Λ and $\bar{\Lambda}$ global polarization from the core-corona model.

Malena Tejeda-Yeomans

Facultad de Ciencias
Universidad de Colima
México

Work done in collaboration with
A. Ayala (ICN-UNAM), I. Domínguez (FCFM-UAS) and I. Maldonado (JINR)

Thanks to CONACyT A1-S-7655 and UNAM-DGAPA-PAPIIT IG100219.

The Team

5 undergrads:

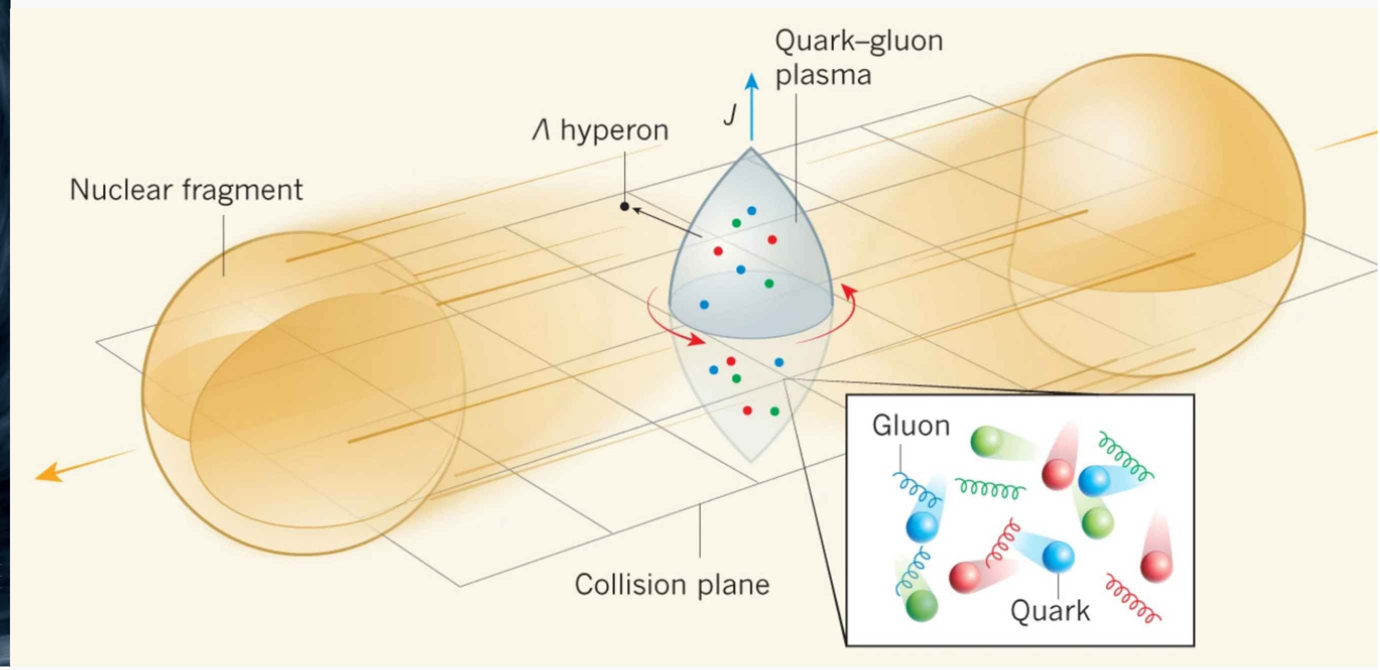
Kitzia Hernandez, Juan Lopez, Ramon Ruiz, Mike Medina, Dominique Padilla

3 postgrads:

Jorge Medina, Julio Maldonado, Pedro Nieto

Hot, dense, whirly QCD matter in HICs

STAR Collaboration, Nature 548 (2017)



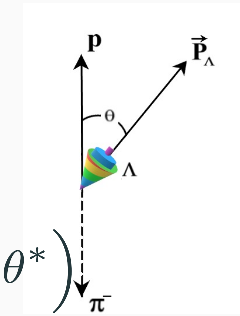
Non-central collisions have large angular momentum $L \sim 10^5 \hbar$.
Shear forces in initial condition introduce vorticity to the QGP.

Spin-orbit coupling: spin alignment, or polarization, along the direction of the vorticity - on average - parallel to J.

Vorticity from Λ global polarization

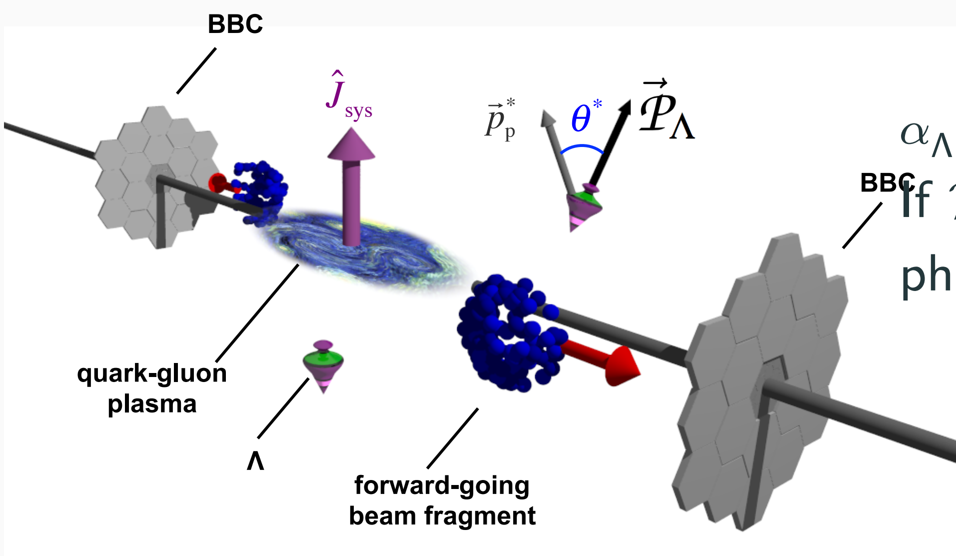
Spin-orbit coupling: spin alignment, or polarization, along the direction of the vorticity - on average - parallel to $\hat{J} = \hat{\mathrm{b}} \times \hat{\mathrm{p}}_{beam}$

STAR Collaboration, Nature 548 (2017)



$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}\left(1 + \alpha_{\mathrm{H}}|\vec{\mathcal{P}}_{\mathrm{H}}|\cos\theta^*\right)$$

$$\alpha_{\Lambda\to p\pi^-} = 0.732 \pm 0.014 \quad (S = 2.3) \text{ PDG avg}$$



If $\vec{\mathcal{P}}_{\mathrm{H}}$ is independent of momentum + avg over phase space $\vec{\mathcal{P}}_{\mathrm{H}} || \hat{J}$

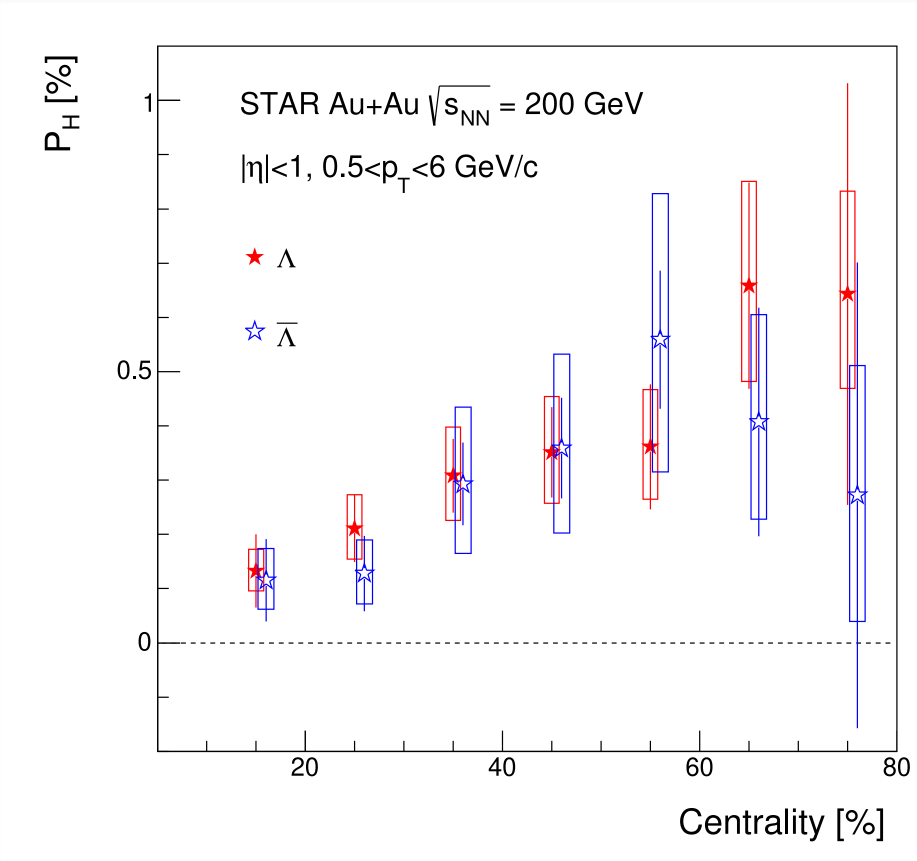
$$\overline{\mathcal{P}}_{\mathrm{H}} \equiv \langle \vec{\mathcal{P}}_{\mathrm{H}} \cdot \hat{J} \rangle = \frac{8}{\pi\alpha_{\mathrm{H}}} \frac{\langle \cos\left(\phi_p^* - \phi_J\right)\rangle}{R_{\mathrm{EP}}}$$

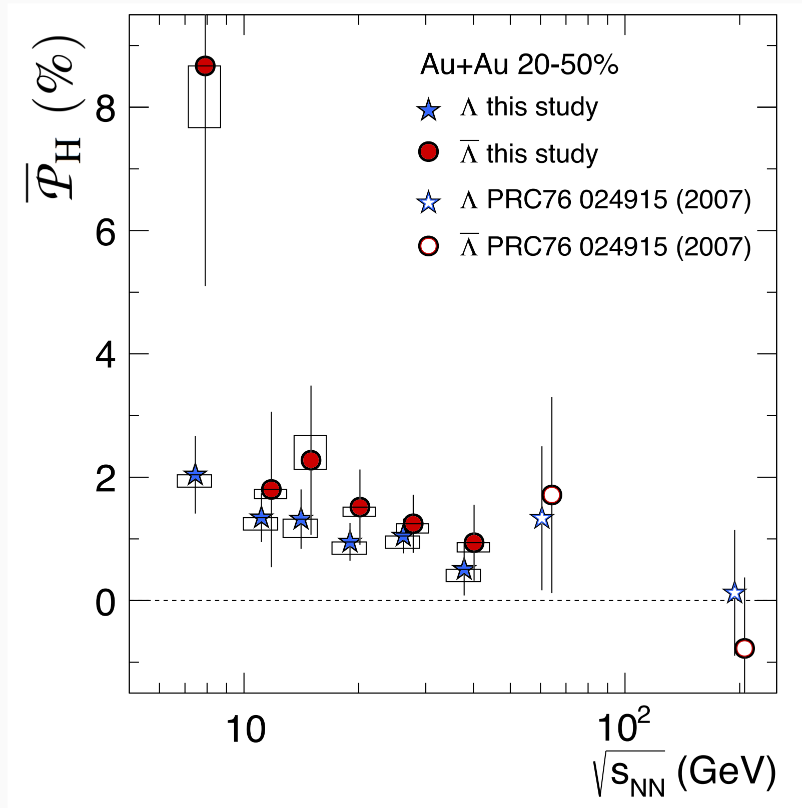
Observable: $\sqrt{s_{NN}}$-averaged polarization measurements of primary hadrons emitted from the fluid proportional to vorticity $\omega = |\vec{\omega}|$

$$\omega = \frac{k_B\ T}{\hbar}\left(\bar{\mathcal{P}}_H + \bar{\mathcal{P}}_{\bar{H}}\right) \quad \longrightarrow \omega \approx (9 \pm 1) \times 10^{21} \mathrm{s}^{-1}$$

Vorticity from Λ global polarization

Meassurement of angular momentum retained at mid-rapidity. In most central collisions: no initial angular momentum, no polarization.





STAR Collaboration, Nature 548 (2017); Phys.Rev.C 98 (2018) 014910

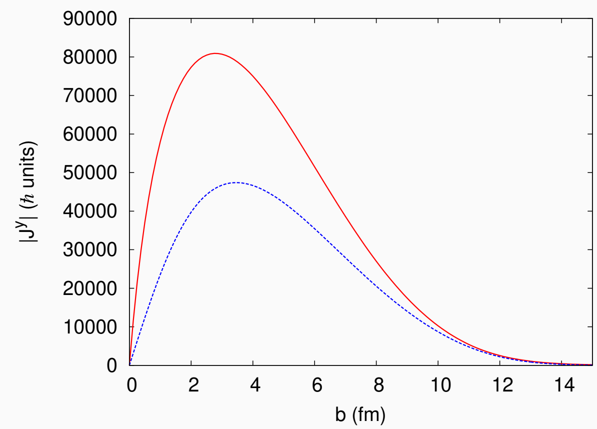
Thermal and kinematic vorticity

F. Becattini et. al. Eur.Phys.J.C 75 (2015), C 78 (2018)

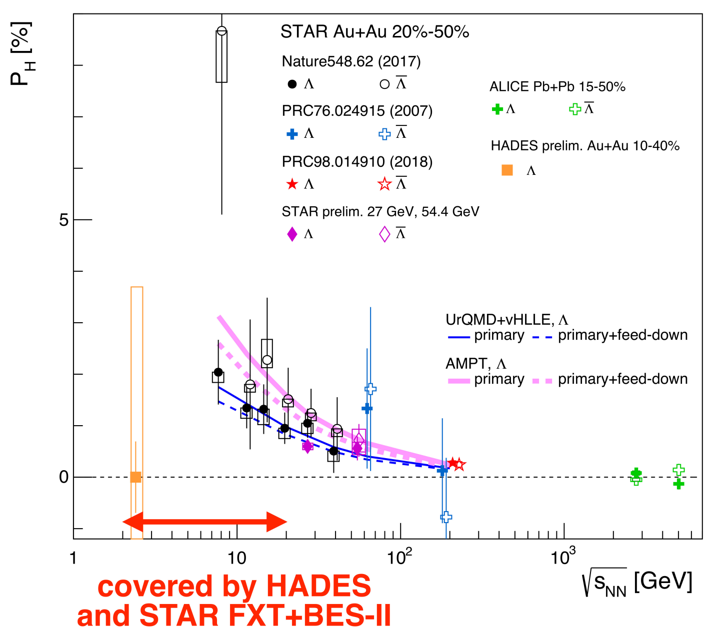
HIC simulations

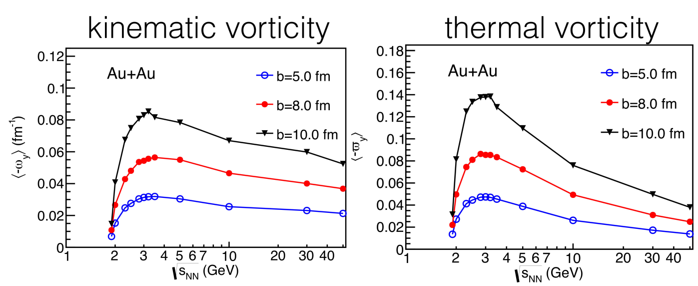
$$\beta_\mu = \beta u_\mu,\ u_\mu = \gamma(1, \vec{v}),\ \beta = 1/T$$

$$\varpi_{\mu\nu} = \frac{1}{2}\left(\partial_\nu \beta_\mu - \partial_\mu \beta_\nu\right) \qquad \omega_{\mu\nu} = \frac{1}{2}\left(\partial_\nu u_\mu - \partial_\mu u_\nu\right)$$



ALICE, PRC101.044611 (2020)
F. Kornas (HADES), SQM2019
J. Adams, K. Okubo (STAR), QM2019





Energy dependence of kinematic and thermal vorticity with UrQMD
X.-G. Deng et al., arXiv:2001.01371

HADES: 2.0-2.4 GeV
STAR FXT: 3-7.7 GeV
STAR BES II: 7.7-19 GeV

$b \sim 5-10$ collisions, favor the development of a larger thermal vorticity
$\rightarrow$ study non-central collisions

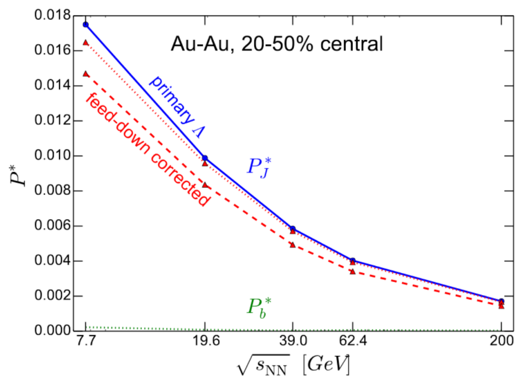
Λ global polarization - models

v-Hydro, partonic/hadronic transport, etc.

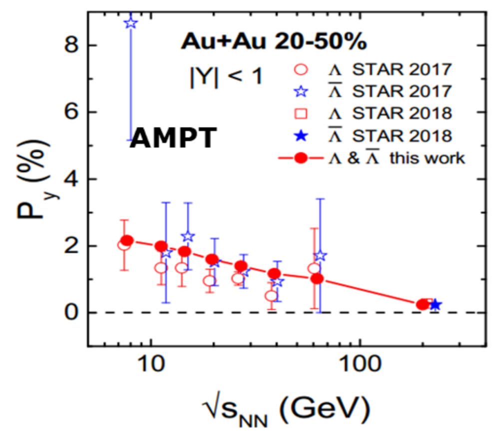
If the system is in thermal equilibrium, then equilibrium of spin degrees of freedom (spin and orbital angular momentum)

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

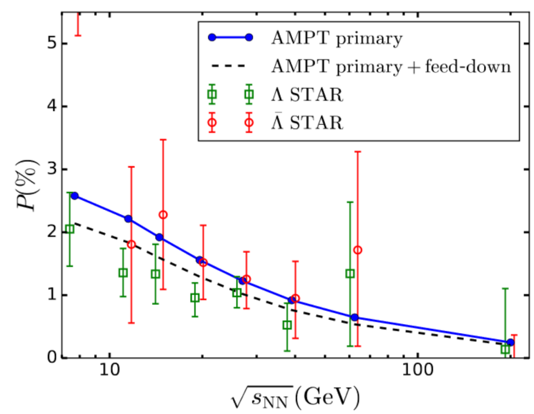
(Karpenko-Becattini EPJC2016)



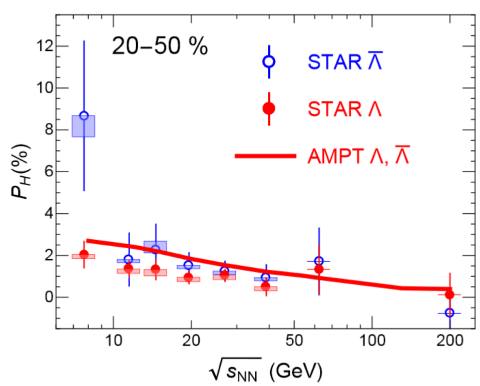
(Wei-Deng-XGH PRC2019)



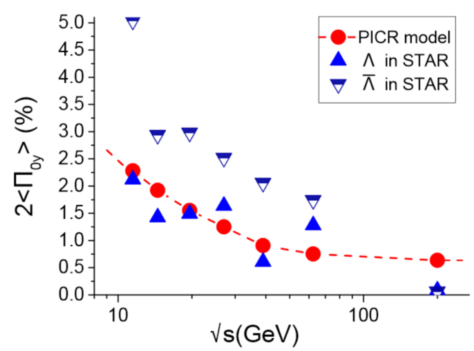
(Li-Pang-Wang-Xia PRC2017)



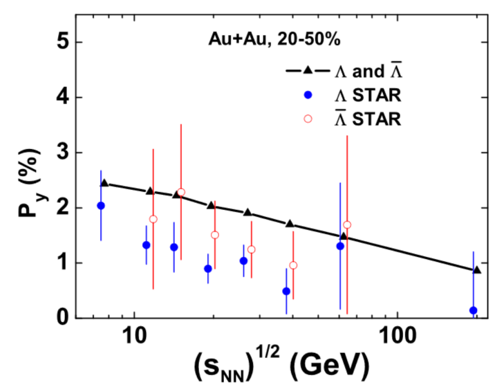
(Shi-Li-Liao PLB2018)



(Xie-Wang-Csernai PRC2017)



(Sun-Ko PRC2017)



In this talk:

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:2106.14379, to appear in PRC as follow-up to PLB 810 (2020).

A two-component model for global $\Lambda/\bar{\Lambda}$ polarization and comparison with key measurements by STAR (2017-2022) and HADES (2021-2022).

✓ centrality dependent model for Λ and $\bar{\Lambda}$ production in heavy-ion collisions

+

✓ relaxation time for quark spin-alignment + thermal vorticity in the hot/dense QGP

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

Alejandro Ayala[1,2], Isabel Domínguez[3], Ivonne Maldonado[3], and María Elena Tejeda-Yeomans[4]
[1] *Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Apartado Postal 70-543, CdMx 04510, Mexico.*
[2] *Centre for Theoretical and Mathematical Physics, and Department of Physics, University of Cape Town, Rondebosch 7700, South Africa.*
[3] *Facultad de Ciencias Físico-Matemáticas, Universidad Autónoma de Sinaloa, Avenida de las Américas y Boulevard Universitarios, Ciudad Universitaria, C.P. 80000, Culiacán, Sinaloa, Mexico.*
[4] *Facultad de Ciencias - CUICBAS, Universidad de Colima, Bernal Díaz del Castillo No. 340, Col. Villas San Sebastián, 28045 Colima, Mexico.*

We compute the Λ and $\overline{\Lambda}$ global polarizations in semi-central heavy-ion collisions using the core-corona model where the source of Λ's and $\overline{\Lambda}$'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 $\overline{\Lambda}$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 $\overline{\Lambda}$ global polarizations should peak at the energy range accessible to NICA and HADES.

I. INTRODUCTION

The polarization properties of Λ and $\overline{\Lambda}$ 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 $\Lambda/\overline{\Lambda}$ decays.

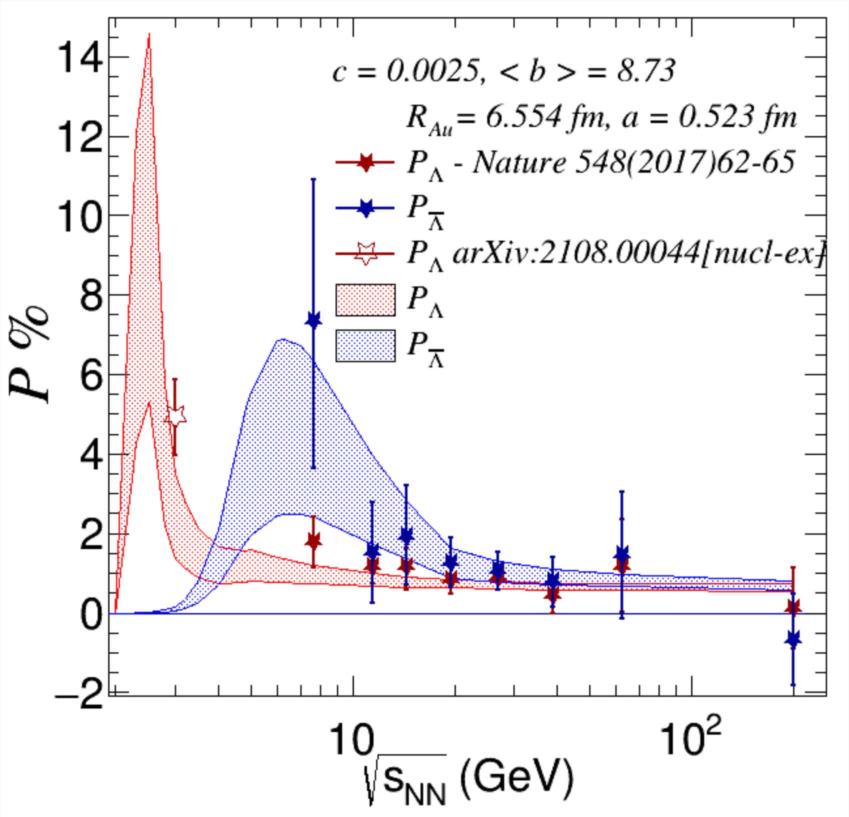
The Beam Energy Scan (BES) at RHIC, performed by the STAR Collaboration [16, 17] has shown a trend for the Λ and $\overline{\Lambda}$ global polarization to increase as the energy of the collision decreases and that this increase is faster for $\overline{\Lambda}$s than for Λs. In addition, the HADES 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 $\overline{\Lambda}$ 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 $\overline{\Lambda}$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 $\overline{\Lambda}$s coming from the corona is combined with a smaller number of Λs coming from the core, compared to those from the

In this talk: core-corona model and recent data

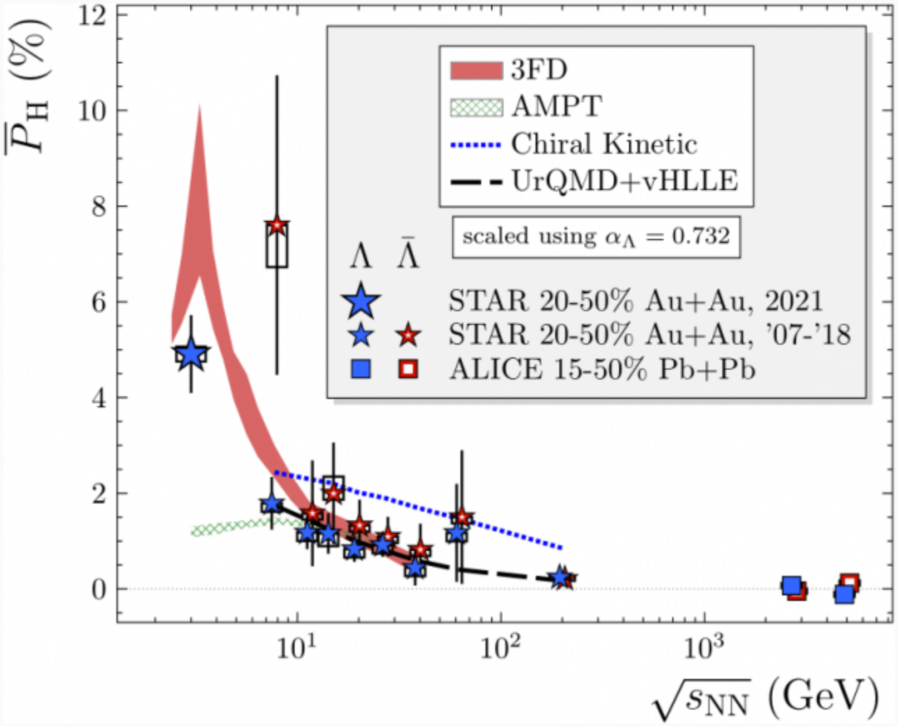
Our model

arXiv:2106.14379v1 - Jun 2021

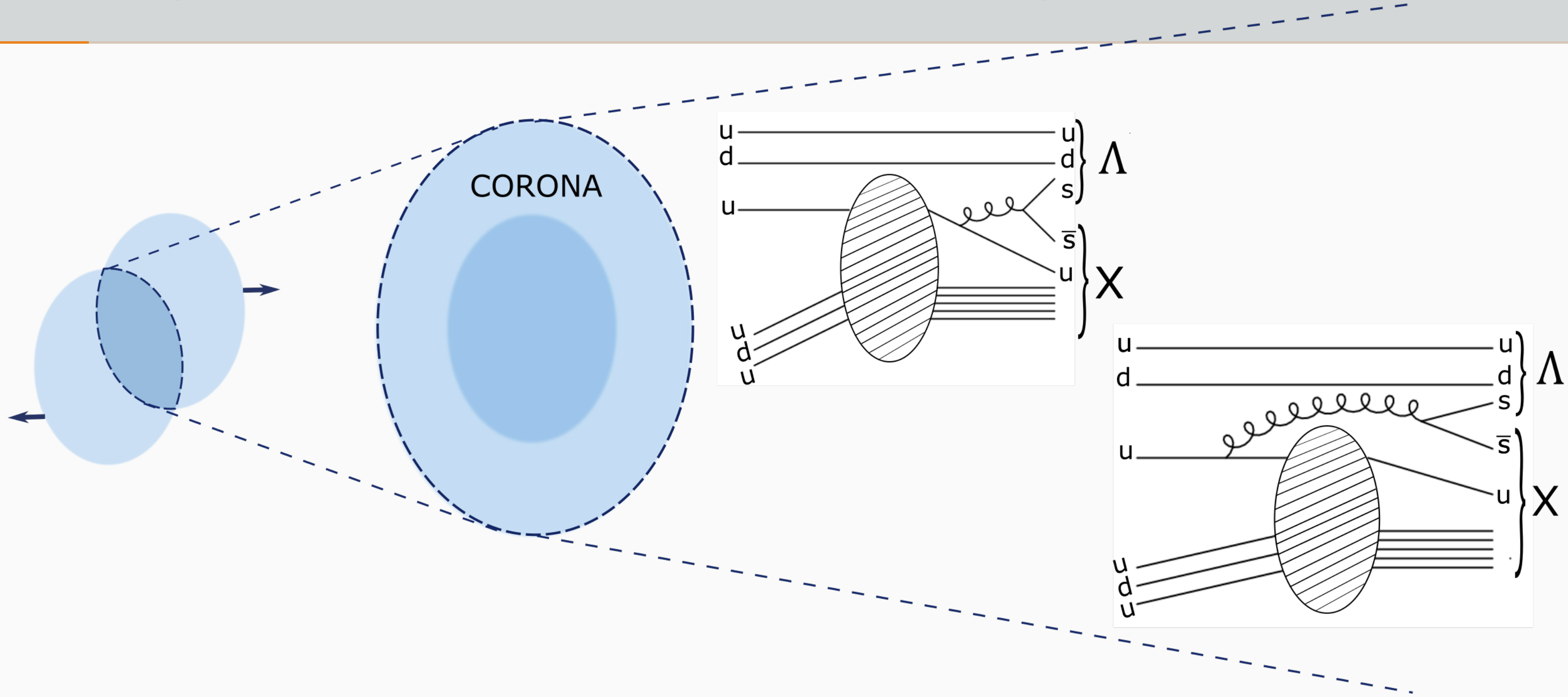


Recent STAR results,

arXiv:2108.00044v2 - Feb 2022



$\Lambda/\bar{\Lambda}$ global polarization from a two-component source

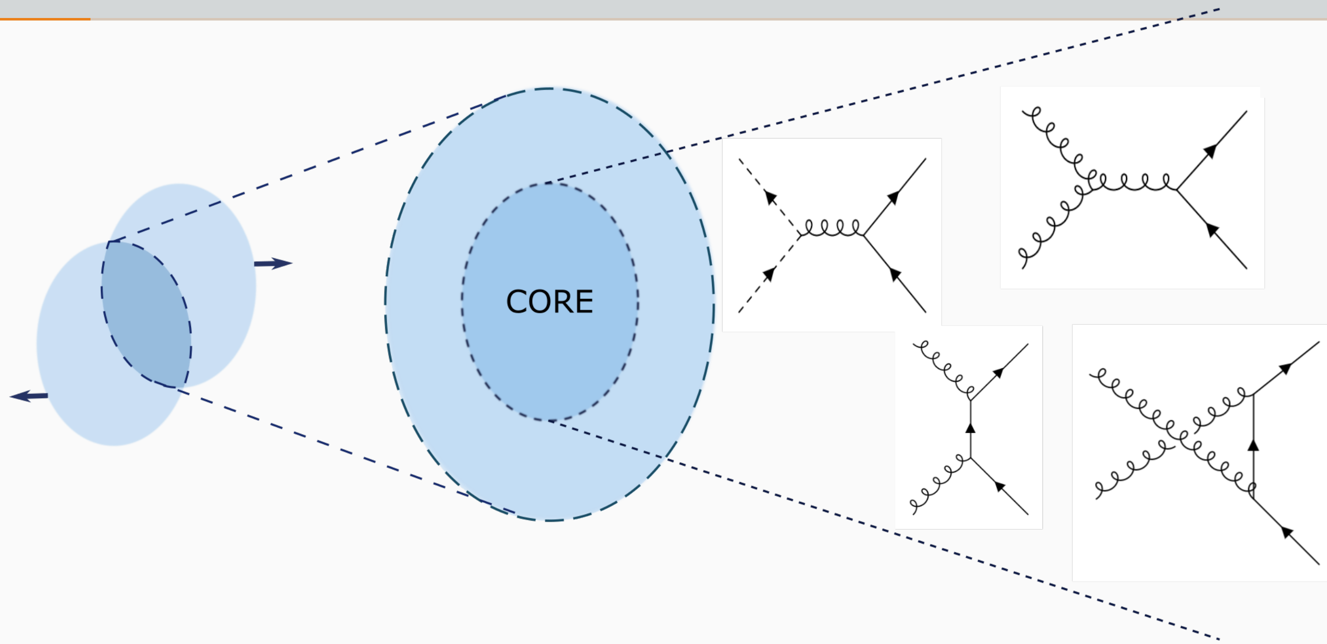


Measurement of Λ pol in inclusive h+N, N-N and N+A (late 70s): Λ spin is that of *s*-quark (*ud*-diquark in spin-isospin singlet)

- Lund model: semiclassical model, color dipole field between the diquark of incoming proton stretches and $s\bar{s}$ pair produced in this field.

- DeGrand-Miettinen model: Thomas precession effect in the quark recombination process, *s*-quark $\vec{v}$ is not parallel to the change of momentum induced by the combination. Spin-orbit interaction term $\vec{s} \cdot \vec{\omega_T}$ where $\vec{\omega_T} \propto \vec{F} \times \vec{v}$
- Gluon bremsstrahlung mechanism: polarized gluon transfers polarization to $s\bar{s}$ pair. A. D. Panagiotou, Int. J. Mod. Phys. A **5** (1990).

$\Lambda/\bar{\Lambda}$ global polarization from a two-component source



Abundance of qs over $\bar{q}$ in HICs leads to a suppression of $\bar{u}$ and $\bar{d}$ and relative enhancement of $\bar{s}$ (not present in the colliding nuclei). So some of the numerous $\bar{s}$ may enter into (qqs) or (qss) anti-baryons.

Rafelski and Hagedorn, CERN-TH-2969 (1980); Rafelski, Phys. Rept. 88, 331 (1982); Rafelski, South Afr. J. Phys. 6, 37-43 (1983)

Strangeness reaches chemical equilibrium during the short lifetime of a QGP: LO $q\bar{q} \to s\bar{s}$, $gg \to s\bar{s}$, crucial to include gluon fusion

J. Rafelski and B. Müller, Phys. Rev. Lett. 48, 1066 (1982) [erratum: Phys. Rev. Lett. 56, 2334 (1986)].

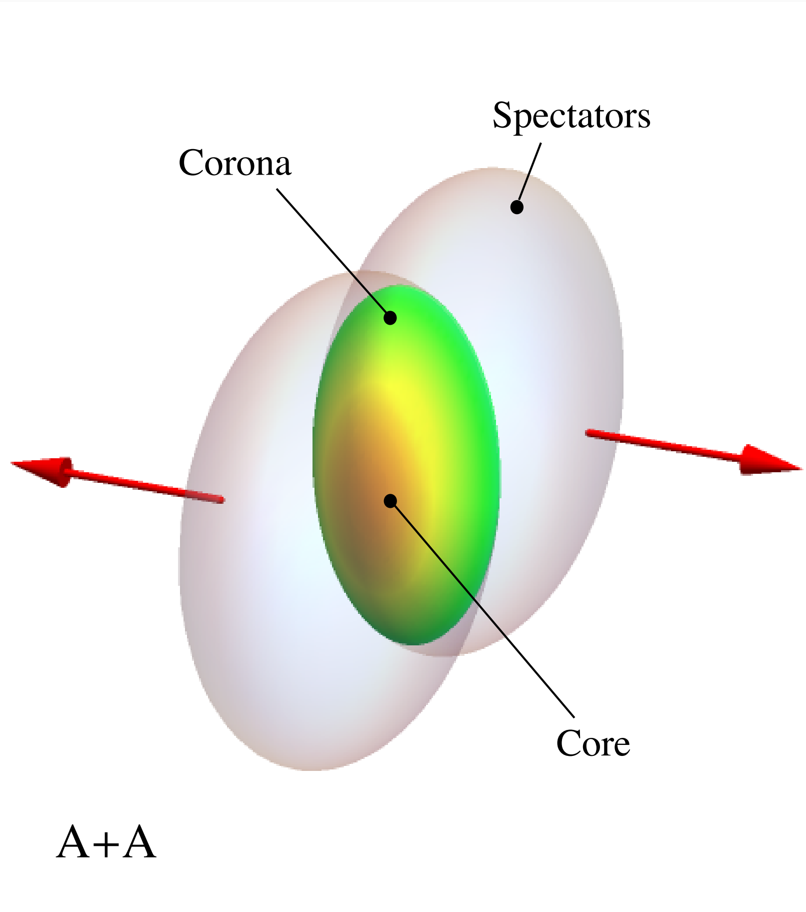
Λ and $\bar{\Lambda}$ polarization mechanism, spin alignment driven by vorticity? magnetic field? other?

$\Lambda/\bar{\Lambda}$ global polarization from a two-component source

Non-central heavy-ion collision of a symmetric system:

$\Lambda/\bar{\Lambda}$s from core via QGP processes

$\Lambda/\bar{\Lambda}$s from corona via p+p reactions



$$N_\Lambda = \overbrace{N_{\Lambda\,\mathrm{QGP}}}^{core} + \overbrace{N_{\Lambda\,\mathrm{REC}}}^{corona}$$

Choose reference direction:

baryon mom $\rightarrow ||$ pol

perp production plane $\rightarrow \perp$ pol

Polarization asymmetry -spin alignment asymmetry- of any baryon species produced in high-energy reactions

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

$N^\uparrow$ and $N^\downarrow$ baryons with spin aligned and opposite to a given direction.

$\Lambda/\bar{\Lambda}$ global polarization from a two-component source

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

...and doing some rewriting 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 contribution to the polarization from Λs ($\bar{\Lambda}$s) produced in the corona is

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

$\Lambda/\bar{\Lambda}$ global polarization from a two-component source

How do we model polarization in the corona?

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

Reactions in cold nuclear matter are less efficient to couple spin with angular momentum. So, the average global polarization for Λs and $\overline{\Lambda}$s from the corona, is negligible.

They are being produced in the corona in abundance, but cannot couple with total angular momentum of system.

See later!

$\Lambda/\bar{\Lambda}$ global polarization from a two-component source

How do we model polarization in the core?

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

Core reactions are more efficient to align particle spin to global angular momentum. Identify *intrinsic* global Λ and $\overline{\Lambda}$ polarizations.

At intermediate to large impact parameters, an amplification effect for the $\overline{\Lambda}$ polarization can occur in spite of $z > \bar{z}$, and this amplification is more prominent for lower collision energies.

$\Lambda/\bar{\Lambda}$ global polarization from a two-component source

How likely it is to create $\overline{\Lambda}$s both in the core and in the corona?

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

In the corona, production is through N+N collisions, so use p+p data to extract w.

In the core, for QGP created at high $\sqrt{s_{NN}}$, efficient processes might make it equally as easy to produce Λs as $\overline{\Lambda}$s, given that in this region qs and $\bar{q}$s are freely available and $(\bar{u}, \bar{d}, \bar{s})$ might find each other as easily as (u, d, s)?

At HADES, NICA and RHIC energies, μ and T of the system, matters.

So, in the core, w' will be calculated along the freezeout trajectory, using equilibrium distributions.

$\Lambda/\bar{\Lambda}$ global polarization from a two-component source

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

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

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

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

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

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

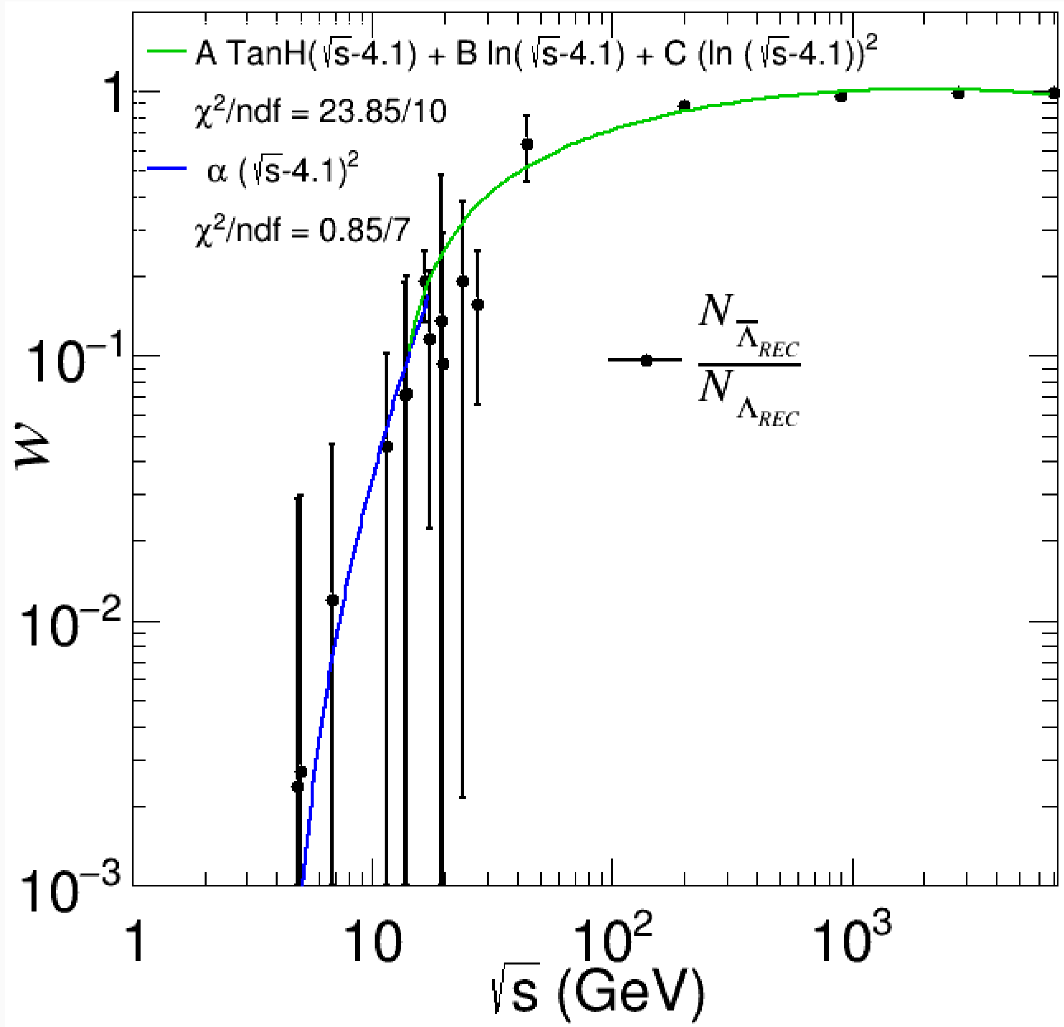
So, global polarization depends on w, w', z, $\bar{z}$ and the ratio $\frac{N_{\Lambda_{QGP}}}{N_{\Lambda_{REC}}}$, which can be either calculated or extracted from data.

The ratio $w = N_{\bar{\Lambda}_{REC}} / N_{\Lambda_{REC}}$ from $p + p$ collision data

- Experimental data for $p + p$ at different collision energies

  Gazdzicki and Rohrich, ZPC71 (1996); Blobel et al. NPB69 (1974); Chapman et al., PLB47 (1973); Brick et al., NPB164 (1980); Höhne, CERN-THESIS-2003-034; Baechler et al. [NA35 Coll.], NPA525 (1991); Charlton et al. PRL30 (1973); Lopinto et al. PRD 22 (1980); Kichimi et al., PRD20 (1979); Busser et al., PLB61 (1976); Erhan, et al., PLB85 (1979); Abelev et al. [STAR Coll], PRC75 (2007); Abbas et al. [ALICE Coll], EPJC73 (2013)

- w defined $\sqrt{s} > 4.1$ GeV. Threshold production via $p + p \to p + p + \Lambda + \bar{\Lambda}$
- $w \lessapprox 1$ for $\sqrt{s} < 1$ TeV



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

At finite $\mu = \mu_B/3$, bias in the production of $\overline{\Lambda}$s vs Λs.

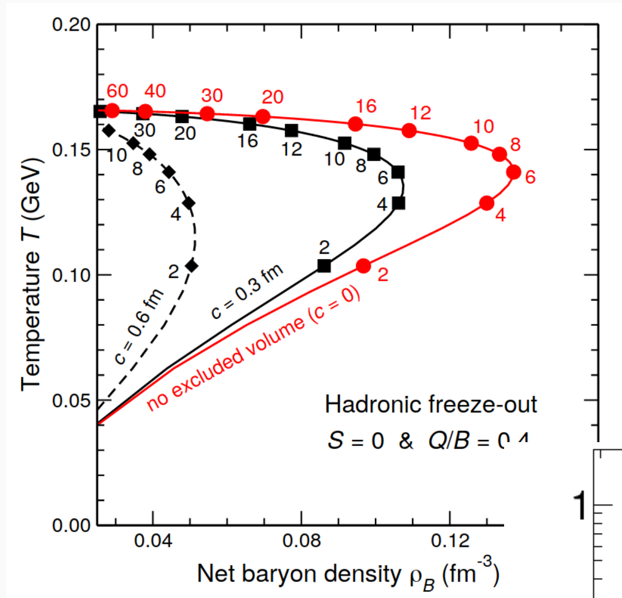
$$w' = \frac{e^{(m_s - \mu)/T} + 1}{e^{(m_s + \mu)/T} + 1}$$

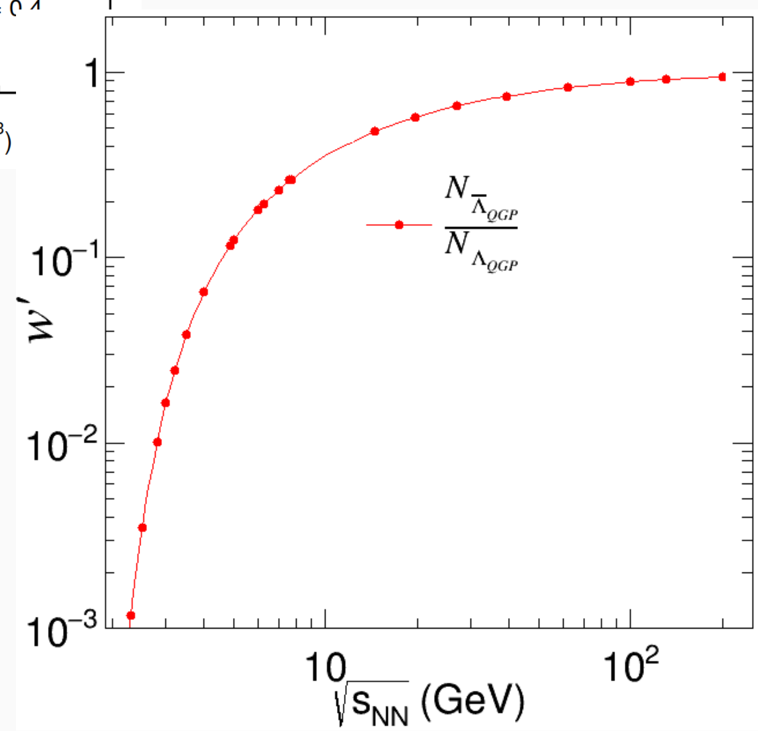
where $m_s = 100$ MeV and

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

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

Randrup and Cleymans, PRC 74 (2006) and EPJ 52 (2016)





Intrinsic polarization $N^{\uparrow}_{\Lambda_{QGP}} - N^{\downarrow}_{\Lambda_{QGP}} = zN_{\Lambda_{QGP}}$

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

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

in terms of the relaxation times τ and $\bar{\tau}$ and the QGP lifetime $\Delta\tau_{QGP}$.

A. Ayala. D. de la Cruz, L. A. Hernández, and J. Salinas, Phys. Rev. D 102, (2020)

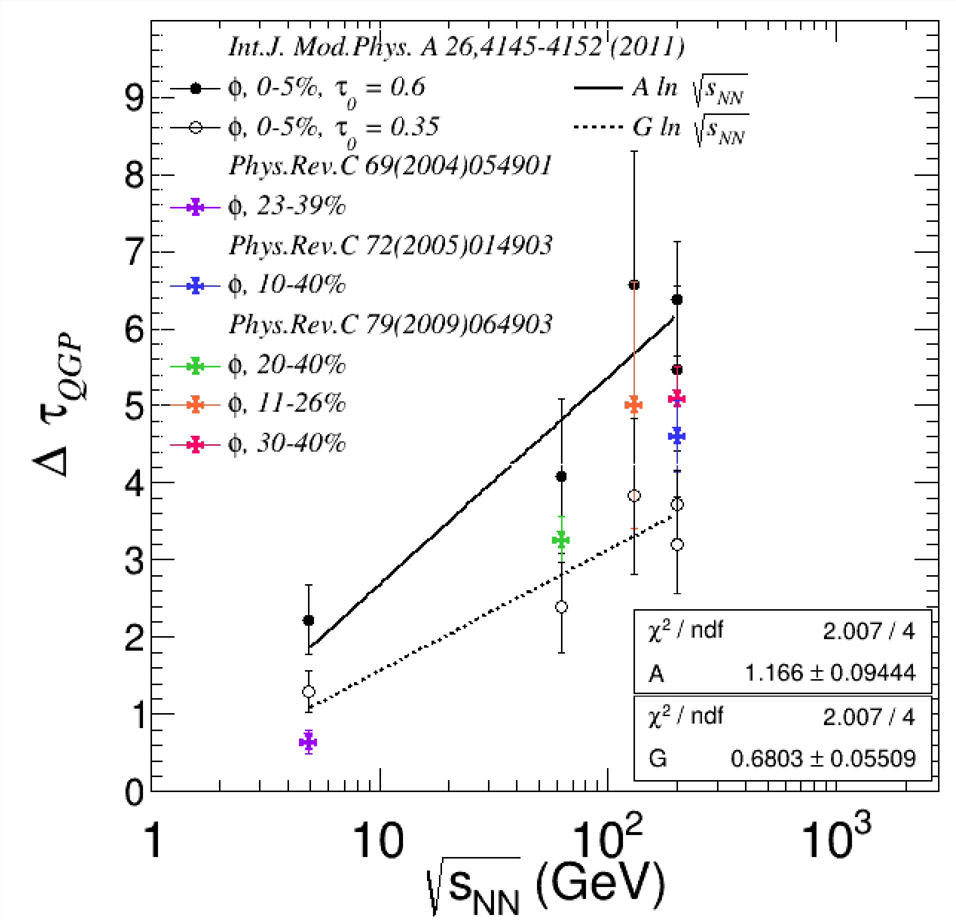
The interaction between the thermal vorticity and the quark spin is modeled by means of an effective vertex ($\tau = 1/\Gamma$) where

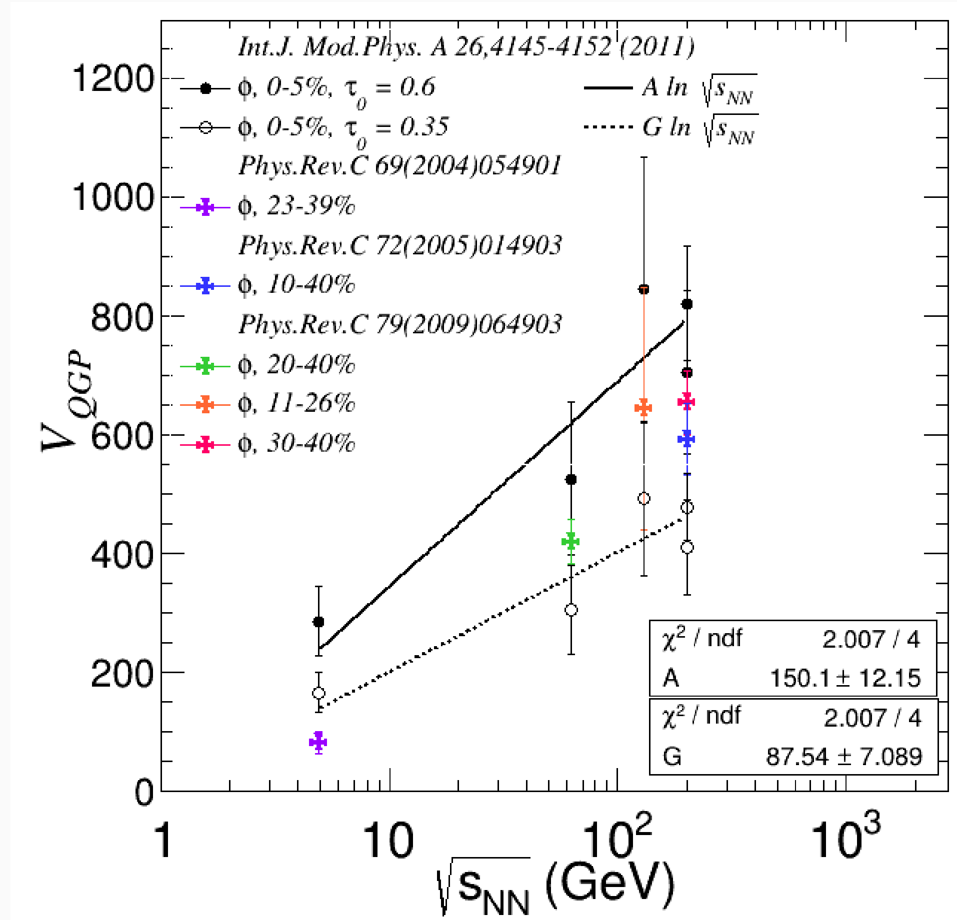
$$\Gamma = V \int \frac{d^3p}{2\pi^3} \Gamma(p_0), \text{ with } V = \pi R^2 \Delta\tau_{QGP}.$$

V is the core volume, related to the QGP lifetime $\Delta\tau_{QGP}$ in a Bjorken expansion scenario

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

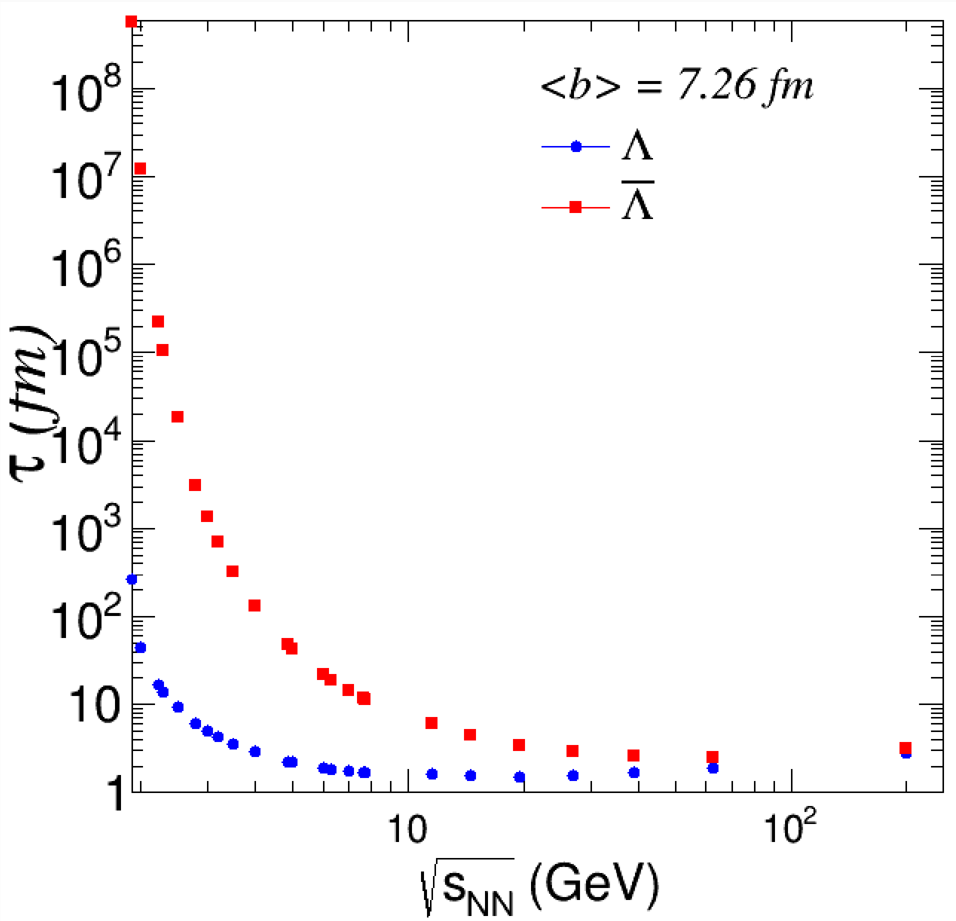
QGP volume and lifetime

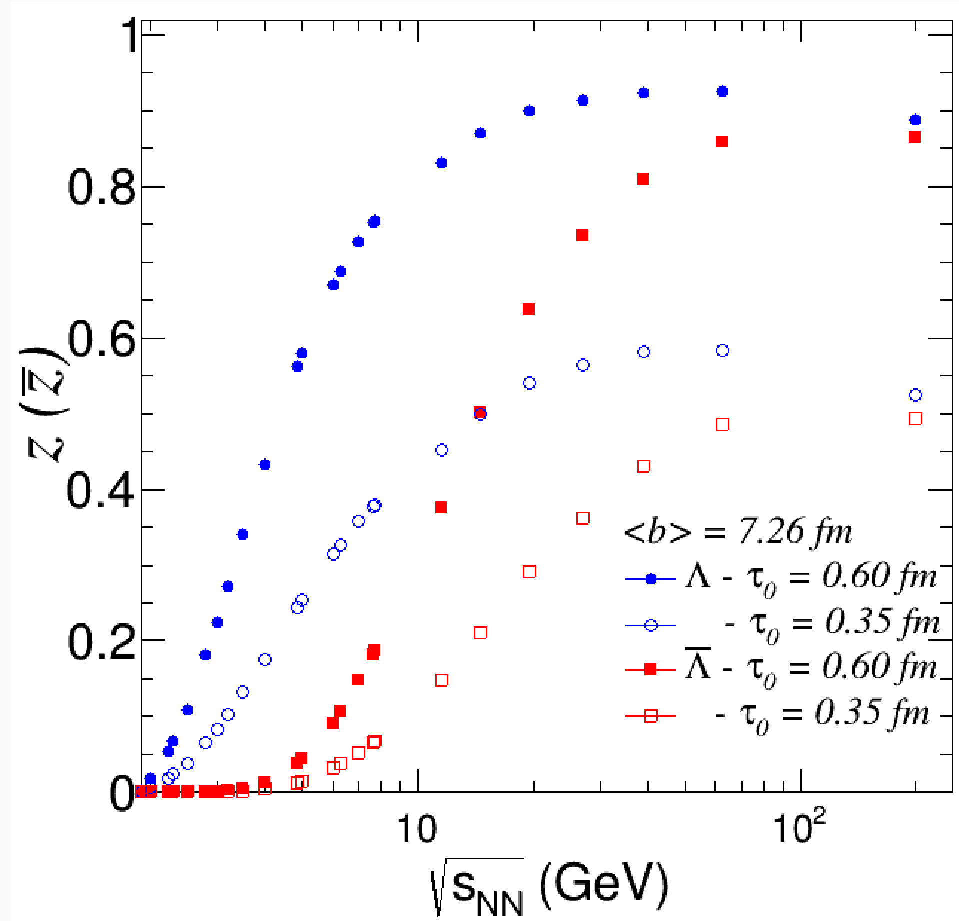




T_0 estimated from ϕ meson p_T distribution, we consider $\tau_0 = 0.35 - 0.60$ fm to incorporate effect of collision centrality and T_f is taken from freeze-out trajectory for maximal chemical potential.

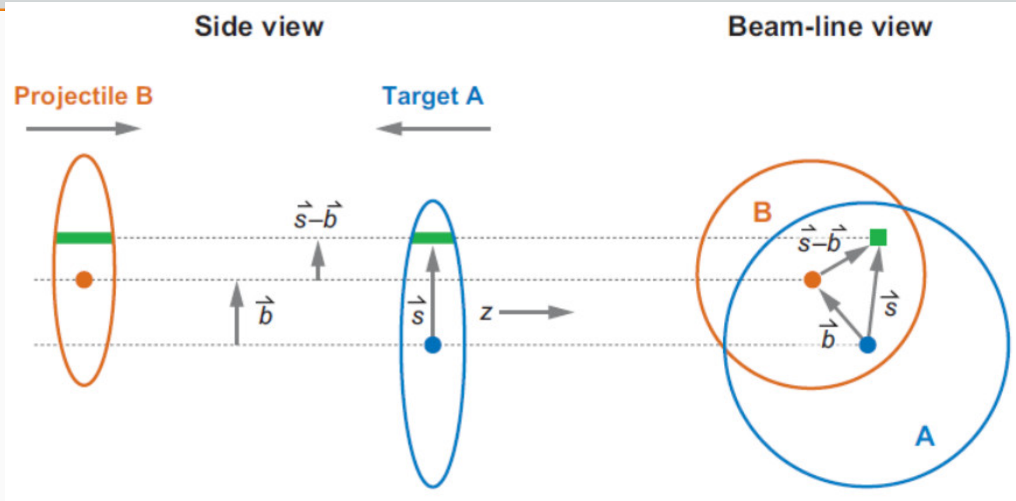
Relaxation time and instrinsic polarization with $\sqrt{s_{NN}}$





For collision energies below Λs threshold production, τ y $\bar{\tau}$ increase dramatically since $\Gamma \to 0$

Λ production: core vs corona, $N_{\Lambda_{QGP}}/N_{\Lambda_{REC}}$



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

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)

$$\langle s\rangle = N_{\Lambda\,\mathrm{QGP}} = c\,N^2_{\mathrm{p\,QGP}}$$

with $0.001 \leq c \leq 0.005$.

Λs are not the only strange hadrons produced in the reaction: $c = 0.0025$

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

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

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

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

Number of Λs from the core

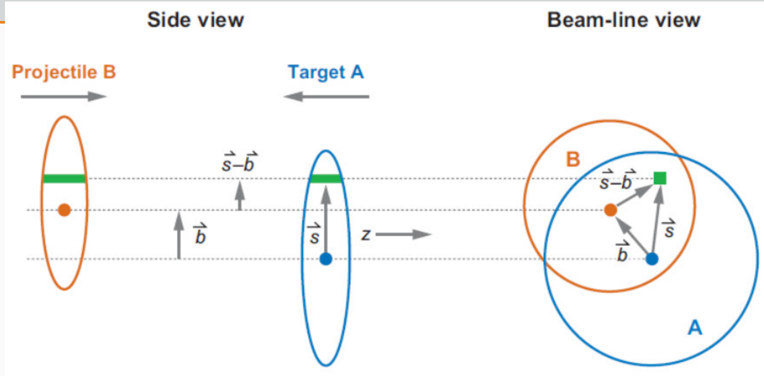
$$N_{\Lambda_{QGP}} = cN^2_{p_{QGP}}$$

where

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

with $n_c = 3.3\ \mathrm{fm}^{-2}$, critical density of participants needed for QGP formation.

Λ production: core vs corona, $N_{\Lambda_{QGP}}/N_{\Lambda_{REC}}$



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

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

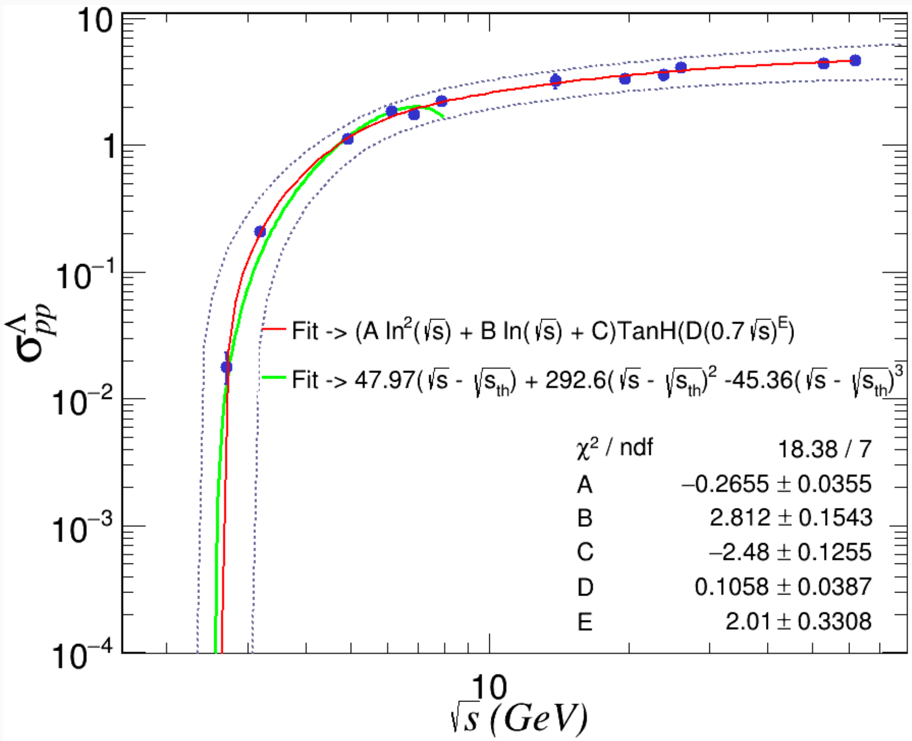
$$+T_B(\mathbf{s}-\mathbf{b})[1 - e^{-\sigma_{NN}T_A(\mathbf{s})}]$$

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

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

Number of Λs from the corona

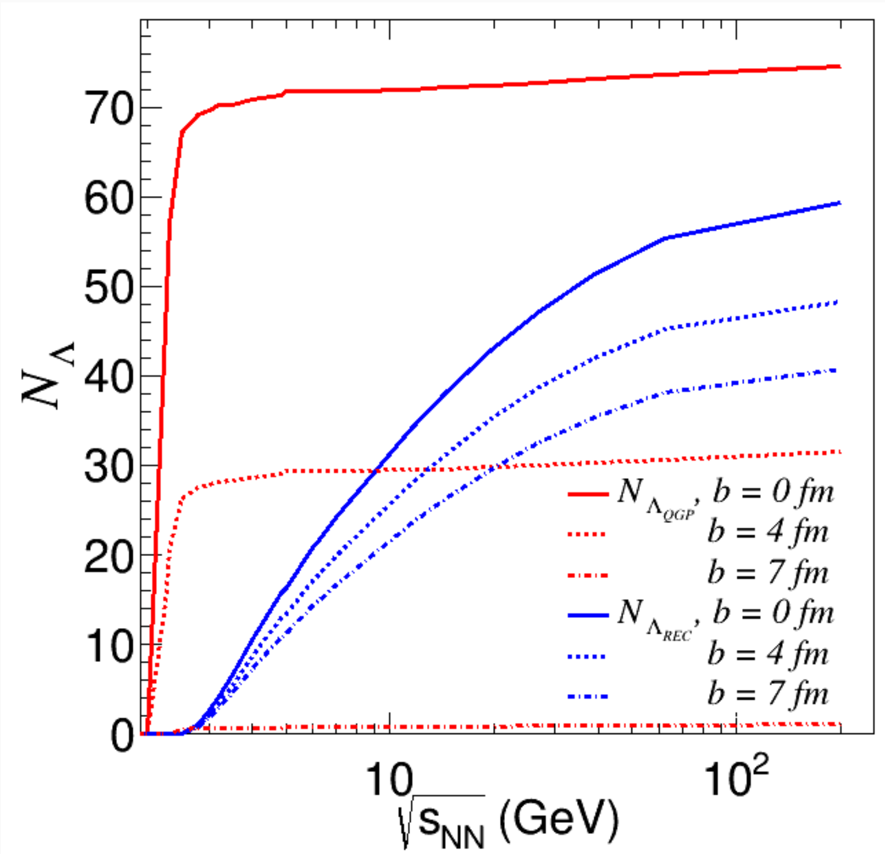
$$N_{\Lambda_{REC}} = \sigma_{NN}^{\Lambda} \int T_B T_A \theta[n_c - n_p(\mathbf{s,b})]d^2s$$



Fits from a few to almost 70 GeV

Gazdzicki and D. Rohrich, ZPC71, 55 (1996); Blobelet et al. NPB69, 454 (1974); Chapman et al PLB47, 465(1973); Bricket et al, NPB164, 1 (1980); Erhan et al PLB 85, 447 (1979); Fickinger et al Phys. Rev.125 (1962); Adamczewski-Muschet (HADES), PRC95, 015207 (2017); Aahlin et al Phys. Scripta21, 12(1980); Boeggildet et al NPB57, 77 (1973); Bogolyubskyet et al. Sov. J. Nucl. Phys.50, 424(1989); Jaeger, et al PRD11, 2405; Shenget al., PRD11, 1733 (1975); Asaiet al.(EHS RCBC), ZPC27, 11 (1985); Drijardet al. ZPC12, 217 (1982).

Λ production: core vs corona, $N_{\Lambda_{QGP}}/N_{\Lambda_{REC}}$

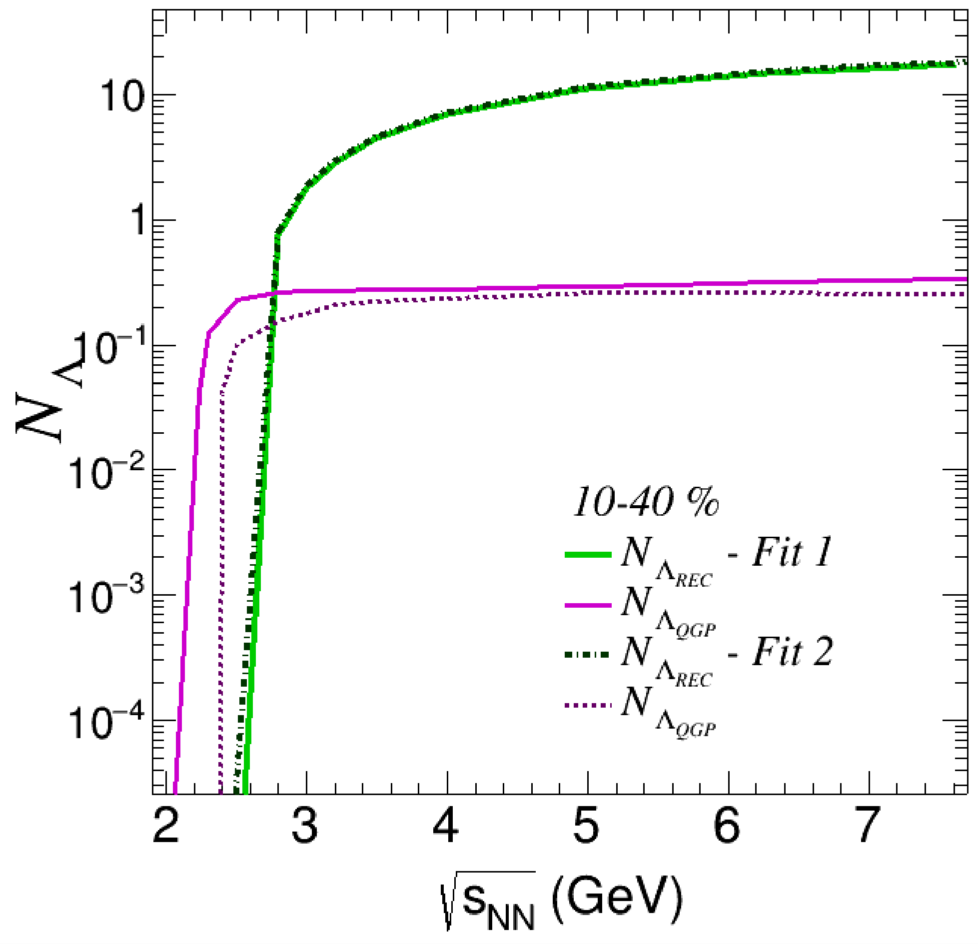


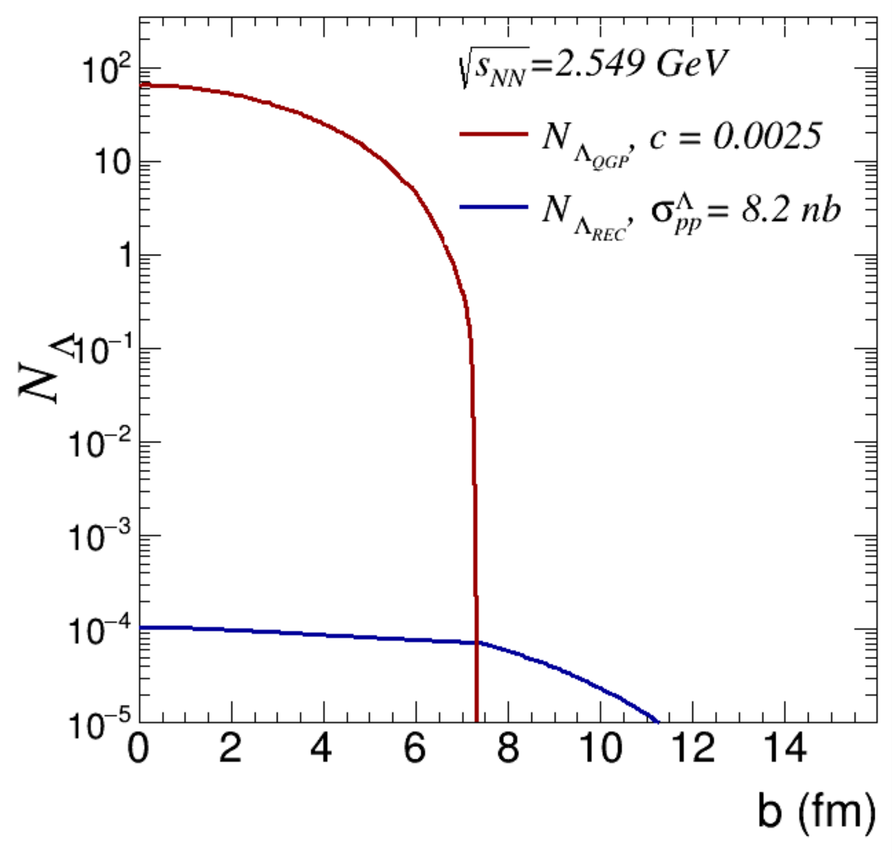
$N_{\Lambda_{QGP}}$ and $N_{\Lambda_{REC}}$ for impact parameters $b = 0, 4, 7$ fm.

- Small b, Λ production is dominated by core.
- Large b, Λ production is dominated by the corona.
  $\rightarrow$ relevant for vorticity and polarization studies

Recall core-corona model has a critical density of participants n_c above which you can produce the QGP in the core. For peripheral collisions - even for larger energies - n_c is hard to reach.

Λ production: core vs corona, $N_{\Lambda_{QGP}}/N_{\Lambda_{REC}}$



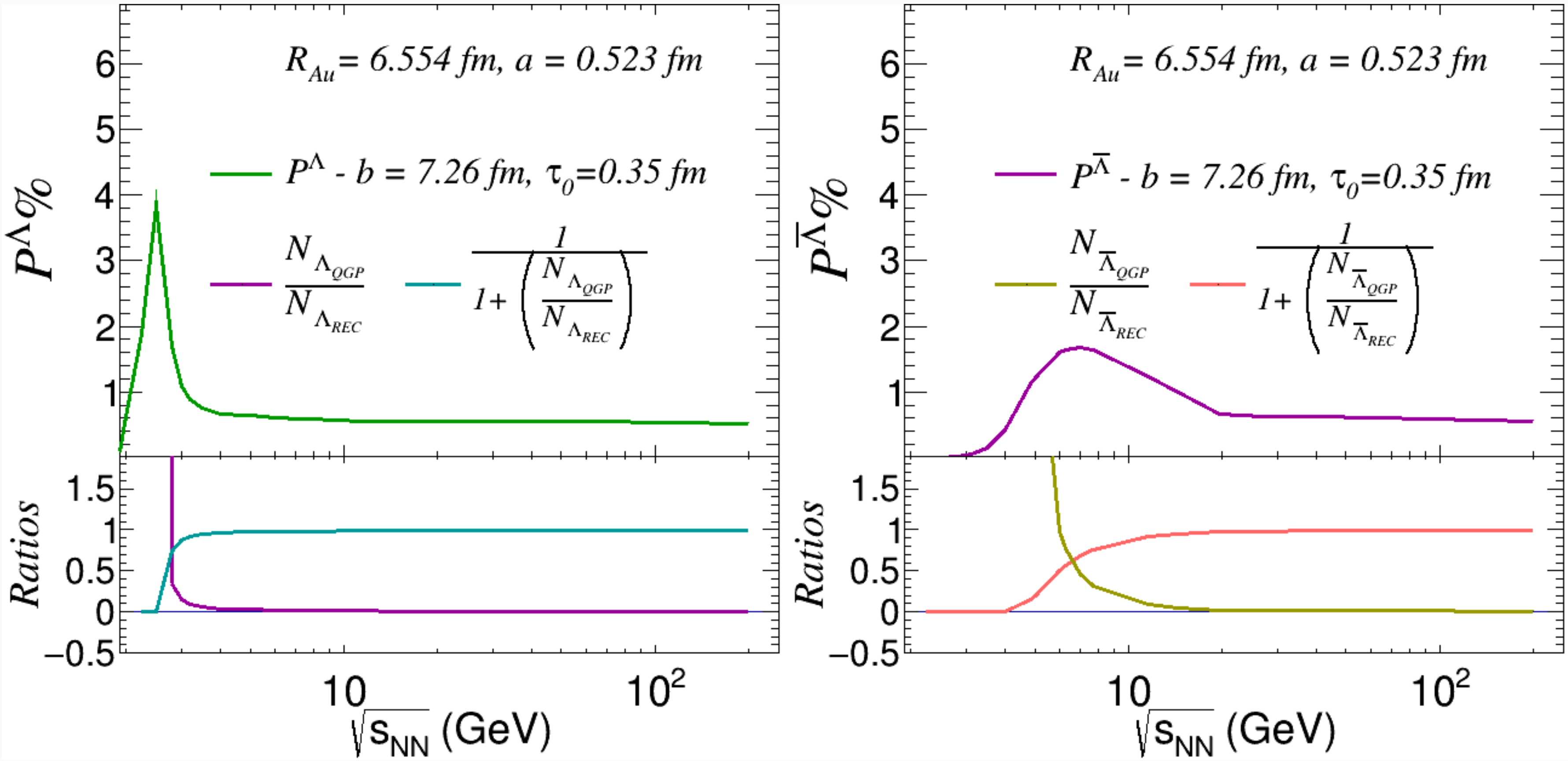


At low collision energies $N_{\Lambda_{QGP}}$ strongly modulated by σ_{NN}. Different fits impact on the magnitude of final polarization.

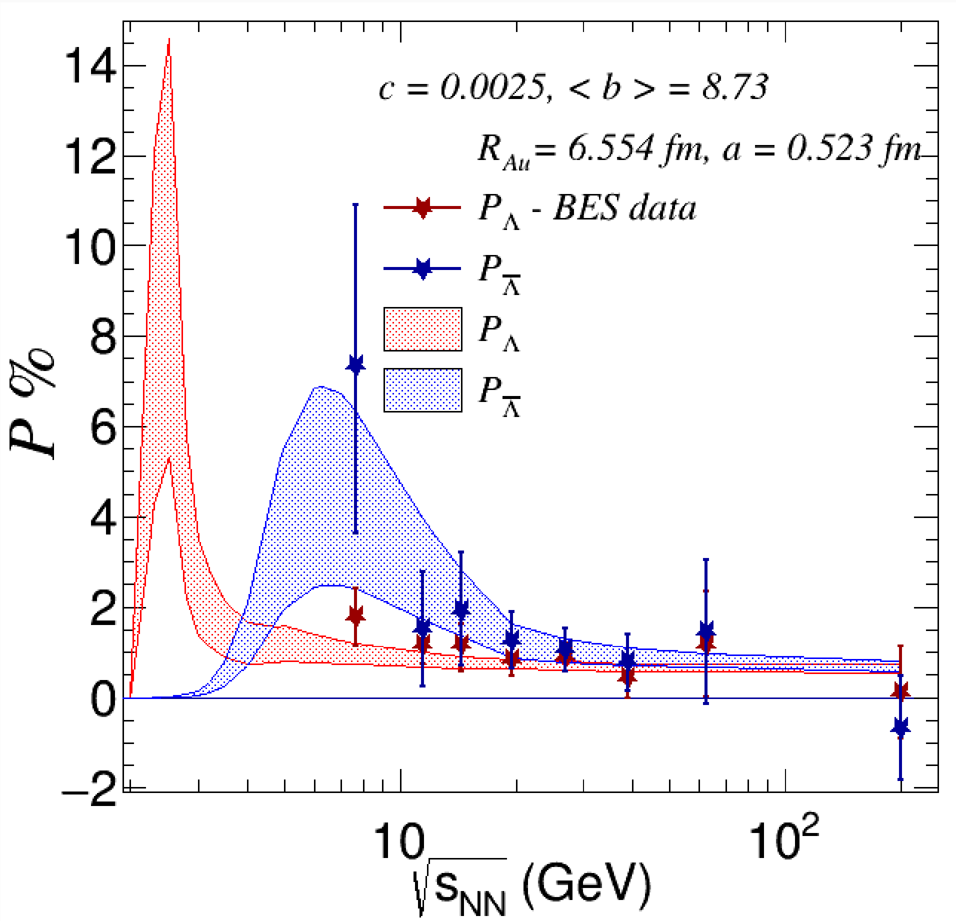
σ_{NN} also controls the ratio $N_{\Lambda QGP}/N_{\Lambda_{REC}}$ and the value of impact parameter b for which this ratio is less than 1.

Results: ratio of global to intrinsic polarization

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



Results: Λ y $\bar{\Lambda}$ global polarization in Au+Au at RHIC-BES



Au+Au 20 - 50 %
STAR Collaboration
Nature 548(2017)62-65

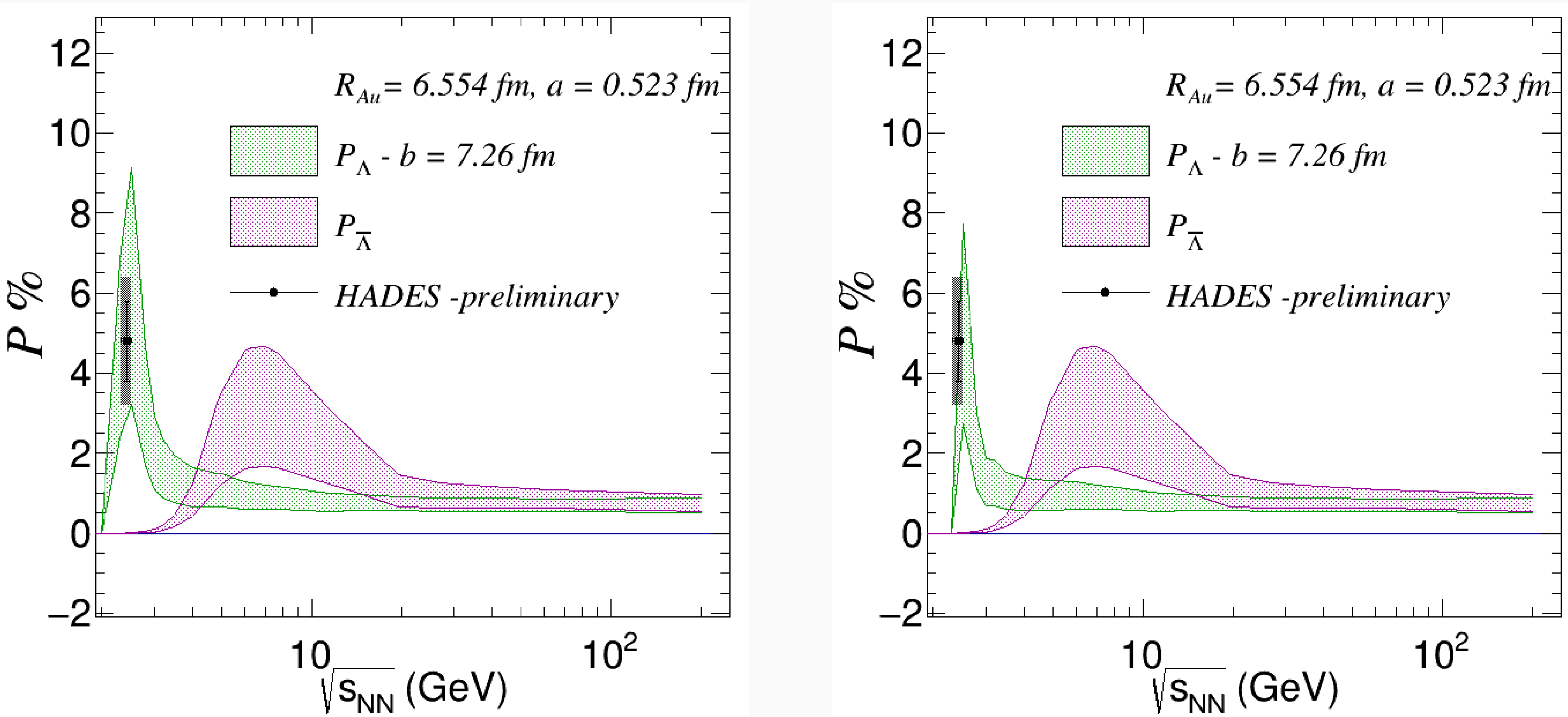
- We see a similar behavior if we look to more peripheral collisions
- Global polarization magnitude increases as we go to more peripheral collisions due to higher angular momentum

Results: Λ y $\bar{\Lambda}$ global polarization in Au+Au at HADES

Au+Au at $\sqrt{s_{NN}} = 2.4$ GeV, 10 - 40%

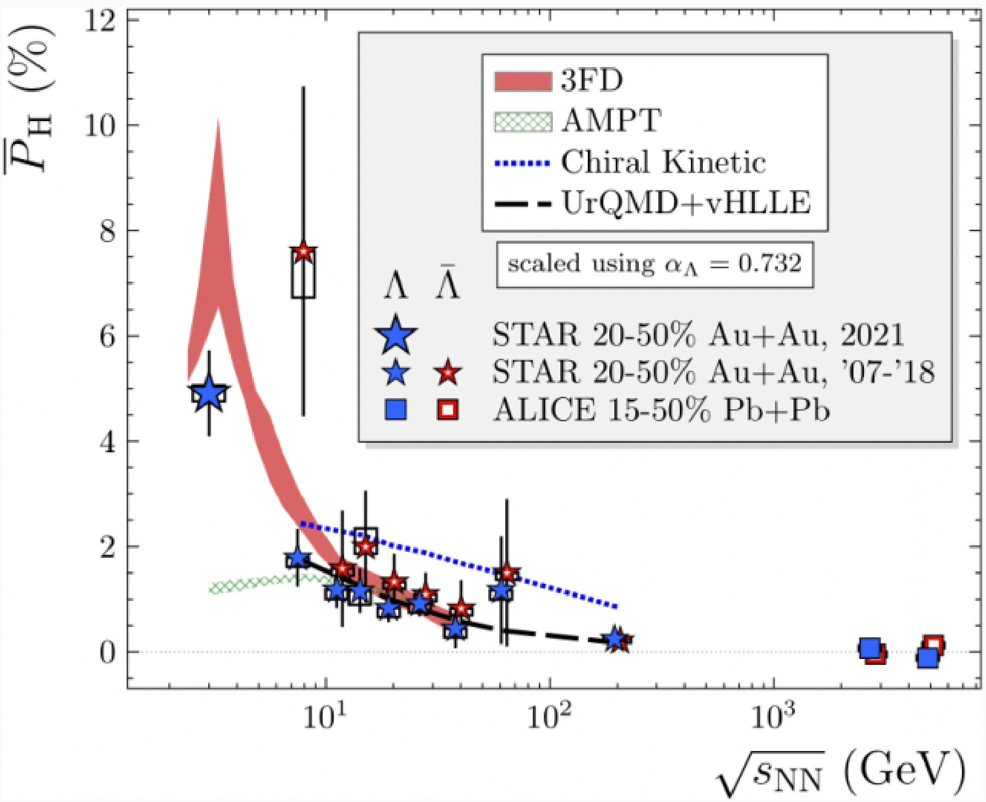
F. J. Kornas for HADES Coll. EPJ Web Conf. 259 (2022) 11016

Fit 1 vs Fit 2 for σ_{NN}

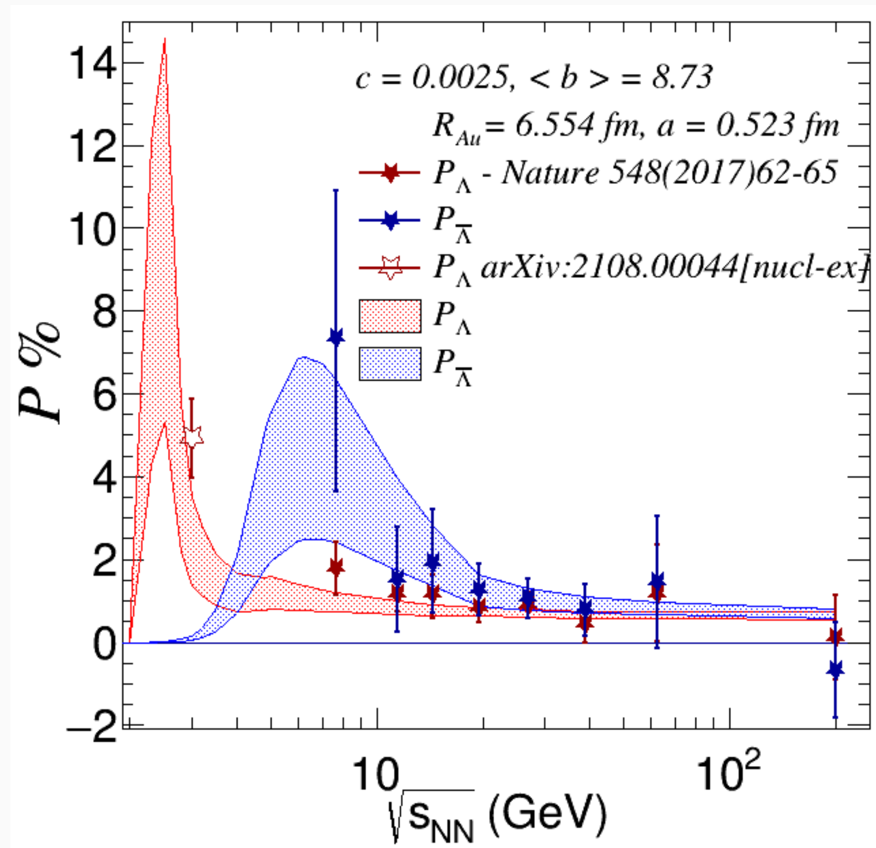


STAR data $Au + Au$ at $\sqrt{s_{NN}} = 3$ GeV

STAR data: arXiv:2108.00044v2 [nucl-ex]



The core-corona model

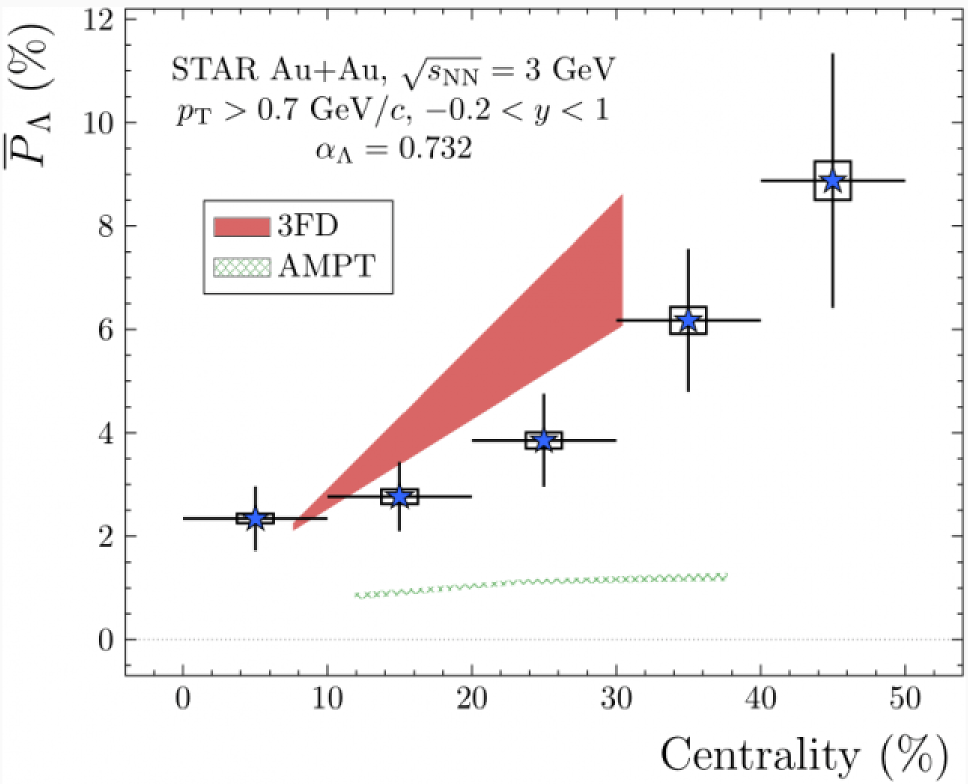


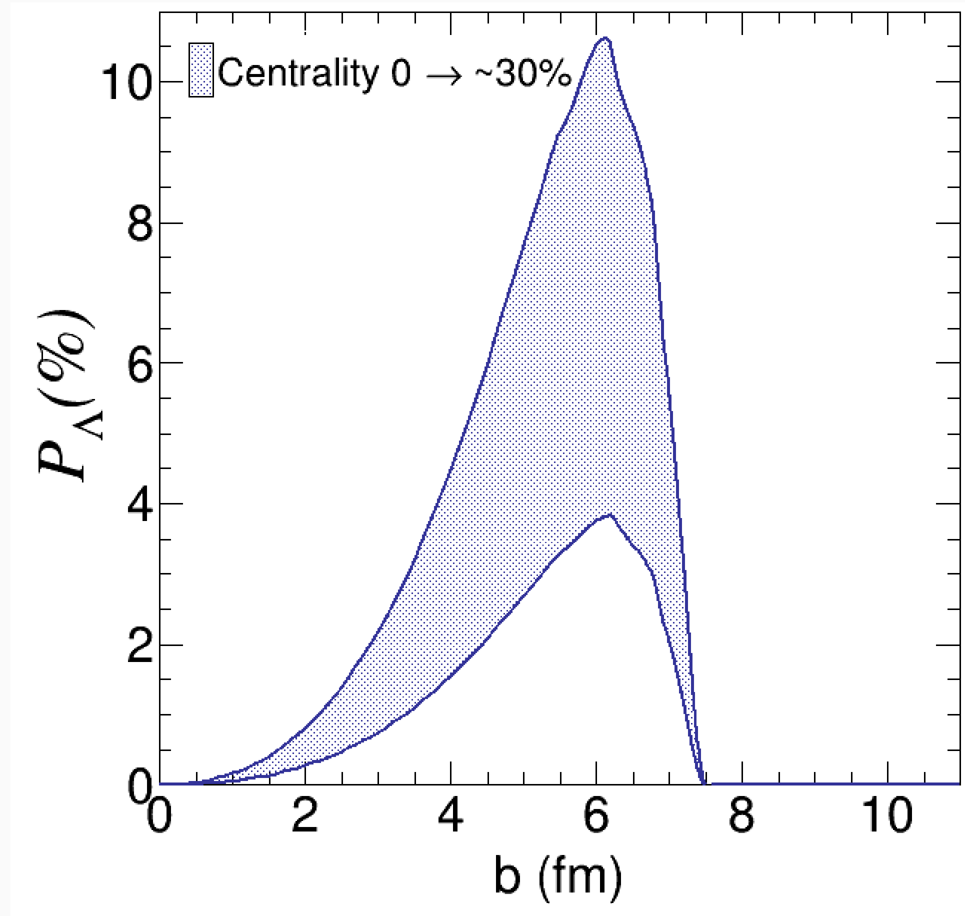
$\Lambda/\bar{\Lambda}$ global polarization from a two-component source

- in non-central collisions Λ and $\overline{\Lambda}$ hyperons can be produced from different density zones within the interaction region: core or corona
- polarization properties of Λ and $\overline{\Lambda}$ differ depending on the region they come from
- since the ratio of the number of $\overline{\Lambda}$s to Λs coming from the corona is less than 1: the global $\overline{\Lambda}$ 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

NEXT STEPS

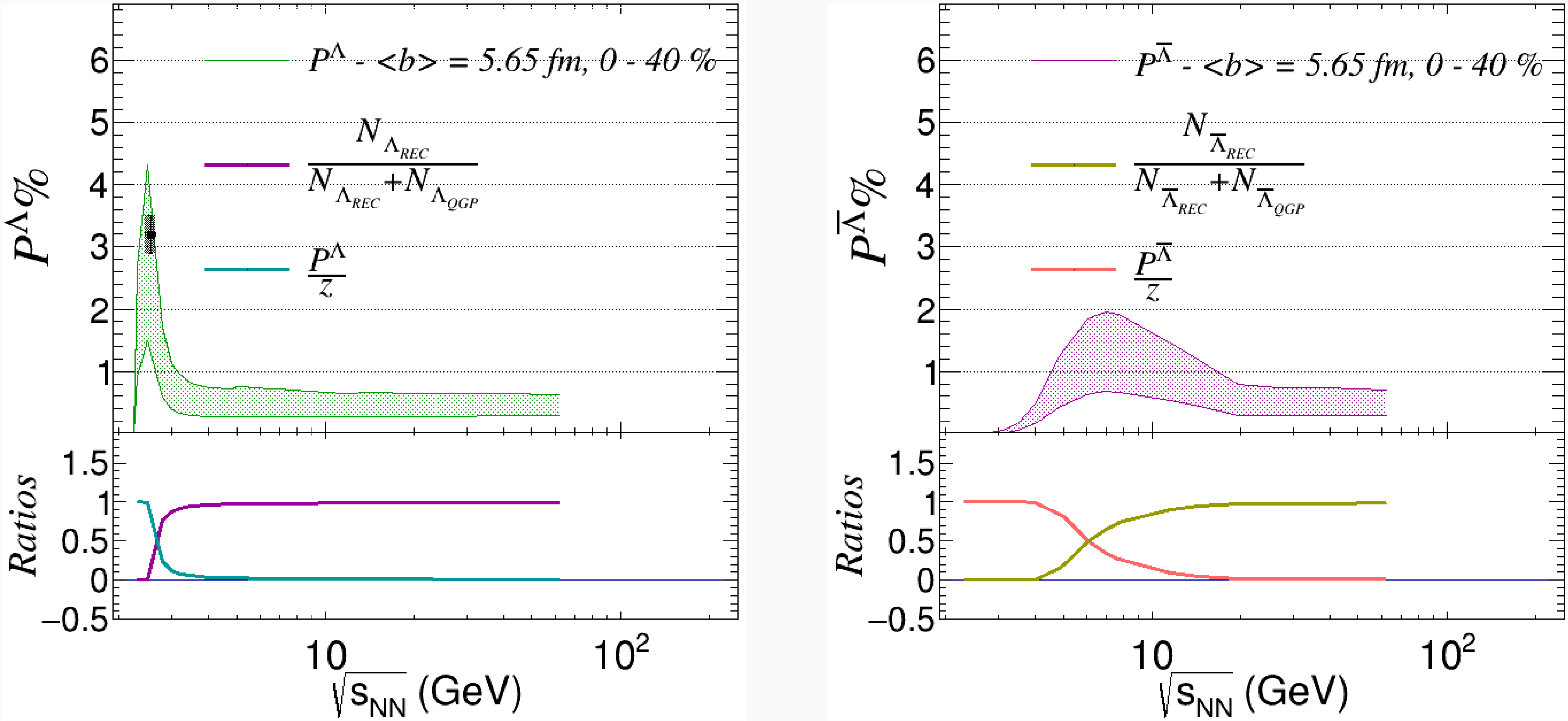
STAR data $Au + Au$ at $\sqrt{s_{NN}} = 3$ GeV for different centralities





In our core-corona model, polarization drops to zero for peripheral collisions, since the system cannot reach n_c and so the number of Λs in the core goes to zero.

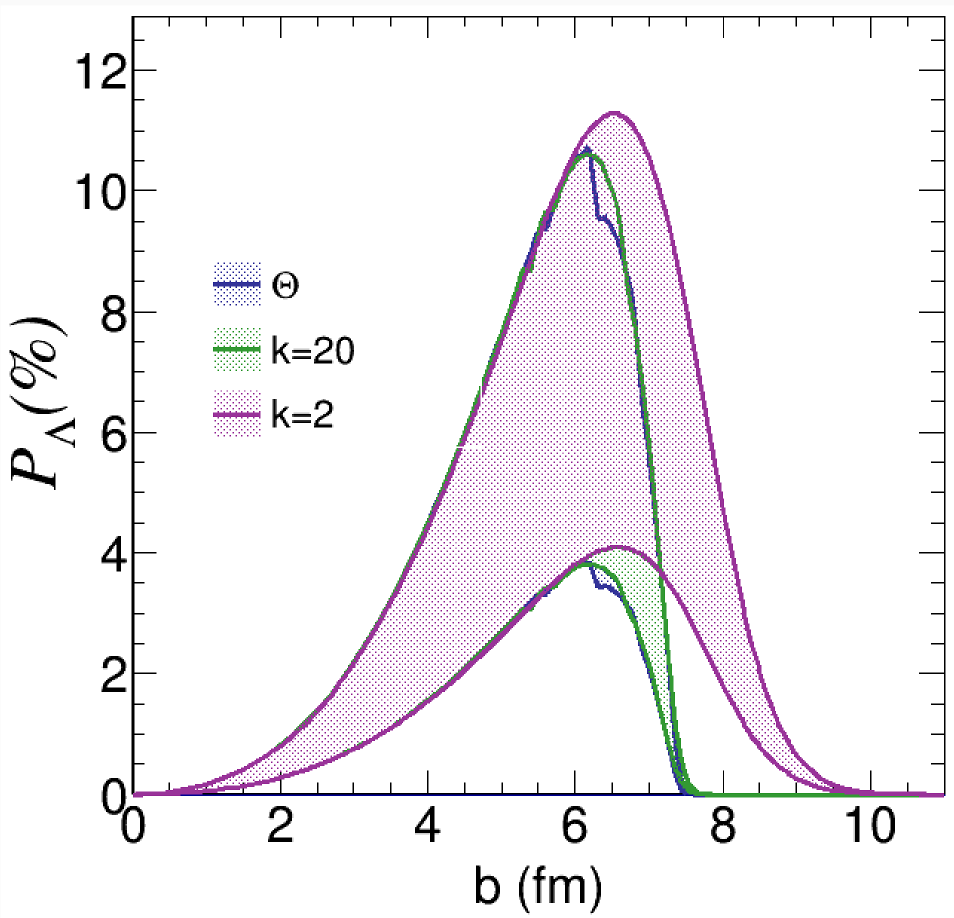
Λ and $\bar{\Lambda}$ polarization $Ag + Ag$ at HADES

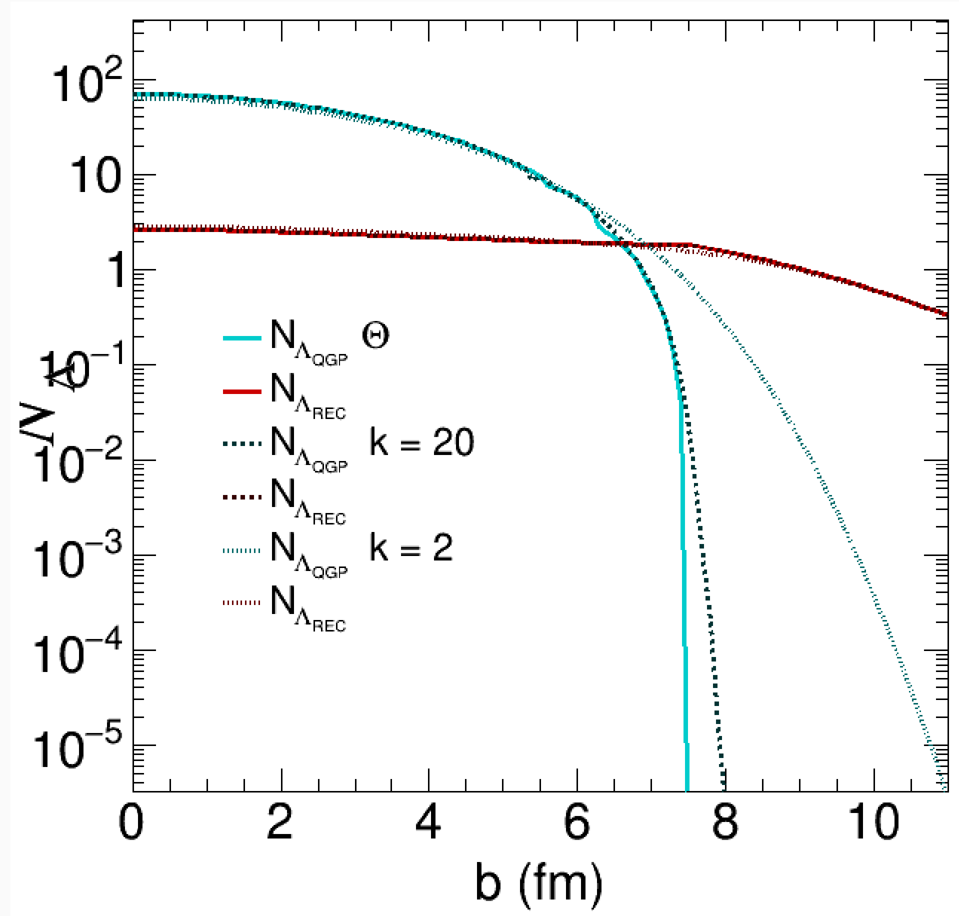


$Ag + Ag$ at $\sqrt{s_{NN}} = 2.55$ GeV system size can barely reach n_c for QGP production in 0-40% centrality range.

Smoothing out the implementation of n_c - work in progress

- Number of Λs depends on $n_c = 3.3$ fm^{-2}.
- $\theta(x) \rightarrow \frac{1}{1+2e^{-2kx}}$ with $k = \{2, 20\}$.
- Bigger $k \rightarrow \theta(x)$





Polarization does increase for the 20-30% centrality bins and it is non-zero for the 30-40% bin, but not a good description for higher centrality bins.

Is P_{REC} negligible? - work in progress

- What is the effect of transverse polarization of Λs in the corona?
- Actually, Λs polarization in p+p is not zero
  - $\sqrt{s} = 19.6\text{GeV} \rightarrow \mathcal{P} = -0.25 \pm 0.26$
  - $\sqrt{s} = 53\text{GeV} \rightarrow \mathcal{P} = -0.34 \pm 0.07$
  - $\sqrt{s} = 62\text{GeV} \rightarrow \mathcal{P} = -0.40 \pm 0.10$

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

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

In peripheral collisions transverse polarization is not diluted in the QGP medium.

How do we transfer the measurement to have it with respect to total angular momentum?

Other methods to measure Λ polarization

Nazarova, et. al. Phys. of Part. and Nuclei Lett., 2021, Vol. 18, No. 4, pp. 429–438; Chin.Phys.C 43 (2019) 1, 014103.

Closing remarks

- This two-component model describes the main characteristics of the Λ and $\bar{\Lambda}$ polarization excitation function in semi-central heavy-ion collisions.
- The change in abundances of Λs created in the core respect to those created in the corona as a function of collision energy, has a direct impact in that both polarizations reach a maximum at collision energies $\sqrt{s_{NN}} \lesssim 10$ GeV
- In a simple system expansion scenario, where we have a handle on the volume and lifetime of the QGP, the spin alignment of an s-quark with the thermal vorticity can lead us to the relaxation time we need to estimate the intrinsic polarization.
- The model provides a differential value for global Λ and $\overline{\Lambda}$ polarization with a maximum that is sensible to production mechanisms in the core and corona at HADES, NICA and RHIC energies.

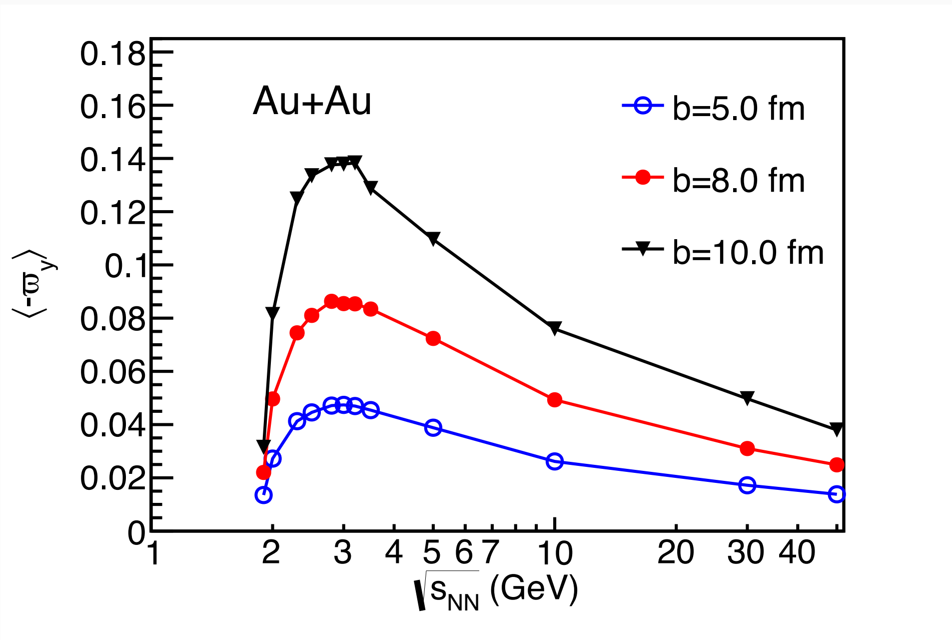
¡GRACIAS!

EXTRAS

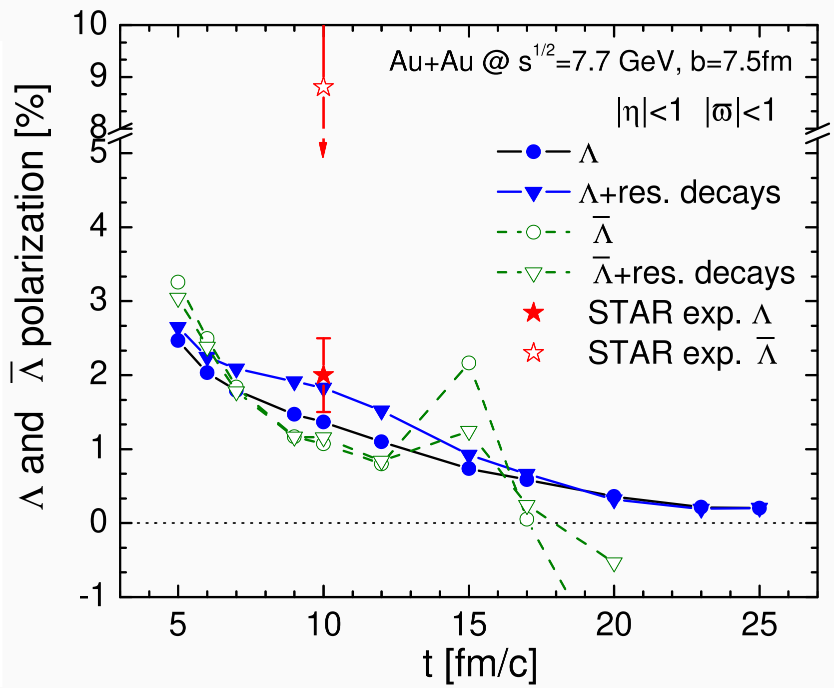
What happens for $\sqrt{s_{NN}} < 7.7$ GeV? (NICA, FAIR, RHIC)

At $\sqrt{s_{NN}} \sim 2m_N$, is $L \sim 0$? Then $\omega \sim 0$? Is thermal vorticity well defined?

X. Deng, et. al. arXiv:2001.01371 [nucl-th] (UrQMD)



E.E. Kolomeitsev, et. al. Phys. Rev. C 97 (2018) (PHSD)



If $\omega \propto \mathcal{P}$ then polarization is consistent with data.