Lambda polarization* and femtoscopy** at RHIC BES energies

Iurii KARPENKO

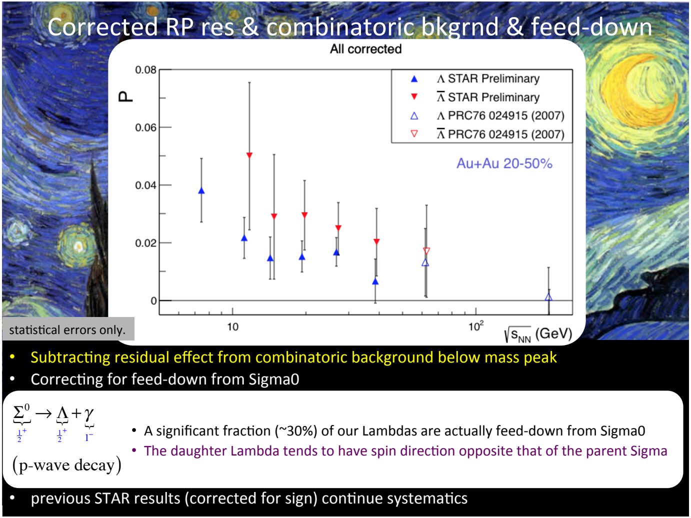
*with Francesco Becattini

**with P.Batyuk, R.Lednicky, L.Malinina, K.Mikhailov, O.Rogachevsky, D.Wielanek

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



This measurement can be realized because of “self-analyzing” nature of Λ decay, which preferentially emits daugter proton in the direction of Λ spin: $\frac{dW}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha P \cos\theta^*)$

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:

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

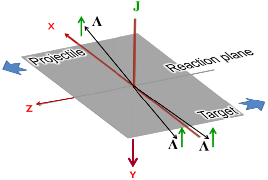
where $\beta_{\mu} = \frac{u_{\mu}}{T}$ is inverse four-temperature field.

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

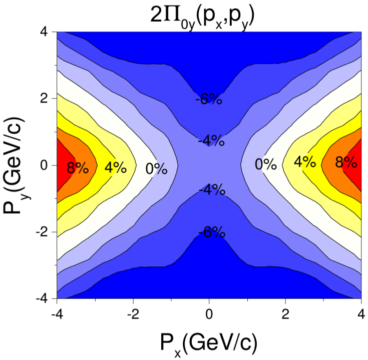
- polarization is close or equal for particles and antiparticles
- caused not only by velocity, but also temperature gradients

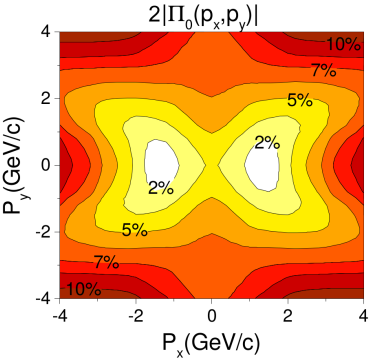
Existing polarization calculations from hydro models (1)

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

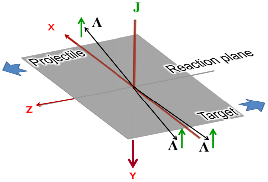




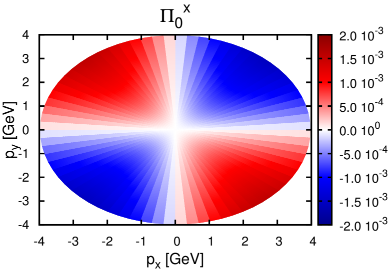
P^y on the order of few % even at $p_x = p_y = 0$ and up to 8% (with opposite sign) for high p_x!

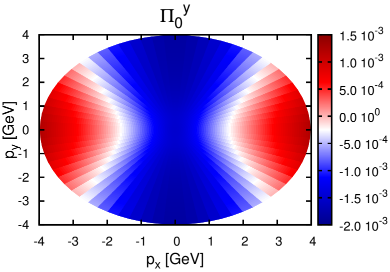
Existing polarization calculations from hydro models (2)

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



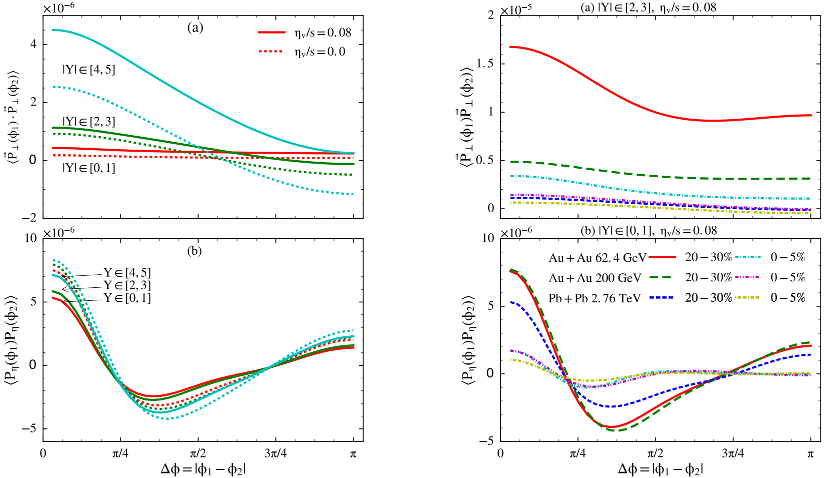


Momentum integrated P^x and P^z average out to zero, and $P^y \approx -0.4\%$.

Existing polarization calculations from hydro models (3)

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

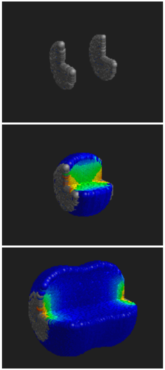
Initial state from AMPT + 3D viscous hydro



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

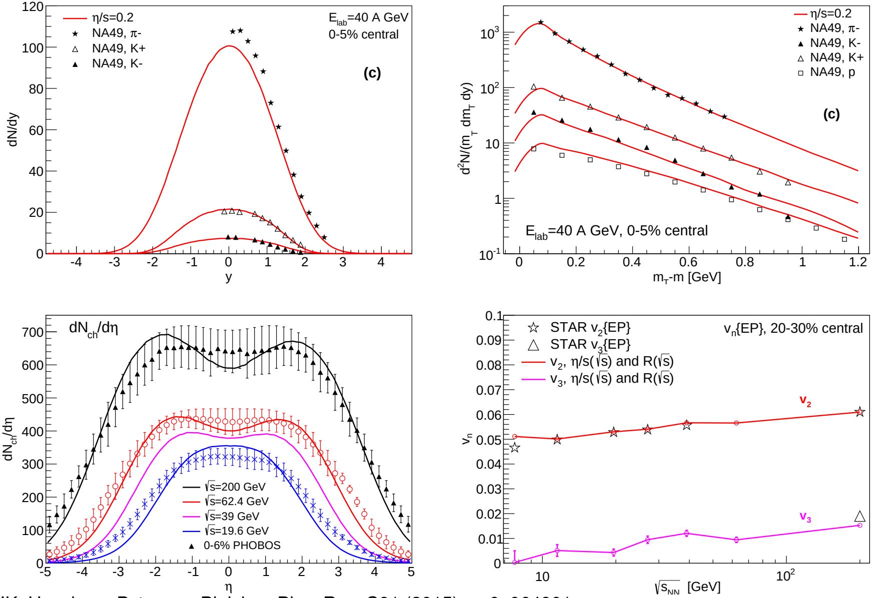
$$p^0 \frac{d^3 n_i}{d^3 p} = \sum f(x,p) p^{\mu} \Delta\sigma_{\mu}$$

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

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

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

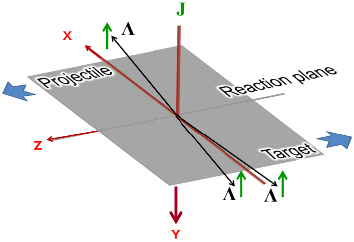
Validating the model for bulk hadronic observables



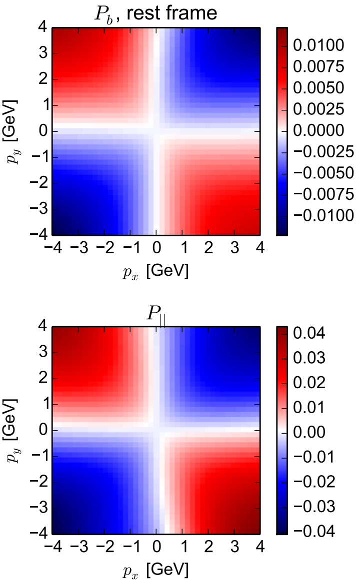
IK, Huovinen, Petersen, Bleicher, Phys.Rev. C91 (2015) no.6, 064901

Λ polarization signal from the model

geometry sketch:



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

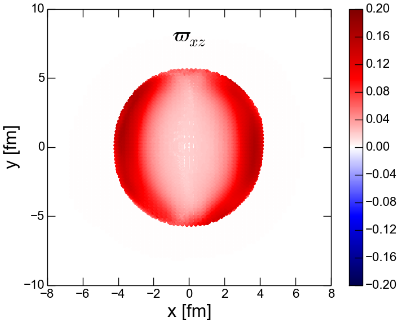


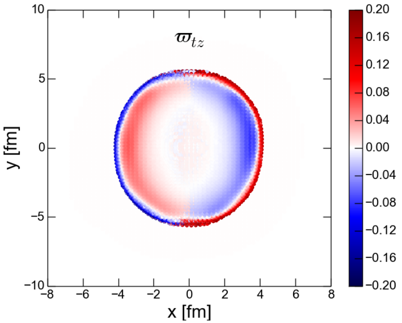
- only Λ produced at particlization
- $P_{||}$ is the largest component at large p_x and p_y
- P_b and $P_{||}$ average out to zero

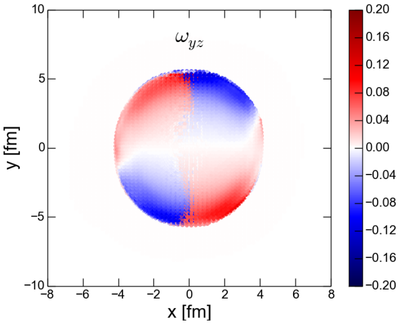
The quadrupole polarization patterns are induced by complex vorticity patterns at the particlization surface:

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

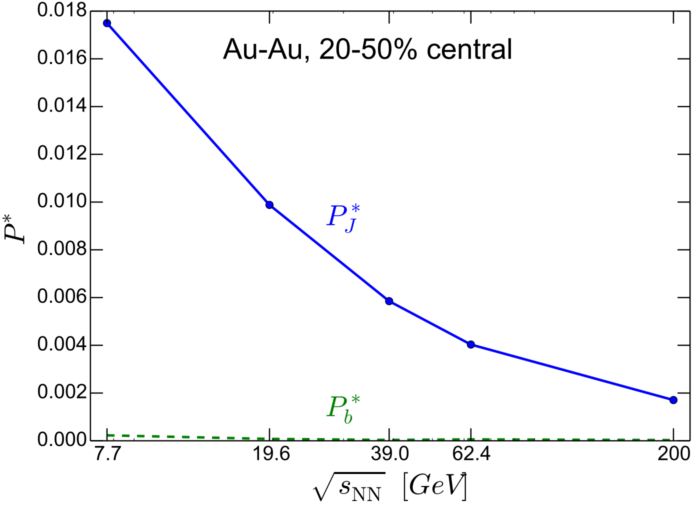
$$\omega_{\mu\nu} = -\frac{1}{2}(\partial_\mu \beta_\nu - \partial_\nu \beta_\mu)$$





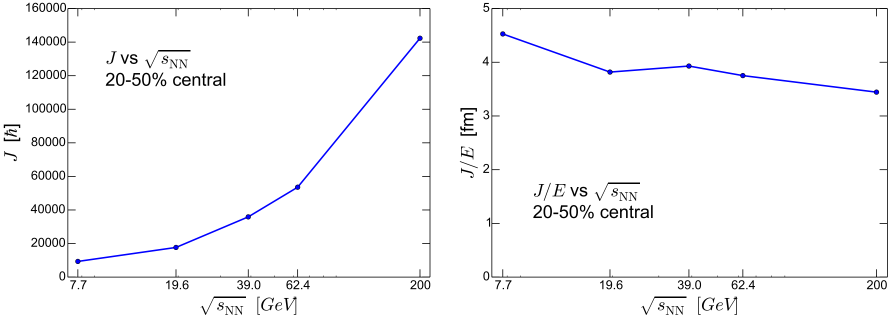


Collision energy dependence



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

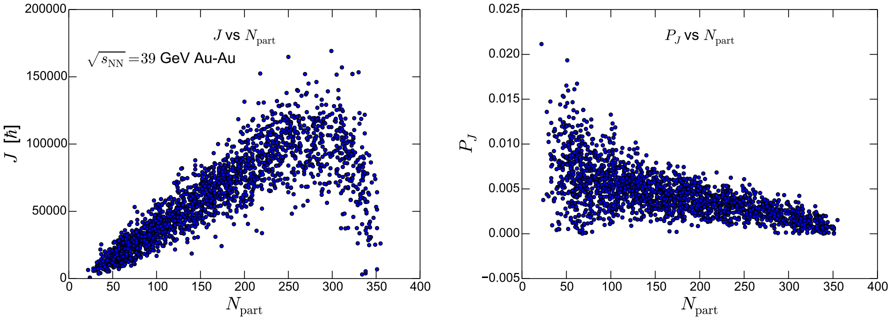
Not really: J_y actually increases with increase of $\sqrt{s_{\rm NN}}$.



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

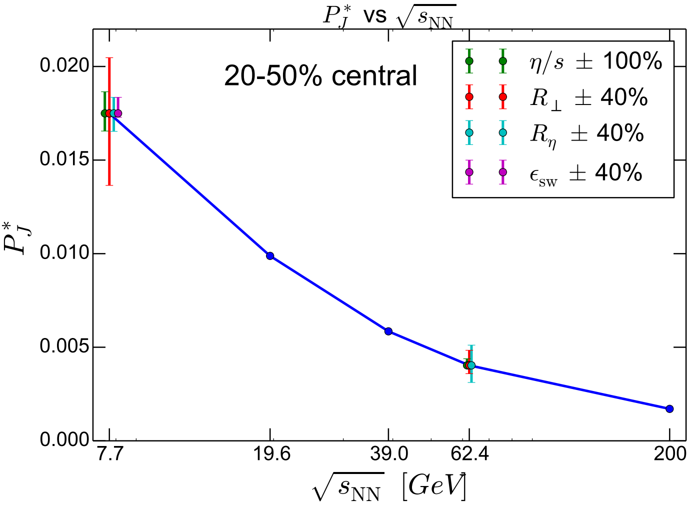
Centrality dependence

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?

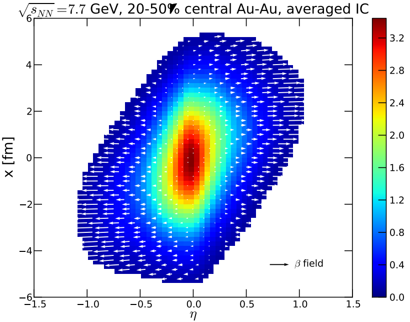
1) Different initial vorticity distribution:

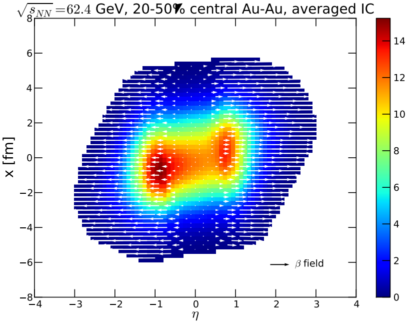
baryon stopping at lower $\sqrt{s_{\rm NN}}$

$\Downarrow$

shear flow in beam direction

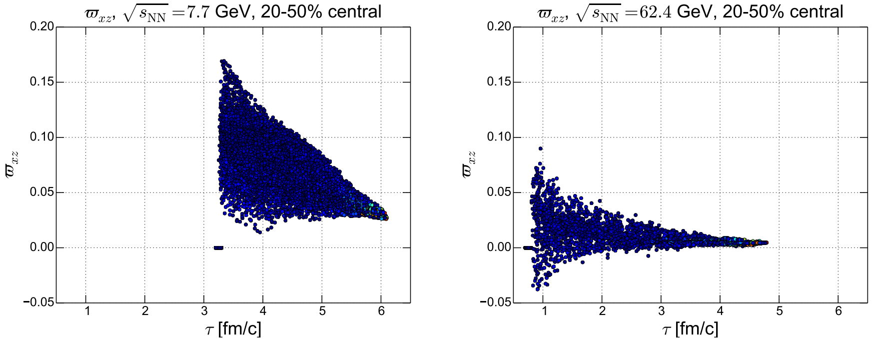
transparency at higher $\sqrt{s_{\rm NN}}$





Why does P_J increase at lower BES energies?

2) Longer hydrodynamic evolution at higher $\sqrt{s_{NN}}$ 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 post-hydro stage

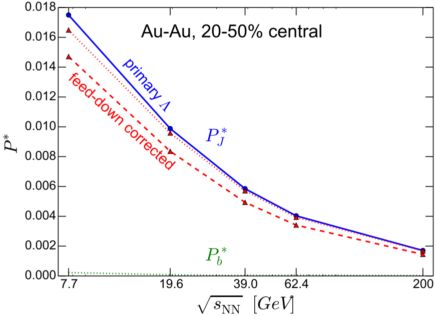
Spin (polarization) transfer in two-body resonance decay: $\mathbf{S}^*_{\Lambda,\Sigma^0} = C_{X\to\Lambda,\Sigma^0}\cdot\mathbf{S}^*_X$

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

X	J^P	$\frac{\mathbf{S}_X}{\mathbf{S}_{\Lambda,\mathrm{prim}}}$	$C_{X\to\Lambda,\Sigma^0}$	$\frac{\mathbf{S}_{\Lambda(X)}}{\mathbf{S}_{\Lambda,\mathrm{prim}}}$
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):

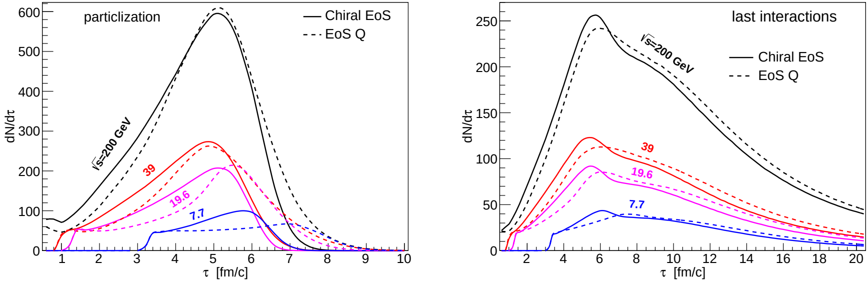
- Λ and Σ^0 actively rescatter in hadronic phase
- Elastic rescatterings are expected to randomize the spin orientation, thus suppressing the polarization signal.

EoS dependence & femtoscopy from the model

Femtoscopy: P.Batyuk, R.Lednicky, L.Malinina, K.Mikhailov, O.Rogachevsky, IK, D.Wielanek

EoS dependence: Chiral EoS vs 'EoS Q'

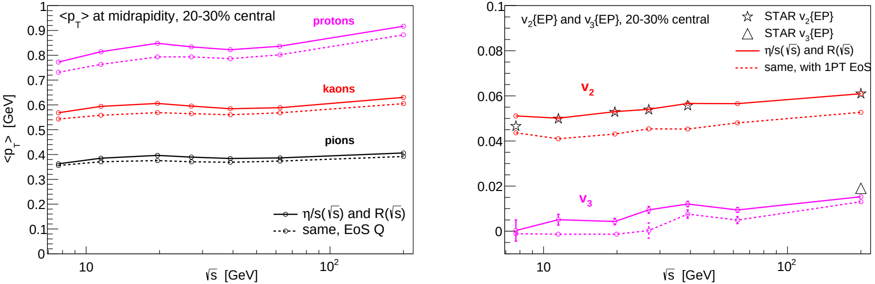
Take same parameters but change the EoS:



- EoS Q increases the average duration of hydro phase, especially at lower collision energies.
- But the difference is smeared by the final stage hadronic cascade

EoS dependence: Chiral EoS vs 'EoS Q'

- Final multiplicities and rapidity distributions are unchanged.

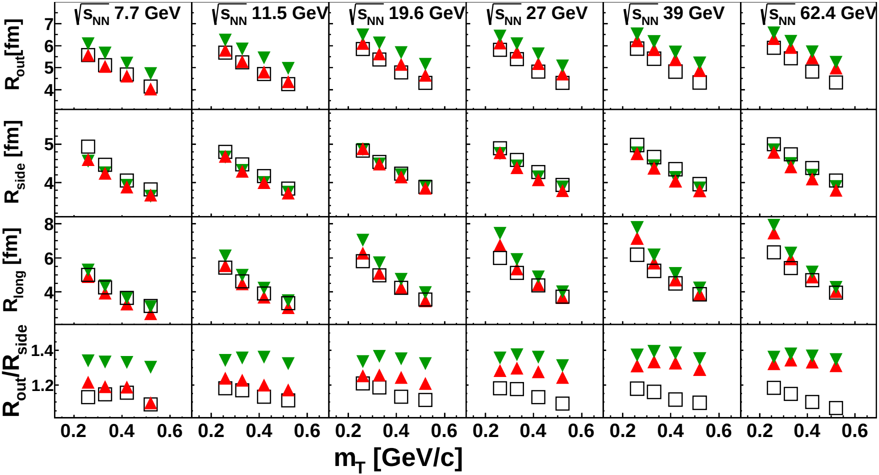


- EoS Q results in slightly less radial flow → mean p_T is decreased.
- The biggest effect is for the elliptic flow.

IK, P.Huovinen, H.Petersen, M.Bleicher, arXiv:1601.00800

Femtoscopic radii from vHLLE+UrQMD

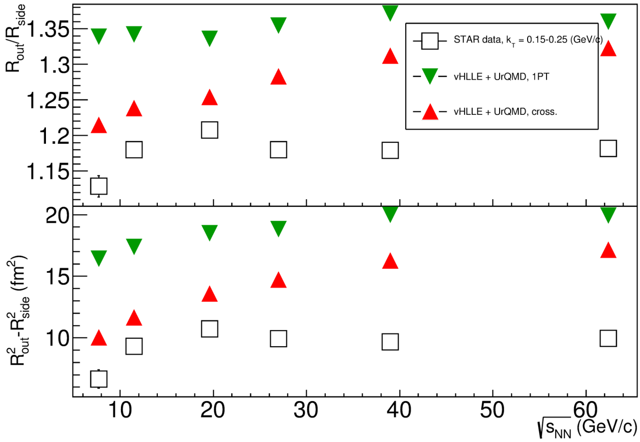
0-5% central Au-Au collisions: vHLLE+UrQMD using crossover EoS, 1PT EoS



P.Batyuk, R.Lednicky, L.Malinina, K.Mikhailov, O.Rogachevsky, IK, D.Wielanek, in preparation

R_{out}/R_{side} and $R^2_{out} - R^2_{side}$

0-5% central Au-Au collisions: vHLLE+UrQMD using crossover EoS, 1PT EoS



P.Batyuk, R.Lednicky, L.Malinina, K.Mikhailov, O.Rogachevsky, IK, D.Wielanek, in preparation

Summary

Polarization:

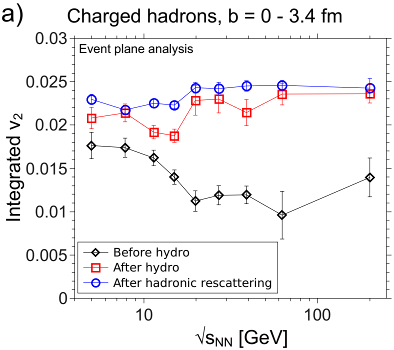
- We observe a strong increase of mean Λ polarization towards lowest RHIC BES energies.
- The P_J is at least twice smaller than the (preliminary) experimental value.
- The collision energy dependence is robust with respect to variation of model parameters.
- Feed-down from Σ^0 and $\Sigma(1385)$ counterplay 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.
- 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.

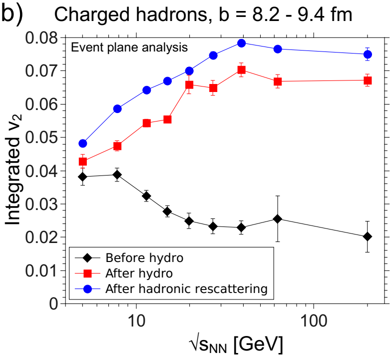
Femtoscopy:

- Femtoscopic observables seems to prefer chiral model EoS over Bag model EoS
- $R^2_{\rm out} - R^2_{\rm side}$ shows monotonic increase in the model, and it essentially magnifies smaller discrepancies for $R_{\rm out}$ and $R_{\rm side}$ between model/experiment.

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

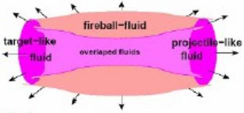
UrQMD 3.4, J. Auvinen, H. Petersen, Phys.Rev.C 88:064908,2013





This can be overcome with multi-fluid dynamics (with cold nuclear matter IC), or with an IC model allowing for dynamical fluidization.

3-Fluid Dynamics



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

Target-like fluid: $\partial_\mu J^\mu_t = 0$ $\qquad \partial_\mu T^{\mu\nu}_t = -F^\nu_{tp} + F^\nu_{ft}$

Leading particles carry bar. charge — exchange/emission

Projectile-like fluid: $\partial_\mu J^\mu_p = 0,$ $\qquad \partial_\mu T^{\mu\nu}_p = -F^\nu_{pt} + F^\nu_{fp}$

Fireball fluid: $J^\mu_f = 0,$ $\qquad \partial_\mu T^{\mu\nu}_f = F^\nu_{pt} + F^\nu_{tp} - F^\nu_{fp} - F^\nu_{ft}$

Baryon-free fluid — Source term — Exchange

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

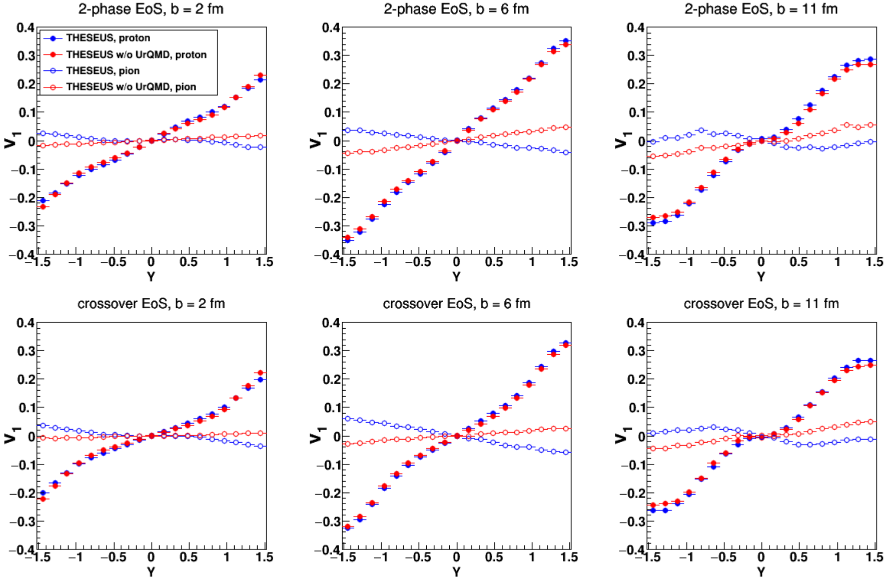
Total energy-momentum conservation:

$$\partial_\mu (T^{\mu\nu}_p + T^{\mu\nu}_t + T^{\mu\nu}_f) = 0$$

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

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

Some preparatory work: coupling old 3-fluid hydro to UrQMD



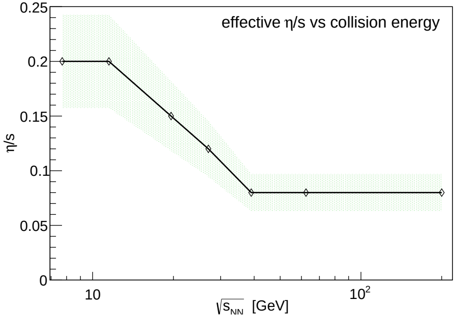
Backup slides

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 $\pm5\%$ 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