Two-component source to explain Λ and $\bar{\Lambda}$ global polarization in non-central heavy-ion collisions

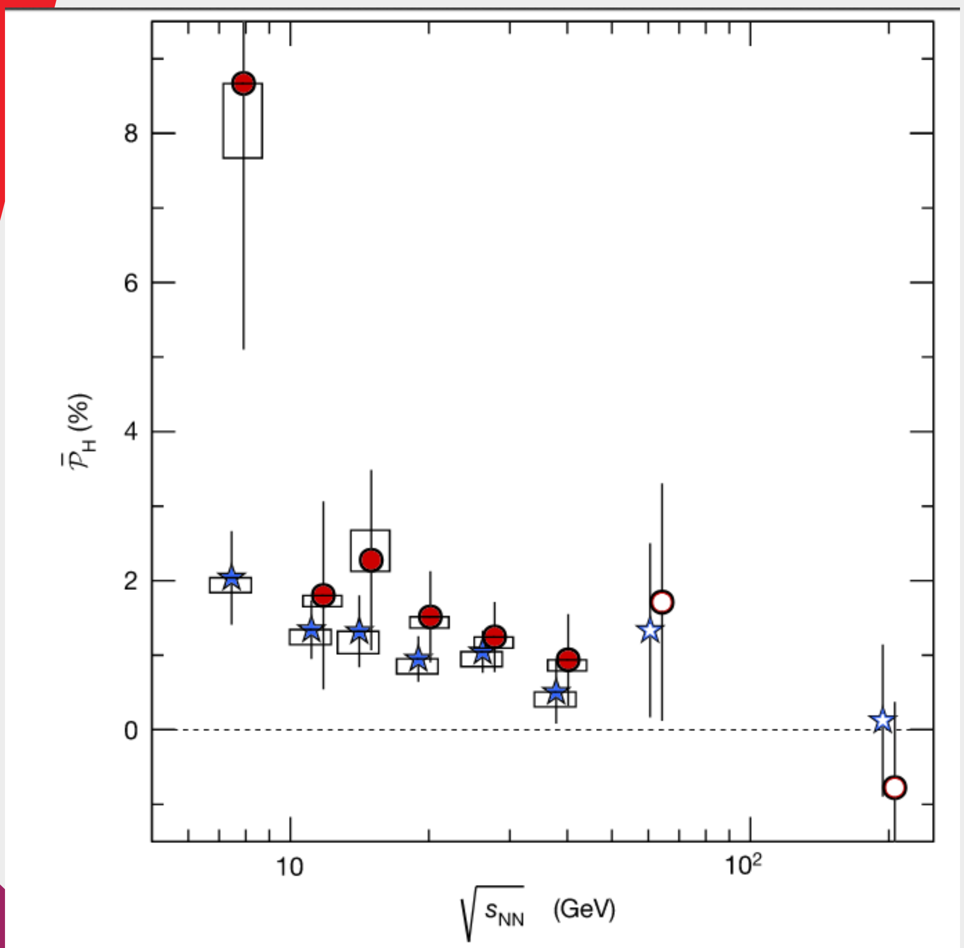
Ivonne Alicia Maldonado Cervantes
ivonne.alicia.maldonado@gmail.com

Colaboration with:
I. Dominguez, A. Ayala, Ma. E. Tejeda Yeomans, E. Cuautle, J. Salinas

March 6th, 2020

Λ $\bar{\Lambda}$ Polarization from STAR

Nature, Vol 548 (2017)



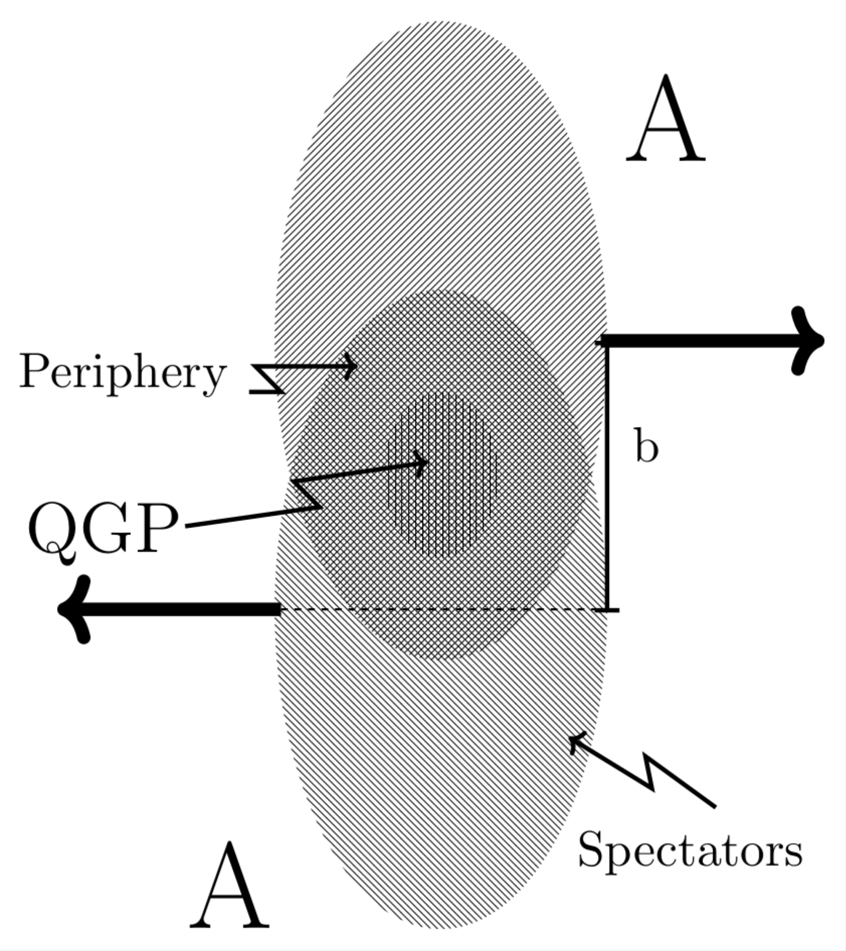
- Polarization is defined as:

$$\mathcal{P} = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}.$$

- Associated with the medium properties:

$$\overline{\omega}_{\mu\nu} = \frac{1}{2}\left(\partial_\nu \beta_\mu - \partial_\mu \beta_\nu\right)$$

Two regions



In heavy-ion collisions, Λ and $\overline{\Lambda}$ come from different density regions.

- From the QGP in processes like

$$q\overline{q} \rightarrow s\overline{s} \text{ and } gg \rightarrow s\overline{s}$$

- From the periphery they are produced by recombination-like processes.

The number of Λs can be written

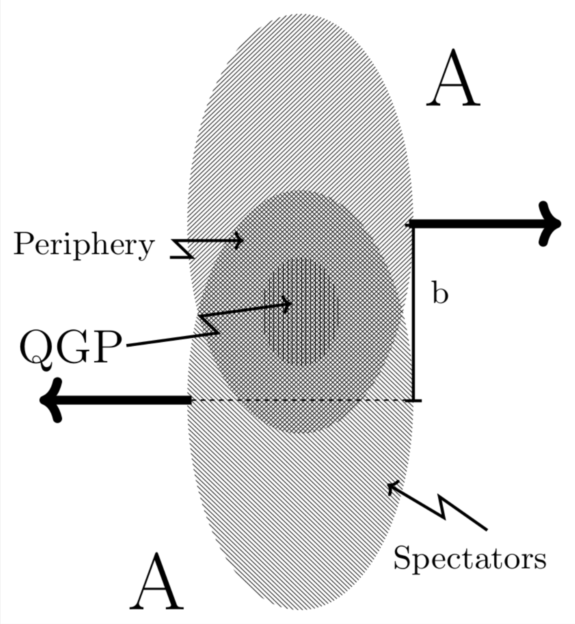
$$N_\Lambda = N_{\Lambda\ \mathrm{QGP}} + N_{\Lambda\ \mathrm{REC}};$$

The polarization can be

$$\mathcal{P} = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}.$$

rewritten in terms of the number of Λs (or $\overline{\Lambda}$s) produced in the different density regions (QGP and Periphery).

Two regions



$$\mathcal{P}^{\Lambda} = \frac{(N^{\uparrow}_{\Lambda\,\mathrm{QGP}} + N^{\uparrow}_{\Lambda\,\mathrm{REC}}) - (N^{\downarrow}_{\Lambda\,\mathrm{QGP}} + N^{\downarrow}_{\Lambda\,\mathrm{REC}})}{(N^{\uparrow}_{\Lambda\,\mathrm{QGP}} + N^{\uparrow}_{\Lambda\,\mathrm{REC}}) + (N^{\downarrow}_{\Lambda\,\mathrm{QGP}} + N^{\downarrow}_{\Lambda\,\mathrm{REC}})}$$

$$\mathcal{P}^{\overline{\Lambda}} = \frac{(N^{\uparrow}_{\overline{\Lambda}\,\mathrm{QGP}} + N^{\uparrow}_{\overline{\Lambda}\,\mathrm{REC}}) - (N^{\downarrow}_{\overline{\Lambda}\,\mathrm{QGP}} + N^{\downarrow}_{\overline{\Lambda}\,\mathrm{REC}})}{(N^{\uparrow}_{\overline{\Lambda}\,\mathrm{QGP}} + N^{\uparrow}_{\overline{\Lambda}\,\mathrm{REC}}) + (N^{\downarrow}_{\overline{\Lambda}\,\mathrm{QGP}} + N^{\downarrow}_{\overline{\Lambda}\,\mathrm{REC}})}$$

Assumptions

After some algebra, we get:

$$\mathcal{P}^{\Lambda} = \frac{\left(\mathcal{P}^{\Lambda}_{\mathrm{REC}} + \frac{N^{\uparrow}_{\Lambda\ \mathrm{QGP}} - N^{\downarrow}_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}\right)}{\left(1 + \frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}\right)}$$

$$\mathcal{P}^{\overline{\Lambda}} = \frac{\left(\mathcal{P}^{\overline{\Lambda}}_{\mathrm{REC}} + \frac{N^{\uparrow}_{\overline{\Lambda}\ \mathrm{QGP}} - N^{\downarrow}_{\overline{\Lambda}\ \mathrm{QGP}}}{N_{\overline{\Lambda}\ \mathrm{REC}}}\right)}{\left(1 + \frac{N_{\overline{\Lambda}\ \mathrm{QGP}}}{N_{\overline{\Lambda}\ \mathrm{REC}}}\right)},$$

Where:

$$\mathcal{P}^{\Lambda}_{\mathrm{REC}} = \frac{N^{\uparrow}_{\Lambda\,\mathrm{REC}} - N^{\downarrow}_{\Lambda\,\mathrm{REC}}}{N^{\uparrow}_{\Lambda\,\mathrm{REC}} + N^{\downarrow}_{\Lambda\,\mathrm{REC}}},$$

$$\mathcal{P}^{\overline{\Lambda}}_{\mathrm{REC}} = \frac{N^{\uparrow}_{\overline{\Lambda}\,\mathrm{REC}} - N^{\downarrow}_{\overline{\Lambda}\,\mathrm{REC}}}{N^{\uparrow}_{\overline{\Lambda}\,\mathrm{REC}} + N^{\downarrow}_{\overline{\Lambda}\,\mathrm{REC}}}.$$

Assumptions

After some algebra, we get:

$$\mathcal{P}^{\Lambda} = \frac{\left(\mathcal{P}^{\Lambda}_{\rm REC} + \frac{N^{\uparrow}_{\Lambda\ \rm QGP} - N^{\downarrow}_{\Lambda\ \rm QGP}}{N_{\Lambda\ \rm REC}}\right)}{\left(1 + \frac{N_{\Lambda\ \rm QGP}}{N_{\Lambda\ \rm REC}}\right)}$$

$$\mathcal{P}^{\overline{\Lambda}} = \frac{\left(\mathcal{P}^{\overline{\Lambda}}_{\rm REC} + \frac{N^{\uparrow}_{\overline{\Lambda}\ \rm QGP} - N^{\downarrow}_{\overline{\Lambda}\ \rm QGP}}{N_{\overline{\Lambda}\ \rm REC}}\right)}{\left(1 + \frac{N_{\overline{\Lambda}\ \rm QGP}}{N_{\overline{\Lambda}\ \rm REC}}\right)},$$

Where:

$$\mathcal{P}^{\Lambda}_{\rm REC} = \frac{N^{\uparrow}_{\Lambda\,\rm REC} - N^{\downarrow}_{\Lambda\,\rm REC}}{N^{\uparrow}_{\Lambda\,\rm REC} + N^{\downarrow}_{\Lambda\,\rm REC}},$$

$$\mathcal{P}^{\overline{\Lambda}}_{\rm REC} = \frac{N^{\uparrow}_{\overline{\Lambda}\,\rm REC} - N^{\downarrow}_{\overline{\Lambda}\,\rm REC}}{N^{\uparrow}_{\overline{\Lambda}\,\rm REC} + N^{\downarrow}_{\overline{\Lambda}\,\rm REC}}.$$

In the periphery polarization from p+p like processes

- Nucleon-nucleon scattering not enough to align Λ spin with angular momentum
- Polarization of Λ and $\overline{\Lambda}$ in this region averages to zero.

$$\mathcal{P}^{\Lambda}_{\rm REC} = \mathcal{P}^{\overline{\Lambda}}_{\rm REC} = 0$$

Assumptions

After some algebra, we get:

$$\mathcal{P}^{\Lambda} = \frac{\left(\mathcal{P}^{\Lambda}_{\rm REC} + \frac{N^{\uparrow}_{\Lambda\ \rm QGP} - N^{\downarrow}_{\Lambda\ \rm QGP}}{N_{\Lambda\ \rm REC}}\right)}{\left(1 + \frac{N_{\Lambda\ \rm QGP}}{N_{\Lambda\ \rm REC}}\right)}$$

$$\mathcal{P}^{\overline{\Lambda}} = \frac{\left(\mathcal{P}^{\overline{\Lambda}}_{\rm REC} + \frac{N^{\uparrow}_{\overline{\Lambda}\ \rm QGP} - N^{\downarrow}_{\overline{\Lambda}\ \rm QGP}}{N_{\overline{\Lambda}\ \rm REC}}\right)}{\left(1 + \frac{N_{\overline{\Lambda}\ \rm QGP}}{N_{\overline{\Lambda}\ \rm REC}}\right)},$$

$$\mathcal{P}^{\Lambda}_{\rm REC} = \mathcal{P}^{\overline{\Lambda}}_{\rm REC} = 0$$

- z and $\bar{z}$ represent the Λ and $\overline{\Lambda}$ intrinsic polarization respectively.
- Assuming the number of $\overline{\Lambda}$s is equal to the number of Λs.

Where:

$$\mathcal{P}^{\Lambda}_{\rm REC} = \frac{N^{\uparrow}_{\Lambda\,\rm REC} - N^{\downarrow}_{\Lambda\,\rm REC}}{N^{\uparrow}_{\Lambda\,\rm REC} + N^{\downarrow}_{\Lambda\,\rm REC}},$$

$$\mathcal{P}^{\overline{\Lambda}}_{\rm REC} = \frac{N^{\uparrow}_{\overline{\Lambda}\,\rm REC} - N^{\downarrow}_{\overline{\Lambda}\,\rm REC}}{N^{\uparrow}_{\overline{\Lambda}\,\rm REC} + N^{\downarrow}_{\overline{\Lambda}\,\rm REC}}.$$

$$N^{\uparrow}_{\Lambda\ \rm QGP} - N^{\downarrow}_{\Lambda\ \rm QGP} = zN_{\Lambda\ \rm QGP}$$

$$N^{\uparrow}_{\overline{\Lambda}\ \rm QGP} - N^{\downarrow}_{\overline{\Lambda}\ \rm QGP} = \bar{z}N_{\overline{\Lambda}\ \rm QGP} \simeq \bar{z}N_{\Lambda\ \rm QGP}$$

Assumptions

After some algebra, we get:

$$\mathcal{P}^{\Lambda} = \frac{\left(\mathcal{P}^{\Lambda}_{\rm REC} + \frac{N^{\uparrow}_{\Lambda\ \rm QGP} - N^{\downarrow}_{\Lambda\ \rm QGP}}{N_{\Lambda\ \rm REC}}\right)}{\left(1 + \frac{N_{\Lambda\ \rm QGP}}{N_{\Lambda\ \rm REC}}\right)}$$

$$\mathcal{P}^{\overline{\Lambda}} = \frac{\left(\mathcal{P}^{\overline{\Lambda}}_{\rm REC} + \frac{N^{\uparrow}_{\overline{\Lambda}\ \rm QGP} - N^{\downarrow}_{\overline{\Lambda}\ \rm QGP}}{N_{\overline{\Lambda}\ \rm REC}}\right)}{\left(1 + \frac{N_{\overline{\Lambda}\ \rm QGP}}{N_{\overline{\Lambda}\ \rm REC}}\right)},$$

$$\mathcal{P}^{\Lambda}_{\rm REC} = \mathcal{P}^{\overline{\Lambda}}_{\rm REC} = 0$$

$$N^{\uparrow}_{\Lambda\ \rm QGP} - N^{\downarrow}_{\Lambda\ \rm QGP} = zN_{\Lambda\ \rm QGP}$$
$$N^{\uparrow}_{\overline{\Lambda}\ \rm QGP} - N^{\downarrow}_{\overline{\Lambda}\ \rm QGP} = \bar{z}N_{\overline{\Lambda}\ \rm QGP} \simeq \bar{z}N_{\Lambda\ \rm QGP}$$

Where:

$$\mathcal{P}^{\Lambda}_{\rm REC} = \frac{N^{\uparrow}_{\Lambda\,\rm REC} - N^{\downarrow}_{\Lambda\,\rm REC}}{N^{\uparrow}_{\Lambda\,\rm REC} + N^{\downarrow}_{\Lambda\,\rm REC}},$$

$$\mathcal{P}^{\overline{\Lambda}}_{\rm REC} = \frac{N^{\uparrow}_{\overline{\Lambda}\,\rm REC} - N^{\downarrow}_{\overline{\Lambda}\,\rm REC}}{N^{\uparrow}_{\overline{\Lambda}\,\rm REC} + N^{\downarrow}_{\overline{\Lambda}\,\rm REC}}.$$

- The number of $\overline{\Lambda}$s in the periphery is proportional to an energy-dependent coefficient w times the number of Λs

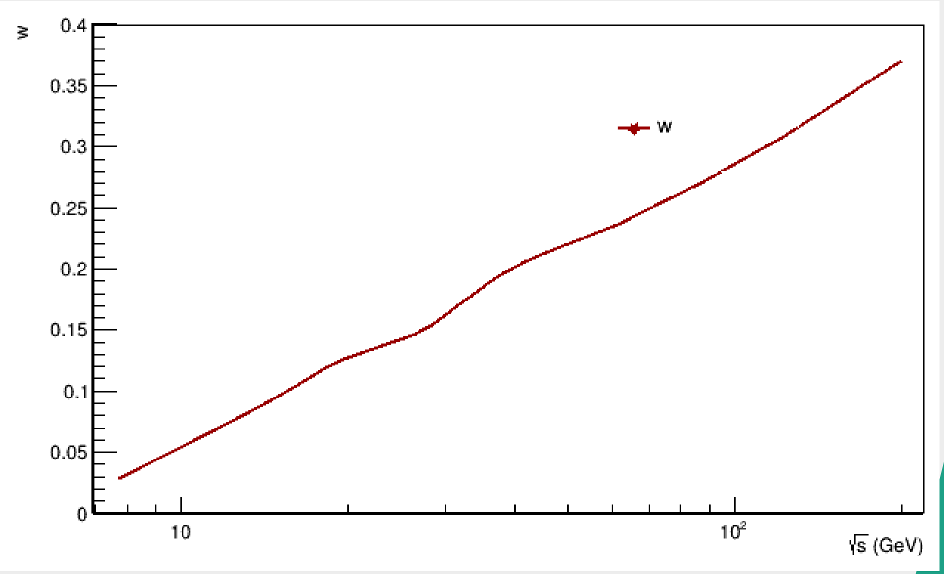
$$N_{\overline{\Lambda}\ \rm REC} \equiv wN_{\Lambda\ \rm REC},$$

The ratio w=$\overline{\Lambda}_{REC}/\Lambda_{REC}$

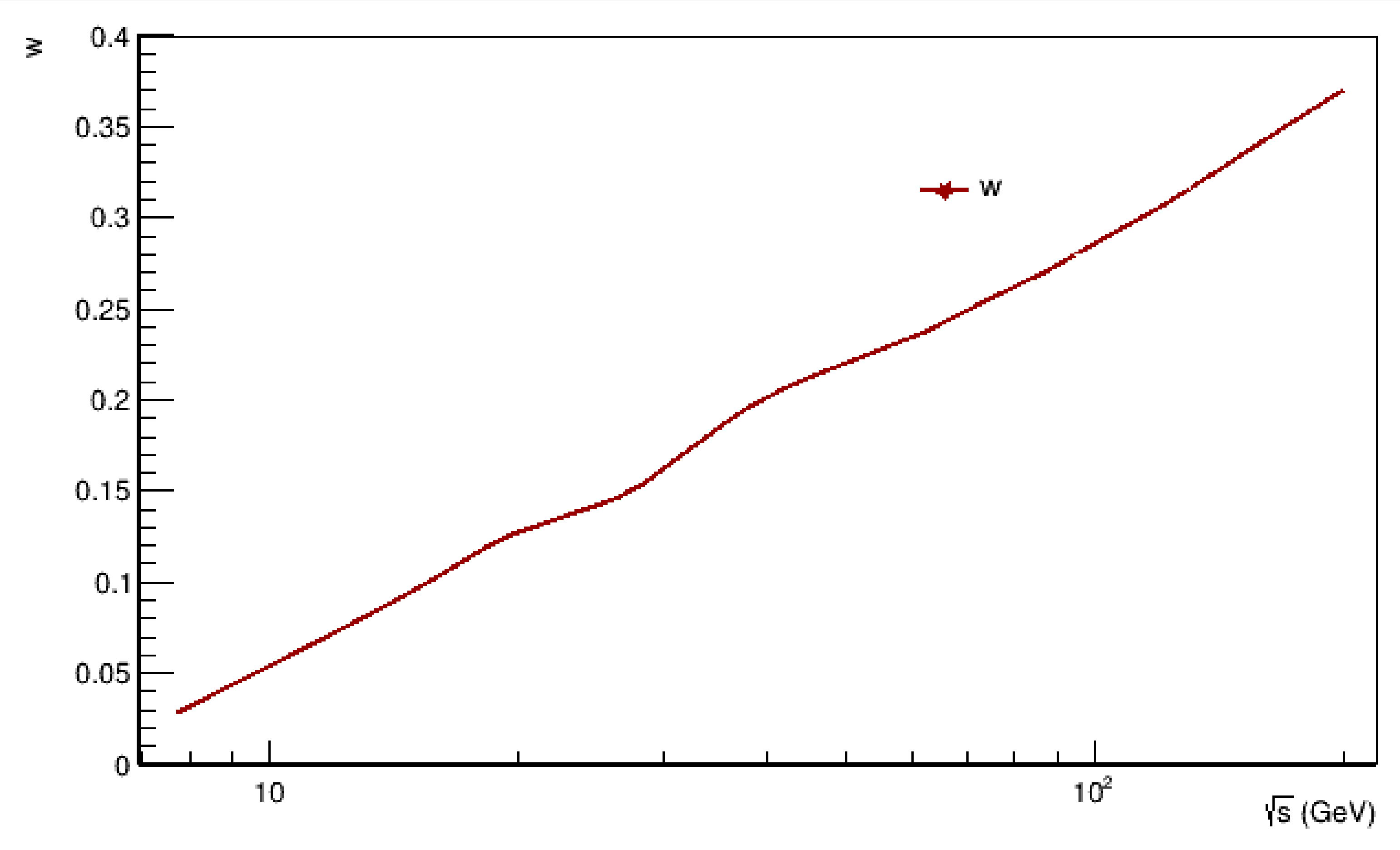
$$\mathcal{P}^{\Lambda} = \frac{z\frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}}{\left(1+\frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}\right)}$$

$$\mathcal{P}^{\overline{\Lambda}} = \frac{\left(\frac{\bar{z}}{w}\right)\frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}}{\left(1+\left(\frac{1}{w}\right)\frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}\right)}.$$

$$N_{\overline{\Lambda}\ \mathrm{REC}} \equiv w N_{\Lambda\ \mathrm{REC}},$$



The ratio $w=\bar{\Lambda}_{REC}/\Lambda_{REC}$



UrQMD generator for pp collisions, w value is smaller than 0.4 for these energies

Assumptions

After some algebra, we get:

$$\mathcal{P}^{\Lambda} = \frac{\left(\mathcal{P}^{\Lambda}_{\mathrm{REC}} + \frac{N^{\uparrow}_{\Lambda\ \mathrm{QGP}} - N^{\downarrow}_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}\right)}{\left(1 + \frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}\right)}$$

$$\mathcal{P}^{\overline{\Lambda}} = \frac{\left(\mathcal{P}^{\overline{\Lambda}}_{\mathrm{REC}} + \frac{N^{\uparrow}_{\overline{\Lambda}\ \mathrm{QGP}} - N^{\downarrow}_{\overline{\Lambda}\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}\right)}{\left(1 + \frac{N_{\overline{\Lambda}\ \mathrm{QGP}}}{N_{\overline{\Lambda}\ \mathrm{REC}}}\right)},$$

Where:

$$\mathcal{P}^{\Lambda}_{\mathrm{REC}} = \frac{N^{\uparrow}_{\Lambda\,\mathrm{REC}} - N^{\downarrow}_{\Lambda\,\mathrm{REC}}}{N^{\uparrow}_{\Lambda\,\mathrm{REC}} + N^{\downarrow}_{\Lambda\,\mathrm{REC}}},$$

$$\mathcal{P}^{\overline{\Lambda}}_{\mathrm{REC}} = \frac{N^{\uparrow}_{\overline{\Lambda}\,\mathrm{REC}} - N^{\downarrow}_{\overline{\Lambda}\,\mathrm{REC}}}{N^{\uparrow}_{\overline{\Lambda}\,\mathrm{REC}} + N^{\downarrow}_{\overline{\Lambda}\,\mathrm{REC}}}.$$

Considering the following restrictions:

$$\mathcal{P}^{\Lambda}_{\mathrm{REC}} = \mathcal{P}^{\overline{\Lambda}}_{\mathrm{REC}} = 0$$

$$N^{\uparrow}_{\Lambda\ \mathrm{QGP}} - N^{\downarrow}_{\Lambda\ \mathrm{QGP}} = z N_{\Lambda\ \mathrm{QGP}}$$

$$N^{\uparrow}_{\overline{\Lambda}\ \mathrm{QGP}} - N^{\downarrow}_{\overline{\Lambda}\ \mathrm{QGP}} = \bar{z} N_{\overline{\Lambda}\ \mathrm{QGP}} \simeq \bar{z} N_{\Lambda\ \mathrm{QGP}}$$

$$N_{\overline{\Lambda}\ \mathrm{REC}} \equiv w N_{\Lambda\ \mathrm{REC}},$$

We can express the polarization as:

$$\mathcal{P}^{\Lambda} = \frac{z \frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}}{\left(1 + \frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}\right)}$$

$$\mathcal{P}^{\overline{\Lambda}} = \frac{\left(\frac{\bar{z}}{w}\right) \frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}}{\left(1 + \left(\frac{1}{w}\right) \frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}\right)}.$$

Analyzing the behavior

$$\mathcal{P}^{\Lambda} = \frac{z\frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}}{\left(1+\frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}\right)}$$

$$\mathcal{P}^{\overline{\Lambda}} = \frac{\left(\frac{\bar{z}}{w}\right)\frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}}{\left(1+\left(\frac{1}{w}\right)\frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}\right)}.$$

Polarization depends on the coefficients:

$z,\ \bar{z}$ and $w,$

And the ratio:

$$\frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}$$

We expect $\bar{z}$ (intrinsic $\overline{\Lambda}$ polarization) to be smaller than z (intrinsic Λ polarization), that is

$$1/w > 1$$

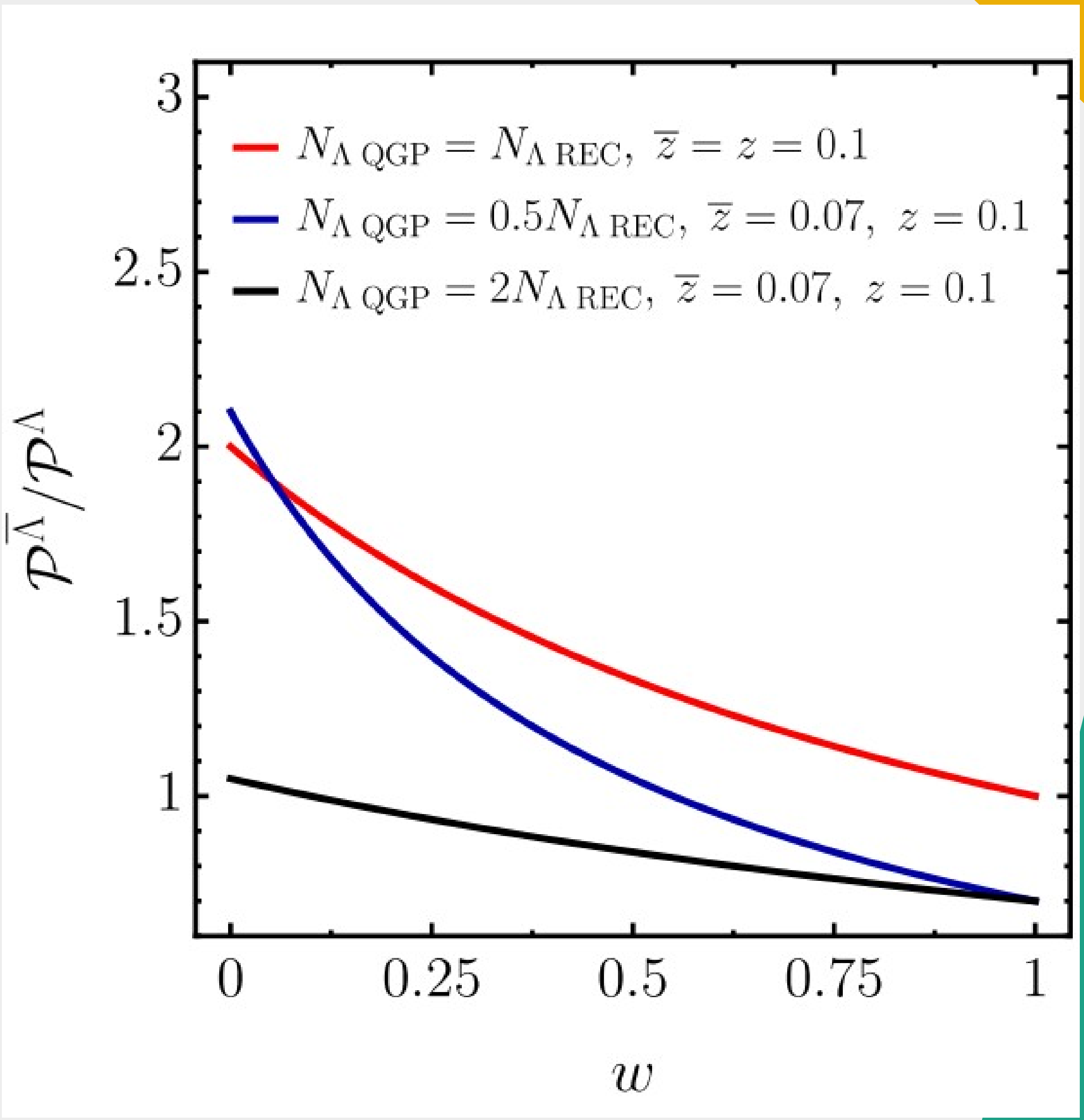
amplifies the $\overline{\Lambda}$ polarization with respect to Λ polarization

$$P^{\overline{\Lambda}} > P^{\Lambda}$$

Analyzing the behavior

$$\mathcal{P}^{\Lambda} = \frac{z\frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}}{\left(1+\frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}\right)}$$

$$\mathcal{P}^{\overline{\Lambda}} = \frac{\left(\frac{\bar{z}}{w}\right)\frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}}{\left(1+\left(\frac{1}{w}\right)\frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}\right)}.$$



Production of Λ_{QGP} and Λ_{REC} .

$$\mathcal{P}^{\Lambda} = \frac{z\frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}}{\left(1+\frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}\right)}$$

$$\mathcal{P}^{\overline{\Lambda}} = \frac{\left(\frac{\bar{z}}{w}\right)\frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}}{\left(1+\left(\frac{1}{w}\right)\frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}\right)}.$$

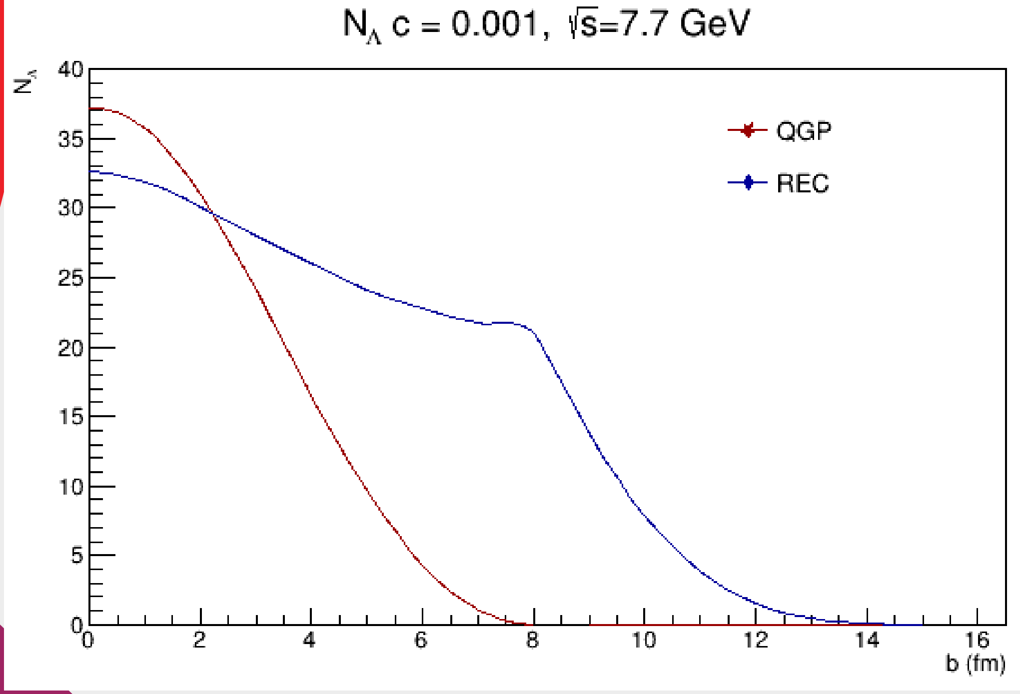
$$\frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}$$

Production of Λ in different regions

$$\frac{N_{\Lambda QGP}}{N_{\Lambda REC}}$$

$$N_{\Lambda QGP} = cN^2_{p\,QGP}$$

$$N_p^{\mathrm{QGP}}(b) = \int n_p(\mathbf{s},\mathbf{b})\,\theta[n_p(\mathbf{s},\mathbf{b}) - n_c]\,d^2s$$



$$n_p(\mathbf{s},\mathbf{b}) = T_A(\mathbf{s})[1 - e^{-\sigma_{NN}T_B(\mathbf{s}-\mathbf{b})}] + T_B(\mathbf{s}-\mathbf{b})[1 - e^{-\sigma_{NN}T_A(\mathbf{s})}],$$

In terms of the thickness function

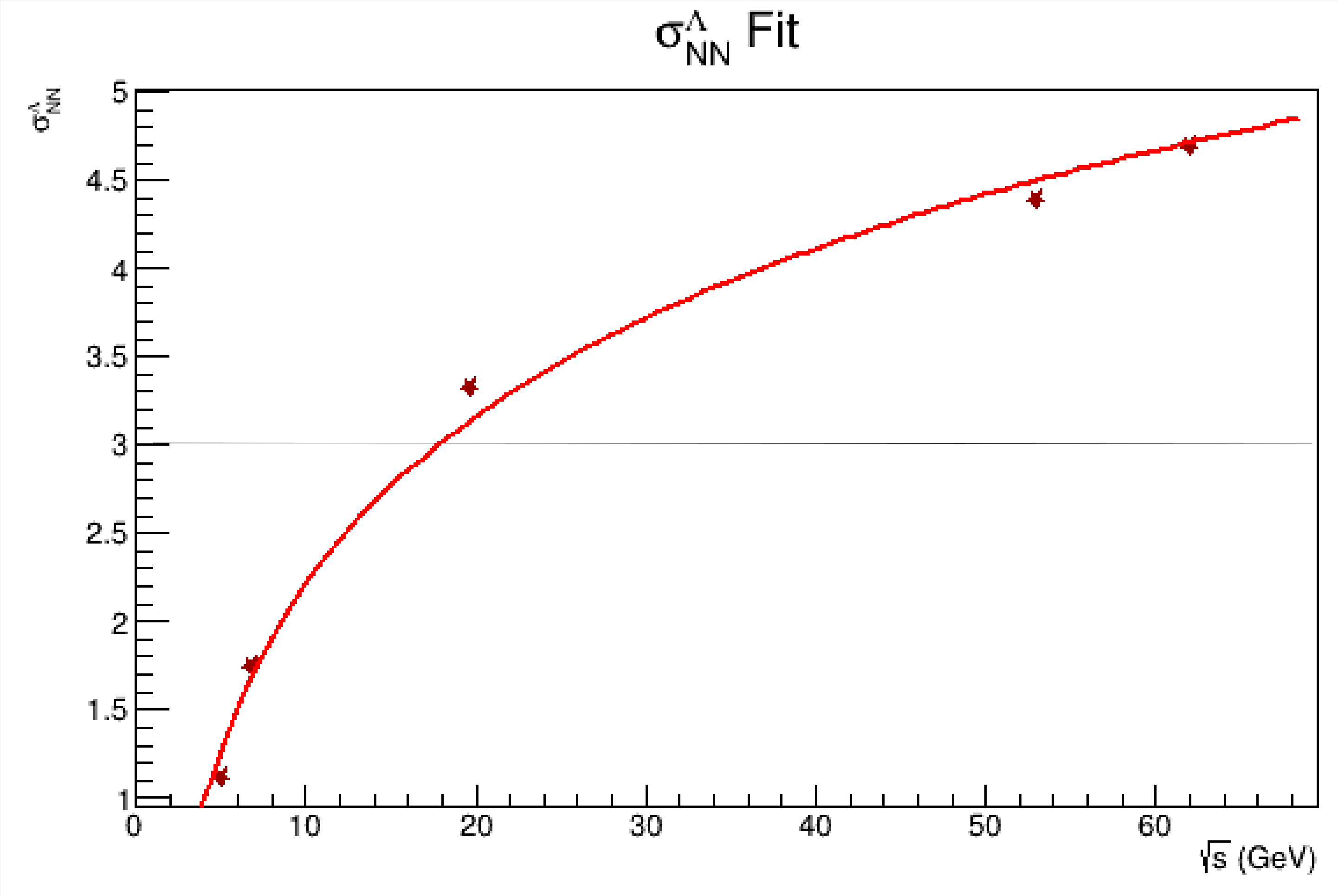
$$T_A(z,s) = \int_{\infty}^{\infty} \rho_A(z,\mathbf{s})dz$$

Woods-Saxon profile density

$$N_{\Lambda REC} = \sigma_{\Lambda}^{NN} \int T_B(\mathbf{b}-\mathbf{s})T_A(\mathbf{s})\theta[n_c - n_p(\mathbf{s},\mathbf{b})]\,d^2s$$

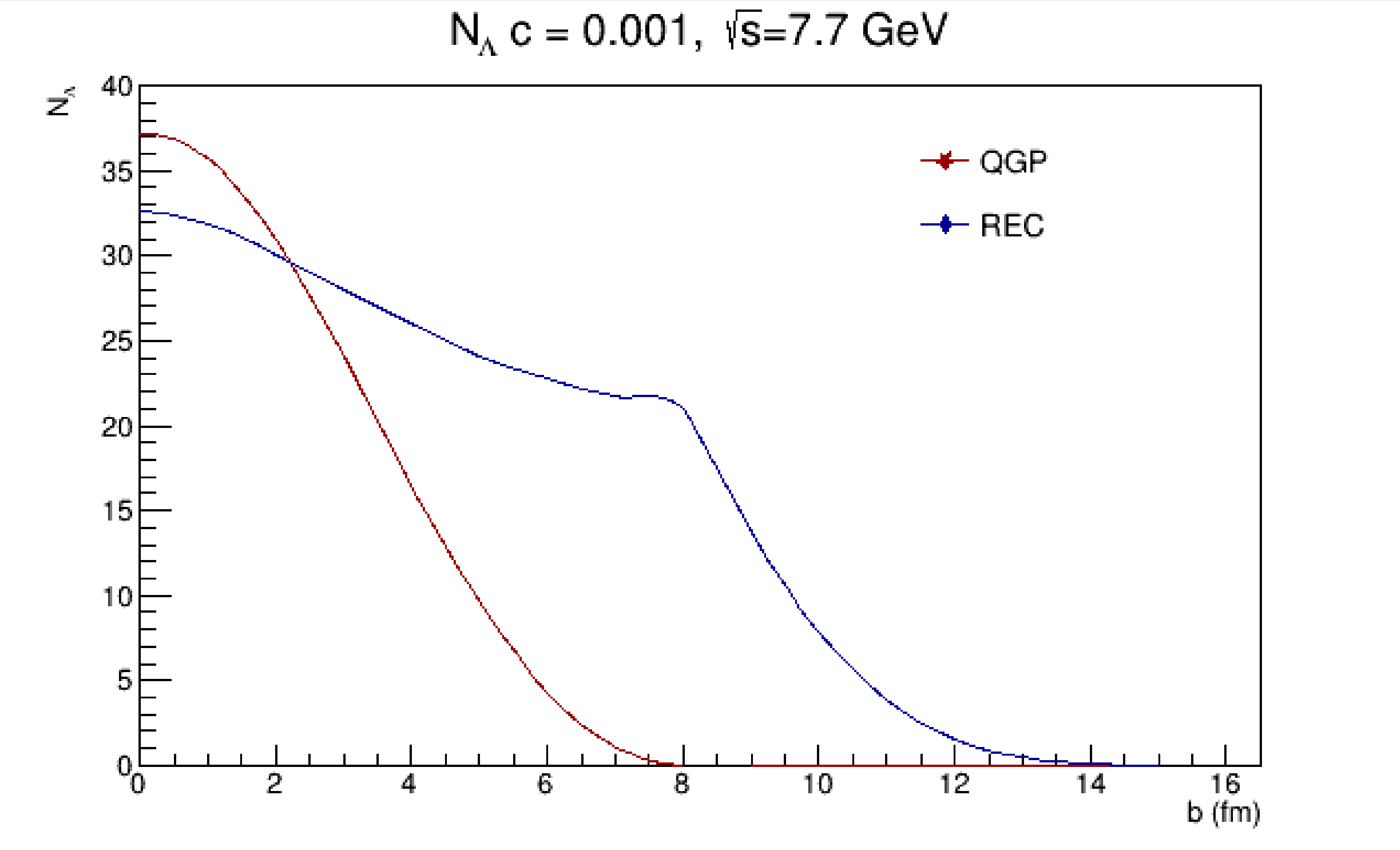
$$\rho_A(\mathbf{r}) = \frac{\rho_0}{1 + e^{(r-R_A)/a}},$$

σ^{Λ}_{NN} Fit

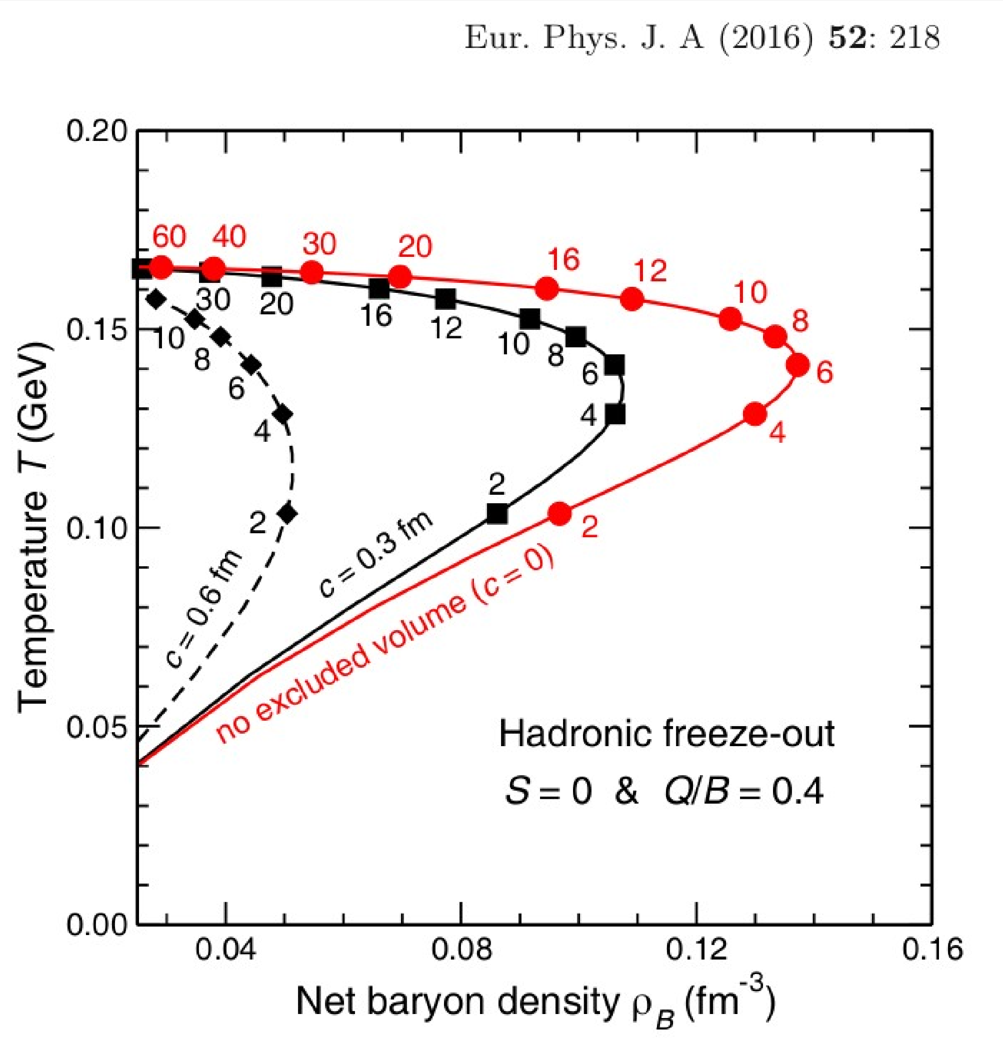


$$\sigma_{\Lambda}^{NN} = 1.37ln(\sqrt{s}) - 0.94$$

Production of Λ in different regions



Parameters to get intrinsic polarization

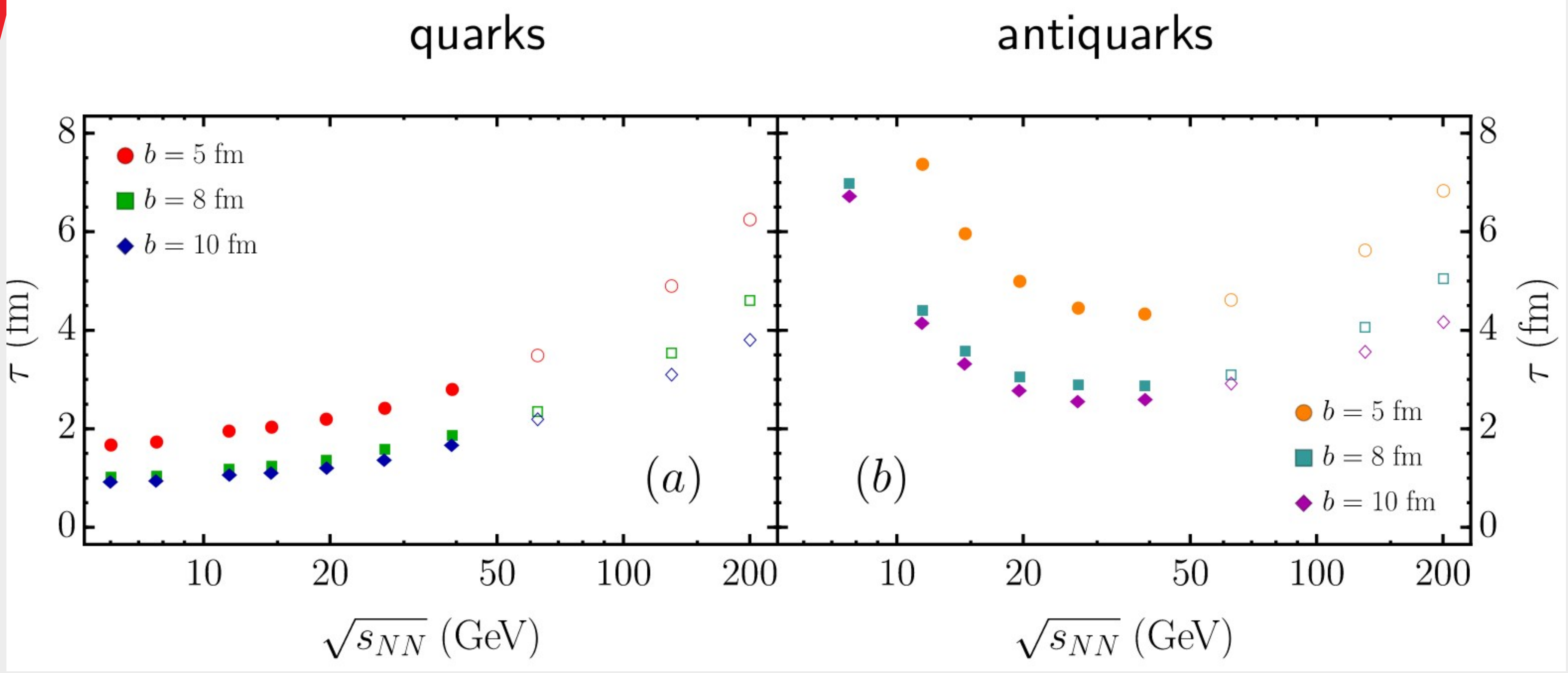


Relaxation time is calculated considering no excluded volume at the freeze out

$$T(\mu_B) = 166 - 139\mu_B^2 - 53\mu_B^4$$

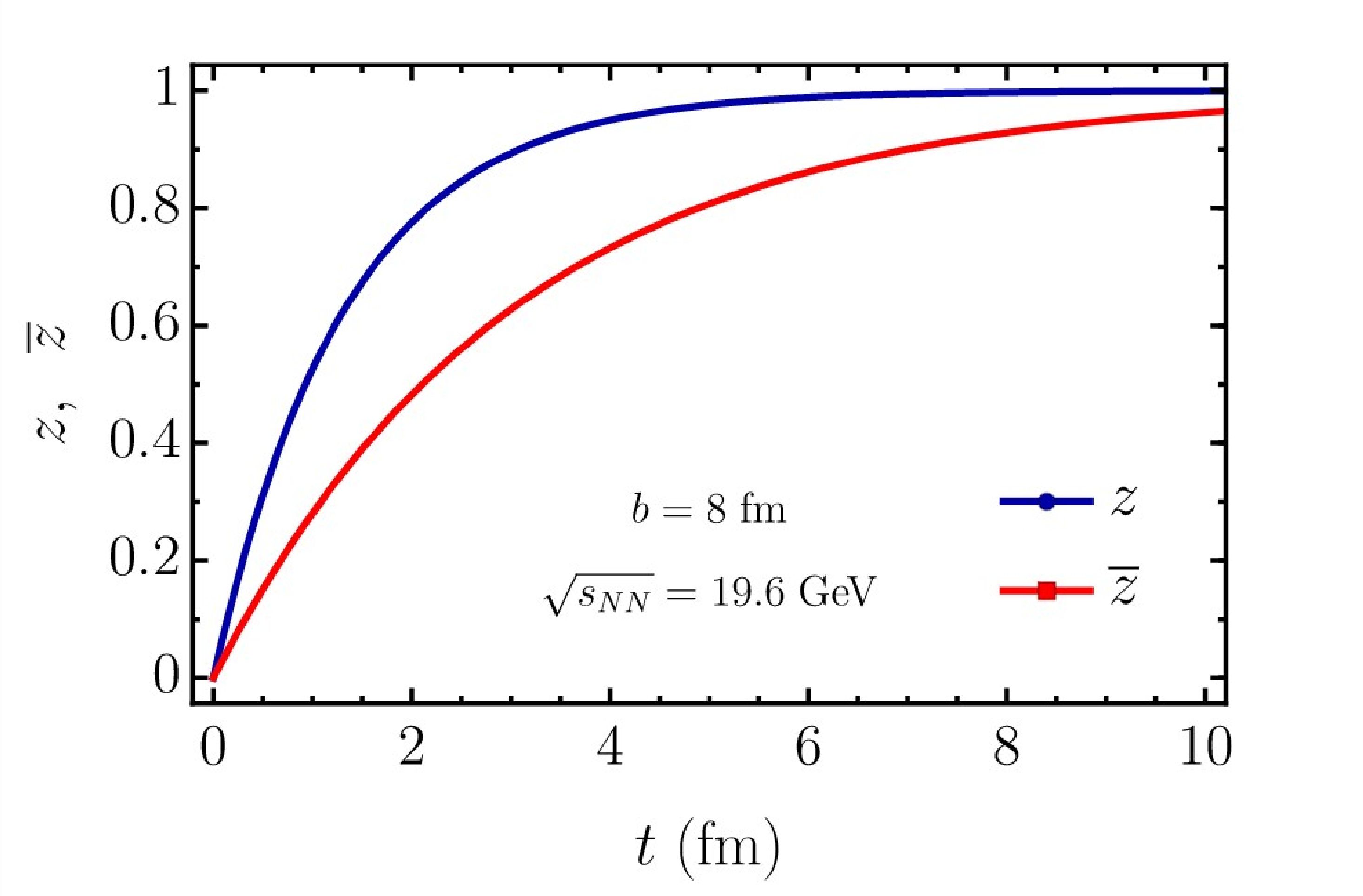
$$\mu_B(\sqrt{s}) = \frac{1308}{1000 + 0.273\sqrt{s}}$$

Relaxation time



Cited by A. Ayala

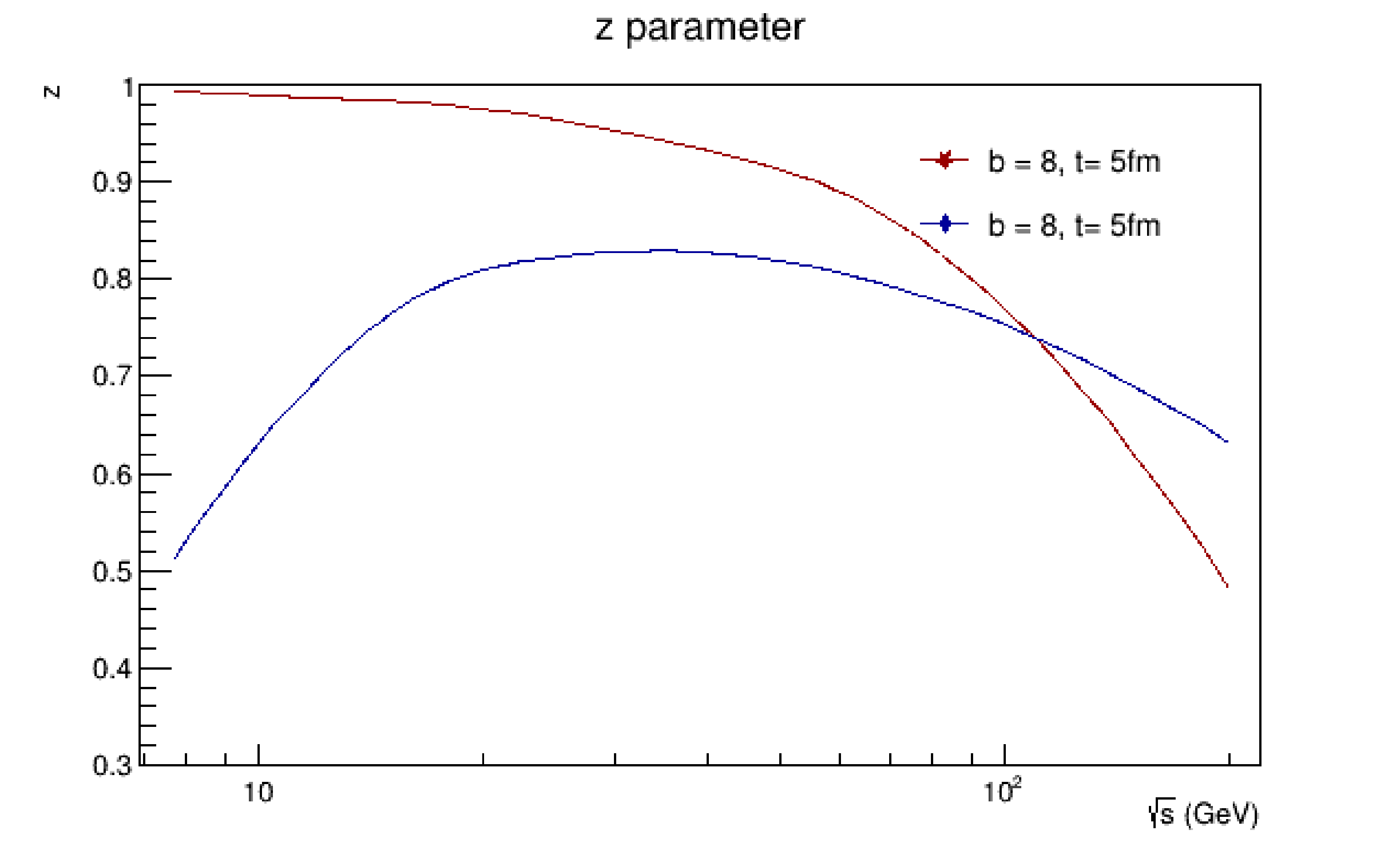
Intrinsic Polarization



$$z = \frac{N}{N^0} = 1 - e^{\frac{-t}{\tau}}$$

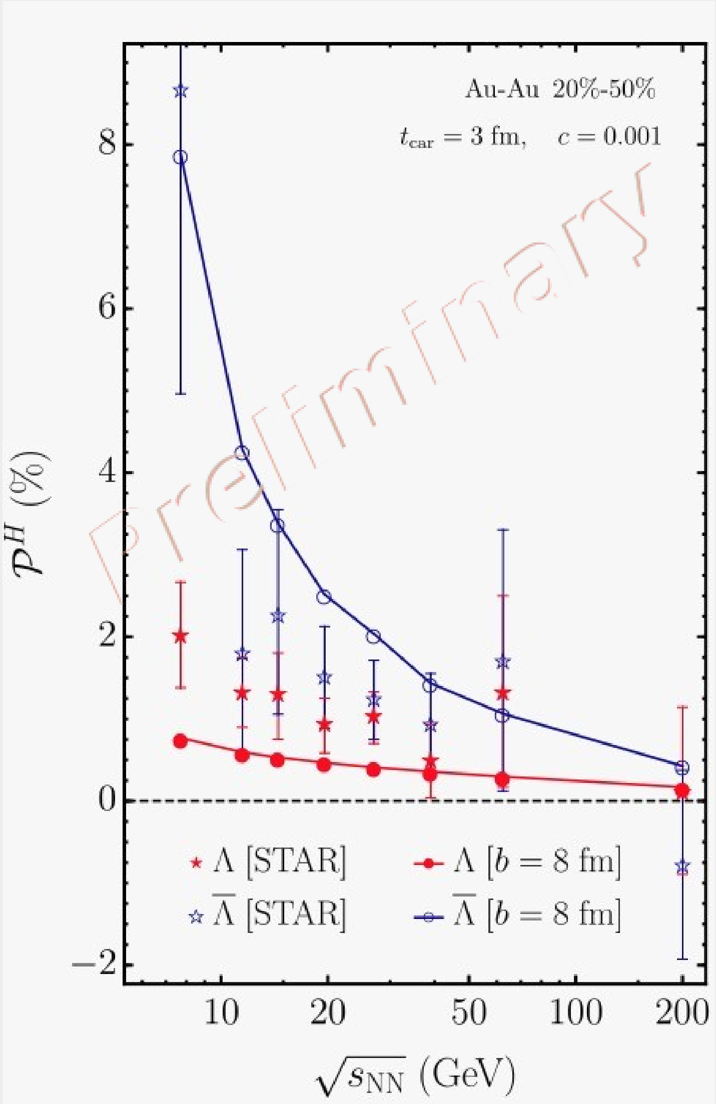
Cited by A. Ayala

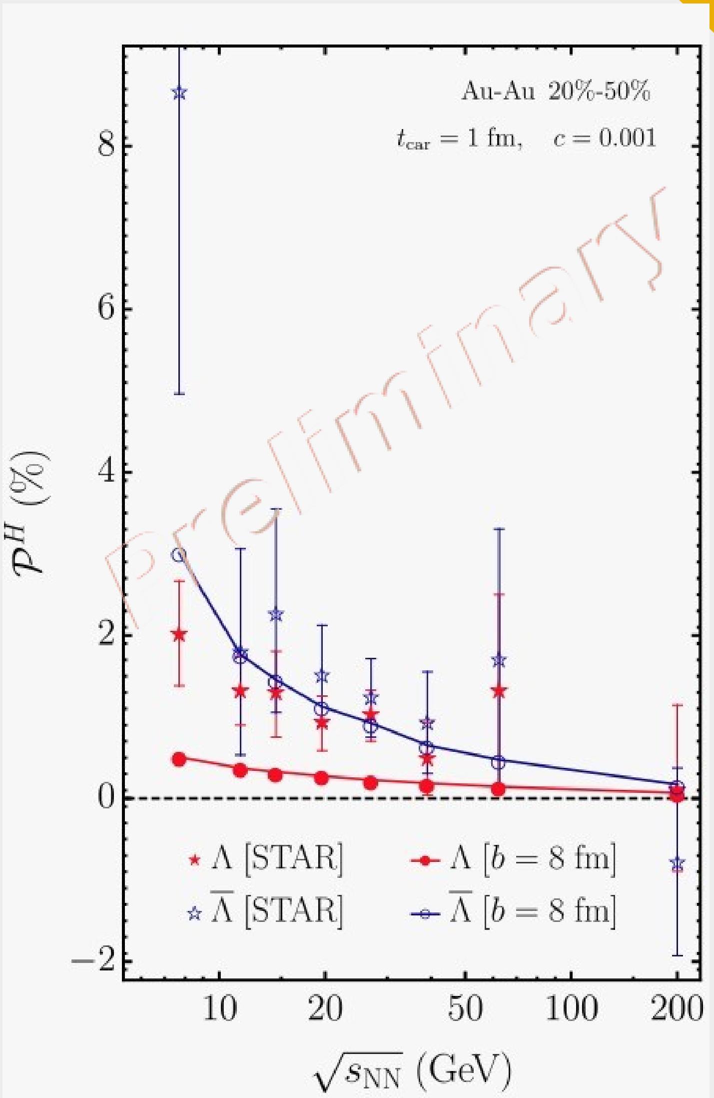
Intrinsic Polarization z and $\bar{z}$ as a function of energy



The intrinsic $\bar{\Lambda}$ polarization is smaller than Λ intrinsic polarization for low energies.

Preliminary





Summary

- STAR has shown that polarization of $\bar{\Lambda}$ is larger than Λ at low energies and the difference decreases as energy increases. This can be understood in a two-component model where Λs come from a dense region (QCD) and a less dense region (pp like processes).
- We have shown that this behavior with the number of Λs coming from different density regions in the collision, when the ratio $N_{\bar{\Lambda}REC}/N_{\Lambda REC}$ is smaller than one, amplifies the global $\bar{\Lambda}$ polarization over that of Λ, in spite of the intrinsic Λ is larger than intrinsic $\bar{\Lambda}$ polarization.
- With reasonable assumption this two component model provides a qualitative and quantitative description of the STAR data. A more detailed analysis, including an average over different impact parameters and characteristic life-times of the system is being performed and will be reported soon.

G r a c i a s