Spin-isospin correlated nuclear configurations for high-energy p-A, d-A and A-A collisions: selected 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

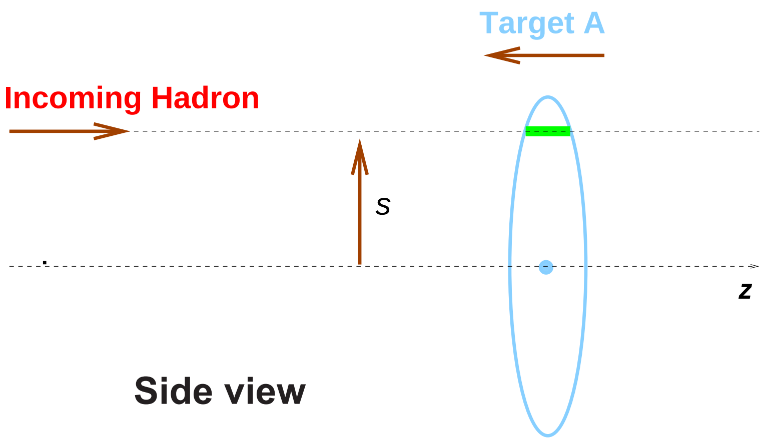
2.b Processes with hard trigger: pA

2.c Processes with hard trigger: dA

2.d Processes with double hard trigger: DPS

1.a - Glauber multiple scattering pA and AA scattering

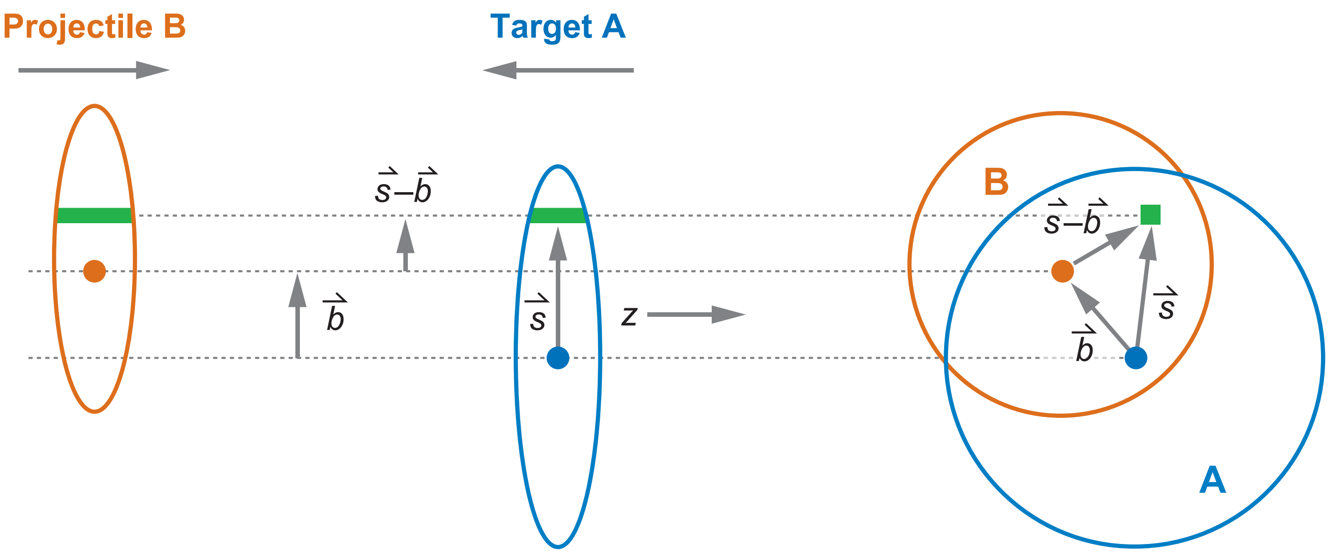
Glauber approach: quantum mechanics of high-energy many-body scattering $\Longrightarrow$ frozen approximation; straight line trajectories



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 $T_A(\boldsymbol{b}) = \int dz \rho(\boldsymbol{b}, z)$, $T_{AA}(\boldsymbol{b}) = \int d\boldsymbol{s} T_A(\boldsymbol{s}) T_A(\boldsymbol{b} - \boldsymbol{s})$:

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

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

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

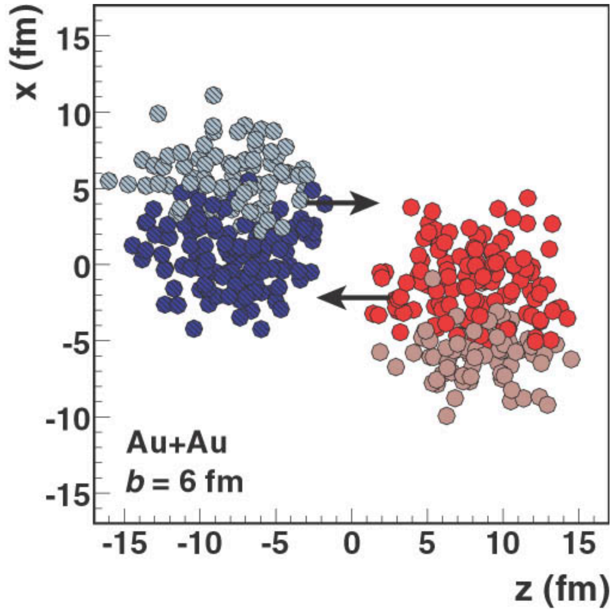
- Optical limit: assuming uncorrelated scattering centers, A$\otimes$A integrations over transverse coordinates are reduced to one integration:

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

- **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***.

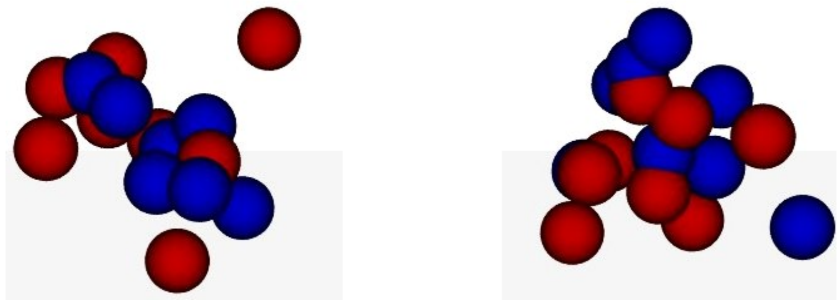
- Charged particle multiplicity scales with N_{part}, N_{coll} $\Leftrightarrow$ ***centrality***

- 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**:

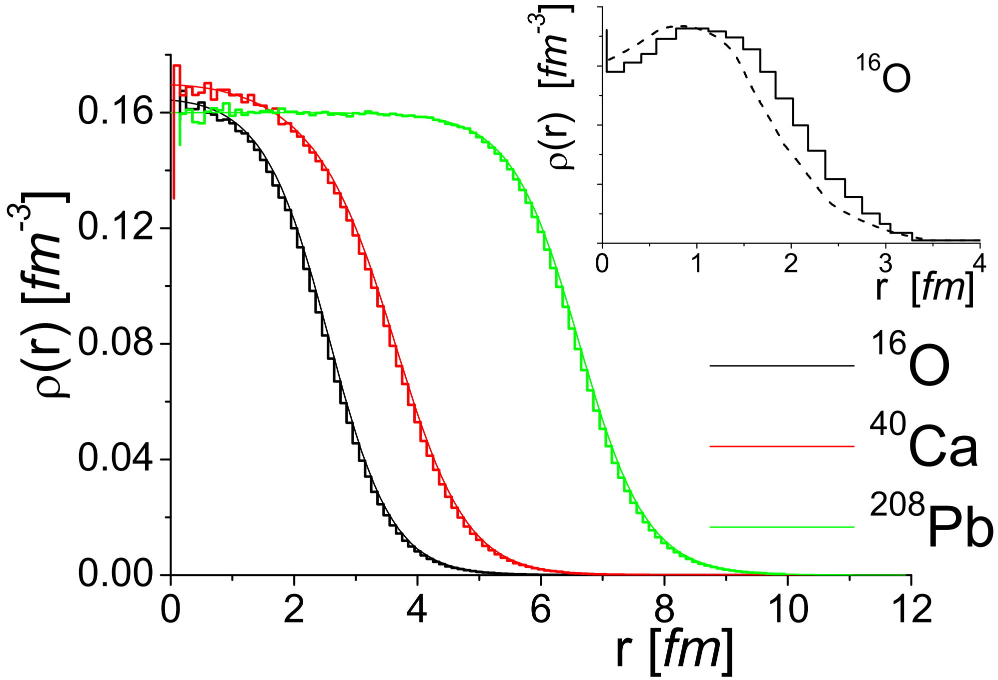
$$\Psi(\boldsymbol{r}_1, ..., \boldsymbol{r}_A) = \prod_{i<j}^{A} \hat{f}(r_{ij})\, \Phi(\boldsymbol{r}_1, ..., \boldsymbol{r}_A)$$



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

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

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



1.b - Correlations and fluctuations in pA collisions

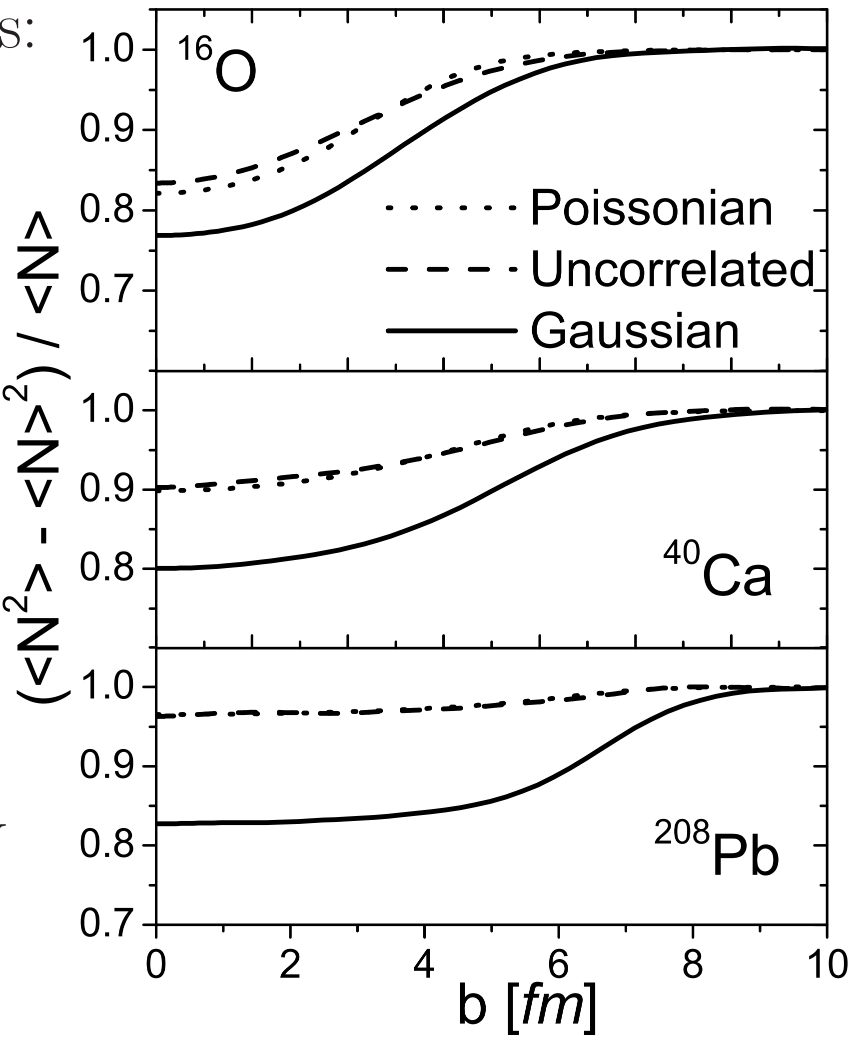
- average number of single and double collisions:

$$\langle N\rangle = \sum_N N\, P_N(b)$$
$$\langle N(N-1)\rangle = \sum_N \left(N^2 - N\right)\, P_N(b)$$

- dispersion: $D(b) = \frac{\langle N^2\rangle - [\langle N\rangle]^2}{\langle N\rangle} \longrightarrow$

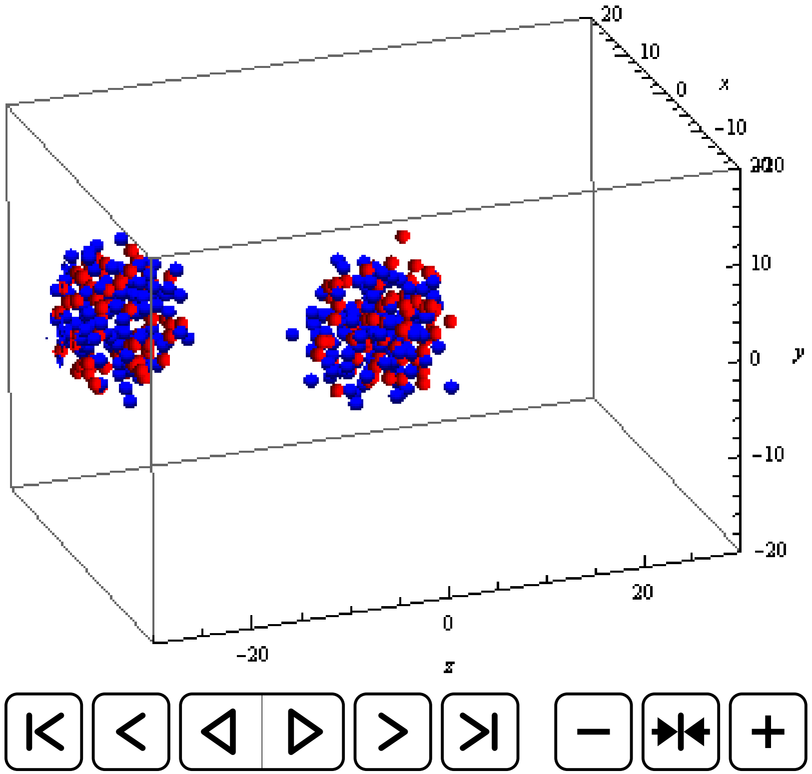
- *Poissonian* result is obtained using

$$P_N(b) = \binom{A}{N}\left(\sigma^{in}_{NN}T(b)\right)^N\left[1-\sigma^{in}_{NN}T(b)\right]^{A-N}$$



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

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



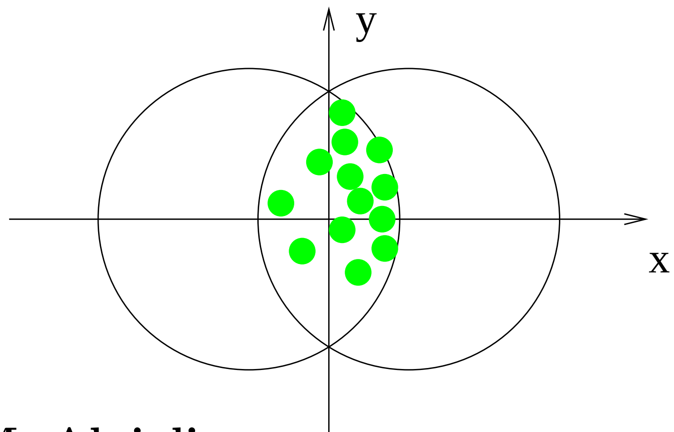
- **Spectator** nucleons ●●relevant for zero degree calorimeter measurement (beam remnant): *Alvioli, Strikman,* ***PRC83*** *(2011)*

- **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

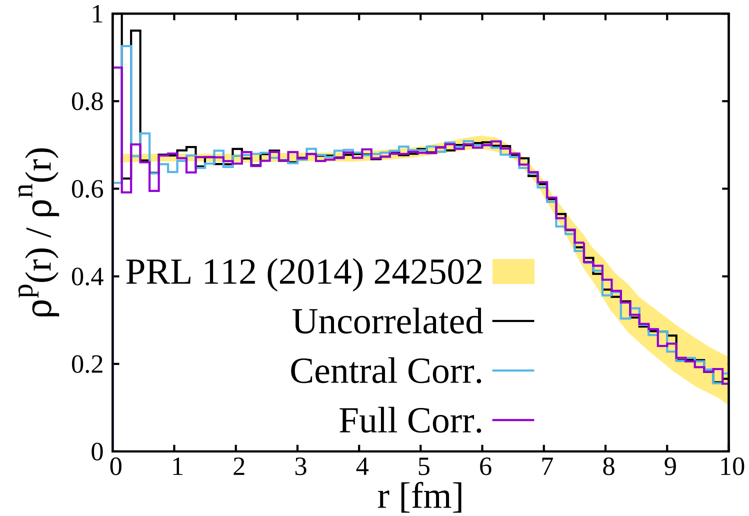
1.c - Configurations with neutron skin

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

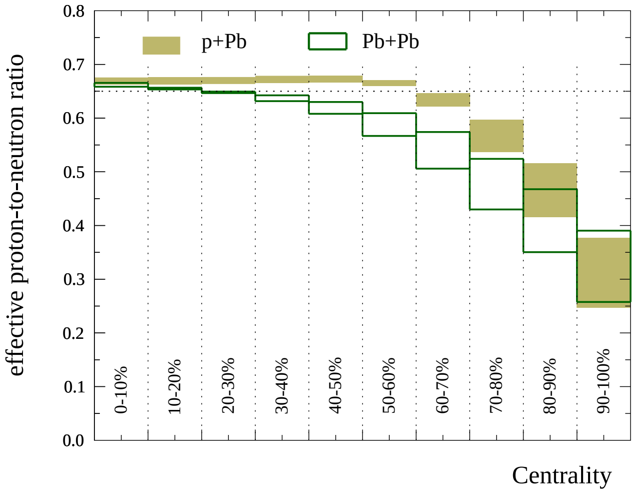
$$\rho(r) = \rho_0^{(p,n)} \;/\; \left(1 + e^{(r-R_0^{p,n})/a^{p,n}}\right)$$

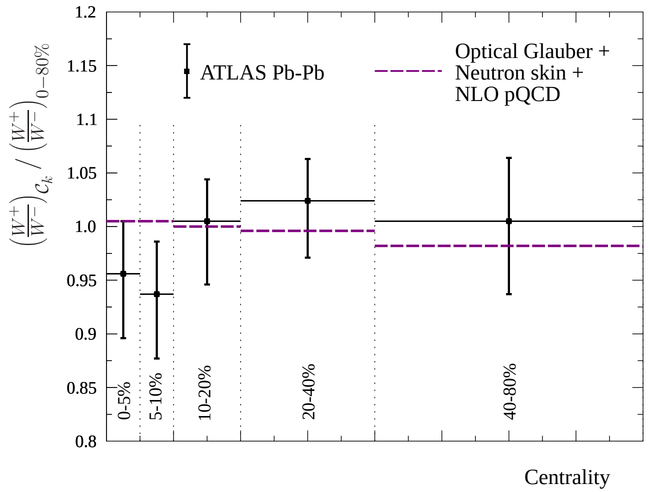
$$(\rho_0^p, R_0^p, a_0^p) \;=\; (\text{"82"}, 6.680 fm, 0.447 fm)$$
$$(\rho_0^n, R_0^n, a_0^n) \;=\; (\text{"126"}, 6.700 fm, 0.550 fm)$$

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

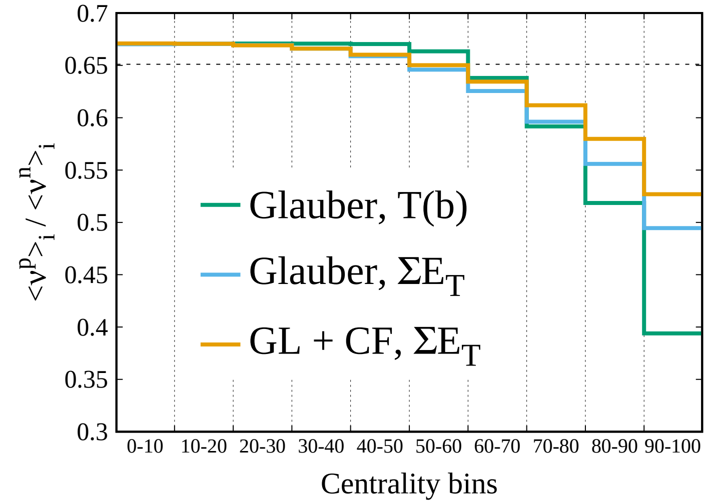


- Suggested as additional tool for determination of centrality:





*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

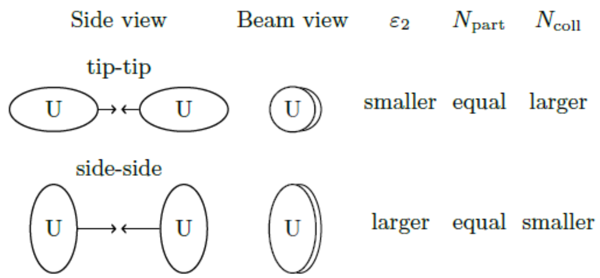
- ***Nucleus deformation*** – modified nuclear profile:

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

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

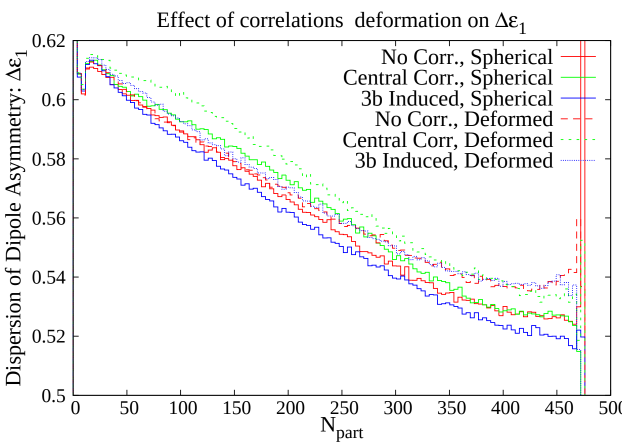
$$Y_{20}(\theta) = \frac{1}{4\,r^2}\sqrt{\frac{5}{\pi}}\left(2z^2 - x^2 - y^2\right)$$

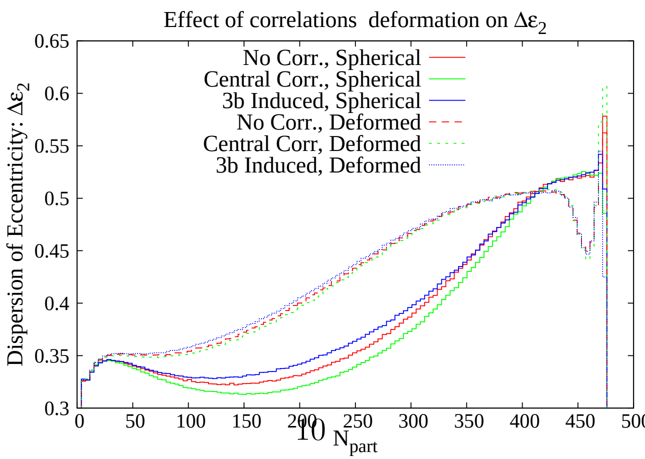
$$Y_{40}(\theta) = \frac{1}{16\,r^4}\sqrt{\frac{9}{\pi}}\left(35z^4 - 30z^2r^2 + 3r^4\right)$$

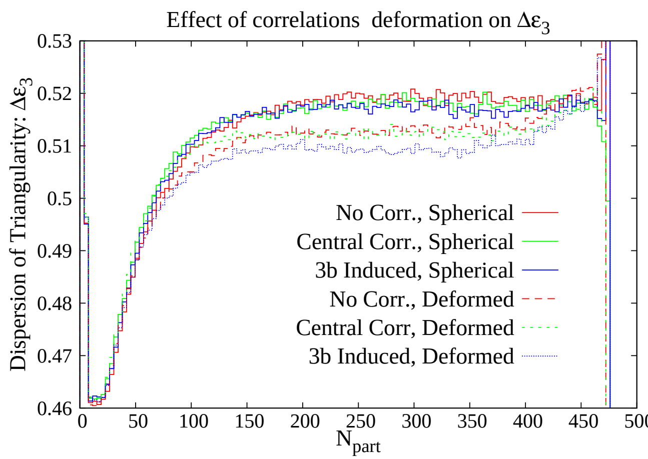


- Studies of isobars/neutorn skin effect at RHIC (J. Hammelmann, A. Soto-Ontoso, M. Alvioli, H. Elfner, M. Strikman **arXiv:1908.10231** [nucl-th])

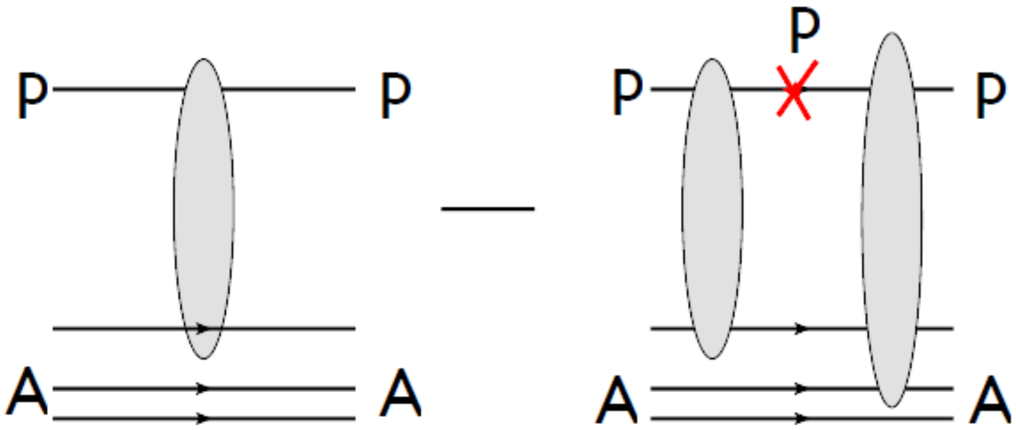
- Effects on *dispersion of moments* in U-U (*unplublished*):



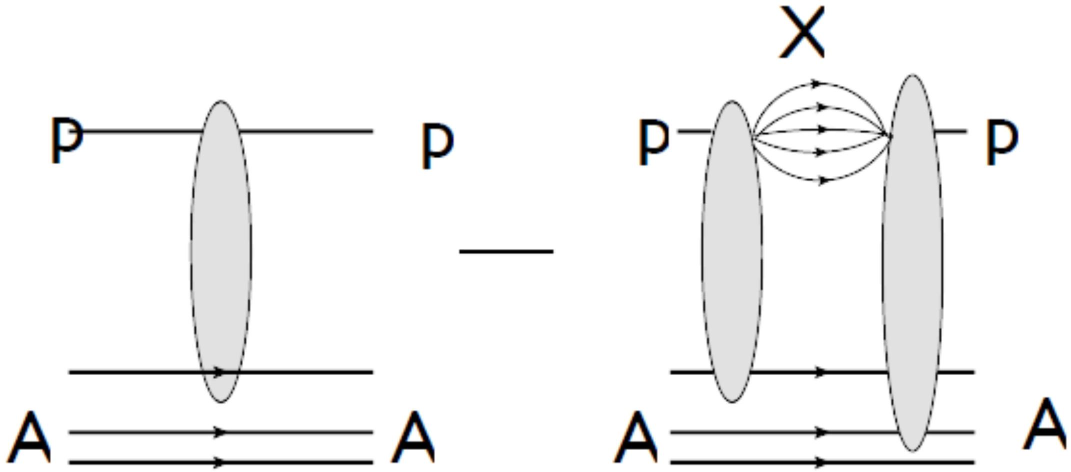




2 - Beyond Glauber approach



$\longrightarrow$ 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)

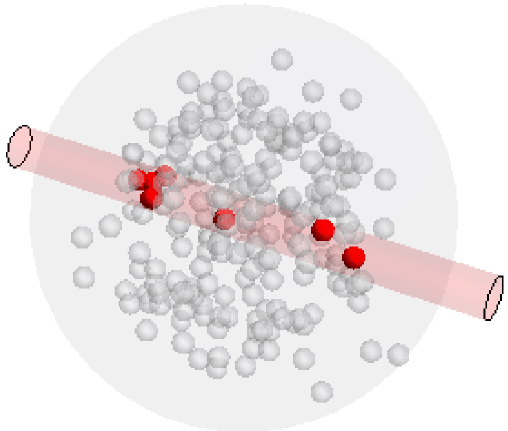
X is a set of intermediate states that stay frozen during $\boldsymbol{pA}$ interaction

2.a - NN interaction with frozen configurations

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

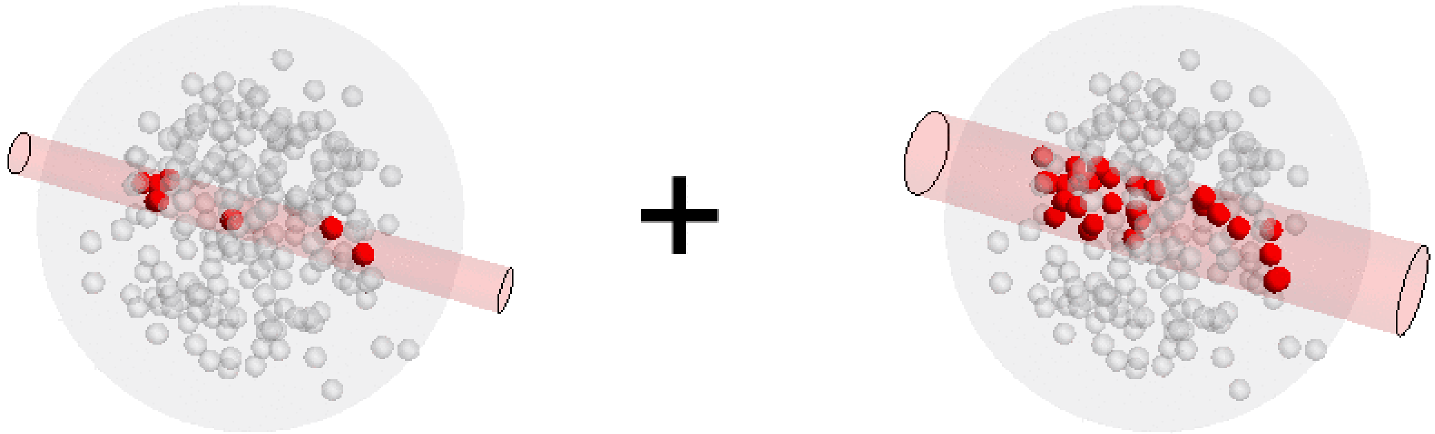
$$2\,R \,<\, 2\,p_{lab}/(M^2 \,-\, m^2)$$

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)*;

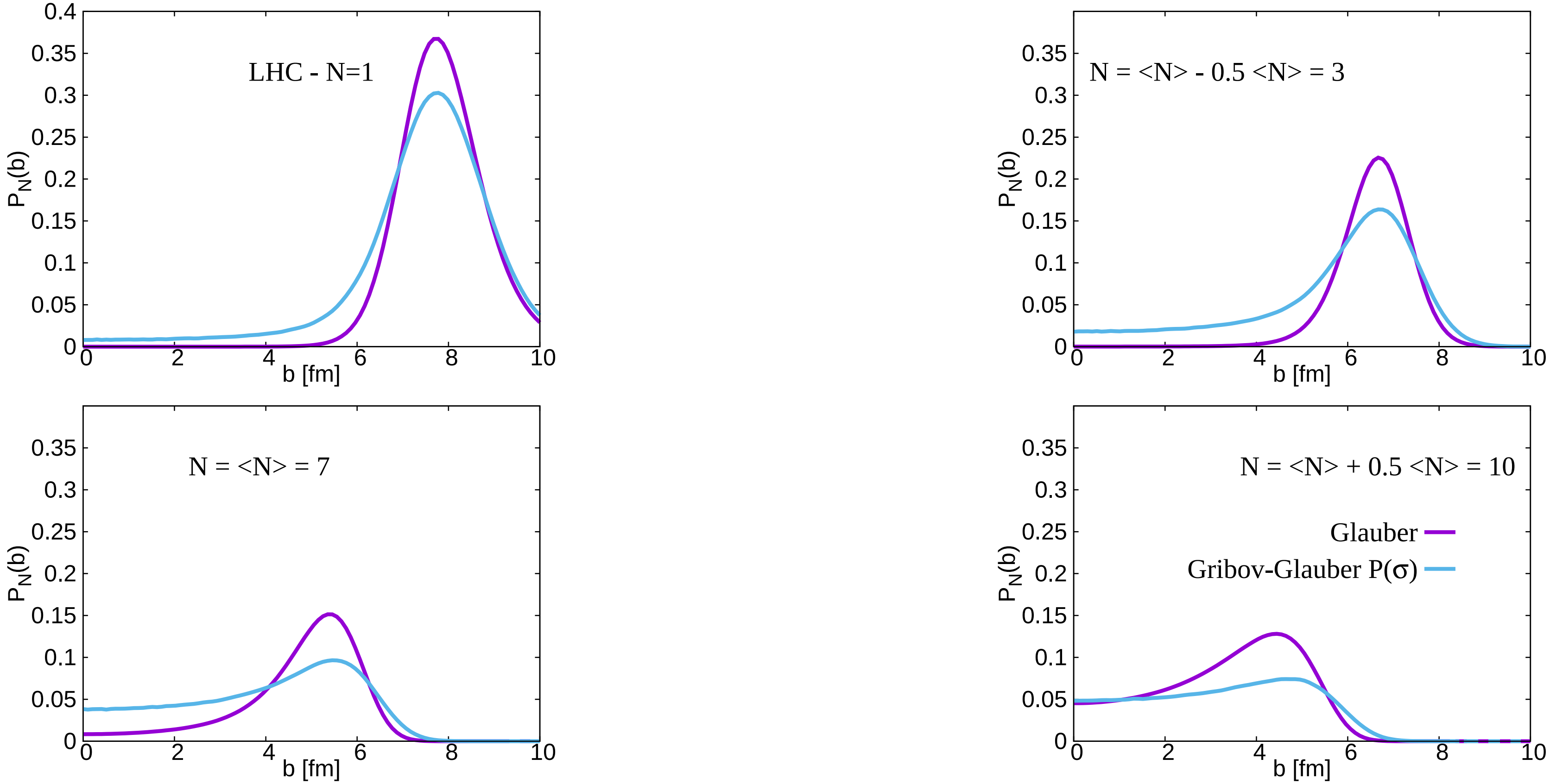
M. Alvioli, L. Frankfurt, D. Perepelitsa, M. Strikman, ***PRD98*** *(2018)*;

M. Alvioli, M. Azarkin, B.B lok, 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**

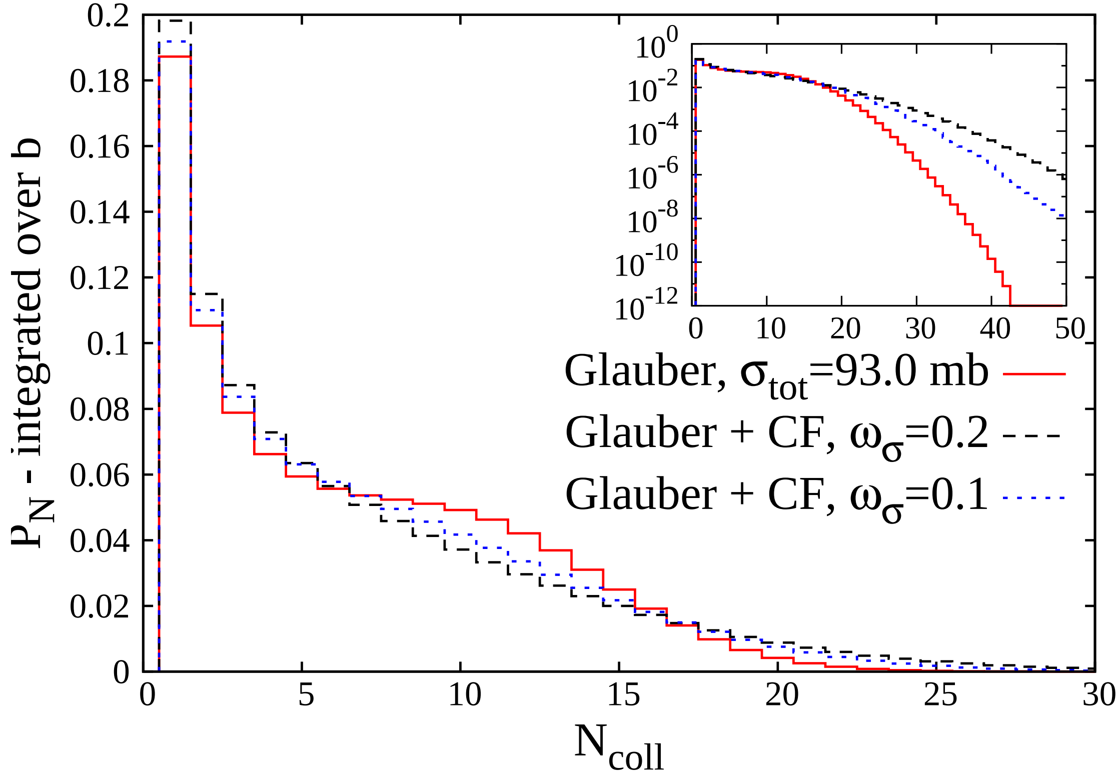


M. Alvioli, M. Strikman, Phys. Lett. ***B722*** *(2013)*

2.a - Color Fluctuations: probability of N interactions

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

- Enhancement of the probability of events with **large** $N = N_{coll}$

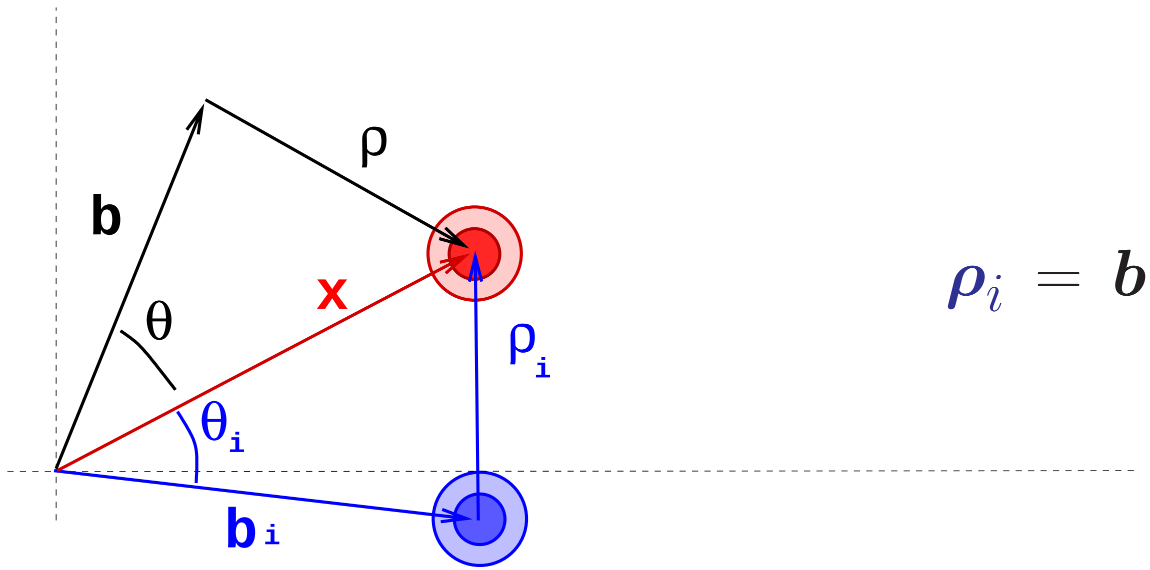


M. Alvioli, M. Strikman, Phys. Lett. ***B722*** *(2013)*

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

2.b - Geometry & hard trigger in pA processes

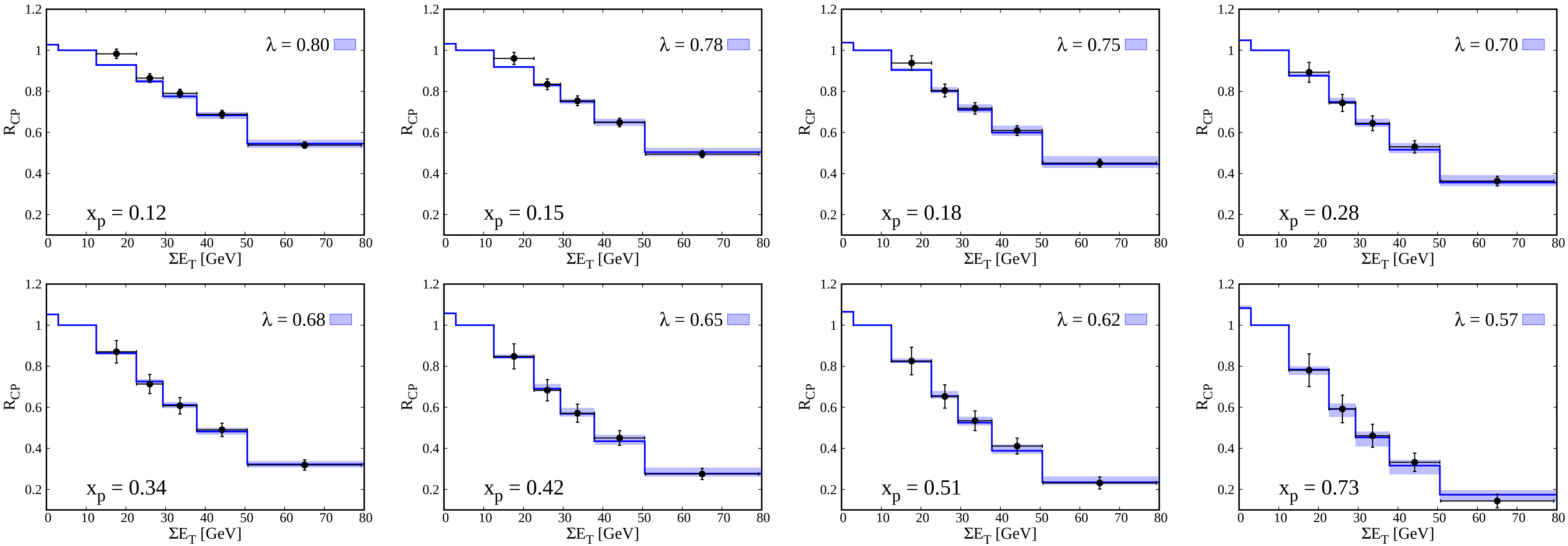
- A model to characterize the probability of events with one hard scattering and the (N_{coll}-1) soft scatterings, as a function of N_{coll}
- Hard event triggered in a probabilistic way, using the gluon distributions in the transverse plane $F_g(\rho) = exp(-\rho^2/B^2)/\pi B^2$
- We have coupled the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

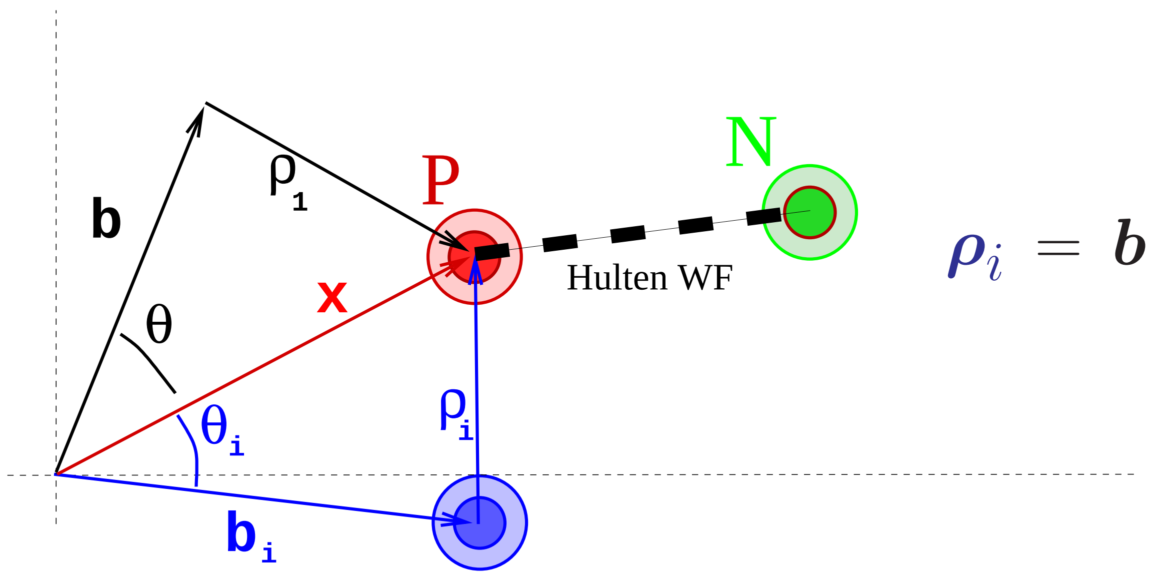
Alvioli, Cole, Frankfurt, Perepelitsa, Strikman, Phys. Rev. ***C93*** *(2016)*

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

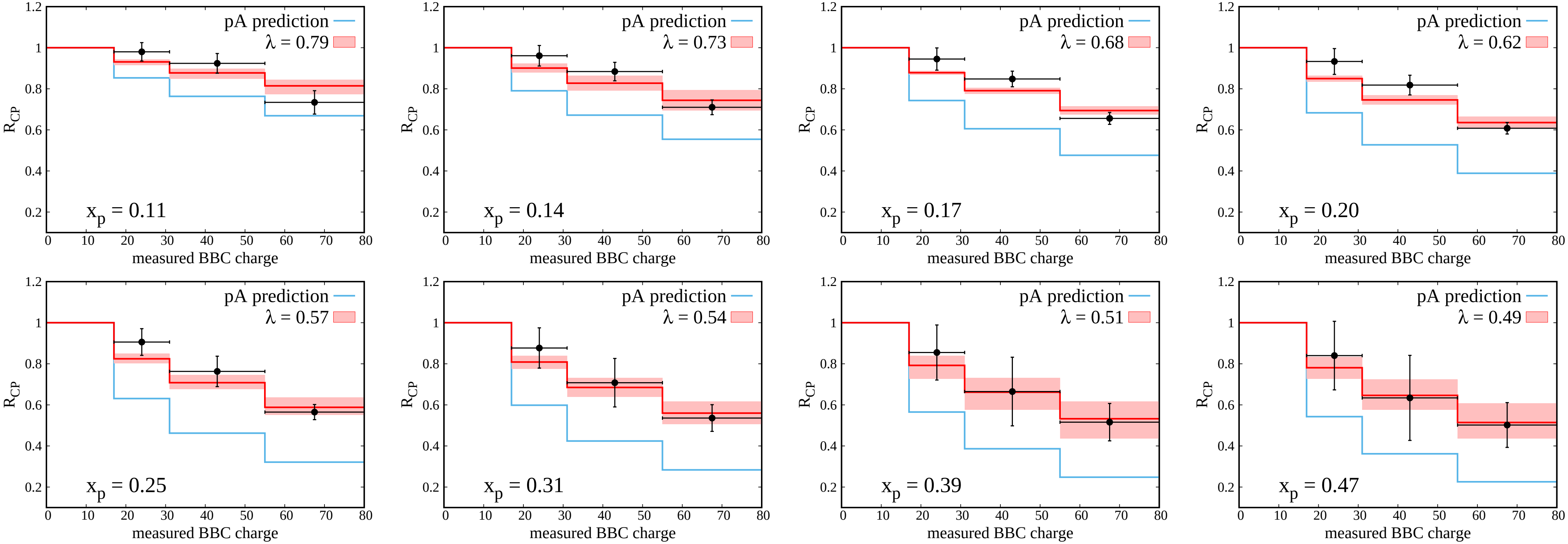
- A model to characterize the probability of events with one hard scattering and the (N_{coll}-1) soft scatterings, as a function of N_{coll}
- The hard event triggered in a probabilistic way
- We have coupled the MCG average ($< \ldots >$) for the N_{coll}-1 soft interactions with 2-d integral over 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 a smaller-than-average cross section: $\lambda = \langle\sigma(x)\rangle/\sigma_{pN}$

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

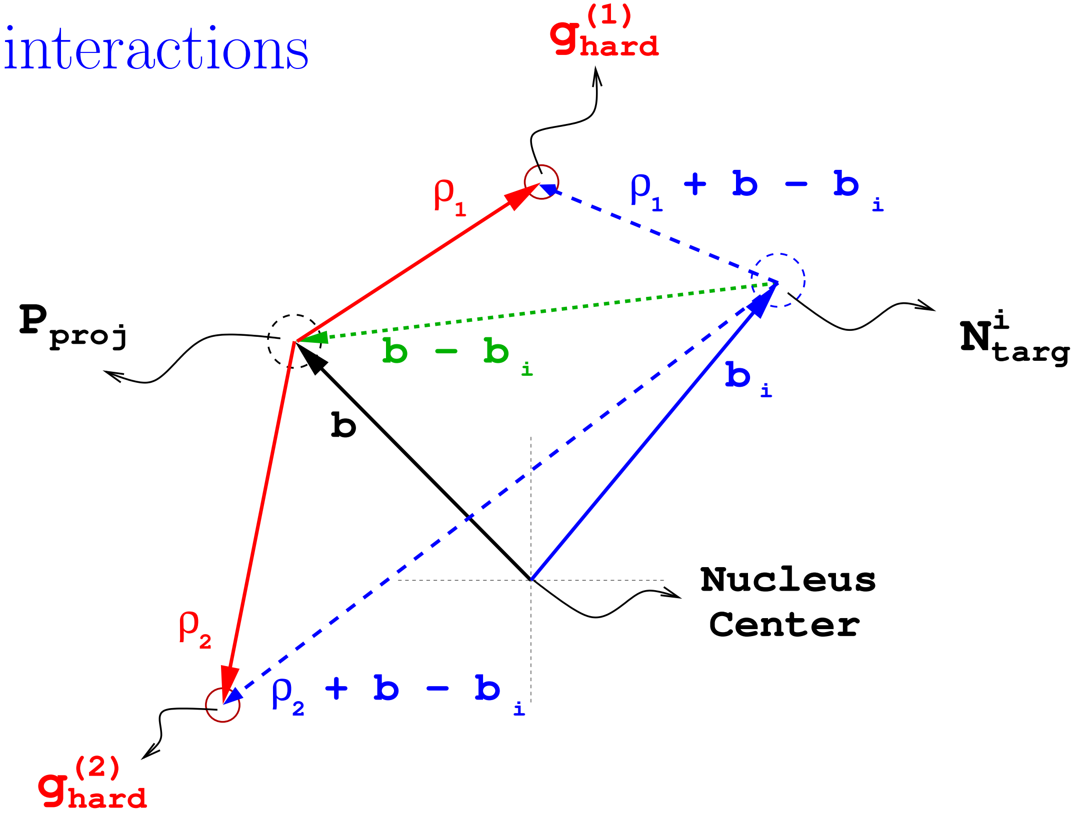
Data: *Adare et al. - PHENIX collaboration - Phys. Rev. Lett.* ***116*** *(2016)*

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

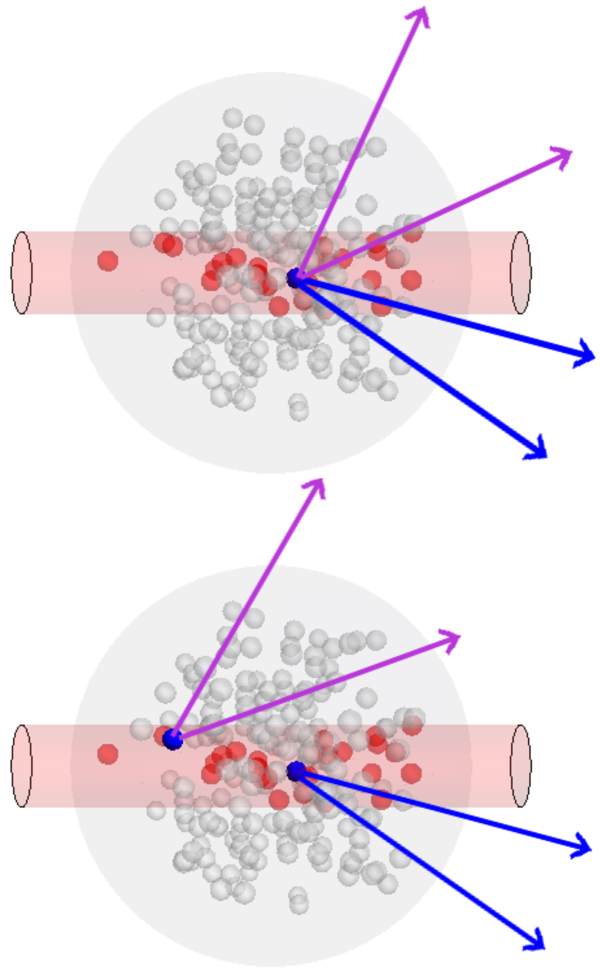


M. Strikman, D. Treleani, Phys. Rev. Lett. ***88*** *(2002)*

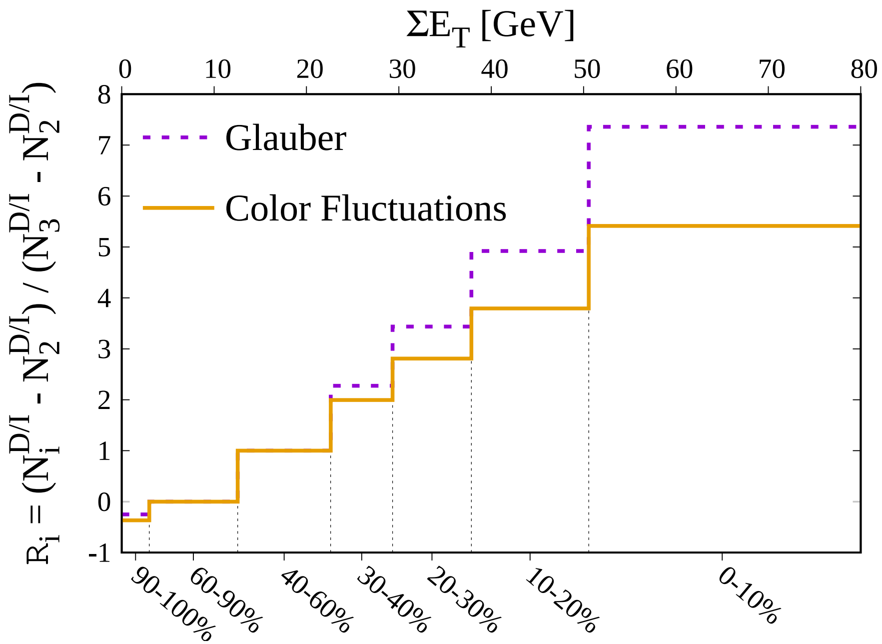
*M. Alvioli, M. Azarkin, B. Blok, M. Stirkman Eur. Phys. J. C**79** (2019)*

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

$\rightarrow$ Already used by many authors and for several *different purposes*

$\rightarrow$ We can produce configurations for *any* A=Z+N

$\rightarrow$ *Deformed* nuclei are implemented as well as (*neutron skin*)

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

$\rightarrow$ Modified N_{coll}-*impact parameter* relationship

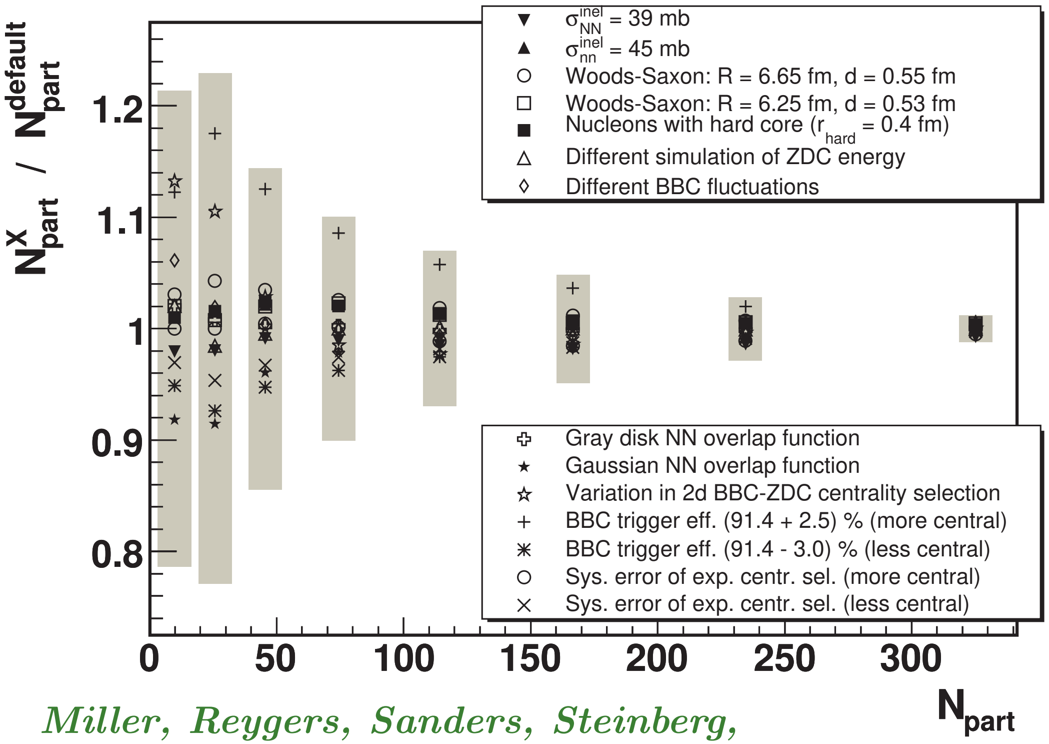
- Selection of events with a *hard-trigger* allows the determination of x-dependence of color fluctuations: both in pA and dA

- 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

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



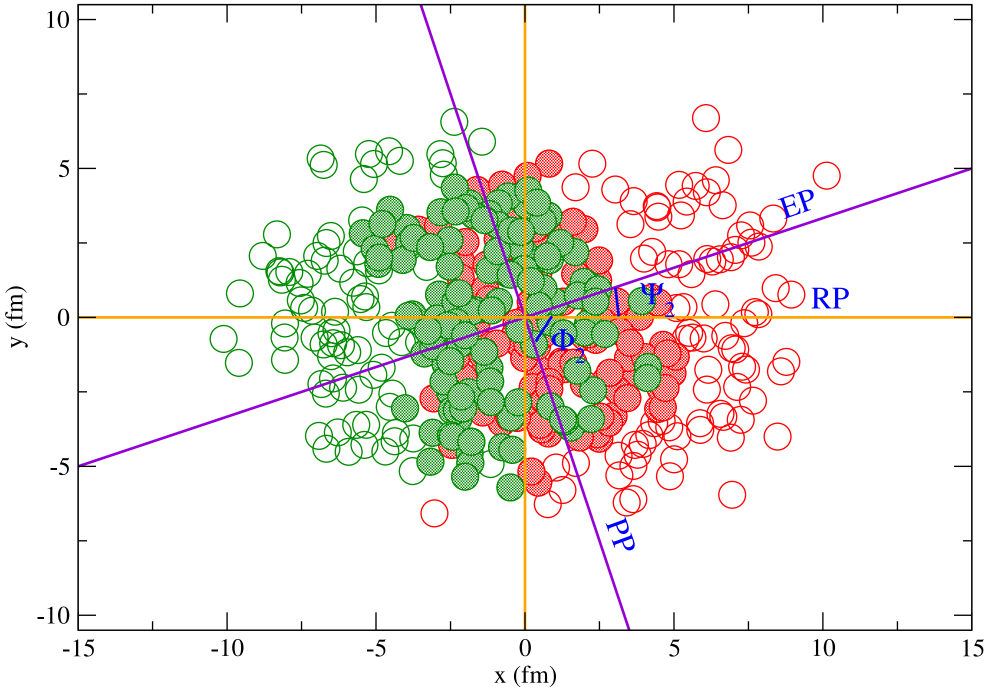
Miller, Reygers, Sanders, Steinberg, Ann. Rev. Nucl. Part. Sci. 57 (2007)

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 $\longrightarrow$ initial geometry
- no black-disk approximation for NN $\longrightarrow P(|\boldsymbol{b} - \boldsymbol{b}_j|)$
- fluctuation of the NN cross section (***color fluctuations***)$\longrightarrow$ average number of participants $\longrightarrow$ different impact parameter dependence

1.c - Sources of event-by-event fluctuations



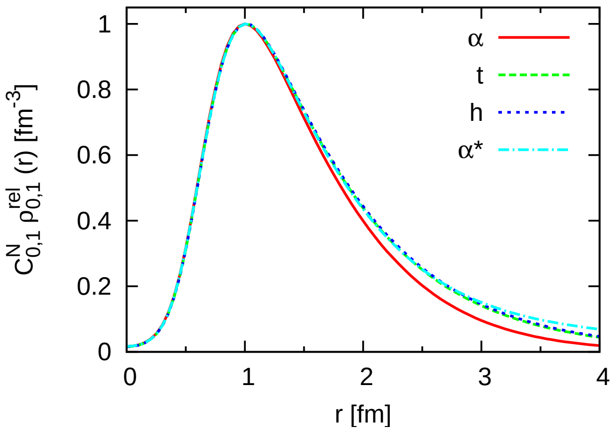
- non-uniform initial densities; modified by inclusion of NN correlations
- spectators ○ and ○ (ZDCs, centrality)
- reaction (RP), event (EP) plane
- moments of participant matter distribution ● and ●

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

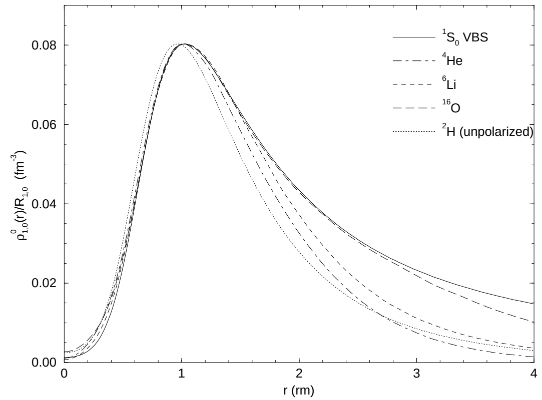
- dispersion of the moments: $\Delta\epsilon_n = \sqrt{\frac{\sum(\epsilon_n^i - \langle\epsilon_i\rangle)^2}{N}}$
- NN int. probability: $P(b_{ij}) = 1 - \left|1 - \Gamma(b_{ij})\right|^2$; $\quad \Gamma(b_{ij}) = \frac{\sigma_{NN}^{tot}}{4\pi B} e^{-b_{ij}^2/2B}$
- *fluctuations of NN cross sections (second part)*

1.b - Correlations signatures in two-body densities

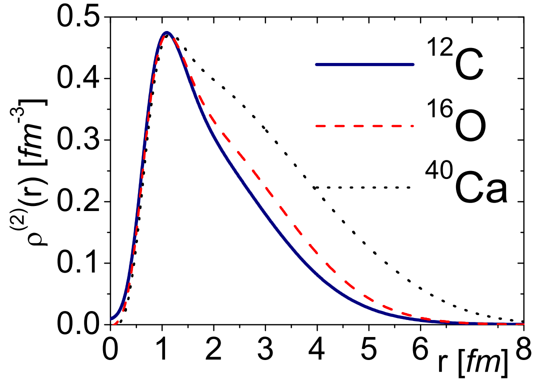
- ***Ab-initio*** two-body densities: $\rho(r) = \int d\boldsymbol{R}\, \rho^{(2)}\Big(\boldsymbol{r} = \boldsymbol{r}_1 - \boldsymbol{r}_2, \boldsymbol{R} = (\boldsymbol{r}_1 + \boldsymbol{r}_2)/2\Big)$



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

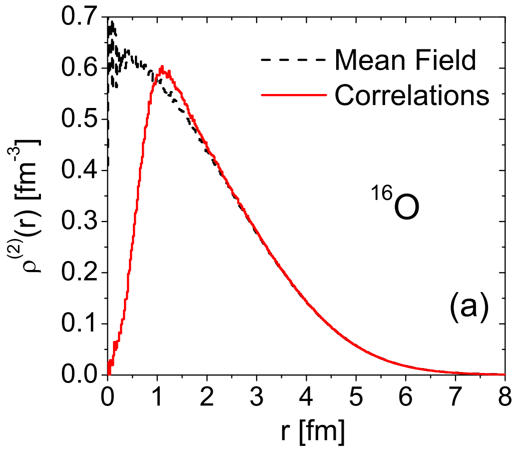


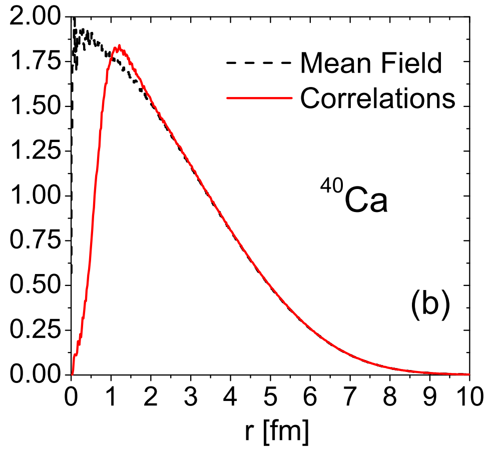
Forest *et al*,
Phys. Rev. **C54** (1996) 646-667

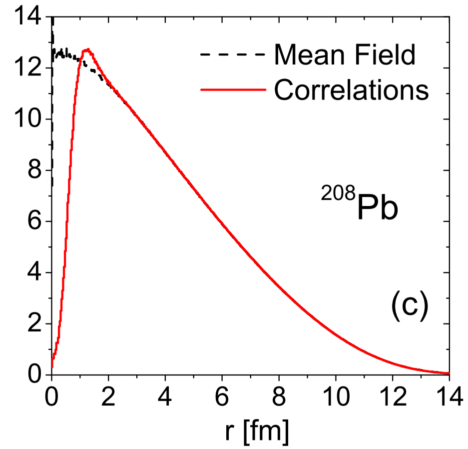


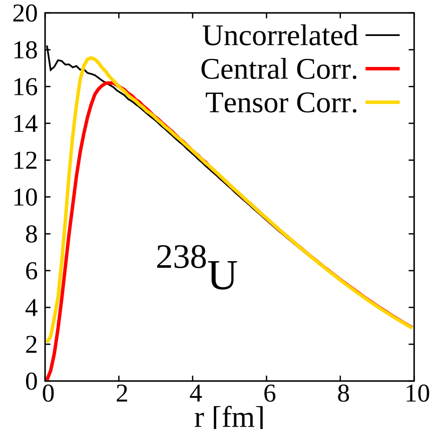
Alvioli *et al*, Phys. Rev. **C72**;
Phys. Rev. Lett. **100** (2008)

- ***MC algorithm***









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

2.a - Glauber-Gribov: probability of N interactions

in the Gribov-Glauber model we have, for the diffraction cross section:

$$\sigma_{in}^{hA} = \int d\boldsymbol{b} \left[1 - (1 - x)^A\right] = \sum_{N_{coll}=1}^{A} \frac{(-1)^{N_{coll}+1} A!}{(A - N_{coll})!\, N_{coll}!} \int d\boldsymbol{b} x^{N_{coll}} ,$$

where $x = \frac{1}{A} \sigma_{in}^{hN} T(b)$, $\int d\boldsymbol{b}\, T(b)$

and we can rewrite

$$\sigma_{in}^{hA} = \sum_{N_{coll}=1}^{A} \sigma_{N_{coll}} , \qquad \frac{A!}{(A - N_{coll})!\, N_{coll}!} \int d\boldsymbol{b} x^{N_{coll}} (1 - x)^{A-N_{coll}}$$

hence the probability of collisions with N_{coll} nucleons and $< N_{coll} >$ are:

$$P_{N_{coll}} = \frac{\sigma_{N_{coll}}}{\sigma_{in}^{hA}} , \qquad < N_{coll} > = \sum_{N_{coll}}^{A} N_{coll} \frac{\sigma_{N_{coll}}}{\sigma_{in}^{hA}} = A \frac{\sigma_{in}}{\sigma_{in}^{hA}}$$

L. Bertocchi, D. Treleani, J. Phys. ***G 3*** *(1977)*

2.a - Color fluctuations: probability of N interactions

we use the distribution $P(\sigma)$ to implement Gribov-Glauber in Monte Carlo:

$$\sigma_{in}^{hA} = \int d\sigma_{in}\, P(\sigma_{in}) \int d\boldsymbol{b} \left[1 - (1 - x)^A\right]$$

where

$$x = \frac{1}{A}\sigma_{in}^{hN}\, T(b)\,, \qquad \int d\boldsymbol{b}\, T(b)$$

and

$$\sigma_{N_{coll}} = \int d\sigma_{in}\, P(\sigma_{in}) \frac{A!}{(A - N_{coll})!\, N_{coll}!} \int d\boldsymbol{b} x^{N_{coll}}\, (1 - x)^{A - N_{coll}}$$

and we have for the probability of collisions with N_{coll} nucleons:

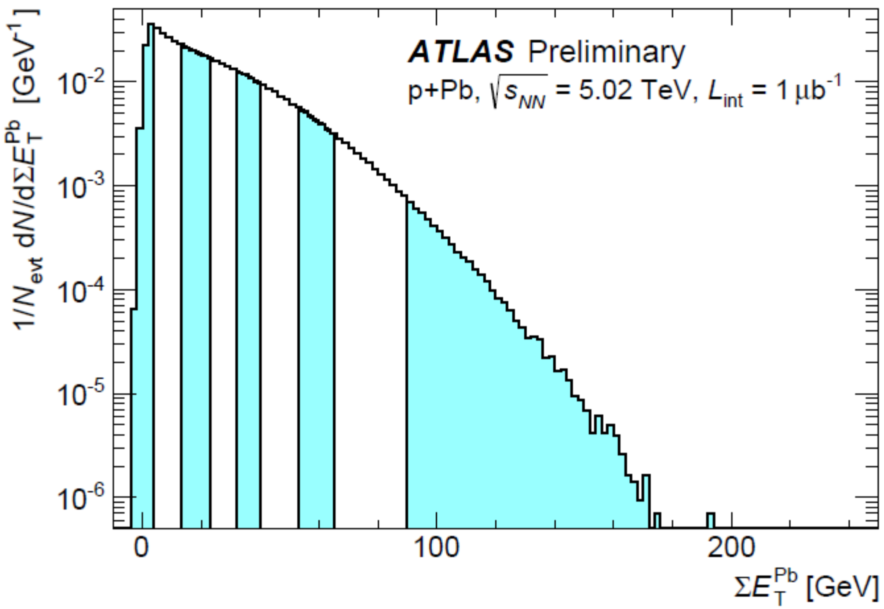
$$P_{N_{coll}} = \frac{\sigma_{N_{coll}}}{\sigma_{in}^{hA}}$$

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

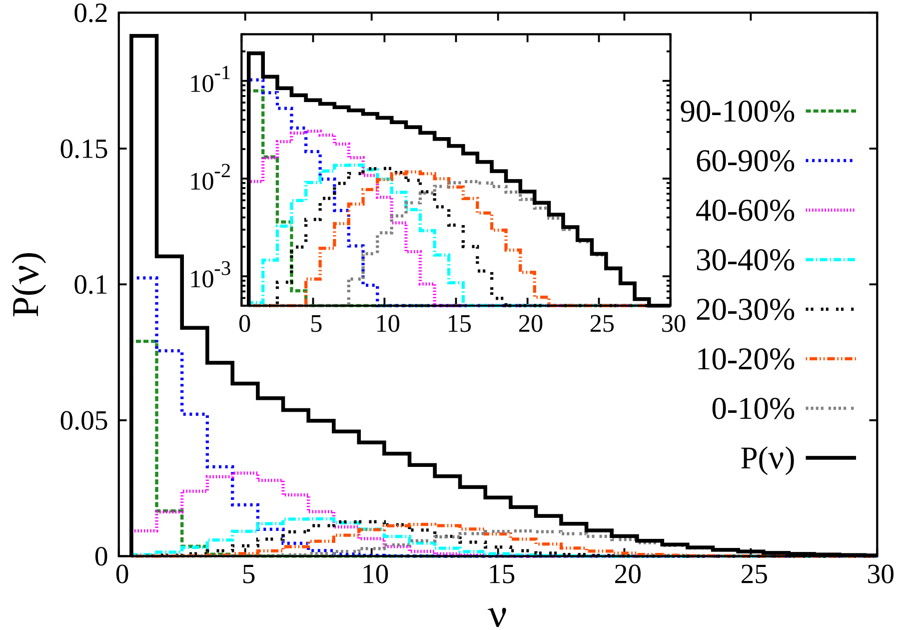
Heiselberg, Baym, Blattel, Frankfurt, Strikman, Phys.rev.Lett. ***70*** *(1993)*

2.a - Color Fluctuations: 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 ($\nu = N_{coll}$)

PHYSICAL REVIEW C **85**, 034902 (2012)

Initial-state anisotropies and their uncertainties in ultrarelativistic heavy-ion collisions from the Monte Carlo Glauber model

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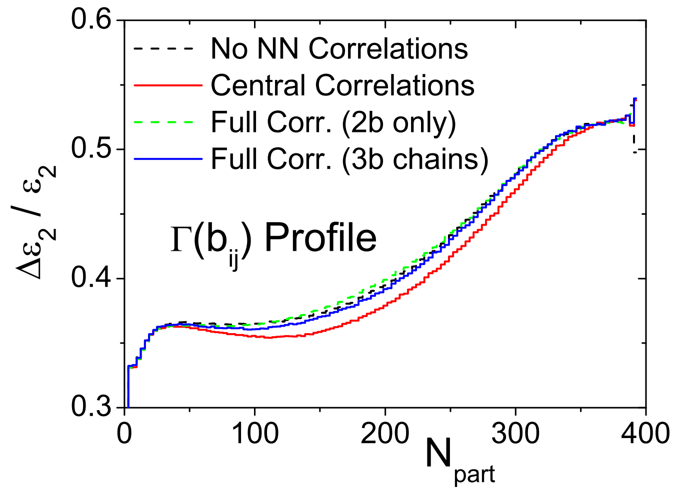
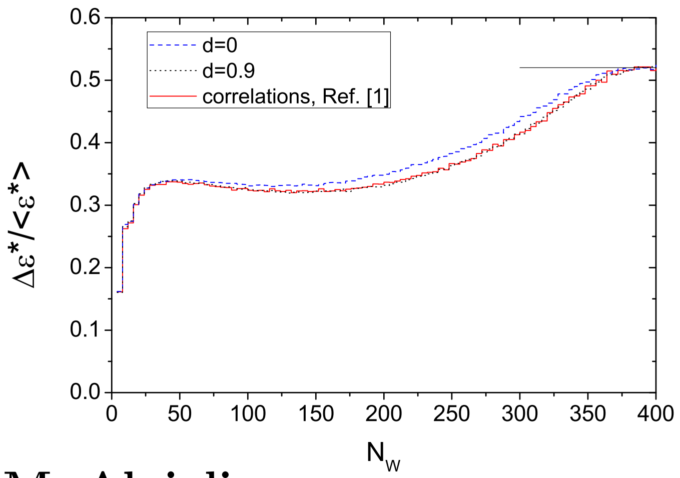
[4]*Frankfurt Institute for Advanced Studies, Ruth-Moufang-Strasse 1, D-60438 Frankfurt am Main, Germany*
[5]*The Pennsylvania State University, 104 Davey Lab, University Park, Pennsylvania 16803, USA*
(Received 28 December 2011; published 7 March 2012)

In hydrodynamical modeling of heavy-ion collisions, the initial-state spatial anisotropies are translated into momentum anisotropies of the final-state particle distributions. Thus, understanding the origin of the initial-state anisotropies and their uncertainties is important before extracting specific QCD matter properties, such as viscosity, from the experimental data. In this work we review the wounded nucleon approach based on the Monte Carlo Glauber model, charting in particular the uncertainties arising from modeling of the nucleon-nucleon interactions between the colliding nucleon pairs and nucleon-nucleon correlations inside the colliding nuclei. We discuss the differences between the black disk model and a probabilistic profile function approach for the inelastic nucleon-nucleon interactions and investigate the i
state-of-the-art modeling of these.

DOI: 10.1103/PhysRevC.85.034902 PACS





PHYSICAL REVIEW C **81**, 064909 (2010)

Two-body nucleon-nucleon correlations in Glauber models of relativistic heavy-ion collisions

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(Received 4 March 2010; revised manuscript received 6 June 2010; published 28 June 2010)

We investigate the influence of the central two-body nucleon-nucleon correlations on several quantities observed in relativistic heavy-ion collisions. It is demonstrated with explicit Monte Carlo simulations that the basic correlation measures observed in relativistic heavy-ion collisions, such as the fluctuations of participant eccentricity, initial size fluctuations, or the fluctuations of the number of sources producing particles, are all sensitive to the inclusion of the two-body correlations. The effect is at the level of about 10–20%. Moreover, the realistic (Gaussian) correlation function gives indistinguishable results from the hard-core repulsion, with the expulsion distance set to 0.9 fm. Thus, we verify that for investigations of the considered correlation measures, it is sufficient to use the Monte Carlo generators accounting for the hard-core repulsion.

DOI: 10.1103/PhysRevC.81.064909 PACS number(s): 25.75.Dw, 25.75.Ld

Computer Physics Communications 185 (2014) 1759–1772

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GLISSANDO 2: GLauber Initial-State Simulation AND mOre…, ver. 2[☆,☆☆]

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SPS

ABSTRACT

We present an extended version of GLISSANDO, a Monte-Carlo generator for Glauber-like models of the
initial stage of relativistic heavy-io
parametrization of shape of nuclei,
deformation, a possibility of using c
an option of overlaying distributio
inclusion of the core–corona effect,
event hydrodynamics. Together wi
models, or the implementation of a
tical approach to describe the early
used in modeling the intermediate
with the ROOT platform. The suppl
such as the multiplicity distributio
correlations, forward–backward co
deuteron–nucleus collisions.

PHYSICAL REVIEW C **90**, 034906 (2014)

Correlations in the Monte Carlo Glauber model

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[2] *The H. Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, PL-31342 Kraków, Poland*
[3] *Institute of Physics, Jan Kochanowski University, PL-25406 Kielce, Poland*

(Received 15 May 2014; revised manuscript received 22 August 2014; published 10 September 2014)

Event-by-event fluctuations of observables are often modeled using the Monte Carlo Glauber model, in which the energy is initially deposited in sources associated with wounded nucleons. In this paper, we analyze in detail the correlations between these sources in proton-nucleus and nucleus-nucleus collisions. There are correlations arising from nucleon-nucleon correlations within each nucleus, and correlations due to the collision mechanism, which we dub twin correlations. We investigate this new phenomenon in detail. At the Brookhaven Relativistic Heavy Ion Collider and CERN Large Hadron Collider energies, correlations are found to have modest effects on size and eccentricity fluctuations, such that the Glauber model produces to a good approximation a collection of independent sources.

DOI: 10.1103/PhysRevC.90.034906 PACS number(s): 25.75.Gz, 25.75.Ld

Effect of initial-state nucleon-nucleon correlations on collective flow in ultra-central heavy-ion collisions

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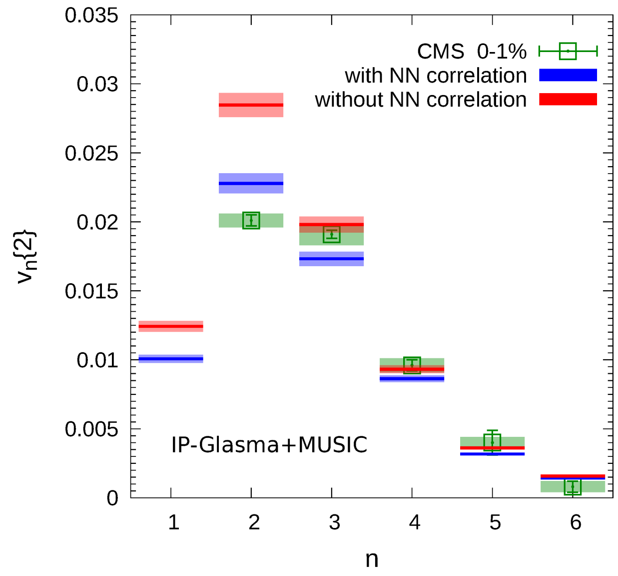
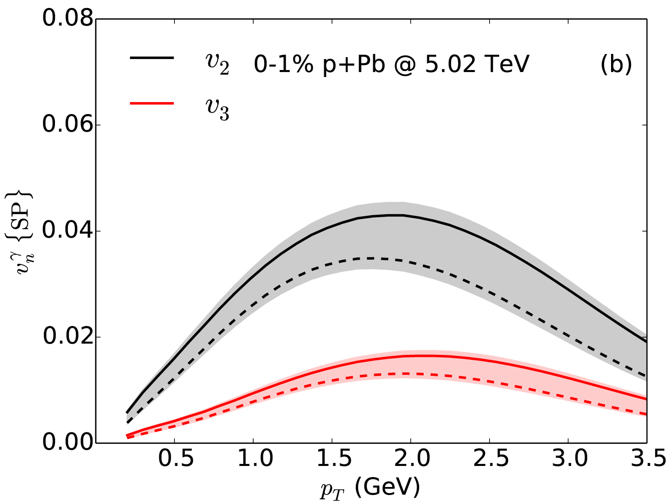
[c] *Physics Department, Bldg. 510A, Brookhaven National Laboratory, Upton, NY-11973, USA*

We investigate the effect of nucleon-nucleon correlations on the initial condition of ultra-central heavy ion collisions at LHC energies. We calculate the eccentricities of the MC-Glauber and IP-Glasma models in the 0–1% centrality class and show that they are considerably affected by the inclusion of such type of correlations. For an IP-Glasma initial condition, we further demonstrate that this effect survives the fluid-dynamical evolution of the system and can be observed in its final state azimuthal momentum anisotropy.

PACS numbers:





Thermal photon radiation in high multiplicity p+Pb collisions at the Large Hadron Collider

C. Shen, J.-F. Paquet, G. S. Denicol, S. Jeon, and C. Gale
Department of Physics, McGill University, 3600 University Street, Montreal, QC, H3A 2T8, Canada

The collective behaviour of hadronic particles has been observed in high multiplicity proton-lead collisions at the Large Hadron Collider (LHC), as well as in deuteron-gold collisions at the Relativistic Heavy-Ion Collider (RHIC). In this work we present the first calculation, in the hydrodynamic framework, of thermal photon radiation from such small collision systems. Owing to their compact size, these systems can reach temperatures comparable to those in central nucleus-nucleus collisions. The thermal photons can thus shine over the prompt background, and increase the low p_T direct photon spectrum by a factor of 2-3 in 0-1% p+Pb collisions at 5.02 TeV. This thermal photon enhancement can therefore serve as a clean signature of the existence of a hot quark-gluon plasma during the evolution of these small collision systems, as well as validate hydrodynamic behavior in small systems.

Shape and flow fluctuations in ultra-central Pb+Pb collisions at the LHC

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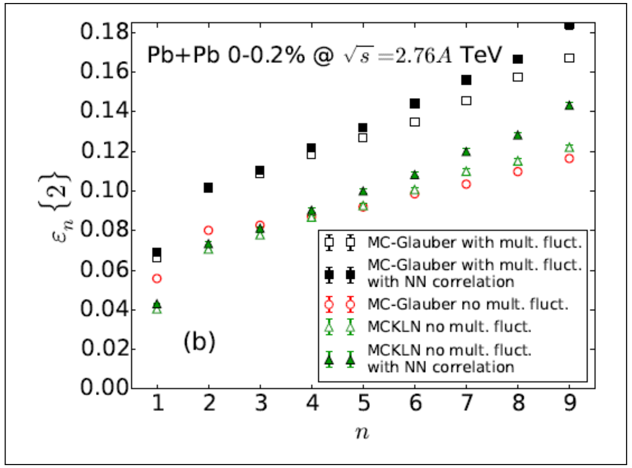
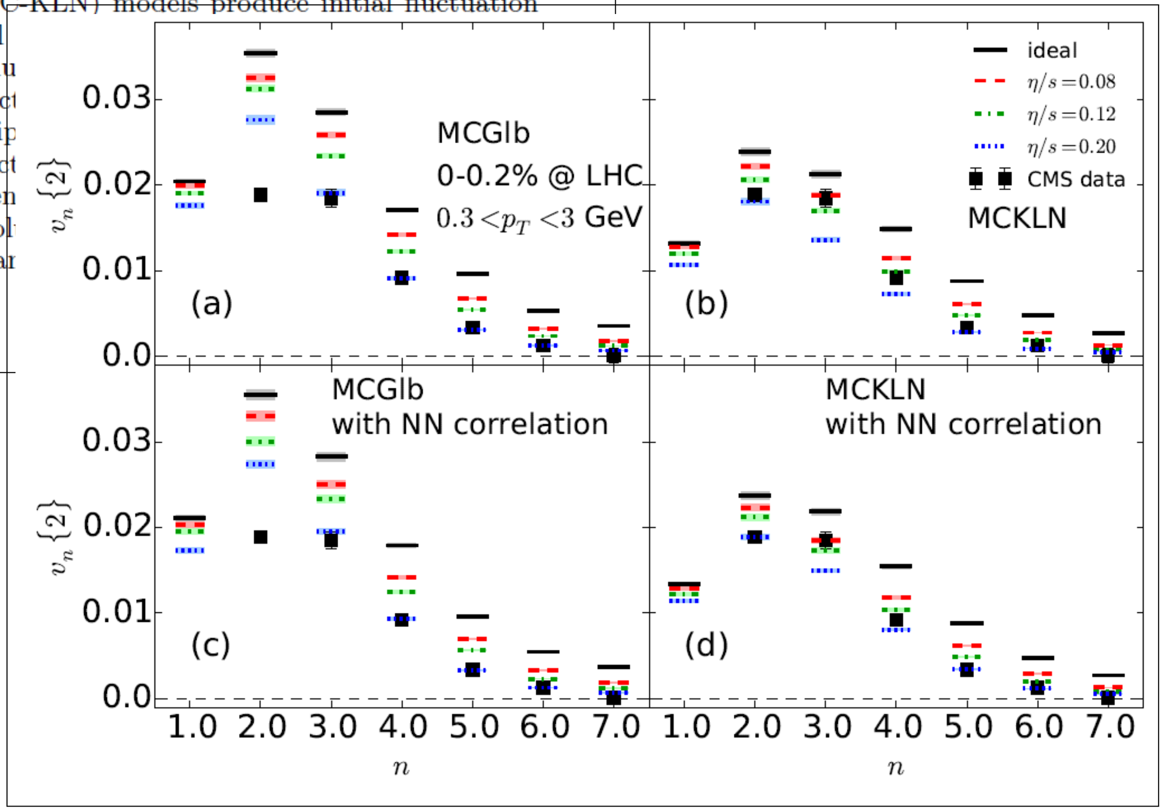
[2] *Department of Physics, McGill University, 3600 University Street, Montreal, QC, H3A 2T8, Canada*

(Dated: June 18, 2015)

In ultra-central heavy-ion collisions, anisotropic hydrodynamic flow is generated by density fluctuations in the initial state rather than by geometric overlap effects. For a given centrality class, the initial fluctuation spectrum is sensitive to the method chosen for binning the events into centrality classes. We show that sorting events by total *initial* entropy or by total *final* multiplicity yields event classes with equivalent statistical fluctuation properties, in spite of viscous entropy production during the fireball evolution. With this initial entropy-based centrality definition we generate several classes of ultra-central Pb+Pb collisions at LHC energies and evolve the events using viscous hydrodynamics with non-zero shear but vanishing bulk viscosity. Comparing the predicted anisotropic flow coefficients for charged hadrons with CMS data we find that both the Monte Carlo Glauber (MC-Glb) and Monte Carlo Kharzeev-Levin-Nardi (MC-KLN) models produce initial fluctuation spectra that are incompatible with the measured final
choice of the specific shear viscosity. In spite of this failu
can qualitatively explain, in terms of event-by-event fluct
and flow angles, the breaking of flow factorization for ellip
sured by the CMS experiment. For elliptic flow, this fact
collisions. We conclude that the bulk of the experimen
effects are qualitatively explained by hydrodynamic evol
their quantitative description requires a better understar

PACS numbers: 25.75.-q, 12.38.Mh, 25.75.Ld, 24.10.Nz





An effective model for entropy deposition in high-energy pp, pA, and AA collisions

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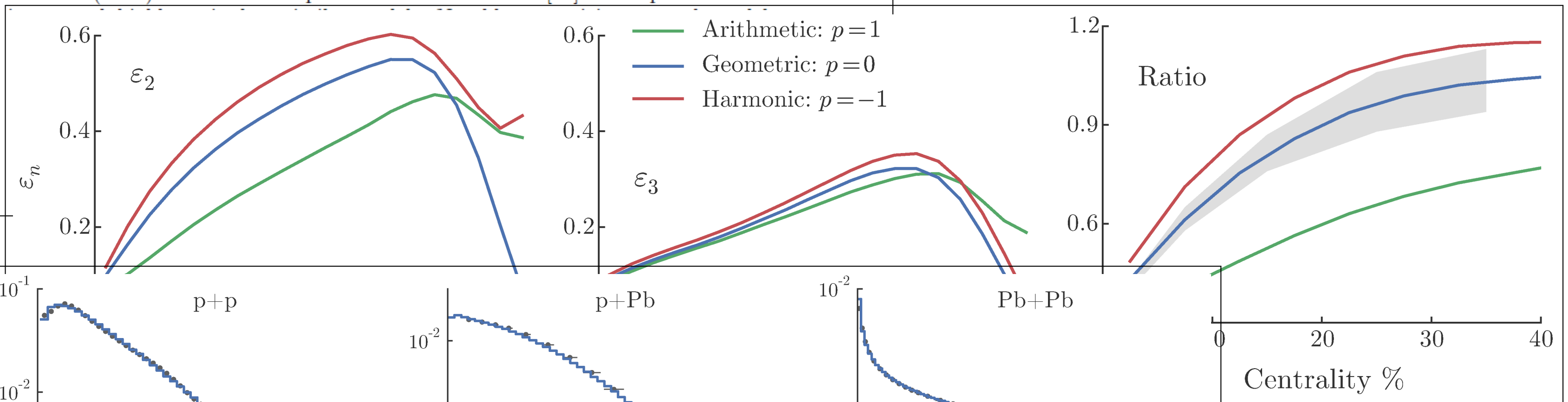
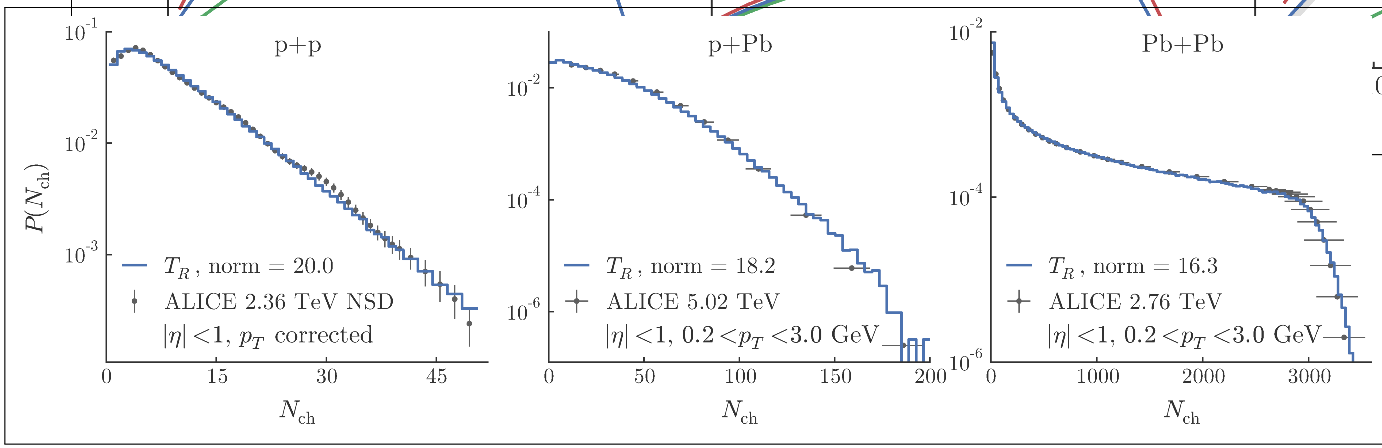
Department of Physics, Duke University, Durham, NC 27708-0305
(Dated: December 16, 2014)

We introduce TRENTo, a new initial condition model for high-energy nuclear collisions based on eikonal entropy deposition via a "reduced thickness" function. The model simultaneously predicts the shapes of experimental proton-proton, proton-nucleus, and nucleus-nucleus multiplicity distributions, and generates nucleus-nucleus eccentricity harmonics consistent with experimental flow constraints. In addition, the model provides a possible resolution to the "knee" puzzle in ultra-central uranium-uranium collisions.

Over the last decade, the ultra-relativistic heavy-ion collision programs at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) have suc-

ticipant and binary nucleon-nucleon collision. Despite its simplicity, the Glauber model has qualitatively fit many experimental measurements [27] and inspired a number of





Wounded quarks in A+A, p+A, and p+p collisions

Piotr Bożek,[1,*] Wojciech Broniowski,[2,3,†] and Maciej Rybczyński[3,‡]

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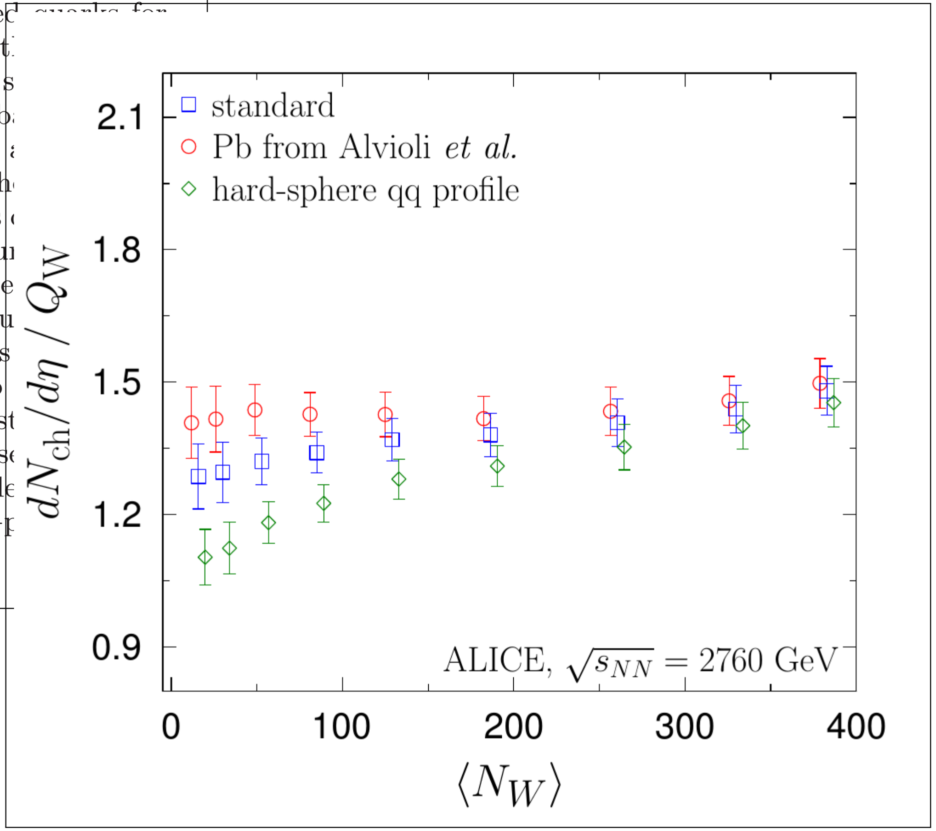
[2] *The H. Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, 31-342 Cracow, Poland*
[3] *Institute of Physics, Jan Kochanowski University, 25-406 Kielce, Poland*

(Dated: ver. 2, 3 May 2016)

We explore predictions of the wounded quark model for particle production and properties of the initial state formed in ultrarelativistic heavy-ion collisions. The approach is applied uniformly to A+A collisions in a wide collision energy range, as well as for p+A and p+p collisions at the CERN Large Hadron Collider (LHC). We find that generically the predictions from wounded such features as eccentricities or initial sizes are close (within 15%) to predictions of t nucleon model with an amended binary component. A larger difference is found for the s system, where the wounded quark model yields a smaller (more compact) initial fireb standard wounded nucleon model. The inclusion of subnucleonic degrees of freedom analyze p+p collisions in an analogous way, with predictions that can be used in furth evolution. The approximate linear dependence of particle production in A+A collisions ber of wounded quarks, as found in previous studies, makes the approach based on wou natural. Importantly, at the LHC energies we find approximate uniformity in particle from wounded quarks, where at a given collision energy per nucleon pair similar produ tial entropy per source is needed to explain the particle production from p+p collisions collisions. We also discuss the sensitivity of the wounded quark model predictions to of quarks in nucleons, distribution of nucleons in nuclei, and to the quark-quark inelast in the impact parameter. In our procedure, the quark-quark inelasticity profile is chos way that the experiment-based parametrization of the proton-proton inelasticity profile reproduced. The parameters of the overlaid multiplicity distribution is fixed from p+p data.




SMASH: A new transport approach for FAIR energies
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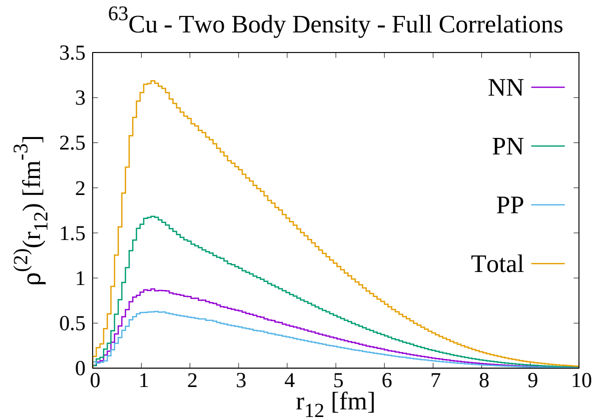
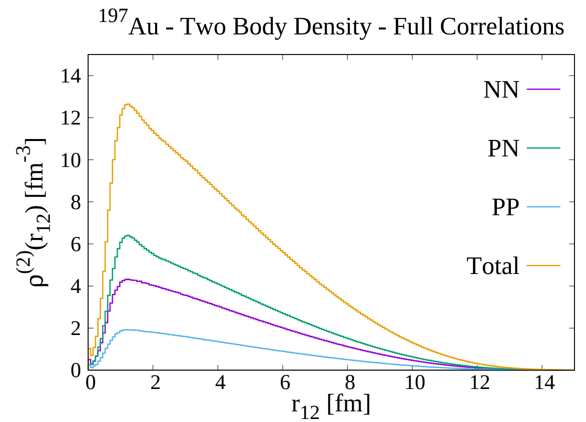
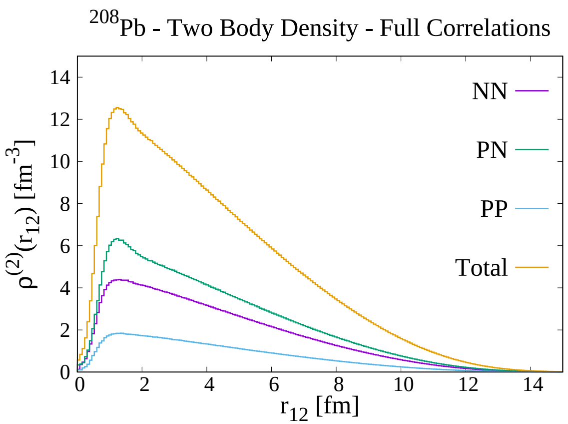
in collaboration with V. Steinberg and H. Petersen
J. Weil et al., Phys.Rev. C94 (2016) no.5, 054905
DO, Hannah Petersen, J.Phys. G44 (2017) no.3, 034001
HELMHOLTZ ASSOCIATION
HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research
HIC for FAIR
Helmholtz International Center


63Cu - Two Body Density - Full Correlations
ρ(2)(r12) [fm-3]
r12 [fm]
NN
PN
PP
Total


197Au - Two Body Density - Full Correlations
ρ(2)(r12) [fm-3]
r12 [fm]
NN
PN
PP
Total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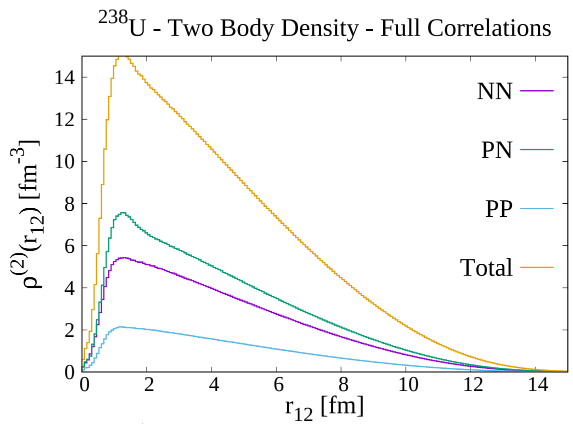
ρ(2)(r12) [fm-3]
r12 [fm]
NN
PN
PP
Total


238U - Two Body Density - Full Correlations
ρ(2)(r12) [fm-3]
r12 [fm]
NN
PN
PP
Total