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Modeling (Anti-)deuteron Formation at RHIC with a Geometric Coalescence Model

Kittiratpattana, A. et al. (2020). *arXiv:2006.03052*.

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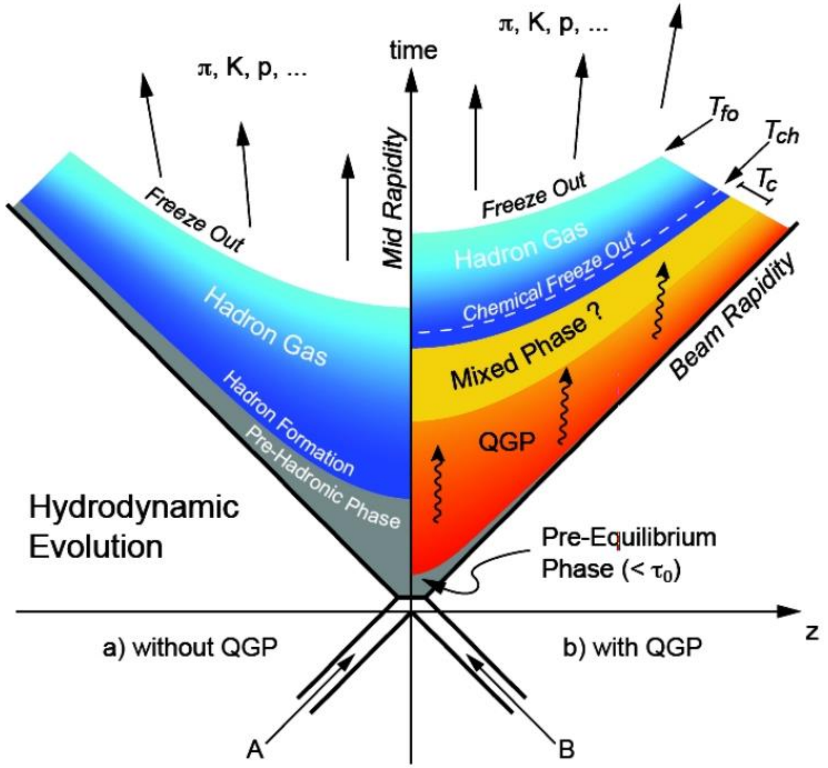
4 - University of Sarajevo, Bosnia and Herzegovina.

Presenter:

Apiwit Kittiratpattana

September 4-11, 2020

Heavy-Ion Collisions



Light nuclei formation can give insightful information,

- Quark Gluon Plasma (QGP)
- Big Bang nucleosynthesis
- Emission source shape

Braun-Munzinger, P., & Dönigus, B. (2019). *Nuclear Physics A*, *987*, 144-201.
https://particlesandfriends.wordpress.com/2016/10/14/evolution-of-collisions-and-qgp/

Coalescence Model

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- Formation Rate
- Source Geometries

Charged Volume
- Charged constrain
- Source Geometries

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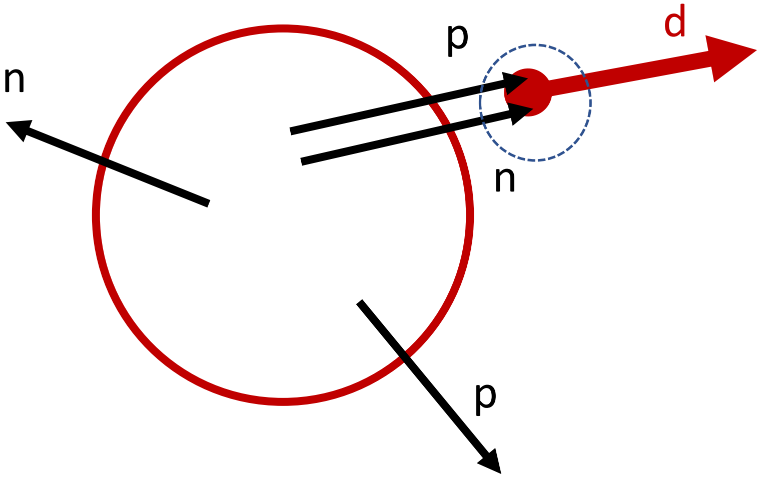
- r_T - Distribution
- Source Geometry

Summary

$$E\frac{d^3\sigma_d}{d\boldsymbol{P}^3} = B_2\left(\frac{E}{2}\frac{d^3\sigma_p}{d\left(\frac{\boldsymbol{P}}{2}\right)^3}\right)\left(\frac{E}{2}\frac{d^3\sigma_n}{d\left(\frac{\boldsymbol{P}}{2}\right)^3}\right) \quad (1)$$

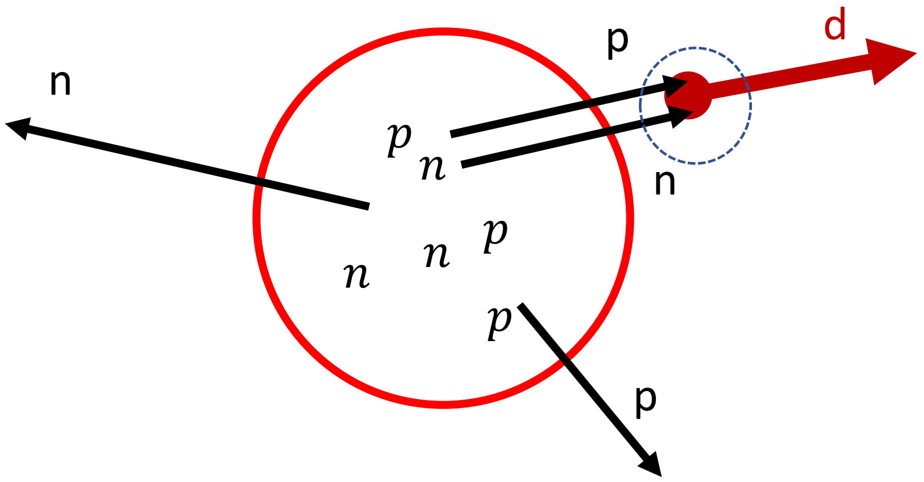
σ_i : Cross section
E : Deuteron energy
$\boldsymbol{P}$: Deuteron momentum
B_2: Coalescence parameter.



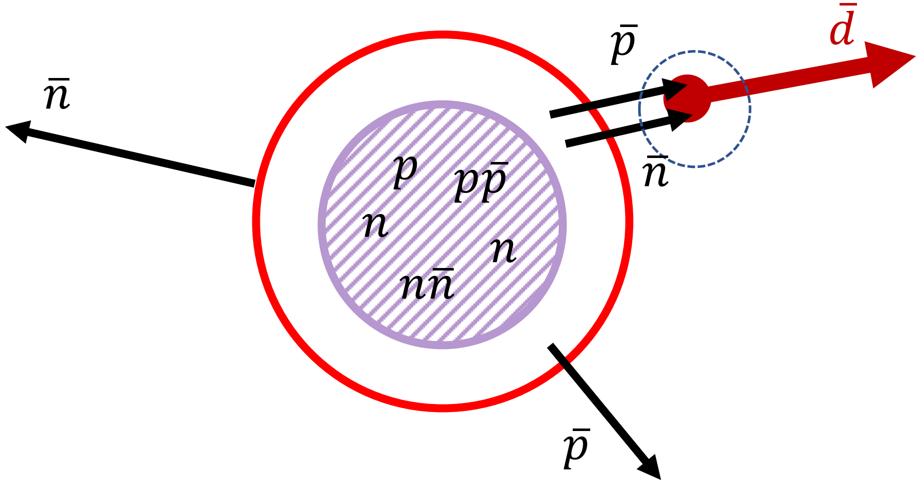
[1] Mrówczyński, S. (1993). Physics Letters B, 308(3-4), 216-219.

Mrowczynski's Coalescence Model

Nucleons are emitted from the **whole** source/fireball volume.



Antinucleons are emitted from the **outer shell** of the fireball volume.



Source Geometry Parametrization

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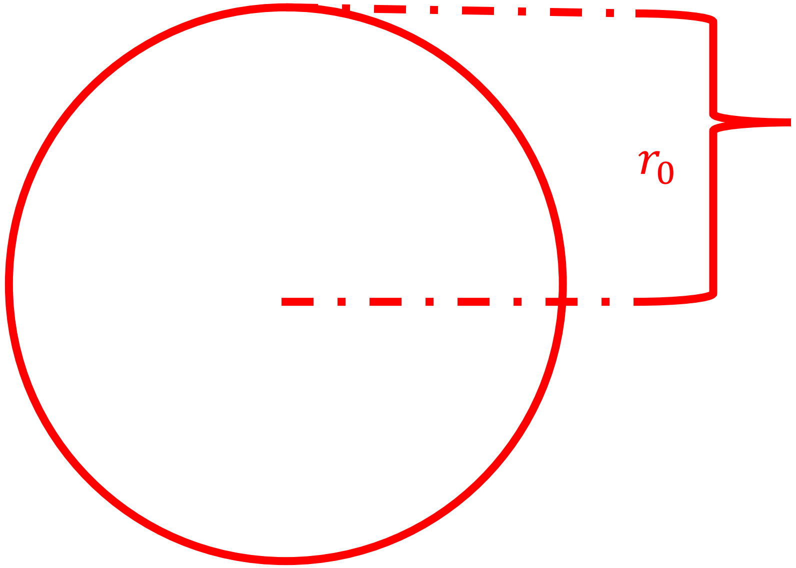
Summary

- **Nucleons :**
  - $\mathcal{D}(r) = \frac{1}{(2\pi)^{\frac{3}{2}} r_0^3} \exp\left(-\frac{r^2}{2r_0^2}\right)$ (2)



- **Antinucleons :**
  - $\bar{\mathcal{D}}(r) = \frac{1}{(2\pi)^{\frac{3}{2}}(r_0^3 - r_*^3)} \left[\exp\left(-\frac{r^2}{2r_0^2}\right) - \exp\left(-\frac{r^2}{2r_*^2}\right)\right]$

Source Geometry Parametrization

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  - $$\mathcal{D}(r) = \frac{1}{(2\pi)^{\frac{3}{2}} r_0^3} \exp\left(-\frac{r^2}{2r_0^2}\right) \quad (2)$$

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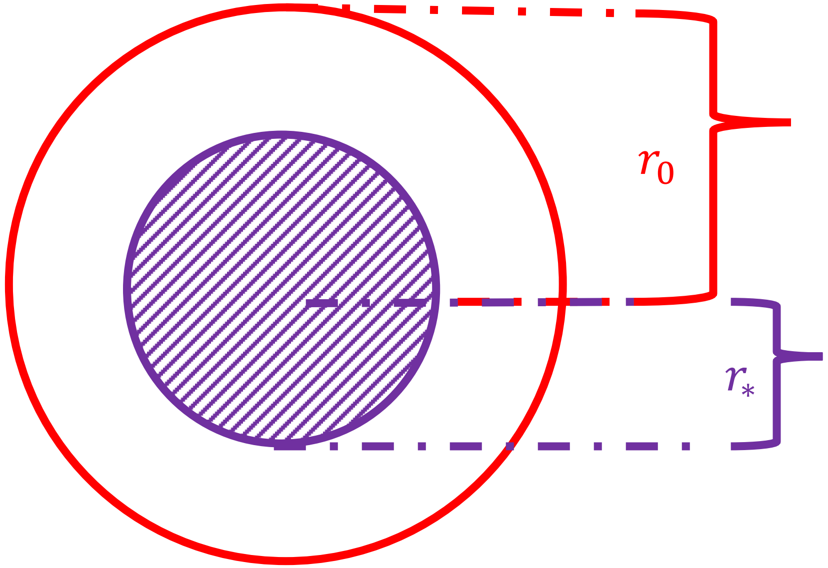

Formation Rate

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Summary

The formation rate is $\left(\frac{d^3N_d}{dP^3}\right)/\left(\frac{d^3N_p}{dP^3}\right)^2$ and is equal to the probability:

$$\mathcal{A}(r_0, r_*) = \int d^3r_p d^3r_n \mathcal{D}(\vec{r}_p)\mathcal{D}(\vec{r}_n)|\phi(\vec{r}_p - \vec{r}_n)^2| \quad (4)$$

Then B_2 is related to formation rate via,

$$\frac{m_N}{2}\mathcal{A}(r_0, r_*) = B_2 \quad (5)$$

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Summary

[2] R. Arsenescu et al. (NA52 (NEWMASS)), J. Phys. G25, 225 (1999)

[3] G. Van Buren (E864), Nucl. Phys. A661, 391 (1999)

[4] T. Armstrong et al. (E864), Phys. Rev. Lett.85, 2685(2000),nucl-ex/0005001

[5] J. Adam et al. (STAR), Phys. Rev. C99, 064905(2019),1903.11778

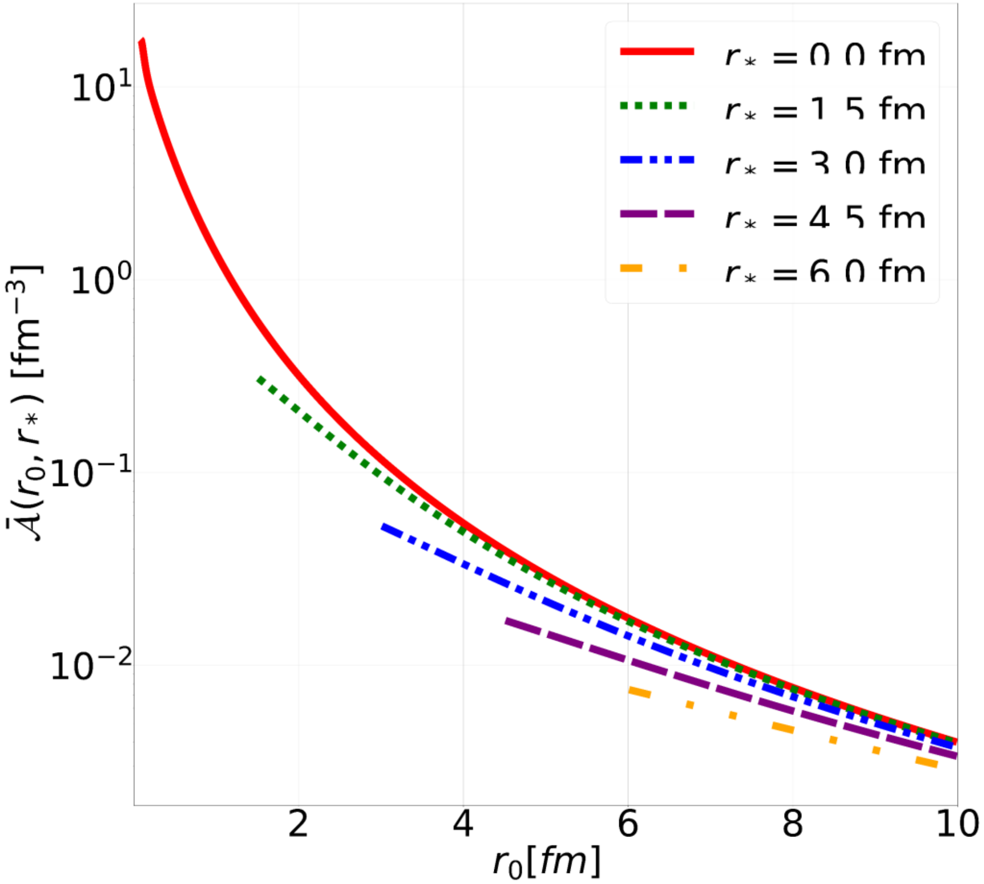

Figure 1: A few calculated formation rates (Eq. 4) varying r_* from 0-6 fm.

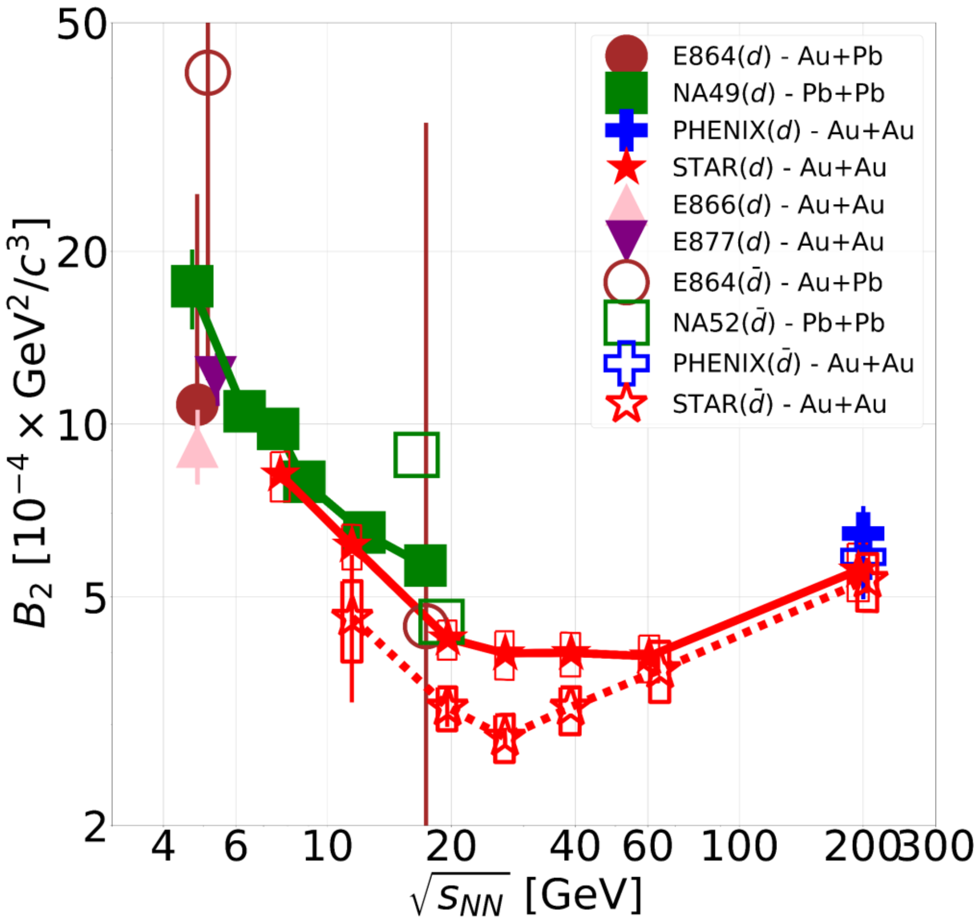

Figure 2: The B2 from experiment used for converting into formation rate as a function of $\sqrt{s_{NN}}$ [2-5].

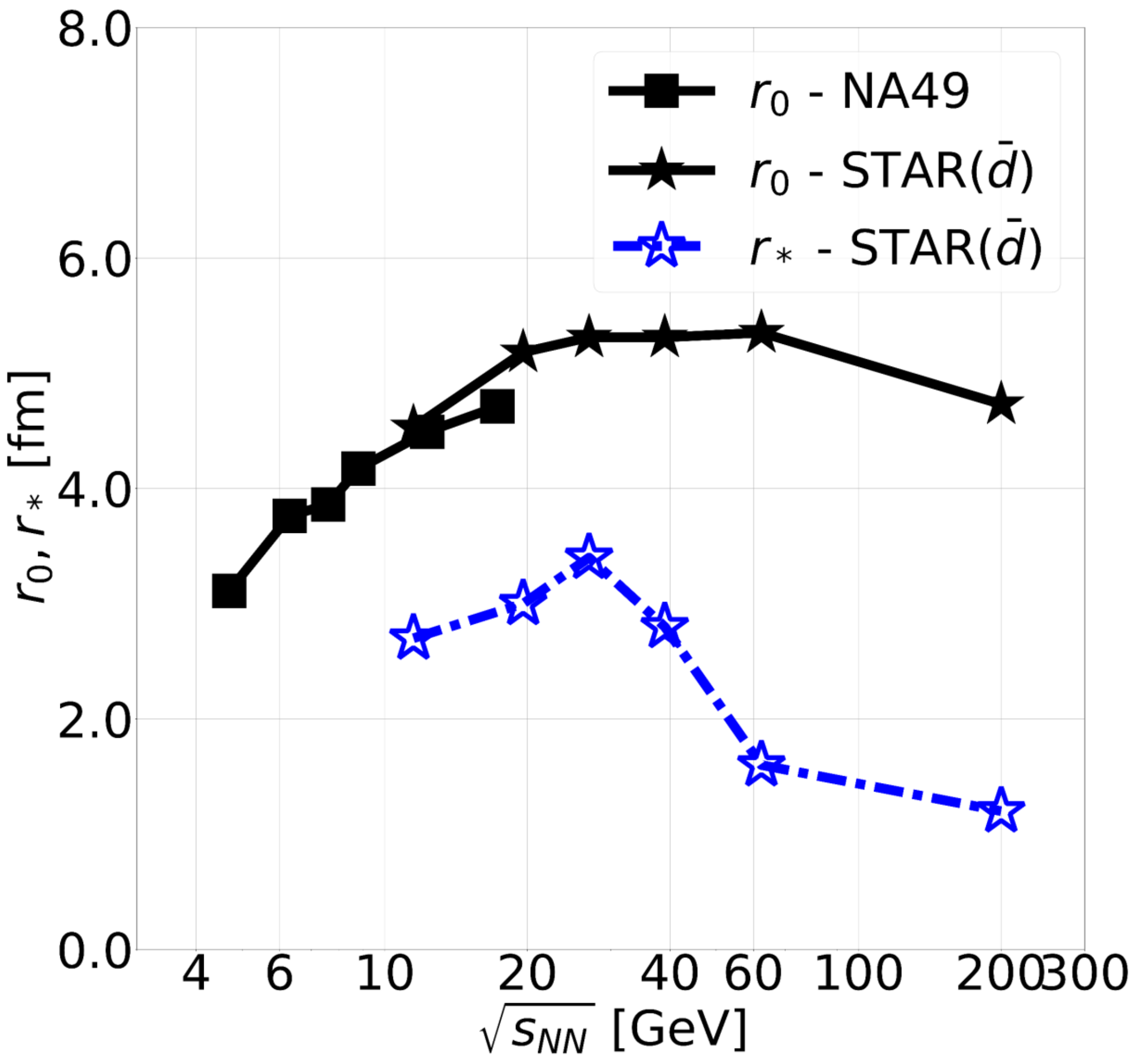

Figure 3: The (anti-)nucleon source radius and the suppression region as a function of energy.

Charged Volume Constraint

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Summary

1. We constrain RMS radius with charged volume data,

$$RMS(r_0, r_*) = const \cdot N_{ch}^{\frac{1}{3}} \qquad (6)$$

2. We use Eq. (5) & (6) to solve for the radii.

[6] - Adare, A. et al (2016). *Physical Review C*, *93*(2), 024901.
[7] - Ghosh, S., (2017). *Physical Review C*, *96*(2), 024912.

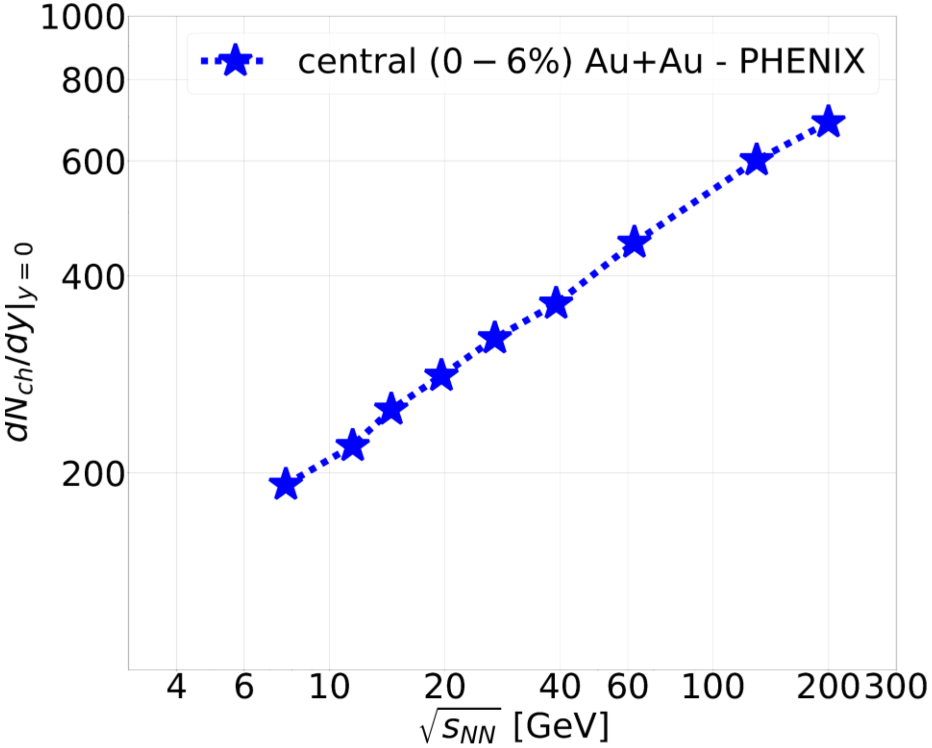


Figure 4: The energy dependence of total charged particle at mid-rapidity from PHENIX [6-7].

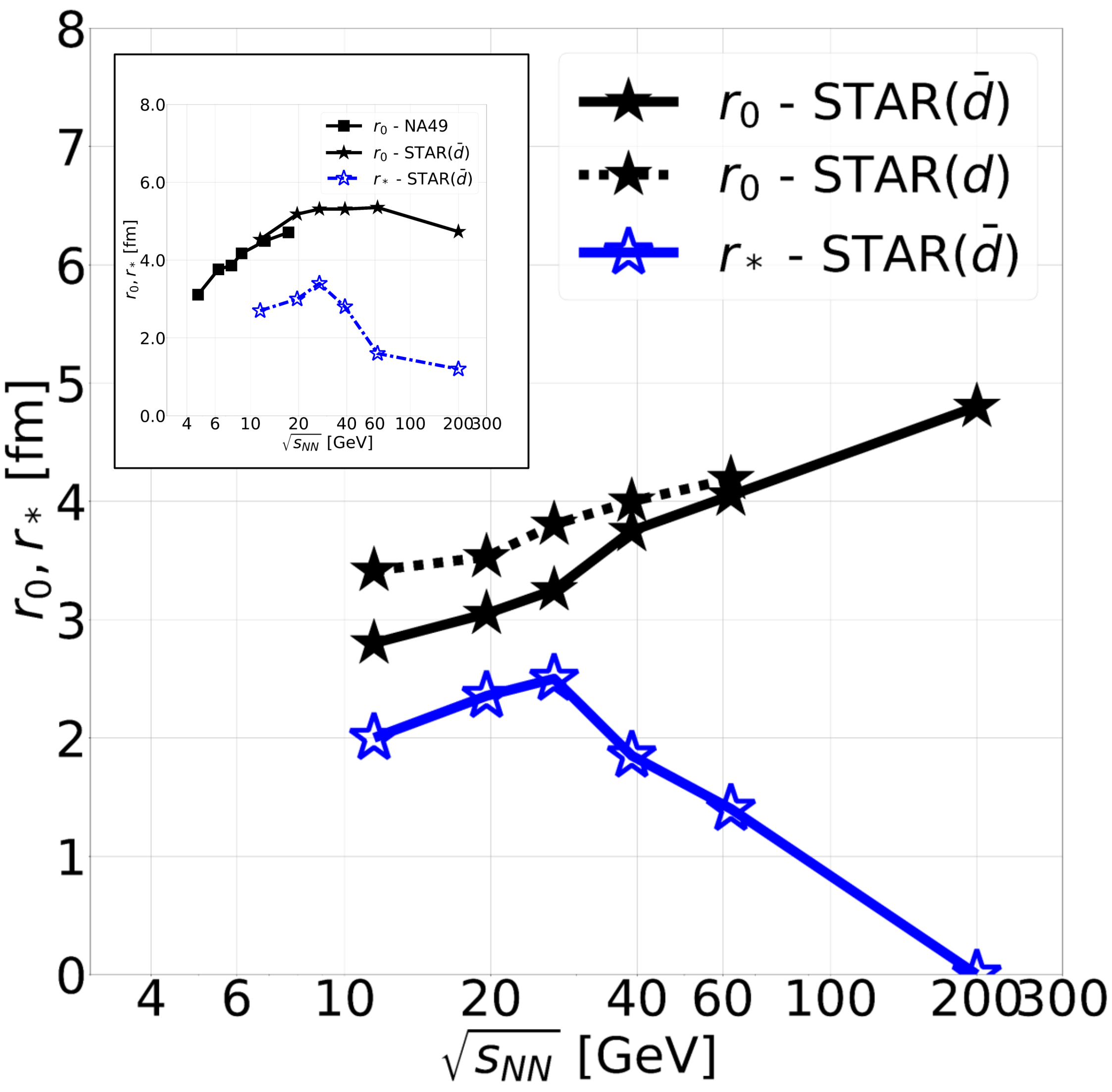


Figure 5: The (anti-)nucleon source radius from charged volume as a function of energy.

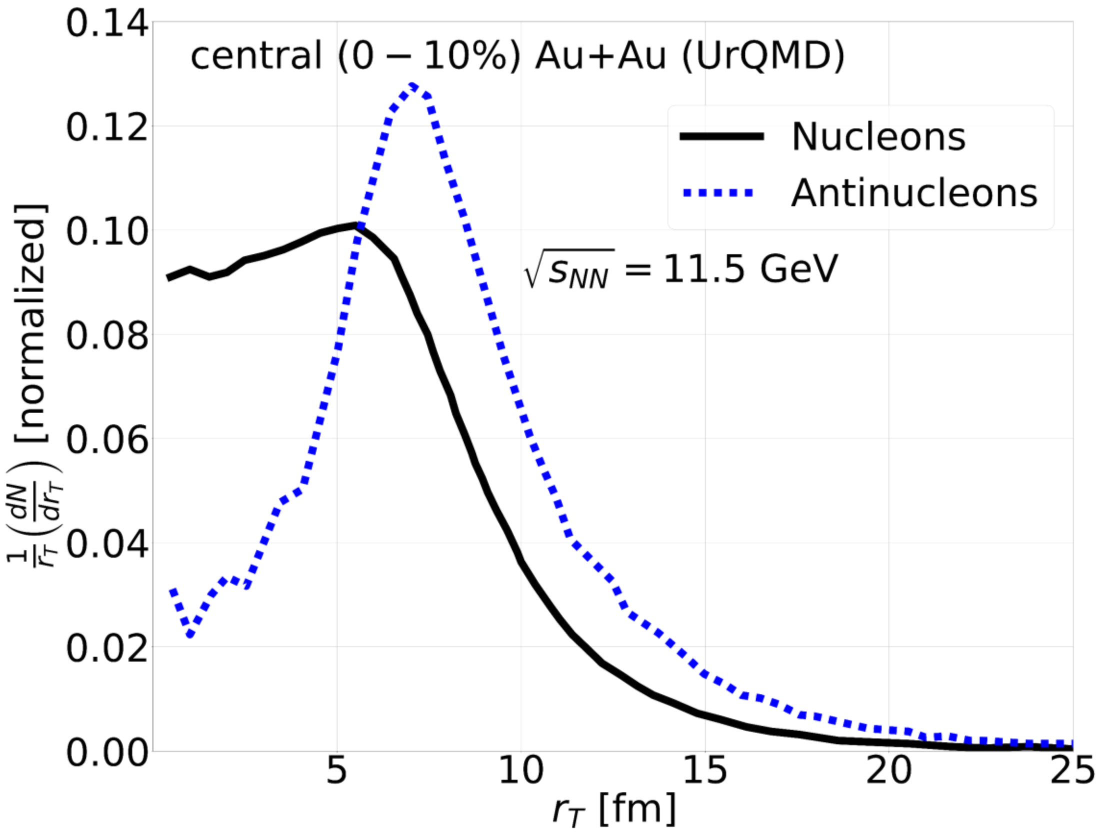
UrQMD

The Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model is a microscopic transport model.

Objective

To extract the freeze-out coordinate of the (anti)nucleons and fit directly with $\mathcal{D}(r)$ and $\overline{\mathcal{D}}(r)$ via transverse radius r_T to get the r_0 and r_* at $7.7 - 200$ GeV.

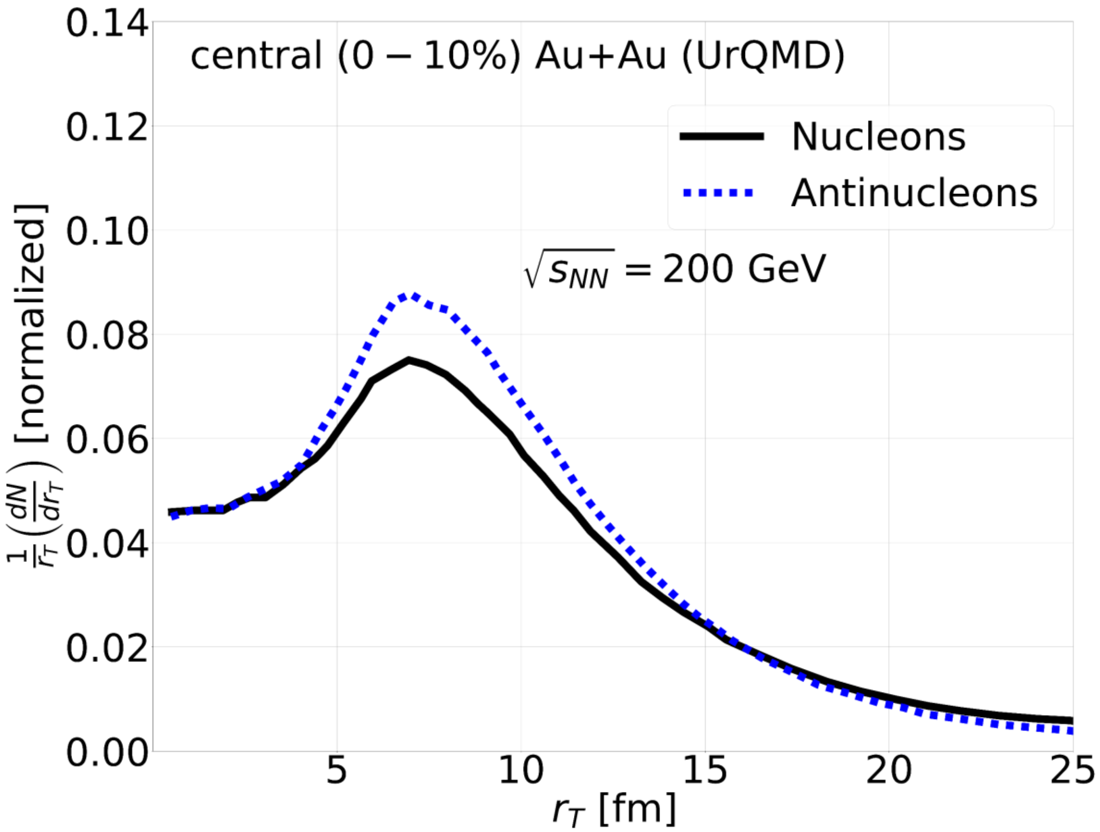
r_T - Distributions



This agrees with the Gaussian source shape as well as the assumed source of an annihilation.

Figure 6: The (anti-)nucleon distributions along the transverse radius r_T at 11.5 GeV.

r_T - Distributions



This means that the nucleon source $\mathcal{D}(r)$ is **ALSO** suppressed in the center.

Figure 7: The (anti-)nucleon distributions along the transverse radius r_T at 200 GeV.

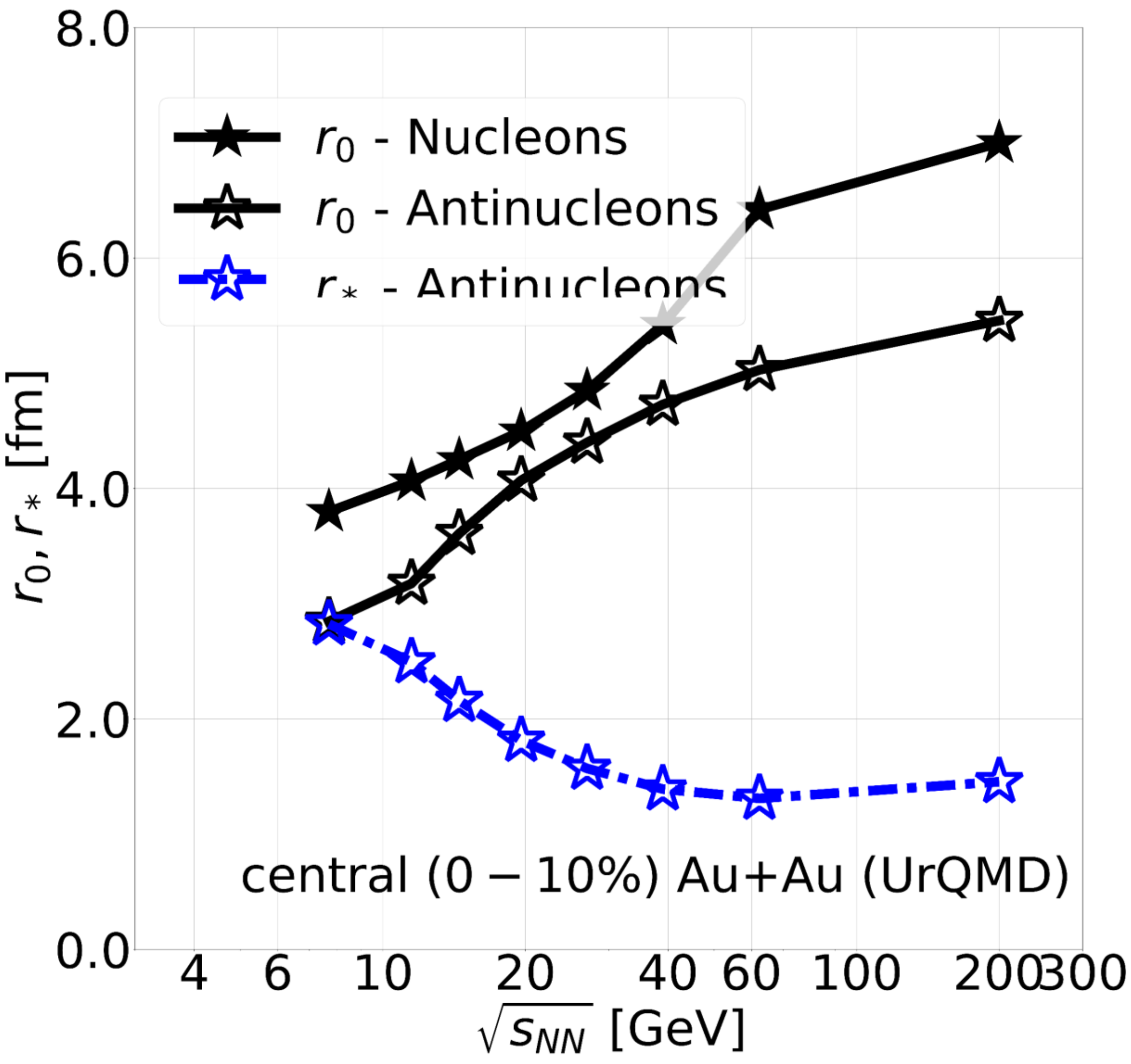


Figure 8: The fireball radius r_0 and the antinucleon suppression region r_* UrQMD.

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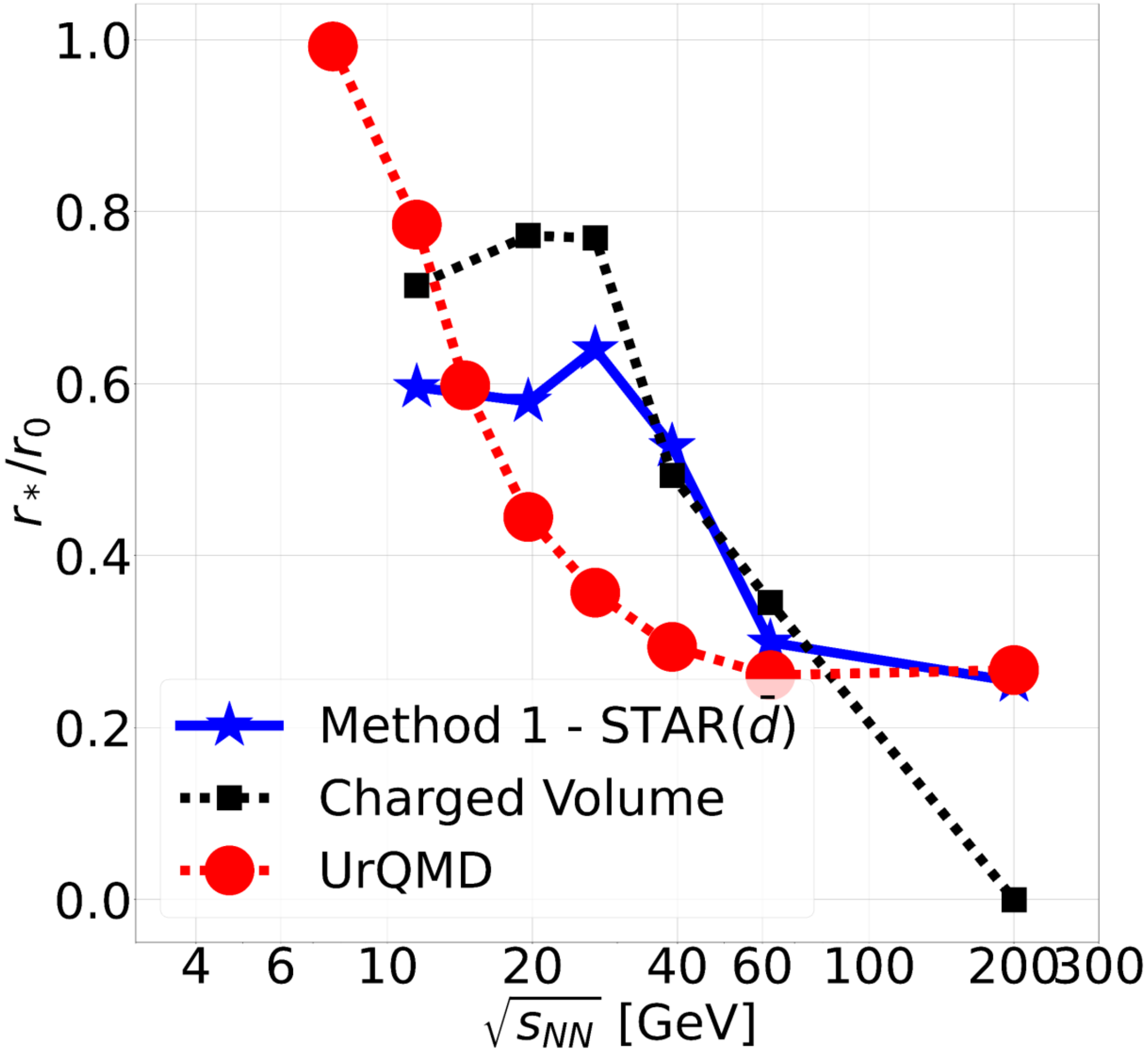


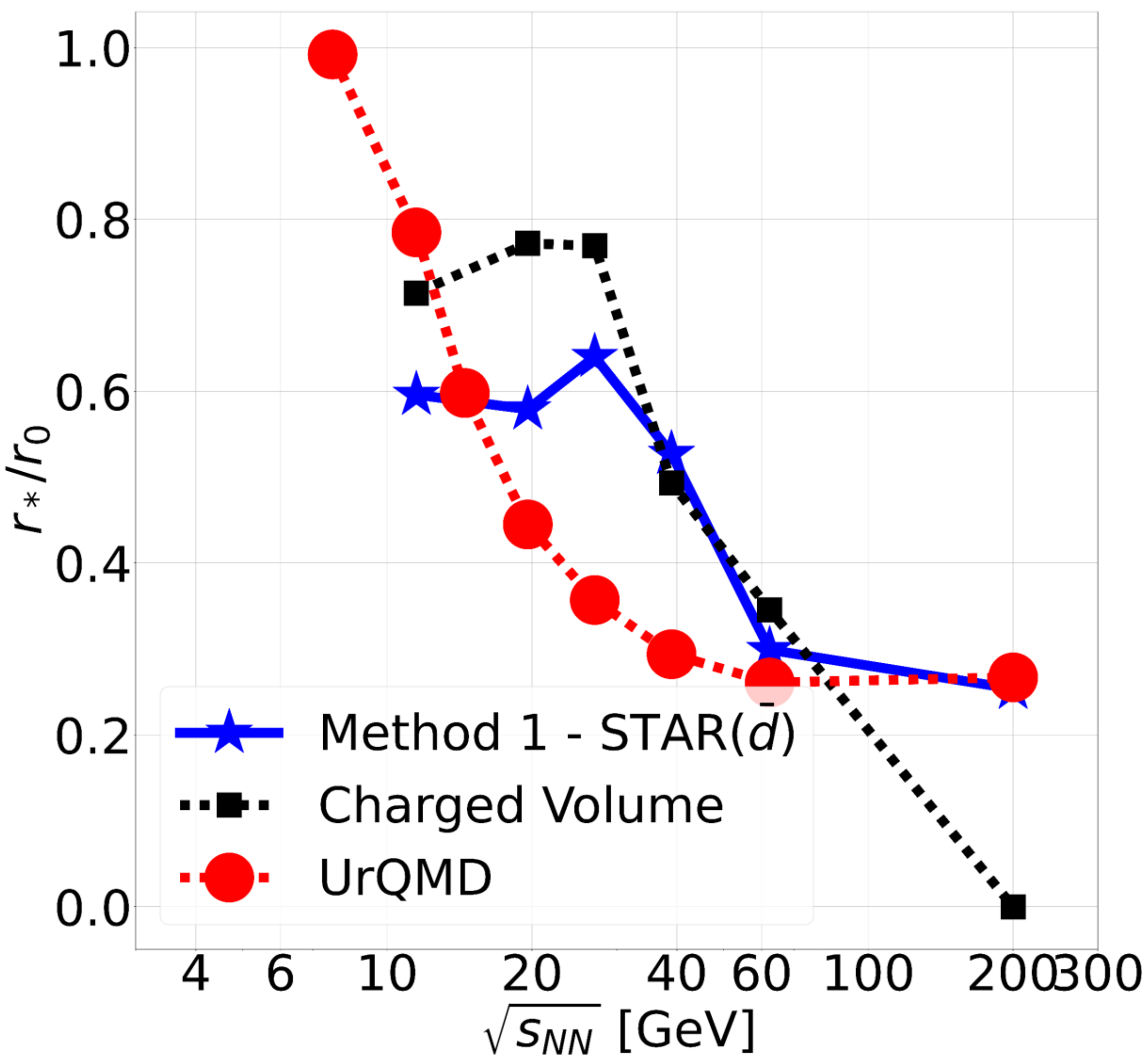
Figure 9: Comparison of ${r_*}/{r_0}$ from different methods.

Summary

- We use Spatial Coalescence model to extract the source geometry, (r0, r*) (Fig 3).
- We extract (r0,r*) from the charged volume constraint (Fig5).
- We extract the source geometry via UrQMD (Fig 8).

All results support our two explanations (Fig 9);

1. The antinucleons are emitted from the outer shell (supported by UrQMD).
2. The pionnic environment affects the source geometries.



BACK UP SLIDES

1. **Density and Wave Function**
2. **Flow Effect**
3. **First Method Flow Chart**
4. **Second Method Flow Chart**

Density & Wave function

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Summary

- **Hulthen Wave function:** $\phi_d(r) = \left(\frac{\alpha\beta(\alpha-\beta)}{2\pi(\alpha+\beta)^2}\right)^{\frac{1}{2}}\left(\frac{e^{-\alpha r}-e^{-\beta r}}{r}\right)$ where $\alpha = 0.23\ \text{fm}^{-1}$ $\beta = 1.61\ \text{fm}^\wedge - 1$
- **Formation rate in relative coordinate:** $\mathcal{A}(r) \equiv (2\pi)^3 \int d^3r\, \mathcal{D}_r(r)|\phi_d(r)|^2$
  - $$\mathcal{D}_r(r) = \frac{1}{(4\pi)^{3/2} r_0^3} e^{\left(-\frac{r^2}{4r_0^2}\right)}$$
  - $$\bar{\mathcal{D}}_r(r) = \frac{r_0^3 e^{-\frac{r^2}{4r_0^2}} + r_*^3 e^{-\frac{r^2}{4r_*^2}} - \frac{2^{\frac{5}{2}} r_0^3 r_*^3}{(r_0^2+r_*^2)^{\frac{3}{2}}} e^{-\frac{r^2}{2(r_0^2+r_*^2)}}}{(4\pi)^{\frac{3}{2}} \left(r_0^3 - r_*^3\right)^2}$$

Flow Effect

In the Mrowczynski's model, the parameter r_0 is to be replace by

$$r_0' = \sqrt{r_0^2 + v^2\,\tau^2}$$

Here v is the velocity of the (anti-)deuterons and τ is the freeze-out duration [7, 8].

[7] Maj, R., & Mrowczynski, S. (2009). Physical Review C, 80(3), 034907.

[8] Mrowczynski, S., & Slon, P. (2019). arXiv:1904.08320.

Flow effects become important only $\sqrt{s_{NN}} \simeq 60$ GeV [9]

[9] Gaebel, V., Bonne, M., et al (2020). arXiv:2006.12951.

Source Geometry

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Summary

1. Convert $B_2(E)$ data into formation rate $\mathcal{A}(E)$

2. Calculate all possible formation $\mathcal{A}(r_0, r_*)$ from any give r_0 and r_*

3. Fit $\mathcal{A}(r_0)$ to extract r_0 first. Then fit $\bar{\mathcal{A}}(r_0, r_*)$ with one from the experiment $\bar{\mathcal{A}}(E)$ to extract the radii.

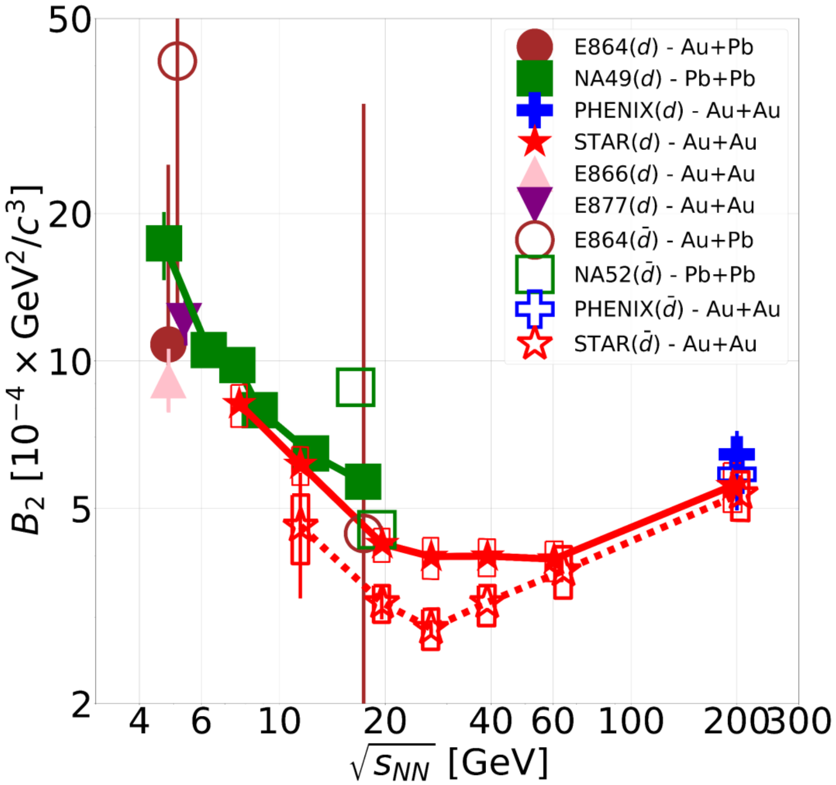

Figure 7: The B2 from experiment used for converting into formation rate as a function of $\sqrt{s_{NN}}$.

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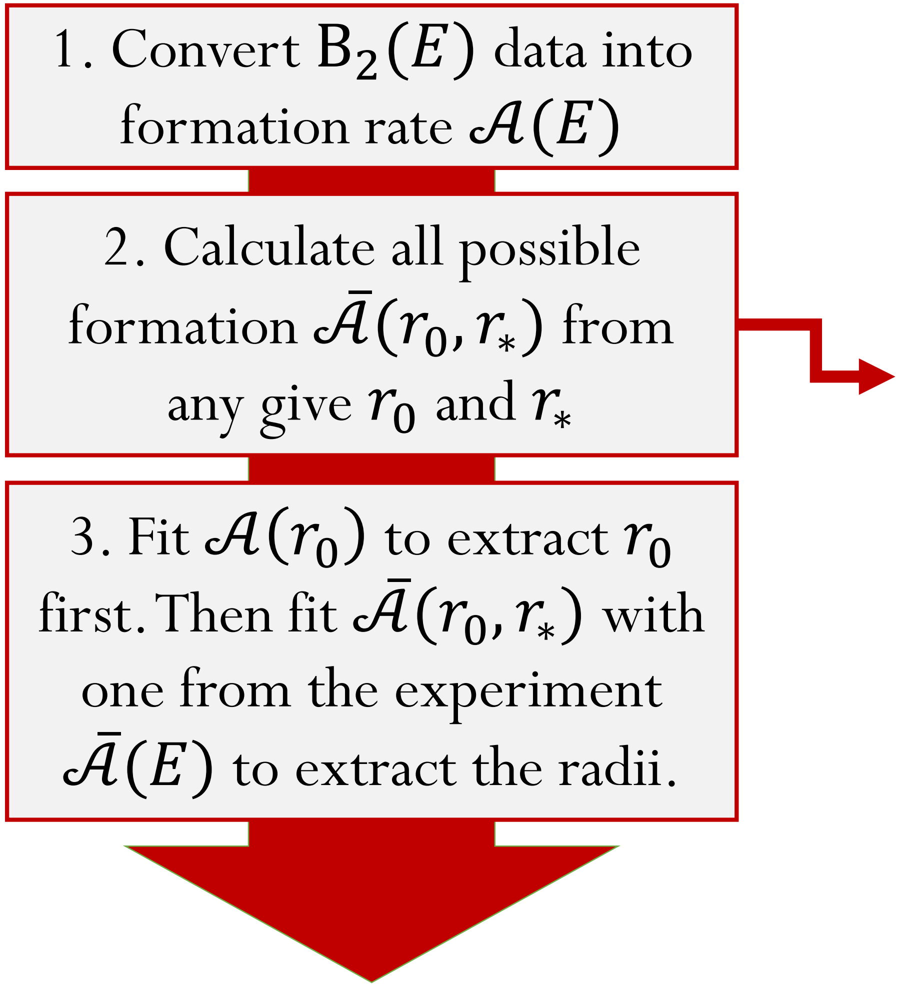

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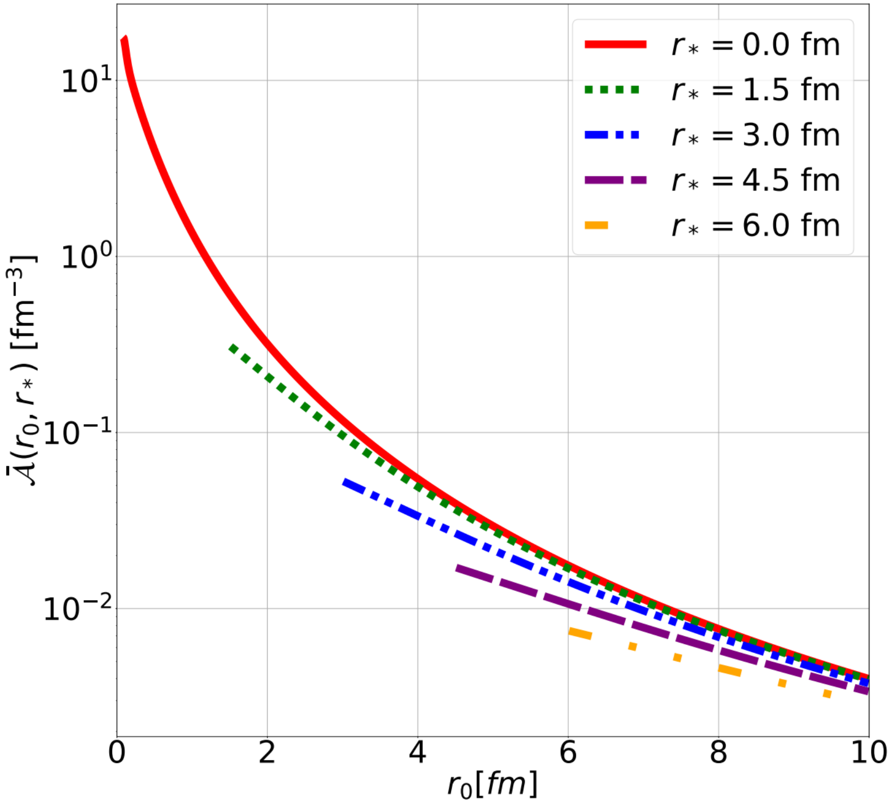

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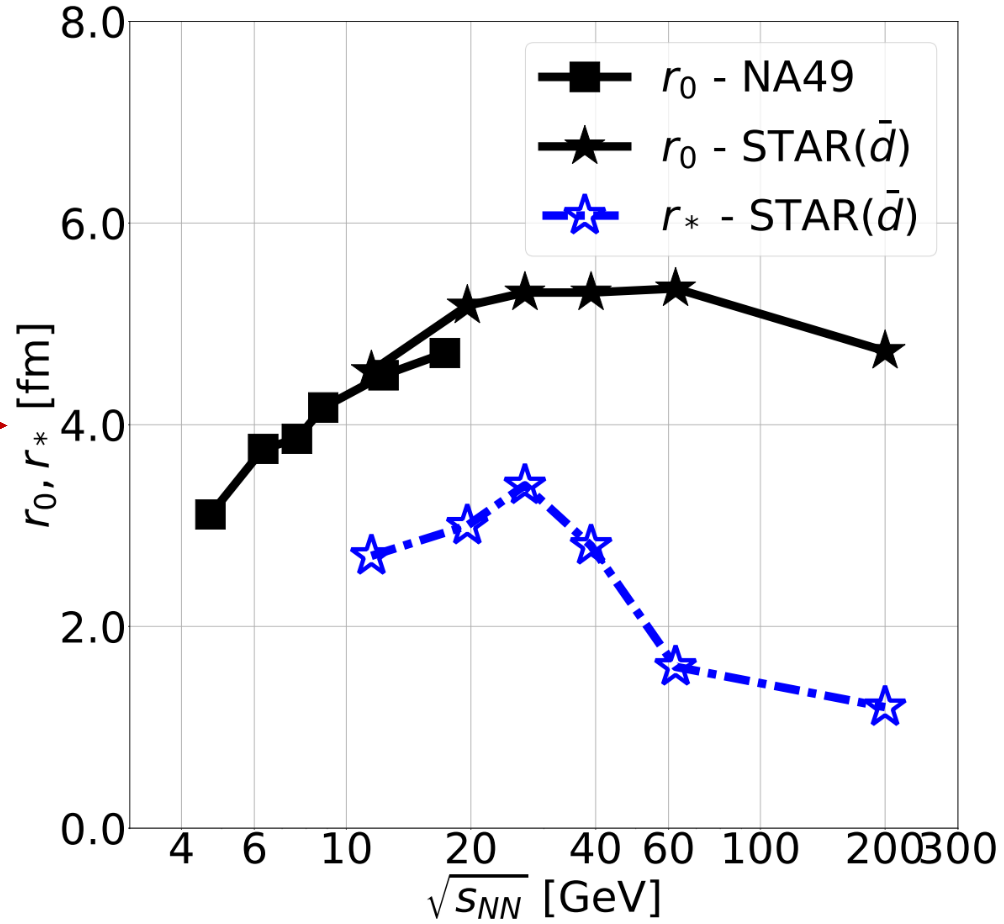

Source Geometry

1. Convert Number of Charged-particle to RMS

$$\langle r^2\rangle \propto N_{ch}^{\frac{1}{3}} \;\; where \; \langle \bar{r}^2\rangle = \sqrt{\frac{3\left(r_0^5 - r_*^5\right)}{\left(r_0^3 - r_*^3\right)}}$$

2. Choose the scaling factor for $const = 0.9$ such that r* is zero at 200 GeV

3. Extract (r_0, r_*) pair simultaneously from

$$\mathcal{A}(r_0, r_*) \propto B_2$$

$$\langle r^2\rangle(r_0, r_*) = Const.\, N_{ch}^{\frac{1}{3}}$$

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