatter

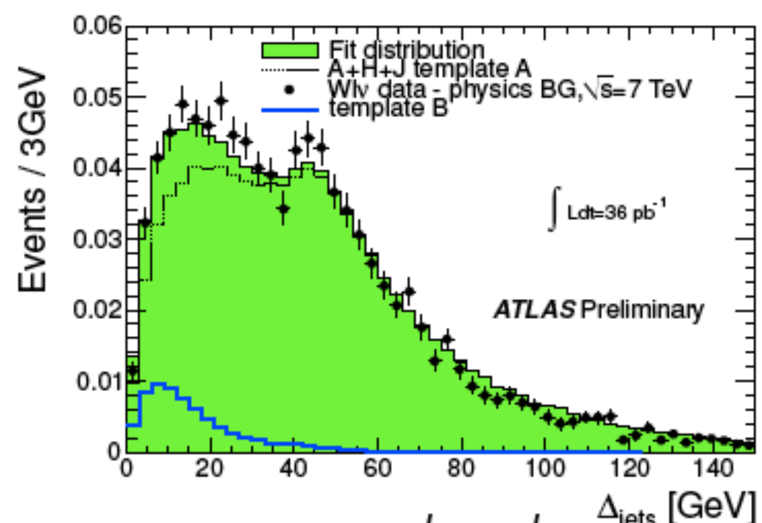
Jet selection
(Minimum bias trigger used to measure di-jet x-section alone)
2 jets, $p_T > 20$ GeV, $|y| < 2.8$

W selection
Single lepton trigger
1 lepton (e, μ) $p_T > 20$ GeV, $\eta < 2.5$
MET > 25 GeV, $m_T > 40$ GeV
2 jets, $p_T > 20$ GeV, $|y| < 2.8$

$$(1 - f^R_{DP}) \cdot A + f^R_{DP} \cdot B$$



$$\Delta^n_{\text{jets}} = \frac{|\vec{p}_T^{J_1} + \vec{p}_T^{J_2}|}{|\vec{p}_T^{J_1}| + |\vec{p}_T^{J_2}|}$$



$$\Delta_{\text{jets}} = |\vec{p}_T^{J_1} + \vec{p}_T^{J_2}|$$

- Low luminosity (PU rejected)
- ME tools used for bkg description (SHERPA etc)
- First DPS result at LHC

$$f^{(D)}_{DP} = 0.08 \pm 0.01\ (\text{stat.}) \pm 0.02\ (\text{sys.})$$
$$\sigma_{\text{eff}} = 15 \pm 3\ (\text{stat.})\ ^{+5}_{-3}\ (\text{sys.})\ \text{mb}$$

- Based on just one DPS observable
- SPS+DPS phase space covering has to be demonstrated yet
- Statistical uncertainty is not negligible (36 pb^{-1} used)

DPS in W+2jets @ CMS

JHEP 1403 (2014) 032

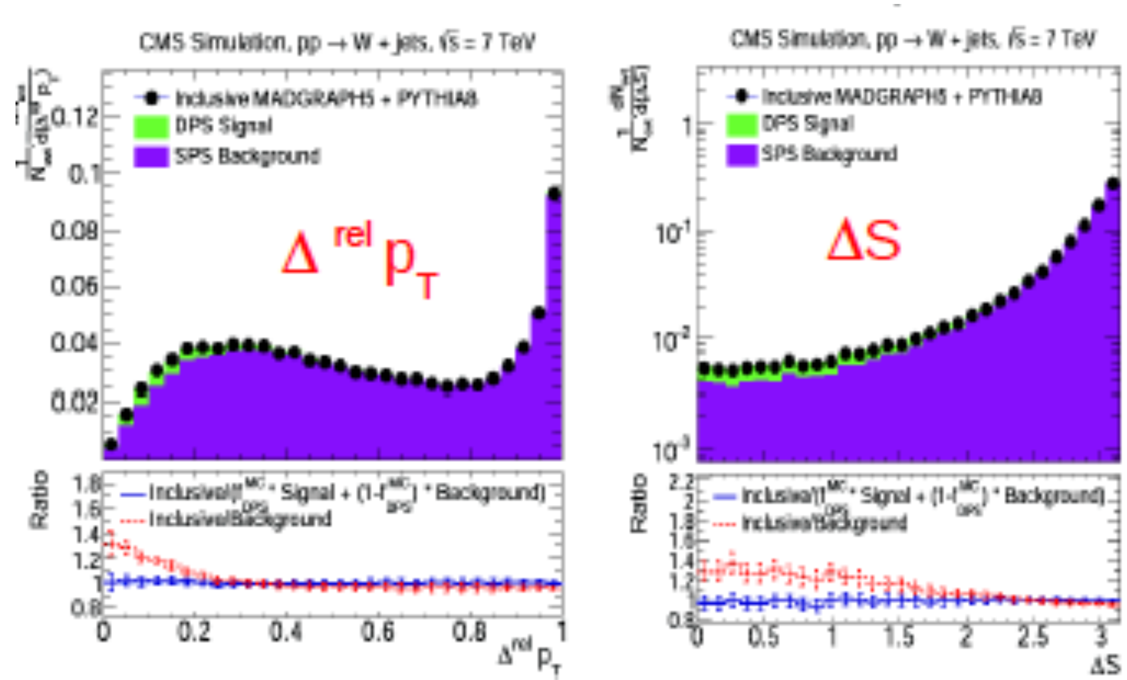
Data:
Full 2011 collision data at √s = 7 TeV, Single Muon data streams with integrated luminosity of ~ 5 fb^{-1}

Signal at small ΔS (DPS is flat while SPS is peaked at π) and small $\Delta^{rel} p_T$ (back-to-back di-jet in transverse plane).

Following ATLAS experience, and including:
higher statistics
unfolding
more MCs
more observables

$\Delta^{rel} p_T = \Delta^{n}_{jets}$ (ATLAS terminology) = relative p_T balance of the di-jet system.
ΔS = Angle between total momenta of paired objects (lν, di-jet) projected in the transverse plane.

- **Signal Template combining W+0jets and di-jet samples.**
- **Backg. Template Madgraph+Pythia 8 (no jets from MPI).**
- **Extract σ_{eff} from signal fraction.**



DPS in W+2jets @ CMS: results

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

  20.7 ± 0.8 (stat.) ± 6.5 (syst.)

- Measured value is consistent (within uncertainties) with previous results by ATLAS, CDF, D0

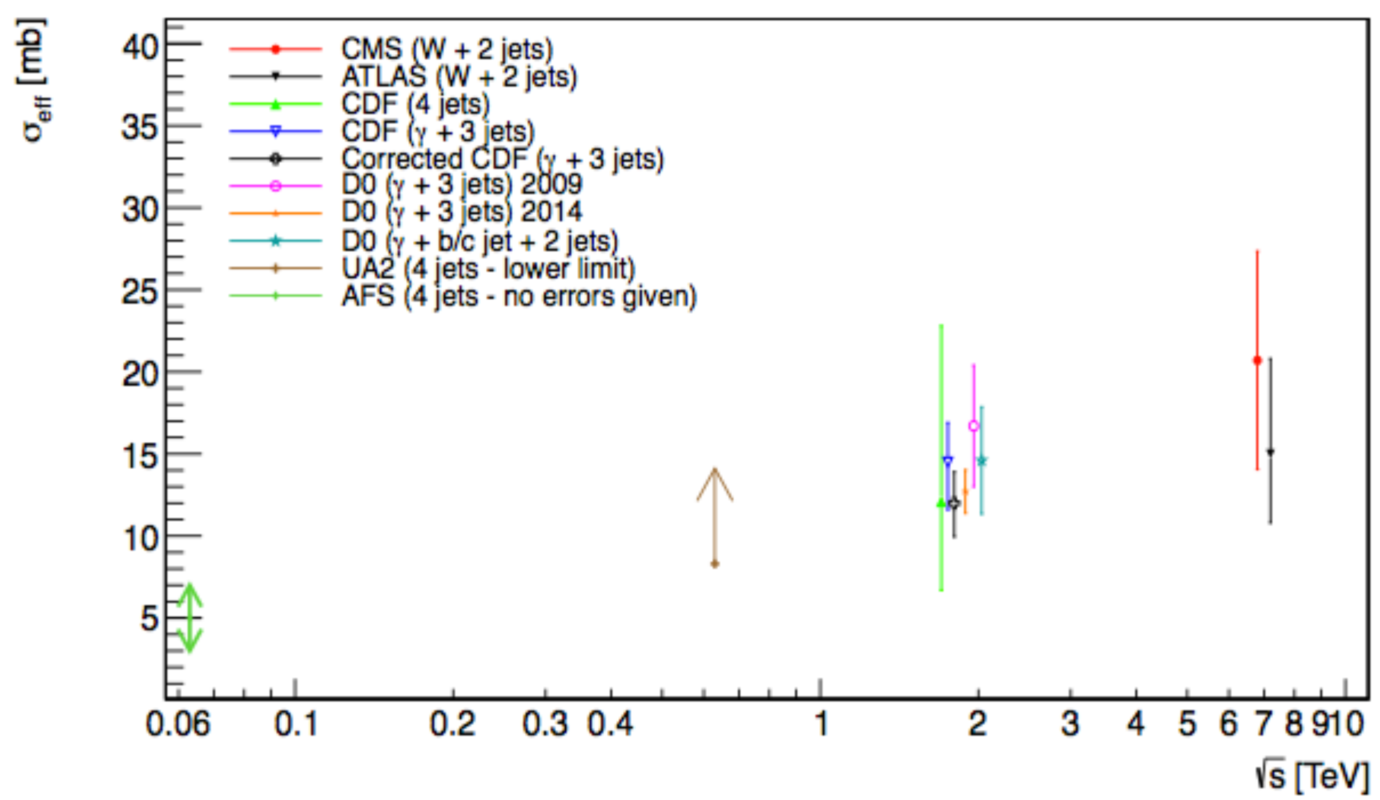
- Consistent with value obtained for Herwig++ by fitting data from LHC and Tevatron

- Main source of systematics from SPS background modeling

Measure di-jet x-section

Measured Ratio between W+2jets and W+0jets x-sections

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



Alternative method for sigma_eff extraction

IDEA: tune the parameters corresponding to the amount of DPS contribution in the available MCs

TOOL: RIVET routines and Professor

HOW TO: generate samples with different choice of the parameter and fit the data to get the best description

WHICH GENERATOR: PYTHIA8, HERWIG++, MADGRAPH+PYTHIA8...

WHICH PARAMETER: MultipleInteraction:expPow → it is the exponent of the matter distribution function of the two protons in PYTHIA8 4C

↑ expPow → overlap decreases faster → less MPI contribution → higher σ_{eff}

↓ expPow → overlap decreases slower → more MPI contribution → lower σ_{eff}

→ ..After the tune (ca. 2 days!):

- plug-in the obtained parameter to see if the agreement improves
- extract from the PYTHIA8 output the effective cross section corresponding to the choice of the parameter

→ At this stage, the uncertainty in σ_{eff} is just the one coming from the fit with Professor!

Benefits:

- Template fits need to split background phase space in two (only possible on Pythia 8 so far)
- All in one fit, no need of deep investigation for signal/ bkg definition
- Tune MC keep informations on soft dynamics. In template fit same contribution to SPS and DPS is assumed

Applying the procedure to W+jets CMS analysis lead to a compatible result:

$$\sigma_{eff} = 25.9^{+2.4}_{-2.9}\ \text{mb}$$ → CMS result $\sigma_{eff} = 20.7 \pm 0.8 \pm 6.5$ mb

CMS-GEN-14-001

DPS in 4jets @ CMS

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

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

Four-jet measurements are sensitive to the hard matrix element and underlying events:

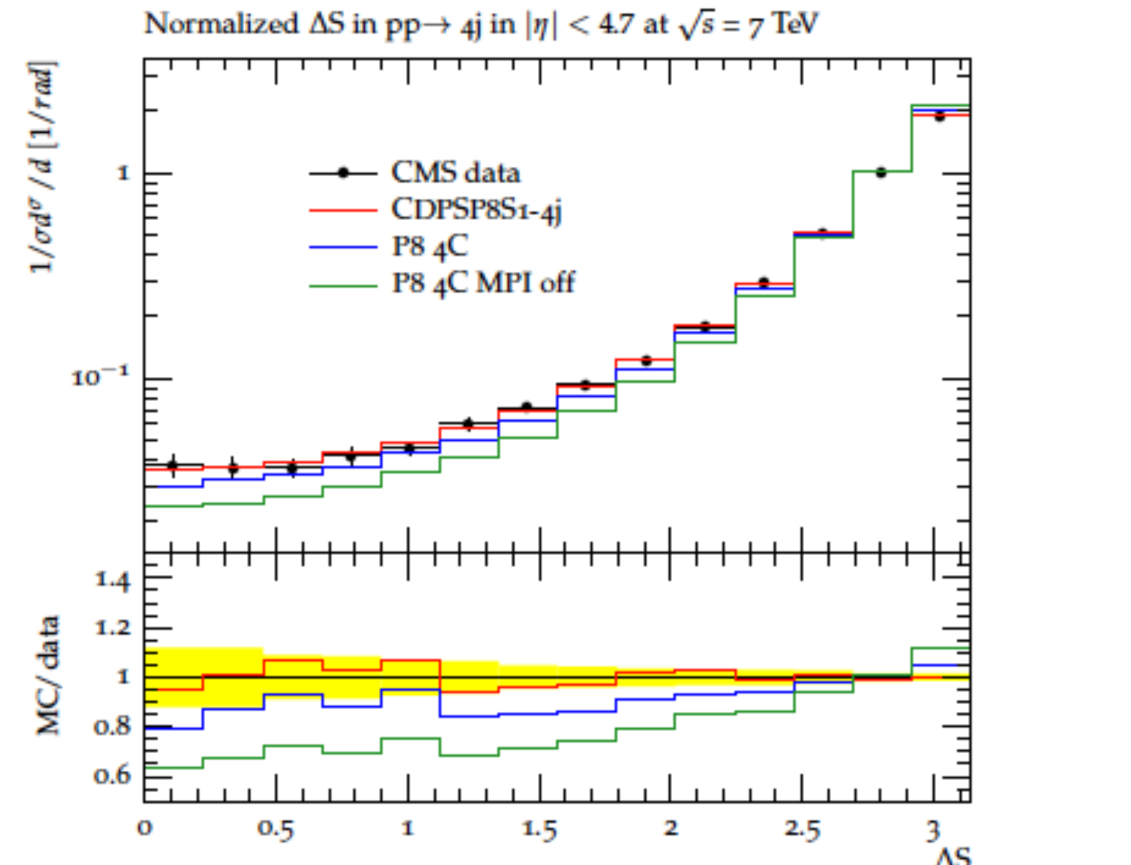
a proper admixture of ME and UE contributions is needed

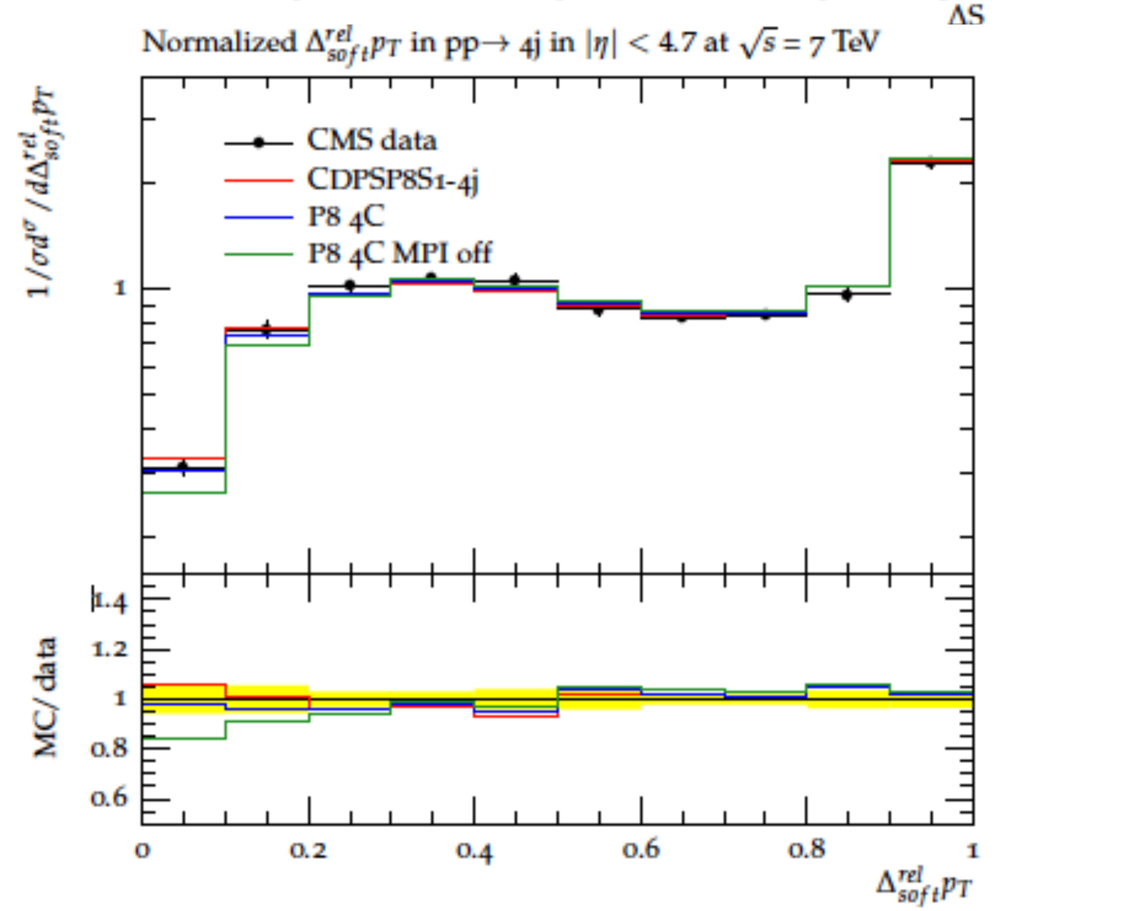
Tuning the four-jet distributions in the tuning range [0.8,2.5]

Parameter	New Tune	4C
MultipleInteractions:expPow	1.160	2.0
+Unc	1.2096	-
-Unc	1.1109	-
Goodness of fit	0.751	-

σ_{eff} extraction with Professor tune:

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





CMS-GEN-14-001

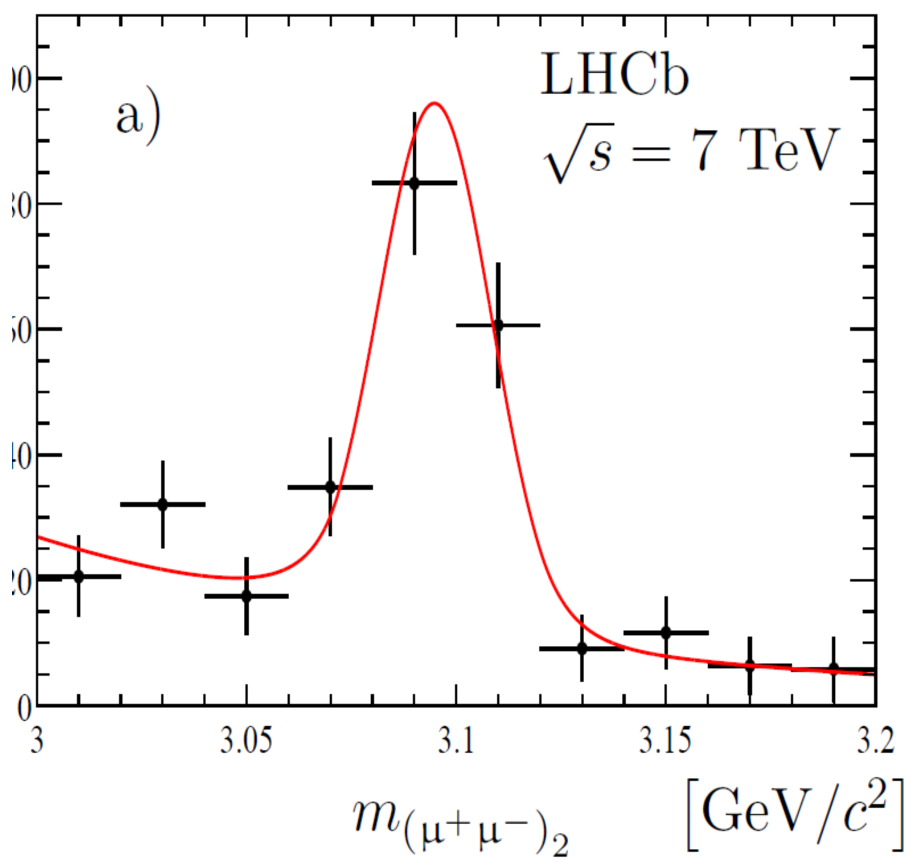
σ_{eff} extraction still ongoing

Phys.Rev. D89 (2014) 092010

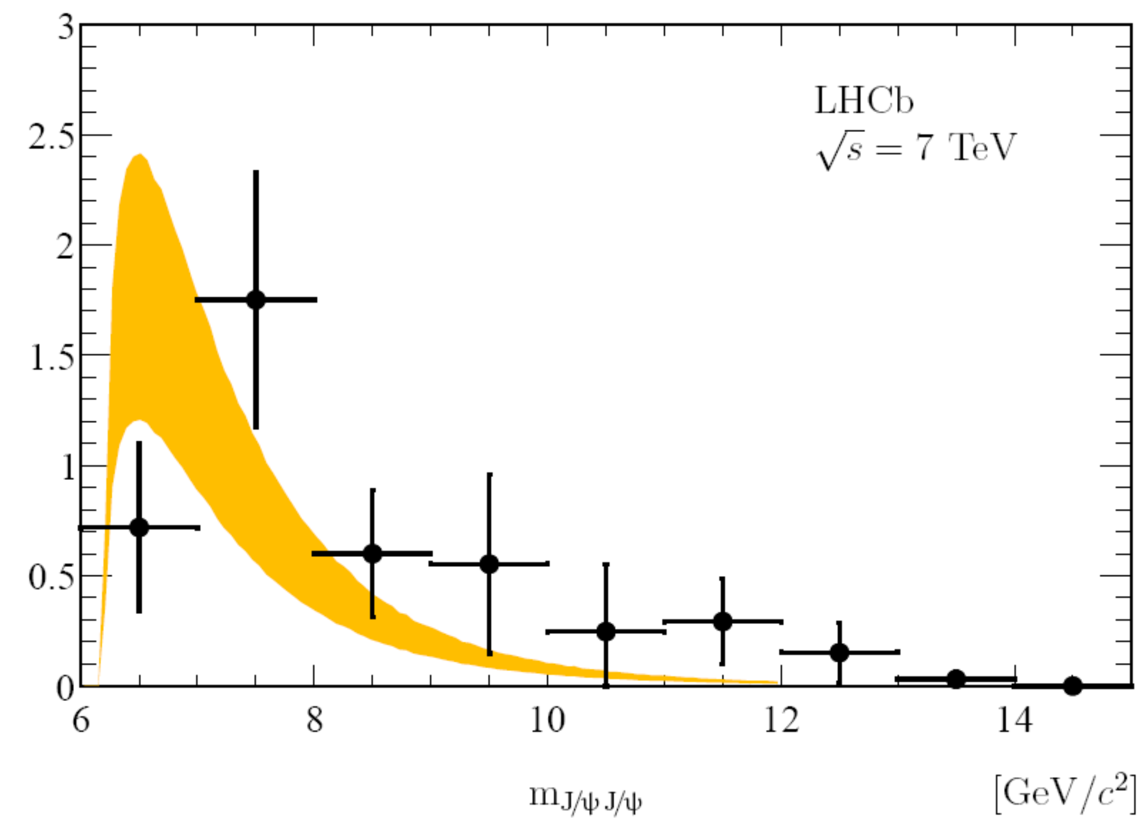
DPS in double J/ψ @ LHCb

p_T^{μ} > 650 MeV ($\mu^+\mu^-$ channel)
$3.0 < m_{\mu+\mu-} < 3.2$ GeV, $2 < y^{J/\psi} < 4.5$,
$p_T^{J/\psi} < 10$ GeV

2×J/ψ : fit one μμ-mass in bins of another μμ-pair mass: 141±19 events



SPS Prediction for $m_{J/\psi J/\psi}$ (in orange) includes direct production and feed down from ψ(2S).



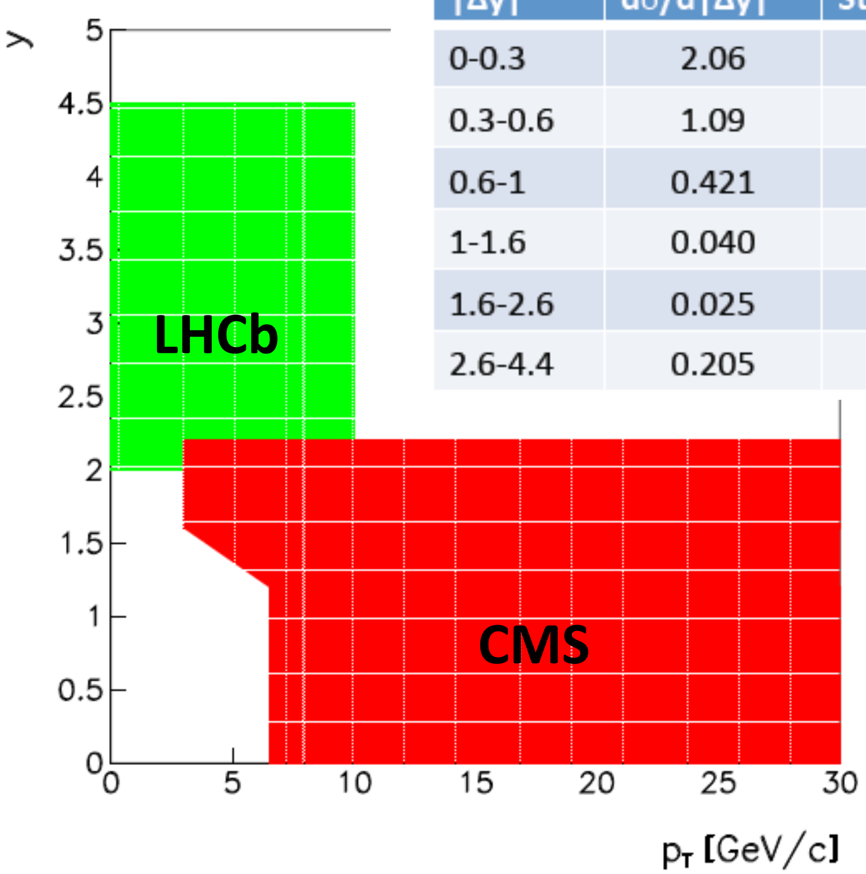
$\sigma^{J/\psi J/\psi}$ = 5.1 +- 1.0 (stat) +- 1.1 (syst) nb
i.e. around 20% higher than the SPS predictions. **Contribution from DPS?**

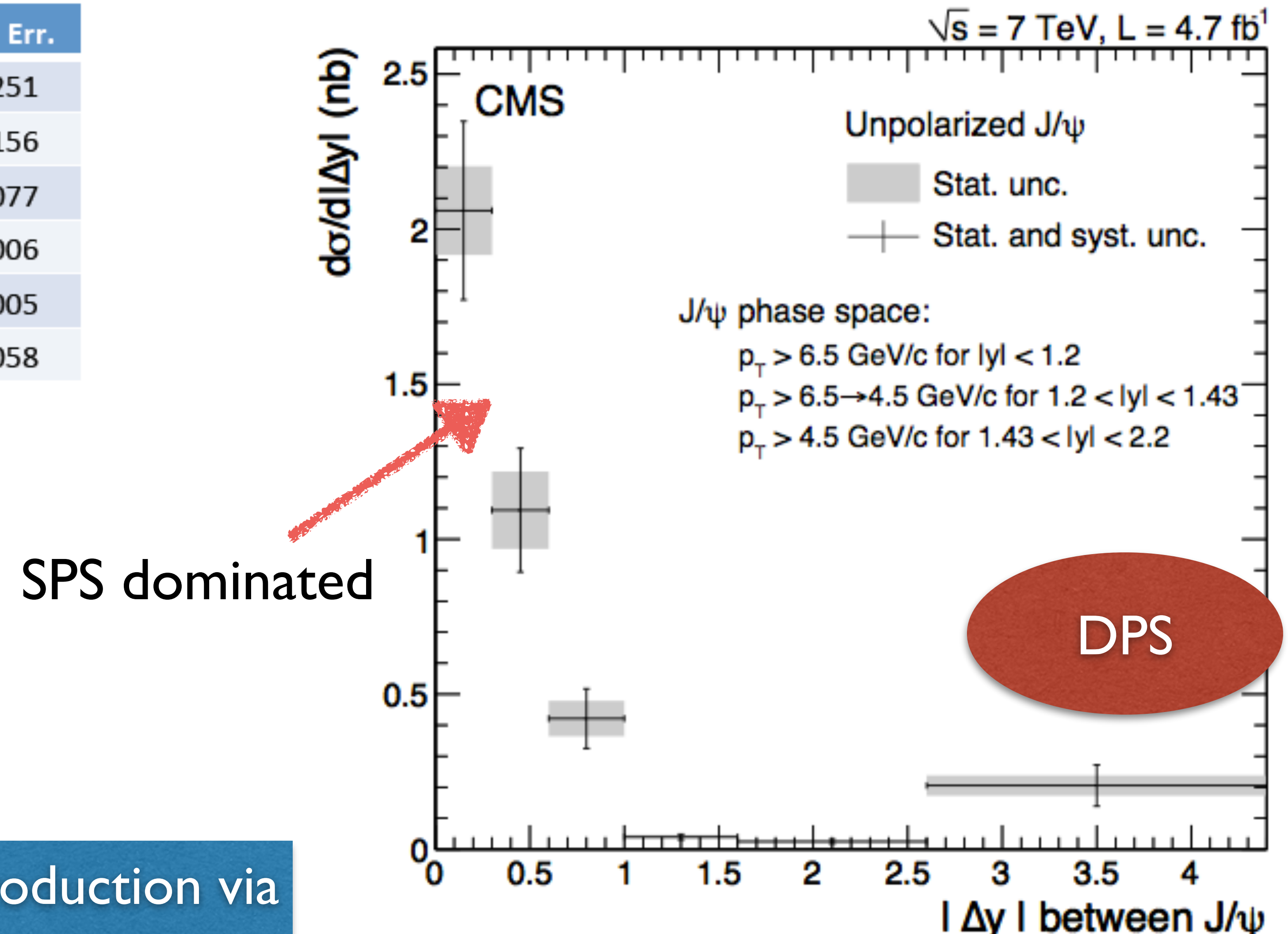
[S.P. Baranov, A.M. Snigirev, N.P. Zotov, Phys. Lett. B 705 (2011) 116–119]

DPS in double J/ψ @ CMS

arXiv:1406.0484

$\lvert\Delta y\rvert$	$d\sigma/d\lvert\Delta y\rvert$ (nb)	Stat. Err. (nb)	Syst. Err. (nb)
0-0.3	2.06	0.143	0.251
0.3-0.6	1.09	0.125	0.156
0.6-1	0.421	0.057	0.077
1-1.6	0.040	0.006	0.006
1.6-2.6	0.025	0.005	0.005
2.6-4.4	0.205	0.033	0.058





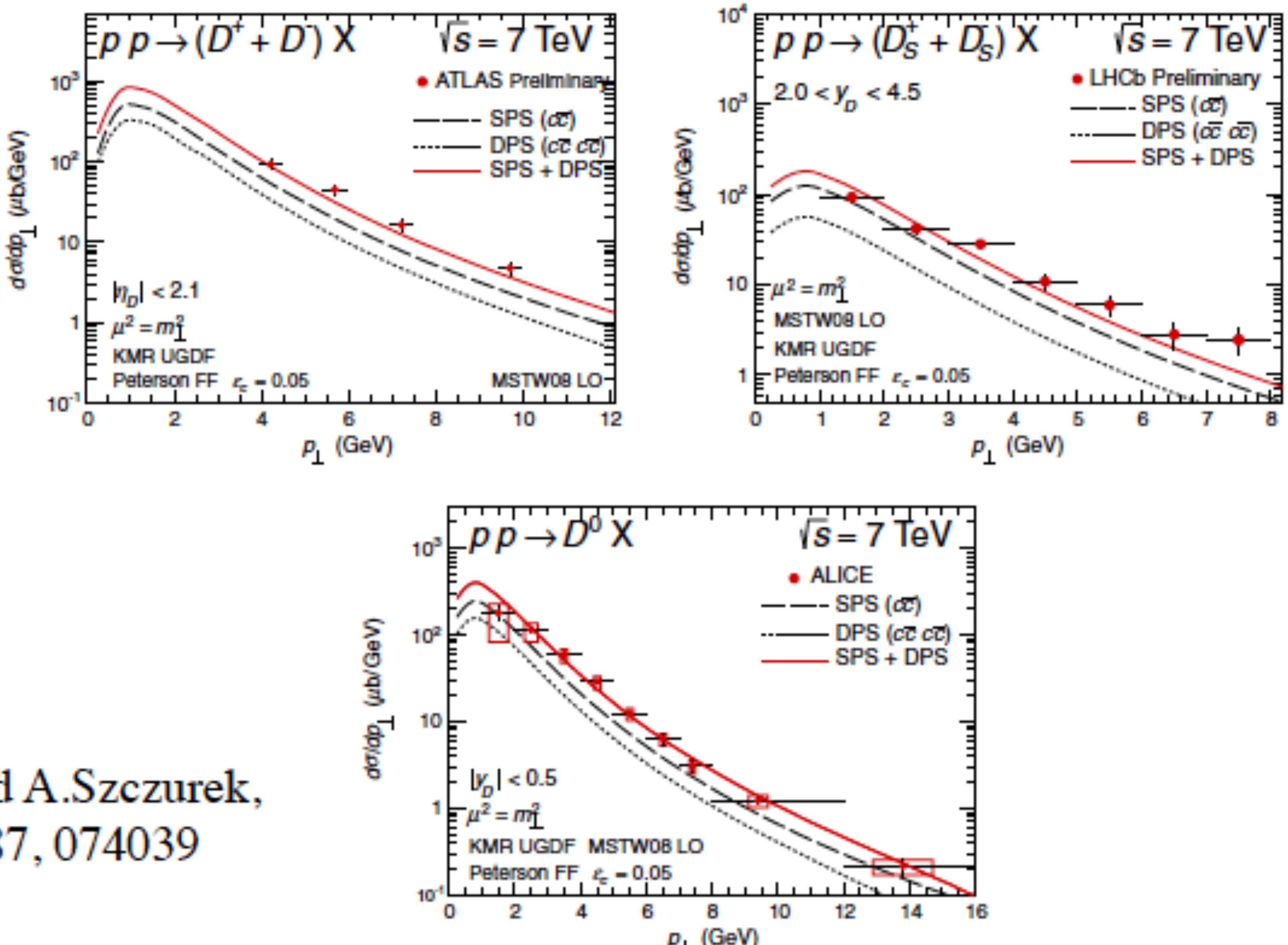
Computations of Double-quarkonium production via SPS at the LHC not developed for CMS acceptance e.g. assume dominance of color−singlet productIon.

Differences expected in Δy and p_T $_{J/\psi J/\psi}$ distributions. (P.Ko et al., Novoselov et al., Berezhnoy, et al., etc.)

Evidence for excess at |Δy| > 2.6

However SPS at large Δy is expected to be very suppressed. Although σ_{eff} is not quoted, to date, this is one of the most promising evidences of DPS production.

DPS in open charm production @ LHC



σ_{eff}= 15 mb

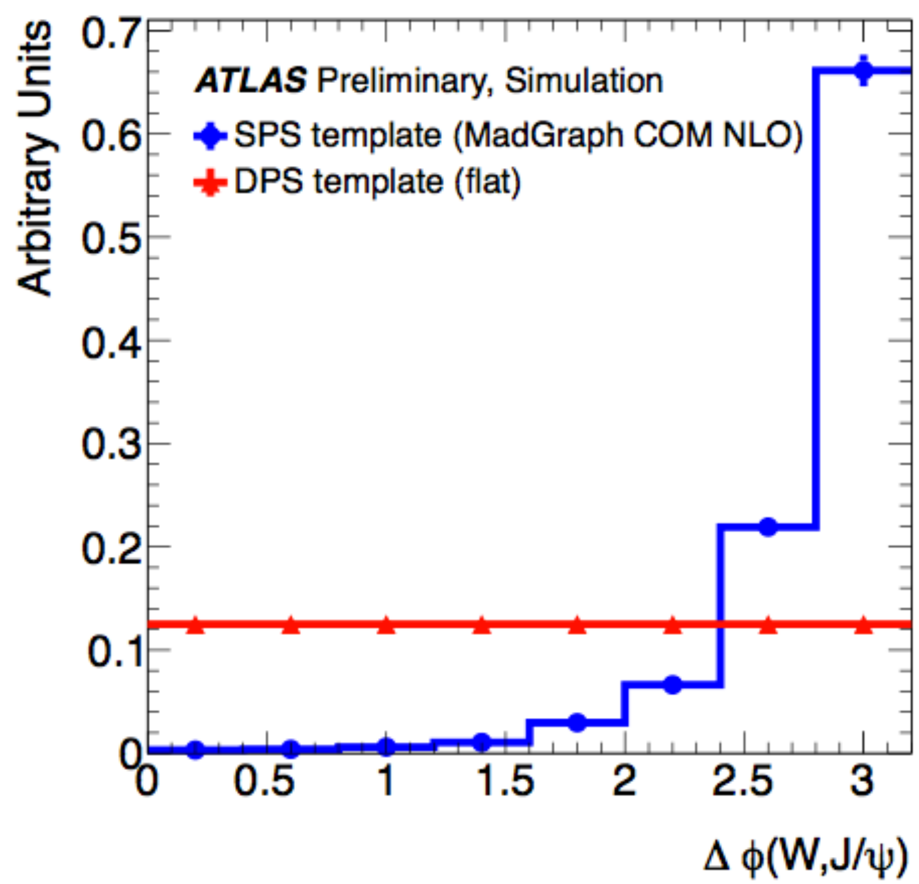
R.Maciula and A.Szczurek,
Phys. Rev. D87, 074039

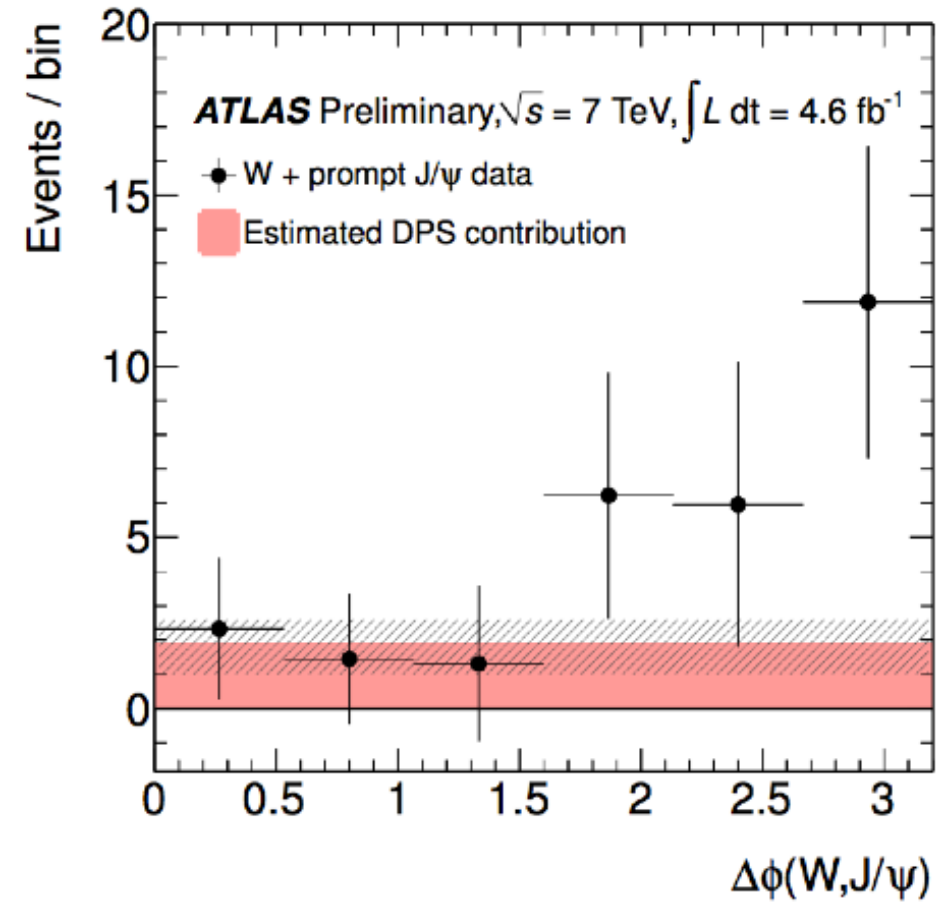
FIG. 12 (color online). Inclusive transverse momentum distributions of different charmed mesons measured by different groups at the LHC. The long-dashed line corresponds to the standard SPS $c\bar{c}$ production, and the dotted line represents the DPS $c\bar{c}c\bar{c}$ contribution.

DPS in W+J/ψ @ ATLAS

In this study from ATLAS the opposite approach is adopted

– σ_{eff} from W+2jets is assumed in order to estimate the DPS contribution to W+J/ψ





- Azimuthal Δφ(W,J/ψ) expected to be flat for Double Parton Scattering (DPS), peak at π for Single Parton Scattering (SPS)
- Both contributions present in sample
- Under the assumption of independent multiple scatters, within the limited precision available, Δφ plot supports σ_{eff}~15mb, as measured in W+2jets

Low statistics may not allow a direct measurement of DPS yield.
Studies with 2012 data are in progress

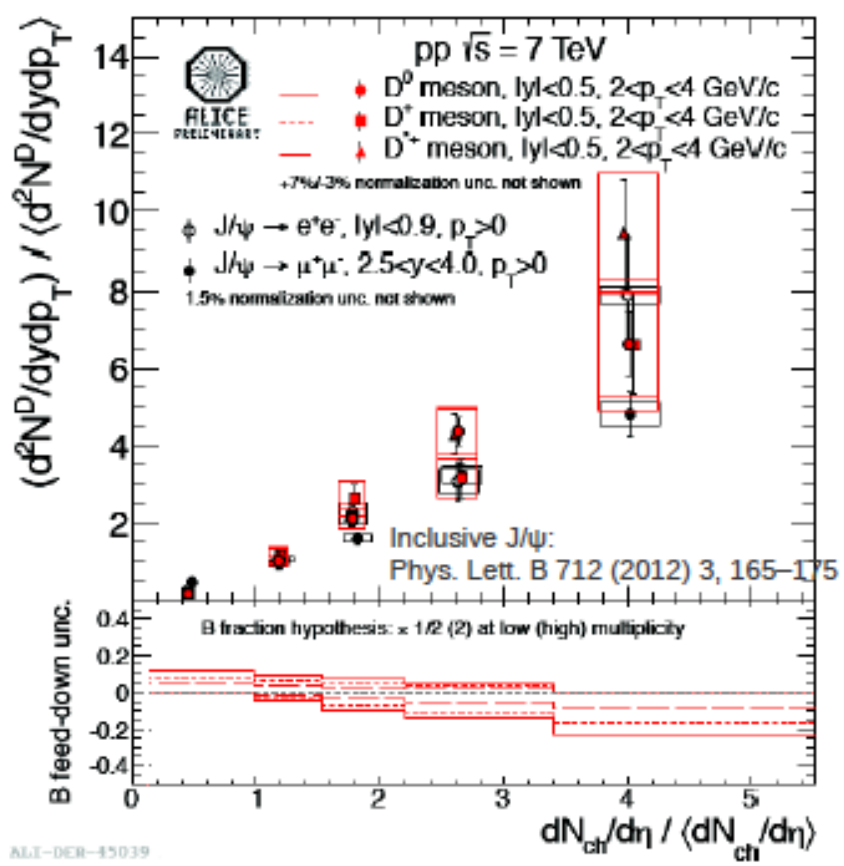
arXiv:1401.2831
CERN-PH-EP-2013-184

DPS in event yield as function of charged particle multiplicity @ ALICE

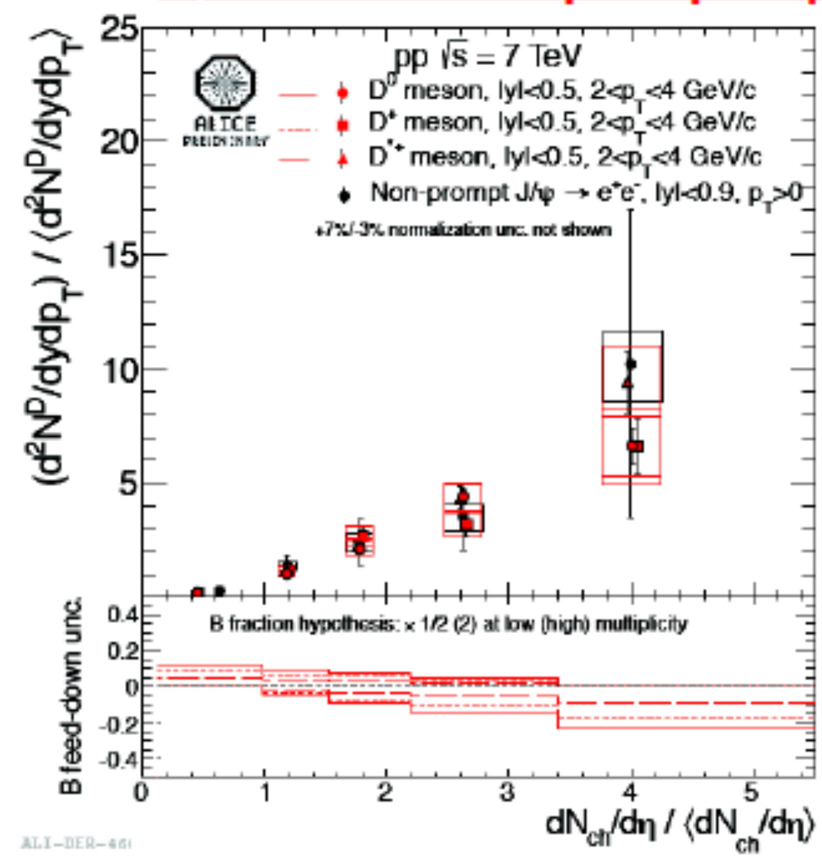
ALICE Coll., Eur. Phys. J. C 68 (2010) 345.

Prompt D meson ($2<p_T<4$ GeV/c) and J/ψ ($p_T>0$) yields (both inclusive and non prompt) show a similar increase with charged particle multiplicity within the current statistical and systematic uncertainties.

D-mesons – inclusive J/ψ



D-mesons – non-prompt J/ψ



- *Reproduced by Pythia 8, which implements Heavy Flavors production in MPI (in contrast to Pythia 6).*
- Interpretation: at least in the pQCD models N_{ch} is basically proportional to N_{MPI}, as a trivial consequence all the yields are expected to be correlated with N_{ch}.

INTERESTING HIGHLIGHT, PREPARING THE GROUND TO THE CONNECTION BETWEEN HARD AND SOFT MPI!

DPS analyses in progress

DPS in same sign W pair @ LHC

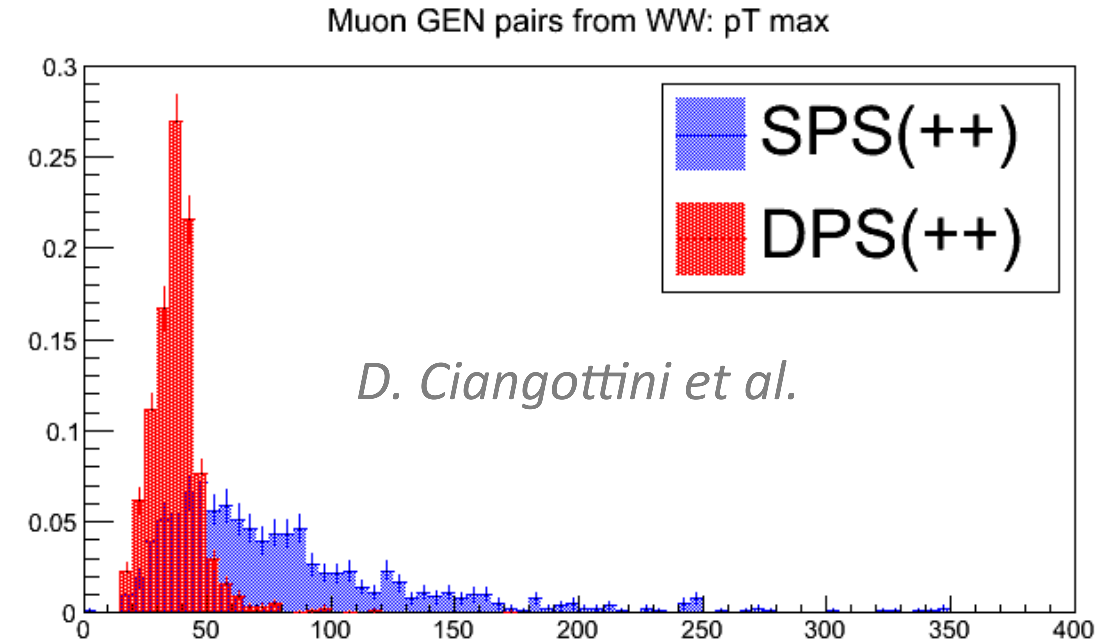
Double Parton Scattering and *Single Parton Scattering* are expected to have comparable cross sections

Model dependence can be strongly suppressed

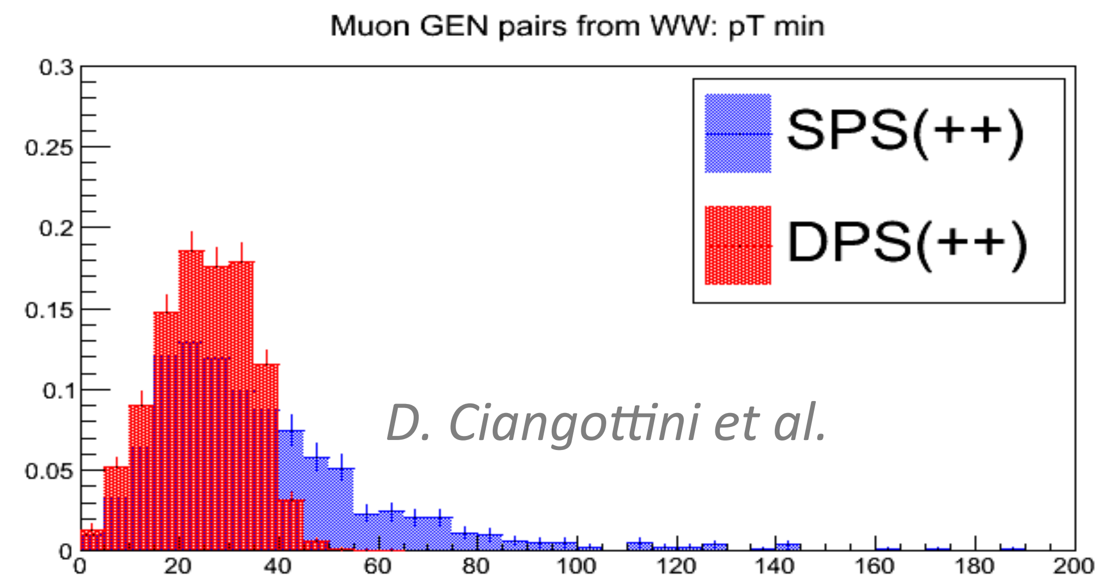
Generator level distributions
$\sqrt{s}$ = 8 TeV
DPS = Pythia 8
SPS = Madgraph

Low statistics at actual luminosity

Refs.
[Stirling et al. arXiv: 1003.3953v1]
[Treleani et al., Int. J. Mod. Phys. A20: 4462-4468 (2005) and Phys. Rev. D 72, 034022 (2005).]



μ-related discriminating observable: p_T^{max}

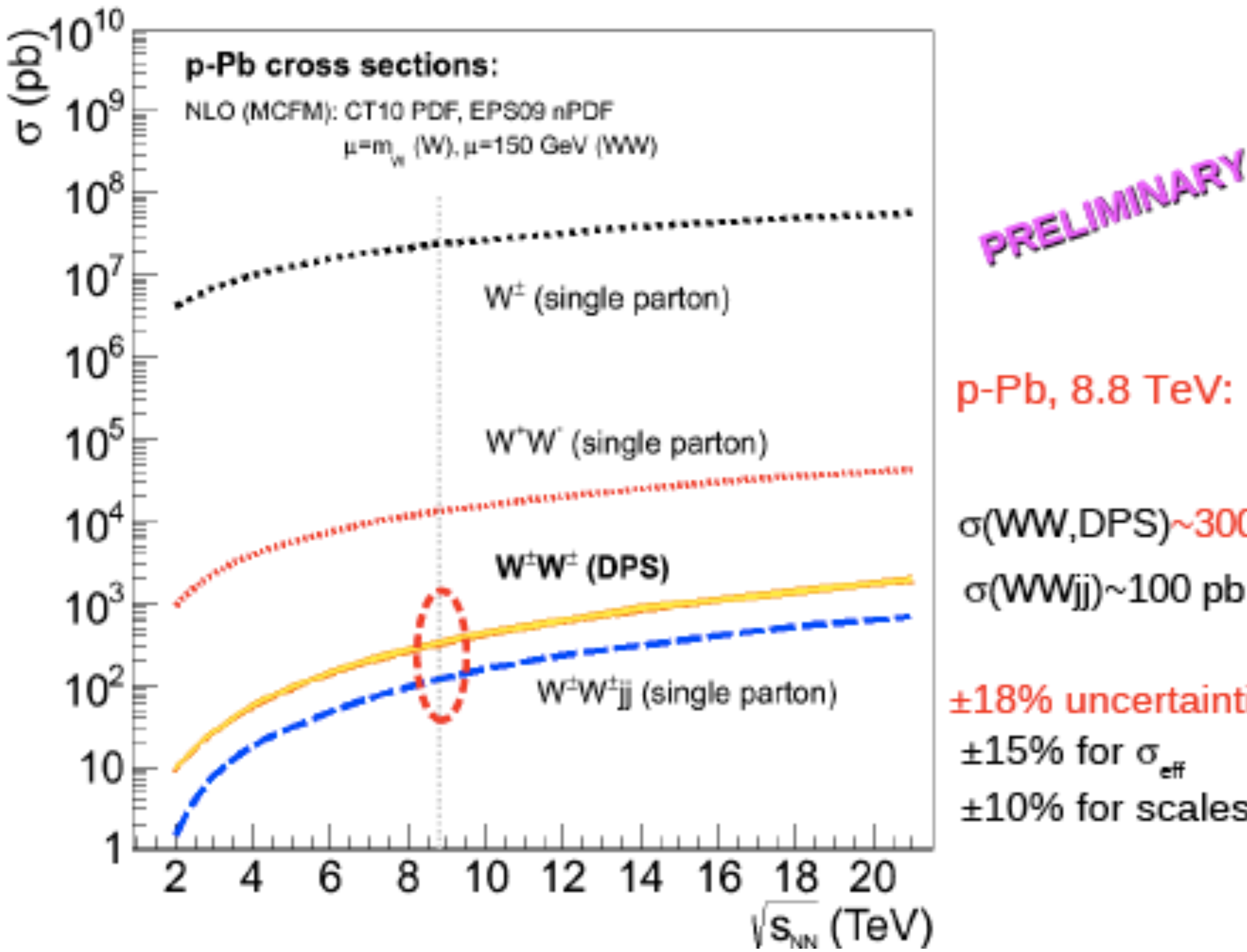


μ-related discriminating observable: p_T^{min}

DPS in same sign W pair in p-pb interactions: looking at the future

D'Enterria & Snigirev, arXiv:1211.0197.

- Cross sections for all relevant SPS and DPS processes vs sqrt(s):



p-Pb, 8.8 TeV:

σ(WW,DPS)~300 pb

σ(WWjj)~100 pb

±18% uncertainties:

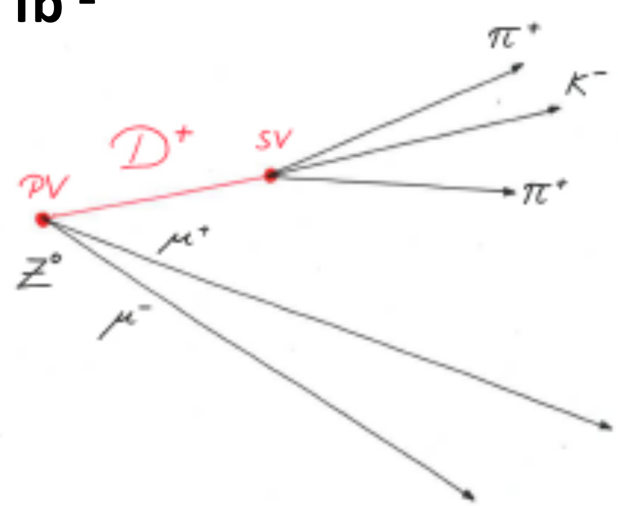
±15% for σ_{eff}

±10% for scales&PDFs

Enhanced DPS p-Pb x-sections: $\sigma_{eff,pp}/\sigma_{eff,pA} \approx 600$
DPS can be observed in p-Pb –> W+W+, W-W- ,
NLO, nuclear PDFs: σ(same-sign WW,DPS) ~ 300 pb (2 – 20 counts/year)

DPS in Z+D @ LHCb

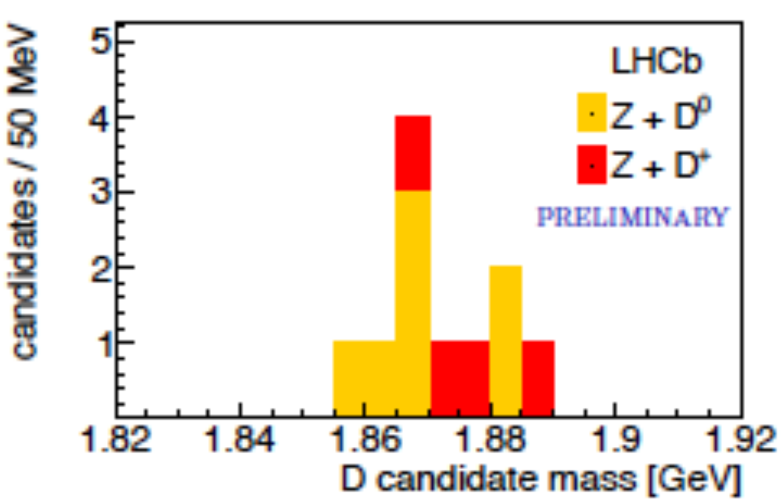
pp collisions at √s = 7 TeV
1 fb^{-1}

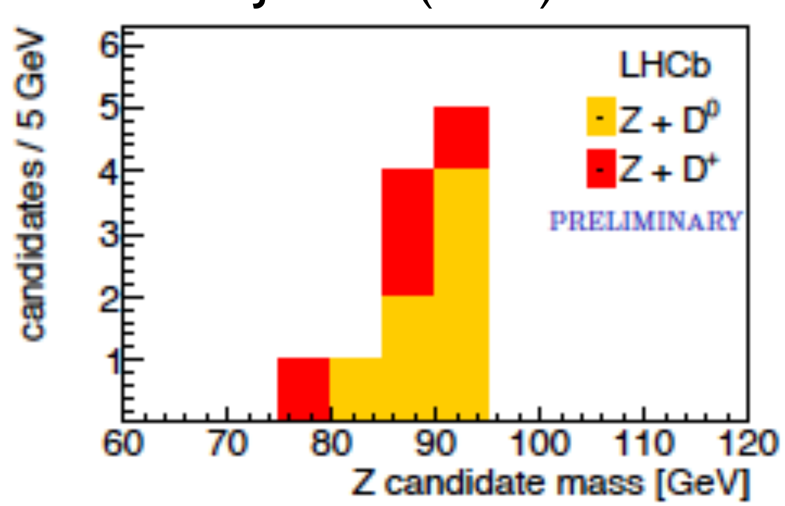


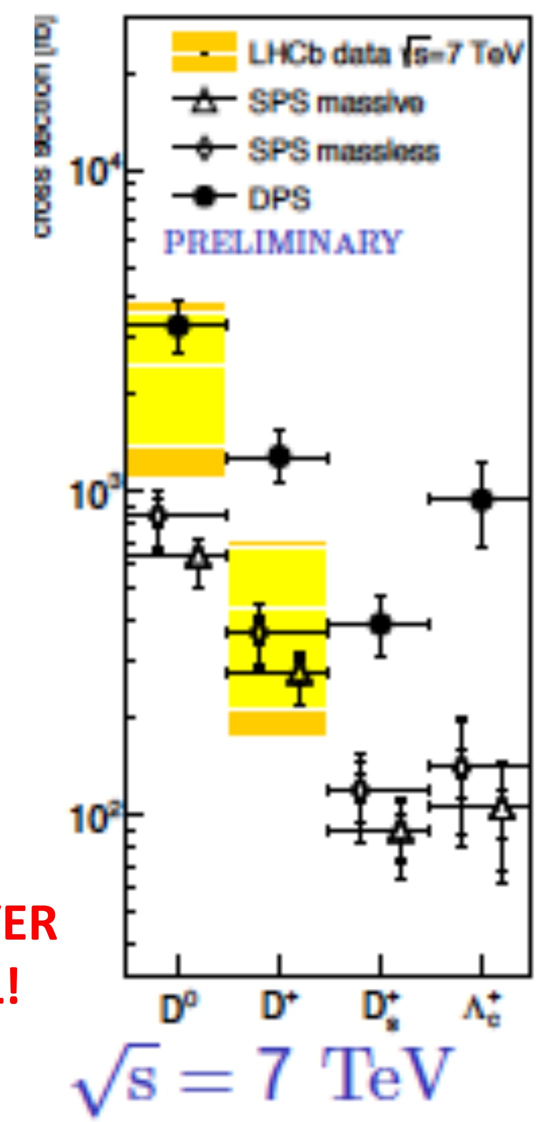
- $q\bar{q}$ initial state
- $2 < \eta_\mu < 4.5$
- $p_{T,\mu} > 20\,\text{GeV}$
- $60 < m_{\mu^+\mu^-} < 120\,\text{GeV}$
- Large statistics available

- D from secondary vertex but associated to the same PV as the Z.
- $2 < p_{T,\text{D}} < 12\,\text{GeV}$

10.1007/JHEP04(2014)091







- Preliminary Measurements!
- $\sigma_{Z\to\mu^+\mu^-,D^0}\mathcal{B}_{Z\to\mu^+\mu^-} = 2.50 \pm 1.12 \pm 0.22\,\text{pb}$
- $\sigma_{Z\to\mu^+\mu^-,D^+}\mathcal{B}_{Z\to\mu^+\mu^-} = 0.44 \pm 0.23 \pm 0.03\,\text{pb}$

VERY FEW EVENTS, HOWEVER SPS BACKGROUND SMALL!

DPS @ LHC: Status and plans

- ✔ Achieved
- ✓ In progress
- ✖ Not possible yet

So far no striking evidence for DPS at hadron collider, need work on model dependence

What is needed

1. Several corrected distributions of observables sensitive to DPS ✔
2. Consistency checks ✓
3. Many processes to study process dependence ✓
4. Differential distributions ✖
5. Additional observables to investigate PDFs factorization and parton correlations ✖

Achieved so far

1. Corrected distributions for: 4jet, 3jets+gamma, W+2jets, W+J/psi, Z+D, double J/psi and double open charm
2. large systematics due to model dependence
3. Precision on measurement doesn't allow further investigation (e.g. differential distributions)

Future…

1. More integrated luminosity is needed for studies on new channels (e.g. same sign W)
2. p-A DPS measurements are expected to have DPS enhanced.

Backup

DPS in W+2jets @ CMS: unfolding

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

Event selection:

– Exactly one μ

– with p_T > 35 GeV, |η| < 2.1

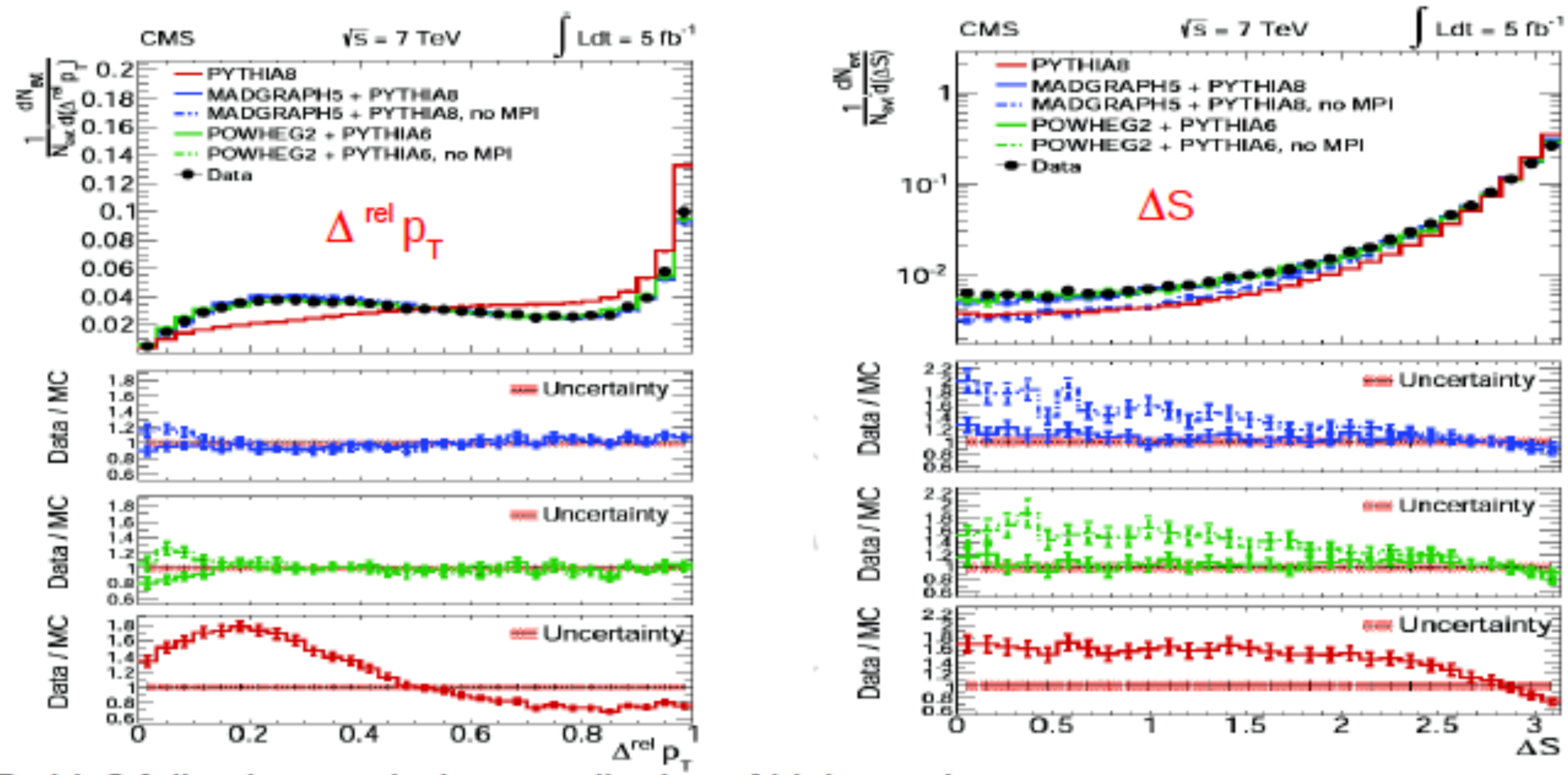
– Required to be isolated and to pass tight ID criteria

– particle flow Missing Transverse Energy, MET > 30 GeV

– transverse mass of (μ and MET) > 50 GeV

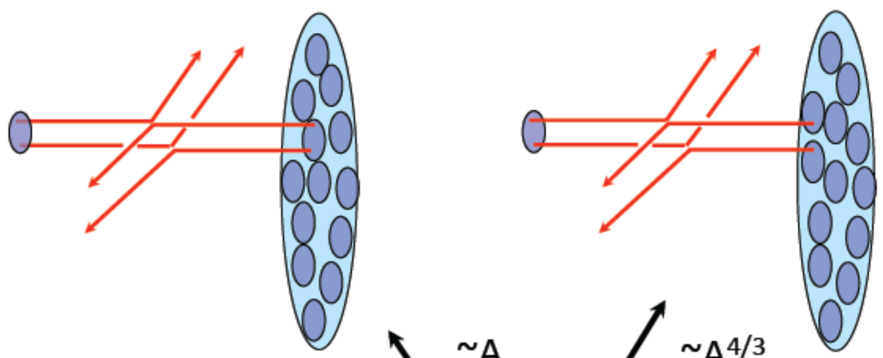
– Exactly 2 anti-KT jets with pT > 20 GeV and |η| < 2.0

(not inclusive, need correction to use the σ_{eff} formalism)



- 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*

DPS in W+2jets in pA



$$\sigma_D^A = \sigma_D^A|_1 + \sigma_D^A|_2$$

$$\sigma_D^{pA}(WJJ)|_1 = \frac{1}{\sigma_{eff}}\left[Z\sigma_S^{p[p]}(W)\sigma_S^{p[p]}(JJ) + (A-Z)\sigma_S^{p[n]}(W)\sigma_S^{p[n]}(JJ)\right]$$

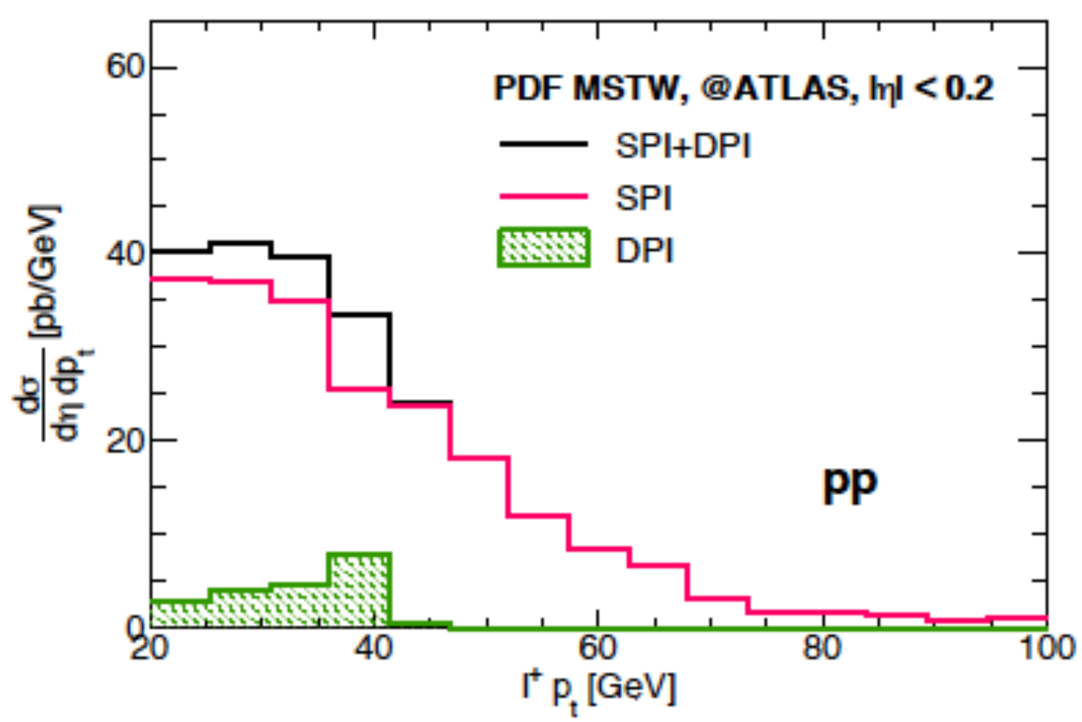
$$\sigma_D^{pA}(WJJ)|_2 = K\left[\frac{Z}{A}\sigma_S^{pp}(W) + \frac{A-Z}{A}\sigma_S^{pn}(W)\right]\sigma_S^{pp}(JJ) \times \left[\int T(B)^2 d^2B - 2\int \rho(B,z)^2 d^2B dz \times r_c \mathcal{C}_K\right]$$

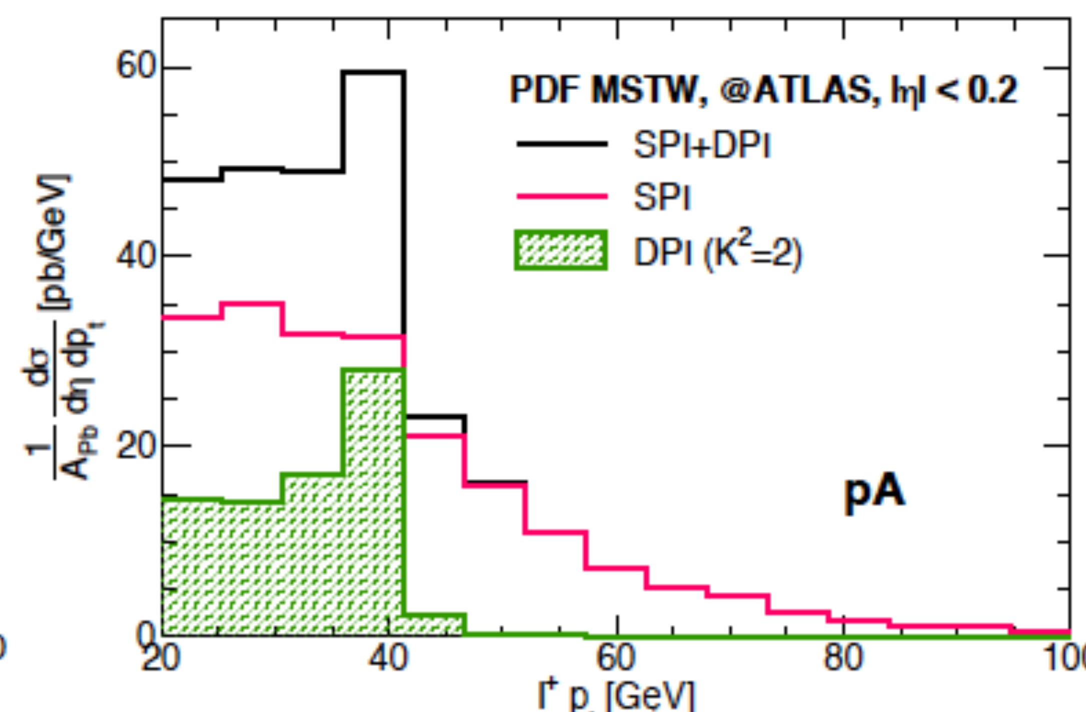
anti-shadowing contribution

short range nuclear correlation

nuclear thickness function => growth as $A^{4/3}$

nuclear density => growth as A





[D.Treleani, MPI@LHC 2013, Antwerpen]

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Enhanced shoulder at ≈ 40 GeV in pA interactions!

Measurement of cross sections and normalized distributions of jet spectra and correlation observables

Data samples

- pp collisions @ 7 TeV
- Integrated luminosity: 36 pb^{-1}
- very low pile-up conditions
- single jet triggers

- Request for at least one good reconstructed primary vertex
- Particle Flow Jets clustered with the 0.5 anti-k_T algorithm
- Selection of exactly four jets in $|\eta| < 4.7$:
  - two jets with $p_T > 50$ GeV
  - two jets with $p_T > 20$ GeV
- Tight selection applied for the selected jets

The jets are associated in pairs:

- **hard-jet pair**: the two leading jets above 50 GeV
- **soft-jet pair**: the other two selected jets above 20 GeV

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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