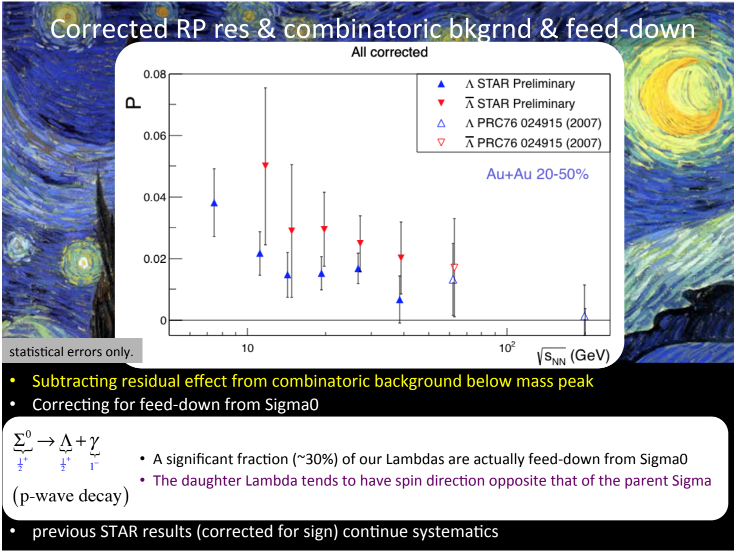
Vorticity in the QGP liquid and Lambda polarization at the RHIC BES energies

Iurii KARPENKO
with Francesco Becattini

Istituto Nazionale di Fisica Nucleare, sezione Firenze

Highlight: recent Λ polarization measurement

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



Corrected RP res & combinatoric bkgrnd & feed-down

statistical errors only.

- 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

This measurement can be realized because of “self-analyzing” nature of Λ decay, which preferentially emits daugter proton in the direction of Λ spin:

$$\frac{dW}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha P \cos\theta^*)$$

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:

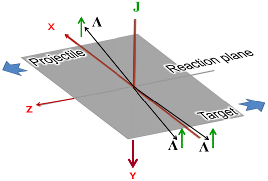
$$\Pi^{\mu}(p) = \frac{1}{8m} \frac{\int d\Sigma_{\lambda} p^{\lambda} f(x,p) \cdot (1 - f(x,p)) \varepsilon^{\mu\nu\rho\sigma} p_{\sigma} \partial_{\nu} \beta_{\sigma}}{\int d\Sigma_{\lambda} p^{\lambda} f(x,p)}$$

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

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

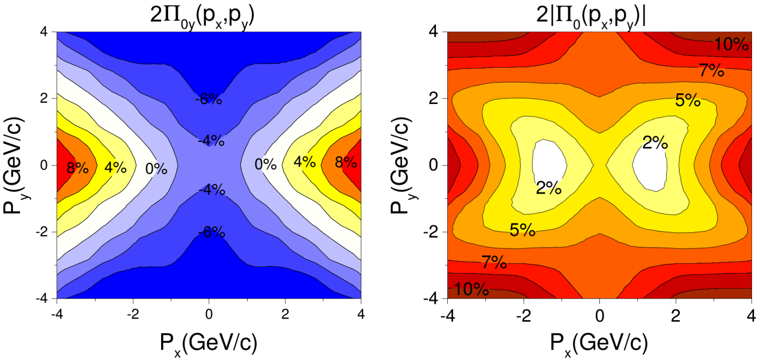
- polarization is equal for particles and antiparticles
- caused not only by velocity, but also temperature gradients

Existing polarization calculations from hydro models (1)



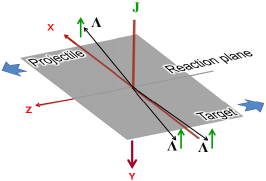
F. Becattini, L.P. Csernai, D.J. Wang, and Y.L. Xie,
Phys. Rev. C 88, 034905 (2013)
$\sqrt{s_{\rm NN}} = 200$ GeV, midrapidity Λ

Initial state from Yang-Mills dynamics + 3D ideal hydro expansion



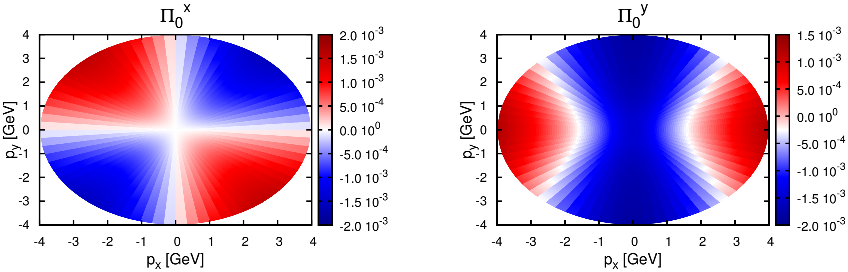
P^y on the order of few % even at $p_x = p_y = 0$ and up to 8% (with opposite sign) for high p_x!

Existing polarization calculations from hydro models (2)



F. Becattini, G. Inghirami et al., Euro Phys. J. C 75:406 (2015)
$\sqrt{s_{\rm NN}} = 200$ GeV, $b = 11.6$ fm, midrapidity Λ

Obtained with optical Glauber IC + parametrized rapidity dependence a-lá P. Bozek and I. Wyskiel, Phys. Rev. C 81 (2010) 054902

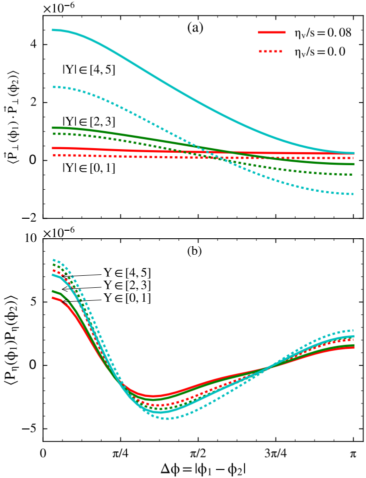


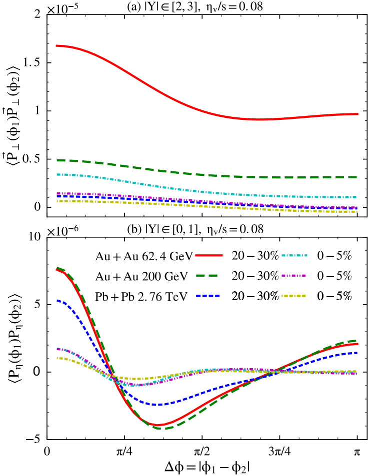
Momentum integrated P^x and P^z average out to zero, and $P^y \approx -0.4\%$.

Existing polarization calculations from hydro models (3)

Long-Gang Pang, Hannah Petersen, Qun Wang, Xin-Nian Wang, arXiv:1605.04024

Initial state from AMPT + 3D viscous hydro





Intermediate summary:

- Most of the results are calculated in hydro models for $\sqrt{s_{\mathrm{NN}}} = 200$ GeV RHIC energy, where STAR only obtained an upper limit $|P| < 0.02$ [1].
- First two results (with differently constructed initial conditions) have almost 1 order of magnitude difference, but both within STAR limits.

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

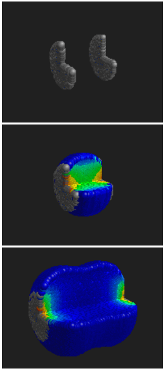
---

[1] STAR Collaboration, Phys.Rev. C 76, 024915 (2007)

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

Hybrid model: initial state + hydrodynamic phase + hadronic cascade

thermalization particlization

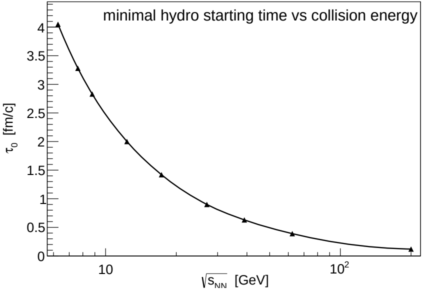


- Initial state: thick pancakes
  - boost ivariance is not a good approximation → need for 3 dimensional evolution
  - CGC picture does not work well either
- Event-by-event hydrodynamical treatment
- Baryon and electric charges
  - obtained from the initial state
  - included in hydro phase
  - taken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

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

Initial (pre-thermal) stage

- pre-thermal evolution: UrQMD cascade
- scatterings allowed until $\sqrt{t^2 - z^2} = \tau_0$
- minimal starting time is $\tau_0 = \frac{2R}{\gamma v_z}$

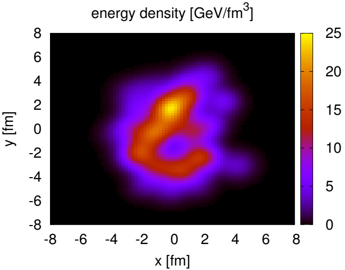


“Thermalization”

At $\tau = \tau_0$ the energy/momentum P^α, baryon and electric charges N^0 of every particle are deposited into fluid cells according to:

$$\Delta P^\alpha_{ijk} = P^\alpha \cdot C \cdot \exp\left(-(\Delta x_i^2 + \Delta y_j^2)/R_\perp^2 - \Delta\eta_k^2 \gamma_\eta^2 \tau_0^2 / R_\eta^2\right)$$

$$\Delta N^0_{ijk} = N^0 \cdot C \cdot \exp\left(-(\Delta x_i^2 + \Delta y_j^2)/R_\perp^2 - \Delta\eta_k^2 \gamma_\eta^2 \tau_0^2 / R_\eta^2\right)$$



Hydrodynamic stage

The hydrodynamic equations:

$$\partial_{;\nu} T^{\mu\nu} = 0, \quad \partial_{;\nu} N^{\nu} = 0$$

Evolution equations for shear/bulk, coming from Israel-Stewart formalism:

$$< u^{\gamma} \partial_{;\gamma} \pi^{\mu\nu} > = -\frac{\pi^{\mu\nu} - \pi^{\mu\nu}_{\text{NS}}}{\tau_{\pi}} - \frac{4}{3} \pi^{\mu\nu} \partial_{;\gamma} u^{\gamma}$$

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

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

`https://github.com/yukarpenko/vhlle` See poster #0814/**74**

Fluid→particle transition and hadronic phase

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

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

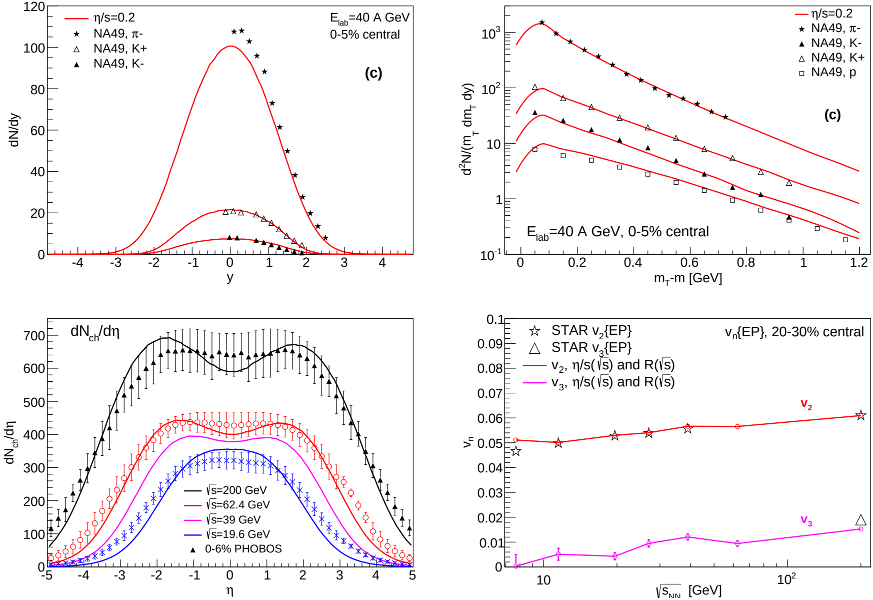
$$f(x,p) = f_{\text{eq}} \cdot \left(1 + (1 \mp f_{\text{eq}}) \frac{p_{\mu} p_{\nu} \pi^{\mu\nu}}{2T^2(\varepsilon + p)} \right)$$

- $\Delta\sigma_i$ 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

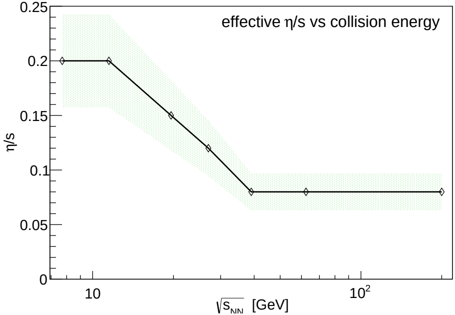


Parameter values used to approach the data

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 $\tau_0 = \frac{2R}{\gamma v_z}$.



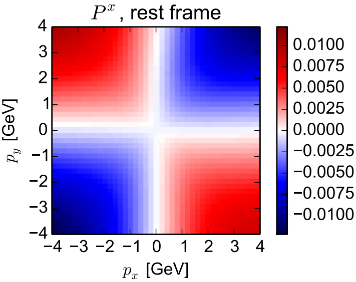
Green band:
same v_2 and ±5% change in $T_{\rm eff}$.

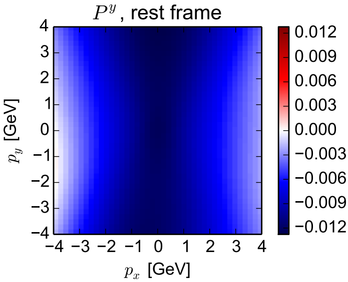
! Actual error bar would require a proper χ^2 fitting of the model parameters (and enormous amount of CPU time).

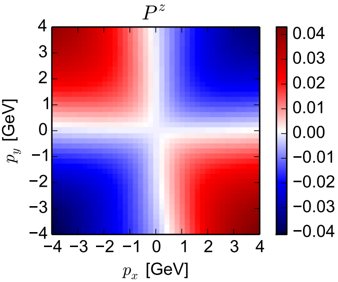
IK, Huovinen, Petersen, Bleicher, Phys.Rev. C91 (2015) no.6, 064901

Λ polarization signal from the model

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

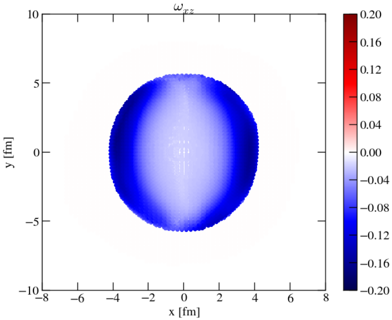


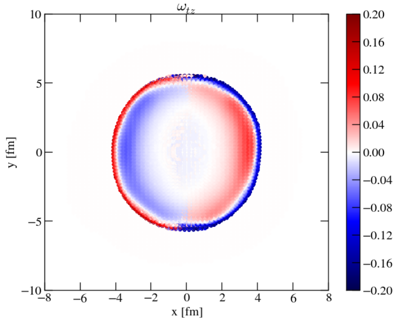


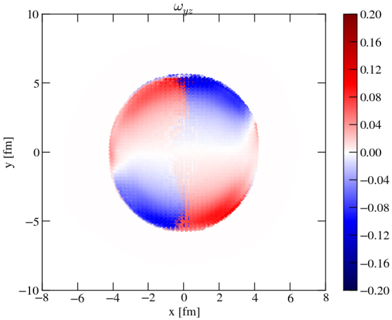


- only Λ produced at particlization
- P^z is the largest component at large p_x and p_y
- P^x and P^z average out to zero

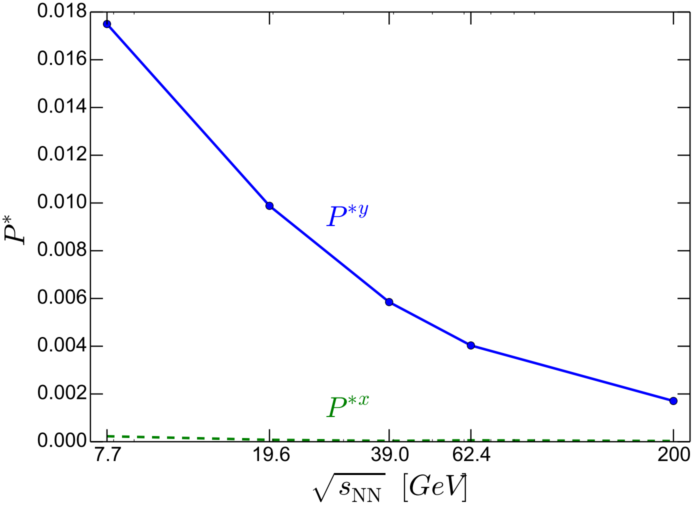
This is a result of complex vorticity pattern at the particlization surface





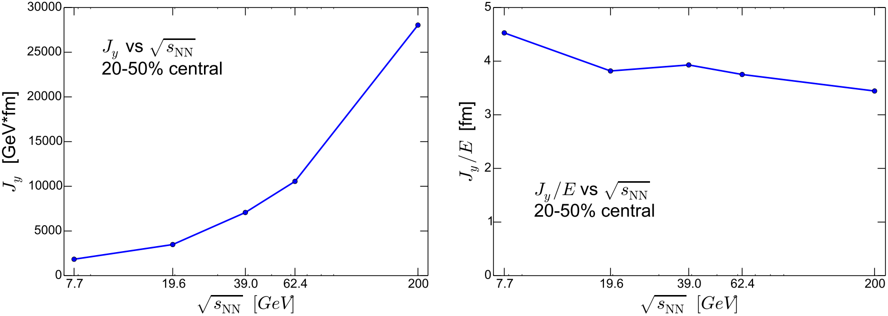


Collision energy dependence



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

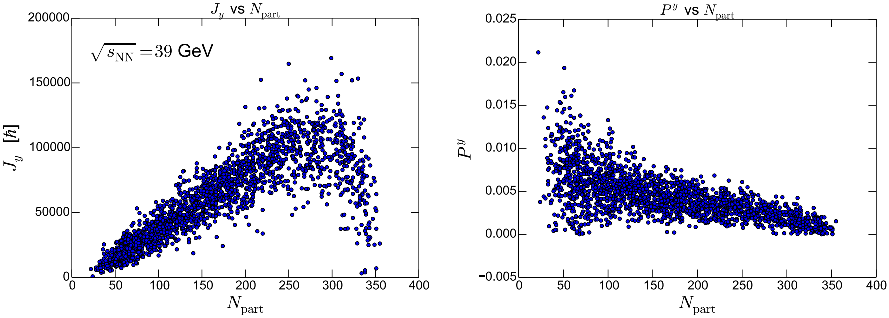
Not really: J_y actually increases with increase of $\sqrt{s_{\mathrm{NN}}}$.



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

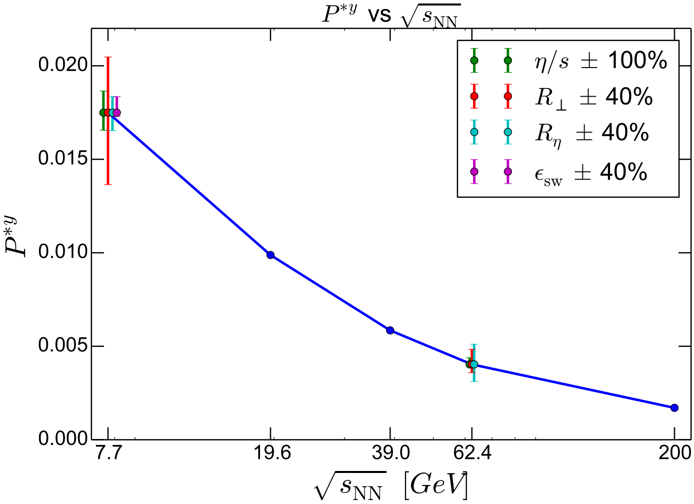
Centrality dependence

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



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

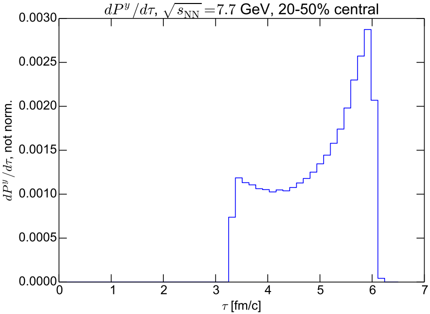
Sensitivity to parameters of the model

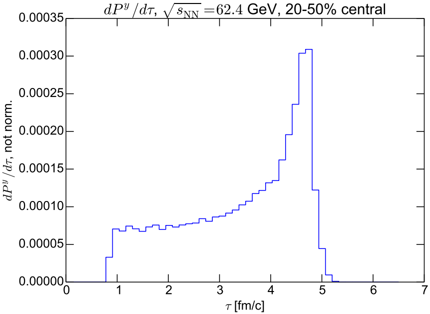


Collision energy dependence is robust with respect to variation of the parameters of the model.

Time-dfferential contributions to resulting (unnormalized) polarization P^y

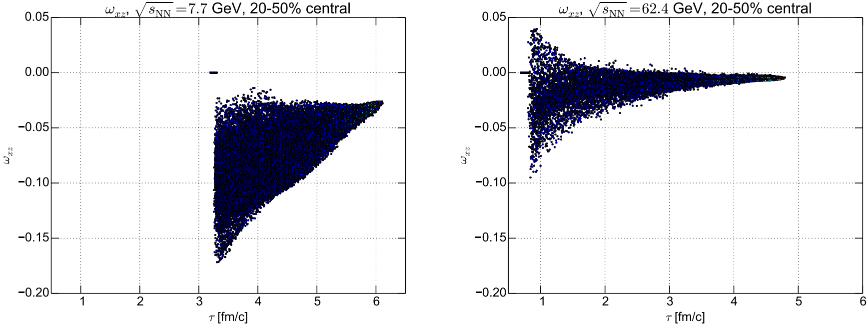
$$p^0 \frac{d^3N}{d^3p} \cdot P^\mu(p=0) = \frac{1}{4m} \int d\Sigma_\lambda p^\lambda f(x,p) \cdot (1-f(x,p)) \varepsilon^{\mu\nu\rho\sigma} p_\sigma \partial_\nu \beta_\sigma$$





Polarization builds up during entire hydro evolution, with largest contribution from the final stage.

Distribution of *xz* component of thermal vroticity (responsible for P^y at $p_x = p_y = 0$) over particlization hypersurface:



- initial vorticity distribution changes with collision energy
- longer hydrodynamic evolution at higher $\sqrt{s_{\rm NN}}$ further dilutes the vorticity
- 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 Λs are the ones which are produced at the particlization surface and leave the system with no rescatterings.

Summary

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

- pre-termal stage: UrQMD
- 3+1D viscous hydrodynamics
- EoS at finite μ_B: Chiral model, `EoS Q`

Conclusions:

- We observe a strong increase of mean Λ polarization at lower RHIC BES energies.
- The P^y 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.
- The polarization is calculated for a fraction (10-15%) of all observable Lambdas only.

Thank you for your attention!

Backup slides

nope, no backup slides here.