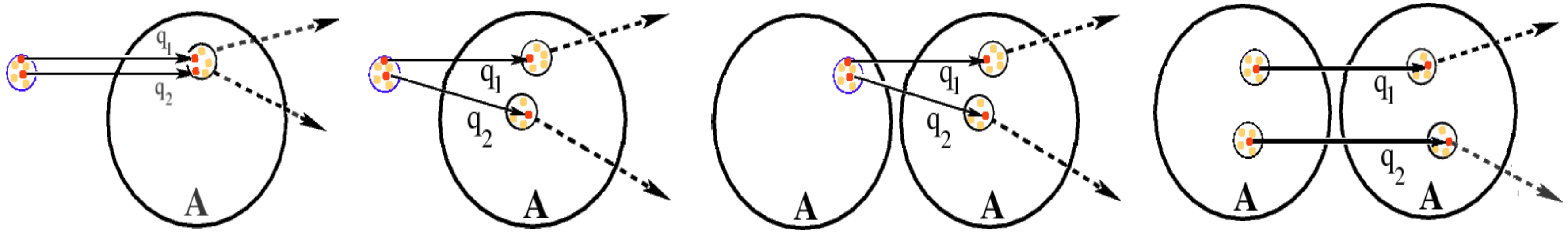


Double & triple parton scatterings in p-A, A-A at the LHC

MPI 2021

Lisbon (Virtual), 15th October 2021

David d'Enterria

CERN

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

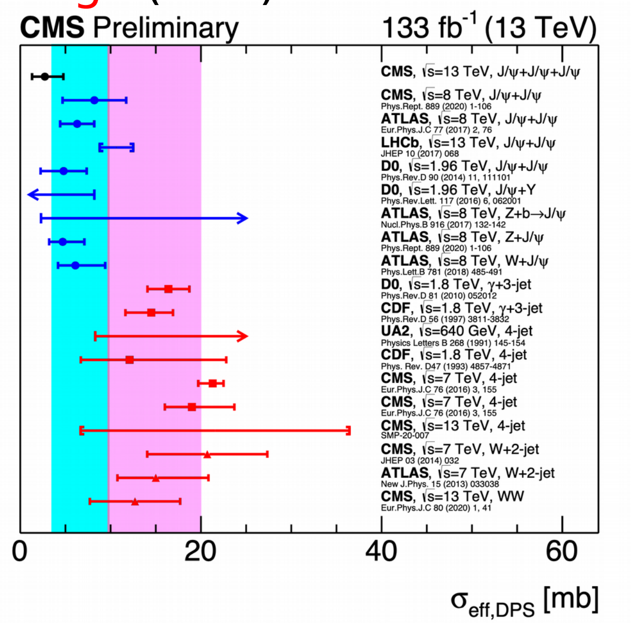
N-parton scatterings in p-p collisions

- Motivation for studies of multiple production of hard/heavy particles:
  - (1) Generalized PDFs (x,Q^2,b) of the proton, in particular 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
- Studies so far focused on double-parton scatterings (DPS):

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

"Pocket formula" assuming no parton correlations:
$\sigma_{\rm eff}$ is a proxy to the mean inter-parton transverse separation squared,
derivable from p-p transverse overlap:

$\sigma_{\rm eff}$ ~ 20–30 mb (PYTHIA8/HERWIG p form-factor)
$\sigma_{\rm eff}$ ~ 15 mb (from DPS of jets, EWK bosons)
$\sigma_{\rm eff}$ ~ 5 mb (from di-quarkonia)



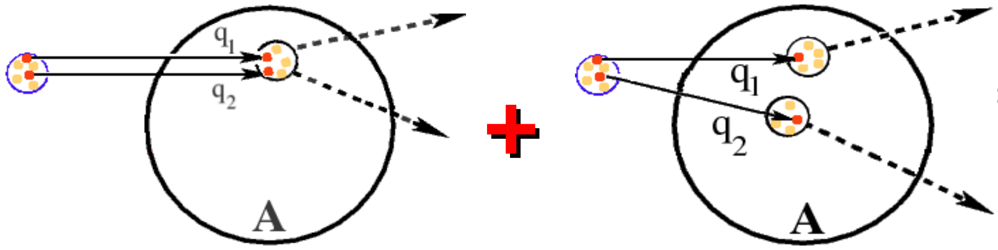
- Reasons: x- q,g-dependent correlations & transverse proton profile?
- Novel observables: Triple-parton scatterings (TPS), DPS/TPS with ions

Double Parton Scatterings

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...]



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

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

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

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:

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

($\sigma_{\rm eff,pp}$=13±2mb)

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

► 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 (not ×208) for p-Pb (!)
- Pb transverse density (F_{pA}) well known: Alternative extraction of $\sigma_{\rm eff,pp}$

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 (×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 (×2)	2.6 μb, 60 nb	2.6 μb, 35 nb	60 nb (×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)

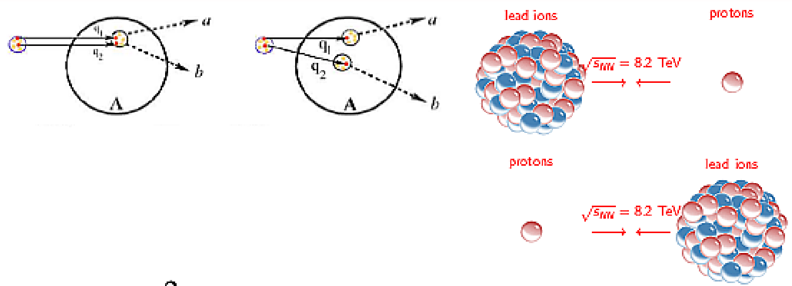
- Many double hard scatterings processes w/ visible p-Pb x-sections at the LHC. (Note: J/ψ values are per unit-|y|).
- Useful independent extraction of $\sigma_{\rm eff,pp}$!

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

[LHCb, PRL 125 (2020) 212001]

double charm production in proton lead collisions

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

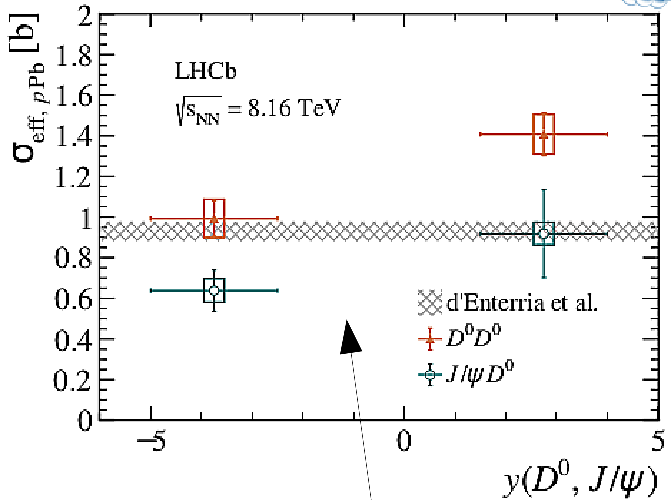


$$R^{D_1 D_2}_{forward} = \frac{\sigma_{D_1 D_2}}{\sigma_{D_1 \bar{D}_2}} = 0.308 \pm 0.015 \pm 0.010$$

$$R^{D_1 D_2}_{backward} = 0.391 \pm 0.019 \pm 0.025$$

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

Like sign charm fraction tripled!



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

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

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

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

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

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

nPDF effects visible in -y/+y results.

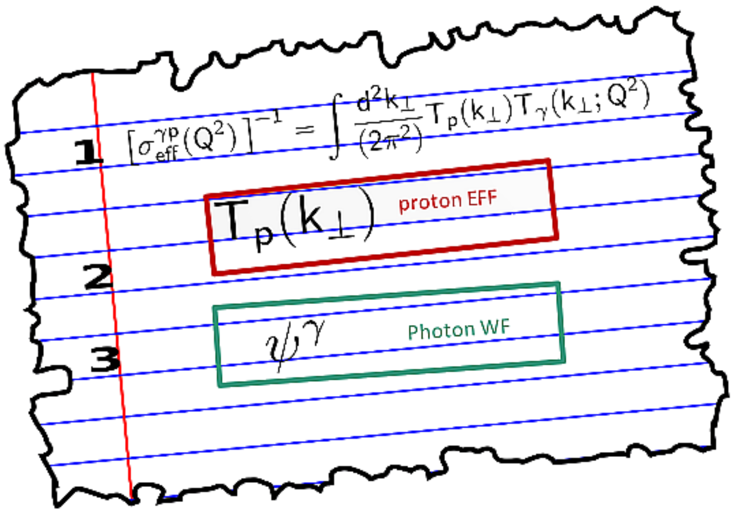
(why LHCb does not quote the equivalent $\sigma_{\text{eff,pp}}$ values?)

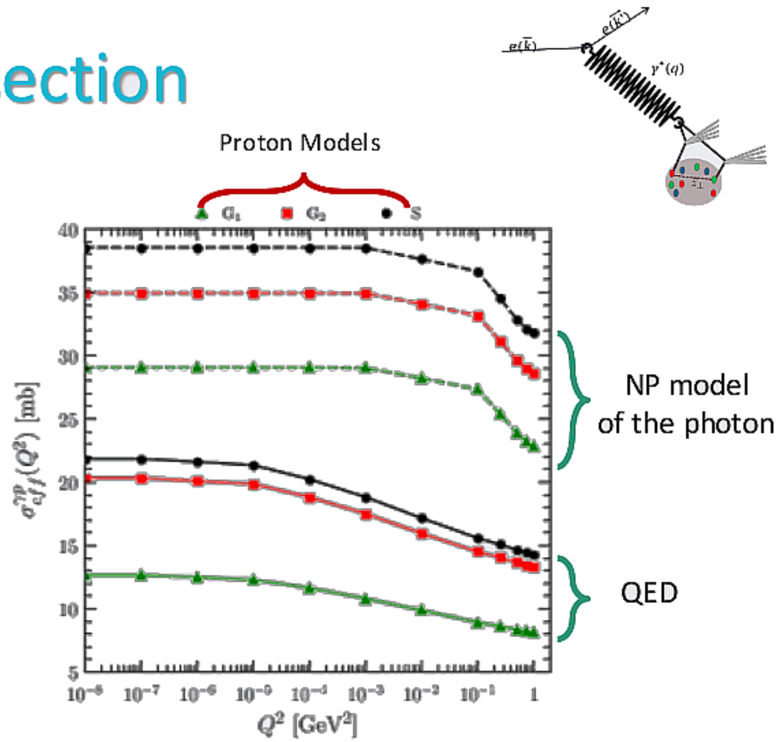
DPS in Ultraperipheral p-Pb collisions?

[M.Rinaldi, Tuesday 12/10/21]

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

6 The γ-p effective cross section





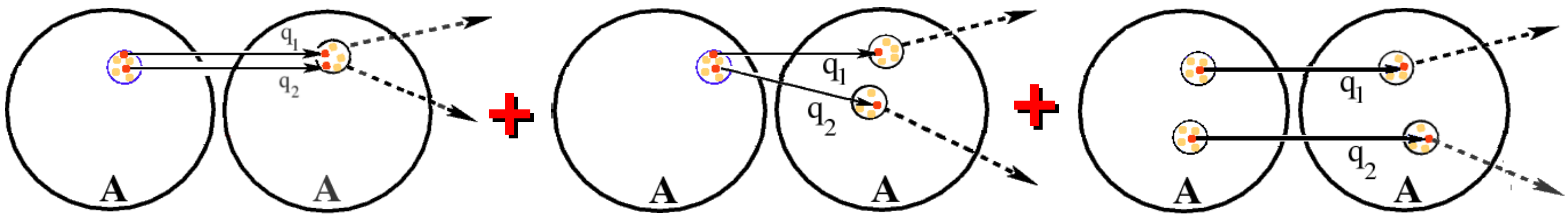
M. R. and F. A. Ceccopieri, arXiv:2103.13480

- 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...)

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:

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

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

(for Pb-Pb collisions)

  - ► 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})	~250	~340	~65	~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})	~95	~35	~8	~15

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

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

Example: Pb-Pb → J/ψ J/ψ at 5.5 TeV

[DdE, Snigirev, PLB727 (2013)157]

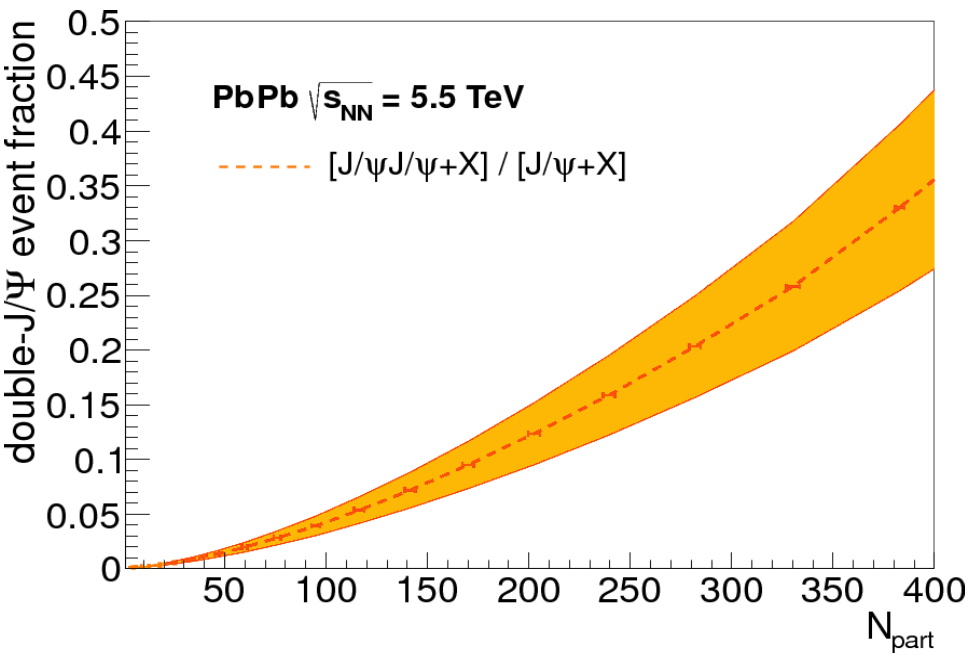
- Visible rates:
  - ► Fiducial x-section per unit-y: $d\sigma_{J/\psi}/dy \approx \sigma_{J/\psi}/8$
  - ► BR(J/ψ→ l^+l^-) ≈ 6%
  - ► Typical ALICE/CMS acceptance & efficiencies: ε ≈ 1/12
- Expected dimuon rates including yield all loses & 1 nb^{-1} integ. luminosity:

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



Triple Parton Scatterings

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

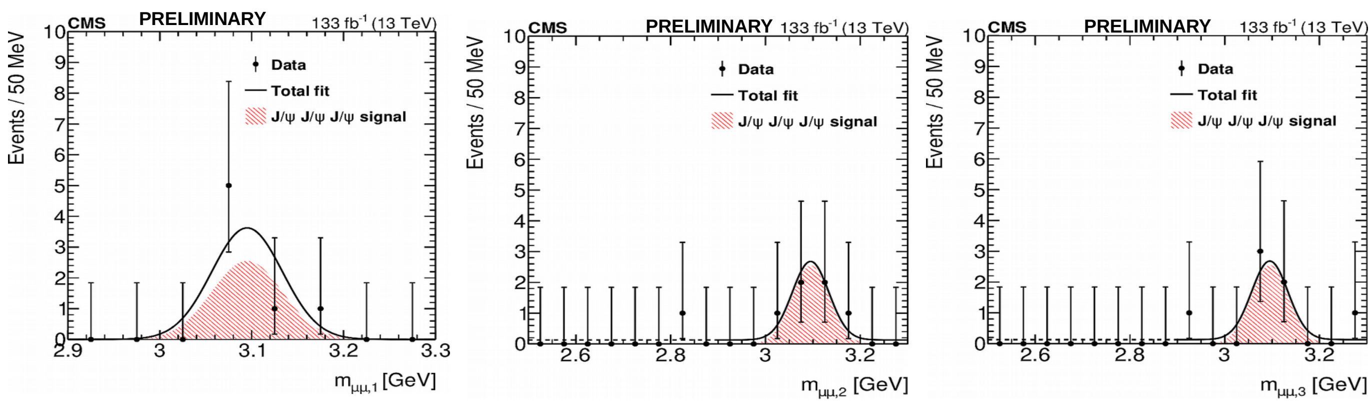
- Triple parton scatterings x-sections in p-p: alternative extraction of $\sigma_{eff,DPS}$

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

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

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

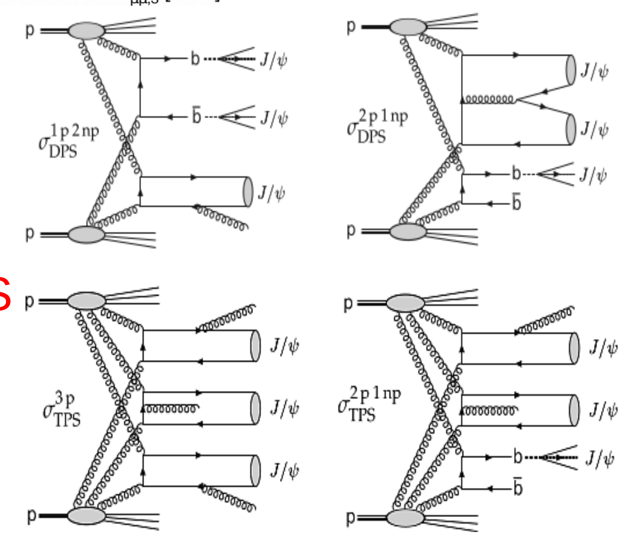
- First observation of triple-J/ψ production (CMS):



[CMS-BPH-18-004]

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

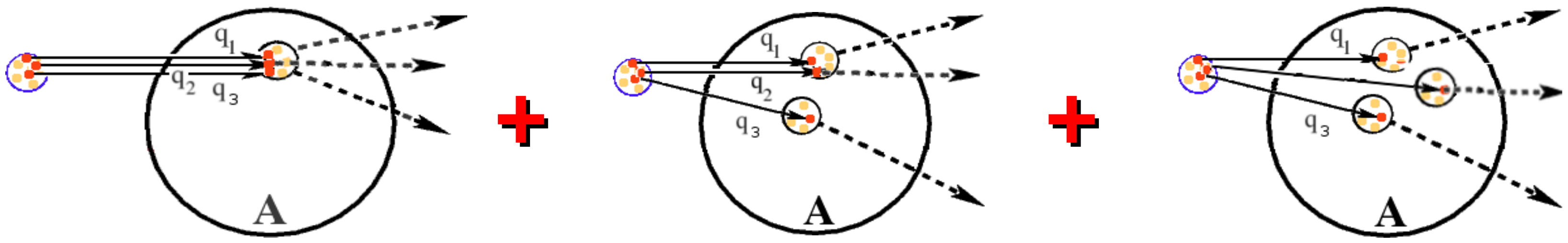
- Pocket formula with (N)NLO for single-,double-, triple-J/ψ SPS x-sections:
  - Triple-J/ψ fractions: ~6% SPS, ~74% DPS, ~20% TPS
  - $\sigma_{eff,DPS} = 2.7\ ^{+1.4}_{-1.0}$ (exp) $^{+1.5}_{-1.0}$ (theo) mb consistent with for di-quarkonia (lower than jet/γ/W/Z DPS results):
    - ▶ q/g x-dependent 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:



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

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

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

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:

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

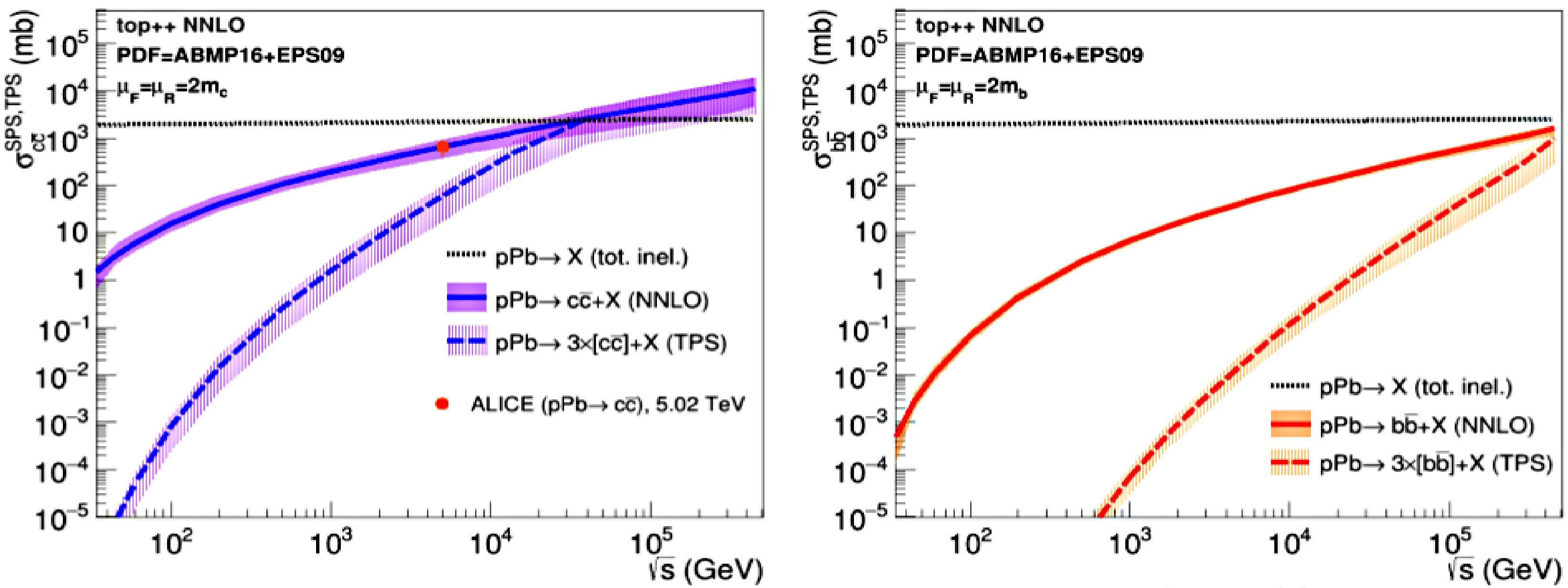
$$\sigma_{\rm eff,TPS,pA} = \left[\frac{A}{\sigma^2_{\rm eff,TPS}} + \frac{3\,F_{\rm pA}[{\rm mb}^{-1}]}{\sigma_{\rm eff,DPS}} + C_{\rm pA}[{\rm mb}^{-2}]\right]^{-1/2}$$

► $\sigma_{\rm eff,TPS,pPb}$ = 0.29 ± 0.04 mb (×45 times the p-p case with $\sigma_{\rm eff,TPS}$= 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 $\sigma_{\rm eff,pp}$

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)
σ^{inel}_{pA}	2.2 ± 0.4 b	2.4 ± 0.4 mb	0.61 ± 0.10 b
$\sigma^{SPS}_{c\bar{c}+X}$	$0.96 \pm 0.45_{sc} \pm 0.10_{PDF}$ b	$3.4 \pm 1.9_{sc} \pm 0.4_{PDF}$ b	$0.75 \pm 0.5_{sc} \pm 0.1_{PDF}$ b
$\sigma^{TPS}_{c\bar{c}\,c\bar{c}\,c\bar{c}+X}$	$200 \pm 140_{tot}$ mb	$8.7^* \pm 6.2_{tot}$ b	$5.0^* \pm 3.6_{tot}$ b
$\sigma^{SPS}_{b\bar{b}+X}$	$72 \pm 12_{sc} \pm 5_{PDF}$ mb	$370 \pm 75_{sc} \pm 30_{PDF}$ mb	$110 \pm 25_{sc} \pm 5_{PDF}$ mb
$\sigma^{TPS}_{b\bar{b}\,b\bar{b}\,b\bar{b}+X}$	$0.084 \pm 0.045_{tot}$ μb	$11 \pm 7_{tot}$ μb	$17 \pm 11_{tot}$ 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 studies with heavy ions

- 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:

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

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

($\sigma_{eff,pp}$=13±2mb)

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

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

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

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

Summary: TPS studies with heavy ions

- 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:

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

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

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

- 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 $\sigma_{\rm eff,pp}$: 1st-ever observation by CMS.

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

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

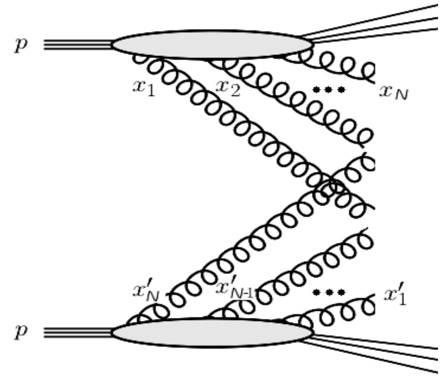
$$\sigma_{\rm eff,TPS,pA} = \left[\frac{A}{\sigma^2_{\rm eff,TPS}} + \frac{3\,F_{\rm pA}[{\rm mb}^{-1}]}{\sigma_{\rm eff,DPS}} + C_{\rm pA}[{\rm mb}^{-2}]\right]^{-1/2}$$

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

Backup slides

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 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:

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

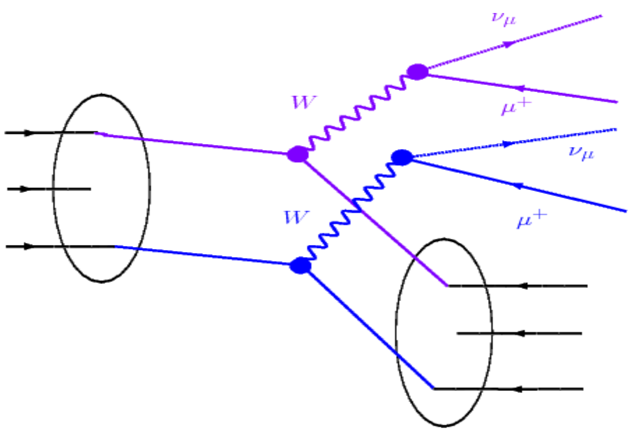
- A generic framework for the most economical (geometrical) expressions for N-parton scattering cross sections is available now.

DPS "golden channel": Same-sign WW

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

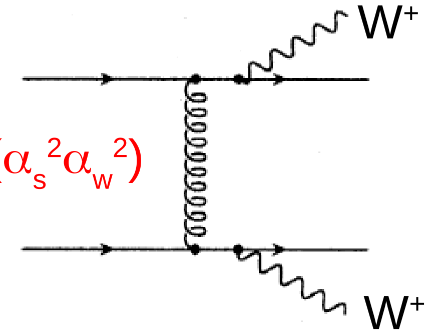
- Same-sign W-W production from 2 independent hard scatterings is a "golden" DPS signature:

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

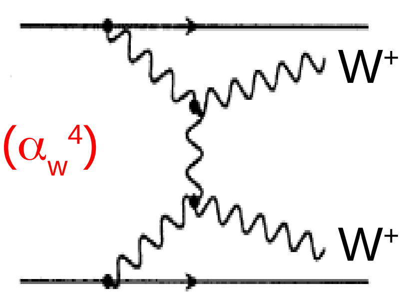


- Backgrounds: Same-sign W-W production in single parton scatterings (SPS) is higher-order and occurs only with 2 extra jets:

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



EWK (α_w^4)

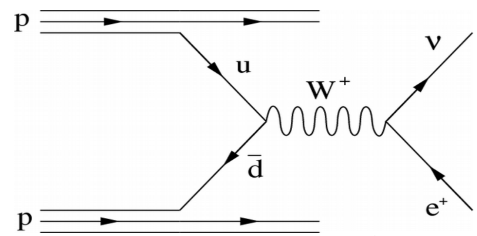


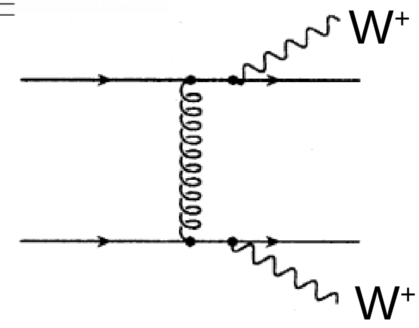
- σ(WW,DPS)~1/3·σ(WWjj,SPS), but SPS background reducible by more than x20 applying jet cuts.

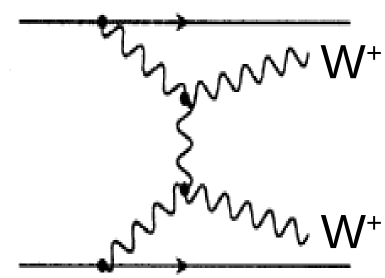
Case study: p-Pb → W^+W^+,W^-W^- at 8.8 TeV

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

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

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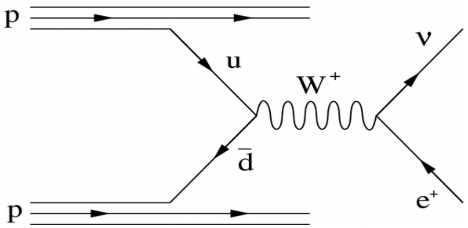
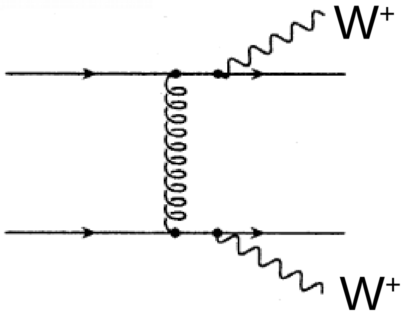
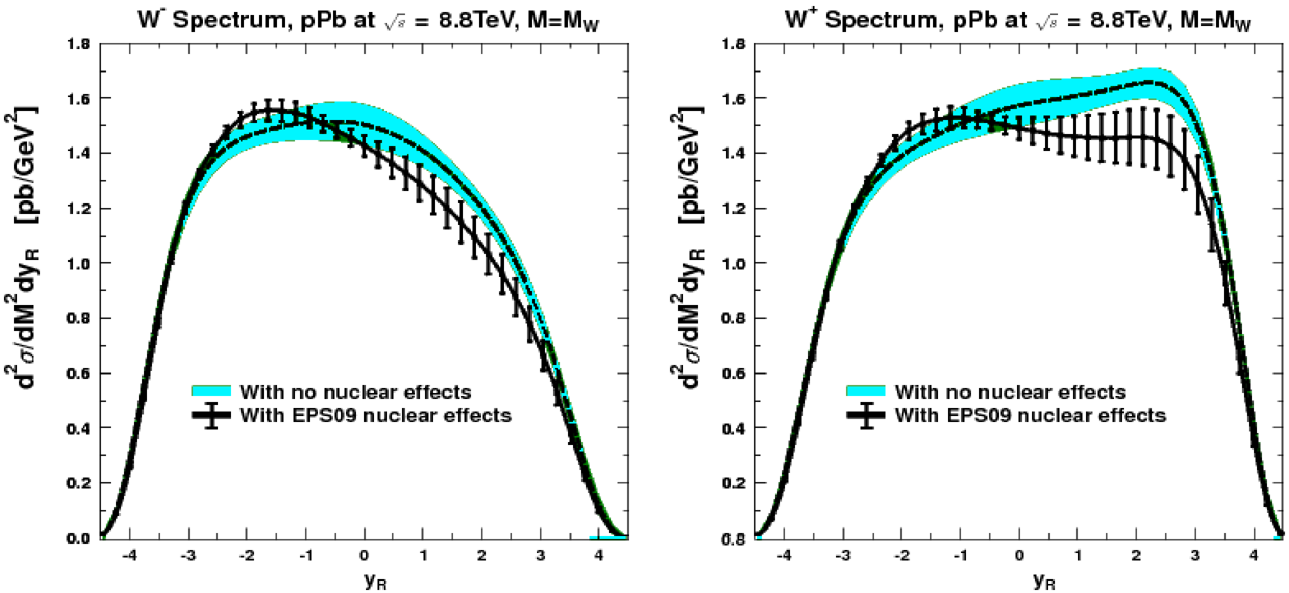




~10% effects due nuclear (anti)shadowing alone:



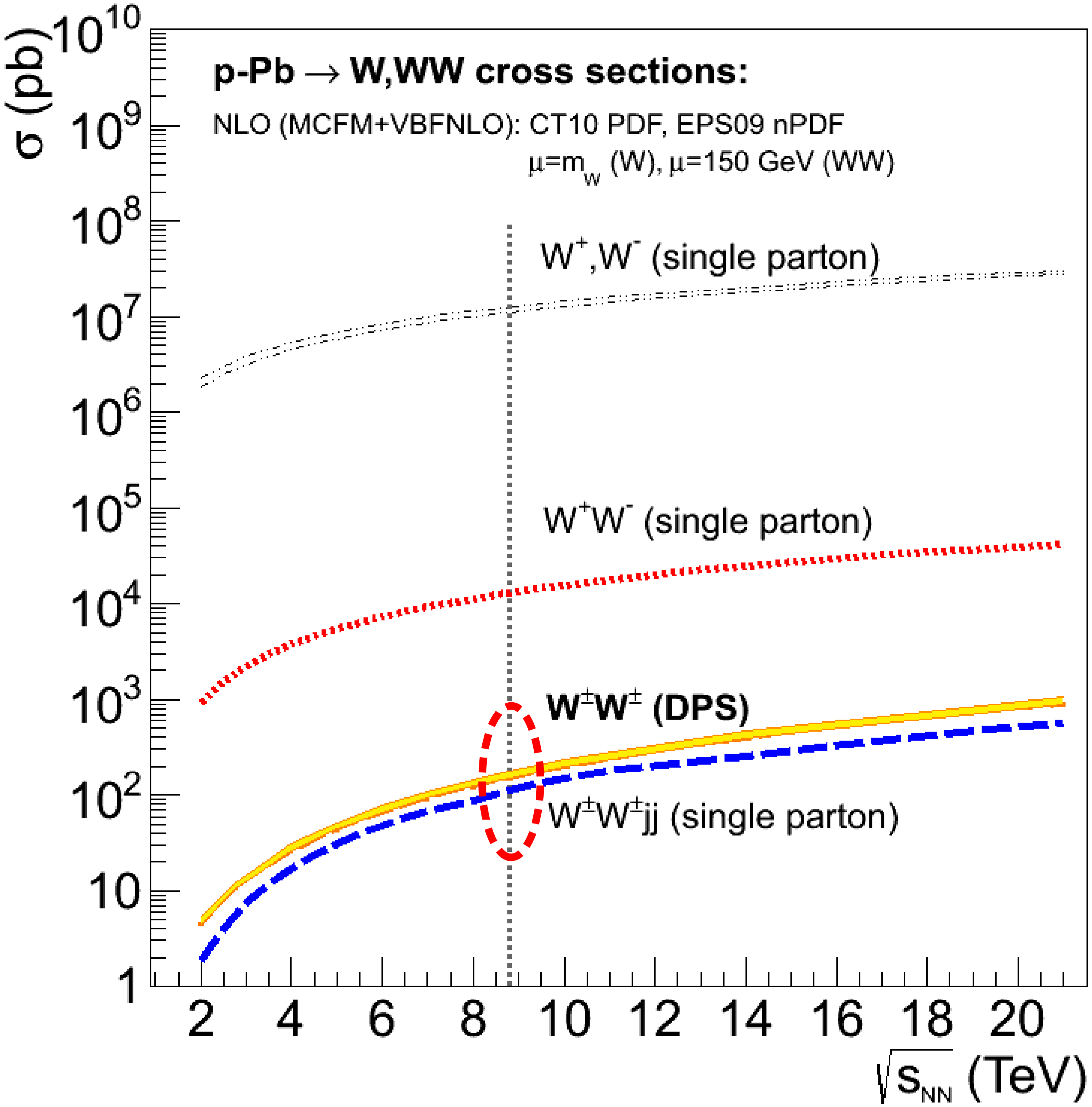
[Paukkunen&Salgado JHEP 1103 (2011) 071]

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

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)$\approx$150 pb

σ(WWjj)$\approx$100 pb

±18% uncertainties:

±15% for σ_{eff}

±10% for scales&PDFs

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

[DdE,Snigirev, PLB718 (2013)1395]

- Measurable final-states:
  - W's branching ratios:
    - BR($W\to l\nu$) ≈ 3 ×1/9, BR($W\to qq'$) ≈ 2/3
    - Both leptonic: 4 final-states ($\mu\mu$,ee,eμ,μe): $4\times(1/9)^2$ ≈ 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:

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

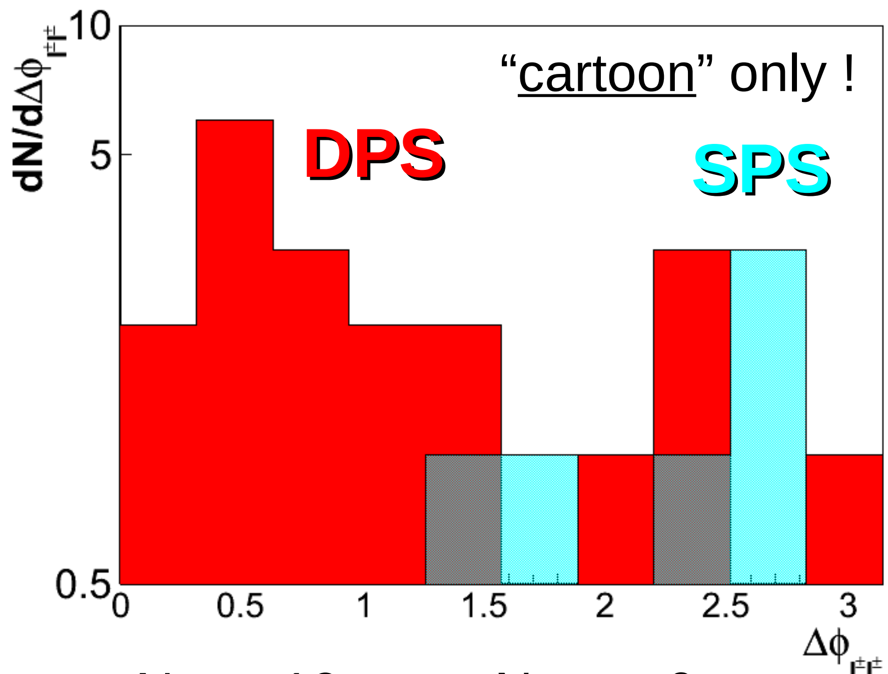
(factor ×6 more in 1 lepton + 1-jet channel)

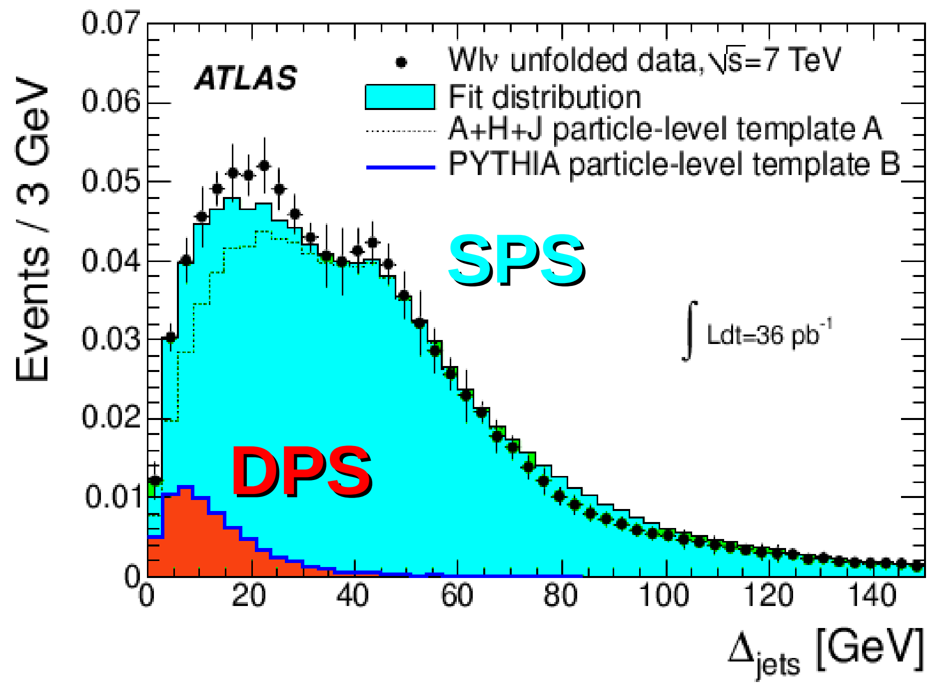
Results: p-Pb → W^+W^+, W^-W^- at 8.8 TeV

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

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

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



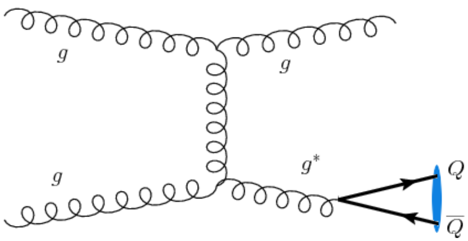


$N_{DPS} \approx 10$ evts $N_{SPS} \approx 6$ evts

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

Example: Pb-Pb → J/ψ J/ψ at 5.5 TeV

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

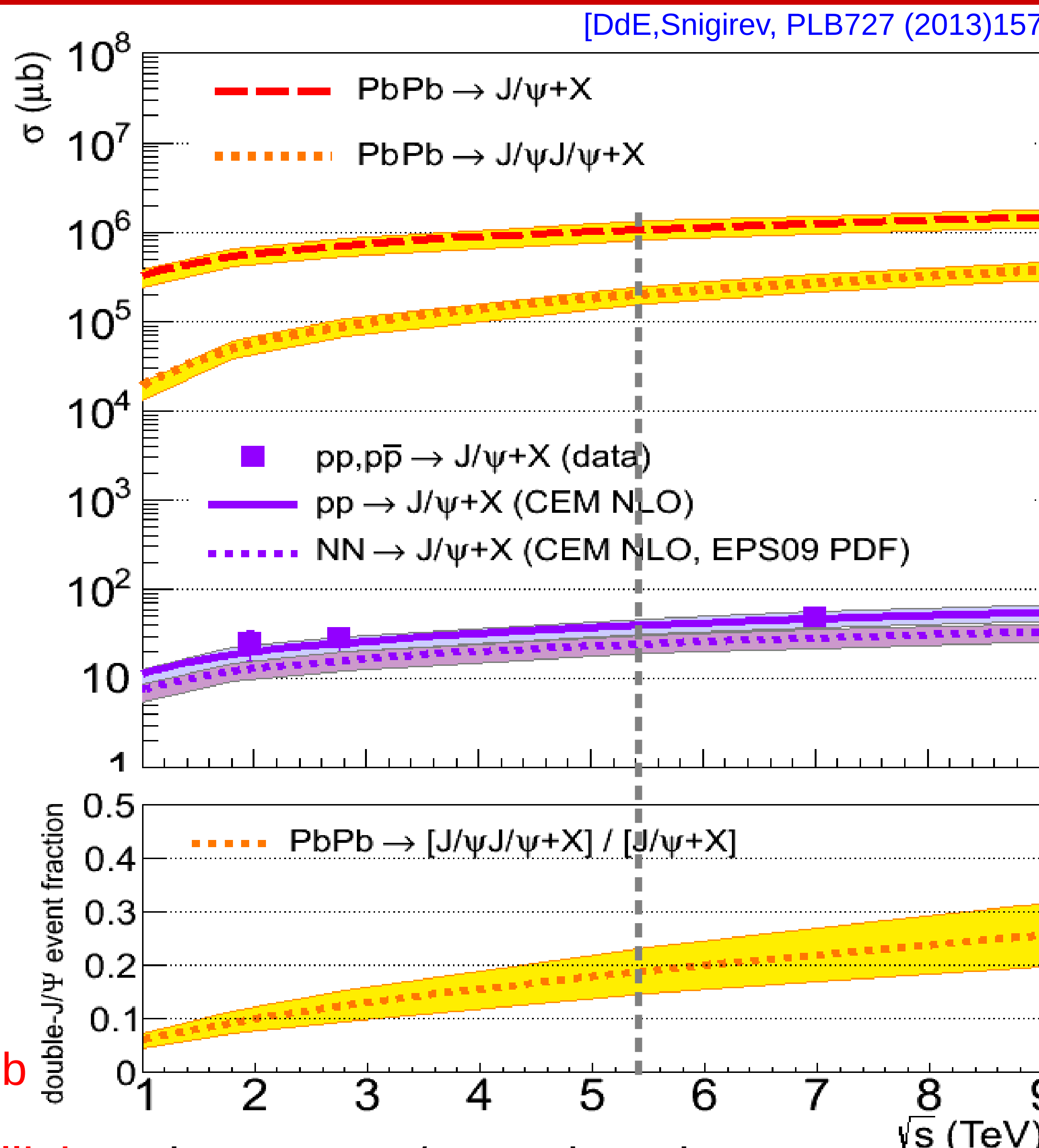


  - NLO accuracy.
  - Scales: $\mu_R = \mu_R = 1.5 \cdot m_c$
  - Good agreement with Tevatron&LHC data
  - EPS09 Pb nPDF

    20–35% shadowing x-section reduction

- At 5.5 TeV:

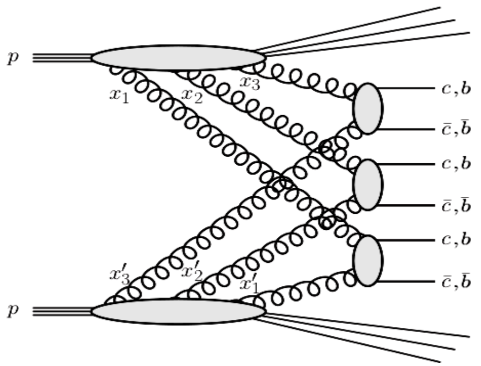
$\sigma^{DPS}(\text{Pb–Pb} \to J/\psi\, J/\psi\, X)$ =200±50 mb



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

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

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

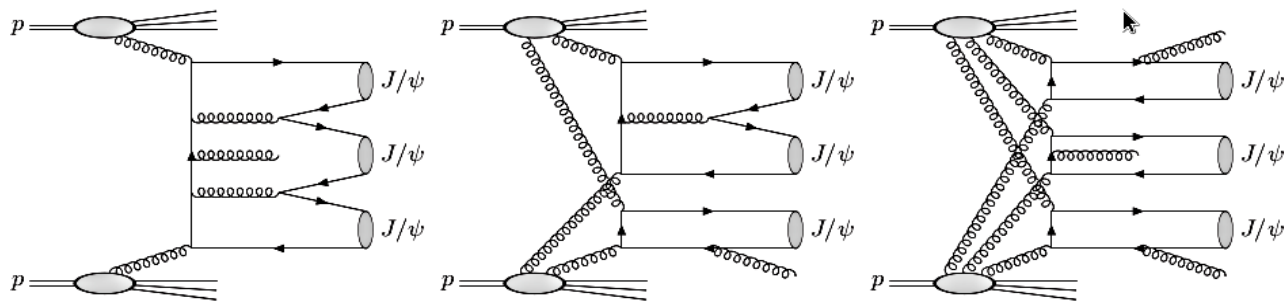
- By testing many proton overlaps/profiles (hard sphere, Gaussian, expo, dipole fit), we find a close relationship between $\sigma_{\rm eff,TPS}$ & $\sigma_{\rm eff}$:

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

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

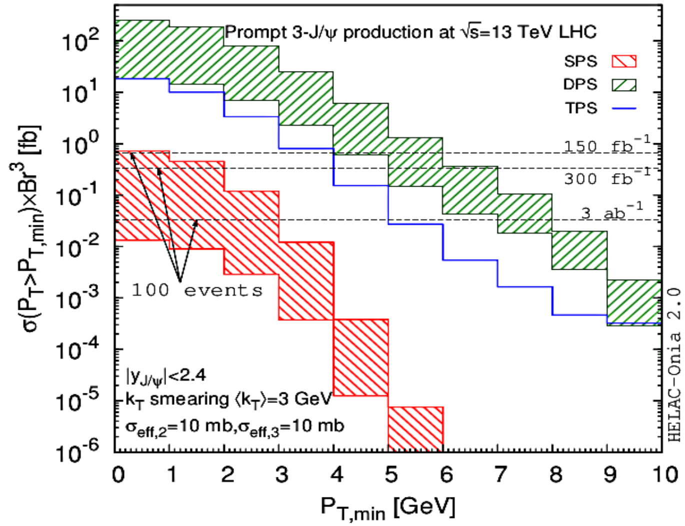
Triple-J/ψ from SPS production (p-p)

- H.-S. Shao et al. [arXiv:1902.04949, PRL 122(2019)192002] computed all triple-J/Ψ x-sections with SPS HELAC-ONIA plus our 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	$(190^{+501}_{-140}) \times \frac{10\text{ mb}}{\sigma_{\text{eff},2}}$	$(7.0^{+18}_{-5.1}) \times \frac{10\text{ mb}}{\sigma_{\text{eff},2}}$	$(50^{+140}_{-37}) \times \frac{10\text{ mb}}{\sigma_{\text{eff},2}}$
	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}!