Global polarization signals from hot, dense and whirly QCD matter

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[a](MexNICA Collaboration) A. Ayala, M. Ayala, E. Cuautle, I. Domínguez, M. Fontaine, I. Maldonado, L. Montano, E. Moreno, P. Nieto, L. Rebolledo, M. Rodríguez, J. Salinas, L. Valenzuela, C. Zepeda

FYI

Please check out recent -review- documents/talks

- *Polarization and Vorticity in the Quark Gluon Plasma*, F. Becattini, M. A. Lisa, e-Print: 2003.03640 [nucl-ex].
- *Chirality and Criticality: Novel Phenomena in Heavy-Ion Collisions*, INT Program INT-20-1c, May 11 - June 5, 2020 $\rightarrow$ 2nd week: vorticity, polarization, transport, in magnetic fields.
- *Thermal vorticity and spin polarization in heavy-ion collisions*, De-Xian Wei, Wei-Tian Deng, and Xu-Guang Huang, Phys. Rev. C 99, 014905 (2019).
- *Vorticity in low-energy heavy-ion collisions*, Xian-Gai Deng, Xu-Guang Huang, Yu-Gang Ma, Song Zhang, e-Print: arXiv:2001.01371 (2020).

Spintronics: nanotechnology + L exchange

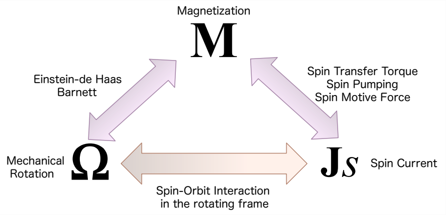
Usual angular-momentum exchange frameworks: magnetization, light polarization but...

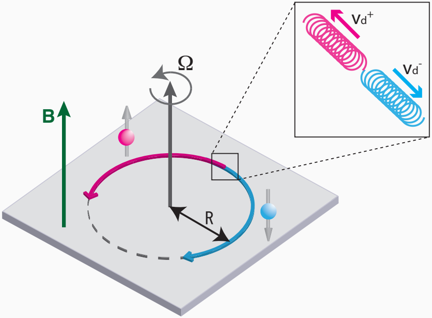
What about the exchange of angular momentum in the context of -plain and simple- matter mechanical rotation?

spin–rotation coupling:

intn of mechanical L and electron spin

M. Matsuo, J. Ieda, E. Saitoh, S. Maekawa PRL 106 (2011)





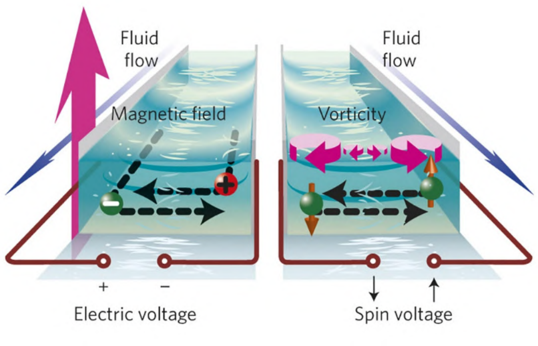
$\Omega \leftrightarrow B$

e's trajectories EoM sol with 2 cyclotron frequencies.

drift $\vec{v}$ of the up-(down-) e's parallel to the azimuthal direction

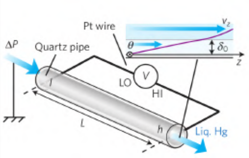
Spin hydrodynamic generation (fluid spintronics)

R. Takahashi et al. Nature Phys. **12** (2016)



magnetohydrodynamics vs spin hydrodynamics

First observation of **coupling between the vorticity of a fluid and the spin of the electron**

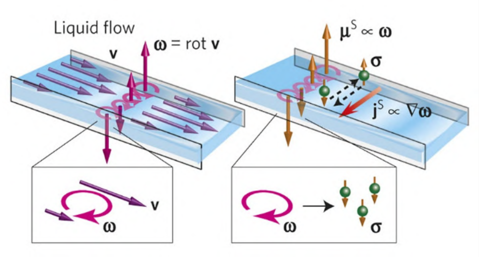


The whirly-ness of the fluid

- generated through shear viscous effects
- flow field around any point is the *vorticity* ω (non-rel: $\vec{\omega} = \frac{1}{2}\vec{\nabla} \times v$)

Spin hydrodynamic generation (fluid spintronics)

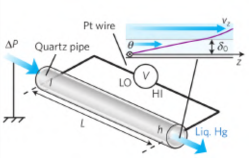
R. Takahashi et. al. Nature Phys **12** (2016)



spin hydrodynamics to generate a voltage
spin electrochemical potential for $e^{\uparrow}$ and $e^{\downarrow}$

$$\mu^S \equiv \mu_{\uparrow} - \mu_{\downarrow}$$

First observation of **coupling between the vorticity of a fluid and the spin of the electron**:



spin–rotation coupling,
mechanical rotation gives rise to a gradient of spin voltage which drives a spin current.

Hot, dense, whirly QCD matter

"subatomic spintronics"- X. Deng et. al. arXiv:2001.01371

Global Λ hyperon polarization in nuclear collisions: evidence for the most vortical fluid.
STAR Collaboration
Nature 548 (2017)

$\omega \approx (9 \pm 1) \times 10^{21}\ \text{s}^{-1}$
sys. in T of a factor of 2

Hot, dense, whirly QCD matter

STAR Collaboration, Nature 548 (2017)

$$\omega \approx (9 \pm 1) \times 10^{21}\ \mathrm{s}^{-1}$$

How whirly is this?

superfluid nanodroplets $10^{7}\ \mathrm{s}^{-1}$

turbulent flow in superfluid He-II $10^{2}\ \mathrm{s}^{-1}$

rotating, heated soap bubbles used to model climate change $10^{2}\ \mathrm{s}^{-1}$

supercell tornado cores $10^{-1}\ \mathrm{s}^{-1}$

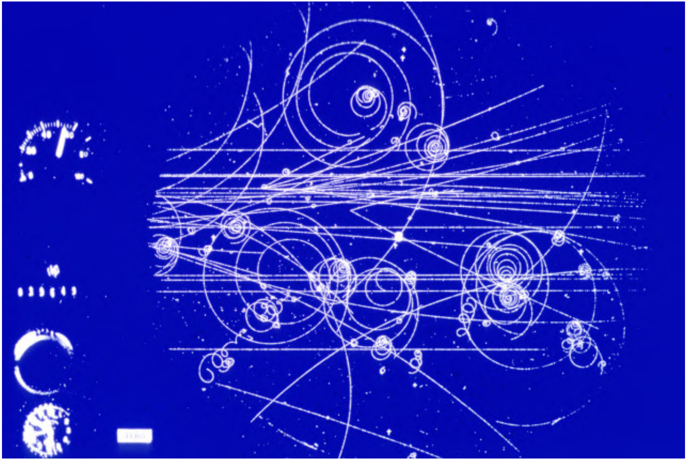
the Great Red Spot of Jupiter $10^{-4}\ \mathrm{s}^{-1}$

large-scale terrestrial atmospheric patterns $10^{-7} - 10^{-5}\ \mathrm{s}^{-1}$

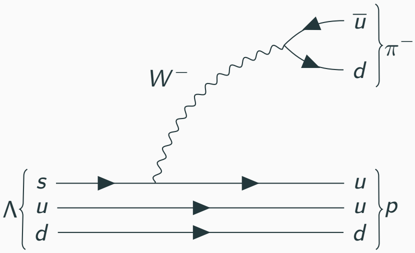
solar subsurface flow $10^{-7}\ \mathrm{s}^{-1}$

Good whirly-ness probe: Λ hyperon

The decay of a lambda particle in the 32 cm diameter hydrogen bubble chamber (π^- @ 16 GeV): $\pi^- + p \rightarrow$ jets. CERN-EX-11465-1 (1960)

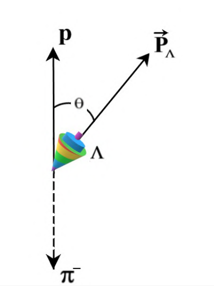


Good whirly-ness probe in HICs: Λ hyperon



Particle Data Group:

- ✓ $m_\Lambda = 1115.683 \pm 0.006$ MeV
  - → lightest hyperon with s content
- ✓ $\tau = 2.632 \pm 0.020 \times 10^{-10}$ s
  ~ 7.9 cm at c
  - → long lifetime: good for tracking
- ✓ $\Gamma_1(\Lambda \to p\pi^-) = (63.9 \pm 0.5)\%$
  $\Gamma_2(\Lambda \to n\pi^0) = (35.8 \pm 0.5)\%$
  - → primary decay channel: good for reconstruction
- ✓ parity-violating weak decay
  - → decay dist not-isotropic: p going off in the direction of Λ spin



In this talk:

I will go through recent measurements of global polarization properties of Λs and $\bar{\Lambda}$s and then put forward a two-component model for global $\Lambda/\bar{\Lambda}$ polarization using

- ✓ centrality dependent model for Λ production in heavy-ion collisions

$+$

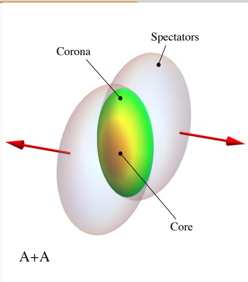
- ✓ relaxation time for quark spin-alignment + thermal vorticity in the hot/dense QGP

"Core meets corona: a two-component source to explain Lambda and anti-Lambda global polarization in semi-central heavy-ion collisions".

MexNICA Collaboration. e-Print: 2003.13757 [hep-ph]

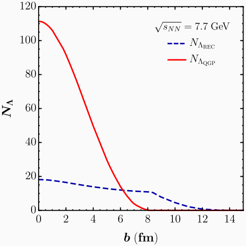
Finally, highlight how this can help us in the upcoming measurements and analysis at MPD-NICA.

In this talk:



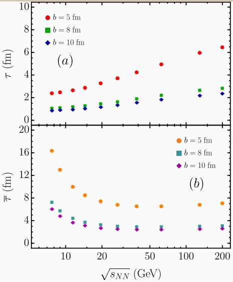
Spectators
Corona
Core
A+A

+



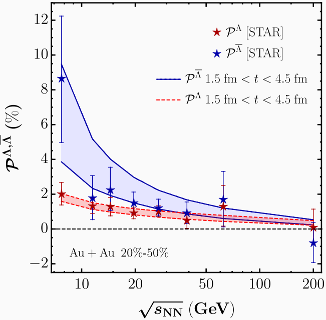
$\sqrt{s_{NN}}$ = 7.7 GeV
$N_{\Lambda_{REC}}$
$N_{\Lambda_{QGP}}$
N_Λ
b (fm)

+



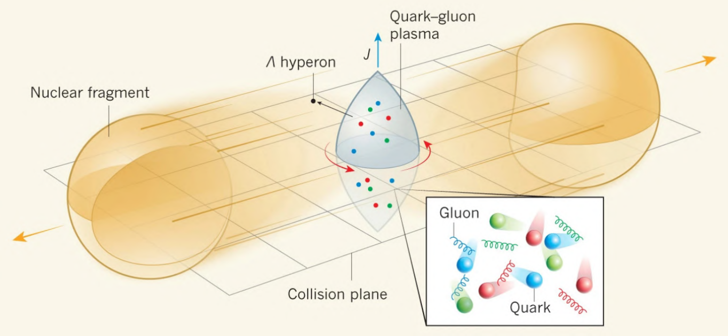
b = 5 fm
b = 8 fm
b = 10 fm
(a)
τ (fm)
(b)
$\overline{\tau}$ (fm)
$\sqrt{s_{NN}}$ (GeV)

=



$\mathcal{P}^{\Lambda}$ [STAR]
$\mathcal{P}^{\overline{\Lambda}}$ [STAR]
$\mathcal{P}^{\overline{\Lambda}}$ 1.5 fm < t < 4.5 fm
$\mathcal{P}^{\Lambda}$ 1.5 fm < t < 4.5 fm
Au + Au 20%-50%
$\mathcal{P}^{\Lambda,\overline{\Lambda}}$ (%)
$\sqrt{s_{NN}}$ (GeV)

Hot, dense, whirly QCD matter in HICs

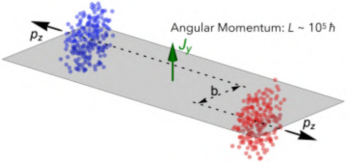


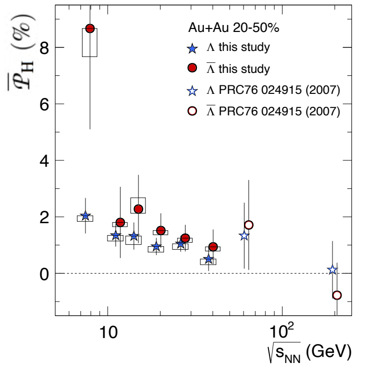
Non-central collisions have large angular momentum $L \sim 10^5 \hbar$.
Shear forces in initial condition introduce vorticity to the QGP.

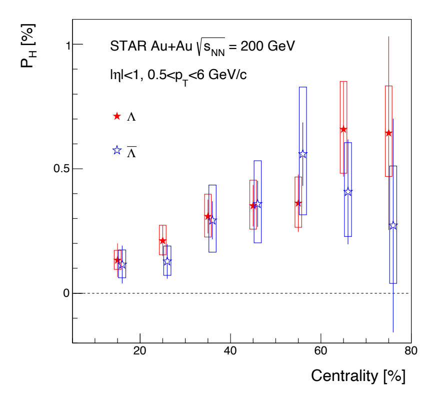
Spin-orbit coupling: spin alignment, or polarization, along the direction of the vorticity - on average - parallel to J.

Vorticity from Λ global polarization

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



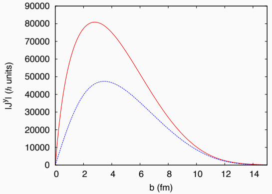




STAR Collaboration, Nature 548 (2017); Phys.Rev.C 98 (2018) 014910

Thermal and kinematic vorticity

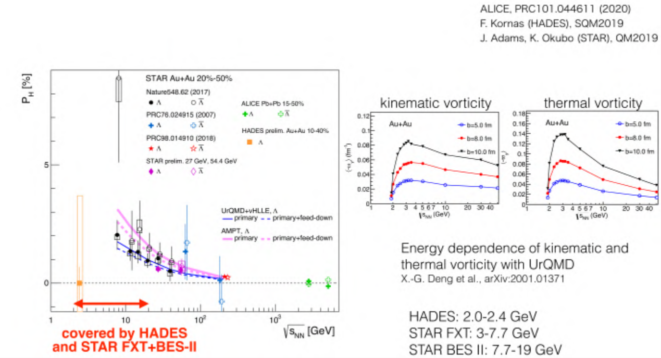
F. Becattini et. al. Eur.Phys.J.C 75 (2015), C 78 (2018)



HIC simulations

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

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



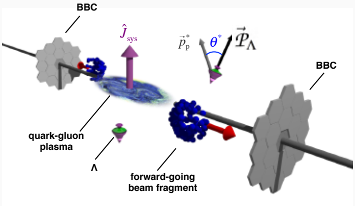
$b \sim 5 - 10$ collisions, favor the development of a larger thermal vorticity

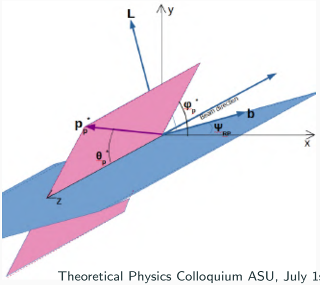
$\rightarrow$ study non-central collisions

Vorticity from Λ global polarization

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

F. Becattini et al Eur.Phys.J.C 75 (2015); Becattini, Karpenko, Lisa, Voloshin, Phys. Rev. C 95 (2017)





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

decay parameter $\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.642 \pm 0.013$

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 $\omega = |\vec{\omega}|$

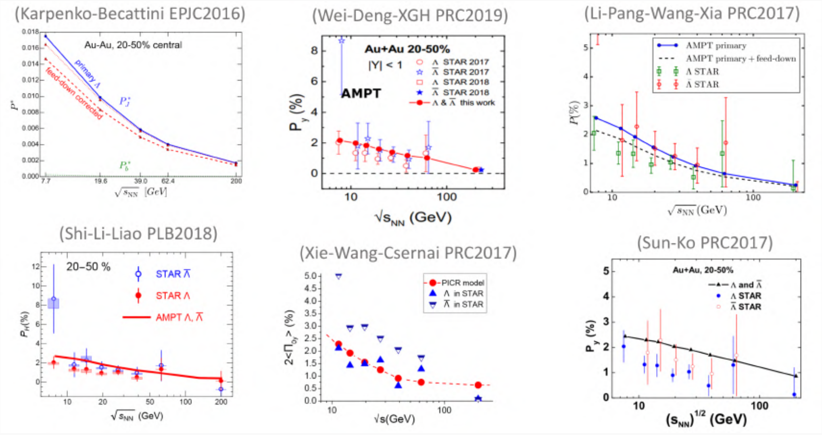
$$\omega = \frac{k_B\ T}{\hbar}\left(\bar{\mathcal{P}}_H + \bar{\mathcal{P}}_{\bar{H}}\right) \quad \longrightarrow \omega \approx (9 \pm 1) \times 10^{21} \mathrm{s}^{-1}$$

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



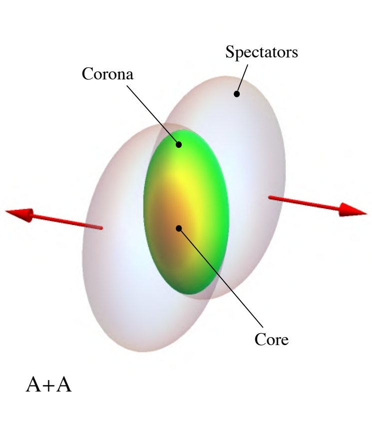
$\Lambda/\bar{\Lambda}$ global polarization from a two-component source

A. Ayala, E. Cuautle, G. Herrera, and L. M. Montaño, Phys. Rev. C **65** (2002)

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 n + n reactions



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

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

Introduce $\mathcal{P}^{\Lambda}_{\rm REC}, \mathcal{P}^{\bar{\Lambda}}_{\rm REC}$ polarization in the corona

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

$$\mathcal{P}^{\bar{\Lambda}} = \frac{\left(\mathcal{P}^{\bar{\Lambda}}_{\rm REC} + \frac{N^{\uparrow}_{\bar{\Lambda}\,\rm QGP} - N^{\downarrow}_{\bar{\Lambda}\,\rm QGP}}{N_{\Lambda\,\rm REC}}\right)}{\left(1 + \frac{N_{\bar{\Lambda}\,\rm QGP}}{N_{\bar{\Lambda}\,\rm REC}}\right)} \quad \text{where} \quad \mathcal{P}^{\bar{\Lambda}}_{\rm REC} = \frac{N^{\uparrow}_{\bar{\Lambda}\,\rm REC} - N^{\downarrow}_{\bar{\Lambda}\,\rm REC}}{N^{\uparrow}_{\bar{\Lambda}\,\rm REC} + N^{\downarrow}_{\bar{\Lambda}\,\rm REC}}, \tag{2}$$

Approximation $\mathcal{P}^{\Lambda}_{\rm REC} = \mathcal{P}^{\bar{\Lambda}}_{\rm REC} = 0$, reactions in cold nuclear matter are less efficient to couple spin with angular momentum

$$\mathcal{P}^{\Lambda} = \frac{\left(\frac{N^{\uparrow}_{\Lambda\,\rm QGP} - N^{\downarrow}_{\Lambda\,\rm QGP}}{N_{\Lambda\,\rm REC}}\right)}{\left(1 + \frac{N_{\Lambda\,\rm QGP}}{N_{\Lambda\,\rm REC}}\right)}, \; \mathcal{P}^{\bar{\Lambda}} = \frac{\left(\frac{N^{\uparrow}_{\bar{\Lambda}\,\rm QGP} - N^{\downarrow}_{\bar{\Lambda}\,\rm QGP}}{N_{\bar{\Lambda}\,\rm REC}}\right)}{\left(1 + \frac{N_{\bar{\Lambda}\,\rm QGP}}{N_{\bar{\Lambda}\,\rm REC}}\right)}. \tag{3}$$

Core features $\rightarrow N_{\Lambda\,\text{QGP}}, N_{\overline{\Lambda}\,\text{QGP}}$

Core reactions are more efficient to align particle spin to global angular momentum, so *intrinsic* global Λ and $\overline{\Lambda}$ polarizations are finite but small

$$
\begin{aligned}
z &= \frac{(N^{\uparrow}_{\Lambda\,\text{QGP}} - N^{\downarrow}_{\Lambda\,\text{QGP}})}{N_{\Lambda\,\text{QGP}}} \\
\bar{z} &= \frac{(N^{\uparrow}_{\overline{\Lambda}\,\text{QGP}} - N^{\downarrow}_{\overline{\Lambda}\,\text{QGP}})}{N_{\overline{\Lambda}\,\text{QGP}}} \underbrace{\simeq}_{N_{\overline{\Lambda}\,\text{QGP}} \simeq N_{\Lambda\,\text{QGP}}} \frac{(N^{\uparrow}_{\overline{\Lambda}\,\text{QGP}} - N^{\downarrow}_{\overline{\Lambda}\,\text{QGP}})}{N_{\Lambda\,\text{QGP}}}
\end{aligned}
$$

Therefore, Eq. (3) can be written as (we expect $z > \bar{z}$)

$$
\mathcal{P}^{\Lambda} = \frac{z \frac{N_{\Lambda\ \text{QGP}}}{N_{\Lambda\ \text{REC}}}}{\left(1 + \frac{N_{\Lambda\ \text{QGP}}}{N_{\Lambda\ \text{REC}}}\right)}, \quad \mathcal{P}^{\overline{\Lambda}} = \frac{\bar{z} \frac{N_{\Lambda\ \text{QGP}}}{N_{\overline{\Lambda}\ \text{REC}}}}{\left(1 + \frac{N_{\Lambda\ \text{QGP}}}{N_{\overline{\Lambda}\ \text{REC}}}\right)}. \tag{4}
$$

Corona features $\rightarrow N_{\Lambda\,\text{REC}}, N_{\overline{\Lambda}\,\text{REC}}$

Cold nuclear matter with $p+p$-like reactions:

s-quark is cheaper than 3 $\bar{q}$'s!

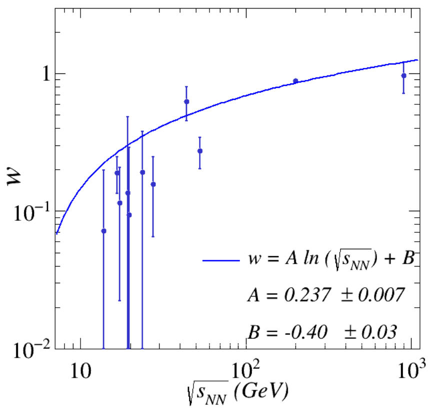
Model $N_{\overline{\Lambda}\,\text{REC}} = wN_{\Lambda\,\text{REC}}$ with $w = w(\sqrt{s_{NN}}) < 1$

$$\mathcal{P}^{\Lambda} = \frac{z\,\frac{N_{\Lambda\ \text{QGP}}}{N_{\Lambda\ \text{REC}}}}{\left(1+\frac{N_{\Lambda\ \text{QGP}}}{N_{\Lambda\ \text{REC}}}\right)}, \quad \mathcal{P}^{\overline{\Lambda}} = \frac{\left(\frac{\bar{z}}{w}\right)\frac{N_{\Lambda\ \text{QGP}}}{N_{\Lambda\ \text{REC}}}}{\left(1+\left(\frac{1}{w}\right)\frac{N_{\Lambda\ \text{QGP}}}{N_{\Lambda\ \text{REC}}}\right)}, \tag{5}$$

Lets find out about this $w = w(\sqrt{s_{NN}})$...

Corona features

Cold nuclear matter (less dense than core): model as p + p intn

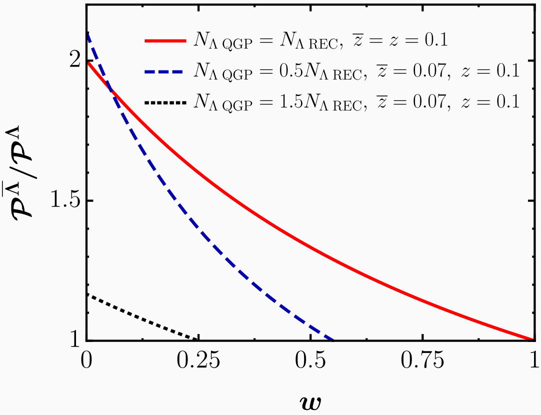


- Experimental data on the ratio $w = N_{\overline{\Lambda}\,\mathrm{REC}}/N_{\Lambda\,\mathrm{REC}}$ obtained from p + p collisions at different energies
- $w = N_{\overline{\Lambda}\,\mathrm{REC}}/N_{\Lambda\,\mathrm{REC}}$ is smaller than 1 except for the largest collision energy considered

M. Gazdzicki and D. Rohrich, Z. Phys. C **71** (1996); J. W. Chapman *et al.*, Phys. Lett. B **47**, 465 (1973); C. Höhne, CERN-THESIS-2003-034; J. Baechler *et al.* (NA35 Collaboration), Nucl. Phys. A **525** (1991); G. Charlton *et al.*, Phys. Rev. Lett. **30** (1973); F. Lopinto *et al.*, Phys. Rev. D **22** (1980); F. W. Busser *et al.*, Phys. Lett. B **61** (1976); D. Brick *et al.*, Nucl. Phys. B **164** (1980); H. Kichimi *et al.*, Phys. Rev. D **20** (1979); S. Erhan, *et al.* Phys. Lett. B **85** (1979); B. I. Abelev *et al.* (STAR Collaboration), Phys. Rev. C **75** (2007); E. Abbas *et al.* (ALICE Collaboration), Eur. Phys. J. C **73** (2013).

$\mathcal{P}^{\bar\Lambda}/\mathcal{P}^{\Lambda}$ in terms of z, $\bar z$, w and $N_{\Lambda\,\mathrm{QGP}}/N_{\Lambda\,\mathrm{REC}}$

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



→ $\mathcal{P}^{\bar\Lambda}/\mathcal{P}^{\Lambda} > 1$ for a range of parameter space

→ $1/w > 1$ amplifying effect

✓ extreme situation $\bar z = z$ and $N_{\Lambda\,\mathrm{QGP}}/N_{\Lambda\,\mathrm{REC}} = 1$, $\mathcal{P}^{\bar\Lambda}/\mathcal{P}^{\Lambda} > 1$ for $0 < w < 1$

✓ realistic scenario with $\bar z < z$ and with $N_{\Lambda\,\mathrm{QGP}}/N_{\Lambda\,\mathrm{REC}} < 1$, $\mathcal{P}^{\bar\Lambda}/\mathcal{P}^{\Lambda} > 1$ for $0 < w < 0.55$

✓ if $N_{\Lambda\,\mathrm{QGP}}/N_{\Lambda\,\mathrm{REC}} > 1$, $\mathcal{P}^{\bar\Lambda}/\mathcal{P}^{\Lambda} > 1$ only for $0 < w < 0.25$

Study $\Lambda/\bar{\Lambda}$ production in QGP vs REC

Do non-central collisions at different energies and impact parameters favor a scenario where $N_{\Lambda\,\mathrm{QGP}}/N_{\Lambda\,\mathrm{REC}} \lesssim 1$ and thus $\mathcal{P}^{\bar{\Lambda}} > \mathcal{P}^{\Lambda}$?

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)

$$\langle s \rangle = N_{\Lambda\,\mathrm{QGP}} = c\,(N_{\mathrm{p\,QGP}})^2 \quad \text{with} \quad 0.001 \le c \le 0.005 \tag{6}$$

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

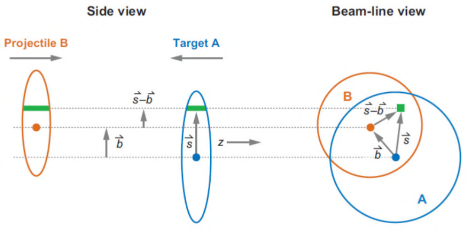
$$N_{\mathrm{p\,QGP}} = \int d^2s \quad n_{\mathrm{p}}(\vec{s},\vec{b}) \quad \theta\left[\overbrace{n_{\mathrm{p}}(\vec{s},\vec{b}) - n_c}^{density\ \ of\ \ participants}\right] \tag{7}$$

$n_c = 3.3\ \mathrm{fm}^{-2}$ critical density of participants above which the QGP can be produced   J. P. Blaizot, J. Y. Ollitrault, Phys. Rev. Lett. **77** (1996)

Study $\Lambda/\bar{\Lambda}$ production in QGP vs REC

$$n_{\rm p}(\vec{s},\vec{b}) = T_A(\vec{s})[1-e^{-\sigma_{NN}(\sqrt{s_{NN}})T_B(\vec{s}-\vec{b})}] + T_B(\vec{s}-\vec{b})[1-e^{-\sigma_{NN}(\sqrt{s_{NN}})T_A(\vec{s})}]$$

thickness functions T_A, T_B
$\vec{b}$ along the impact parameter
σ_{NN} nucleon-nucleon xsec



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

The thickness function T_A

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

Woods-Saxon $\rho_A(r) = (1+e^{(r-R_A)/a})^{-1}$, $a = 0.41$ fm, $R_A = 1.1A^{1/3}$ fm.

Study $\Lambda/\bar{\Lambda}$ production in QGP vs REC

$N_{\Lambda\,\mathrm{QGP}}/N_{\Lambda\,\mathrm{REC}} > 1$ for $b \lesssim 6$ fm

$N_{\Lambda\,\mathrm{QGP}}/N_{\Lambda\,\mathrm{REC}} < 1$ for $b \gtrsim 6$ fm

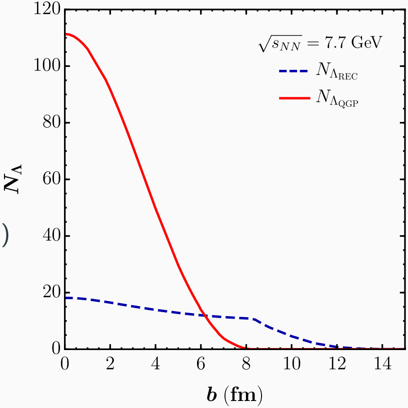
Number of Λs produced in the core

$N_{\Lambda\,\mathrm{QGP}} = (0.0025)\,(N_{\mathrm{p\,QGP}})^2$ where

$$N_{\mathrm{p\,QGP}} = \int d^2s\; n_{\mathrm{p}}(\vec{s},\vec{b})\,\theta\left[n_{\mathrm{p}}(\vec{s},\vec{b}) - n_c\right]$$

Number of Λs produced in the corona

$$N_{\Lambda\,\mathrm{REC}} = \underbrace{\sigma^{\Lambda}_{NN}\,(\sqrt{s_{NN}})}_{\Lambda\ \ p+p\ \ xsec} \int d^2s\; T_B(\vec{b}-\vec{s})\,T_A(\vec{s}) \times \theta\left[n_c - n_{\mathrm{p}}(\vec{s},\vec{b})\right]$$



Fit to experiment $\sigma^{\Lambda}_{NN}\left(\sqrt{s_{NN}}\right) = C \ln \sqrt{s_{NN}} + D$, with $C = 1.67 \pm 0.05$ mb and $D = -1.60 \pm 0.08$ mb. D. Brick *et al.*, Nucl. Phys. B **164** (1980). H. Kichimi *et al.*, Phys. Rev. D **20** (1979). S. Erhan *et al.*, Phys. Lett. B **85** (1979). K. Jaeger *et al.*, Phys. Rev. D **11** (1975). V. Blobel *et al.* (Bonn-Hamburg-Munich Collaboration), Nucl. Phys. B **69** (1974). D. Drijard *et al.* (CERN-Dortmund-Heidelberg-Warsaw Collaboration), Z. Phys. C **12** (1982).

Intrinsic global polarization from relaxation times

Relaxation time for quark/antiquark spin and thermal vorticity alignment in a quark-gluon plasma at finite temperature and quark chemical potential

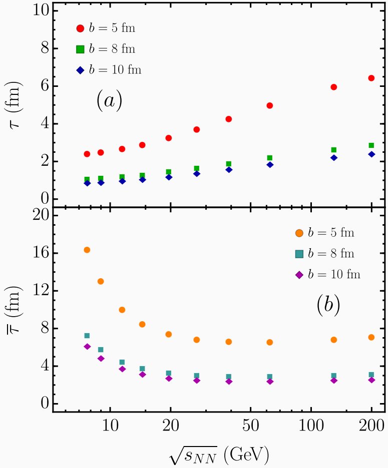
A. Ayala. D. de la Cruz, L. A. Hernández, and J. Salinas, e-Print: arXiv:2003.06545 [hep-ph]

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

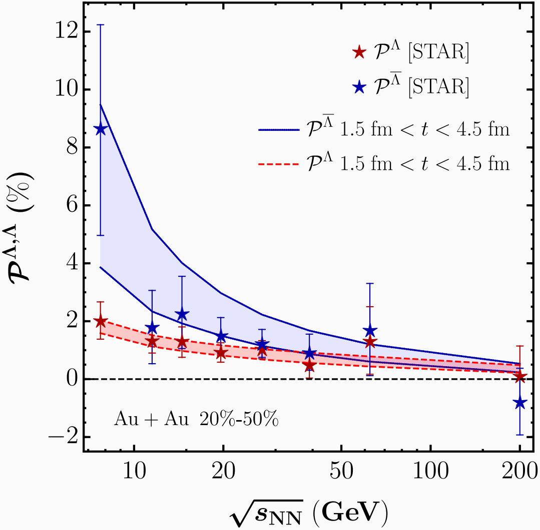
$$z = 1 - \exp\left(-t/\tau\right)$$

$$\bar{z} = 1 - \exp\left(-t/\bar{\tau}\right)$$

as functions of the Λ and $\overline{\Lambda}$ formation time t within the QGP.



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

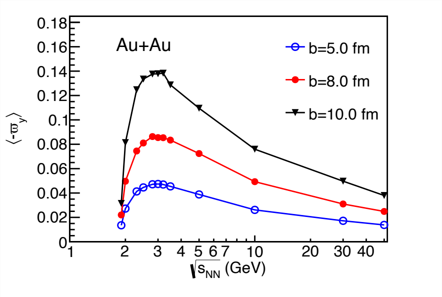


Au + Au 20-50% Λ and $\bar{\Lambda}$ polarization from core-corona model bands: Λ and $\bar{\Lambda}$ formation time in QGP range 1.5 fm $< t <$ 4.5 fm
vs
data STAR-BES Nature 548 (2017)

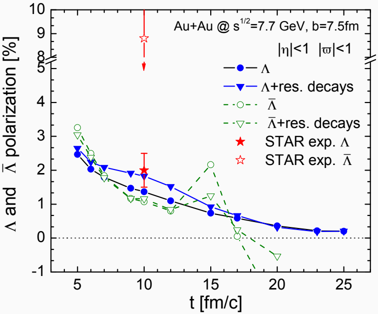
What happens for $\sqrt{s_{NN}} < 7.7$ GeV? (NICA, FAIR, RHIC)

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)



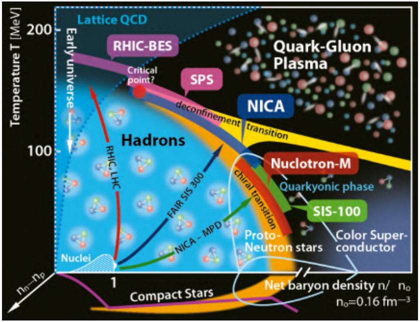
If $\omega \propto \mathcal{P}$ then polarization is consistent with data.

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

To summarize:

- 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
- competing production effects: $N_{\Lambda\,\mathrm{QGP}}/N_{\Lambda\,\mathrm{REC}} > 1$ in central to semi-central collisions and $N_{\Lambda\,\mathrm{QGP}}/N_{\Lambda\,\mathrm{REC}} < 1$ in peripheral collisions
- so global $\overline{\Lambda}$ polarization can be larger than the global Λ polarization in peripheral collisions: corona-like
- in spite of the thermal vorticity-produced, Λ polarization is larger than $\overline{\Lambda}$ polarization in the central collisions: core-like
- in collisions with intermediate to large impact parameters, which correspond to the kind of collisions that favor the development of a larger thermal vorticity, $N_{\Lambda\,\mathrm{QGP}}/N_{\Lambda\,\mathrm{REC}} \lesssim 1$ and thus $\mathcal{P}^{\overline{\Lambda}} > \mathcal{P}^{\Lambda}$

In progress: MexNICA at MPD-NICA

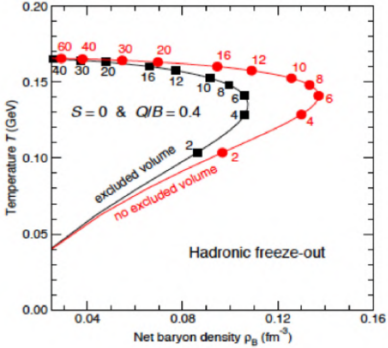


EM field creation in A+A collisions at lower energies and impact on photoproduction, vorticity, hyperon polarization

#8: Exploring high-density baryonic matter: Maximum freeze-out density

Jørgen Randrup[1] and Jean Cleymans[2]

Highest baryon density at freeze-out for $s^{1/2}$~6 GeV, slightly lowering with ex.volume

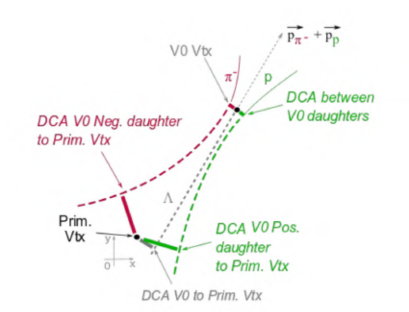


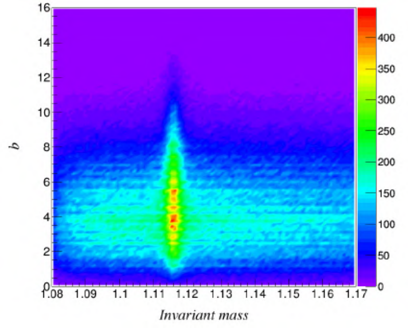
In progress: MexNICA at MPD-NICA - Preliminary

Simulations with UrQMD, PHSD, LAQGSM for A + A at NICA energies to produce and reconstruct hyperons and to simulate the influence of polarization effects: initial conditions, hydro evolution, freeze-out, B-fields, etc.

Preliminary, Bi+Bi @ 9 GeV MPDroot-framework - TPC

Ivonne Maldondado, MexNICA postdoc, UAS





In progress: MexNICA at MPD-NICA - Preliminary

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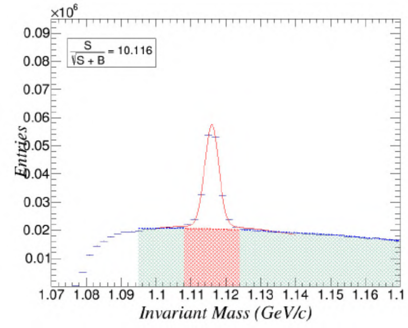
Preliminary, Bi+Bi @ 9 GeV MPDroot-framework - TPC

Ivonne Maldondado, MexNICA postdoc, UAS

Variable	Cuts
Cos of Angle	> 0.98
DCA V0	< 0.45
DCA p-track	> 0.15
DCA π-track	> 0.35

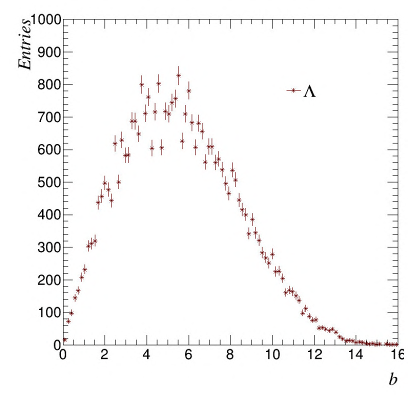


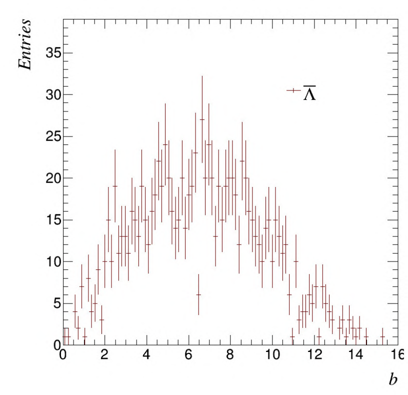
In progress: MexNICA at MPD-NICA - Preliminary

Simulations with UrQMD, PHSD, LAQGSM for A + A at NICA energies to produce and reconstruct hyperons and to simulate the influence of polarization effects: initial conditions, hydro evolution, freeze-out, B-fields, etc.

Preliminary, Bi+Bi @ 9 GeV MPDroot-framework - TPC

Ivonne Maldondado, MexNICA postdoc, UAS





Final remarks

- ✓ Heavy-ion physics: electronics $\rightarrow$ spintronics
- ✓ Interesting sources of vorticity: jets, magnetic field
- ✓ Vorticity and transport mechanisms: viscosity
- ✓ The role of polarization measurements to study vorticity AND mechanisms/sources
- ✓ New experiments coming up - NICA, FAIR, RHIC, many opportunities!

THANKS