Lambda polarization from RHIC BES to LHC energies in viscous hydrodynamic approach

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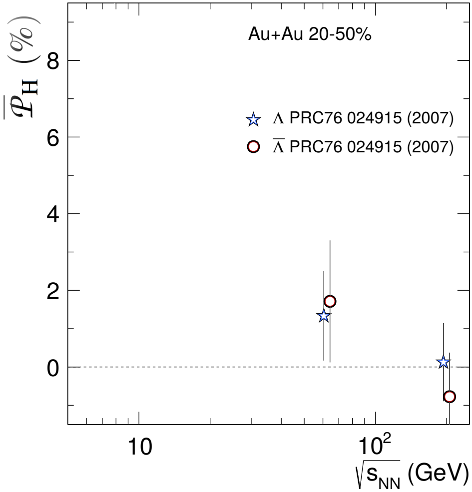
IK, F. Becattini, Eur. Phys. J. C 77, 213 (2017)
F. Becattini, IK, M. Lisa, I. Upsal, S. Voloshin, Phys. Rev. C 95, 054902 (2017)
F. Becattini, IK, Phys. Rev. Lett. 120, 012302 (2018)

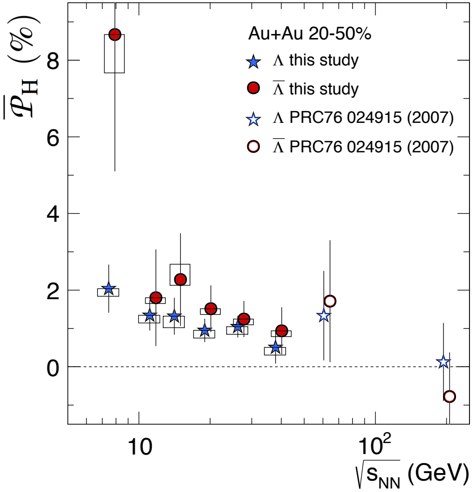
Highlight: recent Λ polarization measurement

B. I. Abelev et al. (STAR Collaboration), Phys. Rev. C 76, 024915 **(2007)**



Highlight: recent Λ polarization measurement

extending to full BES: STAR Collaboration, `arXiv:1701.06657`



"First clear positive signal of global polarization in heavy ion collisions!"

Theory side: polarization of fermions from the fluid

F. Becattini, V. Chandra, L. Del Zanna, E. Grossi, Ann. Phys. 338 (2013) 32

Also: Ren-hong Fang, Long-gang Pang, Qun Wang, Xin-nian Wang, Phys. Rev. C 94 (2016), 024904

Mechanism: spin-vorticity coupling at local thermodynamic equilibrium.

- Cooper-Frye prescription: $p^0 \frac{d^3N}{d^3p} = \int d\Sigma_\lambda p^\lambda \frac{1}{\exp\left(\frac{p\cdot u-\mu}{T}\right)\pm 1}$
- For the spin $\frac{1}{2}$ particles produced at the particlization surface:

$$\langle S(x,p)\rangle = \frac{1}{8m}(1-f(x,p))\varepsilon^{\mu\nu\rho\sigma}p_\sigma\partial_\nu\beta_\rho,$$

where $\beta_\mu = \frac{u_\mu}{T}$ is the inverse four-temperature field.

$$\boxed{S^\mu(p) = \frac{\int d\Sigma_\lambda p^\lambda f(x,p)\langle S(x,p)\rangle}{\int d\Sigma_\lambda p^\lambda f(x,p)}}$$

Polarization depends on the the thermal vorticity $\varpi_{\mu\nu} = -\frac{1}{2}(\partial_\mu\beta_\nu - \partial_\nu\beta_\mu)$.

- polarization is close or equal for particles and antiparticles
- caused not only by velocity, but also temperature gradients

Polarization calculations in hydro models (before 2016)

- F. Becattini, L.P. Csernai, D.J. Wang, Y.L. Xie,
  Phys. Rev. C 88, 034905 (2013)
  IC from Yang-Mills dynamics + 3D ideal hydro
  $\sqrt{s_{\rm NN}} = 200$ GeV Au-Au, $P_J \approx 3\%$
- F. Becattini, G. Inghirami et al., Euro Phys. J. C 75:406 (2015)
  Glauber IC + parametrized rapidity dependence
  $\sqrt{s_{\rm NN}} = 200$ GeV, $b = 11.6$ fm, $P_J \approx 0.2\%$
- Long-Gang Pang, Hannah Petersen, Qun Wang, Xin-Nian Wang,
  arXiv:1605.04024
  AMPT IC + 3D viscous hydro
  $\sqrt{s_{\rm NN}} = 62.4, 200, 2760$ GeV; P_J around few per mille (no exact value).
- +few other papers, where vorticity is visualized, but polarization is not.

All done for $\sqrt{s_{\rm NN}} = 62.4$ GeV and above!

What hydro picture gives us at lower collision energies, where preliminary measurements report essentially non-zero polarization?

The model: UrQMD + vHLLE (+ UrQMD)

Pre-thermal evolution: UrQMD cascade until $\tau = \tau_0 = const$, $\tau_0 = \frac{2R}{\gamma v_z}$
Fluctuating initial state, event-by-event hydrodynamics

Hydrodynamic phase:

$$\partial_{;\nu} T^{\mu\nu} = 0, \quad \partial_{;\nu} N^{\nu} = 0 \qquad < u^{\gamma} \partial_{;\gamma} \pi^{\mu\nu} > = -\frac{\pi^{\mu\nu} - \pi^{\mu\nu}_{\text{NS}}}{\tau_\pi} - \frac{4}{3} \pi^{\mu\nu} \partial_{;\gamma} u^{\gamma}$$

* Bulk viscosity $\zeta = 0$, charge diffusion=0
vHLLE code: free and open source. Comput. Phys. Commun. 185 (2014), 3016
https://github.com/yukarpenko/vhlle

Fluid→particle transition and hadronic phase

Cooper-Frye prescription at $\varepsilon = \varepsilon_{\text{sw}}$:

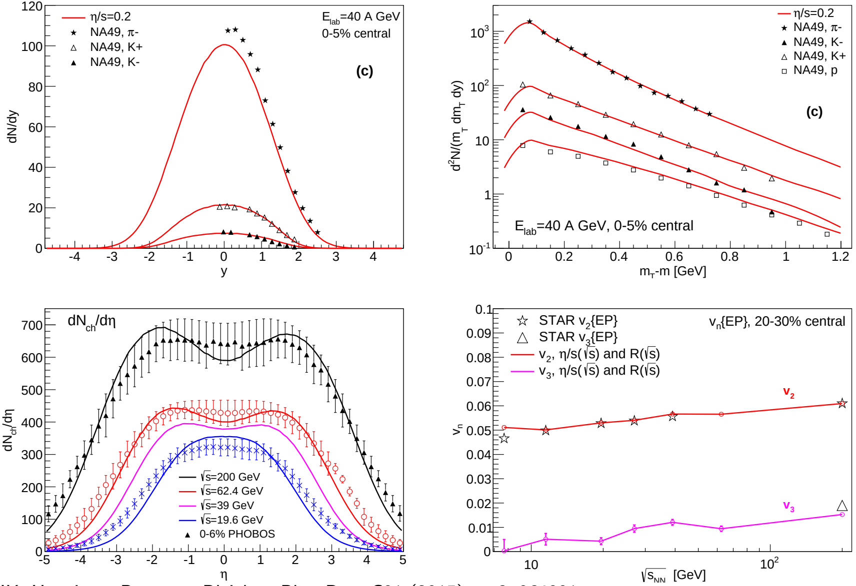
$$p^0 \frac{d^3 n_i}{d^3 p} = \sum f(x,p) p^{\mu} \Delta\sigma_{\mu}$$

$$f(x,p) = f_{\text{eq}} \cdot \left(1 + (1 \mp f_{\text{eq}}) \frac{p_\mu p_\nu \pi^{\mu\nu}}{2T^2(\varepsilon + p)} \right)$$

- $\Delta\sigma_i$ using Cornelius subroutine*
- Hadron gas phase: back to UrQMD cascade

*Huovinen and Petersen, *Eur.Phys.J.* A **48** (2012), 171

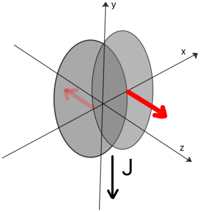
Validating the model for bulk hadronic observables



IK, Huovinen, Petersen, Bleicher, Phys.Rev. C91 (2015) no.6, 064901

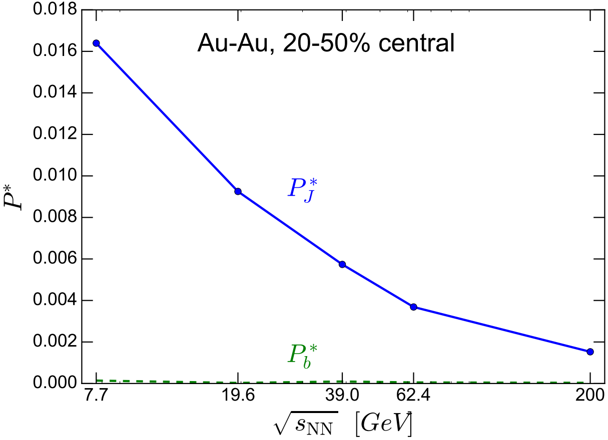
Λ polarization signal from the model

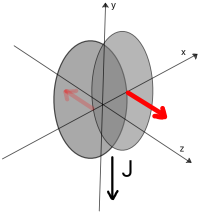
geometry sketch:



Collision energy dependence

P_J: mean polarization of Λ along the angular momentum of the system.





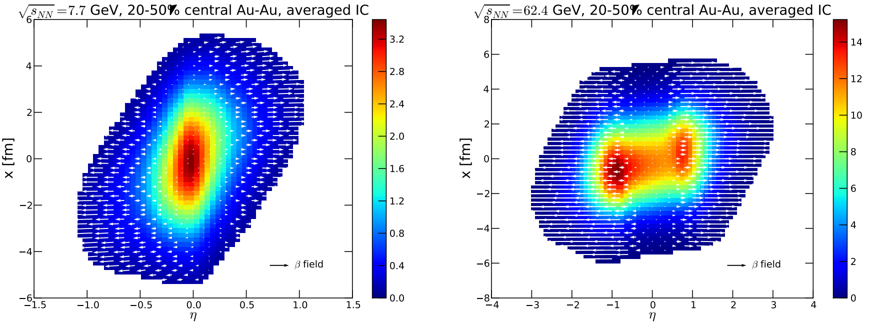
$$P_J \iff \varpi_{xz} \quad (\Omega_J)$$

Why does P_J increase at lower BES energies?

1) Different initial vorticity distribution:

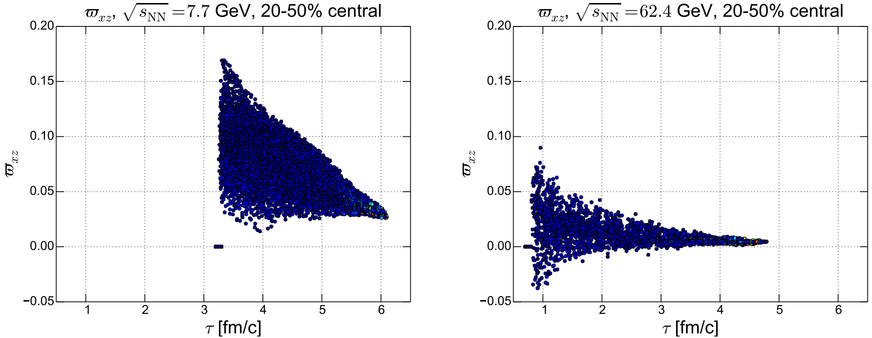
baryon stopping at lower $\sqrt{s_{\rm NN}}$
$\Downarrow$
shear flow in beam direction

transparency at higher $\sqrt{s_{\rm NN}}$



Why does P_J increase at lower BES energies?

2) Longer hydrodynamic evolution at higher $\sqrt{s_{\rm NN}}$ further dilutes the vorticity



Figs: Distribution of xz component of thermal vorticity (responsible for P_J at $p_x = p_y = 0$) over particlization hypersurface.

- these two effects result in lower polarization at higher collision energies

Interactions in the post-hydro stage

F. Becattini, IK, M. Lisa, I. Upsal, S. Voloshin, Phys. Rev. C 95, 054902 (2017)

Only about 25% of Λ are thermal ones! The rest is coming from resonance decays.

Spin (polarization) transfer in two-body resonance decay: $\mathbf{S}^*_{\Lambda,\Sigma^0} = C_{X\to\Lambda,\Sigma^0} \cdot \mathbf{S}^*_X$

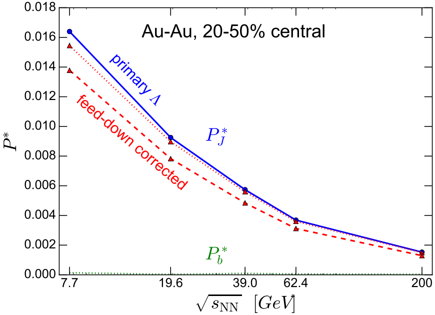
Direct $X \to \Lambda$ and two-step $X \to \Sigma^0 \to \Lambda$ decays are taken into account.

$$\mathbf{S}^*_\Lambda = \frac{N_\Lambda \mathbf{S}^*_{\Lambda,\text{prim}} + \sum_X N_X \mathbf{S}^*_\mathbf{X}\left[C_{X\to\Lambda} b_{X\to\Lambda} - \frac{1}{3} C_{X\to\Sigma^0} b_{X\to\Sigma^0}\right]}{N_\Lambda + \sum_X b_{X\to\Lambda} N_X + \sum_X b_{X\to\Sigma^0} N_X}$$

X	J^P	$\frac{\mathbf{S}_X}{\mathbf{S}_{\Lambda,\text{prim}}}$	$C_{X\to\Lambda,\Sigma^0}$	$\frac{\mathbf{S}_{\Lambda(X)}}{\mathbf{S}_{\Lambda,\text{prim}}}$
Σ^0	$(1/2)^+$	1	$-1/3$	$-1/3$
$\Sigma(1385)$	$(3/2)^+$	5	$1/3$	$5/3$
$\Lambda(1405)$	$(1/2)^-$	1	1	1
$\Lambda(1520)$	$(3/2)^-$	5	$-1/5$	-1
$\Lambda(1600)$	$(1/2)^+$	1	$-1/3$	$-1/3$
$\Sigma(1660)$	$(1/2)^+$	1	$-1/3$	$-1/3$
$\Sigma(1670)$	$(3/2)^-$	5	$-1/5$	-1

Dotted: primary+Σ^0+$\Sigma(1385)$

Dashed: primary+$\Sigma^0+\cdots+\Sigma(1670)$

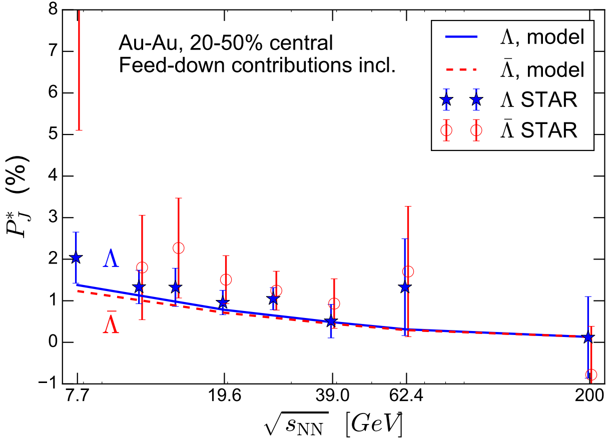


Overall feed-down effect: 15% suppression.

What is not taken into account (yet):

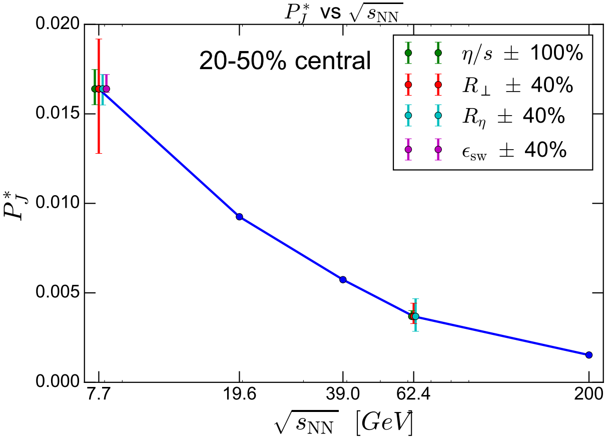
- Λ and Σ^0 actively rescatter in hadronic phase $\to$ expected to suppress polarization

Λ and $\bar{\Lambda}$: UrQMD+vHLLE vs experiment



- Λ within experimentan error bars.
- Much smaller and opposite sign $\bar{\Lambda}$-Λ splitting. Only $\mu_{\rm B}$ effect in the model, and it is small.
- MHD interpretation: vorticity creates the average $\Lambda+\bar{\Lambda}$, magnetic field makes the splitting.
- Magnetic field at particlization?

Sensitivity to parameters of the model



Initial state:
$R_\perp$: transverse granularity
R_η: longitudinal granularity

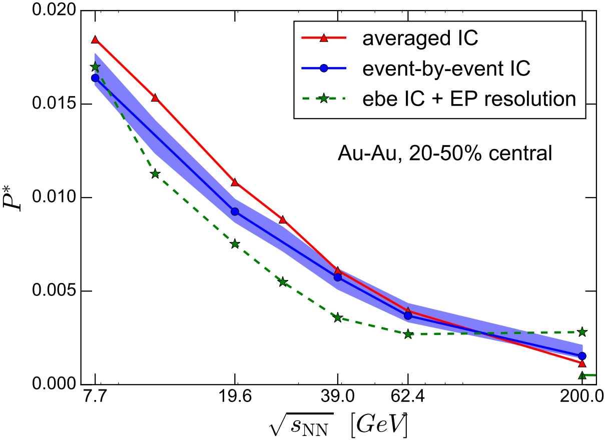
Fluid phase:
η/s: shear viscosity of fluid

Particlization criterion:
$\varepsilon_{\rm sw} = 0.5$ GeV/fm^3

Collision energy dependence is robust with respect to variation of the parameters of the model.

Event-by-event versus single-shot hydro

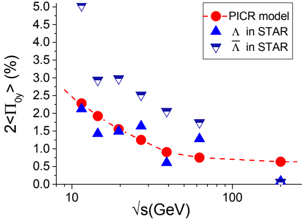
NEW



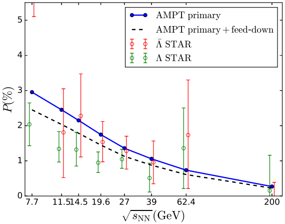
no big difference between event-by-event and single shot hydrodynamic description

Same $P(\sqrt{s_{NN}})$ trend in other hydro and non-hydro models

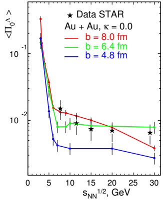
- Y.L. Xie, D.J. Wang, L.P. Csernai, Phys. Rev. C 95, 031901 (2017)



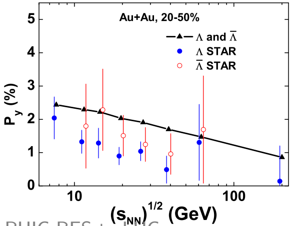
- Hui Li, Long-Gang Pang, Qun Wang, Xiao-Liang Xia, PRC 96, 054908



- M. Baznat, K. Gudima, A. Sorin, O. Teryaev, arXiv:1701.00923

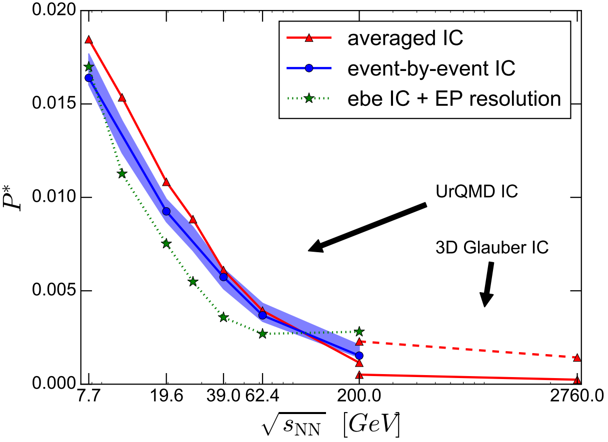


- Yifeng Sun, Che Ming Ko, Phys. Rev. C 96, 024906 (2017)



Extension to 2.76 TeV LHC

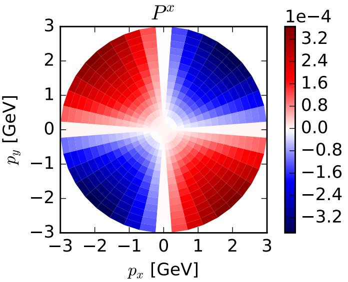
NEW

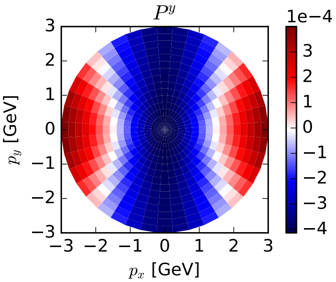


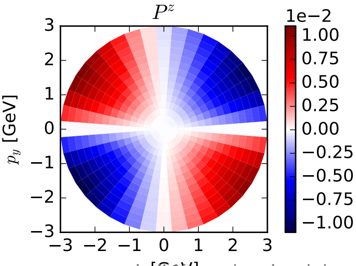
Mean polarization further decreases towards 2.76 TeV LHC energy.

At high energies, the dominant component is P^z

20-50% central Pb-Pb, $s_{\mathrm{NN}} = 2.76$ GeV





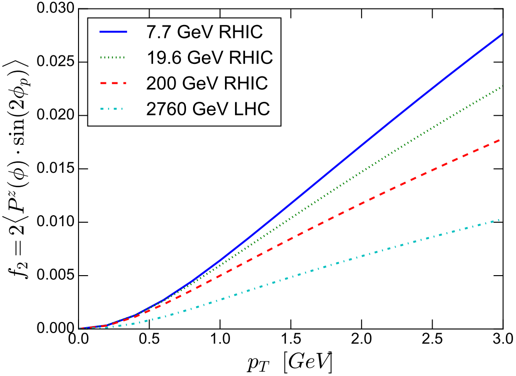


P^z is:

- nonzero in 2D boost-invariant hydrodynamics
- related to transverse expansion

A Fourier expansion for P^z

$$P^z(\mathbf{p_T}, y=0) = \sum_{k=1}^{\infty} f_{2k}(p_T) \sin 2k(\phi_p - \Psi)$$



- requires identification of event plane Ψ
- Blast-Wave model:

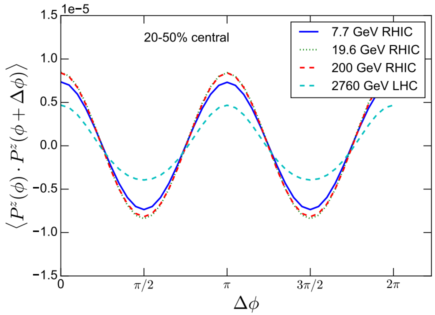
$$\boxed{f_2(p_T) = 2 \frac{dT}{d\tau} \frac{1}{mT} v_2(p_T)}$$

P^z emerges because of anisotropic transverse expansion, same way as v_2.

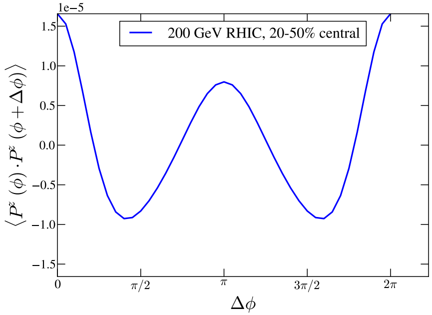
This can be also accessed via correlation of P^z of Λ pairs

$$P^z = P_0^z \sin 2(\phi - \Psi) \quad \Rightarrow \quad \langle P^z(\phi) P^z(\phi + \Delta\phi) \rangle = \frac{1}{2}(P_0^z)^2 \cos 2\Delta\phi$$

single-shot hydro



event-by-event hydro



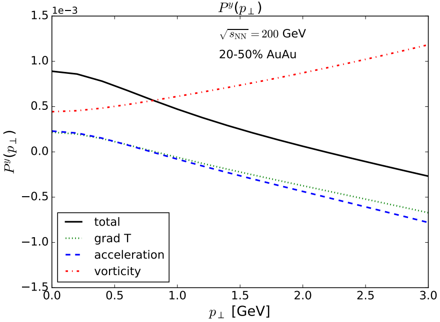
Similar results: Long-Gang Pang et al, Phys.Rev.Lett. 117 (2016) no.19, 192301
Λ spin correlations due to vorticity induced by initial state fluctuations

What causes transverse and longitudinal components of polarization?

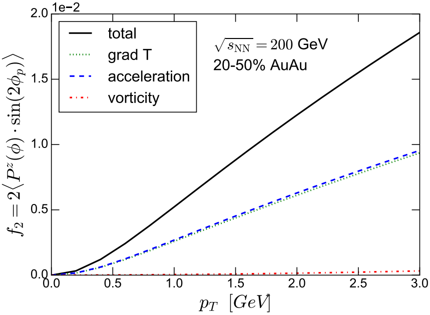
$$S^\mu \propto \varepsilon^{\mu\rho\sigma\tau}\varpi_{\rho\sigma}p_\tau = \varepsilon^{\mu\rho\sigma\tau}(\partial_\rho\beta_\sigma)p_\tau =$$

$$\underbrace{\varepsilon^{\mu\rho\sigma\tau}p_\tau\partial_\rho\left(\frac{1}{T}\right)u_\sigma}_{\text{grad}T} + \underbrace{\frac{1}{T}2\left[\omega^\mu(u\cdot p)-u^\mu(\omega\cdot p)\right]}_{\text{“NR vorticity”}} + \underbrace{\varepsilon^{\mu\rho\sigma\tau}p_\tau A_\sigma u_\rho}_{\text{acceleration}}$$

Global transverse P_J:



Longitudinal quadrupole f_2:

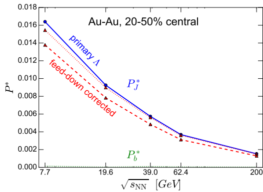


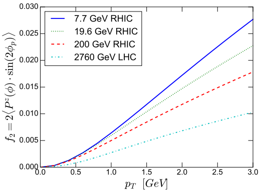
- P^J at low $p_\perp$ is dominated by vorticity
- P^z is dominated by acceleration and gradients of temperature

Summary

Λ polarization is calculated in UrQMD + 3D EbE viscous hydro model for $\sqrt{s_{NN}} = 7.7 \dots 200$ GeV A+A collisions, extended with Glauber + 3D viscous hydro for $\sqrt{s_{NN}} = 2760$ GeV LHC.

- We observe a strong increase of global mean polarization of Λ along the angular momentum direction towards lowest RHIC BES energies.
- The calculated *mean* Λ polarization is (almost) within the experimental error bars.
- Feed-down: $\approx 15\%$ suppression.
- At LHC energies, the largest component of polarization is P^z (along the beam axis), reaching 1% for $p_T = 3$ GeV Λ at midrapidity.
- $P^z(p_T)$ is a more generic effect, emerging in boost-invariant hydrodynamics due to anisotropy of transverse expansion (v_2). It probes velocity/temperature gradients at particlization surface.
- $P_J \Leftrightarrow$ vorticity(ϖ_{xz}), $P^z \Leftrightarrow$ transverse acceleration / grad T.





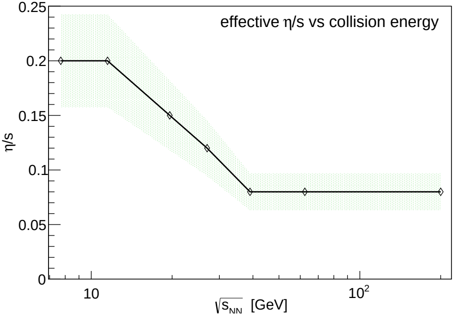
The end (so far)

Parameter values used to approach the basic hadronic observables

EoS: Chiral model, $\varepsilon_{\text{sw}} = 0.5$ GeV/fm^3.

$\sqrt{s}$ [GeV]	τ_0 [fm/c]	$R_\perp$ [fm]	R_z [fm]	η/s
7.7	3.2	1.4	0.5	0.2
8.8	2.83	1.4	0.5	0.2
11.5	2.1	1.4	0.5	0.2
17.3	1.42	1.4	0.5	0.15
19.6	1.22	1.4	0.5	0.15
27	1.0	1.2	0.5	0.12
39	0.9*	1.0	0.7	0.08
62.4	0.7*	1.0	0.7	0.08
200	0.4*	1.0	1.0	0.08

*here we increase τ_0 as compared to $\tau_0 = \frac{2R}{\gamma v_z}$.



Green band:
same v_2 and $\pm 5\%$ change in T_{eff}.

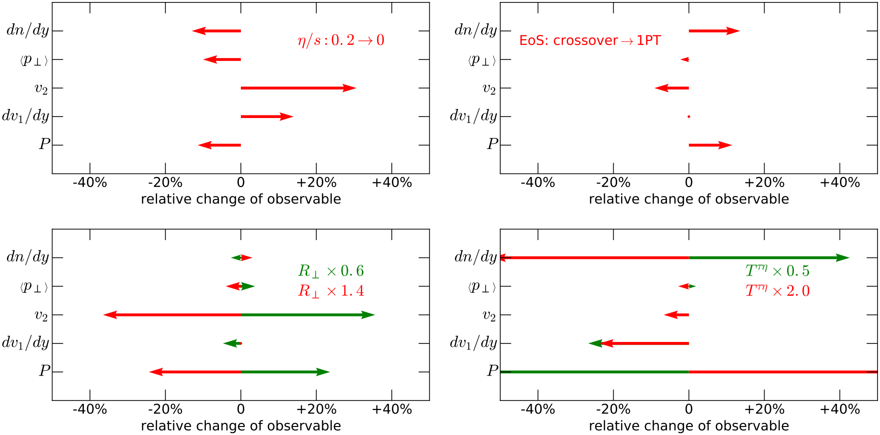
! Actual error bar would require a proper χ^2 fitting of the model parameters (and enormous amount of CPU time).

IK, Huovinen, Petersen, Bleicher, Phys.Rev. C91 (2015) no.6, 064901

A closer look at the parameter dependence

NEW

$\sqrt{s_{\rm NN}} = 7.7$ GeV



- Polarization observable is more sensitive to details of initial state rather than to details of hydro evolution.
- No sensitivity on the value of particlization energy density $\varepsilon_{\rm sw}$.