Four-jet DPS production in pp and pA collisions at the LHC

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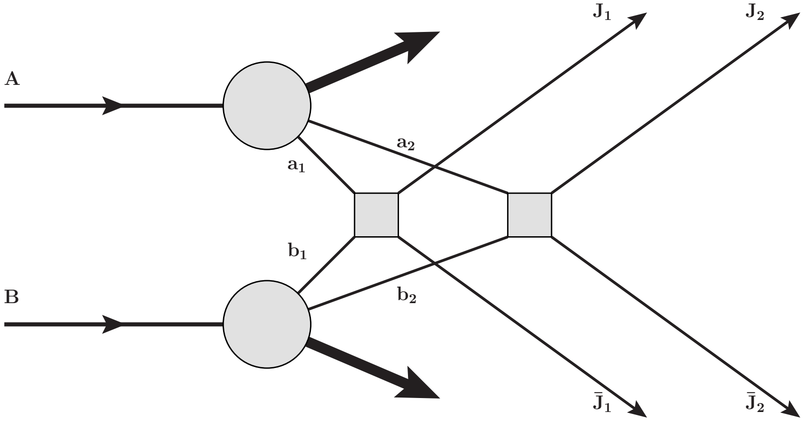
Introduction: what is DPS?

What is double parton scattering?

By *double parton scattering* (DPS) we mean a process when two hard interactions occur per one hadron-hadron collision.



Introduction: some selected papers[1]

How do we describe two hard interactions in one collision?

Field theory approach (pp)

- Goebel *et. al.* 80; Politzer 80; Paver and Treleani 82
- Kirschner 79; Shelest *et. al.* 82;
- Gaunt, Stirling 09; Golec-Biernat *et. al.* 15; Diehl *et. al.* 18

Monte Carlo approach (pp)

- Sjöstrand 85; Sjöstrand, Zijl 87
- Sjöstrand, Skands 04
- Corke, Sjöstrand 10, 11

Field theory approach (pA)

- Goebel *et. al.* 80
- Strikman, Treleani 02; Del Fabbro, Treleani 03
- Blok *et. al.* 13

Monte Carlo approach (pA)

- Anderson *et. al.* 87; Bierlich *et. al.* 16
- Rasmussen, Sjöstrand 16

[1] The list is far not complete.

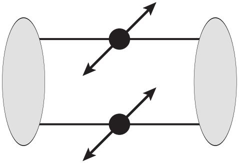
Introduction: Field theory approach

Assuming that hard processes factorize one can write

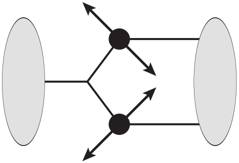
$$\sigma_{AB}(s) = \sum_{i,j,k,l} \int \prod_{a=1}^{4} dx_a \, d^2\mathbf{b} \, \hat{\sigma}_{ik\to A} \, \hat{\sigma}_{jl\to B} \, \Gamma_{ij}\left(x_1, x_2, \mathbf{b}, Q_A^2, Q_B^2\right) \Gamma_{kl}\left(x_3, x_4, \mathbf{b}, Q_A^2, Q_B^2\right)$$

where functions $\Gamma_{ij}\left(x_1, x_2, \mathbf{b}, Q_A^2, Q_B^2\right)$ are called *generalized parton distribution functions* (gPDFs) and give a probability to find two partons, separated by transverse distance **b**, in a hadron.

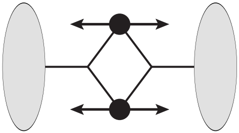
Several different contributions are possible



2v2



1v2



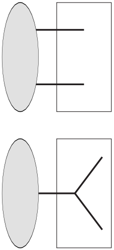
1v1

Introduction: Field theory approach

Assuming that one can factorize out the $\mathbf{b}$-dependence $\Gamma_{ij}\left(x_1, x_2, \mathbf{b}, Q_A^2, Q_B^2\right) \simeq D_p^{ij}\left(x_1, x_2, Q_A^2, Q_B^2\right) F\left(\mathbf{b}\right)$ one can write

$$\sigma_{AB}\left(s\right) = \frac{1}{(1+\delta_{AB})\sigma_{eff}} \sum_{i,j,k,l} \int \prod_{a=1}^{4} dx_a\, D_p^{ij}\left(x_1, x_2, Q_A^2, Q_B^2\right) D_p^{kl}\left(x_3, x_4, Q_A^2, Q_B^2\right) \hat{\sigma}_{ik\to A}\hat{\sigma}_{jl\to B}$$

Functions $D_p^{ij}\left(x_1, x_2, Q_A^2, Q_B^2\right)$ are called *Double Parton Distribution Functions* (dPDFs) and obey a system of "double" DGLAP equations.



$D_p^{ij}\left(x_1, x_2, Q_A^2, Q_B^2\right)$

- 1 to 2 splitting can be included in "double" DGLAP equations (Gaunt and Stirling set)
- In general leads to double counting between DPS and SPS and singular $\sim 1/b^2$ behaviour (Diehl *et al.* 2011, Stirling *et al.* 2011, Gaunt 2012, Blok *et al.* 2011, Singirev 2011)
- A consisted scheme to incorporate all contributions was recently proposed (Diehl *et al.* 2017)

Introduction: Gaunt and Stirling dPDFs

"double" DGLAP equations (Kirschner 79, Shelest *et. al.* 82)

$$
\begin{aligned}
\frac{dD_{j_1 j_2}(x_1, x_2, t)}{dt} = \quad & \frac{\alpha_s}{2\pi} \sum_{j_1'} \int_{x_1}^{1-x_2} \frac{dx_1'}{x_1'} D_{j_1' j_2}(x_1', x_2, t) \, P_{j_1' \to j_1}\left(\frac{x_1}{x_1'}\right) + \\
& \frac{\alpha_s}{2\pi} \sum_{j_2'} \int_{x_2}^{1-x_1} \frac{dx_2'}{x_2'} D_{j_2 j_2'}(x_1, x_2', t) \, P_{j_2' \to j_2}\left(\frac{x_2}{x_2'}\right) + \\
& \frac{\alpha_s}{2\pi} \sum_{j'} D_{j'}(x_1 + x_2, t) \, \frac{1}{x_1 + x_2} \, P_{j' \to j_1 j_2}\left(\frac{x_1}{x_1 + x_2}\right),
\end{aligned}
$$

this can be solved numerically for appropriate initial conditions (J. Gaunt and J. Stirling GS09 set)

Introduction: Gaunt and Stirling dPDFs.

dDGLAP evolution preserves following sum rules
(Gaunt *et. al* 09, Golec-Biernat *et. al.* 15, Diehl *et. al* 18)

$$\sum_{j_2} \int_0^{1-x_1} dx_2\, x_2\, D_p^{j_1 j_2}(x_1, x_2, t) = (1 - x_1)\, D_p^{j_1}(x_1, t),$$

$$\int_0^{1-x_1} dx_2 \left[D_p^{j_1 j_2}(x_1, x_2, t) - D_p^{j_1 \bar{j}_2}(x_1, x_2, t) \right] = N_{j_{2v}}\, D_p^{j_1}(x_1, t), \quad \text{if } j_1 \neq j_2 \text{ or } \bar{j}_2,$$

$$\int_0^{1-x_1} dx_2 \left[D_p^{j_1 j_2}(x_1, x_2, t) - D_p^{j_1 \bar{j}_2}(x_1, x_2, t) \right] = (N_{j_{2v}} - 1)\, D_p^{j_1}(x_1, t), \quad \text{if } j_1 = j_2,$$

$$\int_0^{1-x_1} dx_2 \left[D_p^{j_1 j_2}(x_1, x_2, t) - D_p^{j_1 \bar{j}_2}(x_1, x_2, t) \right] = (N_{j_{2v}} + 1)\, D_p^{j_1}(x_1, t), \quad \text{if } j_1 = \bar{j}_2,$$

where $N_{j_{1v}}$ is a number of valence quarks.

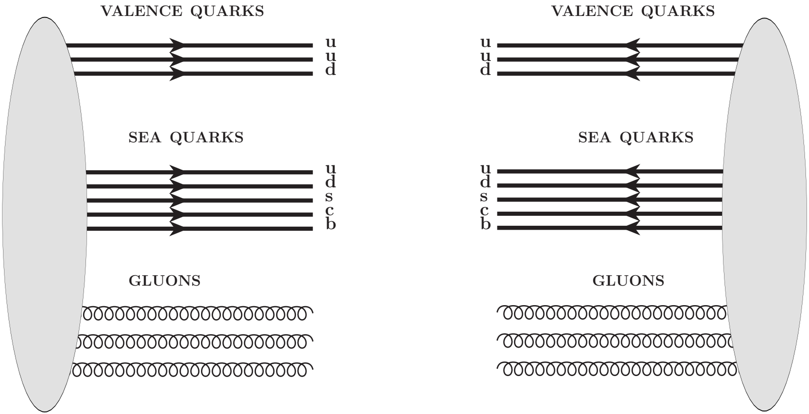
Introduction: Pythia's model of MPI (DPS)[2]

Pythia

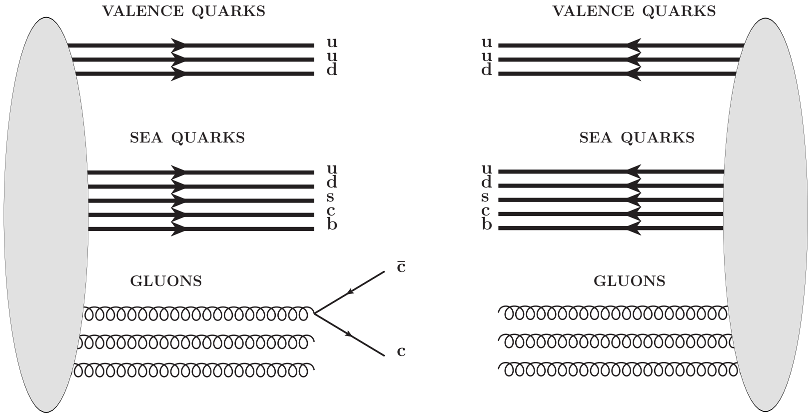
- The probability that n MPIs will happen is due to Poisson statistics $P_n = \frac{\langle n \rangle^n}{n!} e^{-\langle n \rangle}$
- Supports MPI and DPS (flag SecondHard)
- Does not support dPDFs $D_p^{ij}\left(x_1, x_2, Q_A^2, Q_B^2\right)$. Instead "squeezes" and reweights "single" PDFs $f_i\left(x, Q_A^2\right)$ to account for changes in parton content
- Modifies sea and valence PDFs differently
- Accounts for "1v2" splitting only of the type $g \to q\,\bar{q}$
- Does not include double DGLAP evolution effects
- Does not support "1v2" splitting while performing backwards evolution for ISR
- Supports impact-parameter dependence, rescattering and many other effects, see arXiv:1706.02166

[2] For the Herwig's approach see a talk of Baptiste Cabouat

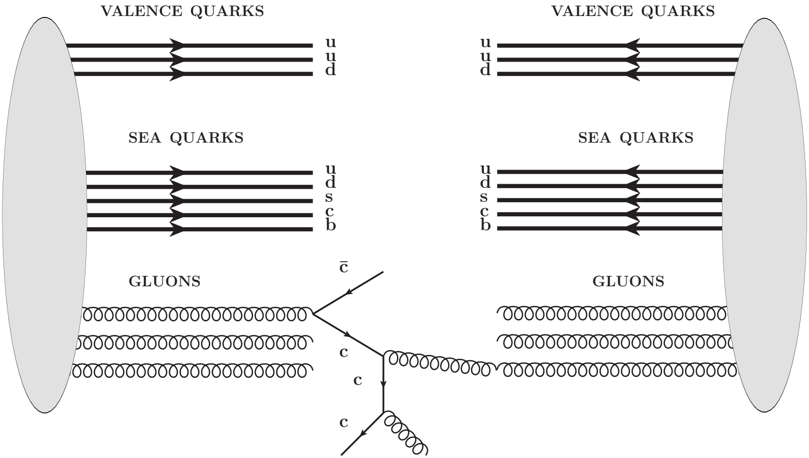
Pythia's dPDFs



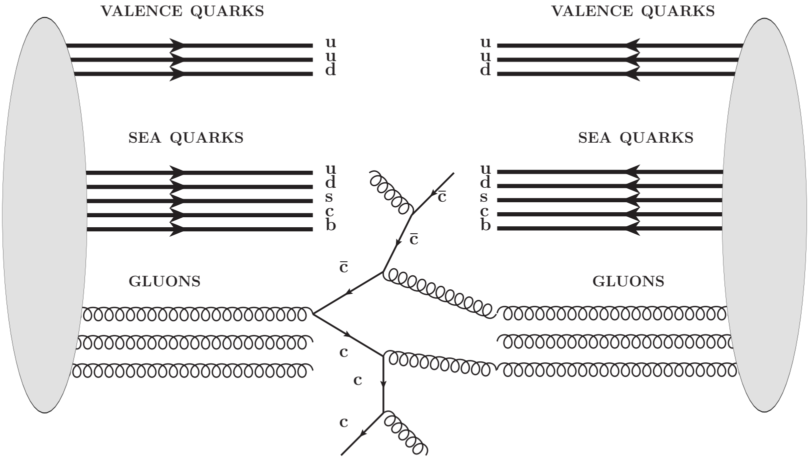
Pythia's dPDFs



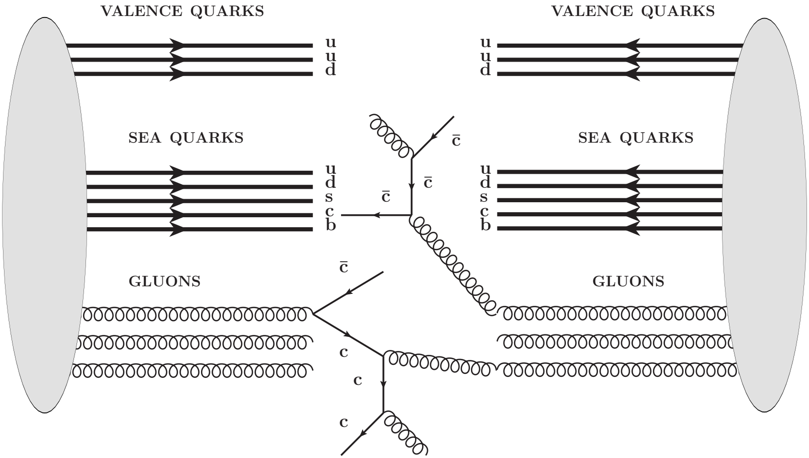
Pythia's dPDFs



Pythia's dPDFs



Pythia's dPDFs



Do Pythia's dPDFs obey GS sum rules?

Consider, for example, a third rule when $j_1 = j_2 = \mathrm{d}$

$$\int_0^{1-x_1} dx_2 \left[D_p^{\mathrm{dd}}(x_1, x_2, t) - D_p^{\mathrm{d\bar{d}}}(x_1, x_2, t) \right] = (N_{j_{2v}} - 1)\, D_p^{\mathrm{d}}(x_1, t),$$

it can be written as

$$\int_0^{1-x_1} dx_2\, R_{\mathrm{dd}}(x_1, x_2, t) = N_{\mathrm{d}} - 1 = 0$$

where $R_{\mathrm{dd}}(x_1, x_2, t) = \left[D_p^{\mathrm{dd}}(x_1, x_2, t) - D_p^{\mathrm{d\bar{d}}}(x_1, x_2, t) \right] / D_p^{\mathrm{d}}(x_1, t)$.

Note that is one neglects a flavour conservation $R_{\mathrm{dd}}(x_1, x_2, t) = D_{d_{val}}(x_2, t)$ a "standard" valence d-quark PDF.

Number sum rule: Pythia vs. GS

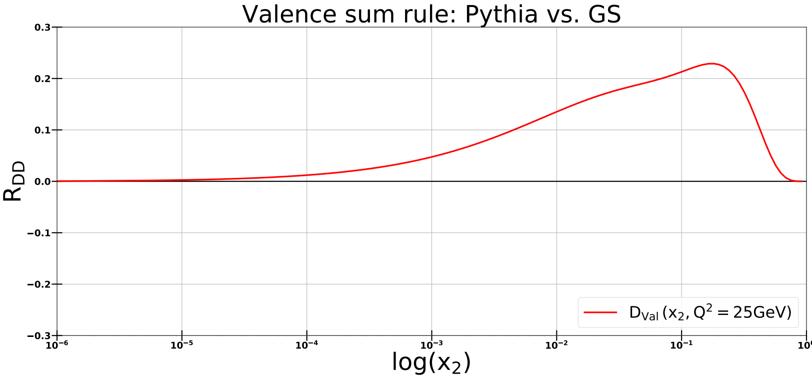
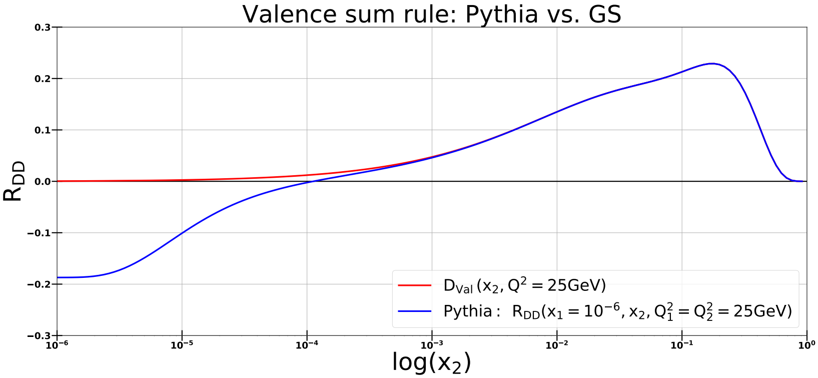


Figure : $R_{\mathrm{dd}}(x_1, x_2, t)$ as a function of x_2 at fixed x_1.

Number sum rule: Pythia vs. GS



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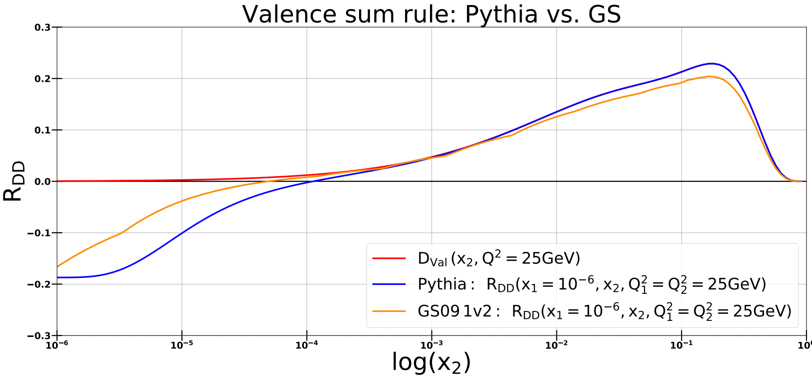

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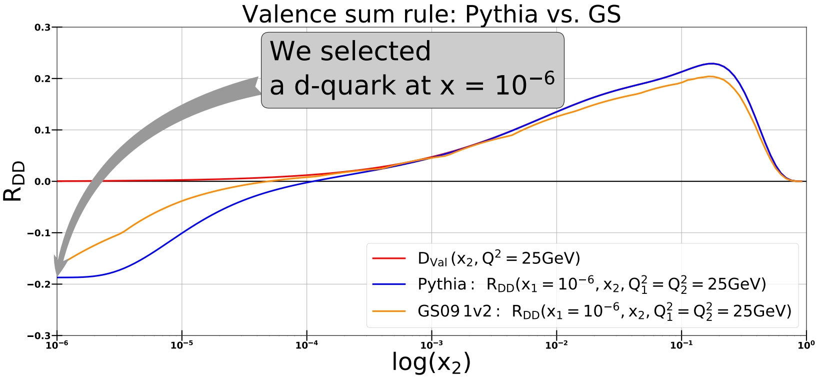

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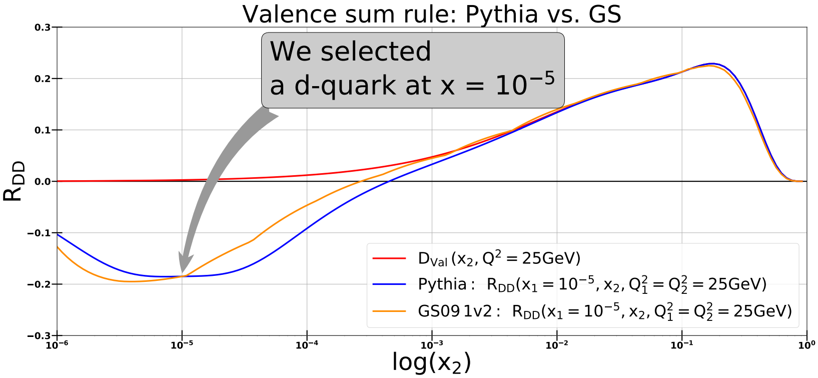

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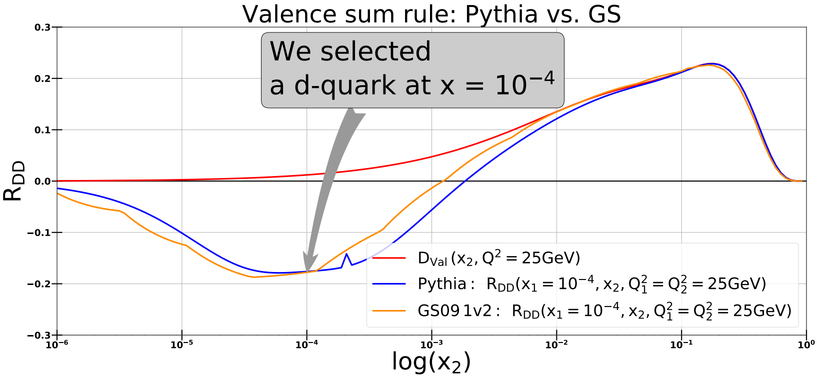

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Number sum rule: Pythia vs. GS

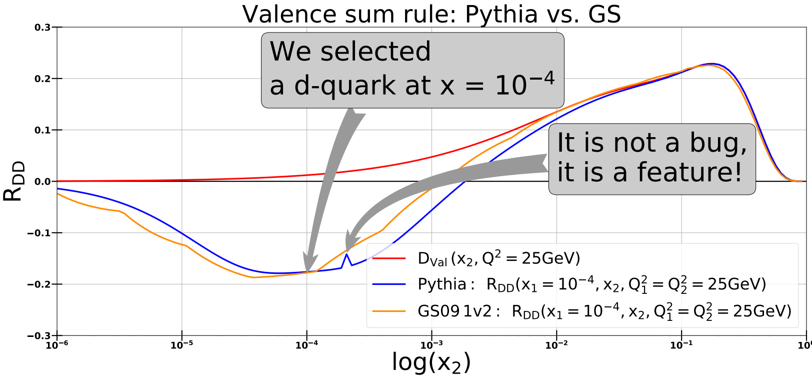


Figure : $R_{\mathrm{dd}}(x_1, x_2, t)$ as a function of x_2 at fixed x_1.

Pythia dPDFs

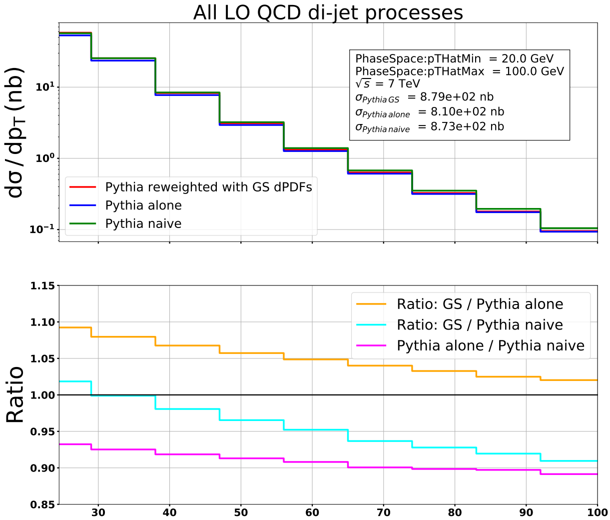


Figure : Distributions in terms of a leading jet $p_\perp$ at $\sqrt{S} = 7\,\mathrm{TeV}$ and scale range $Q_{1,2} \in [20, 100]\,\mathrm{GeV}$.

Pythia dPDFs

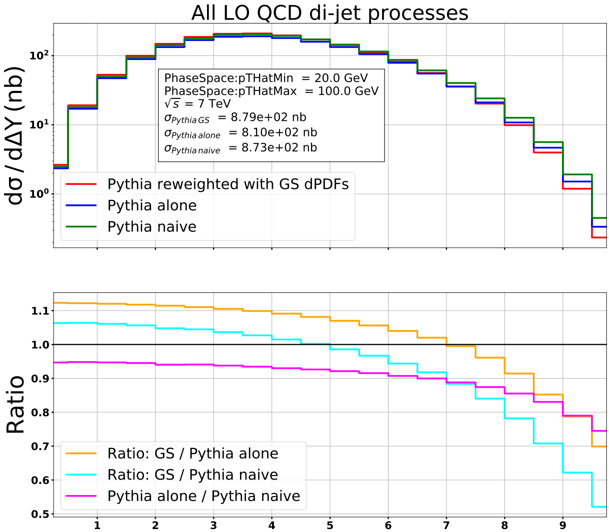


Figure : Distributions in terms of $\Delta \mathrm{Y} = \max |y_i - y_j|$ at $\sqrt{S} = 7\,\mathrm{TeV}$ and scale range $Q_{1,2} \in [20, 100]\,\mathrm{GeV}$.

Summary: GS09 vs. Pythia

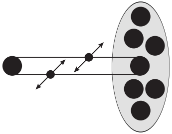
Current results:

- dPDFs being used in Pythia obey the same set of sum rules as Gaunt and Stirling GS09 dPDFs
- Both Pythia and GS09 have a similar description of "1v2" contribution at low values of x
- The description of "1v2" contribution at high values of x is different
- Differential distributions in terms of ΔY show a strong difference between both approaches at large values of ΔY

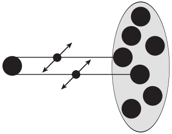
The difference between pp and pA collisions

Unlike pp case several different DPS contributions are possible

- Several authors have predicted the enhancement of the fraction of the DPS events in pA collisions in comparison with pp case (Treleani and Strikman 2001, d'Enterria and Snigirev 2012, Block, Strikman and Wiedemann 2013)



$$\sigma_{AB} \sim A \int \Gamma_p(x_1, x_2, \mathbf{b})\, \Gamma_p(x_3, x_4, \mathbf{b})$$



$$\sigma_{AB} \sim \frac{A-1}{A} \int D_p(x_1, x_2)\, f_p(x_3)\, f_p(x_4)\, \mathrm{T}_A^2(\mathbf{s})$$

Enhancement of the DPS fraction in pA collisions in comparison with pp case

The DPS fraction in pA collisions

$$\sigma_{pA}^{DPS} = \sigma_{pp}^{DPS}\left(A + \sigma_{eff}^{pp} F_{pA}\right) \qquad F_{pA} = \frac{A-1}{A}\int d^2s\, \mathrm{T}_A^2(\mathbf{s}),$$

$$\mathrm{T}_A(\mathbf{s}) = \int dz\, \rho_A(z,\mathbf{s})$$

It is convenient to study the enhancement factor

$$\sigma_{pA}^{DPS}/A\sigma_{pp}^{DPS} = 1 + C_1(A-1)^{C_2} + C_3(A-1)^{C_4} + \ldots$$

which one can evaluate for certain parametrization of nuclear matter density $\rho_A(z,\mathbf{s})$

DPS in pA collisions

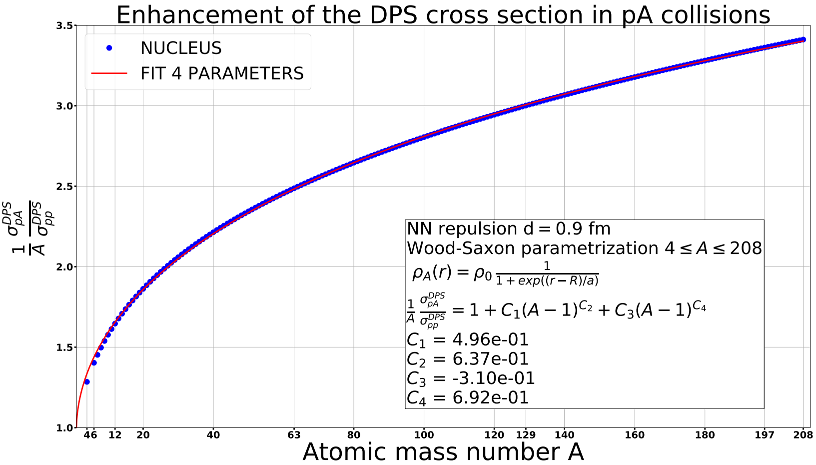
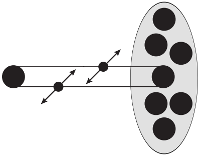


Figure : Enhancement of a total DPS cross section in pA collisions.

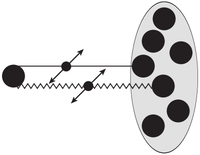
Pythia and Angantyr model[3]

Does Pythia predict enhancement of DPS cross section in pA collisions?



Type I

- Second hard interaction is due to the MPI machinery
- No trigger on it (one has to be patient)



Type II

- Second hard interaction is due to a Pomeron exchange
- No trigger on it (one has to be patient)

[3]See a talk of Christine Rasmussen

DPS in pA collisions. Pythia (Angantyr)

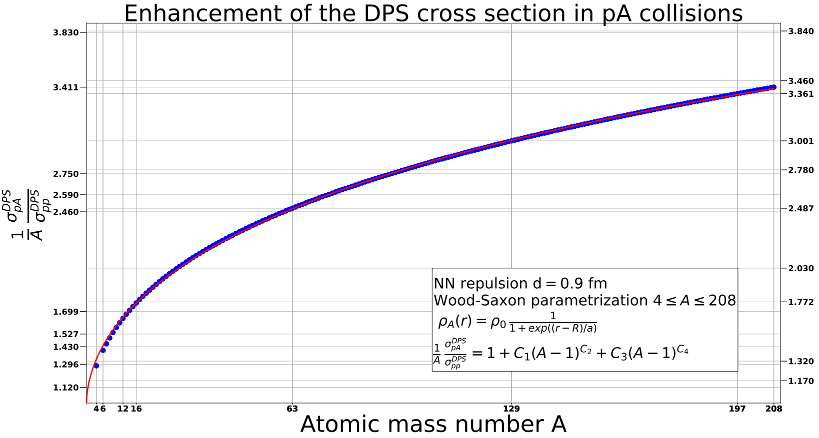
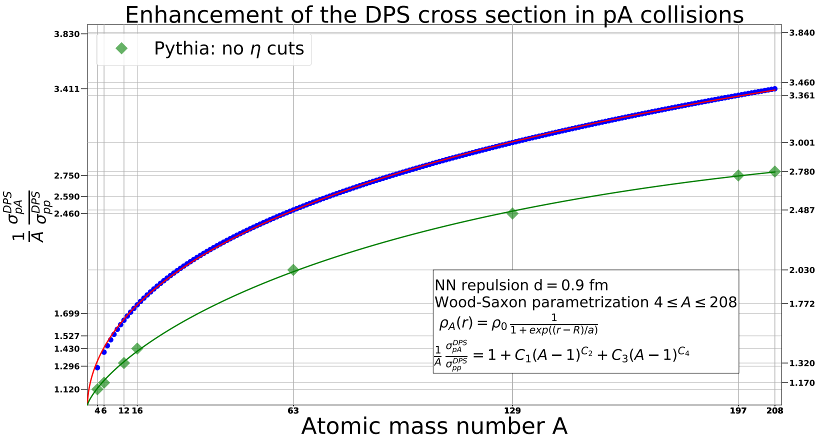


Figure : Enhancement of a total DPS cross section in pA collisions. Predictions of Pythia (Angantyr).

DPS in pA collisions. Pythia (Angantyr)



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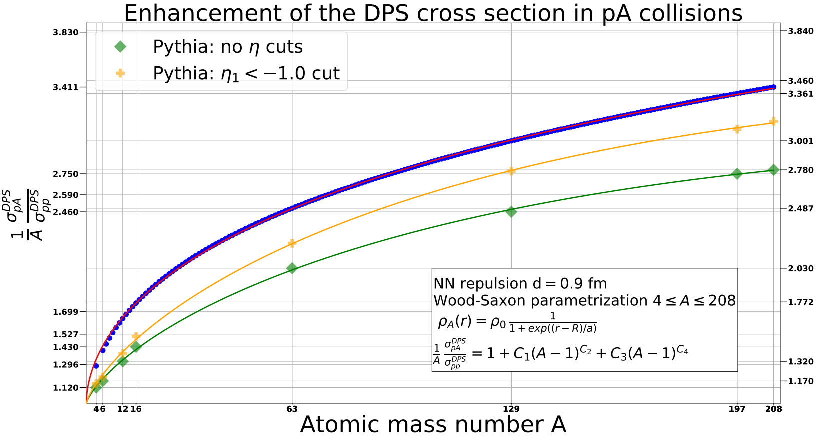

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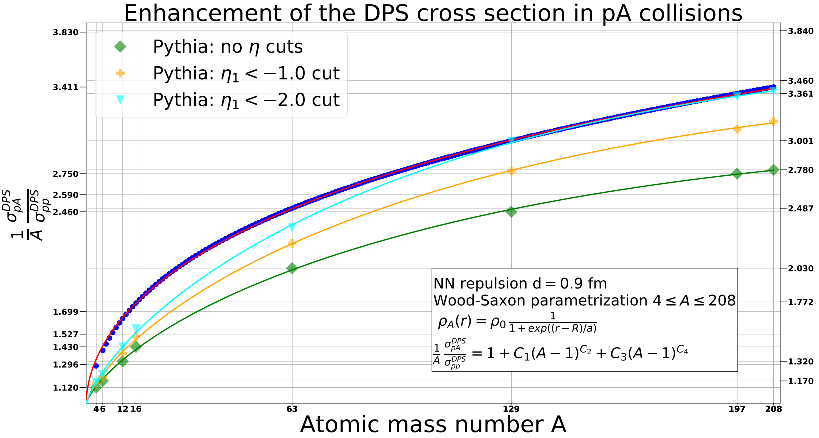

Figure : Enhancement of a total DPS cross section in pA collisions. Predictions of Pythia (Angantyr).

DPS in pA collisions. Pythia (Angantyr)

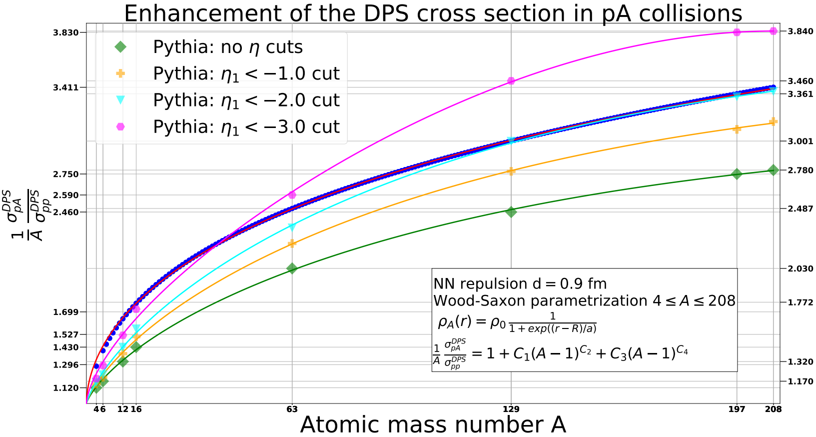

Figure : Enhancement of a total DPS cross section in pA collisions. Predictions of Pythia (Angantyr).

Summary: Angantry and DPS in pA

Current results:

- Angantry correctly describes enhancement of a total DPS cross section in pA collisions
- The enhancement of a total DPS cross section is due to hard diffractive processes
- A collective behaviour built-in Angantyr ("shadowing") has a serious impact on a total DPS cross section
- Angantyr predicts a grows of activity in a direction of nucleus, which allows to control "Type II" contributions

Some improvements to Pythia's code

By construction GS dPDFs are symmetric

$$D_{ij}\left(x_1, x_2, Q_1^2, Q_2^2\right) = D_{ji}\left(x_2, x_1, Q_2^2, Q_1^2\right)$$

But in Pythia

$$\begin{aligned} D_{ij}^{Pythia}\left(x_1, x_2, Q_1^2, Q_2^2\right) &\simeq f^i_{\mathrm{raw}}(x_1, Q_1^2) f^j_{\mathrm{mod}}(x_2, Q_2^2) \neq \\ &\neq f^j_{\mathrm{raw}}(x_2, Q_2^2) f^i_{\mathrm{mod}}(x_1, Q_1^2), \end{aligned}$$

therefore within the Pythia's framework

$$D_{ij}^{Pythia}\left(x_1, x_2, Q_1^2, Q_2^2\right) \neq D_{ji}^{Pythia}\left(x_2, x_1, Q_2^2, Q_1^2\right).$$

Some improvements to Pythia's code

The asymmetry of Pythia's dPDFs leads to ordered DPS events

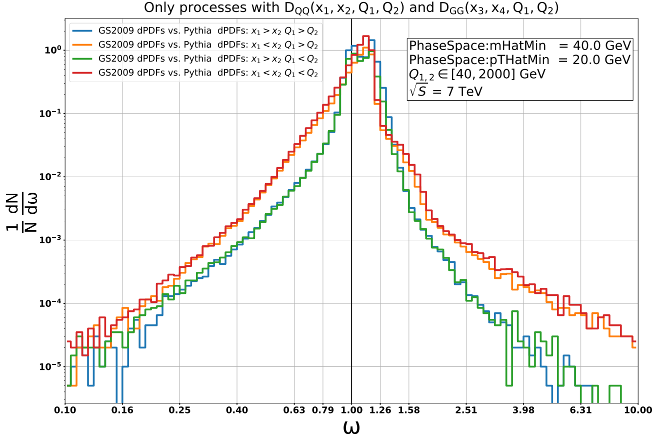

Figure : Distribution of the ratio between GS and Pythia DPS luminosities

Some improvements to Pythia's code

This asymmetry was removed. Starting from Pythia 8.240 DPS events are generated with symmetric dPDFs

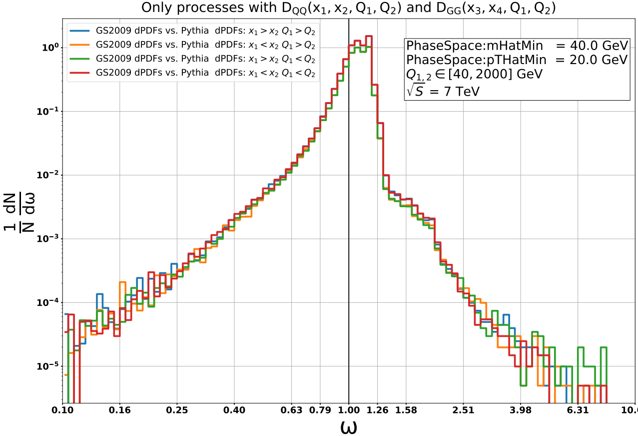

Figure : Distribution of the ratio between GS and Pythia DPS luminosities

Some improvements to Pythia's code

The overall impact of symmetrization is very modest

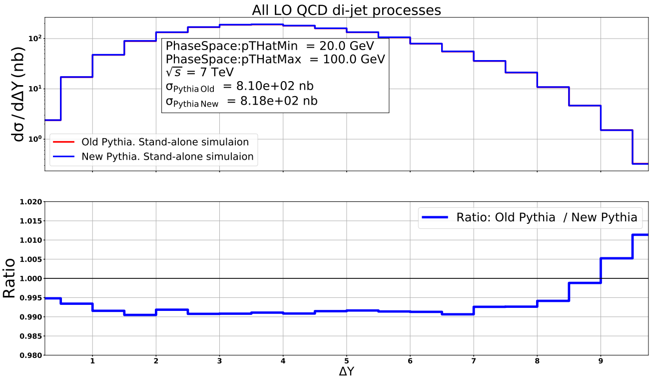

Figure : Distributions in terms of $\Delta Y = \max|y_i - y_j|$ at $\sqrt{S} = 7\,\mathrm{TeV}$ and scale range $Q_{1,2} \in [20, 100]\,\mathrm{GeV}$. Comparison between Pythia 8.235 and Pythia 8.240

Some improvements to Pythia's code

Now Pythia can write, read and "shower" double Les Houches files

ID	Status	Parents	Colour	Four momentum	
21	-1	0 0	101 102	0.00 0.00 10.9 10.9	Event one
21	-1	0 0	102 103	0.00 0.00 -50.5 50.5	
3	1	1 2	101 0	-2.12 23.2 -16.5 28.6	
-3	1	1 2	0 103	2.11 -23.2 -23.1 32.8	
21	-1	0 0	104 105	0.00 0.00 3.14 3.14	Event two
21	-1	0 0	106 104	0.00 0.00 -276 276	
21	1	5 6	106 107	-24.6 -16.1 -146 149	
21	1	5 6	107 105	24.6 16.1 -12.7 130	
#scaleShowers	23.4	29.4			

It also allows to shower DPS events produced with other models (within certain approximation).
Probably will be available in a next version of Pythia.

Afterword

‘There are nine and sixty ways of constructing tribal lays,
And every single one of them is right!’

Rudyard Kipling, *In the Neolithic Age*

‘There are nine and sixty ways to model DPS,
And every single one of them is ~~wrong~~ right!’

Something Rudyard Kipling never said

Thank you for your attention!

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Backup slides

Impact of dPDFs on four-jet production

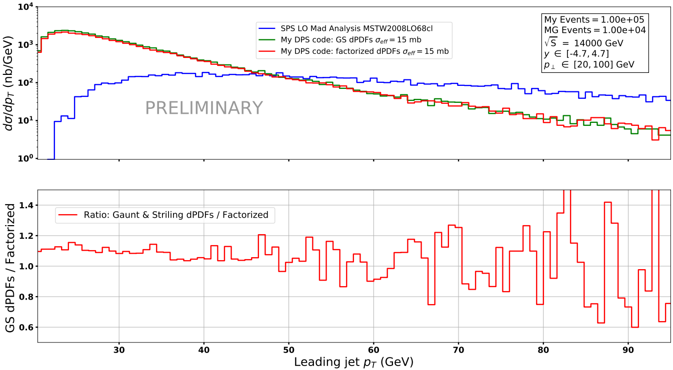


Figure : The $p_\perp$-cuts from below and from above increase the fraction of DPS events
(see Maciuła and Szczurek 2015 and a talk of Hans Van Haevermae).

Impact of dPDFs on four-jet production

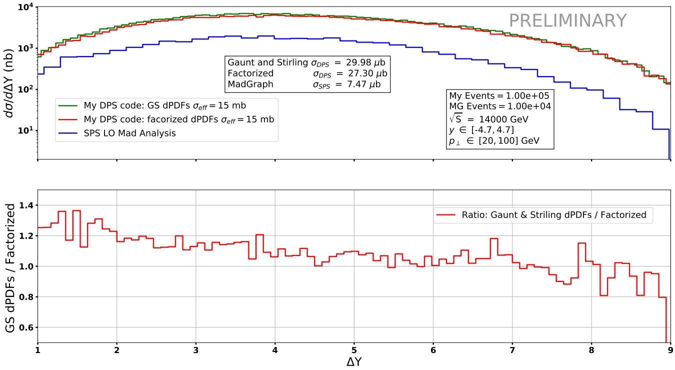


Figure : ΔY distribution, where $\Delta Y = \max|y_i - y_j|$. The DPS distributions were built using Gaunt and Stirling dPDF set and using a product of two standard PDFs
(see Maciuła and Szczurek 2015 and a talk of Hans Van Haevermae).

DPS phase space

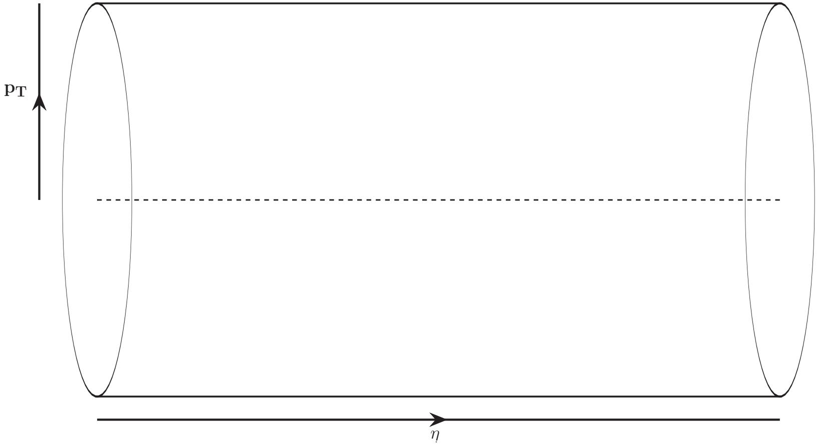


Figure : A schematic representation of collider experiment.

DPS phase space

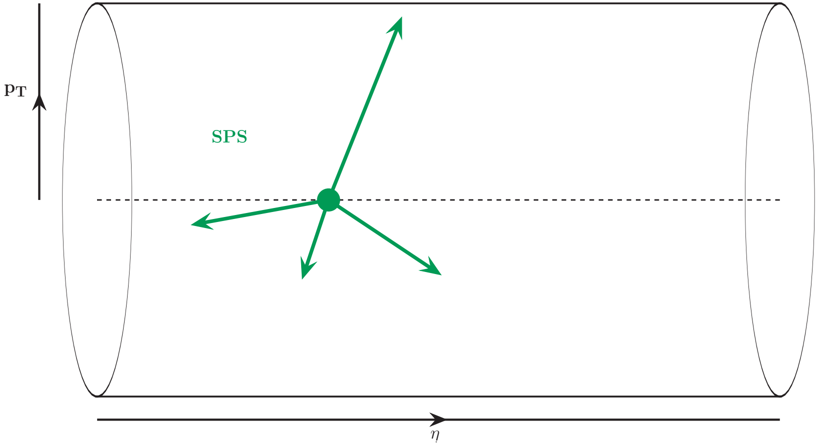


Figure : A schematic representation of collider experiment.

DPS phase space

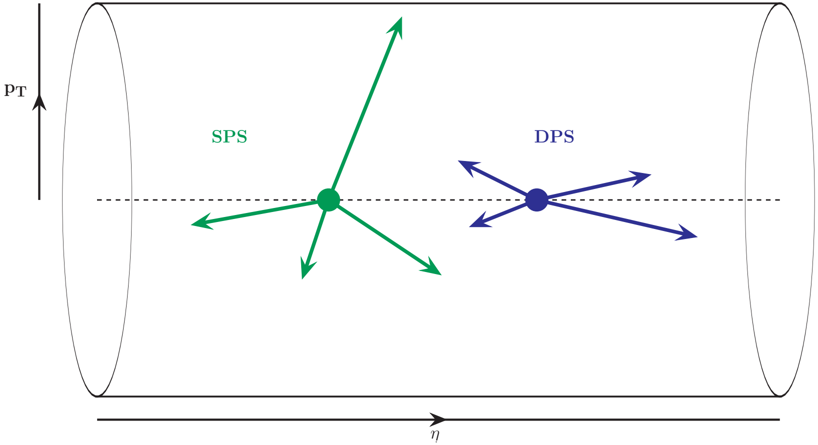


Figure : A schematic representation of collider experiment.

DPS phase space

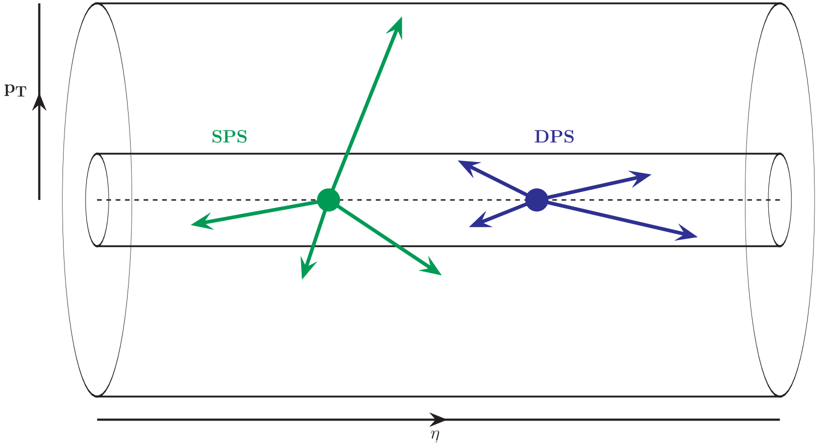


Figure : A schematic representation of collider experiment.

The impact of the nuclear modification factors

The difference between proton PDFs and nuclear PDFs

- There are different nuclear effects that cause the difference between PDFs and nPDFs (Fermi motion, shadowing, anti-shadowing, EMC effect)

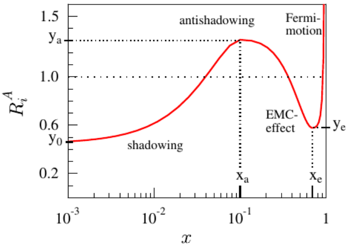


Figure : Different contributions to the nuclear modification factors, from arXiv:0902.4154.

DPS in pA collisions. Impact of nPDFs

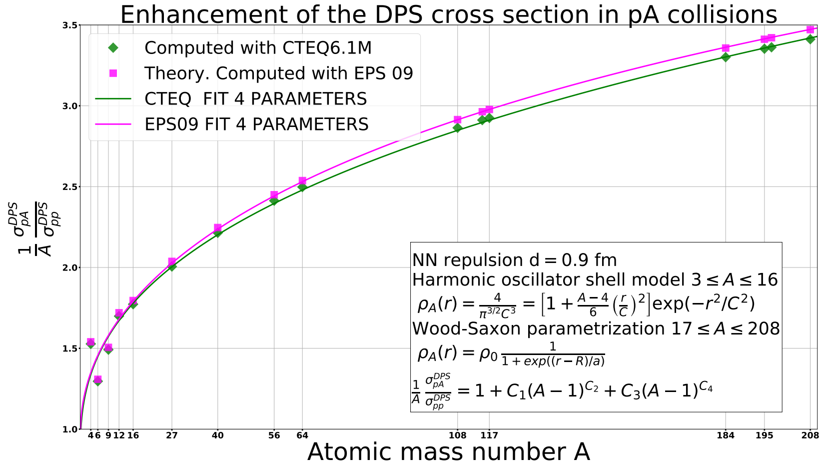
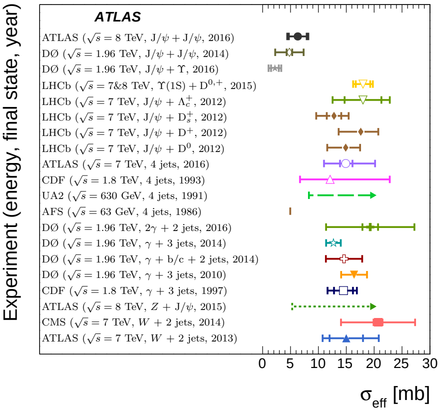


Figure : Enhancement of a total DPS cross section in pA collisions. Impact of nPDFs.

Measurements of σ_{eff}



What is σ_{eff}?

Assuming no correlation in x-space one can write $D_p^{ij}(x_1, x_2) \approx f_i(x_1) f_j(x_2)$

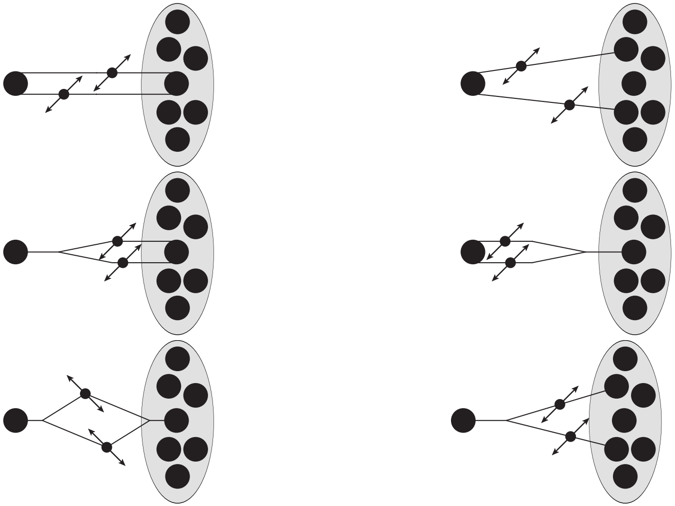
It gives a "pocket formula": $\sigma_{DPS} = \sigma_A \sigma_B / (1 + \delta_{AB}) \sigma_{eff}$

The quantity $1/\sigma_{eff} = \int d^2\mathbf{b}\, [F(\mathbf{b})]^2$ can be extracted from the data

Is two times smaller as one could expect

Figure : Different measurements of σ_{eff} (from arXiv:1704.00059)

DPS in pA collisions



Comparison against results of Maciuła and Szczurek, 2015

$\sqrt{s} = 7\,\mathrm{TeV}$, $\Delta R > 0.7$	DPS fraction (my result)	DPS fraction (Krakow)
$\lvert y \rvert < 4.7$, $p_T \in [35, 100]\,\mathrm{GeV}$	42.5%	42.5%
$\lvert y \rvert < 4.7$, $p_T \in [20, 100]\,\mathrm{GeV}$	72.3%	70.0%
$\lvert y \rvert < 4.7$, $p_T \in [20, 100]\,\mathrm{GeV}$, $\Delta Y > 7.0$	93.46%	86.0%

Table : The relative fraction of the DPS events. PDF set is MSTW2008lo68cl. The factorization and renormalization scales are equal to $\hat{s}$. Only first 4 flavours (considered as massless).

Comparison against results of Maciuła and Szczurek, 2015

$\sqrt{\mathbf{s}} = \mathbf{14}\,\mathrm{TeV}$, $\Delta R > 0.7$	DPS fraction (my result)	DPS fraction (Krakow)
$|\mathbf{y}| < \mathbf{4.7}$, $\mathbf{p_T} \in [\mathbf{35}, \mathbf{100}]\mathrm{GeV}$	61.4%	58.2%
$|\mathbf{y}| < \mathbf{4.7}$, $\mathbf{p_T} \in [\mathbf{20}, \mathbf{100}]\mathrm{GeV}$	83.2%	79.9%
$|\mathbf{y}| < \mathbf{4.7}$, $\mathbf{p_T} \in [\mathbf{20}, \mathbf{100}]\mathrm{GeV}$, $\Delta Y > 7.0$	95.78%	89.0%

Table : The relative fraction of the DPS events. PDF set is MSTW2008lo68cl. The factorization and renormalization scales are equal to $\hat{s}$. Only first 4 flavours (considered as massless).