Double Parton Scattering in pA

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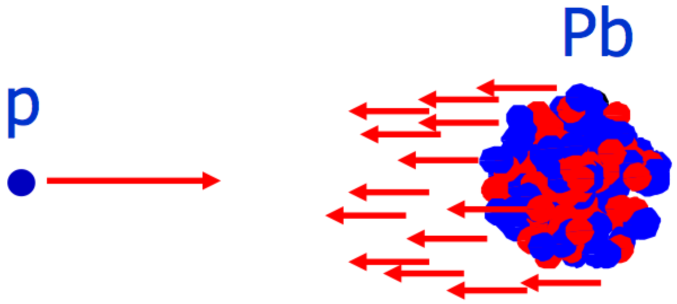
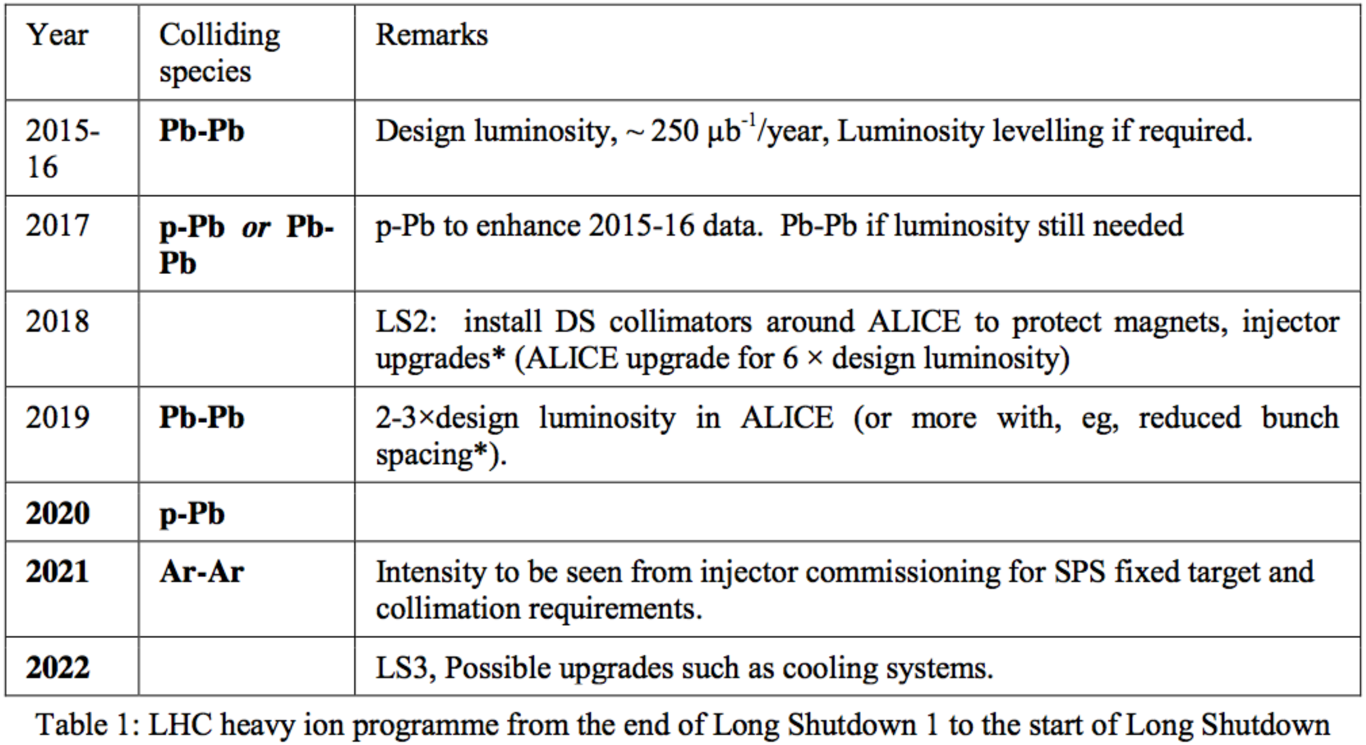


MPI workshop,
6 December 2012
CERN

pA @ LHC

- Is the first LHC ‘upgrade’ (pA not part of original LHC baseline programme)
- Is feasible: p-Pb pilot run during the night of 12-13 September 2012
  http://cdsweb.cern.ch/record/1496101
- Even few hrs pilot run [luminosity O(10^{26}/ cm^2 s)] resulted in physics (publications by ALICE, arXiv:1210.3615, arXiv1210.4520 , CMS arXiv:1210.5482, raw data by LHCb shown at this workshop.) This illustrates how little is known about pA.
- Jan/Feb 2013 first ~4 week pA run
- Further runs are foreseen after LS1

John Jowett, CERN Beam Department
Submission to Cracow Open Symposium of European Strategy Preparatory Group,
https://indico.cern.ch/contributionDisplay.py?contribId=164&confId=175067



Year	Colliding species	Remarks
2015-16	**Pb-Pb**	Design luminosity, ~ 250 μb^{-1}/year, Luminosity levelling if required.
2017	**p-Pb** ***or*** **Pb-Pb**	p-Pb to enhance 2015-16 data. Pb-Pb if luminosity still needed
2018		LS2: install DS collimators around ALICE to protect magnets, injector upgrades* (ALICE upgrade for 6 × design luminosity)
2019	**Pb-Pb**	2-3×design luminosity in ALICE (or more with, eg, reduced bunch spacing*).
2020	**p-Pb**	
2021	**Ar-Ar**	Intensity to be seen from injector commissioning for SPS fixed target and collimation requirements.
2022		LS3, Possible upgrades such as cooling systems.

Table 1: LHC heavy ion programme from the end of Long Shutdown 1 to the start of Long Shutdown

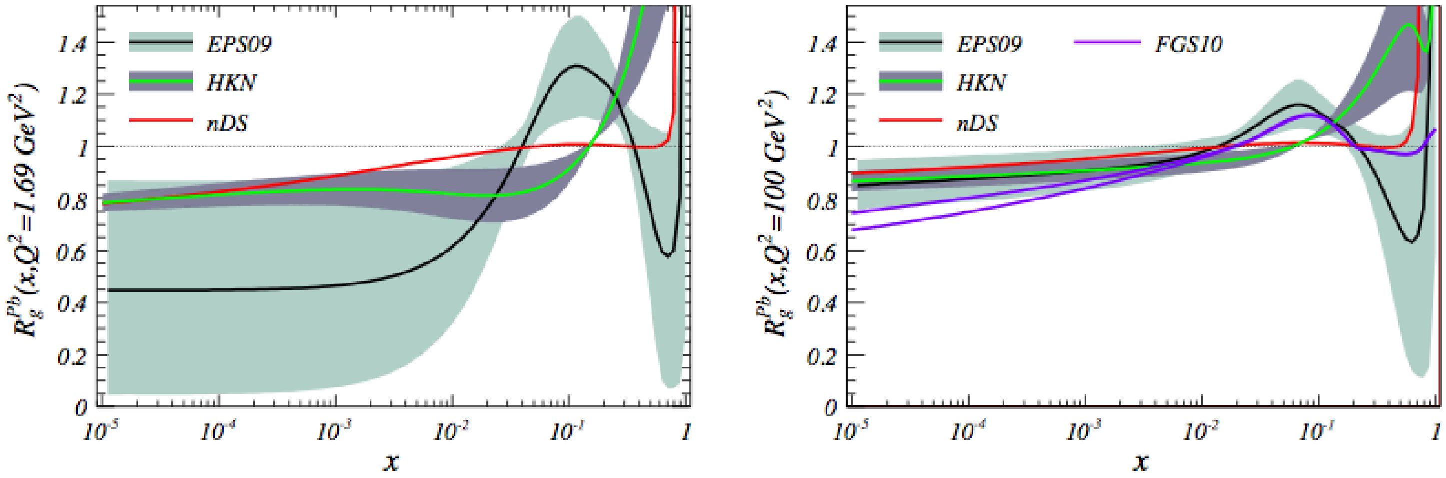
Motivations for pA @ LHC

documented in a CERN workshop report:
C.A. Salgado et al, J.Phys.G39 (2012) 015010

- pA as benchmark for AA collisions
  - nuclear parton distribution functions
  - benchmarking hard processes
- Testing perturbative saturation
- Other physics opportunities (‘exotica’)
  - ultra-peripheral collisions
  - measurements of astrophysical interest

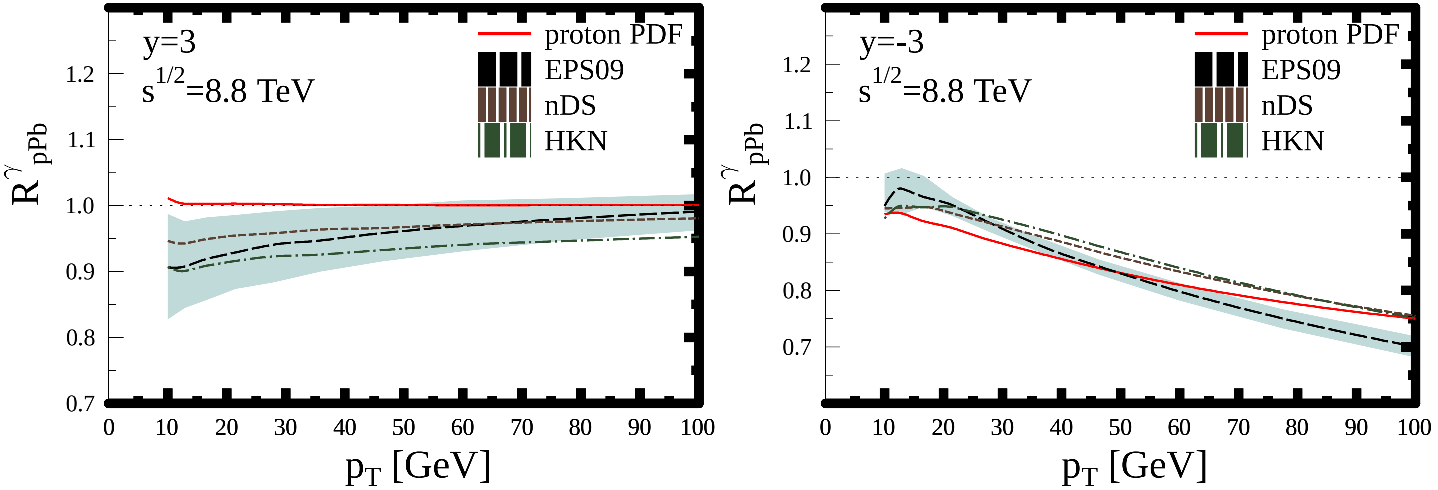
Nuclear pdfs

- Current status of global npdf-fits
  Nuclear modifications concentrated at small/moderate Q^2



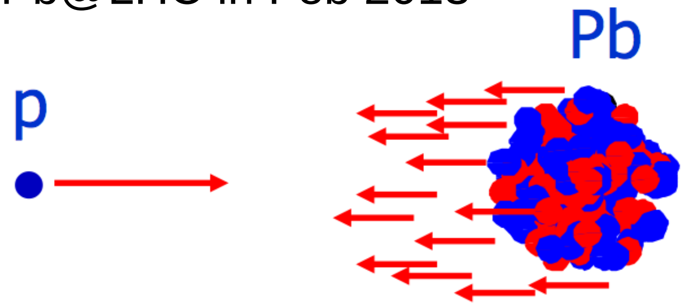
- That nuclear dependence of pdfs can be factorized in process-independent pdfs is a working hypothesis, central for analysis of AA collisions.
  Can be tested/established in pPb@LHC

Arleo et al, arXiv1103.1471



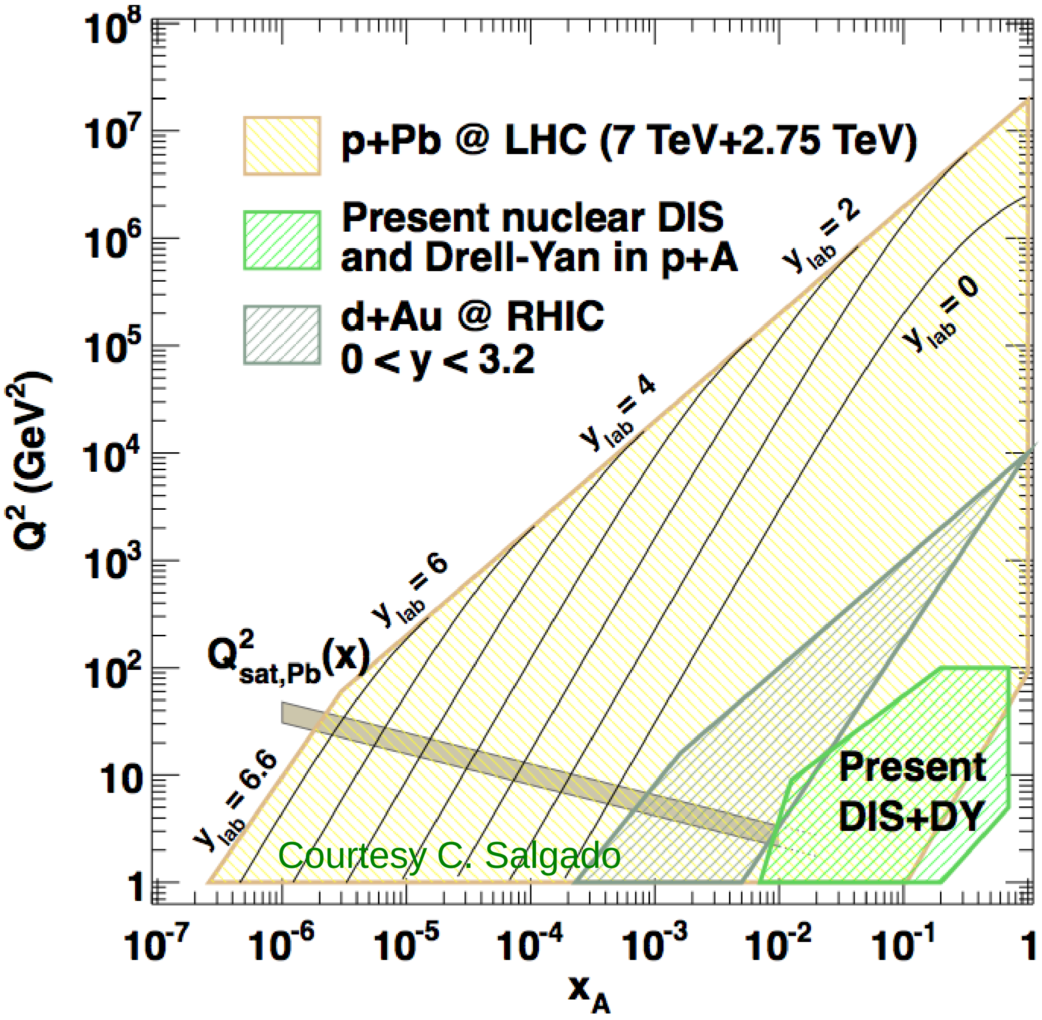
Nuclear pdfs poorly constrained by data

- pPb@LHC in Feb 2013



- $$\boxed{y^{RHIC}_{forward} \Leftrightarrow y^{LHC}_{mid-rapidity}}$$

- pPb@LHC accesses entire kinematic range of currently discussed future e-A colliders (EIC, LHeC)



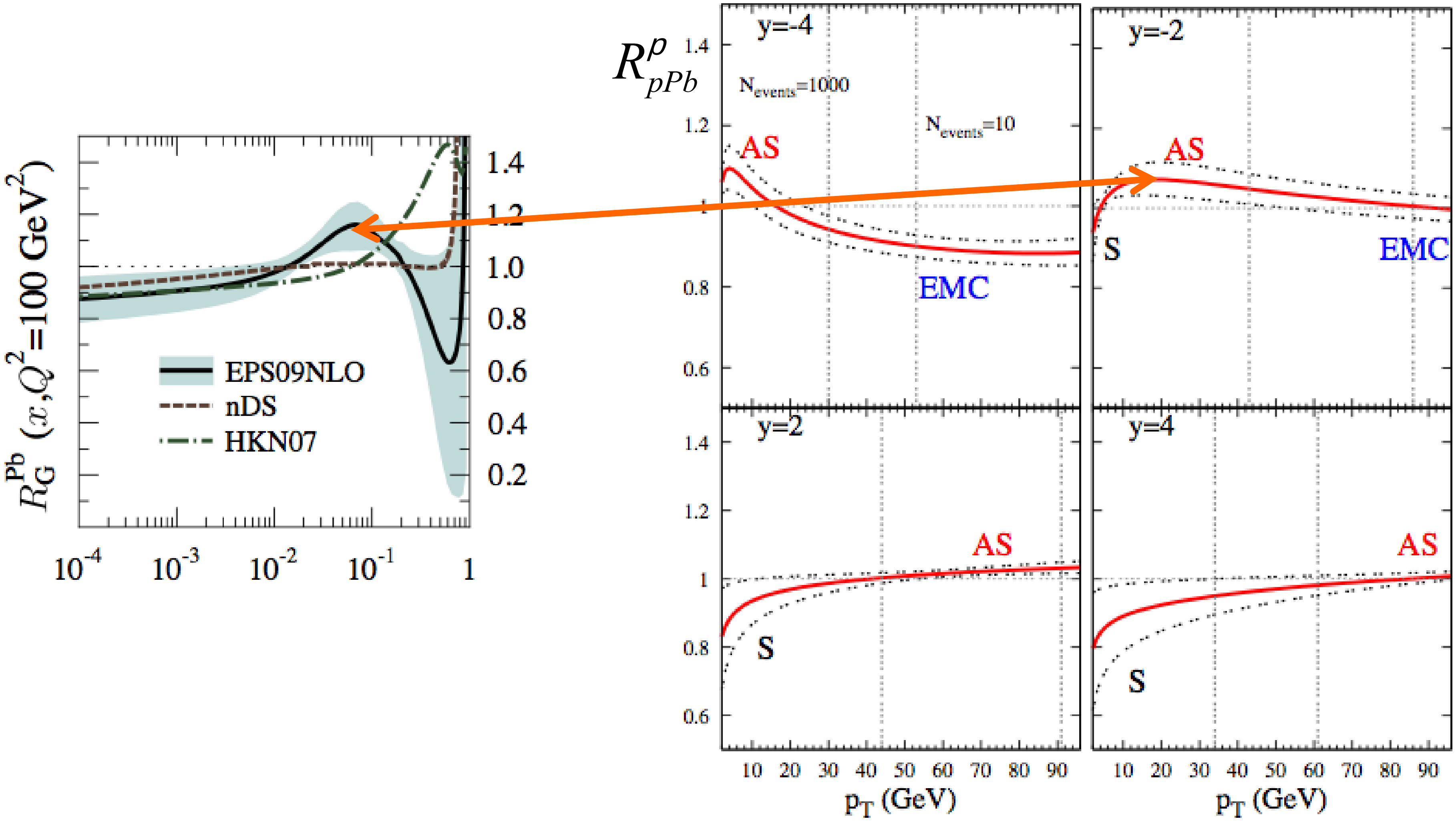
Courtesy C. Salgado

Nuclear modification factors constrain npdfs

- In collinear formalism:

Cronin peak ⇔ Anti-shadowing (**AS**) peak

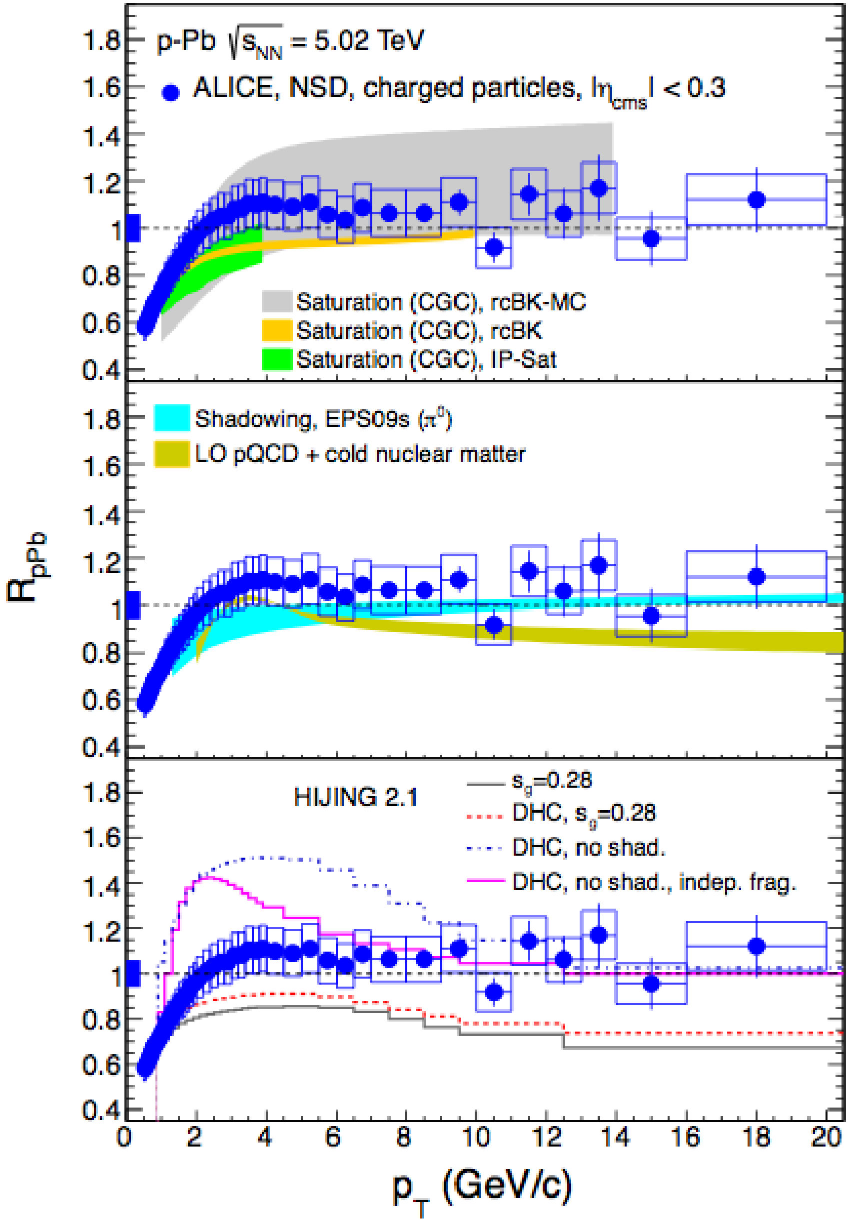
Quiroga et al, arXiv1002.2537



ALICE data on R_{pA} nuclear modification

ALICE, arXiv1210.4520

- In charged hadron spectra, nuclear effects are small at mid-rapidity for p_T > 5-10 GeV



Now to the subject of this talk: DPS in pA

Report on B. Blok, M. Strikman, UAW, arXiv:1210.1477

see also: M. Strikman, D. Treleani, PRL 88 (2002) 031801

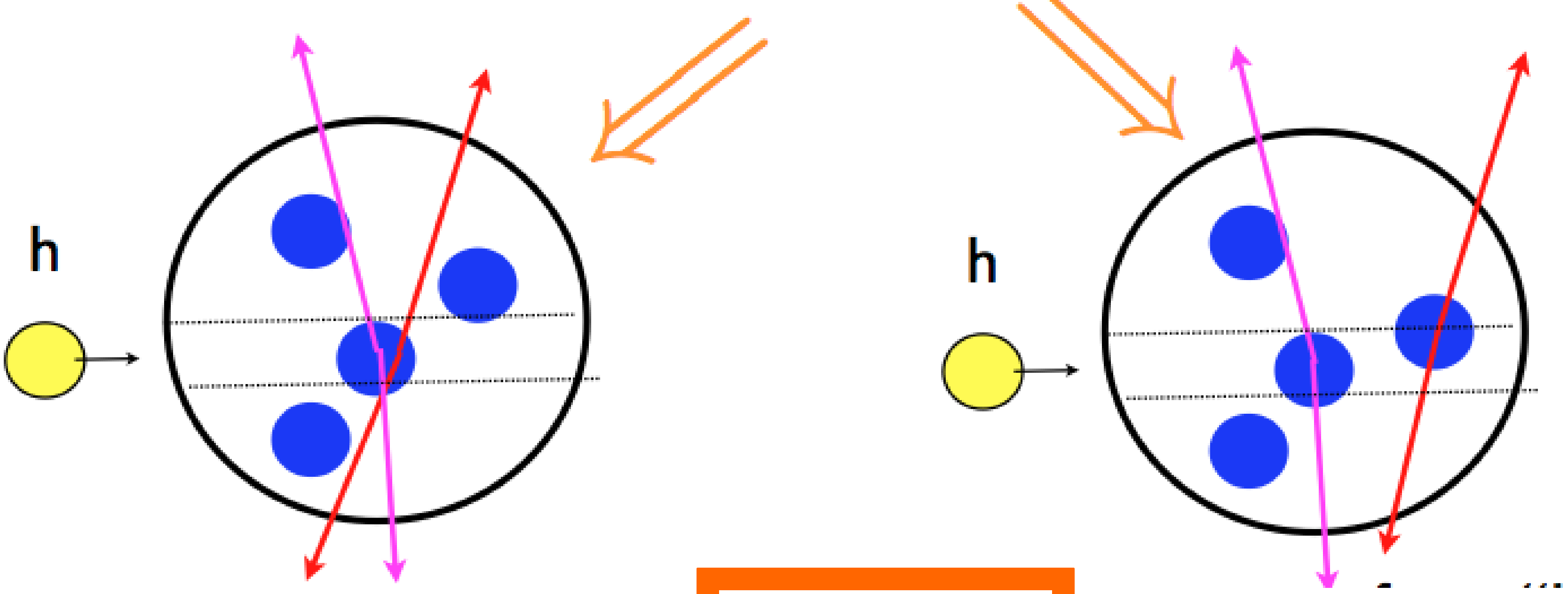
DPS in pA: surge of interesting recent work:

Treleani&Calucci, arXiv:1204.6403
(nucleon structure revealed in d-p)

D'Enterria & Snigirev, arXiv:1211.0197
(same sign WW as DPS signal in p-A&LHC)

DPS in pA – basic idea

$$\sigma = \sigma_1 \cdot A + \sigma_2$$



$$\boxed{s_2 \mu A^{4/3}}$$

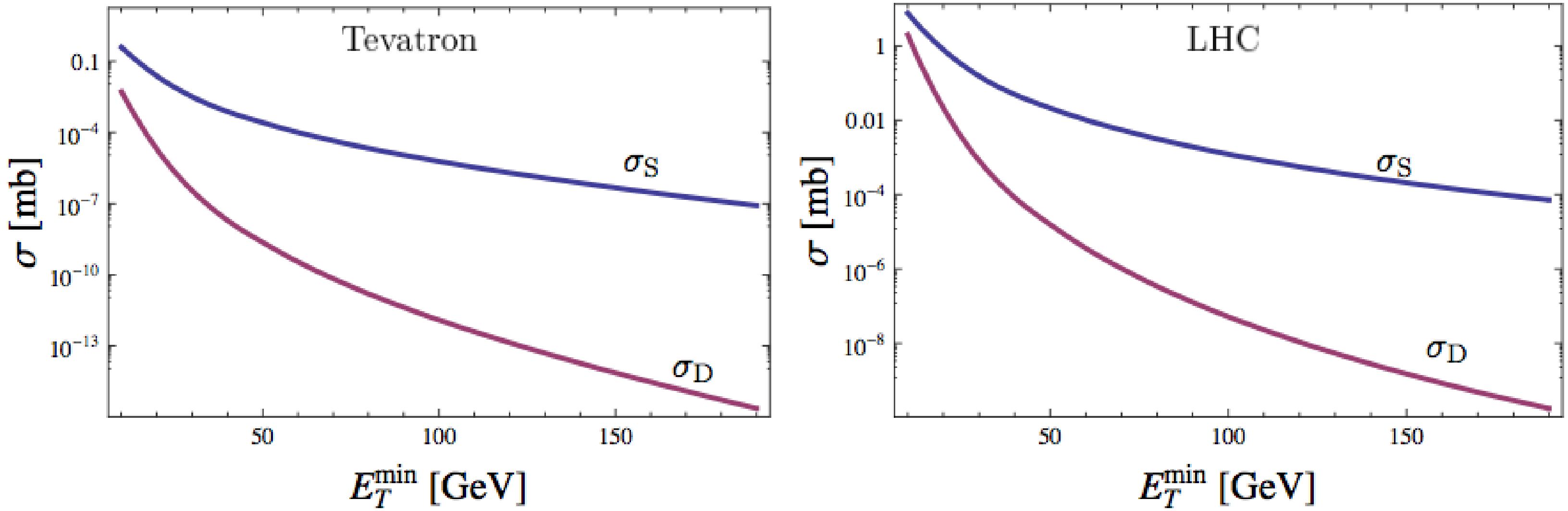
- 2-parton correlations are more important in proton than in nucleus A
- Nucleus may be used as a filter to characterize correlations in proton

DPS in pp@LHC

- In 4-jet events experimentally accessible finally up to E$_{tmin}$ ~ 100 GeV
  Simple estimates may be based on
  (S ~ 15 mb)

$$\frac{ds^{pp}_{4jet}}{dt_1 dt_2} = \frac{1}{S}\frac{ds^{pp}_{2jet}}{dt_1}\frac{ds^{pp}_{2jet}}{dt_2}$$

S. Domdey et al, EPJC65, 153 (2010)

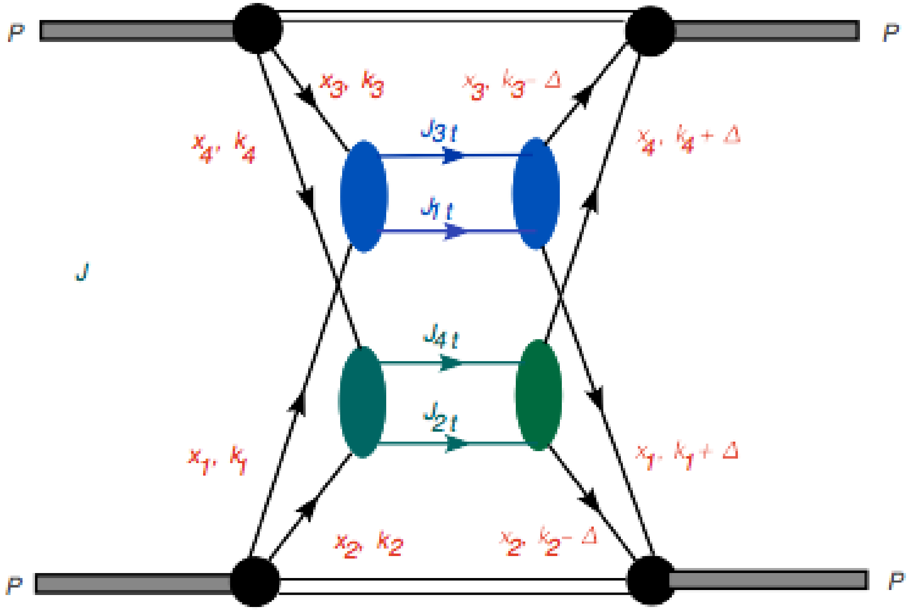


- Consider 4-jet event in back-to-back kinematics, where DPS dominates

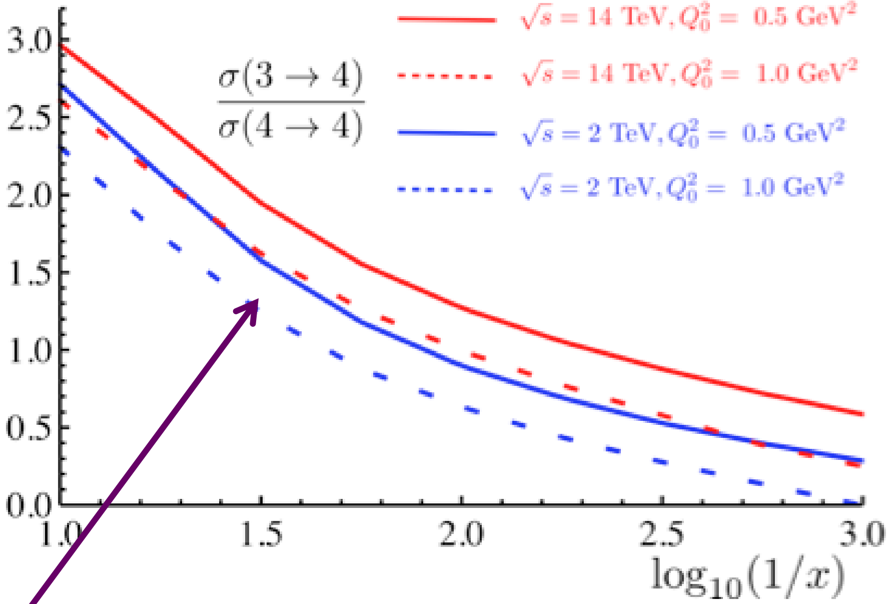
$$d_{13}^2 = \left(\vec{k}_{1t} + \vec{k}_{3t}\right)^2 << k_{1t}^2 \sim k_{3t}^2 \sim Q_1^2$$

$$d_{24}^2 = \left(\vec{k}_{2t} + \vec{k}_{4t}\right)^2 << k_{2t}^2 \sim k_{4t}^2 \sim Q_2^2$$

2GPDs in the proton



Blok et al, arXiv:1206.5594



Perturbatively generated
1 -> 2 contribution

- Generalized 2-parton distributions in the proton

$$ {}_2G_2\left(x_1,x_2,Q_1^2,Q_2^2,\vec{D}\right) = {}_2G_p^{double}\left(x_1,x_2,Q_1^2,Q_2^2,\vec{D}\right) + \boxed{{}_2G_p^{sjingle}\left(x_1,x_2,Q_1^2,Q_2^2,\vec{D}\right)} $$

Blok, Dokshitzer, Frankfurt, Strikman, PRD83 (2011) 071501

${}_2G_p^{sjingle}$
- Gives rise to large 3-> 4 contribution in 4-jet cross section in pp
- Natural source of longitudinal parton correlations in proton

2GPDs in the nucleus

$$ {}_2G_A\left(x_1, x_2, \vec{\Delta}\right) = {}_2G_A^{sjngle,1N}\left(x_1, x_2, \vec{\Delta}\right) + {}_2G_A^{double,1N}\left(x_1, x_2, \vec{\Delta}\right) + {}_2G_A^{2N}\left(x_1, x_2, \vec{\Delta}\right) $$

- This gives rise to 6 different contributions to the 4-jet cross section in pA

Single nucleon scattering terms:

$$ G_p^{double} \otimes G_A^{double,1N} \qquad G_p^{double} \otimes G_A^{sjngle,1N} \qquad G_p^{sjngle} \otimes G_A^{double,1N} $$

Double nucleon scattering terms:

$$ G_p^{double} \otimes G_A^{2N} \qquad G_p^{sjngle} \otimes G_A^{2N} $$

Consider structure of these contributions in independent nucleon approximation of the nucleus, e.g. Blok, Strikman, UAW

$$ G_A^{1N} = \int \frac{1}{\alpha^2}\left(G_N^{sjngle}\left(\frac{x_1}{\alpha}, \frac{x_2}{\alpha}\right) + G_N^{double}\left(\frac{x_1}{\alpha}, \frac{x_2}{\alpha}\right)\right)\rho_A^N(\alpha, p_t)\frac{d\alpha}{\alpha}dp_t $$

Single nucleon scattering terms

$G_p^{double} \otimes G_A^{double,1N}$ $G_p^{double} \otimes G_A^{sjngle,1N}$ $G_p^{sjngle} \otimes G_A^{double,1N}$

In independent nucleon approximation of the nucleus, ansatz in terms of light-cone nucleon density in nucleus

Blok, Strikman, UAW

$$G_A^{1N} = \int \frac{1}{\alpha^2}\left(G_N^{sjngle}\left(\frac{x_1}{\alpha},\frac{x_2}{\alpha}\right) + G_N^{double}\left(\frac{x_1}{\alpha},\frac{x_2}{\alpha}\right)\right) \boxed{\rho_A^N(\alpha,p_t)} \frac{d\alpha}{\alpha}\, dp_t$$

$$= A G_N^{sjngle}(x_1,x_2)\left[1 + O\left(\int (\alpha-1)^2 \rho_A^N(\alpha,p_t)\frac{d\alpha}{\alpha}\, dp_t\right)\right]$$

$$\Rightarrow \quad \frac{d\sigma_{4jet}^{pA,1N}}{dt_1 dt_2} \approx \frac{A}{S}\frac{d\sigma_{2jet}^{pp}}{dt_1}\frac{d\sigma_{2jet}^{pp}}{dt_2}$$

Double nucleon scattering terms

$$G_A^{2N}(x_1,x_2,\vec{\Delta}) \;=\; A(A-1)\int \frac{1}{\alpha_1\alpha_2}\prod_{i=1}^{i=A}\frac{d\alpha_i d^2p_{ti}}{\alpha_i}\,\delta\left(\sum_i \alpha_i - A\right)\delta^{(2)}\left(\sum_i \mathbf{p}_{ti}\right)\psi_A^*(\alpha_1,\alpha_2,p_{t1},p_{t2},....)$$

$$\times\psi_A(\alpha_1,\alpha_2,p_{t1}+\vec{\Delta},p_{t2}-\vec{\Delta},....)G_N(x_1/\alpha_1,|\vec{\Delta}|)G_N(x_2/\alpha_2,|\vec{\Delta}|).$$

$$\boxed{G_A^{2N}(x_1,x_2,\vec{\Delta}) \;=\; A(A-1)G_N(x_1,|\vec{\Delta}|)G_N(x_2,|\vec{\Delta}|)\;F_A^{\mathrm{double}}(\vec{\Delta},-\vec{\Delta})\,,}$$

$$F_A^{\mathrm{double}}(\vec{\Delta},-\vec{\Delta}) \;=\; \int\prod_{i=1}^{i=A}\frac{d\alpha_i d^2p_{ti}}{\alpha_i}\,\delta\left(\sum_i \alpha_i - A\right)\delta^{(2)}\left(\sum_i \mathbf{p}_{ti}\right)\psi_A^*(\alpha_1,\alpha_2,p_{t1},p_{t2},....)$$

$$\times\psi_A(\alpha_1,\alpha_2,p_{t1}+\vec{\Delta},p_{t2}-\vec{\Delta},....)\,.$$

The two-nucleon form factor can be expressed is given by the nuclear thickness function

$$F_A^{double}(\vec{\Delta},-\vec{\Delta}) \cong \left|\int d^3r\,\frac{\rho_A(r)}{A}\exp[i\vec{\Delta}.\vec{r}]\right|^2 \qquad \rho_A(r) \equiv A\psi_N^*(r)\psi_N(r)$$

$$= \left|\frac{1}{A}\int d\vec{b}\,T(\vec{b})\exp[i\vec{\Delta}.\vec{b}]\right|^2$$

$$\propto A^{-2/3}$$

Double nucleon scattering terms, cont’d

$$\boxed{G_p^{double} \text{ Ä } G_A^{2N}}$$

This is the nuclear enhanced 4 ->4 contribution

$$\frac{\sigma_4^{(III)}(x_1', x_2', x_1, x_2)}{d\hat{t}_1 d\hat{t}_2} = \frac{f_p(x_1', x_2')}{f_p(x_1') f_p(x_2')} \frac{d\sigma_{2\mathrm{jet}}^{pp}(x_1', x_1)}{d\hat{t}_1} \frac{d\sigma_{2\mathrm{jet}}^{pp}(x_2', x_2)}{d\hat{t}_2} \frac{(A-1)}{A} \underbrace{\int T^2(b) d^2 b}_{\propto A^{4/3}} .$$

$$\boxed{G_p^{sjngle} \text{ Ä } G_A^{2N}}$$

This is the nuclear enhanced 3 ->4 contribution

$$\frac{d\sigma_4^{(VI)}}{d\hat{t}_1 d\hat{t}_2} = A(A-1) \frac{d\sigma_1}{d\hat{t}_1} \frac{d\sigma_2}{d\hat{t}_2} \int \frac{d^2\vec{\Delta}}{(2\pi)^2} G_p^{single}(x_1', x_2', 0)\, f_N(x_1)\, f_N(x_2)\, F_A^2(\vec{\Delta}) \propto A^{4/3}$$

For 3->4 process, combinatorial factor 2 and geometrical enhancement absent in pA:

$$\left.\frac{s_4^{(VI)}}{s_4^{(III)}}\right|_{pA} \Bigg/ \left.\frac{s_4^{(VI)}}{s_4^{(III)}}\right|_{pp} = const(A)\Big|_{A>>1} \text{ » } \frac{1}{5}$$

Role of longitudinal parton correlations in the nucleon is obviously less important in pA.

Nuclear modification factor for 4-jet events

$$R_{pA}^{4jet}(x_1,x_2,x_1',x_2') \equiv \frac{d\sigma_{4jet}^{pA}(x_1,x_2,x_1',x_2')}{d\hat{t}_1\, d\hat{t}_2} \Big/ \frac{A}{S} \frac{d\sigma_{2\,jet}(x_1',x_1)}{d\hat{t}_1} \frac{d\sigma_{2\,jet}(x_2',x_2)}{d\hat{t}_2}$$

$$R_{pA}^{4\,jet}(x_1,x_2,x'_1,x'_2)=1+SW(A)K(x'_1,x'_2)$$

depends on geometry: $W(A) \equiv \left((A-1)/A^2\right) \int db\, T^2(b)$

and longitudinal correlations: $K(x'_1,x'_2) \equiv \dfrac{G_p(x'_1,x'_2,0)}{f_p(x'_1)\, f_p(x'_2)}$

Experimentally, on can determine the ratio

$$K(x'_1,x'_2) \equiv \frac{R_{pA}^{4\,jet}\left(x_1,x_2,x'_1,x'_2\right)-1}{SW(A)}$$

Deviation of this ratio from unity signals longitudinal two-parton momentum correlations in proton.

Summary

- Full experimental characterization of proton 2GPDs is challenging

- A qualitative characterization of the nature of 2-parton correlations would be an intermediate step towards determining 2GPDs

- pA collisions can contribute to this end by
  ‘filtering out’ longitudinal correlations in the proton

- There are uncertainties:
  - those related to npdf may be taken into account (but expected to be small)

$$K(x'_1,x'_2)|_{\mathrm{npdf\ corrected}} = \frac{R_{pA}^{4jet}(x_1,x_2,x'_1,x'_2)/(R_{pA}^{2jet})^2 - 1}{S\,W(A)}$$

  - other uncertainties (e.g. various interference terms discussed in our paper) are related to the simple picture of the nucleus used here. We have only qualitative arguments of why they should be negligible.