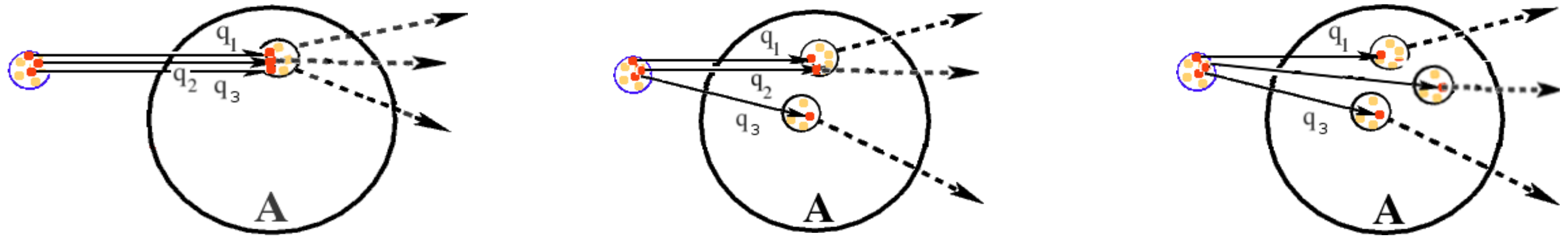


Triple-parton scatterings in high-energy p-p & p-A collisions

MPI-2023

Manchester, 22nd Nov. 2023

David d'Enterria
CERN

(*) Details in DPS/TPS/NPS in pp, pA, AA review:
D.d'E & A.Snigirev: arXiv:1708.07519 [Adv.Ser.Direct.High.En.Phys. 29 (2018) 159]

Double Parton Scattering (DPS) physics

- 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) Learn about 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" for DPS cross sections:

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

$\sigma_{\rm eff}$ ~ <Interparton transv. separation>^{2}
derivable from p-p transverse overlap:

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

$\sigma_{\rm eff}$ ~ 20–30 mb (e.g. from PYTHIA8/HERWIG proton form-factor)

This is NOT expected to be a "universal" rule, but the simplest, most economical, expression assuming DPS to be the factorized product of SPS probabilities.
Deviations from expected geometric $\sigma_{\rm eff}$ value, provide us valuable info on (1), (2)

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) Learn about 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:

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

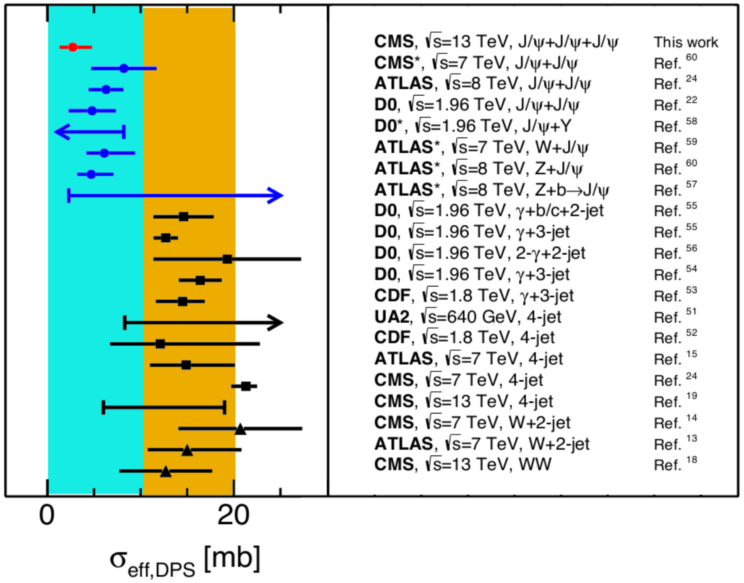
σ_{eff} ~ <Interparton transv. separation>^{2}

derivable from p-p transverse overlap:

σ_{eff} ~ 20–30 mb (PYTHIA8/HERWIG p form-factor)

σ_{eff} ~ 15 mb (from DPS of jets, EWK bosons)

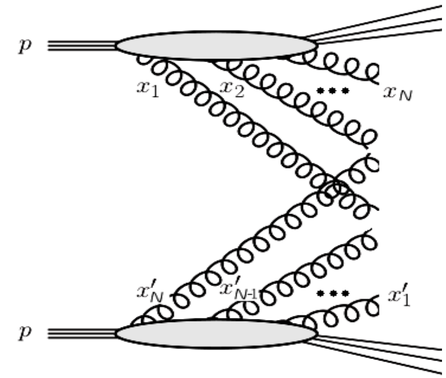
σ_{eff} ~ 5 mb (from di-quarkonia)



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

- Novel observables: Triple-parton scatterings (TPS), DPS/TPS with ions in particular with quarkonia & jets (with largest pQCD x-sections).

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:

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

normalized by the N^{th}–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 $a_1 \neq a_2 \neq a_3$.

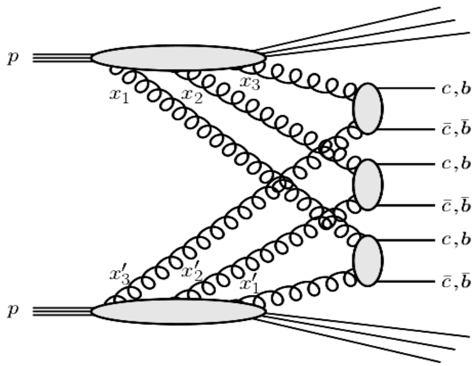
- Ignoring all parton correlations, $\sigma_{\rm eff,NPS}$ is the inverse N^{th}–1 power of the integral of the N^{th} power of the pp overlap function:

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

- Generic formula to derive N-parton scatt. x-sections (as factorized product of SPS scatterings) within simplest (geometric) picture available.

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:



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

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 $\sigma_{\rm eff,TPS}$? Relationship with $\sigma_{\rm eff}$? What values to expect?

- Most generic expression for TPS cross section:

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

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

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

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

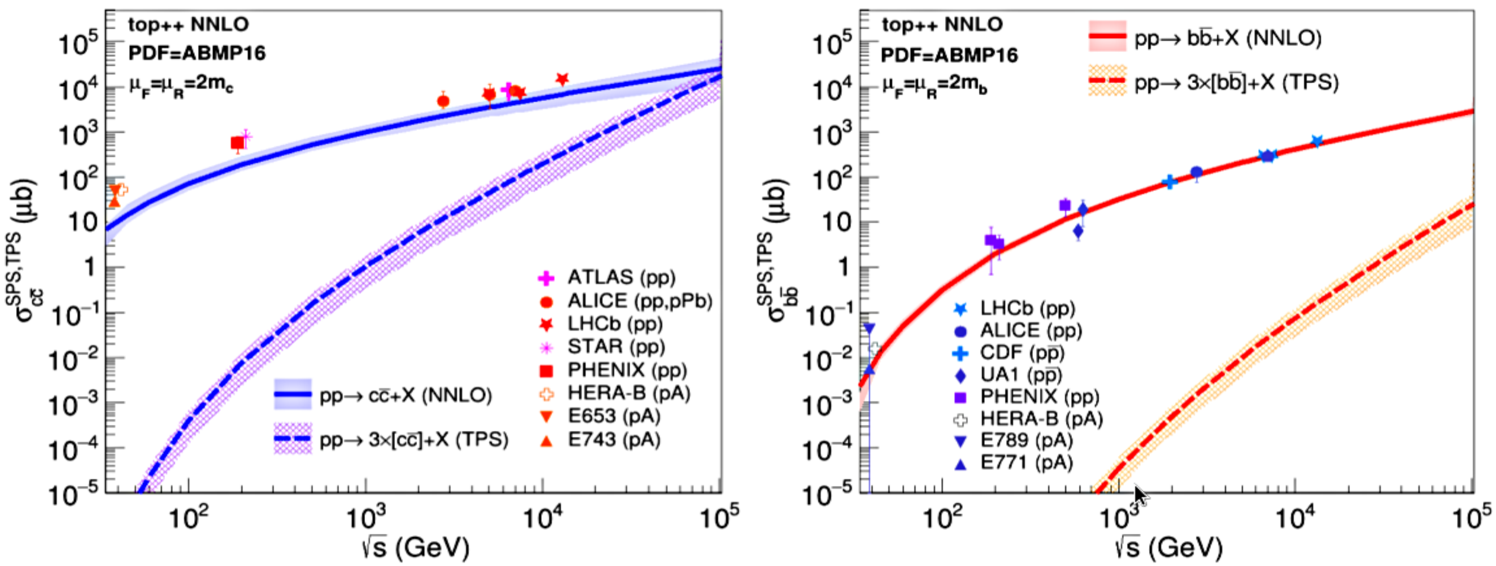
$$\sigma_{\rm eff,TPS} = k \times \sigma_{\rm eff,DPS}, \text{ with } k = 0.82 \pm 0.11$$

[DdE & Snigirev PRL118(2017)122001]

- Measuring TPS provides independent info on $\sigma_{\rm eff}$ & proton transv. profile.

Triple charm & beauty production (p-p)

- TPS x-sections are small: σ(SPS)³/σ(eff)² ≈ 1 fb for σ(SPS) ≈ 1 μb, but rise fast (as the cube of SPS x-section) with c.m. energy.
- Charm & beauty have large enough σ(SPS) to attempt TPS observation:



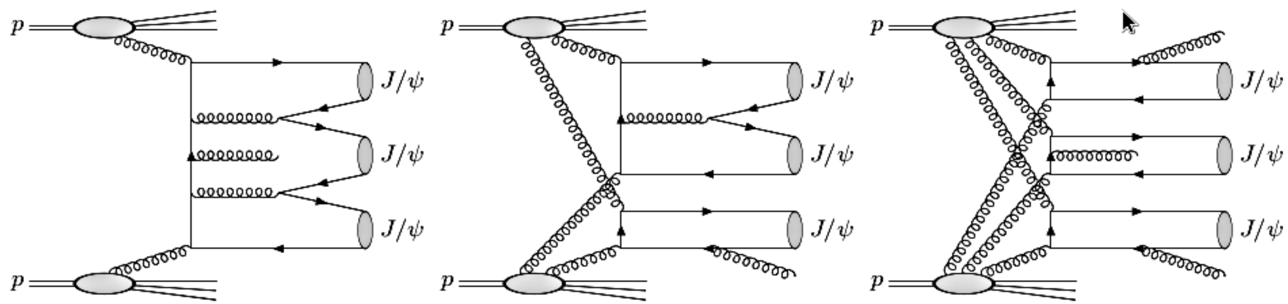
Final state	$\sqrt{s} = 14$ TeV	$\sqrt{s} = 100$ TeV
$\sigma^{SPS}_{c\bar{c}+X}$	$7.1 \pm 3.5_{sc} \pm 0.3_{PDF}$ mb	$25.0 \pm 16.0_{sc} \pm 1.3_{PDF}$ mb
$\sigma^{TPS}_{c\bar{c}\,c\bar{c}\,c\bar{c}+X}$	$0.39 \pm 0.28_{tot}$ mb	$16.7 \pm 11.8_{tot}$ mb
$\sigma^{SPS}_{b\bar{b}+X}$	$0.56 \pm 0.09_{sc}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

[DdE & Snigirev PRL118(2017)122001]

- Triple charm amounts to ~15% (50%) of inclusive charm x-sections at LHC (FCC). What is the “backgd” from SPS triple & DPS double processes?

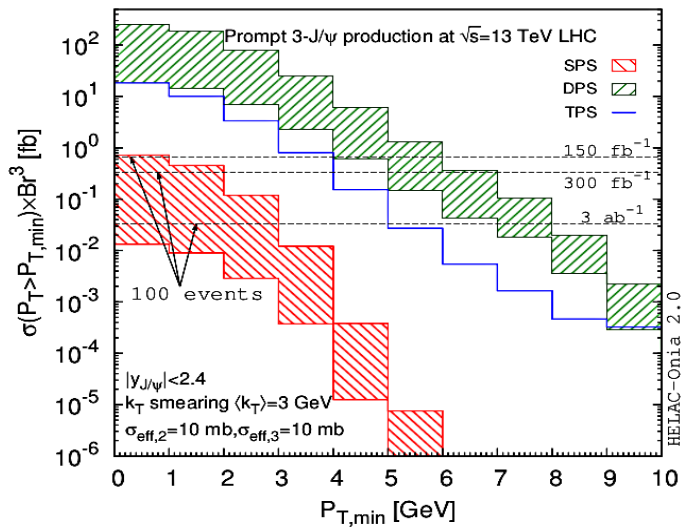
Triple-J/ψ from TPS production (p-p)

- H.-S. Shao et al. [PRL 122(2019)192002, also Mon. talk] computed all triple-J/Ψ x-sections with HELAC-ONIA plus TPS pocket formula:



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



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

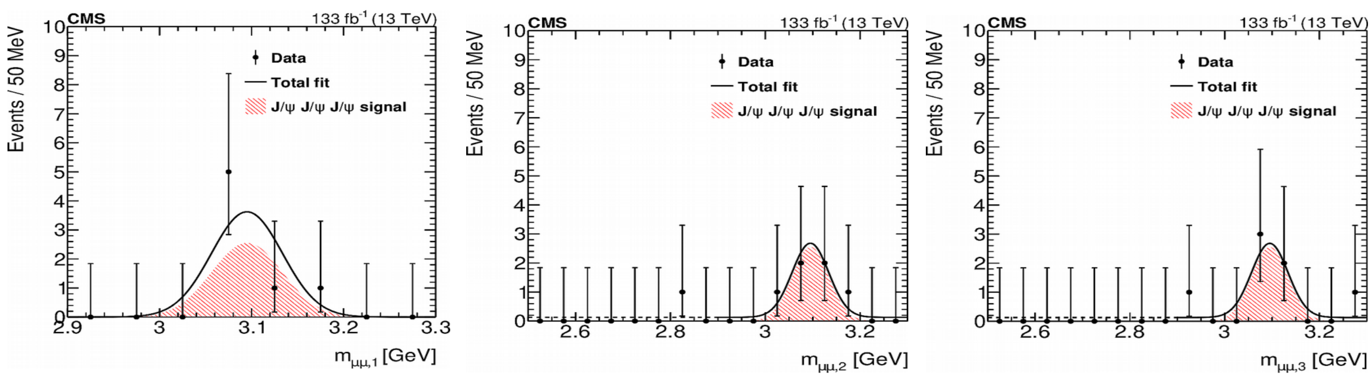
Clear sensitivity to σ_{eff} !

Triple-J/ψ from TPS production (13 TeV, CMS)

- Pocket formula with (N)NLO for single-,double-,triple-J/ψ SPS x-sections:

SPS single-J/ψ production		SPS double-J/ψ production			SPS triple-J/ψ production			
HO(DATA)	MG5NLO+PY8	HO(NLO*)	HO(LO)+PY8	MG5NLO+PY8	HO(LO)	HO(LO)+PY8	HO(LO)+PY8	MG5NLO+PY8
σ^{1p}_{SPS}	σ^{1np}_{SPS}	σ^{2p}_{SPS}	σ^{1p1np}_{SPS}	σ^{2np}_{SPS}	σ^{3p}_{SPS}	σ^{2p1np}_{SPS}	σ^{1p2np}_{SPS}	σ^{3np}_{SPS}
570 ± 57 nb	600^{+130}_{-220} nb	40^{+80}_{-26} pb	24^{+35}_{-16} fb	430^{+95}_{-130} pb	< 5 ab	$5.2^{+9.6}_{-3.3}$ fb	14^{+17}_{-8} ab	12 ± 4 fb

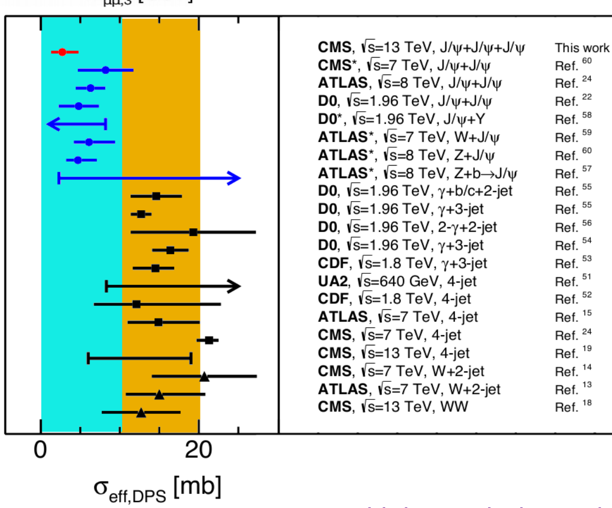
- First observation of triple-J/ψ production (CMS):



[CMS, Nat.Phys 19 (2023) 3 arXiv:2111.05370]

- Measurement of fiducial cross section
  $\sigma(pp \to 3J/\psi) = 272^{+141}_{-104}$ (stat) ± 17 (syst) fb

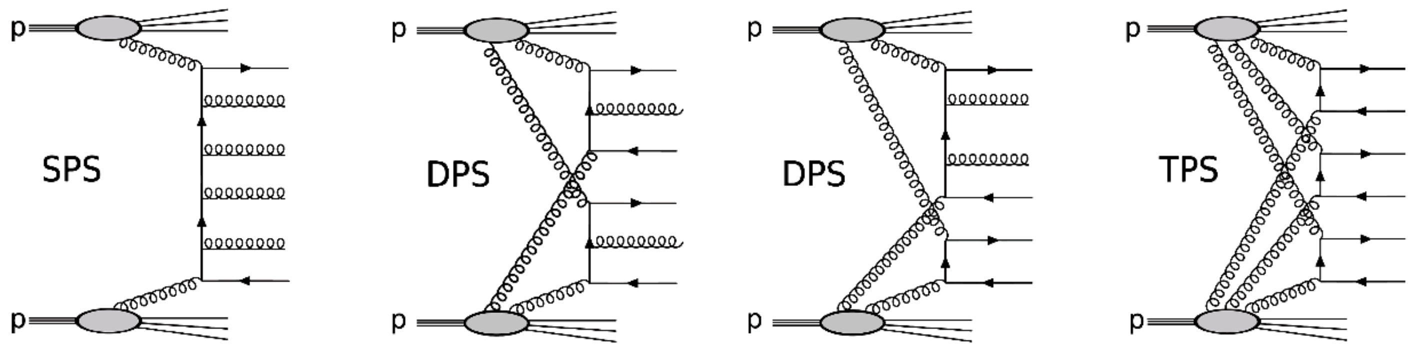
- Triple-J/ψ fractions:
  ~6% SPS, ~74% DPS, ~20% TPS
  $\sigma_{eff,DPS} = 2.7^{+1.4}_{-1.0}$ (exp) $^{+1.5}_{-1.0}$ (theo) mb consistent with di-quarkonia (lower than jet/γ/W/Z DPS results):



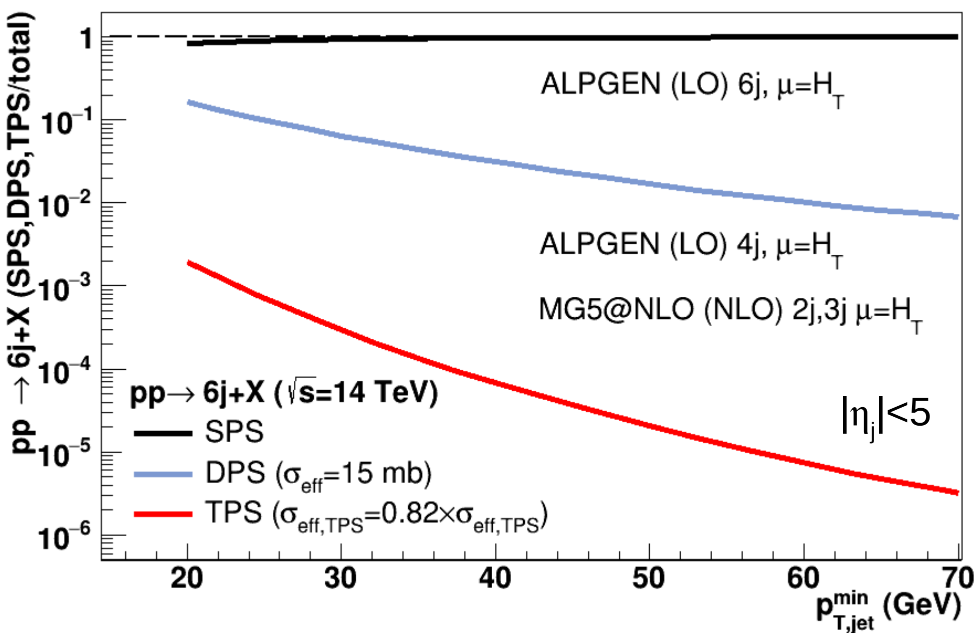
▶ q/g x-dependent transverse profile & correlations

Six-jet production from TPS (p-p)

- SPS/DPS/TPS contributions to 6-jet production in pp(14 TeV) from pocket-formula using NLO,LO SPS 2j,3j,4j,6j (MG5@NLO, AlpGen) x-sections:



M.Maneyro & DdE (Tues. talk)



- 6-jet contributions:

TPS ~10^{-3}, 10^{-5} at p_T= 20, 50 GeV
DPS ~20%, 2% at p_T= 20, 50 GeV

$\sigma_{TPS}(6j) \approx 3$ pb (p_T>35 GeV, $|\eta|$<5)
$\sigma_{DPS}(6j) \approx 4$ nb (p_T>35 GeV, $|\eta|$<5)
$\sigma_{SPS}(6j) \approx 30$ nb (p_T>35 GeV, $|\eta|$<5)

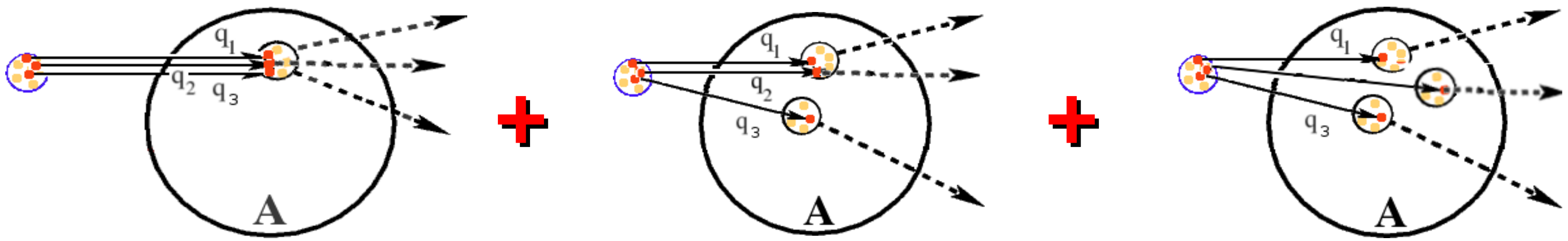
- BDT MVA with single-,double-jet kinematic vars. to identify TPS.

Novel extraction of σ_{eff} at hand.

Triple Parton Scattering x-sections in p-A

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

- 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:

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

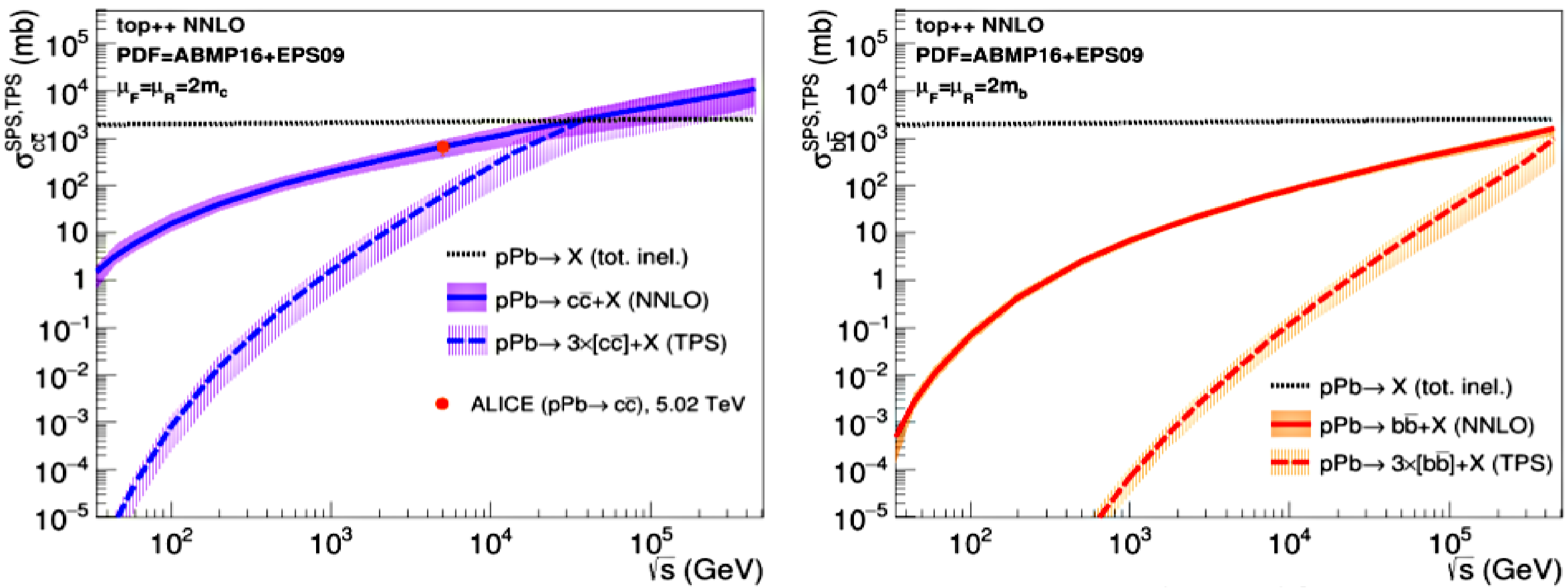
$$\sigma_{\rm eff,TPS,pA} = \left[\frac{A}{\sigma^2_{\rm eff,TPS}} + \frac{3\,F_{\rm pA}[{\rm mb}^{-1}]}{\sigma_{\rm eff,DPS}} + C_{\rm pA}[{\rm mb}^{-2}]\right]^{-1/2}$$

$\sigma_{\rm eff,TPS,pPb}$ = 0.29 ± 0.04 mb (for $\sigma_{\rm eff,TPS}$= 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 in p-Pb colls.

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

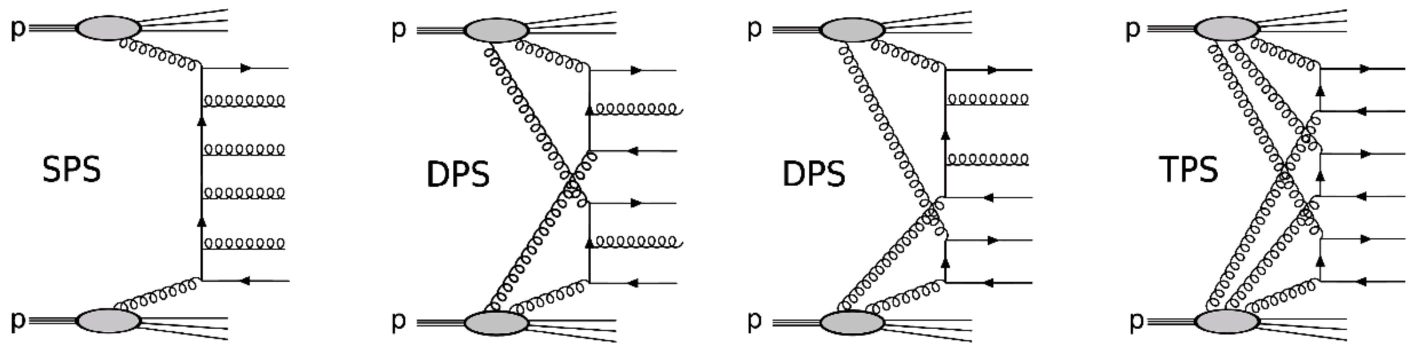


Process	pPb(8.8 TeV)	pPb(63 TeV)	p-Air(430 TeV)
$\sigma^{\rm inel}_{\rm pA}$	2.2 ± 0.4 b	2.4 ± 0.4 mb	0.61 ± 0.10 b
$\sigma^{\rm SPS}_{c\bar{c}+X}$	$0.96 \pm 0.45_{\rm sc} \pm 0.10_{\rm PDF}$ b	$3.4 \pm 1.9_{\rm sc} \pm 0.4_{\rm PDF}$ b	$0.75 \pm 0.5_{\rm sc} \pm 0.1_{\rm PDF}$ b
$\sigma^{\rm TPS}_{c\bar{c}\,c\bar{c}\,c\bar{c}+X}$	$200 \pm 140_{\rm tot}$ 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

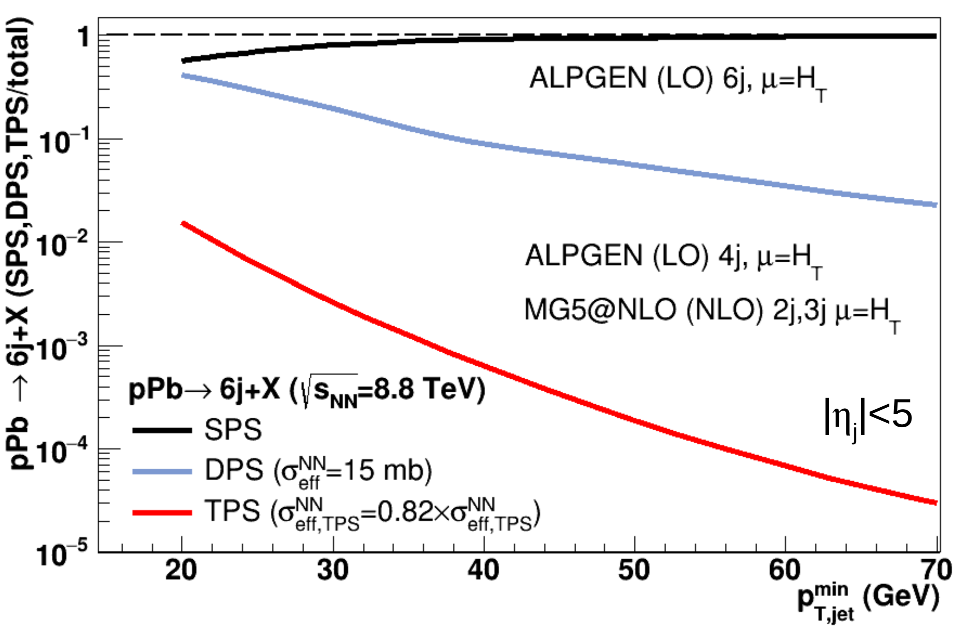
- Triple charm amounts to ~20% (~100%!) of inclusive charm x-sections at LHC (FCC). Large triple J/Ψ production at FCC: $\sigma(J/\psi J/\psi J/\psi + X) \approx 1$ mb
- Triple beauty amounts to ~3% of inclusive beauty x-sections at FCC.

Six-jet production from TPS (p-Pb)

- SPS/DPS/TPS contributions to 6-jet production in pPb(8.8 TeV) from pocket-formula and NLO,LO SPS 2j,3j,4j,6j (MG5@NLO, AlpGen) cross sections:



M.Maneyro & DdE (Tues. talk)



- 6-jet contributions:

TPS ~2%, 10^{-4} at p_T= 20, 50 GeV
DPS ~40%, 6% at p_T= 20, 50 GeV

$\sigma_{TPS}(6j) \approx 1.2$ nb (p_T>35 GeV, $|\eta|<5$)
$\sigma_{DPS}(6j) \approx 800$ nb (p_T>35 GeV, $|\eta|<5$)
$\sigma_{SPS}(6j) \approx 1.2$ μb (p_T>35 GeV, $|\eta|<5$)

- BDT MVA with single-,double-jet kinematic vars. to identify TPS.

Novel extraction of σ_{eff} at hand.

Summary (I)

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

$$\sigma^{\rm NPS}_{hh'\to a_1\dots a_n} = \left(\frac{m}{n!}\right) \frac{\prod_{i=1}^{N} \sigma^{\rm SPS}_{hh'\to a_n}}{\sigma^{n-1}_{\rm eff,NPS}} \qquad \sigma_{\rm eff,NPS} = \left\{\int d^2b\, T^n(\mathbf{b})\right\}^{-1/(n-1)}$$

- Pocket formula for triple parton scatterings in p-p:

$$\sigma^{\rm TPS}_{hh'\to a_1 a_2 a_3} = \left(\frac{m}{3!}\right) \frac{\sigma^{\rm SPS}_{hh'\to a_1}\cdot\sigma^{\rm SPS}_{hh'\to a_2}\cdot\sigma^{\rm SPS}_{hh'\to a_3}}{\sigma^2_{\rm eff,TPS}} \qquad \sigma^2_{\rm eff,TPS} = \left[\int d^2b\, T^3(\mathbf{b})\right]^{-1}$$

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

- Pocket formula for triple parton scatterings in p-A:

$$\sigma^{\rm TPS}_{\rm pA\to abc} = \left(\frac{m}{6}\right) \frac{\sigma^{\rm SPS}_{\rm pN\to a}\cdot\sigma^{\rm SPS}_{\rm pN\to b}\cdot\sigma^{\rm SPS}_{\rm pN\to c}}{\sigma^2_{\rm eff,TPS,pA}} \qquad \sigma_{\rm eff,TPS,pA} = \left[\frac{A}{\sigma^2_{\rm eff,TPS}} + \frac{3\,F_{\rm pA}[\rm mb^{-1}]}{\sigma_{\rm eff,DPS}} + C_{\rm pA}[\rm mb^{-2}]\right]^{-1/2}$$

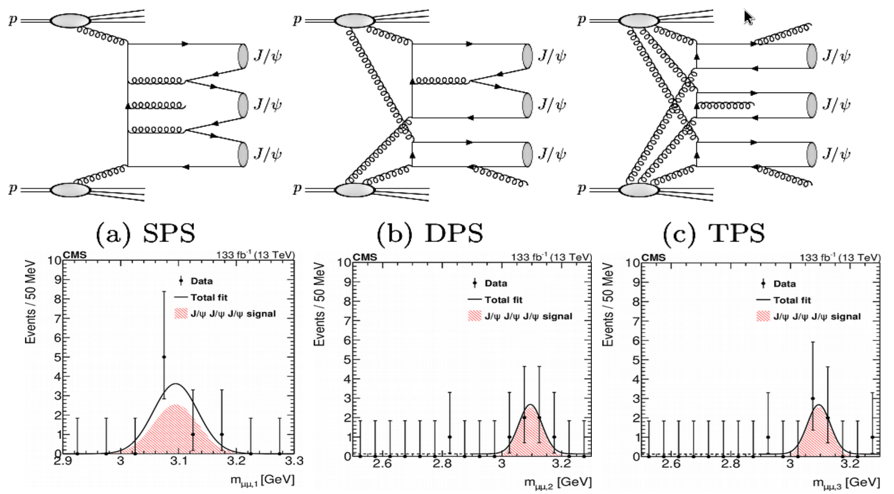
New observables available to extract DPS $\sigma_{\rm eff}$ within the simplest assumption of factorization of multiple hard-scattering probabilities in terms of SPS x-sections

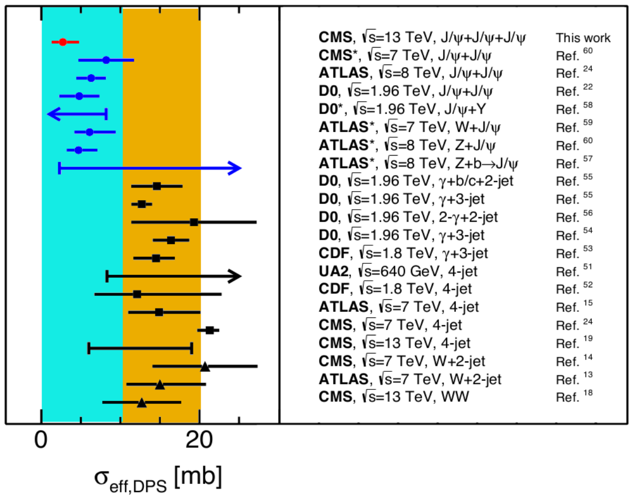
Summary (II)

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

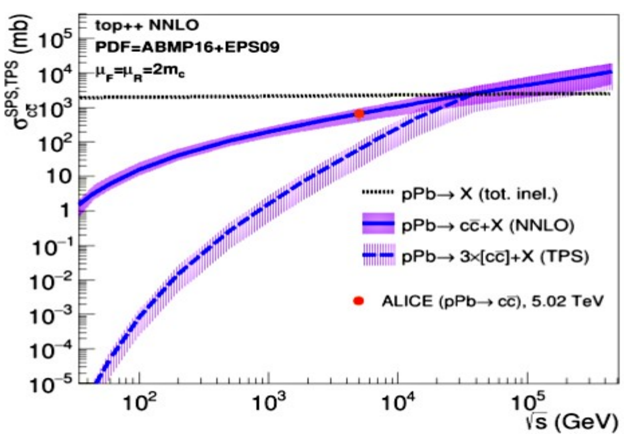
- First TPS constraints from triple-J/ in p-p:

$\sigma_{eff,DPS} = 2.7^{+2.0}_{-1.4}$ mb



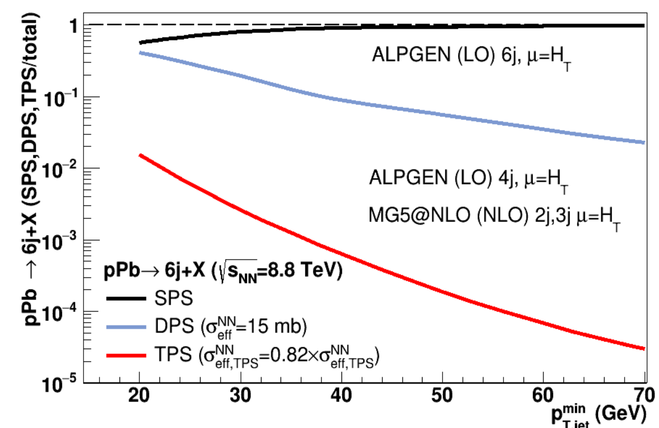


- Large TPS yields in p-Pb (quarkonia, jets):



$\sigma_{TPS}(3c\bar{c}) \approx 200$ mb

$\sigma_{TPS}(6j, 35\text{GeV}) \approx 1.2$ nb

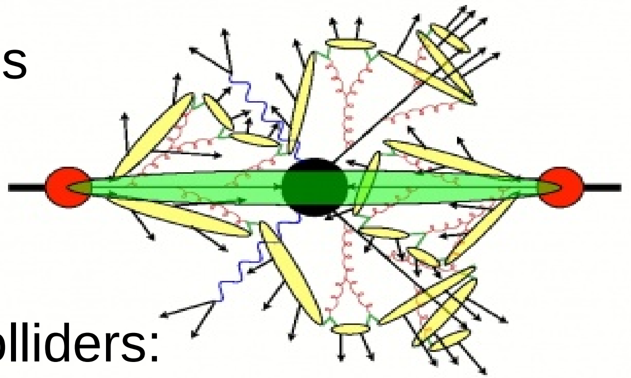


Novel useful independent extractions of $\sigma_{eff,pp}$

Backup slides

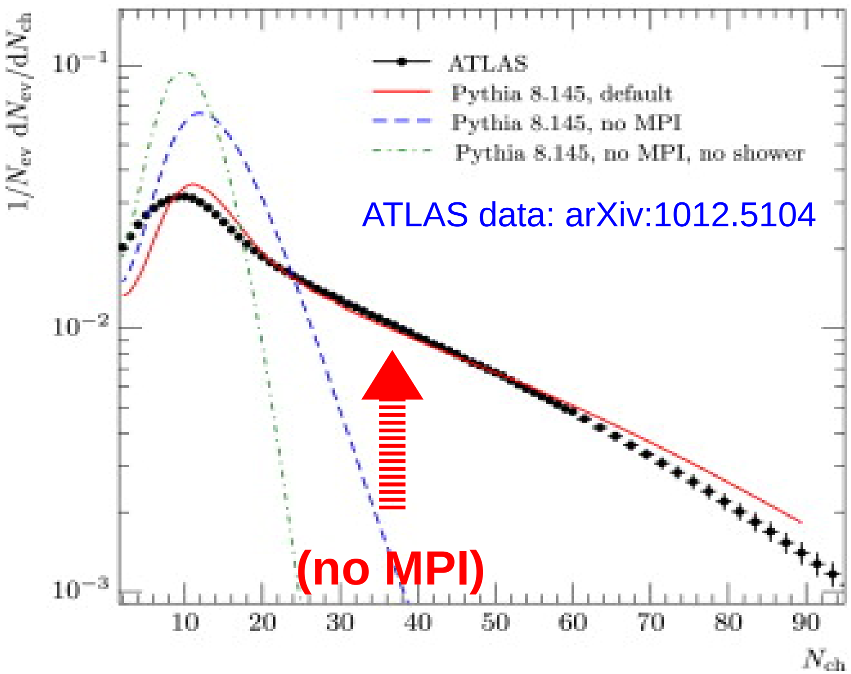
Multi-parton interactions at the LHC

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

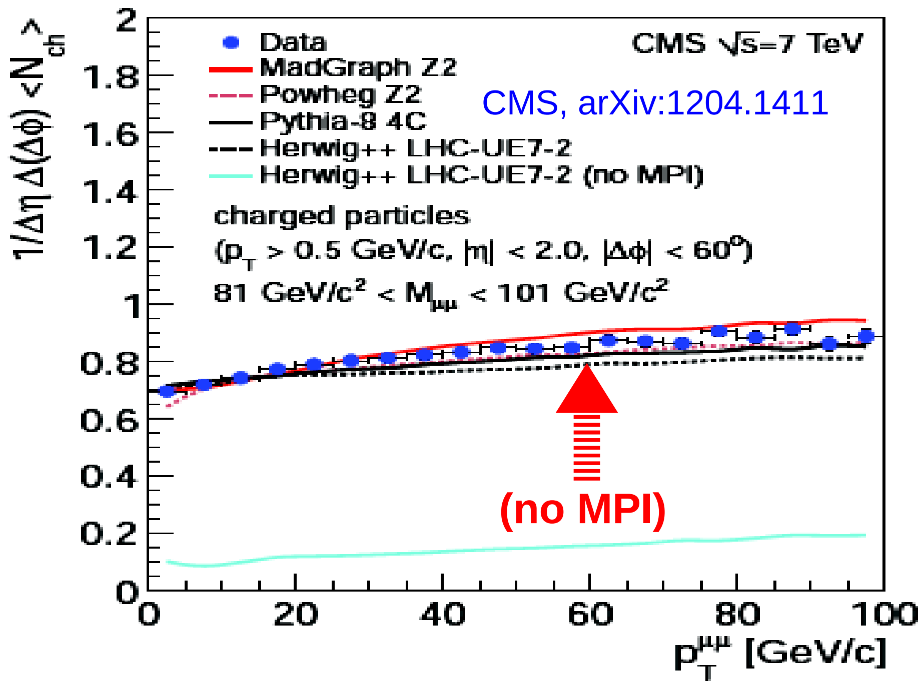


- MPI O(1–3 GeV) clearly observed at hadron colliders:

~50% of total hadron production

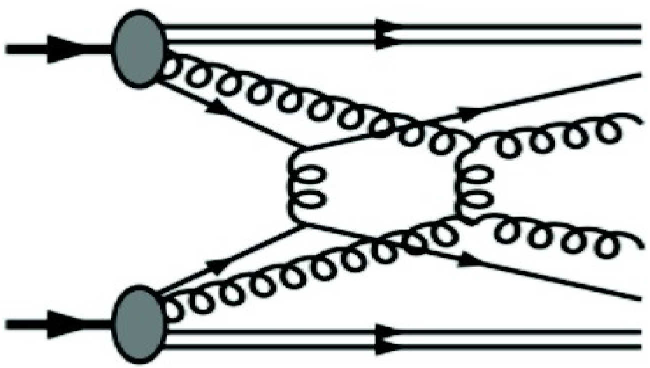


Underlying event in hard scatterings:



- Double hard parton scatts. (p_T,m_X>3 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:

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

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

- How to interpret σ_{eff}? What values one would naively expect for it?

- Let's start with the most generic expression for DPS cross section:

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

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

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

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

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

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

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

Model for density	Form of density, dN/d^3r	Predictions: rms r	Predictions: σ_{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, $\lambda/r_0=0.2$	$(e^{(r-r_0)/\lambda}+1)^{-1}$	$1.07r_0$	$4.6r_0^2$	$r_0=0.56$

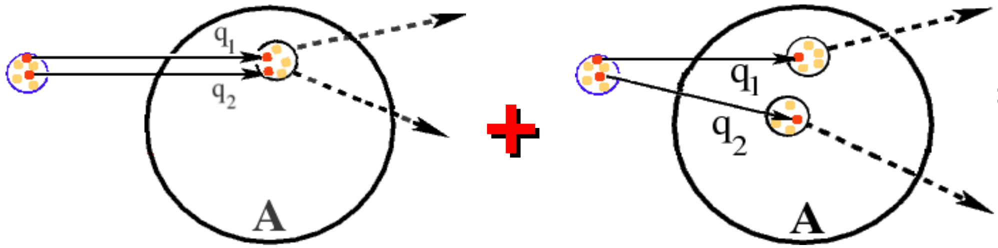
- But experimentally: σ_{eff}(exp) ≈ 15 mb. proton "hard" radius: r = 0.3–0.7 fm appears smaller than e.m. one:

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

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...]



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

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

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

p-A overlap function:

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

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

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

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

($\sigma_{eff,pp}$=13±2mb)

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

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

- DPS x-sections are large in p-A: a factor ×600 (not ×208) for p-Pb (!)
- Pb transverse density (F_{pA}) well known: Alternative extraction of $\sigma_{eff,pp}$

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

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

- Cross sections & rates for DPS processes with J/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
$\rm N^{DPS}_{pPb}$ (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
$\rm N^{DPS}_{pPb}$ (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)

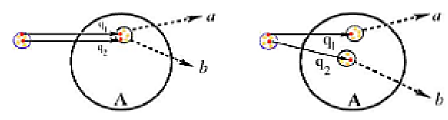
- Many double hard scatterings processes with visible p-Pb x-sections at the LHC. (Note: J/ψ values are per unit-|y|).
- Useful independent extraction of $\sigma_{\rm eff,pp}$!

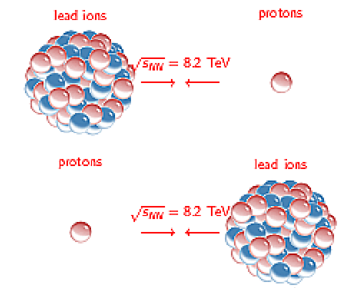
First study of DPS in p-Pb (LHCb, 8.2 TeV)

[LHCb, PRL 125 (2020) 212001]

- **Double-charm production** proton-lead collisions:

  - select pairs of D^0, D^0, D^+, D^-, D_s^+, D_s^- and J/ψ
  - sort them into pair production and "DPS" categories $\sigma_{C_1,C_2} = \alpha \frac{\sigma_{C_1}\sigma_{C_2}}{\sigma_{\text{eff}}}$

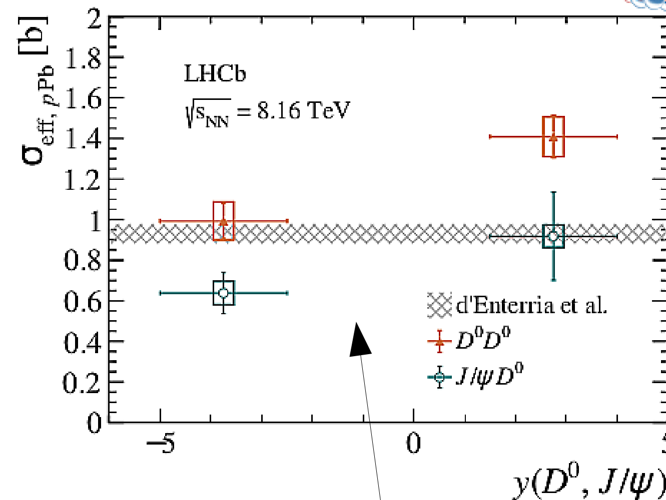




$$R^{D_1D_2}_{forward} = \frac{\sigma_{D_1D_2}}{\sigma_{D_1\bar{D}_2}} = 0.308 \pm 0.015 \pm 0.010$$

$$R^{D_1D_2}_{backward} = 0.391 \pm 0.019 \pm 0.025$$

$$R^{D^0D^0}_{pp} = 0.109 \pm 0.008$$



Like sign charm fraction tripled!

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

Albert Bursche | *charming DPS* | *10^{th} October 2021* | *15 / 17*

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

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

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

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

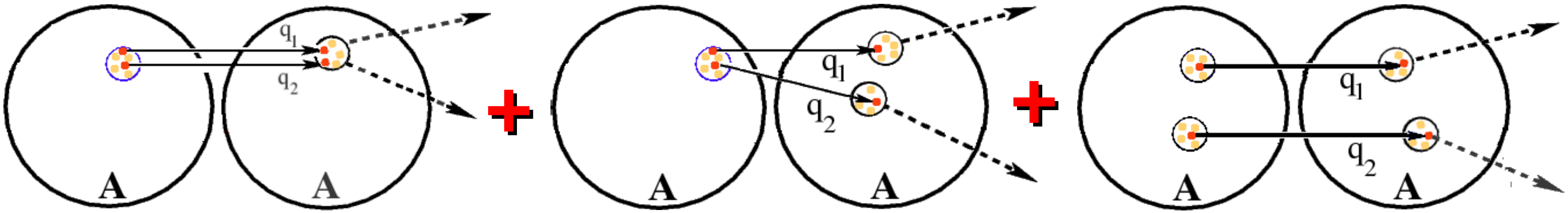
nPDF effects visible in -y/+y results.

(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:



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

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

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

  - ► Third "N_{coll} term" $\propto A^2 \cdot T_{AA}(0)$, clearly dominant (1:4:200 ratio for PbPb)
    "Genuine" DPS (within same nucleon): ~2.5% (in Pb-Pb) or ~13% (Ar-Ar)

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

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

(for Pb-Pb collisions)

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

  - ► 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:

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

Examples: DPS x-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:

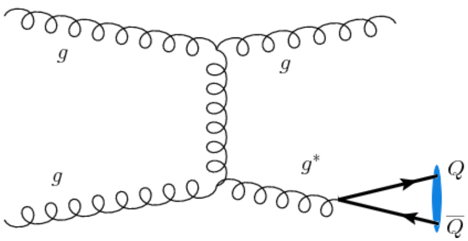
PbPb (5.5 TeV)	$J/\psi + J/\psi$	$J/\psi + \Upsilon$	J/ψ+W	J/ψ+Z
$\sigma^{\rm SPS}_{\rm NN\to a}, \sigma^{\rm SPS}_{\rm NN\to b}$	25 μb ($\times$2)	25 μb, 1.7 μb	25 μb, 30 nb	25 μb, 20 nb
$\sigma^{\rm DPS}_{\rm PbPb}$	210 mb	28 mb	500 μb	330 μb
$\rm N^{DPS}_{PbPb}$ (1 nb^{-1})	$\sim$250	$\sim$340	$\sim$65	$\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! (Note: J/ψ values are per unit-|y|).

Example: Pb-Pb → J/ψ J/ψ at 5.5 TeV

- **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

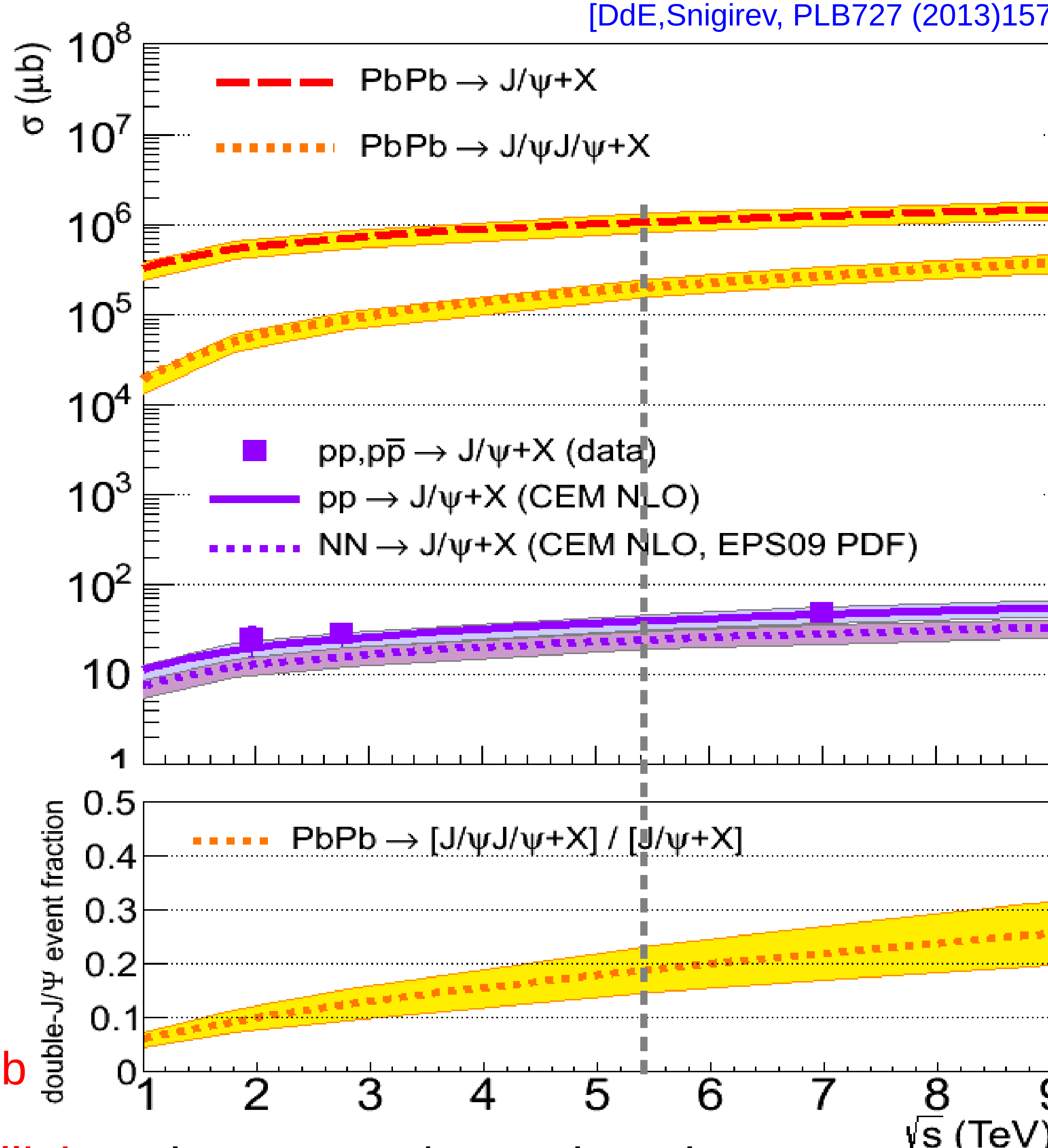
- EPS09 Pb nPDF

  20–35% shadowing x-section reduction

- **At 5.5 TeV:**

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

[DdE,Snigirev, PLB727 (2013)157]



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

Example: Pb-Pb → J/ψ J/ψ at 5.5 TeV

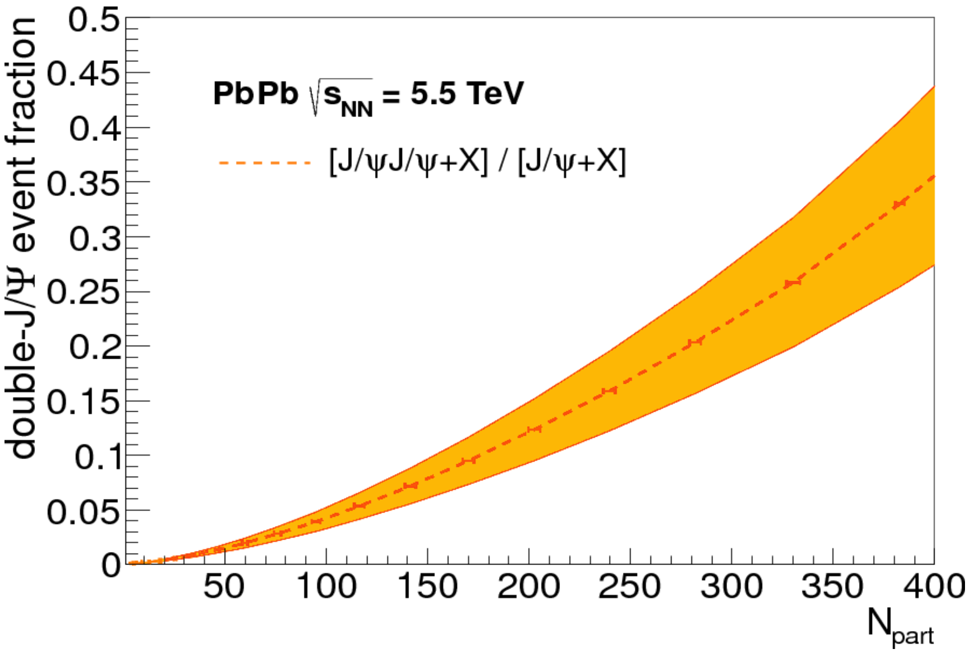
[DdE, Snigirev, PLB727 (2013)157]

- Visible rates:
  - Fiducial x-section 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:

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

(x2 less including final-state suppression)

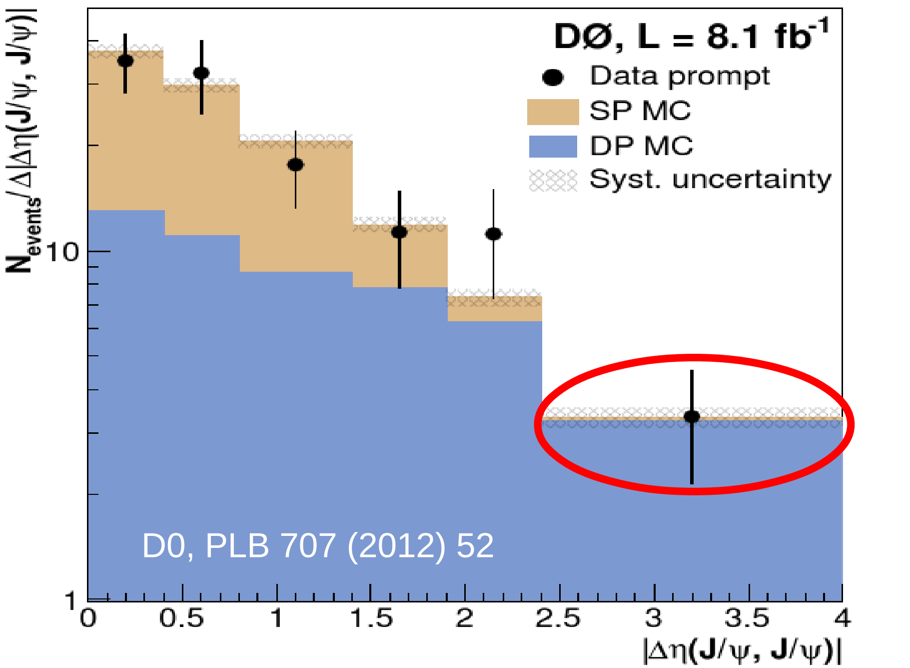
- Centrality dependence of double-J/ψ fraction: 35% of central Pb-Pb collisions have two J/ψ produced !



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

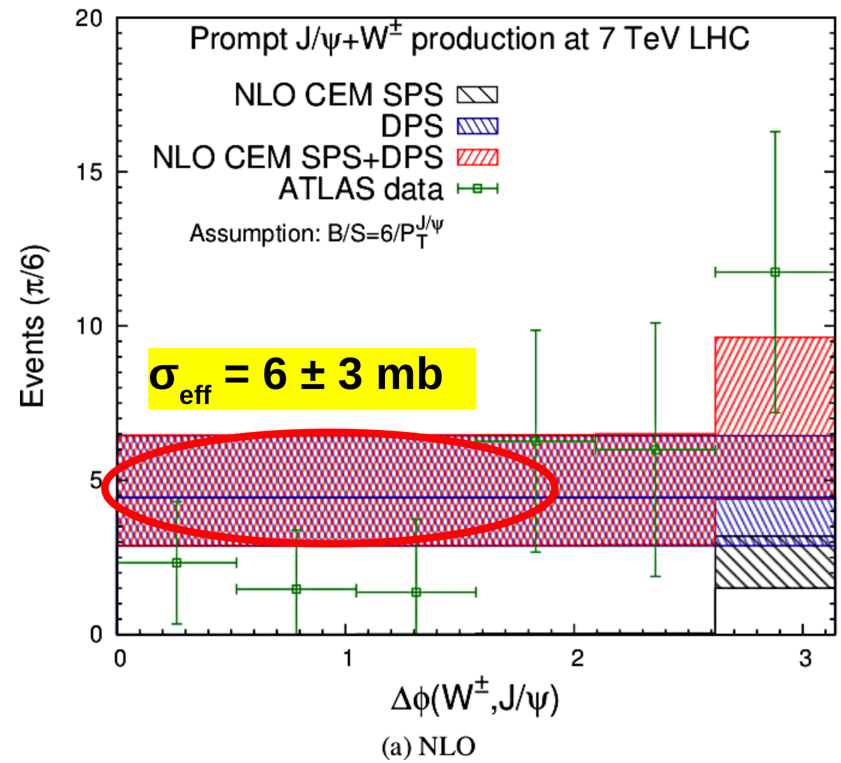
DPS studies with $Q\bar{Q}$: p-p → W^{+}+J/Ψ, J/ΨJ/Ψ

- 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:



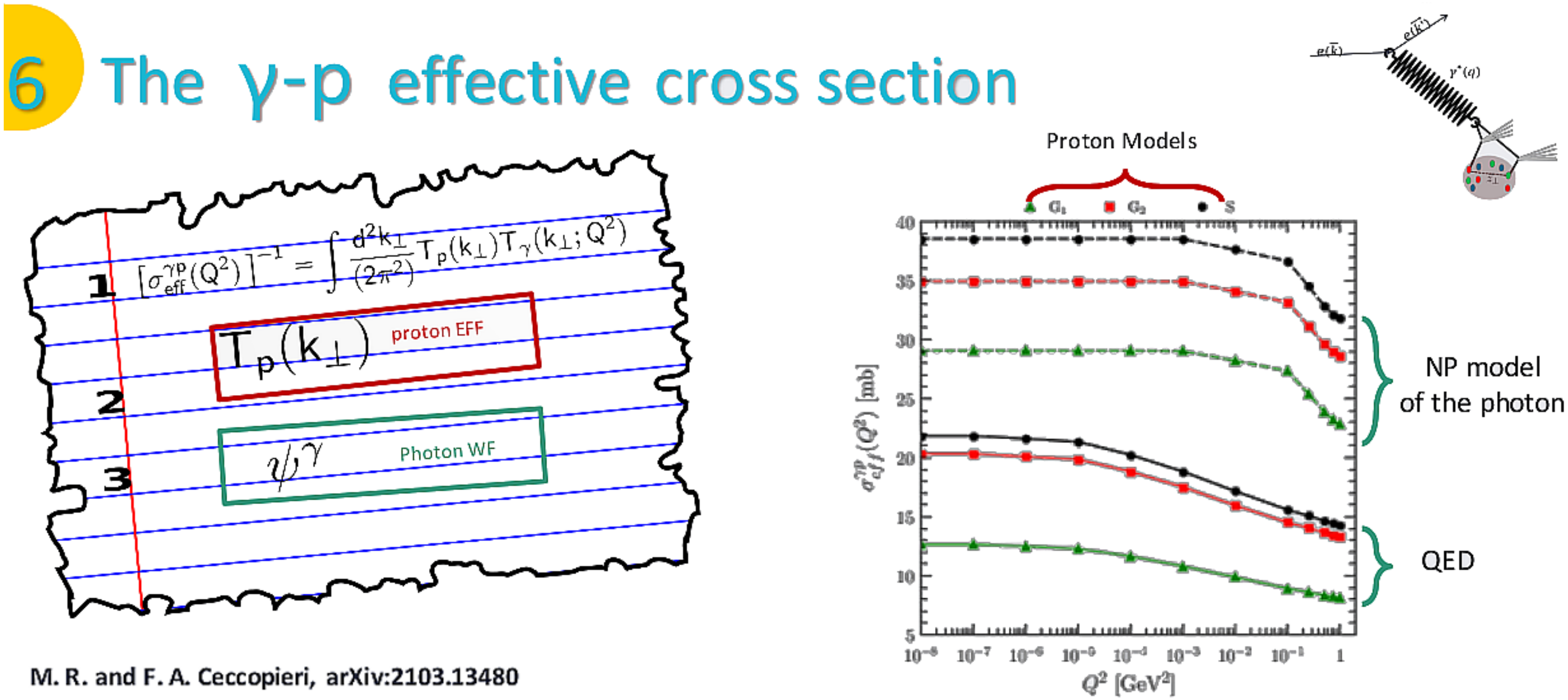
Lansberg&Shao&Yamanaka, PLB781 (2018) 485

- 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?)

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):



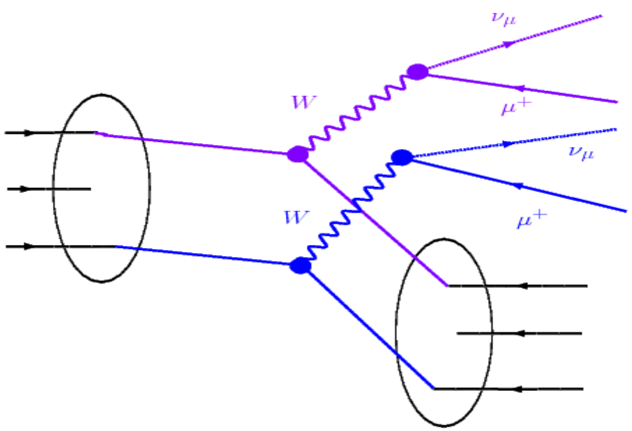
- Such studies (based on HERA data so far) could be tested with UPCs in p-Pb with the photon emitted from the Pb ion (we should go beyond searching for 'ridges' in UPCs, and extract some quantitative x-sections...)

DPS "golden channel": Same-sign WW

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

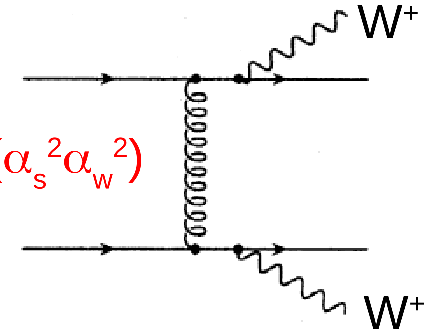
- Same-sign W-W production from 2 independent hard scatterings is a "golden" DPS signature:

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

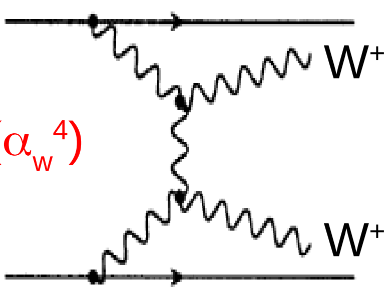


- Backgrounds: Same-sign W-W production in single parton scatterings (SPS) is higher-order and occurs only with 2 extra jets:

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



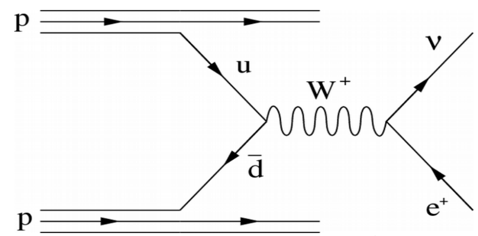
EWK (α_w^4)



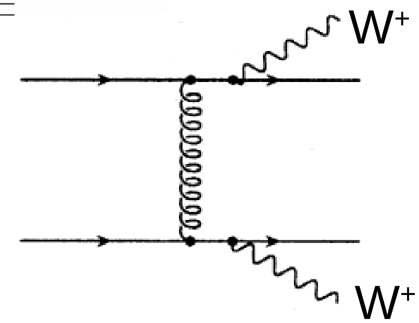
- σ(WW,DPS)~1/3·σ(WWjj,SPS), but SPS background reducible by more than x20 applying jet cuts.

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

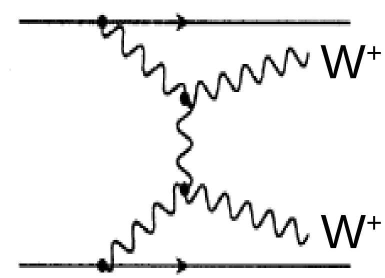
[DdE,Snigirev, PLB718 (2013)1395]



- 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
    - Uncertainties: ~10%



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



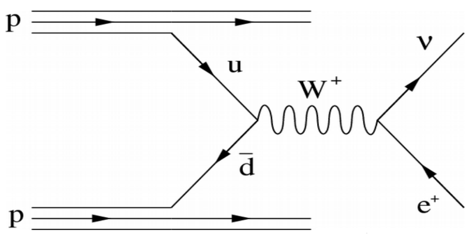
- Cross sections in pb (signal & background):

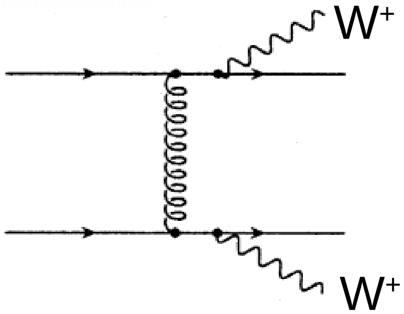
p-Pb final-state: Code (process #): Order (σ units):	W^+ MCFM (1) NLO (μb)	W^- MCFM (6) NLO (μb)	W^+W^- MCFM (61) NLO (nb)	W^+W^+jj (QCD) MCFM (251) 'NLO' (pb)	W^+W^+jj (VBF) VBFNLO (250) NLO (pb)	$W^\pm W^\pm$ (DPS) Eq. (15) (pb)
$\sqrt{s_{NN}}$ = 5.0 TeV	6.85 ± 0.68	5.88 ± 0.59	5.48 ± 0.56	12.1 ± 1.2	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.

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

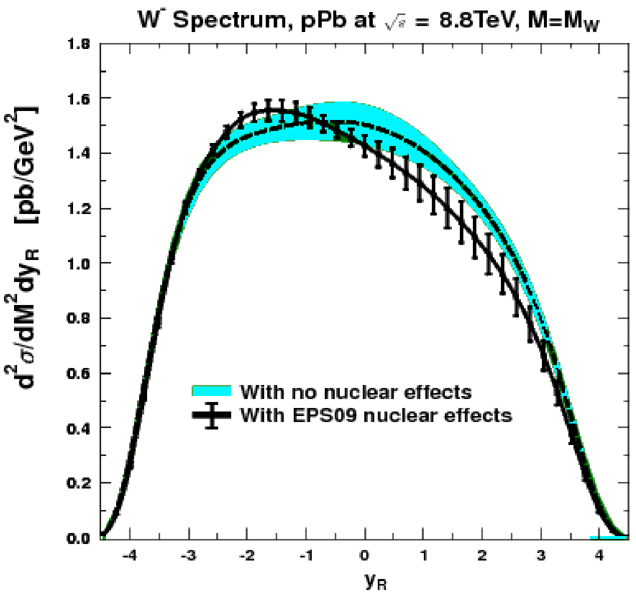
[DdE,Snigirev, PLB718 (2013)1395]

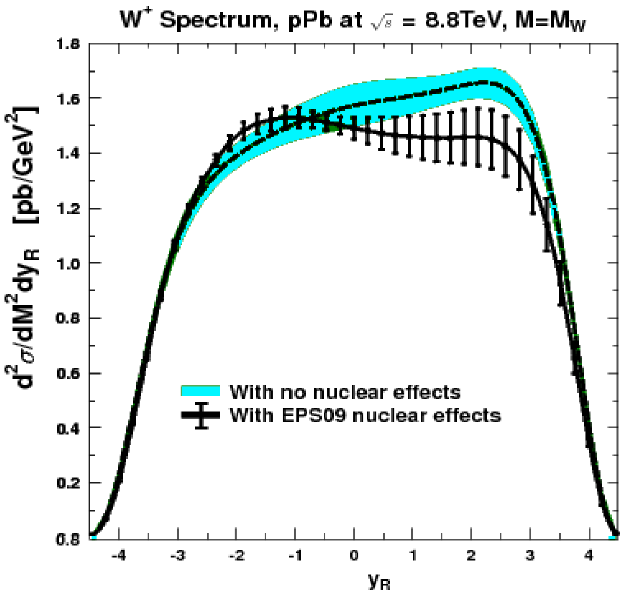
- Theoretical setup:
  - MCFM 6.2: Single-parton W^+,W^-
    W^+W^+jj (QCD) background
    - NLO accuracy.
    - Scales: $\mu(W) = m_W$, $\mu(WW)$ = 150 GeV
    - CT10 proton PDF, EPS09 Pb nuclear PDF:





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





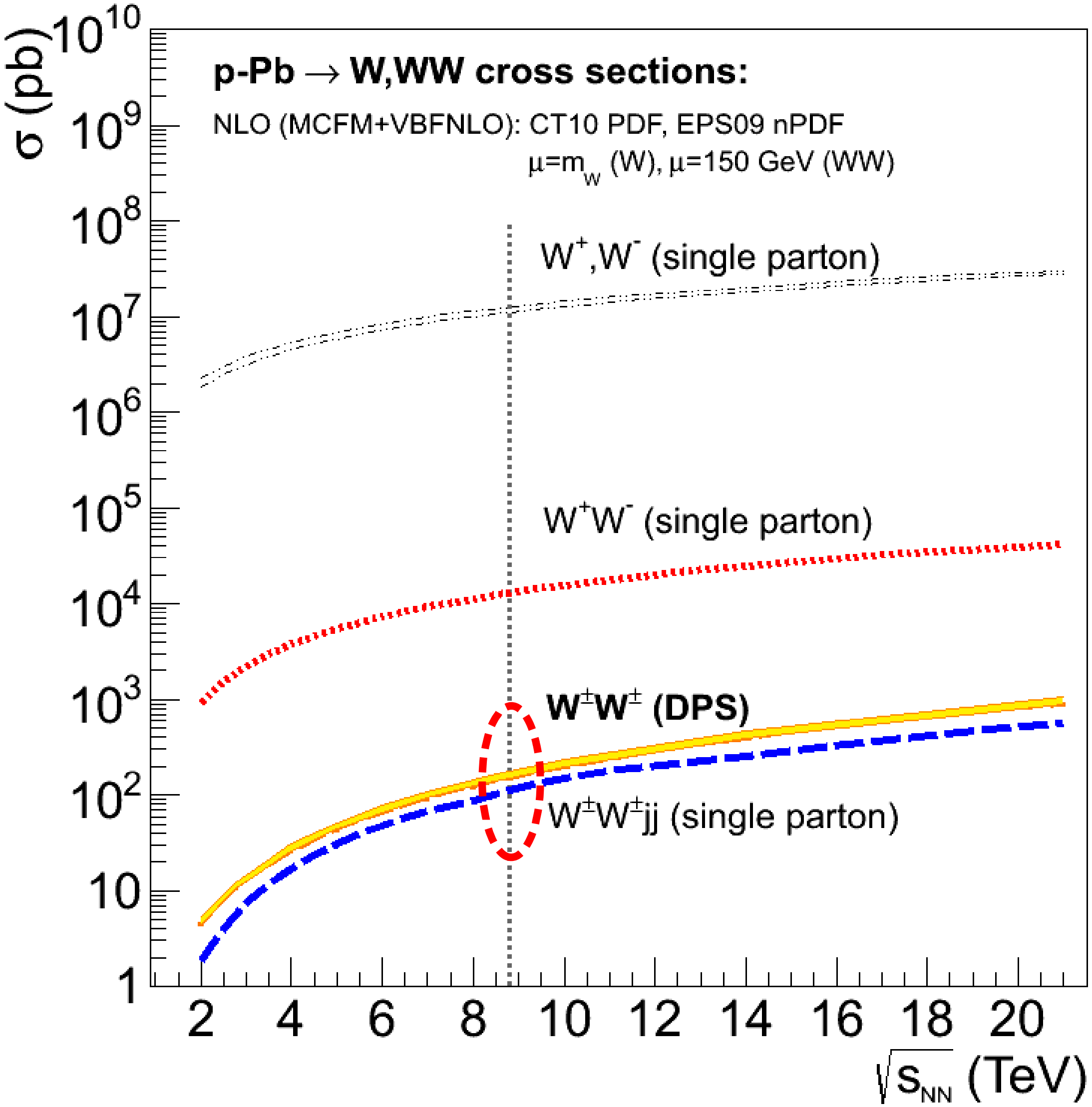
Isospin+shadow. effects on total inclusive x-sections:
W^- : +7%
W^+ : -15%
compared to p-p

[Paukkunen&Salgado JHEP 1103 (2011) 071]

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($W\to l\nu$) ≈ 3 ×1/9, BR($W\to qq'$) ≈ 2/3
    - Both leptonic: 4 final-states ($\mu\mu$,ee,eμ,μe): $4\times(1/9)^2 \approx$ 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 ⇒ $\varepsilon_{WW} \approx 40\%$
- 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:

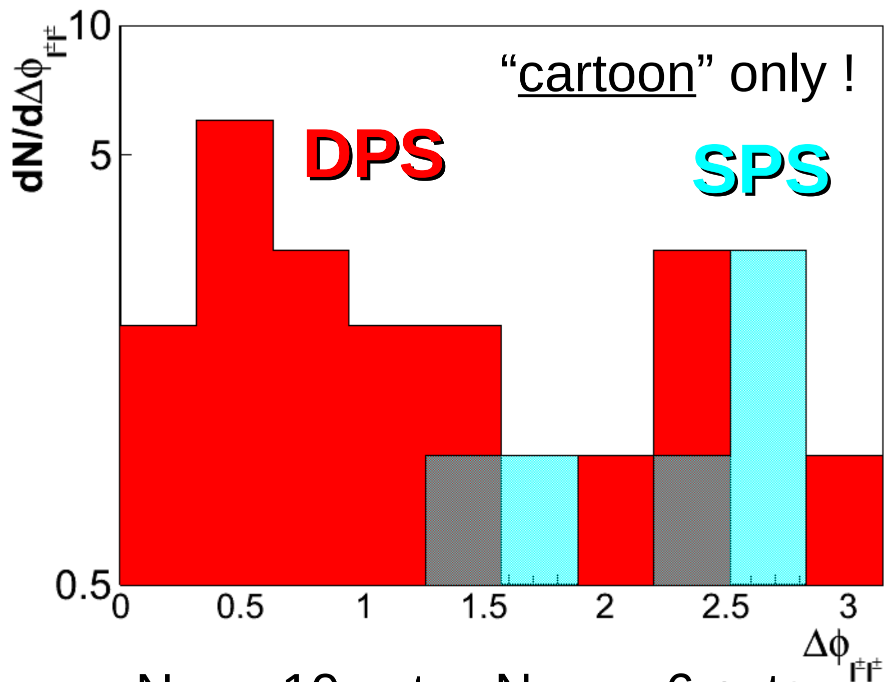
$$\mathcal{N}_{DPS} = \sigma^{\rm DPS}_{pPb\to WW} / (\varepsilon \cdot \mathcal{L}_{\rm int}) \approx \text{1–10 same-sign WW pairs/year}$$

(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:

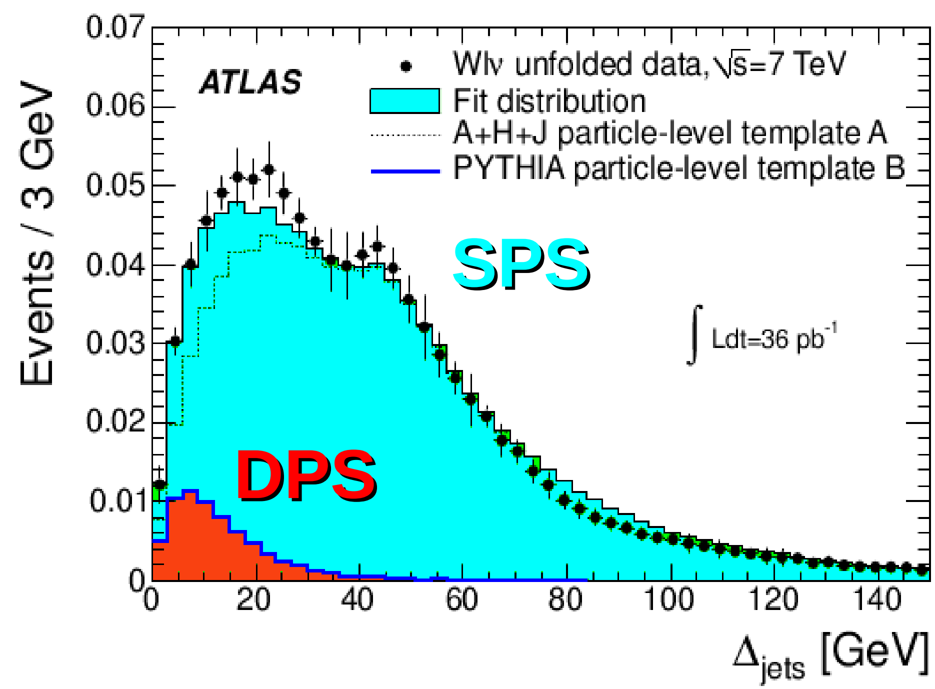
p-Pb @ 8.8 TeV (2 pb^{-1}):
Same-sign leptons
azimuthal separation:



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

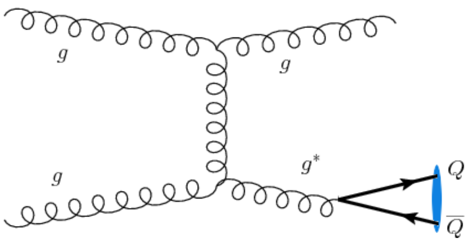
(Other reducible bckgds: WZ,$Z^{(*)}Z^{(*)}$,B^0B^0)

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



Example: Pb-Pb → J/ψ J/ψ at 5.5 TeV

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



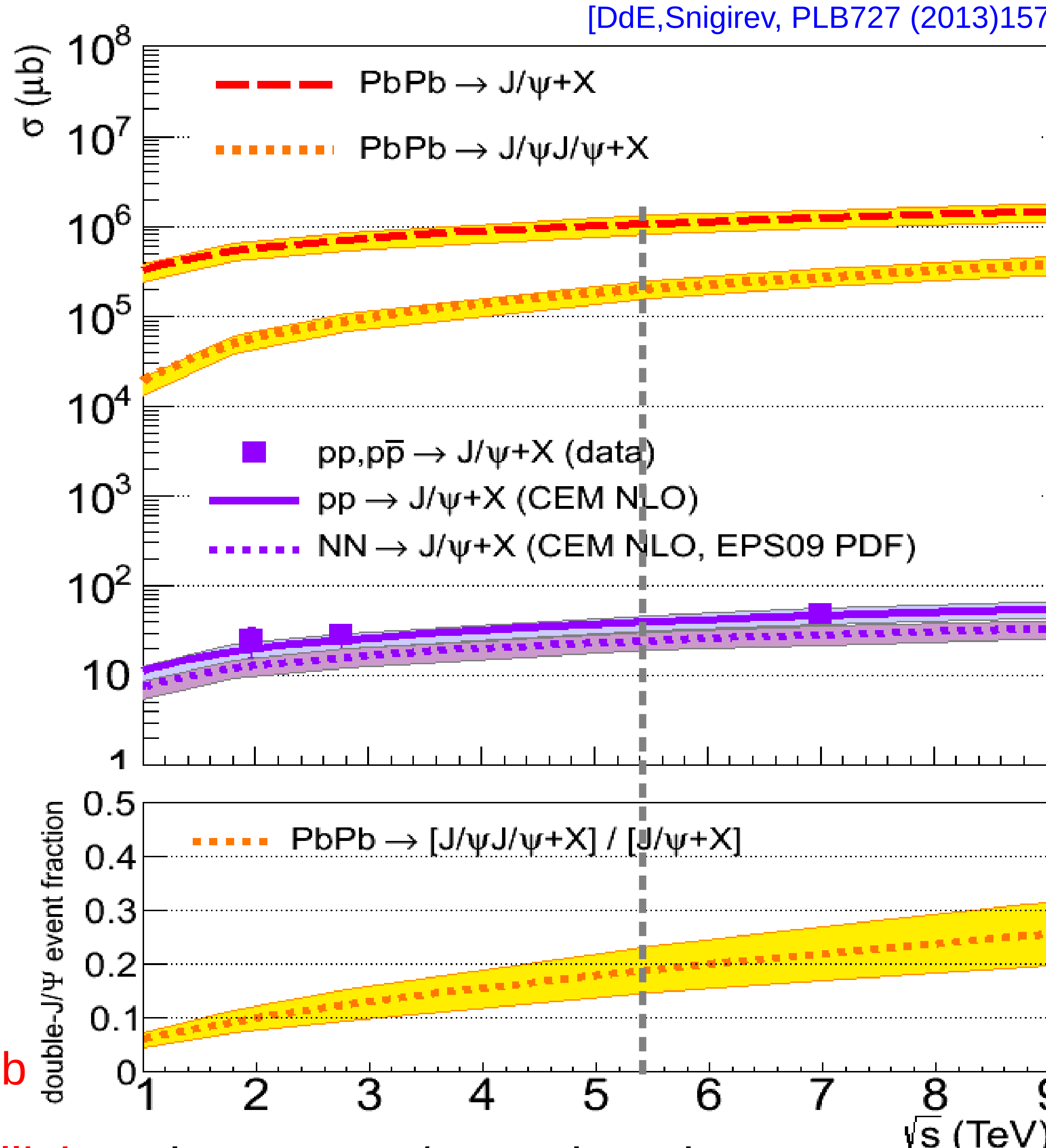
- NLO accuracy.
- Scales: $\mu_R = \mu_R = 1.5 \cdot m_c$
- Good agreement with Tevatron&LHC data

- 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 min.bias Pb-Pb collisions have two J/ψ produced !