$Q\bar{Q}$ production from double-parton scattering in p-A & A-A collisions at the LHC

New observables in $Q\bar{Q}$ production

ECT* Trento, 2nd March 2016

David d'Enterria

CERN

(*) Most of the results based upon:

D.d'E & A.Snigirev, arXiv:1211.0197 [PLB 718 (2013) 1395]

D.d'E & A.Snigirev, arXiv:1301.5845 [PLB 727 (2013) 157]

D.d'E & A.Snigirev, arXiv:1408.5172 [NPA 931 (2014) 303]

Outline

- Introduction – Double Parton Scattering in p-p collisions:
  - Empirical "pocket formula" for the DPS x-sections
  - Experimental DPS studies: difficulties in σ_{eff} extraction

- Double-Parton-Scattering in p-A collisions:
  - DPS "pocket formula" x-section. Enhancement factor wrt. DPS(pp): $\times 3 \cdot A$
  - x-sections & rates for DPS processes with J/ψ,Υ & W,Z bosons: N_{DPS}=5–65
  - Case study: Same-sign WW in p-Pb at 8.8 TeV:

    σ(ssWW,DPS) ≈ 150 pb > σ(ssWWjj,SPS) ≈ 100 pb

    $N_{visible}$(ssWW,DPS) ≈ 5 (leptonic decays) at 8.8 TeV

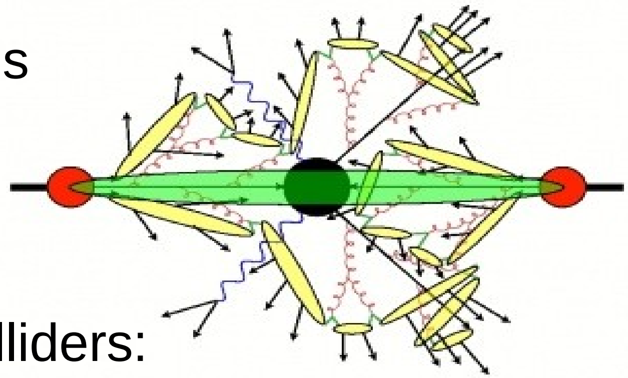
- Double-Parton-Scattering in A-A collisions:
  - DPS "pocket formula" x-section. Enhancement factor wrt. DPS(pp): $\times A^{3.3}/5$
  - x-sections & rates for DPS processes w/ J/ψ,Υ & W,Z bosons: N_{DPS}=10–250
  - Case study: Double-J/ψ in Pb-Pb at 5.5 TeV:

    20% (30%) of MB (central) Pb-Pb colls. produce 2 J/ψ

    $N_{visible}(J/\psi J/\psi \rightarrow l^+l^-l^+l^-) \approx 250$ at 5.5 TeV

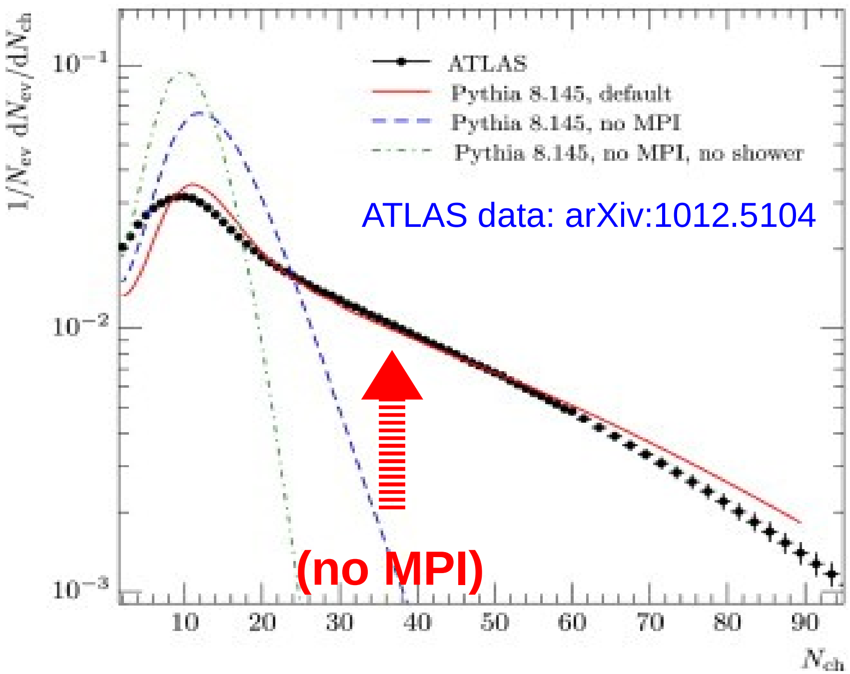
Multi-parton interactions at the LHC

- MPI are intrinsic component of hadron collisions (p,Pb) = non-pointlike objects with finite transverse size and increasingly larger gluon density.

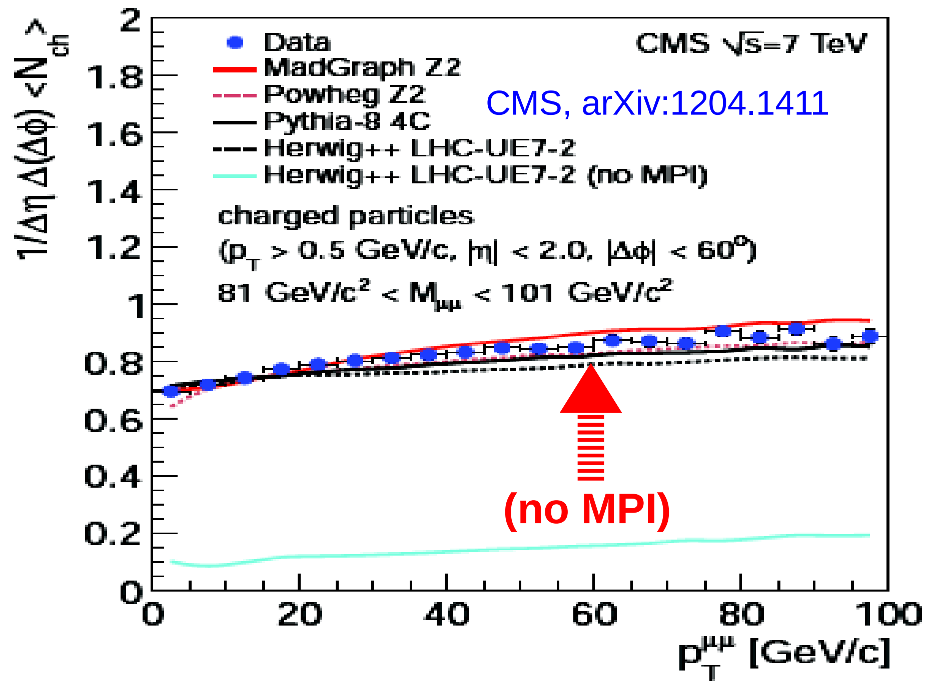


- MPI O(1-3 GeV) clearly observed in hadron colliders:

~50% of total hadron production

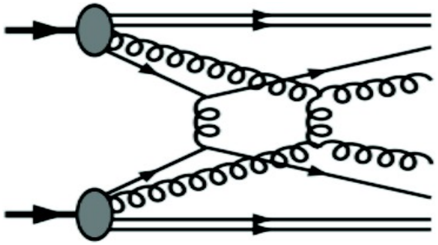


Underlying event in hard scatterings:



- Double hard parton scatts. O(3-100 GeV) should also take place. Seen?

Double Parton Scattering x-sections (p-p)



- Hard DPS provides direct info on transverse parton transverse-profile & correlations in proton:

- pQCD factorized expression for DPS x-section:

$$\sigma^{\rm DPS}_{(hh'\to ab)} = \left(\frac{m}{2}\right)\sum_{i,j,k,l}\int \Gamma^{ij}_{h}(x_1,x_2;\mathbf{b_1},\mathbf{b_2};Q_1^2,Q_2^2)\times\hat{\sigma}^{ik}_{a}(x_1,x_1',Q_1^2)\,\hat{\sigma}^{jl}_{b}(x_2,x_2',Q_2^2)$$
$$\times\Gamma^{kl}_{h'}(x_1',x_2';\mathbf{b_1}-\mathbf{b},\mathbf{b_2}-\mathbf{b};Q_1^2,Q_2^2)\,dx_1dx_2dx_1'dx_2'd^2b_1d^2b_2d^2b$$

Generalized PDFs = f(x,Q^2,**b**)

- Assumption 1: Factorization of transverse & longitudinal components

$$\Gamma^{ij}_{h}(x_1,x_2;\mathbf{b_1},\mathbf{b_2};Q_1^2,Q_2^2) = D^{ij}_{h}(x_1,x_2;Q_1^2,Q_2^2)\,f(\mathbf{b_1})f(\mathbf{b_2})$$

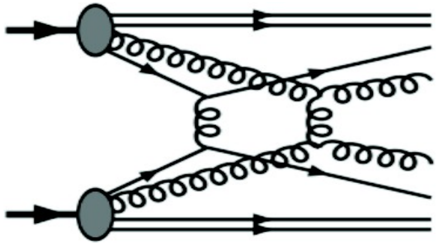
p-p overlap function: $$t(\mathbf{b}) = \int f(\mathbf{b_1})f(\mathbf{b_1}-\mathbf{b})d^2b_1$$

- Assumption 2: Double-PDF = product of 2 single PDF (no correlations)

$$D^{ij}_{h}(x_1,x_2;Q_1^2,Q_2^2) = D^{i}_{h}(x_1;Q_1^2)\,D^{j}_{h}(x_2;Q_2^2)$$

[Treleani, Diehl, Ryskin, Snigirev, Blok, Strikman, Gaunt, ...]

Double Parton Scattering x-sections (p-p)



- Hard DPS provides direct info on transverse parton transverse-profile & correlations in proton:

- pQCD factorized expression for DPS x-section:

$$\sigma^{\rm DPS}_{(hh'\to ab)} = \left(\frac{m}{2}\right)\sum_{i,j,k,l}\int \Gamma^{ij}_{h}(x_1,x_2;\mathbf{b_1},\mathbf{b_2};Q_1^2,Q_2^2)\times\hat{\sigma}^{ik}_{a}(x_1,x_1',Q_1^2)\,\hat{\sigma}^{jl}_{b}(x_2,x_2',Q_2^2)$$
$$\times\Gamma^{kl}_{h'}(x_1',x_2';\mathbf{b_1}-\mathbf{b},\mathbf{b_2}-\mathbf{b};Q_1^2,Q_2^2)\,dx_1dx_2dx_1'dx_2'd^2b_1d^2b_2d^2b$$

Generalized PDFs = f(x,Q^2,**b**)

- Simplified interpretation for DPS x-section:

$$\sigma^{\rm DPS}_{(hh'\to ab)} = \left(\frac{m}{2}\right)\frac{\sigma^{\rm SPS}_{(hh'\to a)}\cdot\sigma^{\rm SPS}_{(hh'\to b)}}{\sigma_{\rm eff}}$$

p-p overlap function (mb^{-1})

$$\sigma_{\rm eff} = \left[\int d^2b\, t^2(\mathbf{b})\right]^{-1} \approx \mathbf{35\ mb}$$

- Experimentally (CDF'97):

$\sigma_{\rm eff}$(exp) ≈ 15 mb ⇒

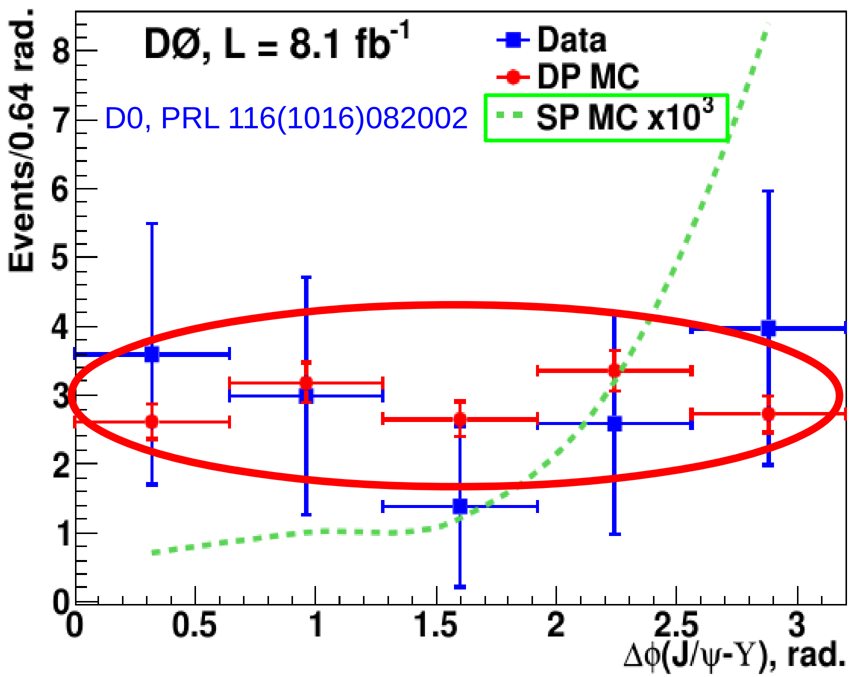
proton "hard" radius: r = 0.3–0.7 fm

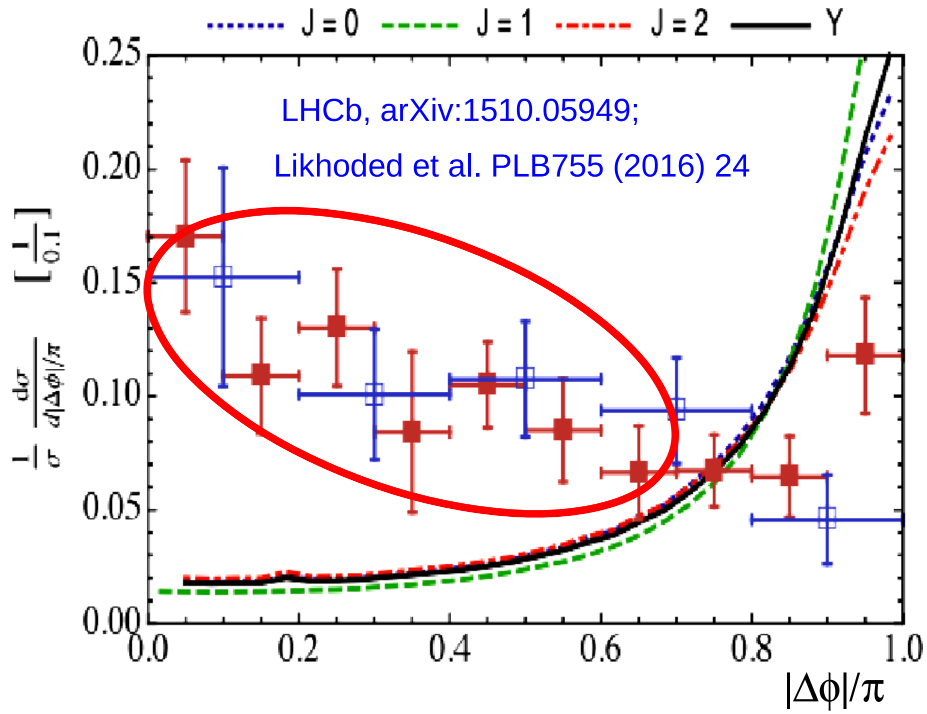
(smaller than e.m. one)

Model for density	Form of density, dN/d^3r	Predictions rms r	Predictions $\sigma_{\rm eff}$	Measurements Scale (fm)
Solid sphere	Constant, $r<r_p$	$\sqrt{3/5}r_p$	$4\pi r_p^2/4.6$	$r_p=0.73$
Gaussian	$e^{-r^2/2\Sigma^2}$	$\sqrt{3}\Sigma$	$4\pi\Sigma^2$	$\Sigma=0.34$
Exponential	$e^{-r/\lambda}$	$\sqrt{12}\lambda$	$35.5\lambda^2$	$\lambda=0.20$
Fermi, $\lambda/r_0=0.2$	$(e^{(r-r_0)/\lambda}+1)^{-1}$	$1.07r_0$	$4.6r_0^2$	$r_0=0.56$

DPS studies with $Q\bar{Q}$: p-$\bar{\text{p}}$,p-p → J/Ψ+Υ, Υ+D

- Uncorrelated J/Ψ+Υ azimuthal production in ppbar at 1.96 TeV:
- Uncorrelated Υ+D azimuthal production in pp at 7 TeV:





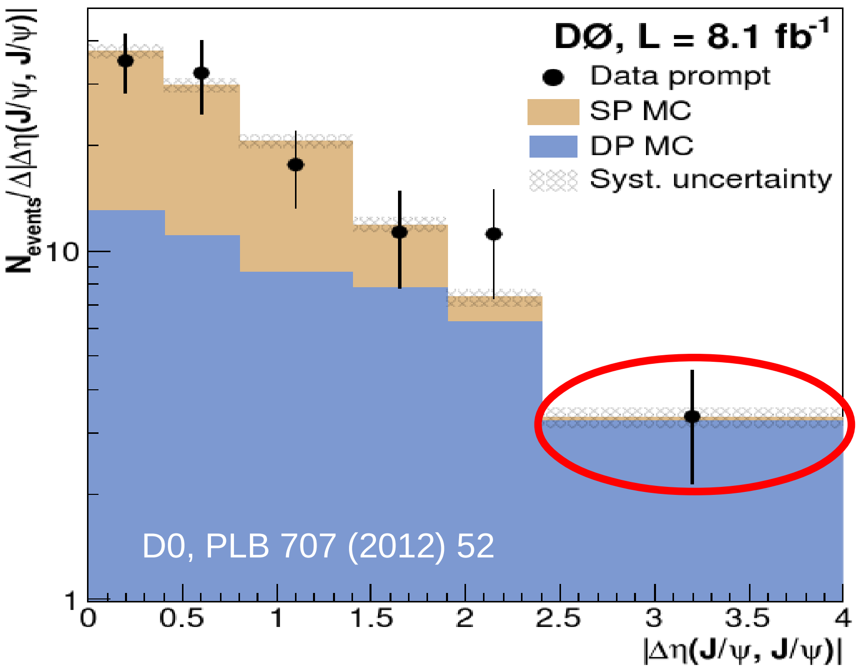
$\sigma_{\text{eff}} = 2.2 \pm 0.7\,(\text{stat}) \pm 0.9\,(\text{syst})\ \text{mb}.$

$\sigma_{\text{eff}}|_{\Upsilon(1S)D} = 18.0 \pm 1.3\,(\text{stat}) \pm 1.2\,(\text{syst})\ \text{mb}$

- Extracted σ_{eff} values differ by up to a factor of 8 for similar (g-induced) processes at 1.96 TeV & 7 TeV:
  – (Higher-order) SPS contributions under control?
  – Energy-dependent parton transverse profile?

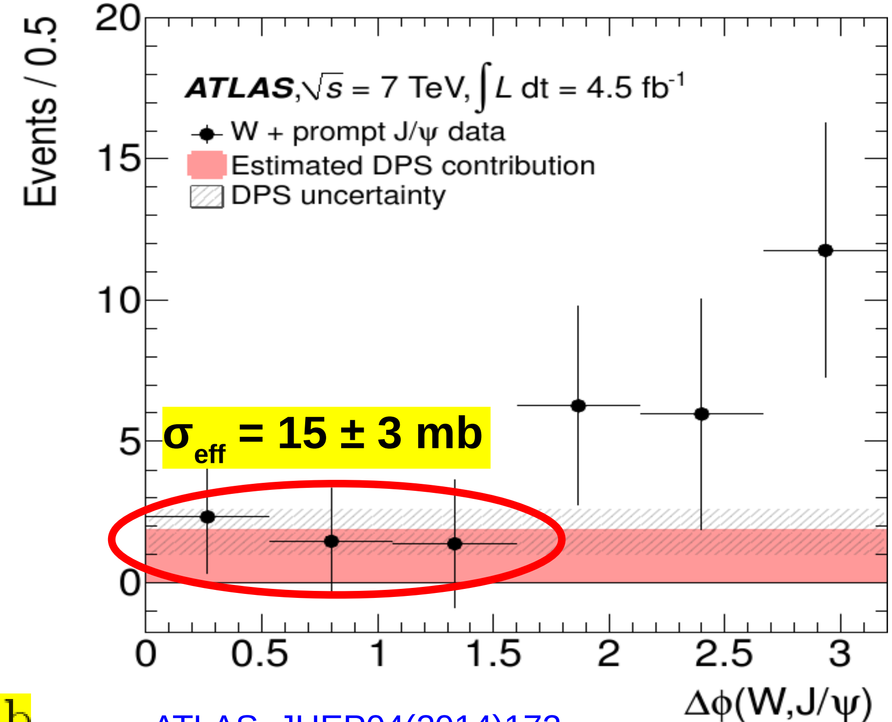
DPS studies with $Q\bar{Q}$: p-p → W^++J/Ψ, J/ΨJ/Ψ

- Uncorrelated J/Ψ+J/Ψ rapidity production in ppbar at 1.96 TeV:



$$\sigma_{\text{eff}} = 4.8 \pm 0.5(\text{stat}) \pm 2.5(\text{syst}) \text{ mb}$$

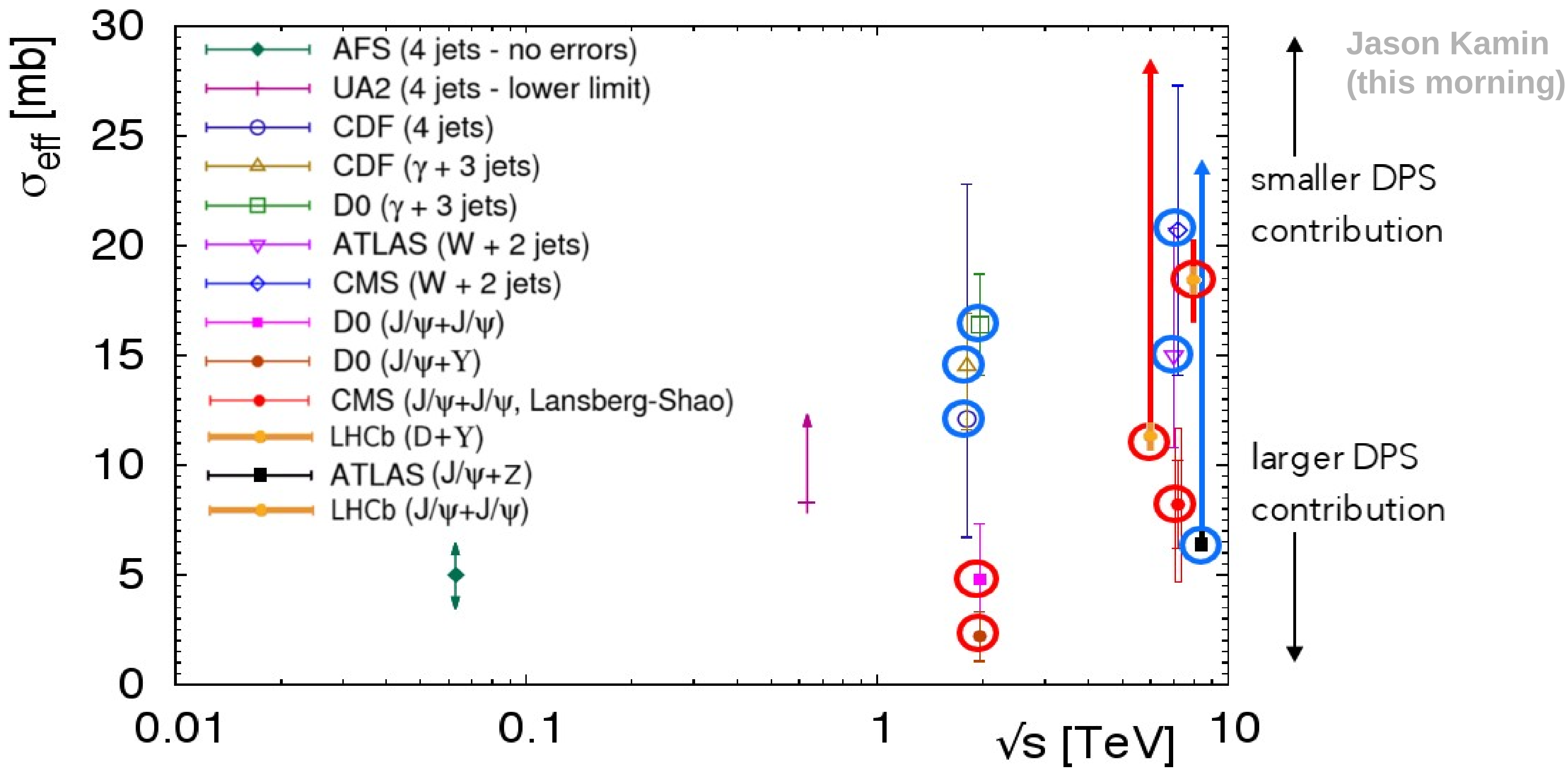
- Uncorrelated W+J/Ψ azimuthal production in pp at 7 TeV:



ATLAS, JHEP04(2014)172

- Extracted σ_{eff} values differ at 1.96 TeV & 7 TeV:
  - (Higher-order) SPS contributions under control?
  - Energy-dependent parton transverse profile? (Quark vs. gluon?)

Summary of world σ_{eff} extractions



- Extracted σ_{eff} values differ from ~2 mb to ~20 mb:
  - (Higher-order) SPS contributions removed differently/properly ?
  - Energy evolution of parton transverse profile ?
  - Different (contradictory?) results for **g-g** & **q-g** processes ?

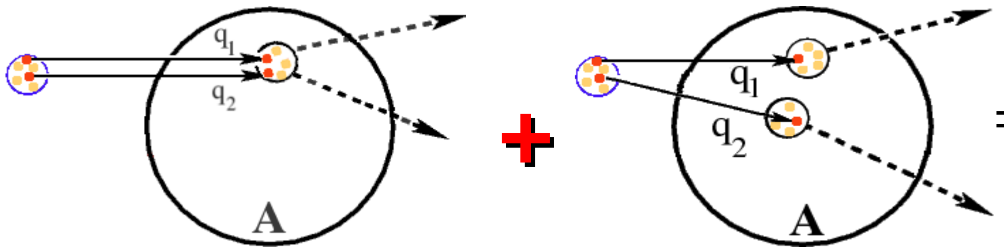
☛ Can p-Pb and Pb-Pb collisions improve our understanding of DPS ?

Double Parton Scatterings in p-Pb at the LHC

Double Parton Scattering x-sections (p-Pb)

[DdE,Snigirev, PLB718 (2013)1395]
[Treleani, Strikman, ...]

- 2 contributions to DPS x-section in p-A:



$$\Rightarrow \sigma^{DPS}_{(pA)} = \sigma^{DPS,1}_{(pA)} + \sigma^{DPS,2}_{(pA)}$$

$$\sigma^{DPS,1}_{(pA\to ab)} = A \cdot \sigma^{DPS}_{(pN\to ab)} \quad + \quad \sigma^{DPS,2}_{(pA\to ab)} = \sigma^{DPS}_{(pN\to ab)} \cdot \sigma_{\rm eff,pp} \cdot \mathrm{F}_{\rm pA}$$

$$\mathrm{F}_{\rm pA} = \int d^2r\, \mathrm{T}^2_{\rm pA}(\mathbf{r}) = 30.4\ \mathrm{mb}^{-1}$$

p-A overlap function

Pb Woods-Saxon density (r=6.62 fm, a=0.546 fm)

► Factorized expression for DPS p-A x-section:

$$\sigma^{DPS}_{(pA\to ab)} = \left(\frac{m}{2}\right) \frac{\sigma^{SPS}_{(pN\to a)} \cdot \sigma^{SPS}_{(pN\to b)}}{\sigma_{\rm eff,pA}}$$

$$\sigma_{\rm eff,pA} = \frac{\sigma_{\rm eff,pp}}{A + \sigma_{\rm eff,pp}\,\mathrm{F}_{\rm pA}} = 21.5 \pm 1.1\ \mu b$$

($\sigma_{\rm eff}$=13±2mb)

► Ratio of DPS p-Pb/p-p x-sections: $\sigma_{\rm eff,pp} / \sigma_{\rm eff,pA} \approx 3\,A \approx 600$!

- DPS processes are large and can be unambiguously observed in p-A.
- Pb transverse density (F_{pA}) well known. Determine $\sigma_{\rm eff,pp}$?

DPS cross sections in p-Pb (8.8 TeV)

[DdE,Snigirev, NPA 931 (2014)303]

- Cross sections & rates for DPS processes with J/ψ,Υ & W, Z bosons:

NLO: $\sigma^{\rm SPS}_{\rm pN\to J/\psi} = 45$ μb, $\sigma^{\rm SPS}_{\rm pN\to\Upsilon} = 2.6$ μb, $\sigma^{\rm SPS}_{\rm pN\to W} = 60$ nb, and $\sigma^{\rm SPS}_{\rm pN\to Z} = 35$ nb

System		$J/\psi+J/\psi$	$J/\psi+\Upsilon$	$J/\psi+\mathrm{W}$	$J/\psi+\mathrm{Z}$
p–Pb	$\sigma^{\rm DPS}$	45 μb	5.2 μb	120 nb	70 nb
8.8 TeV	$\mathrm{N}^{\rm DPS}(1\ \mathrm{nb}^{-1})$	∼65	∼60	∼15	∼3
		$\Upsilon+\Upsilon$	$\Upsilon+\mathrm{W}$	$\Upsilon+\mathrm{Z}$	ss WW
p–Pb	$\sigma^{\rm DPS}$	150 nb	7 nb	4 nb	150 pb
8.8 TeV	$\mathrm{N}^{\rm DPS}(1\ \mathrm{nb}^{-1})$	∼15	∼8	∼1.5	∼5

Leptonic final states: BR(J/ψ,Υ,W,Z) = 6%, 2.5%, 11%, 3.4%

Accept.*effic.= 1% (J/ψ, |y|=0,2), 20% (Υ, |y|<2.5), 50% (W,Z |y|<2.4)

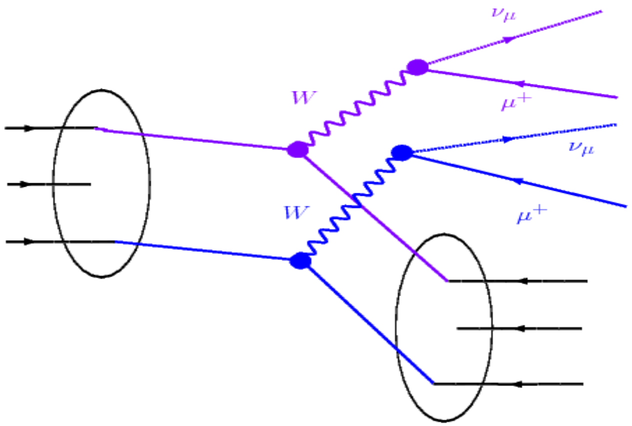
- Many double hard scatterings processes w/ visible p-Pb x-sections

DPS "golden channel": Same-sign WW

[Kulesza, Stirling, Gaunt, Treleani, Del Fabbro, ...]

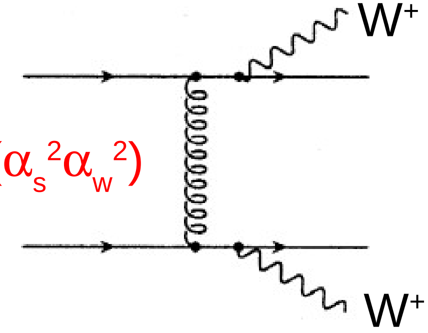
- Same-sign W-W production from 2 independent hard scatterings is a "golden" DPS signature:

  - Well controlled pQCD x-sections.
  - Clean experimental final-state: 2 like-sign leptons + missing-E_T

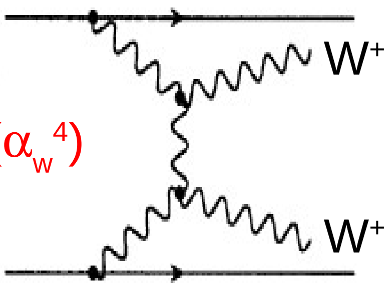


- Backgrounds: Same-sign W-W production in single parton scatterings (SPS) is higher-order and occurs only with 2 extra jets:

QCD ($\alpha_s^2\alpha_w^2$)



EWK (α_w^4)



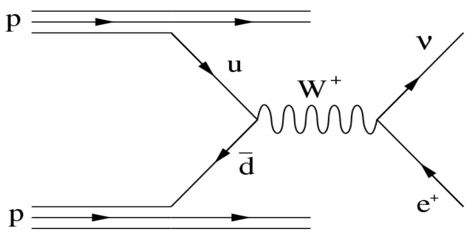
- σ(WW,DPS)~1/3·σ(WWjj,SPS), but SPS background reducible by more than x20 applying jet cuts.

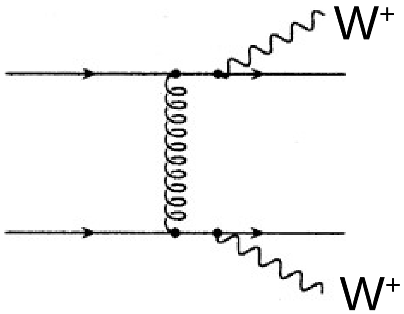
Case study: p-Pb → W^+W^+,W^-W^- at 8.8 TeV

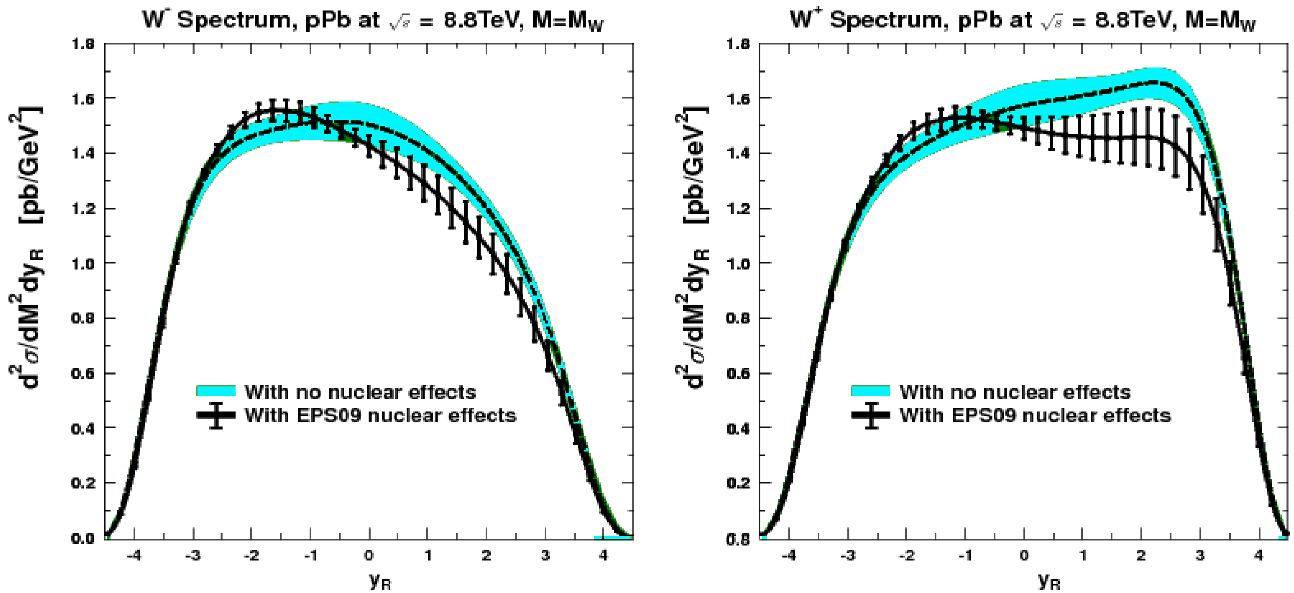
[DdE,Snigirev, PLB718 (2013)1395]

- Theoretical setup:
  - MCFM 6.2: Single-parton W^+,W^-
    W^+W^+jj (QCD) background
    - NLO accuracy.
    - Scales: $\mu(W) = m_W$, $\mu(WW) = 150$ GeV
    - CT10 proton PDF, EPS09 Pb nuclear PDF:

    ~10% effects due nuclear (anti)shadowing alone:







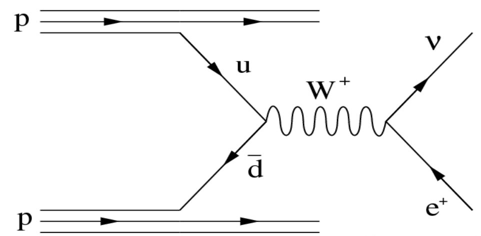
[Paukkunen&Salgado JHEP 1103 (2011) 071]

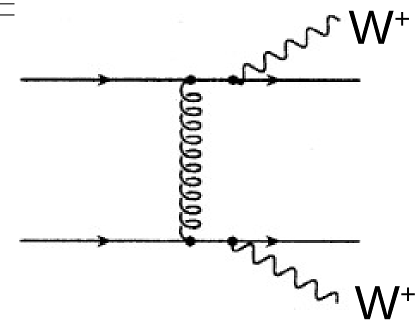
Isospin+shadow. effects on total inclusive x-sections:
W^- : +7%
W^+ : -15%
compared to p-p

Case study: p-Pb → W^+W^+, W^-W^- at 8.8 TeV

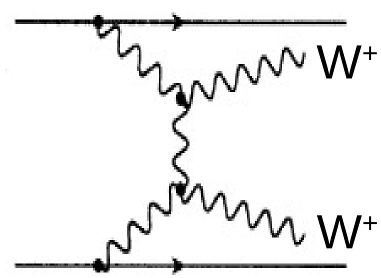
[DdE,Snigirev, PLB718 (2013)1395]

- **Theoretical setup:**
  - MCFM 6.2: Single-parton W^+,W^- W^+W^+jj (QCD) background
    - NLO accuracy.
    - Scales: $\mu(W) = m_W$, $\mu(WW) = 150$ GeV
    - CT10 proton PDF, EPS09 Pb nuclear PDF
    - Uncertainties: ~10%





  - VBFNLO 2.6.0: W^+W^+jj (EWK) background
    - NLO accuracy
    - Scales: $\mu^2 = t_{W,Z}$
    - CT10 PDF
    - Uncertainties: <10%



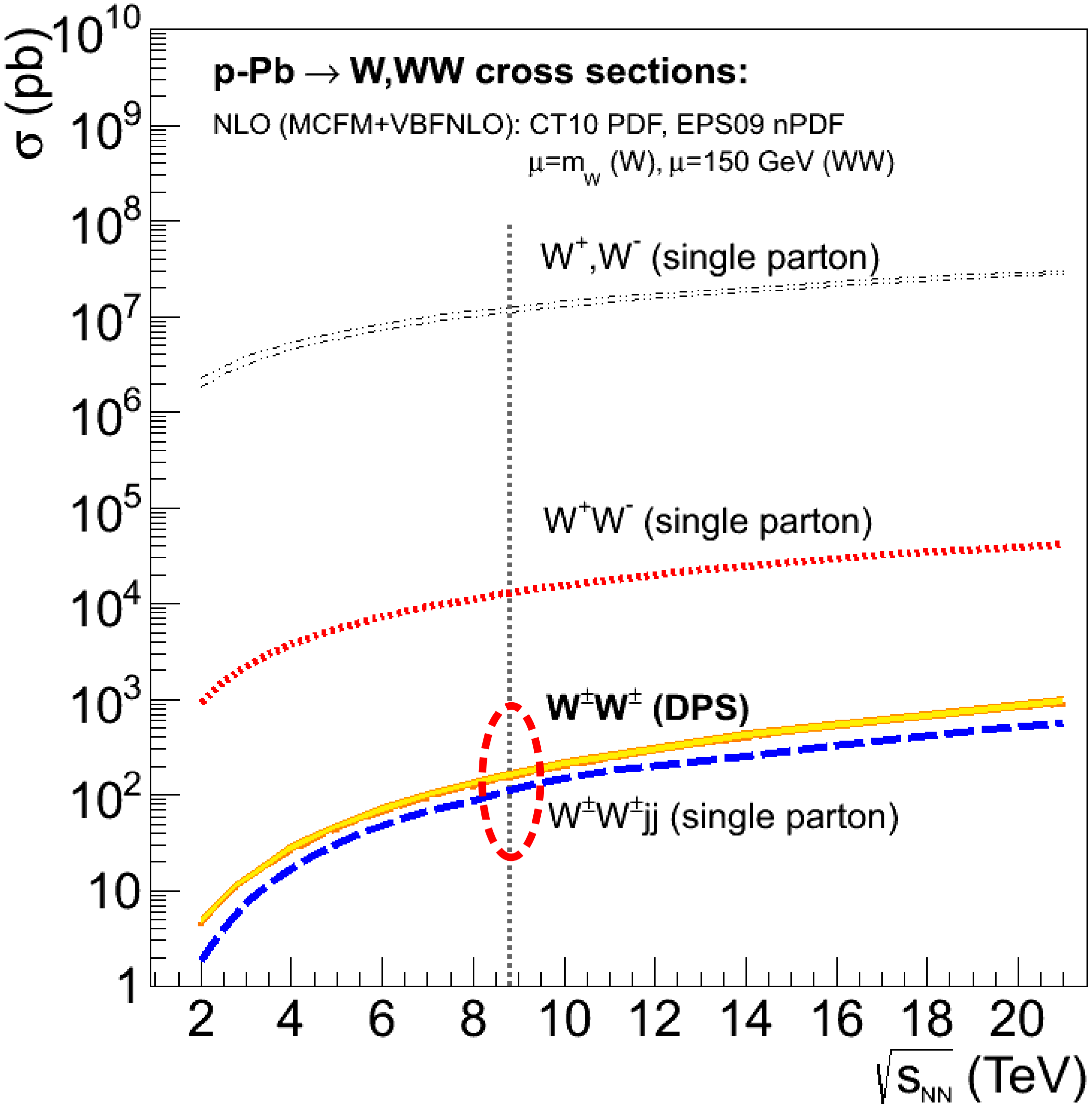
- **Cross sections in pb** (signal & background):

p-Pb final-state:	W^+	W^-	W^+W^-	W^+W^+jj (QCD)	W^+W^+jj (VBF)	$W^\pm W^\pm$ (DPS)
Code (process #):	MCFM (1)	MCFM (6)	MCFM (61)	MCFM (251)	VBFNLO (250)	Eq. (15)
Order (σ units):	NLO (μb)	NLO (μb)	NLO (nb)	'NLO' (pb)	NLO (pb)	(pb)
$\sqrt{s_{NN}} = 5.0$ TeV	6.85 ± 0.68	5.88 ± 0.59	5.48 ± 0.56	12.1 ± 1.2	12.4 ± 0.6	$44. \pm 8.$
$\sqrt{s_{NN}} = 8.8$ TeV	12.6 ± 1.3	11.1 ± 1.1	13.0 ± 1.3	40.4 ± 4.0	51.8 ± 2.0	$152. \pm 27.$

Results: p-Pb → W^+W^+, W^-W^- at 8.8 TeV

[DdE,Snigirev, PLB718 (2013)1395]

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



p-Pb @ 8.8 TeV:

$\sigma(WW,DPS) \approx$ 150 pb

$\sigma(WWjj) \approx$ 100 pb

±18% uncertainties:

±15% for σ_{eff}

±10% for scales&PDFs

Results: p-Pb → W^+W^+, W^-W^- at 8.8 TeV

[DdE,Snigirev, PLB718 (2013)1395]

- Measurable final-states:
  - ► W's branching ratios:
    - BR(W→ lν) ≈ 3 ×1/9, BR(W→qq') ≈ 2/3
    - Both leptonic: 4 final-states (μμ,ee,eμ,μe): $4\times(1/9)^2$ ≈ 1/20, 1/16 (+ τ)

    [1 leptonic + 1 hadronic (jet-charge): 2/9 ×4/3 ≈ 0.3]
  - ► Typical ATLAS/CMS acceptances & efficiencies:
    - Leptons: |y|<2.5, p_T >15 GeV ⇒ ε_{WW} ≈ 40%
- LHC p-Pb luminosities (note: very small pileup):
  - ► $\mathcal{L}_{\rm int}$ = 0.2–2 pb^{-1} (increase to nominal p intensity, reduce beam size)
- Expected (purely leptonic) rates including yield loses & luminosity:

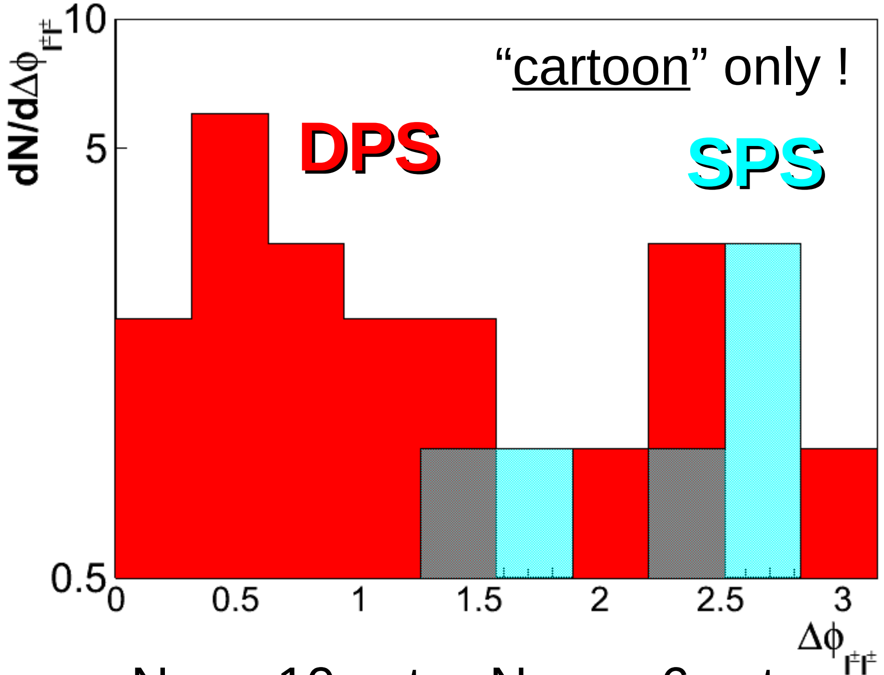
$$N_{\rm DPS} = \sigma^{\rm DPS}_{pPb\to WW}/(\varepsilon\cdot\mathcal{L}_{\rm int}) \approx$$ 1–10 same-sign WW pairs/year

(factor ×6 more in 1 lepton + 1-jet channel)

Results: p-Pb → W^+W^+, W^-W^- at 8.8 TeV

- Typical DPS-sensitive kinematical distributions for signal & background:

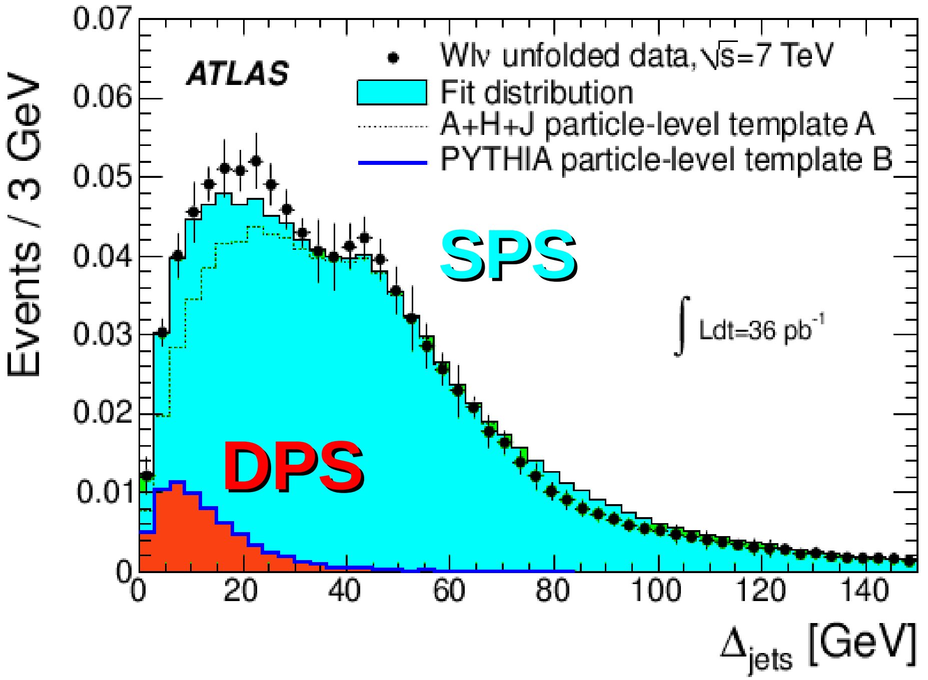
p-Pb @ 8.8 TeV (2 pb^{-1}):
Same-sign leptons
azimuthal separation:



$N_{DPS} \approx 10$ evts $N_{SPS} \approx 6$ evts

(Other reducible bckgds: WZ, $Z^{(*)}Z^{(*)}$, B^0B^0)

Compare to:
p-p → W+2j @ 7 TeV (36 pb^{-1}):
dijet azimuthal separation

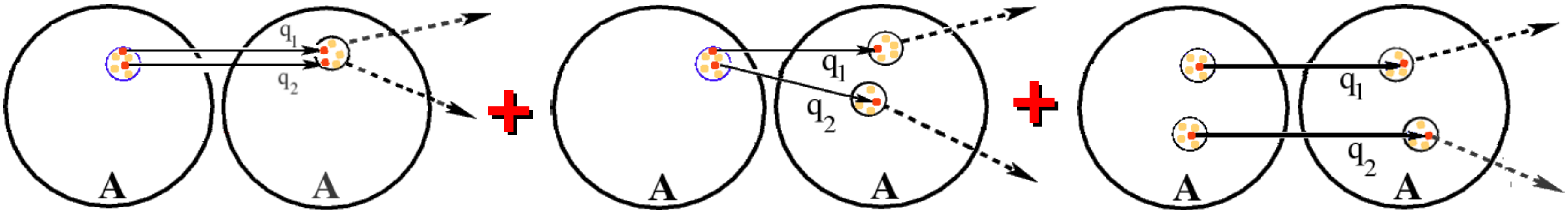


Double Parton Scatterings in Pb-Pb at the LHC

Double Parton Scattering x-sections (Pb-Pb)

[DdE,Snigirev, PLB727 (2013)157]

- 3 contributions to DPS x-section in A-A:



$$\sigma^{\rm DPS,1}_{(AA\to ab)} = A^2 \cdot \sigma^{\rm DPS}_{(NN\to ab)}$$

$$\sigma^{\rm DPS,2}_{(AA\to ab)} \approx 2\sigma^{\rm DPS}_{(NN\to ab)} \cdot \sigma_{\rm eff,pp} \cdot A \cdot T_{AA}(0)$$

$$\sigma^{\rm DPS,3}_{(AA\to ab)} \approx \sigma^{\rm DPS}_{(NN\to ab)} \cdot \sigma_{\rm eff,pp} \cdot A^2/\, 2 \cdot T_{AA}(0)$$

  - ► Third "N_{coll} term" $\propto A^2 \cdot T_{AA}(0)$, clearly dominant (1:4:200 ratio)

    "Genuine" DPS (within same nucleon): ~2.5%

- Factorized expression for DPS A-A x-section:

$$\sigma^{\rm DPS}_{(AA\to ab)} = \left(\frac{m}{2}\right) \frac{\sigma^{\rm SPS}_{(NN\to a)} \cdot \sigma^{\rm SPS}_{(NN\to b)}}{\sigma_{\rm eff,AA}}$$

$$\sigma_{\rm eff,AA} = \frac{1}{A^2[\sigma^{-1}_{\rm eff,pp} + \frac{2}{A}T_{AA}(0) + \frac{1}{2}T_{AA}(0)]} = 1.5\ {\rm nb}$$

  - ► Ratio of DPS Pb-Pb/p-p x-sections: $\sigma_{\rm eff,pp}/\sigma_{\rm eff,AA} \propto A^{3.3}/5 \simeq 9 \cdot 10^6$!

- Strong centrality dependence:

$$\sigma^{\rm DPS}_{(AA\to ab)}[b_1,b_2] \approx \left(\frac{m}{2}\right) \sigma^{\rm SPS}_{(NN\to a)} \cdot \sigma^{\rm SPS}_{(NN\to b)} \cdot f_{\%}\sigma_{AA} \cdot \langle T_{AA}[b_1,b_2]\rangle^2$$

DPS cross sections in Pb-Pb (5.5 TeV)

[DdE,Snigirev, NPA 931 (2014)303]

- Cross sections & rates for DPS processes with J/ψ,Υ & W, Z bosons:

NLO: $\sigma^{\rm SPS}_{\rm NN\to J/\psi} = 25\ \mu{\rm b},\ \sigma^{\rm SPS}_{\rm NN\to \Upsilon} = 1.7\ \mu{\rm b},\ \sigma^{\rm SPS}_{\rm NN\to W} = 30\ {\rm nb},\ \sigma^{\rm SPS}_{\rm NN\to Z} = 20\ {\rm nb}$

System		$J/\psi+J/\psi$	$J/\psi+\Upsilon$	$J/\psi+$W	$J/\psi+$Z
Pb–Pb	$\sigma^{\rm DPS}$	210 mb	28 mb	500 μb	330 μb
5.5 TeV	$N^{\rm DPS}(1\ {\rm nb}^{-1})$	~250	~340	~65	~14
		$\Upsilon+\Upsilon$	$\Upsilon+$W	$\Upsilon+$Z	ss WW
Pb–Pb	$\sigma^{\rm DPS}$	960 μb	34 μb	23 μb	630 nb
5.5 TeV	$N^{\rm DPS}(1\ {\rm nb}^{-1})$	~95	~35	~8	~15

Leptonic final states: BR(J/ψ,Υ,W,Z) = 6%, 2.5%, 11%, 3.4%

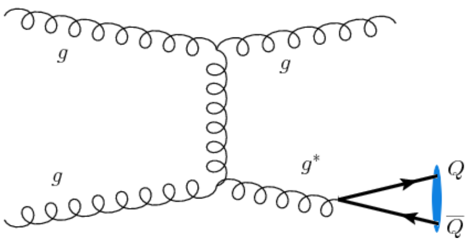
Accept.*effic.= 1% (J/ψ, |y|=0,2), 20% (Υ, |y|<2.5), 50% (W,Z |y|<2.4)

- Visible rates for many double hard scatterings processes in Pb-Pb!

Case study: Pb-Pb → J/ψ J/ψ at 5.5 TeV

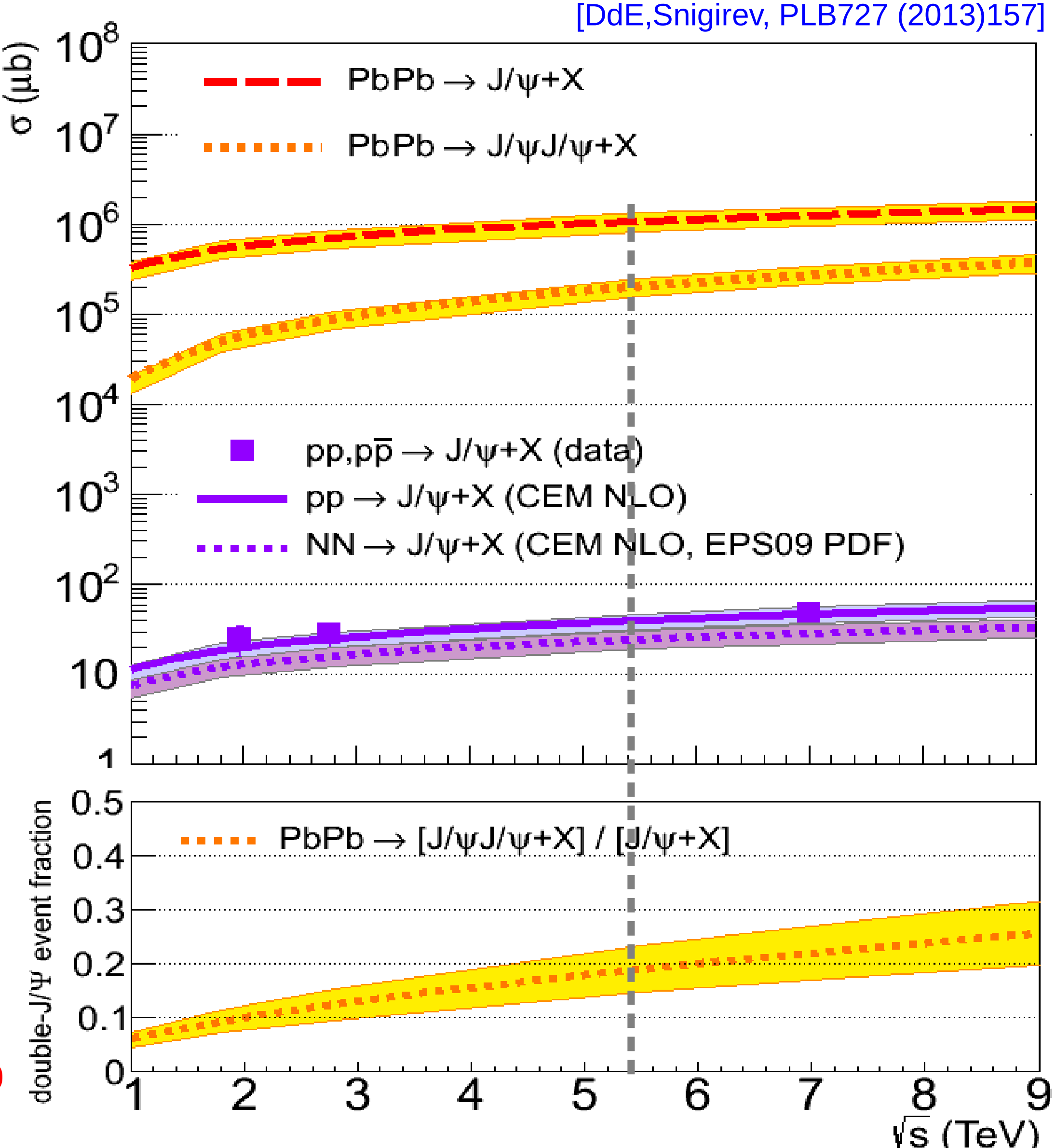
[DdE,Snigirev, PLB727 (2013)157]

- FONLL+CEM (R.Vogt): Single-parton J/ψ



- NLO accuracy.
- Scales: $\mu_R = \mu_R = 1.5 \cdot m_c$
- Good agreement with Tevatron&LHC data
- EPS09 Pb nPDF

20–35% shadowing x-section reduction



- At 5.5 TeV:

$\sigma^{DPS}(\text{Pb–Pb} \to J/\psi\, J/\psi\, X)$ =200±50 mb

20% of Pb-Pb collisions have two J/ψ produced !

Results: Pb-Pb → J/ψ J/ψ at 5.5 TeV

[DdE,Snigirev, PLB727 (2013)157]

- Visible rates:
  - Reduced x-sections per unit-y: $d\sigma_{J/\psi}/dy \approx \sigma_{J/\psi}/8$
  - BR(J/ψ→ l^+l^-) ≈ 6%
  - Typical ALICE/CMS acceptance & efficiencies: $\varepsilon \approx 1/12$

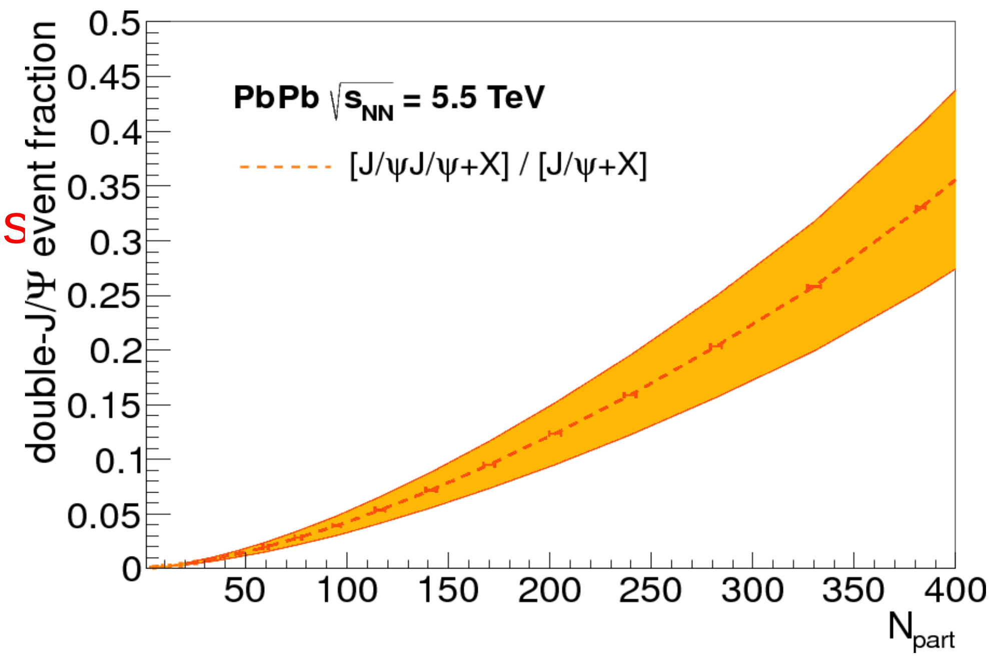
- Expected dimuon rates including yield all loses & 1 nb^{-1} integ. luminosity:

$$\mathcal{N} = \sigma^{\rm DPS}_{\text{Pb-Pb} \to J/\psi\, J/\psi'} / (\varepsilon \cdot \mathcal{L}_{\rm int}) \approx$$ 250 double-J/ψ per year

(x2 less including final-state suppression)

- Centrality dependence of double-J/ψ fraction: 35% of central Pb-Pb collisions have two J/ψ produced !

Seeing 2 J/ψ on event-by-event basis not to be blindly taken as signal of c-cbar recombination.



Summary (I)

- MPI are crucial ingredient of p-p collisions at LHC: MB, UE.
- MPI ⇒ Double hard parton scatterings. p-p cross section:

$$\sigma^{\rm DPS}_{(hh'\to ab)} = \left(\frac{m}{2}\right)\frac{\sigma^{\rm SPS}_{(hh'\to a)}\cdot\sigma^{\rm SPS}_{(hh'\to b)}}{\sigma_{\rm eff}}$$

All details on proton transverse parton density & correlations,... encoded into $\sigma_{\rm eff}$ parameter

- Derived DPS x-sections "pocket formula" for p-A and A-A:

$$\sigma_{\rm eff,pA} = \frac{\sigma_{\rm eff,pp}}{A+\sigma_{\rm eff,pp}\,F_{\rm pA}} = 21.5 \pm 1.1\ \mu b$$

$$\sigma_{\rm eff,AA} = \frac{1}{A^2[\sigma^{-1}_{\rm eff,\,pp} + \frac{2}{A}T_{AA}(0) + \frac{1}{2}T_{AA}(0)]} = 1.5\ {\rm nb}$$

Huge enhancements ! $\sigma_{\rm eff,pp}/\sigma_{\rm eff,pA} \approx 3\,A \approx 600$, $\sigma_{\rm eff,pp}/\sigma_{\rm eff,AA} \propto A^{3.3}/5 \simeq 9\cdot 10^6$

- DPS in p-A can help determine $\sigma_{\rm eff,pp}$. Case-study:
  p-Pb → W^+W^+, W^-W^- , NLO+nuclear PDFs for signal & bckgds.
  σ(same-sign WW,DPS) ≈ 150 pb → 5 counts/year (leptonic decay)
- DPS in A-A clearly dominated by binary-scaling term. Case-study:
  Pb-Pb → J/ψJ/ψ, NLO+nuclear PDFs for signal & bckgds.
  dσ(J/ψJ/ψ,DPS)/dy ≈ 200 mb → 250 counts/year (per dilepton decay)

Summary (II)

- Large x-sections & rates for DPS processes w/ J/ψ,Υ & W,Z bosons:

System		$J/\psi+J/\psi$	$J/\psi+\Upsilon$	$J/\psi+W$	$J/\psi+Z$
p–Pb	σ^{DPS}	45 μb	5.2 μb	120 nb	70 nb
8.8 TeV	$N^{DPS}(1\ nb^{-1})$	~65	~60	~15	~3
		$\Upsilon+\Upsilon$	$\Upsilon+W$	$\Upsilon+Z$	ss WW
p–Pb	σ^{DPS}	150 nb	7 nb	4 nb	150 pb
8.8 TeV	$N^{DPS}(1\ nb^{-1})$	~15	~8	~1.5	~5

- DPS in p-A can help determine $\sigma_{eff,pp}$

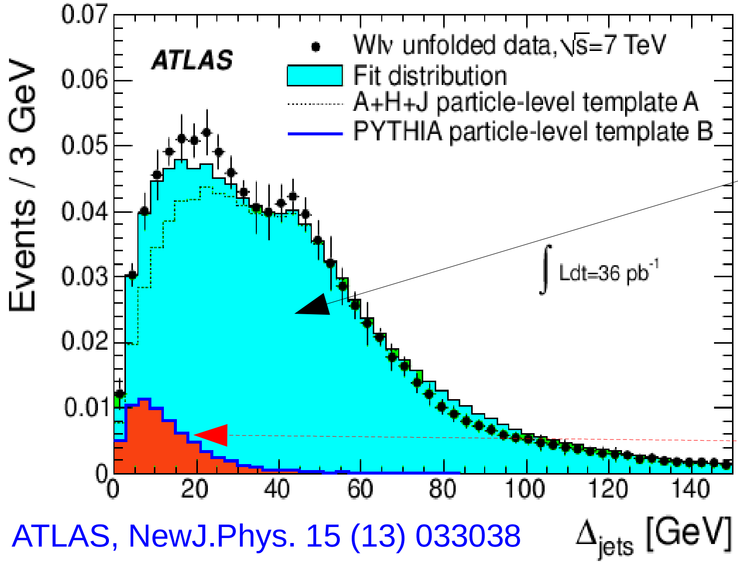
System		$J/\psi+J/\psi$	$J/\psi+\Upsilon$	$J/\psi+W$	$J/\psi+Z$
Pb–Pb	σ^{DPS}	210 mb	28 mb	500 μb	330 μb
5.5 TeV	$N^{DPS}(1\ nb^{-1})$	~250	~340	~65	~14
		$\Upsilon+\Upsilon$	$\Upsilon+W$	$\Upsilon+Z$	ss WW
Pb–Pb	σ^{DPS}	960 μb	34 μb	23 μb	630 nb
5.5 TeV	$N^{DPS}(1\ nb^{-1})$	~95	~35	~8	~15

- ~2.5% yields from "genuine" DPS. Info on parton correlations in nucleus?

Backup slides

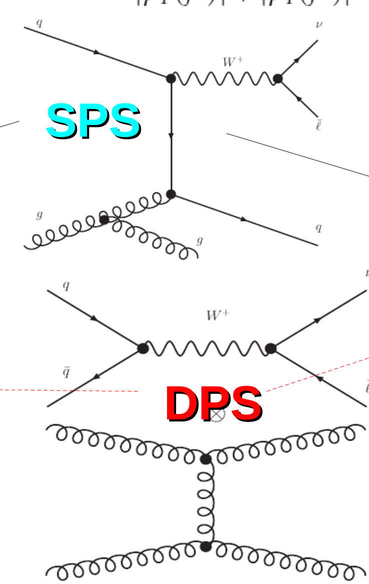
DPS searches at LHC: p-p → W⁺+2j

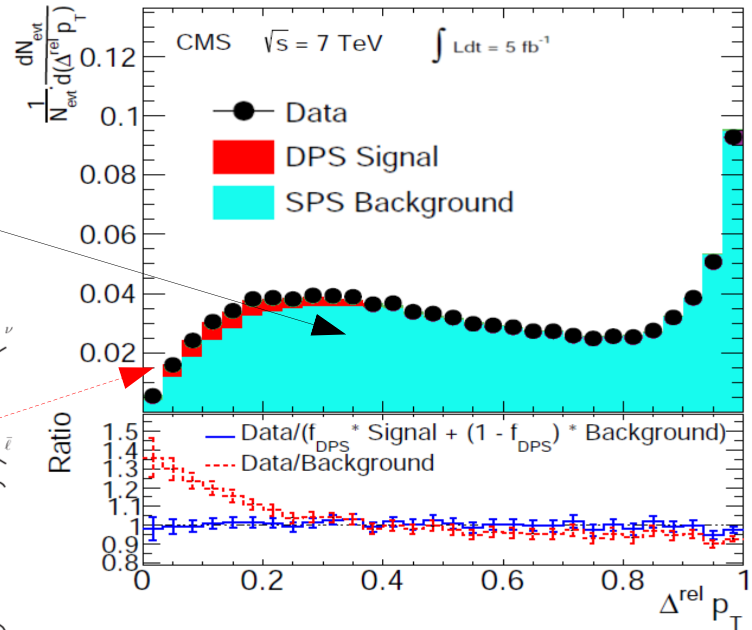
- Small signal in W+2jets events: Via di-jet p_T asymmetry (~0 in DPS)



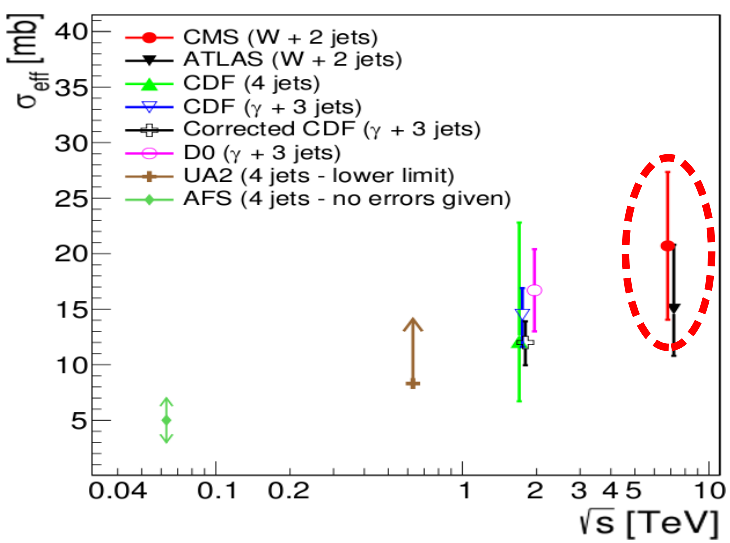
ATLAS, NewJ.Phys. 15 (13) 033038

$$\Delta^{\rm rel}\, p_T = \frac{|\vec{p}_T(j1) + \vec{p}_T(j2)|}{|\vec{p}_T(j1)| + |\vec{p}_T(j2)|}$$





CMS, JHEP 1403 (2014) 032



- Uncertainties on DPS extraction from:
  - Higher-order SPS contributions,
  - (technical) matching between ME hard jets & MPI jets

propagate into large uncertainty on $\sigma_{\rm eff}$

$\sigma_{\rm eff}$ = 15 – 20 mb