Longitudinal fluctuations of the center-of-mass of the participants in heavy-ion collisions

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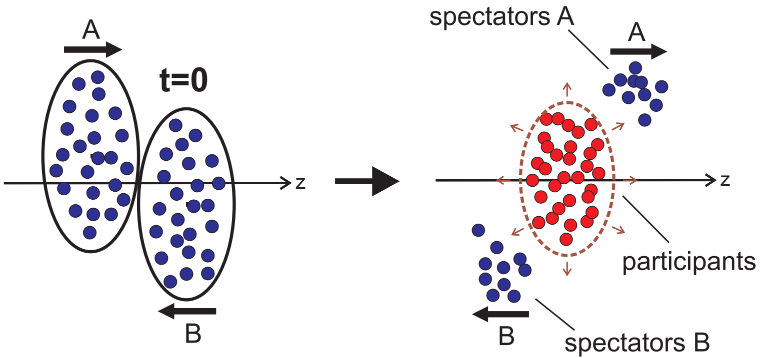
Outline

Participant center-of-mass system

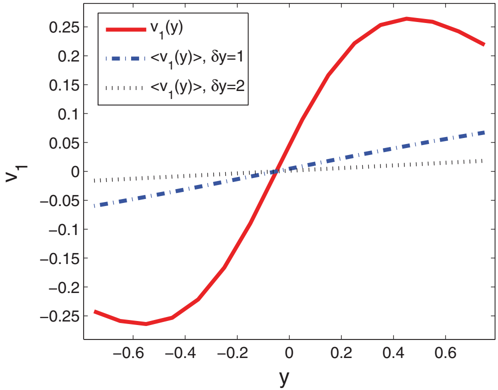


Participant sub-system moves with rapidity $y_{c.m.}$
In general $\langle y_{c.m} \rangle = 0$, but $\langle \delta y_{c.m.}^2 \rangle \neq 0$!
Consequently, participant c.m.s. $\neq$ collider c.m.s. event-by-event

Participant center-of-mass system

$y_{c.m}$ fluctuations may have a substantial influence on fluid dynamical predictions!

$$\text{Assuming } f(y_{c.m}) = \frac{1}{\sqrt{2\pi}\,\delta y}\, e^{\frac{-y_{c.m}^2}{2(\delta y)^2}}$$



Csernai, Magas, Stöcker, Strottman, Phys. Rev. C84, 024914 (2011)

Participant rapidity from spectator numbers

Three subsystems:
target spectators (A) + projectile spectators (B) + participants (P)

Four-momentum conservation (collider c.m.s.)

$$\begin{aligned} E_{\text{tot}} &= E_A + E_B + E_P\,, \\ P^z_{\text{tot}} &= P^z_A + P^z_B + P^z_P \;=\; 0\,. \end{aligned}$$

Participant rapidity from spectator numbers N_A and N_B

$$y_{c.m.} = y_P = arctanh\left(\frac{P^z_P}{E_P}\right) = arctanh\left(\frac{N_B - N_A}{2A - N_A - N_B} v_{in}\right)$$

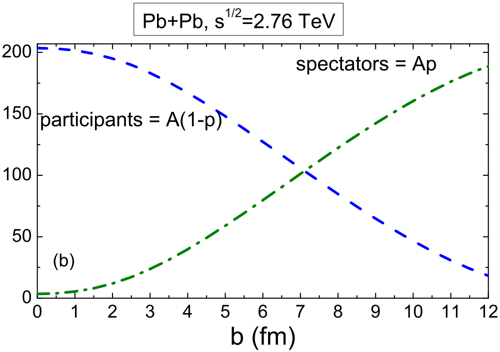
Allows for experimental measurement of $y_{c.m.}$ fluctuations using ZDC.
Csernai, Eyyubova, Magas, Phys. Rev. C86, 024912 (2012)

Spectator probability

Probability of nucleon to be a spectator (Glauber-Sitenko approach)

$$p = \frac{1}{A} \int dx\, dy\, T_A(x - b/2, y) \left(1 - \frac{\sigma_{NN} T_B(x + b/2, y)}{A}\right)^A .$$

$T_{A(B)}$ – thickness function,
σ_{NN} – nucleon-nucleon cross section.



Spectator number probability

Probability of $N_{A(B)}$ spectators

Binomial distribution

$$p(N_A) = \binom{A}{N_A} p^{N_A} (1-p)^{A-N_A} ,$$
$$p(N_B) = \binom{A}{N_B} p^{N_B} (1-p)^{A-N_B} .$$

Allow N_A and N_B to take continuous values,
Gaussian approximation for large Ap and $A(1-p)$

$$p(N_{A(B)}) \Rightarrow \rho(N_{A(B)}) = \frac{\exp\left(-\frac{(N_{A(B)}-Ap)^2}{2Ap(1-p)}\right)}{\sqrt{2\pi Ap(1-p)}} .$$

Rapidity distribution

Approximation: $\rho(N_A, N_B) \approx \rho(N_A)\,\rho(N_B)$.

$$f_P(y) = \int dN_A \int dN_B\, \rho(N_A)\,\rho(N_B)\delta\left[y - y_P(N_A, N_B),\,\right]$$

$$y_P(N_A, N_B) = arctanh\left(\frac{N_B - N_A}{2A - N_A - N_B} v_{in}\right).$$

After integration

Rapidity distribution (general expression)

$$f_P(y) = \sqrt{\frac{A(1-p)}{\pi p}}\, \frac{v_{\text{in}}^2 \exp\left[-\frac{A(1-p)}{p}\frac{\tanh^2 y}{v_{\text{in}}^2 + \tanh^2 y}\right]}{\cosh^2 y\left[v_{\text{in}}^2 + \tanh^2 y\right]^{\frac{3}{2}}}.$$

Rapidity distribution

Ultrarelativistic limit: $v_{\text{in}} \to 1$

Rapidity distribution in ultra-relativistic limit

$$f_P^{\text{UR}}(y) = \sqrt{\frac{A(1-p)}{\pi p}}\, \frac{\exp\left[-\frac{A(1-p)}{p}\,\frac{\tanh^2 y}{1+\tanh^2 y}\right]}{\cosh^2 y \left[1+\tanh^2 y\right]^{\frac{3}{2}}} .$$

Weak energy dependence, only through σ_{NN}

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Weak energy dependence, only through σ_{NN}

Near mid-rapidity y is small $\Rightarrow$ $\tanh y \approx y$, $\cosh y \approx 1$

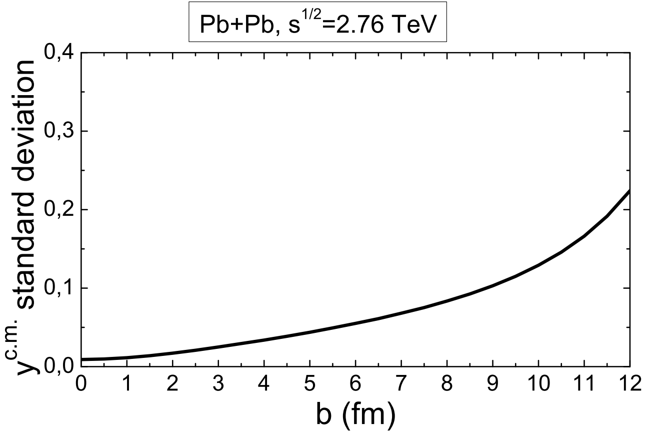
Rapidity distribution at mid-rapidity

$$f_P(y) = \sqrt{\frac{A(1-p)}{\pi p\, v_{\text{in}}^2}}\, \exp\left[-\frac{A(1-p)}{p\, v_{\text{in}}^2}\, y^2\right]\,.$$

Gaussian distribution with $\delta y^2 = \dfrac{p\, v_{\text{in}}^2}{2A(1-p)}$

Distribution at mid-rapidity

$$\delta y^2 = \frac{p\, v_{\rm in}^2}{2A(1-p)}$$

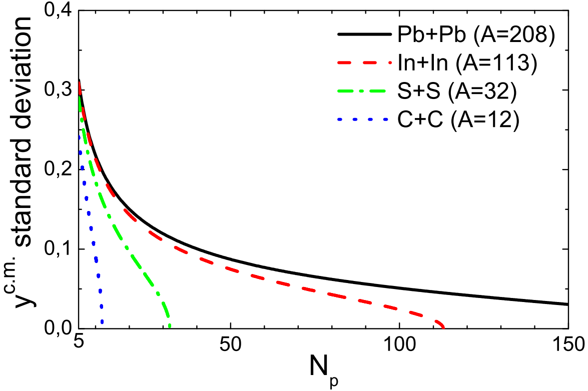


Distribution in form of Gaussian works well for most conditions!

Dependence on mass number A

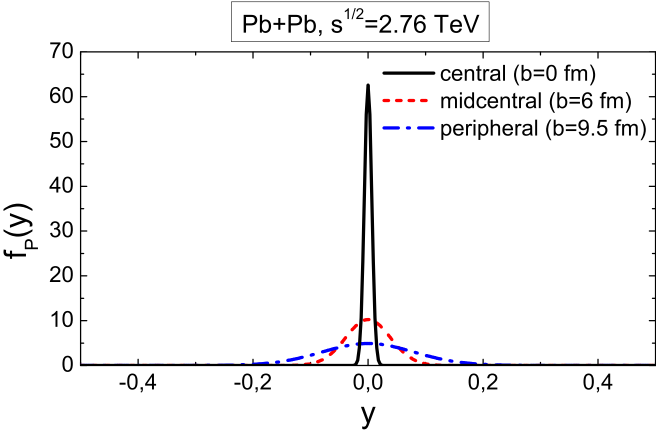
In terms of av. number of participants $N_p = A(1-p)$ from nucleus

$$\delta y^2 = \frac{v_{\rm in}^2}{2}\left(\frac{1}{N_p} - \frac{1}{A}\right)$$



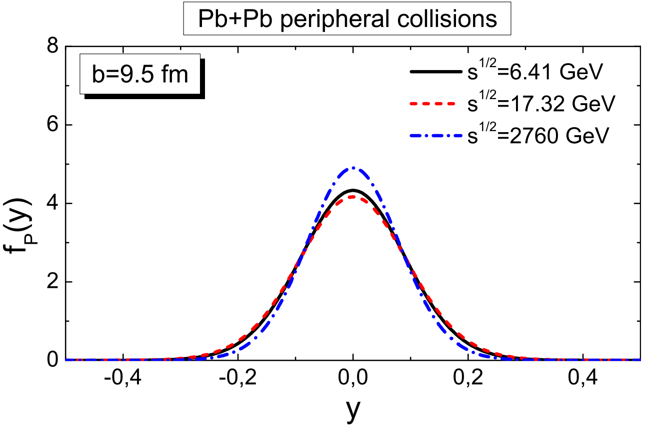
Fluctuations are smaller in "equivalent" collisions with smaller mass number

Rapidity distribution, different centralities



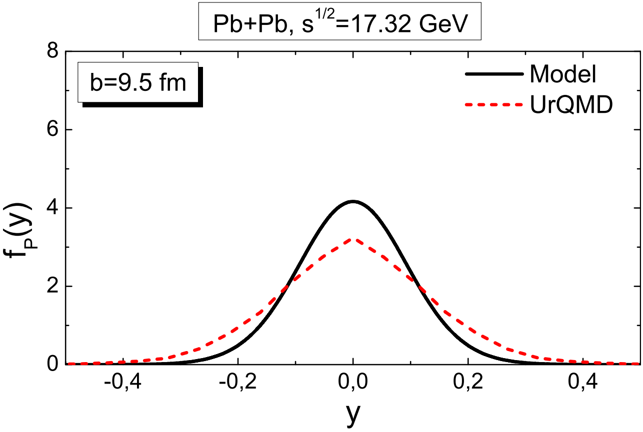
Strong dependence on centrality

Rapidity distribution, different energies



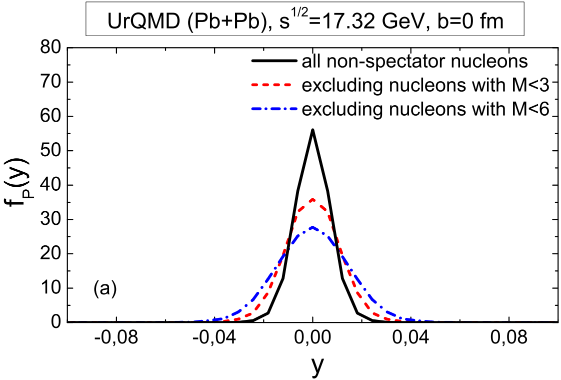
Weak dependence on collision energy

Comparison with microscopic model



Different definitions of "participants"

The separation between spectators and participants is not trivial.



If we exclude nucleons with $M_{\mathrm{coll}} < 6$ from participants the distribution width doubles! The effect is smaller in peripheral collisions.

Conclusions

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2. It is found that the width of the $y^{c.m.}$-distribution increases strongly for more peripheral collisions, while it depends weakly on the collision energy.

Conclusions

1. We show that for most conditions the participant c.m. rapidity distribution is described by Gaussian distribution with a variance determined mostly by the collision centrality.
2. It is found that the width of the $y^{c.m.}$-distribution increases strongly for more peripheral collisions, while it depends weakly on the collision energy.
3. It is shown that when average number of participants is the same the $y_{c.m.}$-fluctuations are stronger for collisions of nuclei with larger mass number.

Details can be found in:

V. Vovchenko, D. Anchishkin, and L. P. Csernai, Longitudinal fluctuations of the center of mass of the participants in heavy-ion collisions, Phys.Rev. C, v.88, p.014901 (2013) [arXiv:1306.5208 [nucl-th]].

Thanks for your attention!

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