

Lambda polarization at the RHIC BES and beyond

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IK, F. Becattini, Eur. Phys. J. C 77, 213 (2017)

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

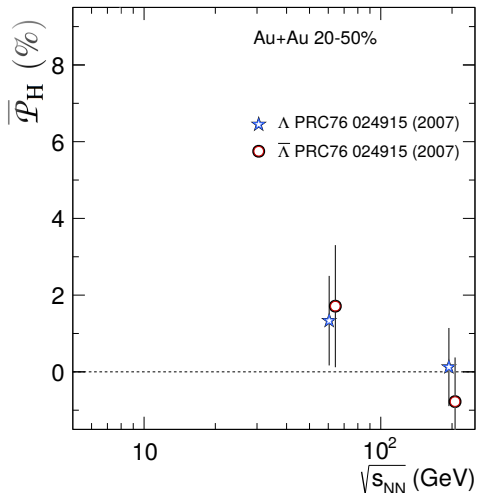
F. Becattini, IK, arXiv:1707.07984



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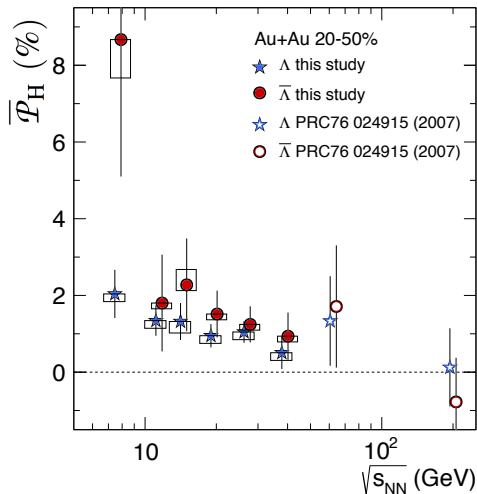
Highlight: recent Λ polarization measurement

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 in 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, ICTS-USTC-16-05, arXiv:1604.04036)

Mechanism: spin-vorticity coupling at local thermodynamic equilibrium.

For the spin $\frac{1}{2}$ particles produced at the particlization surface:

$$S^\mu(p) = \frac{1}{8m} \frac{\int d\Sigma_\lambda p^\lambda f(x, p) \cdot (1 - f(x, p)) \varepsilon^{\mu\nu\rho\sigma} p_\sigma \partial_\nu \beta_\rho}{\int d\Sigma_\lambda p^\lambda f(x, p)}$$

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

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

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

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

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

The model: UrQMD + vHLE (+ UrQMD)

Pre-thermal evolution: UrQMD cascade until $\tau = \tau_0 = \text{const}$, $\tau_0 = \frac{2R}{\gamma v_z}$

Fluctuating initial state, event-by-event hydrodynamics

Hydrodynamic phase:

$$\partial_{;v} T^{\mu\nu} = 0, \quad \partial_{;v} N^v = 0 \quad \langle u^\gamma \partial_{;v} \pi^{\mu\nu} \rangle = -\frac{\pi^{\mu\nu} - \pi_{NS}^{\mu\nu}}{\tau_\pi} - \frac{4}{3} \pi^{\mu\nu} \partial_{;v} u^\gamma$$

* Bulk viscosity $\zeta = 0$, charge diffusion=0

vHLE code: free and open source. *Comput. Phys. Commun.* 185 (2014), 3016

<https://github.com/yukarpenko/vhllc>

Fluid → particle transition and hadronic phase

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

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

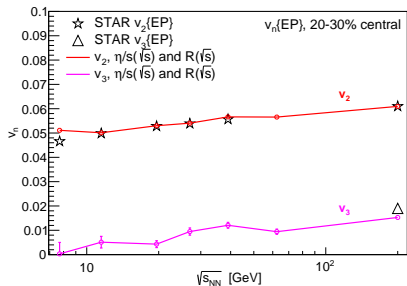
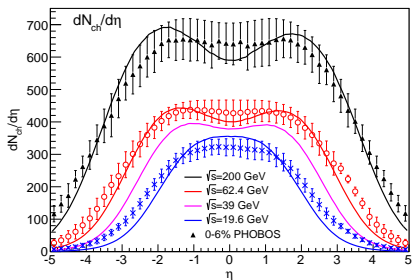
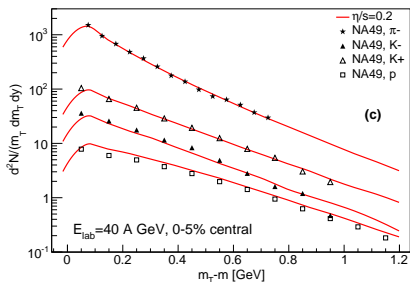
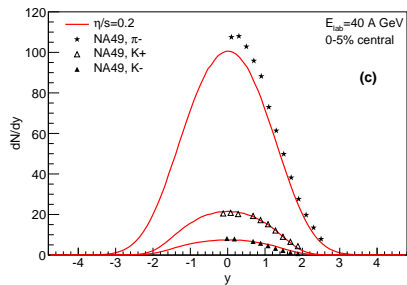
$$f(x, p) = f_{eq} \cdot \left(1 + (1 \mp f_{eq}) \frac{p_\mu p_\nu \pi^{\mu\nu}}{2T^2(\varepsilon + p)} \right)$$

• $\Delta \sigma_i$ using **Cornelius subroutine***

• Hadron gas phase: back to UrQMD cascade

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

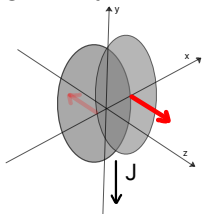
Validating the model for bulk hadronic observables



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

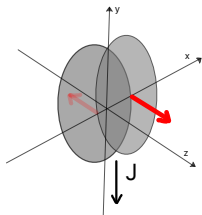
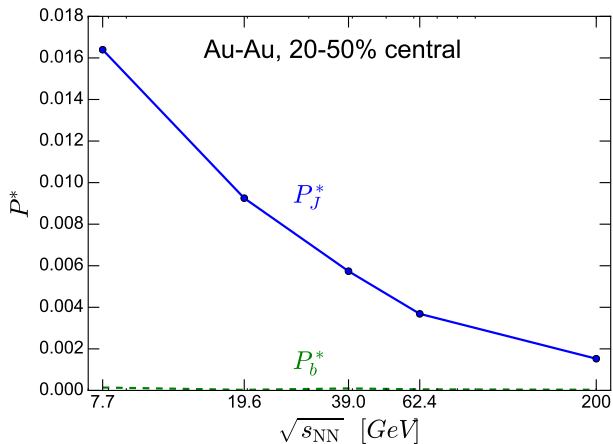
Λ polarization signal from the model

geometry sketch:



Collision energy dependence

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



$$P_J \iff \overline{\omega}_{xz} \quad (\Omega_J)$$

Why does P_J increase at lower BES energies?

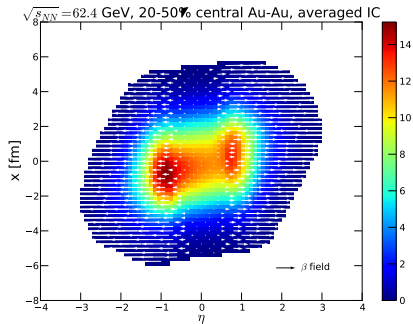
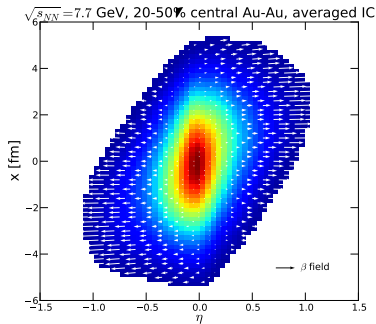
1) Different initial vorticity distribution:

baryon stopping at lower $\sqrt{s_{NN}}$



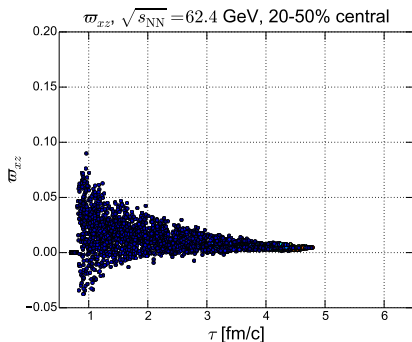
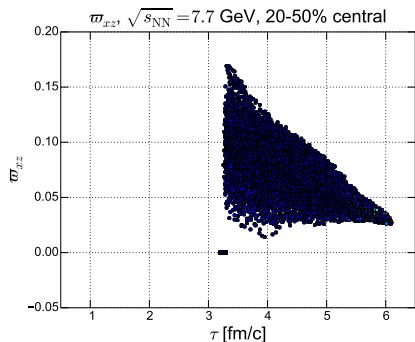
shear flow in beam direction

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



Why does P_J increase at lower BES energies?

2) Longer hydrodynamic evolution at higher $\sqrt{s_{NN}}$ 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. Uppsala, 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: $\mathbf{S}_{\Lambda, \Sigma^0}^* = C_{X \rightarrow \Lambda, \Sigma^0} \cdot \mathbf{S}_X^*$

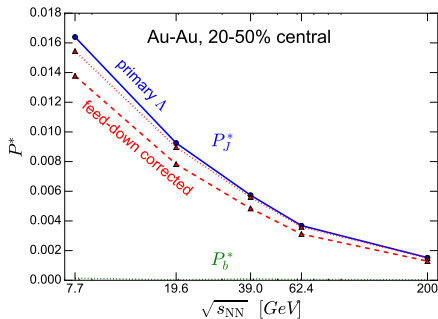
Direct $X \rightarrow \Lambda$ and two-step $X \rightarrow \Sigma^0 \rightarrow \Lambda$ decays are taken into account.

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

X	J^P	$\frac{S_X}{S_{\Lambda, \text{prim}}}$	$C_{X \rightarrow \Lambda, \Sigma^0}$	$\frac{S_{\Lambda(X)}}{S_{\Lambda, \text{prim}}}$
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 + $\Sigma^0 + \Sigma(1385)$

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

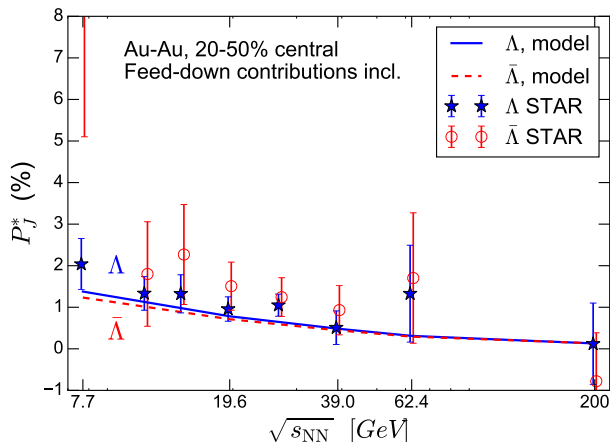


Overall feed-down effect: 15% suppression.

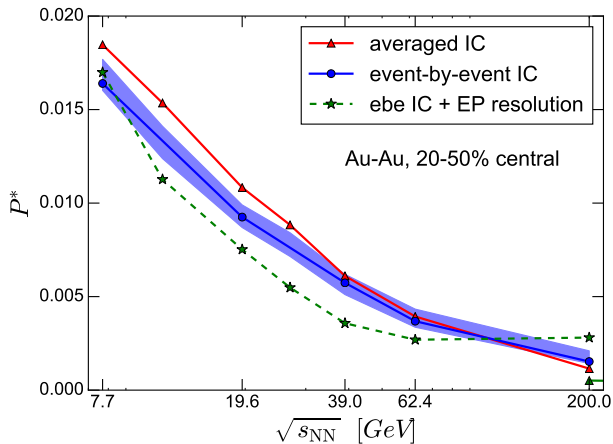
What is not taken into account (yet):

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

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



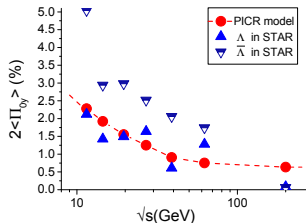
- Λ within experimental error bars.
- Much smaller and opposite sign $\bar{\Lambda}$ - Λ splitting. Only μ_B effect in the model, and it is small.
- MHD interpretation: vorticity creates the average $\Lambda + \bar{\Lambda}$, magnetic field makes the splitting.
- **Magnetic field at hadronization?**



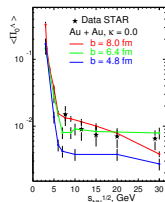
no big difference between event-by-event and single shot hydrodynamic description

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

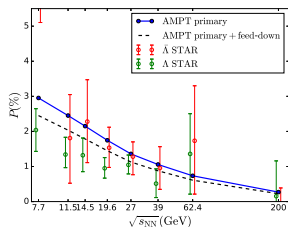
- Y.L. Xie, D.J. Wang, L.P. Csernai, Phys. Rev. C 95, 031901 (2017)



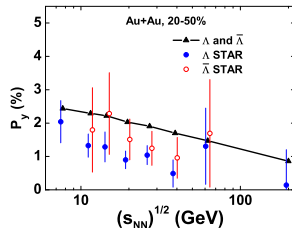
- M. Baznat, K. Gudima, A. Sorin, O. Teryaev, arXiv:1701.00923

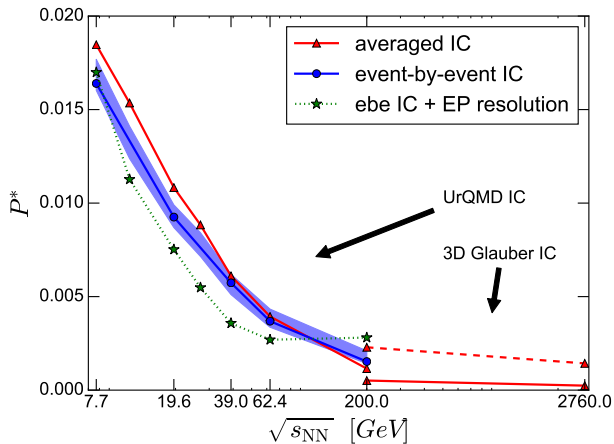


- Hui Li, Long-Gang Pang, Qun Wang, Xiao-Liang Xia, arXiv:1704.01507



- Yifeng Sun, Che Ming Ko, arXiv:1706.09467

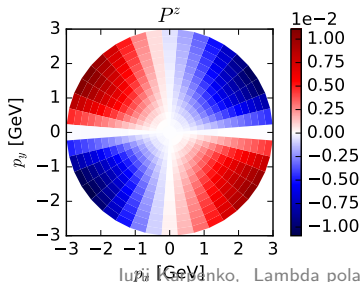
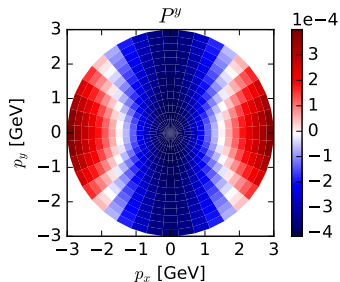
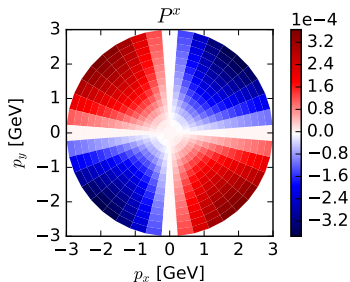




Mean polarization further decreases towards 2.76 TeV LHC energy.

At high energies, the dominant component is P^z

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

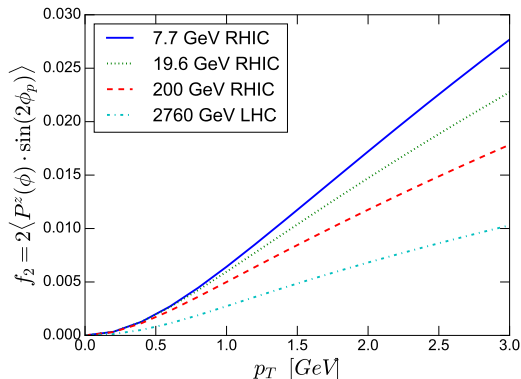


P^z is:

- 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:

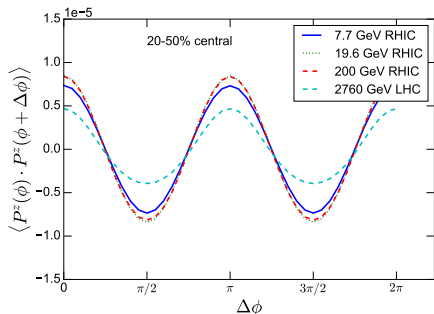
$$f_2(p_T) = 2 \frac{dT}{d\tau} \frac{1}{mT} v_2(p_T)$$

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

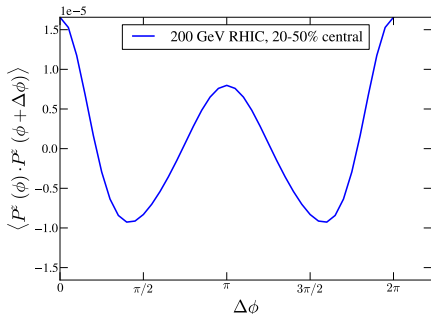
This can be also accessed via correlation of P^z of Λ pairs

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

single-shot hydro



event-by-event hydro



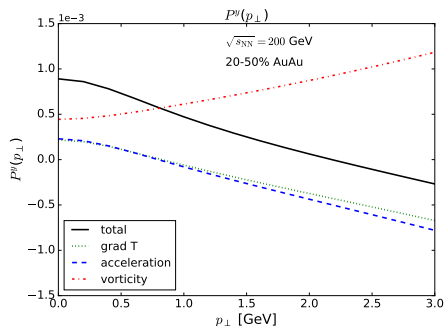
Similar results: Long-Gang Pang et al, Phys.Rev.Lett. 117 (2016) no.19, 192301
 Λ spin correlations due to vorticity induced by initial state fluctuations

What causes transverse and longitudinal components of polarization?

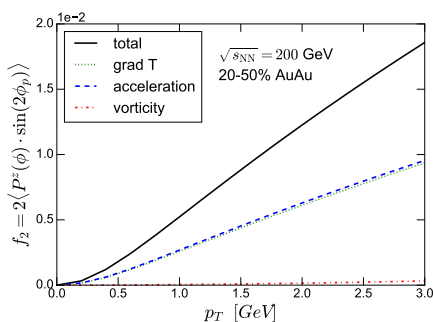
$$S^\mu \propto \varepsilon^{\mu\rho\sigma\tau} \bar{\omega}_{\rho\sigma} p_\tau = \varepsilon^{\mu\rho\sigma\tau} (\partial_\rho \beta_\sigma) p_\tau =$$

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

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

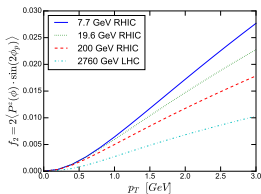
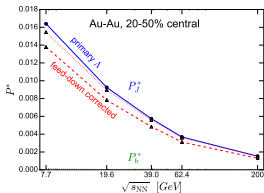
Summary

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($\bar{\omega}_{xz}$), $P^z \Leftrightarrow$ transverse acceleration / grad T .



The end (so far)

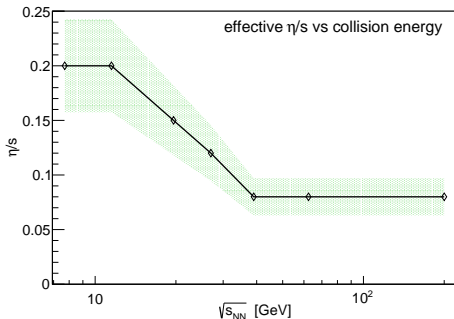
Parameter values used to approach the basic hadronic observables

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

\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

$$\tau_0 = \frac{2R}{\gamma_z}.$$



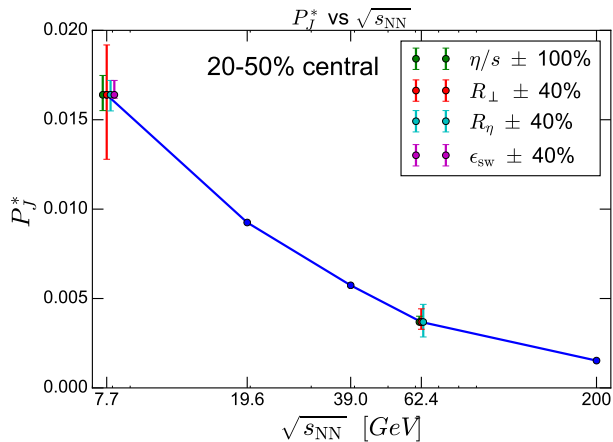
Green band:

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

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:

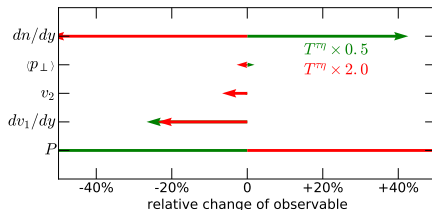
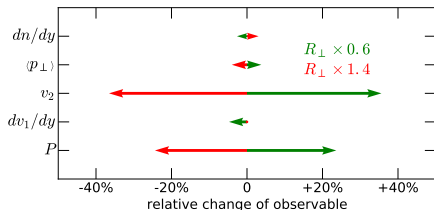
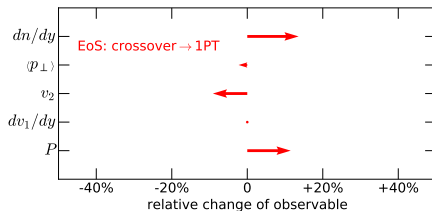
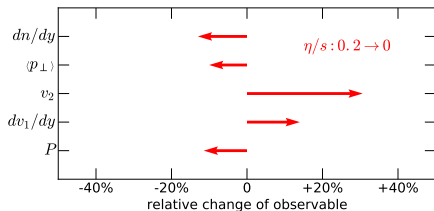
$\epsilon_{sw} = 0.5 \text{ GeV}/\text{fm}^3$

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

A closer look at the parameter dependence

NEW

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



- 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 ϵ_{sw} .