Double (and triple) parton scattering in pA/AA collisions

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THE ROYAL SOCIETY

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INITIAL STAGES
OF HIGH-ENERGY NUCLEAR
COLLISIONS

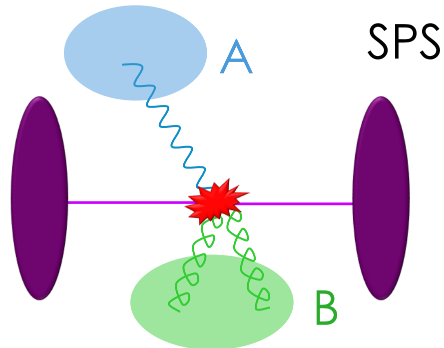
OUTLINE

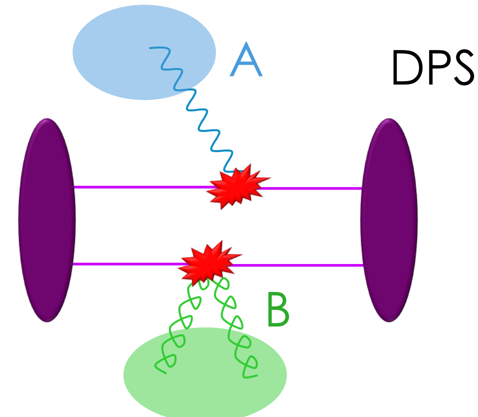
Review recent theoretical work on DPS and TPS in pA and AA collisions.

Main focus: what can we learn from studying DPS/TPS in pA and AA collisions that is complementary to what we learn from pp DPS/TPS?

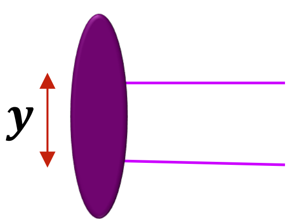
DOUBLE PARTON SCATTERING: BASICS

Double parton scattering (DPS) is where we have **two hard scatters** in one collision





Cross section for DPS in **proton-proton** collisions given by:



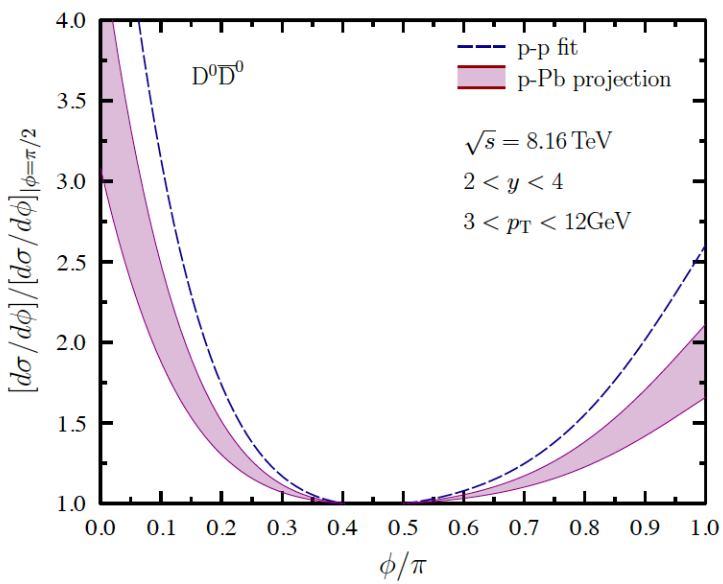
Double parton distributions (DPDs)

$$\sigma_{DPS}^{(A,B)} = \int dx_i dx'_i d^2\boldsymbol{y}\, \Phi^2(yv)\, \boxed{F_{ik}(x_1, x_2, \boldsymbol{y}, \mu_A, \mu_B)}\, \boxed{F_{jl}(x'_1, x'_2, \boldsymbol{y}, \mu_A, \mu_B)}$$
$$\times \boxed{\hat{\sigma}_{ij}^{A}(x_1 x'_1 s, \mu_A)}\, \boxed{\hat{\sigma}_{kl}^{B}(x_2 x'_2 s, \mu_B)}$$

Paver, Treleani, Nuovo Cim. A70 (1982) 215, Mekhfi, Phys.Rev. D32 (1985) 2371, Diehl, Ostermeier, Schafer, JHEP 1203 (2012) 089, Diehl, JG, Schönwald JHEP 1706 (2017) 083…

WHY DPS?

Why is DPS interesting/important?



Helenius, Paukkunen,
Phys.Lett.B 800 (2020) 135084
See talk by H. Paukkunen

(1) Can be an **important background to various single scattering processes.**

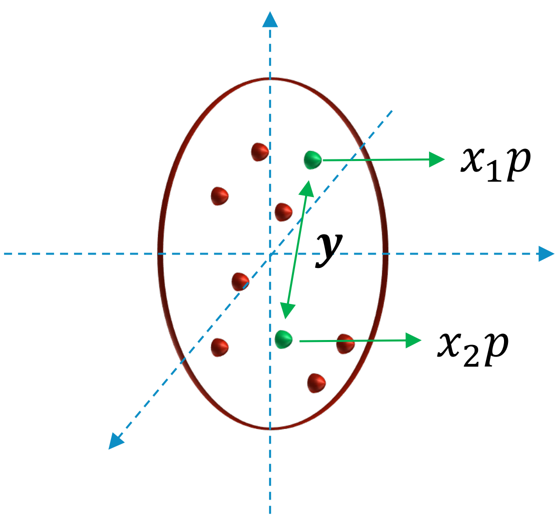
Example in pA: $D^0\overline{D}^0$ meson production

Weakening of "away side" azimuthal peak in pA could be caused by saturation effects…

…but **weakening of peaks can also be caused by DPS** (gives ~ flat distribution in ϕ)

WHY DPS?

(2) DPS gives us **new information on hadronic structure**: namely, **correlations between partons**



Double parton distributions (DPDs)

$$F_{ik}(x_1, x_2, \boldsymbol{y})$$

DPDs are complex objects – possibility of correlations:

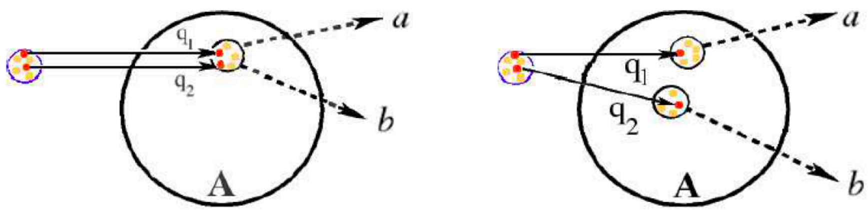
- between x_1 and x_2 dependence (**longitudinal correlations**)
- between x_1, x_2 dependence and y (**transverse correlations**)

pp DPS probes DPDs in a very particular way: $\int F(\boldsymbol{y})F(\boldsymbol{y})d^2\boldsymbol{y}$

Do pA/AA provide additional information?

DPS IN pA COLLISIONS

For pA, **two** possible contributions to DPS:



Nuclear thickness: $T(\boldsymbol{B}) = \int \rho(z, \boldsymbol{B})\, \mathrm{d}z$

Assume this is ~ constant over size of one nucleon. Ignore nuclear matter effects.

Strikman, Treleani, Phys.Rev.Lett. 88 (2002) 031801

$$\sigma_{pA,\,\mathrm{I}}^{\mathrm{DPS}} = \frac{m}{2} \int F(x_1, x_2, \boldsymbol{y}) F(x_1', x_2', \boldsymbol{y}) \hat{\sigma}_a \hat{\sigma}_b dx_i dx_i' \, d^2\boldsymbol{y} \int d^2\boldsymbol{B}\, T(\boldsymbol{B}) = A\sigma_{pp}^{\mathrm{DPS}}$$

Probes L + T correlations in the same way as pp DPS

$$\sigma_{pA,\,\mathrm{II}}^{\mathrm{DPS}} = \frac{m}{2} \frac{A-1}{A} \int f(x_1') f(x_2') \left[\int F(x_1, x_2, \boldsymbol{y})\, d^2\boldsymbol{y} \right] \hat{\sigma}_a \hat{\sigma}_b dx_i dx_i' \int d^2\boldsymbol{B}\, T^2(\boldsymbol{B})$$

Probes longitudinal correlations of **one DPD only**

II contribution in pA probes DPDs in a different way to pp DPS.

DPS IN pA COLLISIONS

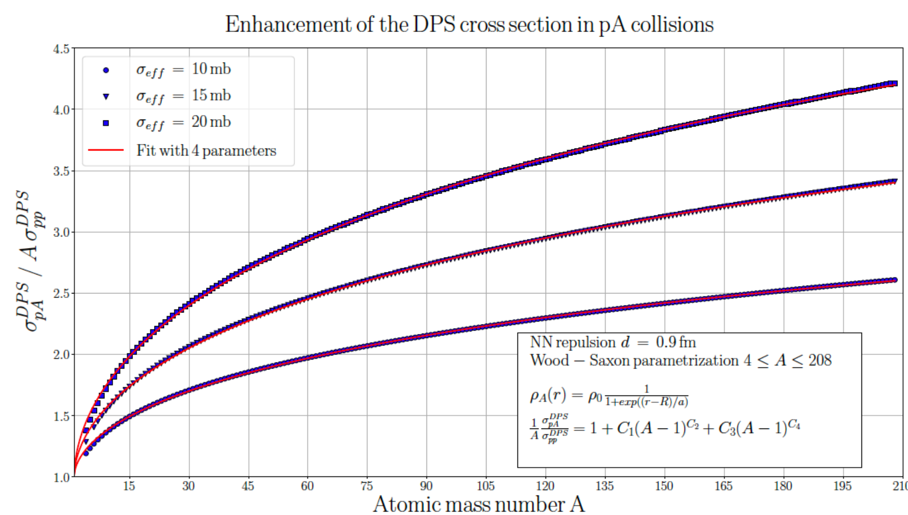
Common simplified ansatz (neglect correlations): $F(x_1, x_2, \boldsymbol{y}) \rightarrow f(x_1)\, f(x_2)\, G(\boldsymbol{y})$

Then: $\sigma_{\mathrm{I}}^{\mathrm{DPS}} = A \frac{m}{2} \frac{\sigma_a \sigma_b}{\sigma_{eff}} = A \sigma_{pp}^{\mathrm{DPS}}$ $\qquad$ $\sigma^{\mathrm{SPS}} = A \sigma_{pp}^{\mathrm{SPS}}$

$$\sigma_{\mathrm{II}}^{\mathrm{DPS}} = \frac{m}{2} \frac{A-1}{A} \sigma_a \sigma_b \int d^2\boldsymbol{B}\, T^2(\boldsymbol{B})$$

If nucleus is sphere of constant density, $\frac{\sigma_{\mathrm{II}}^{\mathrm{DPS}}}{\sigma^{\mathrm{SPS}}} \propto A^{\frac{1}{3}}$. **Relative importance of DPS grows with A in pA.**

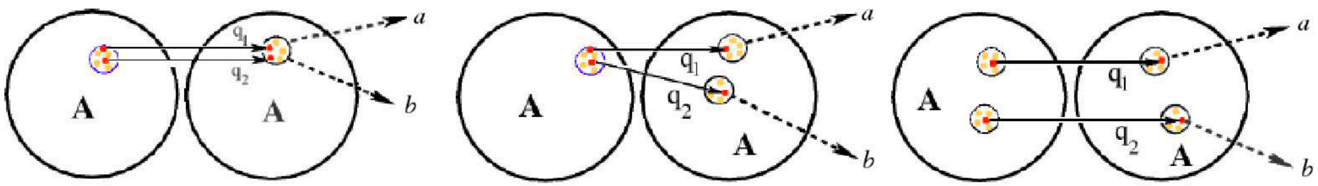
$\frac{\sigma_{\mathrm{II}}^{\mathrm{DPS}}}{\sigma_{\mathrm{I}}^{\mathrm{DPS}}} \sim 2$ at large A, **two contributions comparable**.



Fedkevych, Lonnblad, Phys.Rev.D 102 (2020) 1, 014029

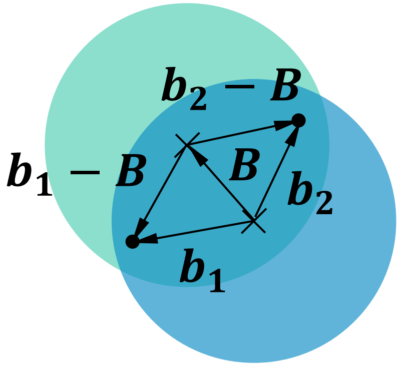
DPS IN AA COLLISIONS

For AA collisions, three contributions to DPS:



$$\sigma_{AA,\mathrm{I}}^{\mathrm{DPS}} = A^2 \sigma_{pp}^{\mathrm{DPS}} \qquad \sigma_{\mathrm{AA,\,II}}^{\mathrm{DPS}} = 2A\sigma_{pA}^{\mathrm{DPS}}$$

$$\sigma_{\mathrm{AA,\,III}}^{\mathrm{DPS}} = \frac{m}{2}\left(\frac{A-1}{A}\right)^2 \sigma_a \sigma_b \times \int T(\boldsymbol{b_1})\,T(\boldsymbol{b_2})T(\boldsymbol{b_1}-\boldsymbol{B})T(\boldsymbol{b_2}-\boldsymbol{B})d^2\boldsymbol{b_1}d^2\boldsymbol{b_2}d^2\boldsymbol{B}$$



This contribution corresponds to **double nucleon-nucleon scattering** – doesn't probe parton-parton correlations.

d'Enterria, Snigirev, *Phys.Lett.B* 727 (2013) 157-162, *Adv.Ser.Direct.High Energy Phys.* 29 (2018) 159-187

DPS IN AA COLLISIONS

Relative size of three contributions? Rough estimate using hard sphere nucleus & large A:

$$\sigma_{AA}^{DPS} \approx A^2 \sigma_{pp}^{\text{DPS}} \left[\underbrace{1}_{\mathrm{I}} + \underbrace{\frac{2}{\pi} A^{1/3}}_{\mathrm{II}} + \underbrace{\frac{1}{2\pi} A^{4/3}}_{\mathrm{III}} \right]$$

Term III grows much faster than the other two, dominates other two for reasonably large A:

$A = 40$ (Ca):	I: II: III = 1: 2.3: 23	87% is term III
$A = 208$ (Pb):	I: II: III = 1: 4: 200	97.5% is term III

d'Enterria, Snigirev, *Phys.Lett.B* 727 (2013) 157-162, *Adv.Ser.Direct.High Energy Phys.* 29 (2018) 159-187

In AA collisions, DPS is dominated by double nucleon-nucleon scattering

DPS IN pA:

pA DPS studied by LHCb in context of charm meson pair production.

LHCb, Phys.Rev.Lett. 125 (2020) 21, 212001

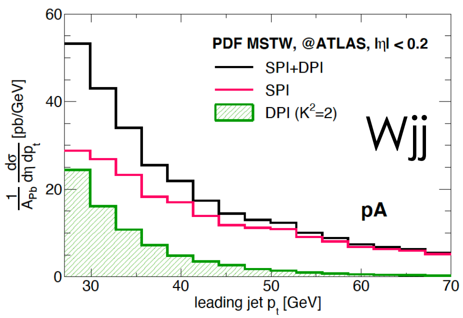
$D^0 D^0$ and $J/\psi D^0$ data **consistent with DPS production alone**, & (mostly) consistent with Strikman-Treleani predictions

$$\underbrace{\frac{m}{2}\,\frac{\sigma^{SPS}_{pA,a}\sigma^{SPS}_{pA,b}}{\sigma^{DPS}_{pA,ab}}\,[b]}_{} \qquad A\sigma_{eff}[b]$$

Pairs	$-5 < y(H_c) < -2.5$	$1.5 < y(H_c) < 4$	pp extrapolation
$D^0 D^0$	$0.99 \pm 0.09 \pm 0.09$	$1.41 \pm 0.11 \pm 0.10$	4.3 ± 0.5
$J/\psi D^0$	$0.64 \pm 0.10 \pm 0.06$	$0.92 \pm 0.22 \pm 0.06$	3.1 ± 0.3

See talk by Yiheng Luo

$$\sim \frac{1}{3}$$



Salvini, Calucci, Treleani, *Phys.Rev.D* 89 (2014) 1, 0 16020

pPb (8.8 TeV)	$J/\psi + J/\psi$	$J/\psi + \Upsilon$	J/ψ+W	J/ψ+Z
$\sigma^{SPS}_{pN\to a}, \sigma^{SPS}_{pN\to b}$	45 μb ($\times 2$)	45 μb, 2.6 μb	45 μb, 60 nb	45 μb, 35 nb
σ^{DPS}_{pPb}	45 μb	5.2 μb	120 nb	70 nb
N^{DPS}_{pPb} (1 pb^{-1})	$\sim$65	$\sim$60	$\sim$15	$\sim$3
	$\Upsilon + \Upsilon$	Υ+W	Υ+Z	ss WW
$\sigma^{SPS}_{pN\to a}, \sigma^{SPS}_{pN\to b}$	2.6 μb ($\times 2$)	2.6 μb, 60 nb	2.6 μb, 35 nb	60 nb ($\times 2$)
σ^{DPS}_{pPb}	150 nb	7 nb	4 nb	150 pb
N^{DPS}_{pPb} (1 pb^{-1})	$\sim$15	$\sim$8	$\sim$1.5	$\sim$4

d'Enterria, Snigirev, *Adv.Ser.Direct.High Energy Phys.* 29 (2018) 159-187

Should be able to observe DPS in various channels for pA.

DPS IN pA: SEPARATING OFF DPS_{II}

Can we separate off novel 'II' component of pA DPS from 'I' component and SPS?

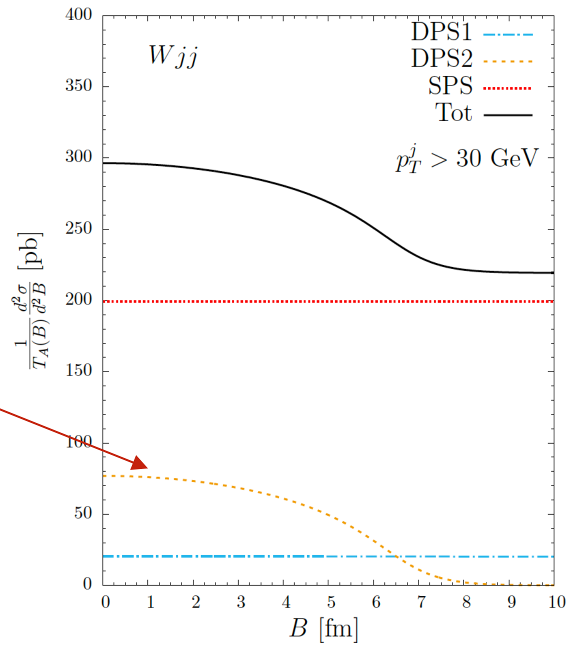
One possible way – use different A dependence of different contributions. Requires pA runs for nuclei with various A values.

Calucci, Treleani, *Phys.Rev.D* 86 (2012) 036003

Alternative approach: exploit the fact that DPS_{II} and DPS_{I} / SPS have a different dependence on impact parameter $\boldsymbol{B}$

Alvioli, Azarkin, Blok, Strikman, *Eur.Phys.J.C* 79 (2019) 6, 482

$$\frac{d\sigma_{pA,\,\text{I}}^{\text{DPS}}}{d^2\boldsymbol{B}},\ \frac{d\sigma^{\text{SPS}}}{d^2\boldsymbol{B}} \propto T(\boldsymbol{B}) \qquad \frac{d\sigma_{pA,\,\text{II}}^{\text{DPS}}}{d^2\boldsymbol{B}} \propto T^2(\boldsymbol{B})$$



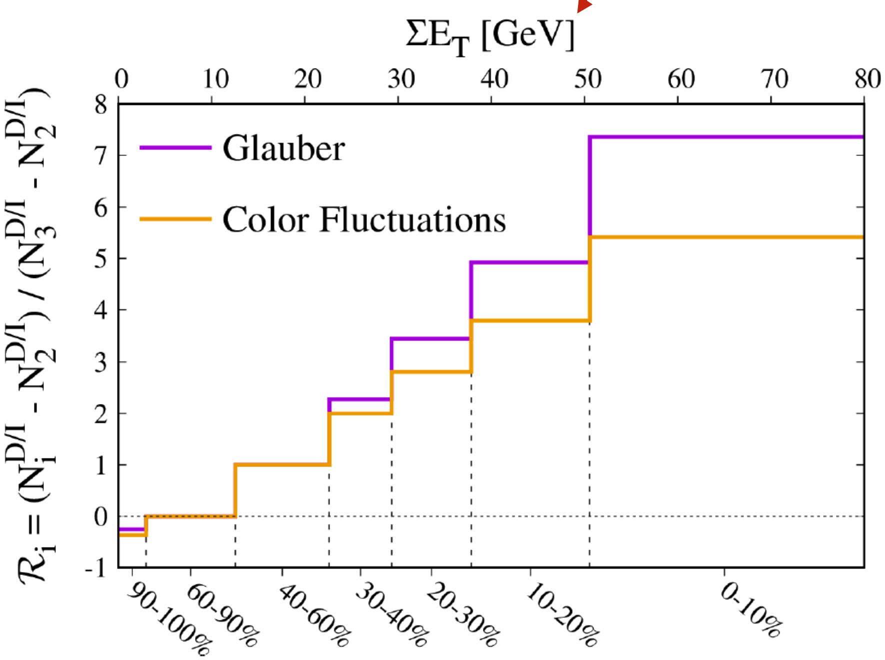
Cannot directly measure $\boldsymbol{B}$ – must use some 'centrality' proxy.

Blok, Ceccopieri, *Eur.Phys.J.C* 80 (2020) 3, 278

DPS IN pA: SEPARATING OFF DPS$_{||}$

$\pi + 2j$ final state:

Measured in $-3.2 \geq \eta \geq -4.9$ (along nucleus direction)



'Centrality bin'

Study using Monte Carlo

- Nucleon-nucleon interactions
- Description of transverse geometry of soft & hard
- Fluctuations in interaction strength of proton with nucleus

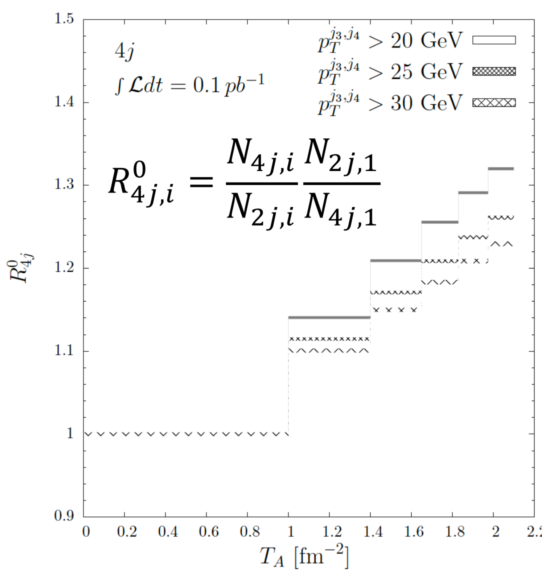
$$N_i^{\mathrm{D/I}} = \frac{N_i(\pi + 2j)}{N_i(2j)}$$

Slope of $N_i^{\mathrm{D/I}}$ determined by DPS$_{||}$ contribution

Alvioli, Azarkin, Blok, Strikman, *Eur.Phys.J.C* 79 (2019) 6, 482

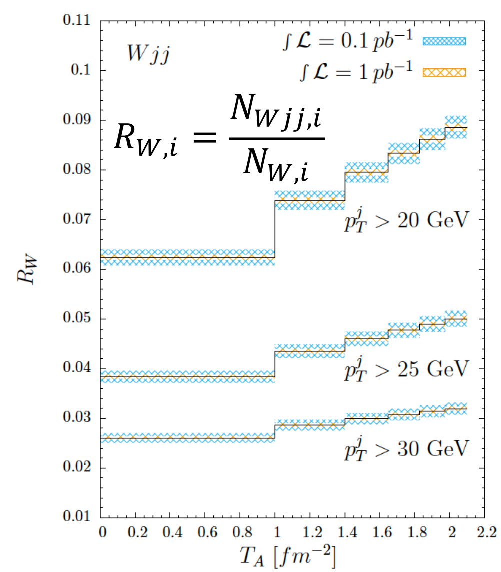
DPS IN pA: SEPARATING OFF DPS$_{\text{II}}$

Four-jet final state:



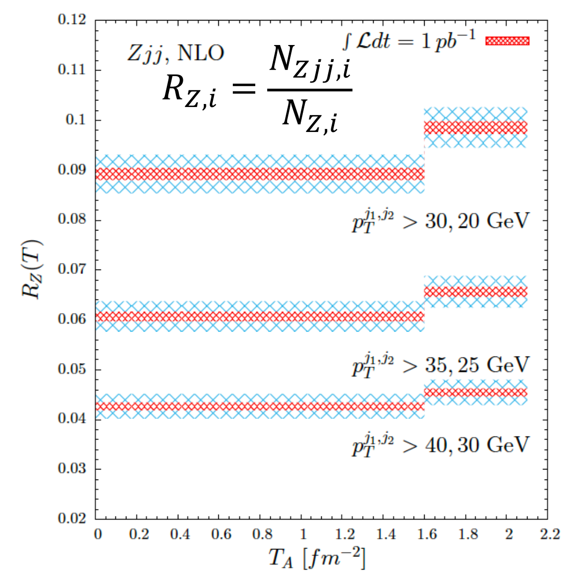
Blok, Ceccopieri,
Phys.Rev.D 101 (2020) 9, 094029

Wjj final state:



Blok, Ceccopieri,
Eur.Phys.J.C 80 (2020) 3, 278

Zjj final state:



Blok, Ceccopieri,
Eur.Phys.J.C 80 (2020) 8, 762

DPS$_{\text{II}}$ contribution in various channels can already be disentangled from SPS & DPS$_{\text{I}}$ using data from 2016 pA run!

pA DPS USING ANGANTYR

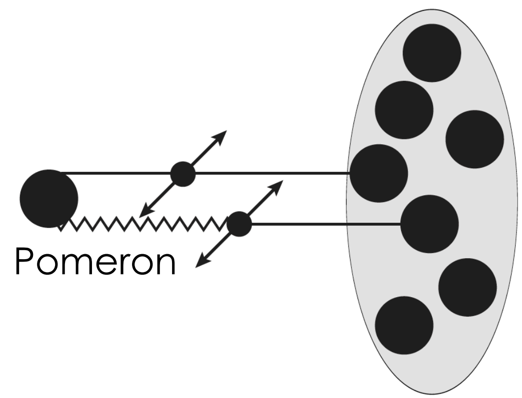
Extension of Pythia for HI collisions: Angantyr.

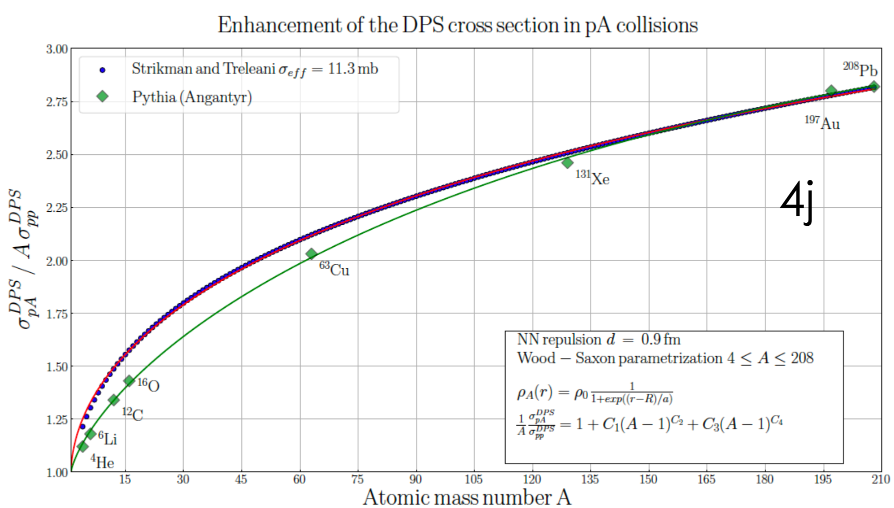
Bierlich, Gustafson, Lönnblad, Shah, *JHEP* 10 (2018) 134

Can be used e.g. to simulate pA DPS events.

Fedkevych, Lönnblad, Phys.Rev.D 102 (2020) 1, 014029

Scatter with two different nucleons modelled using simplified MPI machinery + modified diffraction machinery.

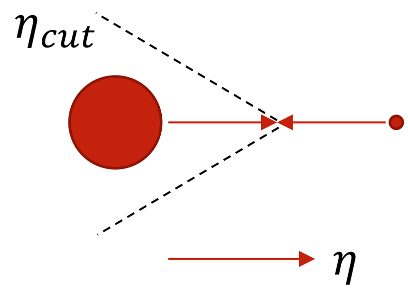




pA DPS enhancement factor shows similar dependence on A to simple Strikman-Treleani formula (at large A)

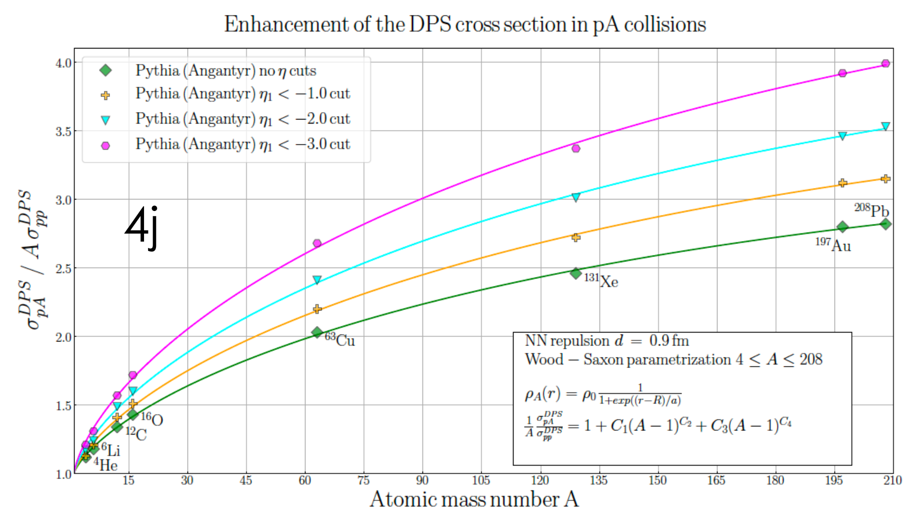
pA DPS USING ANGANTYR

Add cut requiring at least one jet to have an $\eta < \eta_{cut}$



In Angantyr predictions, pA DPS enhancement depends on η_{cut}.

No such dependence in Strikman-Treleani formula.



Fedkevych, Lönnblad, Phys.Rev.D 102 (2020) 1, 014029

NUCLEAR MATTER EFFECTS IN pA/AA DPS

Nuclear matter effects (shadowing…) contained in modifications of nuclear PDFs.

In general will need **impact parameter dependent** nuclear PDFs (inPDFs) $f_N(x, \boldsymbol{b})$ - e.g. expect more shadowing near centre of nucleus.

Usual nuclear PDFs (nPDFs) determined in terms of inPDFs according to:

$$f_N(x) \equiv \int f_N(x, \boldsymbol{b}) T(\boldsymbol{b}) d^2\boldsymbol{b} \,/A$$

For SPS: minimum bias collisions probe only $f_N(x)$. The $f_N(x, \boldsymbol{b})$ will appear in measurements with some centrality selection.

NUCLEAR MATTER EFFECTS IN pA/AA DPS

Since DPS involves two collisions, even minimum-bias DPS can't be written in terms of $f_N(x)$ alone.

For example, in pA, ignoring parton-parton correlations in nucleons:

$$\sigma_{pA,\,\mathrm{I}}^{\mathrm{DPS}} \propto \int [f_N(x,\boldsymbol{b})]^2 T(\boldsymbol{b}) d^2\boldsymbol{b} \qquad \sigma_{pA,\,\mathrm{II}}^{\mathrm{DPS}} \propto \int [f_N(x,\boldsymbol{b})]^2 T(\boldsymbol{b})^2 d^2\boldsymbol{b}$$

➔ **(minimum bias) pA and AA DPS probes the inPDFs, and is a useful source of information on them**!

Proposed by Shao, where full expressions for pA/AA DPS cross sections are given (neglecting parton-parton correlations in nucleons).

Shao, *Phys.Rev.D* 101 (2020) 5, 054036

n.b. for AA DPS dominant term doesn't involve intra-nucleon partonic correlations.

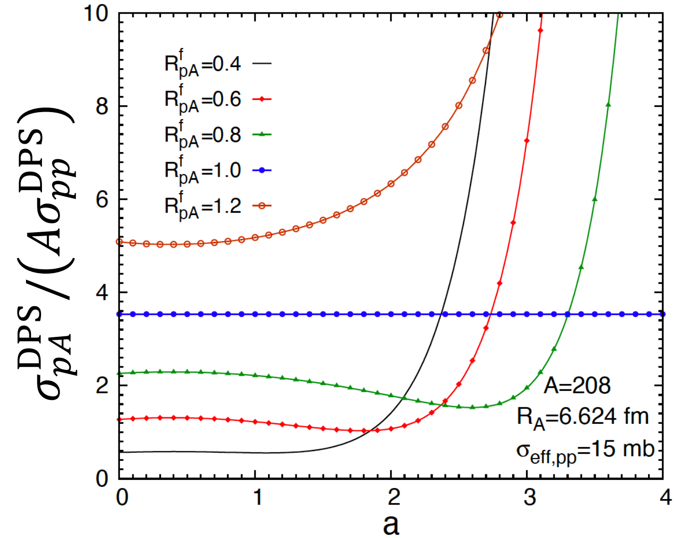
NUCLEAR MATTER EFFECTS IN pA/AA DPS

Possible form for inPDFs:

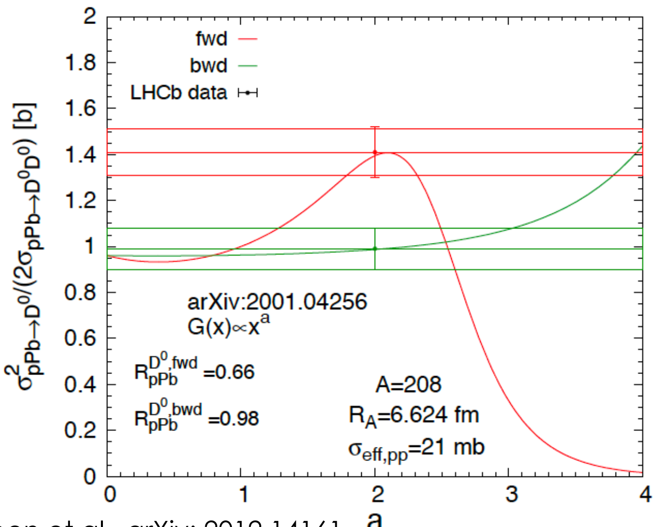
$$f_N(x,\boldsymbol{b}) = f(x) + [f_N(x) - f(x)]G\left[\frac{T(\boldsymbol{b})}{T(\boldsymbol{0})}\right]$$

Shadowing term

Simple ansatz: $G\left[\frac{T(\boldsymbol{b})}{T(\boldsymbol{0})}\right] = \left(\frac{a+3}{3}\right)\left[\frac{T(\boldsymbol{b})}{T(\boldsymbol{0})}\right]^a$



Shao, *Phys.Rev.D* 101 (2020) 5, 054036



Chapon et al., arXiv: 2012.14161

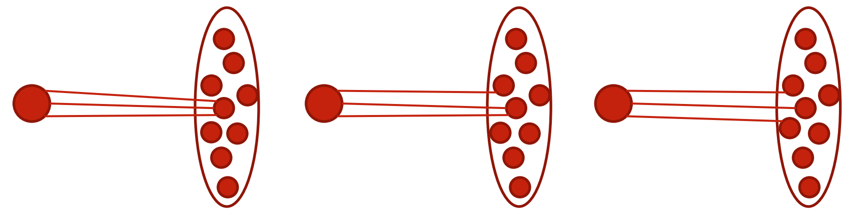
These nuclear effects could explain LHCb observation of non-identical SPS^2/DPS ratio between the forward and backward regions, for D0 meson production in pA.

LHCb, Phys.Rev.Lett. 125 (2020) 21, 212001

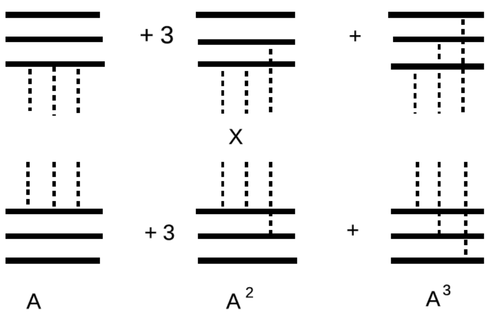
TRIPLE PARTON SCATTERING

Triple parton scattering: **three** hard parton-parton scatters

Three contributions in pA



pPb: 1 : 4.5 : 3.6



AA TPS dominated by terms where all partons originate from different nucleons, $\propto A^{14/3}$

Appreciable pA TPS cross-sections for triple heavy quark pair production, particularly at an FCC.

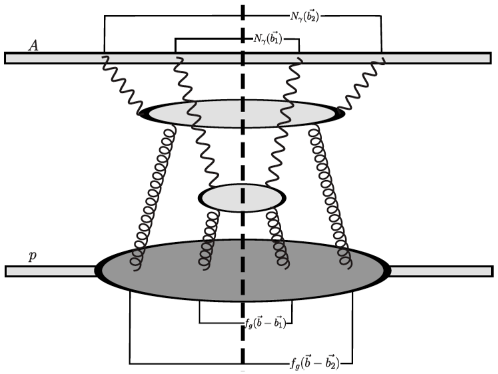
Final state	$\sqrt{s_{\rm NN}} = 8.8$ TeV	$\sqrt{s_{\rm NN}} = 63$ TeV
$\sigma(c\bar{c} + X)$	$960 \pm 450_{\rm sc} \pm 100_{\rm pdf}$	$3400 \pm 1900_{\rm sc} \pm 380_{\rm pdf}$
$\sigma(c\bar{c}\, c\bar{c}\, c\bar{c} + X)$	$200 \pm 140_{\rm tot}$	$8700^{*} \pm 6200_{\rm tot}$
$\sigma(b\bar{b} + X)$	$72 \pm 12_{\rm sc} \pm 5_{\rm pdf}$	$370 \pm 75_{\rm sc} \pm 30_{\rm pdf}$
$\sigma(b\bar{b}\, b\bar{b}\, b\bar{b} + X)$	$0.084 \pm 0.045_{\rm tot}$	$11 \pm 7_{\rm tot}$

d'Enterria, Snigirev, *Eur.Phys.J.C* 78 (2018) 5, 359, *Adv.Ser.Direct.High Energy Phys.* 29 (2018) 159-187

DPS IN UPCs

Possibility to observe DPS in pA or AA UPCs

Huayra, de Oliveira, Pasechnik,
Eur.Phys.J.C 79 (2019) 10, 880,
Eur.Phys.J.C 80 (2020) 8, 772



Formula in pA:

$$\frac{d^4\sigma_{pA\to XA+c\bar{c}+b\bar{b}}}{dy_c dy_{\bar{c}} dy_b dy_{\bar{b}}} = \int d^2b\, \Theta(b - R_A - R_p) \int d^2\vec{b}_{\gamma,1}\, \Theta(b_{\gamma,1} - R_A) \int d^2\vec{b}_{\gamma,2}\, \Theta(b_{\gamma,2} - R_A)$$

$$\times \int d\xi_1 d\xi_2 dx_1 dx_2 N_{\gamma\gamma}(\xi_1, \vec{b}_{\gamma,1}; \xi_2, \vec{b}_{\gamma,2}) G_{gg}(x_1, \vec{b}_{g,1}; x_2, \vec{b}_{g,2}) \frac{d^2\hat{\sigma}_{\gamma g\to c\bar{c}}}{dy_c dy_{\bar{c}}} \frac{d^2\hat{\sigma}_{\gamma g\to b\bar{b}}}{dy_b dy_{\bar{b}}} \quad (2.19)$$

Determined by QED

Offers an alternative way to probe the DPDs.

SUMMARY

Proton-nucleus DPS:

- Two contributions: DPS_{I} & DPS_{II}. $\sigma_{pA,\,\text{II}}^{\text{DPS}}\,/\sigma_{pA,\,\text{I}}^{\text{DPS}}$ ~ 2, and $\sigma_{pA}^{\text{DPS}}\,/\sigma_{pp}^{\text{DPS}}$ ~ 3A.
- DPS_{II} probes DPDs in a different way to pp DPS. New information!
- DPS_{I} & DPS_{II} have different dependencies on centrality – can use to extract DPS_{II}. Pythia/Angantyr also predicts DPS_{I} & DPS_{II} have different dependencies on rapidity of hard system.

Nucleus-nucleus DPS: Three contributions. Dominated by double nucleon-nucleon scattering contribution.

pA & AA DPS offers the prospect to probe **nuclear effects** – provides new information on **impact-parameter dependent nuclear PDFs.**

Triple parton scattering: $\sigma_{pA}^{\text{TPS}}\,/\sigma_{pA}^{\text{DPS}}$ ~ 9A. TPS in AA dominated by triple nucleon-nucleon scattering. Potential to measure in quarkonium production.