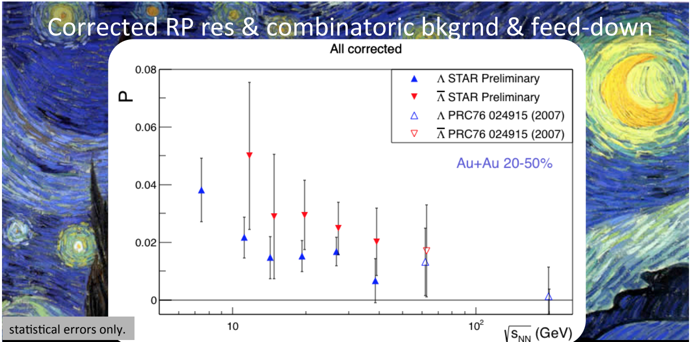
Vorticity in the QGP liquid and Lambda polarization at the RHIC BES energies

Iurii KARPENKO
with Francesco Becattini

Istituto Nazionale di Fisica Nucleare - sezione Firenze,
Universitá di Firenze

Highlight: recent Λ polarization measurement

Preliminary results from STAR, talk of M. Lisa at QCD Chirality Workshop 2016



- Subtracting residual effect from combinatoric background below mass peak
- Correcting for feed-down from Sigma0

$$\underbrace{\Sigma^0}_{\frac{1}{2}^+} \rightarrow \underbrace{\Lambda}_{\frac{1}{2}^+} + \underbrace{\gamma}_{1^-}$$

(p-wave decay)

- A significant fraction (~30%) of our Lambdas are actually feed-down from Sigma0
- The daughter Lambda tends to have spin direction opposite that of the parent Sigma

- previous STAR results (corrected for sign) continue systematics

How is it related to vorticity and angular momentum of the QGP liquid?

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)

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

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

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

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

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

Existing polarization calculations from hydro models

All for $\sqrt{s_{\mathrm{NN}}} \geq 62.4$ GeV.

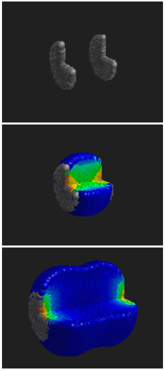
- F. Becattini, L.P. Csernai, D.J. Wang, and Y.L. Xie,
  Phys. Rev. C 88, 034905 (2013)
  IC from Yang-Mills dynamics + 3D ideal hydro
  $\sqrt{s_{\mathrm{NN}}} = 200$ GeV Au-Au, $P_J \approx 3\%$
- F. Becattini, G. Inghirami et al., Euro Phys. J. C 75:406 (2015)
  Glauber IC + parametrized rapidity dependence
  $\sqrt{s_{\mathrm{NN}}} = 200$ 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
  $\sqrt{s_{\mathrm{NN}}} = 62.4, 200, 2760$ GeV; P_J around few per mille.

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

Tool for investigation: cascade+hydro(+cascade) model for BES

Hybrid model: initial state + hydrodynamic phase + hadronic cascade

thermalization (initial state → hydrodynamic phase); particlization (hydrodynamic phase → hadronic cascade)



- Initial state: thick pancakes
  - boost ivariance is not a good approximation $\rightarrow$ need for 3 dimensional evolution
  - CGC picture does not work well either
- Event-by-event hydrodynamical treatment
- Baryon and electric charges
  - obtained from the initial state
  - included in hydro phase
  - taken into account at particlization

Pictures taken from: `https://www.jyu.fi/fysiikka/tutkimus/suurenergia/urhic`

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:

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

* 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 $\varepsilon = \varepsilon_{\rm sw}$:

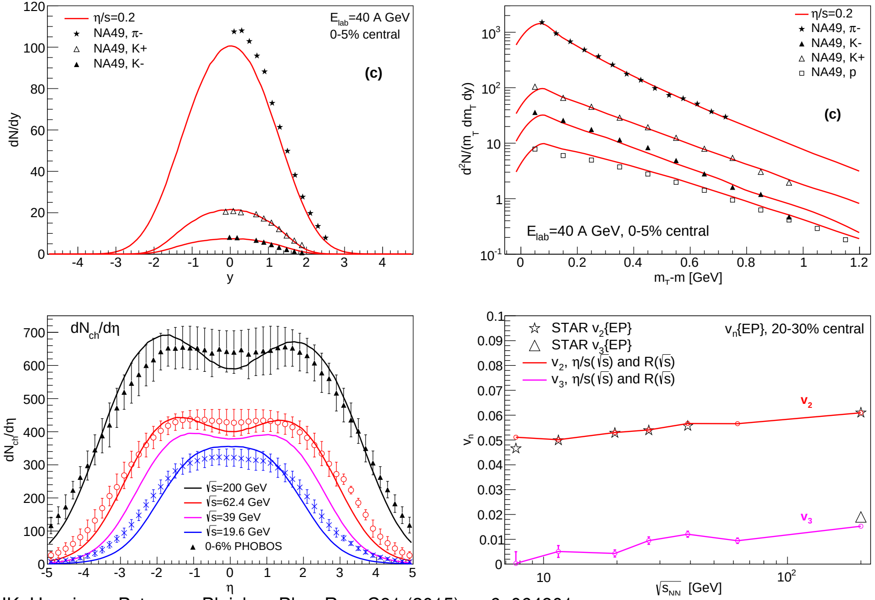
$$p^0 \frac{d^3 n_i}{d^3 p} = \sum f(x,p) p^{\mu} \Delta\sigma_{\mu}$$

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

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

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

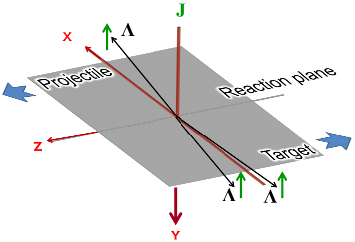
Validating the model for bulk hadronic observables



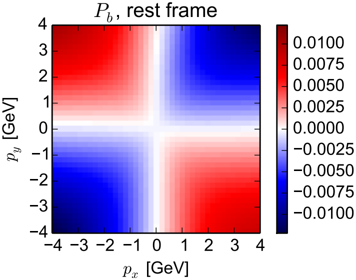
IK, Huovinen, Petersen, Bleicher, Phys.Rev. C91 (2015) no.6, 064901

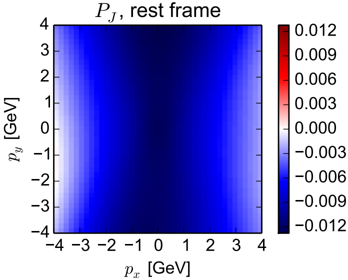
Λ polarization signal from the model

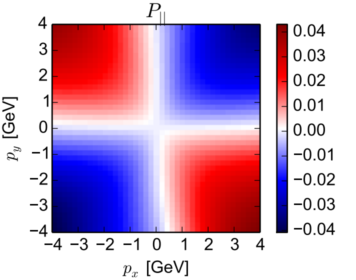
geometry sketch:



p_T differential polarization of Λ, $\sqrt{s_{\rm NN}} = 19.6$ GeV, 40-50% Au-Au





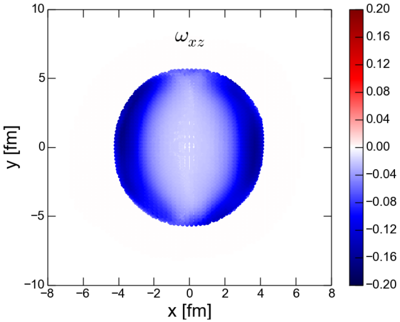


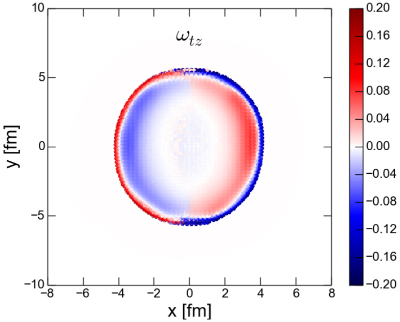
- only Λ produced at particlization
- $P_{||}$ is the largest component at large p_x and p_y
- P_b and $P_{||}$ average out to zero

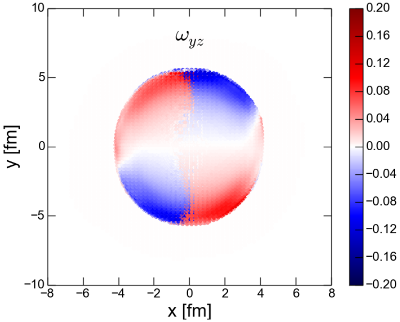
The quadrupole polarization patterns are induced by complex vorticity patterns at the particlization surface:

- $P_b \propto \omega_{tz} p_y$
- $P_J \propto \omega_{xz} p_0$

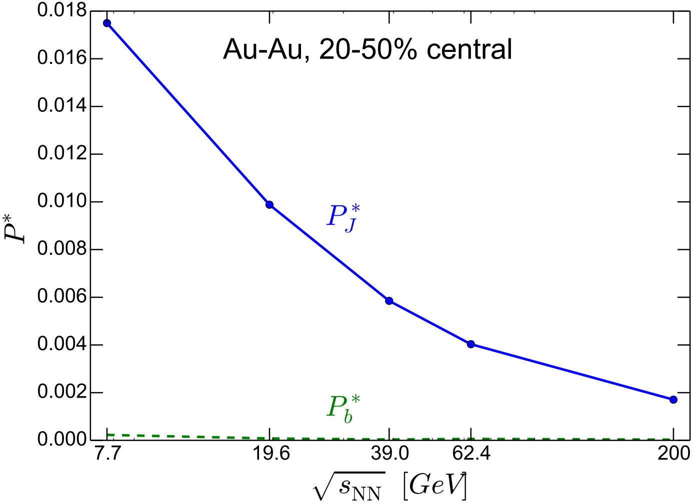
$$\omega_{\mu\nu} = -\frac{1}{2}(\partial_\mu \beta_\nu - \partial_\nu \beta_\mu)$$





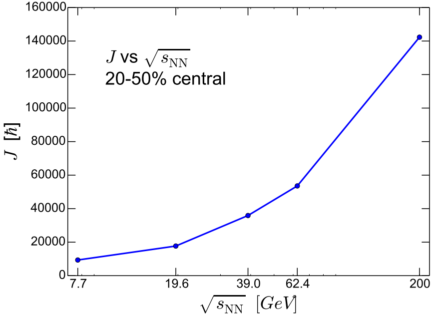


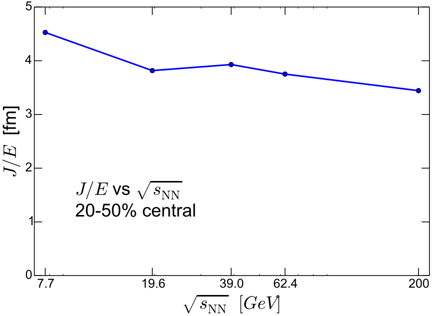
Collision energy dependence



Is it a manifestation of larger fireball angular momentum at lower $\sqrt{s_{NN}}$?

Not really: J_y actually increases with increase of $\sqrt{s_{\rm NN}}$.

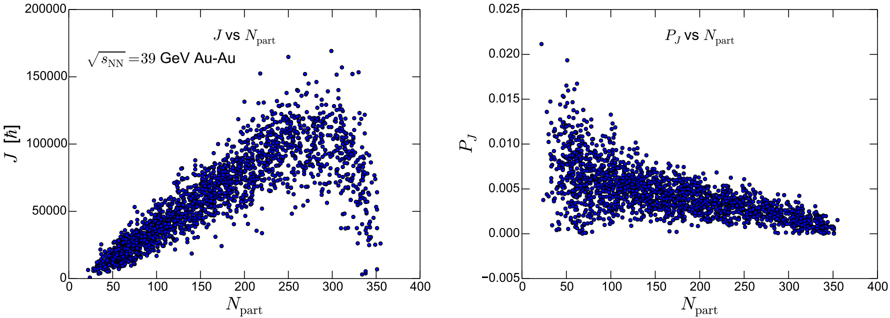




- Total angular momentum increases with increasing energy of the fireball.
- J_y/E shows weak dependence on $\sqrt{s_{\rm NN}}$.

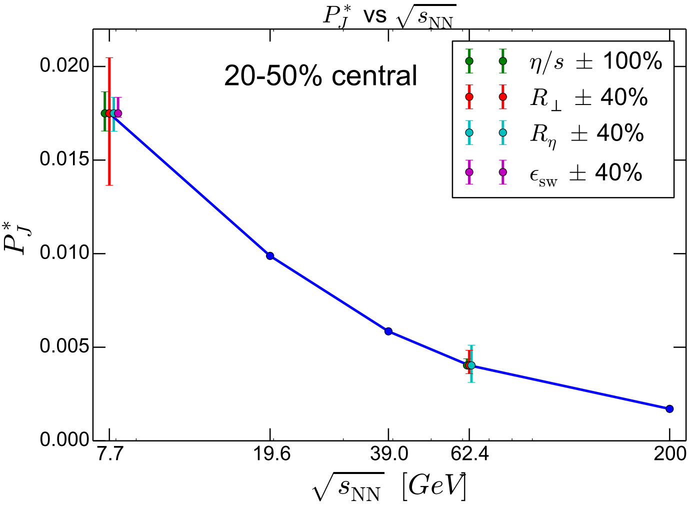
Centrality dependence

Simulation of $\sqrt{s_{\rm NN}} = 39$ GeV Au-Au, 0-50% central events:



Total angular momentum has a peak at a certain $N_{\rm part}$, whereas the polarization steadily increases towards low $N_{\rm part}$.

Sensitivity to parameters of the model



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

Why does P_J increase at lower BES energies?

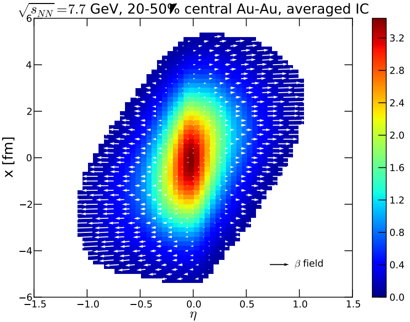
1) Different initial vorticity distribution:

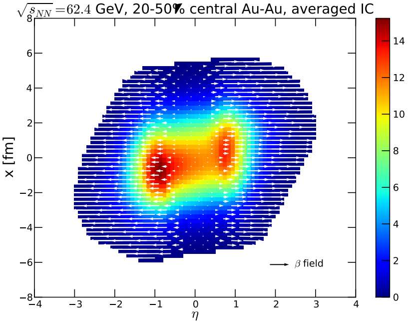
baryon stopping at lower $\sqrt{s_{\rm NN}}$

$\Downarrow$

shear flow in beam direction

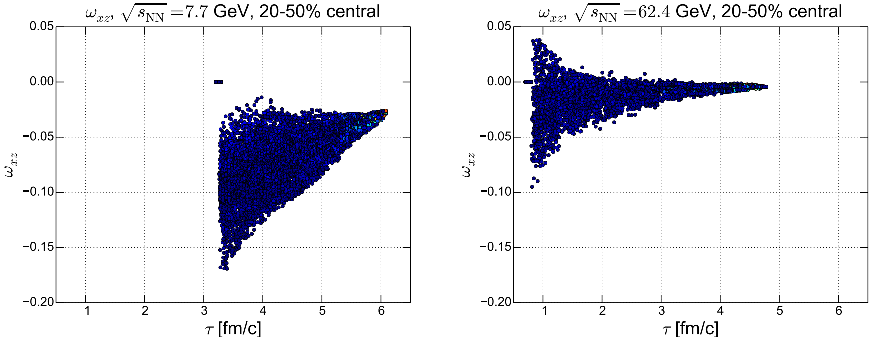
transparency at higher $\sqrt{s_{\rm NN}}$





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 vroticity (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 final state

- $\Sigma(1385)$ $3/2^+$ has a dominant (strong) decay mode $\Sigma(1385) \to \Lambda\pi$ (BR=87%)
- Decay of 100% polarized $\Sigma(1385) \to \Lambda\pi$ results in 55% polarized Λs:
  D. Ashery, H.J. Lipkin, Phys.Lett. B469 (1999) 263;
  arXiv:hep-ph/0002144
  But we do not know the polarization of thermal $\Sigma(1385)$ **yet!**
- Λ also actively rescatters in hadronic phase
- As a result, only about 10-15% of final Λ are the ones which are produced at the particlization surface and leave the system with no rescatterings.

Summary

Λ polarization is calculated in UrQMD + 3+1D EbE viscous hydro model for $\sqrt{s_{NN}} = 7.7 \ldots 200$ GeV A+A collisions.

Conclusions:

- We observe a strong increase of mean Λ polarization at lower RHIC BES energies.
- The P_J is at least twice smaller than the (preliminary) experimental value.
- The collision energy dependence is robust with respect to variation of model parameters.
- The polarization has a potential to rule out the initial state models, especially in the BES energies. Differently prepared initial states can result in same flow observables, but very different final Λ polarization.
- Feed-down from $\Sigma(1385)$ and hadronic rescattering effects on Λ polarization still have to be taken into account.

Thank you for your attention!

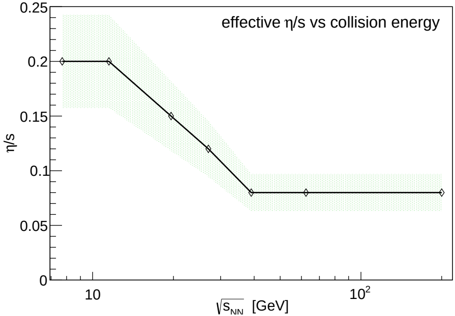
Backup slides

Parameter values used to approach the basic hadronic observables

EoS: Chiral model, $\varepsilon_{sw} = 0.5$ 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