Lambda polarization at RHIC BES and LHC energies in viscous hydrodynamic approach

Iurii KARPENKO

with Francesco Becattini

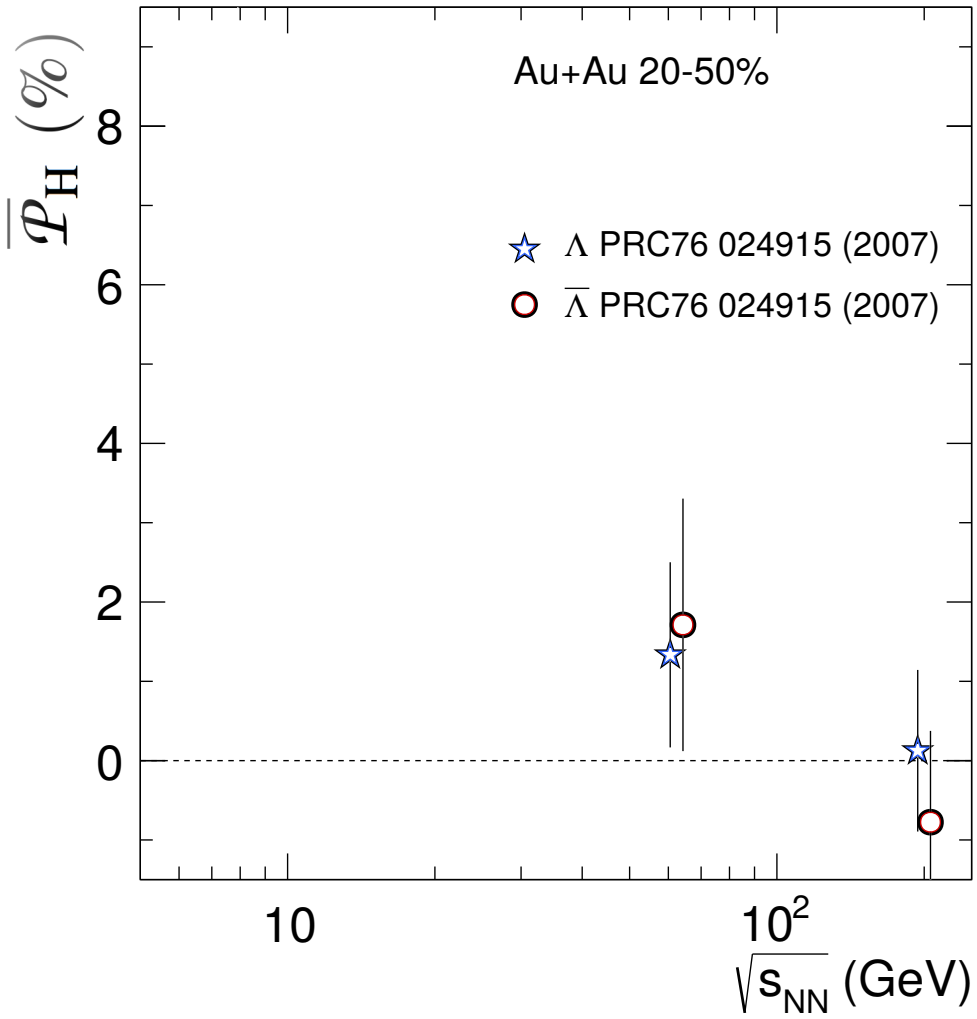
CNRS - SUBATECH Nantes

IK, F. Becattini, Eur. Phys. J. C 77, 213 (2017)
F. Becattini, IK, M. Lisa, I. Upsal, S. Voloshin, Phys. Rev. C 95, 054902 (2017)
F. Becattini, IK, Phys. Rev. Lett. 120, 012302 (2018)

GDRE meeting, 08-14 July 2018, SUBATECH Nantes

Highlight: recent Λ polarization measurement

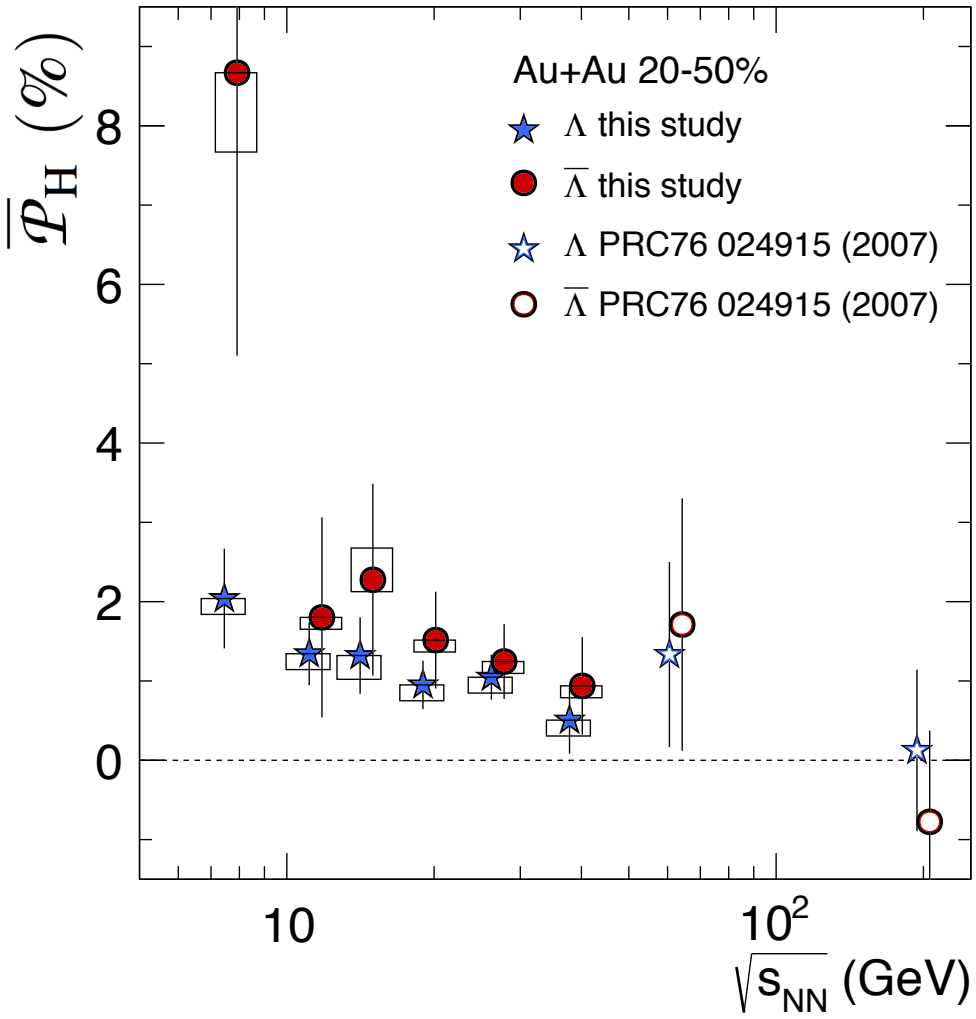
B. I. Abelev et al. (STAR Collaboration), Phys. Rev. C 76, 024915 **(2007)**



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

Highlight: recent Λ polarization measurement

extending to full BES: STAR Collaboration, Nature 548 (2017) 62-65



"First clear positive signal of global polarization in heavy ion collisions!"

Theoretical ideas

1) Early ideas:

Initial angular momentum $\Rightarrow$ polarized quarks $\Rightarrow$ polarized hadrons

Z. T. Liang and X. N. Wang, Phys. Rev. Lett. 94, 102301 (2005)
Z. T. Liang and X. N. Wang, Phys. Lett. B 629, 20 (2005)

2) Later developments:

Initial angular momentum $\Rightarrow$ vortical fluid $\Rightarrow$ polarized hadrons

F. Becattini, V. Chandra, L. Del Zanna and E. Grossi, Annals Phys. 338, 32 (2013)

Theory side: polarization of fermions from the 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, Phys. Rev. C 94 (2016), 024904

Mechanism: spin-vorticity coupling at local thermodynamic equilibrium.

- Cooper-Frye prescription: $p^0 \frac{d^3N}{d^3p} = \int d\Sigma_\lambda p^\lambda \frac{1}{\exp\left(\frac{p\cdot u-\mu}{T}\right)\pm 1}$
- For the spin $\frac{1}{2}$ particles produced at the particlization surface:

$$\langle S(x,p)\rangle = \frac{1}{8m}(1-f(x,p))\varepsilon^{\mu\nu\rho\sigma}p_\sigma\partial_\nu\beta_\rho,$$

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

$$\boxed{S^\mu(p) = \frac{\int d\Sigma_\lambda p^\lambda f(x,p)\langle S(x,p)\rangle}{\int d\Sigma_\lambda p^\lambda f(x,p)}}$$

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

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
  $\sqrt{s_{\rm NN}} = 200$ 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
  $\sqrt{s_{\rm NN}} = 200$ 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
  $\sqrt{s_{\rm NN}} = 62.4, 200, 2760$ GeV; P_J around few per mille (no exact value).
- +few 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?

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:

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

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

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

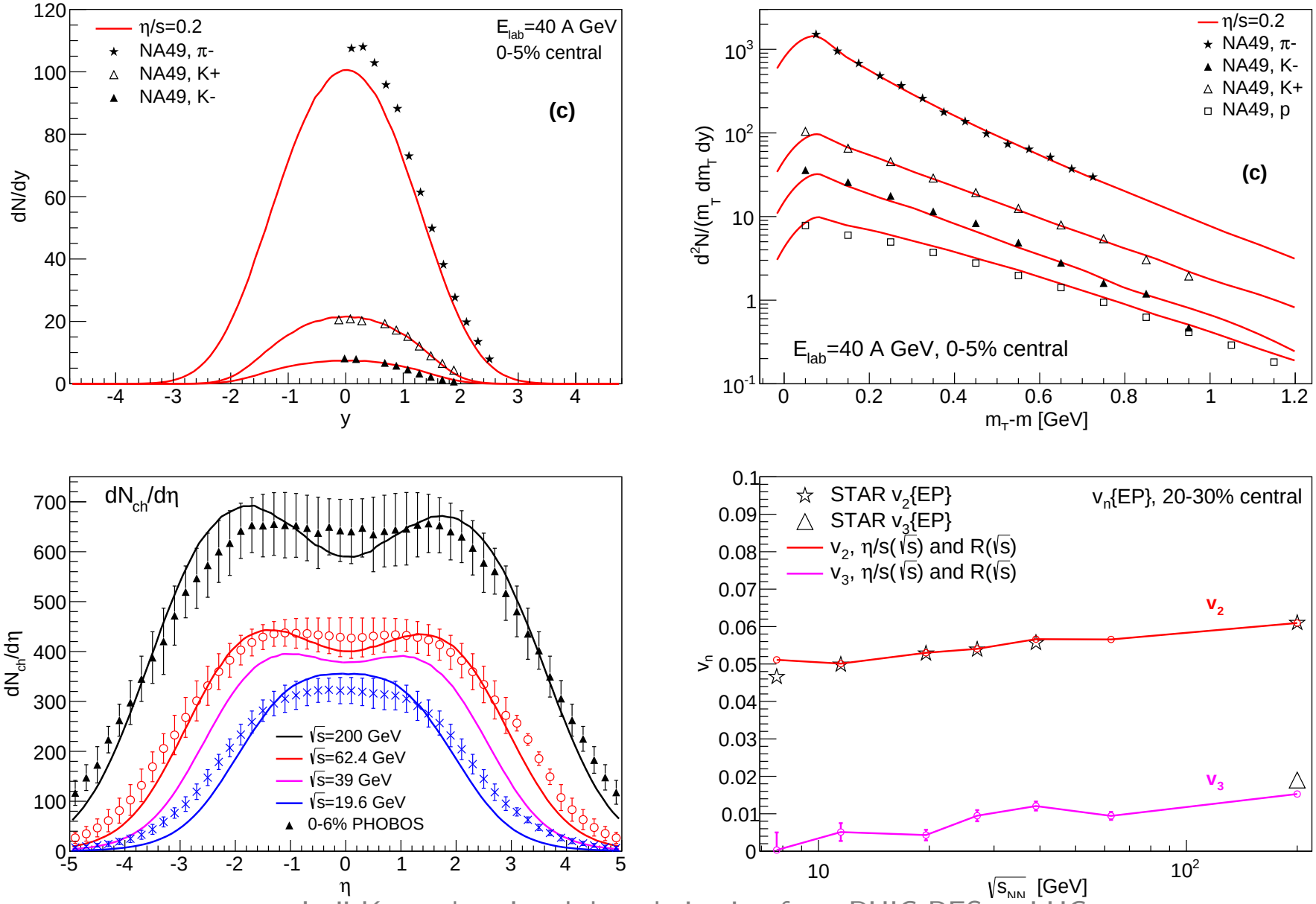
$$f(x,p) = f_{\mathrm{eq}} \cdot \left(1 + (1 \mp f_{\mathrm{eq}}) \frac{p_{\mu} p_{\nu} \pi^{\mu\nu}}{2T^2(\varepsilon + p)} \right)$$

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

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

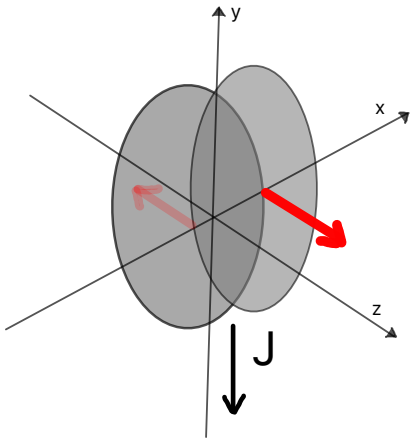
Validating the model for bulk hadronic observables

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

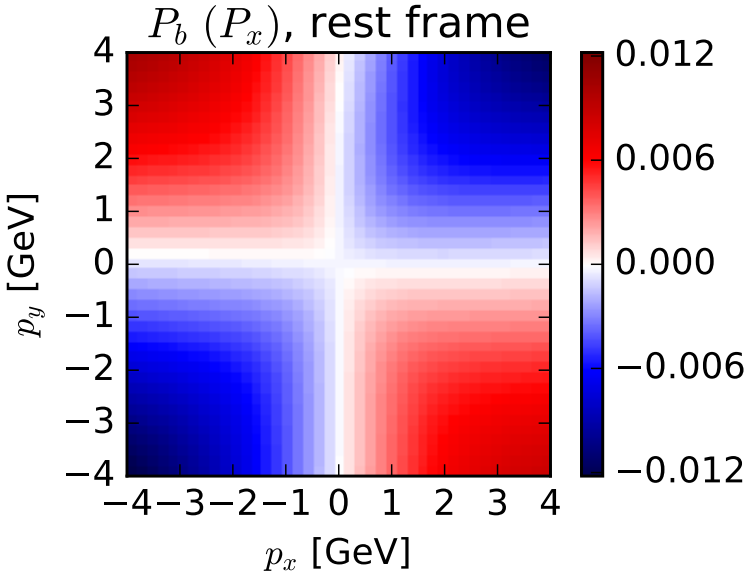


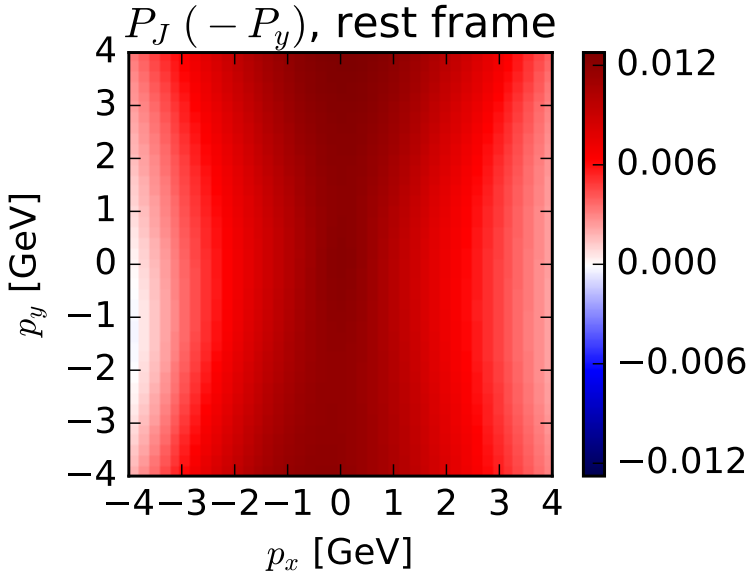
Λ polarization signal from the model

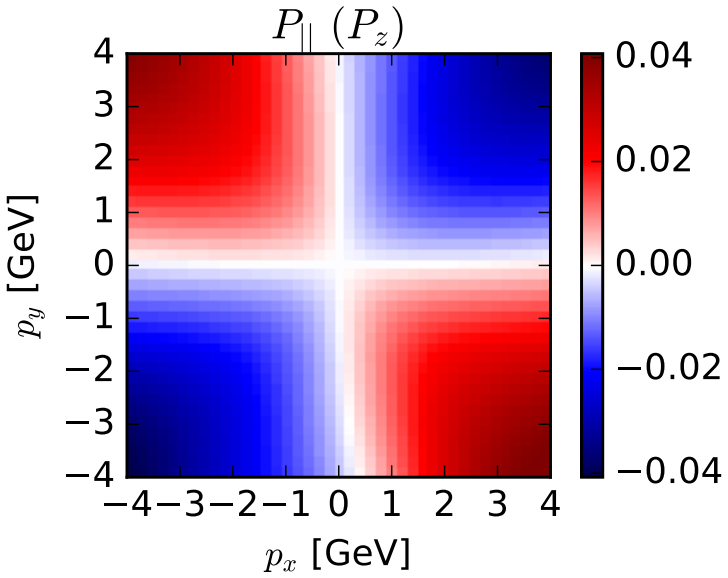
geometry sketch:



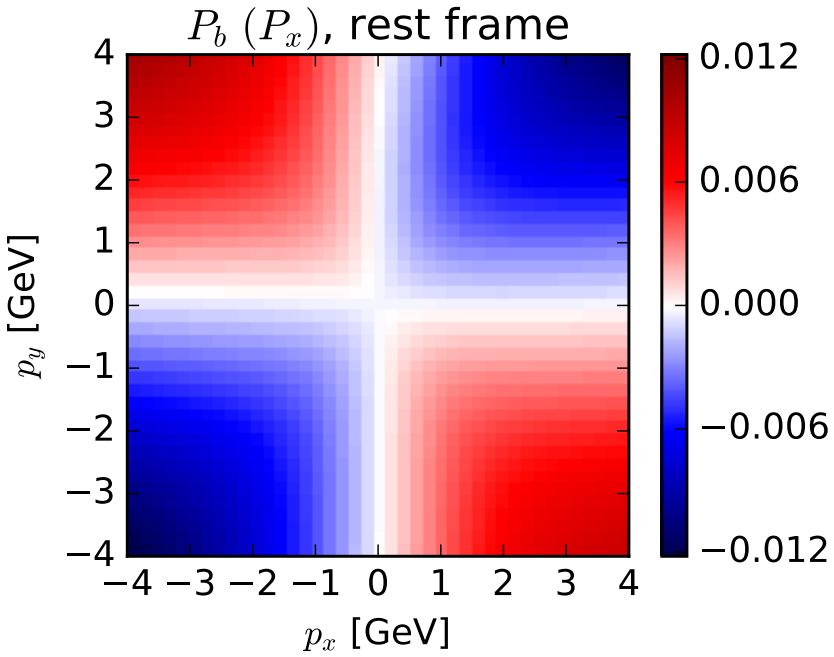
p_T differential polarization of Λ, $\sqrt{s_{\rm NN}} = 19.6$ GeV, 40-50% Au-Au

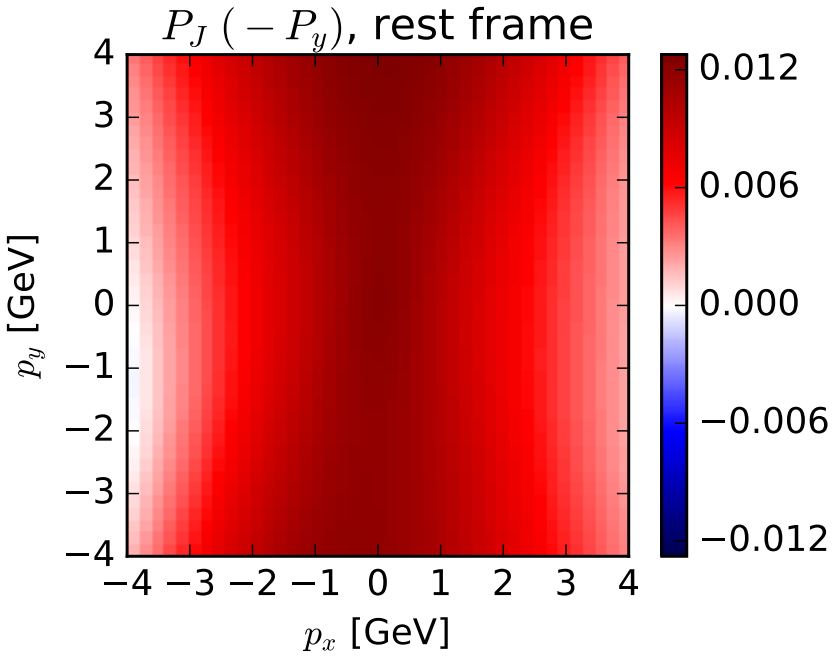






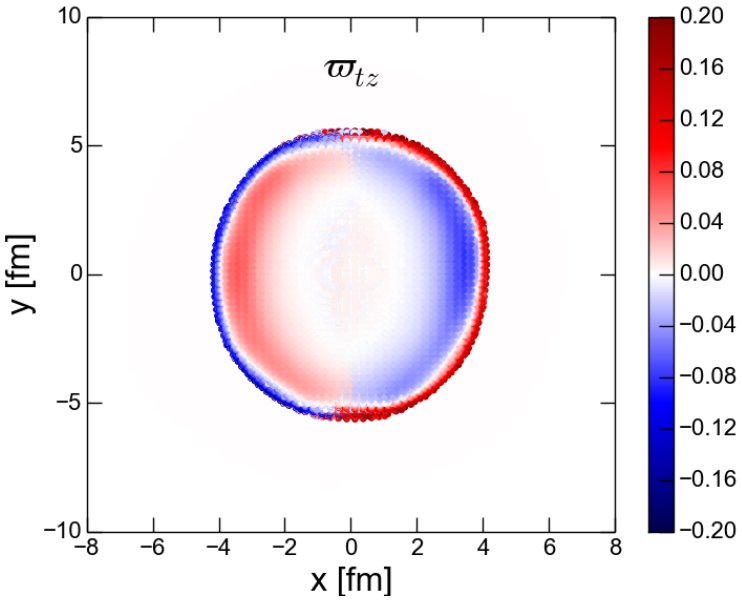
- only Λ produced at particlization
- $P_{||}$ is the largest component at large p_x and p_y
- P_b and $P_{||}$ average out to zero

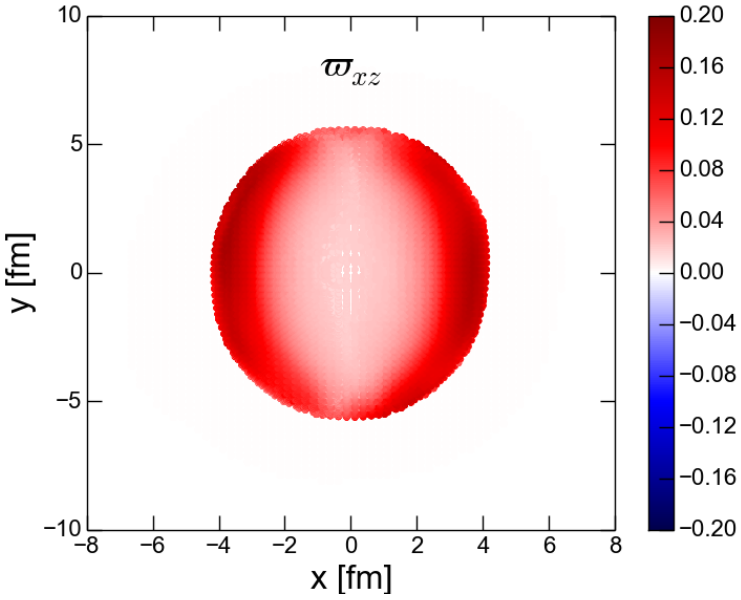




$P_b \propto \varpi_{tz} p_y \quad \Updownarrow$

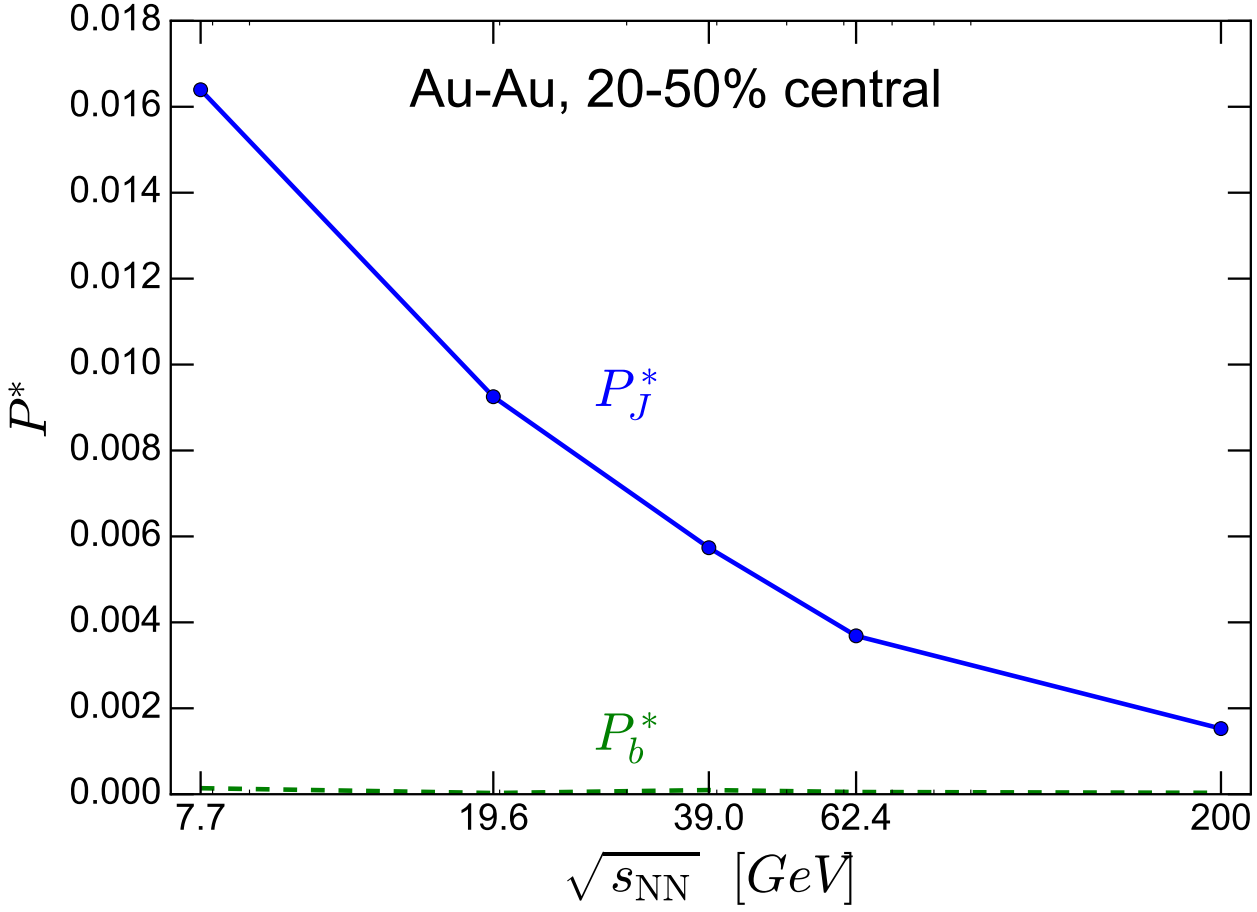
$P_J \propto \varpi_{xz} p_0 \quad \Updownarrow$

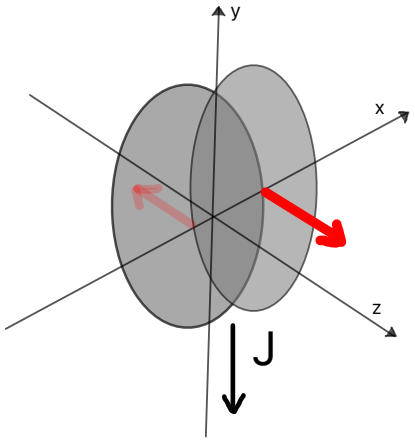




Collision energy dependence

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





$$P_J \iff \varpi_{xz} \quad (\Omega_J)$$

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

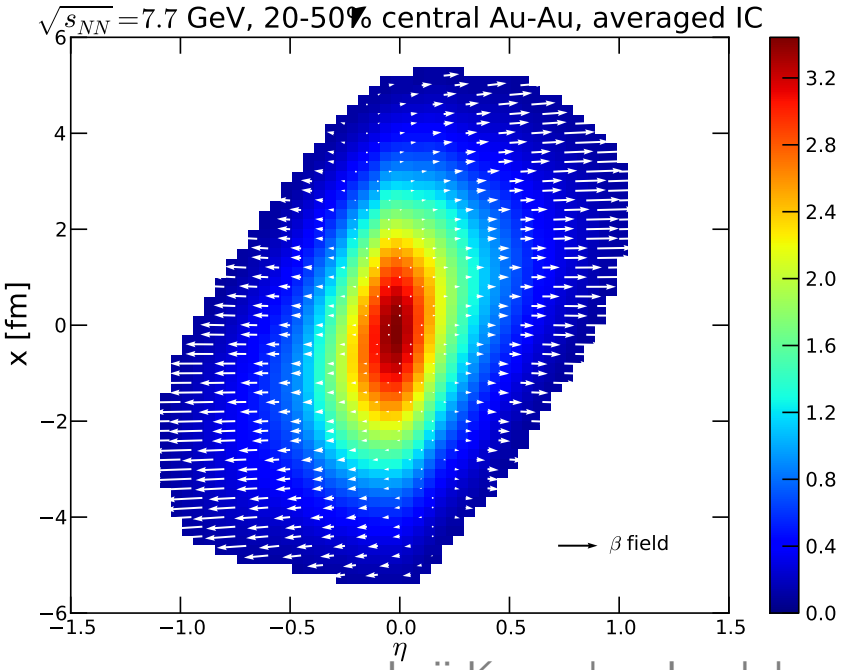
$\Downarrow$

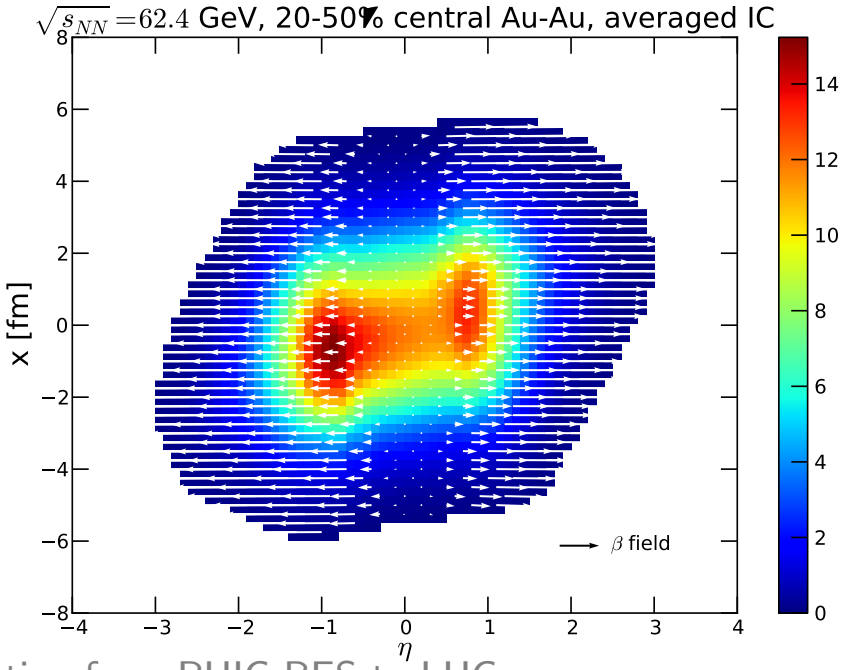
higher initial vorticity at midrapidity

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

$\Downarrow$

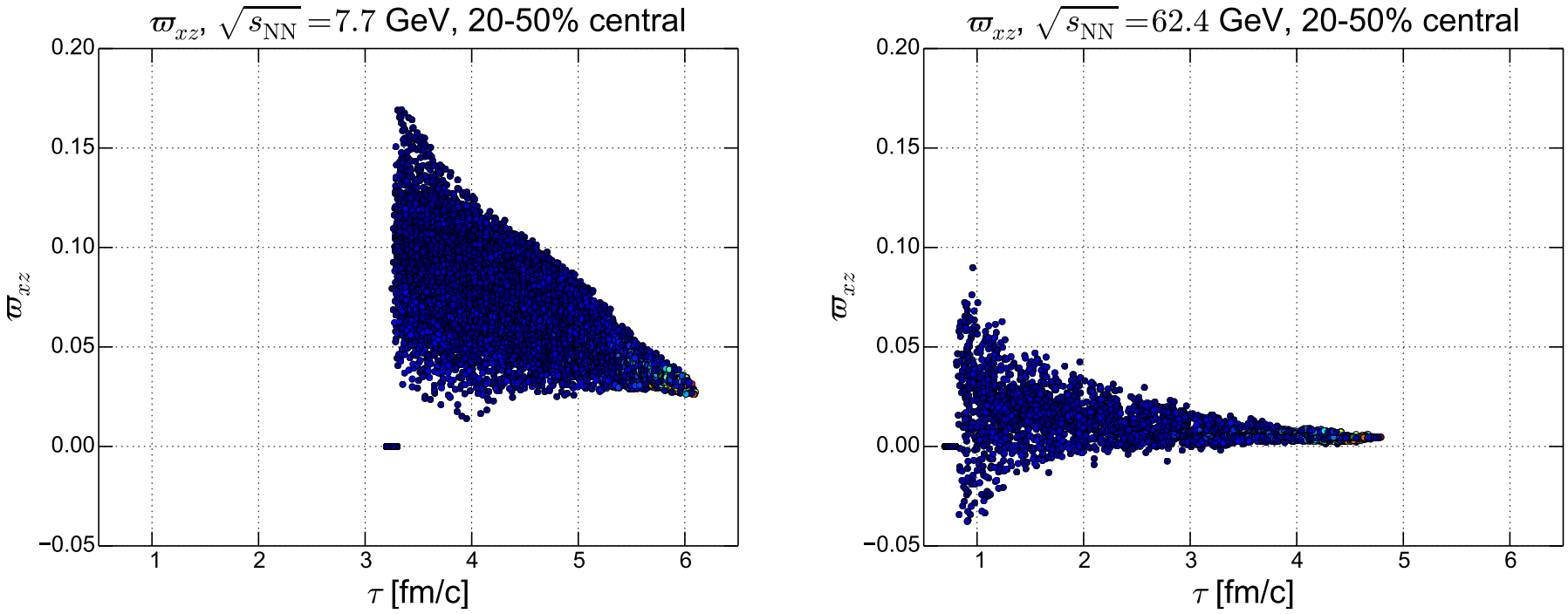
lower initial vorticity at midrapidity





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

Interactions in the post-hydro stage

F. Becattini, IK, M. Lisa, I. Upsal, 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: $\mathbf{S}^*_{\Lambda,\Sigma^0} = C_{X\to\Lambda,\Sigma^0} \cdot \mathbf{S}^*_X$

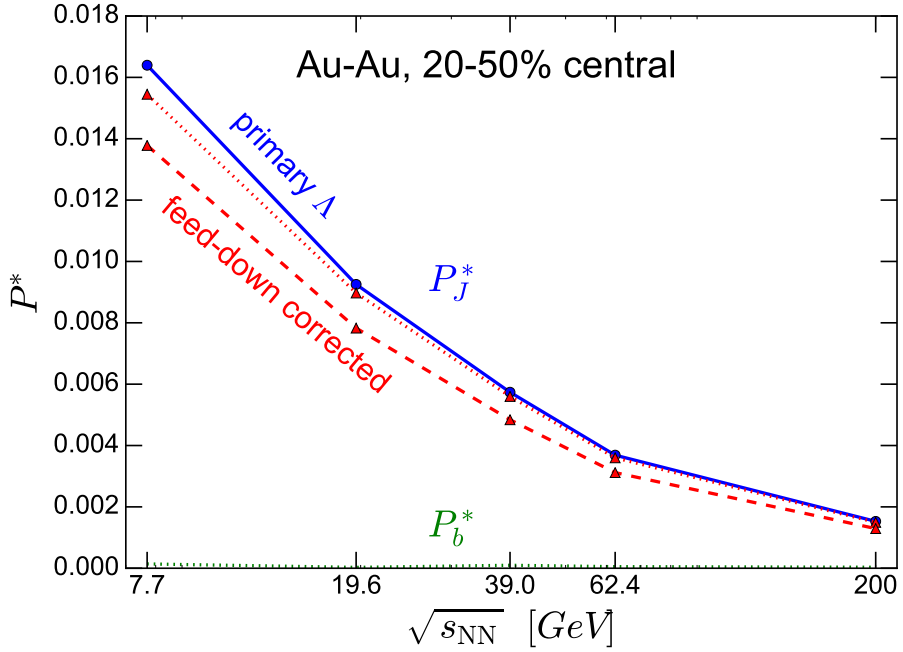
Direct $X \to \Lambda$ and two-step $X \to \Sigma^0 \to \Lambda$ decays are taken into account.

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

X	J^P	$\frac{\mathbf{S}_X}{\mathbf{S}_{\Lambda,\mathrm{prim}}}$	$C_{X\to\Lambda,\Sigma^0}$	$\frac{\mathbf{S}_{\Lambda(X)}}{\mathbf{S}_{\Lambda,\mathrm{prim}}}$
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$+\Sigma^0+\cdots+\Sigma(1670)$

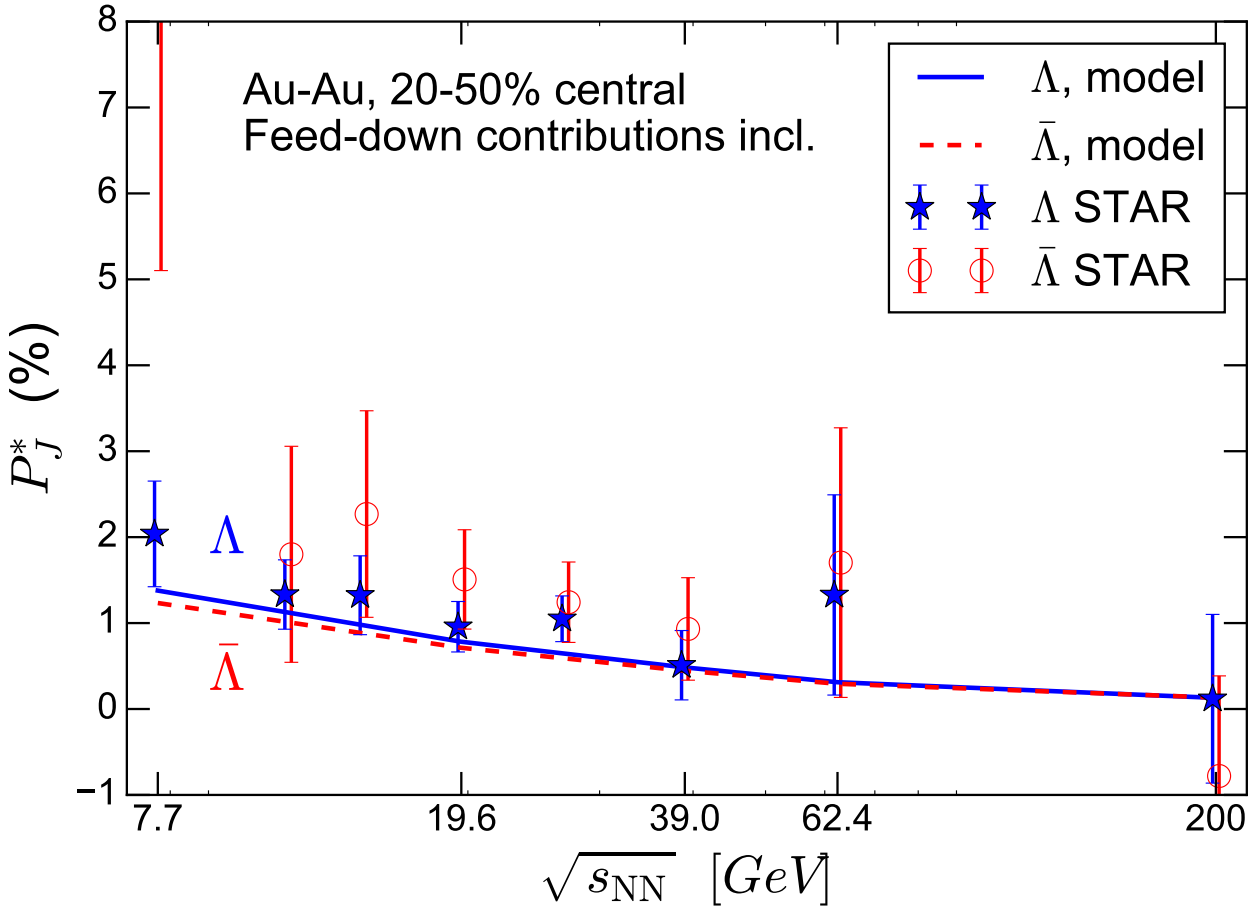


Overall feed-down effect: 15% suppression.

What is not taken into account (yet):

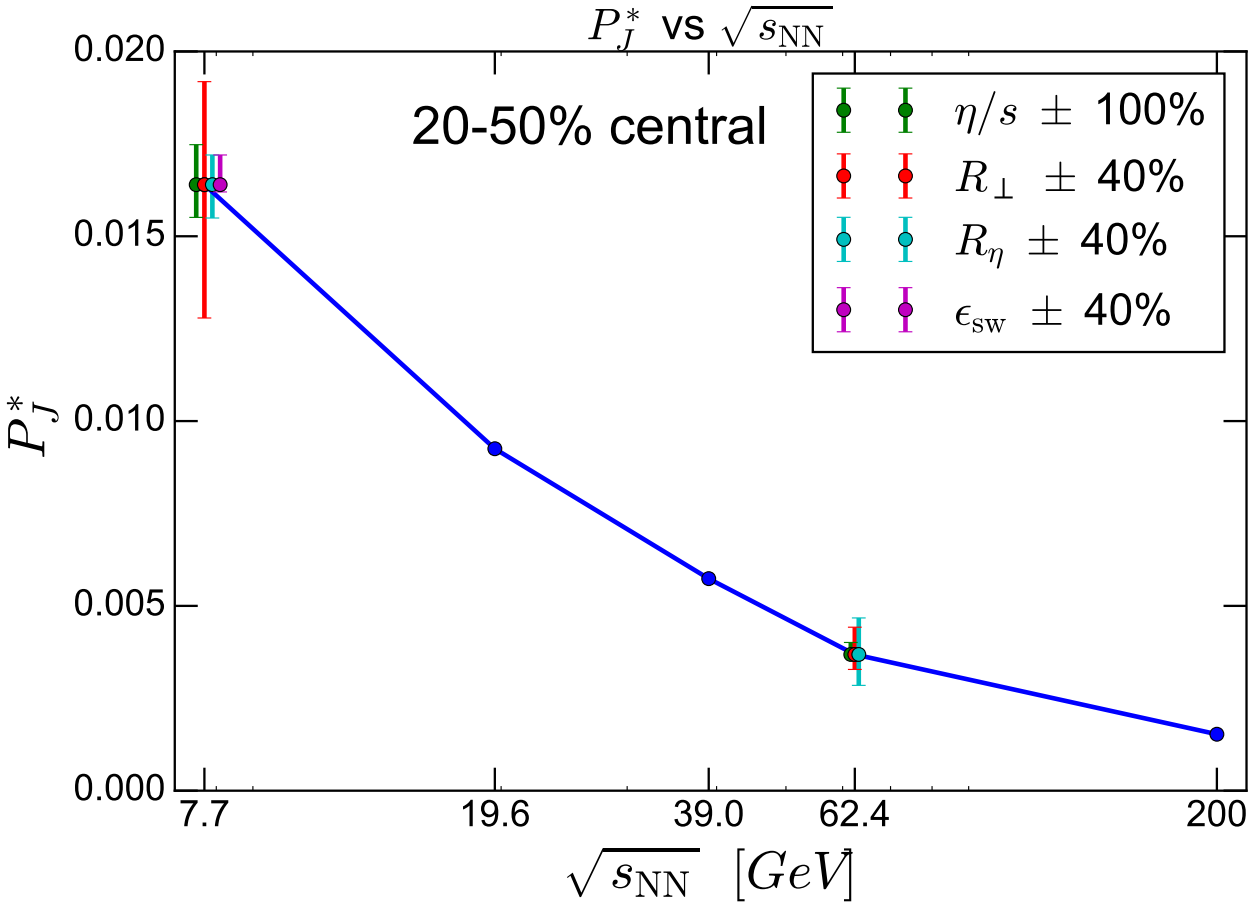
- Λ and Σ^0 actively rescatter in hadronic phase $\to$ expected to suppress polarization

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



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

Sensitivity to parameters of the model



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

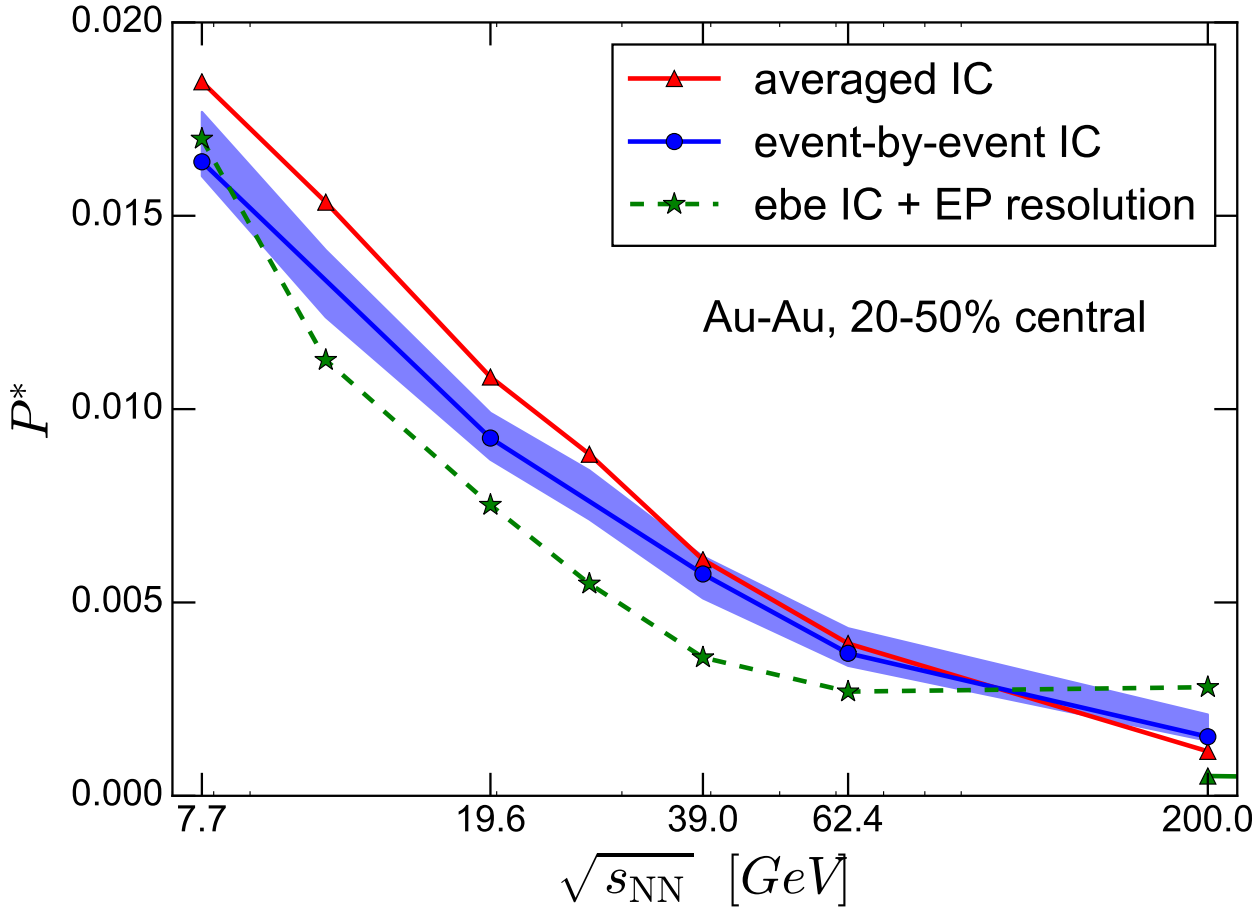
Fluid phase:
η/s: shear viscosity of fluid

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.

Event-by-event versus single-shot hydro

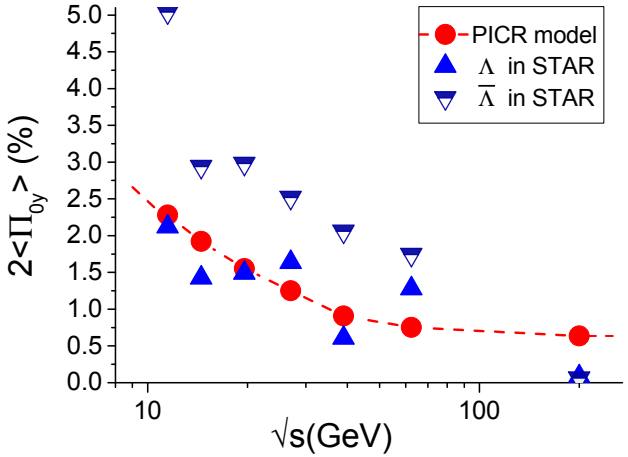
NEW



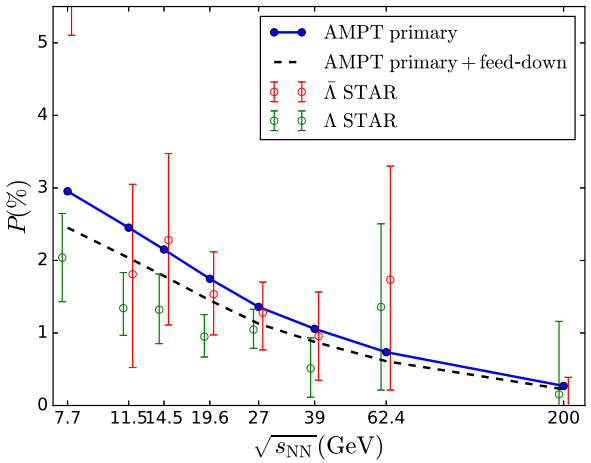
no big difference between event-by-event and single shot hydrodynamic description

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

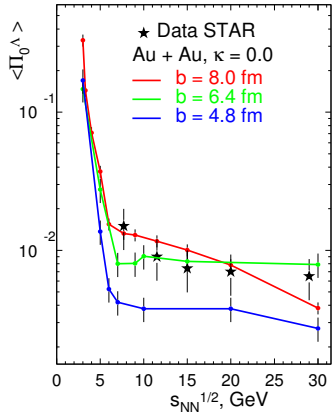
- Y.L. Xie, D.J. Wang, L.P. Csernai, Phys. Rev. C 95, 031901 (2017)



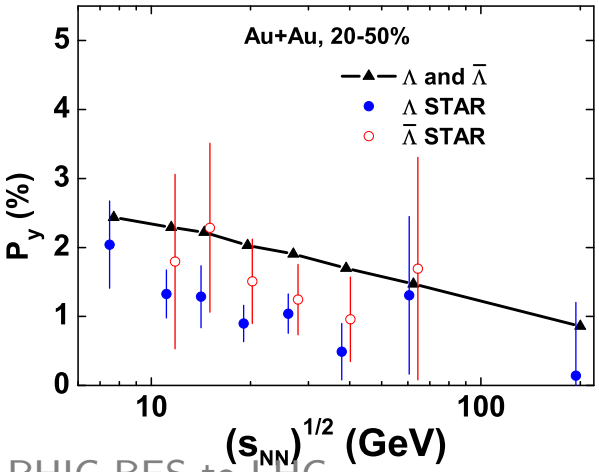
- Hui Li, Long-Gang Pang, Qun Wang, Xiao-Liang Xia, PRC 96, 054908



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

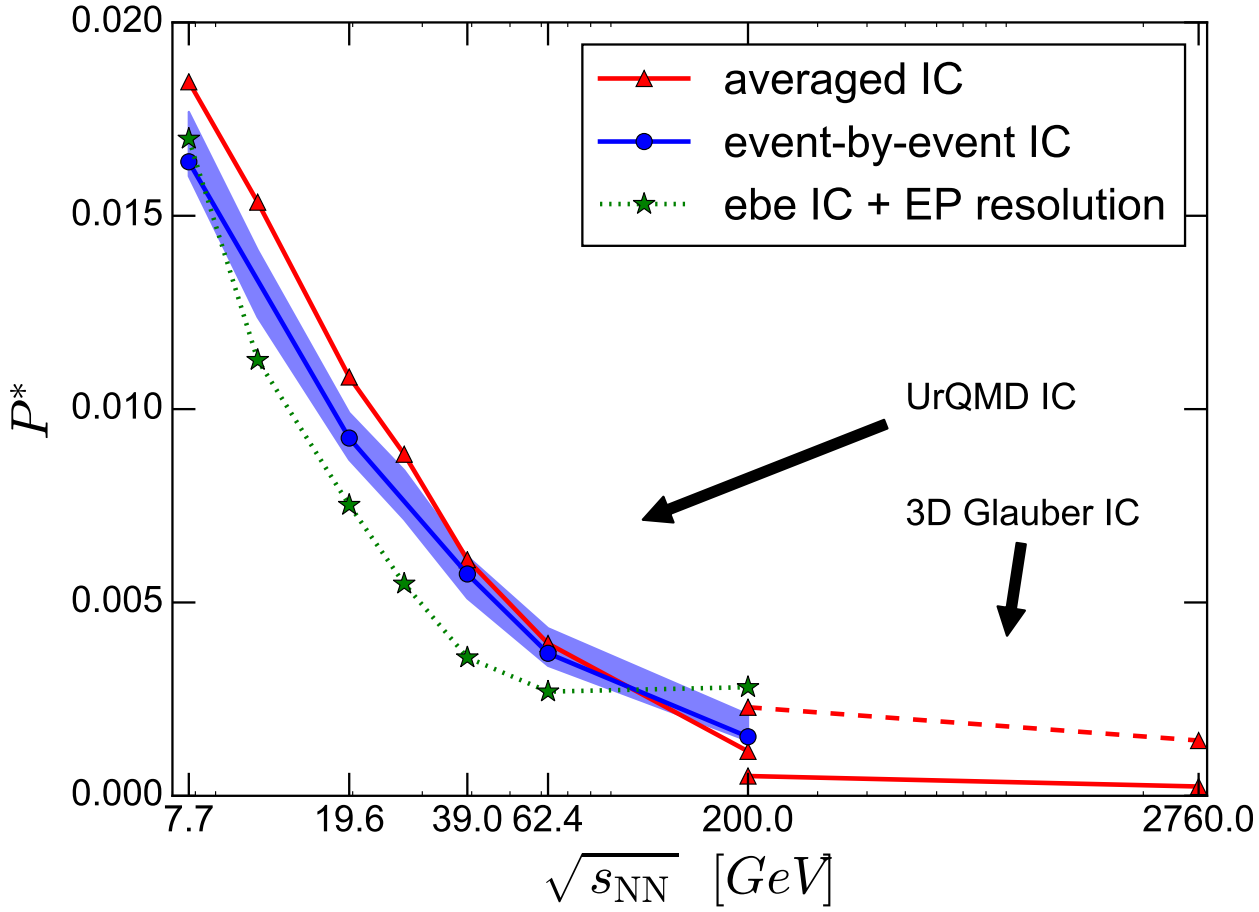


- Yifeng Sun, Che Ming Ko, Phys. Rev. C 96, 024906 (2017)



Extension to 2.76 TeV LHC

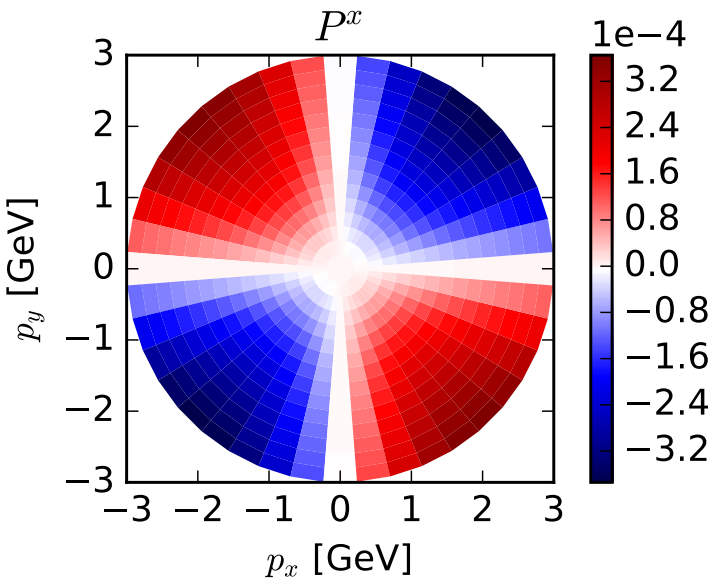
NEW

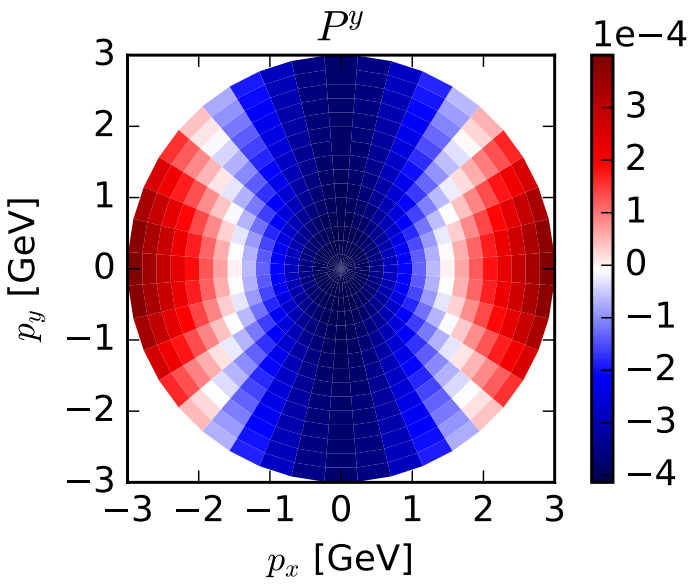


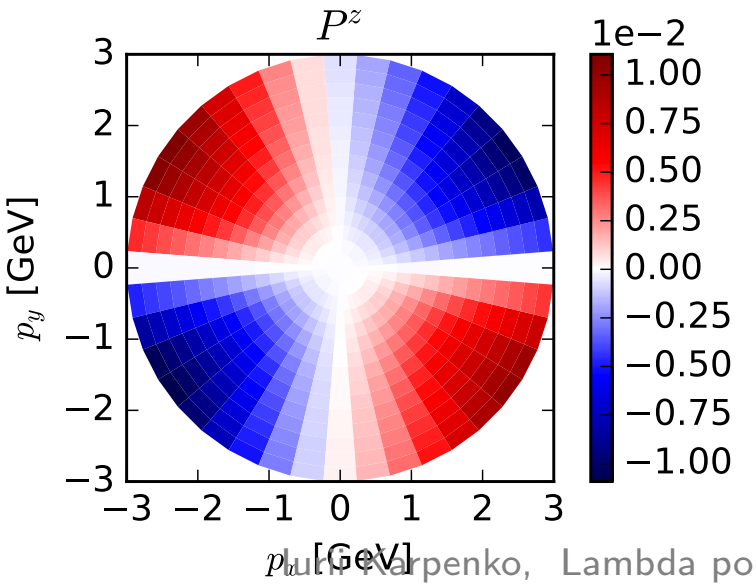
Mean polarization further decreases towards 2.76 TeV LHC energy.

At high energies, the dominant component is P^z

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





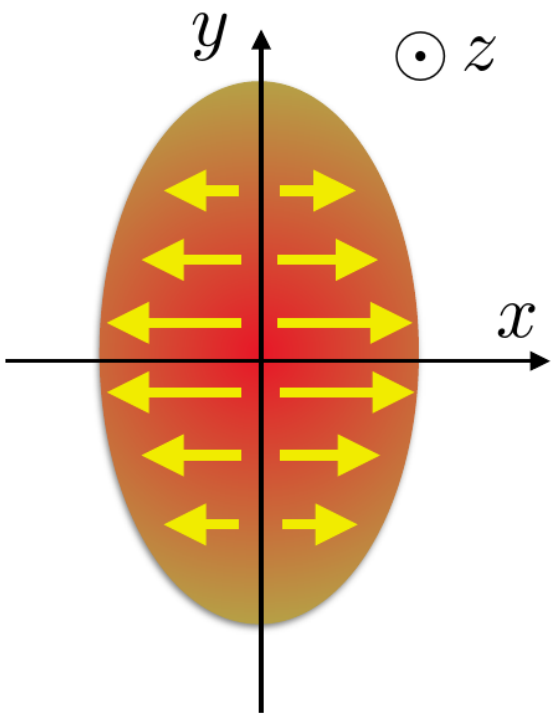


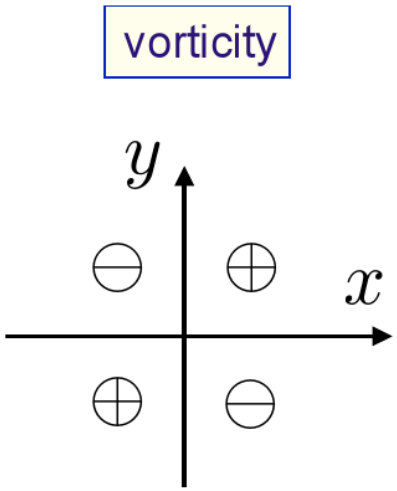
P^z is:

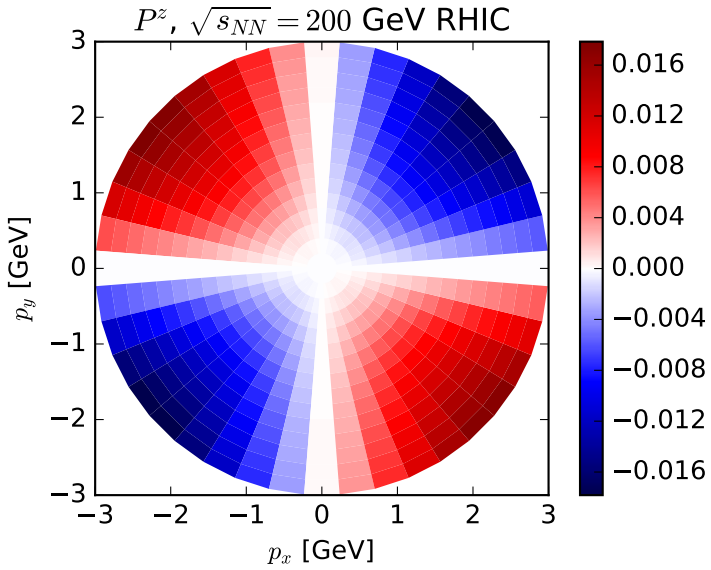
- nonzero in
  2D boost-invariant hydrodynamics
- related to transverse expansion

An oversimplified explanation of the quadrupole structure

(c) Sergei Voloshin, SQM2017

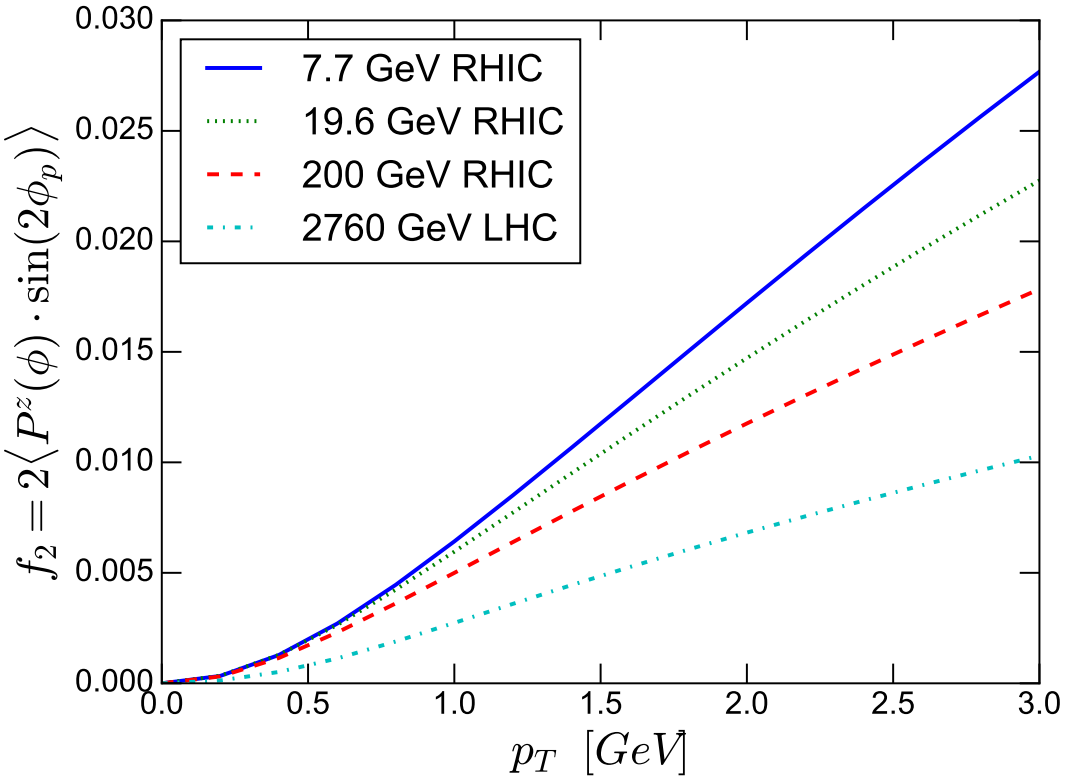






A Fourier expansion for P^z

$$P^z(\mathbf{p_T}, y=0) = \sum_{k=1}^{\infty} f_{2k}(p_T) \sin 2k(\phi_p - \Psi)$$



- requires identification of event plane Ψ
- Blast-Wave model:

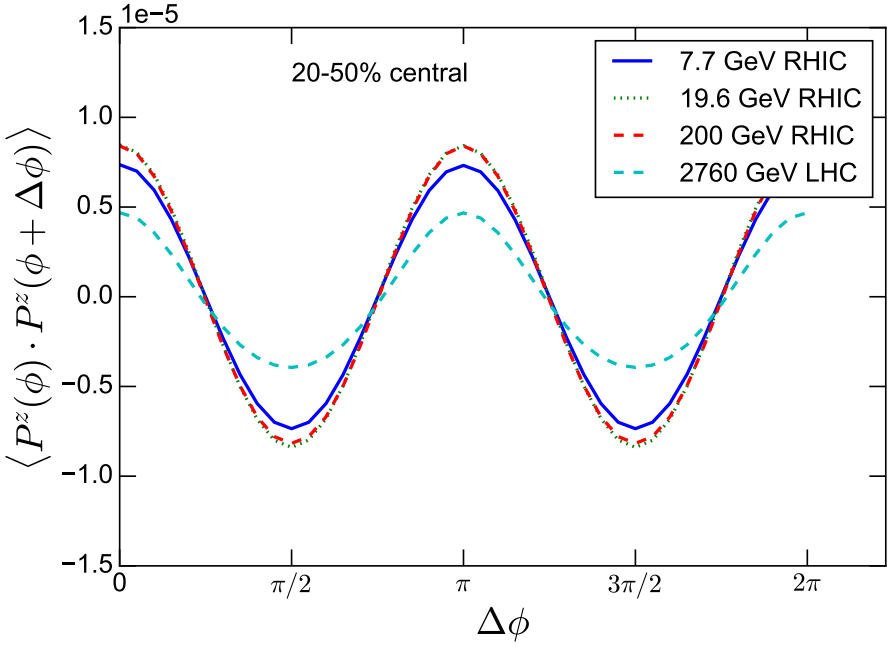
$$f_2(p_T) = 2\frac{dT}{d\tau}\frac{1}{mT}v_2(p_T)$$

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

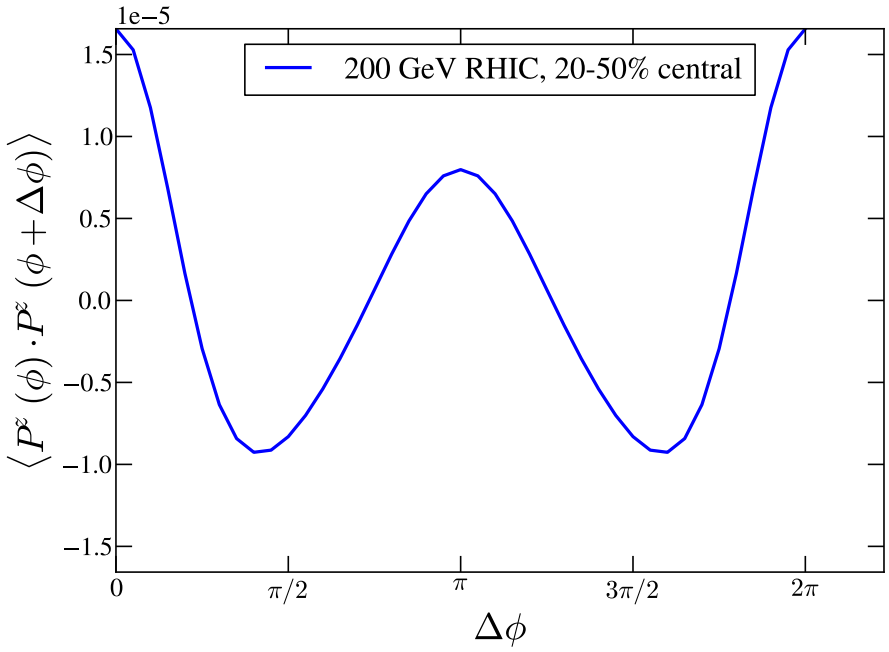
This can be also accessed via correlation of P^z of Λ pairs

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

single-shot hydro



event-by-event hydro



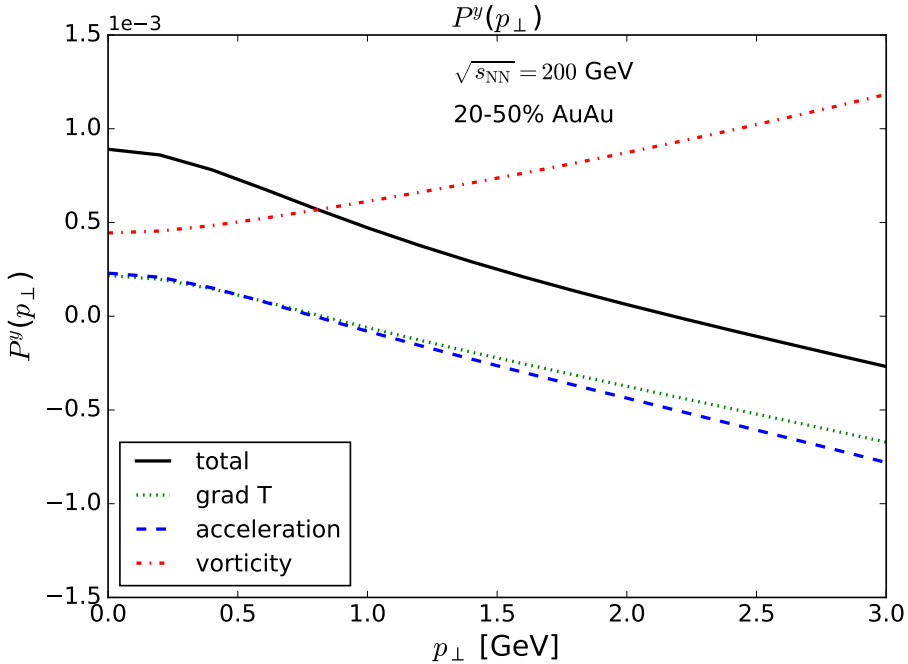
Similar results: Long-Gang Pang et al, Phys.Rev.Lett. 117 (2016) no.19, 192301
Λ spin correlations due to vorticity induced by initial state fluctuations

What causes transverse and longitudinal components of polarization?

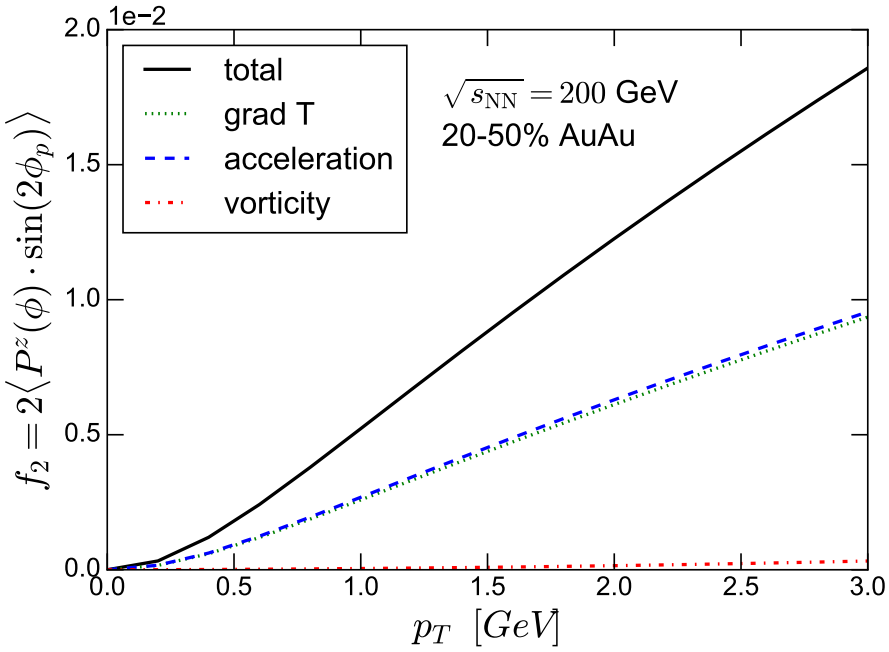
$$S^\mu \propto \varepsilon^{\mu\rho\sigma\tau}\varpi_{\rho\sigma}p_\tau = \varepsilon^{\mu\rho\sigma\tau}(\partial_\rho\beta_\sigma)p_\tau =$$

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

Global transverse P_J:



Longitudinal quadrupole f_2:

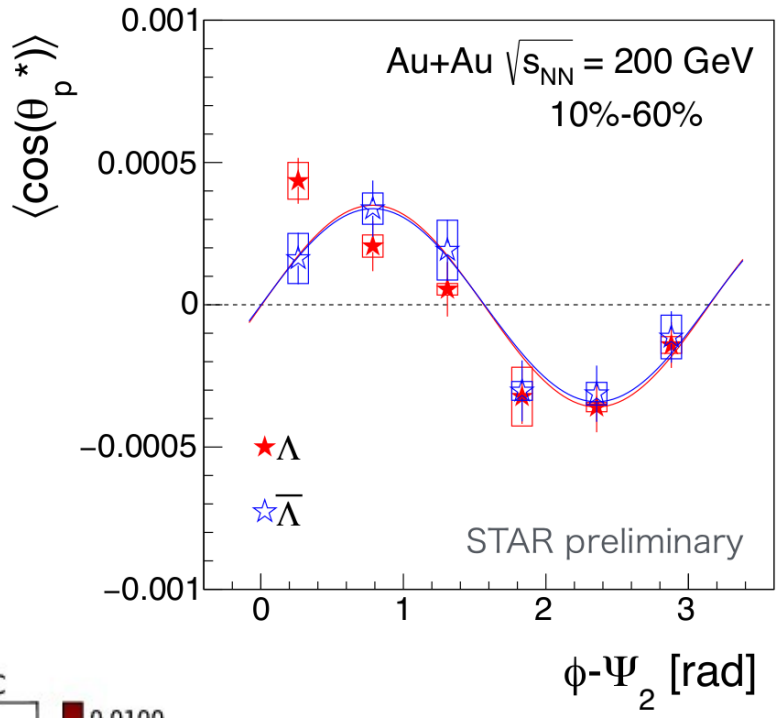


- P^J at low $p_\perp$ is dominated by vorticity
- P^z is dominated by acceleration and gradients of temperature

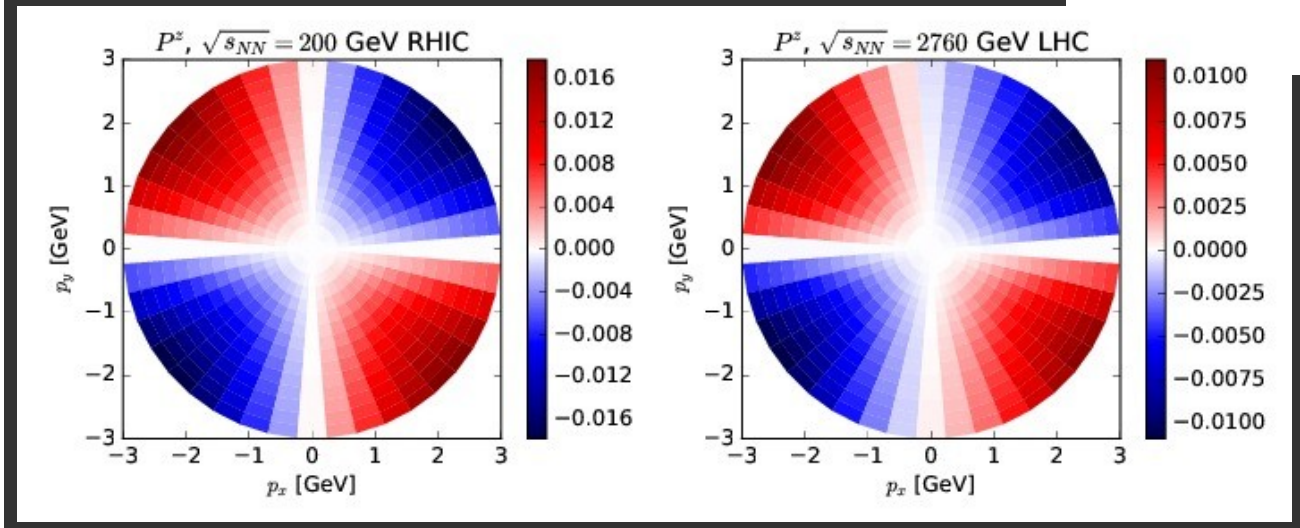
A *sign problem* for the longitudinal component

Quadrupolar structure of longitudinal polarization in the transverse momentum plane, as predicted.
Spectacular confirmation of hydro predictions... yet with a flipped sign!

- Hydro initial conditions? (polarization is a sensitive probe of the initial flow)
- Incomplete local thermodynamic equilibrium for the spin degrees of freedom (spin kinetic theory)?
- Effect of spin dissipative transport coefficients?
- Effect of initial state fluctuations?
- Effect of decays?
- Error in the calculation



Z. Ye, T. Niida, Quark Matter 2018



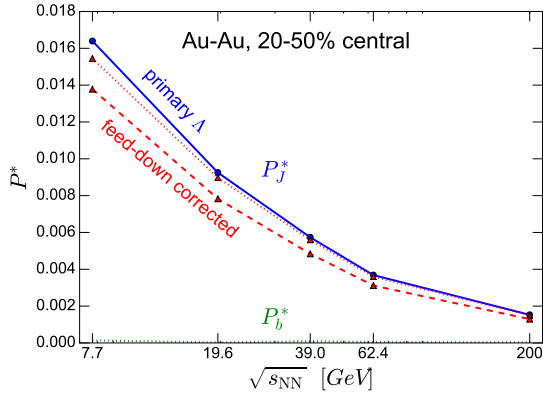
F. B., I. Karpenko, Phys. Rev. Lett. 120 (2018) 012302
S. Voloshin, in SQM 2017

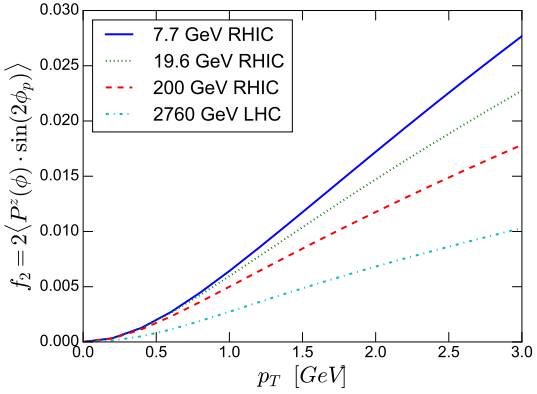
Same pattern found in AMPT+thermal vorticity calculation X. L. Xia, H. Li, Z. B. Tang and Q. Wang, 1803.00867

Summary

Λ polarization in vHLLE+UrQMD, a 3D viscous hydro + cascade model:

- We observe a strong increase of global mean polarization of Λ along the angular momentum direction towards lowest RHIC BES and FAIR/NICA 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.
- FAIR/NICA: both components of polarization should reach several %, can be easily measurable!
- $P^z(p_T)$ 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(ϖ_{xz}), $P^z \Leftrightarrow$ transverse acceleration / grad T.





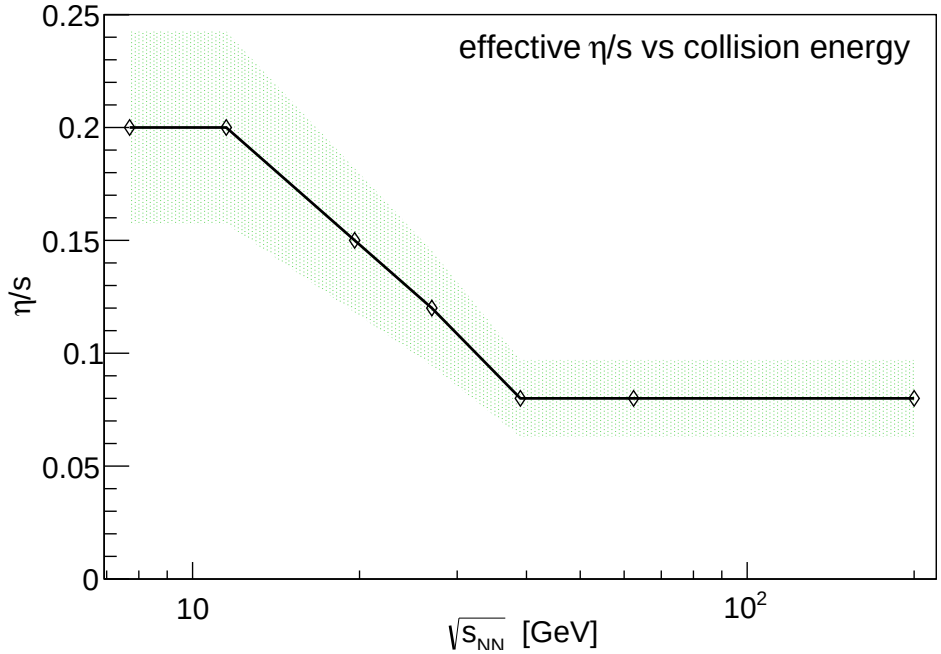
Backup slides

Parameter values used to approach the basic hadronic observables

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

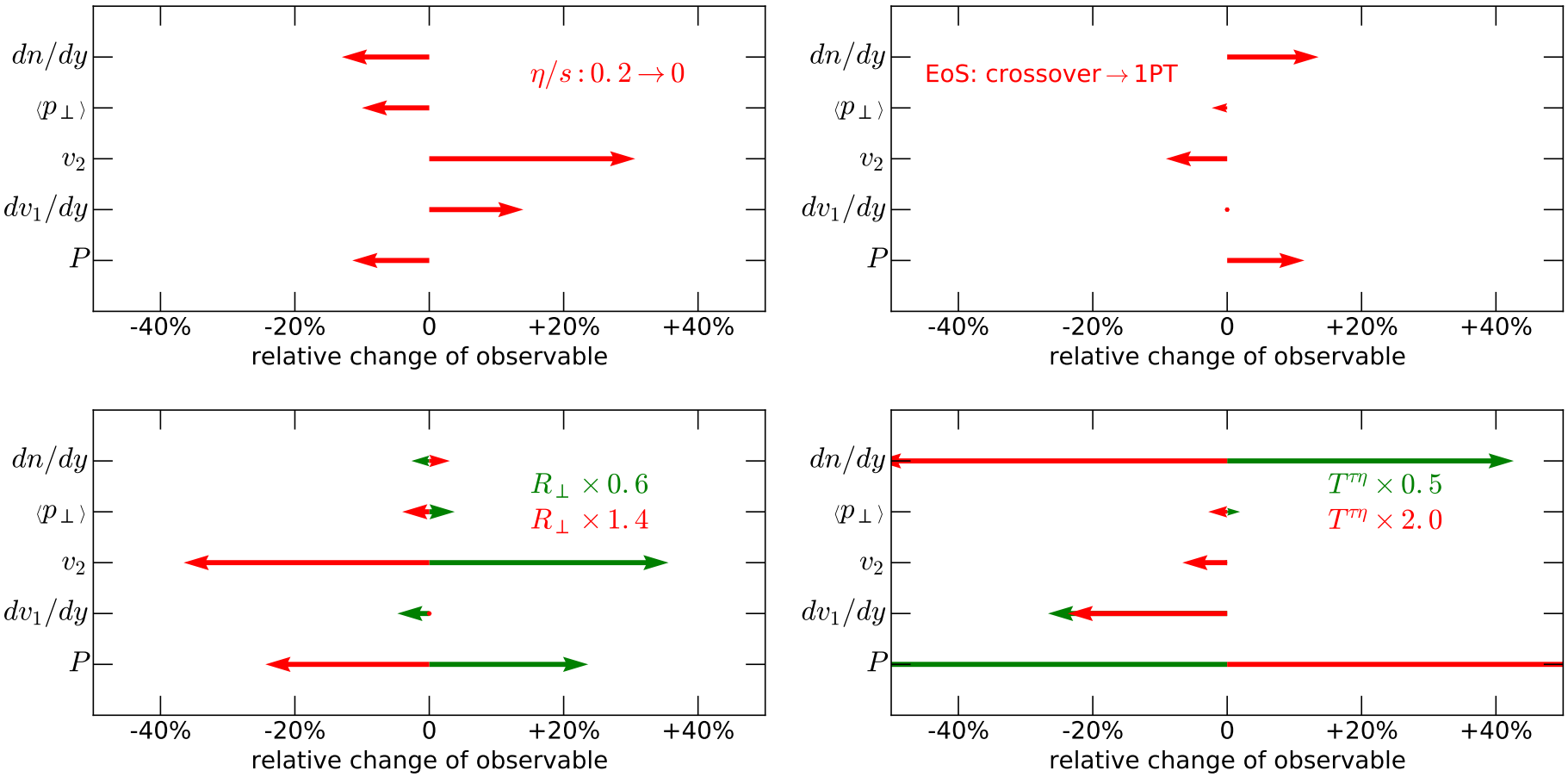
! Actual error bar would require a proper χ^2 fitting of the model parameters (and enormous amount of CPU time).

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

A closer look at the parameter dependence

NEW

$\sqrt{s_{\rm NN}} = 7.7$ 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 $\varepsilon_{\rm sw}$.