Core Corona Model: A tool to study hyperon global polarization using the Multi Purpose Detector at NICA energies

Ivonne Maldonado* for the MPD Collaboration

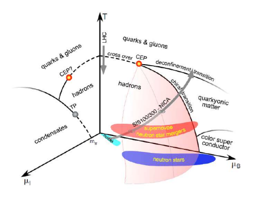
* VBLHEP, JINR ivonne.alicia.maldonado@gmail.com
Work done in collaboration with A. Ayala, I. Dominguez and M.E. Tejeda-Yeomans

November 25^{th}, 2022
XVIII Mexican Workshop on Particles and Fields

Why measure the hyperon global polarization?

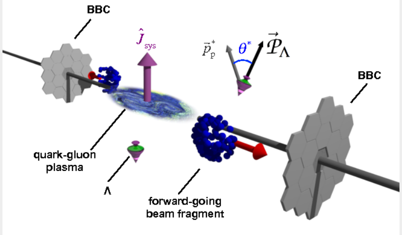
The study of HIC at lower end of relativistic energies became a topic of interest because:

- Onset of deconfinement
- High baryon densities and modest temperatures are produced in contrast to collisions at larger energies



Hyperon Global Polarization $\rightarrow$ to characterize the strongly interacting matter, due the possibility to link with vorticity, viscosity and flow.

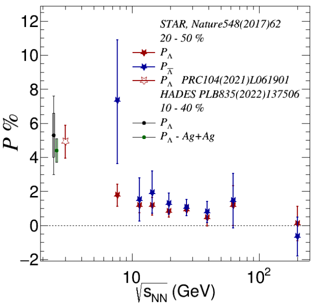
- Non central collision have large angular momentum J $\sim$ 1000 $\hbar$
- Hydrodynamic calculations relate the polarization with the vorticity oriented (in average) in the direction of the total angular momentum $\hat{J}$



Λ and $\bar{\Lambda}$ parity-violating weak decay allows to measure its polarization $\rightarrow$ decayed baryon emitted in the spin direction **Nature 548, 62-65(2017)**

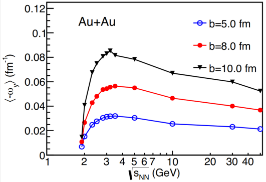
Global Polarization as a function of energy

Results from STAR-BES and HADES.



- Polarization increases as the energy of the collision decreases and then decrease near the threshold energy.
- $\bar{\Lambda}$ polarization is larger.

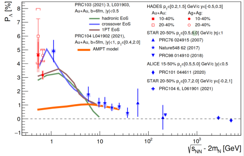
- Thermodynamial approach describes the polarization Annu. Rev. Nucl. Part. Sci. 2020. 70:395–423, but not the large difference between Λ and $\bar{\Lambda}$
- Energy dependence of kinematic vorticity predicted by a transport model (UrQMD) X.-G. Deng et al., PRC101(2020)064908



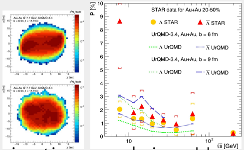
- NICA will cover $\sqrt{s_{NN}} = 4 - 11$ GeV

Difference between Λ and $\bar{\Lambda}$

3FD model predicts a peak Phys. Rev. C 103, L031903 (2021)

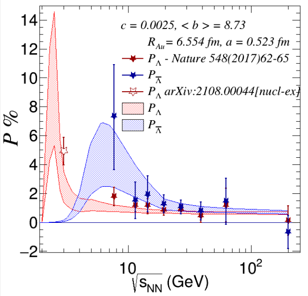


UrQMD model Phys. Lett. B 803(2020)135298



Stronger polarization explained by different space-time distributions of Λ and $\bar{\Lambda}$ and by different freeze-out conditions of both hyperons.

Core-Corona model



The source of Λ and $\bar{\Lambda}$ is taken as consisting of a high-density core and a less dense corona. Properties of polarization are linked with the relative abundance of Λs coming from the core versus those coming from the corona.

Core-Corona Model: Two-component source

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

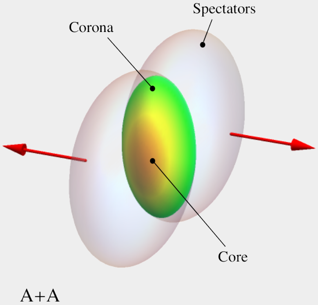
- **Core**: QGP processes (lowest order QCD processes)

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

- **Corona**: Via $n+n$ reactions by recombination-like processes (ud from incoming nucleons + s from sea)

The number of Λs can be written as:

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



Phys.Lett.B 810 (2020) 135818

Another studies with core-corona approach

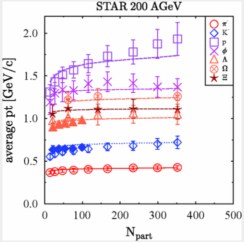
It has been used to explain data from different observables:

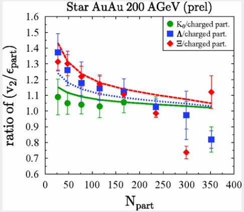
- Centrality Dependence of Strangeness Enhancement in Ultrarelativistic Heavy Ion Collisions - a Core-Corona Effect Phys.Lett.B 673(2009)19-23.
- Is the centrality dependence of the elliptic flow v_2 and of the average $\langle p_T \rangle$ more than a Core-Corona Effect? Phys.Rev.C 82(2010)034906

Observable $O(N_{part})$ as a function of centrality

$$O(N_{part}) = f_{core} O_{core} + (1 - f_{core}) O_{corona}$$

$core$ - central collisions
$corona$ - pp collisions
f_{core} - fraction of core nucleons





Polarization with core-corona approach

The number of Λs can be written as: $N_\Lambda = N_{\Lambda_{QGP}} + N_{\Lambda_{REC}}$ then the polarization given by:

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

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

Global Polarization

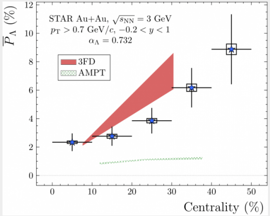
$$\mathcal{P}^{\Lambda} = \frac{\mathcal{P}^{\Lambda}_{REC} + z\frac{N_{\Lambda_{QGP}}}{N_{\Lambda_{REC}}}}{1 + \frac{N_{\Lambda_{QGP}}}{N_{\Lambda_{REC}}}}$$

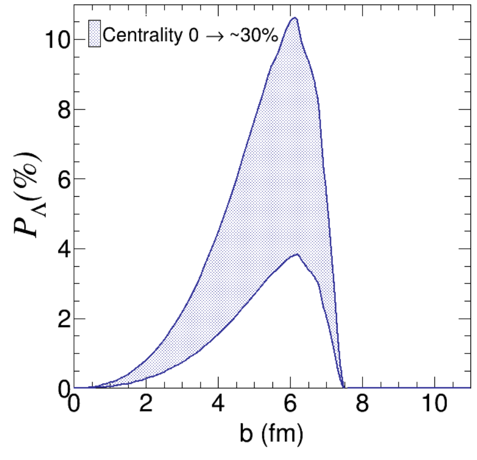
$$\mathcal{P}^{\bar{\Lambda}} = \frac{\mathcal{P}^{\bar{\Lambda}}_{REC} + \bar{z}\left(\frac{w'}{w}\right)\frac{N_{\Lambda_{QGP}}}{N_{\Lambda_{REC}}}}{1 + \left(\frac{w'}{w}\right)\frac{N_{\Lambda_{QGP}}}{N_{\Lambda_{REC}}}}$$

Global polarization **depends on** the coefficients $w = \frac{N_{\bar{\Lambda}_{REC}}}{N_{\Lambda_{REC}}}$, $w' = \frac{N_{\bar{\Lambda}_{QGP}}}{N_{\Lambda_{QGP}}}$, the intrinsic polarization z, $\bar{z}$ of Λ and $\bar{\Lambda}$ and the ratio $\frac{N_{\Lambda_{QGP}}}{N_{\Lambda_{REC}}}$ that can be estimated from data or calculated.

Assuming that nucleon-nucleon scattering not enough to align the spin in the direction of the angular momentum $\rightarrow \mathcal{P}^{\Lambda}_{REC} = \mathcal{P}^{\bar{\Lambda}}_{REC} = 0$.
Phys. Rev. C 105, 034907

Λ polarization as a function of centrality for $Au + Au$ at $\sqrt{s_{NN}} = 3$ GeV





Polarization for more peripheral collisions goes to zero, as the critical density n_c of the system is not achieved, vanishing the number of Λs from the core.

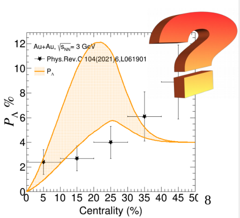
What about the contribution of P_{REC}?

- Which is the effect of transverse Λ polarization in the corona?
- The polarization in pp collisions is not zero[3].
  - At $\sqrt{s} = 19.6\text{GeV} \rightarrow \mathcal{P} = -0.25 \pm 0.26$
  - At $\sqrt{s} = 53\text{GeV} \rightarrow \mathcal{P} = -0.34 \pm 0.07$
  - At $\sqrt{s} = 62\text{GeV} \rightarrow \mathcal{P} = -0.40 \pm 0.10$

$$\mathcal{P}^{\Lambda} = \frac{\mathcal{P}^{\Lambda}_{REC} + z\frac{N_{\Lambda QGP}}{N_{\Lambda REC}}}{1 + \frac{N_{\Lambda QGP}}{N_{\Lambda REC}}}$$

In more peripheral collisions transverse polarization is not diluted by rescattering within QCD medium and can be measured at MPD[4].

Which is the value w.r.t. the angular momentum?



Adding an arbitrary value of $\mathcal{P}^{\Lambda}_{REC}$
Data could be described?

1 2

[1] PoS HEP2005 (2006) 122, V. Blobel et al., Nucl. Phys. B122 (1977) 429, Phys. Rev.,D11:2405, 1975

[2] Nazarova, et. al. Phys. of Part. and Nuclei Lett., 2021, Vol. 18, No. 4, pp. 429–438

Measurement procedure of Hyperon Global Polarization

1. Λ and $\bar{\Lambda}$ identification through their decay products and measurement of the azimuthal angle of the decay baryon in Λ rest frame.

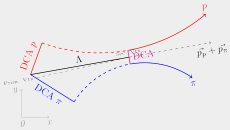
$$\frac{dN}{d\Omega} = \frac{N}{4\pi}\left(1 + \alpha \mathcal{P}_H cos\theta\right)$$

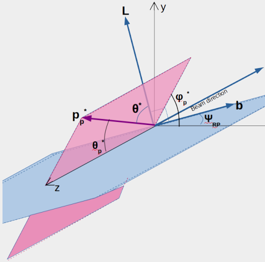
$\alpha_H = 0.732 \pm 0.014$ - new hyperon decay parameter

2. Flow technique measurement $\rightarrow \Psi_{EP}$ and its Resolution R_{EP}
3. Polarization as a function of the difference of these angles

Global Polarization

$$\mathcal{P}_H = \frac{8}{\pi\alpha_H}\frac{\left\langle \sin\left(\phi_p^* - \Psi_{EP}^{(1)}\right)\right\rangle}{R_{EP}}$$





Polarization from Corona region

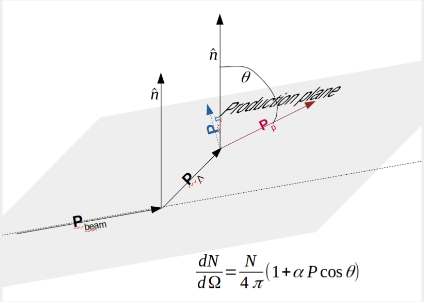
In pp collisions, transverse polarization is measured with respect to production plane.

Polarization along vector $\hat{n}$ perpendicular to the plane defined by the beam $\hat{p}_{beam}$ and Λ directions, p_Λ

$$\hat{n} \equiv \frac{\bar{p}_{beam} \times \bar{p}_\Lambda}{|\bar{p}_{beam} \times \bar{p}_\Lambda|}$$

Assuming the beam direction parallel to $\hat{z}$, we can express $\hat{n}$ like:

$$\hat{n} = \frac{1}{p_{T_\Lambda}}(-p_{y_\Lambda}, p_{x_\Lambda}, 0)$$



Local Polarization projected along angular momentum 1

Assuming that in pp collisions, polarization $\mathcal{P}_T$ is only different from zero along $\hat{n}$; for Λ's in the corona, the contribution to global polarization can be measured by:

$$\frac{dN}{d\Omega} = \frac{N}{4\pi}\left(1 + \alpha\mathcal{P}_T \cos\sigma^*\right)$$

where σ^* is the angle between $\hat{n}$ and the direction of the angular momentum $\hat{L} = \hat{b} \times \hat{p}_{beam} = (\sin\Psi_{RP}, -\cos\Psi_{RP}, 0)$.
Then $cos\sigma^*$ is given by:

$$\cos\sigma^* = \hat{n}\cdot\hat{L} = \frac{1}{p_{T_\Lambda}}\left(-p_{y_\Lambda}\sin\Psi_{RP} - p_{x_\Lambda}\cos\Psi_{RP}\right)$$

Substituting

$$p_{x_\Lambda} = p_\Lambda \sin\theta_\Lambda \cos\phi_\Lambda, p_{y_\Lambda} = p_\Lambda \sin\theta_\Lambda \sin\phi_\Lambda, p_{T_\Lambda} = p_\Lambda \sin\theta_\Lambda$$

Local Polarization projected along angular momentum 2

then

$$\begin{aligned}\cos\sigma^* &= -\sin\phi_\Lambda \sin\Psi_{RP} - \cos\phi_\Lambda \cos\Psi_{RP} \\ &= -\cos\left(\phi_\Lambda - \Psi_{RP}\right)\end{aligned}$$

angular distribution can be rewritten like:

$$\boxed{\frac{dN}{d\Omega} = \frac{N}{4\pi}\left(1 - \alpha\mathcal{P}_T \cos\left(\phi_\Lambda - \Psi_{RP}\right)\right)}$$

Considering $d\Omega = \sin\theta\, d\theta\, d\phi$ and integrating w.r.t. $d\theta$?

$$\begin{aligned}\frac{dN}{d\phi} &= \int_0^\pi \left[\frac{N}{4\pi}\left(1 - \alpha\mathcal{P}_T \cos\left(\phi_\Lambda - \Psi_{RP}\right)\right)\right] \sin\theta\, d\theta \\ &= \frac{N}{2\pi}\left(1 - \alpha\mathcal{P}_T \cos\left(\phi_\Lambda - \Psi_{RP}\right)\right)\end{aligned}$$

Local Polarization projected along angular momentum 3

Calculating the mean angular distribution $\langle \cos(\phi_\Lambda - \Psi_{RP}) \rangle$

$$\langle \cos(\phi_\Lambda - \Psi_{RP}) \rangle = -\frac{\alpha \mathcal{P}_T}{2}$$

The transverse polarization projected along angular momentum should be

$$\mathcal{P}_T = \frac{-2\langle \cos(\phi_\Lambda - \Psi_{RP}) \rangle}{\alpha}$$

that differs from the global polarization given by $\mathcal{P}_\Lambda = -\frac{8\langle \sin(\phi_p - \Psi_{RP}) \rangle}{\pi \alpha}$
There is a similarity between this expression and directed flow for Λs
Can we measure this contribution experimentally?

Perspectives of study at MPD with UrQMD

- The UrQMD generator implements an **hybrid model** that includes an ideal fluid-dynamic evolution for the hot an dense stage[a].
- The **fluid-dynamic evolution** is carried out by the SHASTA (SHarp and Smooth Transport Algorithm)[b]
- Implementation of EoS that includes a **deconfinement plus a chiral phase transition**, through a smooth crossover between a chiral hadronic model and an interacting constituent quark model [c].
- A **core-corona like separation** mechanism for the initial state of the fluid evolution. Quark density cut in η intervals for select particles in the fluid-dynamical evolution [d].

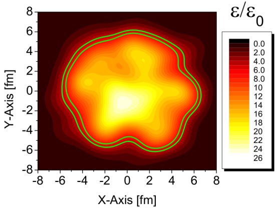


FIG. 1. (Color online) Contour plot of the local rest frame energy density in the transverse plane ($z = 0$) of a central ($b = 0$) collision of Pb+Pb at $E_{lab} = 40A$ GeV. The energy density is normalized to the ground state energy density ($\epsilon_0 \approx$ 145 MeV/fm^3). The two green lines correspond to lines of a constant energy density of $\epsilon/\epsilon_0 = 5$ and 7.

---

[a] Phys. Rev. C 78 (2008) 044901

[b] Nucl.Phys.A595(1995)346, Nucl. Phys.A595(1995)383

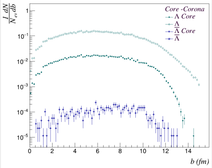
[c] Phys.Rev.C84,045208(2011)

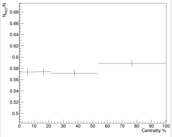
[d] Phys.Rev.C84,024905(2011)

Core-Corona Implementation in MPD

From pure MC $\sim 90\text{k}$ events $\approx 50\%$ came from the corona

dN/db distribution





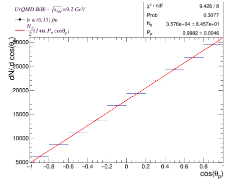
Λ abundances in different regions differs from critical density - Glauber calculation used in our core-corona approach

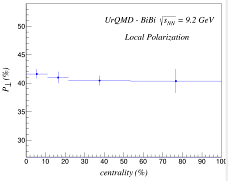
Implementation in MPD

- Transport within mpdroot framework: assign arbitrary local polarization 40% $\rightarrow$ only to corona particles in the $\hat{n}$ direction.
- Transfer polarization to decay particles $\rightarrow$ Employ developed tools to transfer Hyperon Global Polarization within mpdroot for PHSD (PWG2 - E. Nazarova, and V. Voronyuk). See V. Riabov talk
- Λ reconstruction and measurement of Hyperon Global Polarization with MCTracks.

Polarization transfer

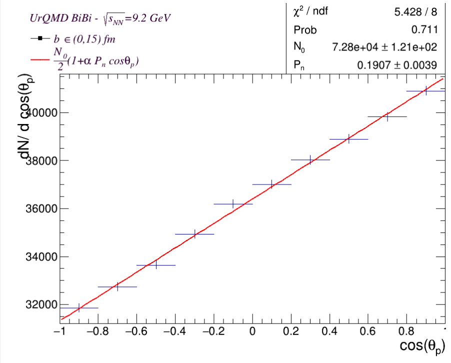
All Λs in the corona are polarized, projection along its own $\mathcal{P}$ is consistent with 100% and along $\hat{n}$ normal to production plane is consistent with 40%





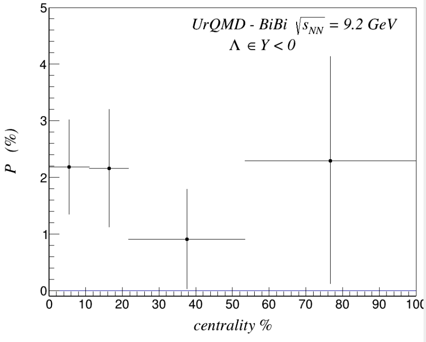
sample $\sim$ 90k events

Local Polarization measured in all the Λ sample, smaller than 40% due to core contribution

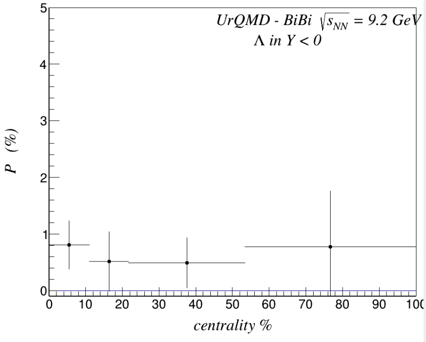


Global Polarization for Λ

Only Λs in the corona



All Λs



Contribution from corona particles looks to dilute due to zero polarization of the core's and secondary Λs

Does local polarization contribute to global polarization? $\rightarrow$ Is work in progress

Summary

- The core-corona model is used to describe the hyperon global polarization experimental data at energy ranges of the HADES, STAR and NICA experiments.
- It has been shown that local polarization could contribute to global polarization with a fraction of the value of transverse polarization measured in pp collisions.
- UrQMD has been proposed to simulate both the hydrodynamic phase of the core and cascade transport of the corona and separate Λ contribution.
- Mpdroot has been used to simulate the decay and transport of polarization in the charged decay of Λ.
- It has been shown that local polarization could contribute to global polarization, however, the results are inconclusive, due to the size of the sample used and the uncertainties of the calculation.

Gracias