Determination of centrality in ion-ion collisions

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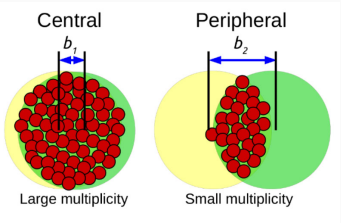
Motivation

Centrality is a measure of the overlap of colliding nuclei and defines initial geometry of the collision system

$$c(b) = \frac{1}{\sigma_{AA}} \int_0^b \frac{d\sigma}{db'} db'$$



The determination of centrality is crucial for most ion-ion collision studies.

The impact parameter (**b**) cannot be measured directly

1. Charged particle multiplicities
2. Deposited energy of spectators

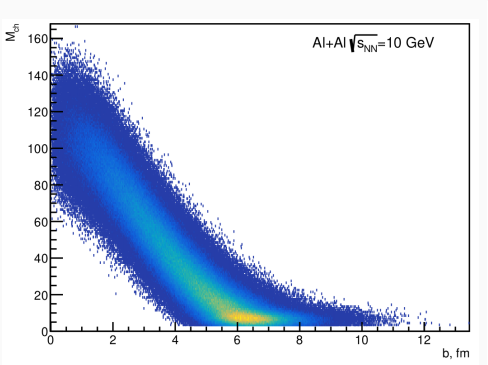
In the SPD experiment, centrality determination faces challenges due to low multiplicities in small collision systems at low energies

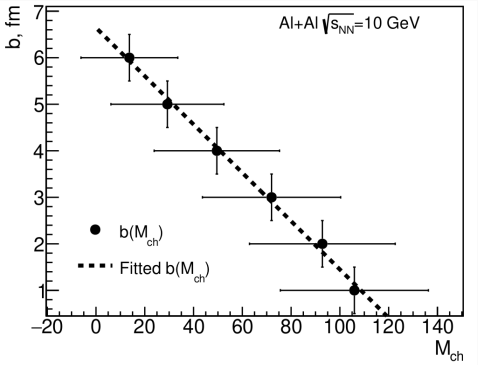
Determination of centrality based on multiplicity

Al+Al, $\sqrt{s_{NN}} = 10$ GeV (*As example of collision system at SPD*)

$$c(b) = \frac{1}{\sigma_{AA}} \int_0^b \frac{d\sigma}{db'} db'; \qquad \frac{d\sigma}{db} \sim b \sim \frac{1}{M_{ch}}$$

Relative uncertainties of charged particle multiplicities method $\gtrsim 30\%$

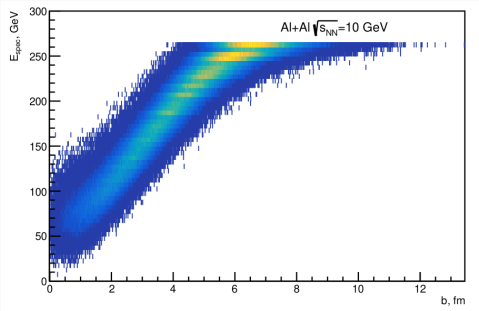


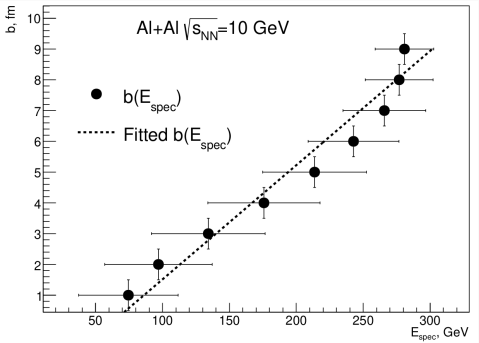


Energy deposition of spectators (ZDC)

Uncertainties of centrality determination can be reduced by using deposed energy of spectators.

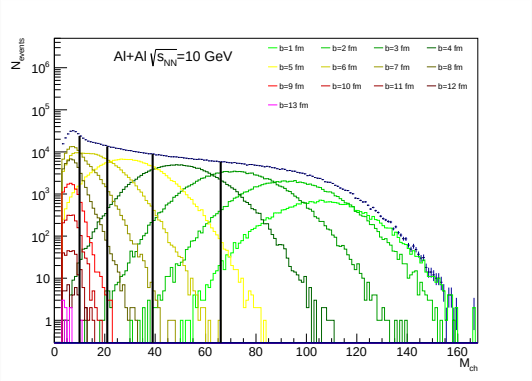
Relative uncertainties of spectators deposed energy method $\gtrsim 9\%$



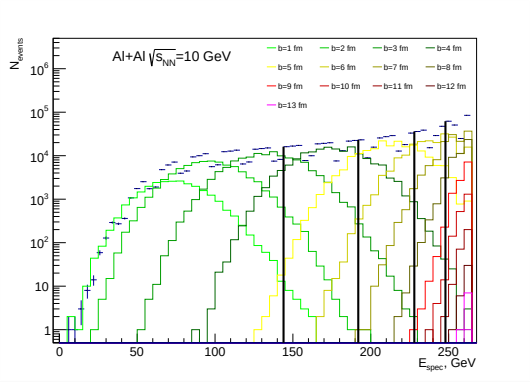


Procedure of centrality determination

Determination of centrality based on multiplicity



Energy deposition of spectators (ZDC)



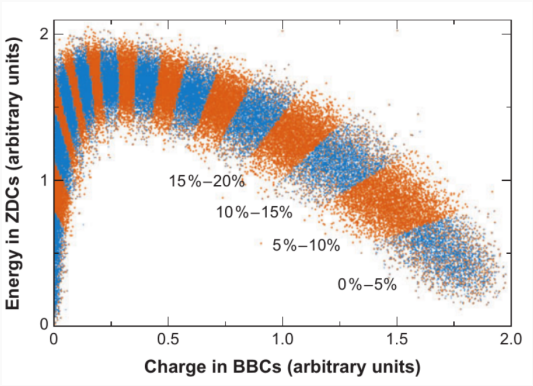
Estimation of uncertainties of combined method for SPD

Uncertainties of charged particle multiplicities method $\gtrsim 30\%$

Uncertainties of spectators deposed energy method $\gtrsim 9\%$

Uncertainties of combined method is $\sim 8.6\%$

(PHENIX example)



Experimental requirements and expected performance

1. **Beam species**: ion-ion collisions (Al+Al, C+C, Ca+Ca)
2. **Collision energy**: $5 - 13$ GeV
3. **Luminosity**: $10^{27} cm^{-2} s^{-1}$
4. **Polarization**: no
5. **Involved SPD subsystems**: ZDC, Straw tracker
6. **Optimal duration of data taking**: minimal
7. **Minimal duration of data taking**: minimal

1. **Simulation information used**: Pythia8-based MC
2. **Total statistics**: 1M events
3. **Statistical accuracy**: -
4. **Main sources of systematics**: Uncertainties related to $b(M_{ch})$ dependency.

Conclusion

1. The charged particle multiplicity method for centrality determination introduces a systematic error of $\gtrsim 30\%$, associated with the standard deviation of the $b(M_{ch})$ dependence.
2. The spectator energy deposition method yields a systematic error of $\gtrsim 9\%$ related to the standard deviation of the $b(E_{ZDC})$ dependence.
3. Combining these two methods reduces the error to $\gtrsim 8.6\%$.
4. Ultraperipheral collisions have a significantly larger impact in ion-ion collisions at SPD compared to other experiments (PHENIX, STAR, MPD). Thus, it may be more accurate to merge all peripheral collisions into a single centrality class rather than using the conventional 10% binning. Separation of events in $\sim$3 centrality classes seems to be optimal, but requires further study.

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Thank you for your attention!

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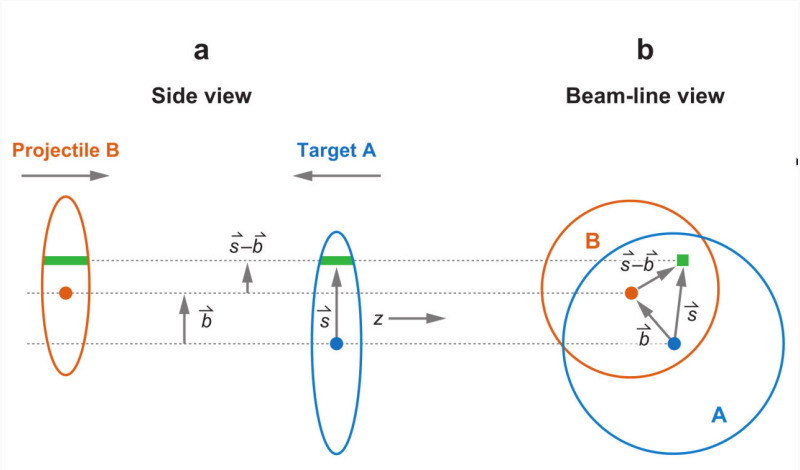
Optical model

The model assumes that at sufficiently high energies trajectories of the constituent nucleons are independent and linear.



Optical model

$$c(b) = \frac{1}{\sigma_{A-A}} \int_0^b \frac{d\sigma}{db'} db'$$

$\hat{T}_A(s) = \int \hat{\rho}_A(s, z_A) dz_A$ - thickness function

$\hat{T}_{AB}(b) = \int \hat{T}_A(s) \hat{T}_B(s - b) d^2 s$ - overlap integral

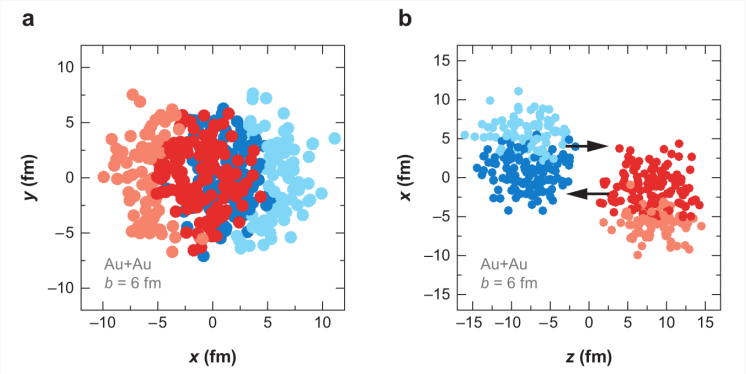
$\frac{d^2\sigma_{inel}^{AB}}{db^2} \equiv \sum_{n=1}^{AB} P(n, b) = 1 - \left[1 - \hat{T}_{AB}(b)\sigma_{inel}^{NN}\right]^{AB}$ - The total probability of an interaction between A and B

$\sigma_{inel}^{AB} = \int_0^\infty 2\pi b db \left(1 - \left[1 - \hat{T}_{AB}(b)\sigma_{inel}^{NN}\right]^{AB}\right)$ - total cross section

The calculations can be simplified by using Glauber model.

Glauber Monte Carlo (GMC) approach

- Monte Carlo distribution of nucleon coordinates according to the nuclear density distribution
- The collision of nuclei is considered as a sequence of independent binary nucleon-nucleon collisions
- Nucleons move along rectilinear trajectories.

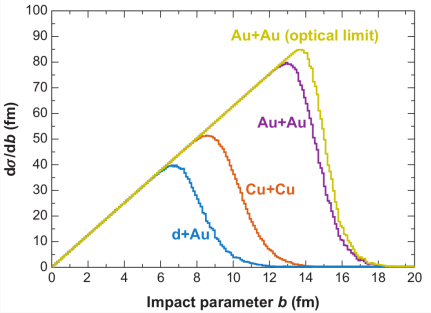


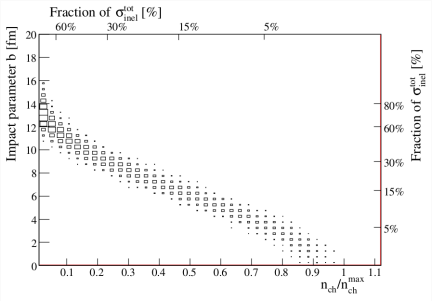
Determination of centrality based on multiplicity (PHENIX example)

The basic assumption underlying the centrality classes is that the impact parameter b is lineary related to the multiplicity of particles in all ranges of rapidity.

- Optical model
- Glauber model

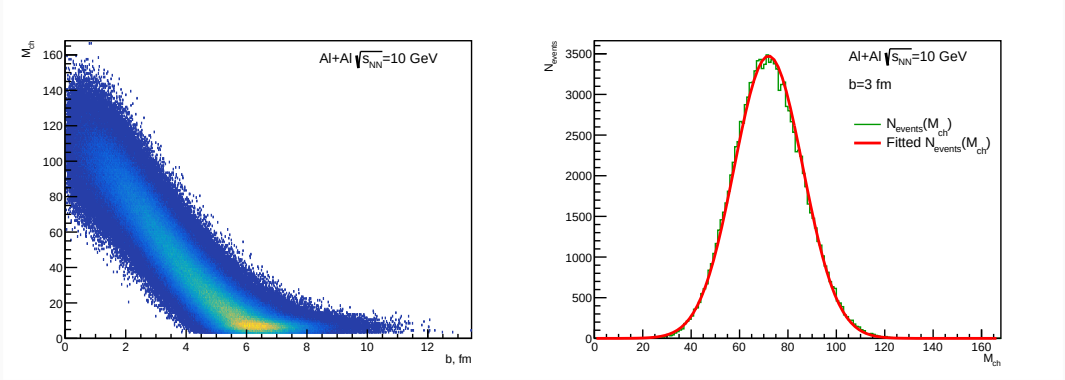
$$\frac{d\sigma}{db} \sim b \sim \frac{1}{M_{ch}}$$





Determination of centrality based on multiplicity

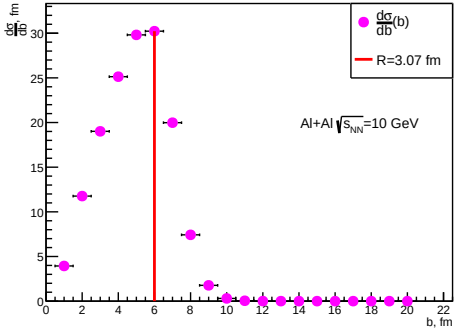
Distribution of charged particle multiplicities vs. impact parameter for SPD (Al+Al, $\sqrt{s_{NN}} = 10$ GeV)

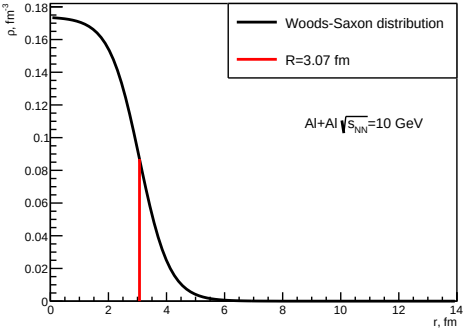


Determination of centrality based on multiplicity

For Al+Al collisions at $\sqrt{s_{NN}} = 10$ GeV:

- larger impact of ultraperipheral collisions ($b > 2 \cdot R_{Al}$);

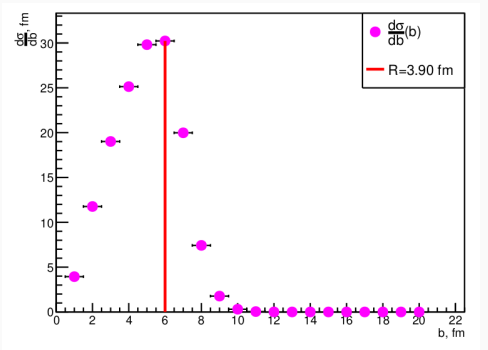


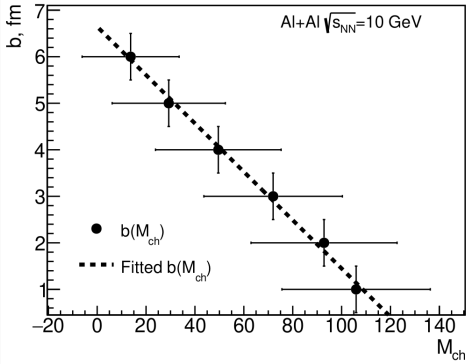


Determination of centrality based on multiplicity

For Al+Al collisions at $\sqrt{s_{NN}} = 10$ GeV:

- larger impact of ultraperipheral collisions ($b > 2 \cdot R_{Al}$);
- larger relative values of standard deviations in $b(M_{ch})$ distribution ($\gtrsim 30\%$).





To Do List

1. Use SPDroot, incorporating the SPD detector system in the analysis.
2. Study and compare centrality determination methods using different detectors (TPC, straw tracker, and their combinations).
3. Since Pythia may be unreliable at energies around 10 GeV, investigate alternative event generators (e.g., hUrQMD).
4. Analyze the applicability and performance of the Modified Glauber model in simulations.