Effects of correlations and fluctuations on the initial state of heavy-ion collisions

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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

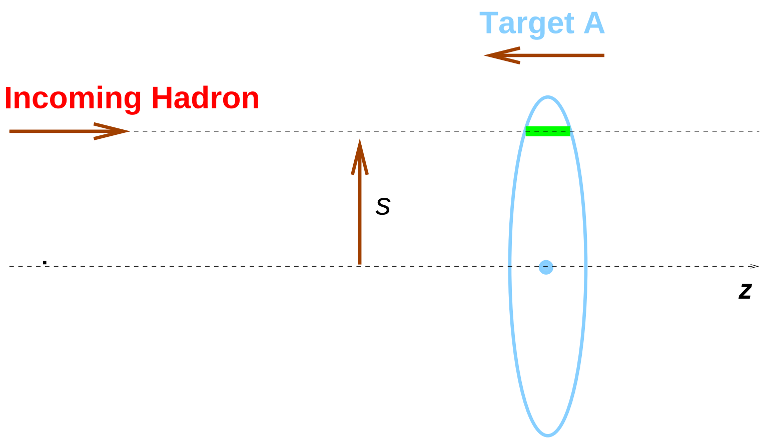
2.d Processes with double hard trigger: DPS

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

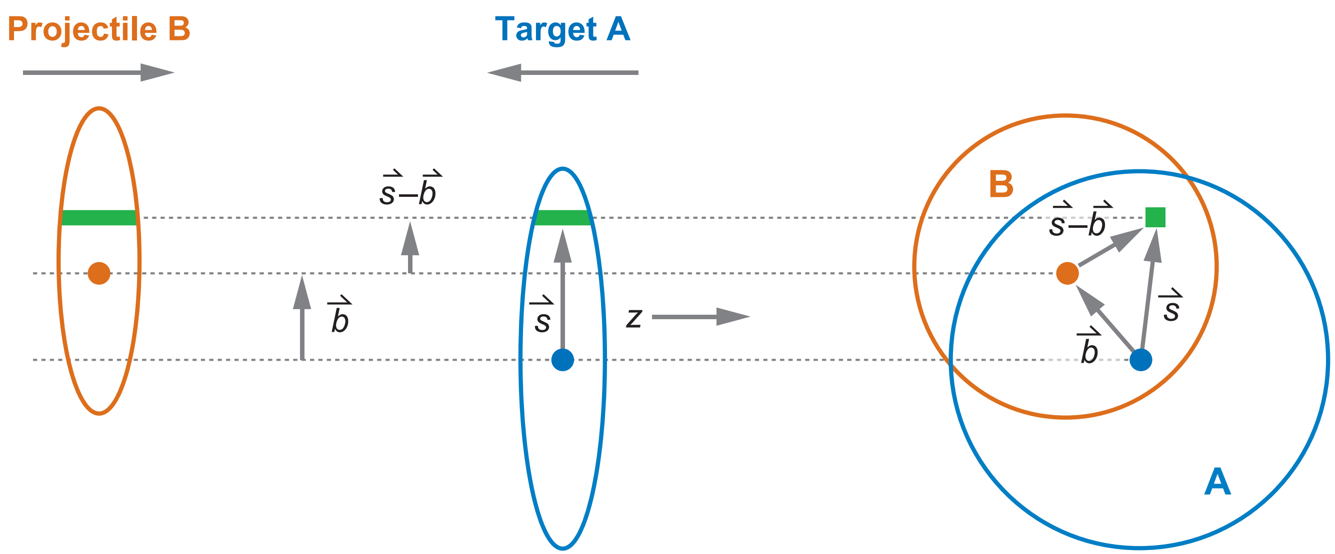


Inputs:

⋆ (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 - 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:

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

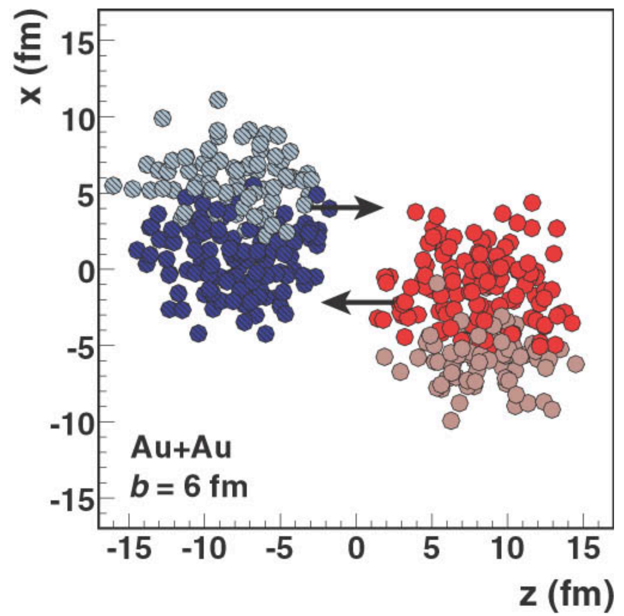
- **Details of density are lost.**
- **Difficult to estimate event-by-event *fluctuations***

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.

- Also used in experimental analyses and event generators

- MCG introduces N_{part} and N_{coll}, not directly measurable, but contain a lot of information about the fluctuating ***collision geometry***.



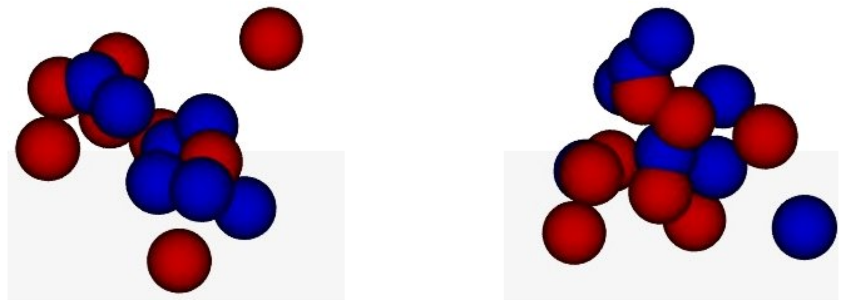
- Charged particle multiplicity scales with N_{part}, N_{coll} $\Leftrightarrow$ ***centrality***

- 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**:

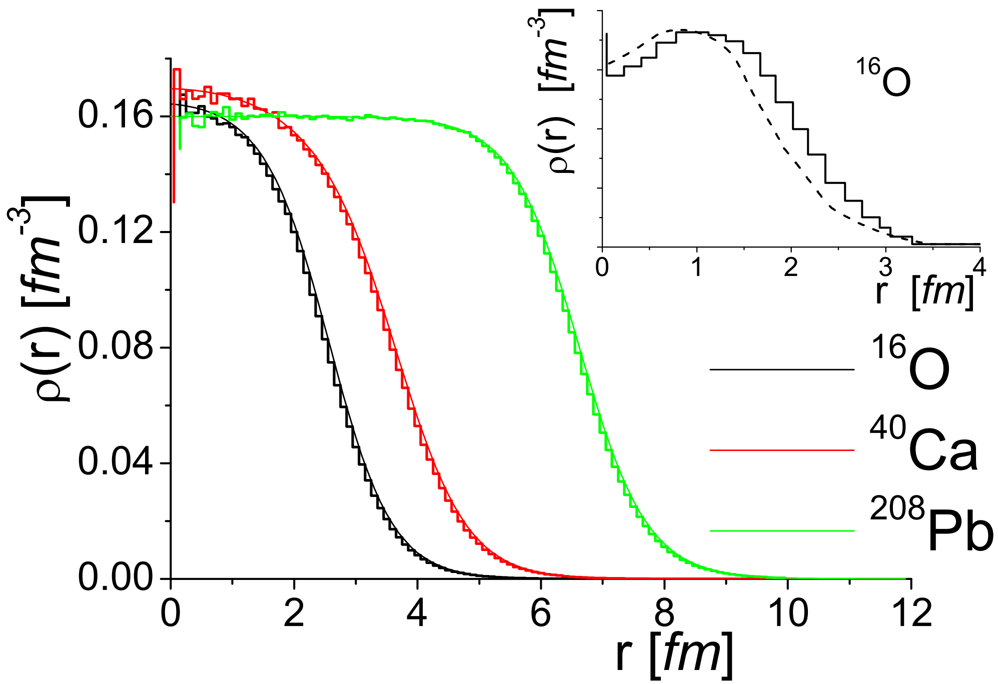
$$\Psi(\boldsymbol{r}_1, ..., \boldsymbol{r}_A) = \prod_{i<j}^{A} \hat{f}(r_{ij})\, \Phi(\boldsymbol{r}_1, ..., \boldsymbol{r}_A)$$



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

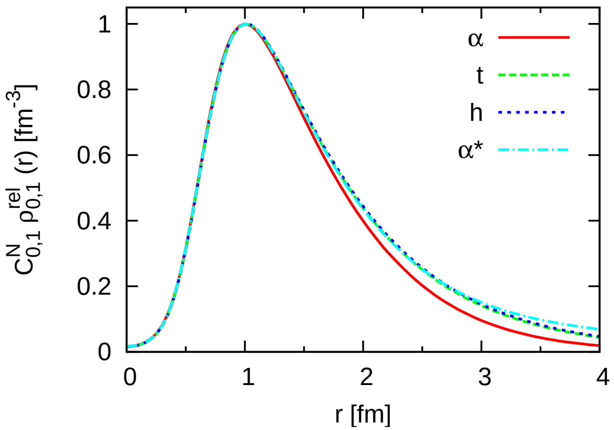
$$\hat{f}(r_{ij}) = \sum_{n=(\mathbb{1},\sigma,\mathbb{S})\otimes\mathbb{1},\tau} \hat{f}^{(n)}(r_{ij})$$

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

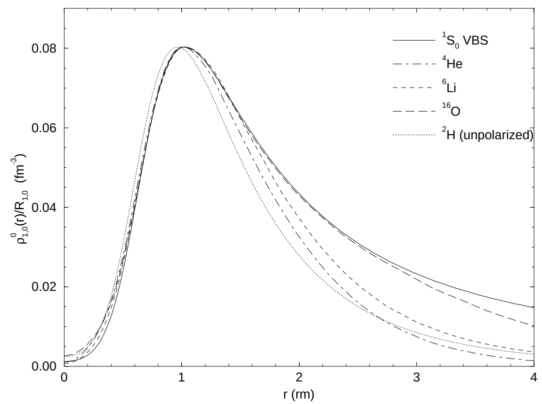


1.b - Correlations signatures in two-body densities

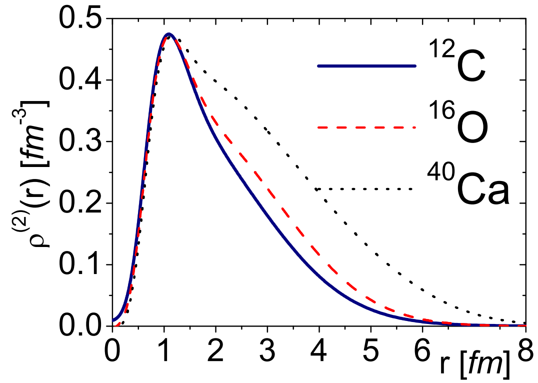
- ***Ab-initio*** two-body densities: $\rho(r) = \int d\boldsymbol{R}\, \rho^{(2)}\Big(\boldsymbol{r} = \boldsymbol{r}_1 - \boldsymbol{r}_2, \boldsymbol{R} = (\boldsymbol{r}_1 + \boldsymbol{r}_2)/2\Big)$



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

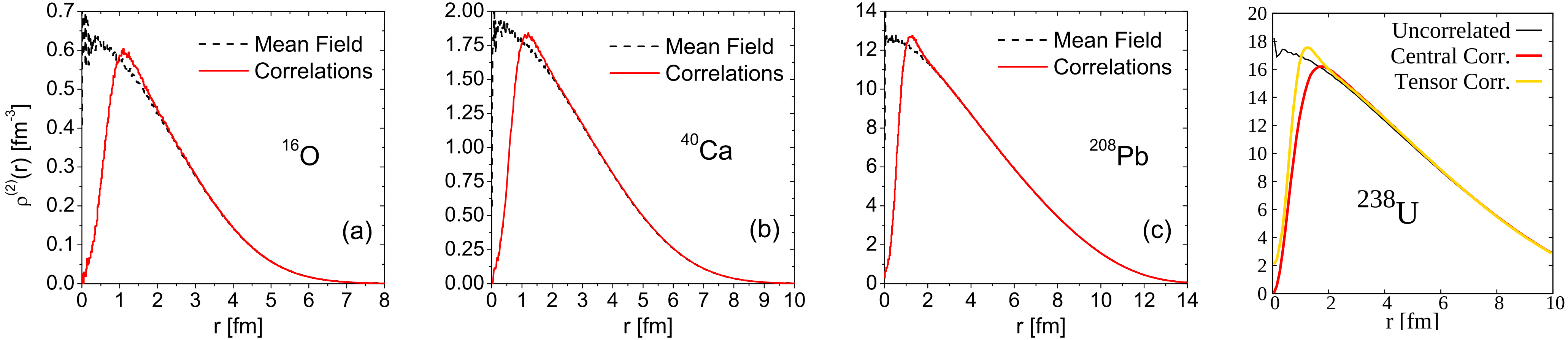


Forest *et al*, Phys. Rev. **C54** (1996) 646-667



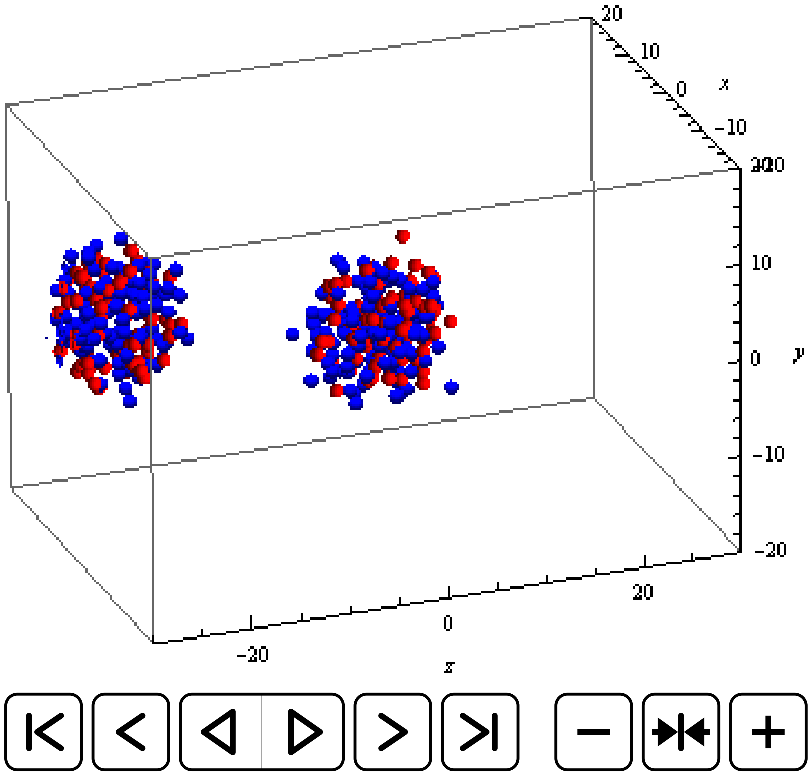
Alvioli *et al*, Phys. Rev. **C72**; Phys. Rev. Lett. **100** (2008)

- ***MC algorithm***



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

1.b - Correlations and fluctuations of participant matter in AA

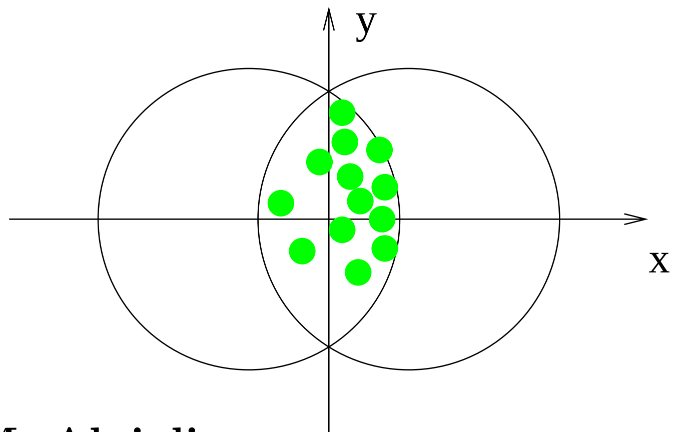


- **Spectator** nucleons ●●relevant for zero degree calorimeter measurement (beam remnant): *Alvioli, Strikman, **PRC83** (2011)*
- **Participant** matter distribution relevant for hydrodynamic evolution:

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

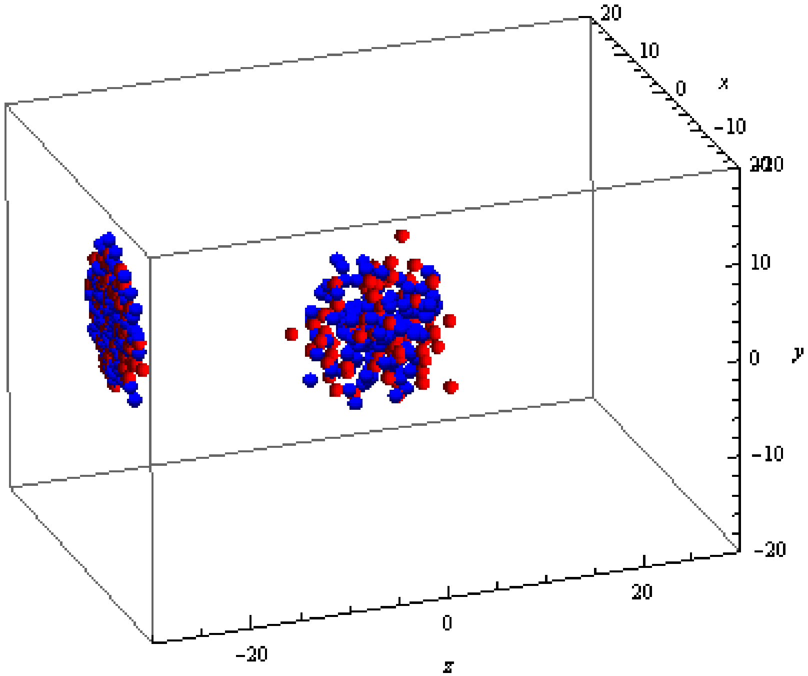
$$\Delta\epsilon_n = \sqrt{\frac{\sum(\epsilon_n^i - \langle \epsilon_i \rangle)^2}{N}}$$

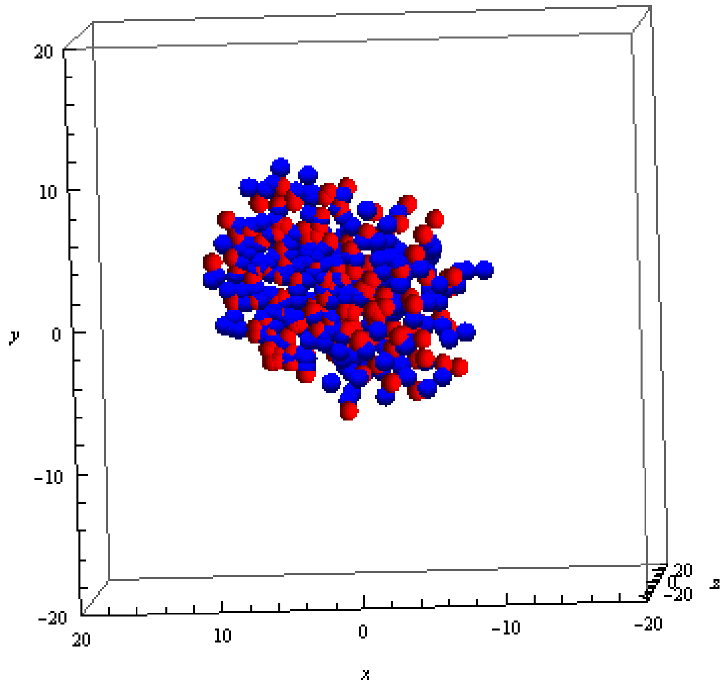
Alvioli, Holopainen, Eskola, Strikman
*Phys. Rev. **C85** (2012)*



$\longrightarrow$ participant nucleons ● in transverse plane

1.b - Spectators in Pb-Pb collisions at 160 A GeV

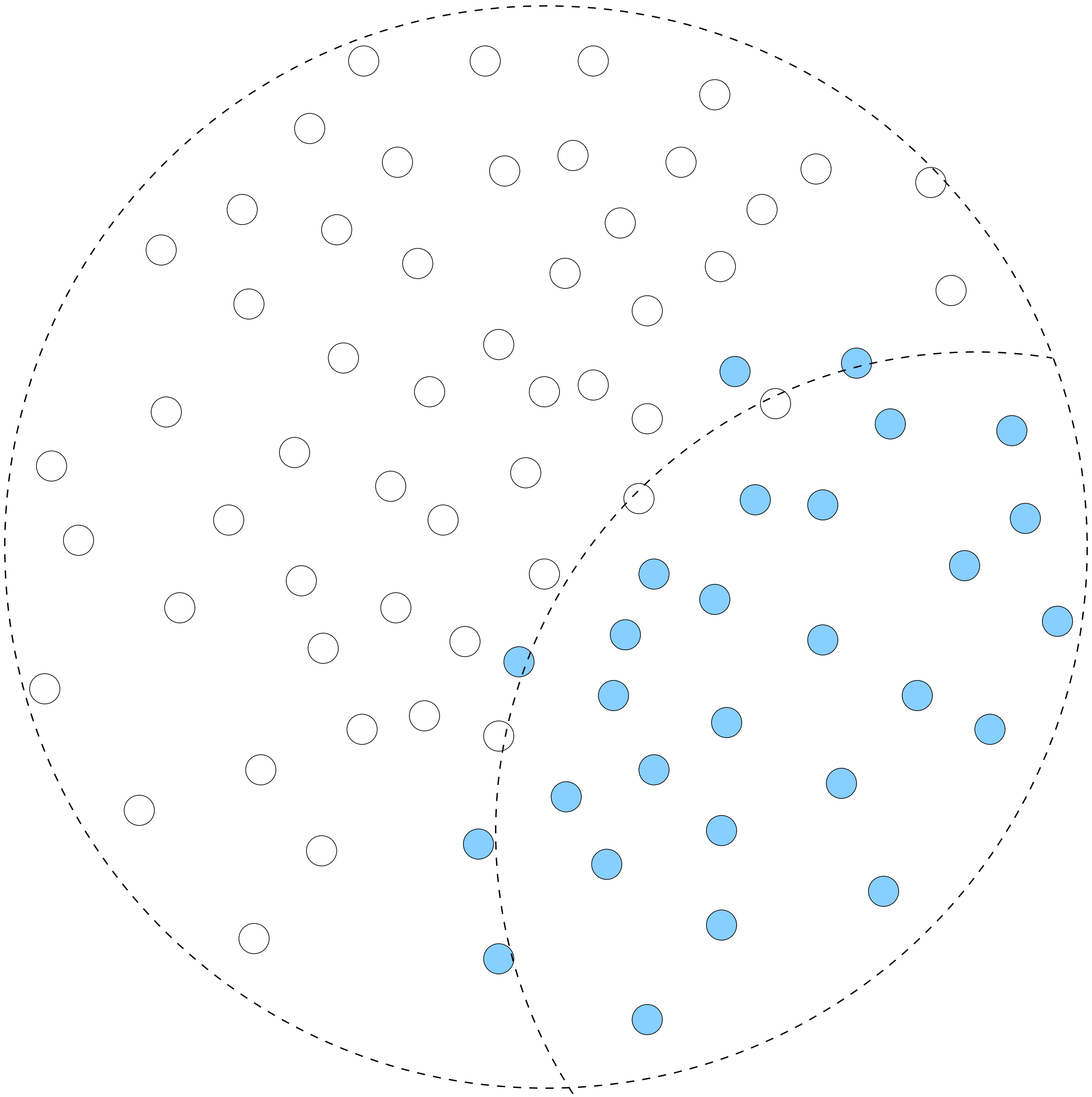




- *protons*
- *neutrons*
- *high-momentum nucleons*

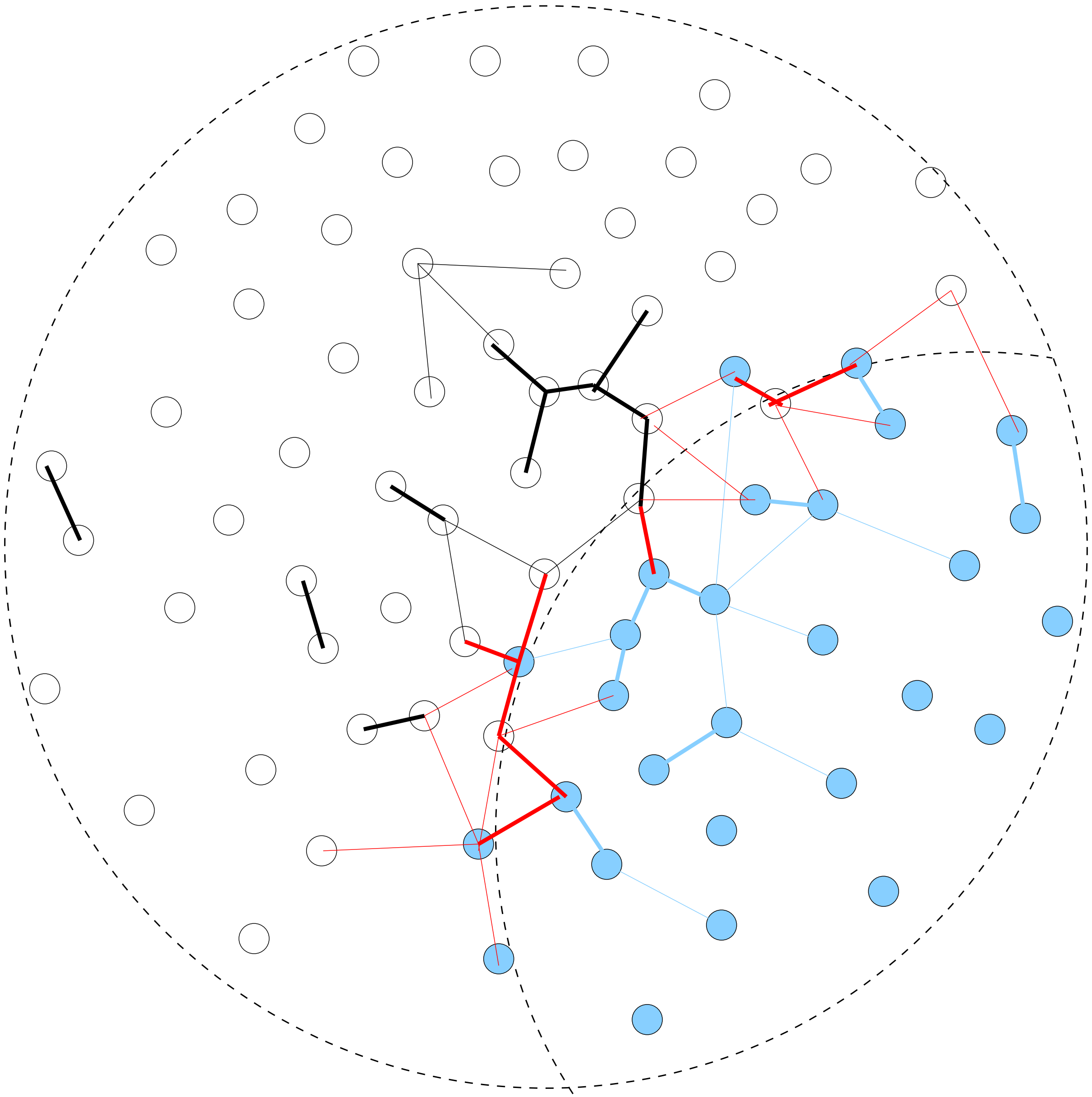
- Nucleons in green • were correlated with one interacting (hidden) nucleon
- Large *energy released* by disrupting correlated pairs
- Correlated nucleons have *high-momentum* and are mostly *pn pairs*

1.b - Instantaneous disruption of NN correlated pairs



* after the instantaneous interaction with the projectile, blue nucleons ● are removed

1.b - Instantaneous disruption of NN correlated pairs

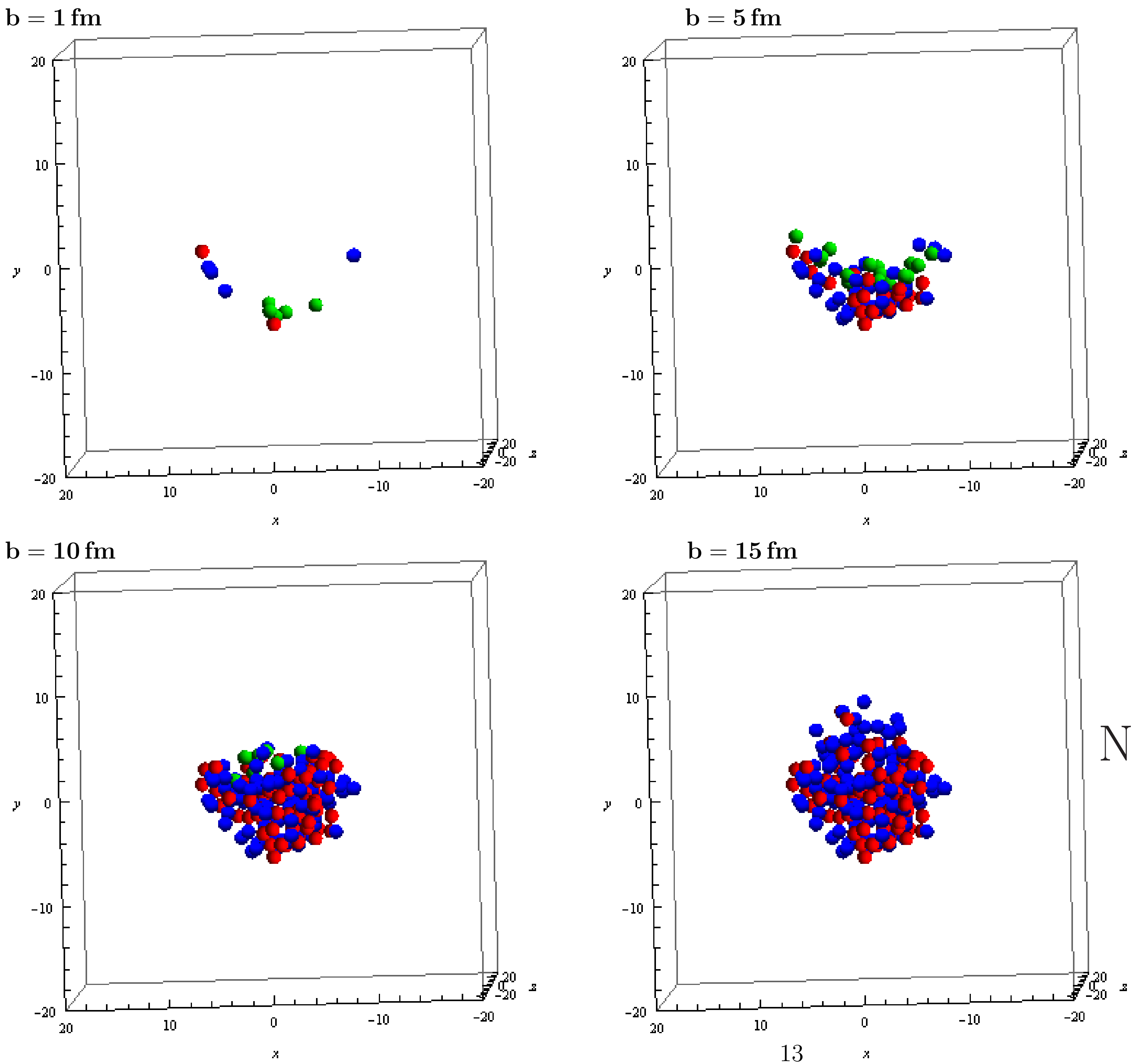


* for a given configuration,

$$V = V_{spect} + V_{int} + V_{transf}$$

* V_{transf} is the (potential) energy freed after removal of participants (as excitation nrg)
* nucleons in correlated pair have much larger relative momemtum than mean field nucleons

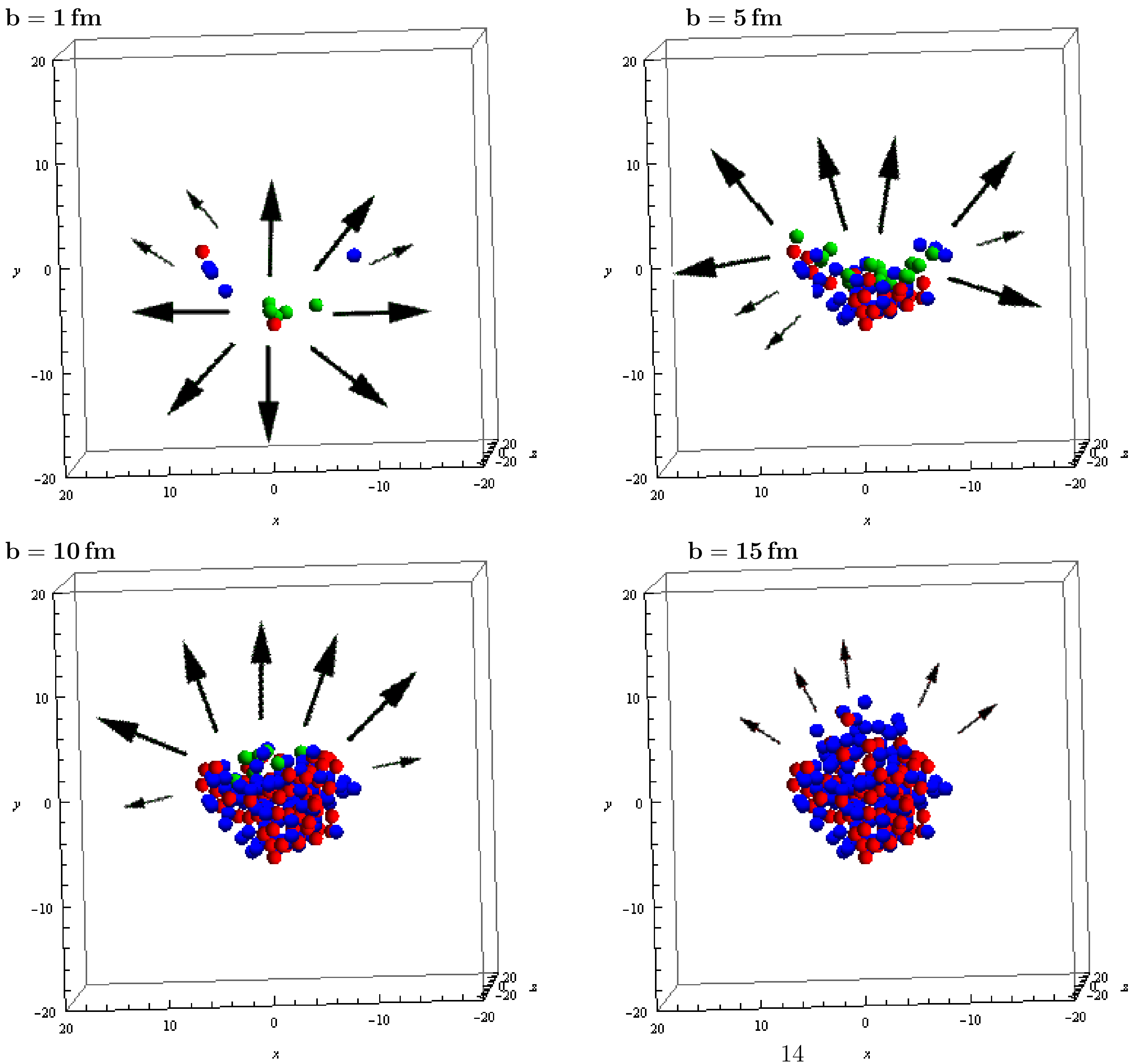
1.b - High-momentum nucleons: asymmetry



- *protons*
- *neutrons*
- *high-momentum nucleons*

potential energy due to NN correlations disruption is transferred to spectator nucleons

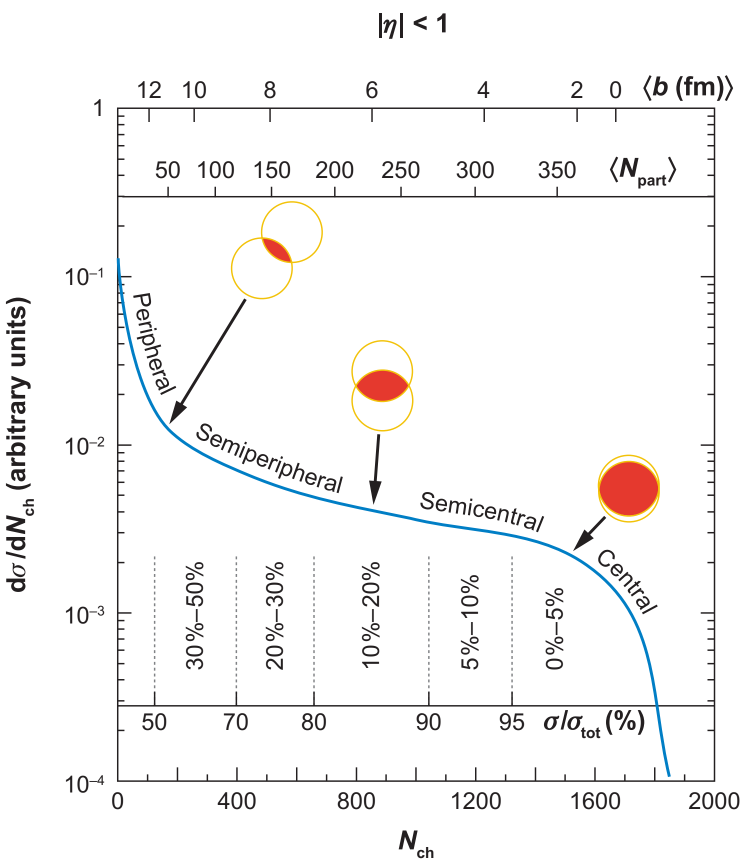
1.b - High-momentum nucleons: asymmetry

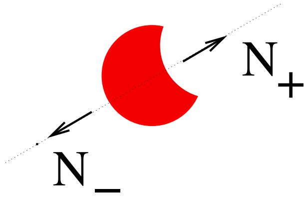


- *protons*
- *neutrons*
- *high-momentum nucleons*

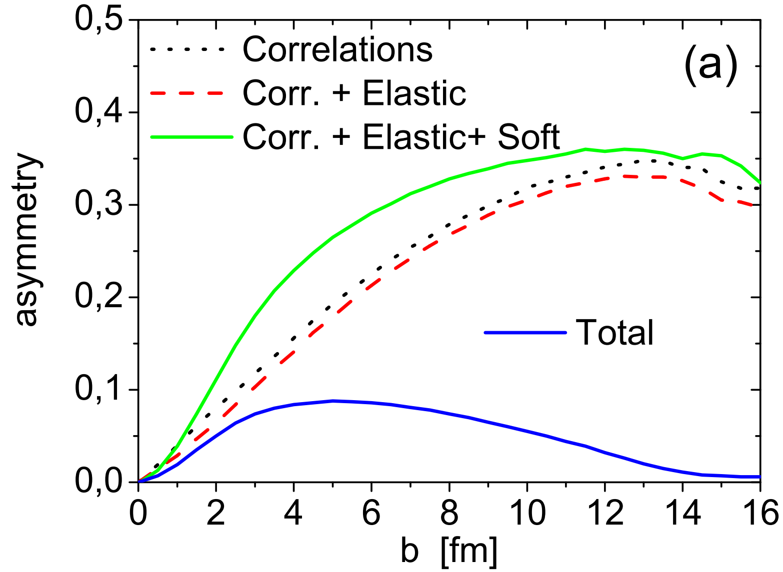
absorption by the spectator system determines asymmetry as a function of b!

1.b - Centrality and asymmetry of emissions





$$A(b) = \frac{N_+ - N_-}{N_+ + N_-}$$



Extraction of impact parameter from the correlation with total charged particle multiplicity in the final state

(from Miller *et al.*, Annu. Rev. Part. Sci. 57, 205 (2007))

Our calculation of asymmetry as a function of impact parameter b

M. Alvioli, M. Strikman,

Phys. Rev. C83 (2011)

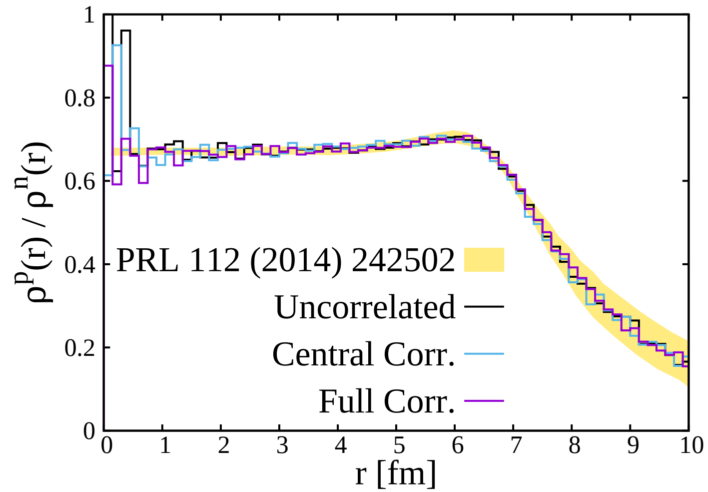
1.c - Configurations with neutron skin

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

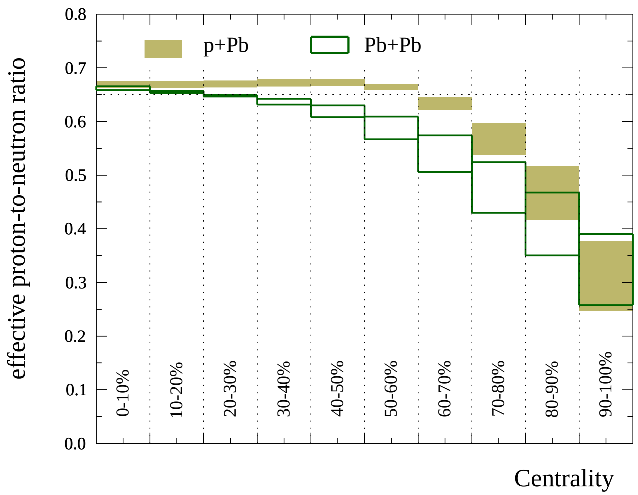
$$\rho(r) = \rho_0^{(p,n)} \;/\; \left(1 + e^{(r - R_0^{p,n})/a^{p,n}}\right)$$

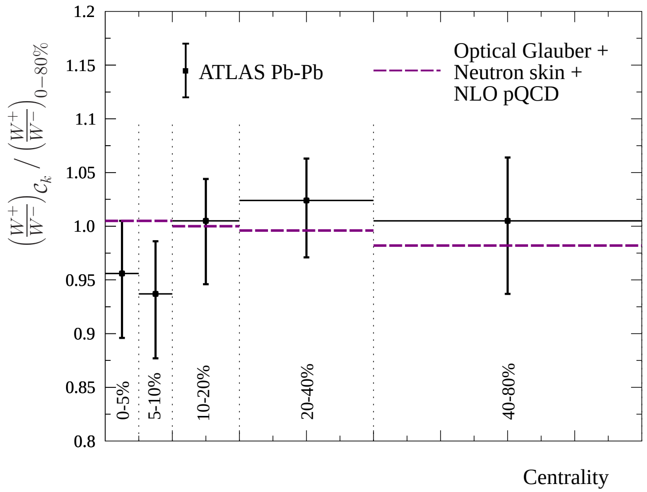
$$(\rho_0^p, R_0^p, a_0^p) \;=\; (\text{"82"}, 6.680 fm, 0.447 fm)$$
$$(\rho_0^n, R_0^n, a_0^n) \;=\; (\text{"126"}, 6.700 fm, 0.550 fm)$$

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

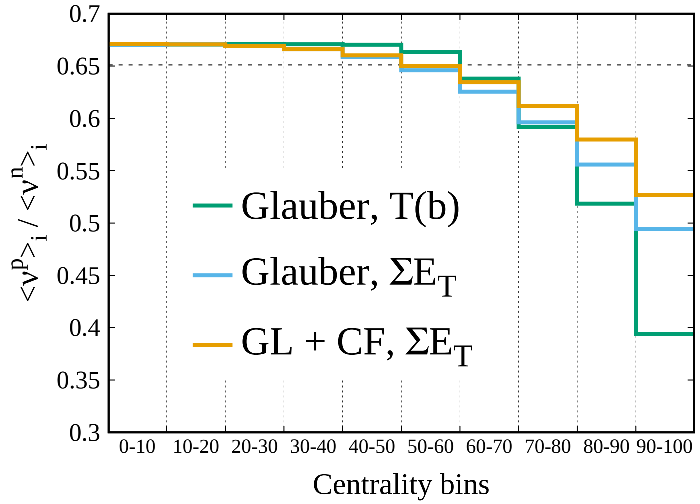


- Suggested as additional tool for determination of centrality:





*H. Paukkunen, PL**B745** (2015)*



*Alvioli, Strikman (**PRC 100**, 2019)*

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

1.d - Configurations of deformed nuclei

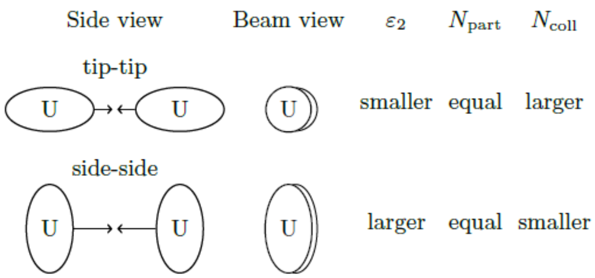
- ***Nucleus deformation*** – modified nuclear profile:

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

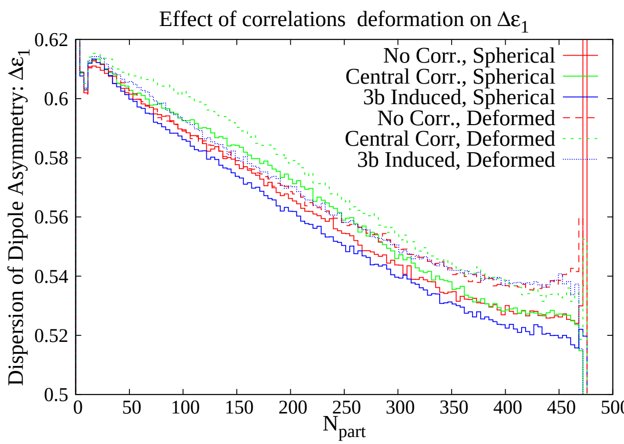
(*P. Filip, R. Lednicky, H. Masui, N. Xu Phys. Lett.* ***C80*** *(2009)*)

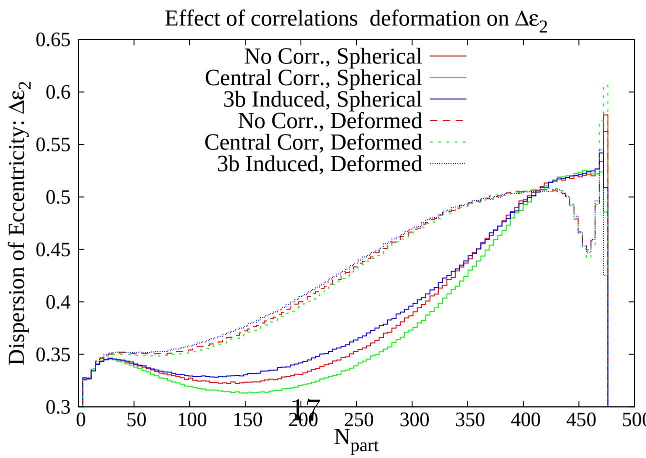
$$Y_{20}(\theta) = \frac{1}{4\,r^2}\sqrt{\frac{5}{\pi}}\left(2z^2 - x^2 - y^2\right)$$

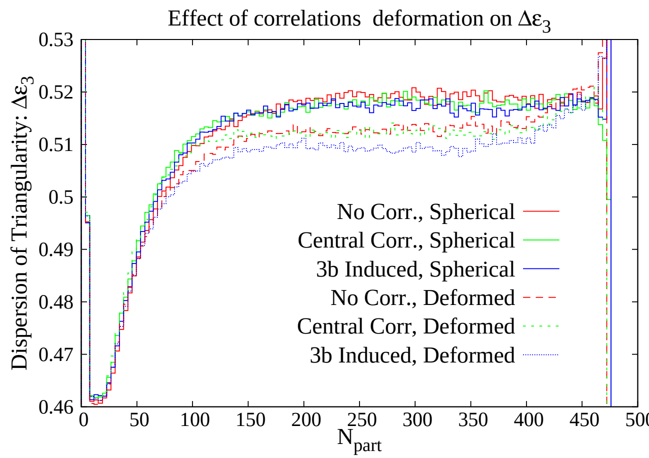
$$Y_{40}(\theta) = \frac{1}{16\,r^4}\sqrt{\frac{9}{\pi}}\left(35z^4 - 30z^2r^2 + 3r^4\right)$$



- 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	✓	✓

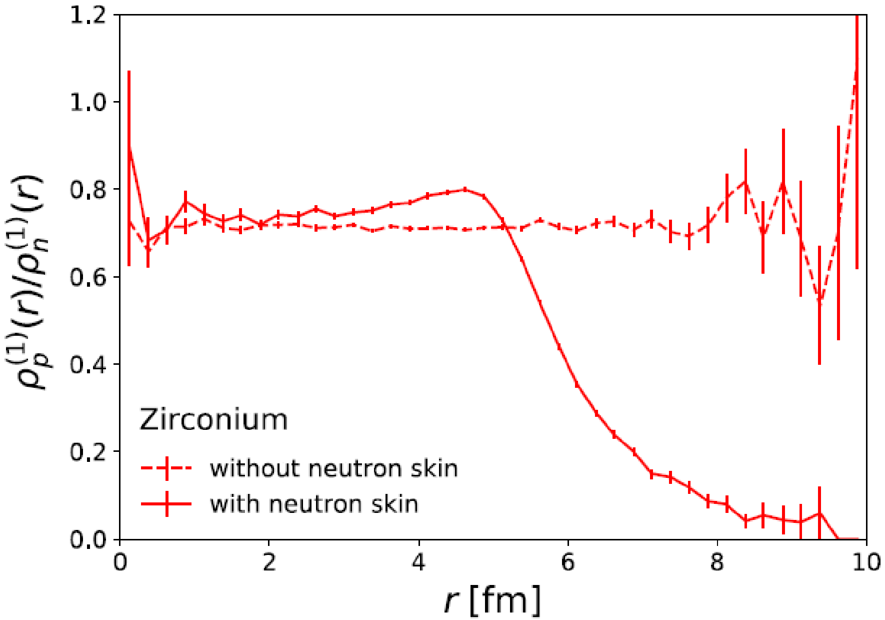
- Charge distribution unfolded for proton size NPA **717** 235 (2003)
- We consider ^{96}Zr as a halo-like nucleus: $R_p \simeq R_m$; $a_n > a_p$
- Parameters without neutron skin from PR**C99** 044908 (2019)

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

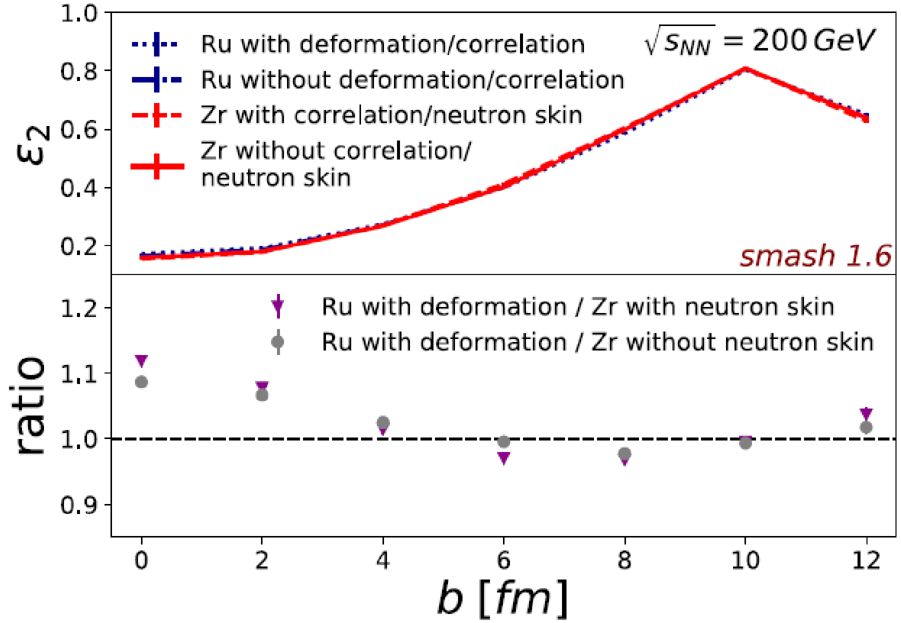
- Final parameters (Ru deformed; Zr with/without neutron skin):

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

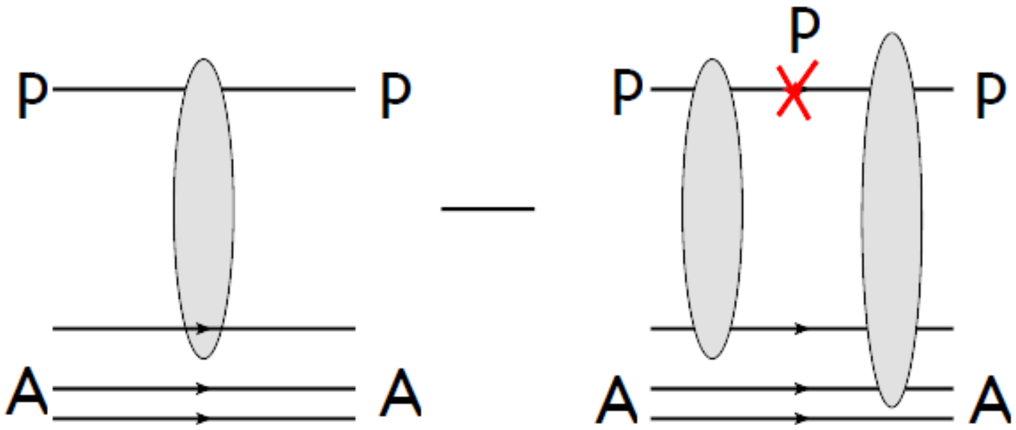


Hammelmann *et. al.*, Phys. Rev. **C101** (2020)

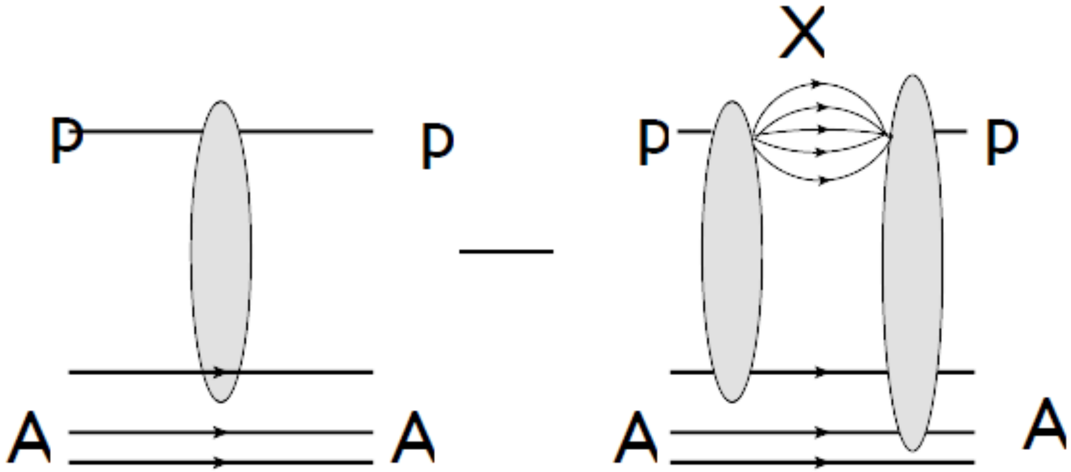
Part II

Effects of color fluctuations

2 - Beyond Glauber approach



$\longrightarrow$ Glauber model: in rescattering diagrams the proton cannot propagate in intermediate states



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

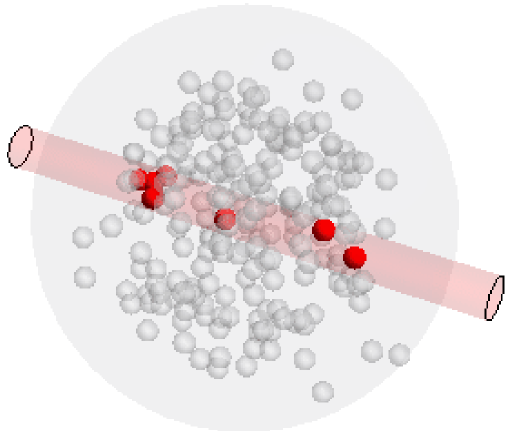
X is a set of intermediate states that stay frozen during $\boldsymbol{pA}$ interaction

2.a - NN interaction with frozen configurations

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

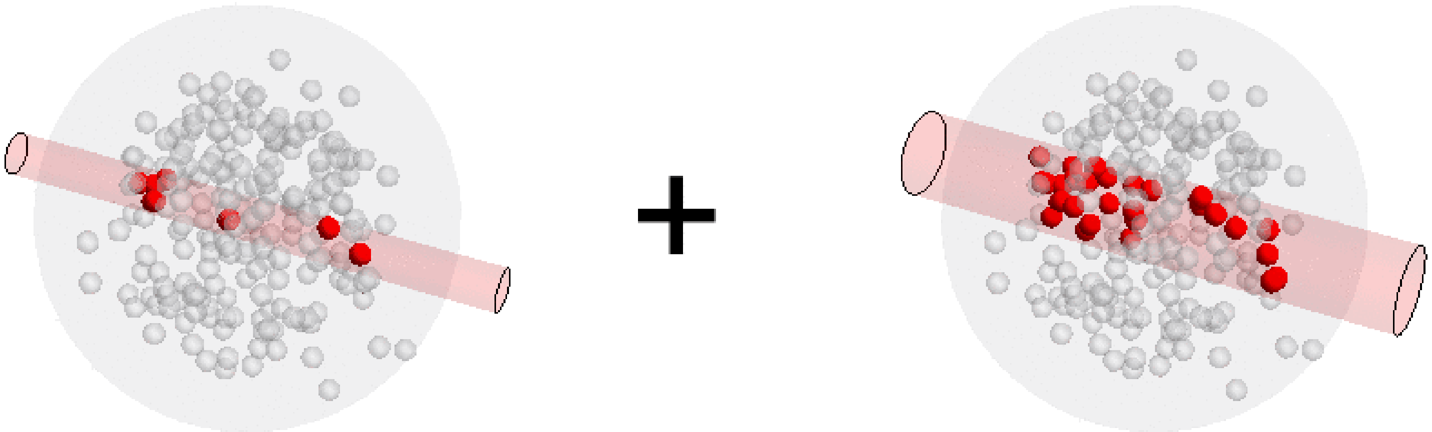
$$2\,R \,<\, 2\,p_{lab}/(M^2 \,-\, m^2)$$

holds, intermediate states are frozen during the pA interaction



2.a - Fluctuations of NN interaction

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



2.a - Color Fluctuations in Monte Carlo Glauber

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

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

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

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

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)*;

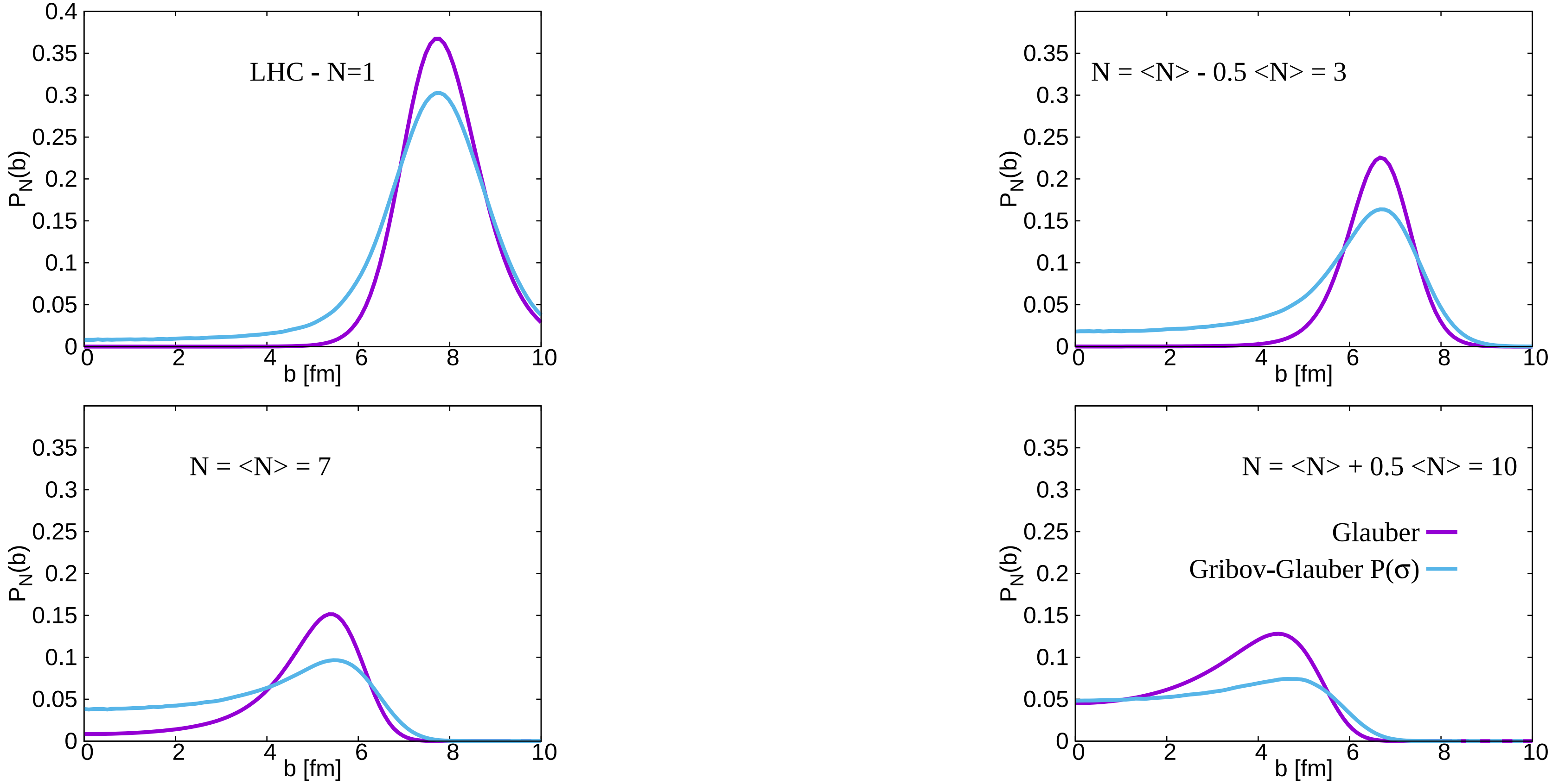
M. Alvioli, L. Frankfurt, D. Perepelitsa, M. Strikman, ***PRD98*** *(2018)*;

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 $\mathbf{b} \Longrightarrow$ **smearing of centrality**

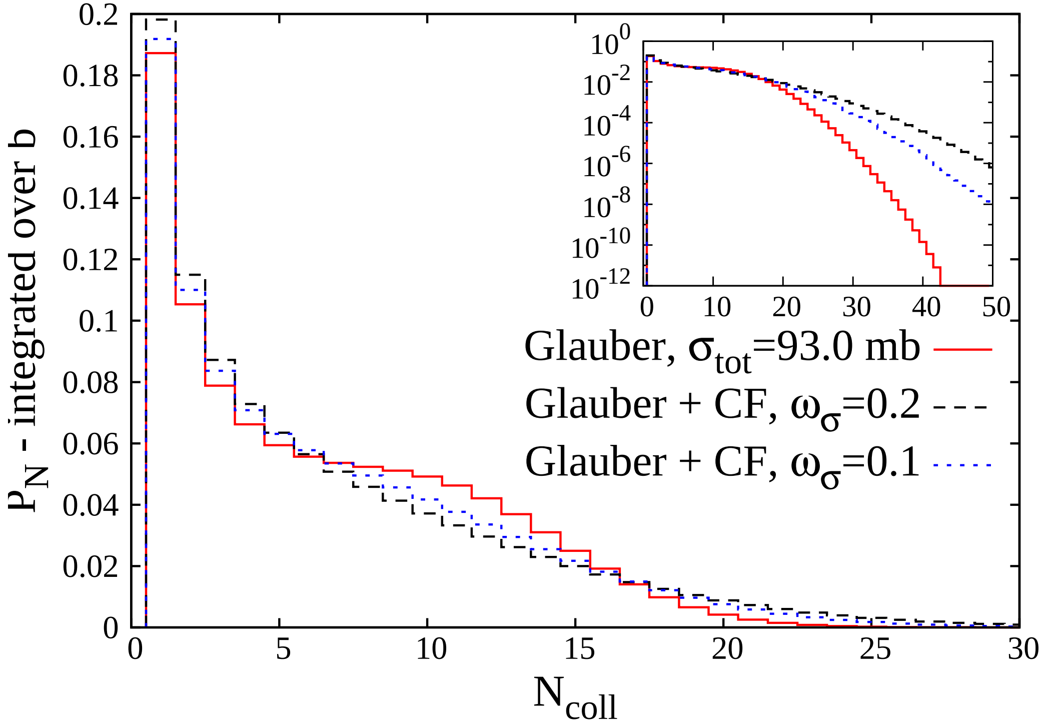


M. Alvioli, M. Strikman, Phys. Lett. ***B722*** *(2013)*

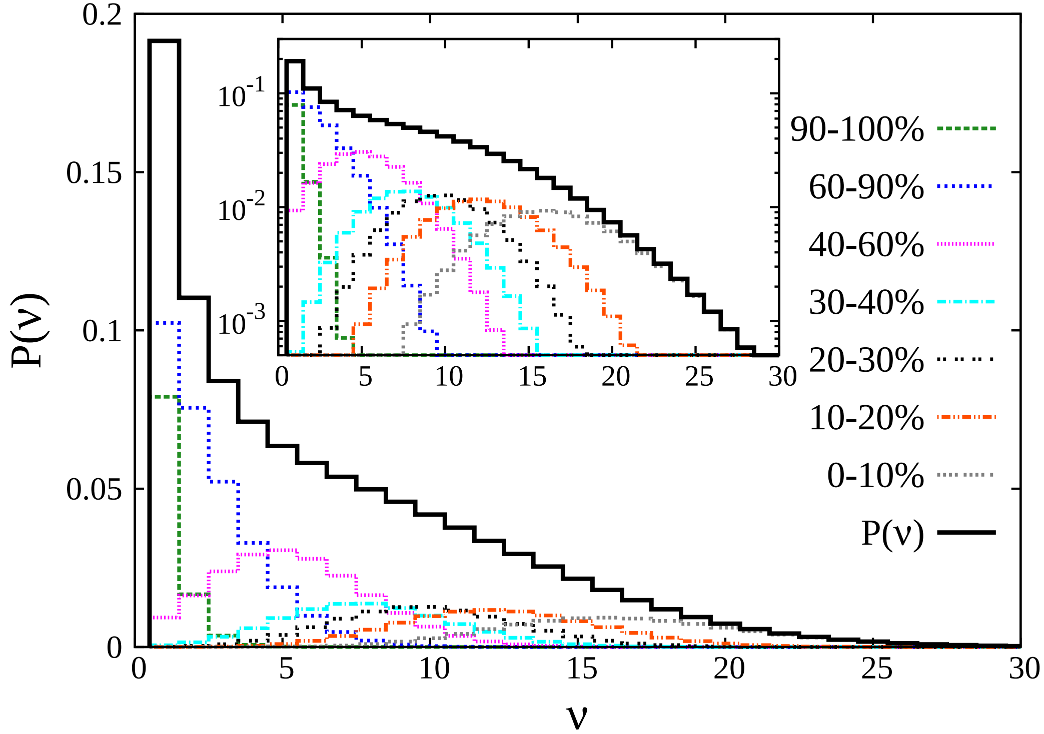
2.a - Color Fluctuations: probability of N interactions

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

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



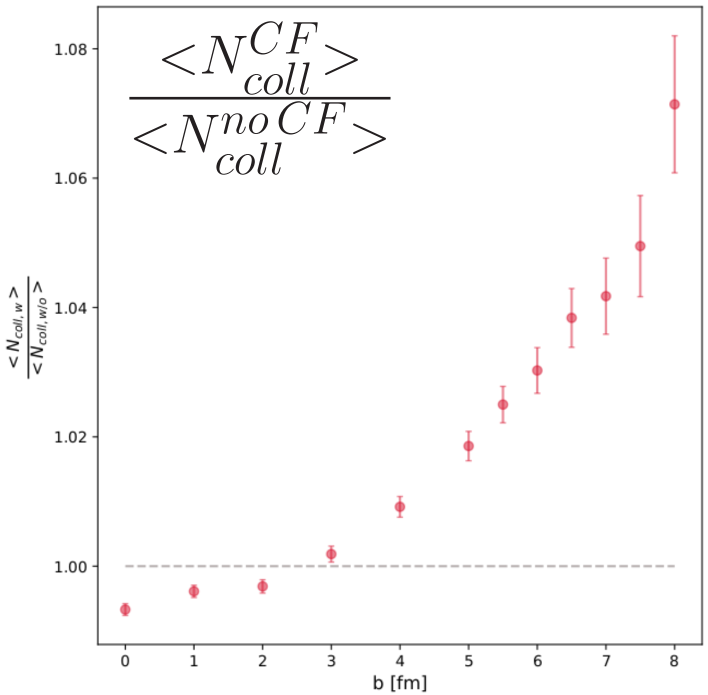
Phys. Lett. ***B722*** *(2013)*
Phys. Rev. ***C90*** *(2014)*

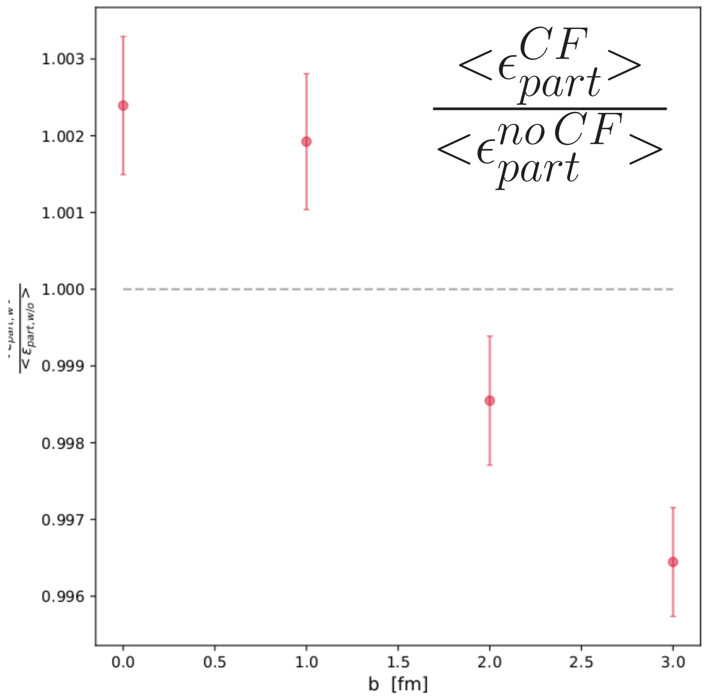


Phys. Rev. ***C93*** *(2016)*
Phys. Rev. ***D98*** *(2018)*

2.a - Color fluctuations + SMASH model

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



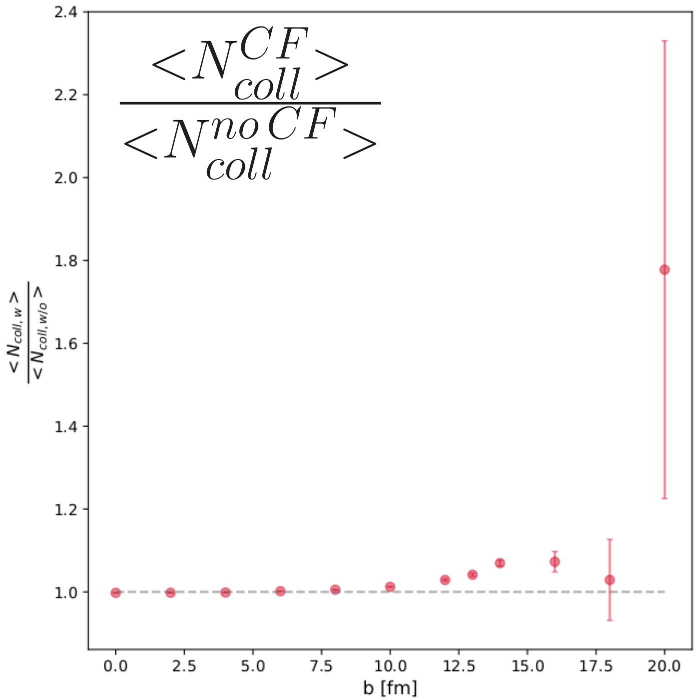


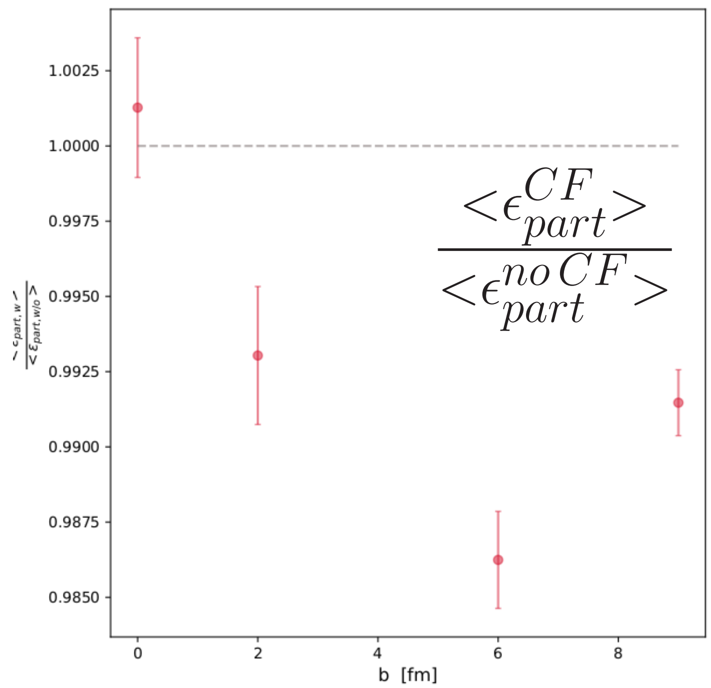
$\rightarrow$ N_{coll} suppressed at small b and enhanced for peripheral collisions

$\rightarrow$ ϵ_{part} increased at small b and decreased at large b

2.a - Color fluctuations + SMASH model

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



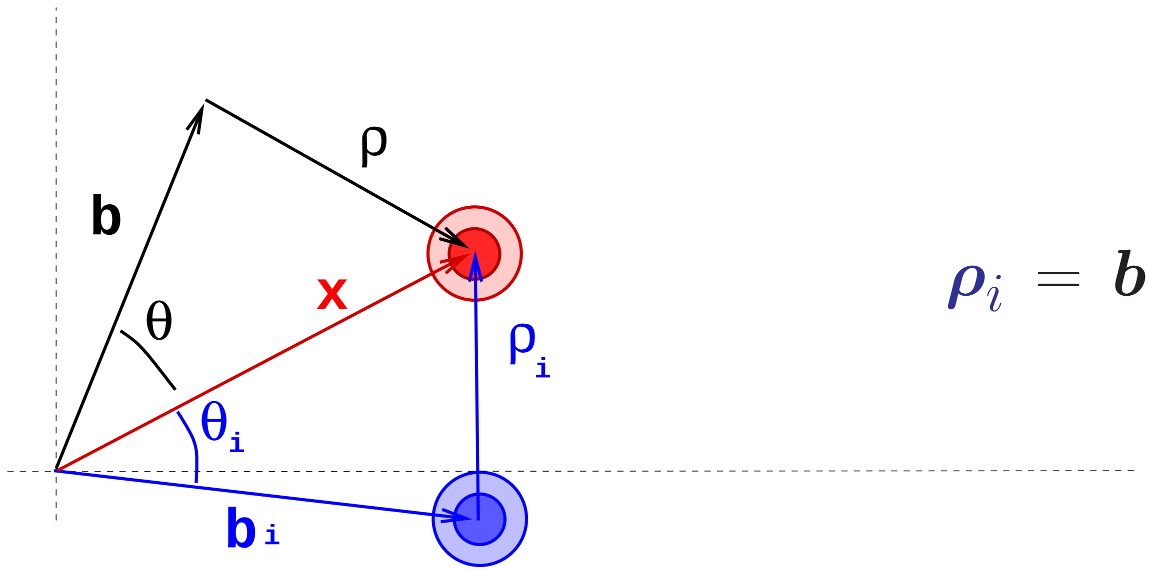


→ Same N_{coll} at small b and enhanced for very peripheral collisions

→ ϵ_{part} decreased at medium and large b

2.b - Geometry & hard trigger in pA processes

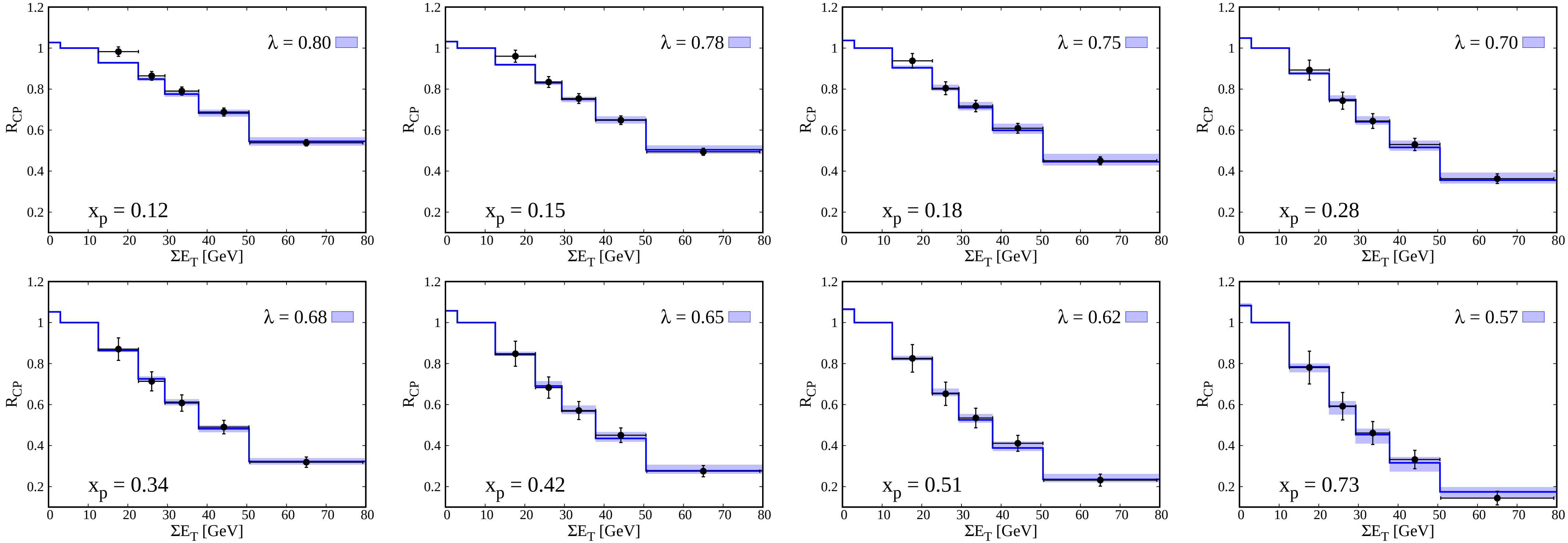
- A model to characterize the probability of events with one hard scattering and the (N_{coll}-1) soft scatterings, as a function of N_{coll}
- Hard event triggered in a probabilistic way, using the gluon distributions in the transverse plane $F_g(\rho) = exp(-\rho^2/B^2)/\pi B^2$
- We have coupled the MCG average ($< \ldots >$) 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:** $\lambda = \langle\sigma(x)\rangle / \langle\sigma_{pN}\rangle$

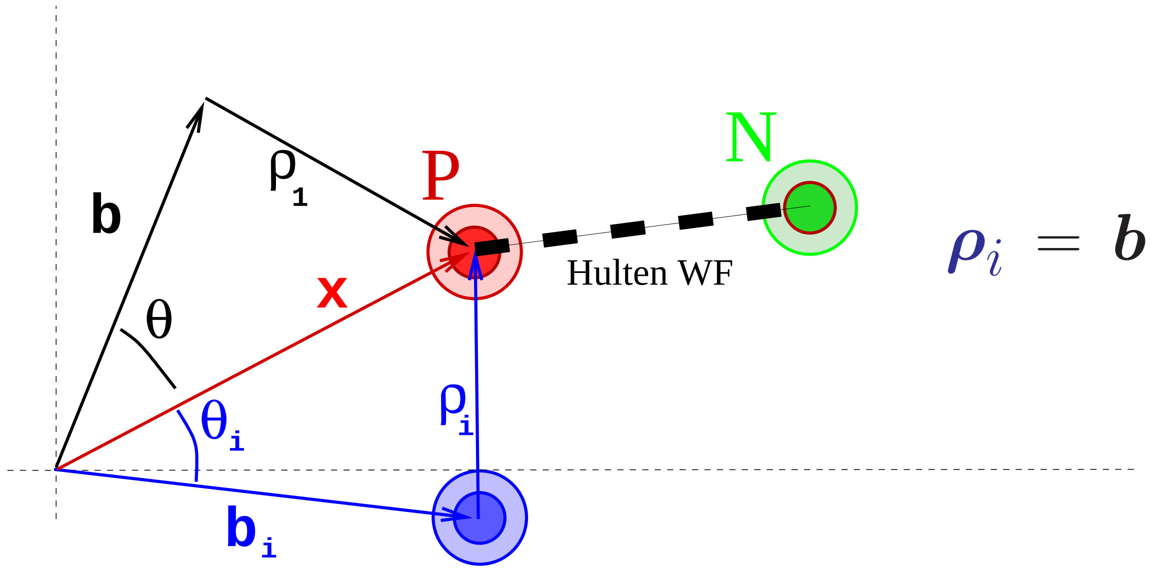
Alvioli, Cole, Frankfurt, Perepelitsa, Strikman, Phys. Rev. ***C93*** *(2016)*

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

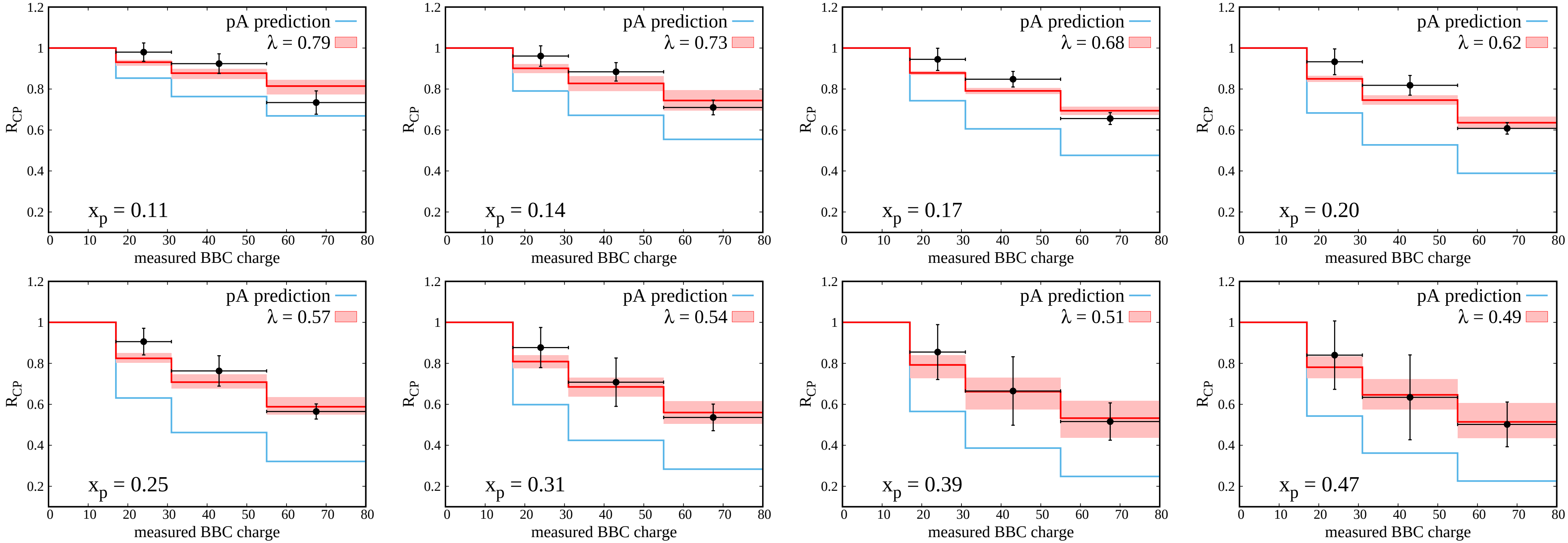
- A model to characterize the probability of events with one hard scattering and the (N_{coll}-1) soft scatterings, as a function of N_{coll}
- The hard event triggered in a probabilistic way
- We have coupled the MCG average ($< \ldots >$) for the N_{coll}-1 soft interactions with 2-d integral over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

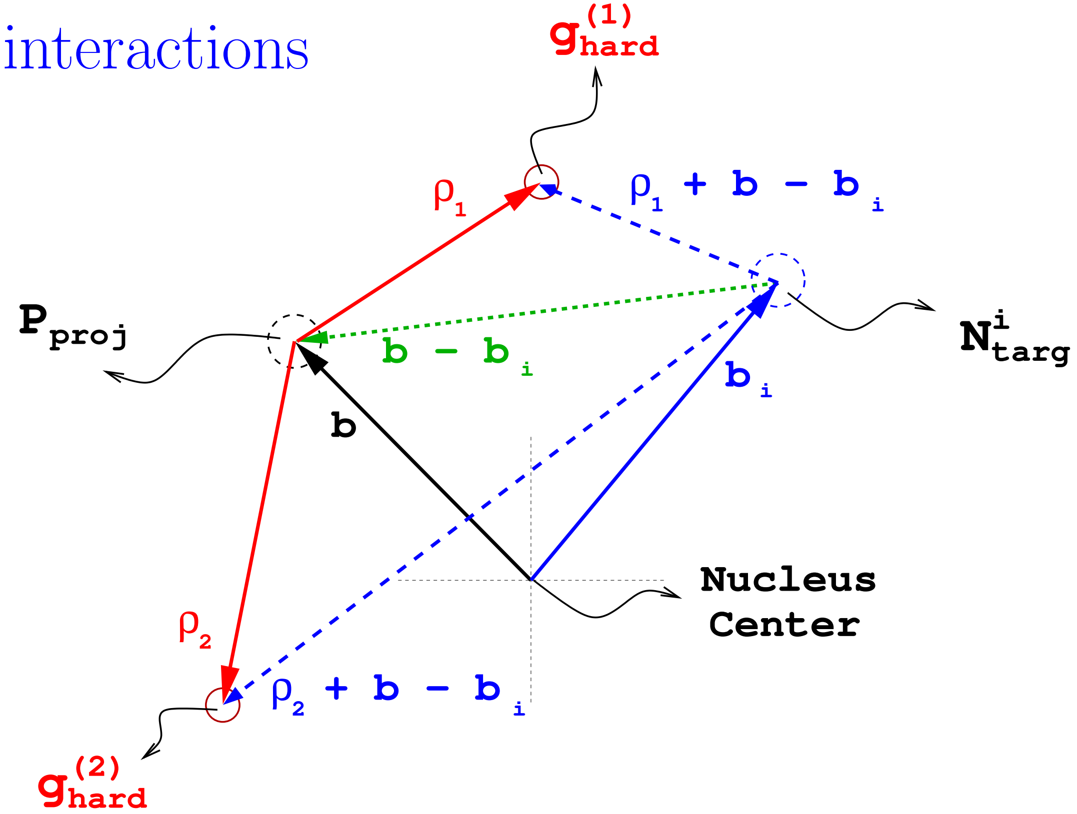
Data: *Adare et al. - PHENIX collaboration - Phys. Rev. Lett.* ***116*** *(2016)*

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

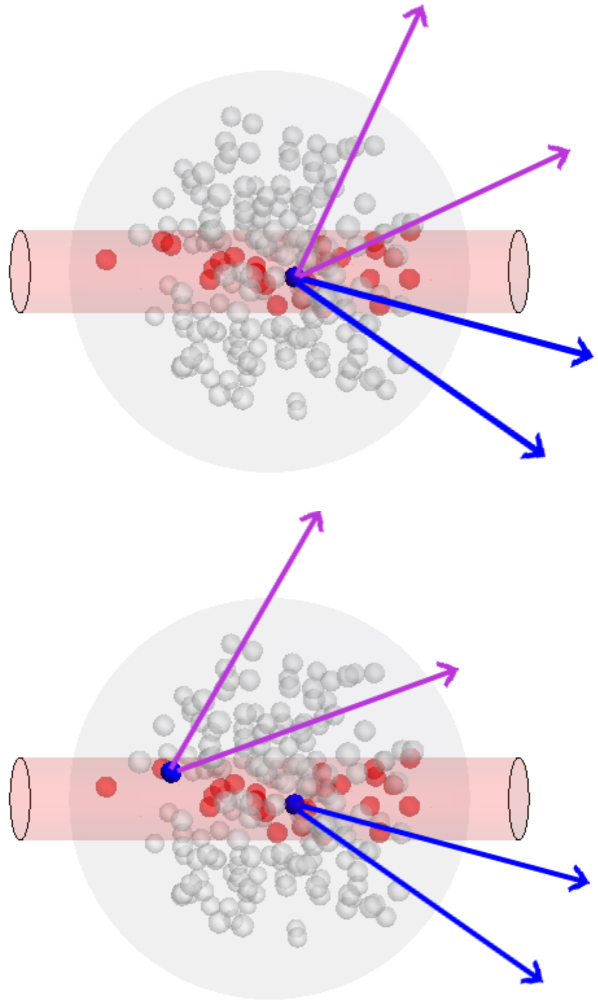


M. Strikman, D. Treleani, Phys. Rev. Lett. ***88*** *(2002)*

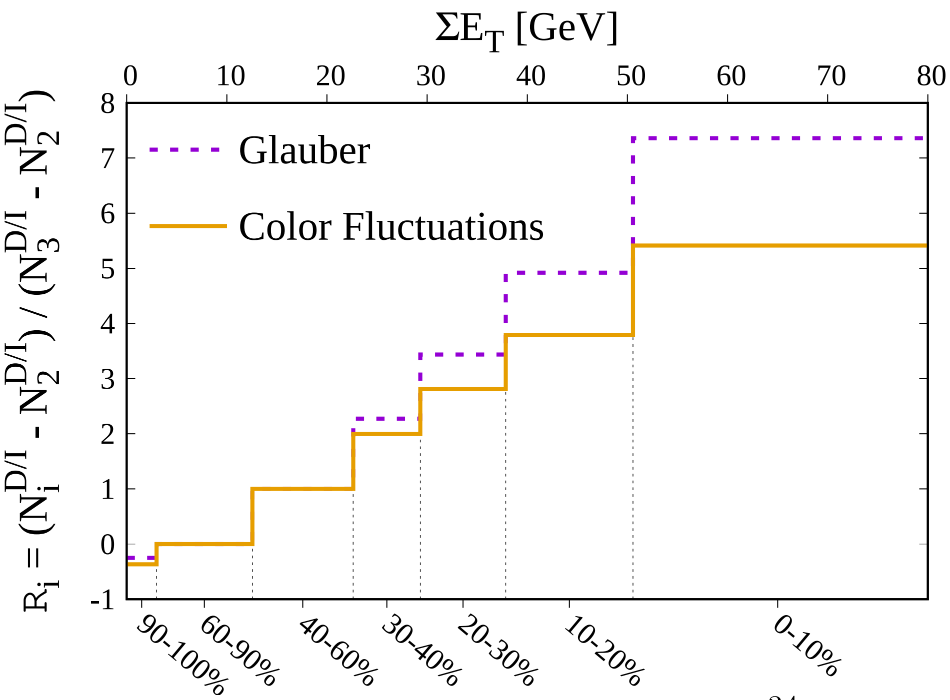
*M. Alvioli, M. Azarkin, B. Blok, M. Stirkman Eur. Phys. J. C**79** (2019)*

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)*

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 distirbution $P(\sigma_{NN})$

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

- Selection of events with a *hard-trigger* allows the determination of x-dependence of color fluctuations: both in pA and dA

- Extension of the *hard-trigger* algorithm to double partonic interactions and introduction of centrality dependence

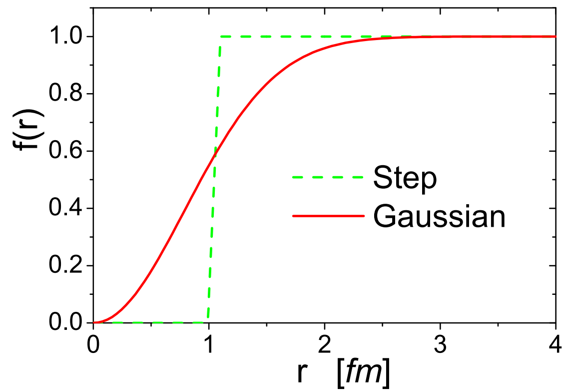
Configurations available at: `http://sites.psu.edu/color`

Additional Slides

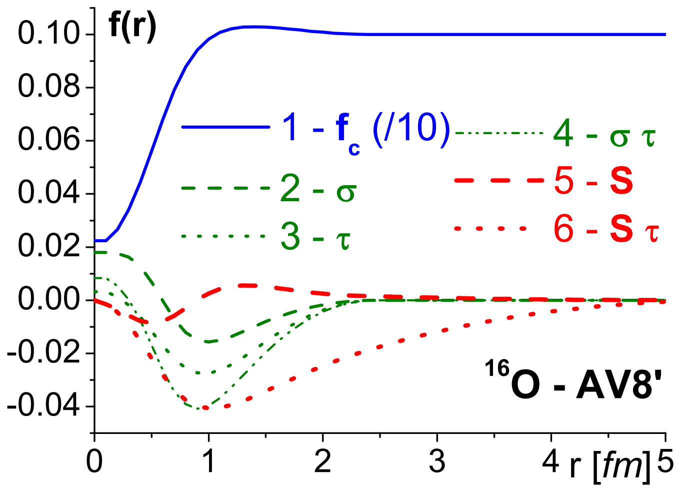
• We used $|\Psi|^2$ as a Metropolis weight function

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

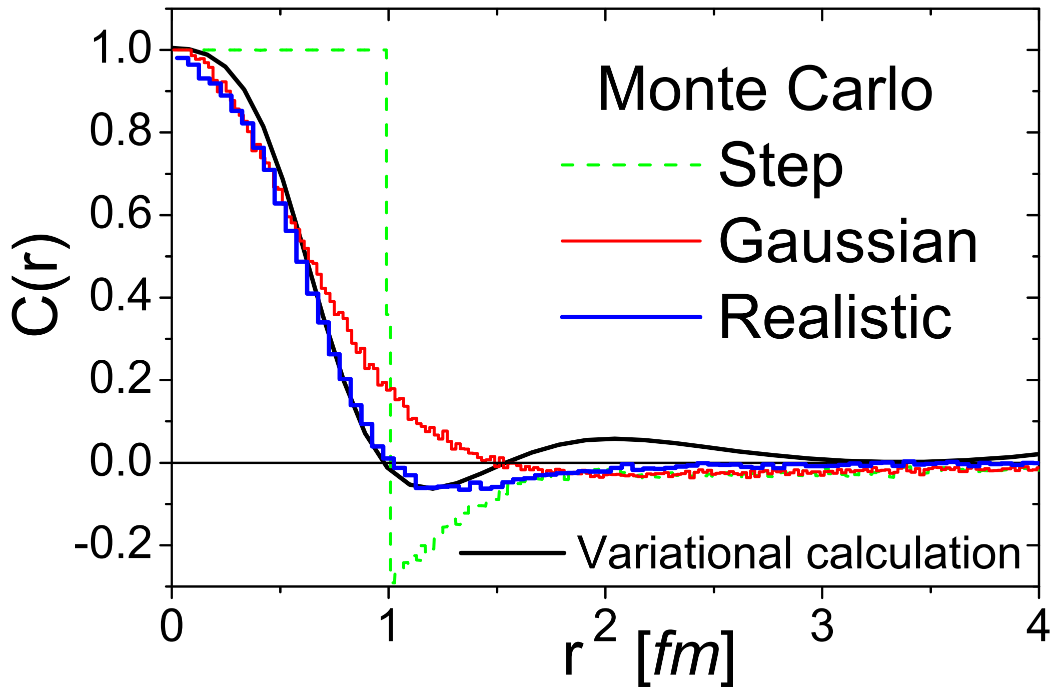
where Φ is given by the independent particle model.



$\Downarrow$



$\Longrightarrow$

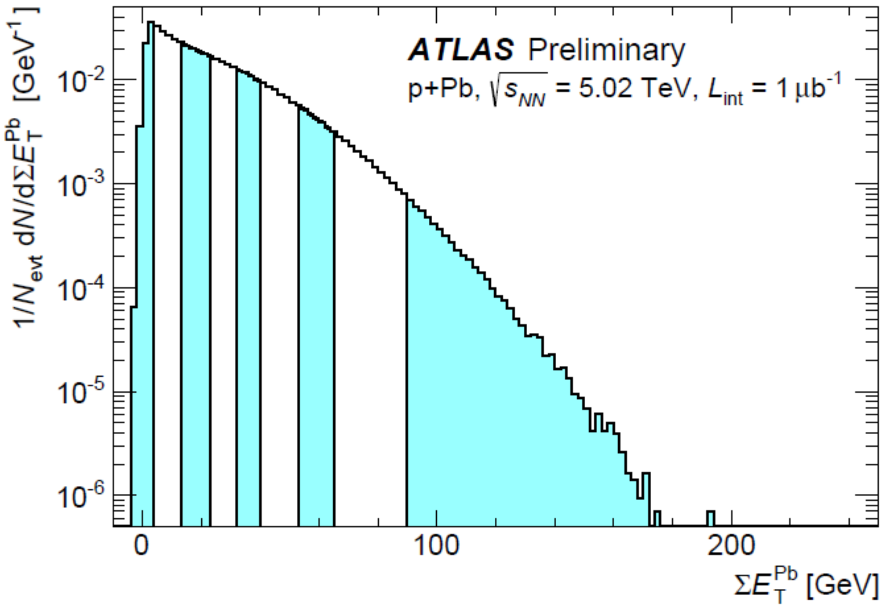


$\Uparrow$

• 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



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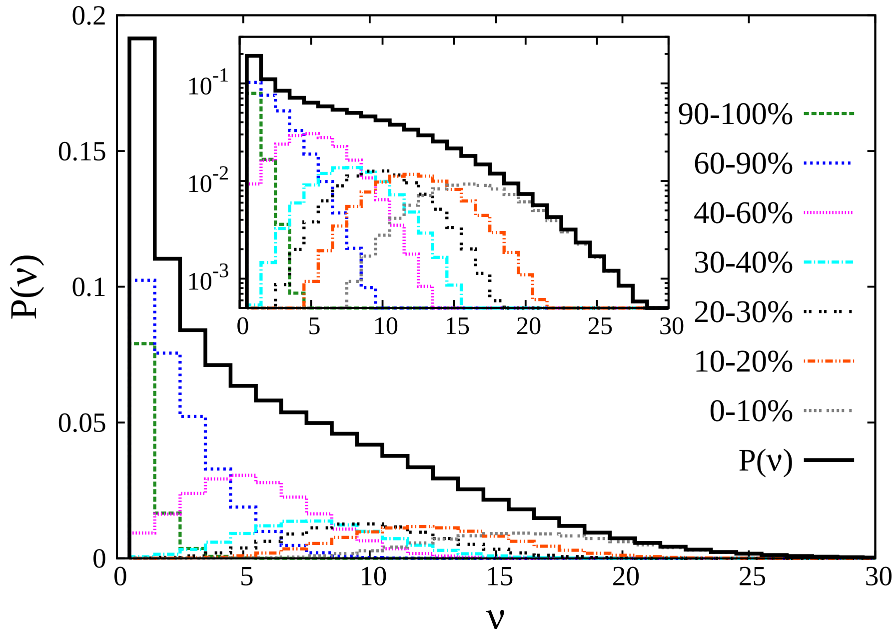
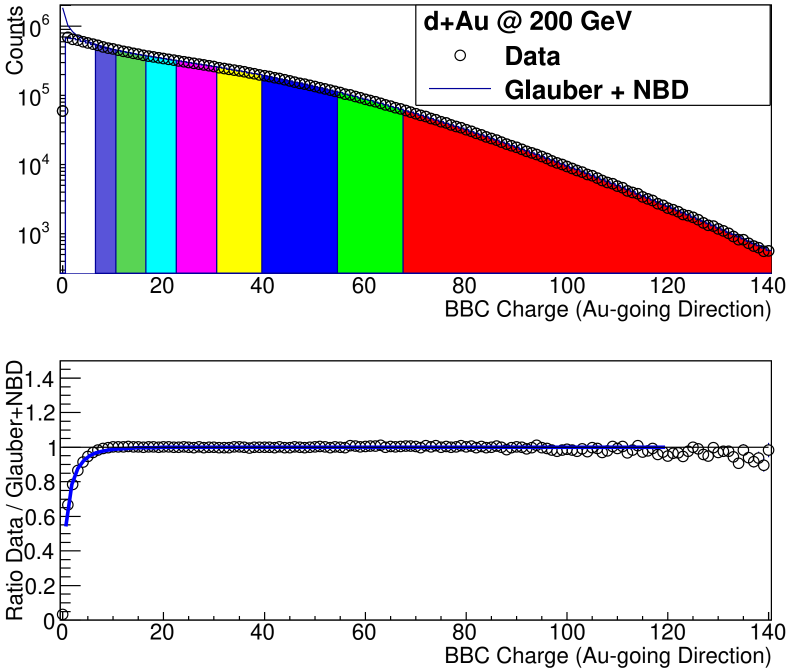


*Alvioli, Cole, Frankfurt, Perepelitsa, Strikman, **PRC93** (2016)*

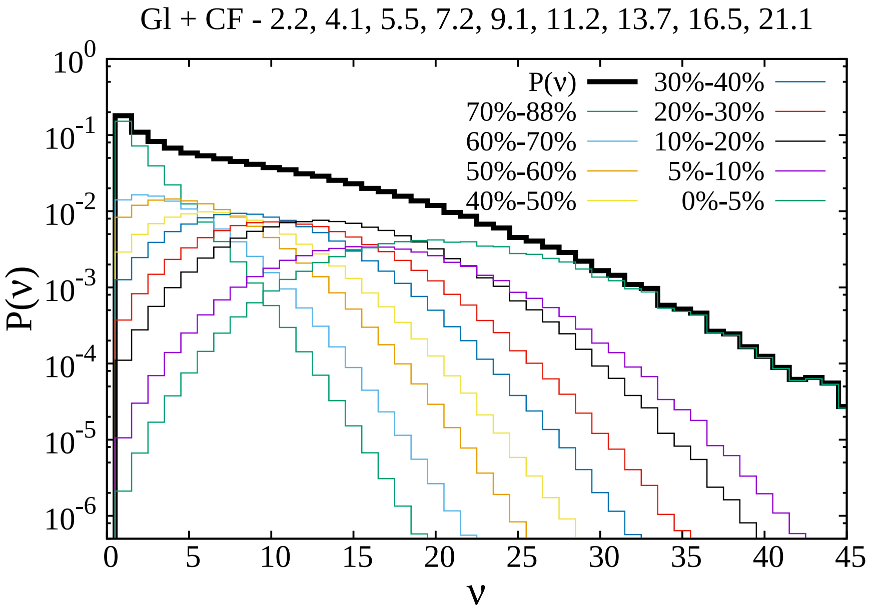
- ATLAS and CMS found deviations from the Glauber model (N_{coll} tail)
- we derive a non-trivial relation between bins in ΔE_T and N_{coll} and thus determine $P(N_{coll})$ dependence on centrality ($\nu = N_{coll}$)

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

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



$\Longrightarrow$



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

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