Spectator matter in collisions of relativistic deformed nuclei

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Introduction

- The studies of collisions of relativistic nuclei at RHIC[1)] and at the LHC[2)] demonstrated the presence of the deconfined state of quarks and gluons (QGP).
- In these studies it is very important to evaluate properly the initial energy density and geometry of the overlap zone of collision partners.
- It was shown that in collisions of deformed nuclei (^{238}U, ^{127}Xe)[3),4)] these initial conditions depend on initial orientation of these nuclei.
- It was proposed to use the number of spectator neutrons measured with neutron Zero Degree Calorimeters (ZDCs) as a variable sensitive to initial orientation of colliding nuclei. [5)]
- In our study we model the emission of spectator neutrons in collisions of deformed nuclei taken into account the fact that a part of neutrons in spectator matter remains bound in spectator fragments. We study various characteristics of spectator neutrons sensitive to nuclear deformation.

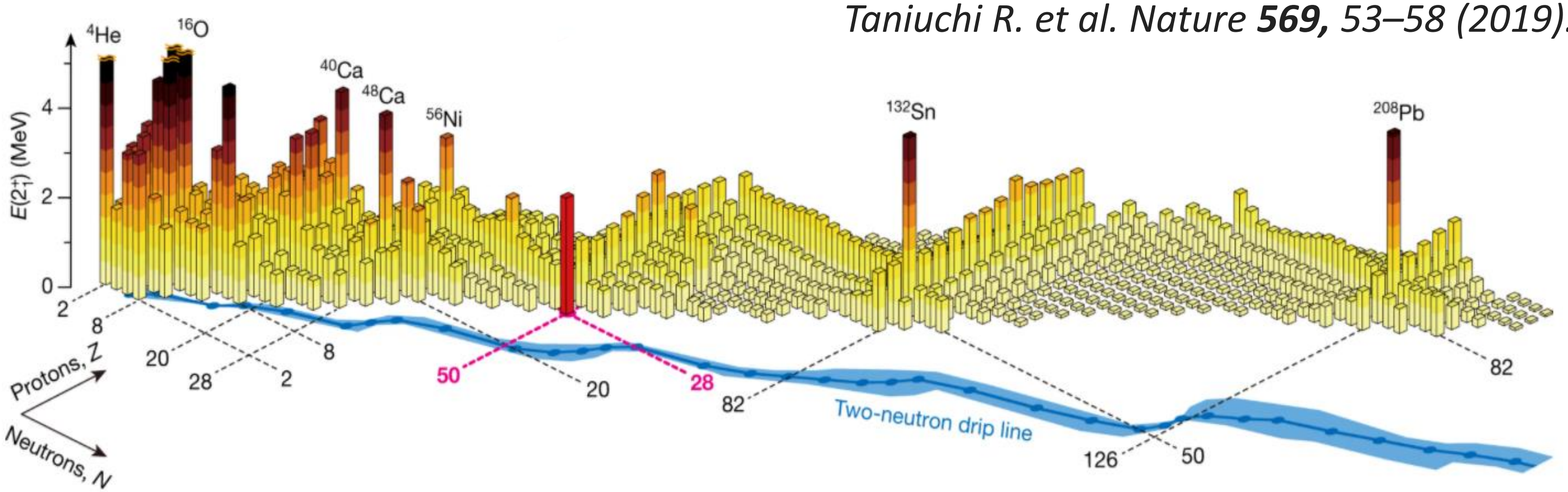
[1)] *STAR Collaboration, Phys. Rev. Lett.* ***115*** *, 222301 (2015)*
[2)] *ALICE Collaboration. Phys. Rev. Lett.* ***105,*** *252302 (2010)*
[3)] *Andy Goldschmidt et al. Phys. Rev. C* ***92****, 044903 (2015)*
[4)] *ALICE Collaboration. Phys. Rev. B,* ***784****, 82-95 (2018)*
[5)] *Sandeep Chatterjee and Prithwish Tribedy Phys. Rev. C* ***92****, 011902 (2015)*

Outline

- Parameters of deformed nuclei and their initial orientations in collisions: tip-body, body-body, tip-tip, side-side.
- Our model: AAMCC.
- Selection of ultracentral ($b \sim 0$) events with certain orientation.
- Initial eccentricity, neutron multiplicity and neutron asymmetry calculated for different orientations.
- Neutron multiplicity in tip-body collisions as a function of deformation parameter β_2.
- Eccentricity in body-body collisions as a function of β_2.

Deformed nuclei

Taniuchi R. et al. Nature ***569,*** *53–58 (2019).*



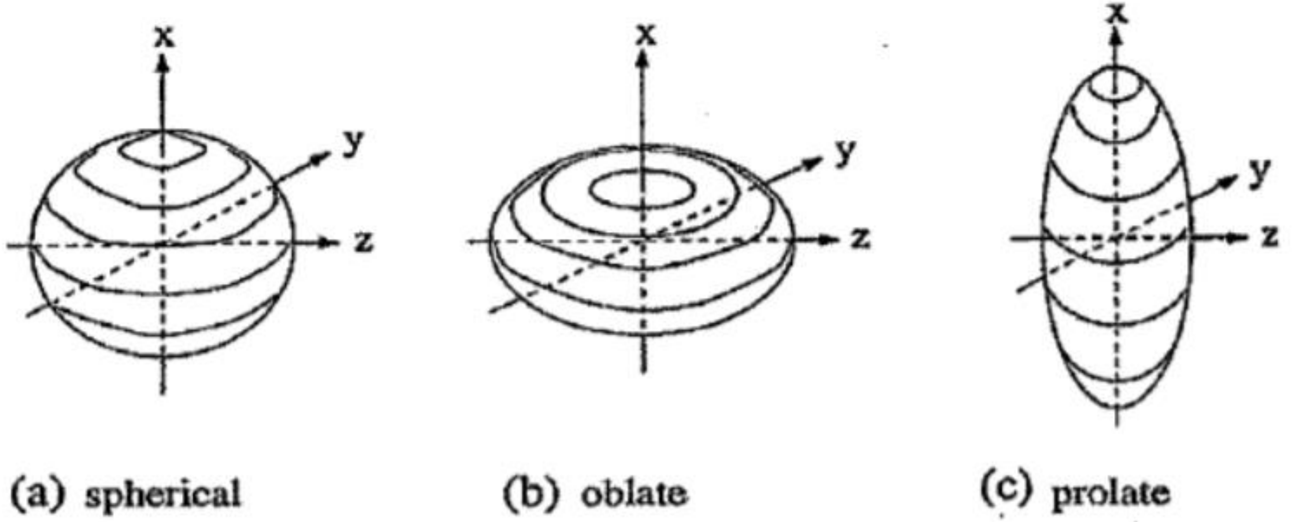
- Nuclei with fully filled nucleon levels has spherical shape. They are characterized by a large value of the energy of the first 2^+ level.

- Other nuclei are usually spherically asymmetric (deformed).

- Nucleon density distributions of such deformed nuclei can be described by the Woods-Saxon distribution using spherical functions:

$$\rho(x,y,z) = \frac{\rho_{0n,p}}{1+\exp\left[(r-R_{n,p}(1+\beta_2 Y_{20}+\beta_4 Y_{40}))/a_{n,p}\right]},$$

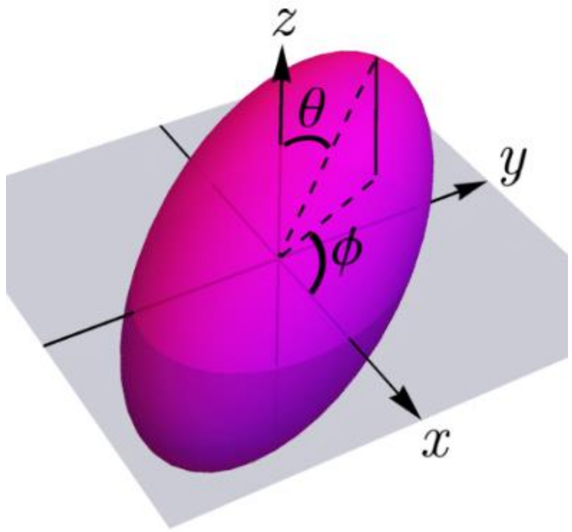
$$Y_{20} = \sqrt{\frac{5}{\pi}}\frac{2z^2-x^2-y^2}{4r^2}, \quad Y_{40} = \frac{3}{\sqrt{\pi}}\frac{35z^4-30z^2r^2+3r^4}{16r^4}$$

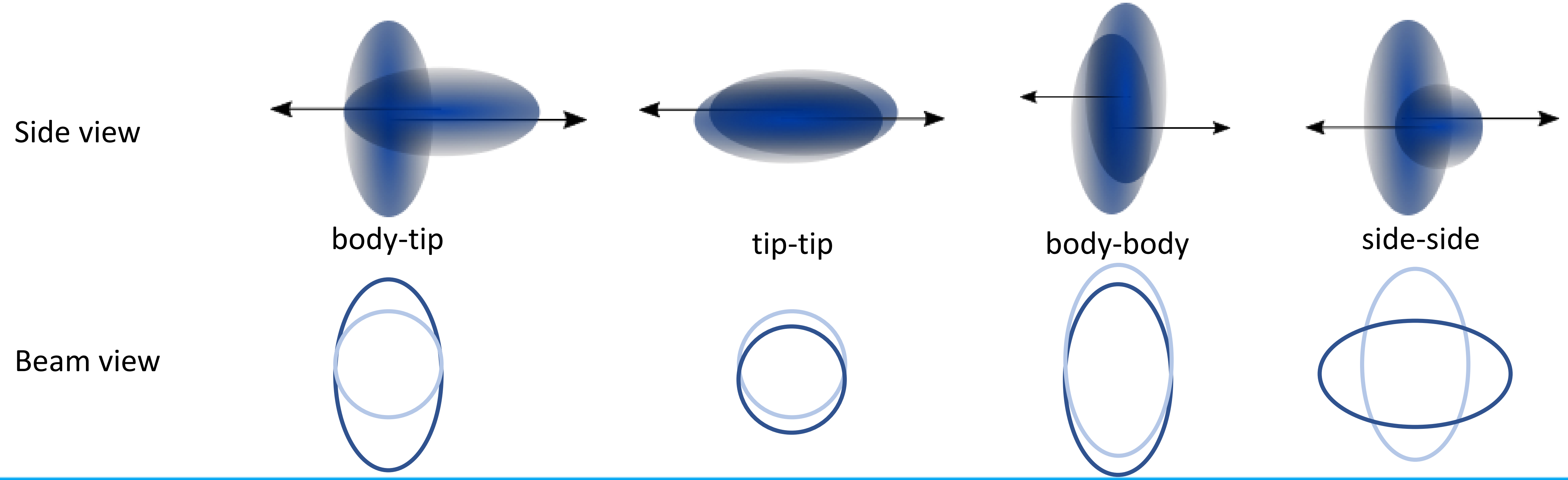


$\beta_2 = 0$ $\quad$ $\beta_2 < 0$ $\quad$ $\beta_2 > 0$

Collisions of relativistic deformed nuclei

- The shape of the fireball in collisions of relativistic deformed nuclei varies due to differences in relative orientation of the nuclei.
- This also causes the differences in the average energy density of a fireball and the changes in radial flow values (ex. v_2).
- Thus there is a need in selecting the events with specific relative orientation of colliding nuclei.

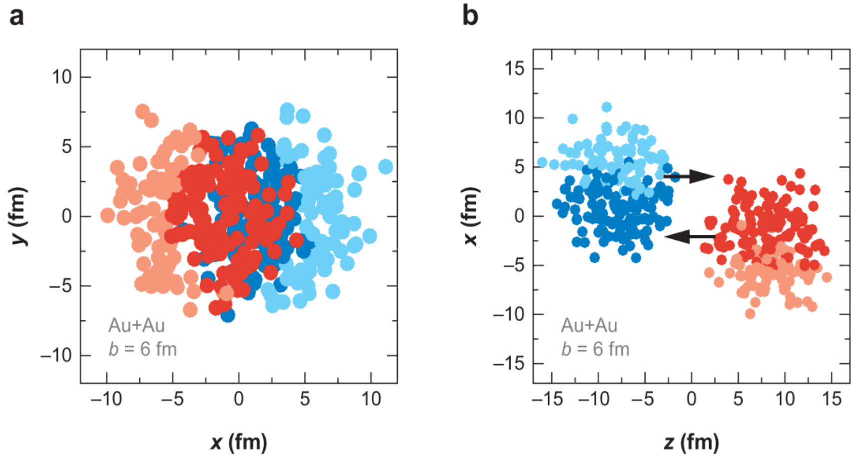




Abrasion-Ablation Monte Carlo for Colliders (AAMCC+MST)

1. Participant and spectator number calculation

Glauber Monte Carlo model



An example of a Monte Carlo simulation of an Au – Au collision. The darker circles represent the nucleons-partisipants, and the light ones refer to the prefragments.

*C. Loizides et al., Phys. Rev. C, **97**, 054910 (2018)*

2. Prefragment excitation

- Ericson's formula

$$\rho_{a_{Ericson}}(E) = \frac{g_0^a}{a!\,(a-1)!} E^{a-1}$$

*T. Ericson, Advances in Physics, **9**, 425–511 (1960)*

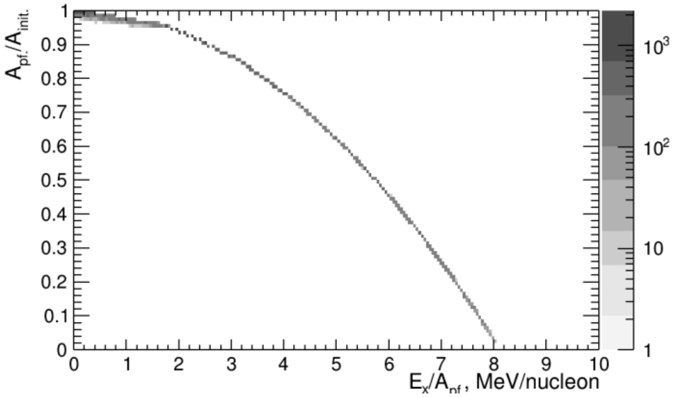
- ALADIN approximation

$$\frac{\langle A_{pf} \rangle}{A_1} = 1 - 0.001\left(\frac{E}{A_{pf}}\right) - 0.015\left(\frac{E}{A_{pf}}\right)^2$$

*A.S Botvina et al., Nucl. Phys. A, **584**, 737–756 (1995)*

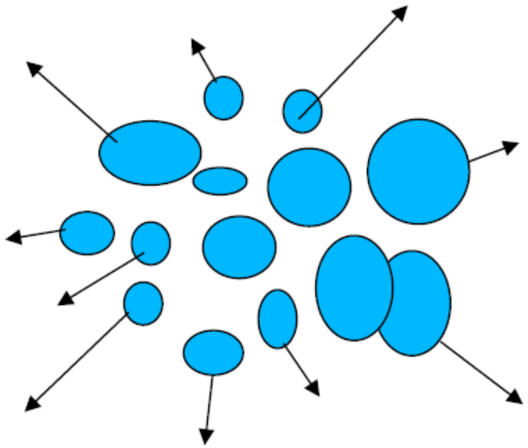
- Hybrid approximation

Peripheral collisions – Ericson, central collisions – ALADIN



3. Prefragment decay

1. Primary separation of a prefragment into clusters using the MST algorithm (dependence on the distance between nucleons)
2. Subsequent decay of the clusters using statistical models of fragmentation of excited nuclei from the Geant4 toolkit

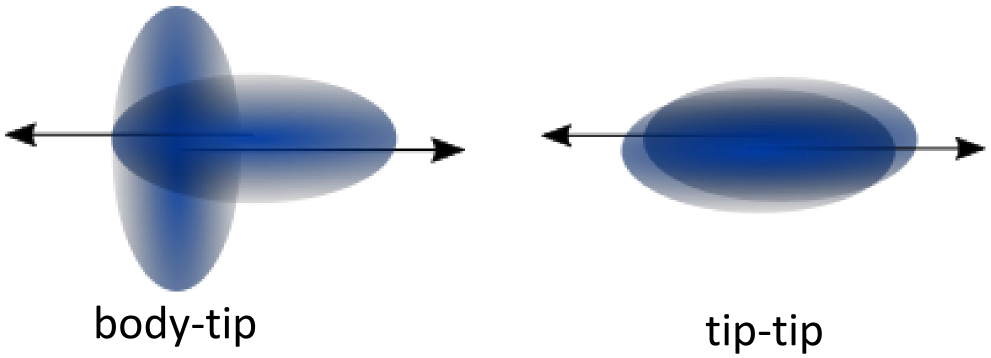


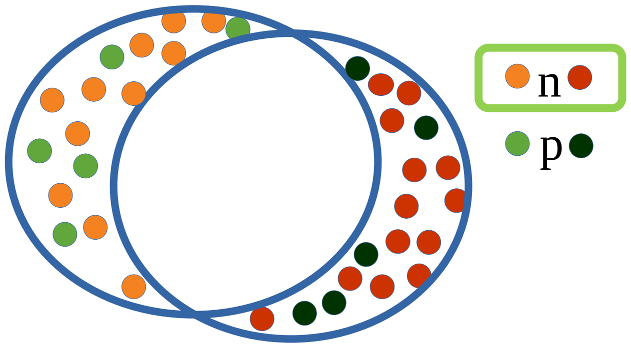
We study neutrons from central ^{238}U-^{238}U collisions

- We expect that spectators produced in ultracentral collisions are the most sensitive to initial orientation of colliding nuclei.

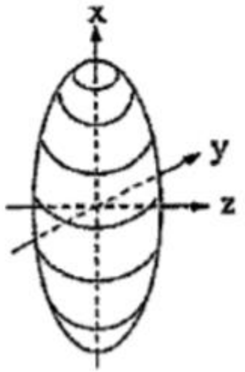
- Spectator neutrons are suitable for detection by means of neutron ZDCs installed at RHIC and the LHC.

- We chose ^{238}U- ^{238}U collisions due to prominent deformation of uranium: $\beta_2 = 0.280$ and $\beta_4 = 0.093$, $R_{\|}/R_{\perp} = 1.29$.
^{238}U- ^{238}U collisions were studied at RHIC at $\sqrt{s_{NN}} = 193$ GeV.



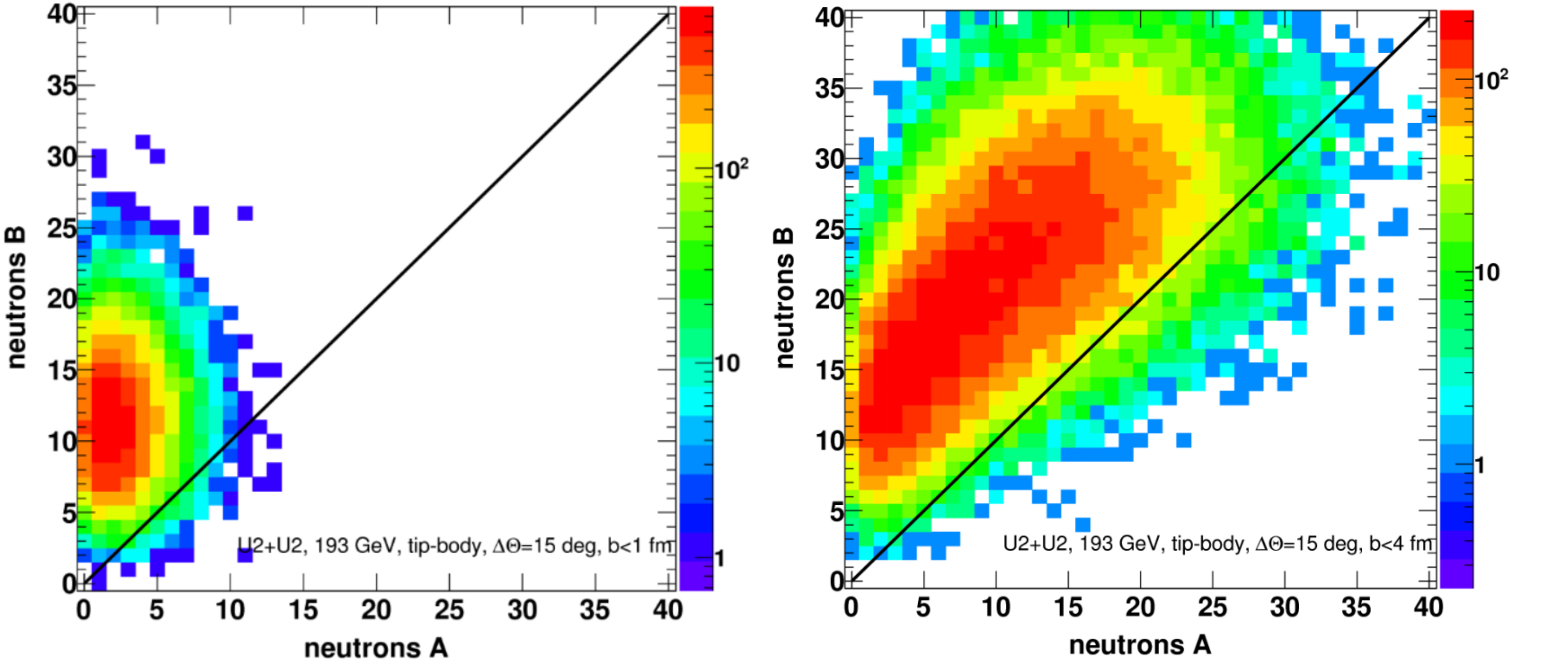


$$\rho(x,y,z) = \frac{\rho_{0n,p}}{1+\exp\left[(r-R_{n,p}(1+\beta_2 Y_{20}+\beta_4 Y_{40}))/a_{n,p}\right]},$$



Impact parameter restrictions

We choose ultracentral collisions (b < 1 fm), because the deformation effects are more noticeable there.
In particular, the neutron multiplicity distribution is narrower compared with other centralities.

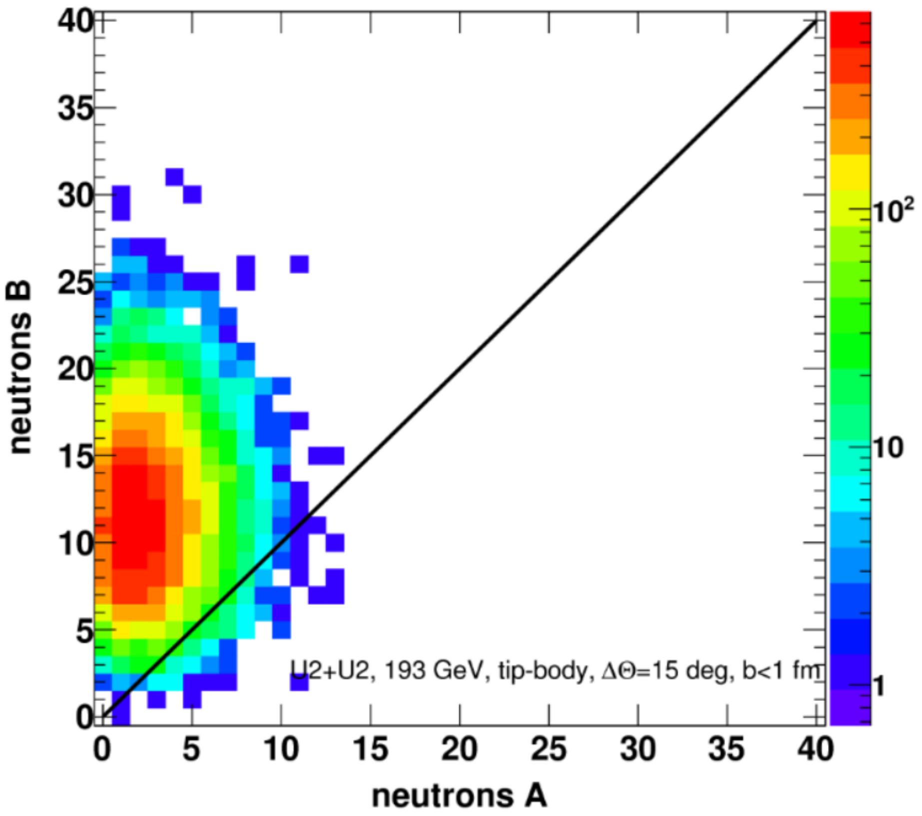


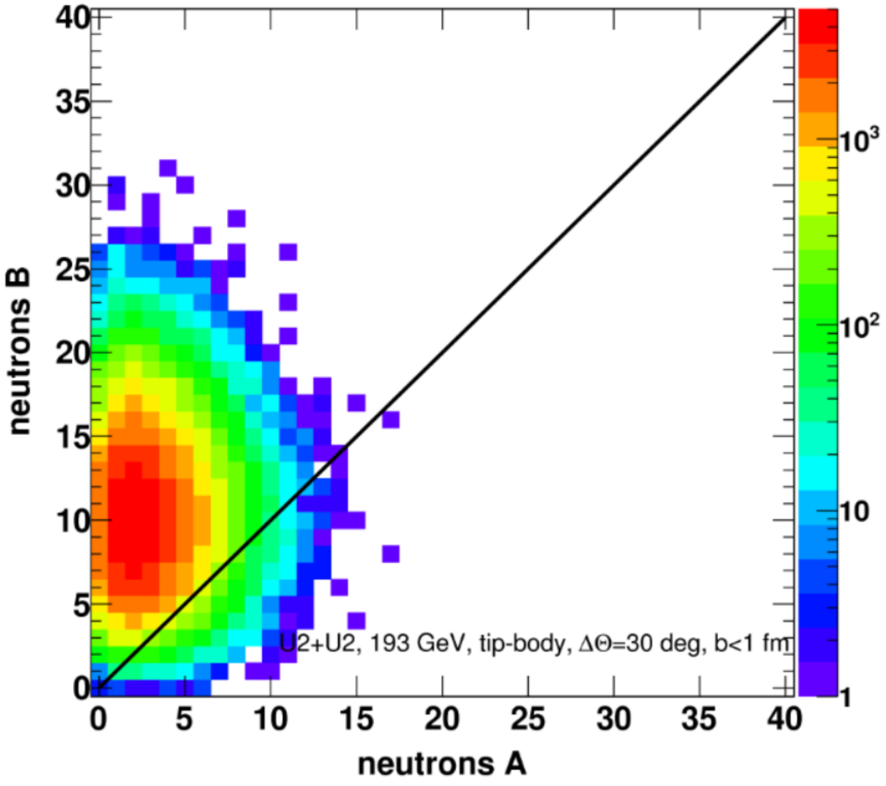
The number of events in simulated data with certain number of neutrons on side A (X-axis) and side B (Y-axis) in tip-body collisions of ^{238}U at $\sqrt{s_{NN}}$ = 193 GeV for two ranges of impact parameter : b < 1fm (left) and b < 4 fm (right).

Angle uncertainty

Δθ represents the angle range by which a nucleus can deviate from the exact orientation (tip-tip, body-body etc.)

No significant differences between neutron multiplicity distributions calculated with $\Delta\theta < 15°$ and $\Delta\theta < 30°$ are seen. In the following calculations we use $\Delta\theta < 15°$.

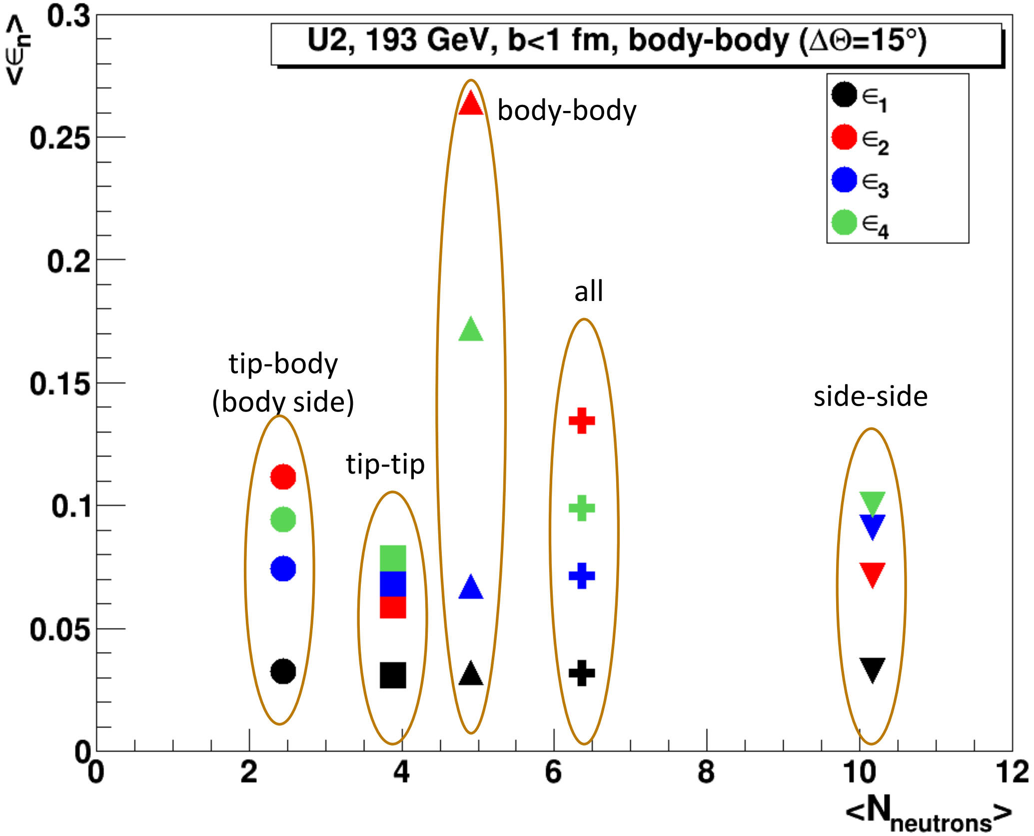




The number of events in simulated date with certain number of neutrons on side A (X-axis) and side B (Y-axis) in tip-body collisions of ^{238}U at $\sqrt{s_{NN}} = 193$ GeV for two different angle uncertainties: $\Delta\theta < 15°$, (left) and $\Delta\theta < 30°$ (right).

Eccentricity variation

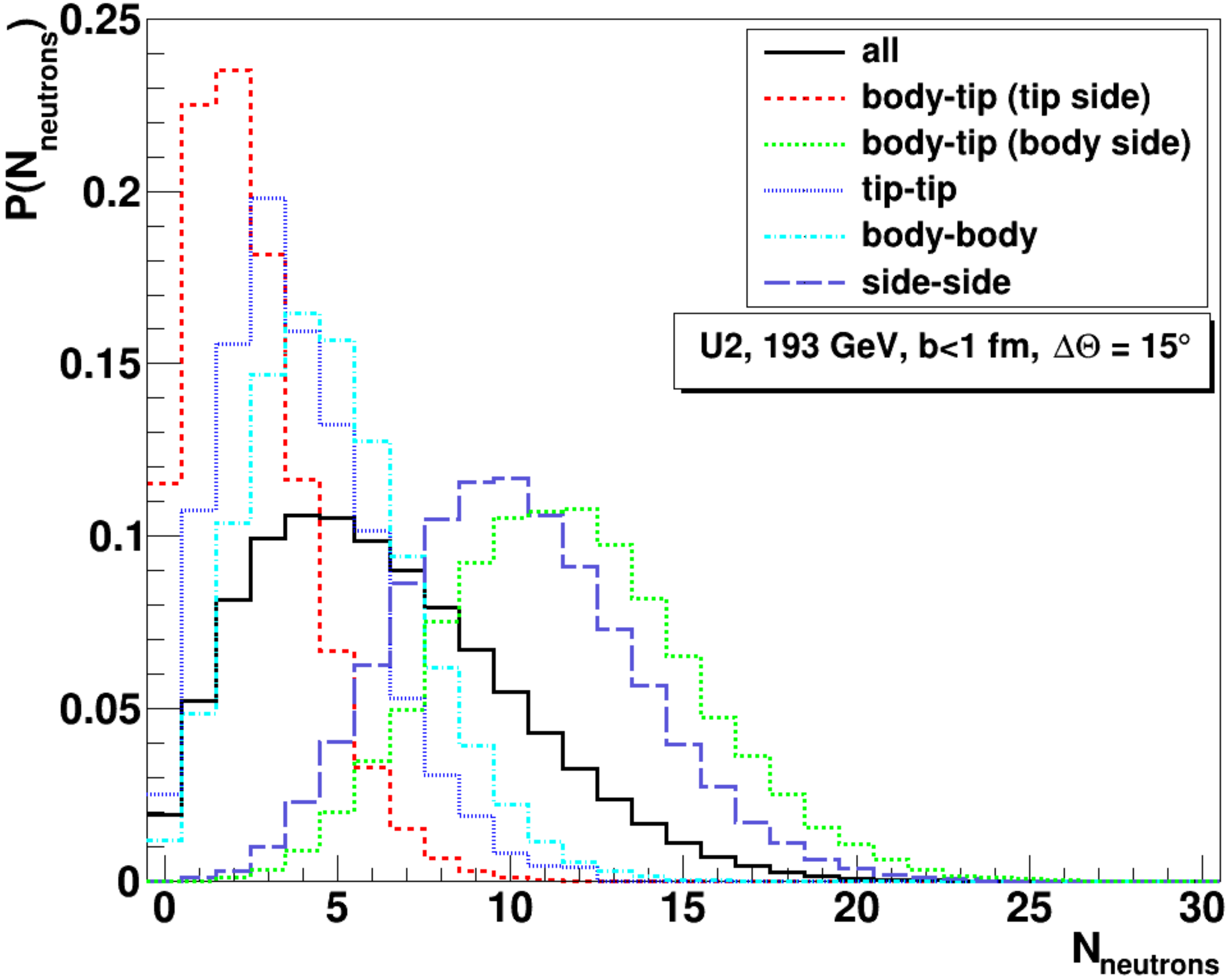
	tip-body	tip-tip	body-body	side-side	all
ε_1	0.0323	0.0309	0.0321	0.0324	0.0317
ε_2	0.1119	0.0591	0.2645	0.0712	0.1342
ε_3	0.0741	0.0681	0.067	0.0809	0.0714
ε_4	0.0945	0.0785	0.1721	0.1001	0.0986
$N_{neutrons}$	2.44	3.89	4.9	10.17	6.36



- As expected, the eccentricity of the collisions with different configuration of colliding nuclei varies significantly. The biggest changes are observed in ε_2 and ε_4
- It was shown that eccentricity ε_n is proportional to the flow coefficients v_n: $\varepsilon_n = kv_n$ [1)]
- According to AAMCC, body-body collisions are characterized by especially large value of ε_2
- Furthermore, the correlation between the initial orientation of the collisions and the average number of neutrons is demonstrated by our calculations.

[1)]*H. Niemi et al. Phys. Rev. C* ***87****, 054901 (2013)*

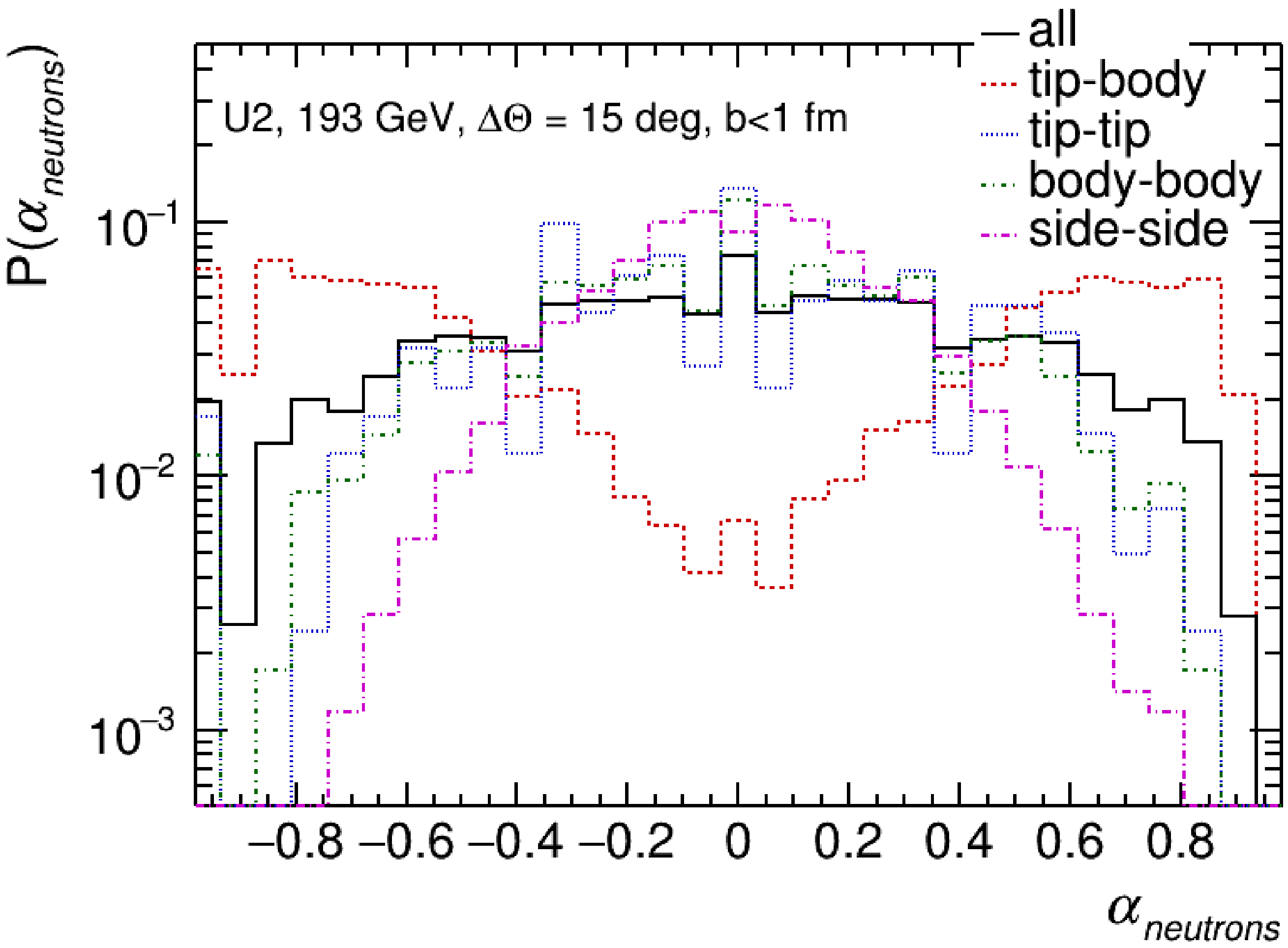
Neutron multiplicity



Neutron multiplicity probability distribution for the events with a certain configuration of colliding nuclei in ^{238}U collisions at $\sqrt{s_{NN}}$ = 193 GeV for b < 1 fm and Δθ = 15°

- Body-tip (body side) and side-side collisions can be distinguished from other configurations by increased neutron multiplicity
- Body-tip collisions are characterized by especially low neutron multiplicity in the tip side
- It is difficult to distinguish tip-tip and body-body collisions

Neutron asymmetry

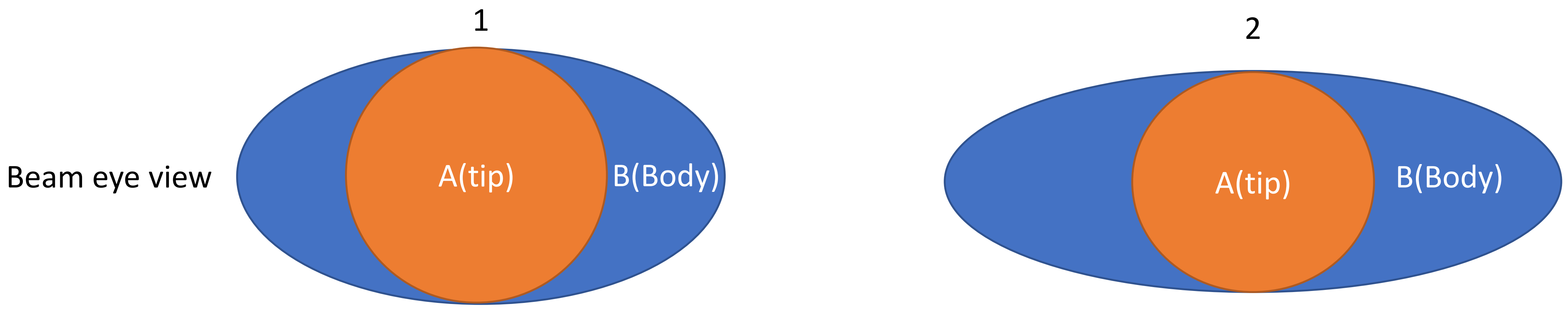


Neutron asymmetry probability distribution for the events with a certain configuration of colliding nuclei in ^{238}U collisions at $\sqrt{s_{NN}}$ = 193 GeV for b < 1 fm and Δθ = 15°

$$\alpha_N = \frac{N_A - N_B}{N_A + N_B}$$

- Tip-body collisions are highly asymmetric
- In contrast, side-side collisions are characterized by a narrow neutron asymmetry distribution.
- Due to this, tip-body and side-side collisions can be distinguished

Nuclear deformation extracted from tip-body collisions?

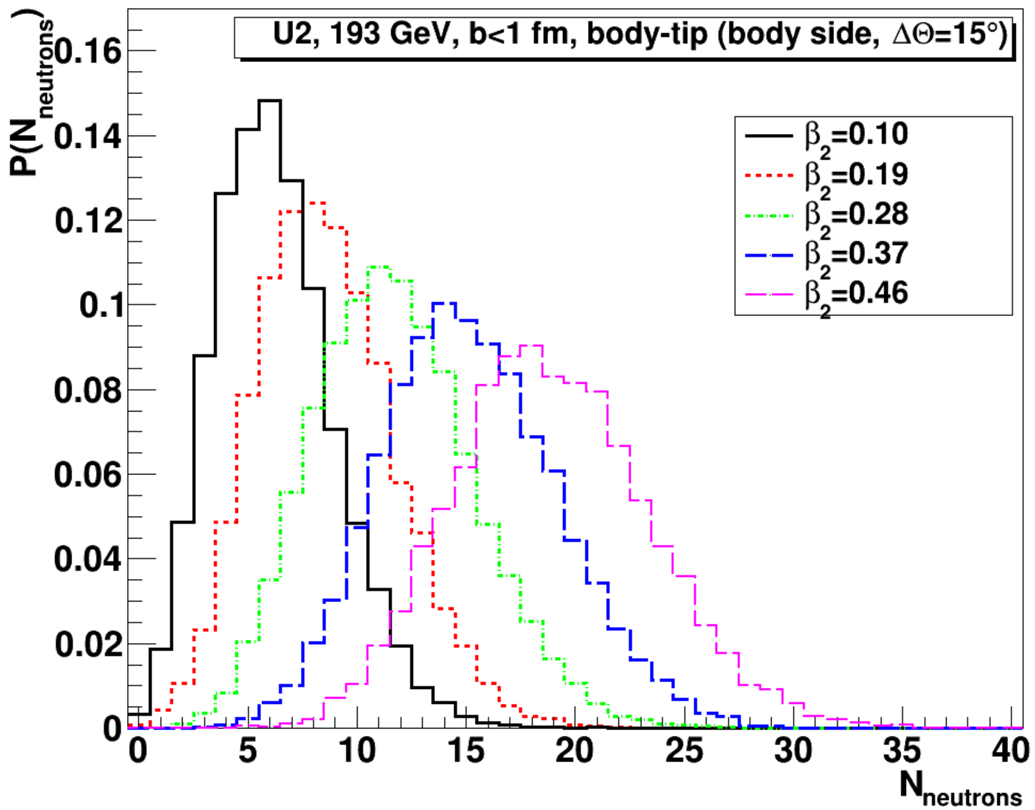


$\beta_{2 \text{ for } 1} < \beta_{2 \text{ for } 2} \Rightarrow N_{\text{neutrons for } 1} < N_{\text{neutrons for } 2}$

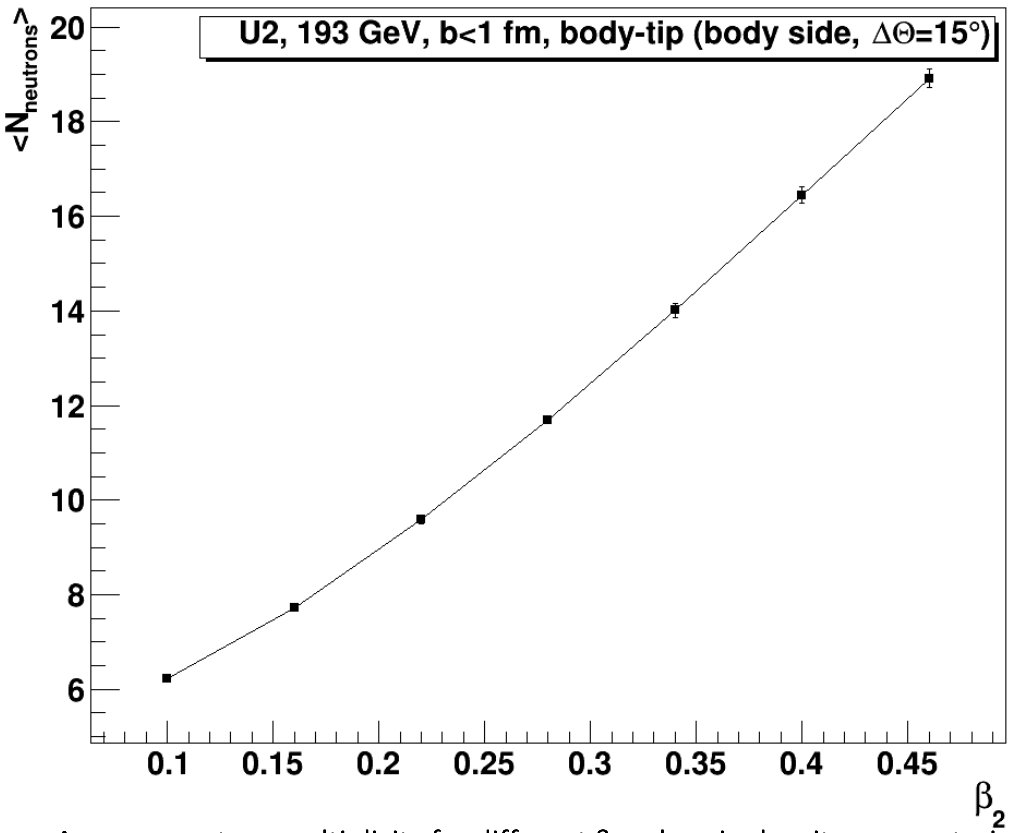
One can expect that the number of spectator neutrons on the body side should depend on nuclear deformation: the more prolate the nuclei, the more spectator neutrons in tip-body collisions.

A new method to restrict the nuclear deformation parameter β_2 can be proposed.

Nuclear deformation extracted from tip-body collisions



Neutron multiplicity probability distribution for different β_2 values in density parameterization of colliding ^{238}U nuclei in tip-body collisions at $\sqrt{s_{NN}}$ = 193 GeV for b < 1 fm and Δθ = 15°

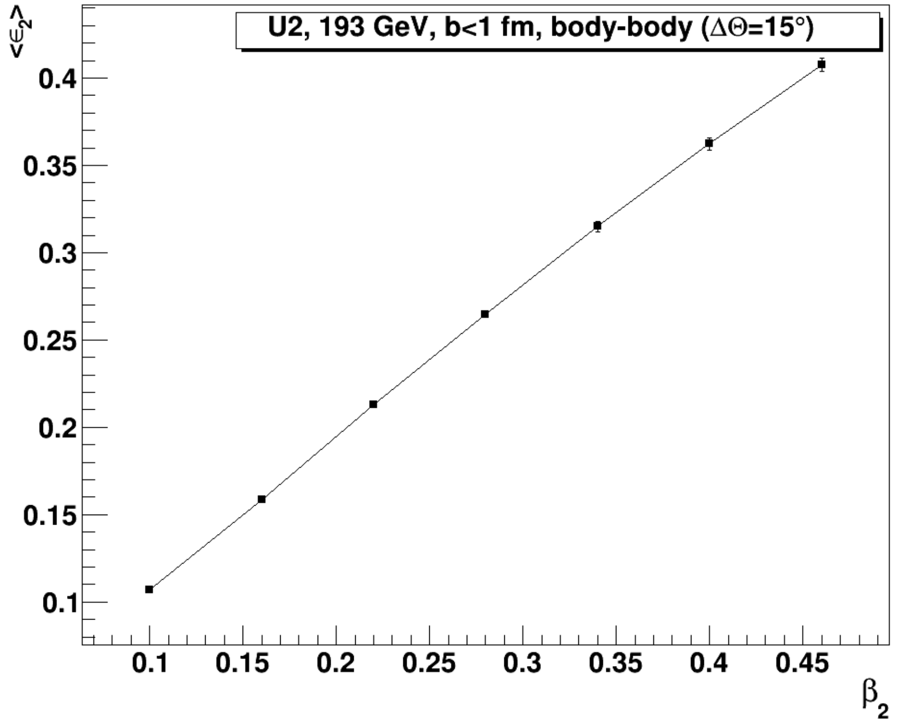


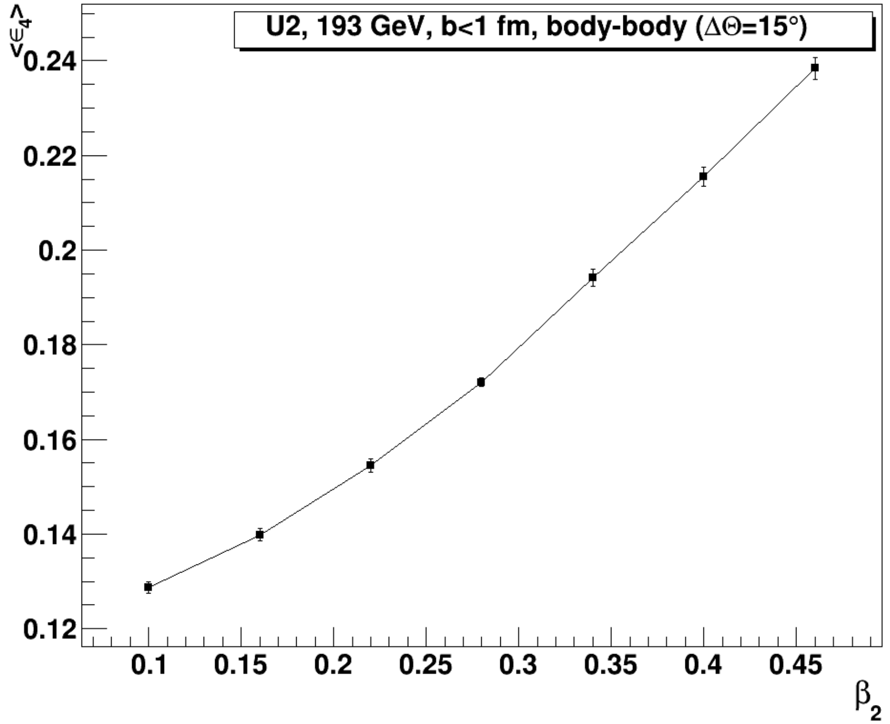
Average neutron multiplicity for different β_2 values in density parameterization of colliding ^{238}U nuclei in tip-body collisions at $\sqrt{s_{NN}}$ = 193 GeV for b < 1 fm and Δθ = 15°

Average calculated neutron multiplicity in tip-body ultracental collisions demonstrates rise with β_2

Body-body collisions and nucleon density parameterization

A similar prediction can be made for body-body collisions: increase in β_2 should result in ε_2 increase due to the corresponding change in the shape of the overlapping area.





Average ε_2 (left) and ε_4 (right) for different β_2 used in density parameterization of colliding ^{238}U nuclei in tip-body collisions at $\sqrt{s_{NN}}$ = 193 GeV for b < 1 fm and Δθ = 15°

Calculated average ε_2 and ε_4 are both sensitive to β_2 of colliding nuclei.

Thus, both eccentricity and neutron multiplicity can be used for restricting β_2.

Conclusions

1. Spectator matter in ultracentral collisions allows to separate tip-body and side-side collisions from other nuclei orientations:
   - Tip-body collisions are characterized by high neutron asymmetry.
   - Side-side collisions are characterized by low neutron asymmetry and high multiplicity of spectator protons.

2. Body-body collisions can be separated via large value of ε_2 and, consequently, v_2.

3. Tip-body and body-body collisions can be used to study the deformation parameterization of colliding nuclei:
   - Average neutron multiplicity in tip-body collisions rises with β_2.
   - ε_2 and ε_4 in body-body collisions rise with β_2.

Thank you for attention!

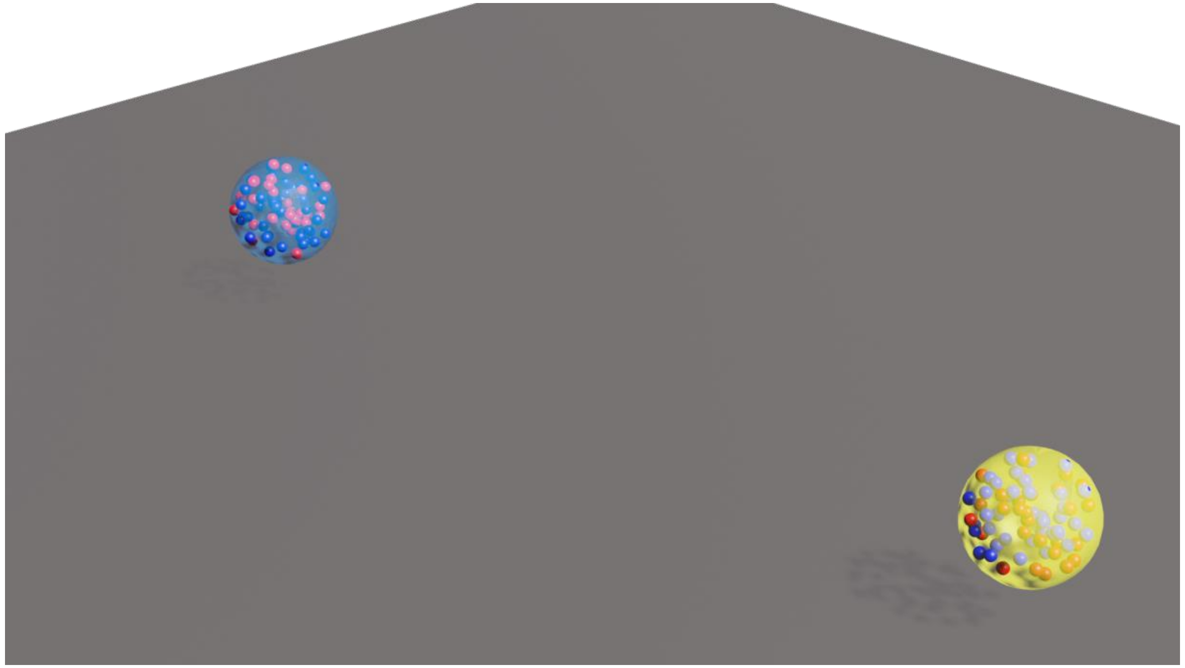
The work has been carried out with financial support of the Russian Foundation for Basic Research within the project 18-02-40035-mega.

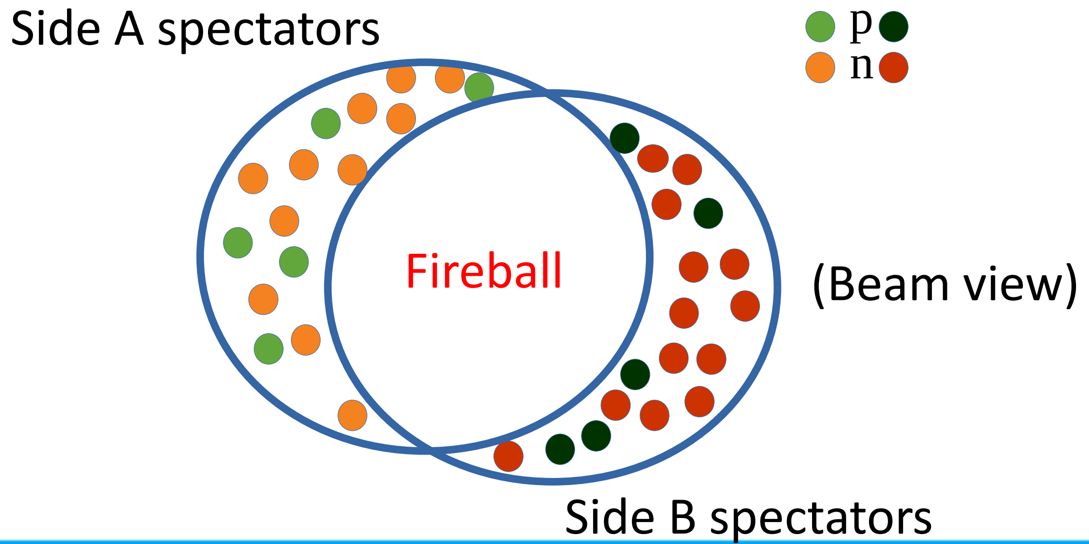
Back-up

Spectator matter in central collisions

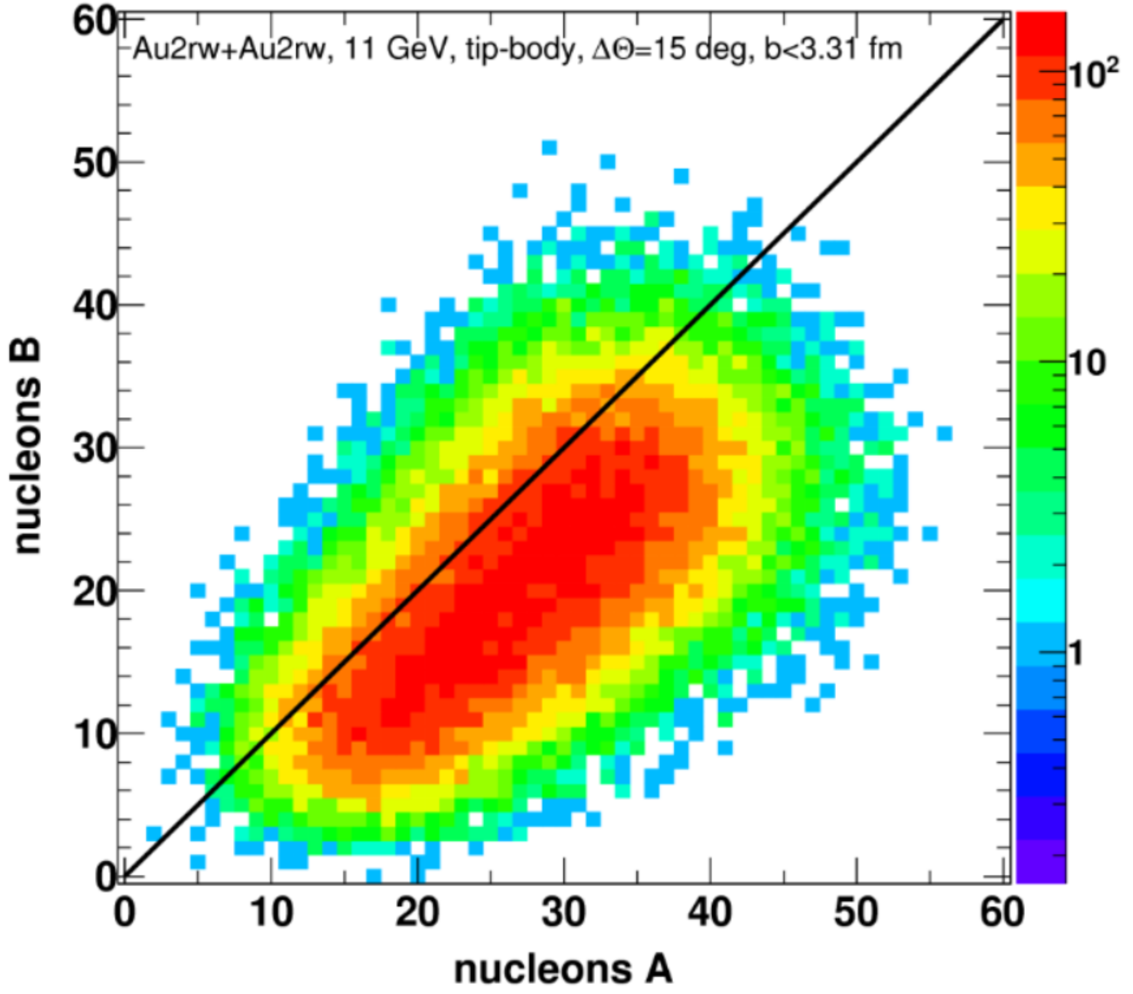
- In the events with a partial overlap of nuclei, nucleons outside the overlap retain their momenta, move forward and form excited spectator matter (prefragment).

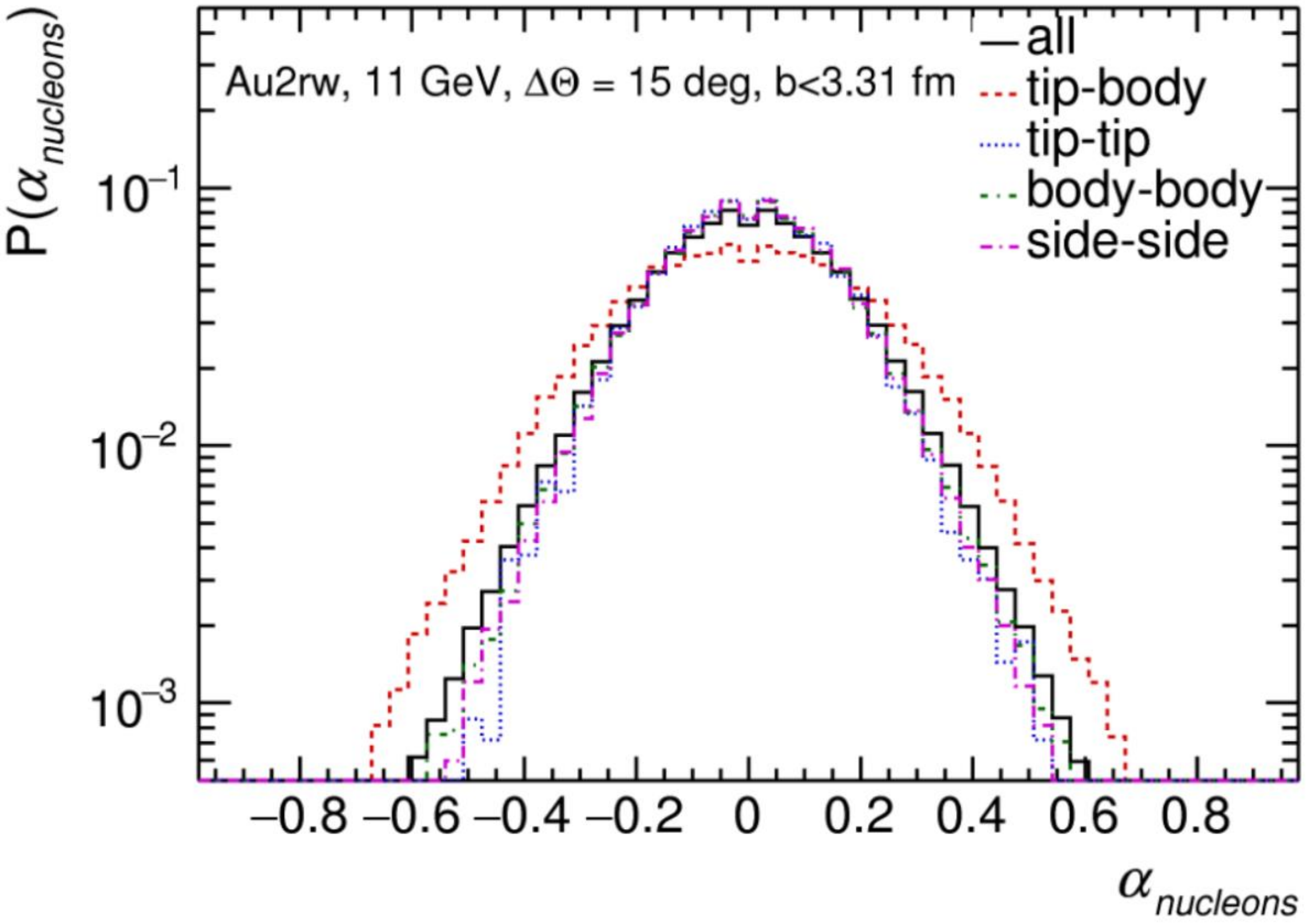
- Spectator matter in central collisions of deformed nuclei can help to separate collisions with different relative orientation of colliding, as the size and the form of the overlapping area also influences spectator matter composition.





^{197}Au


Au2rw+Au2rw, 11 GeV, tip-body, ΔΘ=15 deg, b<3.31 fm
nucleons B
nucleons A
0
10
20
30
40
50
60
1
10
10²


Au2rw, 11 GeV, ΔΘ = 15 deg, b<3.31 fm
all
tip-body
tip-tip
body-body
side-side
P(α_nucleons)
α_nucleons
10⁻¹
10⁻²
10⁻³
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8