Description of the Hyperon global polarization in Heavy-Ion Collisions at HADES, NICA and RHIC energies from the Core-Corona Model

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XIX Mexican School of Particles and Fields

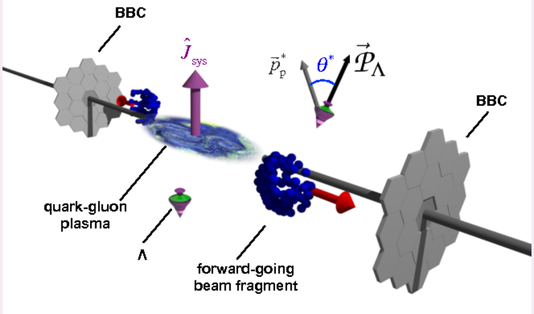
MEX NICA

Outline

Section 1

Motivation

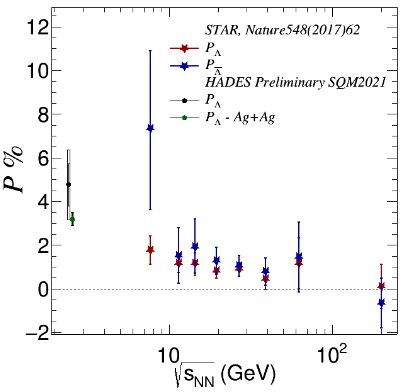
Motivation: Why we are interested in measure Hyperon Global Polarization?



The fluid at midrapidity has a whirling substructure oriented (on average in the direction of the total angular momentum, J. [Nature 548,62-65(2017)]

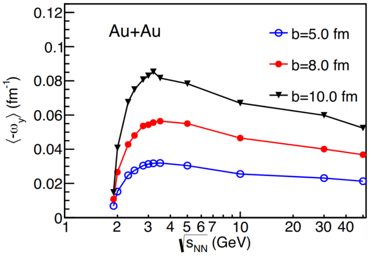
- The Λ and $\bar{\Lambda}$ polarization are linked to the properties of the medium produced in relativistic heavy-ion collisions
- For semicentral collisions, Angular momentum can be quantified in terms of the thermal vorticity
- The global polarization can be measured using the self-analising $\Lambda/\bar{\Lambda}$ decays.

Global Polarization as a function of energy



Energy range $\sqrt{s_{NN}} = \{2, 11\}$GeV can be covered by ongoing/future experiments

STAR BES-II + FXT: 3-19 GeV
HADES:2-3 GeV
NICA:4-11 GeV → MPD



Energy dependence of kinematic vorticity predicted by a transport model (UrQMD) [a]

[a] X.-G. Deng et al., PRC101.064908(2020)

Section 2

Core Corona Model

Core Corona Model: Two-component source

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

- **Core**: Via QGP processes like

$$q\bar{q} \to s\bar{s} \text{ and } gg \to s\bar{s}$$

- **Corona**: Via $n+n$ reactions by recombination-like processes

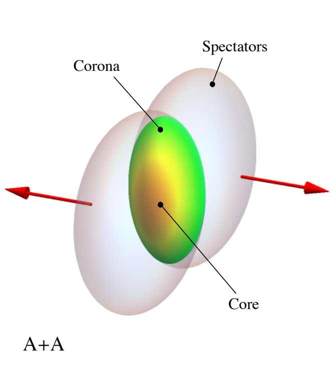
The number of Λs can be written

$$N_\Lambda = N_{\Lambda_{QGP}} + N_{\Lambda_{REC}}$$

The polarization

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

can be rewritten in terms of the number of Λs (or $\bar{\Lambda}$s) produced in the different density regions



Phys.Lett.B 810 (2020) 135818

Rewriting Polarization

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

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

After some algebra, we get:

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

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

Where the polarization along the angular momentum produced in the corona is:

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

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

Assumptions: Polarization of Λ ($\bar{\Lambda}$) from the Corona

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

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

Where

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

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

- Nucleon-Nucleon scattering not enough to align the spin in the direction of the angular momentum
- Polarization of Λ and $\bar{\Lambda}$ averages to zero.

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

Assumptions: Intrinsic Polarization

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

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

We define **z** and **z̄** which represent the Λ and $\bar{\Lambda}$ intrinsic polarization respectively

$$N^{\uparrow}_{\Lambda_{QGP}} - N^{\downarrow}_{\Lambda_{QGP}} = \mathbf{z} N_{\Lambda_{QGP}}$$

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

Assumptions: The ratio $N_{\Lambda_{QGP}}/N_{\Lambda_{REC}}$

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

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

The number of $\bar{\Lambda}$s are proportional to an energy-dependent coefficient **w**(**w**′) times the number of Λs in the corona(core)

$$\begin{aligned} N_{\bar{\Lambda}_{REC}} &= \mathbf{w} N_{\Lambda_{REC}} \\ N_{\bar{\Lambda}_{QGP}} &= \mathbf{w}' N_{\Lambda_{QGP}} \end{aligned}$$

Λ and $\bar{\Lambda}$ global polarization

With this assumptions

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

$$\begin{aligned} N^{\uparrow}_{\Lambda_{QGP}} - N^{\downarrow}_{\Lambda_{QGP}} &= zN_{\Lambda_{QGP}} \\ N^{\uparrow}_{\bar{\Lambda}_{QGP}} - N^{\downarrow}_{\bar{\Lambda}_{QGP}} &= \bar{z}N_{\bar{\Lambda}_{QGP}} \end{aligned}$$

$$\begin{aligned} N_{\bar{\Lambda}_{REC}} &= wN_{\Lambda_{REC}} \\ N_{\bar{\Lambda}_{QGP}} &= w' N_{\Lambda_{QGP}} \end{aligned}$$

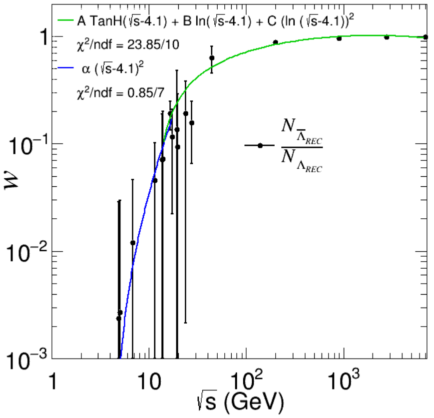
Global polarization depends on the coefficients w, w', z, $\bar{z}$ and the ratio $\frac{N_{\Lambda_{QGP}}}{N_{\Lambda_{REC}}}$ that can be estimated from data or calculated

$$\begin{aligned} \mathcal{P}^{\Lambda} &= \frac{z\frac{N_{\Lambda_{QGP}}}{N_{\Lambda_{REC}}}}{1 + \frac{N_{\Lambda_{QGP}}}{N_{\Lambda_{REC}}}} \\ \mathcal{P}^{\bar{\Lambda}} &= \frac{\bar{z}\left(\frac{w'}{w}\right)\frac{N_{\Lambda_{QGP}}}{N_{\Lambda_{REC}}}}{1 + \left(\frac{w'}{w}\right)\frac{N_{\Lambda_{QGP}}}{N_{\Lambda_{REC}}}} \end{aligned}$$

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

Model as $p + p$ collisions

- Experimental data obtained from $p + p$ collisions at different energies[1]
- w is defined only for $\sqrt{s} > 4.1$GeV. The threshold energy for $p + p \rightarrow p + p + \Lambda + \bar{\Lambda}$
- w is smaller than 1 except for energies $\sqrt{s} > 1$ TeV



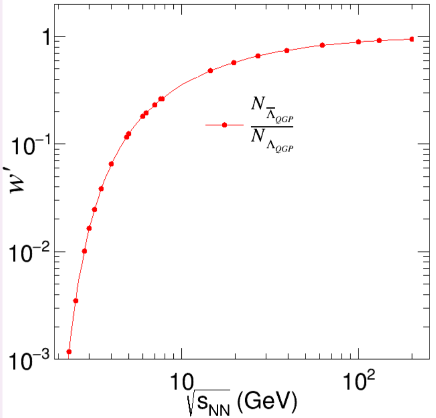
[1] M. Gazdzicki and D. Rohrich, Z. Phys. C 71 (1996) 55; V. Blobel et al. Nucl. Phys. B 69(1974), 454-492; J. W. Chapman et al., Phys. Lett. 47B (1973) 465; D. Brick et al., Nucl. Phys. B 164 (1980) 1; C. Höhne, CERN-THESIS-2003-034; J. Baechler et al. [NA35 Collaboration], Nucl. Phys. A 525 (1991) 221C; G. Charlton et al., Phys. Rev. Lett. 30 (1973) 574; F. Lopinto et al., Phys. Rev. D 22 (1980) 573; H. Kichimi et al., Phys. Rev. D 20 (1979) 37; F. W. Busser et al., Phys. Lett. 61B (1976) 309; S. Erhan, et al., Phys. Lett. 85B(1979) 447; B. I. Abelev et al. [STAR Collaboration], Phys. Rev. C 75 (2007) 064901; E. Abbas et al. [ALICE Collaboration], Eur. Phys. J. C 73 (2013) 2496

The ratio $w' = N_{\bar{\Lambda}_{QGP}}/N_{\Lambda_{QGP}}$

- The coefficient w' is computed as the ratio of the equilibrium distributions of $\bar{s}$ to s-quark for a given temperature and chemical potential $\mu = \mu_B/3$

$$w' = \frac{e^{(m_s-\mu)/T}+1}{e^{(m_s+\mu)/T}+1}$$

m_s the mass of the s-quark and μ_B and T along the maximum chemical potential at freeze out.



Production of Λ in the core and the corona

Number of Λs in the core

$$N_{\Lambda_{QGP}} = c N^2_{p_{QGP}}$$

in which

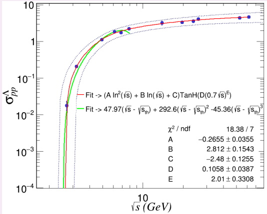
$$N_{p_{QGP}} = \int n_p(\mathbf{s},\mathbf{b})\theta[n_p(\mathbf{s},\mathbf{b}) - n_c] d^2 s$$

with $n_c = 3.3$ fm^{-2}, the critical density required to form the QGP

Number of Λs in the corona

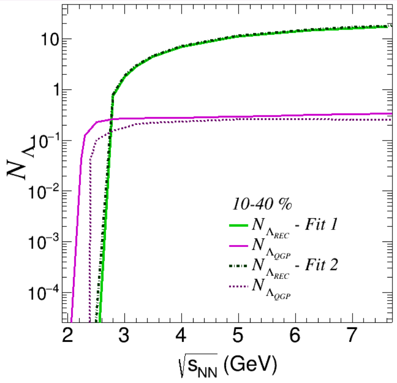
$$N_{\Lambda_{REC}} = \sigma^{\Lambda}_{NN} \int T_B(\mathbf{b}-\mathbf{s}) T_A(\mathbf{s})\theta[n_c - n_p(\mathbf{s},\mathbf{b})] d^2 s$$

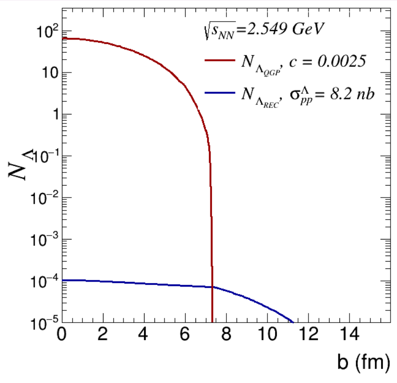
where σ^{Λ}_{NN} is obtained from experimental data



The density of participants $n_p(\mathbf{s},\mathbf{b}) = T_A(\mathbf{s})[1 - e^{-\sigma_{NN} T_B(\mathbf{s}-\mathbf{b})}] + T_B(\mathbf{s}-\mathbf{b})[1 - e^{-\sigma_{NN} T_A(\mathbf{s})}]$,
the thickness function $T_A(z,s) = \int_{\infty}^{\infty} \rho_A(z,\mathbf{s}) dz$ and
the Woods-Saxon profile density $\rho_A(\mathbf{s}) = \frac{\rho_0}{1+e^{(r-R_A)/a}}$

Λs in the Core and Corona





At low energies $N_{\Lambda_{QGP}}$ depends on σ_{NN}, different parametrizations impact on the strenght of polarization

σ_{NN} affects the ratio $N_{\Lambda QGP}/N_{\Lambda_{REC}}$ and the value of b at which the ratio is smaller than 1

Intrinsic Polarization

The intrinsic polarizations are given by:

$$z = 1 - e^{-\Delta\tau_{QGP}/\tau}$$

and

$$\bar{z} = 1 - e^{-\Delta\tau_{QGP}/\bar{\tau}}$$

in terms of the relaxation times τ and $\bar{\tau}$ an the QGP life-time $\Delta\tau_{QGP}$
The relaxation time can be computed as the inverse of the interaction rate

$$\tau \equiv 1/\Gamma$$

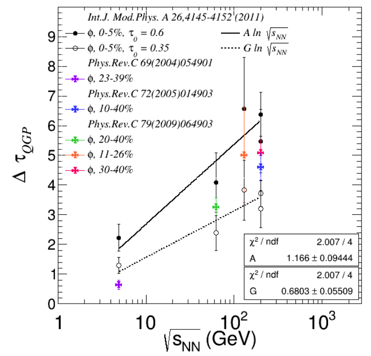
given by

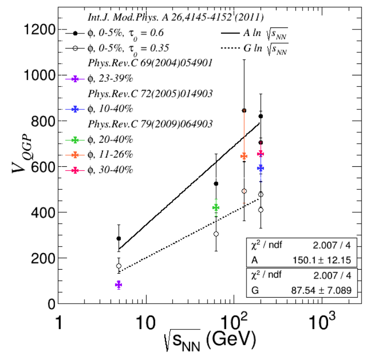
$$\Gamma = V \int \frac{d^3 p}{2\pi^3} \Gamma(p_0), \text{ with } V = \pi R^2 \Delta\tau_{QGP}$$

where V is the volume of the core region, related with the QGP life-time $\Delta\tau_{QGP}$ in the scenario of a Bjorken expansion

$$\Delta\tau_{QGP} = \tau_f - \tau_0 = \tau_0 [\left(\frac{T_0}{T_f}\right)^3 - 1]$$

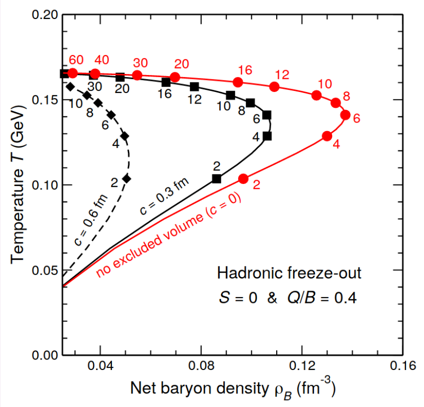
Volume and QGP life-time





T_0 is estimated from p_T of ϕ mesons, $\tau_0 = 0.35 - 0.60$ fm to incorporate the effect of collision centrality, and T_f is taken as the value along the maximum chemical potential curve at freeze-out

μ_B and T at freeze out



Eur.Phys.J. 52 (2016) 218-219

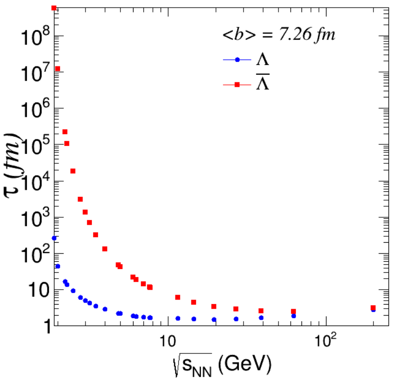
Maximum freeze-out baryon density in nuclear collisions

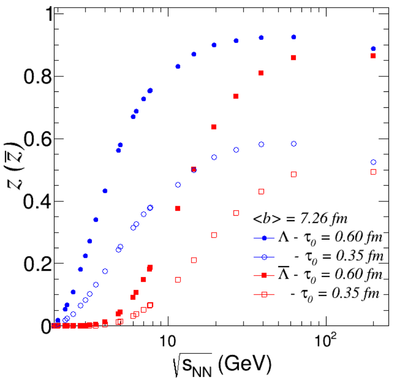
$$T(\mu_B) = 166 - 139\mu_B^2 - 53\mu_B^4$$

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

Phys.Rev.C 74 (2006) 047901

Relaxation time and intrinsic polarization as a function of energy





For energies below the Λ production threshold energy, the τ and $\bar{\tau}$ increase dramatically, as expected, since the interaction rate should vanish below these energies.

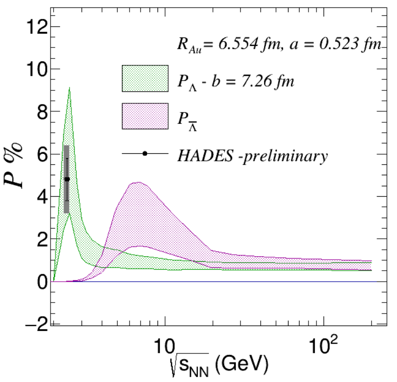
Section 3

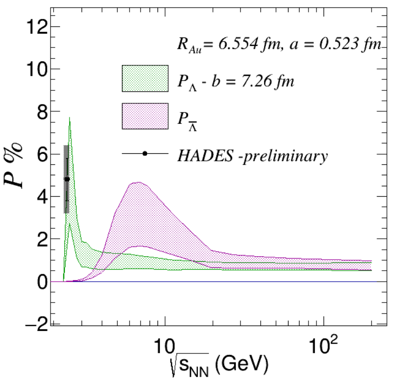
Excitation Function for the Global Λ and $\bar{\Lambda}$ Polarization

MEX NICA

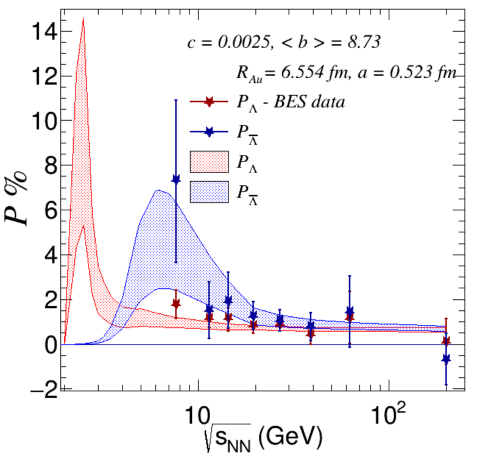
Λ and $\bar{\Lambda}$ polarization in Au+Au at HADES centrality

10 - 40 %





Λ and $\bar{\Lambda}$ polarization in Au+Au at BES centrality



20 - 50 %

- Similar trend to the case of the analysis with smaller centrality
- Magnitude of global polarization increases for larger centrality as a consequence of the angular velocity increase

Section 4

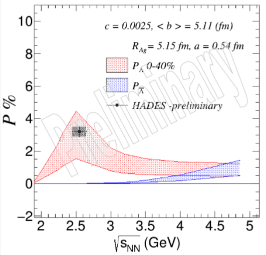
Summary

Summary

- The two component source model describes the main characteristics features of the Λ and $\bar{\Lambda}$ polarization excitation functions in semi central relativistic heavy-ion collisions
- The change of the relative abundance of Λs coming from the core versus those coming from the corona as a function of the collision energy has as a consequence that both polarization peak at collision energies $\sqrt{s_{NN}} \lesssim 10$ GeV
- The relaxation time can be obtained can be obtained from a field theoretical approach that links the alignment of the strange quark spin with the thermal vorticity, modeling the QGP volume and life-time using a simple scenario
- The model predicts a maximum for the Λ and $\bar{\Lambda}$ polarizations which should be possible to be measured in the NICA and HADES energy range.

Work in progress

- Extend the analysis for Ag+Ag collisions to compare with HADES preliminary SQM2021
- Trend looks similar for $0 - 40\%$ of centrality



Thank You