

# Triple parton scatterings in high-energy hadronic collisions



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(\*) Details in: [D.d'E & A.Snigirev: PRL118 \(2017\) 122001, EPJC 78 \(2018\) 359](#)  
[arXiv:1708.07519 \[Adv.Ser.Direct.High.En.Phys. 29 \(2018\) 159\]](#)

# DPS studies at the LHC

- Motivation for studies of multiple production of hard/heavy particles:
  - (1) **Generalized PDFs** ( $x, Q^2, b$ ) of the proton, in particular the unknown energy **evolution of transverse proton profile**.
  - (2) Role of **partonic correlations** (in space,  $p$ ,  $x$ , flavour, colour, spin,...) in hadronic wave functions.
  - (3) **Backgrounds** for rare **(B)SM** resonance decays w/ **multiple heavy particles**

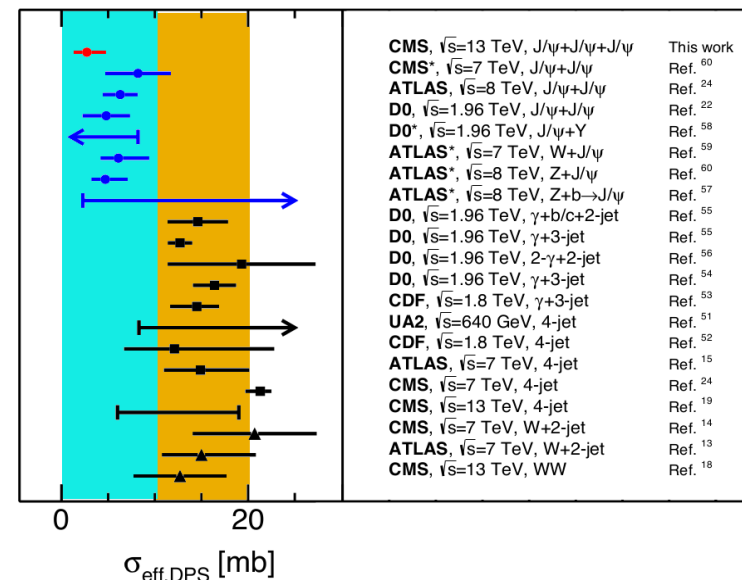
- “Pocket formula” results at the LHC:

$$\sigma_{\text{DPS}}^{\text{pp} \rightarrow \psi_1 \psi_2 + X} = \left(\frac{m}{2}\right) \frac{\sigma_{\text{SPS}}^{\text{pp} \rightarrow \psi_1 + X} \sigma_{\text{SPS}}^{\text{pp} \rightarrow \psi_2 + X}}{\sigma_{\text{eff,DPS}}}$$

$\sigma_{\text{eff}} \approx \langle \text{Interparton transv. separation} \rangle^2$

derivable from p-p transverse overlap:

$$\left\{ \begin{array}{l} \sigma_{\text{eff}} \approx 20\text{--}30 \text{ mb (PYTHIA8/HERWIG p form-factor)} \\ \sigma_{\text{eff}} \approx 15 \text{ mb (from DPS of jets, EWK bosons)} \\ \sigma_{\text{eff}} \approx 5 \text{ mb (from di-quarkonia)} \end{array} \right.$$



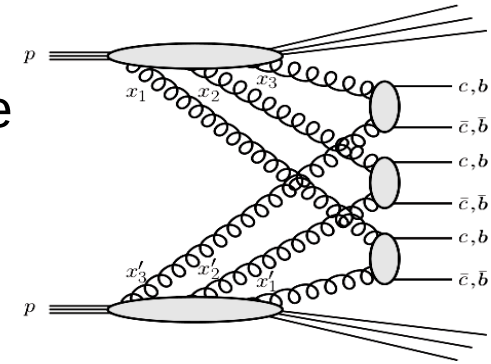
Reasons: Parton **correlations?**  $x$ -,flavour-dependent transverse  $p$  profile?

- Novel observables: **Triple-parton scatterings (TPS)**, **DPS/TPS with ions**, (in particular with **charm**, **bottom** final states: largest pQCD  $x$ -sections)

# 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:

$$\sigma_{hh' \rightarrow a_1 a_2 a_3}^{\text{TPS}} = \left( \frac{m}{3!} \right) \frac{\sigma_{hh' \rightarrow a_1}^{\text{SPS}} \cdot \sigma_{hh' \rightarrow a_2}^{\text{SPS}} \cdot \sigma_{hh' \rightarrow a_3}^{\text{SPS}}}{\sigma_{\text{eff,TPS}}^2}$$



normalized by the square of an eff. x-section ( $\sigma_{\text{eff,TPS}}^2$ ) 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  $\sigma_{\text{eff,TPS}}$ ? Relationship with DPS  $\sigma_{\text{eff}}$ ? What values to expect?
- Most generic expression for TPS cross section:

$$\begin{aligned} \sigma_{hh' \rightarrow a_1 a_2 a_3}^{\text{TPS}} = & \left( \frac{m}{3!} \right) \sum_{i,j,k,l,m,n} \int \Gamma_h^{ijk}(x_1, x_2, x_3; \mathbf{b}_1, \mathbf{b}_2, \mathbf{b}_3; Q_1^2, Q_2^2, Q_3^2) \\ & \times \hat{\sigma}_{a_1}^{il}(x_1, x'_1, Q_1^2) \cdot \hat{\sigma}_{a_2}^{jm}(x_2, x'_2, Q_2^2) \cdot \hat{\sigma}_{a_3}^{kn}(x_3, x'_3, Q_3^2) \\ & \times \Gamma_{h'}^{lmn}(x'_1, x'_2, x'_3; \mathbf{b}_1 - \mathbf{b}, \mathbf{b}_2 - \mathbf{b}, \mathbf{b}_3 - \mathbf{b}; Q_1^2, Q_2^2, Q_3^2) \\ & \times dx_1 dx_2 dx_3 dx'_1 dx'_2 dx'_3 d^2 b_1 d^2 b_2 d^2 b_3 d^2 b. \end{aligned}$$

Generalized PDFs =  $f(x, Q^2, \mathbf{b})$

# 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 ( $\text{mb}^{-1}$ ):  $T(\mathbf{b}) = \int f(\mathbf{b}_1) f(\mathbf{b}_1 - \mathbf{b}) d^2 b_1$ , with  $\int d^2 b T(\mathbf{b}) = 1$ .

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

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

[DdE, Snigirev, PRL 118(2017)122001]

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

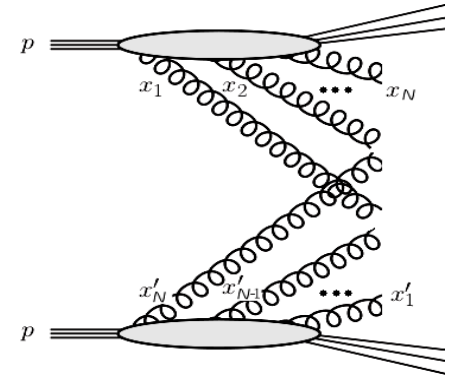
$$\sigma_{\text{eff,TPS}} = k \times \sigma_{\text{eff,DPS}}, \text{ with } k = 0.82 \pm 0.11$$

- Measuring TPS provides a new independent  $\sigma_{\text{eff}}$  extraction.

# Generic 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:

$$\sigma_{hh' \rightarrow a_1 \dots a_n}^{\text{NPS}} = \left( \frac{m}{n!} \right) \frac{\sigma_{hh' \rightarrow a_1}^{\text{SPS}} \cdots \sigma_{hh' \rightarrow a_n}^{\text{SPS}}}{\sigma_{\text{eff,NPS}}^{n-1}}$$



normalized by the  $N^{\text{th}}-1$  power of an effective x-section ( $\sigma_{\text{eff,NPS}}$ ) 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,  $\sigma_{\text{eff,NPS}}$  is the inverse  $N^{\text{th}}-1$  power of the integral of the  $N^{\text{th}}$  power of the pp overlap function:

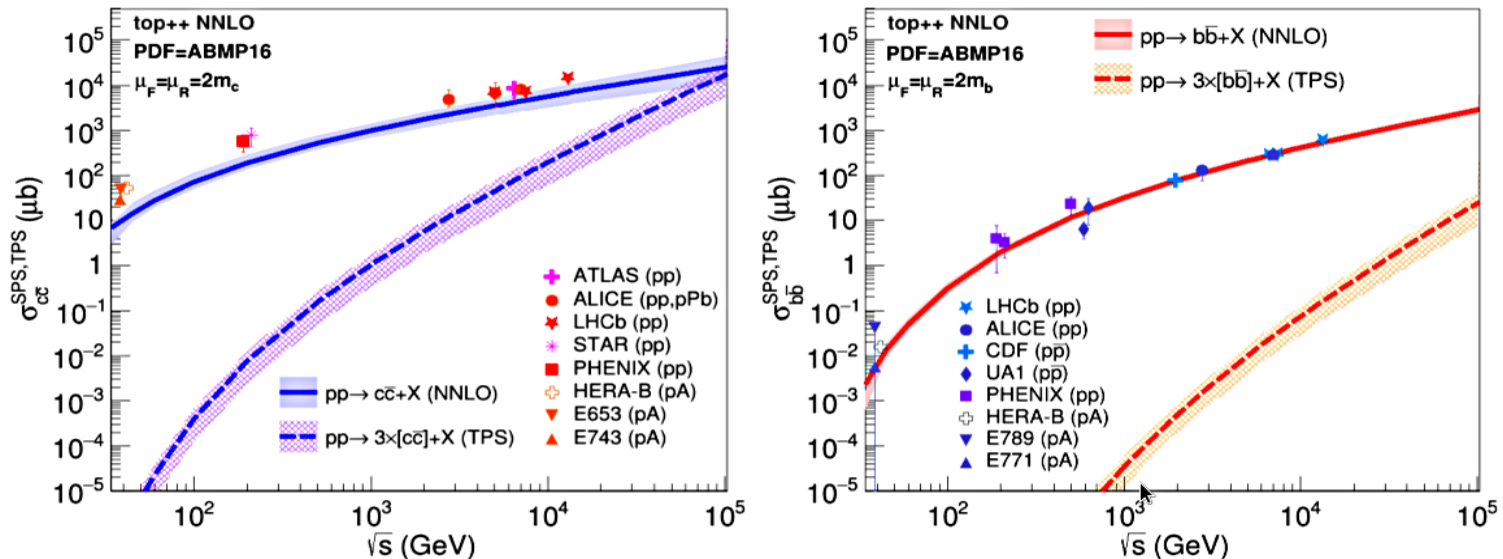
$$\sigma_{\text{eff,NPS}} = \left\{ \int d^2b T^n(\mathbf{b}) \right\}^{-1/(n-1)}$$

[DdE, Snigirev, ASDHEP 29 (2018) 159]

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

# Triple charm & beauty production (p-p)

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

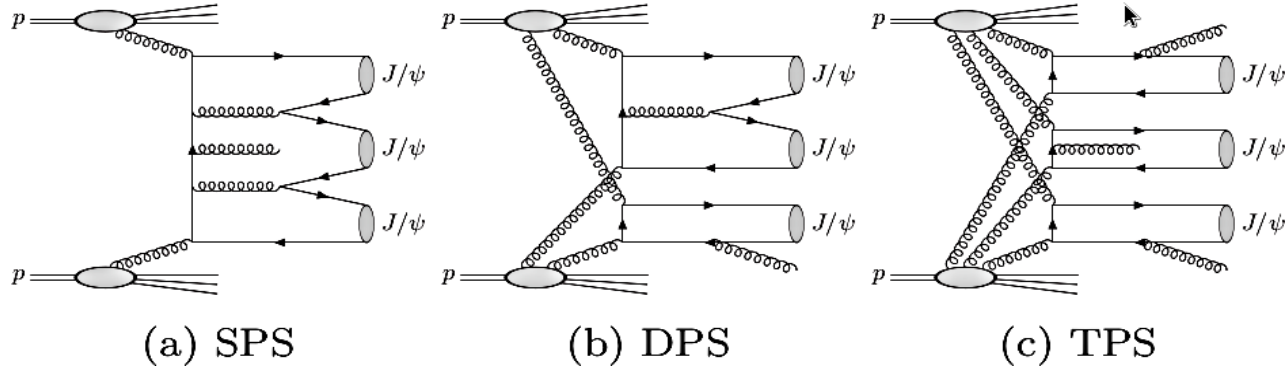


Final state	$\sqrt{s} = 14 \text{ TeV}$	$\sqrt{s} = 100 \text{ TeV}$
$\sigma_{c\bar{c}+X}^{\text{SPS}}$	$7.1 \pm 3.5_{\text{SC}} \pm 0.3_{\text{PDF}} \text{ mb}$	$25.0 \pm 16.0_{\text{SC}} \pm 1.3_{\text{PDF}} \text{ mb}$
$\sigma_{c\bar{c} c\bar{c} c\bar{c}+X}^{\text{TPS}}$	$0.39 \pm 0.28_{\text{tot}}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

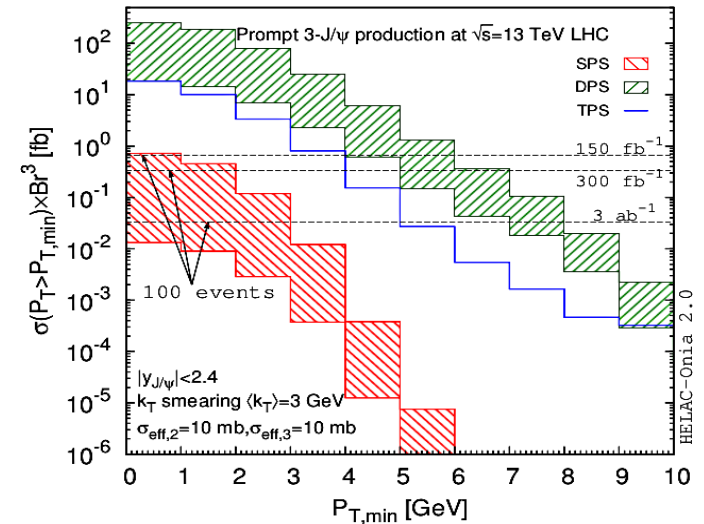
- Triple charm amounts to ~15% (50%) of inclusive charm x-sections at LHC (FCC). Contribution from triple-SPS, double-SPS processes?

# Triple- $J/\psi$ from SPS production (p-p)

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



		inclusive	$2.0 < y_{J/\psi} < 4.5$	$ y_{J/\psi}  < 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	$(190^{+501}_{-140}) \times \frac{10 \text{ mb}}{\sigma_{\text{eff},2}}$	$(7.0^{+18}_{-5.1}) \times \frac{10 \text{ mb}}{\sigma_{\text{eff},2}}$	$(50^{+140}_{-37}) \times \frac{10 \text{ mb}}{\sigma_{\text{eff},2}}$
	TPS	$130 \times \left(\frac{10 \text{ mb}}{\sigma_{\text{eff},3}}\right)$	$1.3 \times \left(\frac{10 \text{ mb}}{\sigma_{\text{eff},3}}\right)$	$18 \times \left(\frac{10 \text{ mb}}{\sigma_{\text{eff},3}}\right)$
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	$(560^{+2900}_{-480}) \times \frac{10 \text{ mb}}{\sigma_{\text{eff},2}}$	$(19^{+97}_{-16}) \times \frac{10 \text{ mb}}{\sigma_{\text{eff},2}}$	$(120^{+630}_{-100}) \times \frac{10 \text{ mb}}{\sigma_{\text{eff},2}}$
	TPS	$570 \times \left(\frac{10 \text{ mb}}{\sigma_{\text{eff},3}}\right)$	$5.0 \times \left(\frac{10 \text{ mb}}{\sigma_{\text{eff},3}}\right)$	$57 \times \left(\frac{10 \text{ mb}}{\sigma_{\text{eff},3}}\right)$
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	$(1900^{+11000}_{-1600}) \times \frac{10 \text{ mb}}{\sigma_{\text{eff},2}}$	$(57^{+340}_{-50}) \times \frac{10 \text{ mb}}{\sigma_{\text{eff},2}}$	$(310^{+2000}_{-270}) \times \frac{10 \text{ mb}}{\sigma_{\text{eff},2}}$
	TPS	$3900 \times \left(\frac{10 \text{ mb}}{\sigma_{\text{eff},3}}\right)$	$27 \times \left(\frac{10 \text{ mb}}{\sigma_{\text{eff},3}}\right)$	$260 \times \left(\frac{10 \text{ mb}}{\sigma_{\text{eff},3}}\right)$
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	$(3400^{+19000}_{-2900}) \times \frac{10 \text{ mb}}{\sigma_{\text{eff},2}}$	$(100^{+550}_{-86}) \times \frac{10 \text{ mb}}{\sigma_{\text{eff},2}}$	$(490^{+3000}_{-430}) \times \frac{10 \text{ mb}}{\sigma_{\text{eff},2}}$
	TPS	$6500 \times \left(\frac{10 \text{ mb}}{\sigma_{\text{eff},3}}\right)$	$45 \times \left(\frac{10 \text{ mb}}{\sigma_{\text{eff},3}}\right)$	$380 \times \left(\frac{10 \text{ mb}}{\sigma_{\text{eff},3}}\right)$



- **SPS negligible, DPS (TPS) dominates at low (high)  $p_T$ .**

Clear sensitivity to  $\sigma_{\text{eff}}$  !



# TPS in p-p collisions (13 TeV, CMS)

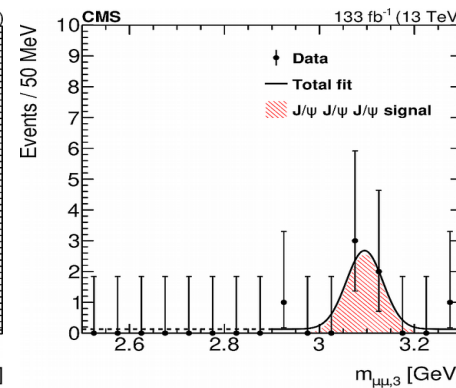
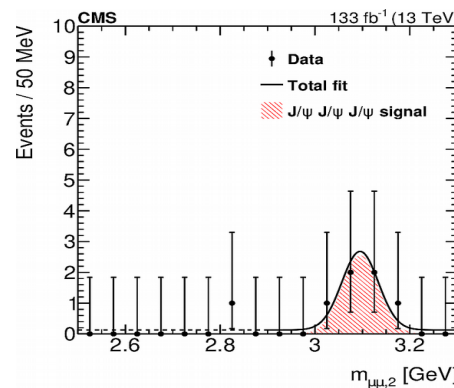
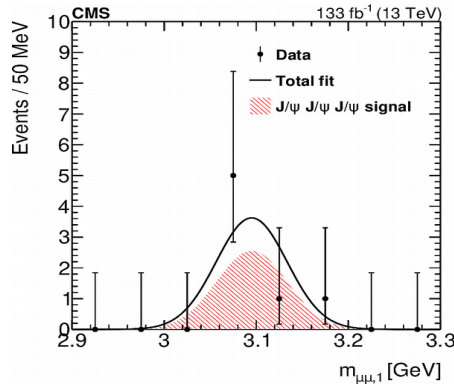
- Triple parton scatterings x-sections in p-p: alternative extraction of  $\sigma_{\text{eff,DPS}}$

$$\sigma_{hh' \rightarrow a_1 a_2 a_3}^{\text{TPS}} = \left( \frac{m}{3!} \right) \frac{\sigma_{hh' \rightarrow a_1}^{\text{SPS}} \cdot \sigma_{hh' \rightarrow a_2}^{\text{SPS}} \cdot \sigma_{hh' \rightarrow a_3}^{\text{SPS}}}{\sigma_{\text{eff,TPS}}^2}$$

$$\sigma_{\text{eff,TPS}} = (0.82 \pm 0.11) \sigma_{\text{eff,DPS}}$$

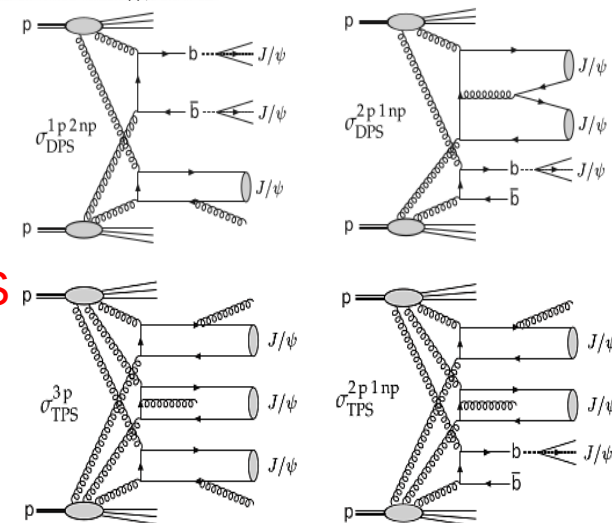
[DdE, Snigirev, PRL 118(2017)122001]

- First observation of triple- $J/\psi$  production (CMS):



[arXiv:2111.05370  
Nat. Phys. to appear]

- Measurement of fiducial cross section  
 $\sigma(pp \rightarrow 3J/\psi) = 272_{-104}^{+141} \text{ (stat)} \pm 17 \text{ (syst) fb}$
- Pocket formula with (N)NLO for single-, double-, triple- $J/\psi$  SPS x-sections:
  - Triple- $J/\psi$  fractions: ~6% SPS, ~74% DPS, ~20% TPS





# TPS in p-p collisions (13 TeV, CMS)

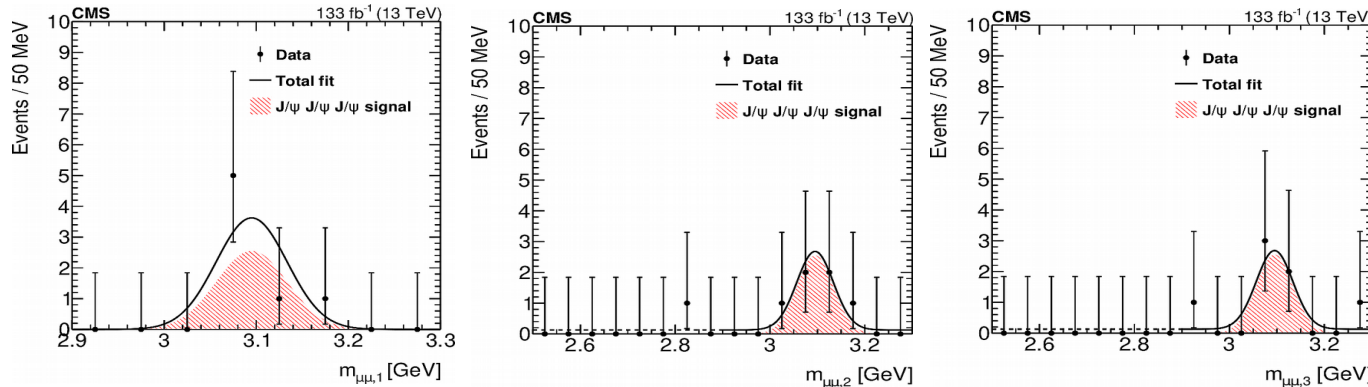
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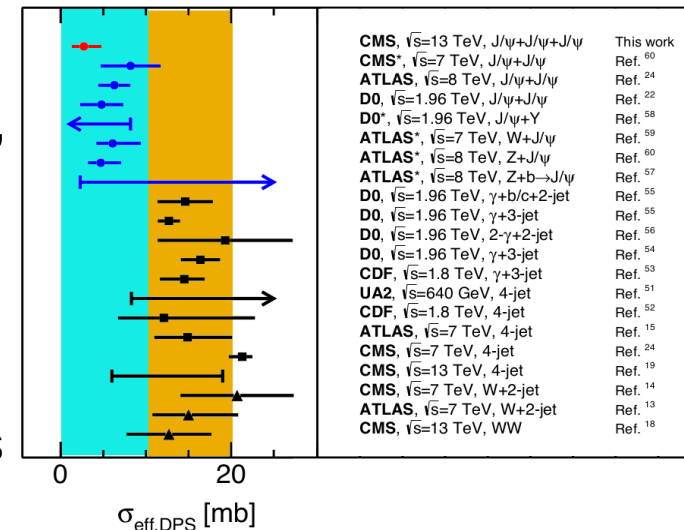
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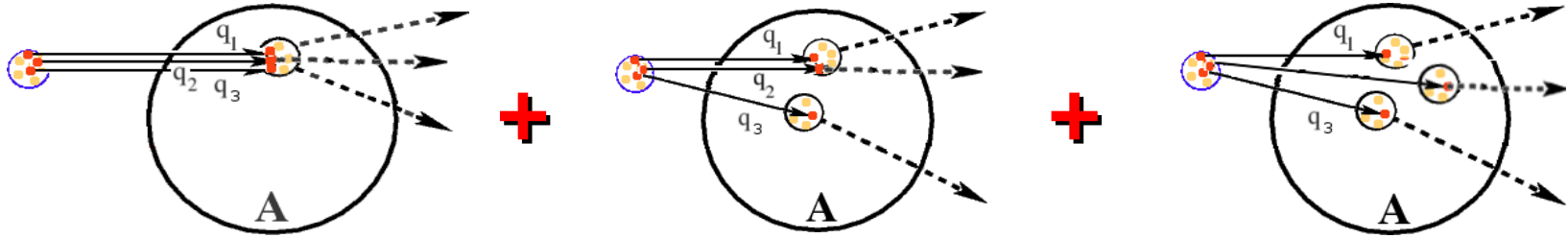
- Measurement of fiducial cross section  
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- Pocket formula with (N)NLO for single-, double-, triple- $J/\psi$  SPS x-sections:
  - Triple- $J/\psi$  fractions:  $\sim 6\%$ ,  $\sim 74\%$ ,  $\sim 20\%$  TPS
  - $\sigma_{\text{eff,DPS}} = 2.7_{-1.0}^{+1.4} \text{ (exp)}_{+1.0}^{+1.5} \text{ (theo) mb}$  consistent with di-quarkonia (lower than jet/ $\gamma$ /W/Z DPS) results:
  - q/g x-dependent transverse profile & correlations



# Triple Parton Scattering x-sections in p-A

[DdE, Snigirev, EPJC 78 (2018)359]

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



$$\sigma_{pA \rightarrow abc}^{\text{TPS},1} = A \cdot \sigma_{pN \rightarrow abc}^{\text{TPS}}, \quad \sigma_{pA \rightarrow abc}^{\text{TPS},2} = \sigma_{pN \rightarrow abc}^{\text{TPS}} \cdot 3 \frac{\sigma_{\text{eff},\text{TPS}}^2}{\sigma_{\text{eff},\text{DPS}}} F_{pA}, \quad \sigma_{pA \rightarrow abc}^{\text{TPS},3} = \sigma_{pN \rightarrow abc}^{\text{TPS}} \cdot \sigma_{\text{eff},\text{TPS}}^2 \cdot C_{pA}, \quad \text{with}$$

$$C_{pA} = \frac{(A-1)(A-2)}{A^2} \int d^2b T_{pA}^3(b),$$

Relative weight of TPS terms:  $\sigma_{pA \rightarrow abc}^{\text{TPS},1} : \sigma_{pA \rightarrow abc}^{\text{TPS},2} : \sigma_{pA \rightarrow abc}^{\text{TPS},3} = 1 : 4.54 : 3.56$ .

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

## ■ "Pocket" formula for TPS p-A x-section:

$$\sigma_{pA \rightarrow abc}^{\text{TPS}} = \left(\frac{m}{6}\right) \frac{\sigma_{pN \rightarrow a}^{\text{SPS}} \cdot \sigma_{pN \rightarrow b}^{\text{SPS}} \cdot \sigma_{pN \rightarrow c}^{\text{SPS}}}{\sigma_{\text{eff},\text{TPS},pA}^2}$$

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

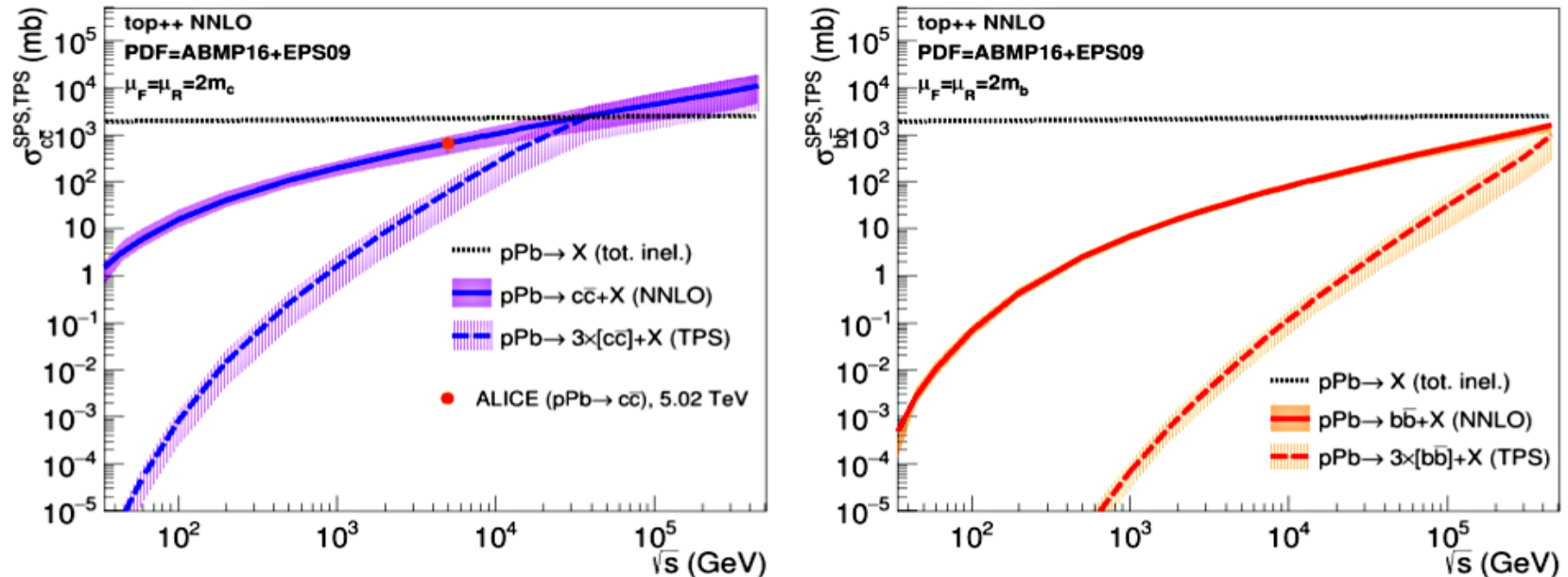
►  $\sigma_{\text{eff},\text{TPS},p\text{Pb}} = 0.29 \pm 0.04 \text{ mb}$  ( $\times 45$  times the p-p case with  $\sigma_{\text{eff},\text{TPS}} = 12.5 \text{ mb}$ )

■ TPS x-sections are large in p-A: a factor  $\times 45$  for p-Pb compared to p-p

■ Pb transv. density ( $F_{pA}$ ,  $C_{pA}$ ) well-known: Alternative extraction of  $\sigma_{\text{eff},pp}$

# Example: Triple charm & beauty in p-Pb colls.

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



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

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

# Summary: Triple parton scatterings

- What's the parton transverse density of a proton? Its energy evolution? How do partons correlate (kinemat., quantum numbers) transversely?
- Derived a generic expression for NPS x-sections in p-p collisions:

$$\sigma_{hh' \rightarrow a_1 \dots a_n}^{\text{NPS}} = \left( \frac{m}{n!} \right) \frac{\sigma_{hh' \rightarrow a_1}^{\text{SPS}} \cdots \sigma_{hh' \rightarrow a_n}^{\text{SPS}}}{\sigma_{\text{eff,NPS}}^{n-1}}$$

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

- And used it to derive pocket formula for triple parton scatterings in p-p...

$$\sigma_{hh' \rightarrow a_1 a_2 a_3}^{\text{TPS}} = \left( \frac{m}{3!} \right) \frac{\sigma_{hh' \rightarrow a_1}^{\text{SPS}} \cdot \sigma_{hh' \rightarrow a_2}^{\text{SPS}} \cdot \sigma_{hh' \rightarrow a_3}^{\text{SPS}}}{\sigma_{\text{eff,TPS}}^2}$$

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

# Summary: Triple parton scatterings

- What's the **parton transverse density** of a proton? Its **energy evolution**?  
How do **partons correlate** (kinemat., quantum numbers) transversely?

- Triple** hard parton scatterings in p-p collisions:

(closely related to DPS in the absence of parton correlations):

$$\sigma_{hh' \rightarrow a_1 a_2 a_3}^{\text{TPS}} = \left(\frac{m}{3!}\right) \frac{\sigma_{hh' \rightarrow a_1}^{\text{SPS}} \cdot \sigma_{hh' \rightarrow a_2}^{\text{SPS}} \cdot \sigma_{hh' \rightarrow a_3}^{\text{SPS}}}{\sigma_{\text{eff,TPS}}^2}$$

$$\sigma_{\text{eff,TPS}} = (0.82 \pm 0.11) \sigma_{\text{eff,DPS}}$$

- Triple charm** amounts to ~15% of inclusive charm x-sections in p-p collisions at the LHC. **Triple-J/ψ** fully dominated by DPS/TPS: “**golden channel**” to extract  $\sigma_{\text{eff,pp}}$ : 1<sup>st</sup>-ever observation by CMS.

- Derived TPS x-sections “**pocket formula**” for p-A:

$$\sigma_{\text{pA} \rightarrow abc}^{\text{TPS}} = \left(\frac{m}{6}\right) \frac{\sigma_{\text{pN} \rightarrow a}^{\text{SPS}} \cdot \sigma_{\text{pN} \rightarrow b}^{\text{SPS}} \cdot \sigma_{\text{pN} \rightarrow c}^{\text{SPS}}}{\sigma_{\text{eff,TPS,pA}}^2}$$

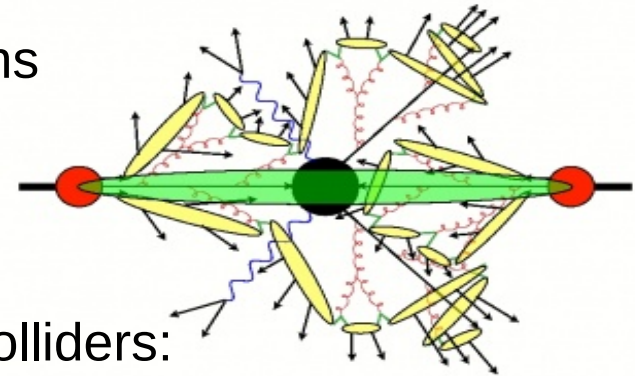
$$\sigma_{\text{eff,TPS,pA}} = \left[ \frac{A}{\sigma_{\text{eff,TPS}}^2} + \frac{3 F_{\text{pA}}[\text{mb}^{-1}]}{\sigma_{\text{eff,DPS}}} + C_{\text{pA}}[\text{mb}^{-2}] \right]^{-1/2}$$

- Large TPS yields in p-Pb**, e.g.  $\sigma_{\text{TPS}}(\text{triple-ccbar}) = 200 \text{ mb}$  (~20% of incl. ccbar x-section): provide useful **independent extractions** of  $\sigma_{\text{eff,pp}}$ .  
[Don't be shy to attempt a 1<sup>st</sup>-ever measurement in p-Pb...].

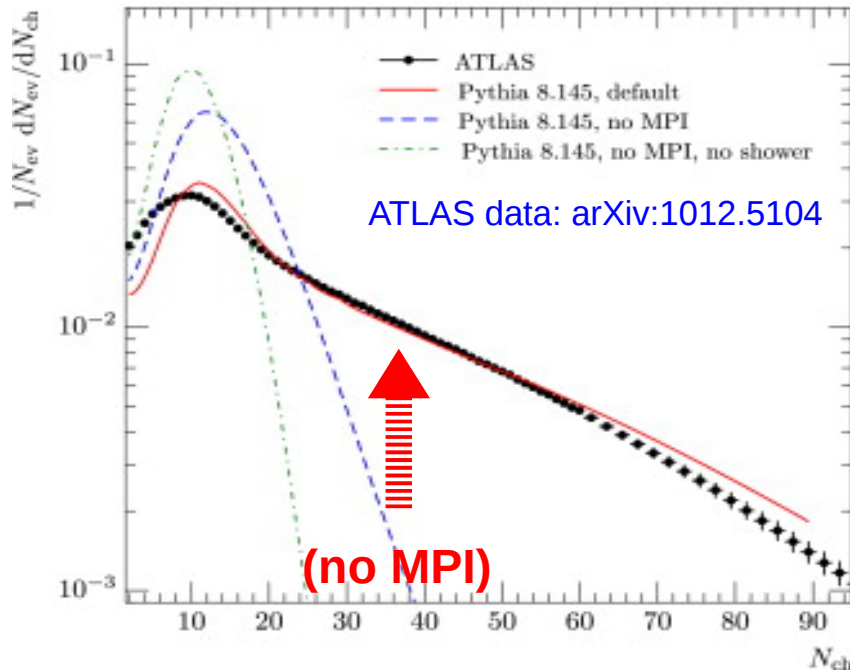
# Backup slides

# Multi-parton interactions at the LHC

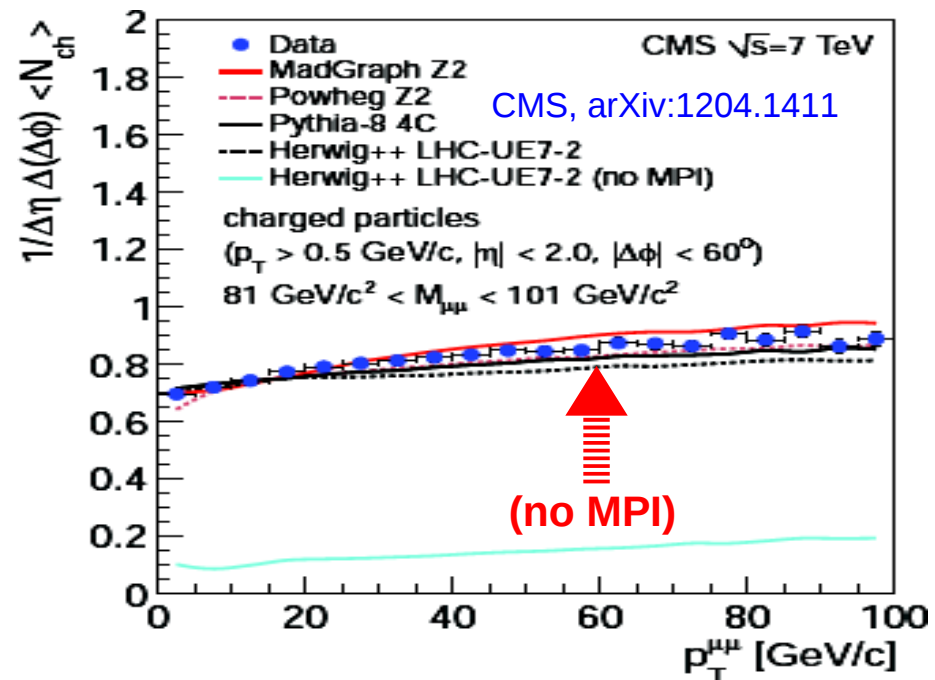
- MPI are intrinsic component of hadron collisions  
(p,Pb) = non-pointlike objects with finite  
transverse size and increasingly  
larger gluon density with  $\sqrt{s}$ .



- MPI  $O(1-3 \text{ GeV})$  clearly observed at hadron colliders:  
~50% of total hadron production



Underlying event in hard scatterings:



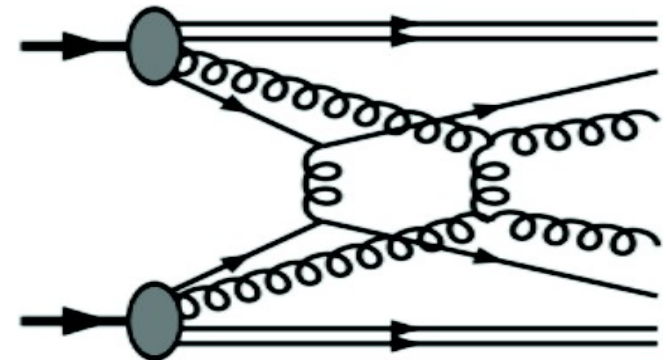
- Double hard parton scatts. ( $p_T, m_x > 3 \text{ GeV}$ ) happen also & been observed



# Double Parton Scattering x-sections (p-p)

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

$$\sigma_{(hh' \rightarrow ab)}^{\text{DPS}} = \left(\frac{m}{2}\right) \frac{\sigma_{(hh' \rightarrow a)}^{\text{SPS}} \cdot \sigma_{(hh' \rightarrow b)}^{\text{SPS}}}{\sigma_{\text{eff}}}$$



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

- How to interpret  $\sigma_{\text{eff}}$ ? What values one would naively expect for it?
- Let's start with the most generic expression for DPS cross section:

$$\sigma_{(hh' \rightarrow ab)}^{\text{DPS}} = \left(\frac{m}{2}\right) \sum_{i,j,k,l} \int \Gamma_h^{ij}(x_1, x_2; \mathbf{b}_1, \mathbf{b}_2; Q_1^2, Q_2^2) \times \hat{\sigma}_a^{ik}(x_1, x'_1, Q_1^2) \hat{\sigma}_b^{jl}(x_2, x'_2, Q_2^2) \\ \times \Gamma_{h'}^{kl}(x'_1, x'_2; \mathbf{b}_1 - \mathbf{b}, \mathbf{b}_2 - \mathbf{b}; Q_1^2, Q_2^2) dx_1 dx_2 dx'_1 dx'_2 d^2 b_1 d^2 b_2 d^2 b$$

Generalized PDFs =  $f(x, Q^2, \mathbf{b})$

# Double Parton Scattering x-sections (p-p)

- Assumption 1: Generalized PDFs factorize into longitudinal & transverse components: transv. density =  $f(\mathbf{b})$

$$\Gamma_h^{ij}(x_1, x_2; \mathbf{b}_1, \mathbf{b}_2; Q_1^2, Q_2^2) = D_h^{ij}(x_1, x_2; Q_1^2, Q_2^2) f(\mathbf{b}_1) f(\mathbf{b}_2)$$

p-p transv. overlap function ( $\text{mb}^{-1}$ ):  $t(\mathbf{b}) = \int f(\mathbf{b}_1) f(\mathbf{b}_1 - \mathbf{b}) d^2 b_1$

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

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

- $\sigma_{\text{eff}} = \langle \text{Interparton transv. separation} \rangle^2$ . Derivable from geometric p-p overlap with naive expected size of  $\sigma_{\text{eff}} \approx 30 \text{ mb}$

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

- But experimentally:

$$\sigma_{\text{eff}}(\text{exp}) \approx 15 \text{ mb.}$$

proton “hard” radius:  
 $r = 0.3\text{--}0.7 \text{ fm}$  appears  
 smaller than e.m. one:

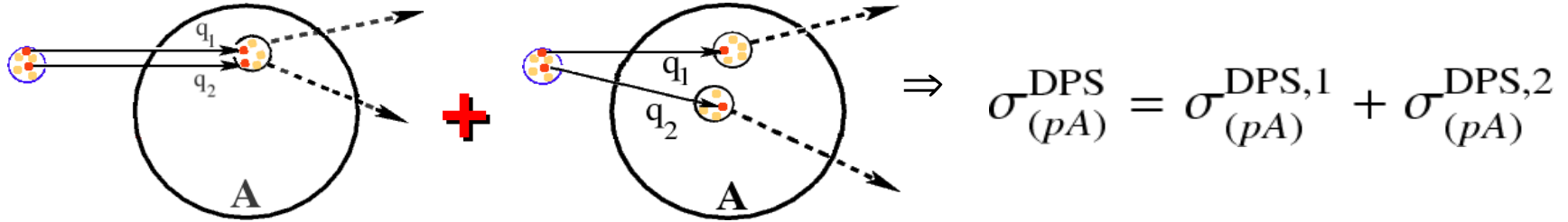
Model for density	Form of density, $dN/d^3r$	Predictions rms $r$	$\sigma_{\text{eff}}$	Measurements Scale (fm)
Solid sphere	Constant, $r < r_p$	$\sqrt{3/5} r_p$	$4\pi r_p^2/4.6$	$r_p = 0.73$
Gaussian	$e^{-r^2/2\Sigma^2}$	$\sqrt{3}\Sigma$	$4\pi\Sigma^2$	$\Sigma = 0.34$
Exponential	$e^{-r/\lambda}$	$\sqrt{12}\lambda$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

Understandable: Probability of 2<sup>nd</sup> scatt. is larger if 1<sup>st</sup> scatter already took place (“centrality bias”).

# Double Parton Scattering x-sections in p-A

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

[DdE, Snigirev, PLB 718 (2013)1395]  
[Also Treleani, Strikman, Blok...]



$$\sigma_{(pA \rightarrow ab)}^{\text{DPS},1} = A \cdot \sigma_{(pN \rightarrow ab)}^{\text{DPS}} + \sigma_{(pA \rightarrow ab)}^{\text{DPS},2} = \sigma_{(pN \rightarrow ab)}^{\text{DPS}} \cdot \sigma_{\text{eff,pp}} \cdot F_{pA}$$

p-A overlap function:

$$F_{pA} = \int d^2r T_{pA}^2(\mathbf{r}) = 30.4 \text{ mb}^{-1}$$

Pb Woods-Saxon density  
( $r=6.62 \text{ fm}$ ,  $a=0.546 \text{ fm}$ )

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

## ■ “Pocket” formula for DPS p-A x-section:

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

$$\sigma_{\text{eff,pA}} = \frac{\sigma_{\text{eff,pp}}^{(\sigma_{\text{eff,pp}}=13 \pm 2 \text{ mb})}}{A + \sigma_{\text{eff,pp}} F_{pA}} = 21.5 \pm 1.1 \mu\text{b}$$

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

■ DPS x-sections are large in p-A: a factor  $\times 600$  (not  $\times 208$ ) for p-Pb (!)

■ Pb transverse density ( $F_{pA}$ ) well known: Alternative extraction of  $\sigma_{\text{eff,pp}}$

# Examples: DPS x-sections in p-Pb (8.8 TeV)

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

- Cross sections & rates for **DPS processes with  $J/\psi$ ,  $Y$  &  $W$ ,  $Z$  bosons**  
[Also V. Goncalves (2018): double- $J/\psi$ ; Paukunen (2019): double- $D$ ,...]

pPb (8.8 TeV)	$J/\psi + J/\psi$	$J/\psi + \Upsilon$	$J/\psi + W$	$J/\psi + Z$
$\sigma_{pN \rightarrow a}^{\text{SPS}}, \sigma_{pN \rightarrow b}^{\text{SPS}}$	45 $\mu\text{b}$ ( $\times 2$ )	45 $\mu\text{b}$ , 2.6 $\mu\text{b}$	45 $\mu\text{b}$ , 60 nb	45 $\mu\text{b}$ , 35 nb
$\sigma_{pPb}^{\text{DPS}}$	45 $\mu\text{b}$	5.2 $\mu\text{b}$	120 nb	70 nb
$N_{pPb}^{\text{DPS}} (1 \text{ pb}^{-1})$	<b><math>\sim 65</math></b>	<b><math>\sim 60</math></b>	<b><math>\sim 15</math></b>	<b><math>\sim 3</math></b>
	$\Upsilon + \Upsilon$	$\Upsilon + W$	$\Upsilon + Z$	ss WW
$\sigma_{pN \rightarrow a}^{\text{SPS}}, \sigma_{pN \rightarrow b}^{\text{SPS}}$	2.6 $\mu\text{b}$ ( $\times 2$ )	2.6 $\mu\text{b}$ , 60 nb	2.6 $\mu\text{b}$ , 35 nb	60 nb ( $\times 2$ )
$\sigma_{pPb}^{\text{DPS}}$	150 nb	7 nb	4 nb	150 pb
$N_{pPb}^{\text{DPS}} (1 \text{ pb}^{-1})$	<b><math>\sim 15</math></b>	<b><math>\sim 8</math></b>	<b><math>\sim 1.5</math></b>	<b><math>\sim 4</math></b>

Leptonic final states:  $\text{BR}(J/\psi, Y, W, Z) = 6\%, 2.5\%, 11\%, 3.4\%$

Accept.\*Effic.= 1% ( $J/\psi$ ,  $|y|=0,2$ ), 20% ( $Y$ ,  $|y|<2.5$ ), 50% ( $W, Z$   $|y|<2.4$ )

- **Many double hard scatterings** processes with visible p-Pb x-sections at the LHC. (Note:  $J/\psi$  values are per unit- $|y|$ ).
- Useful **independent extraction of  $\sigma_{\text{eff,pp}}$**  !

# First study of DPS in p-Pb (LHCb, 8.2 TeV)

[LHCb, PRL 125 (2020) 212001]

## double charm production in proton lead collisions

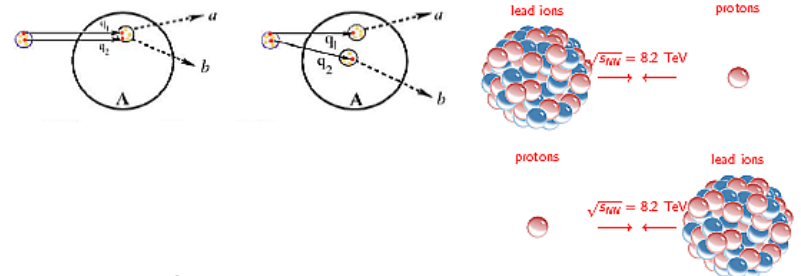
- select pairs of  $D^0$ ,  $\bar{D}^0$ ,  $D^+$ ,  $D^-$ ,  $D_s^+$ ,  $D_s^-$  and  $J/\psi$
- sort them into pair production and “DPS” categories

$$\sigma_{C_1, C_2} = \alpha \frac{\sigma_{C_1} \sigma_{C_2}}{\sigma_{\text{eff}}}$$

$$R_{\text{forward}}^{D_1 D_2} = \frac{\sigma_{D_1 D_2}}{\sigma_{D_1 \bar{D}_2}} = 0.308 \pm 0.015 \pm 0.010$$

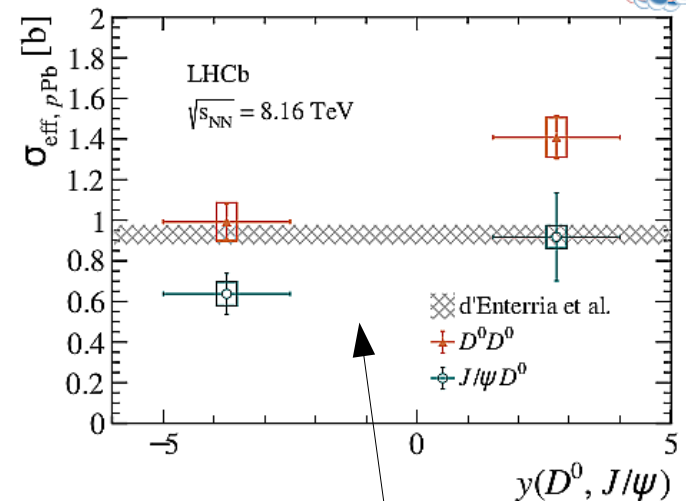
$$R_{\text{backward}}^{D_1 D_2} = 0.391 \pm 0.019 \pm 0.025$$

$$R_{pp}^{D^0 \bar{D}^0} = 0.109 \pm 0.008$$



Like sign charm fraction tripled!

$$\sqrt{s_{\text{NN}}} = 8.2 \text{ TeV} \quad \text{Phys. Rev. Lett. 125 (2020) 212001}$$



Albert Bursche

charming DPS

10<sup>th</sup> October 2021

15 / 17

- Useful independent extraction of  $\sigma_{\text{eff,pp}}$ :

$$\sigma_{\text{eff,pA}} = \frac{\sigma_{\text{eff,pp}}}{A + \sigma_{\text{eff,pp}} F_{\text{pA}}}$$

$$\sigma_{\text{eff,pp}}(D^0 \bar{D}^0) = 7\text{--}16 \text{ mb}$$

$$\sigma_{\text{eff,pp}}(J/\psi D^0) = 13\text{--}40 \text{ mb}$$

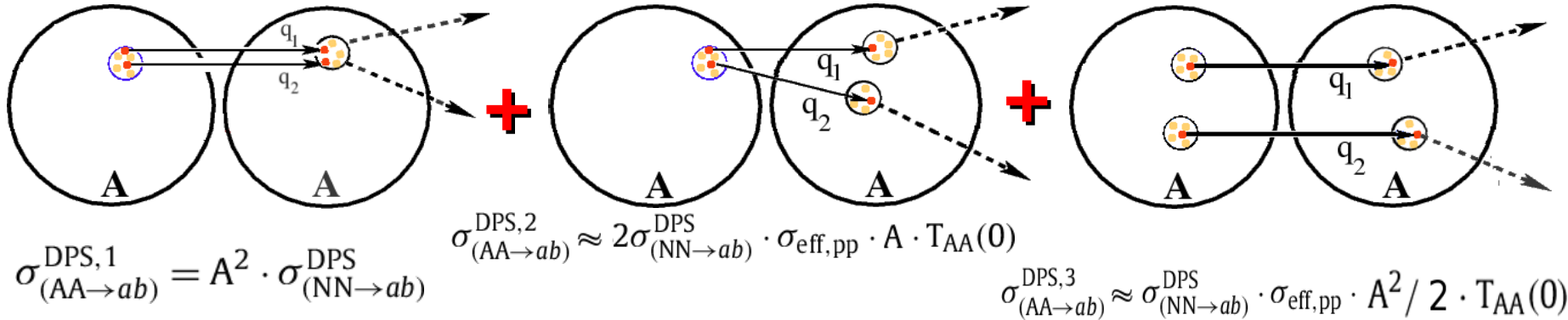
nPDF effects visible in -y/+y results.

(why LHCb does not quote the equivalent  $\sigma_{\text{eff,pp}}$  values?)

# Double Parton Scattering x-sections in A-A

[DdE, Snigirev, PLB727 (2013)157]

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



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

“Genuine” DPS (within same nucleon):  $\sim 2.5\%$  (in Pb-Pb) or  $\sim 13\%$  (Ar-Ar)

## ■ “Pocket formula” for DPS A-A x-section:

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

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

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

## ■ Strong centrality dependence:

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

# Examples: DPS x-sections in Pb-Pb (5.5 TeV)

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

- Cross sections & rates for **DPS processes with  $J/\psi$ ,  $\Upsilon$  & W, Z bosons:**

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

Leptonic final states:  $\text{BR}(J/\psi, \Upsilon, W, Z) = 6\%, 2.5\%, 11\%, 3.4\%$

Accept.\*effic.= 1% ( $J/\psi$ ,  $|y|=0,2$ ), 20% ( $\Upsilon$ ,  $|y|<2.5$ ), 50% (W,Z  $|y|<2.4$ )

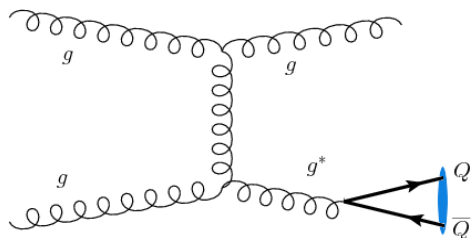
- **Visible rates for many double hard scatterings** processes in Pb-Pb!  
(Note:  $J/\psi$  values are per unit- $|y|$ ).



# Example: Pb-Pb $\rightarrow$ J/ $\psi$ J/ $\psi$ at 5.5 TeV

[DdE, Snigirev, PLB727 (2013)157]

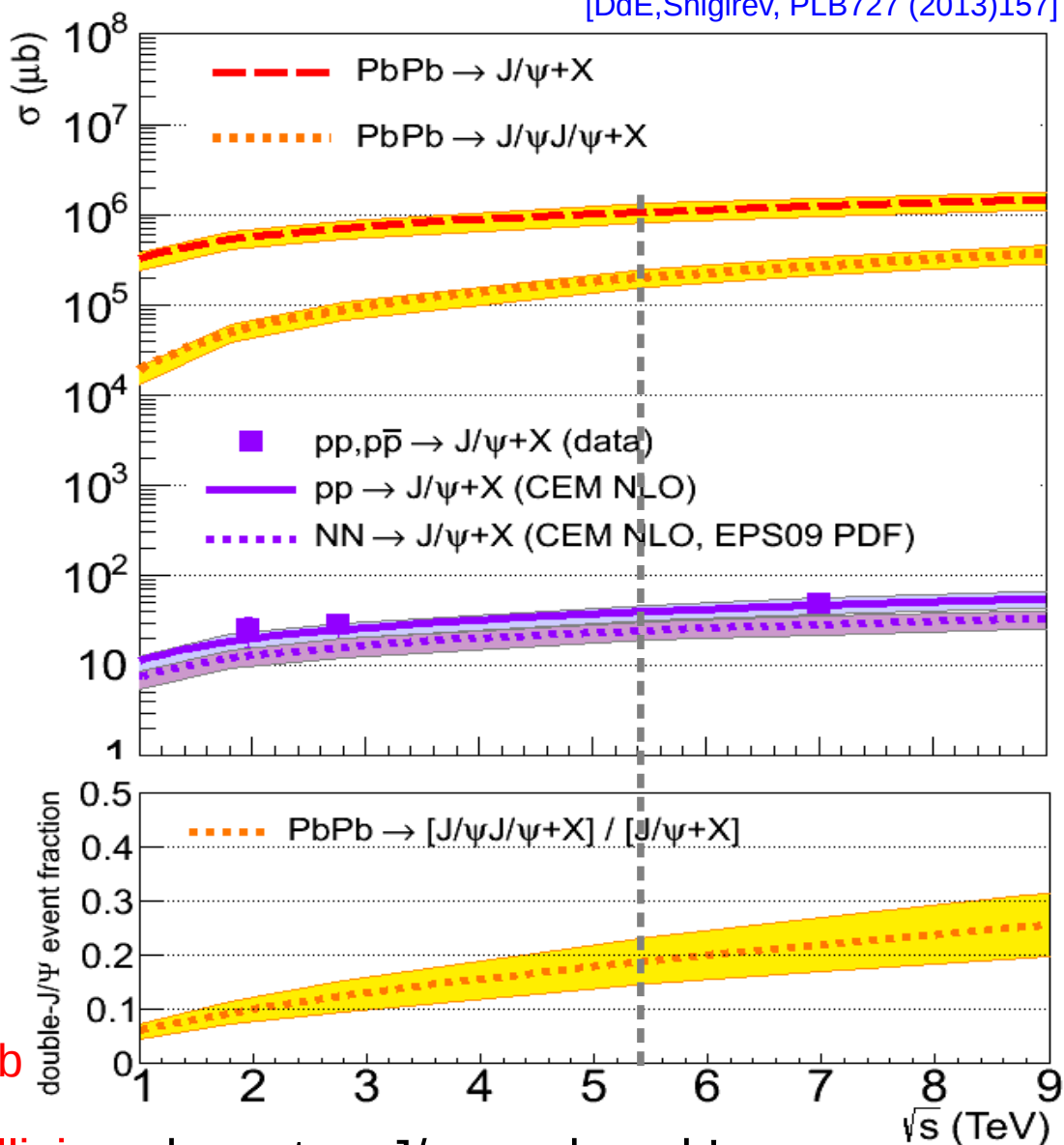
## ■ FONLL+CEM (R.Vogt): Single-parton J/ $\psi$



- **NLO** accuracy.
- **Scales:**  $\mu_R = \mu_F = 1.5 \cdot m_c$
- Good agreement with Tevatron&LHC data
- **EPS09 Pb nPDF**  
20–35% shadowing  
x-section reduction

## ■ At 5.5 TeV:

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



**20% of min.bias Pb-Pb collisions have two J/ $\psi$  produced !**

# Example: Pb-Pb $\rightarrow$ J/ $\psi$ J/ $\psi$ at 5.5 TeV

[DdE, Snigirev, PLB727 (2013)157]

## ■ Visible rates:

- ▶ Fiducial x-section per unit-y:  $d\sigma_{J/\psi}/dy \approx \sigma_{J/\psi}/8$
- ▶  $\text{BR}(J/\psi \rightarrow l^+l^-) \approx 6\%$
- ▶ Typical ALICE/CMS acceptance & efficiencies:  $\varepsilon \approx 1/12$

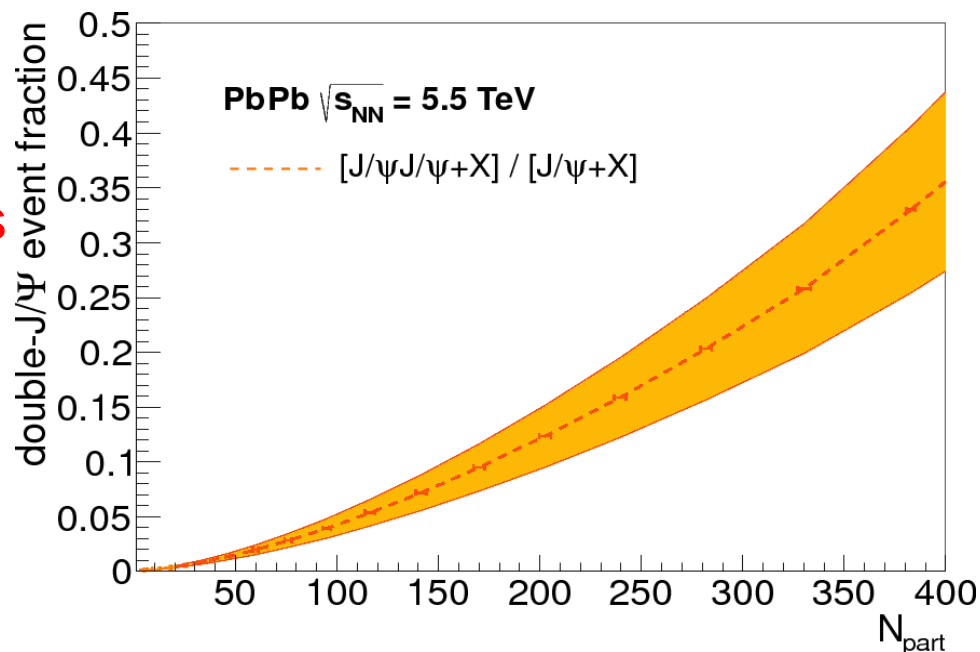
## ■ Expected dimuon rates including yield all losses & 1 nb<sup>-1</sup> integ. luminosity:

$$\mathcal{N} = \sigma_{\text{Pb-Pb} \rightarrow J/\psi J/\psi}^{\text{DPS}} / (\varepsilon \cdot \mathcal{L}_{\text{int}}) \approx \text{250 double-J/}\psi \text{ per year (per unit-|y|)}$$

(x2 less including final-state suppression)

## ■ Centrality dependence of double-J/ $\psi$ fraction: 35% of central Pb-Pb collisions have two J/ $\psi$ produced !

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



# Summary: DPS studies

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

$$\sigma_{(hh' \rightarrow ab)}^{\text{DPS}} = \left(\frac{m}{2}\right) \frac{\sigma_{(hh' \rightarrow a)}^{\text{SPS}} \cdot \sigma_{(hh' \rightarrow b)}^{\text{SPS}}}{\sigma_{\text{eff}}}$$

In absence of parton correlations:

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

geom. overlap area of 2 proton transv. profiles

- $\sigma_{\text{eff}}(\text{exp}) \approx 2\text{--}20 \text{ mb}$  at Tevatron/LHC. Can HI colls. help to clarify this?

- Available DPS x-sections “pocket formula” for p-A and A-A:

( $\sigma_{\text{eff,pp}} = 13 \pm 2 \text{ mb}$ )

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

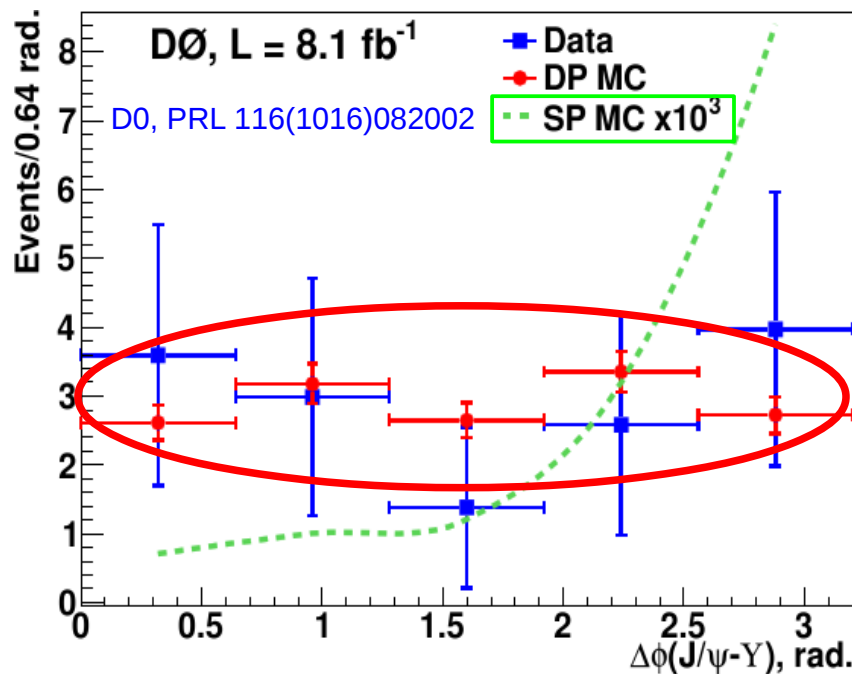
$$\sigma_{\text{eff,AA}} = \frac{1}{A^2 [\sigma_{\text{eff,pp}}^{-1} + \frac{2}{A} T_{\text{AA}}(0) + \frac{1}{2} T_{\text{AA}}(0)]} = 1.5 \text{ nb}$$

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

- **p-Pb: Large DPS yields** in p-A (in particular with quarkonia) provide many useful independent **extractions of  $\sigma_{\text{eff,pp}}$** . 1<sup>st</sup>-ever measurement by **LHCb**.
- **Pb-Pb: Large DPS** but dominated by scatts. **from different nucleons**. (~16% sensitivity on  $\sigma_{\text{eff,pp}}$  from DPS with lighter ions such as Ar-Ar).

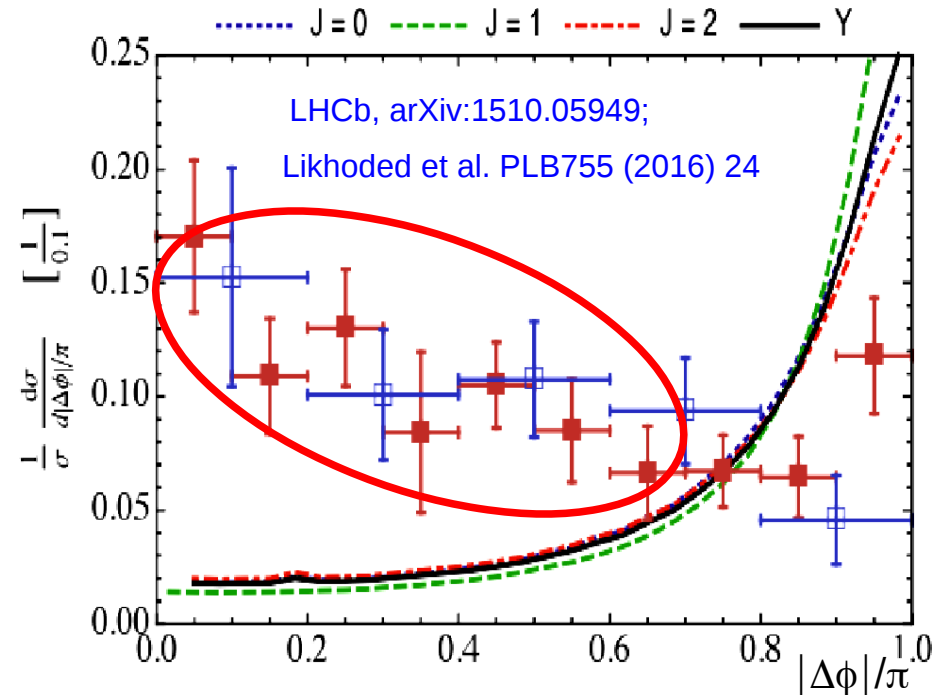
# DPS studies with $Q\bar{Q}$ : $p\text{-}p \rightarrow J/\psi + Y, Y + D$

- Uncorrelated  $J/\psi + Y$  azimuthal production in ppbar at 1.96 TeV:



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

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

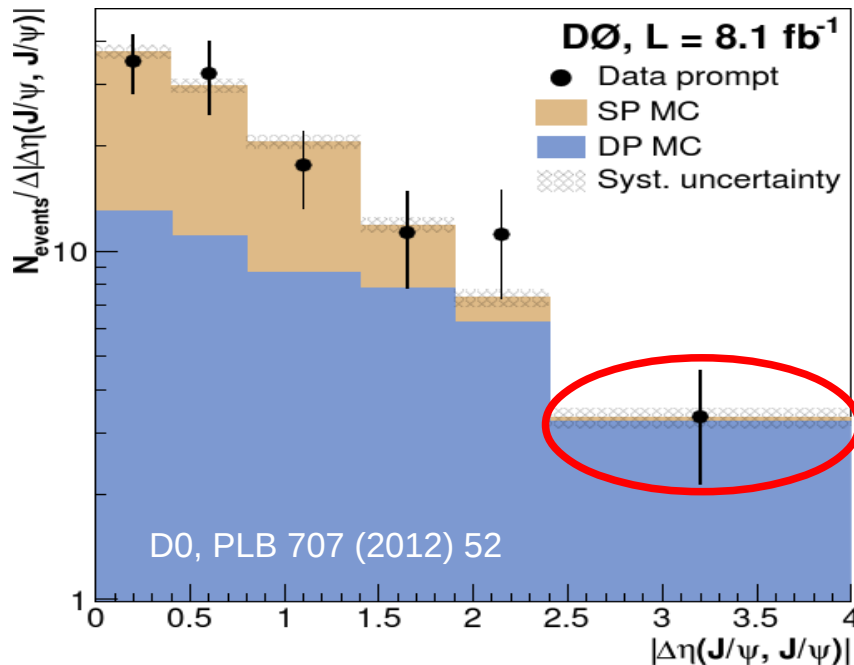


$$\sigma_{\text{eff}}|_{\Upsilon(1S)D} = 18.0 \pm 1.3 (\text{stat}) \pm 1.2 (\text{syst}) \text{ mb}$$

- Extracted  $\sigma_{\text{eff}}$  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?

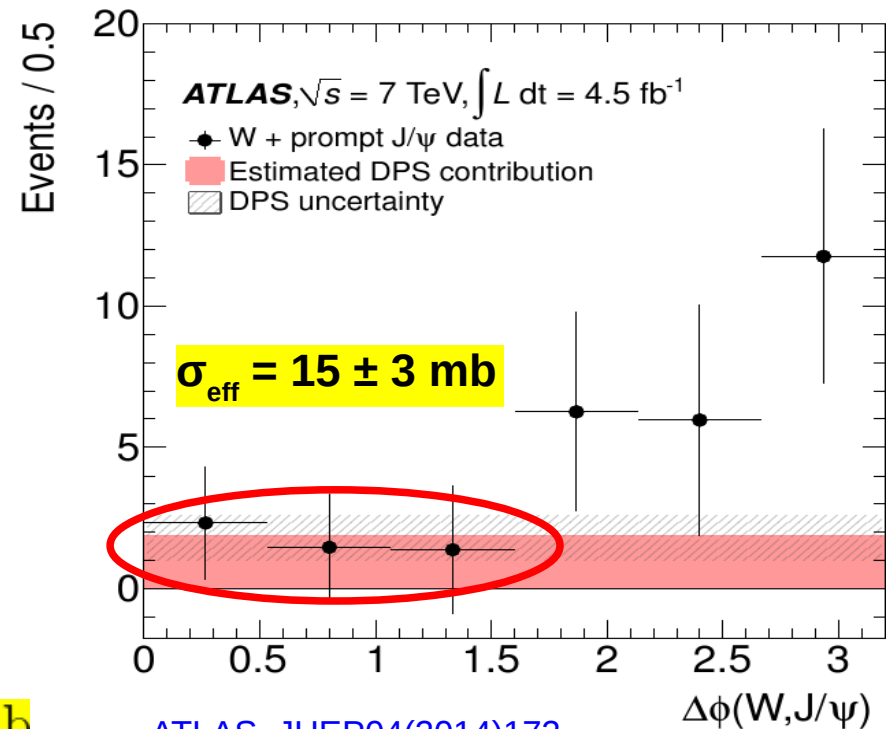
# DPS studies with $Q\bar{Q}$ : $p\text{-}p \rightarrow W^+ + J/\psi, J/\psi J/\psi$

- Uncorrelated  $J/\psi + J/\psi$  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  $W + J/\psi$  azimuthal production in pp at 7 TeV:

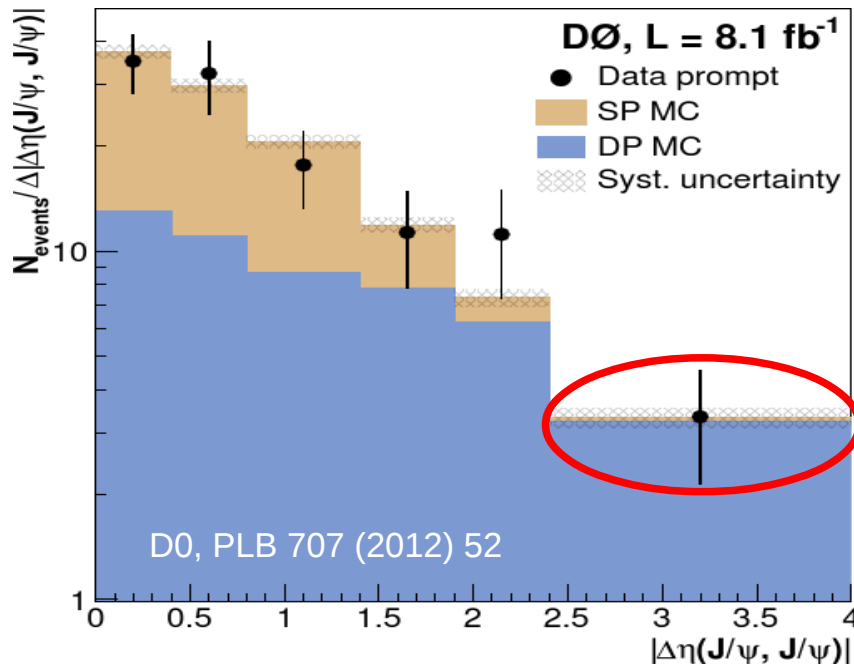


ATLAS, JHEP04(2014)172

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

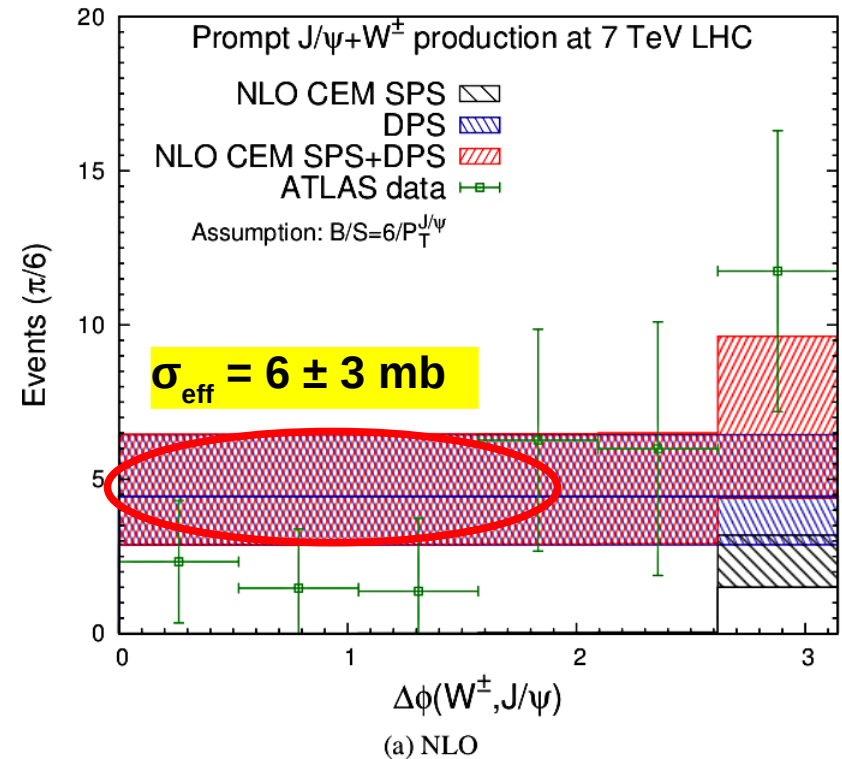
# DPS studies with $Q\bar{Q}$ : $p\text{-}p \rightarrow W^+ + J/\psi, J/\psi J/\psi$

- Uncorrelated  $J/\psi + J/\psi$  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  $W + J/\psi$  azimuthal production in pp at 7 TeV:



Lansberg&Shao&Yamanaka,  
PLB781 (2018) 485

- Extracted  $\sigma_{\text{eff}}$  values differ at 1.96 TeV & 7 TeV:

- (Higher-order) SPS contributions under control?
- Energy-dependent parton transverse profile? (Quark vs. gluon?)

# DPS in Ultraperipheral p-Pb collisions?

[M.Rinaldi, et al.]

- Rinaldi&Ceccopieri (also Blok & Strikman) have proposed to study DPS from photon-proton collisions (where photon = vector meson):

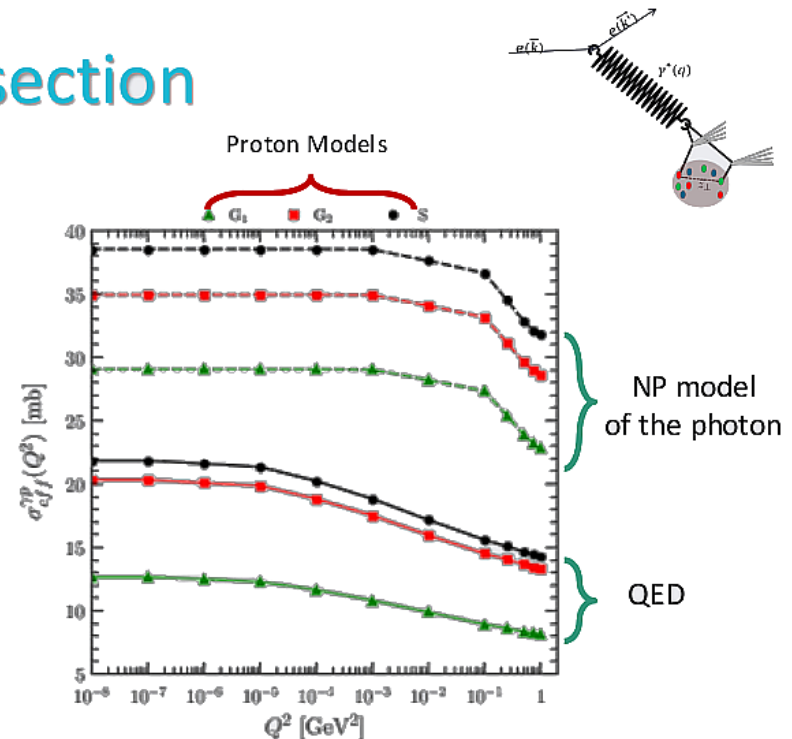
## 6 The $\gamma$ -p effective cross section

$$1 \quad [\sigma_{\text{eff}}^{\gamma p}(Q^2)]^{-1} = \int \frac{d^2 k_{\perp}}{(2\pi)^2} T_p(k_{\perp}) T_{\gamma}(k_{\perp}; Q^2)$$

2  $T_p(k_{\perp})$  proton EFF

3  $\psi/\gamma$  Photon WF

M. R. and F. A. Ceccopieri, arXiv:2103.13480



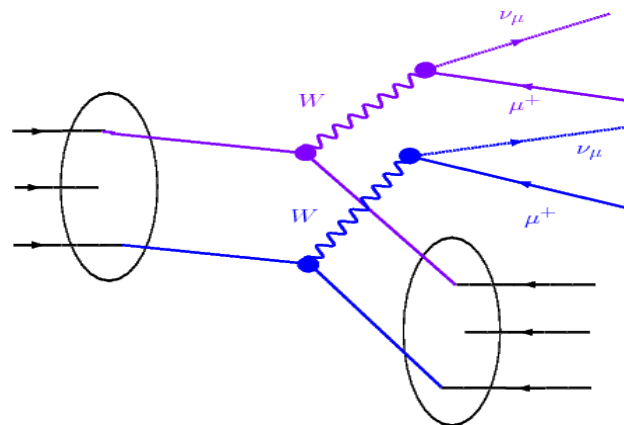
- Such studies (based on HERA data so far) could be tested with UPCs in p-Pb with the photon emitted from the Pb ion (we should go beyond searching for 'ridges' in UPCs, and extract some quantitative x-sections...)



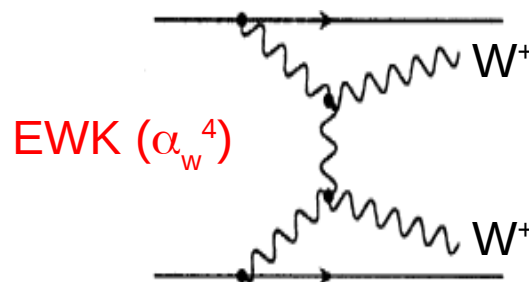
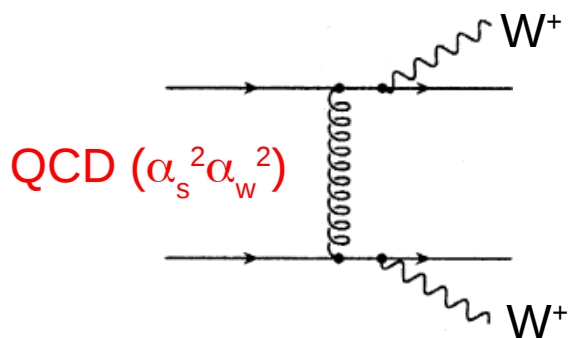
# DPS “golden channel”: Same-sign WW

- 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- $E_T$

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



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



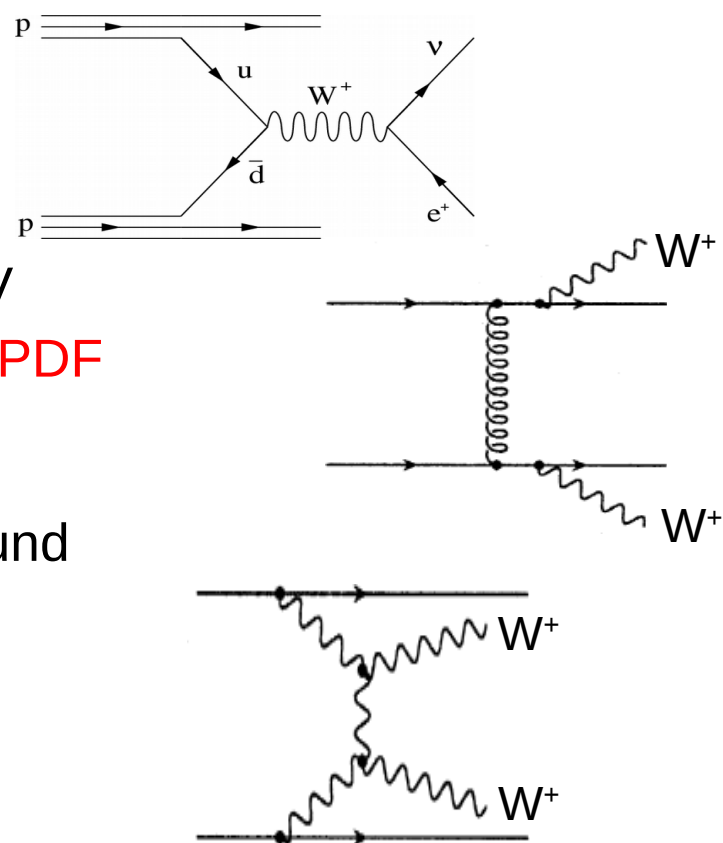
- $\sigma(WW, \text{DPS}) \sim 1/3 \cdot \sigma(WWjj, \text{SPS})$ , but SPS background reducible by more than x20 applying jet cuts.

# Case study: p-Pb $\rightarrow W^+W^+, W^-W^-$ 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:  $\sim 10\%$
- **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 ( $\sigma$ units):	NLO ( $\mu b$ )	NLO ( $\mu b$ )	NLO (nb)	'NLO' (pb)	NLO (pb)	(pb)
$\sqrt{s_{NN}} = 5.0$ TeV	$6.85 \pm 0.68$	$5.88 \pm 0.59$	$5.48 \pm 0.56$	$12.1 \pm 1.2$	$12.4 \pm 0.6$	$44. \pm 8.$
$\sqrt{s_{NN}} = 8.8$ TeV	$12.6 \pm 1.3$	$11.1 \pm 1.1$	$13.0 \pm 1.3$	$40.4 \pm 4.0$	$51.8 \pm 2.0$	$152. \pm 27.$

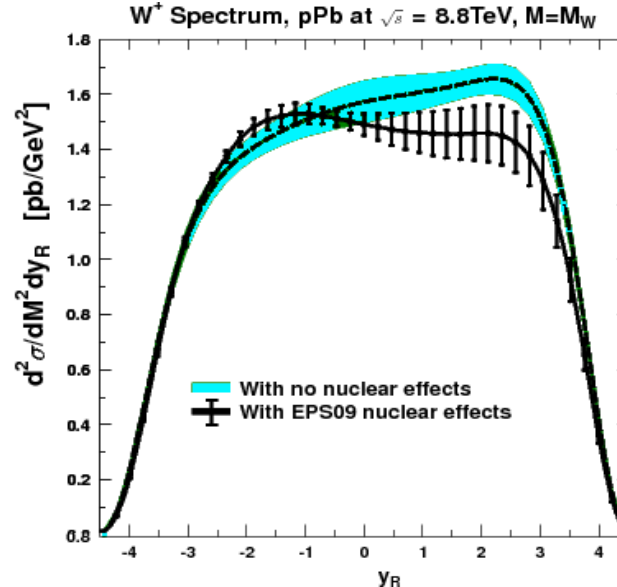
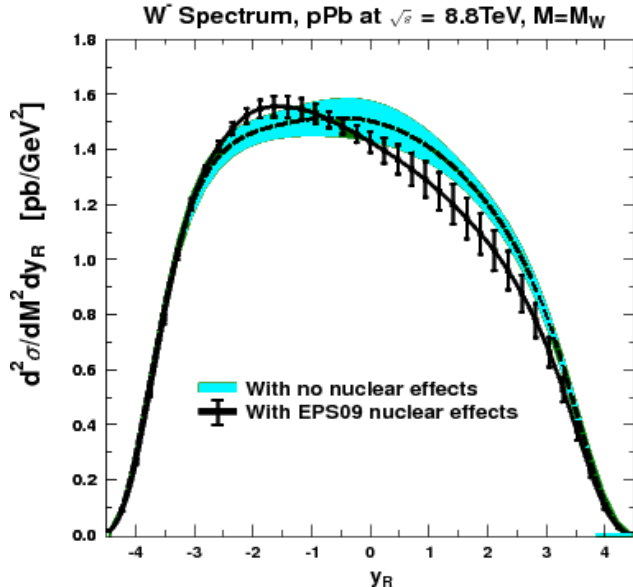
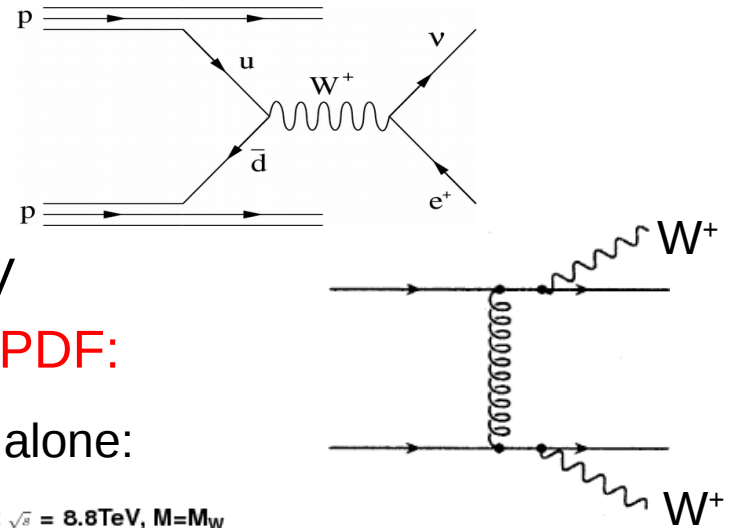
# Case study: $p\text{-Pb} \rightarrow W^+W^+, W^-W^-$ at 8.8 TeV

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- Scales:  $\mu(W) = m_W$ ,  $\mu(WW) = 150$  GeV
- CT10 proton PDF, EPS09 Pb nuclear PDF:

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



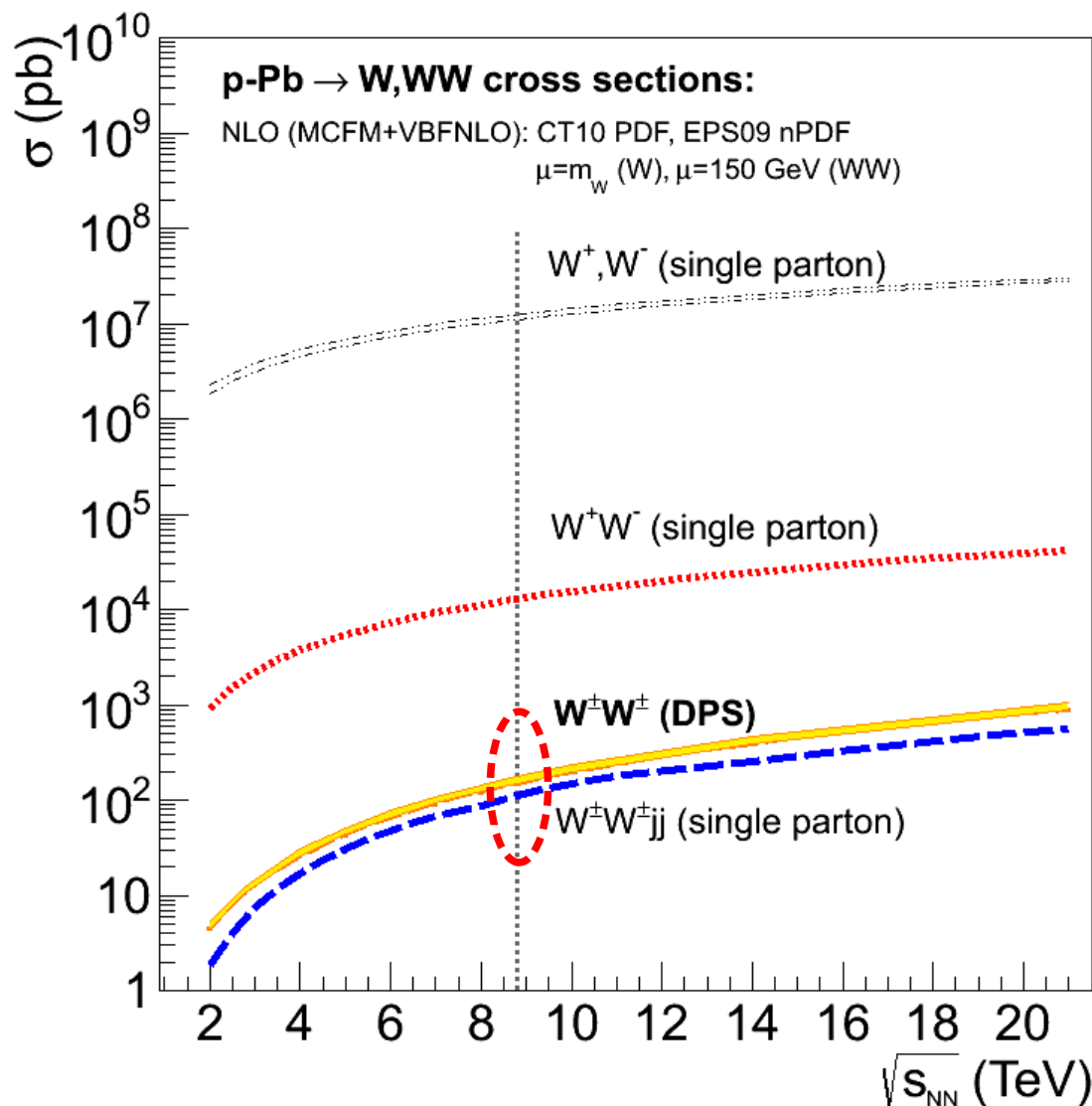
Isospin+shadow.  
effects on total  
inclusive x-sections:  
 $W^-$  : +7%  
 $W^+$  : -15%  
compared to p-p

[Paukkunen&Salgado JHEP 1103 (2011) 071]

# Results: $p\text{-Pb} \rightarrow W^+W^+, W^-W^-$ 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:

$\sigma(WW, \text{DPS}) \approx 150\text{ pb}$

$\sigma(WWjj) \approx 100\text{ pb}$

**$\pm 18\%$  uncertainties:**

$\pm 15\%$  for  $\sigma_{\text{eff}}$

$\pm 10\%$  for scales&PDFs

# Results: $p\text{-Pb} \rightarrow W^+W^+, W^-W^-$ at 8.8 TeV

[DdE, Snigirev, PLB718 (2013)1395]

## ■ Measurable final-states:

### ► $W$ 's branching ratios:

- $\text{BR}(W \rightarrow l\nu) \approx 3 \times 1/9$ ,  $\text{BR}(W \rightarrow qq') \approx 2/3$
- **Both leptonic**: 4 final-states ( $\mu\mu, ee, e\mu, \mu e$ ):  $4 \times (1/9)^2 \approx 1/20, 1/16 (+ \tau)$   
[1 leptonic + 1 hadronic (jet-charge):  $2/9 \times 4/3 \approx 0.3$ ]

### ► Typical ATLAS/CMS acceptances & efficiencies:

- Leptons:  $|y| < 2.5$ ,  $p_T > 15$  GeV  $\Rightarrow \epsilon_{WW} \approx 40\%$

## ■ LHC $p\text{-Pb}$ luminosities (note: very small pileup):

- $\mathcal{L}_{\text{int}} = 0.2\text{--}2 \text{ pb}^{-1}$  (increase to nominal  $p$  intensity, reduce beam size)

## ■ Expected (purely leptonic) rates including yield losses & luminosity:

$$\mathcal{N}_{\text{DPS}} = \sigma_{pPb \rightarrow WW}^{\text{DPS}} / (\epsilon \cdot \mathcal{L}_{\text{int}}) \approx \text{1--10 same-sign } WW \text{ pairs/year}$$

(factor  $\times 6$  more in 1 lepton + 1-jet channel)

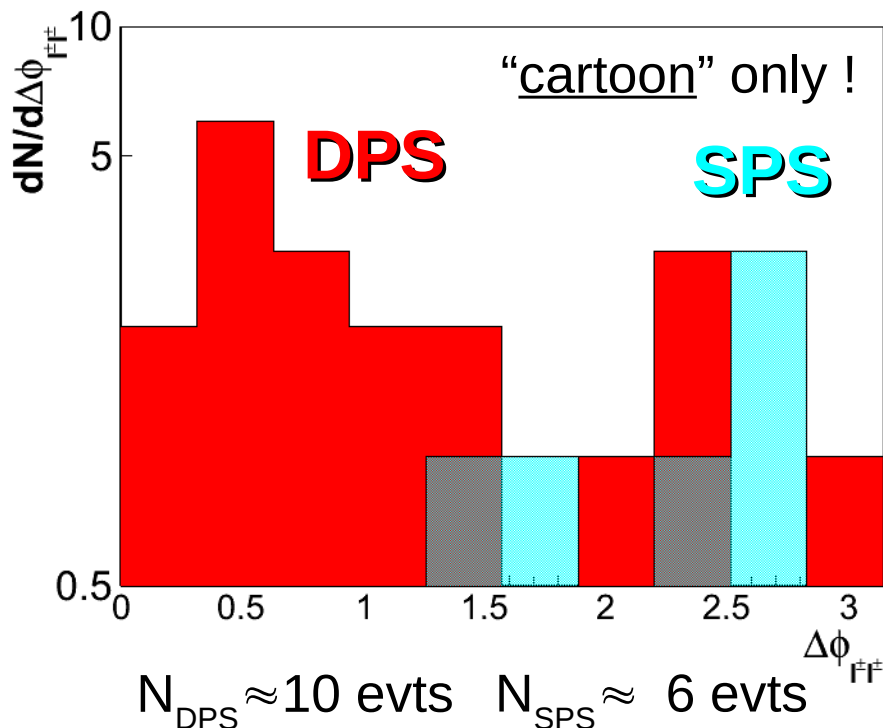
# Results: p-Pb $\rightarrow W^+W^+, W^-W^-$ at 8.8 TeV

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

p-Pb @ 8.8 TeV ( $2 \text{ pb}^{-1}$ ):

Same-sign leptons

azimuthal separation:



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

Compare to:

p-p  $\rightarrow W+2j$  @ 7 TeV ( $36 \text{ pb}^{-1}$ ):

dijet azimuthal separation

