Correlations and fluctuations in pA, dA and AA collisions

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OUTLINE

1.a Monte Carlo Glauber approach for pA and AA

1.b Nuclear configurations including NN correlations

1.c Recent updates on configurations

1.d Energy transferred to spectator nucleons in AA collisions

2. Beyond the Glauber approach

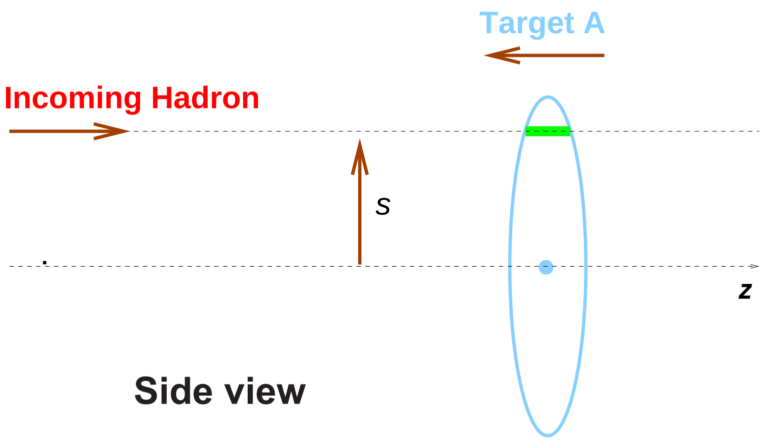
2.a NN interaction strenght fluctuations

2.b Processes with hard trigger: pA

2.c Processes with hard trigger: dA

1.a - Glauber multiple scattering pA and AA scattering

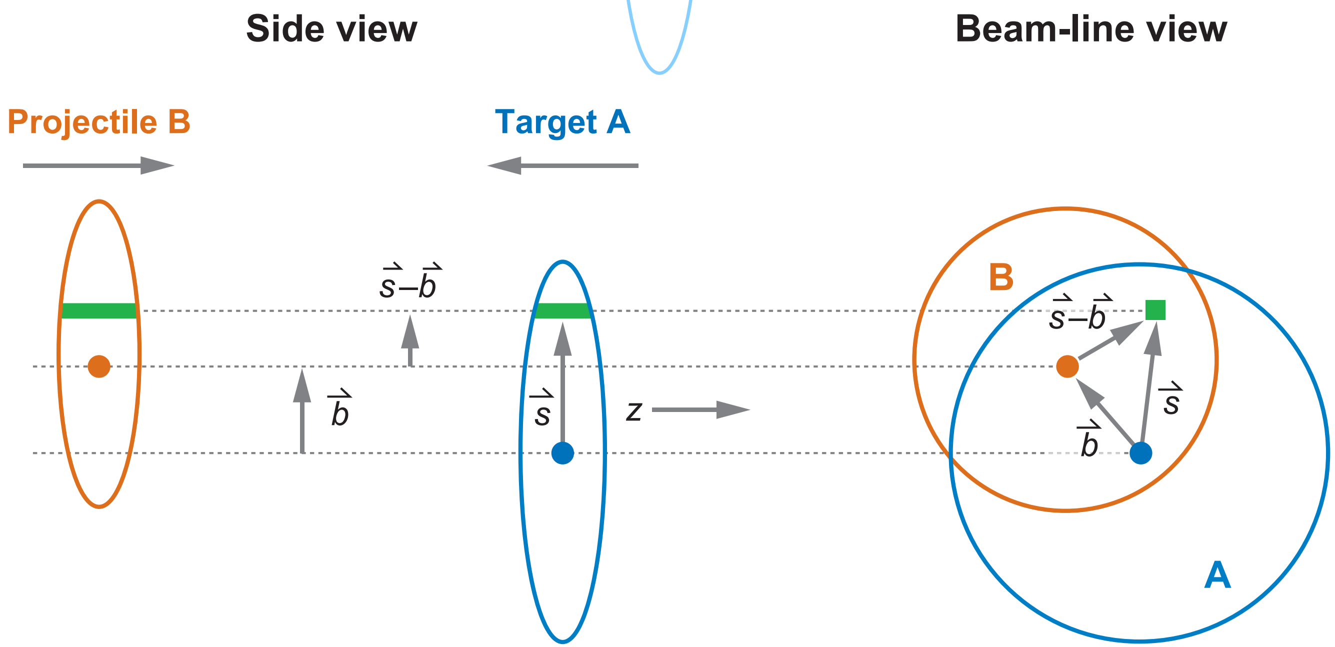
Glauber approach: quantum mechanics of high-energy many-body scattering $\Longrightarrow$ frozen approximation; straight line trajectories



Inputs:

⋆ (charge) densities of nuclei

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



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:

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

- Mostly accurate. *Finite radius of NN interaction neglected.* Details of density are lost. Difficult to estimate event-by-event ***fluctuations***

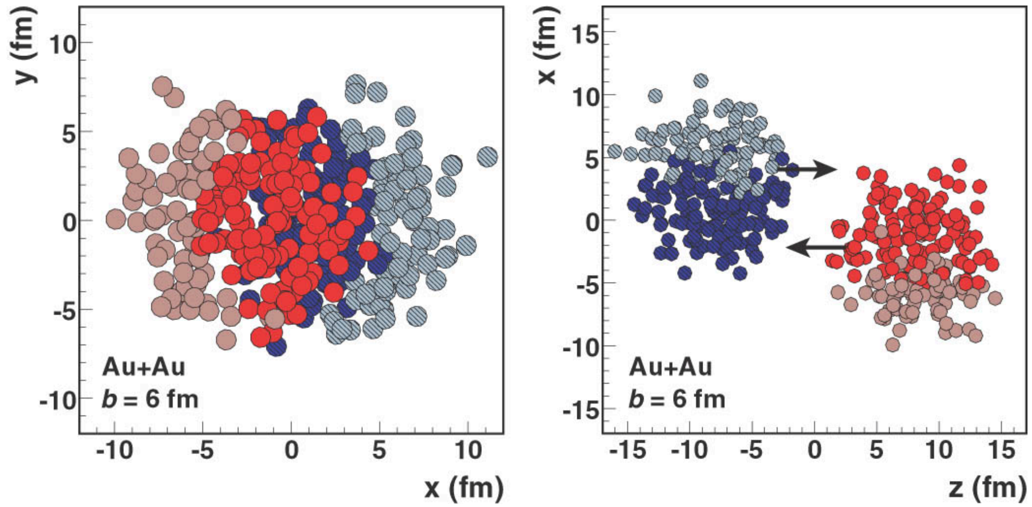
1.a - Monte Carlo Glauber (MCG) description

- event-by-event simulation: details of density distributions by randomly generated ***nucleons positions***: in average give the nucleus density.
- MCG introduces N_{part} and N_{coll}, not directly measurable, but contain information about the ***fluctuating collision geometry***.

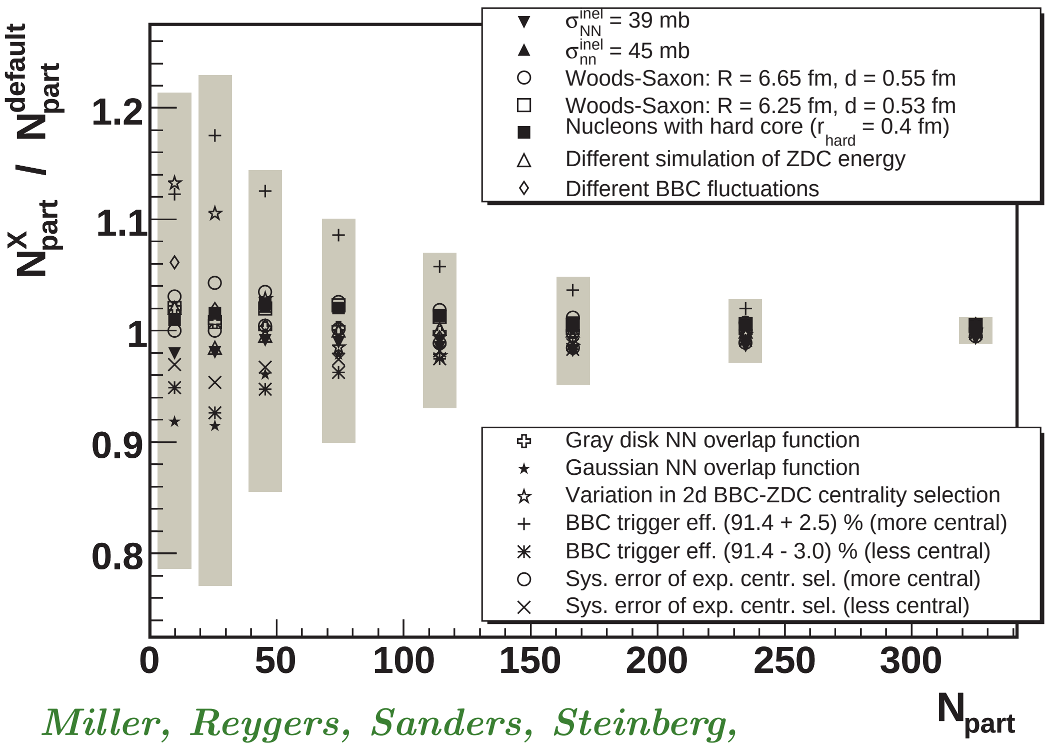
→ N_{part}, N_{coll} experimentally related to charged particle multiplicity

→ *Spectator* nucleons related to ZDCs measurements

- MCG is a starting point for models requiring *production points* for any individual subprocesses
- also used in experimental analyses



1.a - Monte Carlo Glauber (MCG) description: fluctuations



Miller, Reygers, Sanders, Steinberg,
Ann. Rev. Nucl. Part. Sci. 57 (2007)

effects of *different sources* of fluctuations and parameter dependencies within MGC and detector simulation

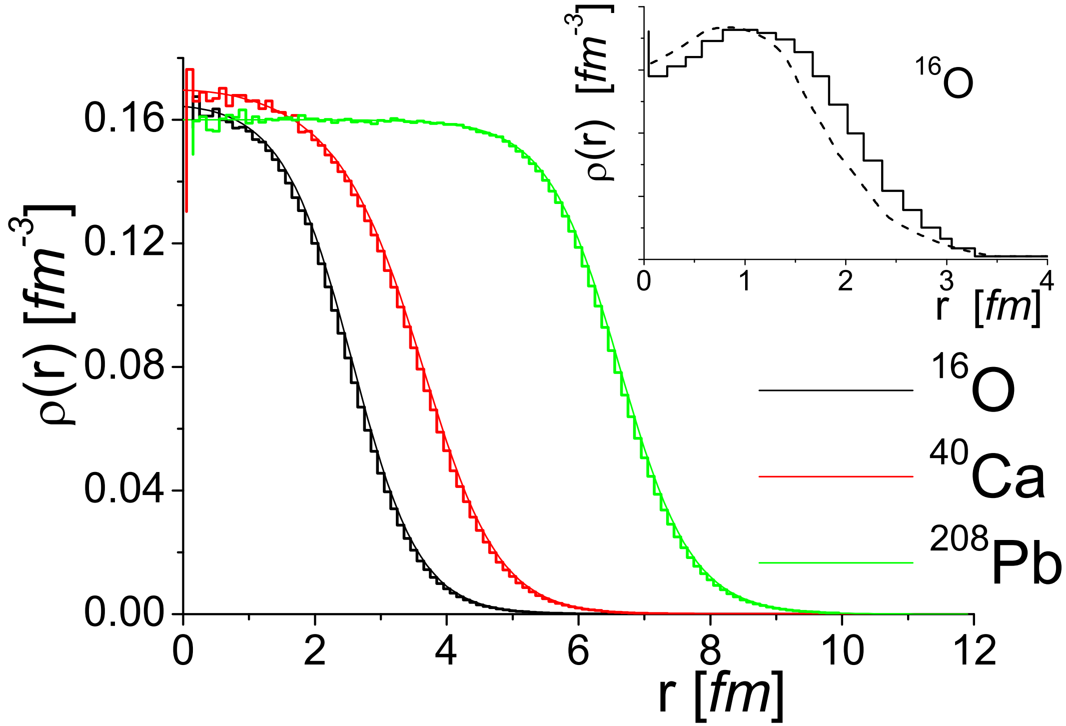
We focus on fluctuations due to:

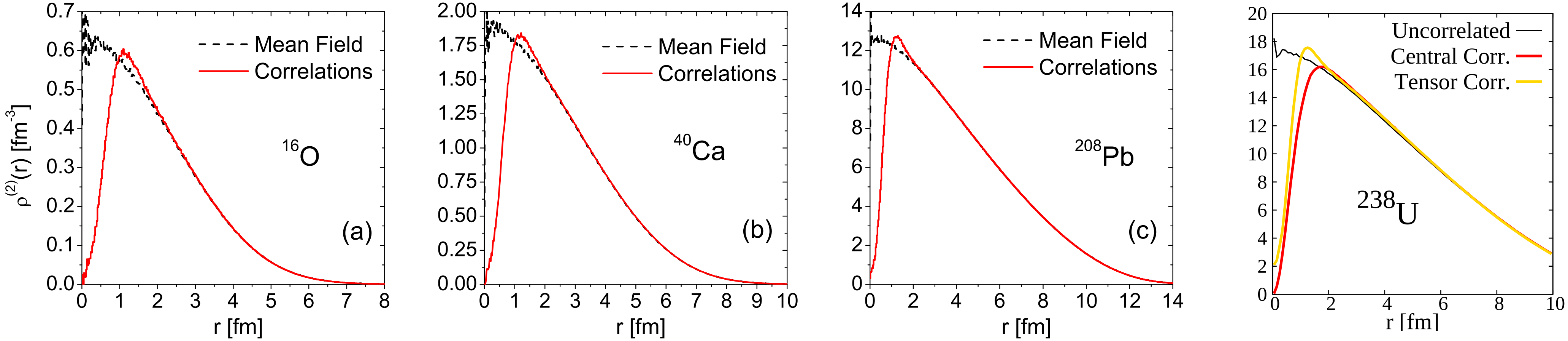
- inclusion of NN correlations in preparing nuclear configurations
- initial nucleon positions ⟶ initial geometry
- no black-disk approximation for NN ⟶ $P(|\boldsymbol{b}-\boldsymbol{b}_j|)$
- fluctuation of the NN cross section (***color fluctuations***) ⟶ average number of participants ⟶ different impact parameter dependence

1.b - A Monte Carlo generator for nucleon configurations

- We developed a Metropolis code which includes **realistic NN correlations functions** in a way which is consistent with the input one-body density

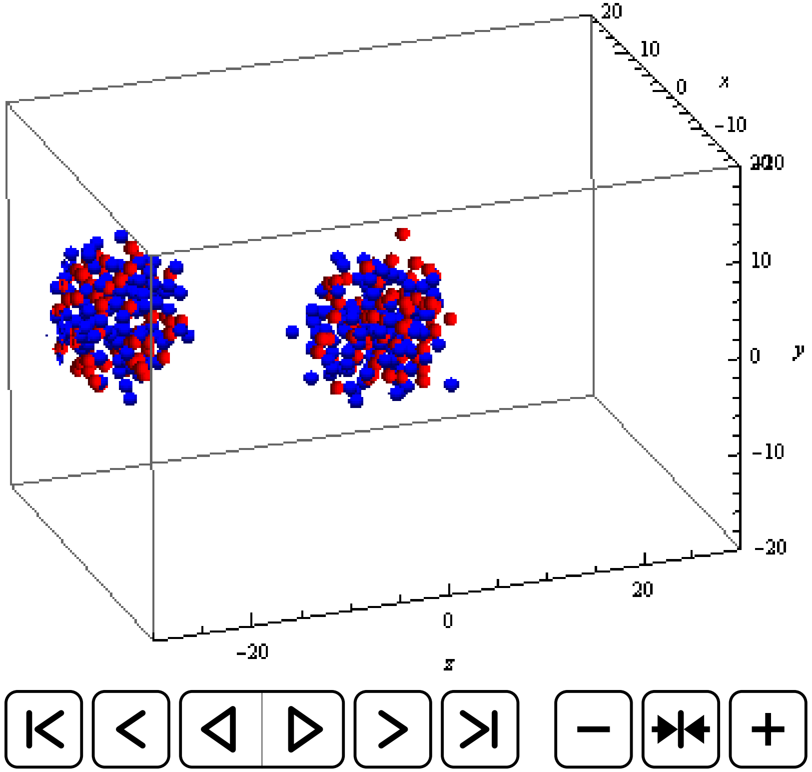
- We also have a two-body density comparable to the one obtained in microscopic calculations of w.f.





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

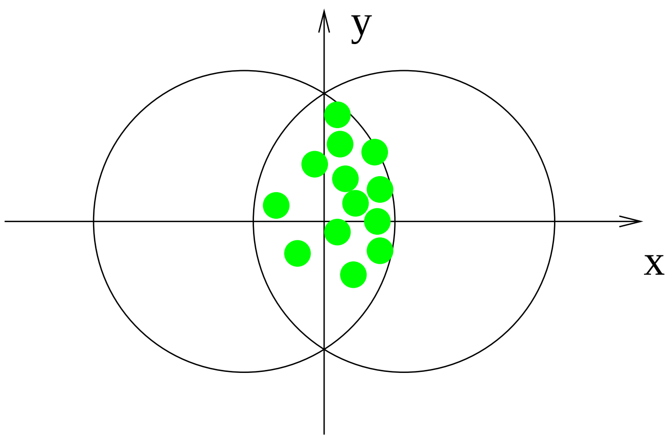
1.c - Fluctuations of the geometry of participant matter



- Fluctuations effects on geometry investigated through participant matter distribution moments and their dispersion

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

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



$\longrightarrow$ participant nucleons • in transverse plane

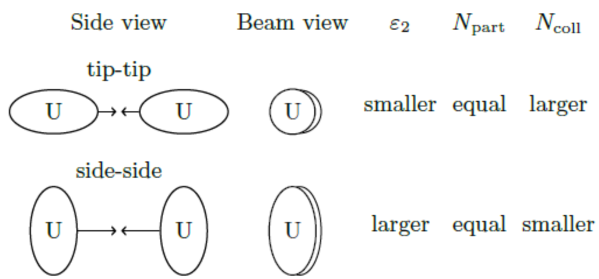
1.c - Latest updates of nuclear configurations - I

- ***Nucleus deformation*** – for ^{238}U we use a modified WS profile:

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

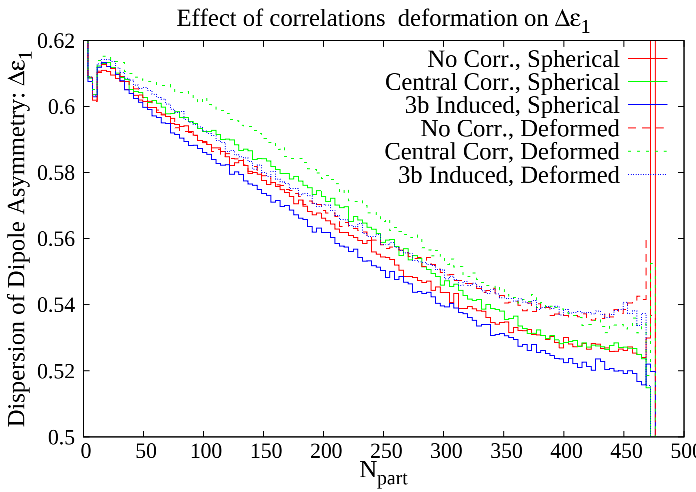
$$Y_{20}(\theta) = \frac{1}{4\,r^2}\sqrt{\frac{5}{\pi}}\left(2z^2 - x^2 - y^2\right)$$

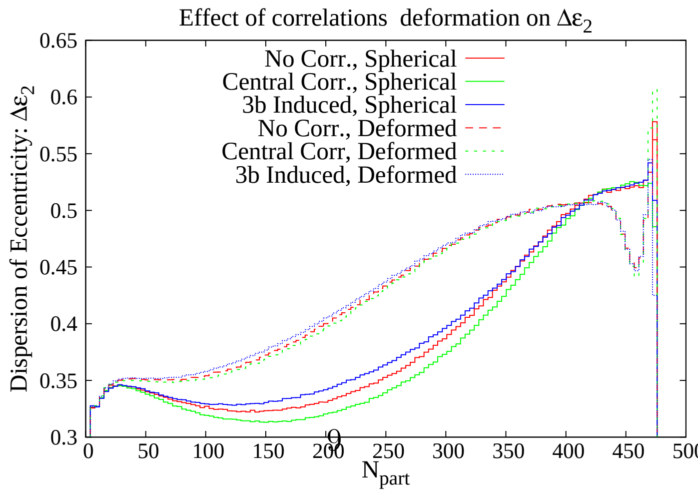
$$Y_{40}(\theta) = \frac{1}{16\,r^4}\sqrt{\frac{9}{\pi}}\left(35z^4 - 30z^2r^2 + 3r^4\right)$$

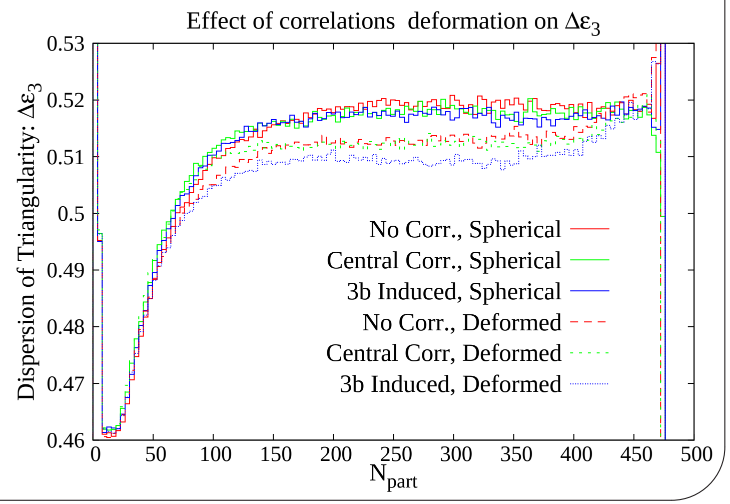


(*P. Filip, R. Lednicky, H. Masui, N. Xu Phys. Lett.* ***C80*** *(2009)*)

- deformation effect on dispersion of moments (*unplublished*):







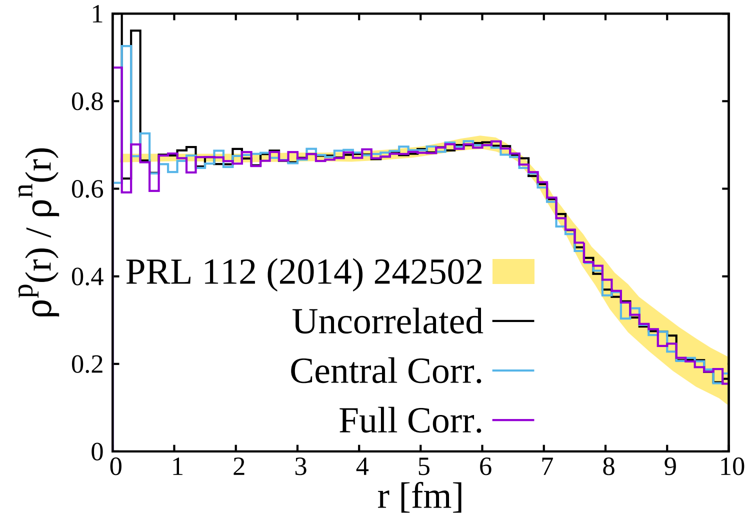
1.c - Latest updates of nuclear configurations - II

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

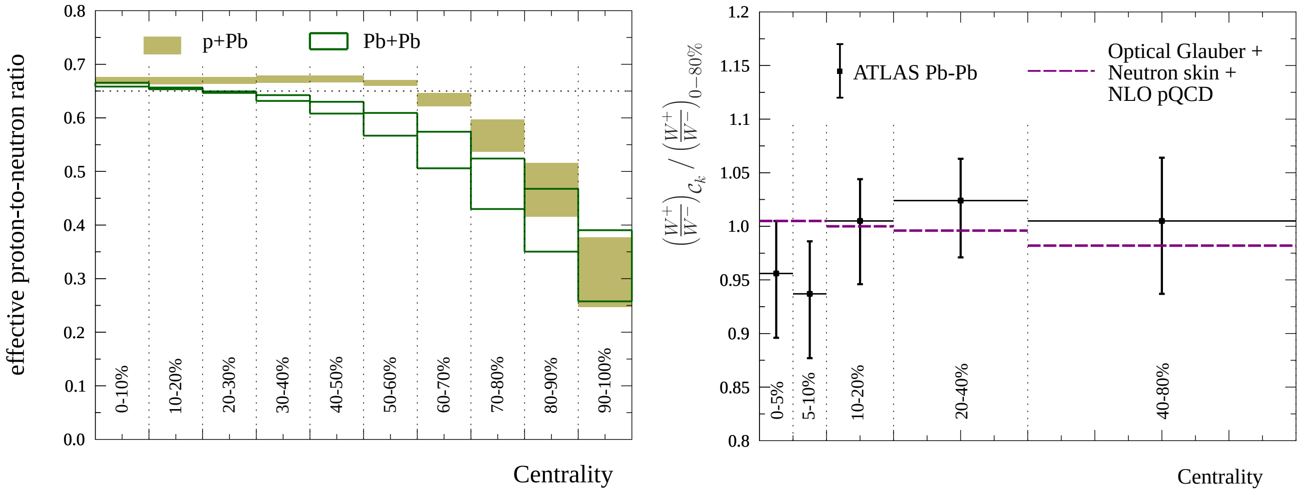
$$\rho(r) = \rho_0^{(p,n)} \;/\; \left(1 + e^{(r-R_0^{p,n})/a^{p,n}}\right)$$

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

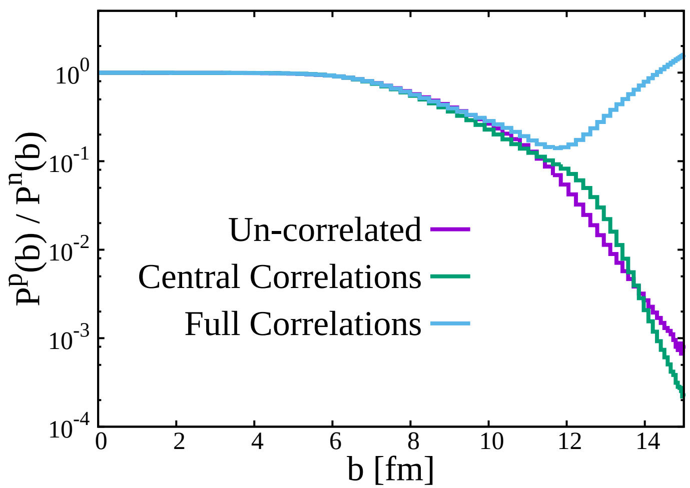
(*C.M. Tarbert et al., Phys. Rev. Lett.* ***112*** *(2014)*)



- additional tool for determination of centrality:



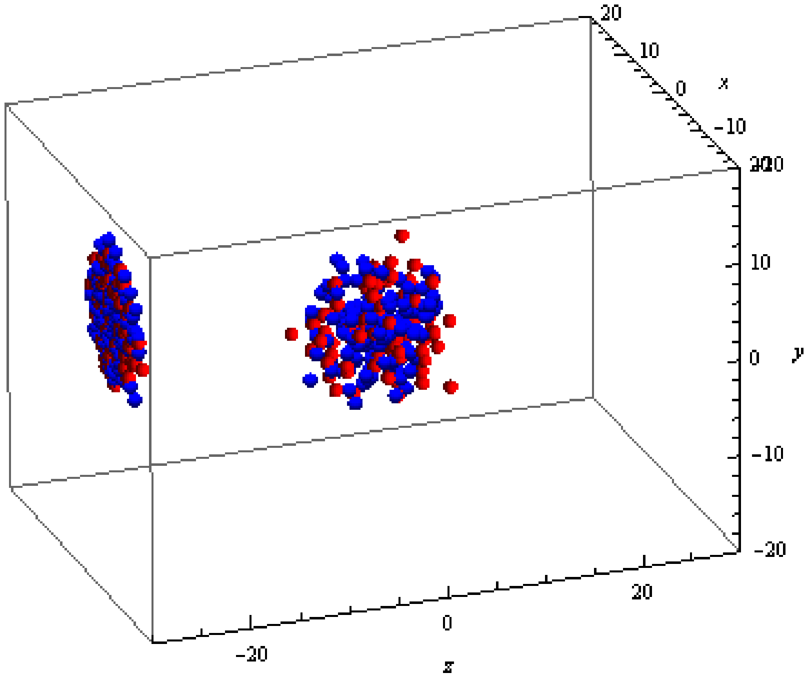
*H. Paukkunen, PL****B745*** *(2015)*

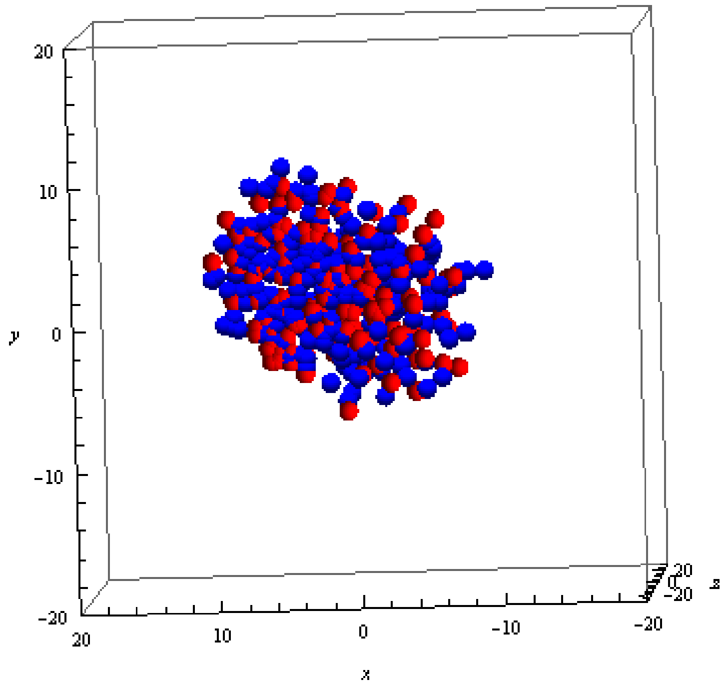


Alvioli, Strikman (unpublished)

- The smearing of impact parameter is expected to reduce the p/n difference

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



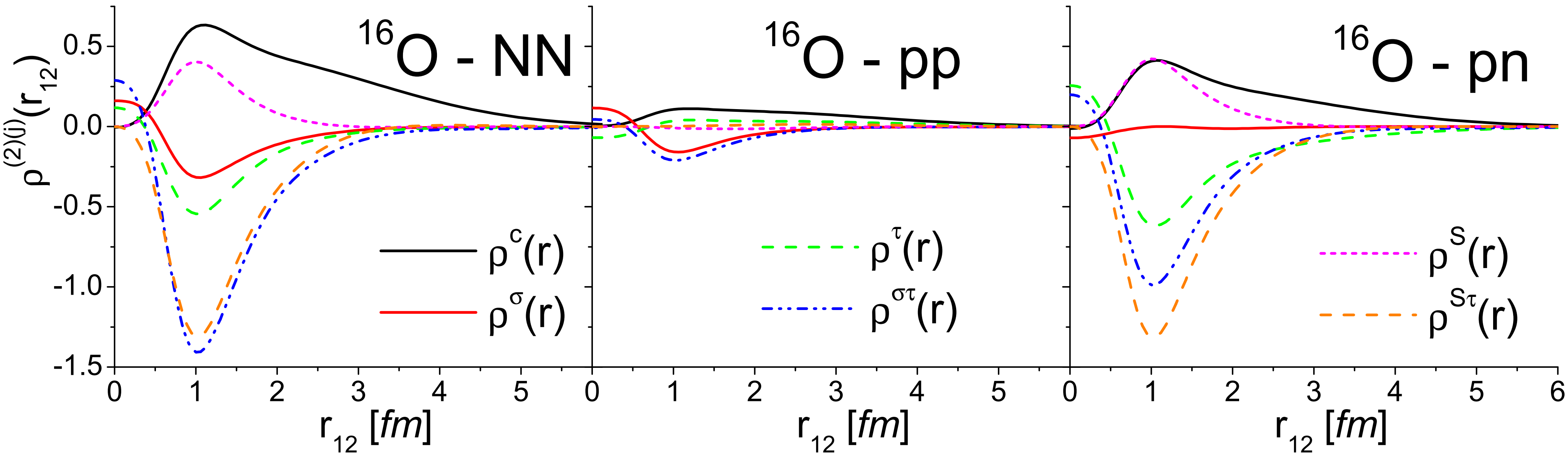


- *protons*
- *neutrons*
- *high-momentum nucleons*

- 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.d - Potential energy: *pn* and *pp* contributions

$$\langle V \rangle_{pN} = \sum_{i<j} V_{ij} = \sum_j \int d\boldsymbol{r}_{12}\; v_{pN}^{(j)}(r_{12})\; \rho_{pN}^{(2)(j)}(r_{12})$$

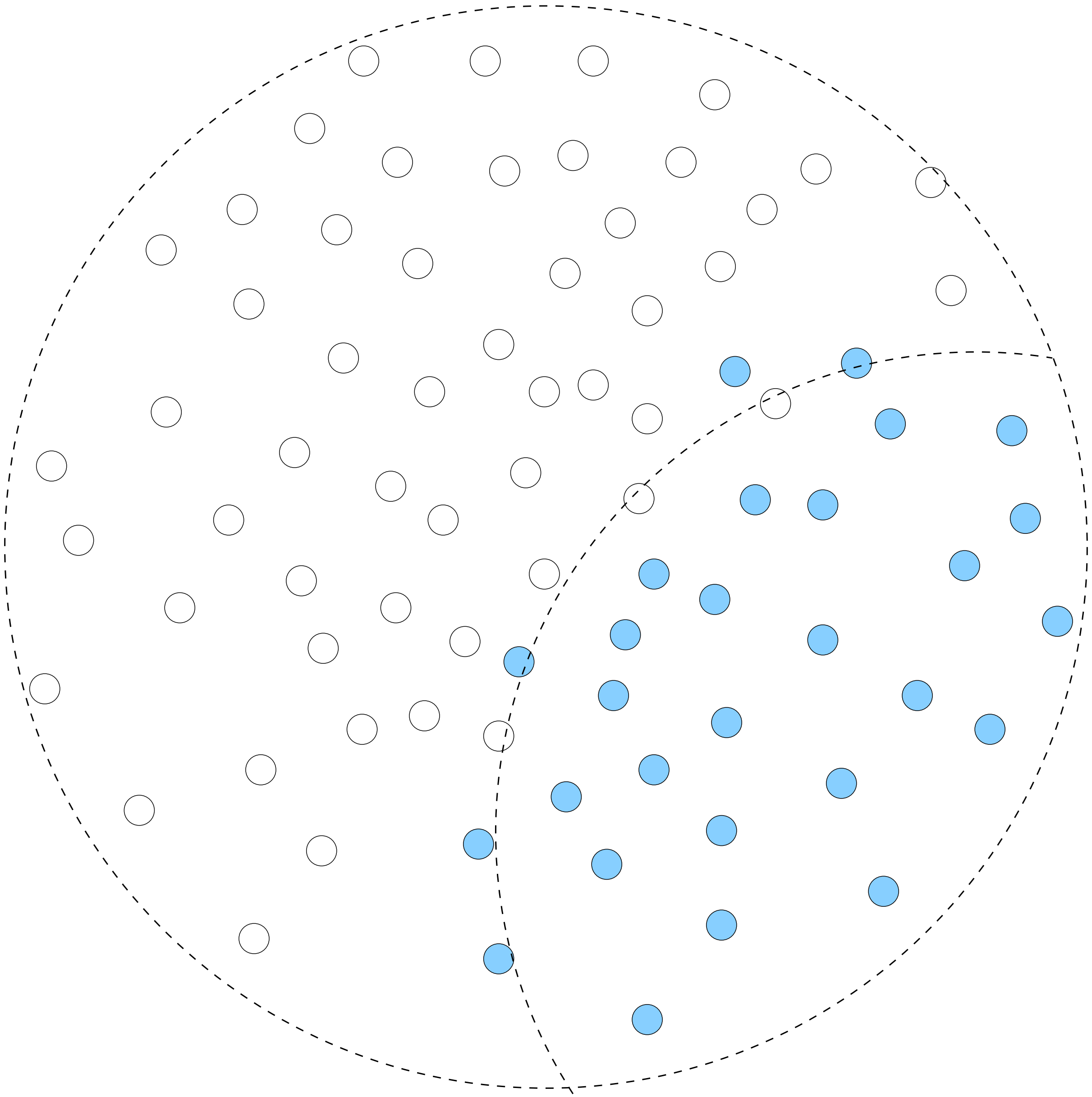


A	$\langle V \rangle_{pp} (= \langle V \rangle_{nn})$	$\langle V \rangle_{pn}$
16	8%	83%
40	9%	82%

mostly pn pairs

removed nucleons $\longrightarrow$ disrupted pairs $\longrightarrow$ *potential energy* ***freed***

1.d - Potential energy transferred to the spectators

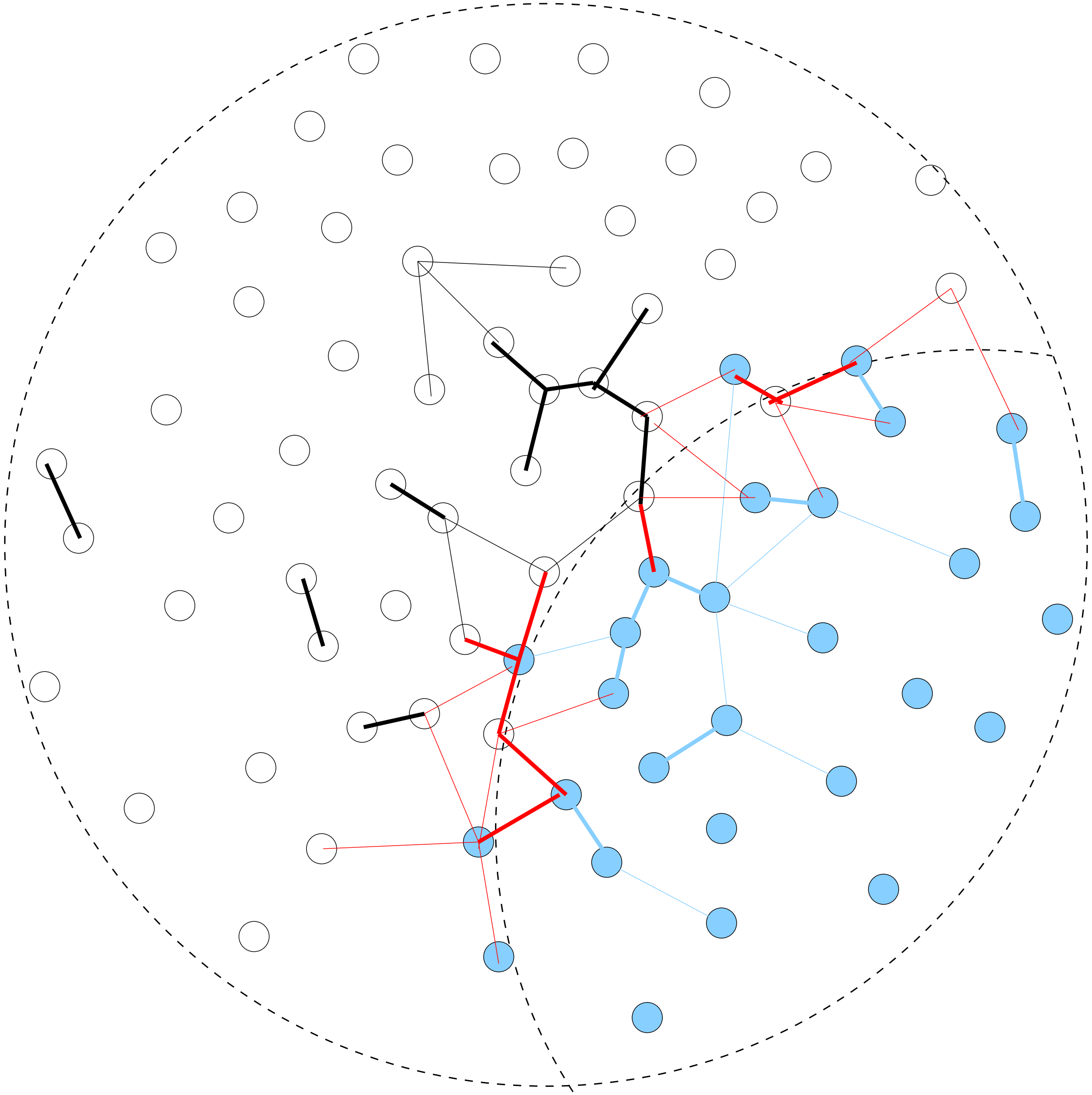


* after the instantaneous interaction with the projectile, blue nucleons • are removed
* for a given configuration,

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

* we consider V_{transf} as the energy transferred to the spectator system on a layer around the interaction surface

1.d - Potential energy transferred to the spectators

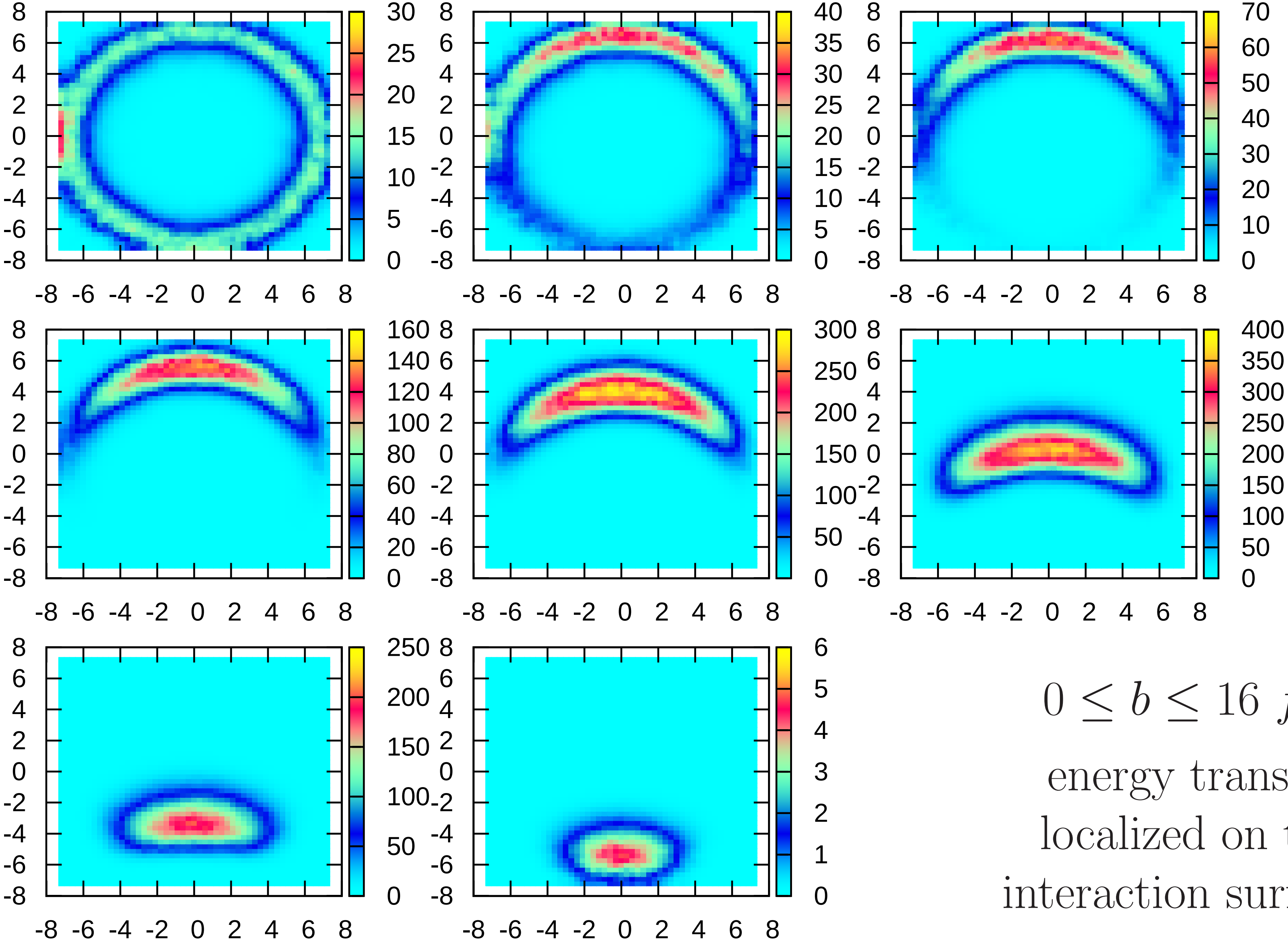


- after the instantaneous interaction with the projectile, blue nucleons ● are removed
- for a given configuration,

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

- we consider V_{transf} as the energy transferred to the spectator system on a layer around the interaction surface

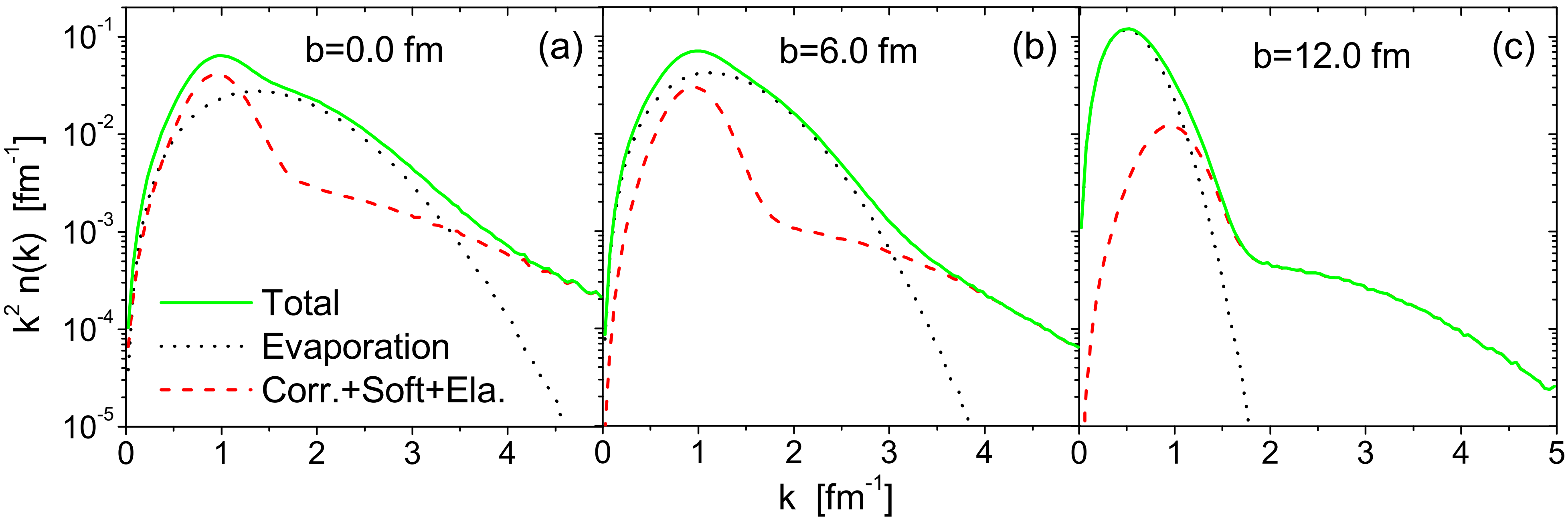
1.d - Freed potential Energy $< V >$ transferred to target in Pb-Pb



$0 \leq b \leq 16\ fm$

energy transfer
localized on the
interaction surface!

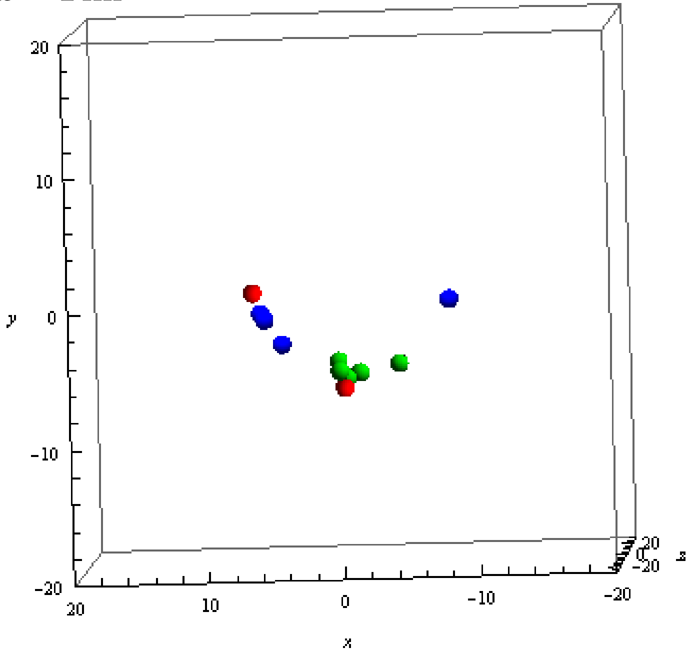
1.d - Potential & Kinetic Energy



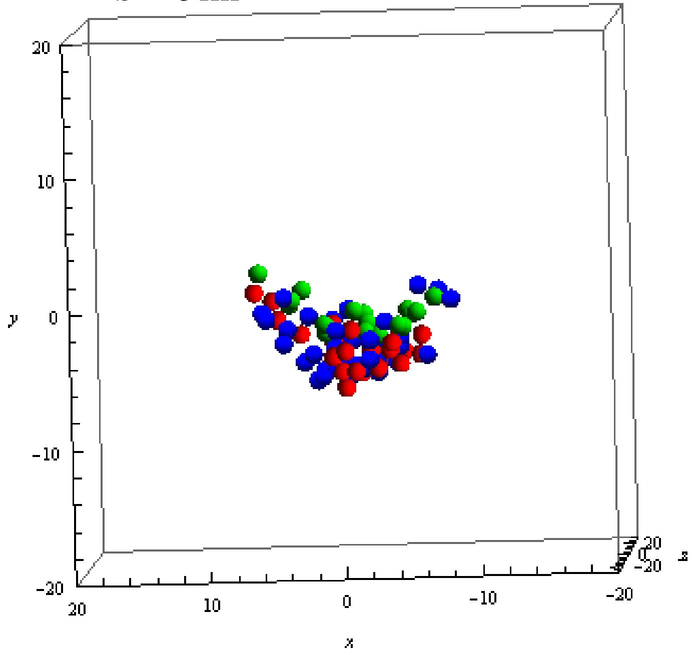
- cannot directly transform *potential* to *kinetic* energy to calculate momentum distributions of emitted nucleons
- we rely on variational $n(k)$ calculations as probability distributions
- the total probability distribution is a sum of evaporation, soft, correlated & elastic scattering contributions

1.d - High-momentum nucleons: asymmetry

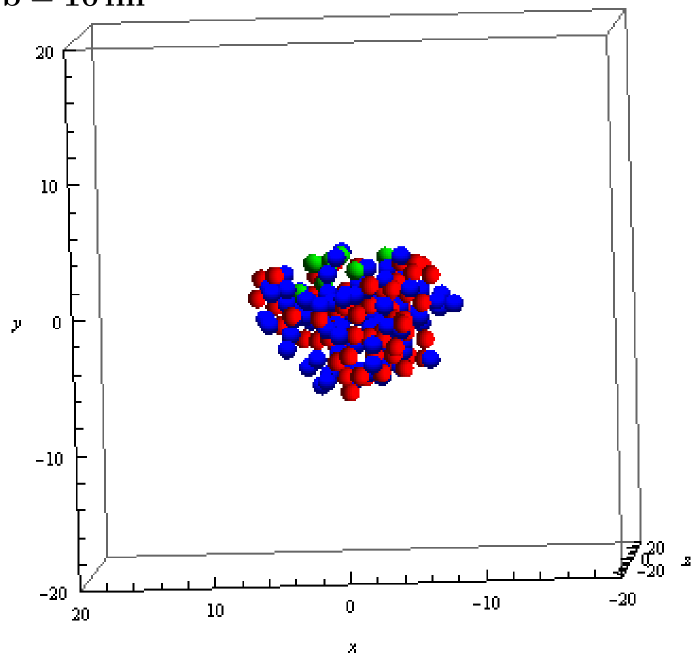
b = 1 fm



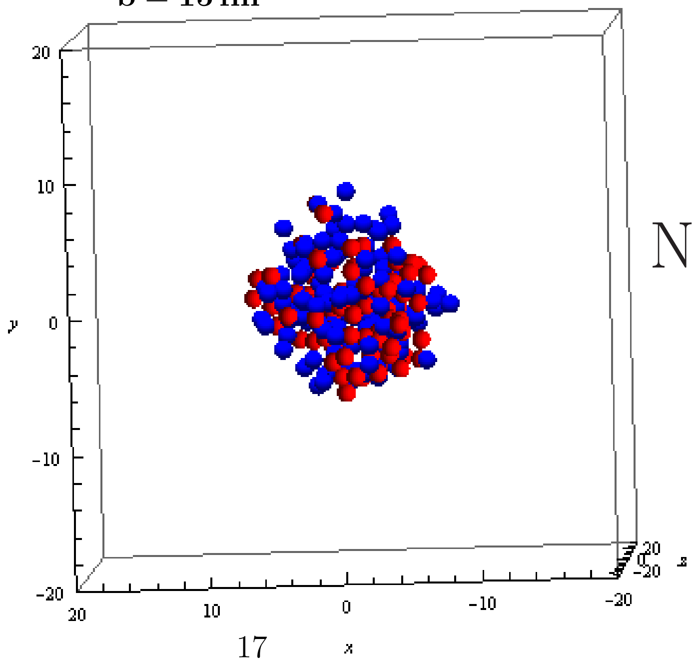
b = 5 fm



b = 10 fm



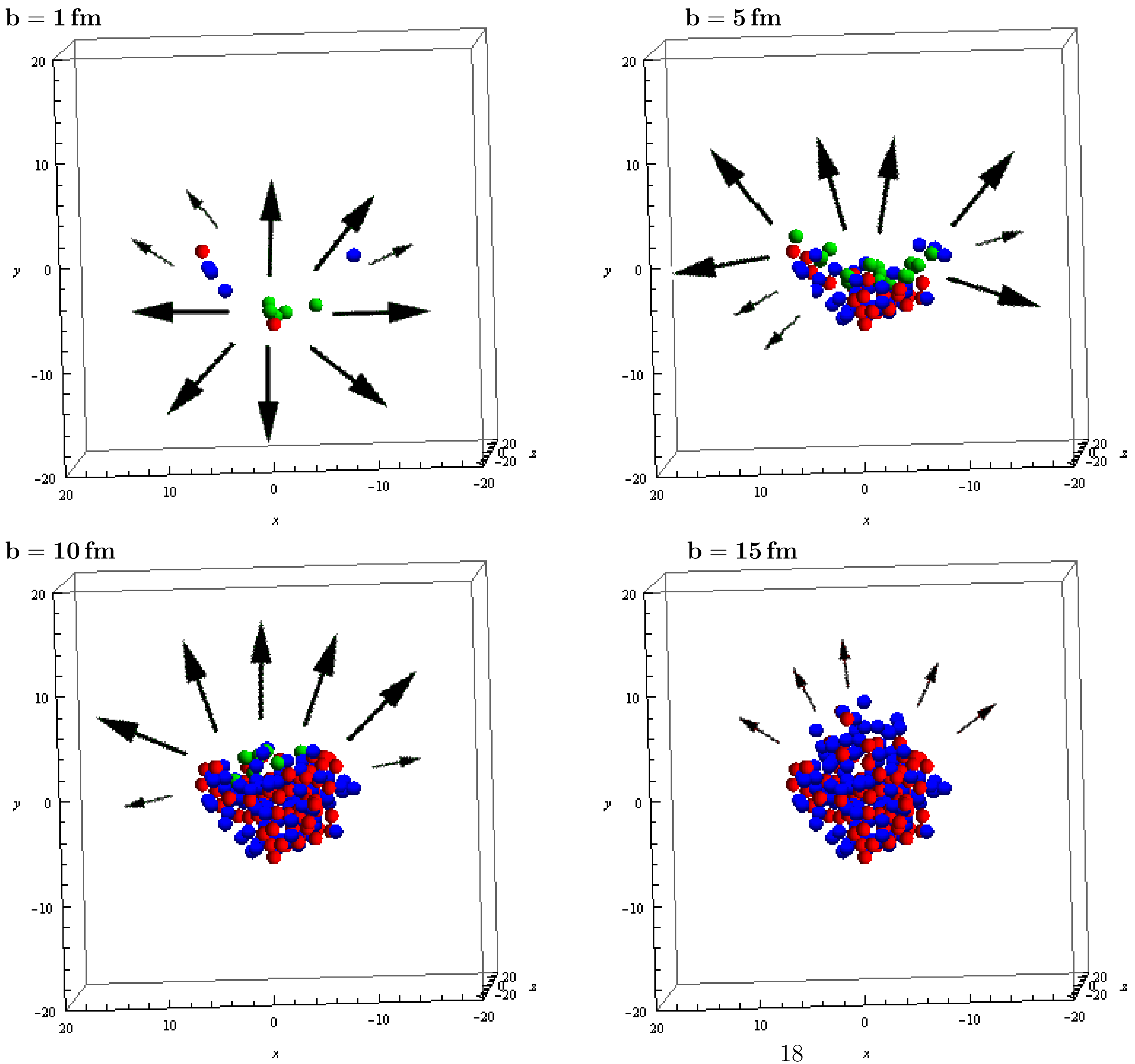
b = 15 fm



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

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

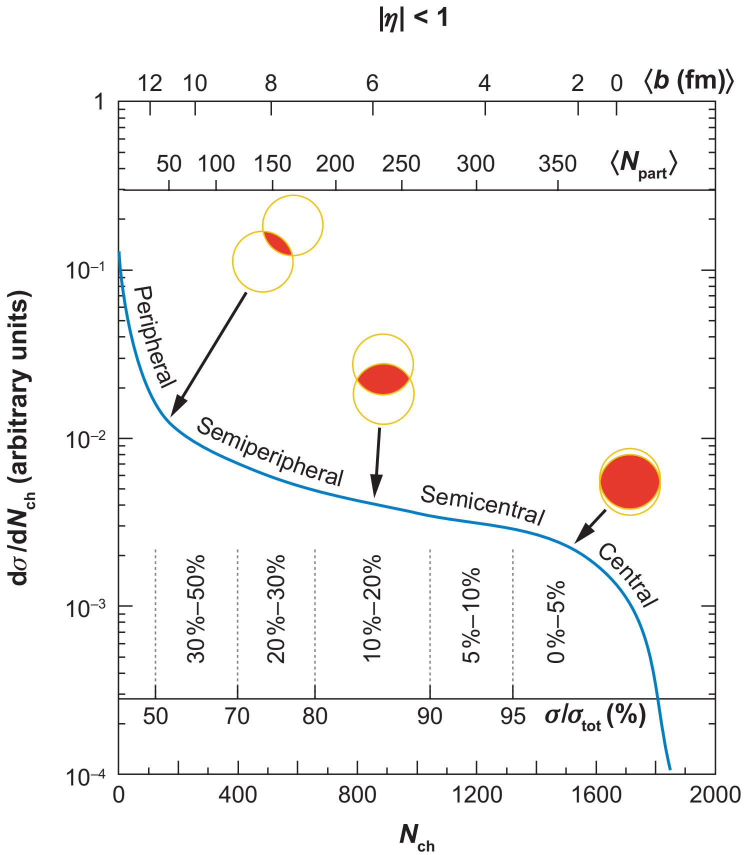
1.d - High-momentum nucleons: asymmetry



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

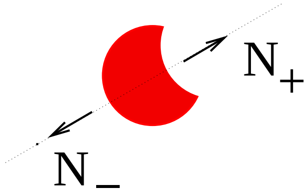
absorption by the spectator system determines asymmetry as a function of b!

1.d - Centrality and asymmetry of emissions

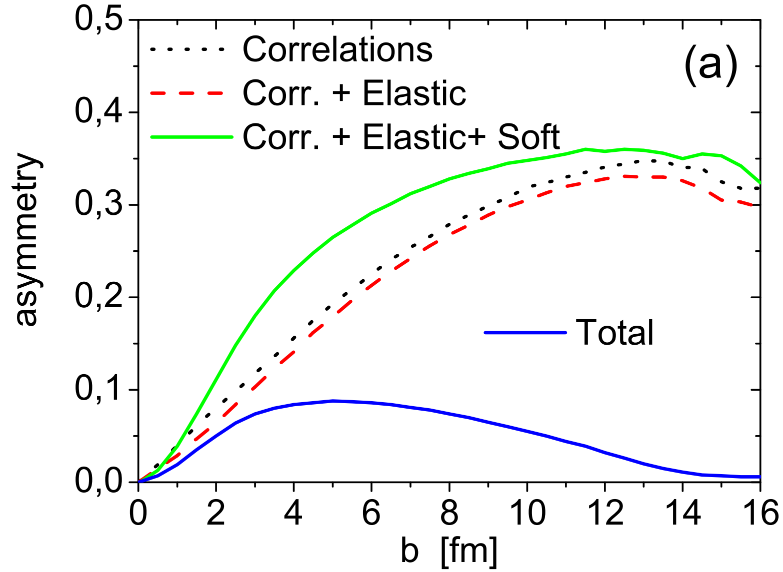


Extraction of impact parameter from the correlation with total charged particle multiplicity in the final state

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



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

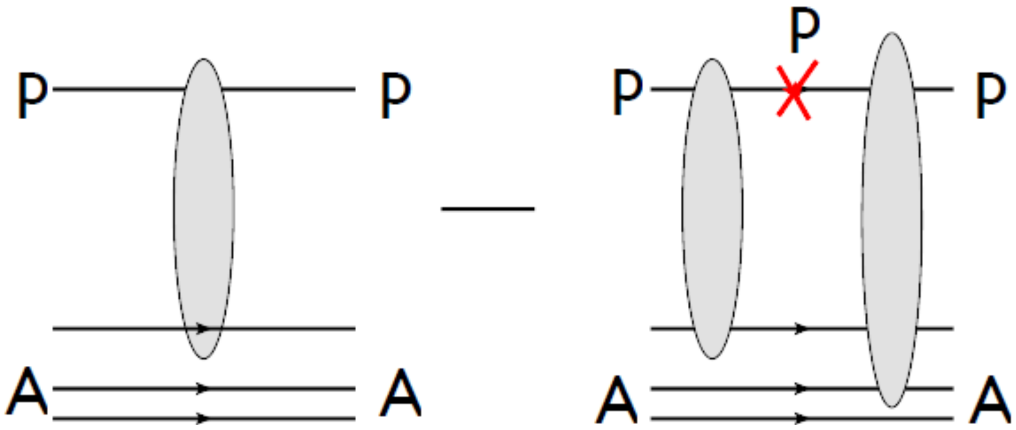


Our calculation of asymmetry as a function of impact parameter b

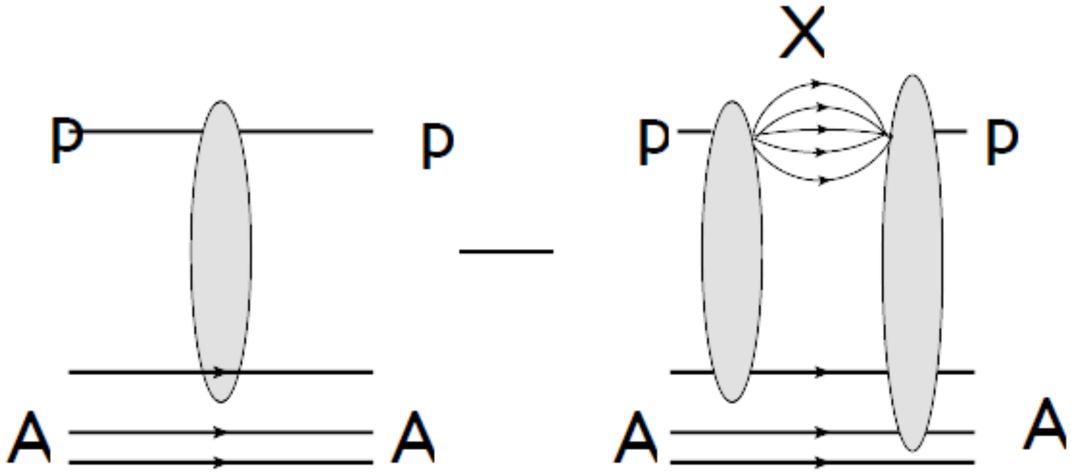
M. Alvioli, M. Strikman,

Phys. Rev. C83 (2011)

2 - Beyond Glauber approach (*also Mark's talk*)



⟶ 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

- the fluctuations into intermediate states, i.e. different internal configurations, is a manifestation of the structure of the proton

- the transverse spatial extent of the color field and of the momentum distribution in each particular configuration determines the $h_M - N$ interaction strength

- different configurations $\longrightarrow$ different cross sections $\longrightarrow$ relation with color transparency/opacity phenomena

G. Baym, B. Blattel, L. Frankfurt, M. Strikman, Phys.Rev. ***D47*** *(1993)*

Heiselberg, Baym, Blattel, Frankfurt, Strikman, Phys.Rev.Lett. ***70*** *(1993)*

2.a - Color Fluctuations in high-energy pA scattering

- GMC: pA process calculated for different configurations with given σ, which do not interfere with each other, then averaged over all possible configurations with a ***weight*** given by the probability of the configuration, $P(\sigma)$

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

$$\int d\sigma\, P(\sigma) = 1\,, \qquad \int d\sigma\, \sigma\, P(\sigma) = \sigma_{tot}$$

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

proposed by

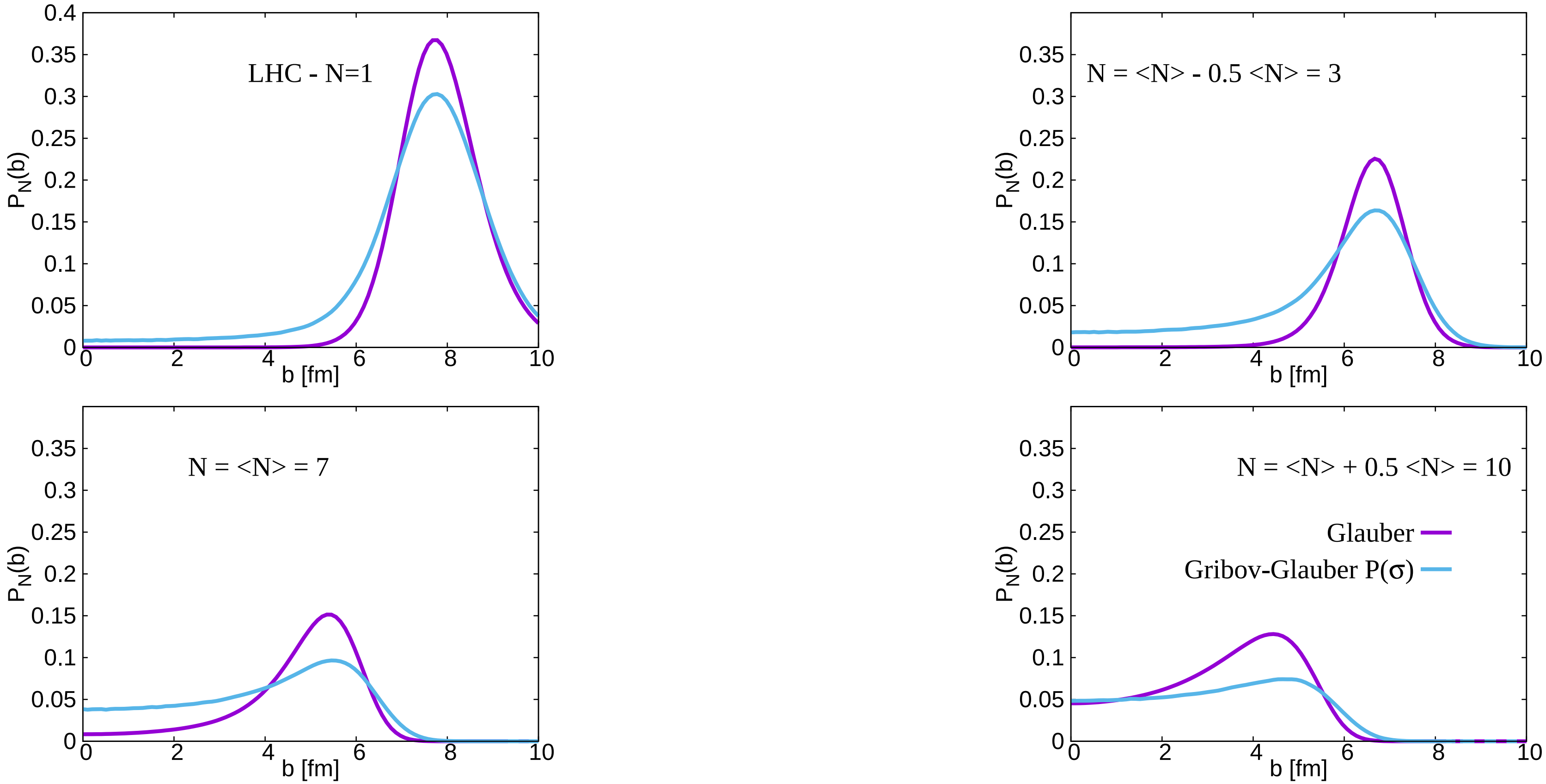
G. Baym, B. Blattel, L. Frankfurt, M. Strikman, Phys.Rev. ***D47*** *(1993)*

parametrized in *V. Guzey, M. Strikman, Phys. Lett.* ***B633*** *(2006)*

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

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

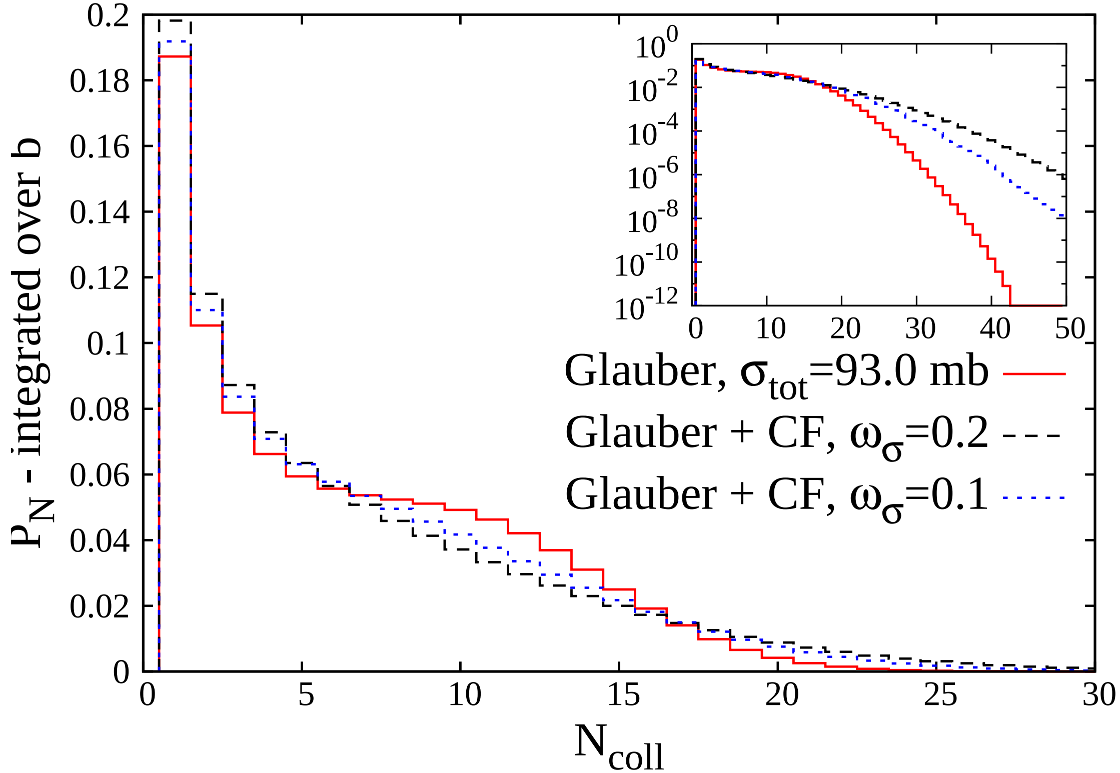
- fluctuations of the number of wounded nucleons $\mathbf{N_{coll}}$ for given impact parameter $\mathbf{b} \Longrightarrow$ smearing of centrality



- we find enhancement of the probability of events with large $N = N_{coll}$ *M. Alvioli, M. Strikman, Phys. Lett.* ***B722*** *(2013)*

2.a - Color Fluctuations: probability of N interactions

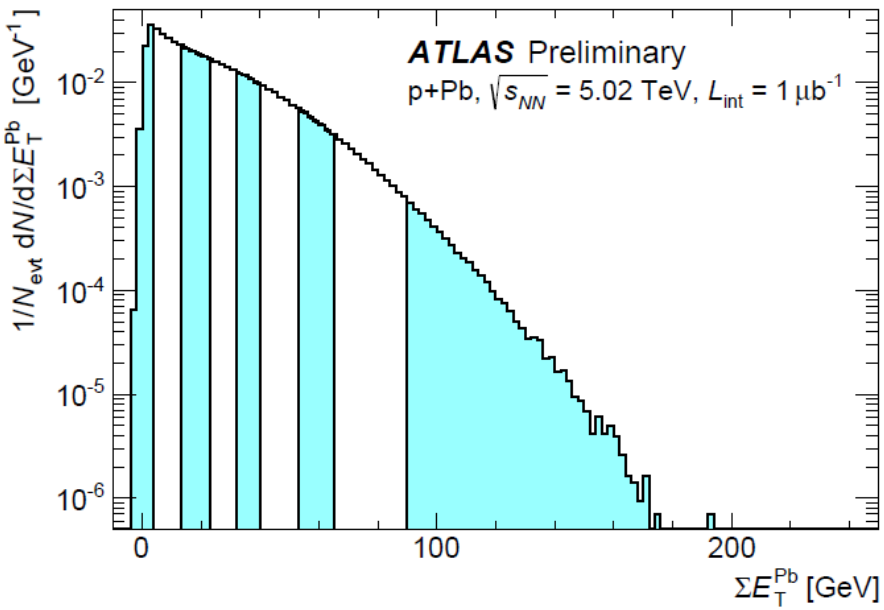
- fluctuations of the number of wounded nucleons $\mathbf{N_{coll}}$ for given impact parameter $\mathbf{b} \Longrightarrow$ smearing of centrality
- $P_N = \int d\boldsymbol{b}\, P_N(b)$; $N = N_{coll}$



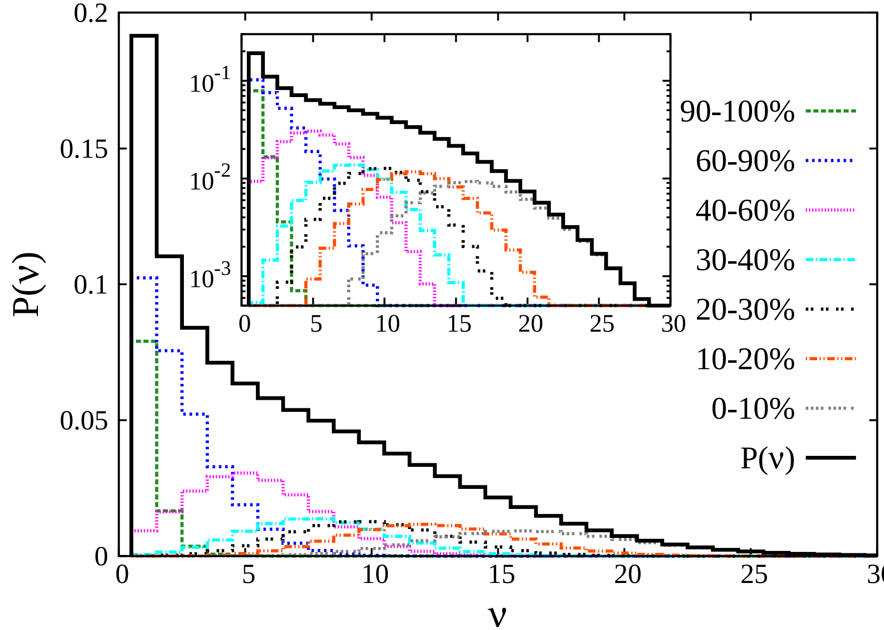
M. Alvioli, M. Strikman, Phys. Lett. ***B722*** *(2013)*
M. Alvioli, V. Guzey, L. Frankfurt, M. Strikman, Phys. Rev. ***C90*** *(2014)*

2.a - Color Fluctuations: N_{coll} and b dependence (Dennis' talk)

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



$\Longrightarrow$

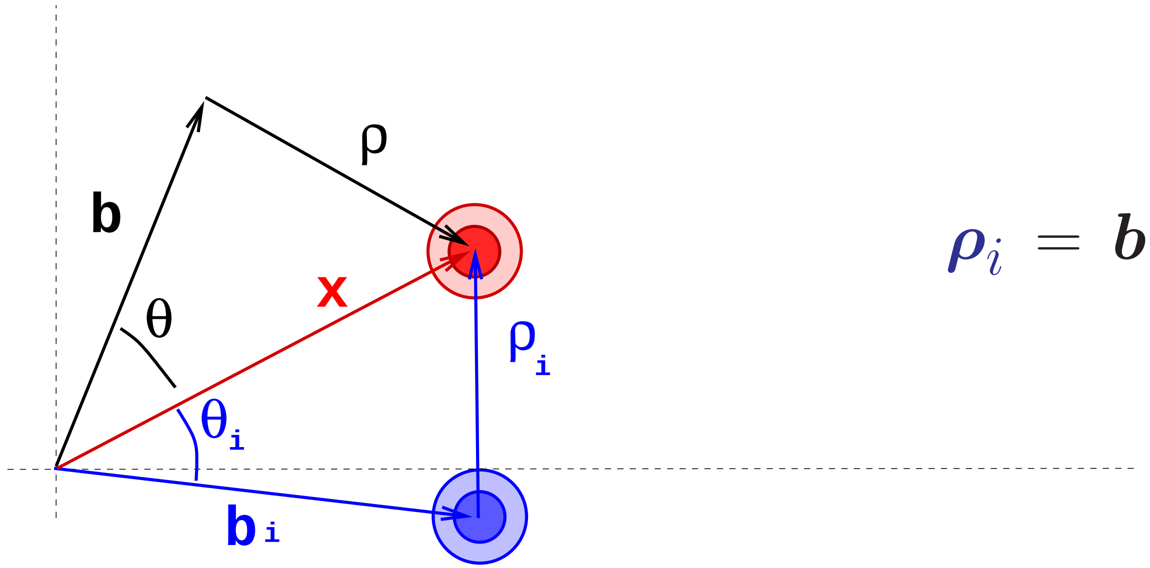


*Alvioli, Cole, Frankfurt, Perepelitsa, Strikman, **PRC93** (2016)*

- 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.b - Geometry & hard trigger in pA processes (*Mark's talk*)

- We have developed a model to characterize events with one hard scattering and the remaining soft scatterings, as a function of $\nu = N_{coll}$
- The hard event (HT) is 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-1 soft interactions with 2-d integral over the position of the hard scattering

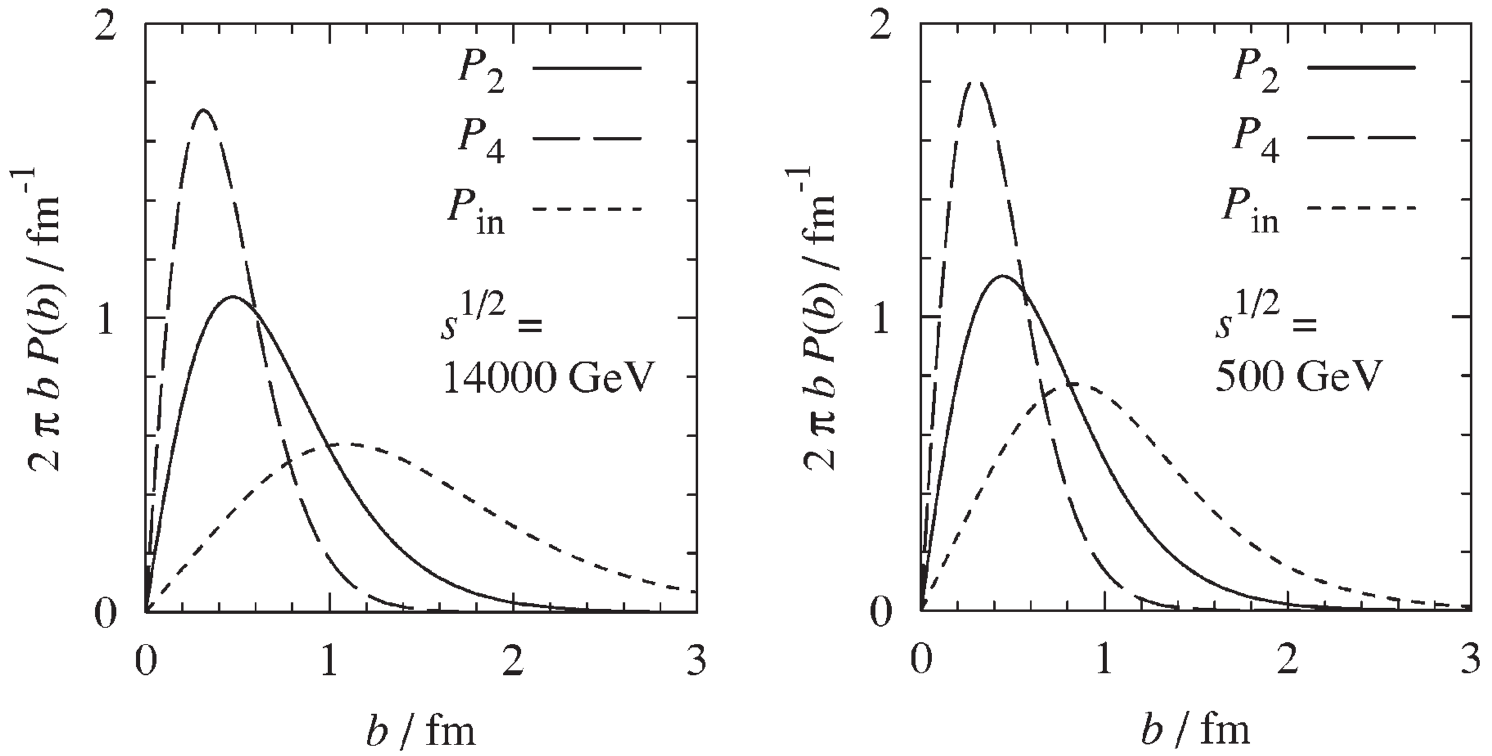


$$\boldsymbol{\rho}_i = \boldsymbol{b} + \boldsymbol{\rho} - \boldsymbol{b}_i$$

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

2.b - Hard interaction vs. soft interaction ranges

- Probability of interaction:



L. Frankfurt, M. Strikman, C. Weiss, Phys. Rev. ***D69*** *(2004)*

2.b - Geometry & hard trigger in pA processes (*Mark's talk*)

- The particular target nucleon j that undergoes hard scattering is selected in each event according to the probability

$$p_j = \frac{F_g(\boldsymbol{b} + \boldsymbol{\rho} - \boldsymbol{b}_j)}{\sum_{k=1}^{A} F_g(\boldsymbol{b} + \boldsymbol{\rho} - \boldsymbol{b}_k)}, \qquad \boldsymbol{\rho}_j = \boldsymbol{b} + \boldsymbol{\rho} - \boldsymbol{b}_j$$

$$Rate(N_{coll}) =< \sigma_{HT} \int d\boldsymbol{b} d\boldsymbol{\rho} \prod_{i=1}^{A} d\boldsymbol{\rho}_i F_g(\rho) \sum_{i=1}^{A} F_g(\rho_i)\, p_{hard}(N_{coll}) >$$

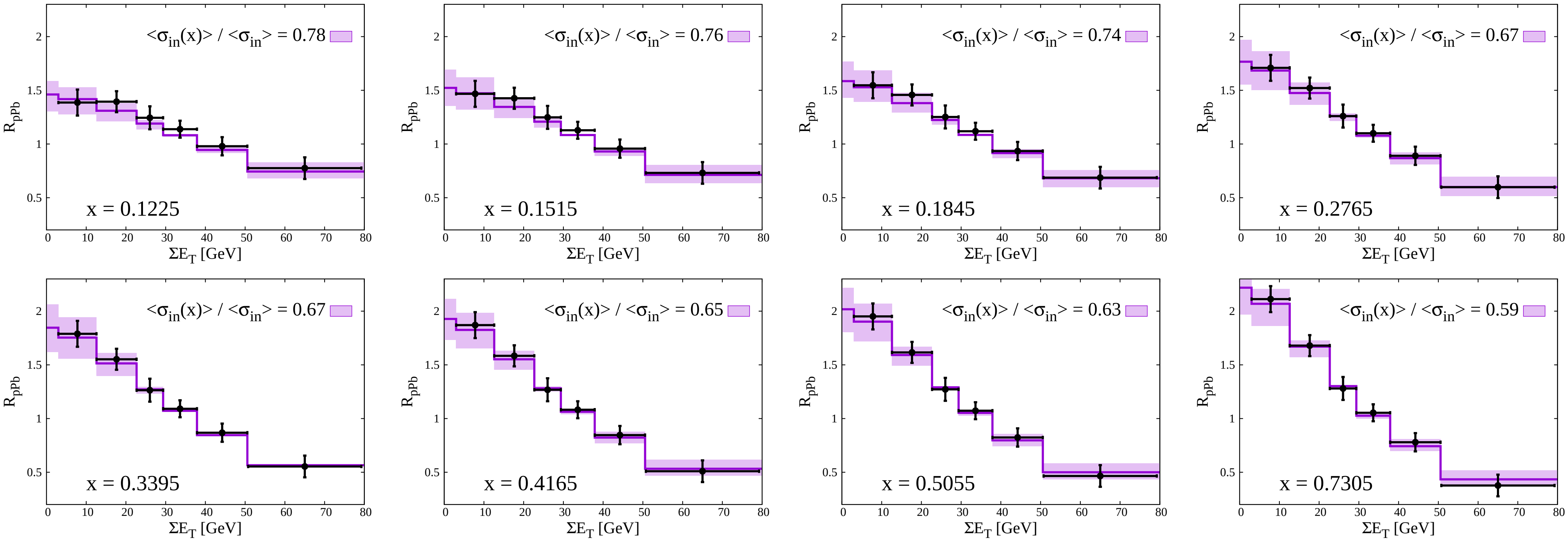
- where p_{hard} is the (MC-calculated) probability that the event contains

$$N_{coll} = N_{coll}(other) + 1\,,$$

with $N_{coll}(other)$ denoting all the inelastic interaction in the event, but the one with target nucleon j, which we selected as a hard trigger

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

2.b - X-dependent Color Fluctuations in pA (Dennis & Mark)



- The proton interacts with a smaller-than-average cross section

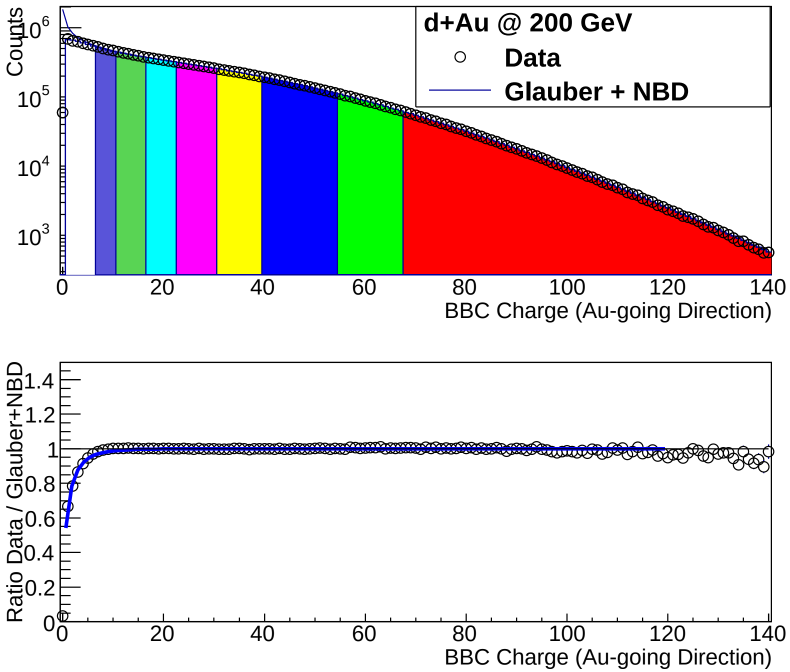
Alvioli, Cole, Frankfurt, Perepelitsa, Strikman, Phys. Rev. ***C93*** *(2016)*

Alvioli, Frankfurt, Perepelitsa, Strikman, ***in progress***

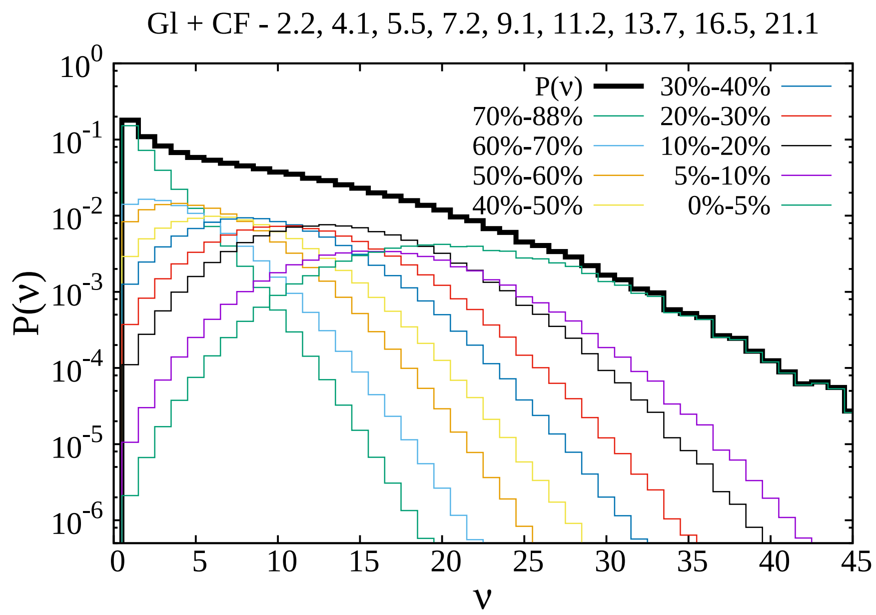
Data: *Aad et al. - ATLAS collaboration - Phys. Lett.* ***B748*** *(2015)*

2.c - Color Fluctuations: N_{coll} and b dependence (Dennis' talk)

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



$\Longrightarrow$



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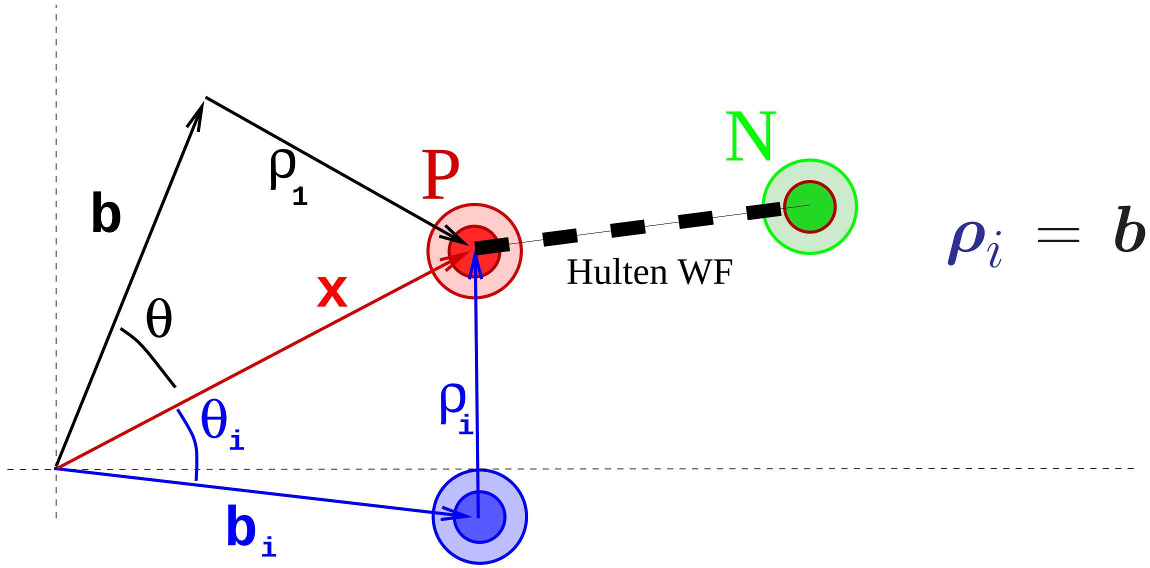
- same approach as in the pA case
- non -trivial relation between N_{coll} and centrality

2.c - Geometry & hard trigger in dA processes (*Mark's talk*)

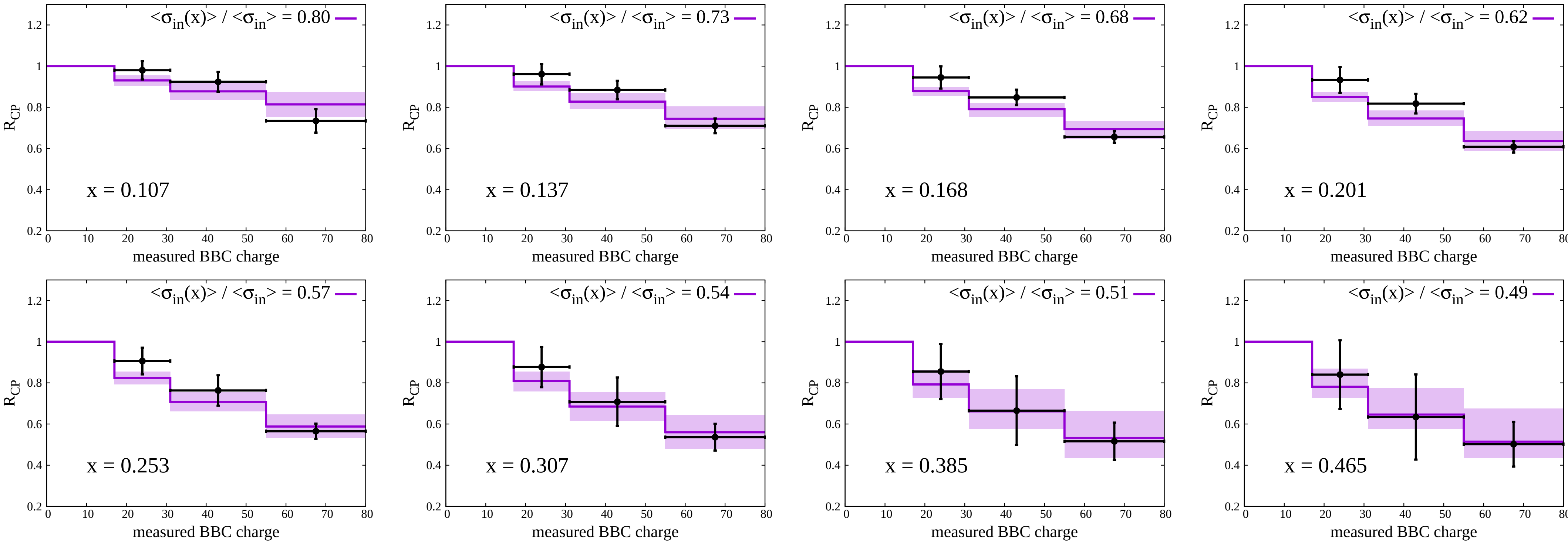
- We have developed a model to characterize events with one hard scattering and the remaining soft scatterings, as a function of $\nu = N_{coll}$
- The hard event (HT) is triggered in a probabilistic way
- We have coupled the MCG average (< ... >) for the N-1 soft interactions with 2-d integral over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



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

M. Alvioli, L. Frankfurt, D. Perepelitsa, M. Strikman, ***in progress***

2.c - X-dependent Color Fluctuations in dA (Dennis & Mark)



- The nucleon interacts with a smaller-than-average cross section

Alvioli, Frankfurt, Perepelitsa, Strikman, ***in progress***

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

Summary

- We generate *nuclear configurations* including 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

  → Different proton and neutron profiles are implemented (*neutron skin*)

- Application: model for energy transferred to *spectator* nucleons

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

  → *Number of collisions-impact parameter* relationship modified

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

  → *More in Mark's talk*