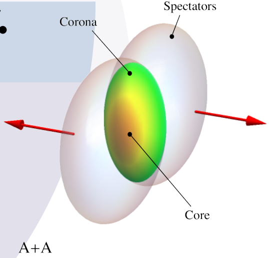
Core Corona approach, a model to explain Hyperon Global Polarization and other phenomena in semi-central heavy-ion collisions at low energy.



Ivonne Maldonado[1]

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September 9^{th}, 2022

Work done in collaboration with

A. Ayala (ICN-UNAM), I. Domínguez (FCFM-UAS)and M.E. Tejeda-Yeomans(UCol)

Reunión Anual de la División de partículas y Campos de la Sociedad Mexicana de Física

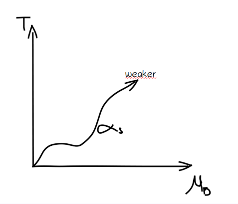
Outline

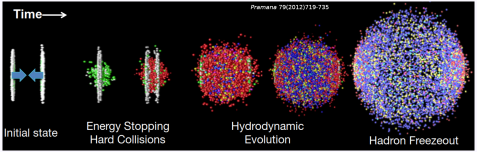
Section 1

Heavy-Ion Collisions at low energy

QGP and Heavy-Ion Collisions

- The QCD predicts a new phase of matter the QGP.
- It exist at early universe, 10 μs after the big bang.
- Heavy-Ion Collisions reproduce conditions at 10 μs after Big-Bang
- Transition from QGP to hadron gas.
- Strongly interacting matter in equilibrium is characterized by two quantities T and μ_B (or n_B)

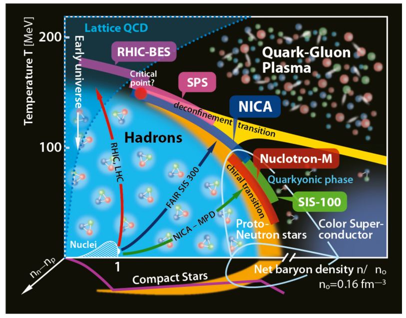




Due to asymptotic freedom, α_s diminishes with increasing the energy scale producing that interactions among strongly interacting particles will get weaker as T or μ_B are increased.

J.Phys.Conf.Ser. 50 (2006) 238-242

Exploration of the QCD Phase Diagram



MPD experiment is focus in look for new phenomena in the baryon-rich region of QCD phase diagram

Different experiments allow us to:

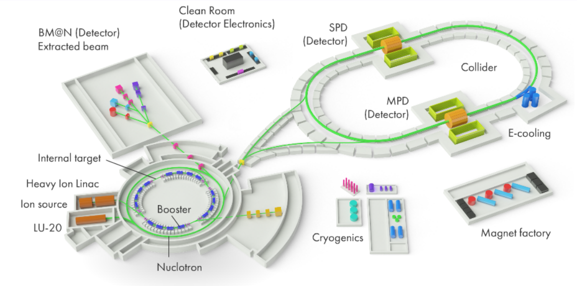
- Scan different parts of the QCD phase diagram which has different characteristics
- At Low energy collisions, matter differ form that studied at SPS, RHIC or LHC, because it consist principally for baryons and few mesons and can be compressed until 3 times the density of nuclear matter for approx 10-12 fm/c
- State of matter produced in HIC has fluid properties.
- Non-central collisions have a large angular momentum and strong vortical structure.

Section 2

MPD Experiment

NICA The Nuclotron Ion fAcility

Aimed at study of hot and dense nuclear and baryonic matter in HIC at a center of mass energies in the range $\sqrt{s_{NN}} = 4 - 11$ GeV. The average luminosity expected is $1 \cdot 10^{27}$ cm^{-2}s$^{-}1$.



It look for sheed light on

- In-medium properties of hadrons and the nuclear matter equation of state (EoS)
- The onset of deconfinement (OD) and/or chiral symmetry restoration (CSR)
- Phase transition (PT)
- Mixed Phase (MP)
- The Critical End Point (CEP)

Multi-Purpose Detector (MPD) Collaboration

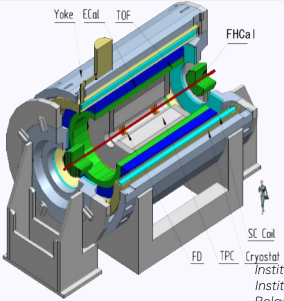
MPD International Collaboration was established in **2018**
to construct, commission and operate the detector

10 Countries $>$ 450 participants, **31** institutes and **JINR**

Organization

Acting Spokesperson:	**Victor Riabov**
Deputy Spokesperson:	**Zebo Tang**
Institutional Board Chair:	**Alejandro Ayala**
Project Manager:	**Slava Golovatyuk**

Joint Institute for Nuclear Research
AANL, Yerevan, ***Armenia;***
University of Plovdiv, ***Bulgaria;***
Tsinghua University, Beijing, ***China;***
USTC, Hefei, ***China;***
Huzhou University, Huizhou, ***China;***
Institute of Nuclear and Applied Physics, CAS, Shanghai, ***China;***
Central China Normal University, ***China;***
Shandong University, Shandong, ***China;***
IHEP, Beijing, ***China;***
University of South China, ***China;***
Three Gorges University, ***China;***
Institute of Modern Physics of CAS, Lanzhou, ***China;***
Tbilisi State University, Tbilisi, ***Georgia;***
FCFM-BUAP (Heber Zepeda) Puebla, ***Mexico;***
FC-UCOL (Maria Elena Tejeda), Colima, ***Mexico;***
FCFM-UAS (Isabel Dominguez), Culiacán, ***Mexico;***
ICN-UNAM (Alejandro Ayala), Mexico City, ***Mexico;***

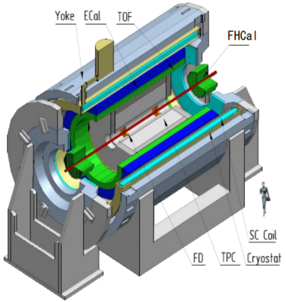


Institute of Applied Physics, Chisinev, ***Moldova;***
Institute of Physics and Technology, ***Mongolia;***
Belgorod National Research University, ***Russia;***
INR RAS, Moscow, ***Russia;***
MEPhI, Moscow, ***Russia;***
Moscow Institute of Science and Technology, ***Russia;***
North Osetian State University, ***Russia;***
NRC Kurchatov Institute, ITEP, ***Russia;***
Kurchatov Institute, Moscow, ***Russia;***
St. Petersburg State University, ***Russia;***
SINP, Moscow, ***Russia;***
PNPI, Gatchina, ***Russia;***
Vinča Institute of Nuclear Sciences, ***Serbia;***
Pavol Jozef Šafárik University, Košice, ***Slovakia***

Multi Purpose Detector

MPD physics goals

- Hadrochemistry.
- Anisotropic flow measurements.
- Intensity interferometry.
- Fluctuations.
- Short lived resonances.
- Electromagnetic probes.

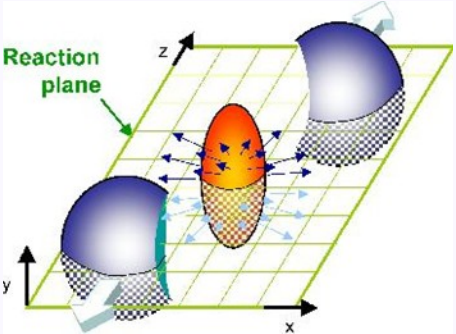


Signals at systematically changing conditions of collision (energy, centrality, system size) using as bulk observables; multi-strange hyperon yields and spectra (OD, EOS); electromagnetic probes (CSR, OD); azimuthal charged-particle cor relations (LPV); event-by-event fluctuation in hadron productions (CEP); correlations involving π, K, p, Λ (OD); directed and elliptic flows for identified hadron species (EOS,OD); reference data (i.e. p + p) will be taken at the same experimental conditions; study of hyperon polarisation and other polarisation phenomena including possible study of the nucleon spin structure via the Drell-Yan (DY) processes after the MPD upgrade

Section 3

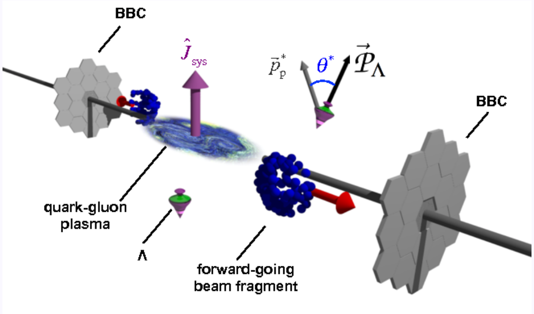
Hyperon Global Polarization and vorticity

Global Vorticity and polarization in heavy Ion collisions



- Non-central collisions have large angular momentum $L \sim 10^5 \hbar$.
- Shear forces in initial condition introduce vorticity to the QGP.
- Spin-orbit coupling: spin alignment, or polarization, along the direction of the vorticity -on average- parallel to J.

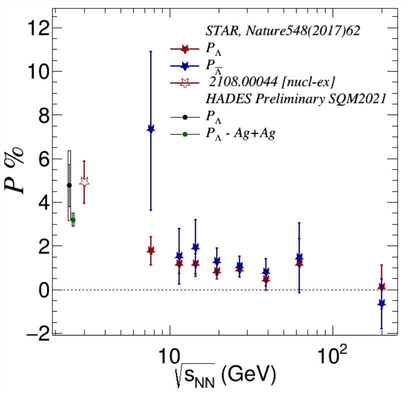
Why are we interested in measure Hyperon Global Polari



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

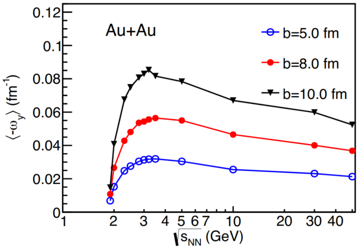
- The Λ and $\bar{\Lambda}$ polarization are linked to the properties of the medium produced in relativistic heavy-ion collisions.
- For semi-central collisions, Angular momentum can be quantified in terms of the thermal vorticity
- The global polarization can be measured using the self-analysing $\Lambda/\bar{\Lambda}$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

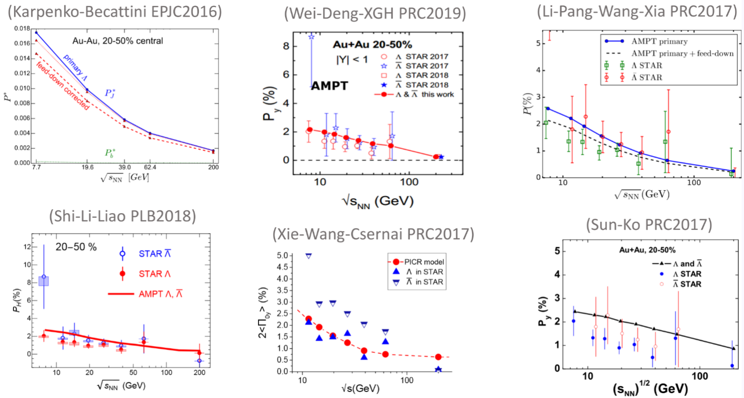
[a] X.-G. Deng et al., PRC101.064908(2020)

Λ Global Polarization models

v-Hydro, partonic/hadronic transport, etc.

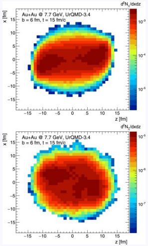
redIf the system is in thermal equilibrium, then equilibrium of spin degrees of freedom (spin and orbital angular momentum)

Summary from Xu-Guang Huang (Fudan University) - QM 2019

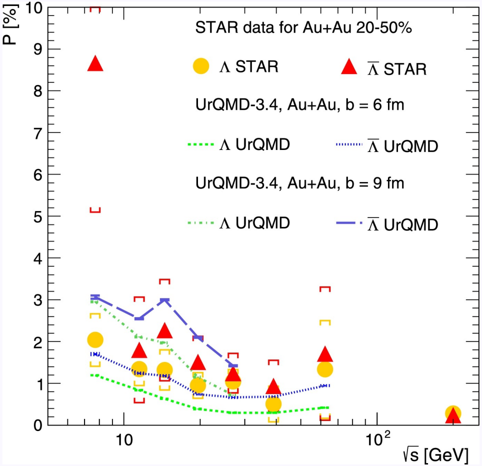


$\bar{\Lambda}$ Polarization

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



Density distributions of Λ (upper plot) and $\bar{\Lambda}$(bottom plot) in the reaction plane in UrQMD calculations of Au+Au collisions.



Phys.Lett.B.803(2020)135298

Section 4

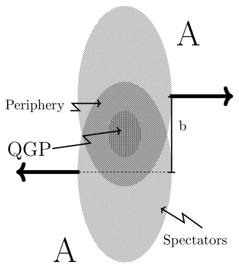
Core-Corona Model

Core-Corona Model

... finding new probes for the existence of a QGP, can make polarization measurements a powerful analyzing tool in high energy heavy-ion collisions.

Ayala, Cuautle, Herrera and Montaño, Phys.Rev.C 65 (2002) 024902

Change in polarization w.r.t. $p + p$ collisions as a means to identify the production of deconfined matter.



- In the Corona, reactions like:
  $p + p \to K + \Lambda + p$
  Polarization is described by Lund Model, DeGrand-Miettinen model or Gluon bremsstrahlung mechanism.
  Λ spin is that of s-quark
- In the Core: spin aligment driven by vorticity or magnetic field

Another studies with core-corona approach

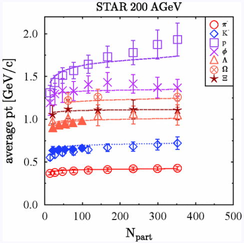
Core-Corona approach has been used to explain data from different experiments

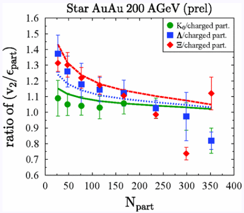
- Centrality Dependence of Strangeness Enhancement in Ultrarelativistic Heavy Ion Collisions - a Core-Corona Effect[1].
- Is the centrality dependence of the elliptic flow v_2 and of the average $\langle p_T \rangle$ more than a Core-Corona Effect?[2]

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





[1] Phys.Lett.B 673(2009)19-23
[2] Phys.Rev.C 82(2010)034906

Our approach for Hyperon Global Polarization with Core-Model

- **Core meets corona: A two-component source to explain Λ and $\bar{\Lambda}$ global polarization in semi-central heavy-ion collisions** Phys.Lett.B Volume 810, (2020) 135818
- **The rise and fall of Λ and $\bar{\Lambda}$ global polarization in semi-central heavy-ion collisions at HADES, NICA and RHIC energies from the core-corona model** arXiv:2106.14379v1 [hep-ph] 28 Jun 2021

The rise and fall of Λ and $\bar{\Lambda}$ global polarization in semi-central heavy-ion collisions at HADES, NICA and RHIC energies from the core-corona model

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[2] *Centre for Theoretical and Mathematical Physics, and Department of Physics, University of Cape Town, Rondebosch 7700, South Africa.*
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[4] *Facultad de Ciencias - CUICBAS, Universidad de Colima, Bernal Díaz del Castillo No. 340, Col. Villas San Sebastián, 28045 Colima, Mexico.*

arXiv:2106.14379v1 [hep-ph] 28 Jun 2021

We compute the Λ and $\bar{\Lambda}$ global polarizations in semi-central heavy-ion collisions using the core-corona model where the source of Λ's and $\bar{\Lambda}$'s is taken as consisting of a high-density core and a less dense corona. We show that the overall properties of the polarization excitation functions can be linked to the relative abundance of Λs coming from the core versus those coming from the corona. For low collision energies, the former are more abundant whereas for higher energies the latter become more abundant. The main consequence of this reversing of the relative abundance is that both polarizations peak at collision energies $\sqrt{s_{NN}} \lesssim 10$ GeV. The exact positions and heights of these peaks depend not only on this reversal of relative abundances, but also on the centrality class, which is directly related to the QGP volume and lifetime, as well as on the relative abundances of Λs and $\bar{\Lambda}$s in the core and corona regions. The intrinsic polarizations are computed from a field theoretical approach that links the alignment of the strange quark spin with the thermal vorticity and modeling the QGP volume and lifetime using a Bjorken expansion scenario. We predict that the Λ and $\bar{\Lambda}$ global polarizations should peak at the energy range accessible to NICA and HADES.

I. INTRODUCTION

The polarization properties of Λ and $\bar{\Lambda}$ have received increasing attention over the last years due to the possibility to link this observable to the properties of the medium produced in relativistic heavy-ion collisions [1–13]. For semi-central collisions, the matter density profile in the transverse plane develops an angular momentum [14] which can be quantified in terms of the thermal vorticity [15]. When this vorticity is transferred to spin degrees of freedom, the global polarization can be measured using the self-analising $\Lambda/\bar{\Lambda}$ decays.

The Beam Energy Scan (BES) at RHIC, performed by the STAR Collaboration [16, 17] has shown a trend for the Λ and $\bar{\Lambda}$ global polarization to increase as the energy of the collision decreases and that this increase is faster for $\bar{\Lambda}$s than for Λs. In addition, the HADES Collaboration has recently provided preliminary results on the Λ global polarization in Au+Au collisions at $\sqrt{s_{NN}} = 2.42$

short-lived but intense magnetic fields [21–23] and the possibility that Λ and $\bar{\Lambda}$ align their spins with the direction of the angular momentum created in the reaction during the life-time of the evolving system [24, 25].

In a recent work [26], we have shown that when in semi-central heavy-ion collisions, the source of Λs and $\bar{\Lambda}$s is modeled as a high-density core and a less dense corona, the global polarization properties of these hyperons, as a function of the collision energy, are well described. The QGP is produced in the core when the density of participants is larger than a critical value. At the same time, this region corresponds to the low baryon density. On the other hand, the corona corresponds to the region with the overall larger baryon density. For a given impact parameter (or rather, a centrality class), the volume in the corona becomes larger for lower energies. We found that when the larger abundance of Λs compared to $\bar{\Lambda}$s coming from the corona is combined with a smaller number of Λs coming from the core, compared to those from the

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)

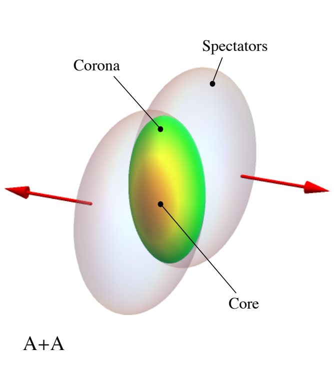
$$q\bar{q} \to s\bar{s} \text{ and } gg \to s\bar{s}$$

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

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



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:

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

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

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.

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

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 $N_{\bar{\Lambda}_{REC(QGP)}}/N_{\Lambda_{REC(QGP)}}$

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

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

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**:

Polarization from Corona

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

Ratio $\bar{\Lambda}/\Lambda$

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

Intrinsic Polarization

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

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.

Global Polarization

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

Estimating from data - $\bar{\Lambda}/\Lambda$ in the Corona

Ratio $\bar{\Lambda}/\Lambda$

$$\boxed{N_{\bar{\Lambda}_{REC}} = wN_{\Lambda_{REC}}}$$

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

Global Polarization

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

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

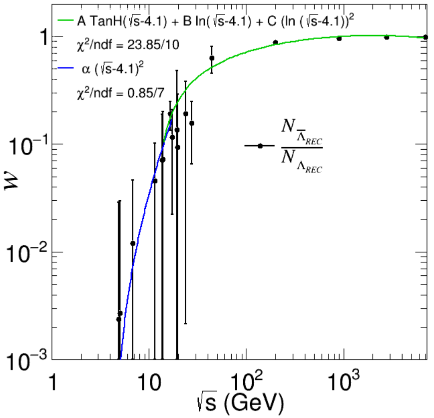
The ratio $w = N_{\bar{\Lambda}_{REC}} / N_{\Lambda_{REC}}$

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



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[3] 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

Calculating ratio $\bar{\Lambda}/\Lambda$ in the core

Ratio $\bar{\Lambda}/\Lambda$

$$N_{\bar{\Lambda}_{REC}} = wN_{\Lambda_{REC}}$$

$$\boxed{N_{\bar{\Lambda}_{QGP}} = w' N_{\Lambda_{QGP}}}$$

Global Polarization

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

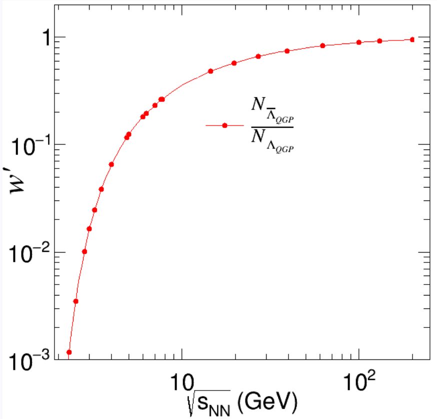
$$\mathcal{P}^{\bar{\Lambda}} = \frac{\bar{z}\left(\frac{w'}{w}\right)\frac{N_{\Lambda_{QGP}}}{N_{\Lambda_{REC}}}}{1+\left(\frac{w'}{w}\right)\frac{N_{\Lambda_{QGP}}}{N_{\Lambda_{REC}}}}$$

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 T and chemical potential $\mu = \mu_B/3$ given by:

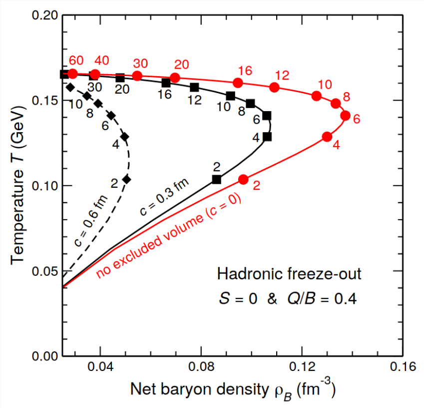
$$w' = \frac{e^{(m_s-\mu)/T}+1}{e^{(m_s+\mu)/T}+1}$$

where $m_s = 100$ MeV is the mass of the s-quark and T and μ_B are taken along the curve of the maximum chemical potential at freeze out.



μ_B and T at freeze out

Randrup and Cleymans



Eur.Phys.J. 52 (2016) 218–219

At maximum freeze-out baryon density in nuclear collisions, the extracted values of T and μ_B exhibits a smooth and monotonic dependence on the collision energy

$$
\begin{aligned}
T(\mu_B) &= 166 - 139\mu_B^2 - 53\mu_B^4 \\
\mu_B(\sqrt{s_{NN}}) &= \frac{1308}{1000 + 0.273\sqrt{s_{NN}}}
\end{aligned}
$$

Phys.Rev.C 74 (2006) 047901

Calculating intrinsic

Intrinsic Polarization

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

Global Polarization

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

Intrinsic Polarization

Intrinsic polarization is given by:

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

in terms of the relaxation times τ and $\bar{\tau}$ and the QGP life-time $\Delta\tau_{QGP}$.
The relaxation time can be computed as the inverse of the interaction rate between the thermal vorticity and the quark spin, which is modeled by an effective vertex

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

where

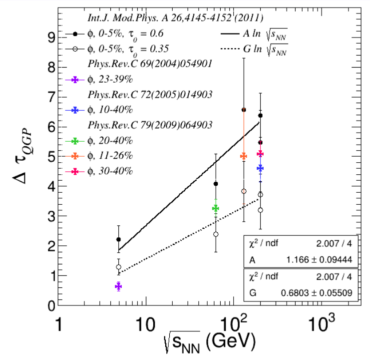
$$\Gamma = V\int \frac{d^3p}{2\pi^3}\Gamma(p_0), \text{ with } V = \pi R^2 \Delta\tau_{QGP}$$

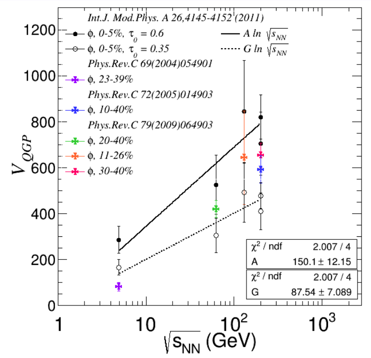
V is the volume of the core region[4], related to the QGP life-time $\Delta\tau_{QGP}$ in a Bjorken expansion scenario.

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

[4] A. Ayala. D. de la Cruz, L. A. Herńandez, and J. Salinas, Phys.Rev.D 102,056019 (2020)

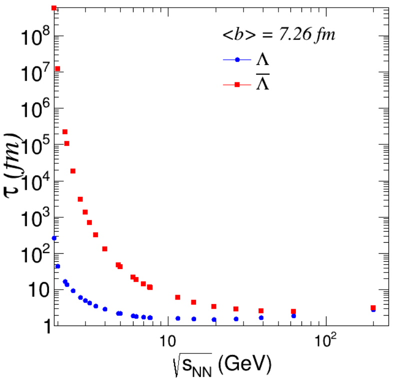
Volume and QGP life-time $\Delta\tau_{QGP} = \tau_0[\left(\frac{T_0}{T_f}\right)^3 - 1]$

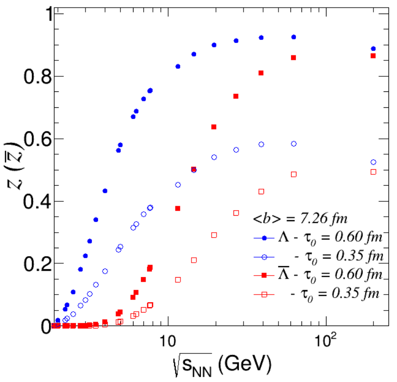




T_0 is estimated from p_T of ϕ mesons, $\tau_0 = 0.35 - 0.60$ fm to incorporate the effect of collision centrality, and T_f is taken as the value along the maximum chemical potential curve at freeze-out

Relaxation time and intrinsic polarization as a function o





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.

Calculating Λ abundances

Ratio Core/Corona

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

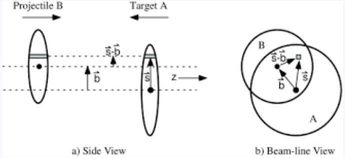
Global Polarization

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

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

Production of Λ in the core and the corona

The nuclear overlap model, as described by Eskola in Nucl. Phys. B323(1989)37



Michael L. Miller et. al. Ann.Rev.Nucl.Part.Sci.57 (2007)

Describes the density of participants of the collision

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

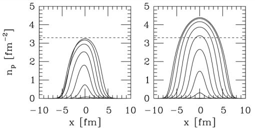
The thickness function T_A in terms of Woods-Saxon profile density ρ_A

$$\begin{aligned} T_A(z,s) &= \int_{\infty}^{\infty} \rho_A(z,\mathbf{s})\,dz \\ \rho_A(\mathbf{s}) &= \frac{\rho_0}{1+e^{(r-R_A)/a}} \end{aligned}$$

J/Ψ suppression at Pb+Pb collisions: a Hint of Quark Gluon Plasma Production?

Critical Density $n_c = 3.3fm$

Participants required to QGP formation Phys.Rev.Lett. 77 (1996)1703-1706



The density of participants $n_p(s)$, for s along the direction of the impact parameter, for various values of the impact parameter: $b = 0, 2, 4 \cdots$ fm. left: S–U collision; right: Pb–Pb collision. The horizontal dashed line corresponds to the largest density achieved in the S–U system, $n_p = 3.3$fm^{-2}

Production of Λ in the core and the corona

Number of Λs in the core

Average number of strange quarks produced in the QGP scales with the number of participants in the collision.

J. Letessier, J. Rafelski and A. Tounsi, Phys. Lett. B 389 (1996)

$$\langle s \rangle = N_{\Lambda_{QGP}} = cN^2_{p_{QGP}}$$

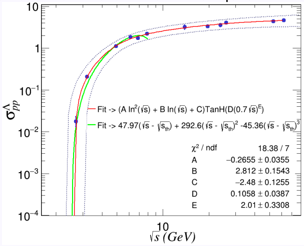
with $0.001 \leq c \leq 0.005$. Λs are not the only strange hadrons produced in the reaction $c = 0.0025$

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

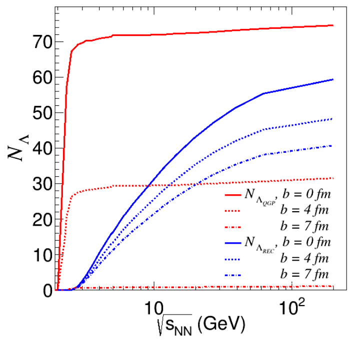
Number of Λs in the corona

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

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



Number of Λs and $\bar{\Lambda}$s as a function of energy

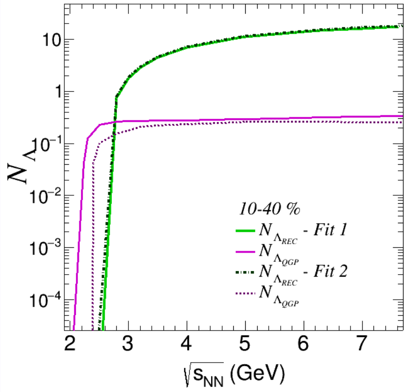


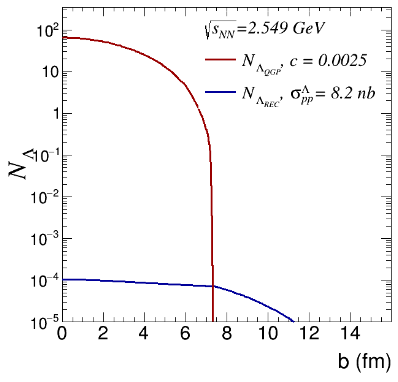
$N_{\Lambda_{QGP}}$ and $N_{\Lambda_{REC}}$ as a function of the collision energy for impact parameters $b = 0, 4, 7$ fm.

- At small b, Λ particle production is dominated by the core region.
- For peripheral collisions, Λ particle production is dominated by the corona region $\rightarrow$ relevant for vorticity and polarization studies.

Core-corona model introduces a critical density of participants n_c above which the core can be produced. For peripheral collisions is difficult to achieve this critical density n_c, even for the largest collision energies.

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

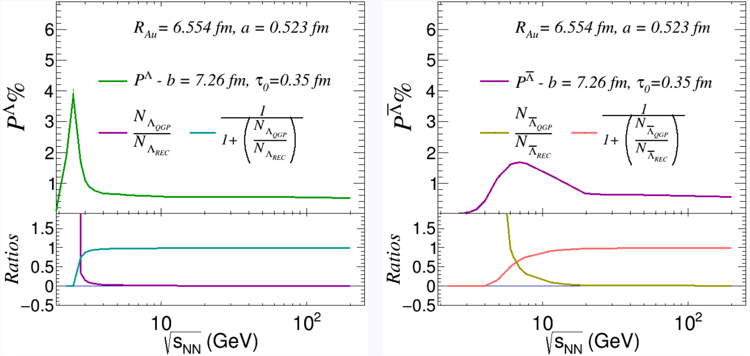
Section 5

Excitation function for the Global Hyperon Polarization

The ratios describing the polarization

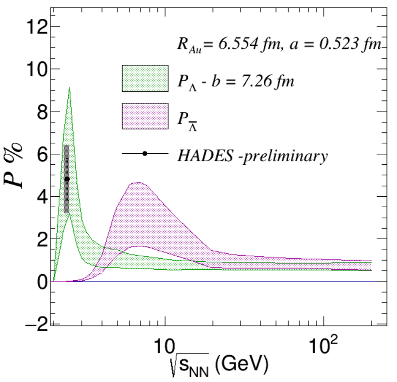
$$\mathcal{P}^{\Lambda}/z = \frac{\frac{N_{\Lambda_{QGP}}}{N_{\Lambda_{REC}}}}{1+\frac{N_{\Lambda_{QGP}}}{N_{\Lambda_{REC}}}}$$

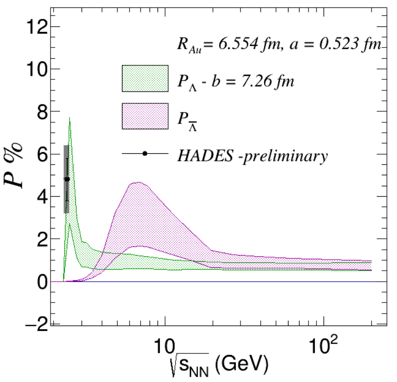
$$\mathcal{P}^{\bar{\Lambda}}/\bar{z} = \frac{\left(\frac{w'}{w}\right)\frac{N_{\Lambda_{QGP}}}{N_{\Lambda_{REC}}}}{1+\left(\frac{w'}{w}\right)\frac{N_{\Lambda_{QGP}}}{N_{\Lambda_{REC}}}}$$



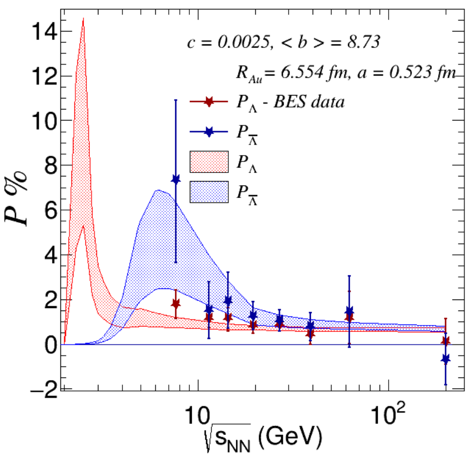
Λ and $\bar{\Lambda}$ polarization in Au+Au at HADES centrality

10 - 40 %





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

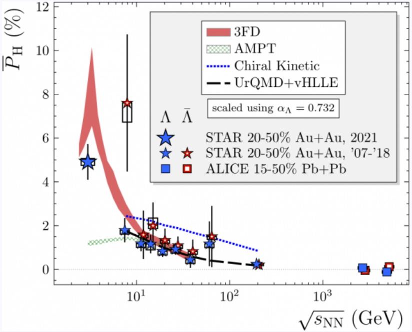


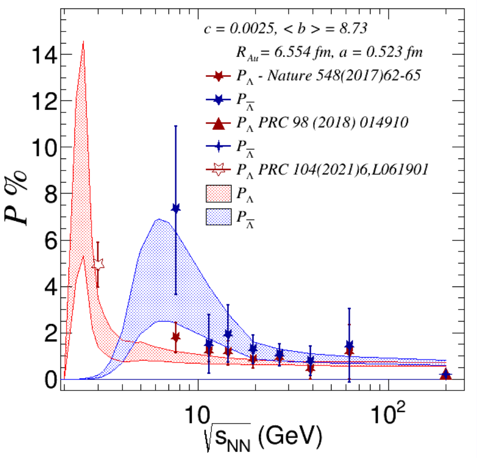
20 - 50 %

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

Recent Results - $Au + Au$ at $\sqrt{s_{NN}} = 3$ GeV

Recently STAR collaboration presents:
Phys.Rev.C 104(2021)6,L061901

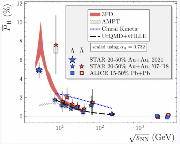


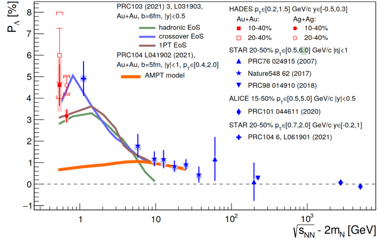


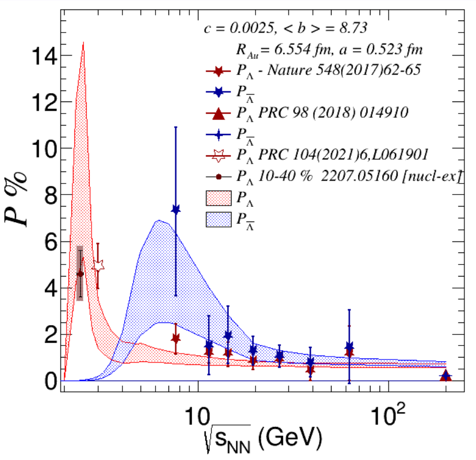
Our previous prediction fits the new value.
3FD model predicts also a peak.

More Recent Results - $Au + Au$ at $\sqrt{s_{NN}} = 2.42$ GeV

Recently HADES collaboration presents:
arXiv:2207.05160 [nucl-ex]



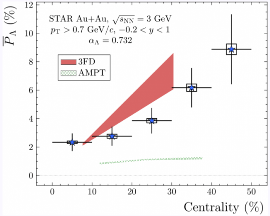


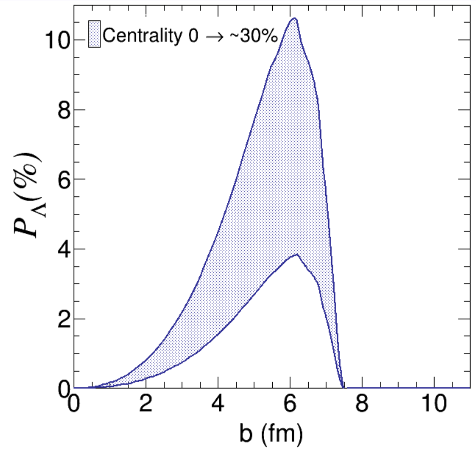


Our previous prediction fits the new value.
3FD model peak is shown for $b = 8$fm (left) and $b = 5$fm (right)

- In non-central collisions Λ and $\bar{\Lambda}$ hyperons can be produced from different density zones within the interaction region: core or corona.
- Polarization properties of Λ and $\bar{\Lambda}$ differ depending on the region they come from.
- Since the ratio of the number of $\bar{\Lambda}$s to Λs coming from the corona is less than 1: the global $\bar{\Lambda}$ polarization can be larger than the global Λ polarization.
- This amplifying effect is favored when the number of Λs coming from the core is smaller than the number of Λs coming from the corona.
- This happens for collisions with intermediate to large impact parameters, which correspond to the kind of collisions that favor the development of a larger thermal vorticity.

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

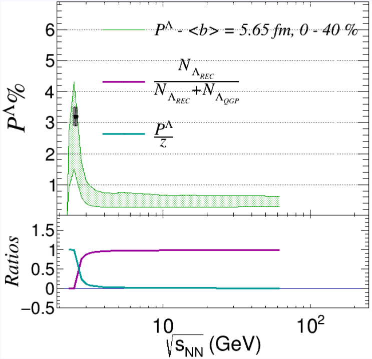


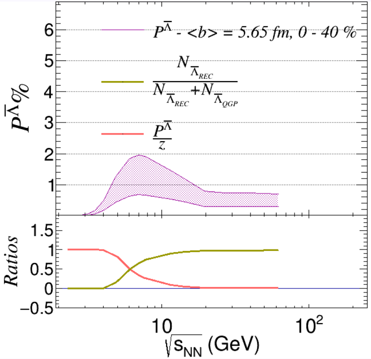


Polarization for more peripheral collisions goes to zero, as the critical density n_c of the system is not achieved, vanishing the number of Λs from the core.

Λ and $\bar{\Lambda}$ polarization in $Ag+Ag$ collisions

Similar trend to Au+Au



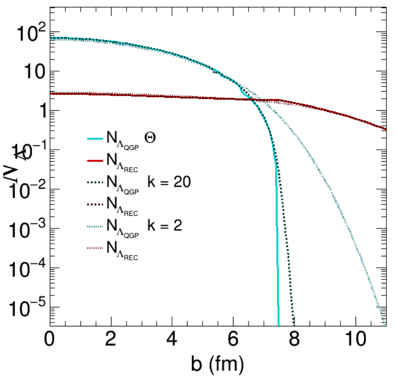


Due the system's size, the minimum critical density n_c to produce QGP is barely achieved for non-central collisions.

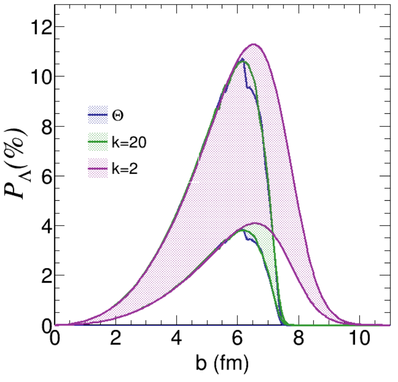
A change in the critical densisty n_c

The number of Λ's is dependent on the critical density $n_c = 3.3$ fm^{-2}.

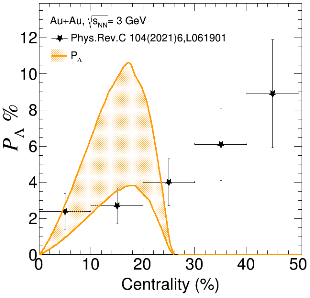
- A change in the value of the n_c, allow the QGP formation for higher b.
- Change $\theta(x) \to \frac{1}{1+2e^{-2kx}}$ with $k = \{2, 20\}$.
- Higher $k \to \theta(x)$

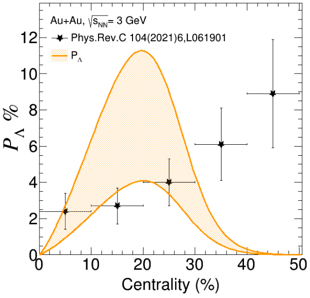


Polarization as a function of centrality



The polarization increases for 20-30% centrality bin, and is different from zero for 30-40% however does not describe data at higher bins of centrality





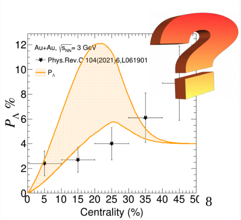
What about the contribution of P_{REC}?

- 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 $\sqrt{s} = 62\text{GeV} \rightarrow \mathcal{P} = -0.40 \pm 0.10$

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

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?

5 6

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

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

Section 6

Polarization from Corona region

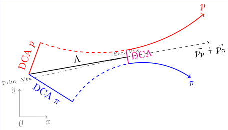
Measurement procedure of Hyperon Global Polarization

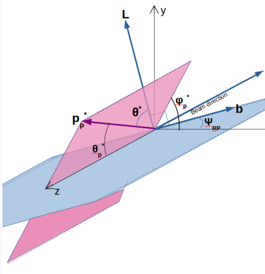
1. Λ and $\bar{\Lambda}$ identification through their decay products and measurement of the azimuthal angle of the decay baryon in Λ rest frame.

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

$\alpha_H = 0.732 \pm 0.014$ - 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

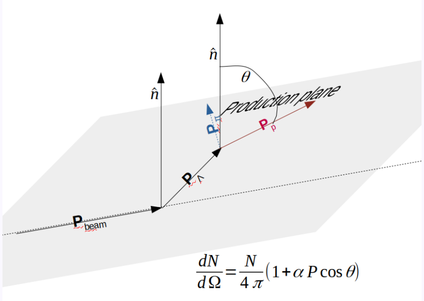
In pp collisions, transverse polarization is measured with respect to production plane.

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:

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

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:

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

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?

Section 7

Implementation at MPD

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].

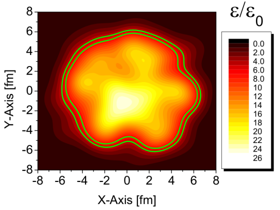


FIG. 1. (Color online) Contour plot of the local rest frame energy density in the transverse plane ($z = 0$) of a central ($b = 0$) collision of Pb+Pb at $E_{lab} = 40A$ GeV. The energy density is normalized to the ground state energy density ($\epsilon_0 \approx 145$ MeV/fm^3). The two green lines correspond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

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

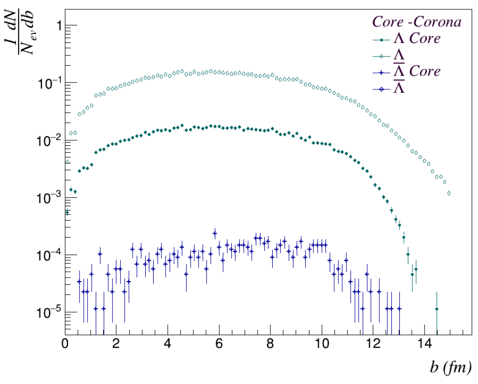
[b] Nucl.Phys.A595(1995)346, Nucl. Phys.A595(1995)383

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

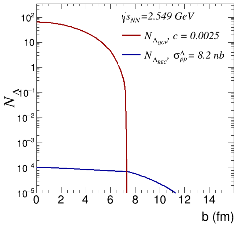
[d] Phys.Rev.C84,024905(2011)

Core-Corona dN/db

From pure MC $\sim$ 89k events



Λ abundances in different regions differs from critical density - Glauber calculation



However we can use it to estimate the contribution to Global polarization

Implementation in MPD

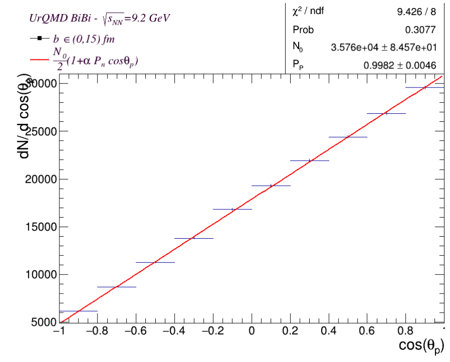
As a first attempt assign an arbitrary local polarization $\rightarrow$ 40% only to corona particles.

- Class MpdUrQMDGenerator $\rightarrow$ modified to read parent process type.
- Assign a fixed local polarization value to Λs in the corona in the $\hat{n}$ direction
- Transfer polarization to decay particles by the same procedure developed to Hyperon Global Polarization transfer in PHSD (PWG2 - E. Nazarova, and V. Voronyuk, [7])
- Λ reconstruction and measurement of Hyperon Global Polarization with MCTracks.

[7] https://indico.jinr.ru/event/3202/contributions/17250/attachments/12925/21604/Nazarova_26_07_22.pdf

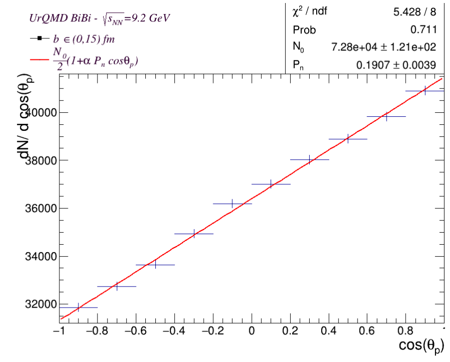
Polarization transfer

All Λs in the corona are polarized, projection along its own $\mathcal{P}$ is consistent with 100%

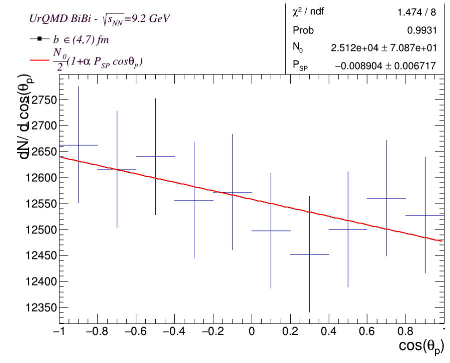


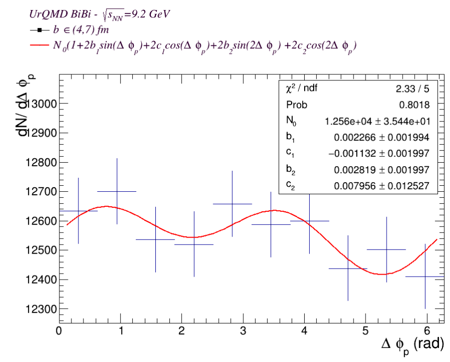
sample ~ 36k events

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



Polarization for Λ produced at $b \in (4,7) fm$





$$\mathcal{P} \sim -0.009$$

$$\mathcal{P} = -\frac{8}{\pi\alpha_\Lambda}\frac{b_1}{R_{SP}} \rightarrow \sim -0.010$$

Does local polarization contribute to global polarization?

Section 8

Summary

Summary

- The description of global polarization has been shown with the core-corona model, which describes the 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 !

IX Collaboration Meeting of the MPD Experiment at the NICA Facility

Work in progress and future plans

- Increase the size of the sample to repeat measurements and verify results.
- Get polarization with reconstructed tracks.
- Contribute to the implementation of core separation to another measurements within MPD.