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DPS cross sections in proton-nucleus and nucleus-nucleus collisions

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PARTON MODEL

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Elastic scattering : electron — proton

——–> proton (hadron) is NOT point-like

Deep inelastic scattering : electron — proton

——–> proton (hadron) consists of point-like particles-partons

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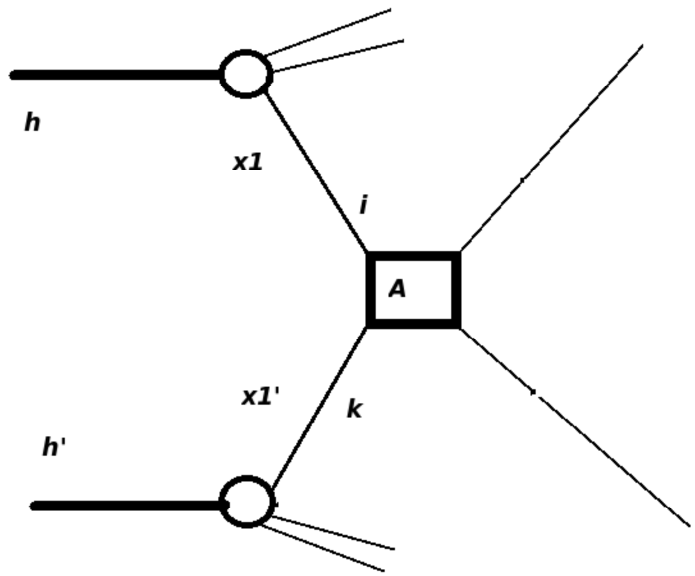
$$\text{Cross section (hadron)} \quad = \quad \Sigma \text{ cross section (parton)} \times \text{weights}$$

Weights — probabilities in the system of infinite momentum

(Bjorken, Feynman)

IN QCD weights depend on Q of hard processes
(SCALING VIOLATION, improved PM)



$$\boldsymbol{\sigma}^A_{\mathrm{SPS}} = \sum_{i,k} \int D^i_h(x_1; Q_1^2)\hat{\boldsymbol{\sigma}}^A_{ik}(x_1, x_1^{'}) D^k_{h'}(x_1^{'}; Q_1^2) dx_1 dx_1^{'}$$

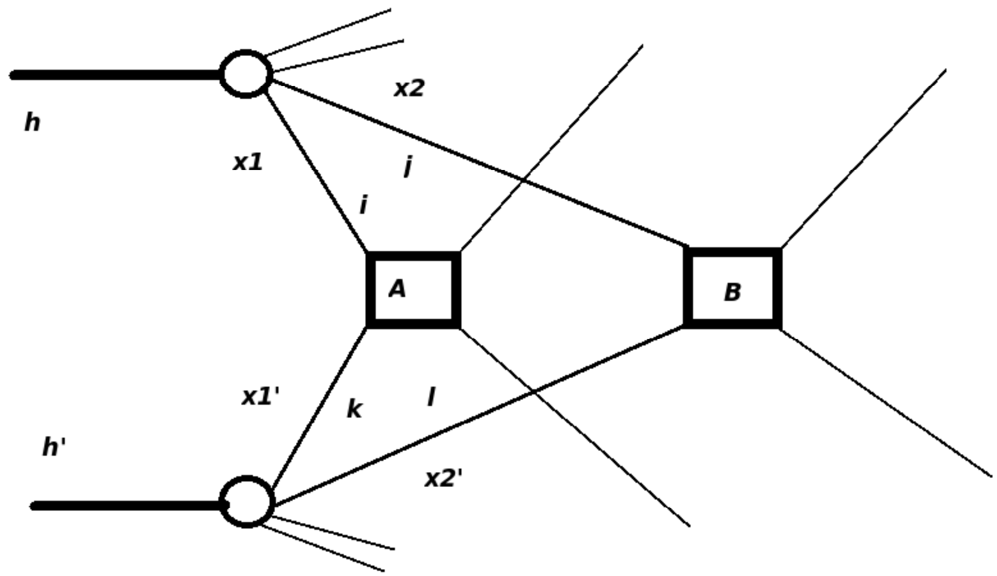
Scaling violation (dependence on Q) from
DGLAP (*Dokshitzer-Gribov-Lipatov-Altarelli-Parisi*) equations:

$$\frac{dD_i^j(x,t)}{dt} = \sum_{j'} \int_x^1 \frac{dx'}{x'} D_i^{j'}(x',t) P_{j' \to j}\left(\frac{x}{x'}\right)$$

$$t = \frac{1}{2\pi b} \ln\left[1 + \frac{g^2(\mu^2)}{4\pi} b \ln\left(\frac{Q^2}{\mu^2}\right)\right] = \frac{1}{2\pi b} \ln\left[\frac{\ln\left(\frac{Q^2}{\Lambda^2_{QCD}}\right)}{\ln\left(\frac{\mu^2}{\Lambda^2_{QCD}}\right)}\right], \quad b = \frac{33 - 2n_f}{12\pi},$$

where $g(\mu^2)$ is the running coupling constant at the reference scale μ^2,
n_f is the number of active flavours,
Λ_{QCD} is the dimensional QCD parameter.

It is possible (BUT very rarely): hard double parton scattering (subprocesses *A* and *B*)



The inclusive cross section of a double parton scattering process in a hadron collision is written in the following form (with only the assumption of factorization of the two hard parton subprocesses *A* and *B*)
(Paver, Treleani,..., Blok,...., Diehl,...).

$$\boldsymbol{\sigma^{AB}_{DPS} = \frac{m}{2} \sum_{i,j,k,l} \int \Gamma_{ij}(x_1, x_2; \mathrm{b}_1, \mathrm{b}_2; Q_1^2, Q_2^2) \hat{\sigma}^A_{ik}(x_1, x_1', Q_1^2) \hat{\sigma}^B_{jl}(x_2, x_2', Q_2^2)}$$

$$\boldsymbol{\times \Gamma_{kl}(x_1', x_2'; \mathrm{b}_1 - \mathrm{b}, \mathrm{b}_2 - \mathrm{b}; Q_1^2, Q_2^2) dx_1 dx_2 dx_1' dx_2' d^2b_1 d^2b_2 d^2b,}$$

where $\mathbf{b}$ is the impact parameter — the distance between centers of colliding (e.g., the beam and the target) hadrons in transverse plane.

$\Gamma_{ij}(x_1, x_2; \mathbf{b_1}, \mathbf{b_2}; Q_1^2, Q_2^2)$ are the double parton distribution functions, which depend on the longitudinal momentum fractions x_1 and x_2, and on the transverse position $\mathbf{b_1}$ and $\mathbf{b_2}$ of the two parton undergoing hard processes A and B at the scales Q_1 and Q_2.

$\hat{\sigma}^A_{ik}$ and $\hat{\sigma}^B_{jl}$ are the parton-level subprocess cross sections.

The factor $m/2$ appears due to the symmetry of the expression for interchanging parton species i and j. $m = 1$ if $A = B$, and $m = 2$ otherwise.

The double parton distribution functions $\Gamma_{ij}(x_1, x_2; \mathbf{b_1}, \mathbf{b_2}; Q_1^2, Q_2^2)$ are the main object of interest as concerns multiple parton interactions. In fact, these distributions contain all the information when probing the hadron in two different points simultaneously, through the hard processes A and B.

It is typically assumed that the double parton distribution functions may be decomposed in terms of longitudinal and transverse components as follows:

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

where $f(\mathbf{b_1})$ is supposed to be a universal function for all kinds of partons with the fixed normalization

$$\boldsymbol{\int f(\mathrm{b}_1) f(\mathrm{b}_1 - \mathrm{b}) d^2 b_1 d^2 b = \int T(\mathrm{b}) d^2 b = 1,}$$

and

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

is the overlap function (not calculated in pQCD).

If one makes the further assumption that the longitudinal components $D_h^{ij}(x_1, x_2; Q_1^2, Q_2^2)$ reduce to the product of two independent one parton distributions,

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

the cross section of double parton scattering can be expressed in the simple form

$$\sigma_{\mathrm{DPS}}^{\mathrm{AB}} = \frac{m}{2} \frac{\sigma_{\mathrm{SPS}}^{A} \sigma_{\mathrm{SPS}}^{B}}{\sigma_{\mathrm{eff}}},$$

$$\pi R_{\mathrm{eff}}^2 = \sigma_{\mathrm{eff}} = [\int d^2b (T(\mathrm{b}))^2]^{-1}$$

is the effective interaction transverse area (effective cross section) R_{eff} is an estimate of the size of the hadron.

The momentum (*instead of the mixed (momentum and coordinate)*) representation is more convenient sometimes:

$$\sigma^{AB}_{DPS} = \frac{m}{2} \sum_{i,j,k,l} \int \Gamma_{ij}(x_1, x_2; \mathrm{q}; Q_1^2, Q_2^2)\hat{\sigma}^A_{ik}(x_1, x_1^{'})\hat{\sigma}^B_{jl}(x_2, x_2^{'})$$

$$\times \Gamma_{kl}(x_1^{'}, x_2^{'}; -\mathrm{q}; Q_1^2, Q_2^2) dx_1 dx_2 dx_1^{'} dx_2^{'} \frac{d^2 q}{(2\pi)^2}.$$

Here the transverse vector q is equal to the difference of the momenta of partons from the wave function of the colliding hadrons in the amplitude and the amplitude conjugated. Such dependence arises because the difference of parton transverse momenta within the parton pair is not conserved.

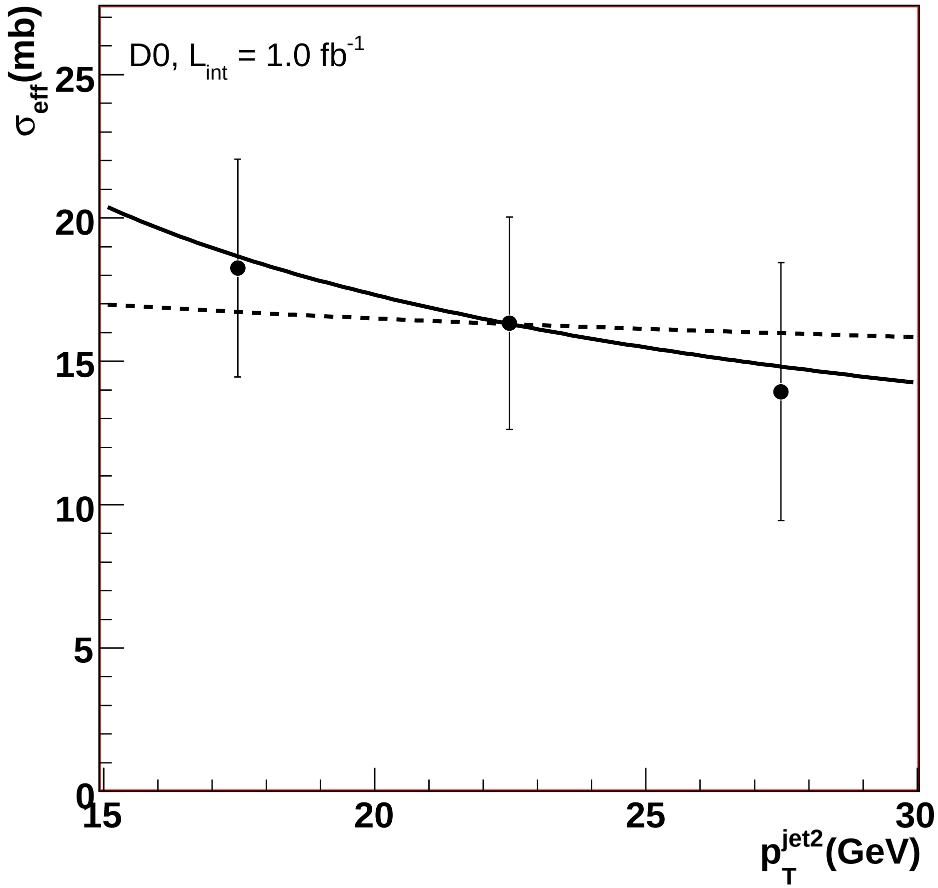
The main problems are

* **to make the correct calculation of the two-parton functions**
$\Gamma_{ij}(x_1, x_2; \mathbf{q}; Q_1^2, Q_2^2)$ **WITHOUT simplifying factorization assumptions**
(*which are not sufficiently justified and should be revised:*
(Blok, Dokshitzer, Frankfurt, Strikman; Diehl, Schafer;
Gaunt, Stirling; Ryskin, Snigirev,......))

* **to find (observe) longitudinal momentum parton correlations and deviation from the factorization form of DPS cross section:**

D0 Collaboration (Tevatron) has measured σ_{eff} **at 3 different scales in process with** γ **+3 jets in final state.**

These results can be interpreted as a first inderect observation of the QCD evolution of double parton distributions
(Snigirev; Flensburg, Gustafson, Lonnblad, Ster;
Blok, Dokshitzer, Frankfurt, Strikman)



Experimental extraction:

$$\frac{\sigma_{DPS}^{\gamma+3j}}{\sigma^{\gamma j}\sigma^{jj}} = [\sigma_{\text{eff}}^{\text{exp}}]^{-1}$$

Theoretical "prediction":

$$\sigma_{\text{eff}}^{\text{exp}} = \sigma_{\text{eff}}^{0}[1 + k\ln(p_T^{\text{jet2}}/p_{T0}^{\text{jet2}}]^{-1}$$

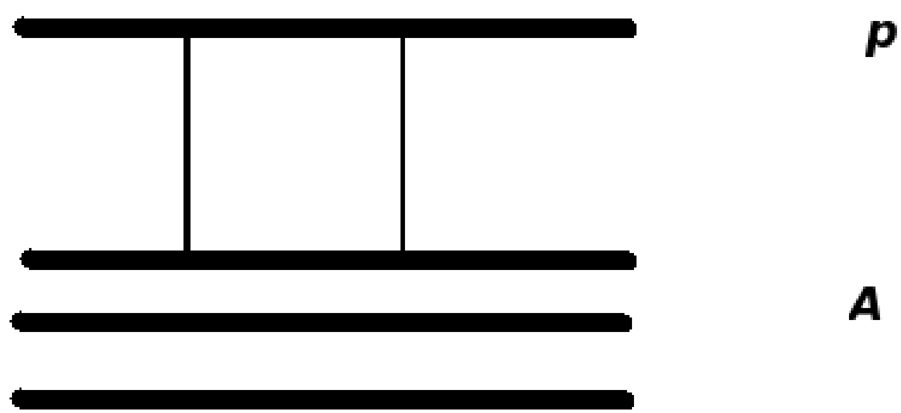
inspired by the explicit expression for the correlation term and the evolution variable t ($k = 0.1$ (dashed line) and $k = 0.5$ (solid line))

Promising candidate processes to probe DPS at the LHC:

- same-sign W production (“pure”, BUT very rare)
- $\gamma + 3$ jets (Tevatron also: D0, CDF)
- $W(Z) + 2$ jets (ATLAS — first measurement σ_{eff} at LHC)
- 4 jets (Tevatron also: CDF)
- $b\bar{b}$ pair $+2$ jets
- $b\bar{b}$ pair $+$ W boson
- pairs of heavy mesons (in particular, double J/ψ production)
  (LHCb — first measurement of double J/ψ production)
- ....

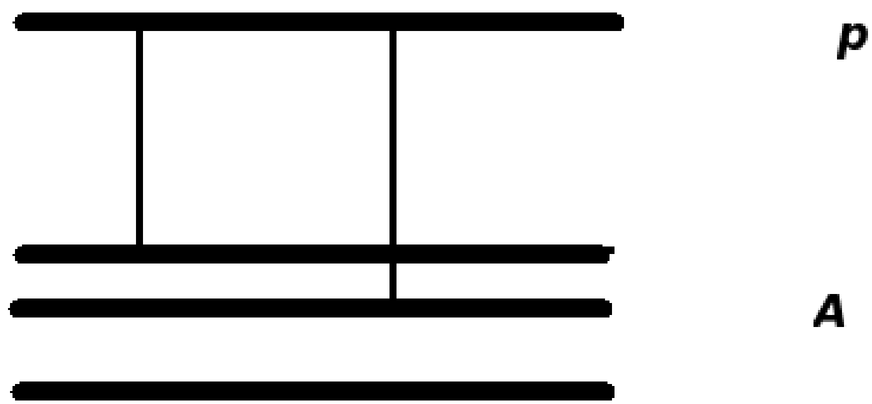
DPS in pA
(Strikman, Treleani; Blok, Strikman, Wiedemann; d'Enterria, Snigirev,.....) **:**

1. The two partons of the nucleus belong to the same nucleon



Nuclear enhancement factor: A **as for SPS**

2. The two partons of the nucleus belong to the different nucleons



Nuclear enhancement factor: $\propto A^2/A^{2/3} = A^{1+1/3}$
($A^{2/3}$ due to the difference of the transverse sizes between p and A)

The final DPS cross section "pocket formula" in pA collisions:

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

where

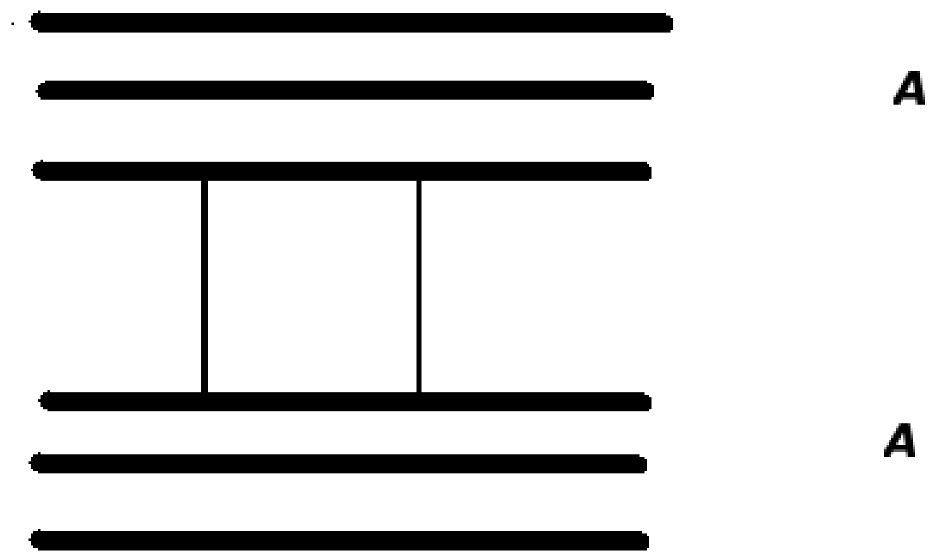
$$\boldsymbol{\sigma_{\rm eff,pA} = \frac{1}{A\left[\sigma^{-1}_{\rm eff,pp} + \frac{1}{A}\,\mathrm{T}_{\rm AA}(0)\right]} = 21.5\mu\mathrm{b}}$$

for p-Pb at $\sigma_{\rm eff,pp} = 14$ mb and $\mathrm{T}_{\rm AA}(0) = 30.4$ 1/mb for the standard nuclear overlap function normalized to A^2.

The relative contribution of the two terms are approximately 1 : 2

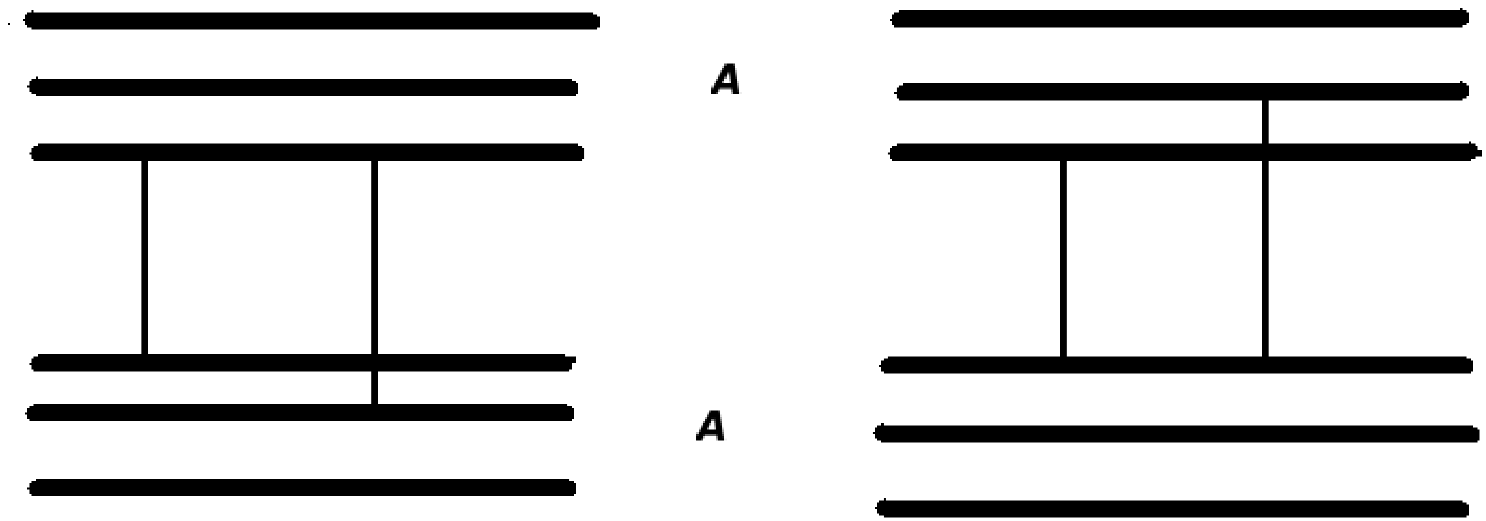
DPS in AA :

1. The two colliding partons belong to the same pair of nucleons



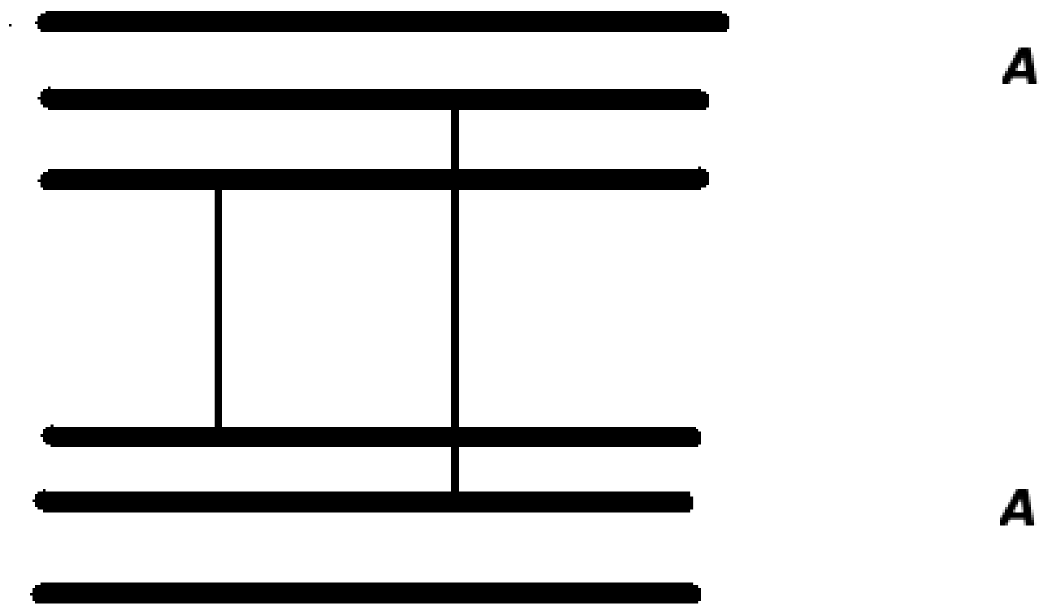
Nuclear enhancement factor: A^2 as for SPS

2. Partons from one nucleon in one nucleus collide with partons from two different nucleons in the other nucleus



Nuclear enhancement factor: $\propto A^3/A^{2/3} = A^{2+1/3}$

3. The two colliding partons belong to two different nucleons from both nuclei (in fact, double nucleon scattering)



Nuclear enhancement factor: $\propto A^4/A^{2/3} = A^{2+4/3}$

The final DPS cross section "pocket formula" in AA collisions:

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

where

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

for Pb-Pb at $\sigma_{\mathrm{eff,pp}} = 14$ mb and $\mathrm{T}_{\mathrm{AA}}(0) = 30.4$ 1/mb for the standard nuclear overlap function normalized to A^2.

The relative contribution of the three terms are approximately 1 : 4 : 200

Centrality-dependence of the DPS

The cross section for SPS and DPS an interval of impact parameters $[b_1, b_2]$, corresponding a given centrality percentile, $f_{\%} = 0 - 100\%$, of the total A-A cross section σ_{AA}, with average overlap function $< T_{AA}[b_1, b_2] >$ are

$$\boldsymbol{\sigma^{\mathrm{SPS}}_{(AA\to ab)}[b_1, b_2] = A^2 \cdot \sigma^{\mathrm{SPS}}_{(NN\to ab)} \cdot f_1[b_1, b_2]}$$

$$\boldsymbol{= \sigma^{\mathrm{SPS}}_{(NN\to ab)} f_{\%} \sigma_{AA} < T_{AA}[b_1, b_2] >,}$$

$$\boldsymbol{\sigma^{\mathrm{DPS}}_{(AA\to ab)}[b_1, b_2] = A^2 \cdot \sigma^{\mathrm{DPS}}_{(NN\to ab)} \cdot f_1[b_1, b_2]}$$

$$\times \left[\mathbf{1} + \frac{\mathbf{2}}{\boldsymbol{A}} \boldsymbol{\sigma_{eff,pp}} \, \mathrm{\mathbf{T_{AA}}}(\mathbf{0}) \, \frac{\mathbf{f_2[b_1, b_2]}}{\mathbf{f_1[b_1, b_2]}} + \boldsymbol{\sigma}_{\mathbf{eff,pp}} \, \mathrm{\mathbf{T_{AA}}}(\mathbf{0}) \, \frac{\mathbf{f_3[b_1, b_2]}}{\mathbf{f_1[b_1, b_2]}} \right],$$

the three dimensionless and appropriately-normalized fractions read

$$\boldsymbol{f_1[b_1, b_2] = \frac{2\pi}{A^2} \int_{b_1}^{b_2} bdb\, \mathrm{T_{AA}(b)} = \frac{\mathrm{f_{\%}}\sigma_{\mathrm{AA}}}{\mathrm{A}^2} < \mathrm{T_{AA}[b_1, b_2]} >,}$$

$$\boldsymbol{f_2[b_1, b_2] = \frac{2\pi}{A\, \mathrm{T_{AA}(0)}} \int_{b_1}^{b_2} bdb \int d^2 b_1\, \mathrm{F_A(b_1) F_A(b_1 - b) F_A(b_1 - b)},}$$

(cannot expressed in terms $\mathrm{T_{AA}(b)}$ only
$\mathrm{F_A}(\mathbf{b})$ — the nuclear thickness functions)

$$\boldsymbol{f_3[b_1, b_2] = \frac{2\pi}{A^2\, \mathrm{T_{AA}(0)}} \int_{b_1}^{b_2} bdb\, \mathrm{T^2_{AA}(b)}.}$$

For not very peripheral collisions ($f_{\%} < 0 - 65\%$) DPS cross section (in a thin impact-parameter range) can be approximated by third dominant term

$$\boldsymbol{\sigma^{\rm DPS}_{(AA\to ab)}[b_1,b_2] \simeq \sigma^{\rm DPS}_{(NN\to ab)} \cdot \sigma_{eff,pp} \cdot f_{\%}\sigma_{AA} \cdot < T_{AA}[b_1,b_2] >^2}$$

$$\boldsymbol{= \frac{m}{2}\sigma^{\rm SPS}_{(NN\to a)} \cdot \sigma^{\rm SPS}_{(NN\to b)} \cdot f_{\%}\sigma_{AA} \cdot < T_{AA}[b_1,b_2] >^2 .}$$

For ratio

$$\boldsymbol{\frac{\sigma^{\rm DPS}_{(AA\to ab)}[b_1,b_2]}{\sigma^{\rm SPS}_{(AA\to a)}[b_1,b_2]} \simeq \frac{m}{2}\sigma^{\rm SPS}_{(NN\to b)} \cdot < T_{AA}[b_1,b_2] > .}$$

In the centrality percentile $f_{\%} \simeq 65 - 100\%$ the second term would add about 20% more DPS cross section.

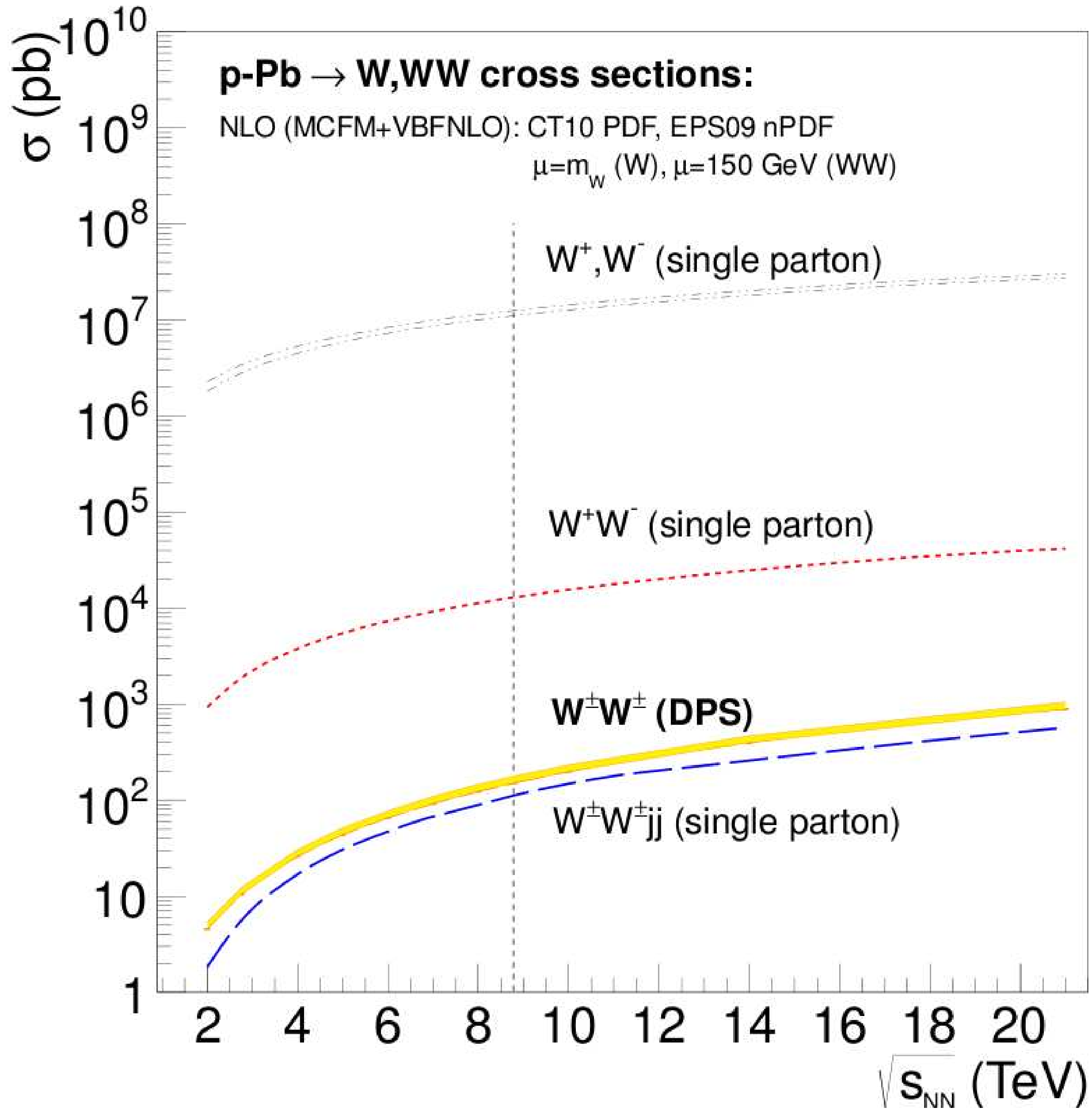
For very peripherical collisions ($f_{\%} \simeq 85 - 100\%$, where $< T_{AA}[b_1,b_2] >$ is order or less than $1/\sigma_{eff,pp}$) the contributions from the first term are also non-negligible (dominant in the limit $1/b \to 0$).

The formalism of DPS was applied first to study:

same-sign W-boson pair production in pPb collisions at LHC energies

J/ψ**-pair production in Pb-Pb collisions at LHC energies**

Specification in calculations, results and plots
— in original papers (+ nice presentations (*d'Enterria*) on Hard Probes 2013, Quark Matter 2014)



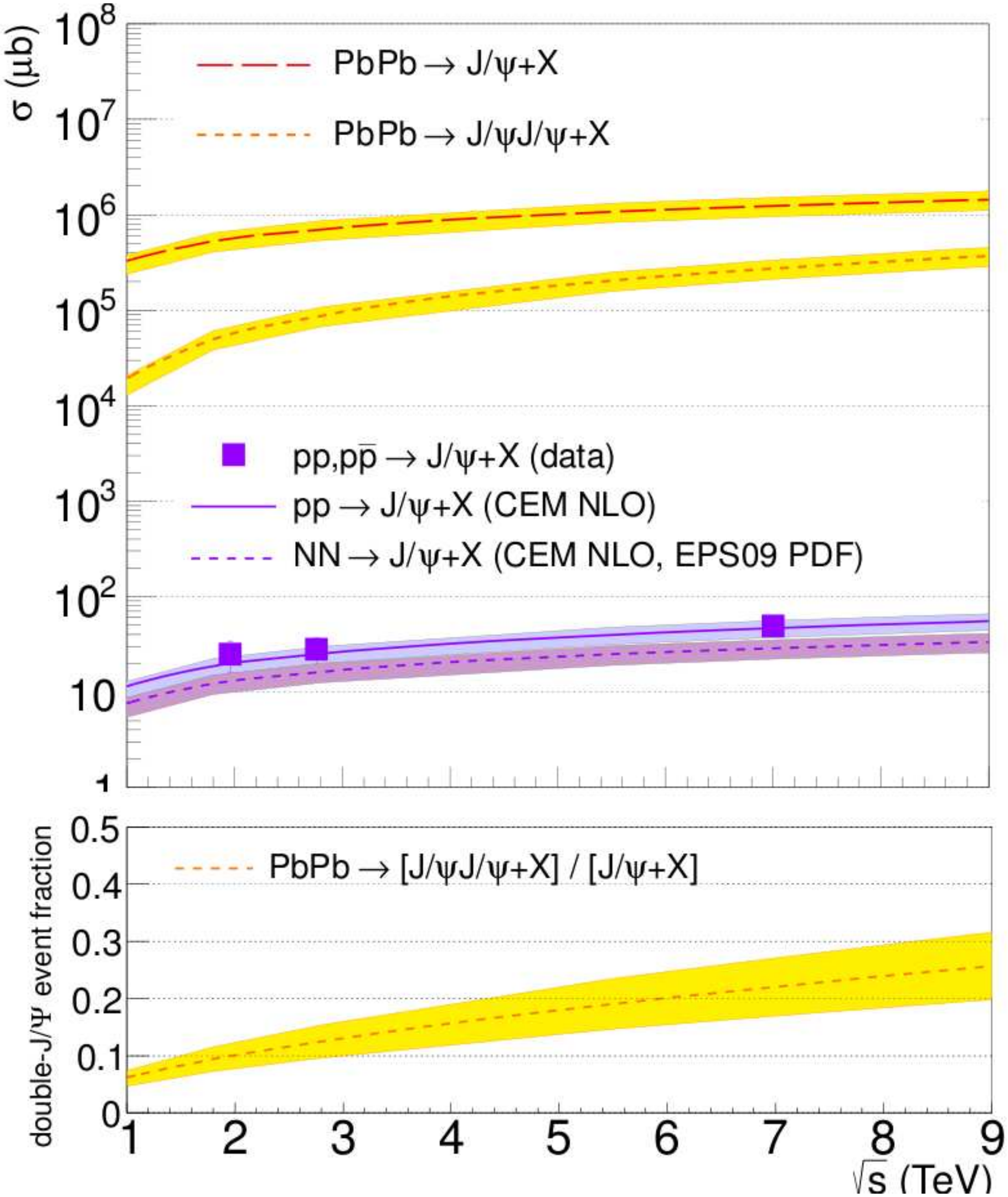
p-Pb → W,WW cross sections:
NLO (MCFM+VBFNLO): CT10 PDF, EPS09 nPDF
μ=m_W (W), μ=150 GeV (WW)
W+,W- (single parton)
W+W- (single parton)
W±W± (DPS)
W±W±jj (single parton)
σ (pb)
1
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^10
2
4
6
8
10
12
14
16
18
20
√s_NN (TeV)

Only main conclusions

p-Pb collisions:

* At the nominal $\sqrt{s_{NN}} = 8.8$ TeV energy, the DPS cross section for like-sign WW production is about 150 pb, i.e. 600 times larger than that in proton-proton collisions at the same c.m. energy and 1.5 times higher than the same-sign WW+2-jets background.

* The measurement of such a process, where 10 events with fully leptonic W's decays are expected after cuts in 2 pb^{-1}, would constitute an unambiguous DPS signal at the LHC, and would help determine the effective σ_{eff} parameter characterizing the area of double parton interactions in hadronic collisions.


σ (μb)
PbPb → J/ψ+X
PbPb → J/ψJ/ψ+X
pp,pp̄ → J/ψ+X (data)
pp → J/ψ+X (CEM NLO)
NN → J/ψ+X (CEM NLO, EPS09 PDF)
double-J/Ψ event fraction
PbPb → [J/ψJ/ψ+X] / [J/ψ+X]
√s (TeV)

Pb-Pb collisions:

* DPS constitute an important fraction of the total prompt-J/ψ cross sections, amounting to 20 % (35%) of the primordial production in minimum-bias (most central) Pb-Pb collisions.

* At 5.5 TeV, about 240 double-J/ψ events are expected per unit rapidity in the dilepton decay channels (in the absence of final-state suppression) for an integrated luminosity of 1 nb^{-1}, providing interesting insights on the event-by-event dynamics of J/ψ production in Pb-Pb collisions.

DPS production cross sections of

double-J/ψ, $J/\psi+\Upsilon$, J/ψ+W, J/ψ+Z,

double-Υ, Υ+W, Υ+Z, and same-sign WW

in Pb-Pb and p-Pb at the LHC:

System		J/ψ + J/ψ	J/ψ + Υ	J/ψ+W	J/ψ+Z	Υ + Υ	Υ+W	Υ+Z	ss WW
Pb-Pb	σ^{DPS}	210 mb	28 mb	500 μb	330 μb	960 μb	34 μb	23 μb	630 nb
5.5 TeV	N^{DPS} (1 nb^{-1})	~250	~340	~65	~14	~95	~35	~8	~15
p-Pb	σ^{DPS}	45 μb	5.2 μb	120 nb	70 nb	150 nb	7 nb	4 nb	150 pb
8.8 TeV	N^{DPS} (1 pb^{-1})	~65	~60	~15	~3	~15	~8	~1.5	~4

(from arXiv:1408.5172 [hep-ph]; Nucl. Phys. A (in press))

The corresponding DPS yields, after (di)lepton decays and acceptance+efficiency losses, are given for 1 nb^{-1} and 1 pb^{-1} respectively.

Thus, the simultaneous production of quarkonia and/or electroweak bosons from DPS processes have large visible cross sections and are open to study in p-Pb and Pb-Pb at the LHC.