MPI@LHC 2013, Antwerpen

December 2-6, 2013

DPS in p-A and A-A collisions

David d'Enterria, Alexander M. Snigirev
D.V.Skobeltsyn Institute of Nuclear Physics
M.V.Lomonosov Moscow State University
Moscow, Russia, 119991

Phys. Lett. B 718, 1395 (2013)
Phys. Lett. B 727, 157 (2013)

PARTON MODEL

————————————————————————————————

Elastic scattering : electron — proton

——–> proton (hadron) NOT point-like

Deep inelastic scattering : electron — proton

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

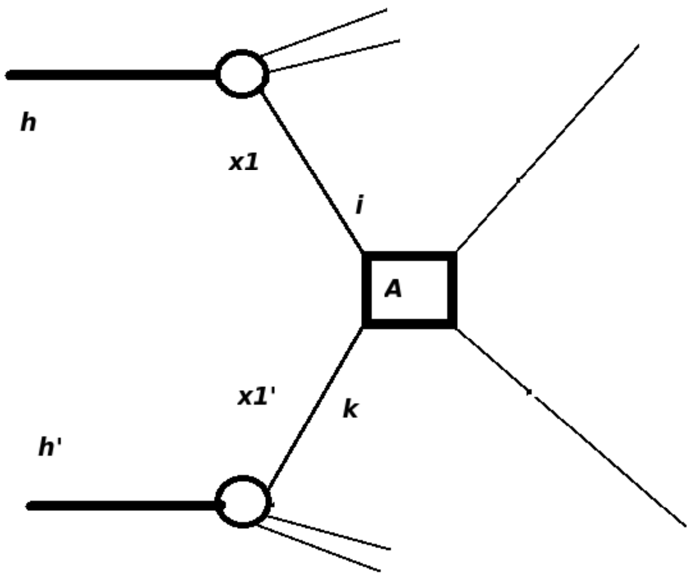
————————————————————————————————

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

Weights — probabilities in the system of infinite momentum

(Bjorken, Feynman)

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



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

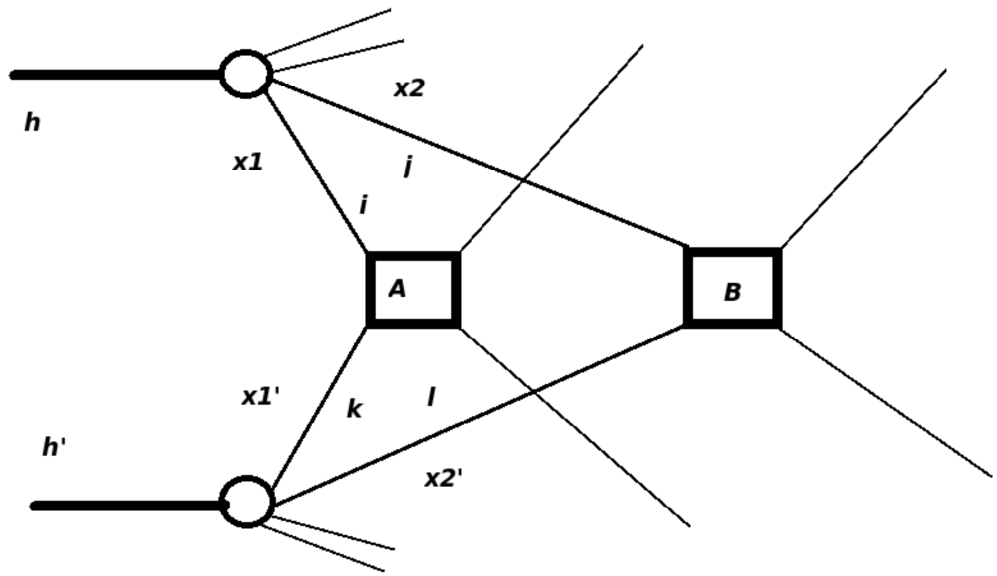
Scaling violation (dependence on Q) from
DGLAP (*Dokshitzer-Gribov-Lipatov-Altarelli-Parisi*) equations:

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

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

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 seldom): 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,...)

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

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

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:

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

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

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

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

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

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

is the effective interaction transverse area (effective cross section). $r_{\rm eff}$ is an estimate of the size of the hadron.

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

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

$$\times\Gamma_{kl}(x_1^{'}, x_2^{'}; -\mathrm{q}; Q_1^2, Q_2^2)dx_1dx_2dx_1^{'}dx_2^{'}\frac{d^2q}{(2\pi)^2}.$$

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.

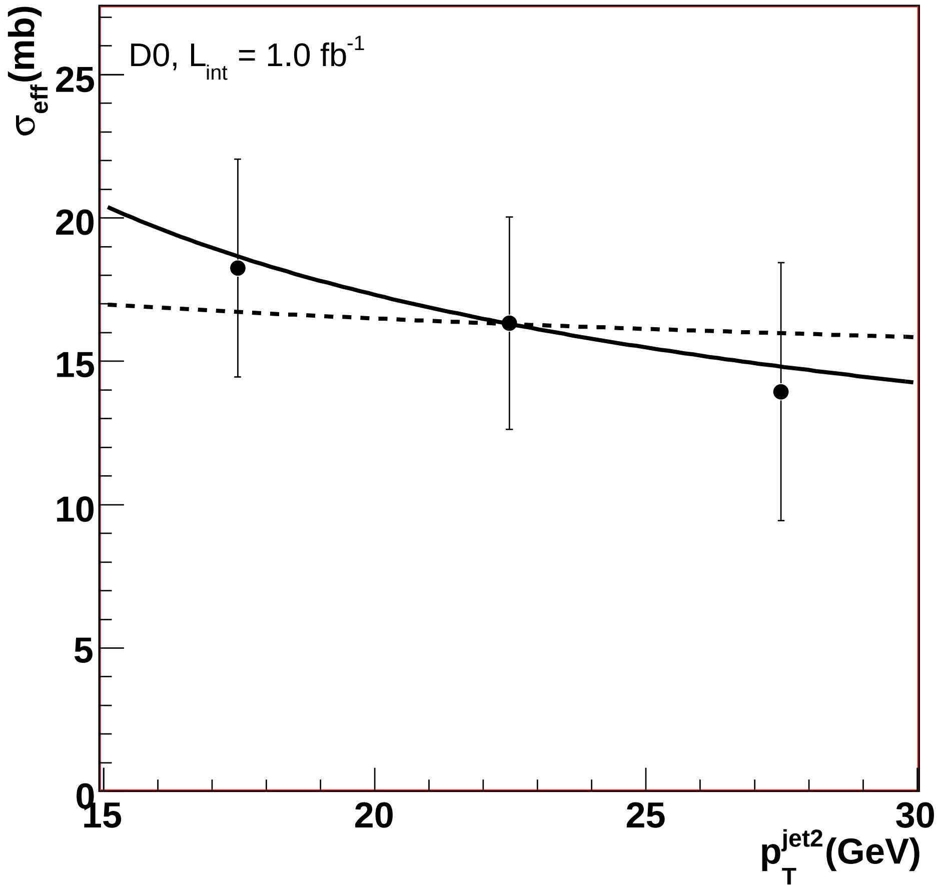
The main problems are

* **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 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:

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

Theoretical "prediction":

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

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

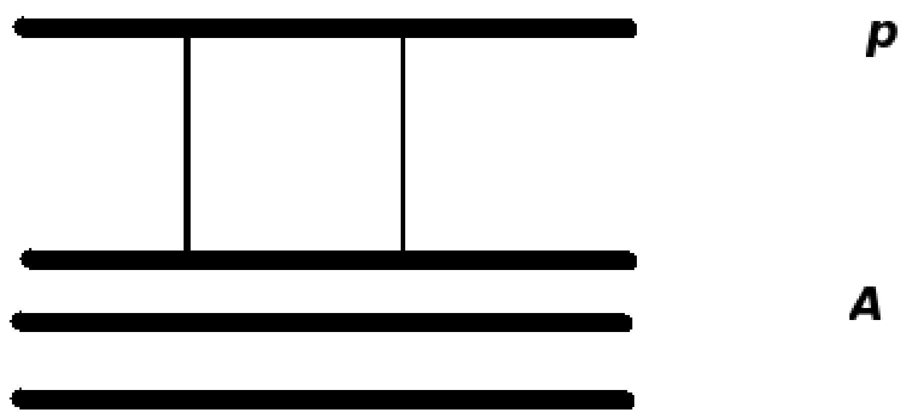
Promising candidate processes to probe DPS at the LHC:

- same-sign W production ("pure", BUT very rare)
- γ + 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 p-A

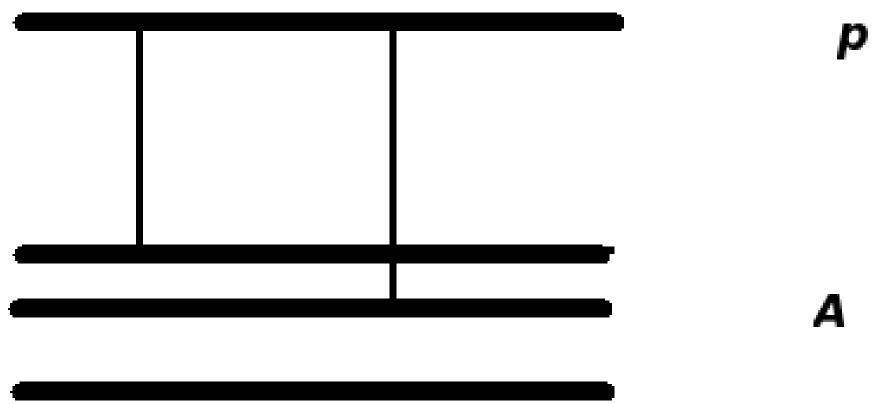
(Strikman, Treleani; Blok, Strikman, Wiedemann; d'Enterria, Snigirev,.....) **:**

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 p-A collisions:

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

where

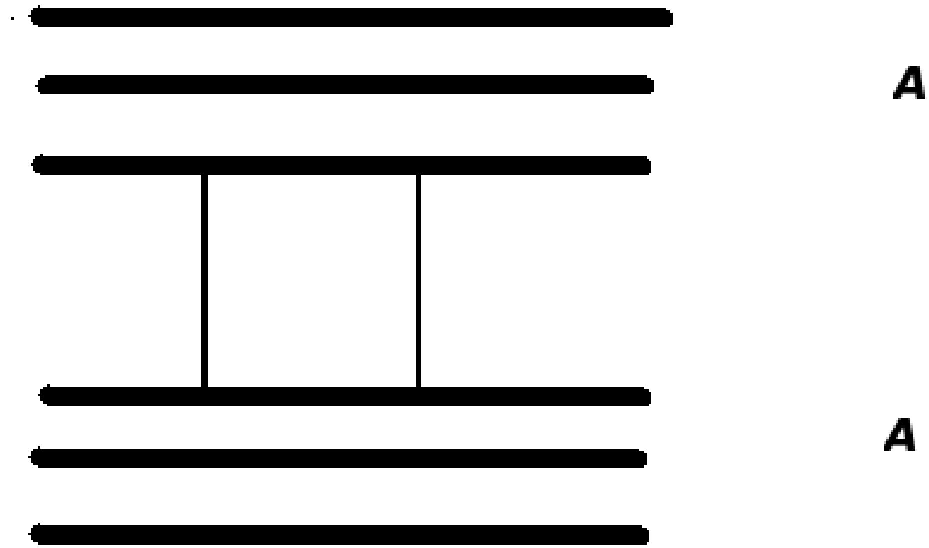
$$\boldsymbol{\sigma}_{\mathrm{eff,pA}} = \frac{1}{A\left[\boldsymbol{\sigma}^{-1}_{\mathrm{eff,pp}} + \frac{1}{A}\,\mathrm{T}_{\mathrm{AA}}(0)\right]} = 21.5\mu\mathrm{b}$$

for p-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 two terms are approximately 1 : 2

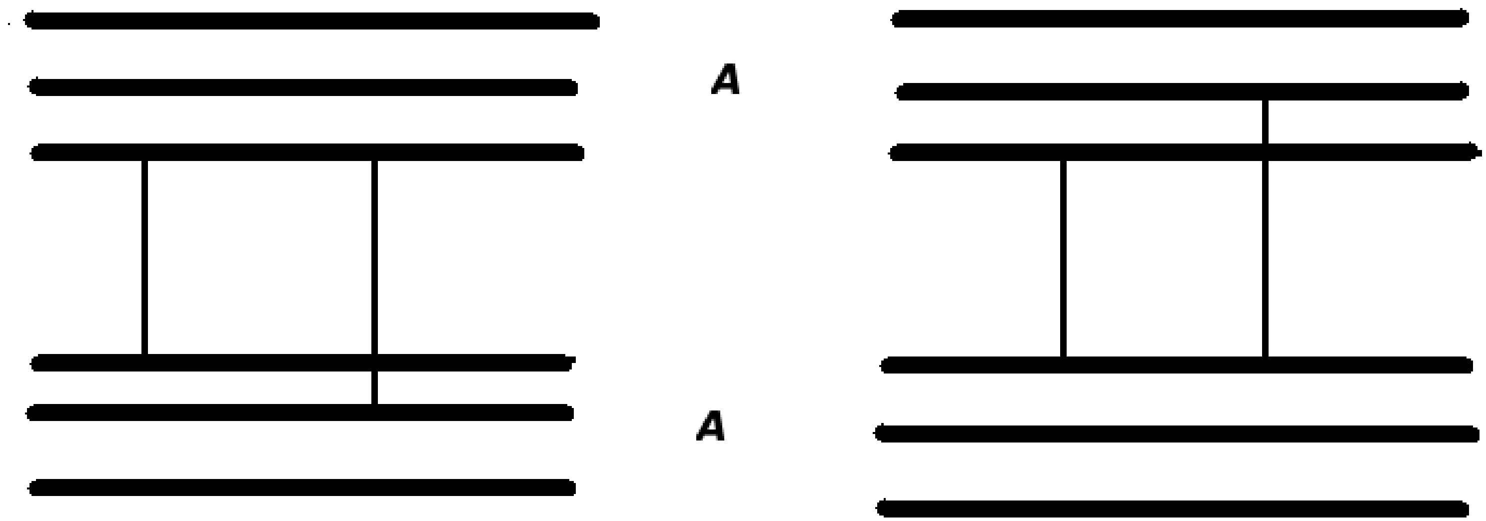
DPS in A-A :

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



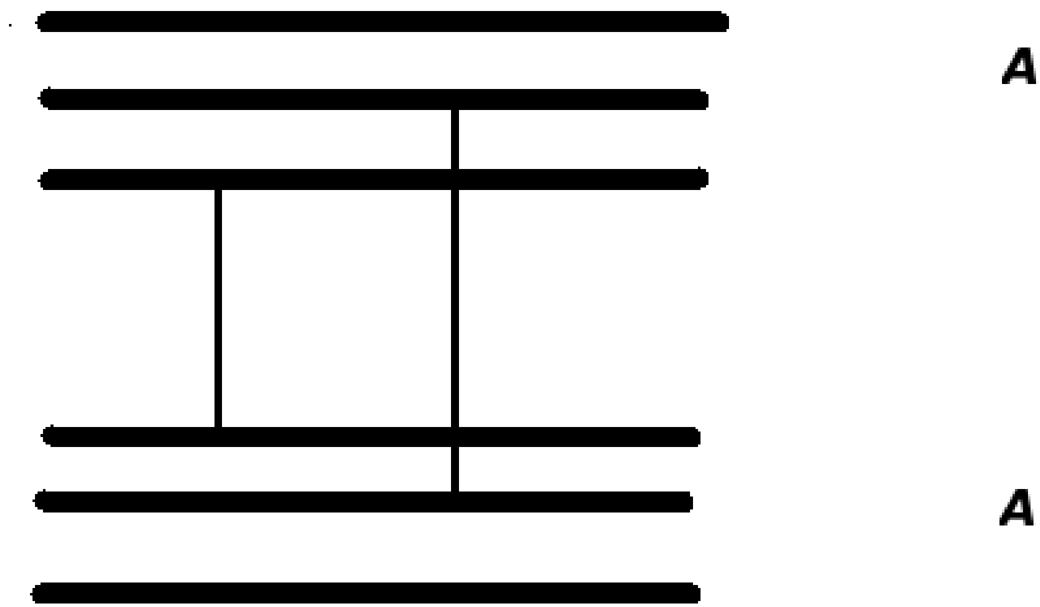
Nuclear enhancement factor: A^2 as for SPS

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 A-A collisions:

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

where

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

for Pb-Pb at $\sigma_{\rm eff,pp} = 14$ mb and ${\rm T}_{\rm AA}(0) = 30.4$ 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 within 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

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

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

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

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

the three dimensionless and appropriately-normalized fractions read

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

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

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

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

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

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

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

For ratio

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

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 to study:

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

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

Plots and results (+ specificity in calculations)
— in a nice presentation (*d'Enterria*) on
Hard Probes 2013: http://www.phy.uct.ac.za/hp2013/

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 in proton-proton collisions at the same c.m. energy and 1.5 times higher than the single-parton 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 σ_{eff} parameter characterising the effective transverse parton area of hard interactions in hadronic collisions.

Pb-Pb collisions:

* DPS constitute an important fraction of the total prompt-J/ψ cross sections, amounting to 20% (35%) of the primodal 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 effects) for an integrated luminosity of 1 nb^{-1}, providing a quantitative test of the predictions presented here.