Λ and $\overline{\Lambda}$ global polarization at HADES and NICA energies using the core-corona model

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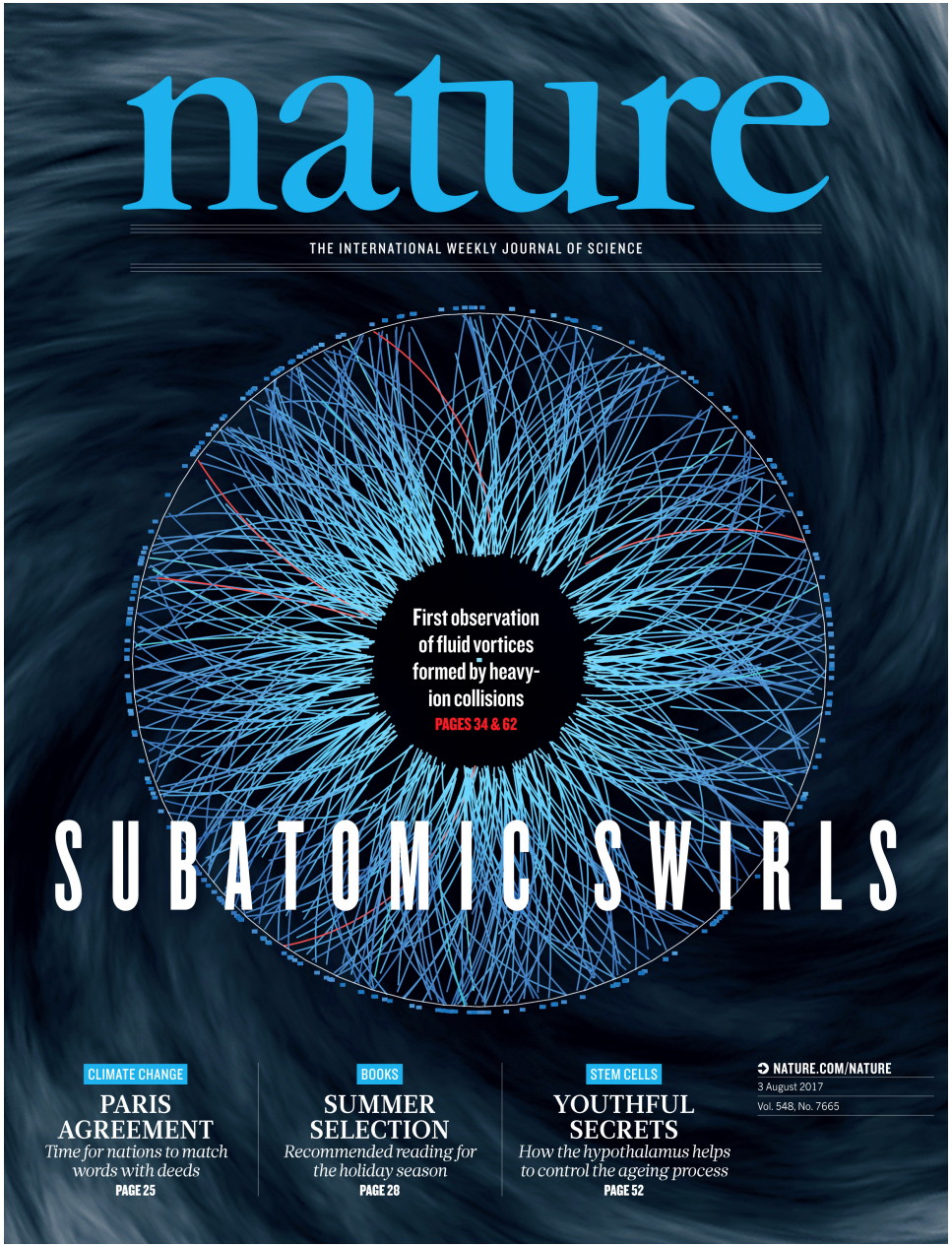
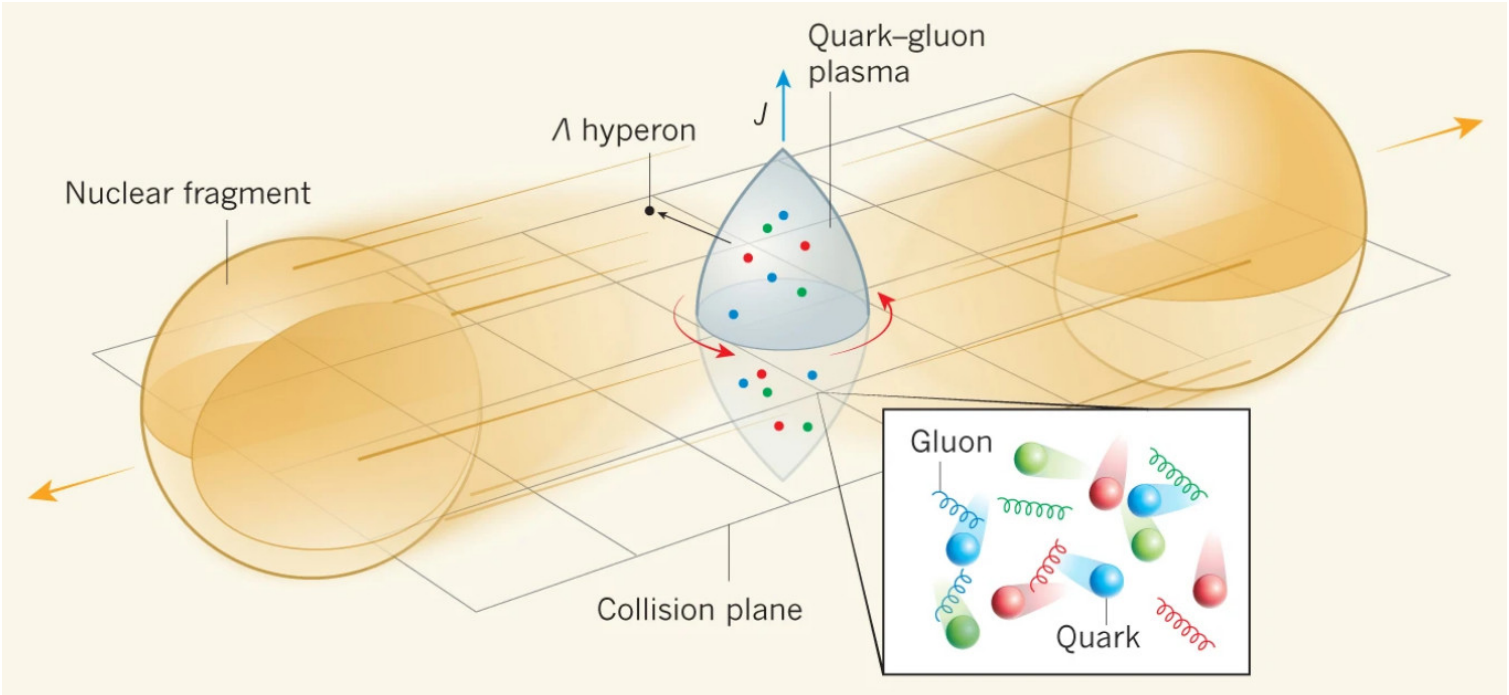
Hot, dense, **swirling** QCD matter



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

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

Hot, dense, swirling QCD matter in HICs

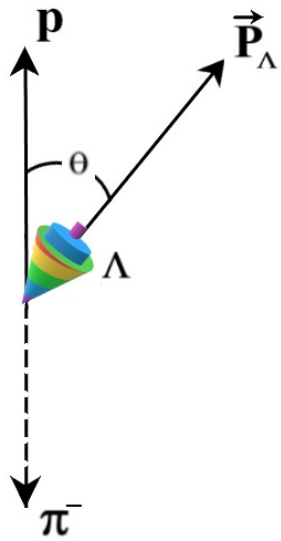


Non-central collisions have large angular momentum $L \sim 10^5 \hbar$.
Shear forces in initial condition introduce vorticity to the QGP.

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

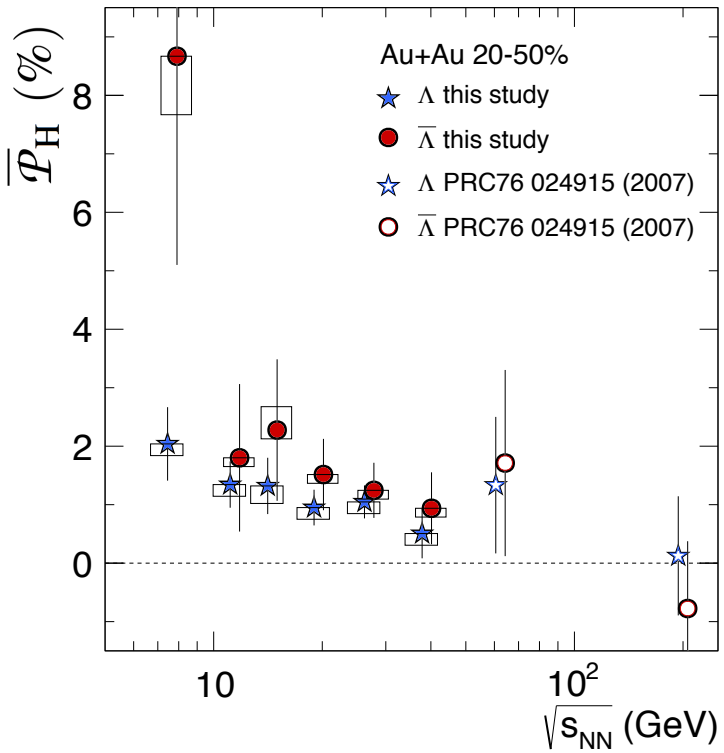
Good swirling-ness probe in HICs: Λ hyperon

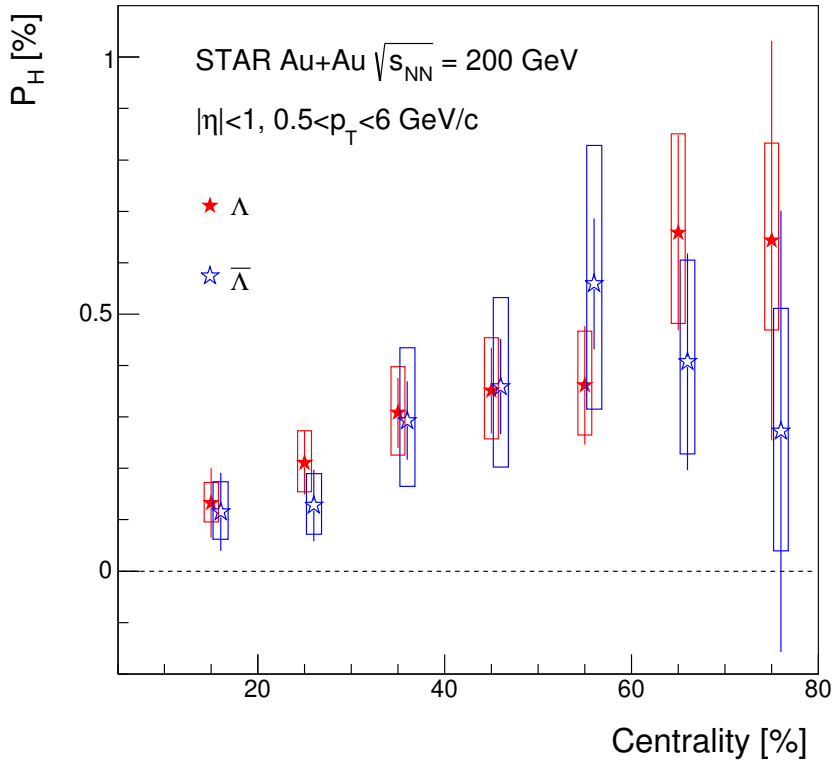
- Particle Data Group:
  - $m_\Lambda = 1115.683 \pm 0.006$ MeV
  - $\tau = 2.632 \pm 0.020 \times 10^{-10}$ s (~ 7.9 cm at c)
  - $\Gamma_1(\Lambda \to p\pi^-) = (63.9 \pm 0.5)\%$
  - $\Gamma_2(\Lambda \to n\pi^0) = (35.8 \pm 0.5)\%$
- Advantages:
  - lightest hyperon with s content
  - long lifetime: good for fiducial track/reco
  - parity-violating weak decay - sort of self-analyzing
  - decay dist not-isotropic: p going off in the direction of Λ spin



lobal Λ, $\overline{\Lambda}$ polarization BES-STAR

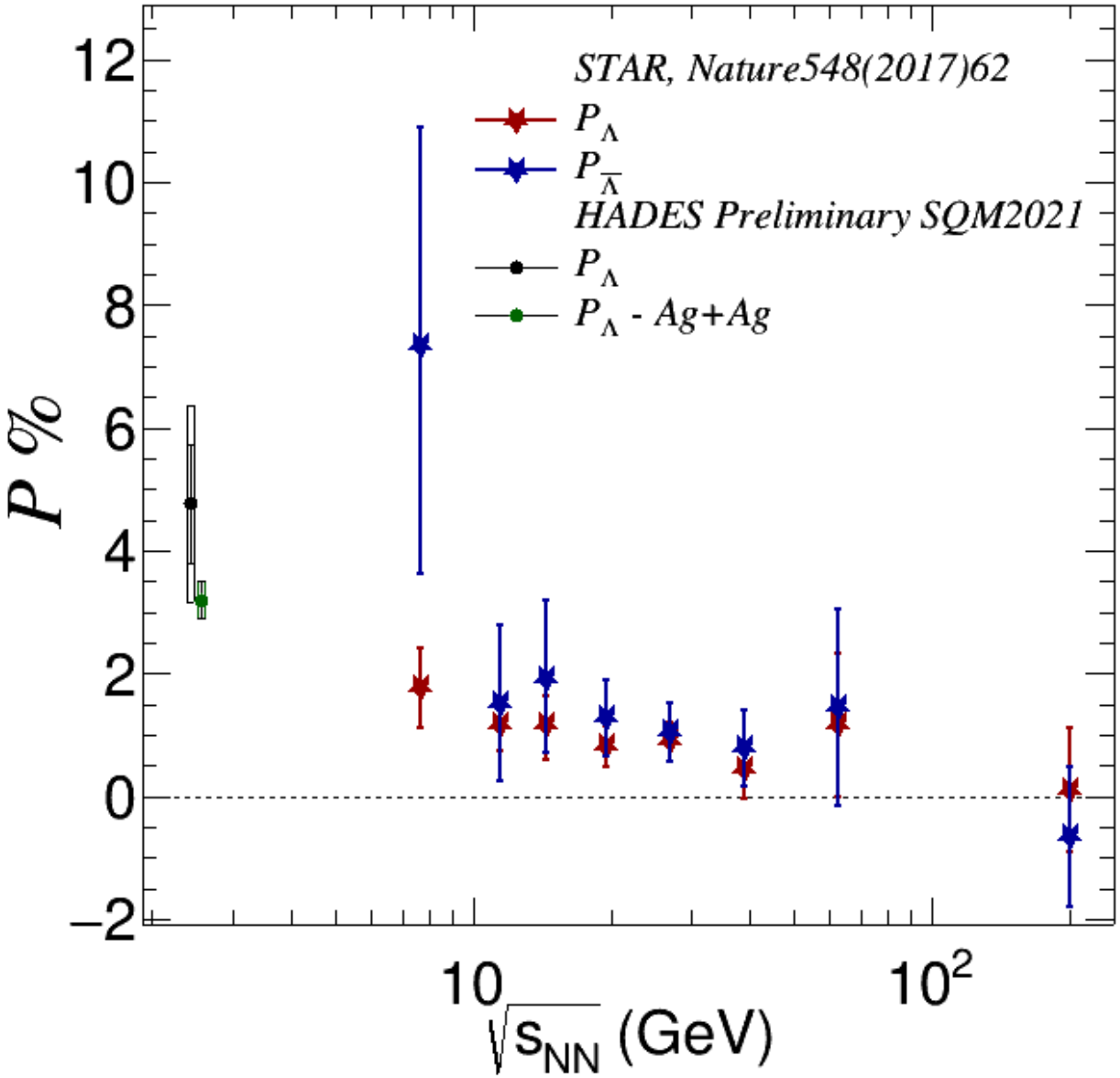
Meassurement of angular momentum retained at mid-rapidity. In most central collisions: no initial angular momentum, no polarization.





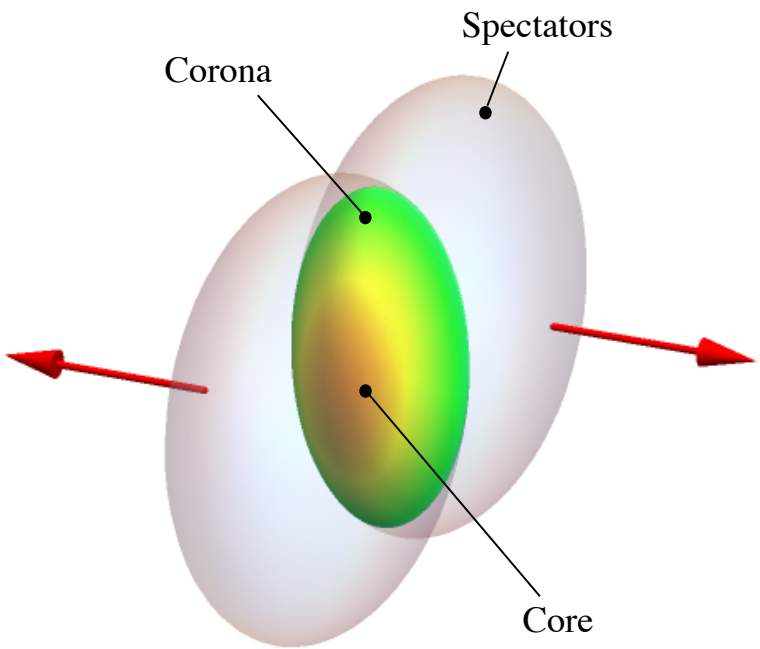
STAR Collaboration, Nature 548 (2017); Phys.Rev.C 98 (2018) 014910

Global Λ, $\overline{\Lambda}$ polarization: HADES & BES-STAR



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

Non-central heavy-ion collision of a symmetric system:
Λ, $\bar{\Lambda}$s from core via QGP processes
Λ, $\bar{\Lambda}$s from corona via n + n reactions



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

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.

Λ, $\bar{\Lambda}$ polarization

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

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

After a bit of straightforward algebra, we can express the Λ and $\bar{\Lambda}$ polarization as

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

where

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

Λ, $\bar{\Lambda}$ polarization

- Notice that $\mathcal{P}^{\Lambda}_{\rm REC}$ and $\mathcal{P}^{\bar{\Lambda}}_{\rm REC}$ refer to the polarization along the global angular momentum produced in the **corona.**
- Although nucleons colliding in the corona partake of the vortical motion, reactions in cold nuclear matter are less efficient to align the spin in the direction of the angular momentum than in the QGP.
- As a working approximation we set $\mathcal{P}^{\Lambda}_{\rm REC} = \mathcal{P}^{\bar{\Lambda}}_{\rm REC} = 0$ to write

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

- Also notice that it is desirable to express the polarizations in terms of the ratio

$$N_{\Lambda\ \rm QGP}/N_{\Lambda\ \rm REC}$$

Λ, $\bar{\Lambda}$ polarization

- For this purpose we introduce the auxiliary variables

$$w = N_{\bar{\Lambda}\,\mathrm{REC}}/N_{\Lambda\,\mathrm{REC}} \quad \text{and} \quad w' = N_{\bar{\Lambda}\mathrm{QGP}}/N_{\Lambda\ \mathrm{QGP}}$$

  and define the intrinsic polarizations

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

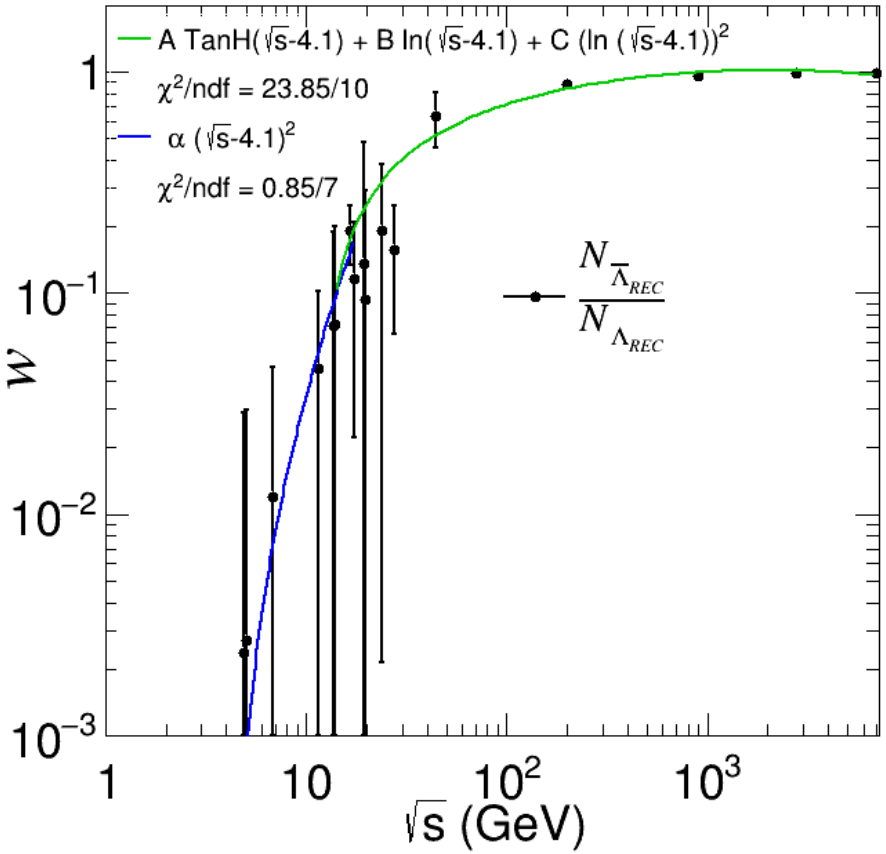
- Therefore,

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

- The ratios w and w' can be estimated either from data or from simper considerations as follows:

Corona features: the ratio w

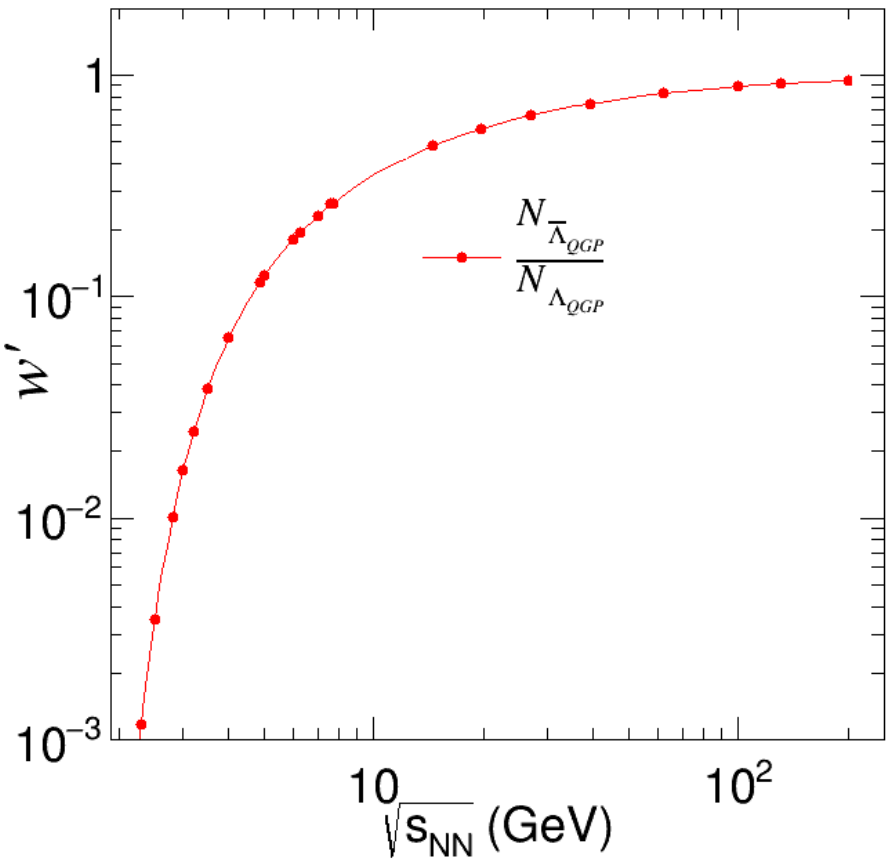
- Cold nuclear matter (less dense than core): model as p + p collisions



- 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).

Core features: the ratio w'



- In the core, $w' = N_{\bar{\Lambda}\text{QGP}}/N_{\Lambda\ \text{QGP}}$ computed as the ratio of the equilibrium distributions of $\bar{s}$ to s-quarks for a given temperature and chemical potential $\mu = \mu_B/3$
- $$w' = \frac{e^{(m_s-\mu)/T}+1}{e^{(m_s+\mu)/T}+1},$$ is smaller than 1 except for the largest collision energy considered

Λ, $\bar{\Lambda}$ production in QGP vs REC: Glauber model

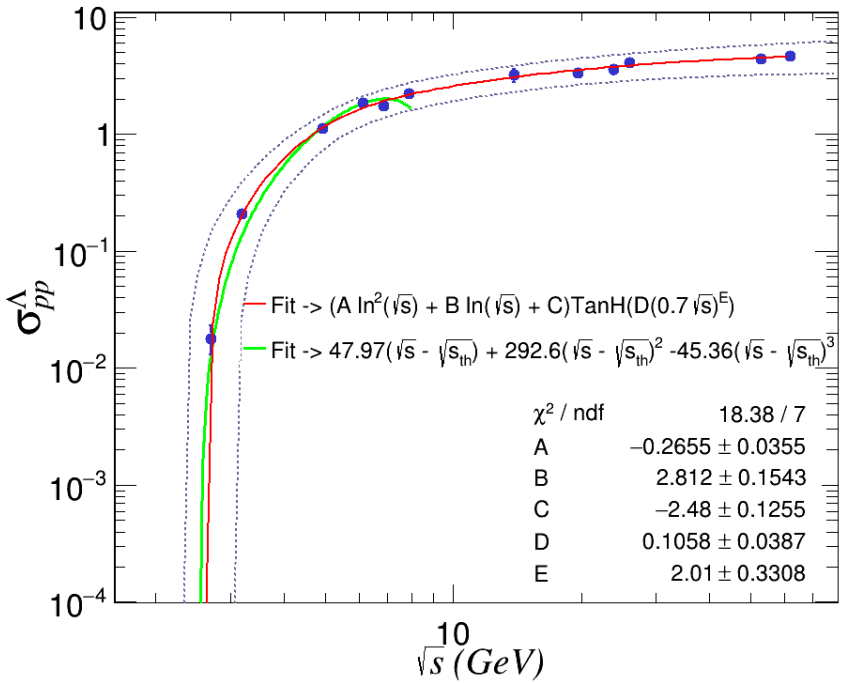
Number of Λs produced in the core $\propto$

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

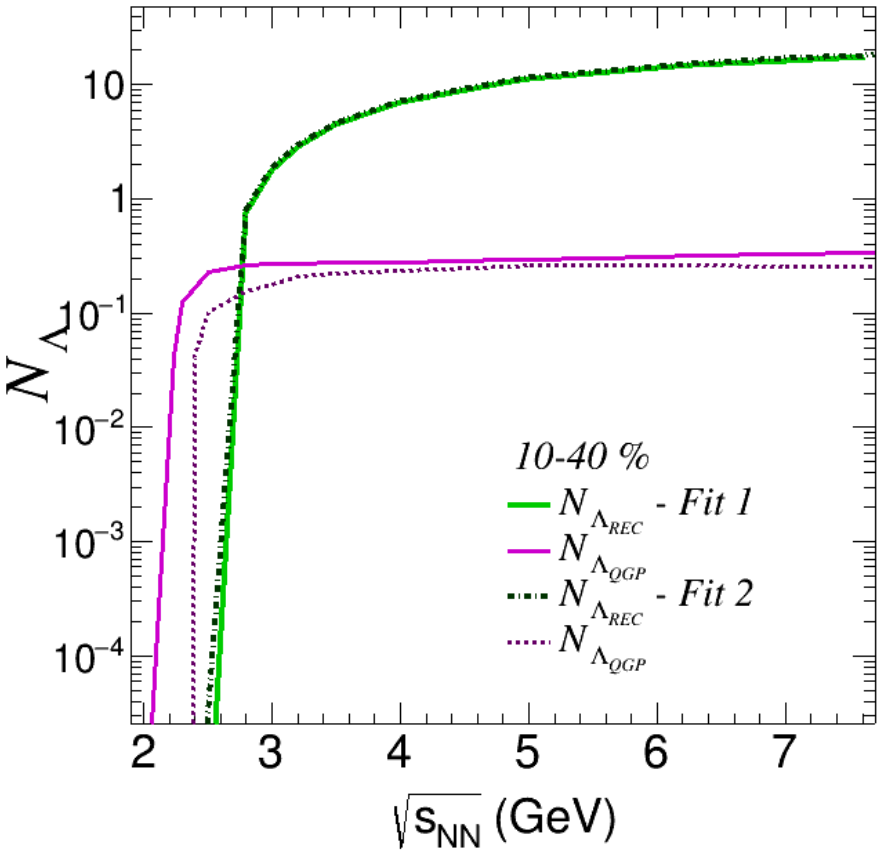
Number of Λs produced in the corona

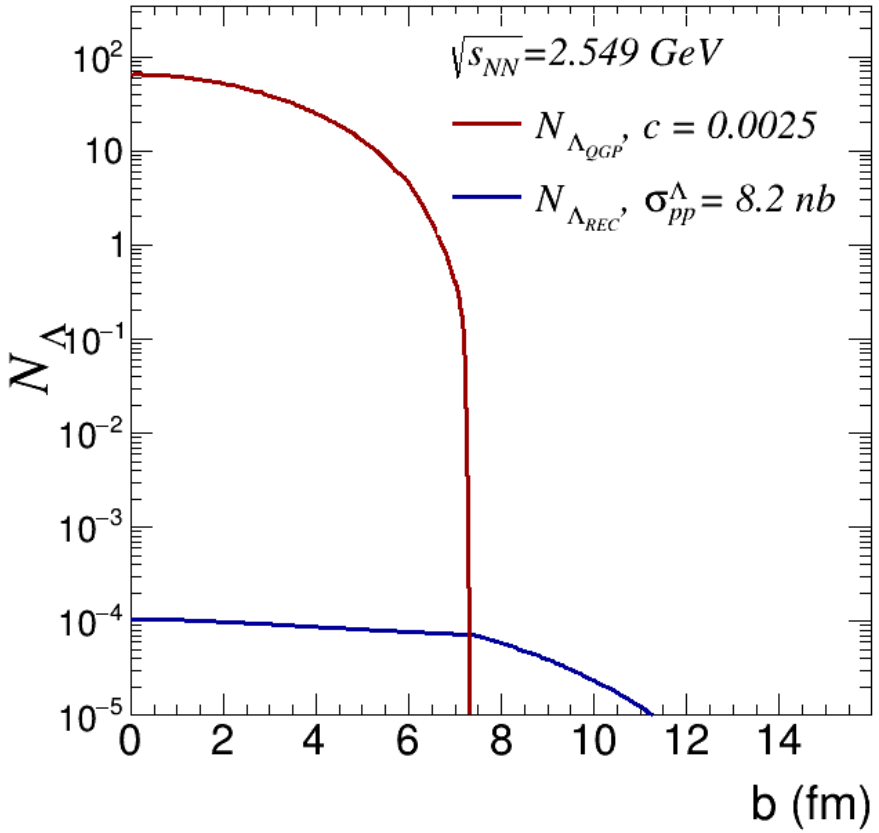
$$N_{\Lambda\,\mathrm{REC}} \propto \sigma^{\Lambda}_{NN} \int d^2s\; T_B(\vec{b}-\vec{s})\,T_A(\vec{s}) \times \theta\left[n_c - n_{\mathrm{p}}(\vec{s},\vec{b})\right]$$

- $n_c = 3.3$ fm^{-2} is the **critical density** above (below) which, the QGP is (is not) formed.



Number of Λ, $\bar{\Lambda}$ in QGP and corona





Intrinsic polarizations z and $\bar{z}$: relaxation time for the alignment of spin with vorticity

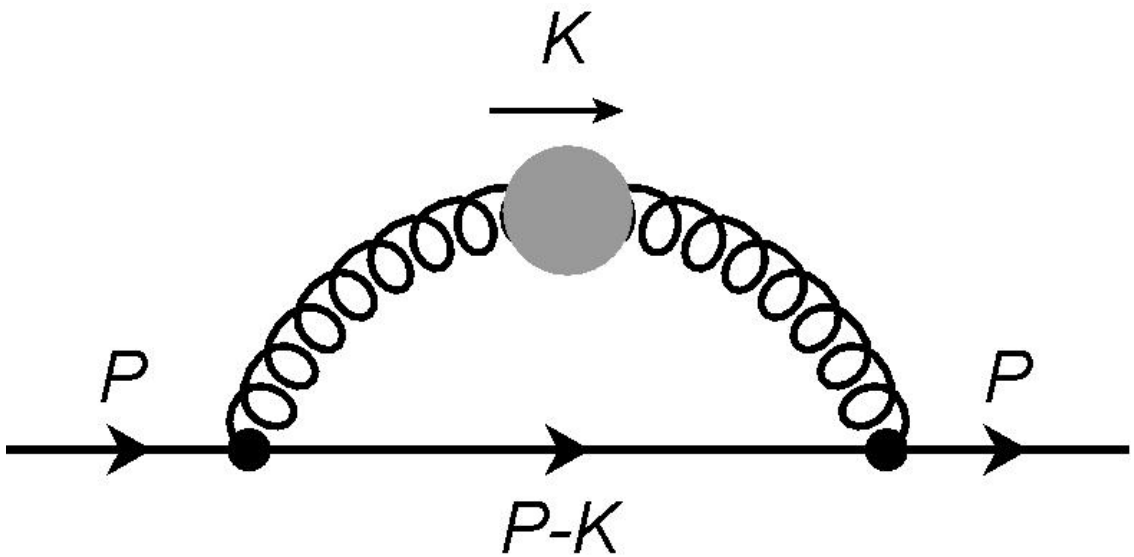
$$\mathcal{P}^{\Lambda} = \frac{z\,\frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}}{\left(1+\frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}\right)}, \quad \mathcal{P}^{\bar{\Lambda}} = \frac{\bar{z}\left(\frac{w'}{w}\right)\frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}}{\left(1+\left(\frac{w'}{w}\right)\frac{N_{\Lambda\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

- The intrinsic polarizations are given in terms of the relaxation times τ and $\bar{\tau}$ and the QGP life-time $\Delta\tau_{QGP}$

$$\begin{aligned} z &= \frac{(N^{\uparrow}_{\Lambda\,\mathrm{QGP}} - N^{\downarrow}_{\Lambda\,\mathrm{QGP}})}{N_{\Lambda\,\mathrm{QGP}}} = 1 - e^{-\Delta\tau_{QGP}/\tau} \\ \bar{z} &= \frac{(N^{\uparrow}_{\bar{\Lambda}\,\mathrm{QGP}} - N^{\downarrow}_{\bar{\Lambda}\,\mathrm{QGP}})}{N_{\bar{\Lambda}\,\mathrm{QGP}}} = 1 - e^{-\Delta\tau_{QGP}/\bar{\tau}} \end{aligned}$$

Relaxation time: inverse of imaginary part of self-energy with vorticity-spin interaction

$$\begin{aligned} \varpi_{\mu\nu} &= \frac{1}{2}\left(\partial_\nu \beta_\mu - \partial_\mu \beta_\nu\right) \\ \beta_\mu &= u_\mu(x)/T(x), \quad \varpi_{\mu\nu}\sigma^{\mu\nu} \propto \omega/T \end{aligned}$$



$$\Gamma(p_0) = \tilde{f}(p_0)\mathrm{Tr}\left[\gamma^0 \mathrm{Im}\Sigma\right], \quad \lambda_a^\mu = g\frac{\sigma^{\alpha\beta}}{2}\varpi_{\alpha\beta}\gamma^\mu t_a \qquad (1)$$

Gluon propagator at finite T and μ_B

- In a covariant gauge, the Hard Thermal Loop (HTL) approximation to the effective gluon propagator is given by

$$^*G_{\mu\nu}(K) = {}^*\Delta_L(K) P_{L\,\mu\nu} + {}^*\Delta_T(K) P_{T\,\mu\nu}$$

- The gluon propagator functions for longitudinal and transverse modes, ${}^*\Delta_{L,T}(K)$, are

$$^*\Delta_L(K)^{-1} = K^2 + 2m^2 \frac{K^2}{k^2}\left[1 - \left(\frac{i\omega_n}{k}\right) Q_0\left(\frac{i\omega_n}{k}\right)\right],$$

$$^*\Delta_T(K)^{-1} = -K^2 - m^2\left(\frac{i\omega_n}{k}\right)\left\{\left[1 - \left(\frac{i\omega_n}{k}\right)^2\right] Q_0\left(\frac{i\omega_n}{k}\right) + \left(\frac{i\omega_n}{k}\right)\right\}$$

$$\begin{aligned} m^2 &= \frac{1}{6} g^2 C_A T^2 + \frac{1}{12} g^2 C_F \left(T^2 + \frac{3}{\pi^2}\mu^2\right), \; C_A = 3, \; C_F = 4/3, \\ \alpha_s &= g^2/4\pi = 1/3 \end{aligned}$$

Relaxation time

- The total interaction rate is obtained by integrating over the available phase space

$$\Gamma = V \int \frac{d^3p}{(2\pi)^3} \Gamma(p_0)$$

where V is the volume of the overlap region in the collision

$$V = \pi R^2 \Delta\tau_{QGP}$$

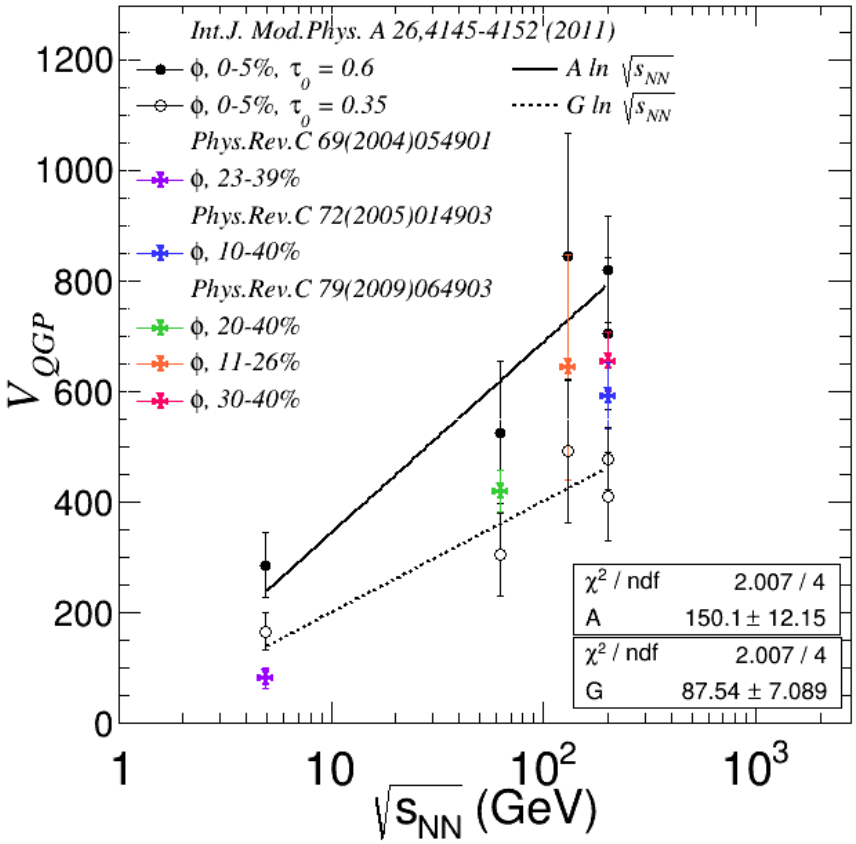
and $\Delta\tau_{QGP}$ is the QGP life-time

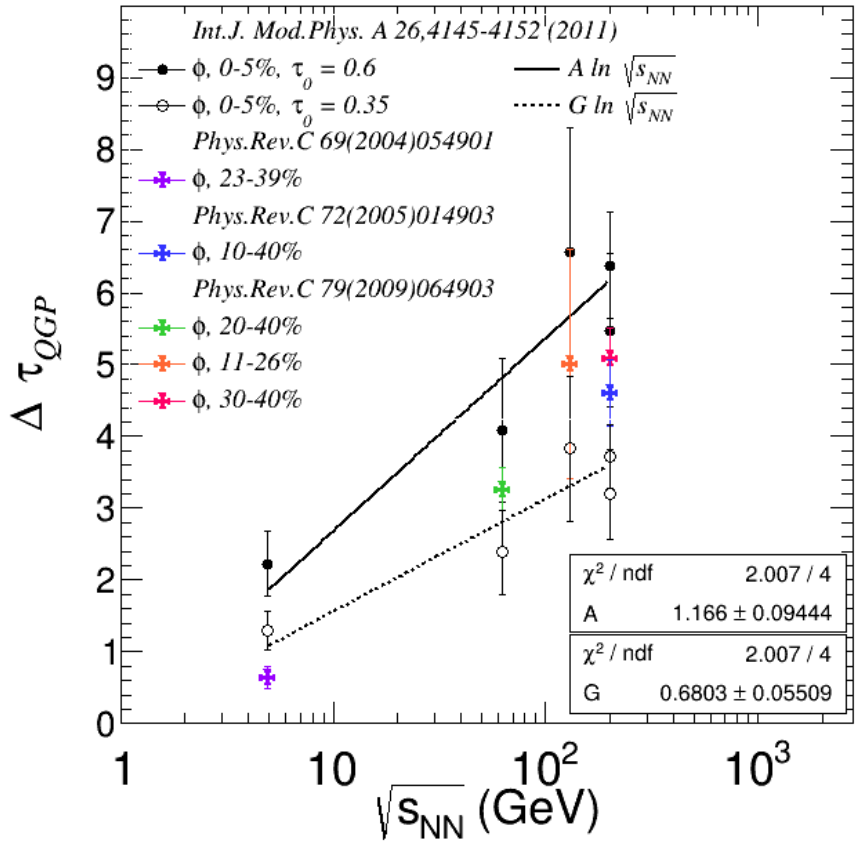
$$\Delta\tau_{QGP} = \tau_f - \tau_0 = \tau_0 \left[\left(\frac{T_0}{T_f} \right)^3 - 1 \right].$$

- The relaxation time for spin and vorticity alignment is

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

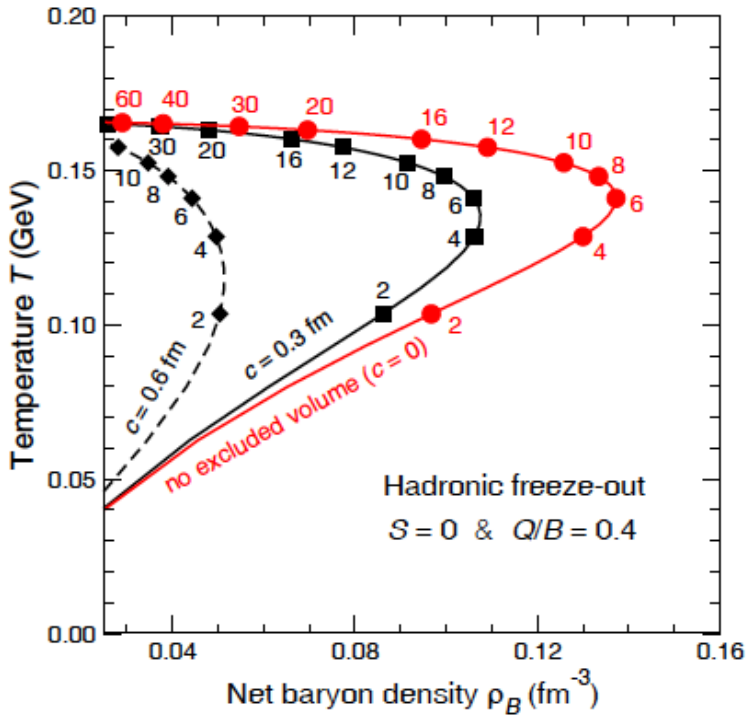
Volume and QGP life-time as a function of $\sqrt{s_{NN}}$





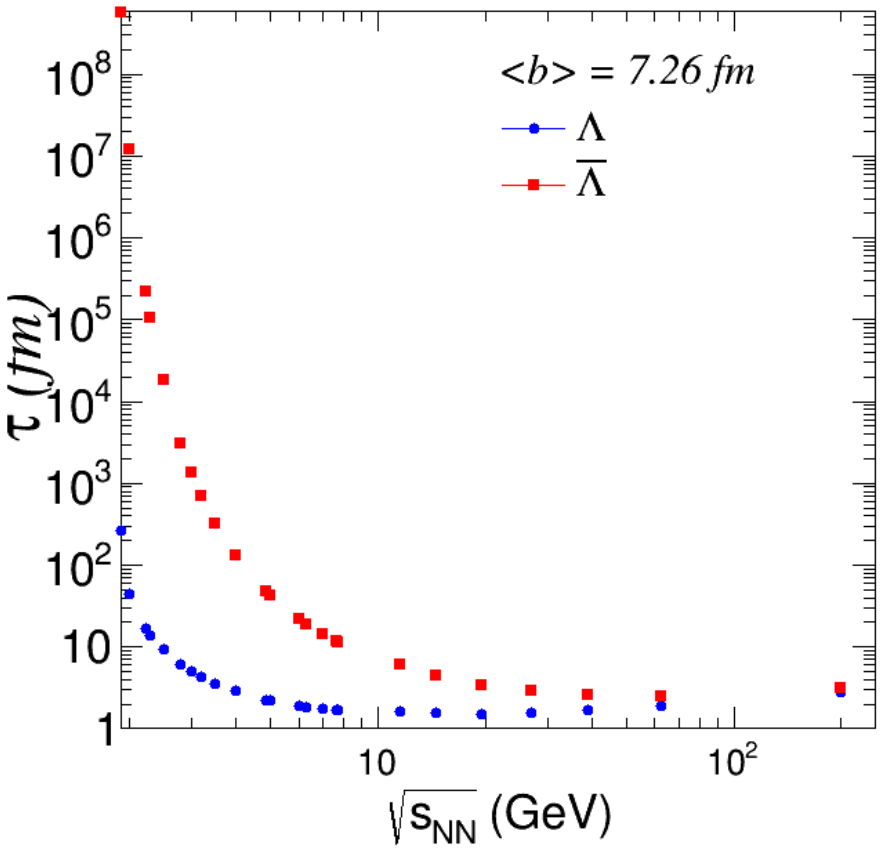
Maximum freeze-out density,

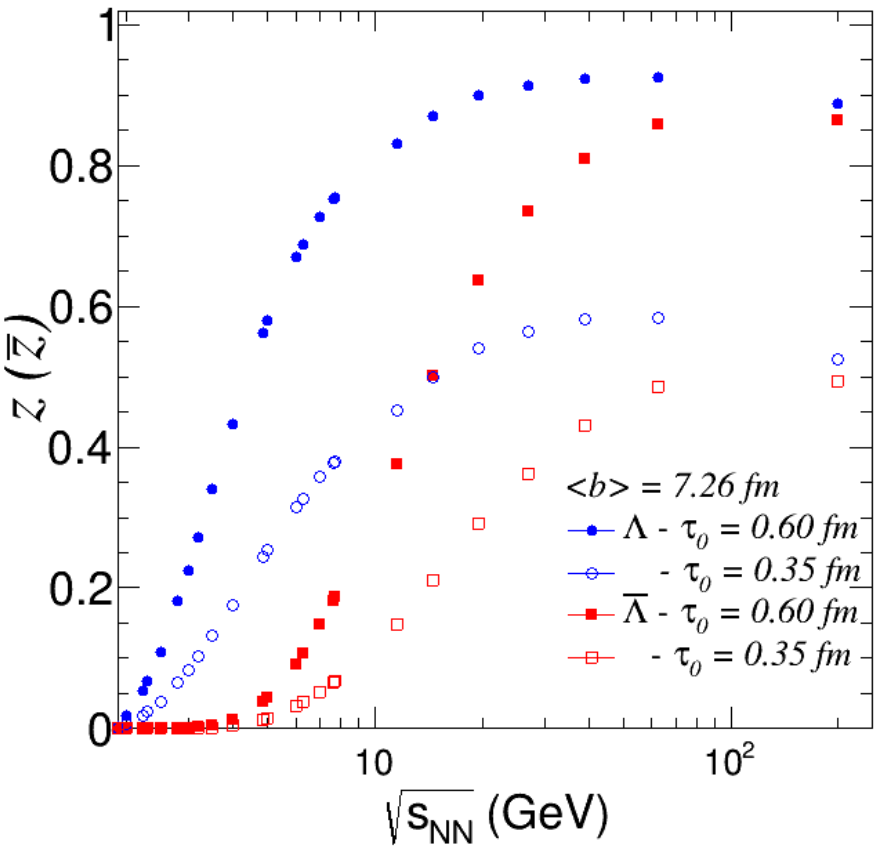
J. Randrup and J. Cleymans, Phys. Rev. **C** 74, 047901 (2006)



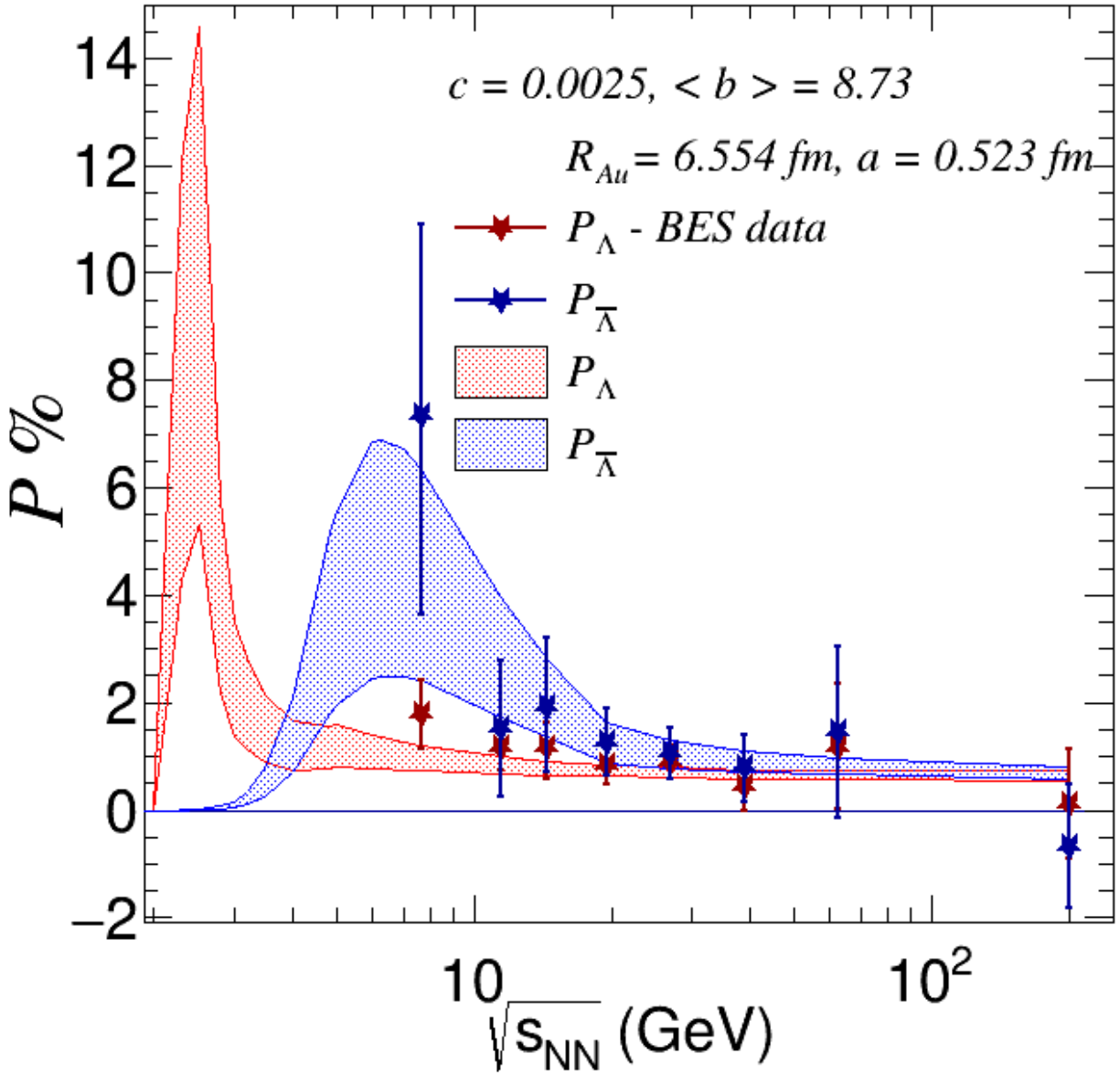
$$T(\mu_B) = 166 - 139\mu_B^2 - 53\mu_B^4, \quad \mu_B(\sqrt{s_{NN}}) = \frac{1308}{1000 + 0.273\sqrt{s_{NN}}}$$

Relaxation time and polarizations $\sqrt{s_{NN}}$

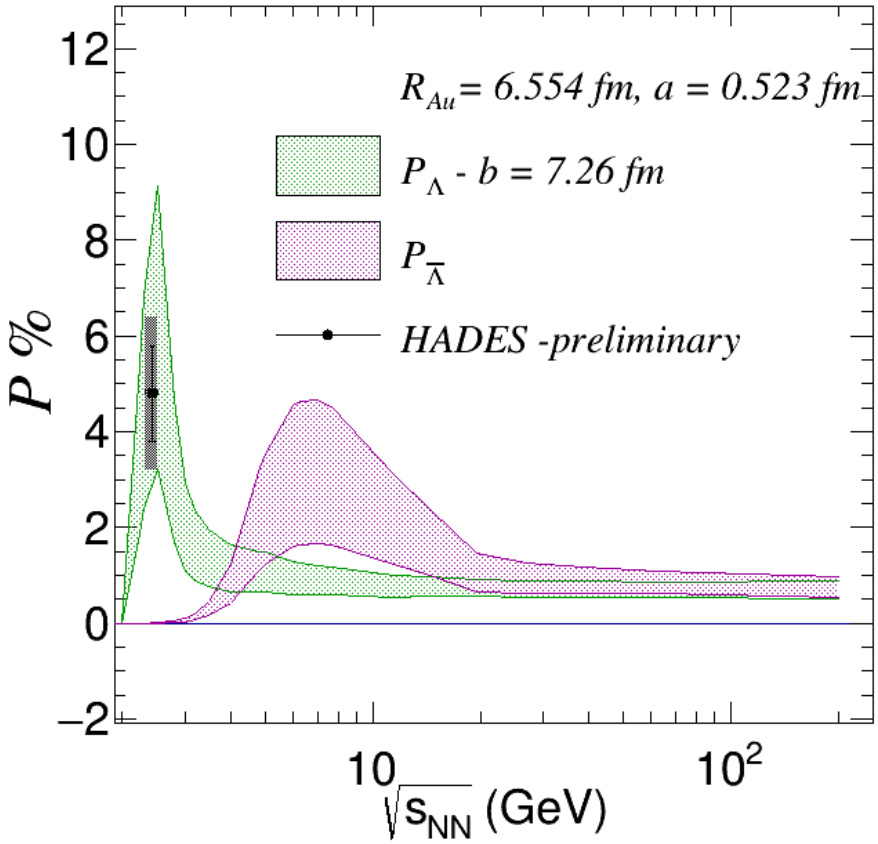


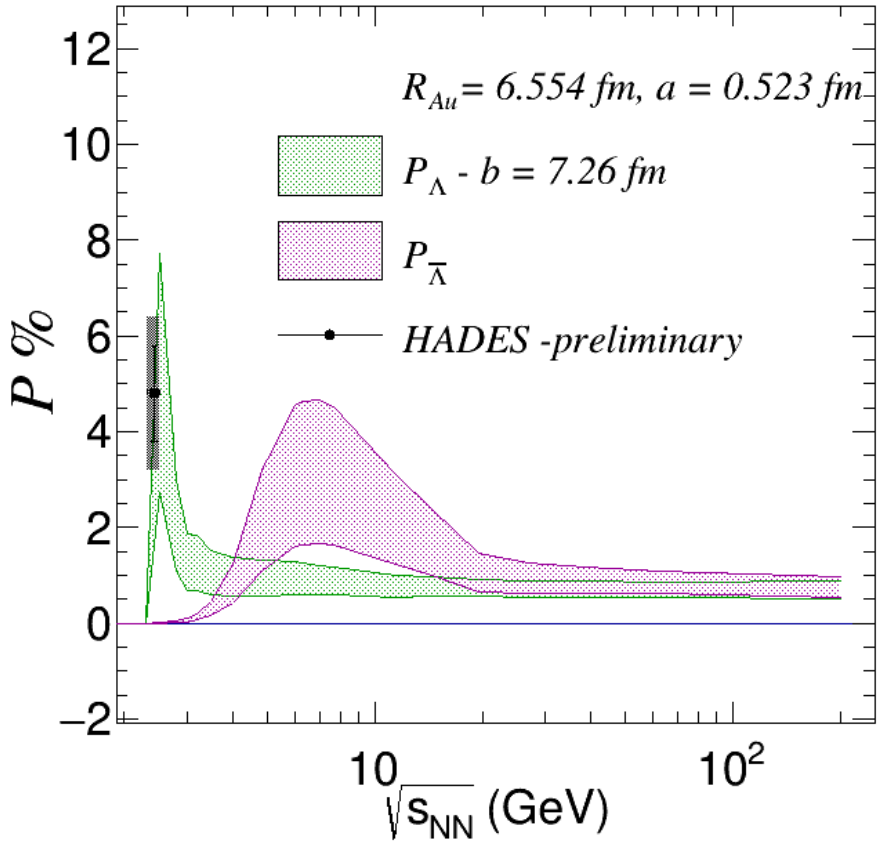


Λ, $\bar{\Lambda}$ global polarization Au+Au: STAR-BES



Λ, $\bar{\Lambda}$ global polarization Au+Au: HADES (Fit1 & Fit2)





Conclusions

- Two component source explains the excitation function of Λ and $\overline{\Lambda}$ polarization.
- **Essential ingredient:** behaviour of

$$N_{\Lambda\ \mathrm{QGP}}/N_{\Lambda\ \mathrm{REC}}$$

  with collision energy
- **Intrinsic** Λ and $\overline{\Lambda}$ polarization from field theoretical calculation of quark self-energy in a thermal QCD medium with an effective coupling between thermal vorticity and spin can be used to compute the relaxation times and from these the intrinsic polarizations.
- **Different global polarizations** for Λ and $\overline{\Lambda}$ can be obtained, a feature not usually found with other approaches.
- Model predicts maxima of the polarization excitation functions at HADES-NICA energies.

¡GRACIAS!