Vorticity in the QGP liquid and Lambda polarization at the RHIC Beam Energy Scan

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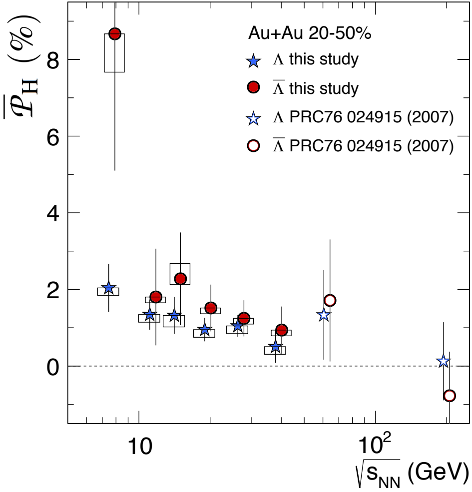
IK, Becattini `arXiv:1610.04717`
Becattini, IK, Lisa, Upsal, Voloshin `arXiv:1610.02506`

Highlight: recent Λ polarization measurement

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)

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

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

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

The 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

Existing polarization calculations in hydro models

- Becattini, Csernai, Wang, Xie, Phys. Rev. C 88, 034905 (2013)
  IC from Yang-Mills dynamics + 3D ideal hydro
  $\sqrt{s_{\rm NN}} = 200$ GeV Au-Au, $P_J \approx 3\%$
- Becattini, 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, 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).

+several other papers, where vorticity is visualized, but polarization is not.

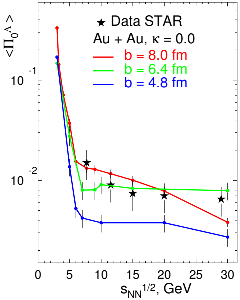
All done for $\sqrt{s_{\rm NN}} = 62.4$ GeV and above!

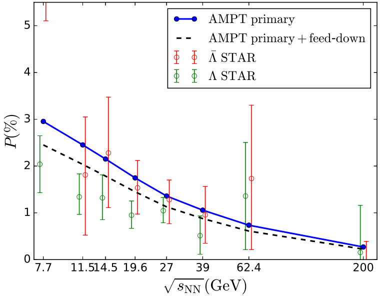
What hydro picture gives us at lower collision energies, where preliminary measurements report essentially non-zero polarization?

Existing polarization calculations in non-hydro models

- Baznat, Gudima, Sorin, Teryaev, arXiv:1701.00923
  QGSM model + Axial Vortical Effect
- Hui Li, Long-Gang Pang, Qun Wang, Xiao-Liang Xia, arXiv:1704.01507
  AMPT model + spin-vorticity coupling, vorticity is calculated via coarse-graining

Both calculations provide $\sqrt{s_{\rm NN}}$ dependence!

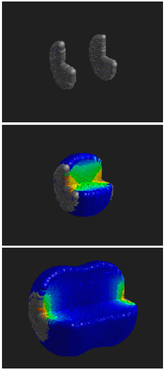




Tool for investigation: cascade+hydro(+cascade) model for BES

Hybrid model: initial state + hydrodynamic phase + hadronic cascade

thermalization — particlization



Challenges at lower collision energies:

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

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:

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

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

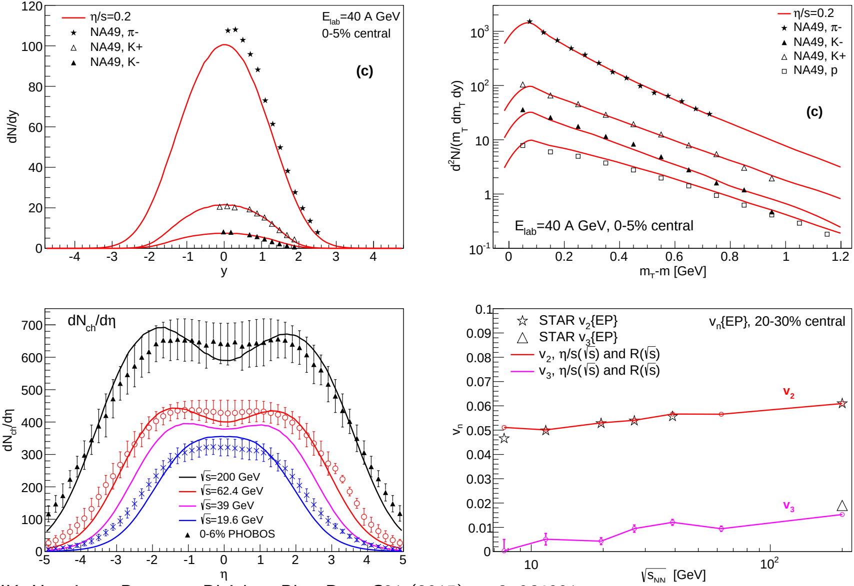
$$p^0 \frac{d^3 n_i}{d^3 p} = \sum f(x,p) p^{\mu} \Delta\sigma_{\mu}$$

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

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

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

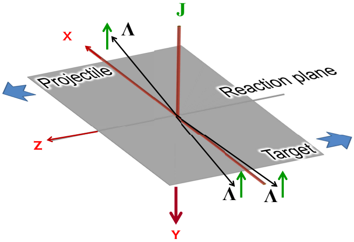
Validating the model for bulk hadronic observables



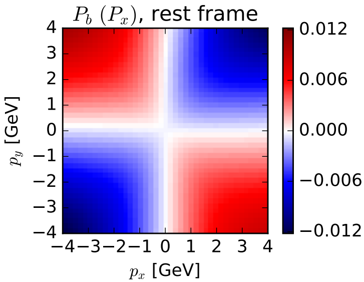
IK, Huovinen, Petersen, Bleicher, Phys.Rev. C91 (2015) no.6, 064901

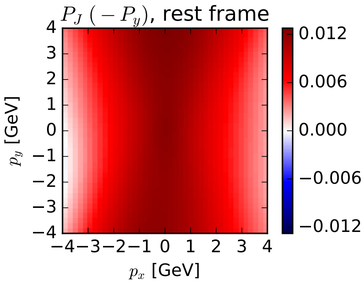
Λ polarization signal from the model

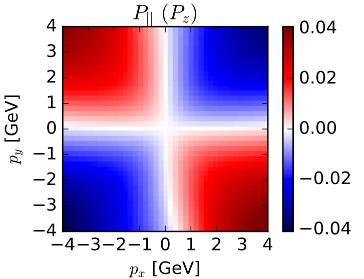
geometry sketch:



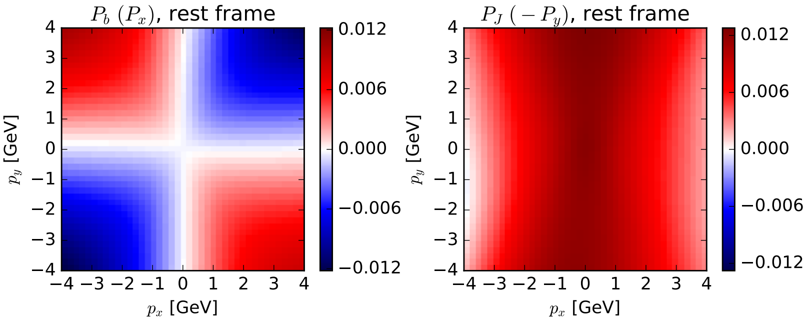
p_T differential polarization of Λ, $\sqrt{s_{\mathrm{NN}}} = 19.6$ GeV, 40-50% Au-Au



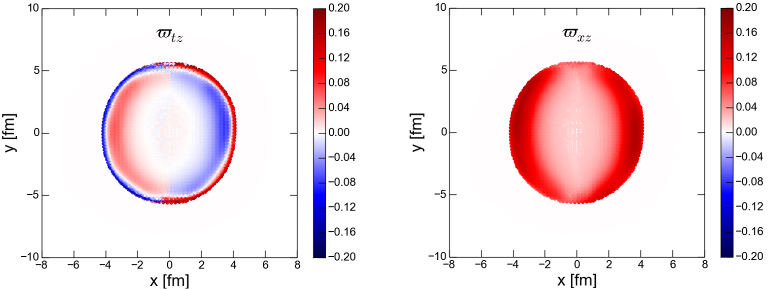




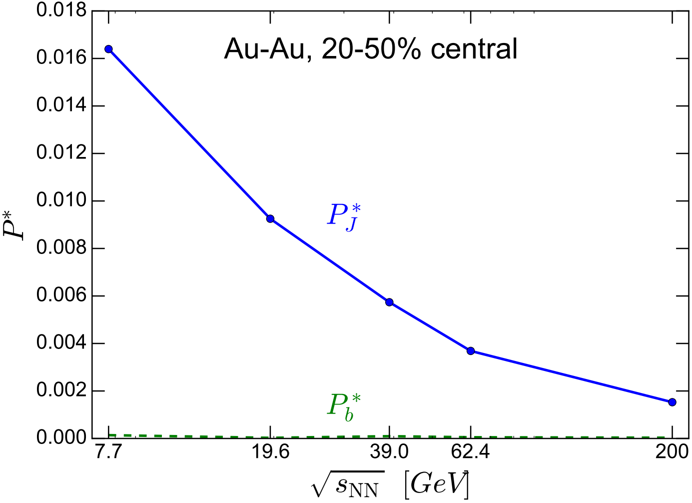
- only Λ produced at particlization
- $P_{||}$ is the largest component at large p_x and p_y
- P_b and $P_{||}$ average out to zero



$P_b \propto \varpi_{tz} p_y \quad \Updownarrow$ $\qquad$ $P_J \propto \varpi_{xz} p_0 \quad \Updownarrow$

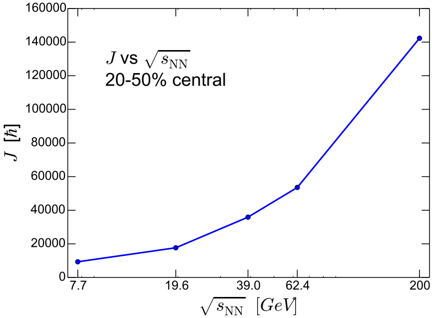


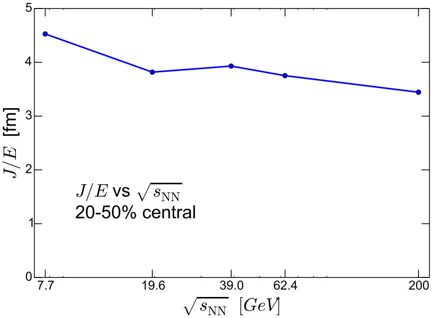
Collision energy dependence



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

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

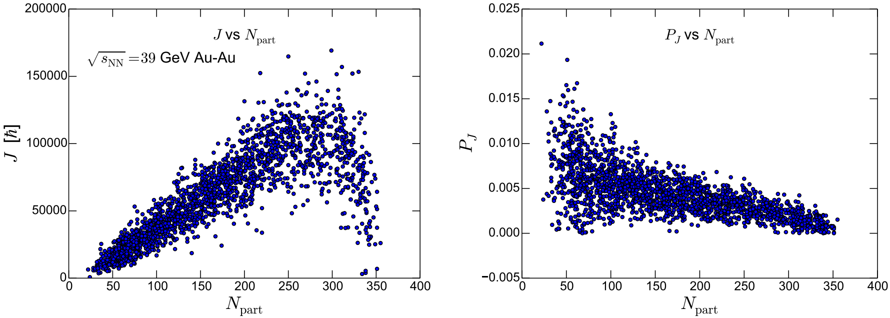




- Total angular momentum increases with increasing energy of the fireball.
- J_y/E shows weak dependence on $\sqrt{s_{\rm NN}}$.

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 $N_{\rm part}$.

Why does P_J increase at lower BES energies?

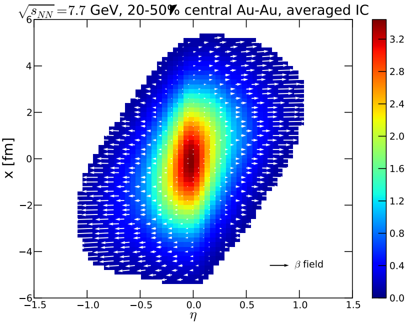
1) Different initial vorticity distribution:

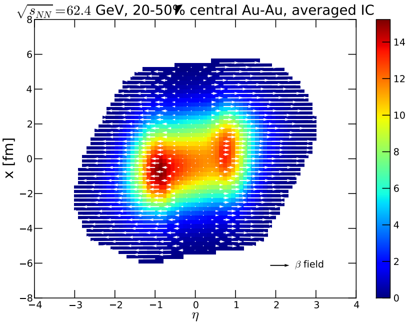
baryon stopping at lower $\sqrt{s_{\mathrm{NN}}}$

$\Downarrow$

shear flow in beam direction

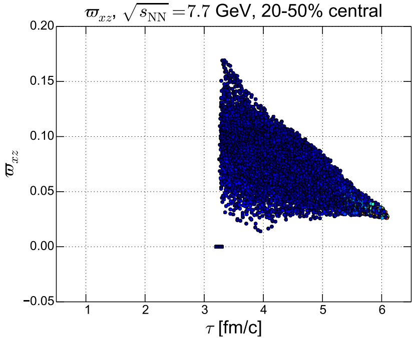
transparency at higher $\sqrt{s_{\mathrm{NN}}}$

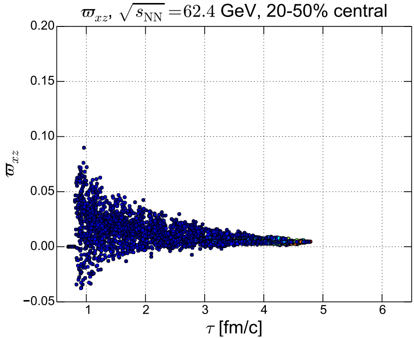




Why does P_J increase at lower BES energies?

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

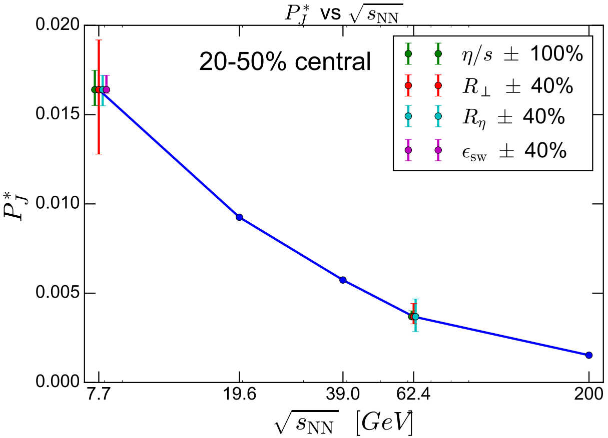




Figs: Distribution of xz component of thermal vorticity (responsible for P_J at $p_x = p_y = 0$) over particlization hypersurface.

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

Sensitivity to parameters of the model



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

Fluid phase:
η/s: shear viscosity of fluid

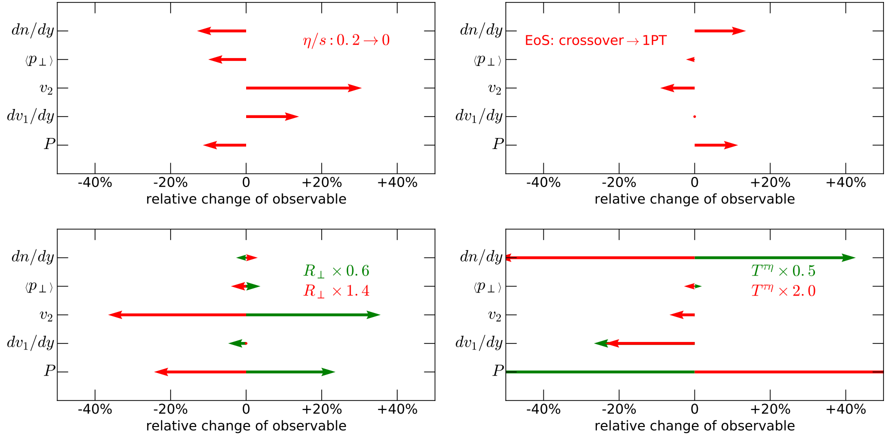
Particlization criterion:
$\varepsilon_{\rm sw} = 0.5$ GeV/fm^3

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

A closer look at the parameter dependence

NEW

$\sqrt{s_{NN}} = 7.7$ 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 ε_{sw}.

Interactions in the post-hydro stage

NEW

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

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

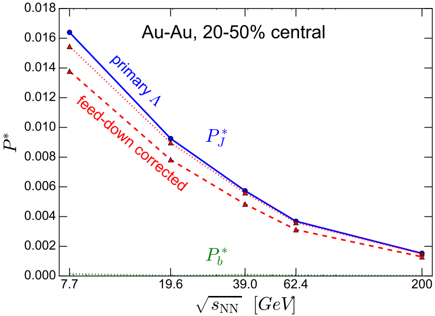
Direct $X\to\Lambda$ and two-step $X\to\Sigma^0\to\Lambda$ decays are taken into account.

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

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$+\Sigma^0+\Sigma(1385)$

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

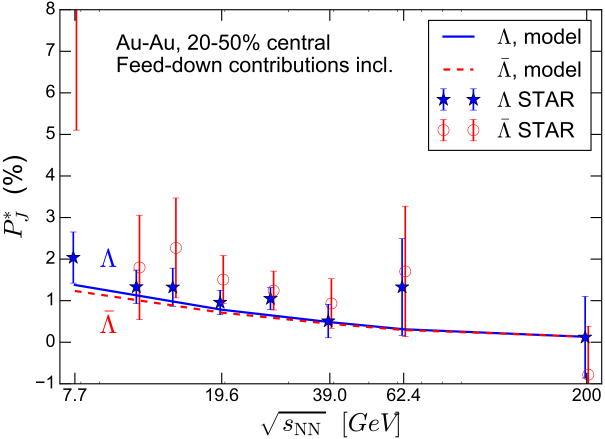


What is not taken into account (yet):

- Λ and Σ^0 actively rescatter in hadronic phase
- Elastic rescatterings are expected to randomize the spin orientation, thus suppressing the polarization signal.

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

NEW



- Λ within experimentan 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 particlization?

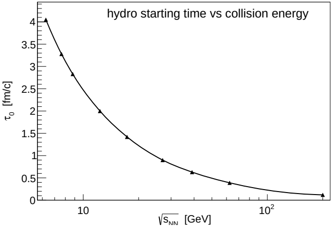
Polarization summary

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

- We observe a strong increase of mean Λ polarization towards lowest RHIC BES energies.
- The calculated Λ polarization is (almost) within the experimental error bars.
- The collision energy dependence is robust with respect to variation of model parameters.
- The polarization is sensitive to the parameters of the initial state, and can be used to constrain it.
- Feed-down from Σ^0 and $\Sigma(1385)$ counterplay and leave the polarization almost unchanged. As more resonances are included, the resulting Λ polarization goes down by 15%.
- Elastic rescatterings are expected to suppress the calculated polarization signal.

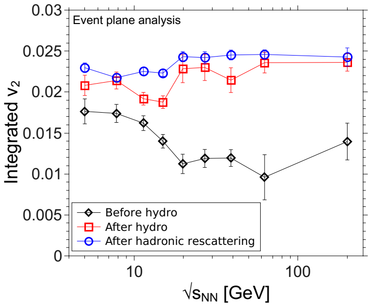
Outlook for NICA modeling:

At lower end of the BES, pre-hydro stage in a "sandwich" approach is too long:

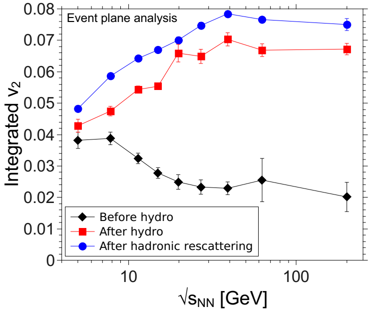


UrQMD 3.4 (UrQMD IC + ideal hydro + UrQMD afterburner)
J. Auvinen, H. Petersen, Phys.Rev.C 88:064908,2013

a) Charged hadrons, b = 0 - 3.4 fm



b) Charged hadrons, b = 8.2 - 9.4 fm



One must start hydro description early!

Multi-fluid dynamics

Hydrodynamic description starts from the very beginning of the collision.

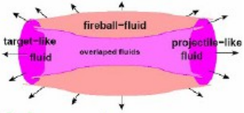
Difficulty: reasonability of fluid description at the very start of heavy ion collision?

Dynamical fluidization (1 fluid)

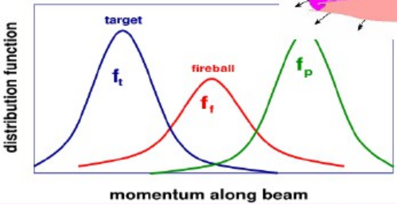
Regions of fluid phase are created dynamically, where (and when) the density is large enough.

Difficulty: how to treat non-fluid and fluid phase together (in the intial state)?

3-Fluid Dynamics



Produced particles populate mid-rapidity $\Rightarrow$ fireball fluid



Target-like fluid: $\partial_\mu J_t^\mu = 0$ $\quad \partial_\mu T_t^{\mu\nu} = -F_{tp}^\nu + F_{ft}^\nu$

Leading particles carry bar. charge — exchange/emission

Projectile-like fluid: $\partial_\mu J_p^\mu = 0,$ $\quad \partial_\mu T_p^{\mu\nu} = -F_{pt}^\nu + F_{fp}^\nu$

Fireball fluid: $J_f^\mu = 0,$ $\quad \partial_\mu T_f^{\mu\nu} = F_{pt}^\nu + F_{tp}^\nu - F_{fp}^\nu - F_{ft}^\nu$

Baryon-free fluid — Source term — Exchange

The source term is delayed due to a formation time $\tau \sim 1$ fm/c

Total energy-momentum conservation:

$$\partial_\mu (T_p^{\mu\nu} + T_t^{\mu\nu} + T_f^{\mu\nu}) = 0$$

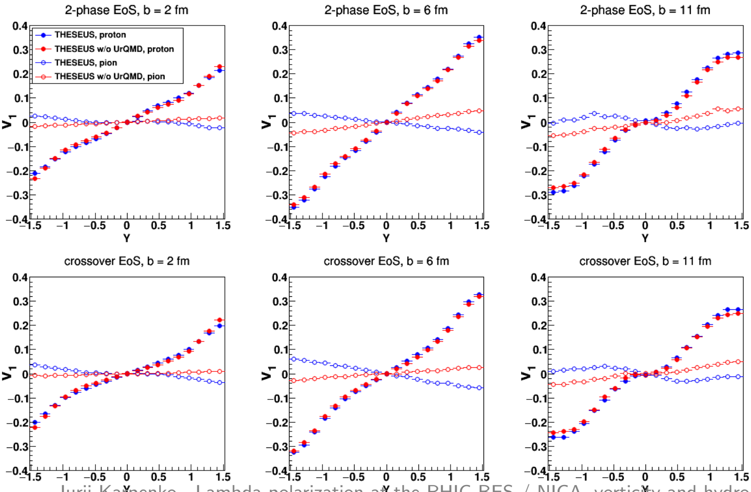
http://theory.gsi.de/~ivanov/mfd/

Yu.B. Ivanov, V.N. Russkikh and V.D. Toneev, Phys. Rev. C73, 044904 (2006)

THESEUS: 3-Fluid Dynamics + UrQMD

P. Batyuk, D. Blaschke, M. Bleicher, Yu. B. Ivanov, Iu. Karpenko, S. Merts, M. Nahrgang, H. Petersen, and O. Rogachevsky, Phys. Rev. C 94, 044917 (2016)

The scheme: 3-fluid hydro + particlization + hadronic cascade



The end (so far)

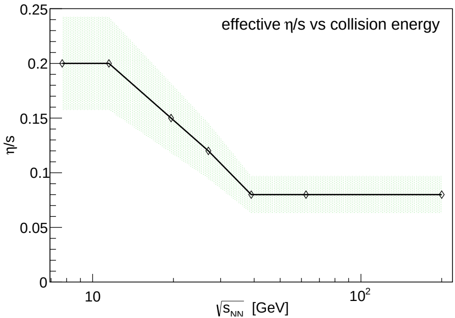
Backup material

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 $\pm5\%$ 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