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 strength 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 $\rightarrow$ frozen approximation; straight line trajectories

Inputs:
- (charge) densities of nuclei
- energy-dependent Nucleon-Nucleon (NN) cross sections

for given energy and AA impact parameter $b$:

$\rightarrow$ interacting

$\rightarrow$ spectators

$\rightarrow$ elastically scattered

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CERN, July ’16
1.a - Glauber: semi-analytic description

- continuous density distributions of nuclei, $\rho(\mathbf{r}); \mathbf{r} = (b, z)$
- probability of $n$ binary collisions in AA using binomial distribution and thickness functions $T_A(b) = \int dz \rho(b, z)$, $T_{AA}(b) = \int ds T_A(s) T_A(b - s)$:
  \[ P_n(b) = \binom{A^2}{n} \left[ T_{AA}(b) \sigma_{NN}^{in} \right]^n \left[ 1 - T_{AA}(b) \sigma_{NN}^{in} \right]^{A^2-n} \]
- e.g., total AA inelastic cross section requires multidimensional integrations:
  \[ \sigma_{AA}^{in} = \int db \int \prod_i^{A \times A} ds_i T_A(s_i) \left\{ 1 - \prod_j^A \prod_k^A \sigma(b - s_j + s_k) \right\} \]
- optical limit: assuming uncorrelated scattering centers, $A \times A$ integrations over transverse coordinates are reduced to one integration:
  \[ \sigma_{AA}^{in, opt} = \int db \left\{ 1 - \left[ 1 - \sigma_{NN}^{in} T_{AA}(b) \right]^{A^2} \right\} \]
- 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 $N_{\text{part}}$ and $N_{\text{coll}}$, not directly measurable, but contain information about the *fluctuating collision geometry*.

$\rightarrow N_{\text{part}}, N_{\text{coll}}$ experimentally related to charged particle multiplicity
$\rightarrow Spectator$ 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

We focus on fluctuations due to:

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

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

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.
1.c - Fluctuations of the geometry of participant matter

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

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

\[ \Delta \epsilon_n = \sqrt{\frac{\sum (\epsilon_i^n - \langle \epsilon_i \rangle)^2}{N}} \]

→ participant nucleons ● in transverse plane
1.c - Latest updates of nuclear configurations - I

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

$$
\rho(r) = \frac{\rho_0}{1 + e^{(r-R_0)/a}} \quad \rightarrow \quad \rho(r, \theta) = \frac{\rho_0}{1 + e^{(r-R_0-R_0\beta_2Y_{20}(\theta)-R_0\beta_4Y_{40}(\theta))/a}}
$$

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

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

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

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

![Graphs showing effect of correlations deformation on dispersions of moments](image)
**Neutron skin** – p/n profiles for $^{208}\text{Pb}$:

$$
\rho(r) = \frac{\rho_0^{(p,n)}}{1 + e^{(r-R_0^{p,n})/\alpha^{p,n}}}
$$

$$(\rho_0^p, R_0^p, \alpha_0^p) = ("82", 6.680 \text{ fm}, 0.447 \text{ fm})$$

$$(\rho_0^n, R_0^n, \alpha_0^n) = ("126", 6.700 \text{ fm}, 0.550 \text{ fm})$$


- additional tool for determination of centrality:

$$(P_{p}(b) / P_{n}(b))_{\text{corr}}$$

H. Paukkunen, PLB745 (2015)

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

\[
\langle V \rangle_{pN} = \sum_{i<j} V_{ij} = \sum_j \int d\mathbf{r}_{12} \, v_{pN}^{(j)}(r_{12}) \, \rho_{pN}^{(2)(j)}(r_{12})
\]

\[
\langle V \rangle_{pp} = \langle V \rangle_{nn}
\]

\begin{center}
\begin{tabular}{c|c|c}
$A$ & $\langle V \rangle_{pp} (= \langle V \rangle_{nn})$ & $\langle V \rangle_{pn}$ \\
\hline
16 & 8\% & 83\% \\
40 & 9\% & 82\% \\
\end{tabular}
\end{center}

removed nucleons $\rightarrow$ disrupted pairs $\rightarrow$ potential energy \textit{freed}

\begin{center}
\textbf{mostly } pn \textbf{ pairs}
\end{center}

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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

$0 \leq b \leq 16 \text{ fm}$

energy transfer
localized on the interaction surface!
• cannot directly transform \textit{potential} to \textit{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

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

- protons
- neutrons
- high-momentum nucleons

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1.d - High-momentum nucleons: asymmetry

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

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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,

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 states as in pN diffraction; relevant at high energies (\(E_{\text{inc}} \gg 10\) GeV).

X is a set of intermediate states that stay frozen during \(pA\) interaction.
2.a - NN interaction with frozen configurations

- at sufficiently high energy, i.e. when the relation
  \[ 2R < 2p_{lab}/(M^2 - m^2) \]
  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 $\rightarrow$ different cross sections $\rightarrow$ relation with color transparency/opacity phenomena


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

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

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

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

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

proposed by


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

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

\[ P_N(b) \]

- we find enhancement of the probability of events with large $N = N_{\text{coll}}$

2.a - Color Fluctuations: probability of $N$ interactions

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

- $P_N = \int db \, P_N(b); \, N = N_{\text{coll}}$

2.a - Color Fluctuations: $N_{\text{coll}}$ and $b$ dependence (Dennis’ talk)

- We use ATLAS (ATLAS-CONF-2013-096) model for $\Delta E_T$ in $pp$ collisions with a convolution to obtain the $pA$ model.

ATLAS Preliminary

\[ p+Pb, \sqrt{s_{NN}} = 5.02 \text{ TeV}, L_{\text{int}} = 1 \mu \text{b}^{-1} \]

\[
\begin{align*}
1/N_{\text{evt}} & dN/d\Delta E_T^\text{Pb} [\text{GeV}] \\
\end{align*}
\]

\[
\begin{align*}
0 & \quad 10^{-2} \\
10^{-3} & \quad 10^{-4} \\
10^{-5} & \quad 10^{-6} \\

\sum E_T^\text{Pb} [\text{GeV}] & \\
\end{align*}
\]

\[
\begin{align*}
0 & \quad 10^{-3} \\
5 & \quad 10^{-2} \\
10 & \quad 10^{-1} \\
15 & \quad 0 \\
20 & \quad 0.05 \\
25 & \quad 0.1 \\
30 & \quad 0.15 \\
\end{align*}
\]

\[
\begin{align*}
\nu & \\
0-10\% & \\
10-20\% & \\
20-30\% & \\
30-40\% & \\
40-60\% & \\
60-90\% & \\
90-100\% & \\
P(\nu) & \\
10^{-3} & \\
10^{-2} & \\
10^{-1} & \\
0 & 5 & 10 & 15 & 20 & 25 & 30 & \\
\end{align*}
\]

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

- ATLAS and CMS found deviations from the Glauber model ($N_{\text{coll}}$ tail)
- We derive a non-trivial relation between bins in $\Delta E_T$ and $N_{\text{coll}}$ and thus determine $P(N_{\text{coll}})$ dependence on centrality ($\nu = N_{\text{coll}}$)
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 \( \nu = N_{\text{coll}} \)
- The hard event (HT) is triggered in a probabilistic way, using the gluon distributions in the transverse plane \( F_g(\rho) = \exp\left(-\frac{\rho^2}{B^2}\right)/\pi B^2 \)
- We have coupled the MCG average (\( < \ldots > \)) for the N-1 soft interactions with 2-d integral over the position of the hard scattering

\[
\rho_i = b + \rho - b_i
\]

2.b - Hard interaction vs. soft interaction ranges

- Probability of interaction:

\[ s^{1/2} = 14000 \text{ GeV} \]
\[ s^{1/2} = 500 \text{ GeV} \]

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

\[
p_j = \frac{F_g(b + \rho - b_j)}{\sum_{k=1}^{A} F_g(b + \rho - b_k)}, \quad \rho_j = b + \rho - b_j
\]

\[
\text{Rate}(N_{\text{coll}}) = \langle \sigma_{HT} \int d\mathbf{b} d\mathbf{\rho} \prod_{i=1}^{A} d\rho_i F_g(\rho) \sum_{i=1}^{A} F_g(\rho_i) p_{\text{hard}}(N_{\text{coll}}) \rangle
\]

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

\[
N_{\text{coll}} = N_{\text{coll}}(\text{other}) + 1,
\]

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

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


Alvioli, Frankfurt, Perepelitsa, Strikman, in progress

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

\[ P(\nu) \]

Alvioli, Frankfurt, Perepelitsa, Strikman, in progress

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

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We have developed a model to characterize events with one hard scattering and the remaining soft scatterings, as a function of $\nu = N_{\text{coll}}$.

The hard event (HT) is triggered in a probabilistic way.

We have coupled the MCG average ($\langle \ldots \rangle$) 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.

$$\rho_i = b + \rho - b_i$$

**M. Alvioli, L. Frankfurt, D. Perepelitsa, M. Strikman, *in progress***
The nucleon interacts with a smaller-than-average cross section

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


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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 \( \sigma_{NN} \), \( P(\sigma_{NN}) \)
  → *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*