Double & triple charm & beauty from N-parton scatterings in p-p, p-A, A-A at the LHC

Exploring matter with charm & beauty prod.

Chia, Sardegna, 3rd September 2019

David d'Enterria

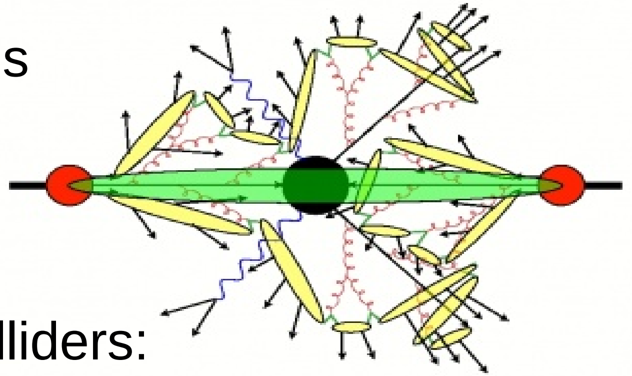
CERN

(*) Results based upon:

D.d'E & A.Snigirev: arXiv:1211.0197 [PLB 718 (2013) 1395]
arXiv:1301.5845 [PLB 727 (2013) 157]
D.d'E & A.Snigirev: arXiv:1612.05582 [PRL 118 (2017) 122001]
arXiv:1612.08112 [EPJC 78 (2018) 359]
D.d'E & A.Snigirev: arXiv:1708.07519 [Adv.Ser.Direct.HEP29 (2018) 159]

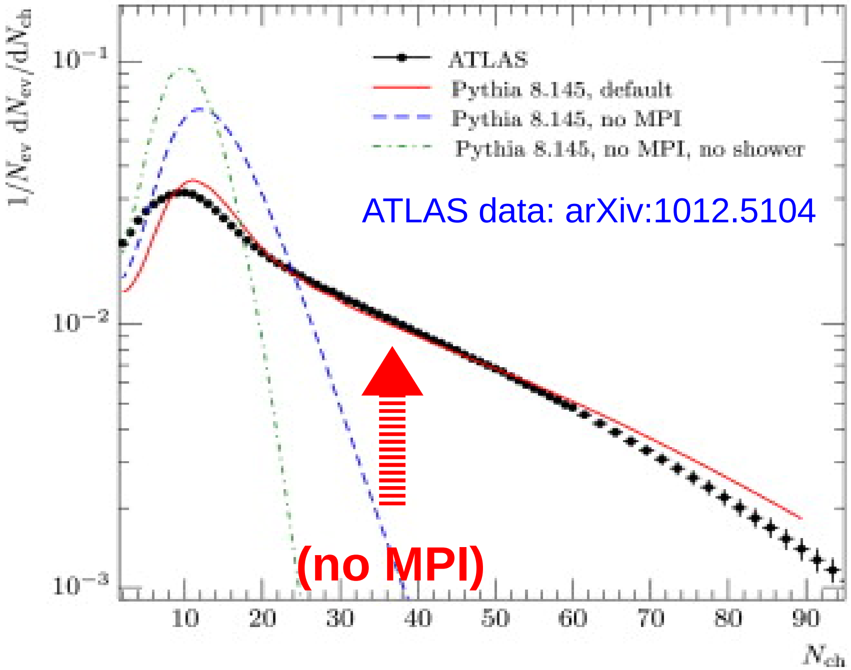
Multi-parton interactions at the LHC

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

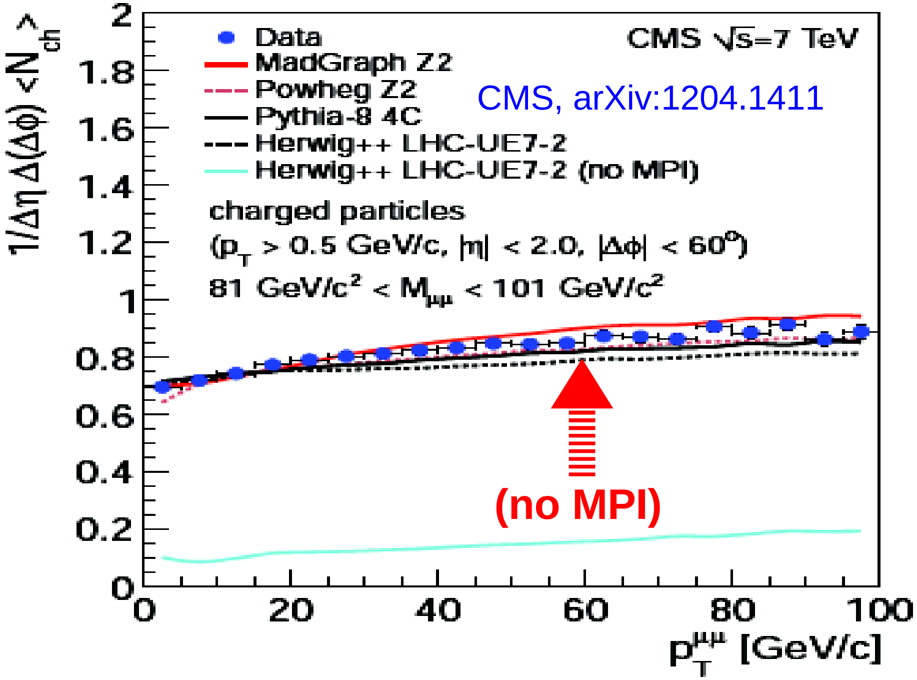


- MPI O(1-3 GeV) clearly observed in hadron colliders:

~50% of total hadron production



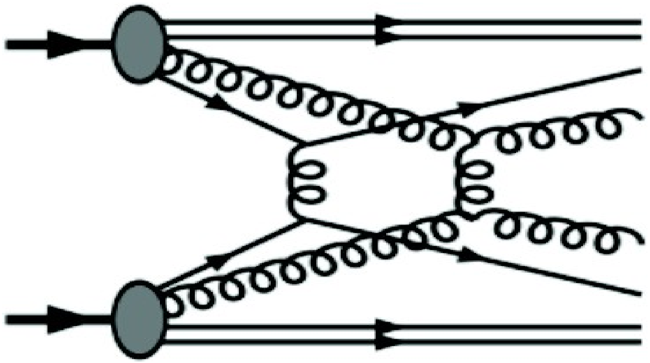
Underlying event in hard scatterings:



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

Double Parton Scattering x-sections (p-p)

- Assuming that the probability to produce two hard collisions is independent, one can economically write double parton scatterings (DPS) cross section as the product of two single-parton scatterings (SPS) ones:



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

normalized by an effective x-section ($\sigma_{\rm eff}$) and with a trivial combinatorial factor (m) to avoid double-counting in case of same particles produced.

- How to interpret $\sigma_{\rm eff}$? What values one would naively expect for it?

- The most generic expression for DPS cross section reads:

$$\sigma^{\rm DPS}_{(hh' \to ab)} = \left(\frac{m}{2}\right) \sum_{i,j,k,l} \int \Gamma^{ij}_{h}(x_1, x_2; \mathbf{b_1}, \mathbf{b_2}; Q_1^2, Q_2^2) \times \hat{\sigma}^{ik}_{a}(x_1, x_1', Q_1^2)\, \hat{\sigma}^{jl}_{b}(x_2, x_2', Q_2^2)$$
$$\times \Gamma^{kl}_{h'}(x_1', x_2'; \mathbf{b_1} - \mathbf{b}, \mathbf{b_2} - \mathbf{b}; Q_1^2, Q_2^2)\, dx_1 dx_2 dx_1' dx_2' d^2b_1 d^2b_2 d^2b$$

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

Double Parton Scattering x-sections (p-p)

- Assumption 1: Generalized PDFs factorize into longitudinal & transverse components:

Transv. density = f(**b**)

$$\Gamma_h^{ij}(x_1, x_2; \mathbf{b_1}, \mathbf{b_2}; Q_1^2, Q_2^2) = D_h^{ij}(x_1, x_2; Q_1^2, Q_2^2) f(\mathbf{b_1}) f(\mathbf{b_2})$$

p-p transv. overlap function (mb^{-1}): $t(\mathbf{b}) = \int f(\mathbf{b_1}) f(\mathbf{b_1} - \mathbf{b}) d^2 b_1$

- Assumption 2: The longitudinal double-PDF is the product of 2 single PDF (i.e. no parton correlations in colour, momentum, flavour, spin,…)

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

- Then, σ_{eff} corresponds to simple geom. overlap x-section of 2 protons:

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

with naif expected size of $\sigma_{eff} \approx$ 35 mb

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, $\lambda/r_0=0.2$	$(e^{(r-r_0)/\lambda}+1)^{-1}$	$1.07r_0$	$4.6r_0^2$	$r_0=0.56$

- Experimentally:

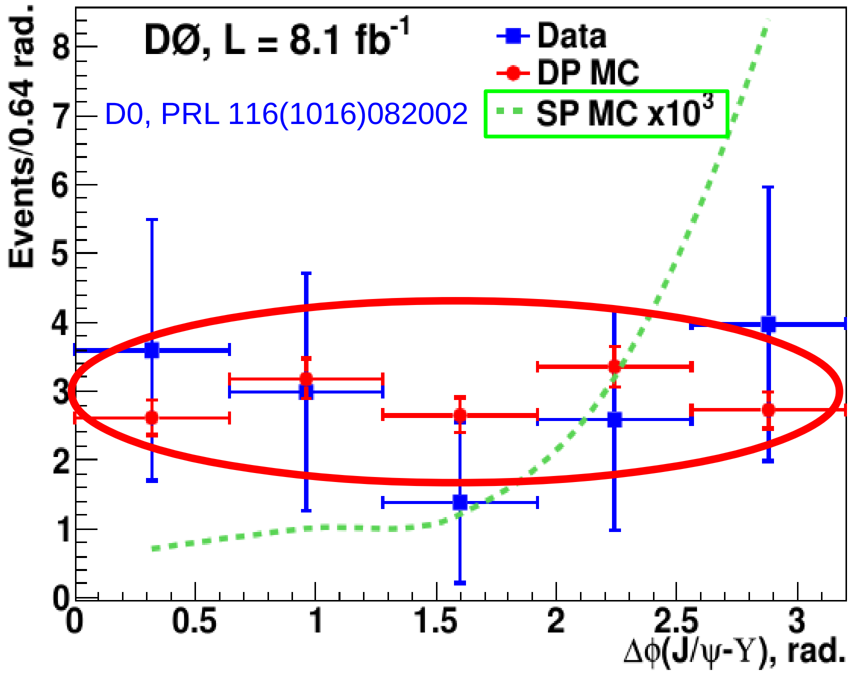
  σ_{eff}(exp) ≈ 15 mb.

  proton "hard" radius: r = 0.3–0.7 fm appears smaller than e.m. one.

Understandable: Probability of 2nd scatt. is larger if 1st scatter already took place (centrality bias).

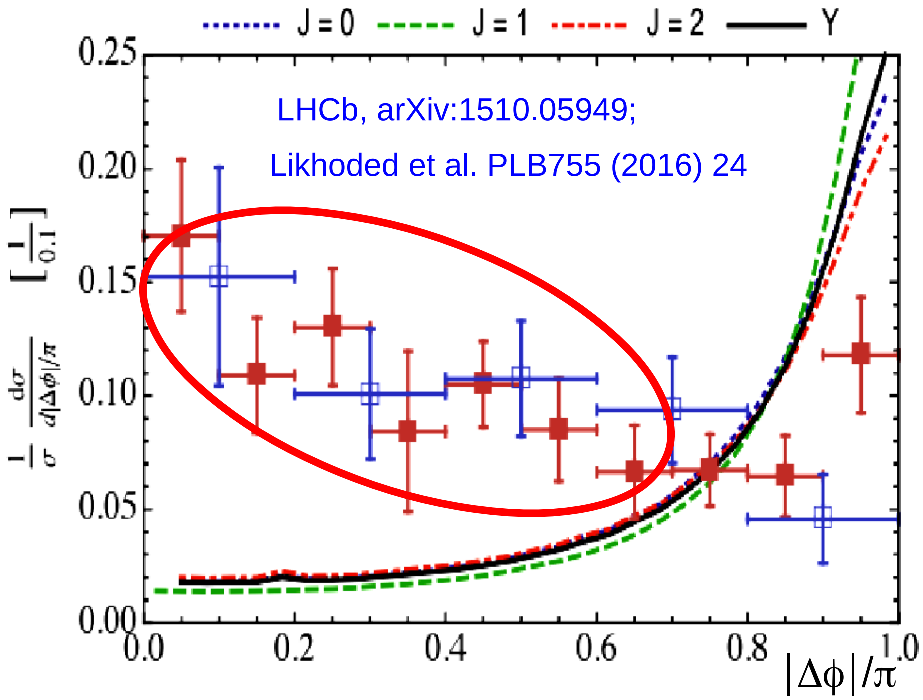
DPS studies with $Q\bar{Q}$: p-p → J/Ψ+Υ, Υ+D

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



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

- Uncorrelated Υ+D azimuthal production in pp at 7 TeV:

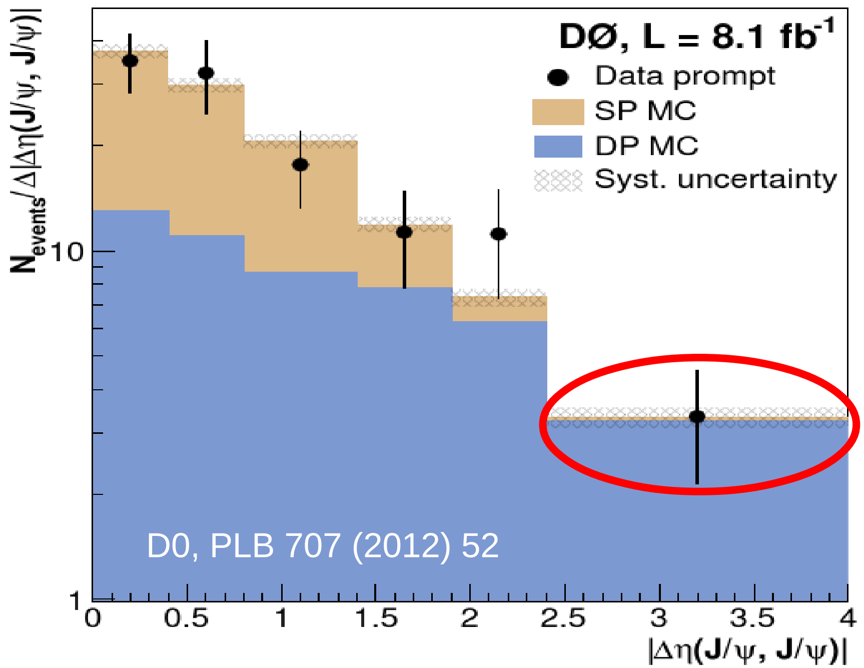


$\sigma_{\rm eff}|_{\Upsilon(1S)D} = 18.0 \pm 1.3\,({\rm stat}) \pm 1.2\,({\rm syst})$ mb

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

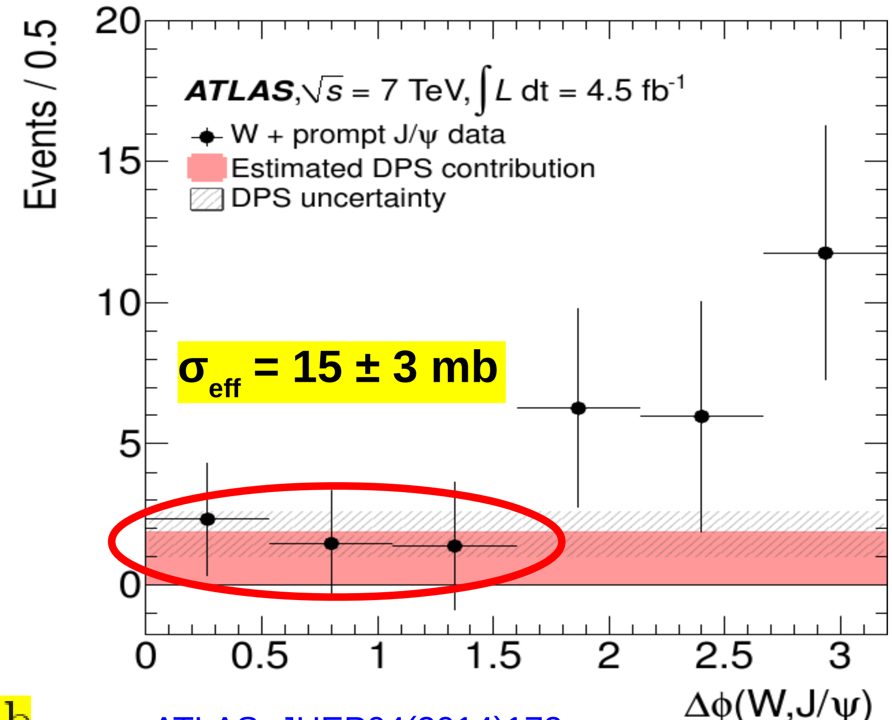
DPS studies with $Q\bar{Q}$: p-p → W^{+}+J/Ψ, J/ΨJ/Ψ

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



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

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

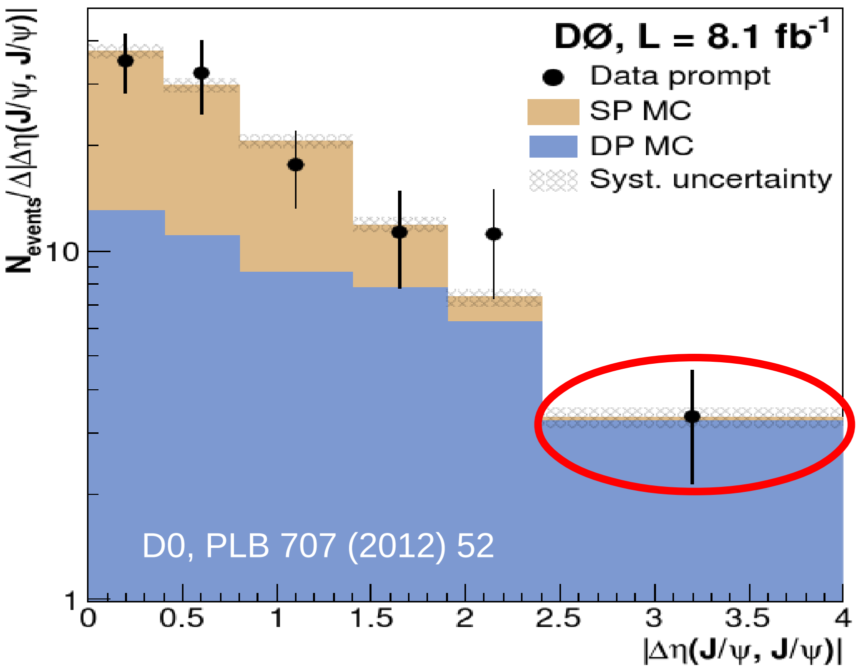


ATLAS, JHEP04(2014)172

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

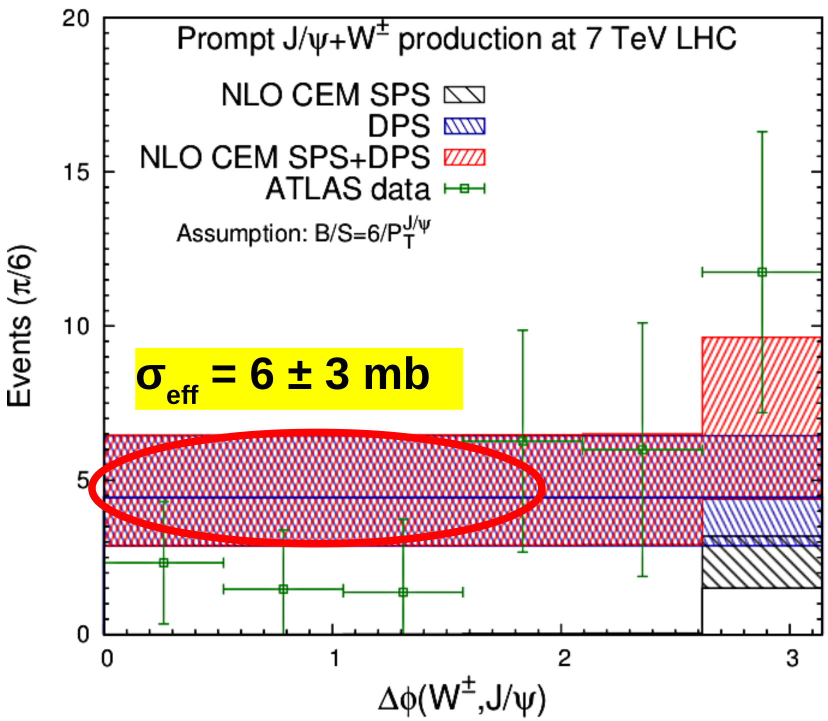
DPS studies with $Q\bar{Q}$: p-p → W^{+}+J/Ψ, J/ΨJ/Ψ

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



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

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

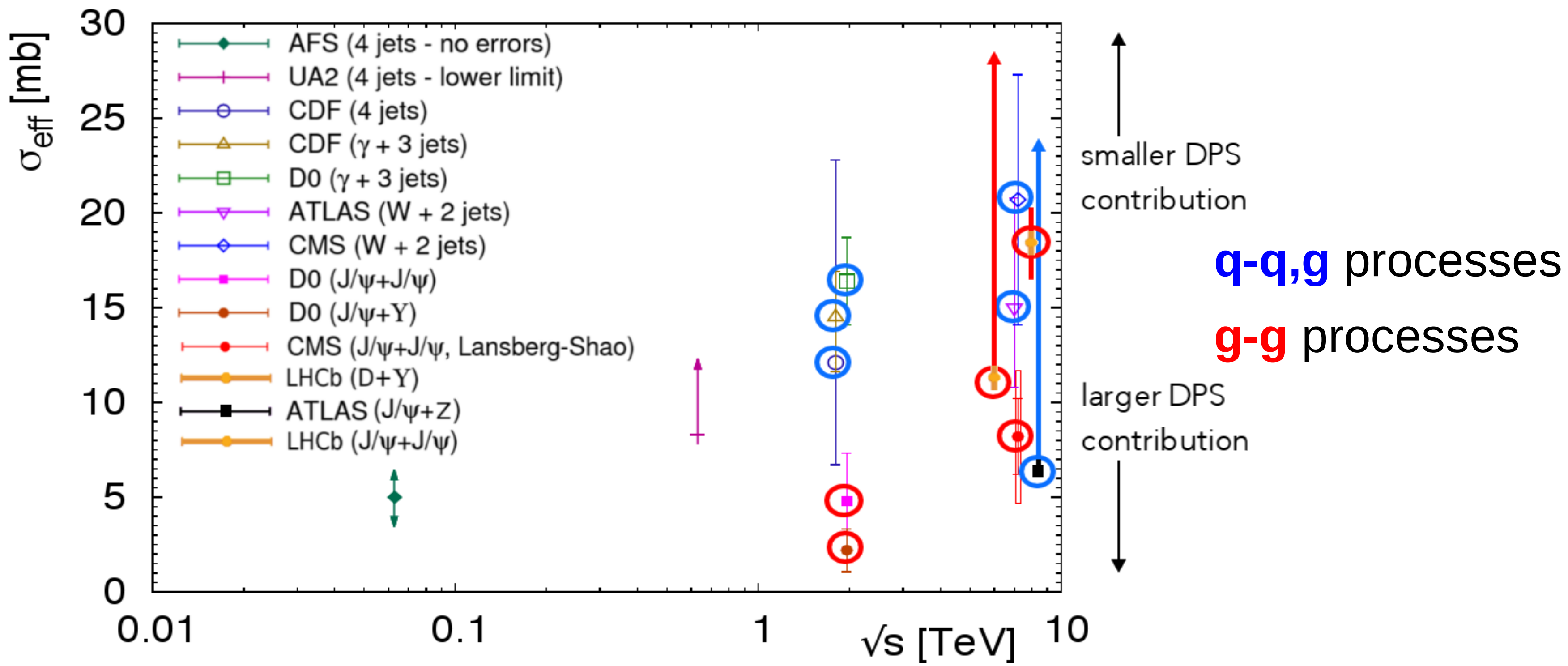


(a) NLO

Lansberg&Shao&Yamanaka, PLB781 (2018) 485

- Extracted $\sigma_{\rm eff}$ 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 vs. √s



- Extracted σ_{eff} differ from ~2 mb (large DPS) to ~20 mb (small DPS):
  - (Higher-order) SPS contributions removed differently/properly?
  - Energy evolution of parton transverse profile?
  - Invalid σ_{eff} geometric interpretation? Complicated parton correlations

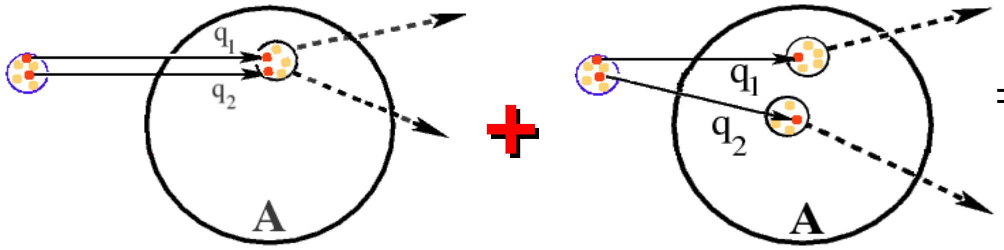
☛ Can 3-,N-scatterings improve our understanding of transv. proton profile?

☛ Can p-Pb & Pb-Pb improve our understanding of transv. proton profile?

Double Parton Scatterings in p-A collisions

Double Parton Scattering x-sections (p-A)

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



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

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

p-A overlap function

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

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

Relative weight of DPS terms: $\sigma^{\rm DPS,1} : \sigma^{\rm DPS,2}$ = 0.7 : 0.3 (small A), 0.33 : 0.66 (large A)

- "Pocket" formula for DPS p-A x-section:

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

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

($\sigma_{\rm eff}$=13±2mb)

  - ► Ratio of DPS p-Pb/p-p x-sections: $\sigma_{\rm eff,DPS}/\sigma_{\rm eff,DPS,pA} \approx [A + A^{4/3}/\pi]$

- DPS x-sections are large in p-A: a factor ×600 for p-Pb (!)
- Pb transverse density (F_{pA}) well known. Alternative extraction of $\sigma_{\rm eff,pp}$

DPS cross sections (p-Pb, 8.8 TeV)

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

- Cross sections & rates for DPS processes with J/ψ,Υ & W, Z bosons
  (Also V. Goncalves(2018) double-J/ψ, Paukunen(2019) double-D,...)

pPb (8.8 TeV)	$J/\psi + J/\psi$	$J/\psi + \Upsilon$	J/ψ+W	J/ψ+Z
$\sigma^{\rm SPS}_{{\rm pN}\to a}, \sigma^{\rm SPS}_{{\rm pN}\to b}$	45 μb ($\times$2)	45 μb, 2.6 μb	45 μb, 60 nb	45 μb, 35 nb
$\sigma^{\rm DPS}_{\rm pPb}$	45 μb	5.2 μb	120 nb	70 nb
$N^{\rm DPS}_{\rm pPb}$ (1 pb^{-1})	~65	~60	~15	~3
	$\Upsilon + \Upsilon$	Υ+W	Υ+Z	ss WW
$\sigma^{\rm SPS}_{{\rm pN}\to a}, \sigma^{\rm SPS}_{{\rm pN}\to b}$	2.6 μb ($\times$2)	2.6 μb, 60 nb	2.6 μb, 35 nb	60 nb ($\times$2)
$\sigma^{\rm DPS}_{\rm pPb}$	150 nb	7 nb	4 nb	150 pb
$N^{\rm DPS}_{\rm pPb}$ (1 pb^{-1})	~15	~8	~1.5	~4

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)

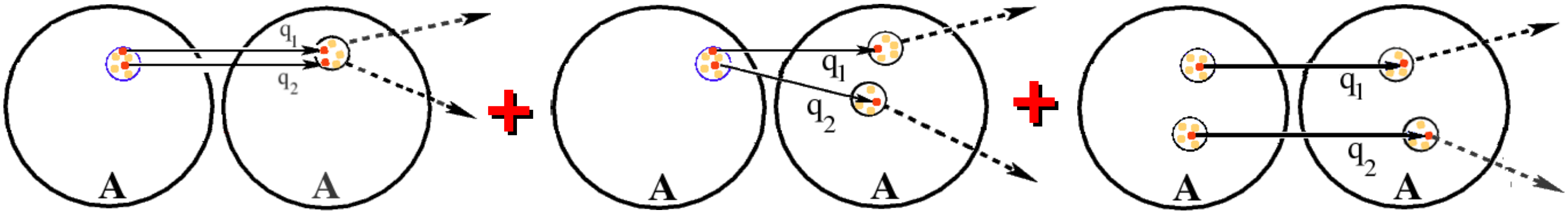
- Many double hard scatterings processes w/ visible p-Pb x-sections
- Useful independent extraction of $\sigma_{\rm eff}$ (pp) possible.

► LHCb is an excellent experiment to try such 1st-ever measurements.

Double Parton Scatterings in A-A collisions

Double Parton Scattering x-sections (A-A)

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



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

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

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

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

"Genuine" DPS (within same nucleon): ~2.5% (in Pb-Pb) or ~13% (Ar-Ar)

- "Pocket formula" for DPS A-A x-section:

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

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

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

- Strong centrality dependence:

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

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:

PbPb (5.5 TeV)	$J/\psi + J/\psi$	$J/\psi + \Upsilon$	J/ψ+W	J/ψ+Z
$\sigma^{\rm SPS}_{\rm NN\to a}, \sigma^{\rm SPS}_{\rm NN\to b}$	25 μb ($\times$2)	25 μb, 1.7 μb	25 μb, 30 nb	25 μb, 20 nb
$\sigma^{\rm DPS}_{\rm PbPb}$	210 mb	28 mb	500 μb	330 μb
$\rm N^{DPS}_{PbPb}$ (1 nb^{-1})	$\sim$250	$\sim$340	$\sim$65	$\sim$14
	$\Upsilon + \Upsilon$	Υ+W	Υ+Z	ss WW
$\sigma^{\rm SPS}_{\rm NN\to a}, \sigma^{\rm SPS}_{\rm NN\to b}$	1.7 μb ($\times$2)	1.7 μb, 30 nb	1.7 μb, 20 nb	30 nb ($\times$2)
$\sigma^{\rm DPS}_{\rm PbPb}$	960 μb	34 μb	23 μb	630 nb
$\rm N^{DPS}_{PbPb}$ (1 nb^{-1})	$\sim$95	$\sim$35	$\sim$8	$\sim$15

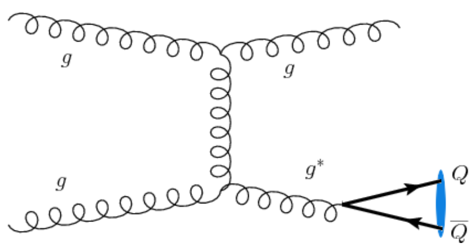
Leptonic final states: BR(J/ψ,Υ,W,Z) = 6%, 2.5%, 11%, 3.4%
Accept.*effic.= 1% (J/ψ, |y|=0,2), 20% (Υ, |y|<2.5), 50% (W,Z |y|<2.4)

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

Example: Pb-Pb → J/ψ J/ψ at 5.5 TeV

[DdE,Snigirev, PLB727 (2013)157]

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

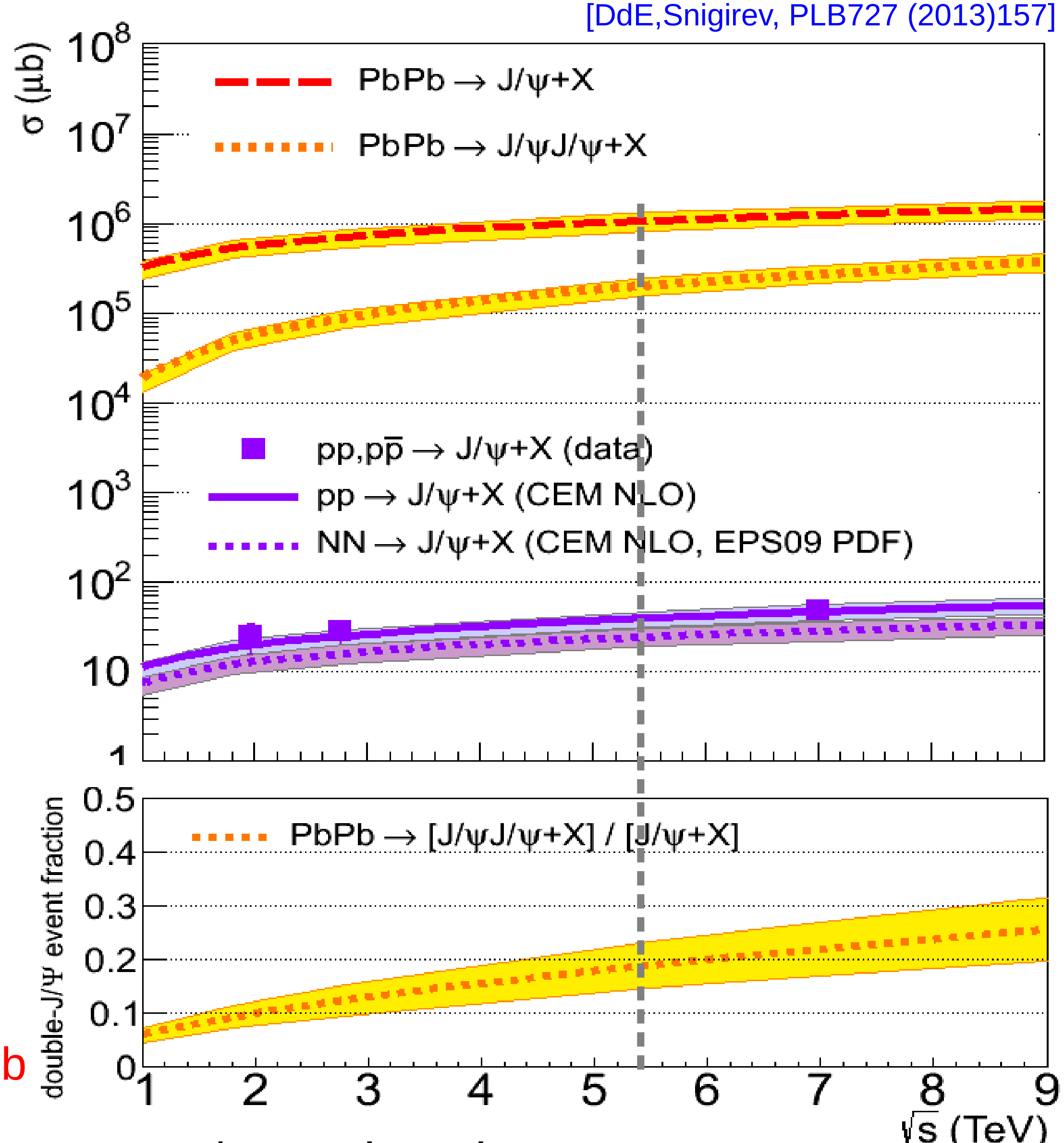


- NLO accuracy.
- Scales: $\mu_R = \mu_R = 1.5 \cdot m_c$
- Good agreement with Tevatron&LHC data

- EPS09 Pb nPDF
  20–35% shadowing x-section reduction

- At 5.5 TeV:

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



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

Example: Pb-Pb → J/ψ J/ψ at 5.5 TeV

[DdE,Snigirev, PLB727 (2013)157]

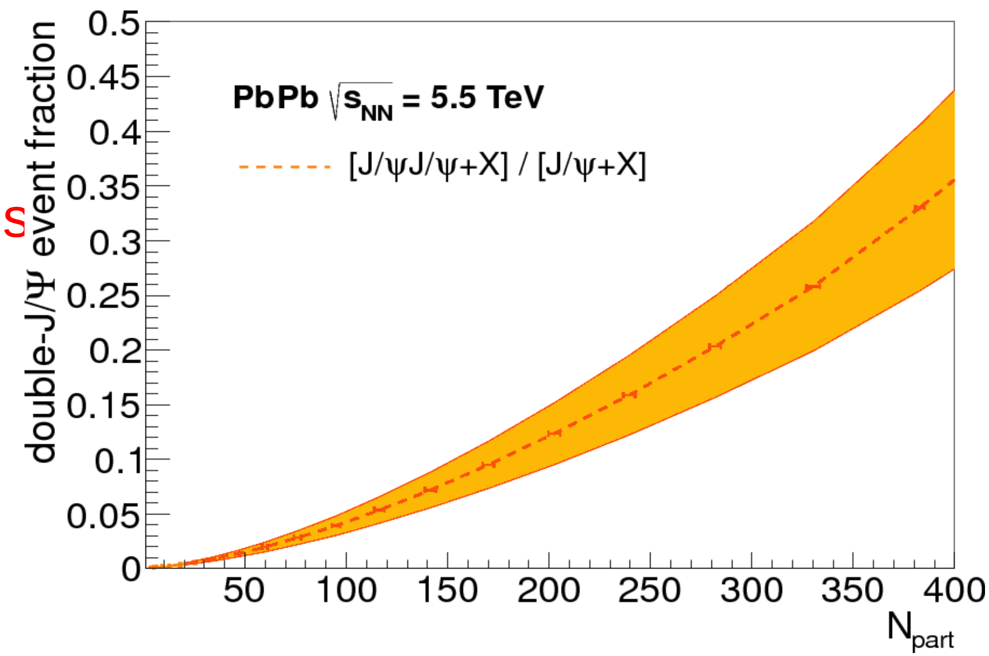
- Visible rates:
  - Reduced x-sections per unit-y: $d\sigma_{J/\psi}/dy \approx \sigma_{J/\psi}/8$
  - BR(J/ψ→ l^+l^-) ≈ 6%
  - Typical ALICE/CMS acceptance & efficiencies: ε ≈ 1/12
- Expected dimuon rates including yield all loses & 1 nb^{-1} integ. luminosity:

$$\mathcal{N} = \sigma^{DPS}_{\text{Pb-Pb} \to J/\psi\, J/\psi'} / (\varepsilon \cdot \mathcal{L}_{\text{int}}) \approx$$ 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 !

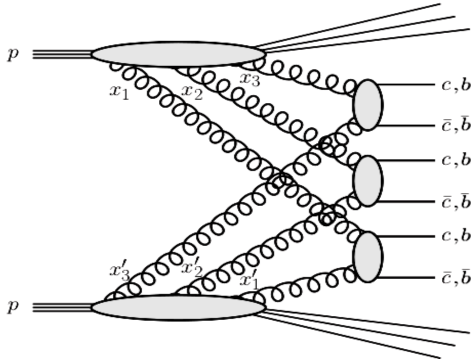
Seeing 2 J/ψ on event-by-event basis not to be blindly taken as signal of c-cbar recombination.



Triple-, N-Parton Scatterings

Triple parton scattering x-sections (p-p)

- Assuming that the probabilities for 3 hard collisions to be independent of each other, one can again write a pocket-formula for TPS x-section:



$$\sigma^{\rm TPS}_{hh'\to a_1a_2a_3} = \left(\frac{m}{3!}\right)\frac{\sigma^{\rm SPS}_{hh'\to a_1}\cdot\sigma^{\rm SPS}_{hh'\to a_2}\cdot\sigma^{\rm SPS}_{hh'\to a_3}}{\sigma^2_{\rm eff,TPS}}$$

normalized by the square of an eff. x-section ($\sigma^2_{\rm eff,TPS}$) plus a trivial combinatorial factor (m/3!) to avoid triple-counting in case of same particles produced: $m = 1$ if $a_1 = a_2 = a_3$;
$m = 3$ if $a_1 = a_2$, or $a_1 = a_3$, or $a_2 = a_3$; and
$m = 6$ if $a_1 \neq a_2 \neq a_3$.

- How to interpret $\sigma_{\rm eff,TPS}$? What values one naively expects for it?
- Most generic expression for TPS cross section:

$$\sigma^{\rm TPS}_{hh'\to a_1a_2a_3} = \left(\frac{m}{3!}\right)\sum_{i,j,k,l,m,n}\int \Gamma^{ijk}_h(x_1,x_2,x_3;\mathbf{b_1},\mathbf{b_2},\mathbf{b_3};Q_1^2,Q_2^2,Q_3^2)$$
$$\times\hat\sigma^{il}_{a_1}(x_1,x_1',Q_1^2)\cdot\hat\sigma^{jm}_{a_2}(x_2,x_2',Q_2^2)\cdot\hat\sigma^{kn}_{a_3}(x_3,x_3',Q_3^2)$$
$$\times\Gamma^{lmn}_{h'}(x_1',x_2',x_3';\mathbf{b_1}-\mathbf{b},\mathbf{b_2}-\mathbf{b},\mathbf{b_3}-\mathbf{b};Q_1^2,Q_2^2,Q_3^2)$$
$$\times dx_1dx_2dx_3dx_1'dx_2'dx_3'd^2b_1d^2b_2d^2b_3d^2b.$$

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

Triple parton scattering x-sections (p-p)

- Assumption 1: Factorize generalized Triple-PDF into longitudinal & transverse components:

$$\Gamma_h^{ijk}(x_1,x_2,x_3;\mathbf{b_1},\mathbf{b_2},\mathbf{b_3};Q_1^2,Q_2^2,Q_3^2) = D_h^{ijk}(x_1,x_2,x_3;Q_1^2,Q_2^2,Q_3^2)f(\mathbf{b_1})f(\mathbf{b_2})f(\mathbf{b_3}),$$

p-p transv. overlap function (mb^{-1}): $T(\mathbf{b}) = \int f(\mathbf{b_1})f(\mathbf{b_1}-\mathbf{b})d^2b_1$, with $\int d^2b T(\mathbf{b}) = 1.$

- Assumption 2: Longitudinal triple-PDF is the product of 3 single PDFs (i.e. no parton correlations in colour, momentum, flavour, spin,…)

$$D_h^{ijk}(x_1,x_2,x_3;Q_1^2,Q_2^2,Q_3^2) = D_h^i(x_1;Q_1^2)D_h^j(x_2;Q_2^2)D_h^k(x_3;Q_3^2)$$

- Then, $\sigma^2_{\text{eff,TPS}}$ is simply the inverse of the cube of the transv. pp overlap:

$$\sigma^2_{\text{eff,TPS}} = \left[\int d^2b\, T^3(\mathbf{b})\right]^{-1}$$

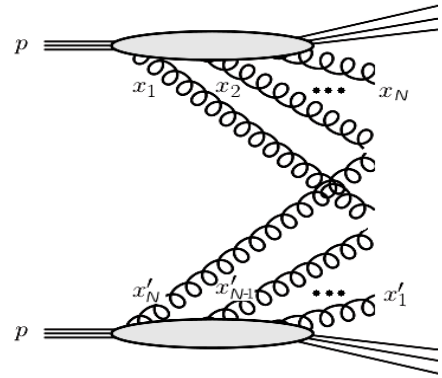
- By testing many proton overlaps/profiles (hard sphere, Gaussian, expo, dipole fit), we find a close relationship between $\sigma_{\text{eff,TPS}}$ & σ_{eff}:

$$\sigma_{\text{eff,TPS}} = k \times \sigma_{\text{eff,DPS}},\ \text{with}\ k = 0.82 \pm 0.11$$

- Measuring TPS provides independent info on σ_{eff} and p transv. profile.

N-parton scattering x-sections (p-p)

- Assuming that the probabilities for N hard collisions to be independent of each other, one can write a generic pocket-formula for NPS x-section:



$$\sigma^{\rm NPS}_{hh'\to a_1\dots a_n} = \left(\frac{m}{n!}\right) \frac{\sigma^{\rm SPS}_{hh'\to a_1}\cdots\sigma^{\rm SPS}_{hh'\to a_n}}{\sigma^{n-1}_{\rm eff,NPS}}$$

normalized by the Nth-1 power of an effective x-section ($\sigma_{\rm eff,NPS}$) plus a trivial combinatorial factor (m/n!) to avoid double,triple,N-counting in case of same particles produced:

- DPS: $m = 1$ if $a_1 = a_2$; and $m = 2$ if $a_1 \neq a_2$.
- TPS: $m = 1$ if $a_1 = a_2 = a_3$; $m = 3$ if $a_1 = a_2$, or $a_1 = a_3$, or $a_2 = a_3$; and $m = 6$ if $a_1 \neq a_2 \neq a_3$.

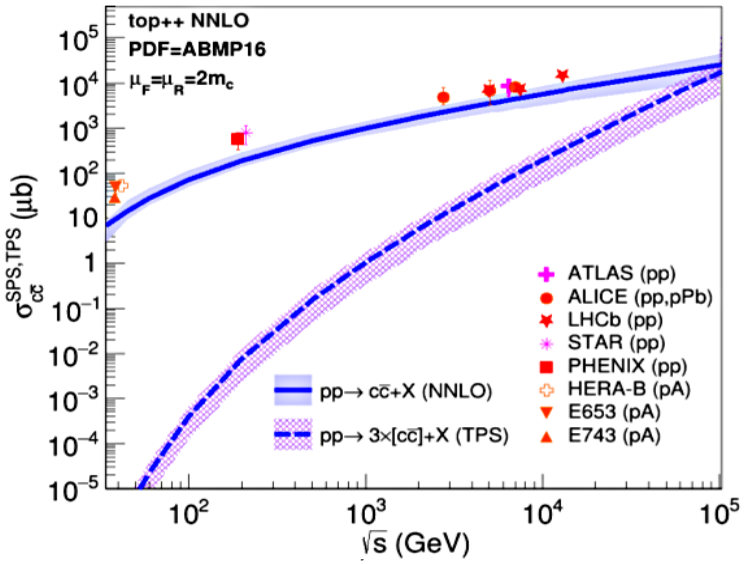
- Ignoring all parton correlations, $\sigma_{\rm eff,NPS}$ is the inverse Nth-1 power of the integral of the Nth power of the pp overlap function:

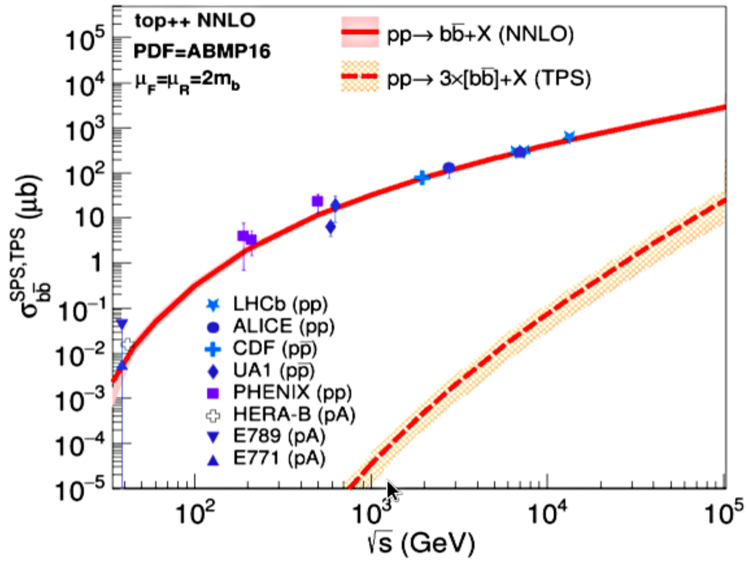
$$\sigma_{\rm eff,NPS} = \left\{\int d^2b\, T^n(\mathbf{b})\right\}^{-1/(n-1)}$$

- A generic framework for the most economical (geometrical) expressions for N-parton scattering cross sections is available now.

Triple charm & beauty production (p-p)

- TPS x-sections are small: $\sigma(\mathrm{SPS})^3/\sigma(\mathrm{eff})^2 \approx 1$ fb for $\sigma(\mathrm{SPS}) \approx 1\ \mu$b, but rise fast (cube of SPS) with c.m. energy.
- Charm & beauty have large enough $\sigma(\mathrm{SPS})$ to attempt TPS observation:



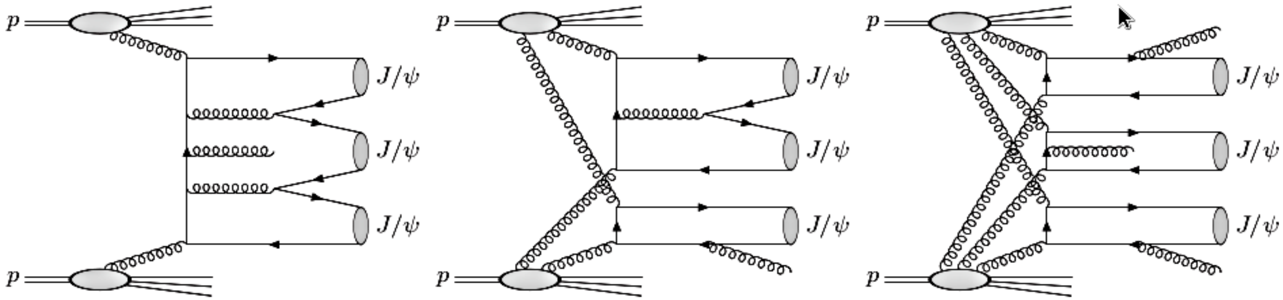


Final state	$\sqrt{s} = 14$ TeV	$\sqrt{s} = 100$ TeV
$\sigma^{\mathrm{SPS}}_{c\bar{c}+X}$	$7.1 \pm 3.5_{\mathrm{sc}} \pm 0.3_{\mathrm{PDF}}$ mb	$25.0 \pm 16.0_{\mathrm{sc}} \pm 1.3_{\mathrm{PDF}}$ mb
$\sigma^{\mathrm{TPS}}_{c\bar{c}\,c\bar{c}\,c\bar{c}+X}$	$0.39 \pm 0.28_{\mathrm{tot}}$ mb	$16.7 \pm 11.8_{\mathrm{tot}}$ mb
$\sigma^{\mathrm{SPS}}_{b\bar{b}+X}$	$0.56 \pm 0.09_{\mathrm{sc}} \pm 0.01_{\mathrm{PDF}}$ mb	$2.8 \pm 0.6_{\mathrm{sc}} \pm 0.1_{\mathrm{PDF}}$ mb
$\sigma^{\mathrm{TPS}}_{b\bar{b}\,b\bar{b}\,b\bar{b}+X}$	$0.19 \pm 0.12_{\mathrm{tot}}\ \mu$b	$24 \pm 17_{\mathrm{tot}}\ \mu$b

- Triple charm amounts to ~15% (50%) of inclusive charm x-sections at LHC (FCC). Contribution from triple-SPS, double-SPS processes?

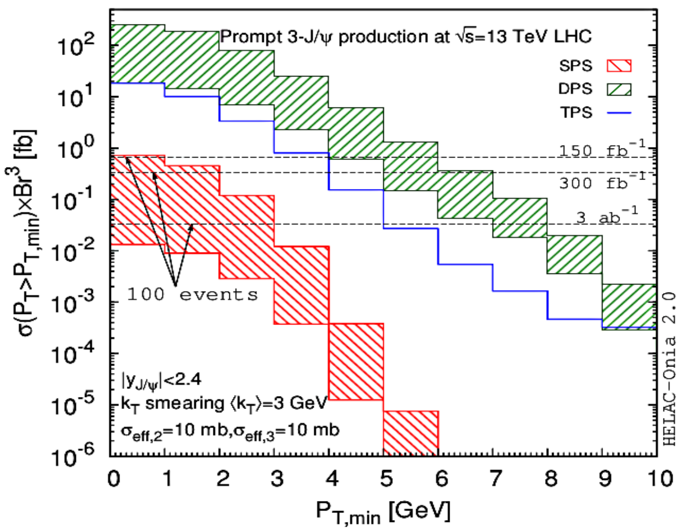
Triple-J/ψ from SPS production (p-p)

- H.-S. Shao et al. [arXiv:1902.04949, PRL 122(2019)192002] computed all triple-J/Ψ x-sections with SPS HELAC-ONIA plus pocket formulas:



(a) SPS (b) DPS (c) TPS

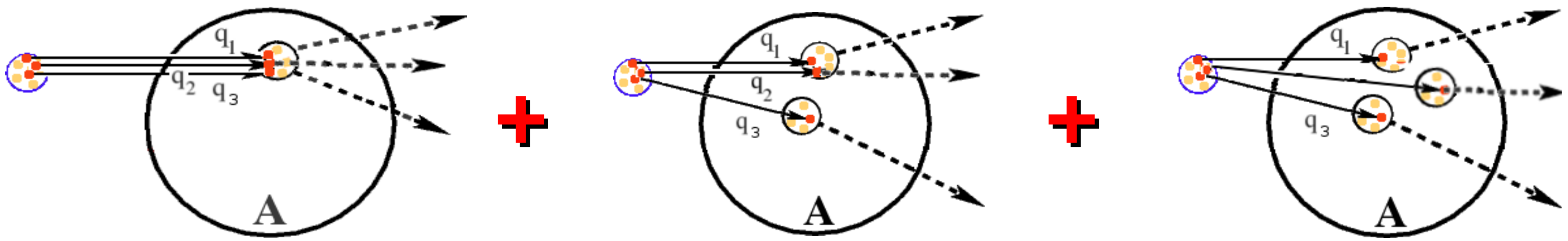
		inclusive	$2.0 < y_{J/\psi} < 4.5$	$\lvert y_{J/\psi}\rvert < 2.4$
13 TeV	SPS	$0.41^{+2.4}_{-0.34} \pm 0.0083$	$(1.8^{+11}_{-1.5} \pm 0.18) \times 10^{-2}$	$(8.7^{+56}_{-7.5} \pm 0.098) \times 10^{-2}$
	DPS	$(190^{+501}_{-140}) \times \frac{10\text{ mb}}{\sigma_{\rm eff,2}}$	$(7.0^{+18}_{-5.1}) \times \frac{10\text{ mb}}{\sigma_{\rm eff,2}}$	$(50^{+140}_{-37}) \times \frac{10\text{ mb}}{\sigma_{\rm eff,2}}$
	TPS	$130 \times \left(\frac{10\text{ mb}}{\sigma_{\rm eff,3}}\right)^2$	$1.3 \times \left(\frac{10\text{ mb}}{\sigma_{\rm eff,3}}\right)^2$	$18 \times \left(\frac{10\text{ mb}}{\sigma_{\rm eff,3}}\right)^2$
27 TeV	SPS	$0.46^{+2.9}_{-0.39} \pm 0.022$	$(3.2^{+22}_{-2.8} \pm 0.21) \times 10^{-2}$	$(5.8^{+39}_{-5.1} \pm 0.29) \times 10^{-2}$
	DPS	$(560^{+2900}_{-480}) \times \frac{10\text{ mb}}{\sigma_{\rm eff,2}}$	$(19^{+97}_{-16}) \times \frac{10\text{ mb}}{\sigma_{\rm eff,2}}$	$(120^{+630}_{-100}) \times \frac{10\text{ mb}}{\sigma_{\rm eff,2}}$
	TPS	$570 \times \left(\frac{10\text{ mb}}{\sigma_{\rm eff,3}}\right)^2$	$5.0 \times \left(\frac{10\text{ mb}}{\sigma_{\rm eff,3}}\right)^2$	$57 \times \left(\frac{10\text{ mb}}{\sigma_{\rm eff,3}}\right)^2$
75 TeV	SPS	$0.59^{+4.4}_{-0.52} \pm 0.016$	$(3.0^{+25}_{-2.7} \pm 0.23) \times 10^{-2}$	$(7.2^{+63}_{-6.5} \pm 0.38) \times 10^{-2}$
	DPS	$(1900^{+11000}_{-1600}) \times \frac{10\text{ mb}}{\sigma_{\rm eff,2}}$	$(57^{+340}_{-50}) \times \frac{10\text{ mb}}{\sigma_{\rm eff,2}}$	$(310^{+2000}_{-270}) \times \frac{10\text{ mb}}{\sigma_{\rm eff,2}}$
	TPS	$3900 \times \left(\frac{10\text{ mb}}{\sigma_{\rm eff,3}}\right)^2$	$27 \times \left(\frac{10\text{ mb}}{\sigma_{\rm eff,3}}\right)^2$	$260 \times \left(\frac{10\text{ mb}}{\sigma_{\rm eff,3}}\right)^2$
100 TeV	SPS	$1.1^{+8.4}_{-1.0} \pm 0.044$	$(4.5^{+33}_{-4.0} \pm 0.72) \times 10^{-2}$	$(36^{+290}_{-32} \pm 1.8) \times 10^{-2}$
	DPS	$(3400^{+19000}_{-2900}) \times \frac{10\text{ mb}}{\sigma_{\rm eff,2}}$	$(100^{+550}_{-86}) \times \frac{10\text{ mb}}{\sigma_{\rm eff,2}}$	$(490^{+3000}_{-430}) \times \frac{10\text{ mb}}{\sigma_{\rm eff,2}}$
	TPS	$6500 \times \left(\frac{10\text{ mb}}{\sigma_{\rm eff,3}}\right)^2$	$45 \times \left(\frac{10\text{ mb}}{\sigma_{\rm eff,3}}\right)^2$	$380 \times \left(\frac{10\text{ mb}}{\sigma_{\rm eff,3}}\right)^2$



- SPS negligible, DPS (TPS) dominates at low (high) p_T. Clear sensitivity to $\sigma_{\rm eff}$. Strong case for LHCb!

Triple Parton Scattering x-sections (p-A)

- Three contributions to TPS x-section in p-A:



$$\sigma^{\rm TPS,1}_{\rm pA\to abc} = A\cdot\sigma^{\rm TPS}_{\rm pN\to abc}$$

$$\sigma^{\rm TPS,2}_{\rm pA\to abc} = \sigma^{\rm TPS}_{\rm pN\to abc}\cdot 3\,\frac{\sigma^2_{\rm eff,TPS}}{\sigma_{\rm eff,DPS}}\,F_{\rm pA},$$

$$\sigma^{\rm TPS,3}_{\rm pA\to abc} = \sigma^{\rm TPS}_{\rm pN\to abc}\cdot\sigma^2_{\rm eff,TPS}\cdot C_{\rm pA},\quad \text{with}\quad C_{\rm pA} = \frac{(A-1)(A-2)}{A^2}\int d^2b\,T^3_{\rm pA}(\mathbf{b}),$$

Relative weight of TPS terms: $\sigma^{\rm TPS,1}_{\rm pA\to abc} : \sigma^{\rm TPS,2}_{\rm pA\to abc} : \sigma^{\rm TPS,3}_{\rm pA\to abc} = 1 : 4.54 : 3.56$

(TPS yields in pPb: 10% "genuine", 50% involve 2 nucleons, 40% involve 3 different Pb nucleons)

- “Pocket” formula for TPS p-A x-section:

$$\sigma^{\rm TPS}_{\rm pA\to abc} = \left(\frac{m}{6}\right)\frac{\sigma^{\rm SPS}_{\rm pN\to a}\cdot\sigma^{\rm SPS}_{\rm pN\to b}\cdot\sigma^{\rm SPS}_{\rm pN\to c}}{\sigma^2_{\rm eff,TPS,pA}}$$

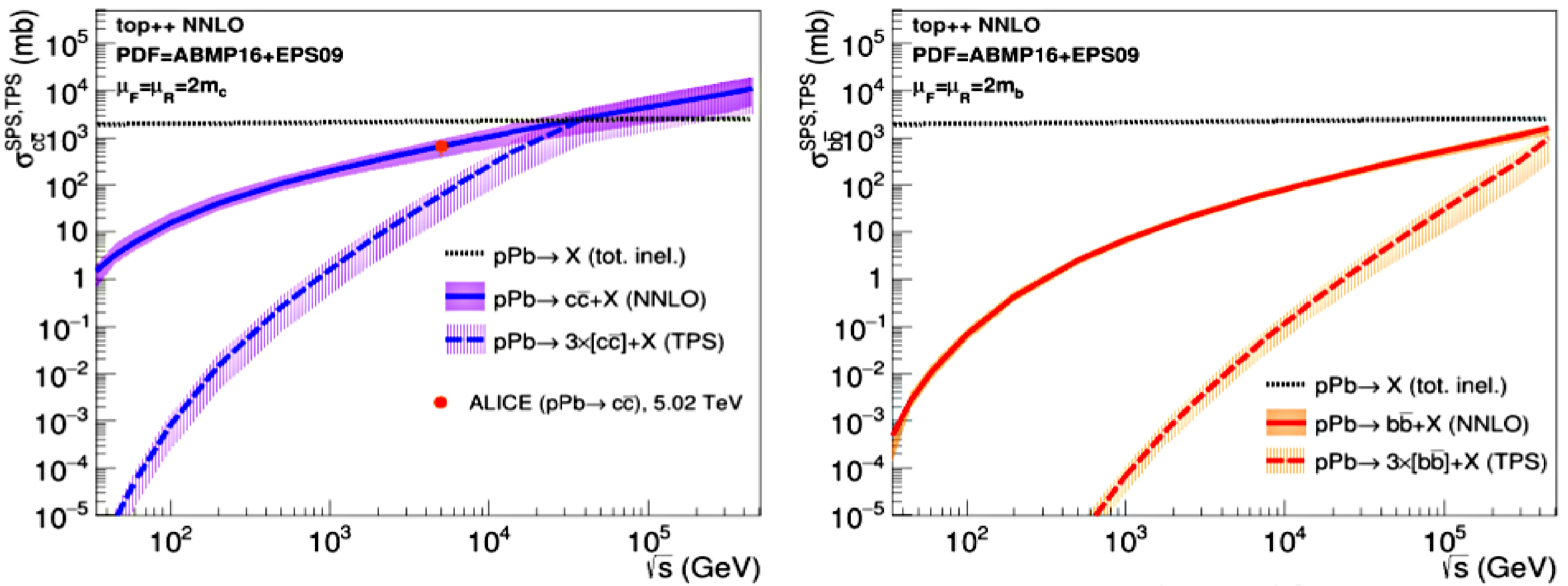
$$\sigma_{\rm eff,TPS,pA} = \left[\frac{A}{\sigma^2_{\rm eff,TPS}} + \frac{3\,F_{\rm pA}[{\rm mb}^{-1}]}{\sigma_{\rm eff,DPS}} + C_{\rm pA}[{\rm mb}^{-2}]\right]^{-1/2}$$

  - ► $\sigma_{\rm eff,TPS,pPb} = 0.29 \pm 0.04$ mb (x45 smaller than $\sigma_{\rm eff,TPS} = 12.5$ mb)

- TPS x-sections are large in p-A: a factor ×45 for p-Pb compared to p-p
- Pb transv. density ($F_{\rm pA}$, $C_{\rm pA}$) well-known: Alternative extraction of $\sigma_{\rm eff,pp}$

Triple charm & beauty production (p-Pb)

- Charm & beauty have very large TPS x-sections at the LHC & above:



Process	pPb(8.8 TeV)	pPb(63 TeV)	p-Air(430 TeV)
$\sigma^{\rm inel}_{\rm pA}$	2.2 ± 0.4 b	2.4 ± 0.4 mb	0.61 ± 0.10 b
$\sigma^{\rm SPS}_{c\bar{c}+X}$	$0.96 \pm 0.45_{\rm sc} \pm 0.10_{\rm PDF}$ b	$3.4 \pm 1.9_{\rm sc} \pm 0.4_{\rm PDF}$ b	$0.75 \pm 0.5_{\rm sc} \pm 0.1_{\rm PDF}$ b
$\sigma^{\rm TPS}_{c\bar{c}\,c\bar{c}\,c\bar{c}+X}$	$200 \pm 140_{\rm tot}$ mb	$8.7^* \pm 6.2_{\rm tot}$ b	$5.0^* \pm 3.6_{\rm tot}$ b
$\sigma^{\rm SPS}_{b\bar{b}+X}$	$72 \pm 12_{\rm sc} \pm 5_{\rm PDF}$ mb	$370 \pm 75_{\rm sc} \pm 30_{\rm PDF}$ mb	$110 \pm 25_{\rm sc} \pm 5_{\rm PDF}$ mb
$\sigma^{\rm TPS}_{b\bar{b}\,b\bar{b}\,b\bar{b}+X}$	$0.084 \pm 0.045_{\rm tot}$ μb	$11 \pm 7_{\rm tot}$ μb	$17 \pm 11_{\rm tot}$ μb

- Triple charm amounts to ~20% (~100%!) of inclusive charm x-sections at LHC (FCC). Large triple J/Ψ production at FCC: $\sigma(J/\psi J/\psi J/\psi + X) \approx 1$ mb
- Triple beauty amounts to ~3% of inclusive beauty x-sections at FCC.

Summary (DPS)

- What's the parton transverse density of a proton? Its energy evolution? How do partons correlate (kinemat., quantum numbers) transversely?
- Double hard parton scatterings. p-p cross section:

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

In absence of parton correlations:

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

geom. overlap area of 2 proton transv. profiles

- σ_{eff}(exp) ≈ 2–20 mb at Tevatron/LHC. Can HI colls. help to clarify this?
- Derived DPS x-sections "pocket formula" for p-A and A-A:

$$\sigma_{\rm eff,pA} = \frac{\sigma_{\rm eff,pp}}{A+\sigma_{\rm eff,pp}\,F_{pA}} = 21.5\pm1.1\ \mu b$$

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

Huge enhancements ! $\sigma_{\rm eff,DPS}/\sigma_{\rm eff,DPS,pA} \approx 600$, $\sigma_{\rm eff,pp}/\sigma_{\rm eff,AA} \propto A^{3.3}/5 \simeq 9\cdot10^6$

- Large DPS yields in p-A (in particular with quarkonia, → LHCb) provide many useful independent extractions of $\sigma_{eff,pp}$.
- Large DPS in Pb-Pb but dominated by scatts. from different nucleons. (~16% sensitivity on $\sigma_{eff,pp}$, from DPS with lighter ions such as Ar-Ar).

Summary (NPS, TPS)

- Derived a generic expression for NPS x-sections in p-p collisions:

$$\sigma^{\rm NPS}_{hh'\to a_1\dots a_n} = \left(\frac{m}{n!}\right)\frac{\sigma^{\rm SPS}_{hh'\to a_1}\cdots\sigma^{\rm SPS}_{hh'\to a_n}}{\sigma^{n-1}_{\rm eff,NPS}}$$

$$\sigma_{\rm eff,NPS} = \left\{\int d^2b\, T^n(\mathbf{b})\right\}^{-1/(n-1)}$$

- Applied to TPS case, it gives a very simple relationship between effective double and triple-parton cross sections:

$$\sigma_{\rm eff,TPS} = k\times\sigma_{\rm eff,DPS},\ \ \text{with}\ \ k = 0.82\pm 0.11$$

- Triple charm amounts to ~15% (50%) of inclusive charm x-sections in p-p collisions at LHC (FCC). Triple-J/Ψ, dominated by DPS/TPS, is a "golden channel" to extract $\sigma_{\rm eff,pp}$ at the LHC (→LHCb)!

- Derived TPS x-sections "pocket formula" for p-A:

$$\sigma^{\rm TPS}_{\rm pA\to abc} = \left(\frac{m}{6}\right)\frac{\sigma^{\rm SPS}_{\rm pN\to a}\cdot\sigma^{\rm SPS}_{\rm pN\to b}\cdot\sigma^{\rm SPS}_{\rm pN\to c}}{\sigma^{2}_{\rm eff,TPS,pA}}$$

$$\sigma_{\rm eff,TPS,pA} = \left[\frac{A}{\sigma^2_{\rm eff,TPS}} + \frac{3\,F_{\rm pA}[\rm mb^{-1}]}{\sigma_{\rm eff,DPS}} + C_{\rm pA}[\rm mb^{-2}]\right]^{-1/2}$$

- Large TPS yields in p-A (in particular with charm) provide useful independent extractions of $\sigma_{\rm eff,pp}$.

Backup slides

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

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

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	$\rm N^{DPS}(1\ nb^{-1})$	~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	$\rm N^{DPS}(1\ nb^{-1})$	~95	~35	~8	~15

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

Outline

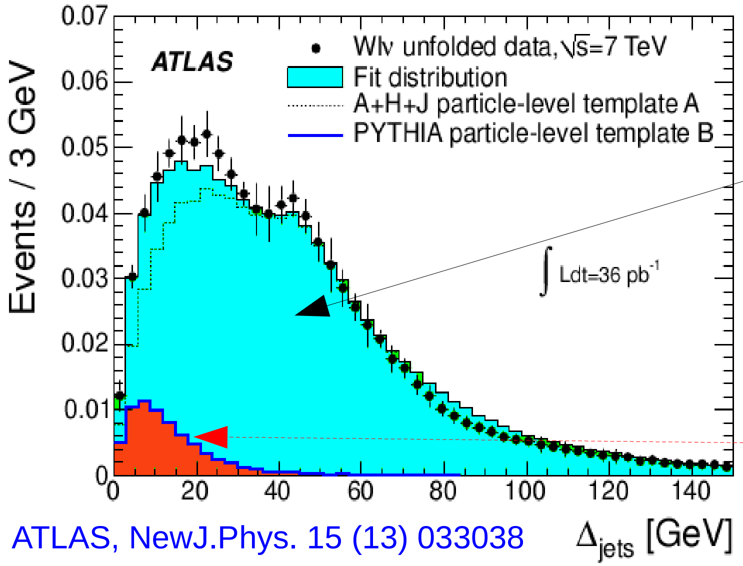
- Introduction – Double Parton Scattering in p-p collisions:
  - Empirical "pocket formula" for the DPS x-sections
  - Experimental DPS studies: difficulties in σ_{eff} extraction

- 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 $J/\psi, \Upsilon$ & W,Z bosons: N_{DPS}=5–65
  - Case study: Same-sign WW in p-Pb at 8.8 TeV:
    σ(ssWW,DPS) $\approx$ 150 pb > σ(ssWWjj,SPS) $\approx$ 100 pb
    $N_{visible}$(ssWW,DPS) $\approx$ 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/ $J/\psi, \Upsilon$ & 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

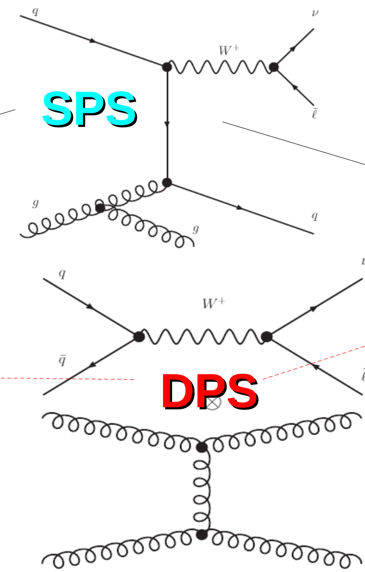
DPS searches at LHC: p-p → W^{+}+2j

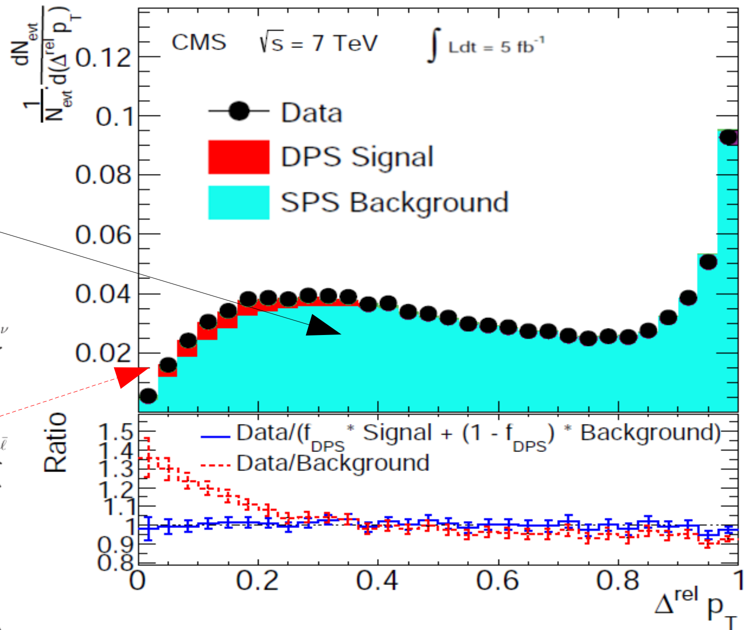
- Small signal in W+2jets events: Via di-jet p_T asymmetry (~0 in DPS)



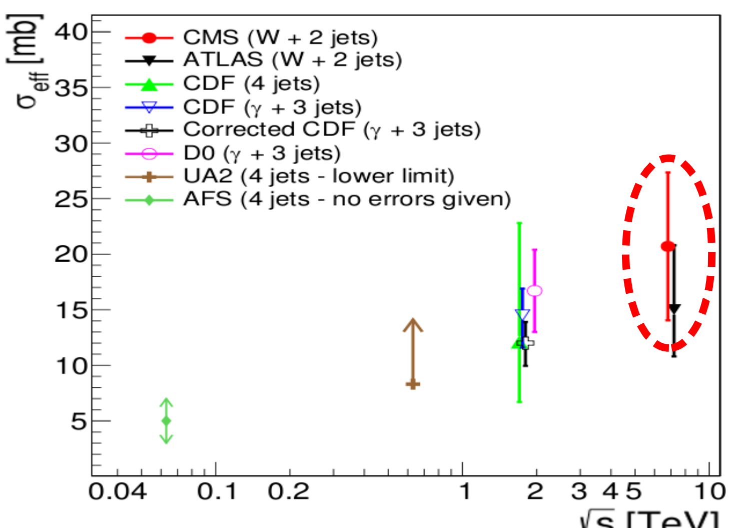
ATLAS, NewJ.Phys. 15 (13) 033038

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





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 σ_{eff}

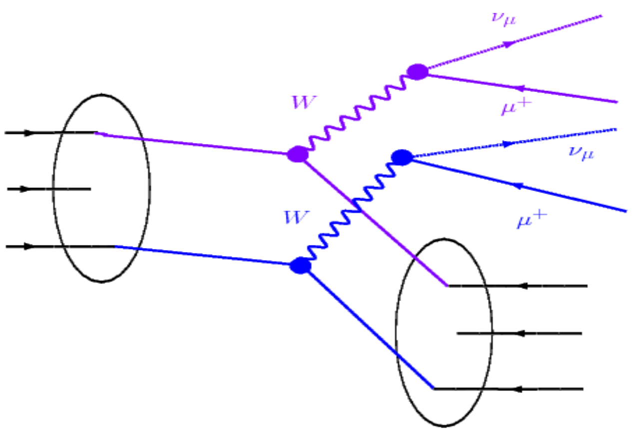
σ_{eff} = 15 – 20 mb

DPS "golden channel": Same-sign WW

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

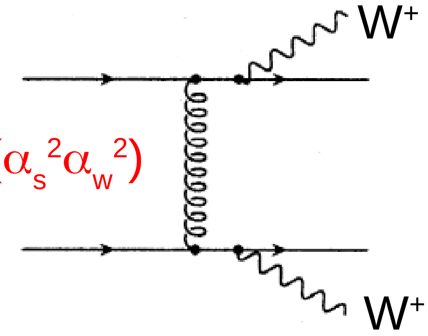
- Same-sign W-W production from 2 independent hard scatterings is a "golden" DPS signature:

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

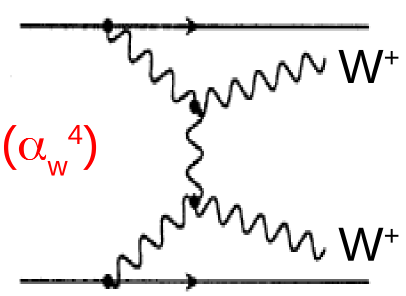


- Backgrounds: Same-sign W-W production in single parton scatterings (SPS) is higher-order and occurs only with 2 extra jets:

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



EWK (α_w^4)

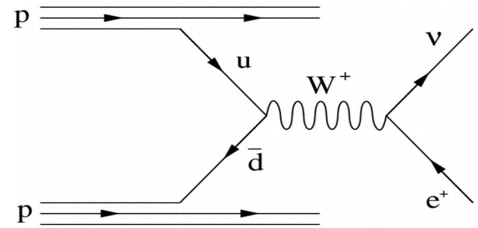


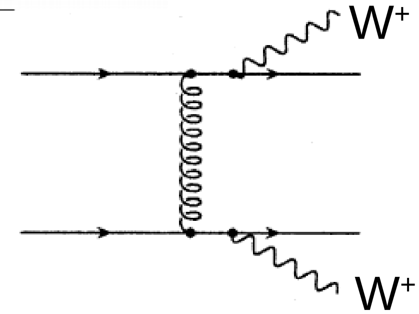
- σ(WW,DPS)~1/3·σ(WWjj,SPS), but SPS background reducible by more than x20 applying jet cuts.

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

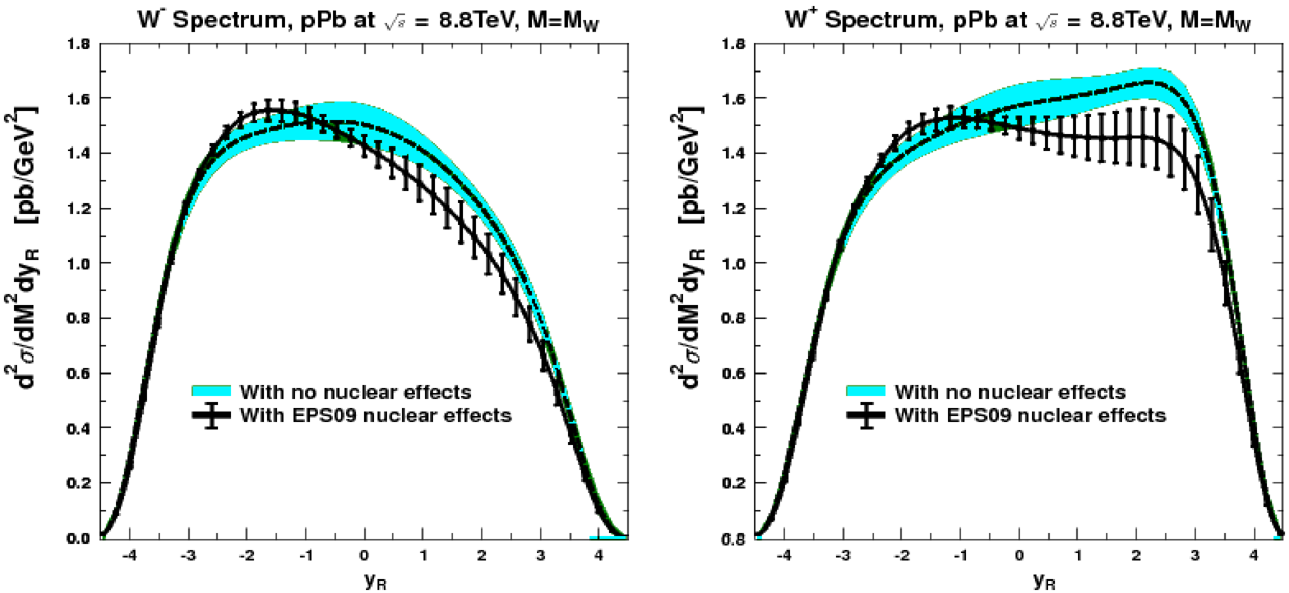
[DdE,Snigirev, PLB718 (2013)1395]

- 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:

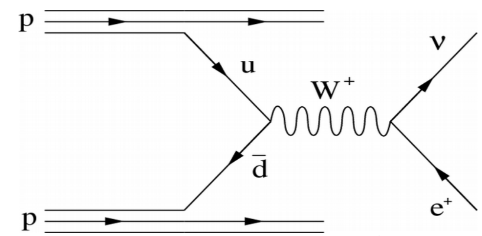


[Paukkunen&Salgado JHEP 1103 (2011) 071]

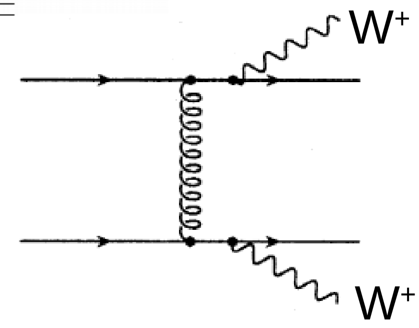
Isospin+shadow. effects on total inclusive x-sections:
W^- : +7%
W^+ : -15%
compared to p-p

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

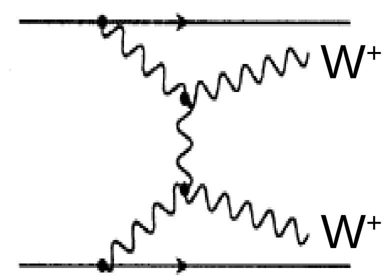
[DdE,Snigirev, PLB718 (2013)1395]



- **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%



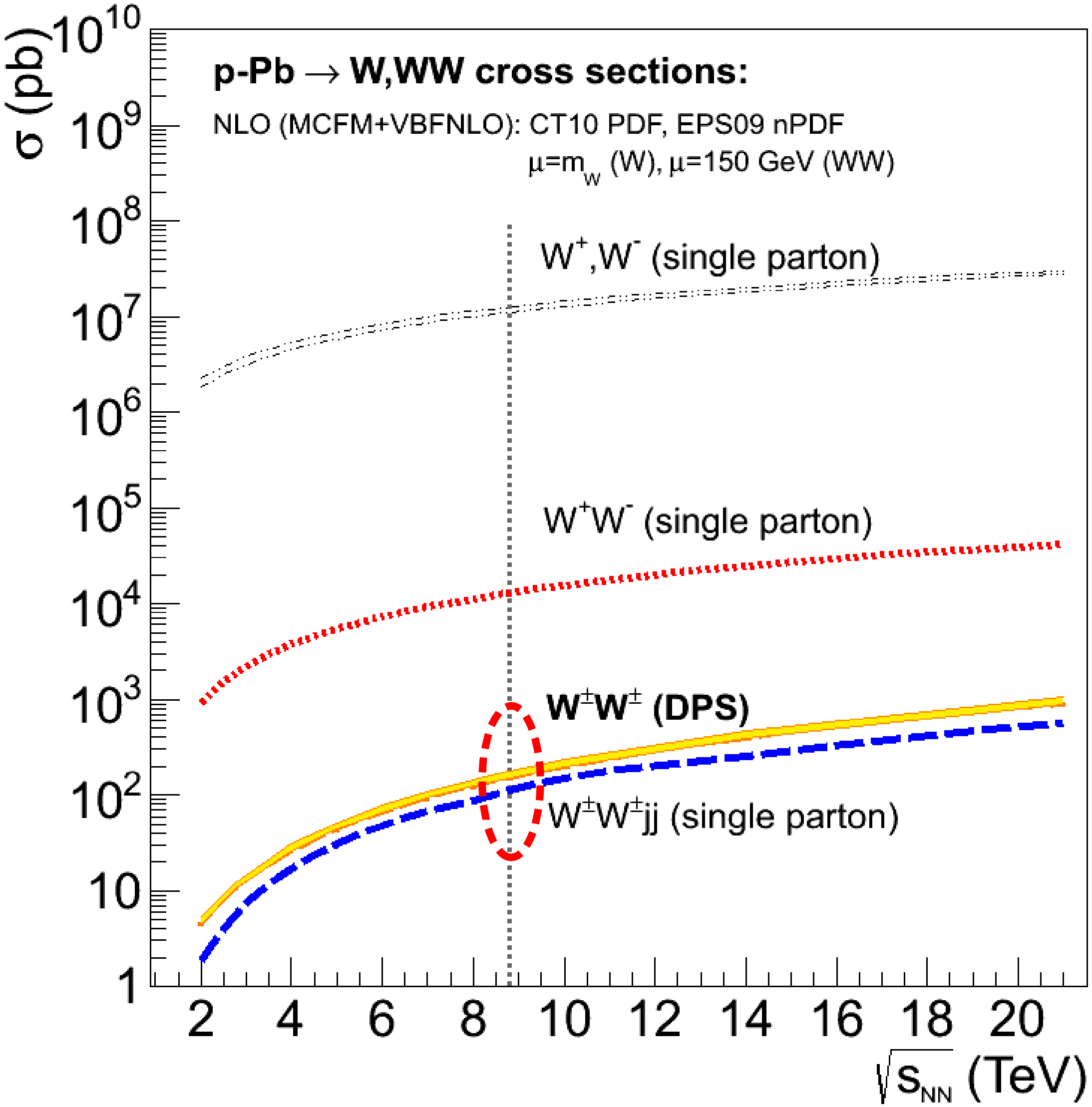
- **Cross sections in pb** (signal & background):

p-Pb final-state: Code (process #): Order (σ units):	W^+ MCFM (1) NLO (μb)	W^- MCFM (6) NLO (μb)	W^+W^- MCFM (61) NLO (nb)	W^+W^+jj (QCD) MCFM (251) 'NLO' (pb)	W^+W^+jj (VBF) VBFNLO (250) NLO (pb)	$W^\pm W^\pm$ (DPS) Eq. (15) (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. ± 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. ± 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:

σ(WW,DPS)≈150 pb

σ(WWjj)≈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:

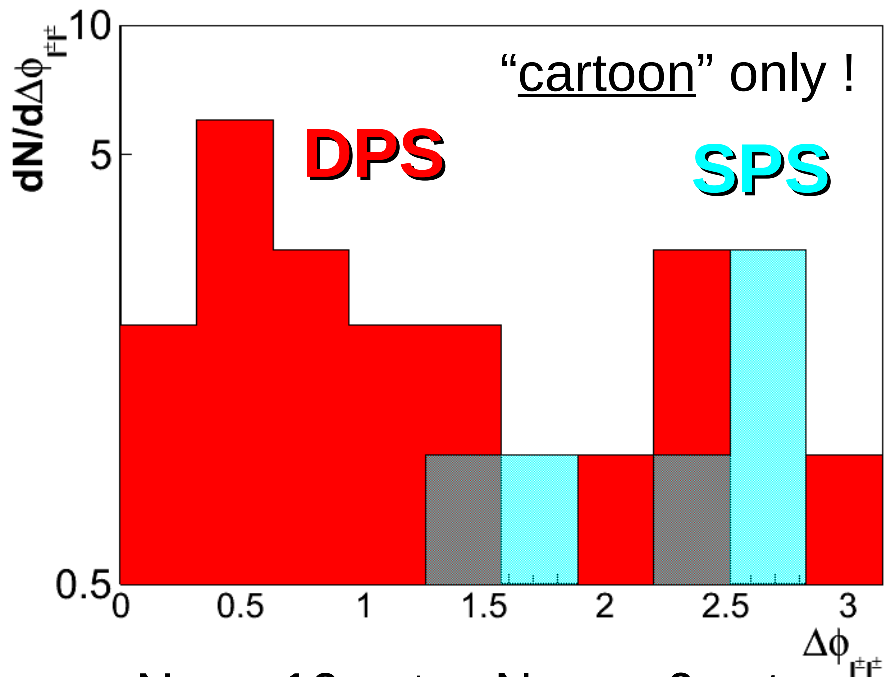
$$N_{\rm DPS} = \sigma^{\rm DPS}_{pPb\to WW}/(\varepsilon\cdot\mathcal{L}_{\rm int}) \approx$$ 1–10 same-sign WW pairs/year

(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