Nucleon configurations for heavy–ion initial–state and applications

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OUTLINE

1. Monte Carlo Glauber (MCG) approach for pA and AA
   - 1.a Nuclear configurations for MCG. Including:
   - 1.b nucleon-nucleon (NN) correlations
   - 1.c neutron skin
   - 1.d nuclear deformations

2. Beyond the Glauber approach
   - 2.a Fluctuations of NN interaction strenght
   - 2.b Processes with hard trigger: pA
   - 2.c Processes with hard trigger: dA
   - 2.d Processes with double hard trigger: DPS

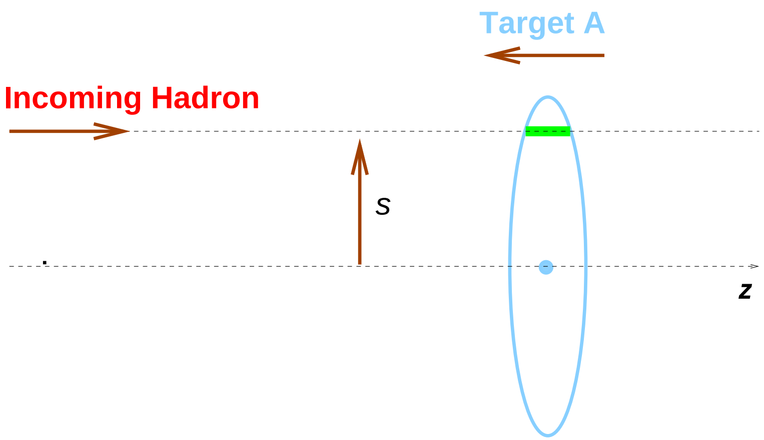
3. Energy loss and evidence for an EMC effect for antiquarks

Part I

Nucleon-nucleon correlations in Monte Carlo Glauber models

1.a - Glauber multiple scattering pA and AA scattering

Glauber approach: quantum mechanics of high-energy many-body scattering $\Longrightarrow$ frozen approximation; straight line trajectories

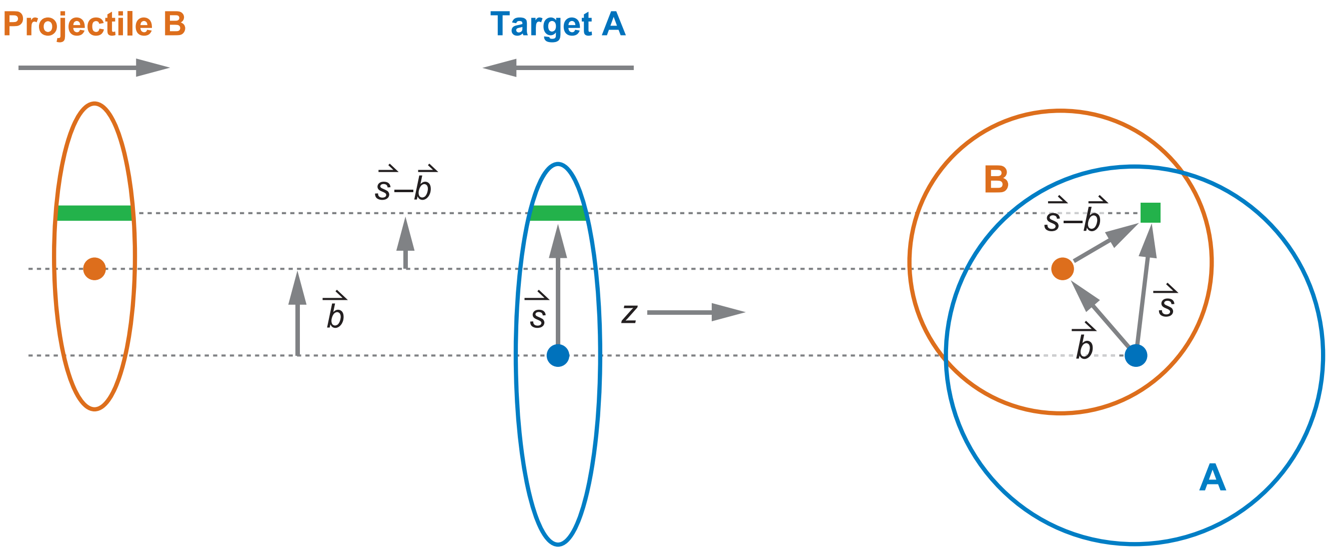


Inputs:

⋆ (charge) densities of nuclei

⋆ energy-dependent Nucleon--Nucleon (NN) cross sections

Side view **Beam-line view**



for given energy and AA impact parameter $\boldsymbol{b}$:

$\longrightarrow$ *interacting*

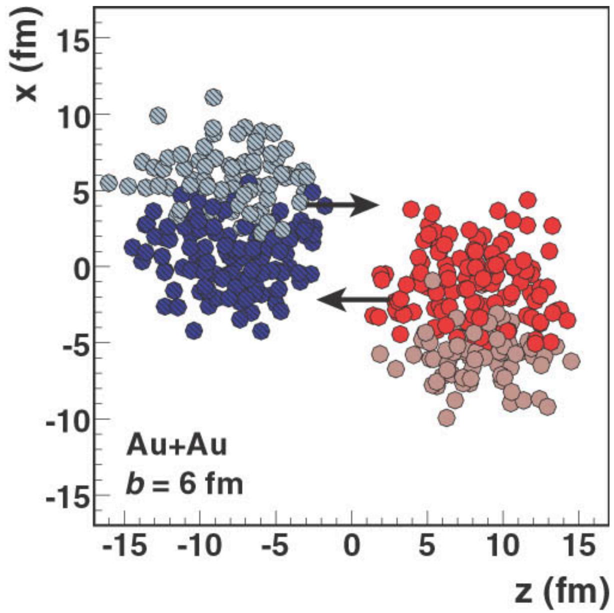
$\longrightarrow$ *spectators*

$\longrightarrow$ *elastically scattered*

1.a - Monte Carlo Glauber (MCG) description

- **Event-by-event** simulation. Details of density distributions by randomly generated ***nucleons positions***: in average give the nuclear density.

- MCG introduces N_{part} and N_{coll}, not directly measurable, but contain a lot of information about the fluctuating ***collision geometry*** and allows increased precision in preparing the ***initial state*** of colliding nuclei.



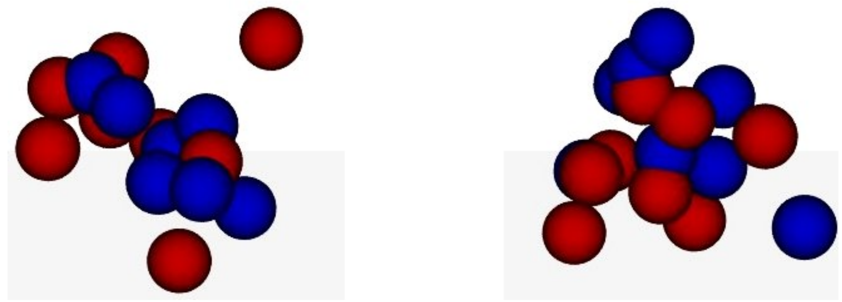
- Charged particle multiplicity scales with N_{part}, N_{coll} $\Leftrightarrow$ ***centrality***

- MCG is a starting point for models that require *production points* for individual subprocesses (HIJING, SMASH, GLISSANDO, Angantyr ..)

1.b - A Monte Carlo generator for nucleon configurations

- Nuclear configurations generated using $|\Psi|^2$ as a **probability density**:

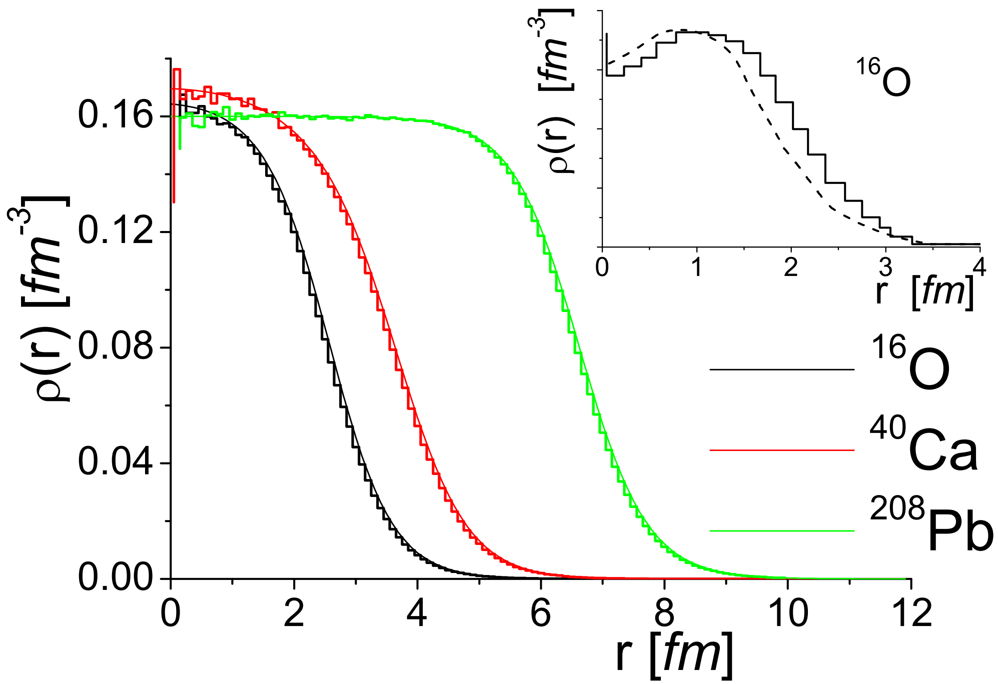
$$\Psi(\boldsymbol{r}_1, ..., \boldsymbol{r}_A) = \prod_{i<j}^{A} \hat{f}(r_{ij})\, \Phi(\boldsymbol{r}_1, ..., \boldsymbol{r}_A)$$



- **Spin-isospin** correlation operators from variational calculations:

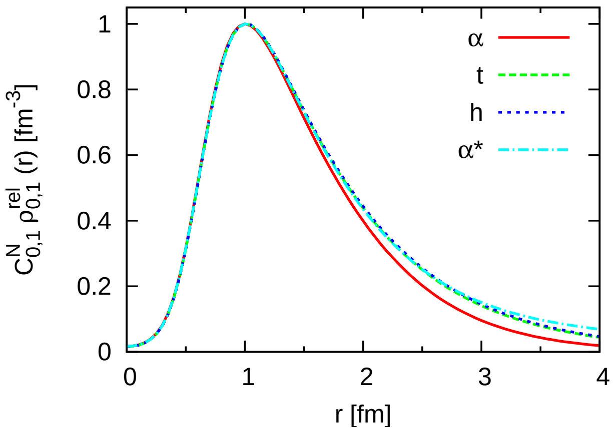
$$\hat{f}(r_{ij}) = \sum_{n=(\mathbb{1},\sigma,\mathbb{S})\otimes\mathbb{1},\tau} \hat{f}^{(n)}(r_{ij})$$

- Reproduces any **nuclear profile** (one-body density)
- Two-body density also reproduced

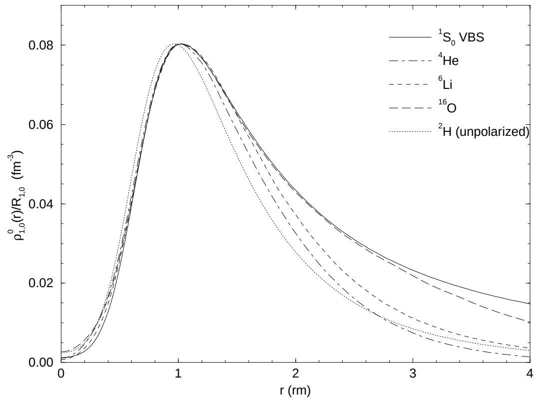


1.b - Correlations signatures in two-body densities

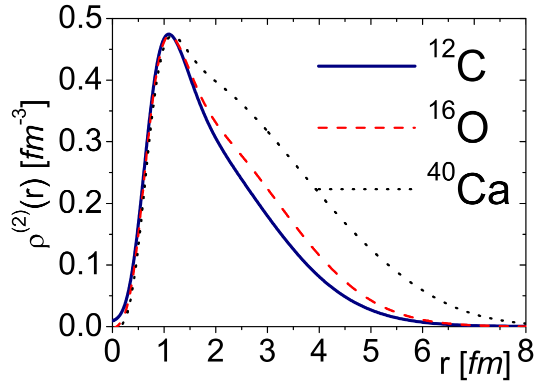
- ***Ab-initio*** two-body densities: $\rho(r) = \int d\boldsymbol{R}\, \rho^{(2)}\Big(\boldsymbol{r} = \boldsymbol{r}_1 - \boldsymbol{r}_2, \boldsymbol{R} = (\boldsymbol{r}_1 + \boldsymbol{r}_2)/2\Big)$



Feldemeier *et al*, Phys. Rev. **C84**, 054003 (2011)

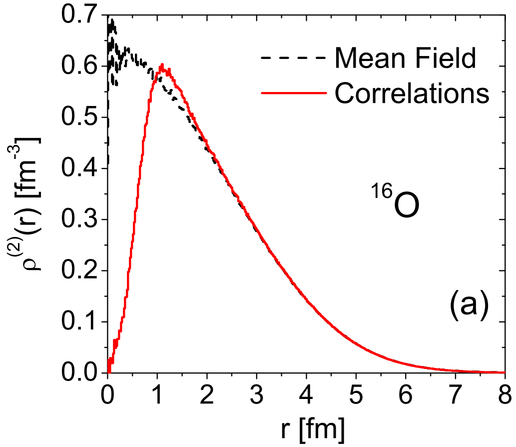


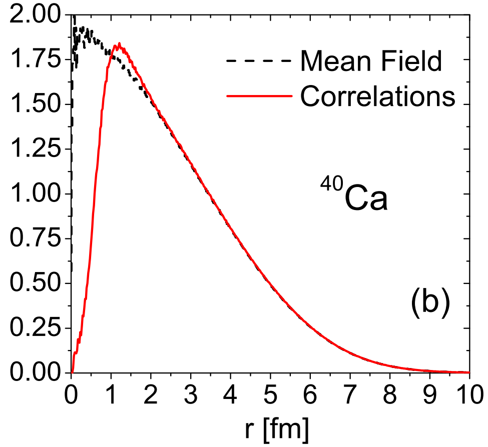
Forest *et al*, Phys. Rev. **C54** (1996) 646-667

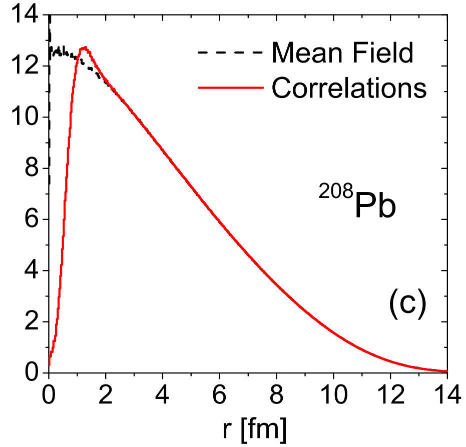


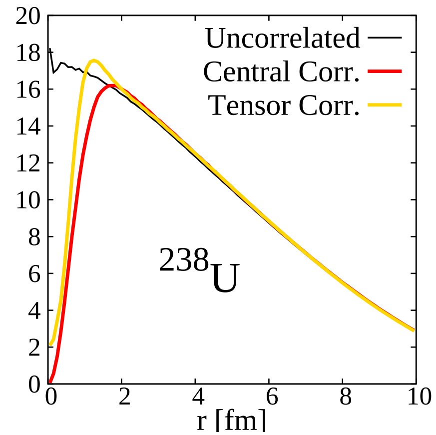
Alvioli *et al*, Phys. Rev. **C72**; Phys. Rev. Lett. **100** (2008)

- ***MC algorithm***

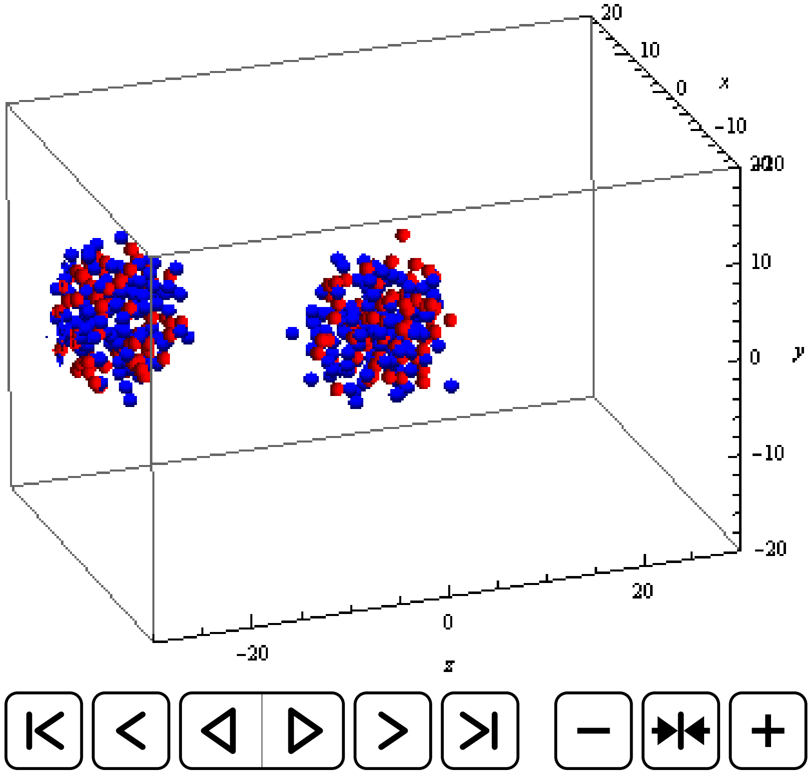


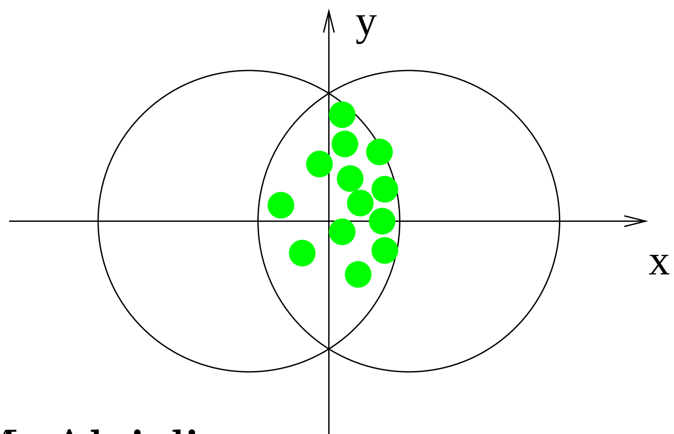






M. Alvioli, H.-J. Drescher, M. Strikman, Phys. Lett. **B680** (2009) 225





- **Spectator** nucleons ●●relevant for zero degree calorimeter measurement (beam remnant): *Alvioli, Strikman, **PRC83** (2011)*
- **Participant** matter distribution relevant for hydrodynamic evolution:

$$\epsilon_n = -\frac{\langle w(r)\, \cos n(\phi - \psi_n)\rangle}{\langle w(r)\rangle}$$

$$\Delta\epsilon_n = \sqrt{\frac{\sum(\epsilon_n^i - \langle\epsilon_i\rangle)^2}{N}}$$

Alvioli, Holopainen, Eskola, Strikman
*Phys. Rev. **C85** (2012)*

$\longrightarrow$ participant nucleons ● in transverse plane

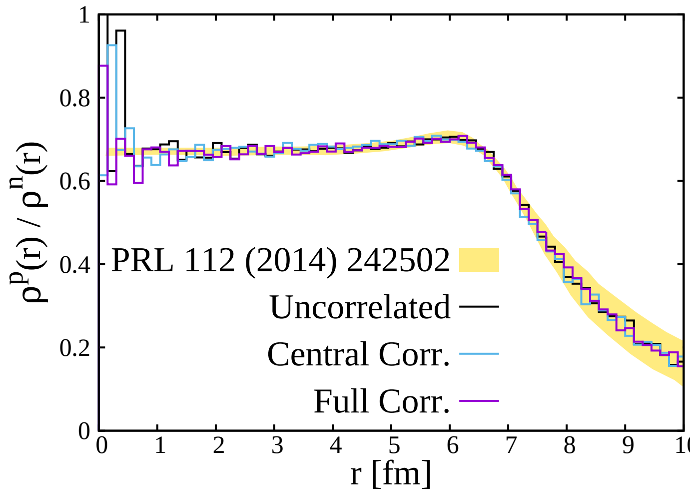
1.c - Configurations with neutron skin

- ***Neutron skin*** – **p/n** profiles for ^{208}Pb:

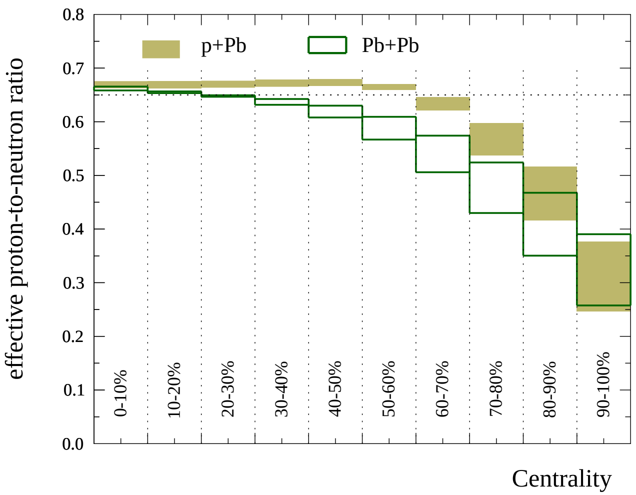
$$\rho(r) = \rho_0^{(p,n)} \; / \; \left(1 + e^{(r - R_0^{p,n})/a^{p,n}}\right)$$

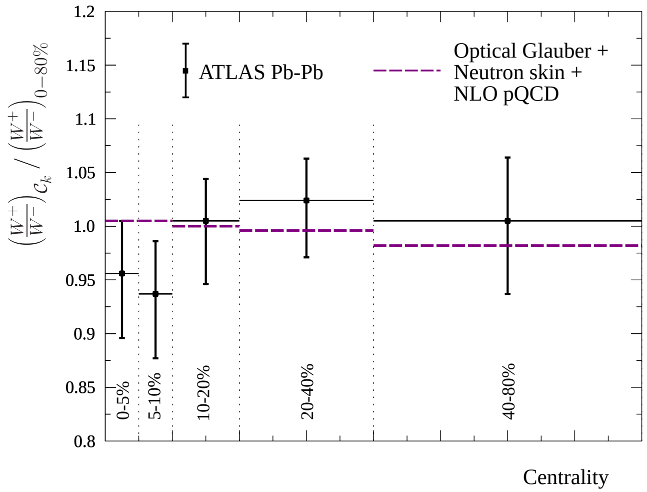
$$(\rho_0^p, R_0^p, a_0^p) \;=\; (\text{"82"}, 6.680\,fm, 0.447\,fm)$$
$$(\rho_0^n, R_0^n, a_0^n) \;=\; (\text{"126"}, 6.700\,fm, 0.550\,fm)$$

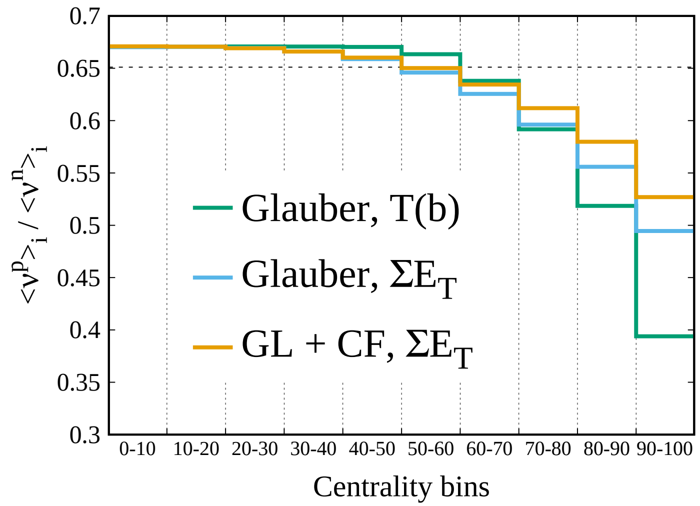
(*C.M. Tarbert et al., Phys. Rev. Lett.* ***112*** *(2014)*)



- Suggested as additional tool for determination of centrality:







H. Paukkunen, PL ***B745*** *(2015)* *Alvioli, Strikman (* ***PRC 100****, 2019)*

- **Smearing of impact parameter (CF)** $\Longrightarrow$ increase p/n effective ratio

1.d - Configurations of deformed nuclei

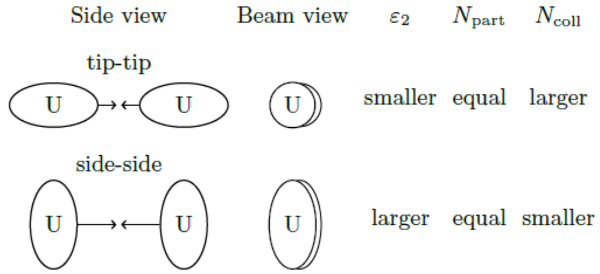
- ***Nucleus deformation*** – modified nuclear profile:

$$\rho(r) = \frac{\rho_0}{1 + e^{(r-R_0)/a}} \longrightarrow \rho(r,\theta) = \frac{\rho_0}{1 + e^{(r-R_0-R_0\beta_2 Y_{20}(\theta)-R_0\beta_4 Y_{40}(\theta))/a}}$$

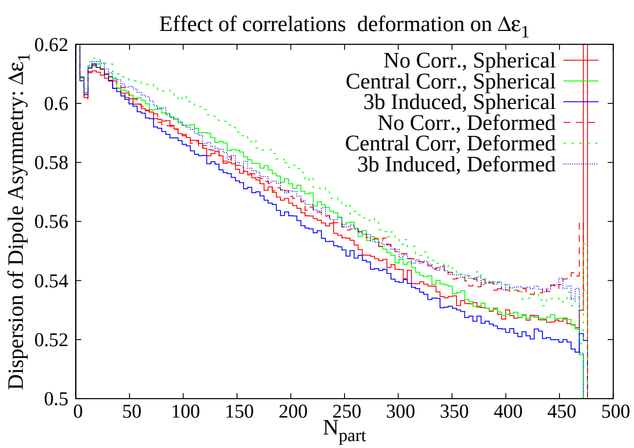
(*P. Filip, R. Lednicky, H. Masui, N. Xu Phys. Lett.* ***C80*** *(2009)*)

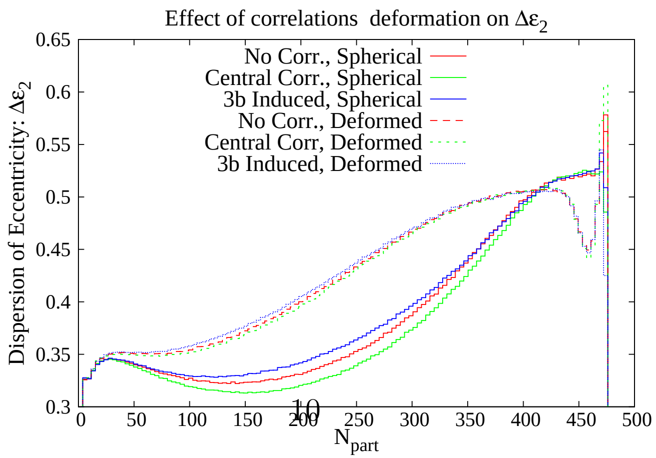
$$Y_{20}(\theta) = \frac{1}{4\,r^2}\sqrt{\frac{5}{\pi}}\left(2z^2 - x^2 - y^2\right)$$

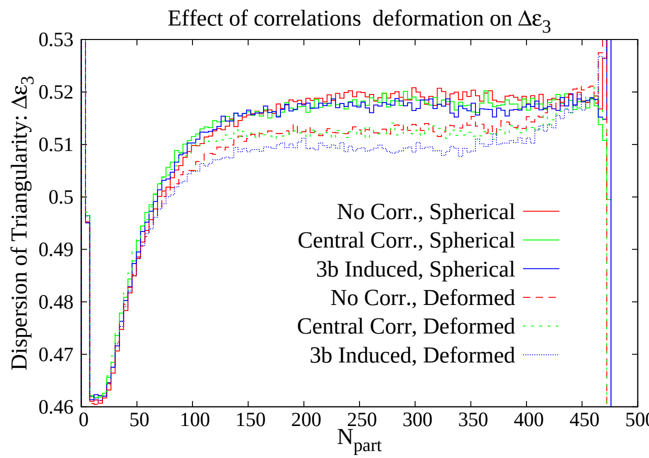
$$Y_{40}(\theta) = \frac{1}{16\,r^4}\sqrt{\frac{9}{\pi}}\left(35z^4 - 30z^2r^2 + 3r^4\right)$$



- Studies of isobars/neutron skin effect at RHIC – Phys. Rev. **C101** (2020)
- Effects on *dispersion of moments* in U-U (*unplublished*) within MGC:







1.(c+d) - Parameters for ^{96}Ru and ^{96}Zr isobars

- *We include both deformation and neutron skin, using WS profiles:*

$$\rho(r,\theta) = \rho_0 / \left(1 + e^{(r - R_0^{p,n} - R_0^{p,n}\beta_2 Y_{20}(\theta))/a_{p,n}}\right)$$

Nucleus	A	Z	N	N/Z	Skin	DEF
^{96}Ru	96	44	52	1.18	×	✓
^{96}Zr	96	40	56	1.40	✓	×
^{197}Au	197	79	118	1.49	✓	✓
^{208}Pb	208	82	126	1.54	✓	×
^{238}U	238	92	146	1.59	✓	✓

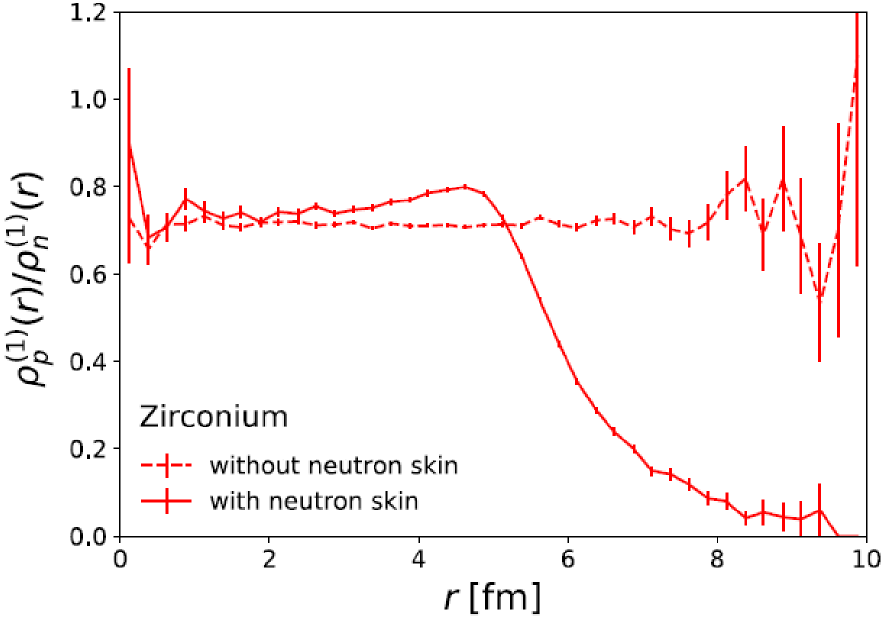
- Charge distribution unfolded for proton size NPA **717** 235 (2003)
- We consider ^{96}Zr as a halo-like nucleus: $R_n \simeq R_p$; $a_n > a_p$
- Parameters without neutron skin from PR**C99** 044908 (2019)

1.(c+d) - Parameters for ^{96}Ru and ^{96}Zr isobars

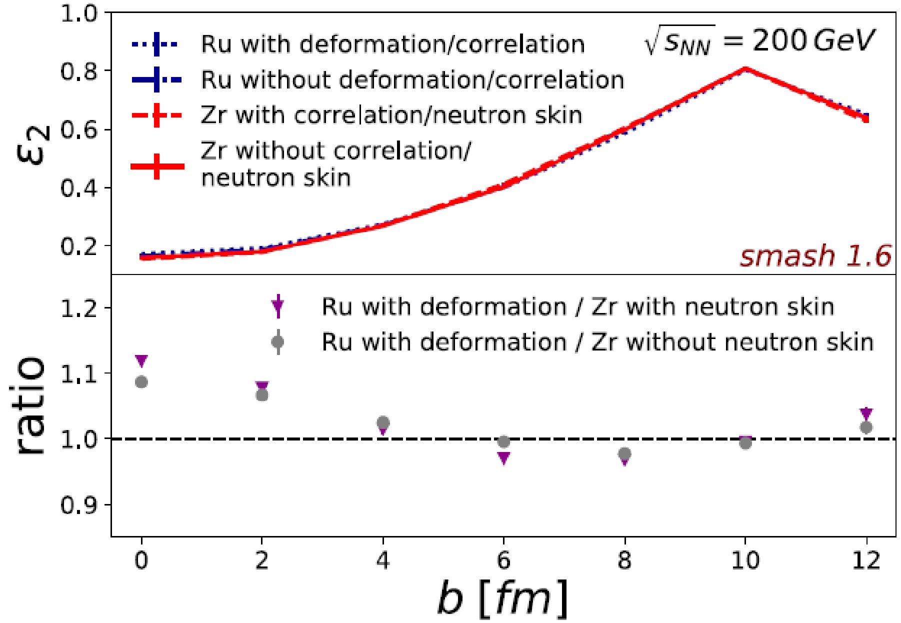
- Final parameters (Ru deformed; Zr with/without neutron skin):

Nucleus	Skin	DEF	R_0^p [fm]	a_p [fm]	R_0^n [fm]	a_n [fm]	β_2
^{96}Ru	×	✓	5.085	0.46	5.02	0.46	0.158
^{96}Zr	×	×	5.020	0.46	5.020	0.46	0
^{96}Zr	✓	×	5.08	0.34	5.08	0.46	0

proton/neutron ratio of one–body densities



Participant eccentricity & effect of neutron skin

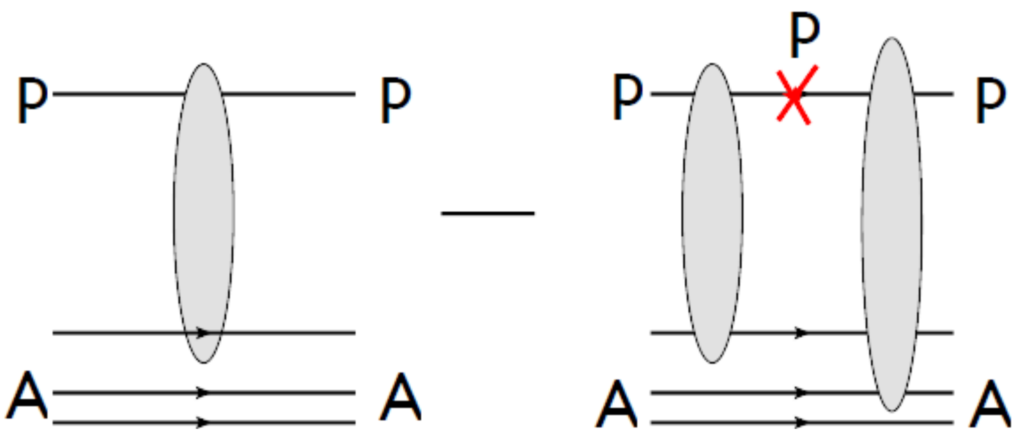


Hammelmann *et. al.*, Phys. Rev. **C101** (2020)

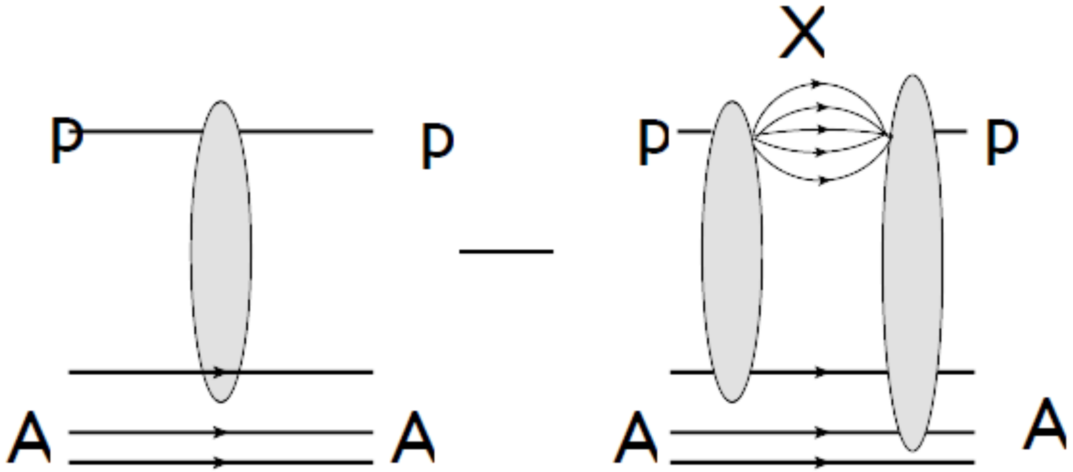
Part II

Effects of color fluctuations
and
modeling of hard triggers in MGC

2 - Beyond Glauber approach



⟶ Glauber model: in rescattering diagrams the proton cannot propagate in intermediate states



⟶ Gribov-Glauber model: the proton can access a set of intermediate state as in pN diffraction; relevant at high energies ($E_{inc} >> 10$ GeV)

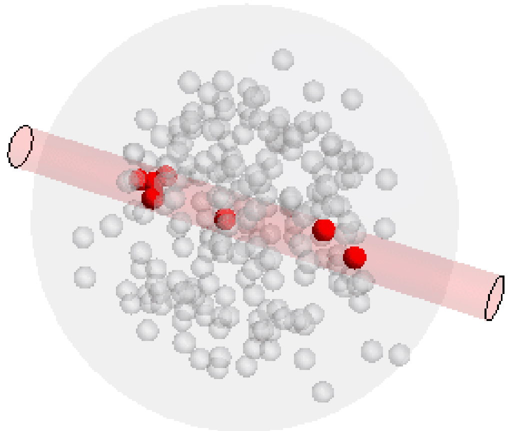
X is a set of intermediate states that stay frozen during $\boldsymbol{pA}$ interaction

2.a - NN interaction with frozen configurations

- at sufficiently high energy, i.e. when the relation

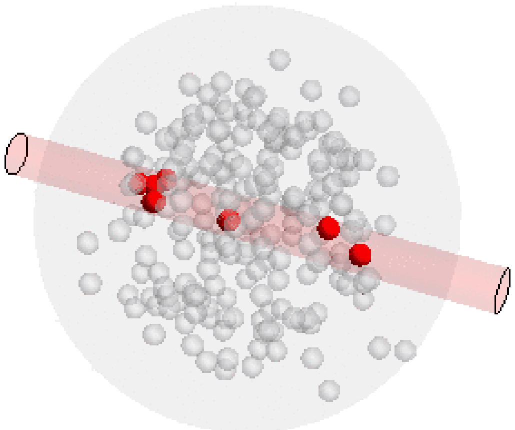
$$2\,R < 2\,p_{lab}/(M^2 - m^2)$$

holds, intermediate states are frozen during the pA interaction



2.a - Fluctuations of NN interaction

- structure of the proton ⟶ fluctuations into intermediate states
- different internal configurations ⟶ different cross sections
- relation with **color transparency/opacity phenomena**



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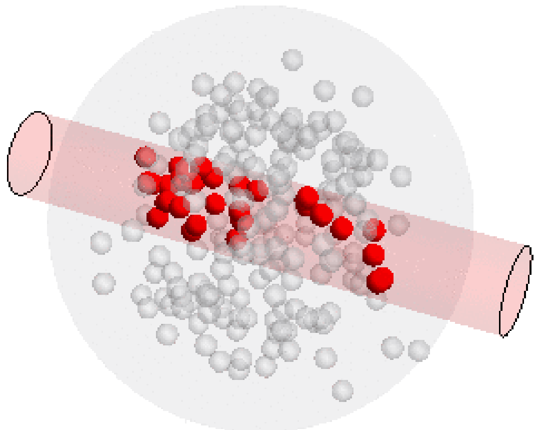


2.a - Color Fluctuations in Monte Carlo Glauber

- Gribov-Glauber dynamics: effective cross-section sampled event-by-event from a **distribution** $P(\sigma)$

$$P(\sigma) = \gamma \frac{\sigma}{\sigma+\sigma_0} e^{-\frac{\sigma/(\sigma_0-1)^2}{\Omega^2}},$$

$$\int d\sigma\, P(\sigma) = 1$$

$$\int d\sigma\, \sigma\, P(\sigma) = \sigma_{tot}$$

$$\frac{1}{\sigma_{tot}^2} \int d\sigma\, (\sigma-\sigma_{tot})^2\, P(\sigma) = \omega_\sigma$$

proposed by *V. Guzey, M. Strikman, Phys. Lett.* ***B633*** *(2006)*

used **in MCG**: *M. Alvioli, M. Strikman, Phys. Lett.* ***B722*** *(2013)*;

M. Alvioli, V. Guzey, L. Frankfurt, M. Strikman, ***PRC90*** *(2014)*;

M.Alvioli, B.Cole, L.Frankfurt, D.Perepelitsa, M.Strikman, ***PRC93*** *(2016)*;

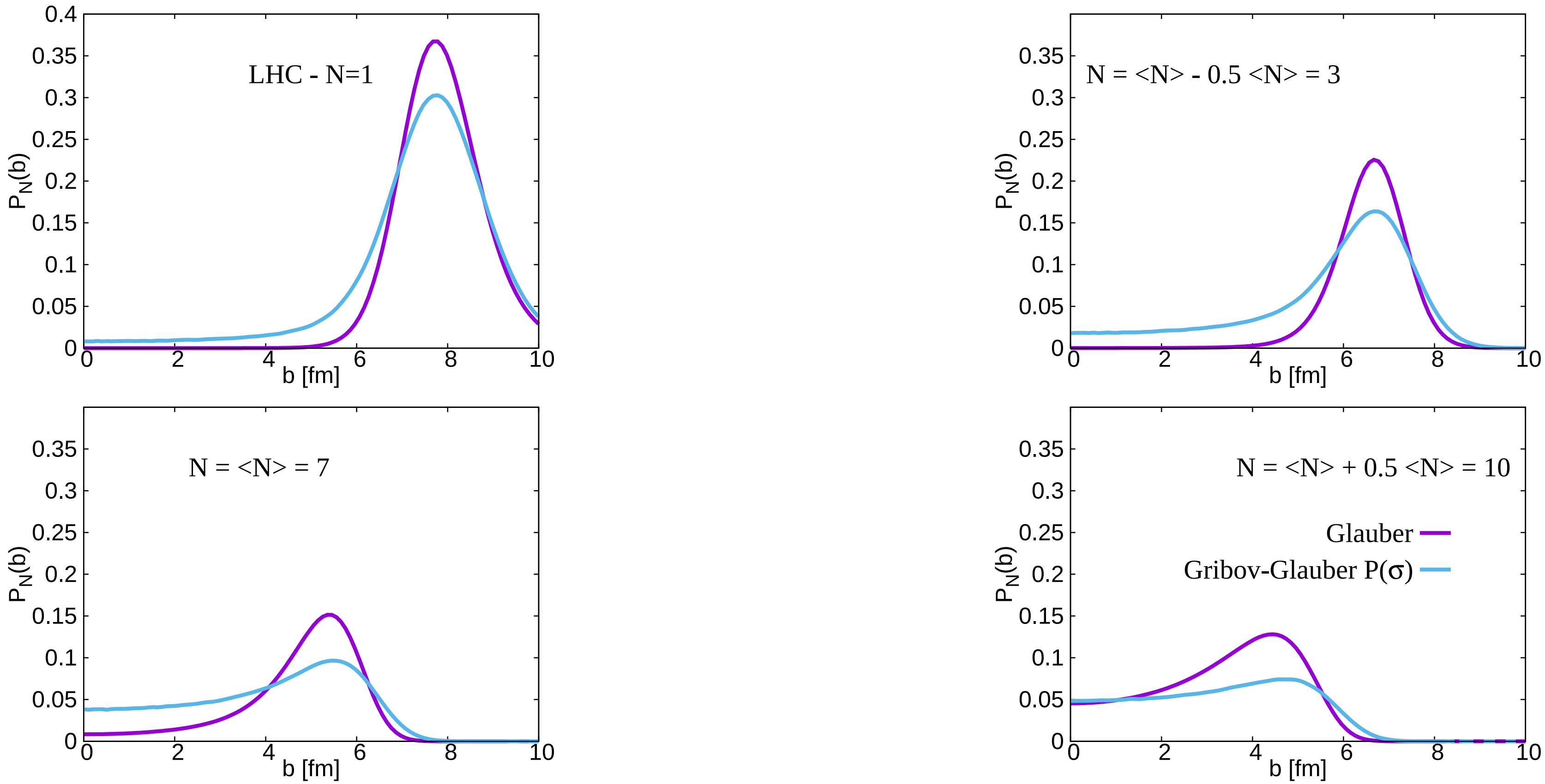
M. Alvioli, L. Frankfurt, D. Perepelitsa, M. Strikman, ***PRD98*** *(2018)*;

M. Alvioli, M. Azarkin, B. Blok, M. Strikman, ***EPJC79*** *(2019)*;

M. Alvioli, M. Strikman, ***PRC100*** *(2019)*

2.a - Color Fluctuations: probability of N interactions at b

- fluctuations of the number of wounded nucleons $\mathbf{N_{coll}}$ for given impact parameter **b** $\Longrightarrow$ **smearing of centrality**

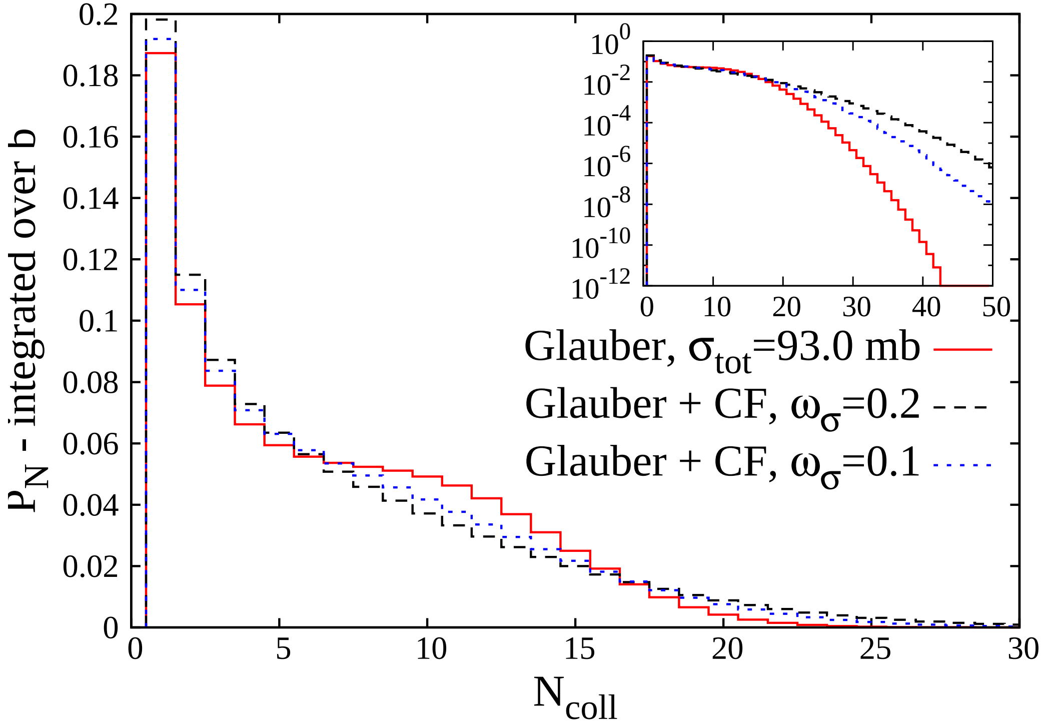


M. Alvioli, M. Strikman, Phys. Lett. ***B722*** *(2013)*

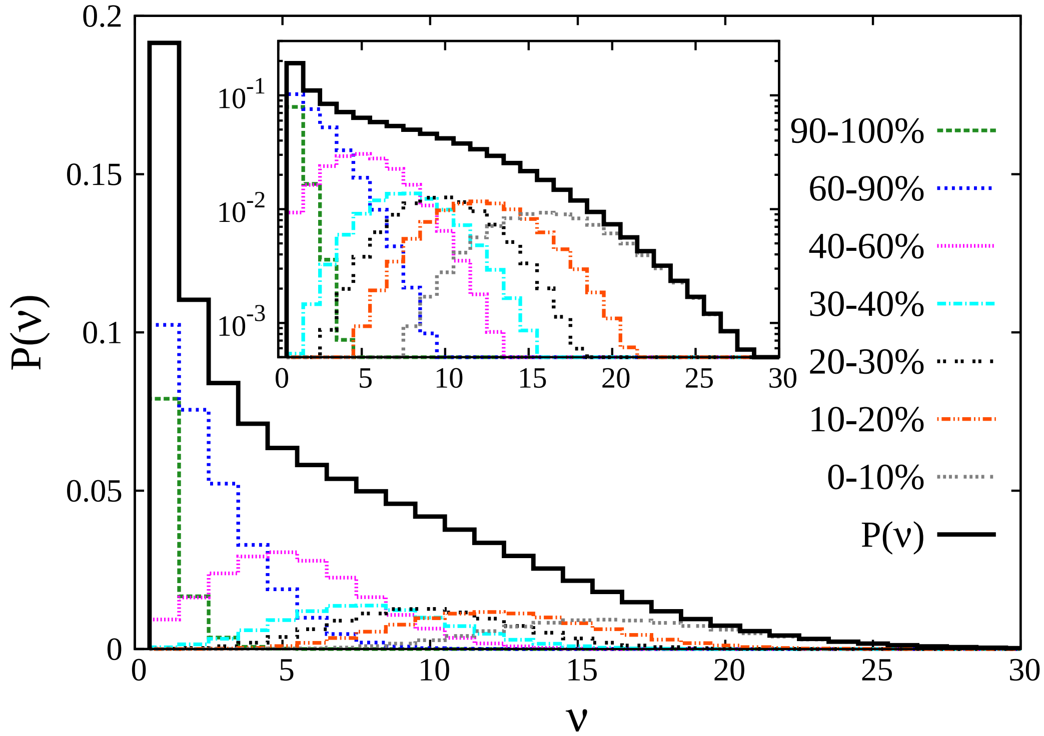
2.a - Color Fluctuations: probability of N interactions

$$P_N = \int d\boldsymbol{b}\, P_N(b) \;\; , \; N = N_{coll} = \nu$$

- Probability of events with **large N_{coll} enhanced**
- Experimental centrality classes $\leftrightarrow$ N_{coll} distibutions



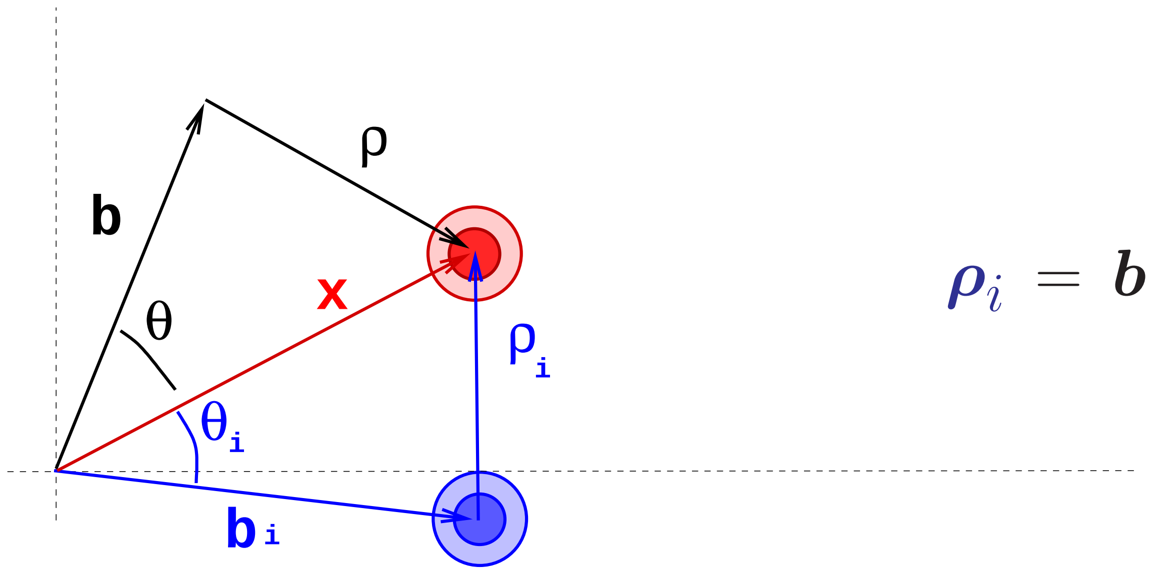
Phys. Lett. ***B722*** *(2013)*
Phys. Rev. ***C90*** *(2014)*



Phys. Rev. ***C93*** *(2016)*
Phys. Rev. ***D98*** *(2018)*

2.b - Geometry & hard trigger in pA processes

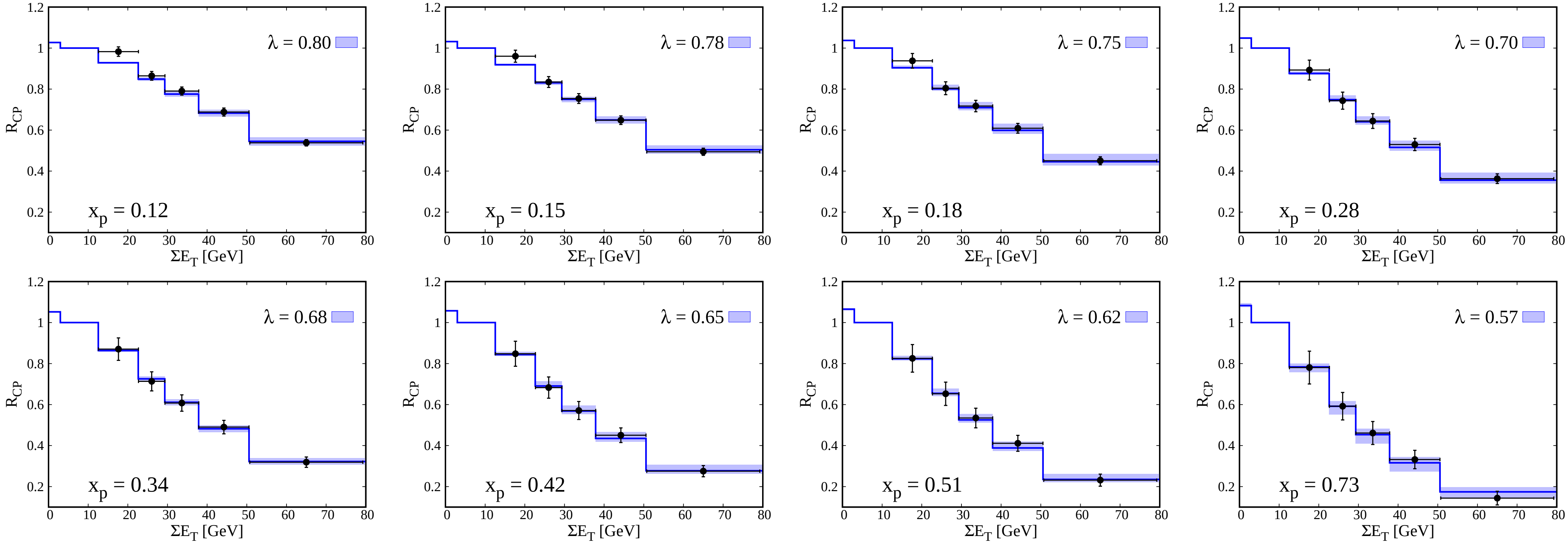
- A model to characterize the probability of events with one hard scattering and the (N_{coll}-1) soft scatterings, as a function of N_{coll}
- Hard event triggered in a probabilistic way, using the gluon distributions in the transverse plane $F_g(\rho) = exp(-\rho^2/B^2)/\pi B^2$
- We have coupled the MCG average ($< ... >$) for the N_{coll}-1 soft interactions with 2-d integral over the (random) position of hard scattering



$$\boldsymbol{\rho}_i = \boldsymbol{b} + \boldsymbol{\rho} - \boldsymbol{b}_i$$

M. Alvioli, L. Frankfurt, V. Guzey, M. Strikman, Phys. Rev. ***C90*** *(2014)*

2.b - X-dependent Color Fluctuations in pA



- The proton has **smaller-than-average cross section:** $\lambda = \langle\sigma(x)\rangle/\langle\sigma_{pN}\rangle$

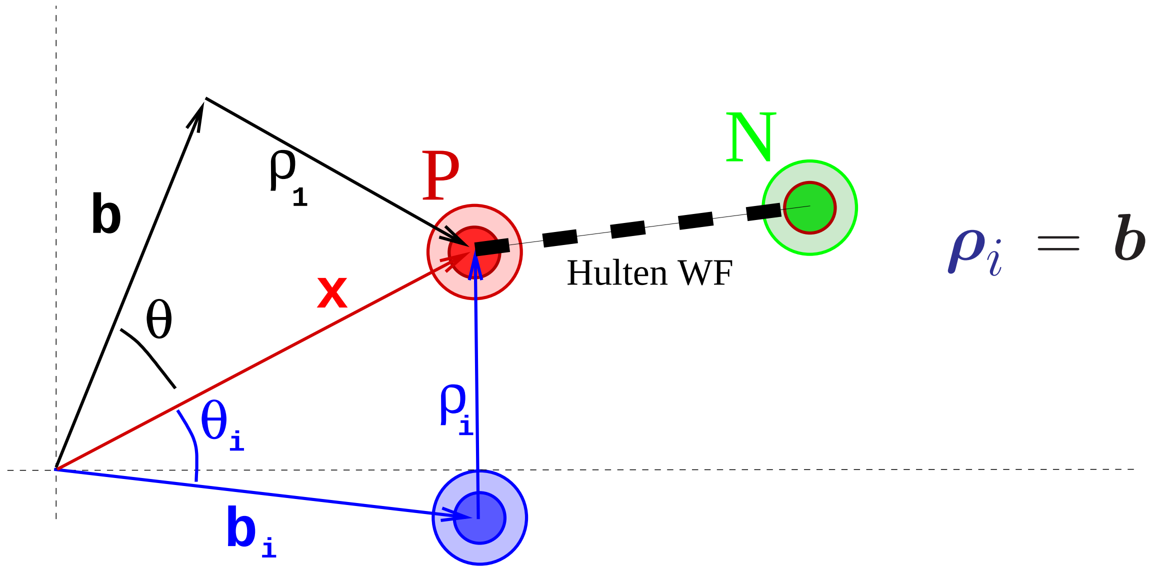
Alvioli, Cole, Frankfurt, Perepelitsa, Strikman, Phys. Rev. ***C93*** *(2016)*

Alvioli, Frankfurt, Perepelitsa, Strikman, Phys. Rev. ***D98*** *(2018)*

Data: *Aad et al. - ATLAS collaboration - Phys. Lett.* ***B748*** *(2015)*

2.c - Geometry & hard trigger in dA processes

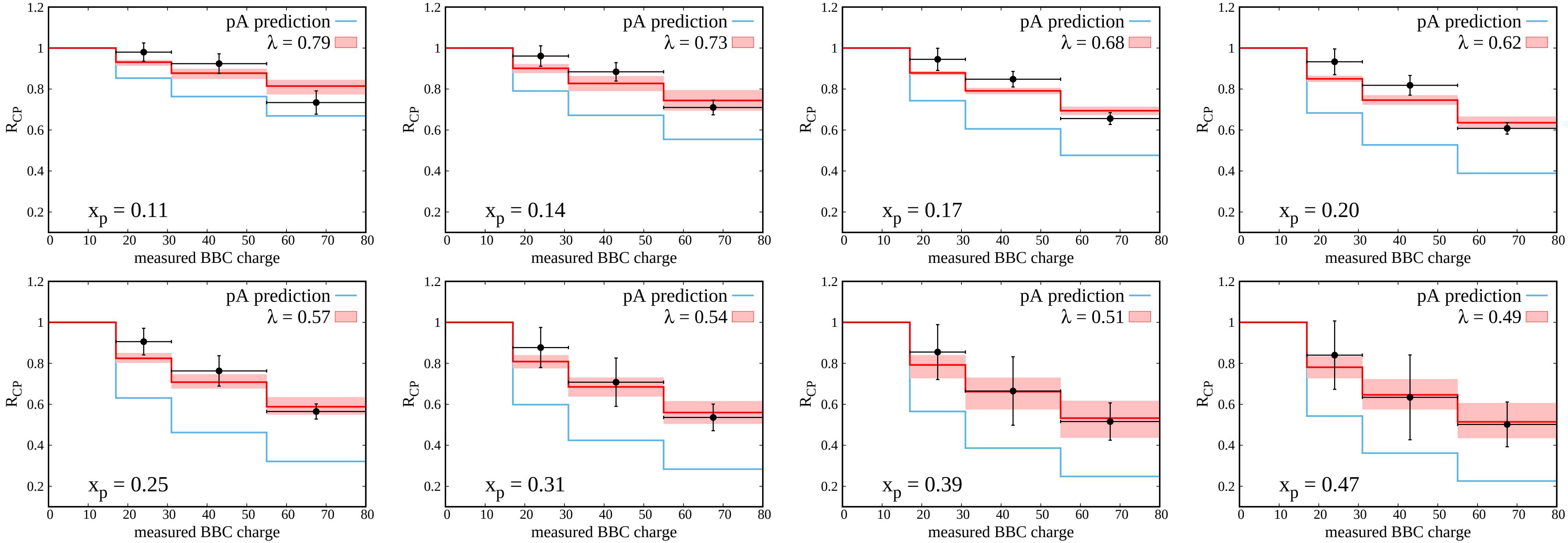
- A model to characterize the probability of events with one hard scattering and the (N_{coll}-1) soft scatterings, as a function of N_{coll}
- The hard event triggered in a probabilistic way
- We have coupled the MCG average ($< \ldots >$) for the N_{coll}-1 soft interactions with 2-d integral over the (random) position of the hard scattering of one of the nucleons - in the figure, the proton



$$\boldsymbol{\rho}_i = \boldsymbol{b} + \boldsymbol{\rho} - \boldsymbol{b}_i$$

Alvioli, Frankfurt, Perepelitsa, Strikman, Phys. Rev. ***D98*** *(2018)*

2.c - X-dependent Color Fluctuations in dA



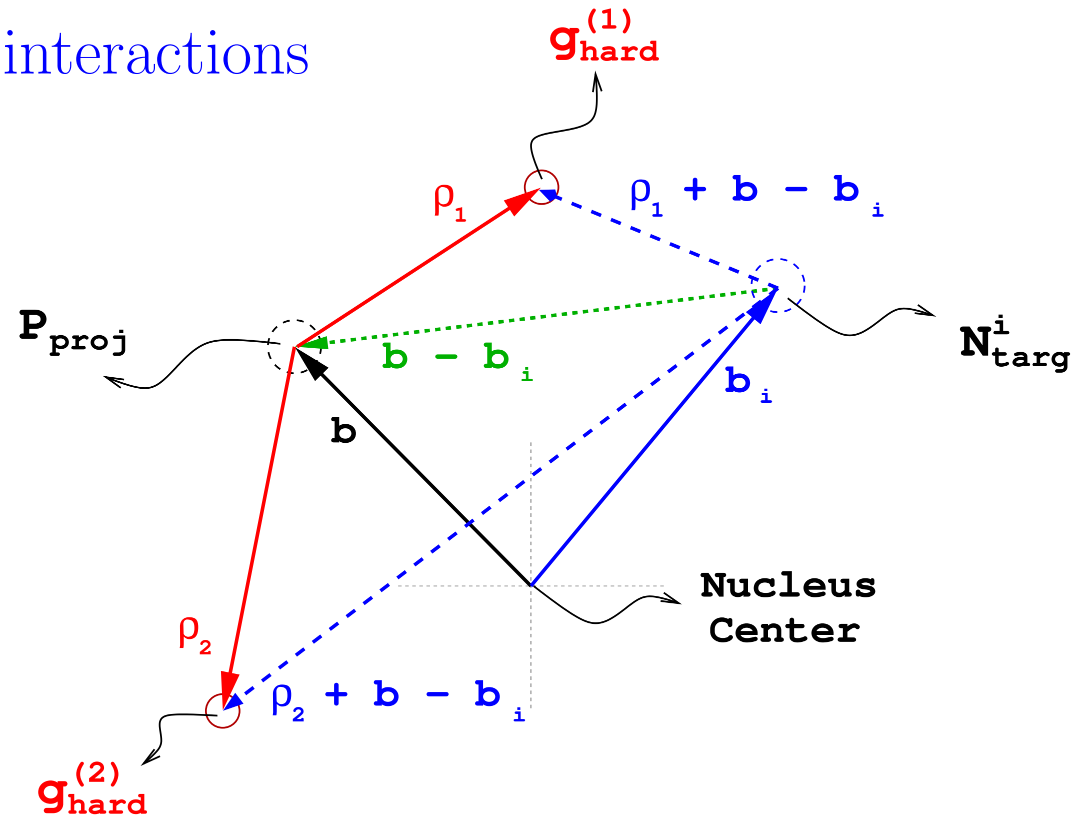
- The proton has **smaller-than-average cross section:** $\lambda = \langle\sigma(x)\rangle / \langle\sigma_{pN}\rangle$

Alvioli, Frankfurt, Perepelitsa, Strikman, Phys. Rev. ***D98*** *(2018)*

Data: *Adare et al. - PHENIX collaboration - Phys. Rev. Lett.* ***116*** *(2016)*

2.d - Modeling Double Partonic Interactions

- Extension of the hard-trigger formalism to double-hard trigger + (N-2) soft interactions
- Integration of two hard-scattering point on the transverse plane, event-by-event
- Full impact parameter dependence of single and double dijet events



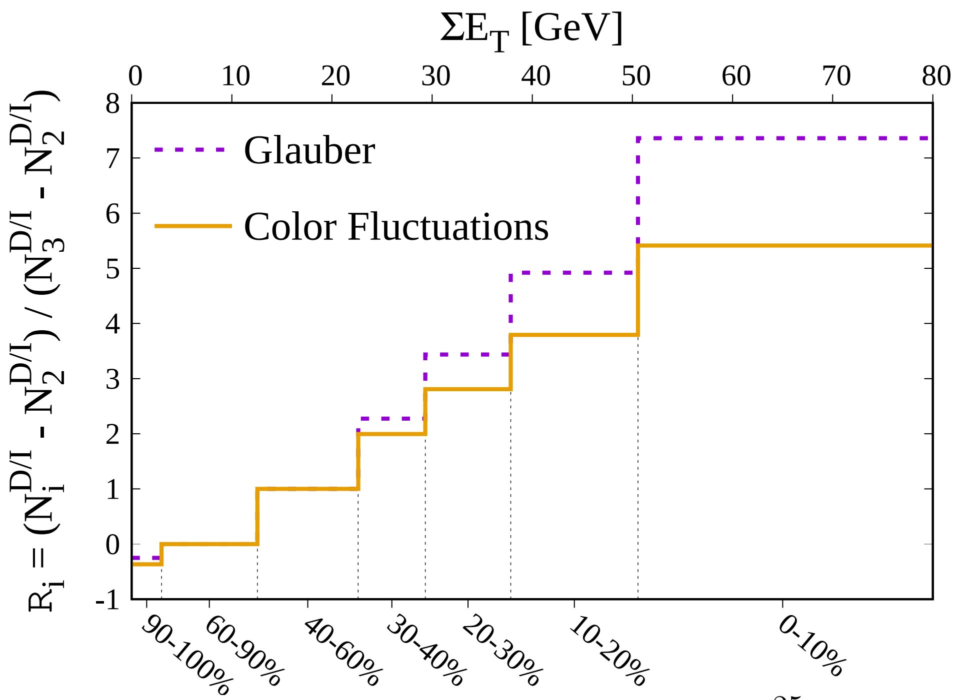
M. Strikman, D. Treleani, Phys. Rev. Lett. ***88*** *(2002)*

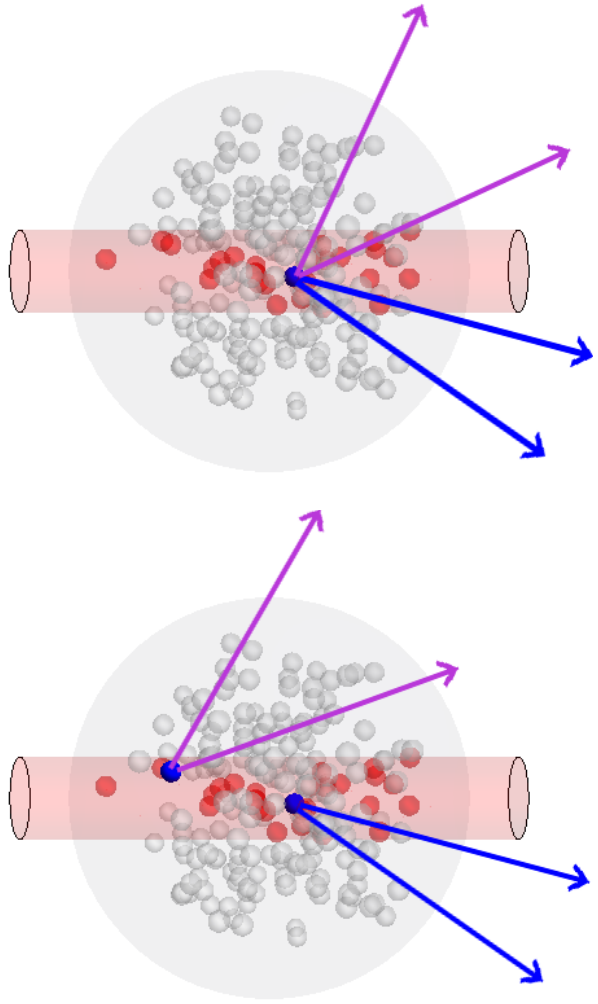
*M. Alvioli, M. Azarkin, B. Blok, M. Stirkman Eur. Phys. J. C****79*** *(2019)*

2.d - Centrality dependence of double parton scattering

- In **pA**, the DPS contribution grows with **centrality** much faster than the competing **LT**
- MCG distinguishes DPS from the **same nucleon** or **two different nucleons**

$$N = \frac{Mult_{DPS}}{Mult_{LT}}, \qquad R_i = \frac{N_i - N_2}{N_3 - N_2}$$





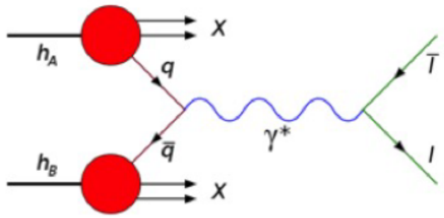
*M. Alvioli et al., Eur. Phys. J. C**79** (2019)*

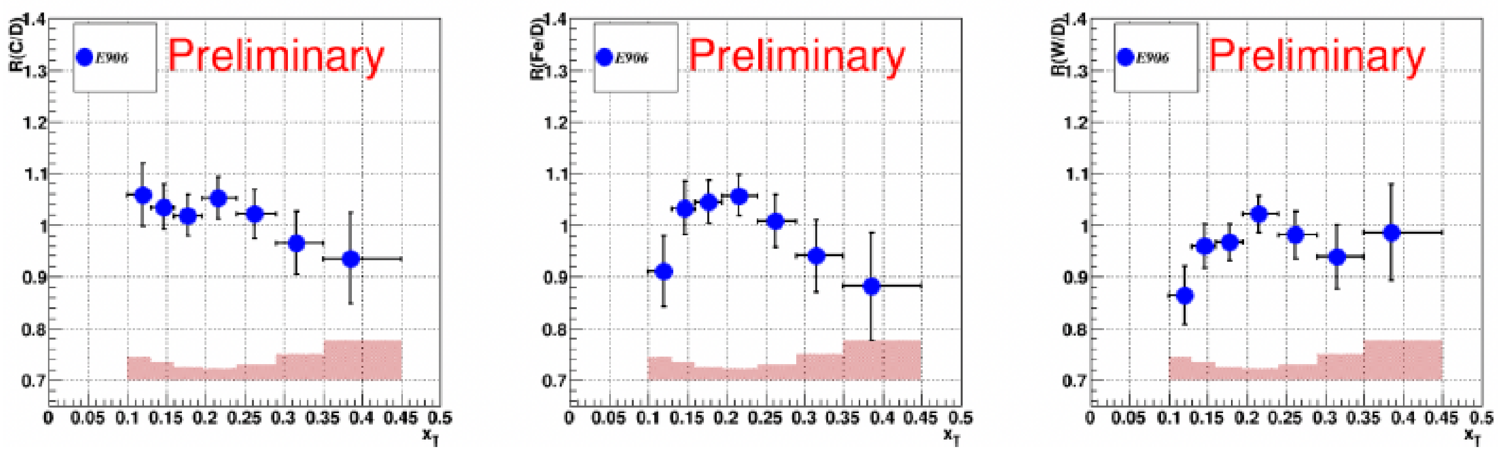
Part III

Energy loss and evidence for an EMC effect for antiquarks

3 - Energy loss vs. SeaQuest Drell–Yan data

- We consider preliminary data from Fermilab E906/SeaQuest experiment
- Study of **anti–quark distributions** of nucleons and nuclei in DY
- 120 GeV proton beam on nuclear targets
- Probe $0.1 < x < 0.45$ for anti–quarks
- Cross section ratio $R_{pA} = 2\sigma_{pA}/A\sigma_{pD}$

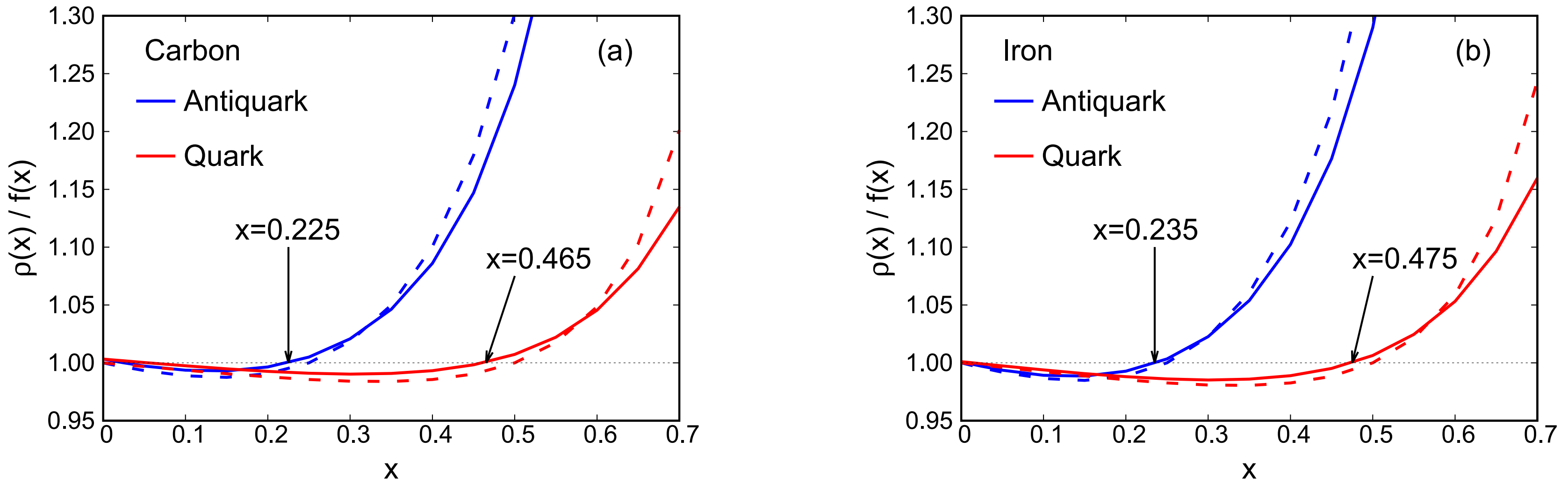




Data from: *Arun Tadepalli, PhD Thesis*
Rutgers, The State University of New Jersey (2019)

3 - Energy loss vs. SeaQuest Drell–Yan data

- Hunting for an EMC–like effect for antiquarks



$$\rho(x)/f_j(x) = \int d\boldsymbol{k} n(k) f_j(x/\alpha) \,/\, f_j(x)\,, \qquad \alpha = 1 + k_3/\sqrt{m^2+k^2}$$

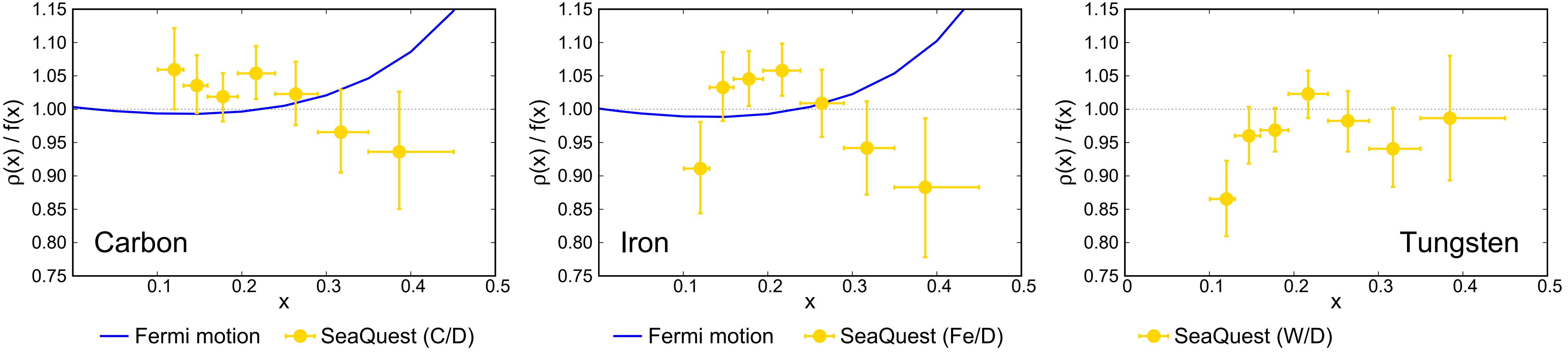
- Curves cross 1 at $x_{crossover} = 2/(n+1)$; $n = 3$ for q, $n = 7$ for $\bar{q}$
- $x \sim 0.2 - 0.3$: **suppression of Fermi motion contribution** to $\bar{q}_A/\bar{q}_N$

M. Alvioli, M. Strikman - arXiv:2210.12597 [hep-ph]

L. Frankfurt, M. Strikman - Phys. Rept. ***160*** *235 (1988)*

3 - Energy loss vs. SeaQuest Drell–Yan data

- Compare with *preliminary* SeaQuest data



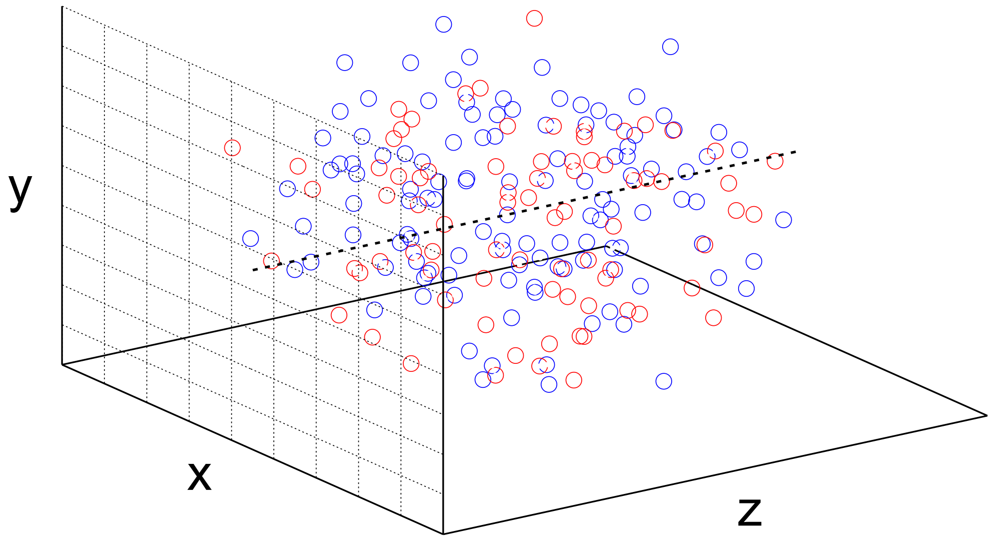
- $x \sim 0.2 - 0.3$: **suppression of Fermi motion contribution** to $\bar{q}_A/\bar{q}_N$
- **Data not compatible with predictions from Fermi motion**

M. Alvioli, M. Strikman - arXiv:2210.12597 [hep-ph]

Data from: *Arun Tadepalli, PhD Thesis (2019)*

3 - Energy loss vs. SeaQuest Drell–Yan data

- Energy loss of the quark travelling through the nuclear medium
- Would reduce the cross section for given x_p, mimick an EMC–like effect
- Effect proportional to the average gluon density a quark traveled through



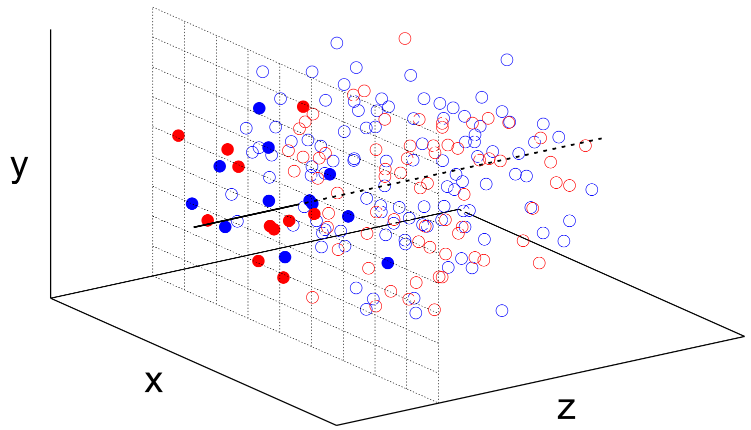
- MC code with nuclear configurations of: *PRC* ***100*** *024912 (2019)*
- Hard trigger of: *PRC* ***93*** *011902 (2016)*, *PRD* ***98*** *071502 (2018)*

3 - Energy loss vs. SeaQuest Drell–Yan data

- Energy loss proportional to the gluon density a quark traveled through
- **Hard trigger** of: *PRC **93** 011902 (2016)*, *PRD **98** 071502 (2018)*

$$Z_h(b,\nu) = \int d\boldsymbol{\rho} \sum_{j=1}^{A} \theta(\mathbf{z_{hard}} - z_j)\,\frac{1}{\pi B}\, e^{-(\boldsymbol{b}+\boldsymbol{\rho}-\boldsymbol{b}_j)^2/B}$$

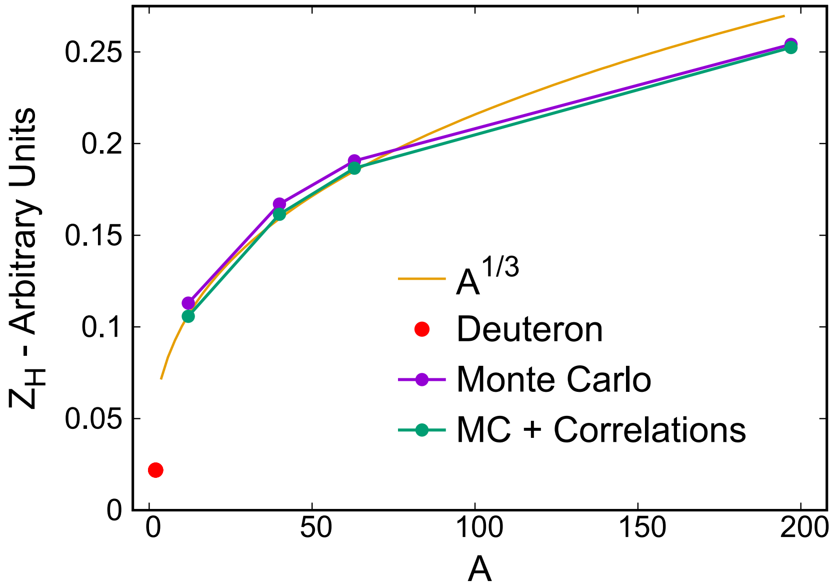
$$Z_H = \frac{\sum_{\nu=1}^{A} \nu \int d\boldsymbol{b}\,\langle Z_h(b,\nu)\rangle_{conf}}{\sum_{\nu=1}^{A} \int d\boldsymbol{b}\,\langle Z_h(b,\nu)\rangle_{conf}}$$

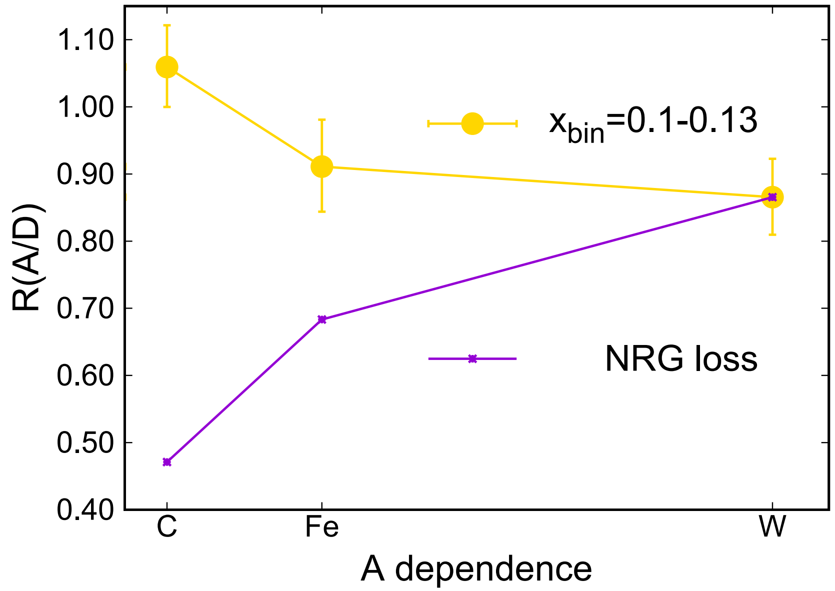


M. Alvioli, M. Strikman - arXiv:2210.12597 [hep-ph]

3 - Energy loss vs. SeaQuest Drell–Yan data

- NRG loss maximum in the smallest–$x = x_A$ data bin
- We normalize to the experimental data point for tungsten





- A–dependence of NRG loss not compatible with preliminary data
- **First evidence for the EMC effect for antiquarks?!?**

M. Alvioli, M. Strikman - arXiv:2210.12597 [hep-ph]

Summary

- We generate *nuclear configurations* including spin-isospin-dependent Nucleon-Nucleon correlations

  → Already used by many authors and for several *different purposes*

  → We can produce configurations for *any* A=Z+N

  → *Deformed* nuclei are implemented as well as *neutron skin*

- *Color fluctuations* implemented in MCG by fluctuating σ_{NN}, by means of a probability distribution $P(\sigma_{NN})$

  → Modified N_{coll}-*impact parameter* relationship

- Selection of events with a *hard-trigger* allows study of x-dependence of CF in pA, dA and centrality dependence of double partonic interactions

- We estimate NRG loss effect in SeaQuest DY data with the *hard-trigger* algorithm

Configurations available at: `http://sites.psu.edu/color`

Additional Slides

1.a - Glauber: semi-analytic description

- Continuous density distributions of nuclei, $\rho(\boldsymbol{r})$; $\boldsymbol{r} = (\boldsymbol{b}, z)$
- Probability of n binary collisions in AA using *binomial distribution* and thickness functions $T_A(\boldsymbol{b}) = \int dz \rho(\boldsymbol{b}, z)$, $T_{AA}(\boldsymbol{b}) = \int d\boldsymbol{s} T_A(\boldsymbol{s}) T_A(\boldsymbol{b} - \boldsymbol{s})$:

$$P_n(\boldsymbol{b}) = \binom{A^2}{n} \left[T_{AA}(\boldsymbol{b})\sigma_{NN}^{in}\right]^n \left[1 - T_{AA}(\boldsymbol{b})\sigma_{NN}^{in}\right]^{A^2-n}$$

- E.g., total AA inelastic cross section requires multidimensional integrations:

$$\sigma_{AA}^{in} = \int d\boldsymbol{b} \int \prod_i^{A\otimes A} d\boldsymbol{s}_i T_A(\boldsymbol{s}_i) \left\{1 - \prod_j^A \prod_k^A \sigma(\boldsymbol{b} - \boldsymbol{s}_j + \boldsymbol{s}_k)\right\}$$

- Optical limit: assuming uncorrelated scattering centers, A⊗A integrations over transverse coordinates are reduced to one integration:

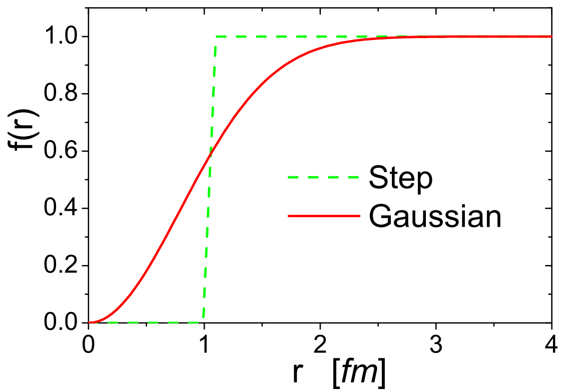
$$\sigma_{AA}^{in,opt} = \int d\boldsymbol{b} \left\{1 - \left[1 - \sigma_{NN}^{in} T_{AA}(\boldsymbol{b})\right]^{A^2}\right\}$$

- **Details of density are lost.**
- **Difficult to estimate event-by-event *fluctuations***

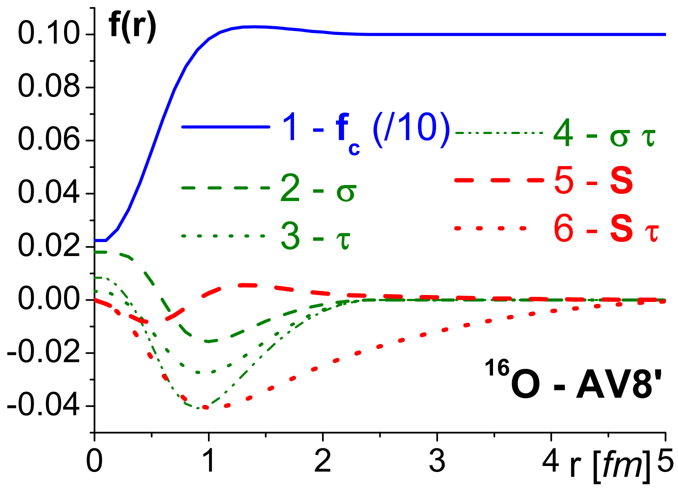
- We used $|\Psi|^2$ as a Metropolis weight function

$$\Psi(\boldsymbol{r}_1, ..., \boldsymbol{r}_A) = \prod_{i<j}^{A} \hat{f}(r_{ij})\,\Phi(\boldsymbol{r}_1, ..., \boldsymbol{r}_A)$$

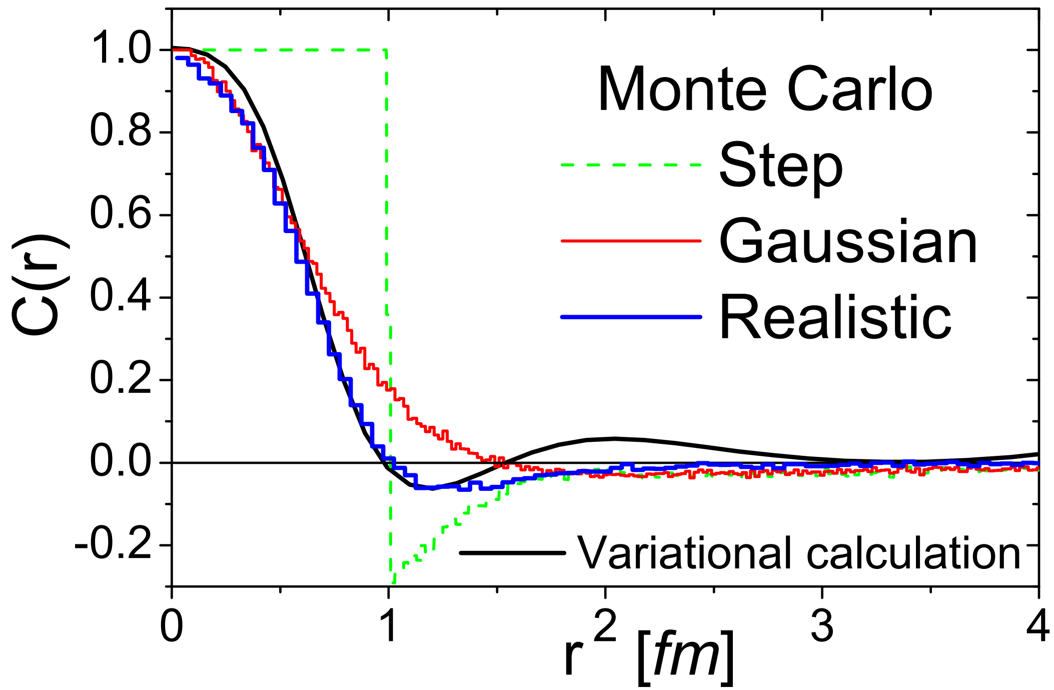
where Φ is given by the independent particle model.



$\Downarrow$



$\Longrightarrow$

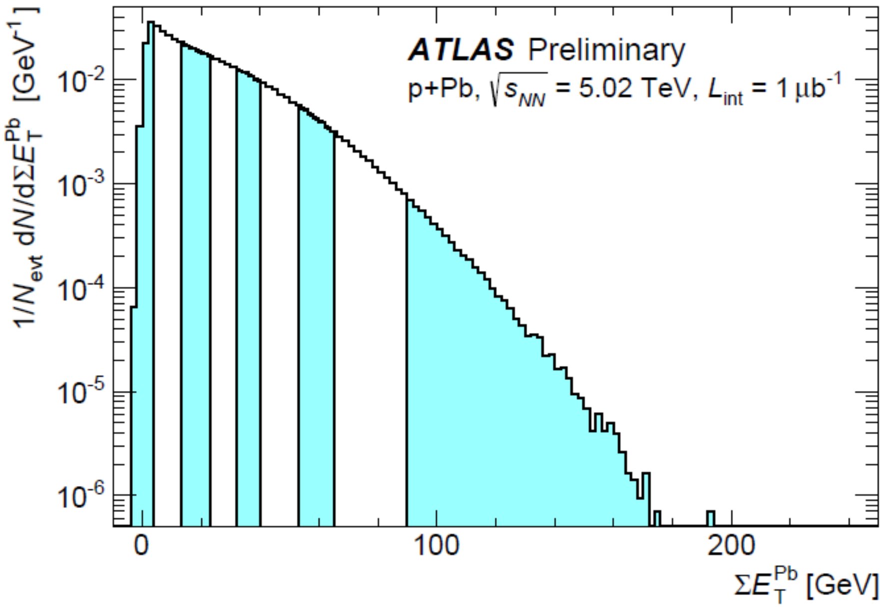


$\Uparrow$

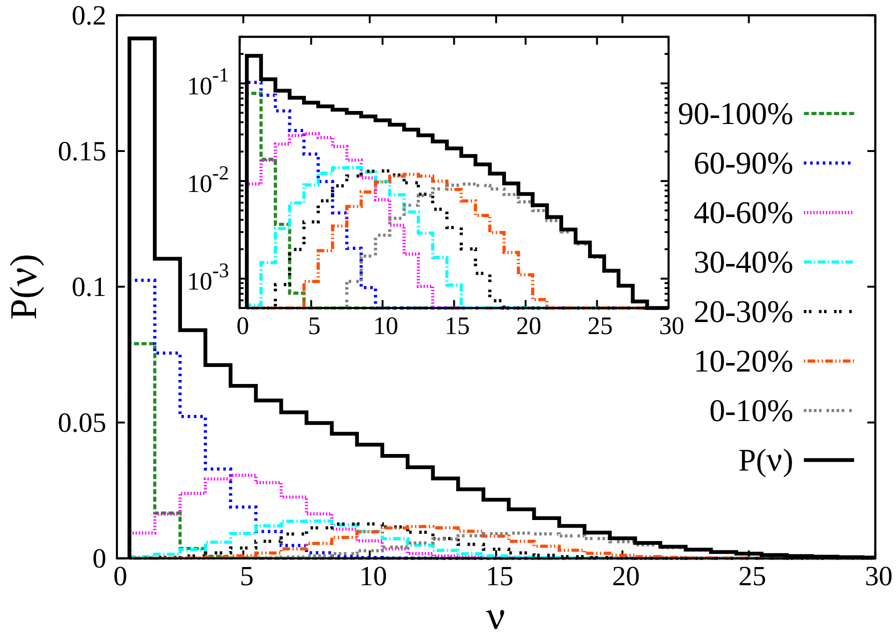
- We use **realistic correlation functions** from variational calculation

2.a - Color Fluctuations: N_{coll} and b dependence

- We use ATLAS (*ATLAS-CONF-2013-096*) model for ΔE_T in pp collisions with a convolution to obtain the pA model



$\Longrightarrow$

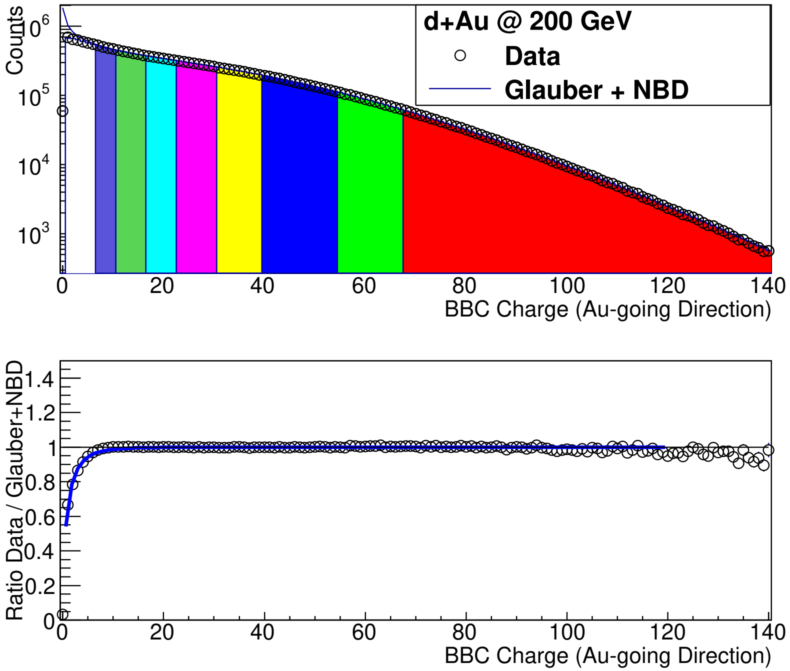


Alvioli, Cole, Frankfurt, Perepelitsa, Strikman, ***PRC93*** *(2016)*

- ATLAS and CMS found deviations from the Glauber model (N_{coll} tail)
- we derive a non-trivial relation between bins in ΔE_T and N_{coll} and thus determine $P(N_{coll})$ dependence on centrality ($\nu = N_{coll}$)

2.c - Color Fluctuations: N_{coll} and b dependence

- We use PHENIX (*Adare et al., PRC90 (2014)*) model for multiplicity in the dA case



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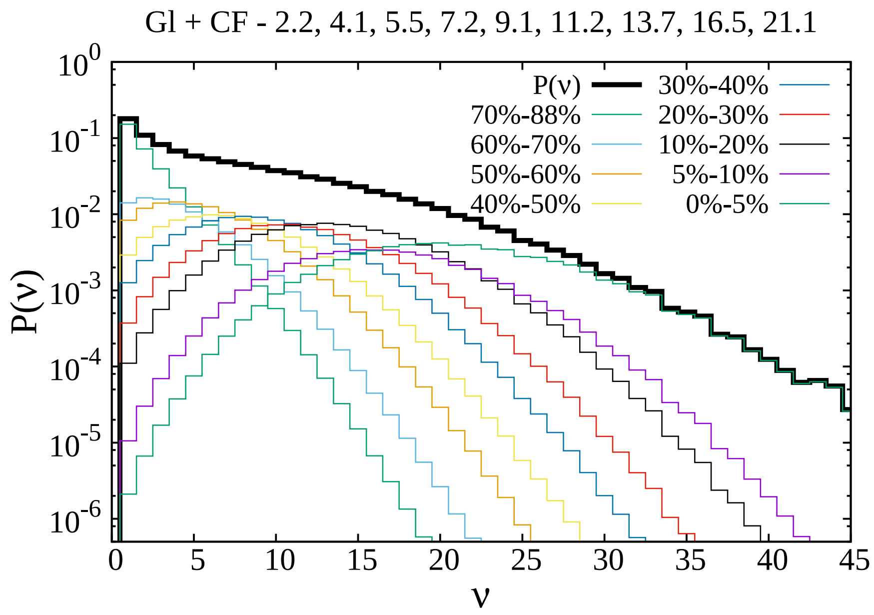
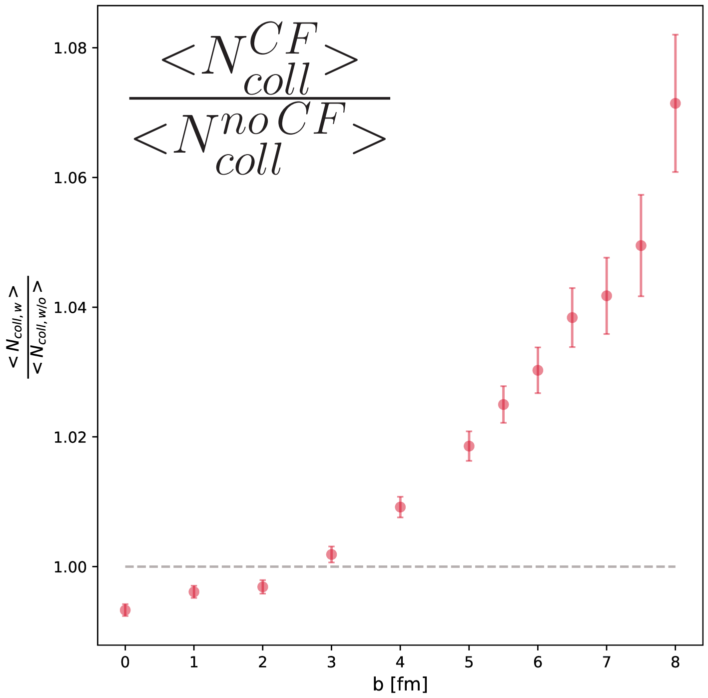


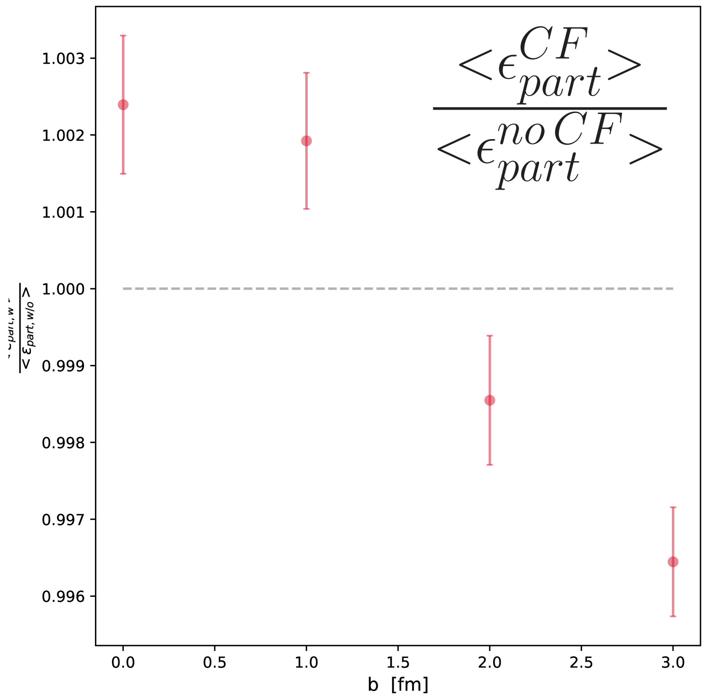
Alvioli, Frankfurt, Perepelitsa, Strikman, ***arXiv:1709:04993 [hep-ph]***

- same approach as in the pA case
- non -trivial relation between N_{coll} and centrality

2.a - Color fluctuations + SMASH model

- Dynamical transport model (*A. Bozic's Thesis*)
- Color fluctuation effects on N_{coll} and *eccentricity*: **O–O collisions**



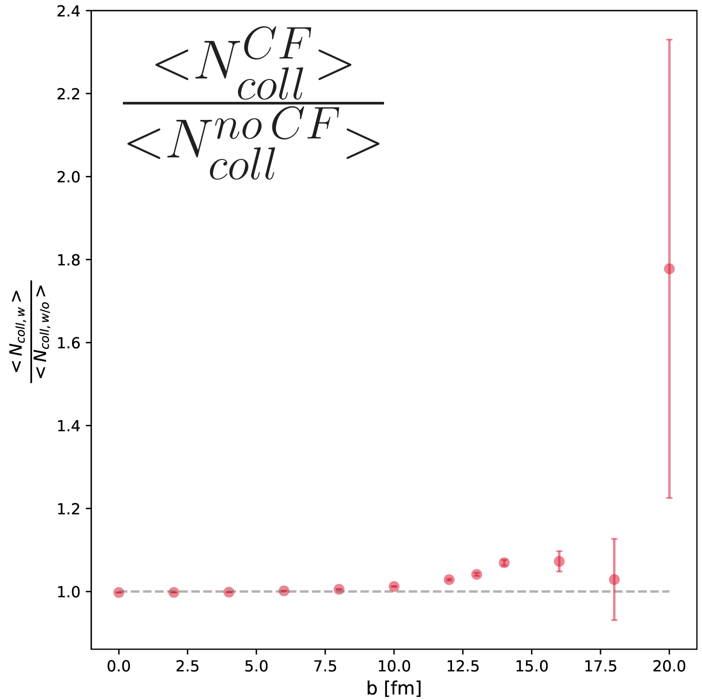


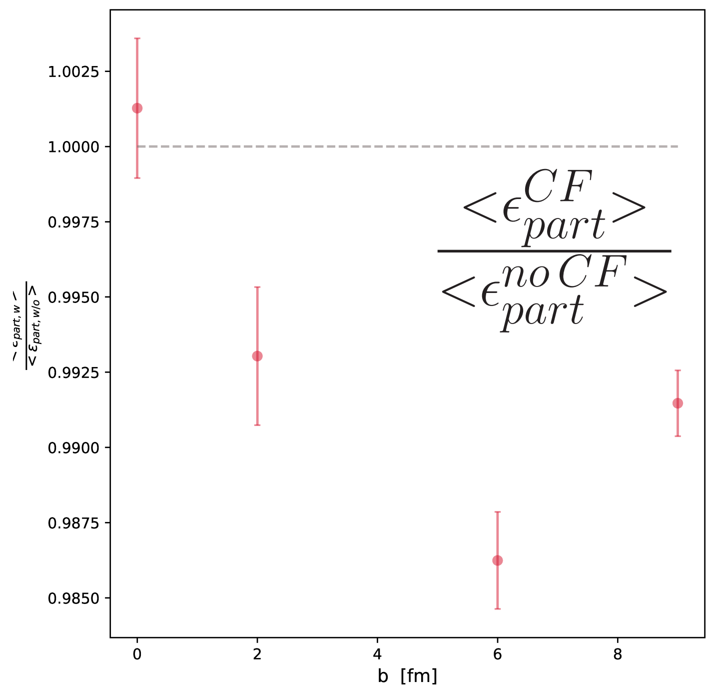
→ N_{coll} suppressed at small b and enhanced for peripheral collisions

→ ϵ_{part} increased at small b and decreased at large b

2.a - Color fluctuations + SMASH model

- Dynamical transport model (*A.Bozic's Thesis*)
- Color fluctuation effects on N_{coll} and *eccentricity*: **Au–Au collisions**





→ Same N_{coll} at small b and enhanced for very peripheral collisions

→ ϵ_{part} decreased at medium and large b