

Double-parton scatterings in p-A & A-A collisions at the LHC

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(*) Most of the results based upon:

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

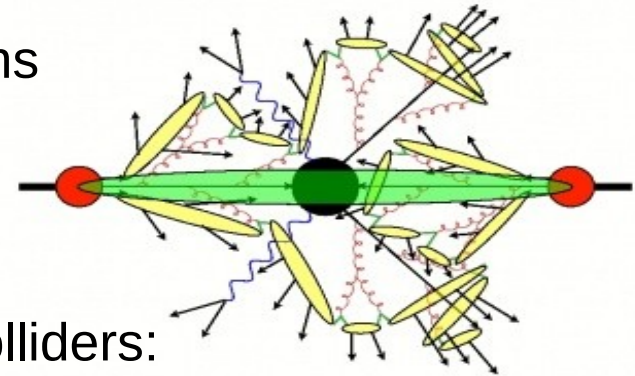
D.d'E & A.Snigirev, arXiv:1301.5845 [PLB 727 (2013) 157]

Outline

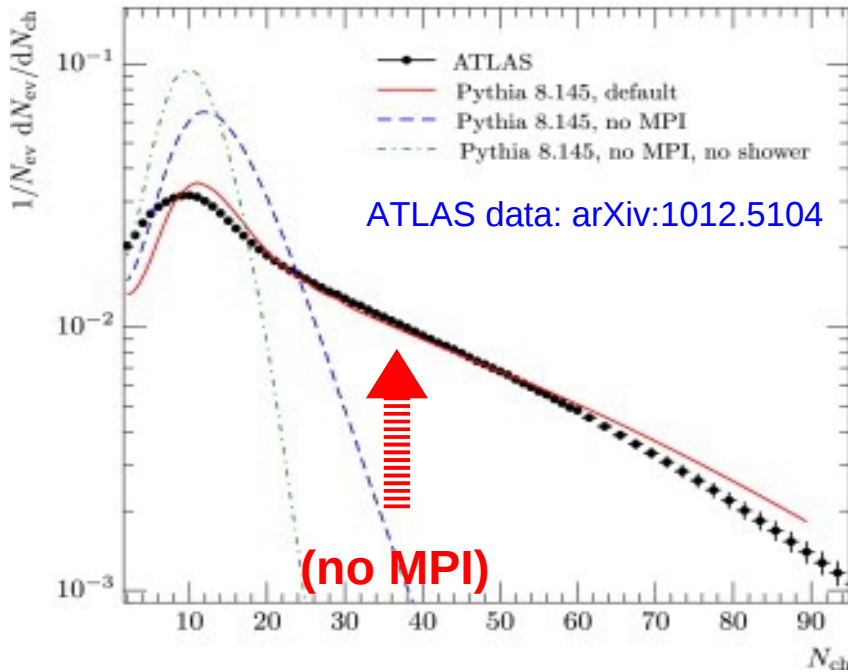
- Introduction – Double Parton Scattering in **p-p collisions**:
 - **Multi-parton interactions.**
 - Phenomenological “**pocket formula**” for the DPS x-sections
 - **Experimental** DPS searches
- **Double-Parton-Scattering in p-A collisions**:
 - DPS “pocket formula” x-section. **Enhancement** factor wrt. DPS(pp): $\times 3 \cdot A$
 - Case study: **Same-sign WW in p-Pb at the LHC**:
 $\sigma(ssWW, DPS) \approx 150 \text{ pb} > \sigma(ssWWjj, SPS) \approx 100 \text{ pb}$
 $N_{\text{visible}}(ssWW, DPS) \approx 10$ (leptonic decays) at 8.8 TeV
- **Double-Parton-Scattering in A-A collisions**:
 - DPS “pocket formula” x-section. **Enhancement** factor wrt. DPS(pp): $\times A^{3.3/5}$
 - Case study: **Double-J/φ in Pb-Pb at the LHC**:
20% (30%) of MB (central) Pb-Pb colls. produce 2 J/φ
 $N_{\text{visible}}(J/\phi J/\phi \rightarrow l^+ l^- l^+ l^-) \approx 240$ at 5.5 TeV

Multi-parton interactions at the LHC

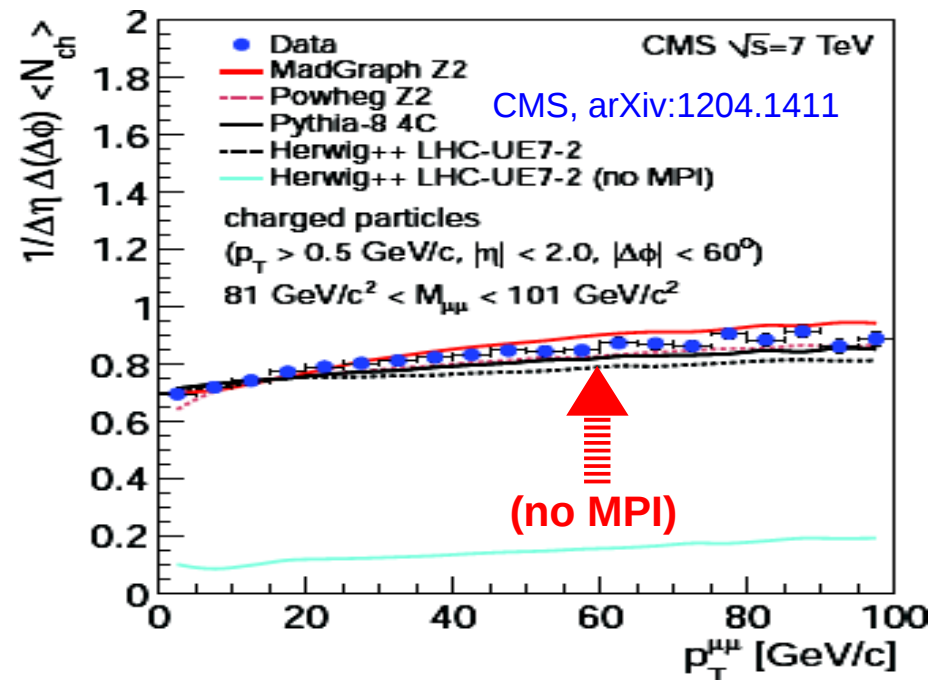
- MPI are intrinsic component of hadron collisions
(p,Pb) = non-pointlike objects with finite transverse size and increasingly larger gluon density.



- MPI O(1-3 GeV) clearly observed in hadron colliders:
~50% of total hadron production



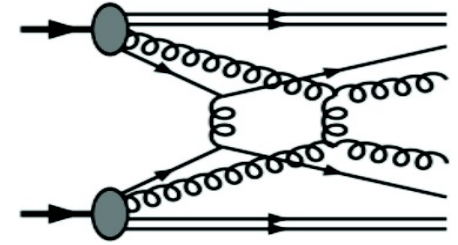
Underlying event in hard scatterings:



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

Double Parton Scattering x-sections (p-p)

- Hard DPS provides **direct info on transverse parton density-profile & correlations in proton:**
- **pQCD** factorized expression for **DPS** x-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 = $f(x, Q^2, \mathbf{b})$

- Assumption 1: **Factorization of transverse & longitudinal** components

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

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

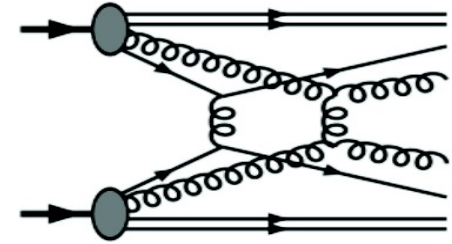
- Assumption 2: **Double-PDF = product of 2 single PDF (no correlations)**

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

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

Double Parton Scattering x-sections (p-p)

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



- pQCD factorized expression for **DPS x-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 = $f(x, Q^2, \mathbf{b})$

- **Final simplified form for DPS x-section**:

$$\sigma_{(hh' \rightarrow ab)}^{\text{DPS}} = \left(\frac{m}{2}\right) \frac{\sigma_{(hh' \rightarrow a)}^{\text{SPS}} \cdot \sigma_{(hh' \rightarrow b)}^{\text{SPS}}}{\sigma_{\text{eff}}} \quad \sigma_{\text{eff}} = \left[\int d^2 b \overbrace{t^2(\mathbf{b})}^{\text{p-p overlap function}} \right]^{-1} \approx 13 \pm 2 \text{ mb}$$

ISR, SppS
Tevatron

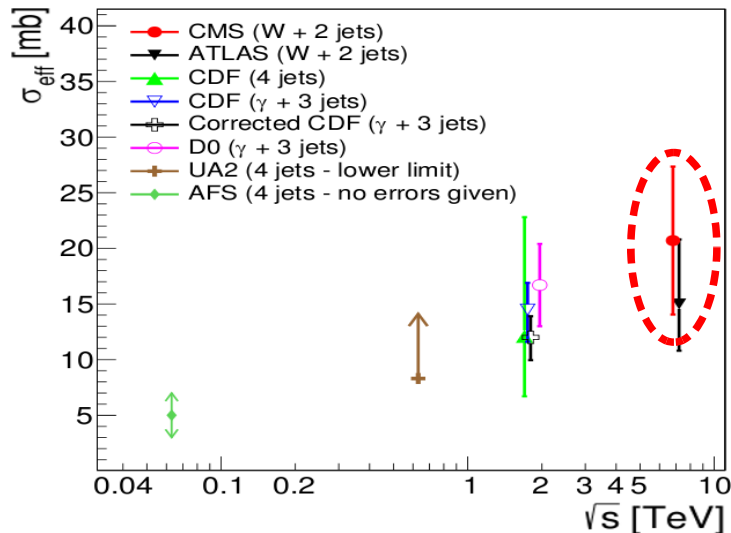
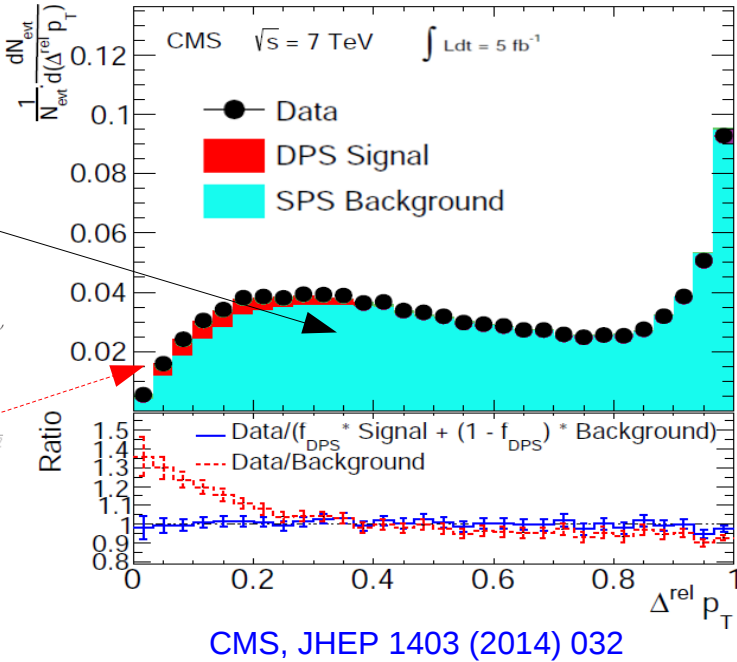
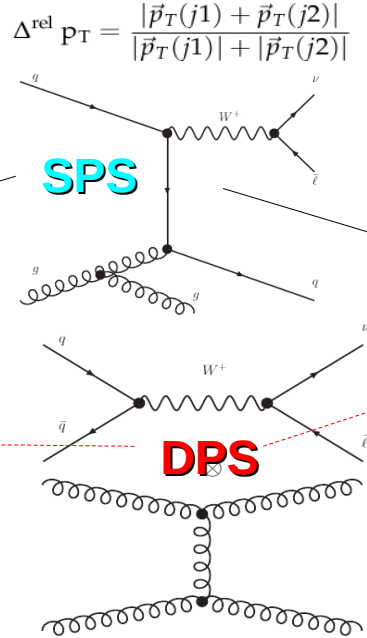
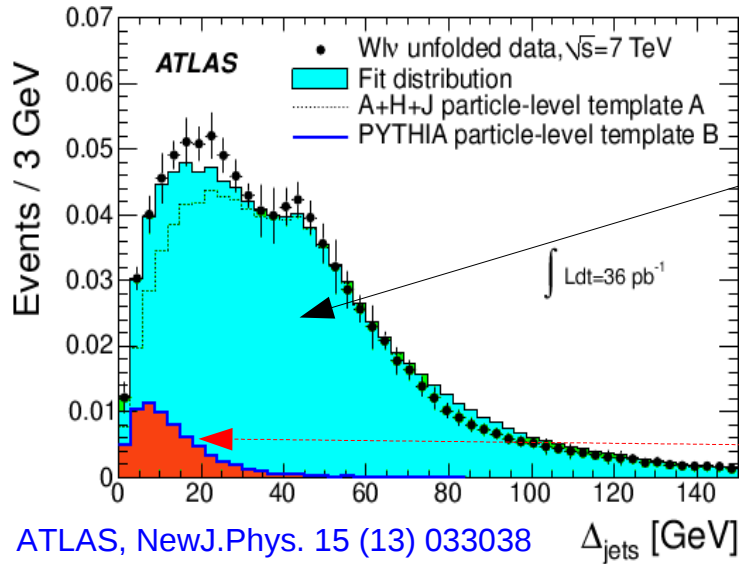
- Corresponding **parton transverse profile** of the proton (CDF'97):

Effective DPS radius:
 $r \sim 0.3 - 0.7 \text{ fm}$
smaller than e.m. one

Model for density	Form of density, dN/d^3r	Predictions rms r	σ_{eff}	Measurements Scale (fm)
Solid sphere	Constant, $r < r_p$	$\sqrt{3/5} r_p$	~14.5 mb	$r_p = 0.73$
Gaussian	$e^{-r^2/2\Sigma^2}$	$\sqrt{3}\Sigma$		$\Sigma = 0.34$
Exponential	$e^{-r/\lambda}$	$\sqrt{12}\lambda$		$\lambda = 0.20$
Fermi, $\lambda/r_0 = 0.2$	$(e^{(r-r_0)/\lambda} + 1)^{-1}$	$1.07r_0$		$r_0 = 0.56$

DPS searches at LHC: $p-p \rightarrow W^+ + 2j$

■ **Small signal in $W+2j$ events:** Via di-jet p_T asymmetry (~ 0 in DPS)



■ **Uncertainties on DPS extraction from:**

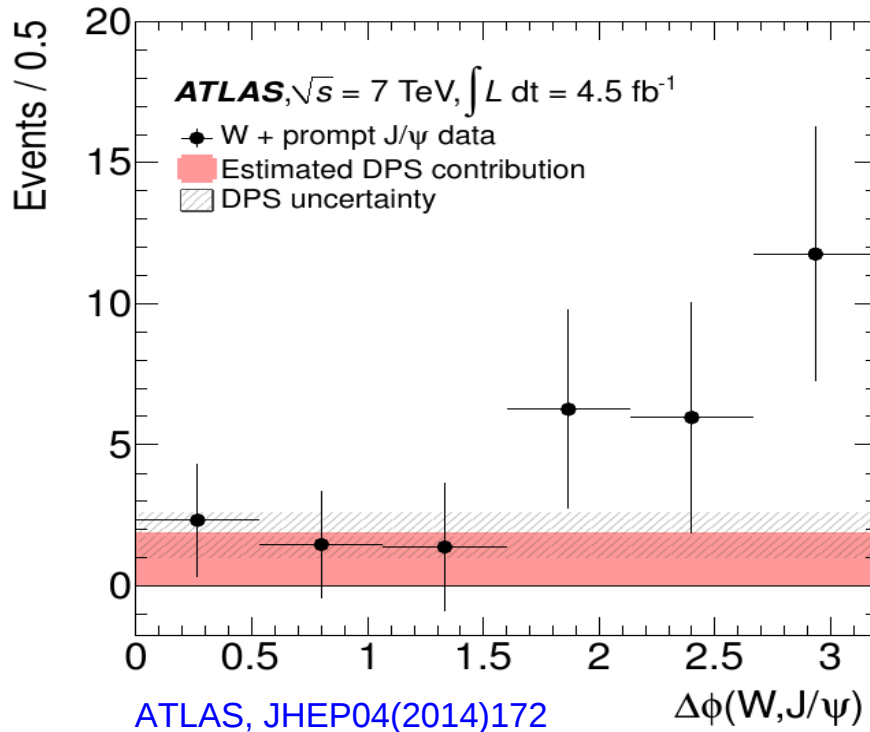
- Higher-order SPS contributions,
- (technical) matching between ME hard jets & MPI jets

propagate into large uncertainty on σ_{eff}

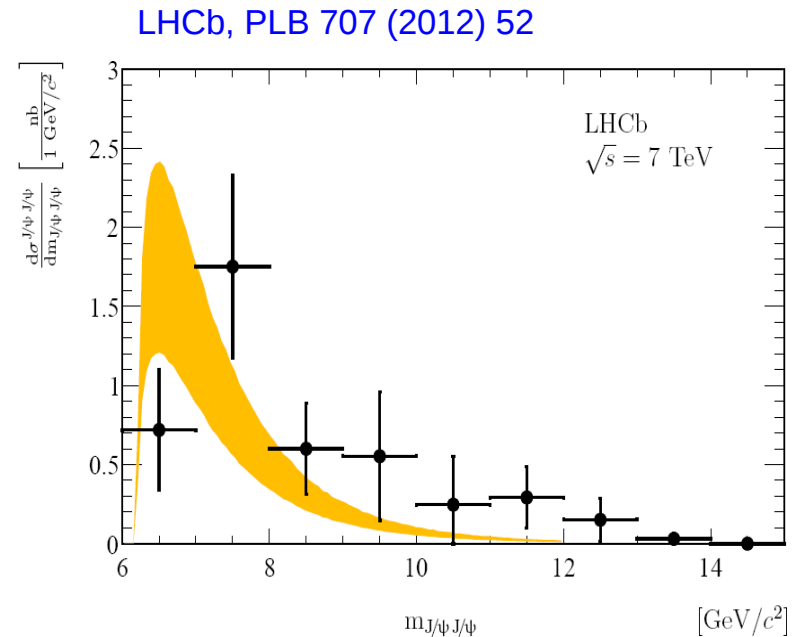
$$\sigma_{\text{eff}} = 15 - 20 \text{ mb}$$

DPS searches at LHC: $p\text{-}p \rightarrow W^+ + J/\psi, J/\psi J/\psi$

- Strong? signal in $W + J/\psi$ events:
Azimuthal W & J/ψ correlation



- Less clear in double- J/ψ production:



$$\sigma_{J/\psi J/\psi} = 5.1 \pm 1.0 \pm 1.1 \text{ nb}$$

$$\sigma_{\text{SPS}}^{J/\psi J/\psi} + \sigma_{\text{DPS}}^{J/\psi J/\psi} \sim 4 \text{ nb} + 2 \text{ nb} = 6 \text{ nb}$$

- Current TH uncertainties prevent from obtaining precise measurements of DPS fraction and σ_{eff} parameter at LHC.

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

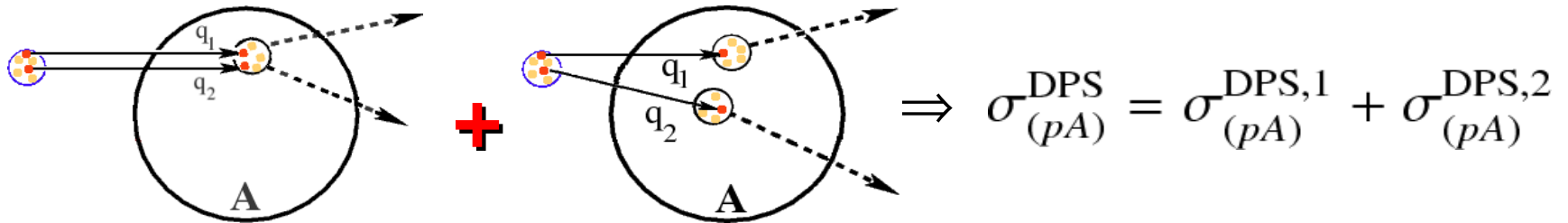
Double Parton Scatterings in p-Pb at the LHC

Double Parton Scattering x-sections (p-Pb)

[DdE, Snigirev, arXiv:1211.0197]

[Treleani, Strikman, ...]

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



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

p-A overlap function

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

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

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

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

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

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

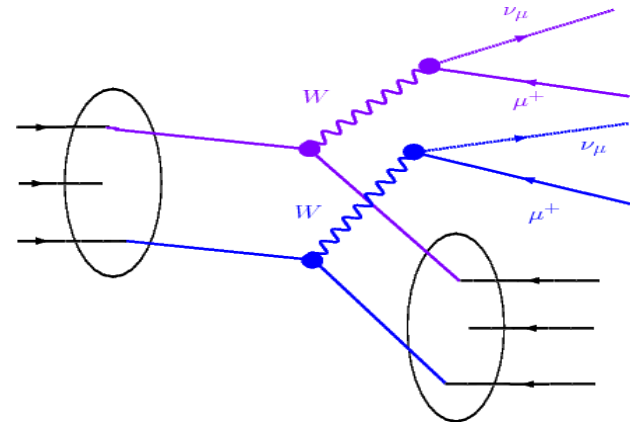
- DPS processes are large and can be unambiguously observed in p-A.

- Pb transverse density better known than proton. Determine $\sigma_{\text{eff,pp}}$?

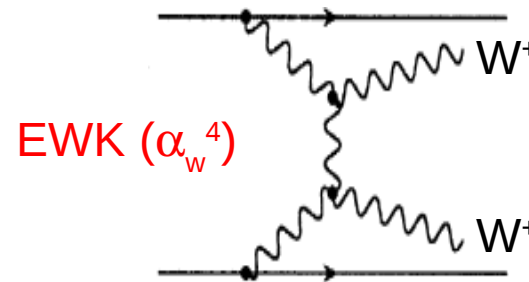
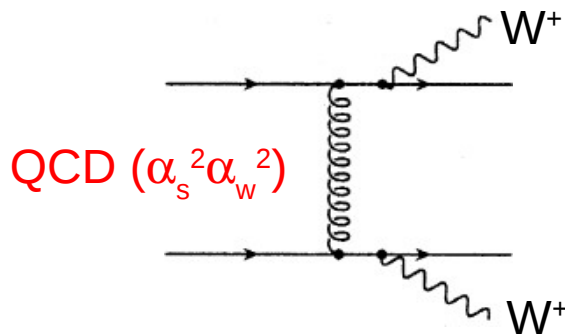
DPS “golden channel”: $p-p \rightarrow W^+W^+, W^-W^-$

- Same-sign W - W production from 2 independent hard scatterings is an excellent 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:



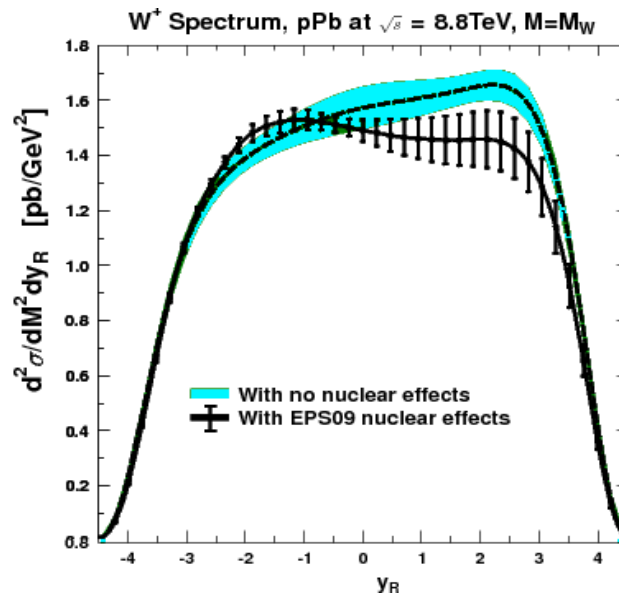
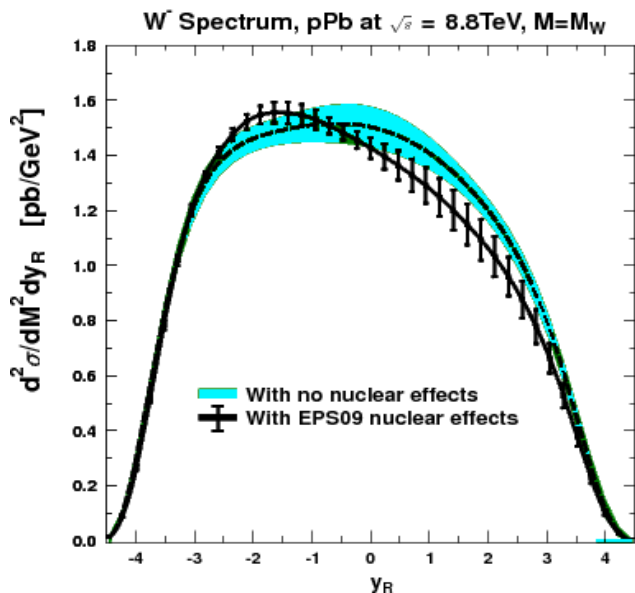
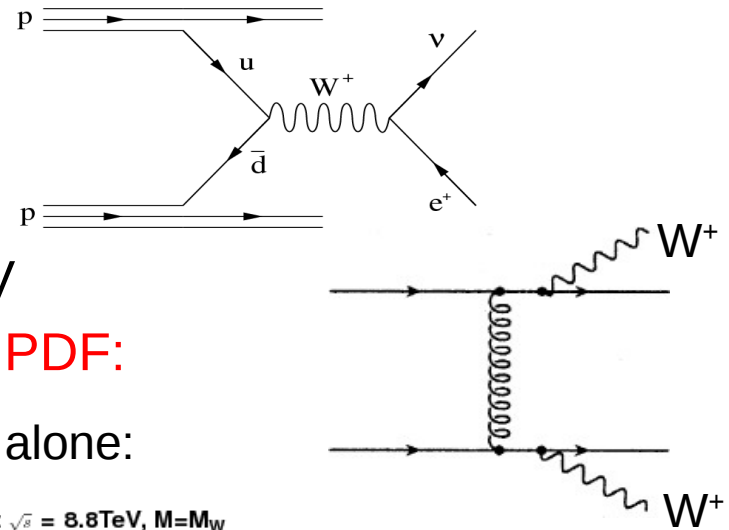
- $\sigma(WW, DPS) \sim 1/3 \sigma(WWjj, SPS)$, but SPS background reducible by more than x20 applying jet cuts.

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

[DdE, Snigirev, arXiv:1211.0197]

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

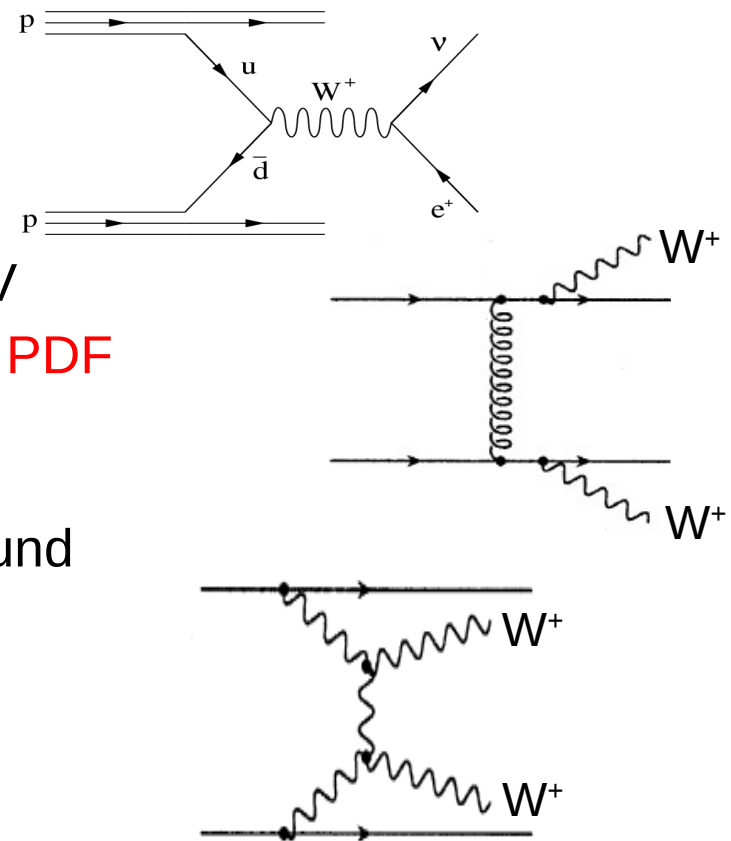
[Paukkunen&Salgado JHEP 1103 (2011) 071]

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



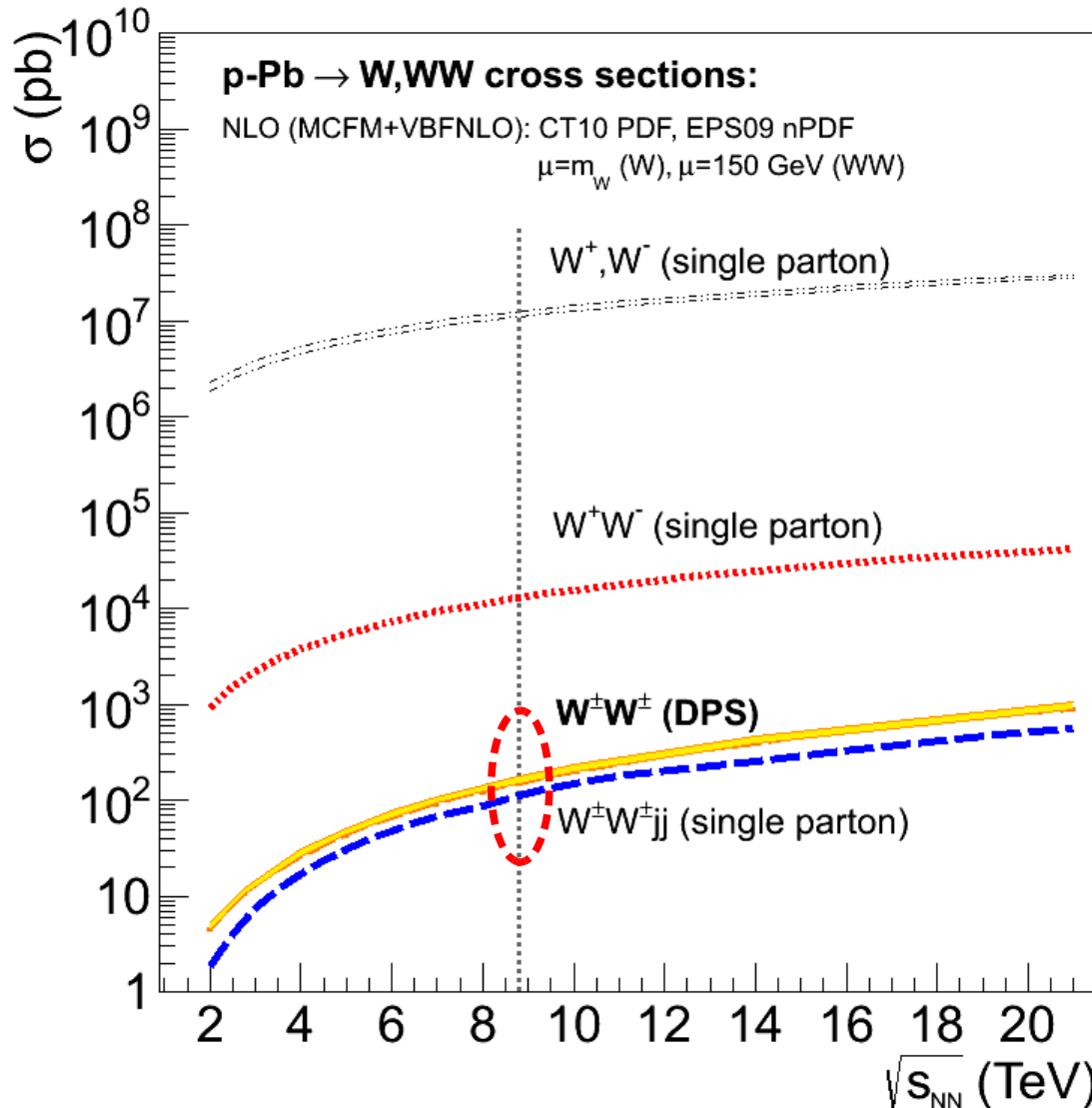
x-sections in pb (signal & background):

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

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

[DdE, Snigirev, arXiv:1211.0197]

- Cross sections for all relevant SPS and DPS processes vs \sqrt{s} :



p-Pb @ 8.8 TeV:

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

$\sigma(WWjj) \approx 100$ pb

$\pm 18\%$ uncertainties:

$\pm 15\%$ for σ_{eff}

$\pm 10\%$ for scales&PDFs

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

[DdE, Snigirev, arXiv:1211.0197]

- Measurable final-states:
 - ▶ **W's branching ratios:**
 - BR($W \rightarrow lv$) $\sim 3 \times 1/9$, BR($W \rightarrow qq$) $\sim 2/3$
 - **Both leptonic:** 4 final-states ($\mu\mu, ee, e\mu, \mu e$): $(4/9)^2 \sim 1/20, 1/16$ (+ τ)
[1 leptonic + 1 hadronic (jet-charge): $(2/9 \times 4/3)^2 \sim 0.3$]
 - ▶ **Typical ATLAS/CMS acceptances & efficiencies:**
 - Leptons: $|y| < 2.5, p_T > 15$ GeV $\Rightarrow \epsilon_{WW} \sim 40\%$

- LHC p-Pb **luminosities** (note: very small pileup !):

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

- **Expected (purely leptonic) rates** including yield losses & luminosity:

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

(factor ~ 10 more in 1 lepton + 1-jet channel ?)

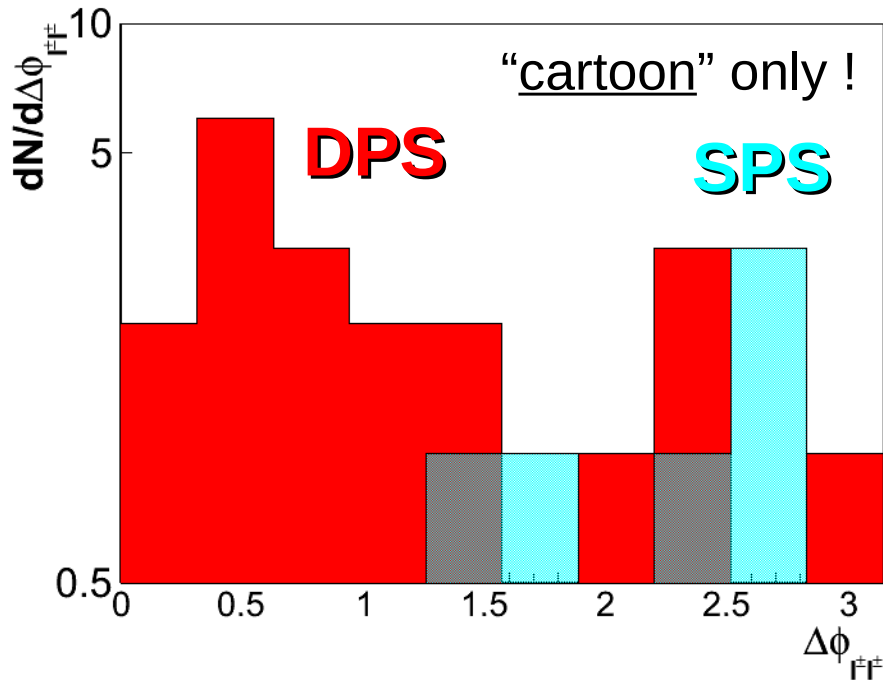
Results: $p\text{-Pb} \rightarrow W^+W^+, W^-W^-$ at 8.8 TeV

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

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

Same-sign leptons

azimuthal separation:



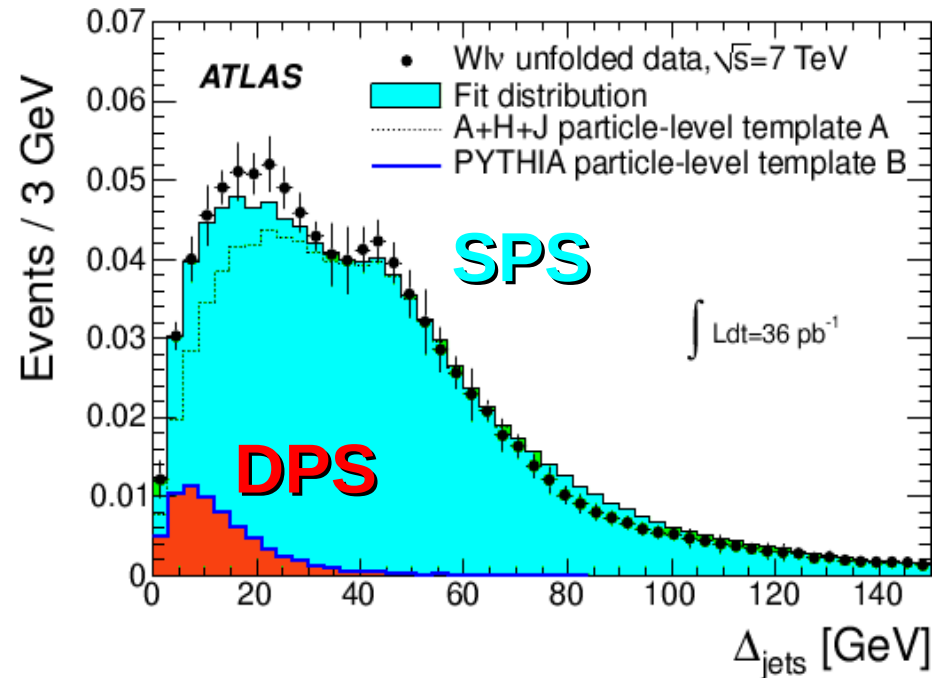
$N(\text{DPS}) \approx 10 \text{ evts}$ $N(\text{SPS}) \approx 6 \text{ evts}$

Other reducible bckgds ($WZ, Z^{(*)}Z^{(*)}, B^0B^0$)
would need to be considered

Compare to:

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

dijet azimuthal separation

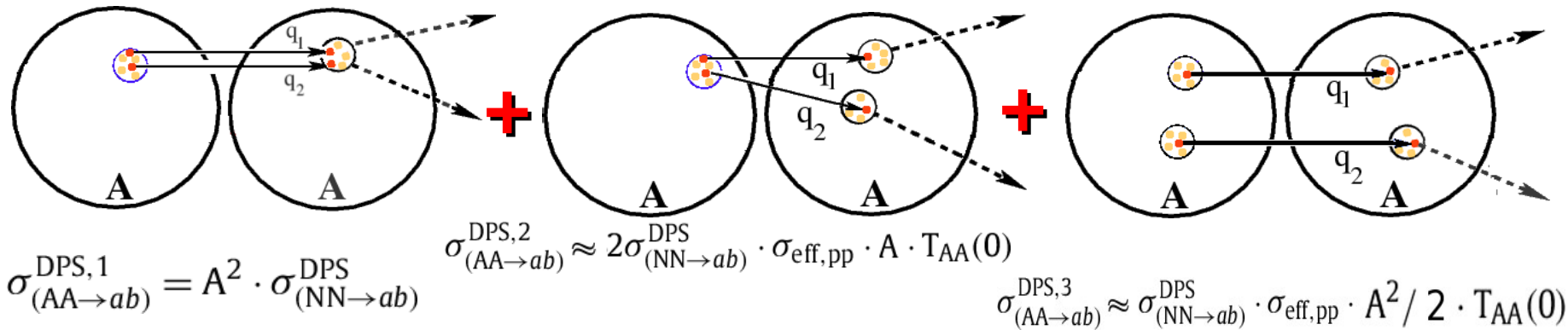


Double Parton Scatterings in Pb-Pb at the LHC

Double Parton Scattering x-sections (Pb-Pb)

[DdE, Snigirev, arXiv:1301.5845]

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



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

Factorized expression for DPS A-A x-section:

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

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

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

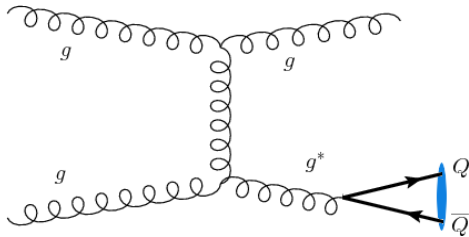
Strong centrality dependence:

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

Case study: Pb-Pb \rightarrow J/ ψ J/ ψ at 5.5 TeV

[DdE, Snigirev, arXiv:1301.5845]

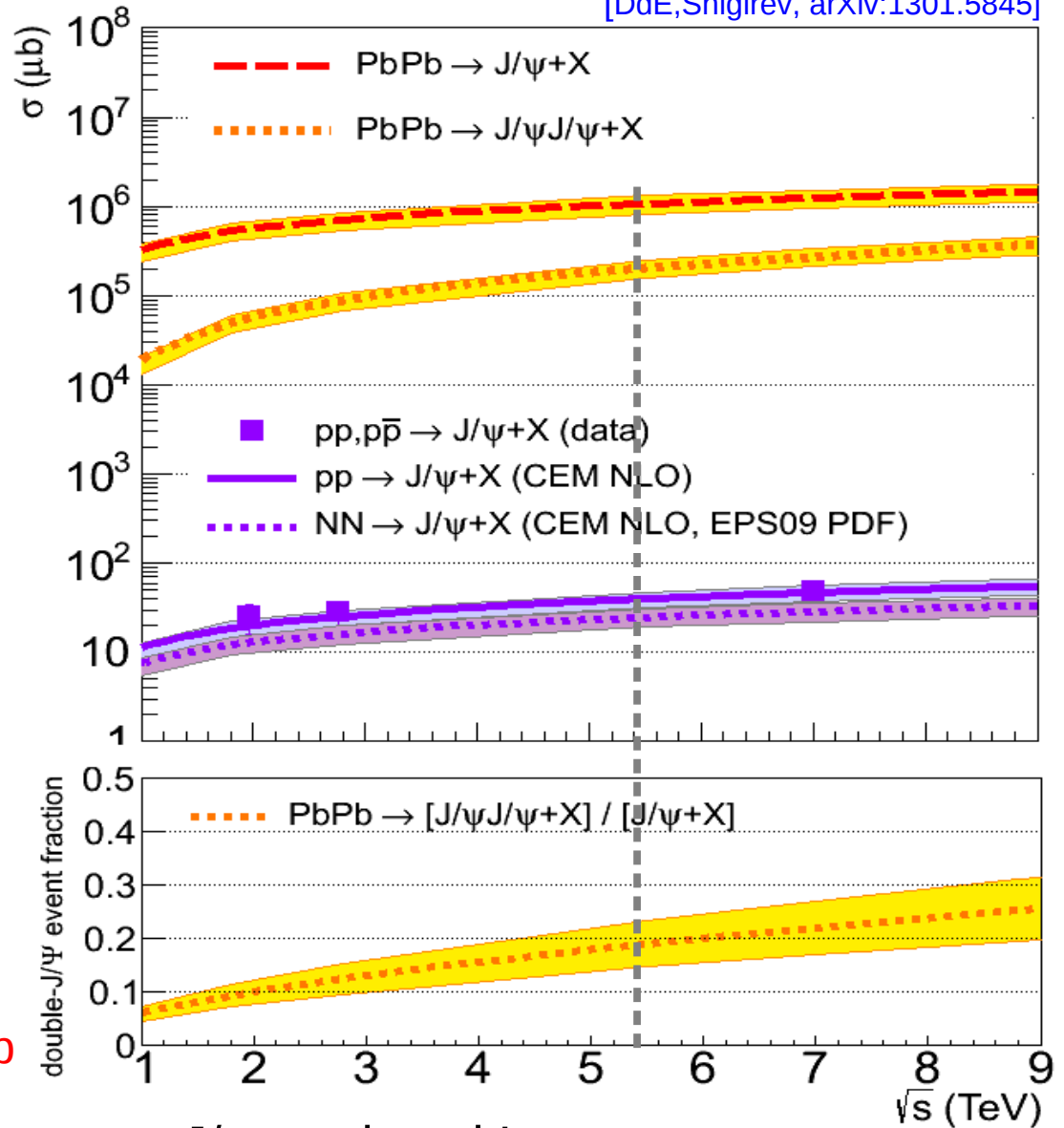
FONLL+CEM (R.Vogt): Single-parton J/ ψ



- 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:

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



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

Results: Pb-Pb \rightarrow J/ ψ J/ ψ at 5.5 TeV

[DdE, Snigirev, arXiv:1301.5845]

■ Visible rates:

- ▶ Reduced x-sections per unit-y: $d\sigma_{J/\psi}/dy \approx \sigma_{J/\psi}/8$
- ▶ 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⁻¹ luminosity:

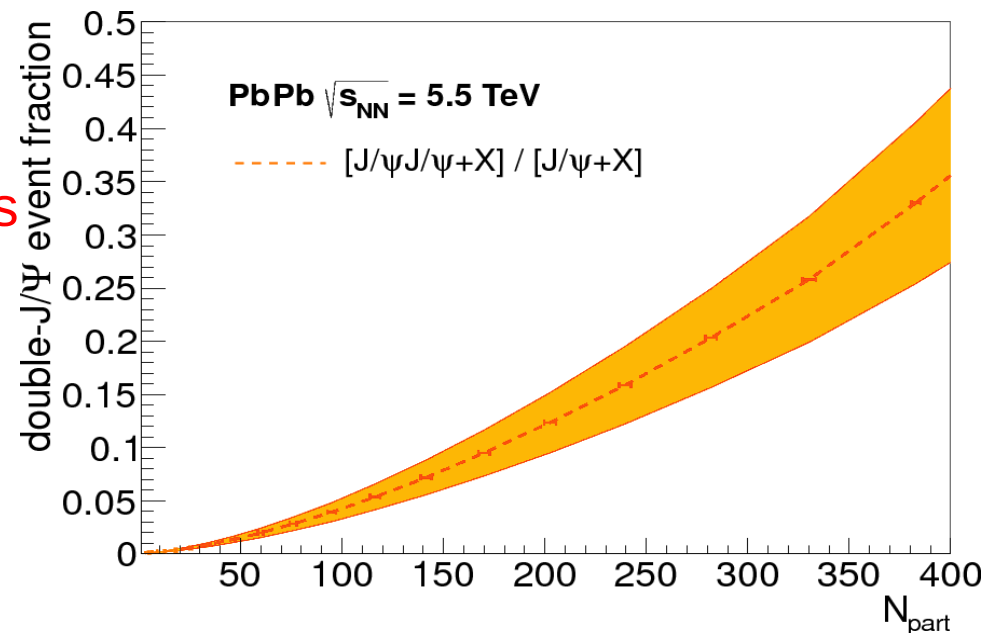
$$\mathcal{N} = \sigma_{\text{Pb-Pb} \rightarrow J/\psi J/\psi}^{\text{DPS}} / (\varepsilon \cdot \mathcal{L}_{\text{int}}) \approx 240 \text{ double-J}/\psi \text{ per year}$$

(factor 2 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.



Other DPS p-Pb & Pb-Pb x-sections

- Expected rates for DPS processes involving J/ψ and/or weak bosons (leptonic final states, after acc,*eff. cuts):

		$J/\psi J/\psi$	$J/\psi+W$	$J/\psi+Z$	ss WW
Pb-Pb 5.5 TeV	σ^{DPS}	200 mb	500 μb	330 μb	630 nb
	$N^{\text{DPS}}(1 \text{ nb}^{-1})$	~240	~80	~10	~20
p-Pb 8.8 TeV	σ^{DPS}	45 μb	120 nb	70 nb	140 pb
	$N^{\text{DPS}}(1 \text{ pb}^{-1})$	~60	~15	~2	~5

(Double-Y, and Y+W should be also visible, but DPS ZZ not)

- Many double hard scatterings processes visible in p-Pb & Pb-Pb !
- Valuable information on partonic transverse size of the proton (pA) & partonic correlations in the nucleus (AA).

Summary

- MPI are crucial to understand p-p collisions at LHC: MB, UE ...
- MPI \Rightarrow Double hard parton scatterings (pQCD framework available)

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

All details on proton **transverse** parton density/correlations encoded into σ_{eff} parameter

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

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

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

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

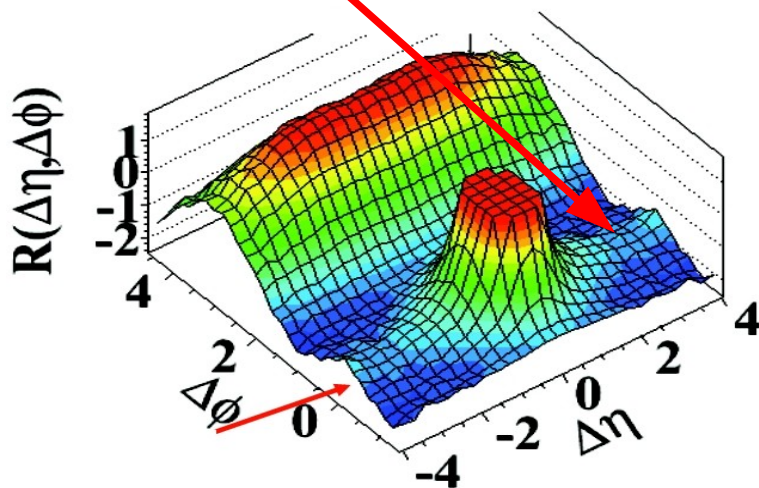
- DPS in p-A can help **determine** $\sigma_{\text{eff,pp}}$
 p-Pb $\rightarrow W^+W^+$, W^-W^- , NLO+nuclear PDFs for signal & bckgds.
 $\sigma(\text{same-sign WW,DPS}) \approx 150 \text{ pb} \rightarrow 10 \text{ counts/year (leptonic decay)}$
- DPS in A-A are clearly dominated by binary-scaling term.
 Pb-Pb $\rightarrow J/\psi J/\psi$, NLO+nuclear PDFs.
 $d\sigma(J/\psi J/\psi, \text{DPS})/dy \approx 200 \text{ mb} \rightarrow 240 \text{ counts/year } (\mu\mu \text{ decay})$

Backup slides

MPI evidence (LHC, p-p “central”): “ridge” ?

- Observation of long-range (over $\Delta\eta \sim 8$!) near-side hadron correlations: “Ridge” in “central” (high multiplicity) p-p collisions

(d) $N > 110$, $1.0 \text{ GeV}/c < p_{\perp} < 3.0 \text{ GeV}/c$

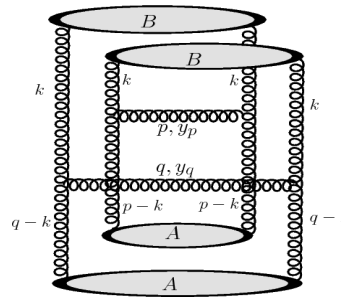


[CMS, JHEP 1009 (2010) 091]

- Interpretations:

- Correlated gluons in initial-state ?

$$|k_{\perp}| \sim |p_{\perp} - k_{\perp}| \sim |q_{\perp} \pm k_{\perp}| \sim Q_s$$



Multi-parton-interactions:

α_s^8 enhancement of near-side diagram

[R.Venugopalan et al.]

- Final-state collective parton-flow ?

PYTHIA + $\beta_T=0.5$ generates structure

- Remains an intriguingly large effect without clearcut explanation currently
- Enhanced ridge also observed in p-Pb at 5 TeV

Multi-parton interactions in p-p

- pQCD (mini)jet production x-section is **bigger** than total inel p-p x-section for $p_{Tmin} \sim 5-7$ GeV at the LHC !

$$\sigma_{hard}(p_{\perp min}) = \int_{p_{\perp min}^2}^{s/4} \frac{d\sigma}{dp_{\perp}^2} dp_{\perp}^2$$

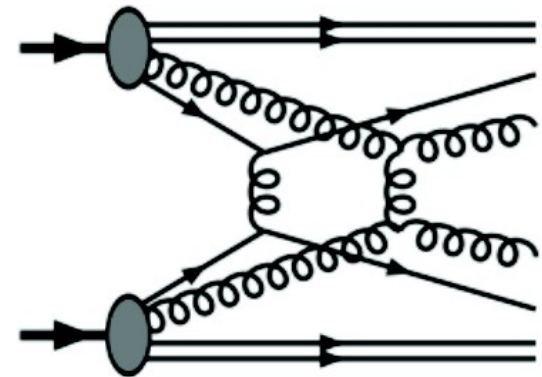
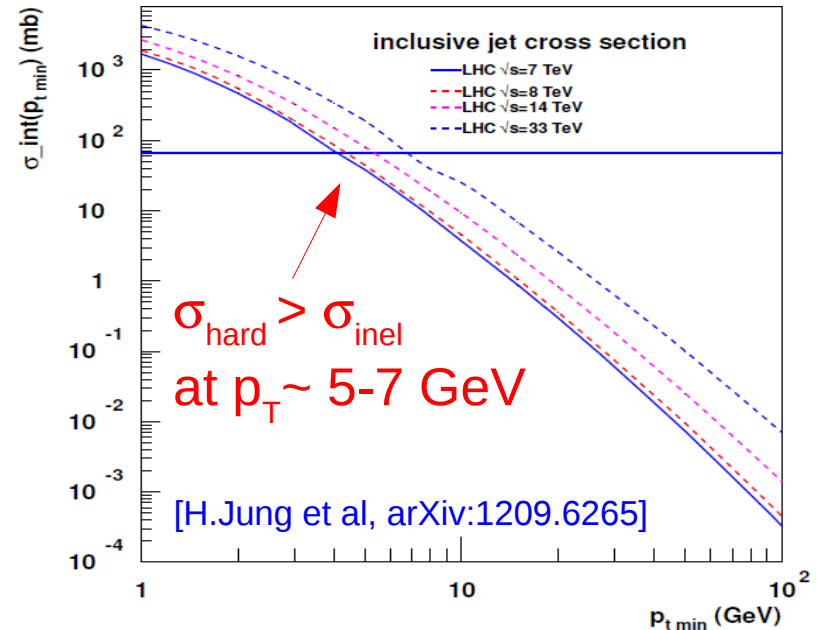
... Why this happens ?

- Very high gluon densities at small-x.
- **Solution (2): Multi-parton interactions**

Interpret $\langle n \rangle = \frac{\sigma_{hard}(p_{\perp min})}{\sigma_{inel}}$

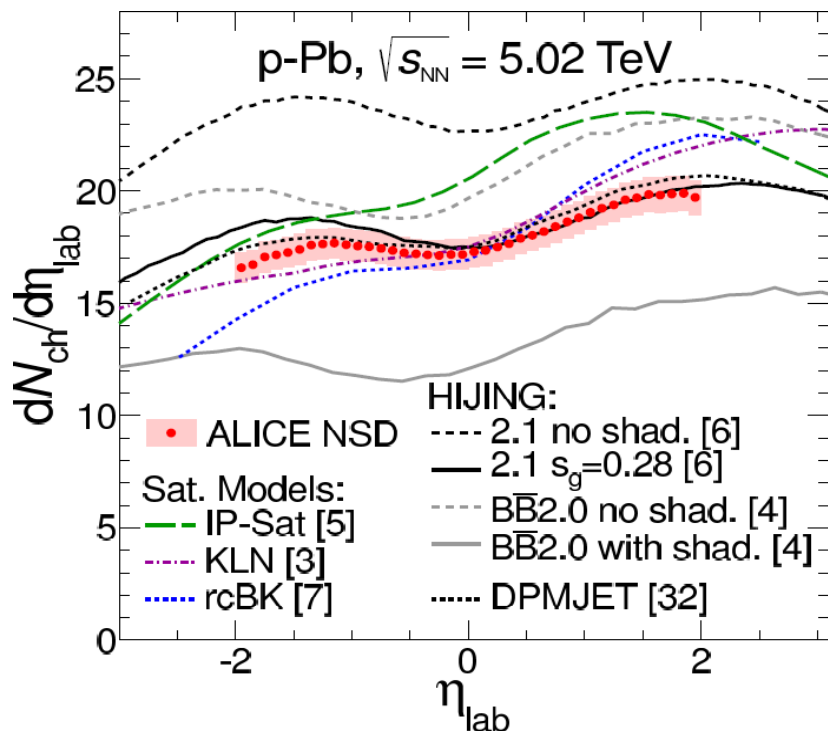
= average number of parton-parton scatterings above $p_{\perp min}$ in an event

- PYTHIA, HERWIG include them via **transverse parton density profile**.



MPI evidence (LHC, p-Pb): inclusive hadron prod.

[ALICE, arXiv:1210.3615]



- Center-of-mass dependence:
Power-law exponent: $n \sim 0.10$

Naive expectations:
 Gluon sat: $n \sim 0.11-0.14$
 Pure RFT: $n \sim 0.10$
 Minijets: $n \sim 0.15$

- Inclusive hadron production in p-Pb at 5.02 TeV:

Models need shadowing/
saturation of Pb gluon PDF
to reproduce the data

