$\Lambda-$polarization in heavy-ion collisions at 7.7-200 GeV

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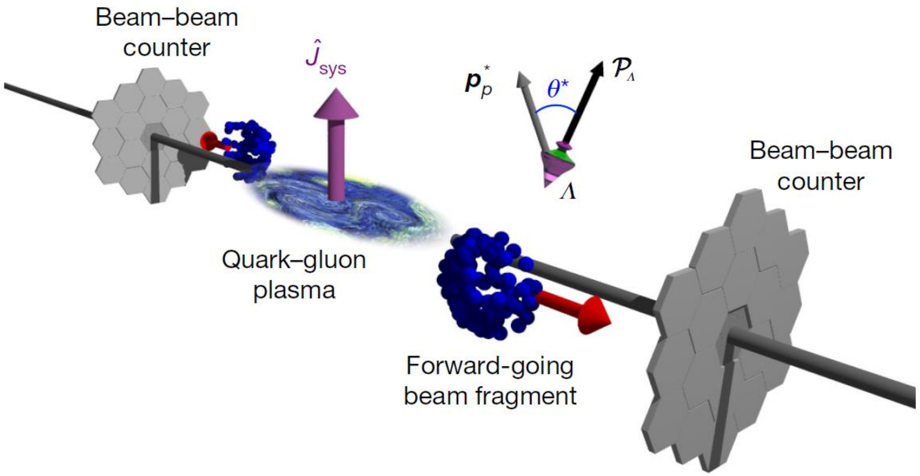
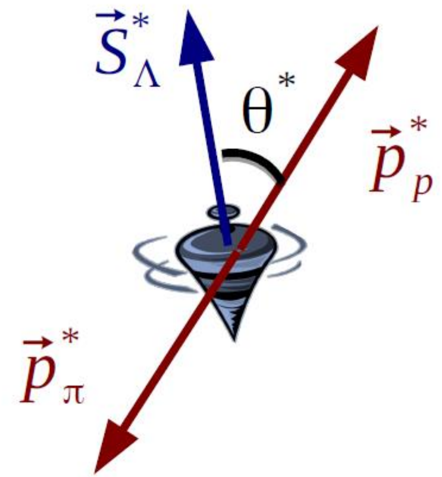
第十七届全国核物理大会，武汉

Introduction

Polarization:



STAR Collaboration, Nature 548, 62 (2017)



Niida, Quark Matter 2018

- Global polarization: Spin-orbital correlation
- Local polarization: Structure in momentum space
- Measurements: parity-violating decay of hyperons

$$\Lambda \to p + \pi^-$$

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_H \mathbf{P}_H \cdot \mathbf{p}_\mathbf{p}^*)$$

P_H: Λ polarization

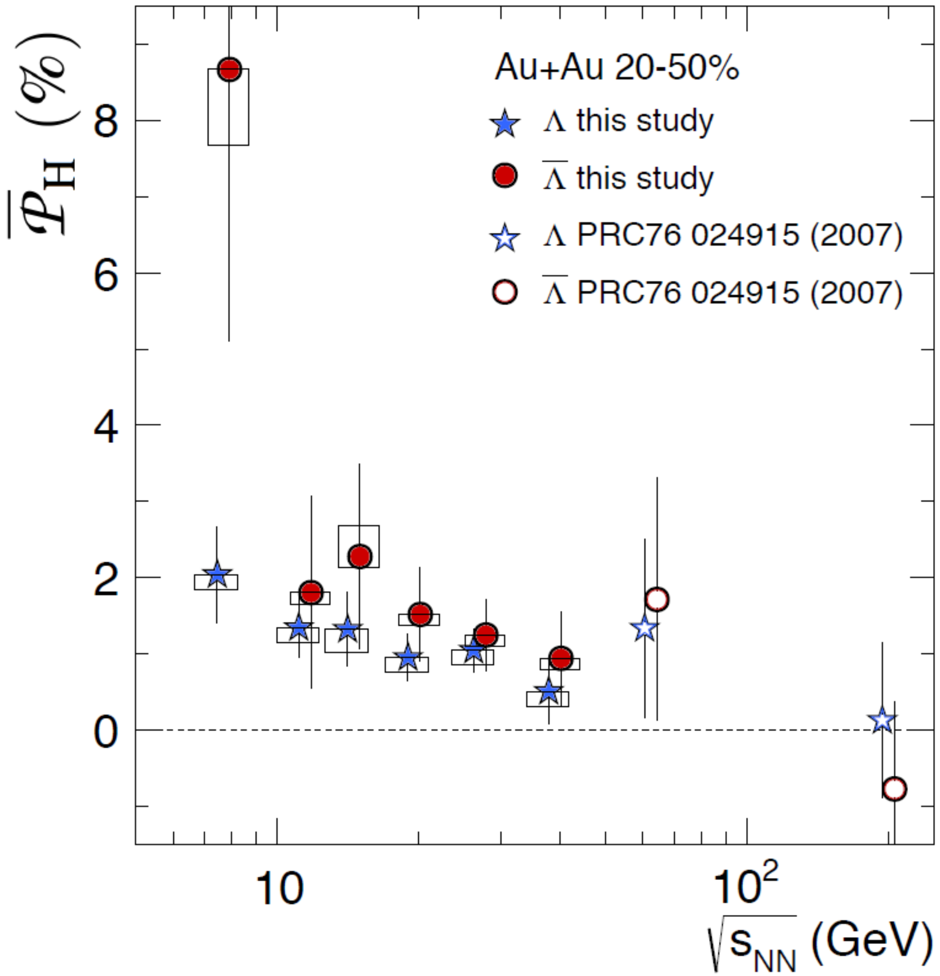
p_p^*: proton momentum in Λ rest frame

α_H: Λ decay parameter

($\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.642 \pm 0.013$)

Global Polarization:

STAR Collaboration, Nature 548, 62 (2017)

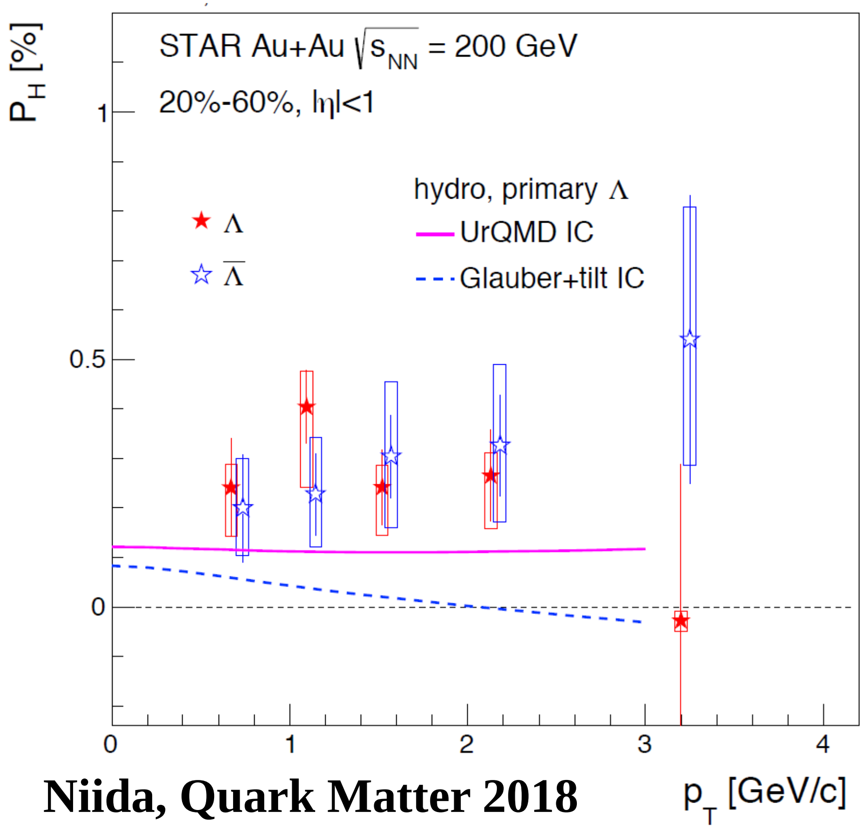


The most vortical fluid ever observed!

$$\omega = (P_\Lambda + P_{\bar{\Lambda}})k_B T/\hbar \sim 10^{22} s^{-1} \quad (T = 160 \text{ MeV})$$

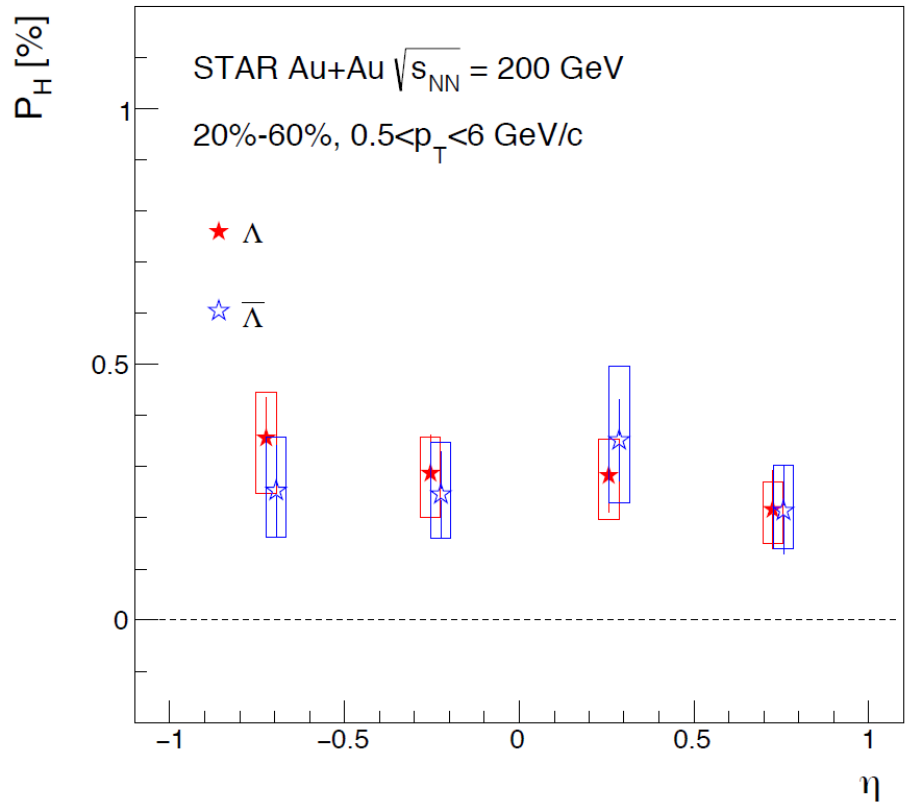
Local Polarization:

p_T − dependence of P_H



Niida, Quark Matter 2018

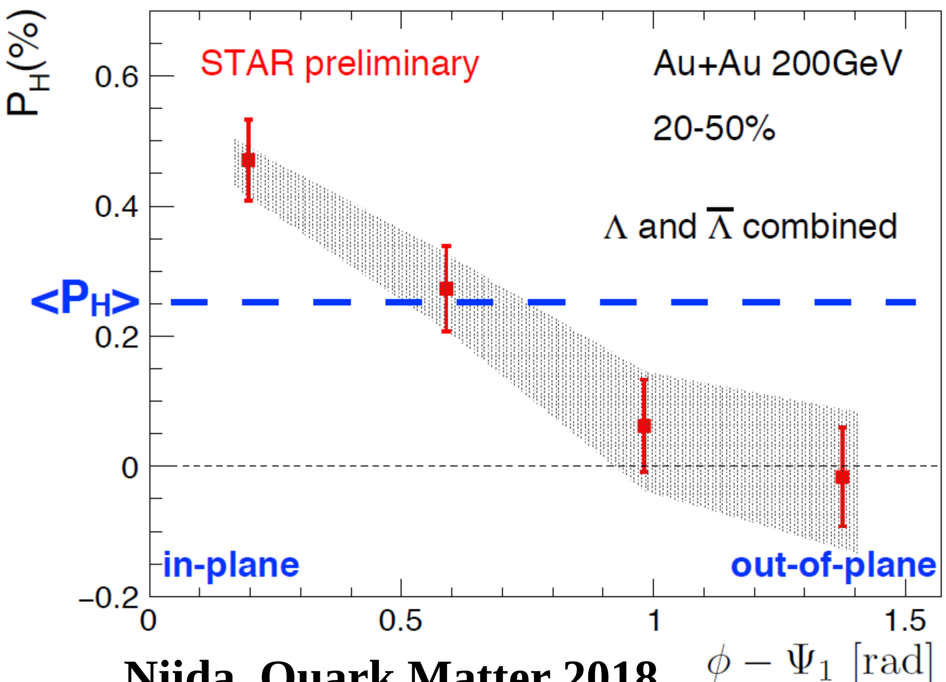
η − dependence of P_H



- No significant dependence on p_T/η

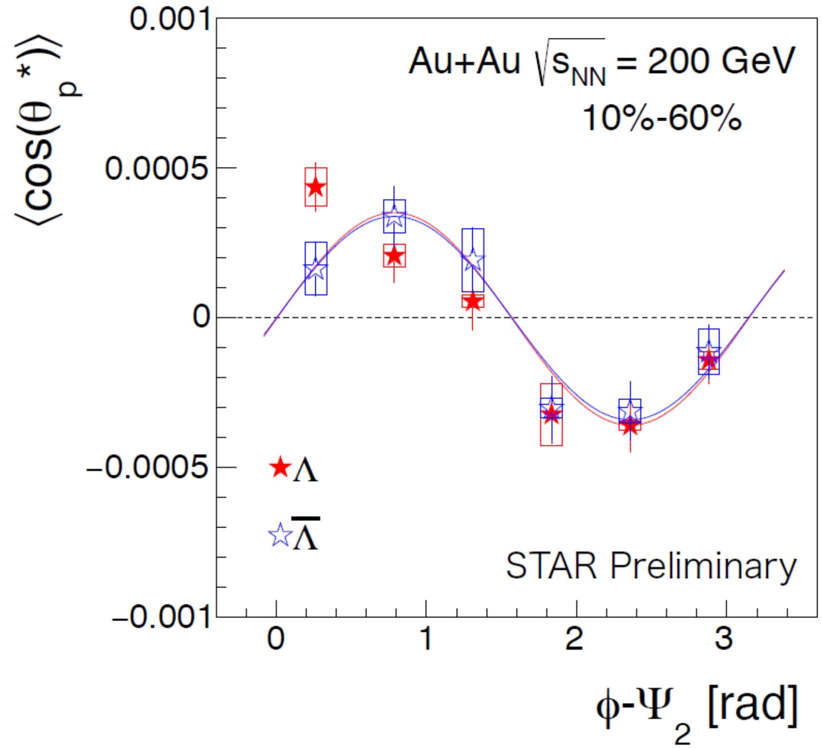
Local Polarization:

azimuthal dependence of P_H



Niida, Quark Matter 2018

azimuthal dependence of P_Z



- Significant ϕ-dependence of the polarization along y/z direction

Polarization (The theory side):

- **Early works:**

Polarization from global orbital angular momentum by spin-orbital correlation

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

Polarized secondary particles in un-polarized hadron-hadron collisions

Voloshin nucl-th/0410089

- **Spin-vorticity coupling**

local thermodynamic equilibrium for spin degree of freedom

- Statistical-hydro model **F. Becattini, et al. Annals Phys. 338 32 (2013).**
- Kinetic model with Wigner functions **R. Fang, et al. Phys. Rev. C94 (2016) 024904**

$$\boxed{S^{\mu}(x,p) = -\frac{1}{8m}\big(1-f(x,p)\big)\epsilon^{\mu\nu\rho\sigma}p_{\sigma}\varpi_{\nu\rho}}$$

$$\boxed{P^{\mu} = \frac{1}{S}S^{\mu}}$$

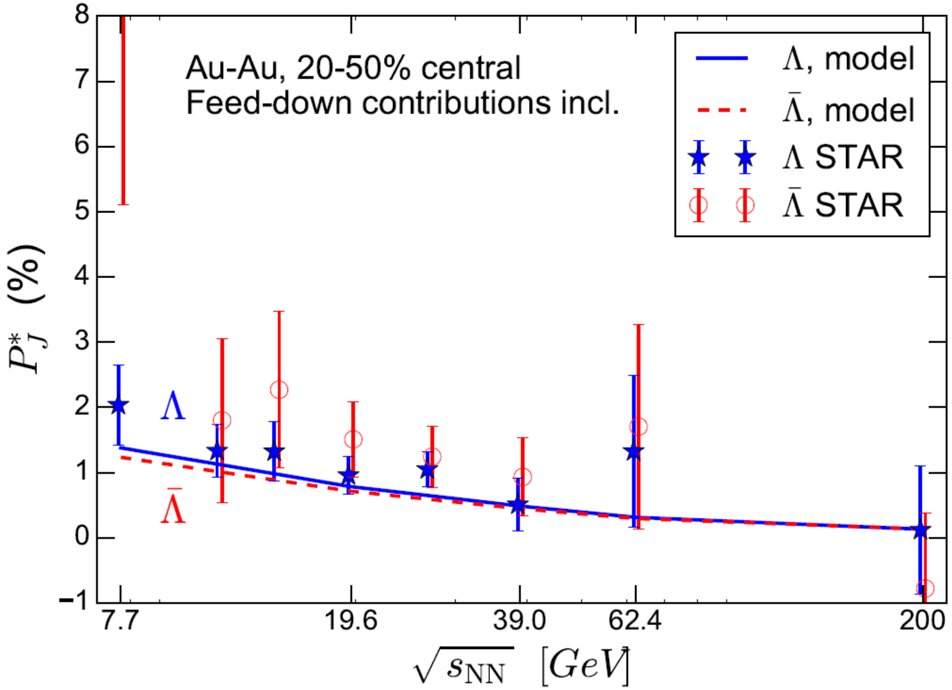
Thermal vorticity: $\varpi_{\mu\nu} = -\frac{1}{2}(\partial_{\mu}\beta_{\nu} - \partial_{\nu}\beta_{\mu})$

$\beta_{\mu} = u_{\mu}/T$

Some results from spin-vorticity coupling model

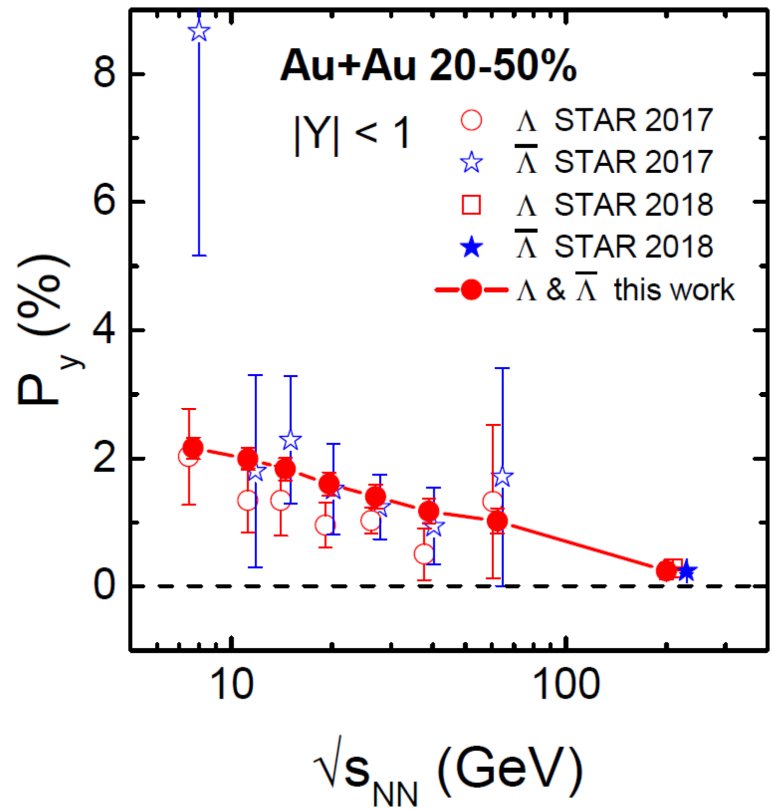
UrQMD + Hydro

I. Karpenko, Quark Matter 2018



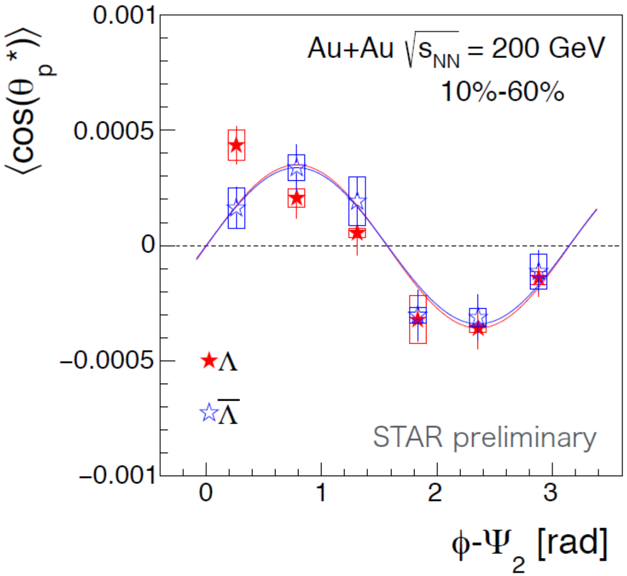
AMPT

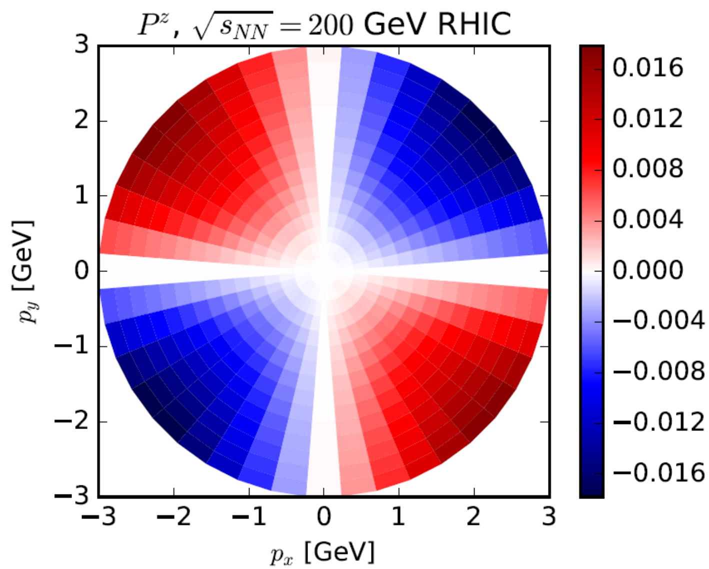
Wei, Deng and Huang,
Phys.Rev. C99 (2019) no.1, 014905



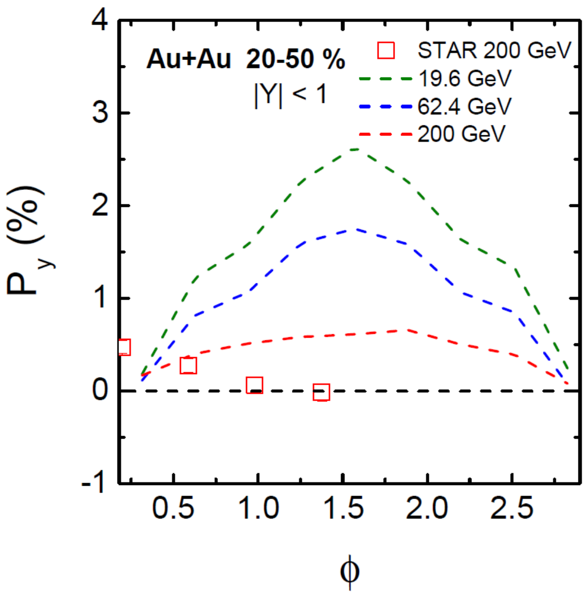
Global trend could be reproduced by hydro and non-hydro models

Some results from spin-vorticity coupling model





UrQMD + Hydro
I. Karpenko,
Quark Matter 2018



AMPT
Wei, Deng and Huang,
Phys.Rev. C99 (2019) no.1, 014905

But for local structure, models show opposite sign or opposite trend

Polarization from the Hybrid model

B. Fu, K. Xu, H. Song and X. Huang,
in preparation

The hybrid model:

AMPT → MUSIC → iSS → UrQMD

AMPT: Providing $T^{\mu\nu}$ *and* N^{μ} as the hydro initial condition at hypersurface $\tau = \tau_0$

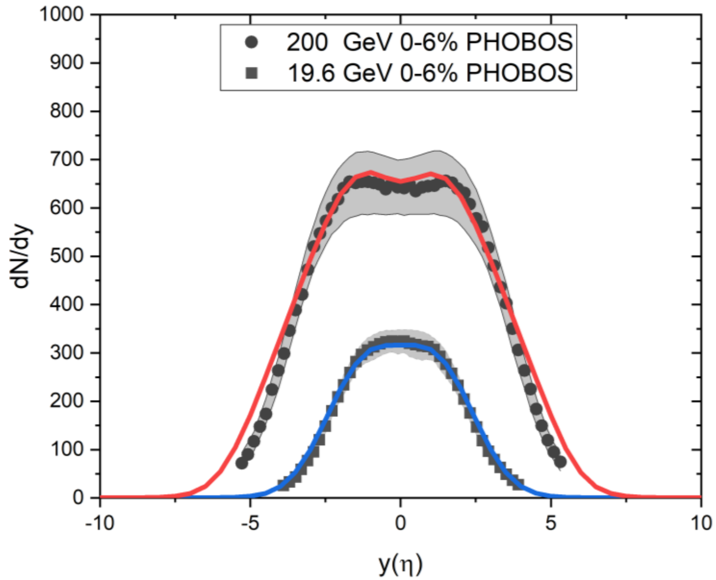
MUSIC: 3+1-d viscous hydrodynamics

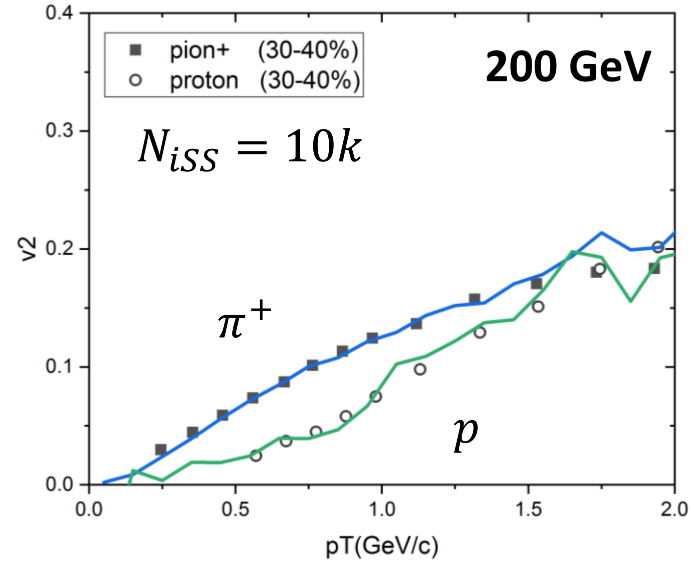
iSS: Monte-Carlo particle generator on the freeze-out surface

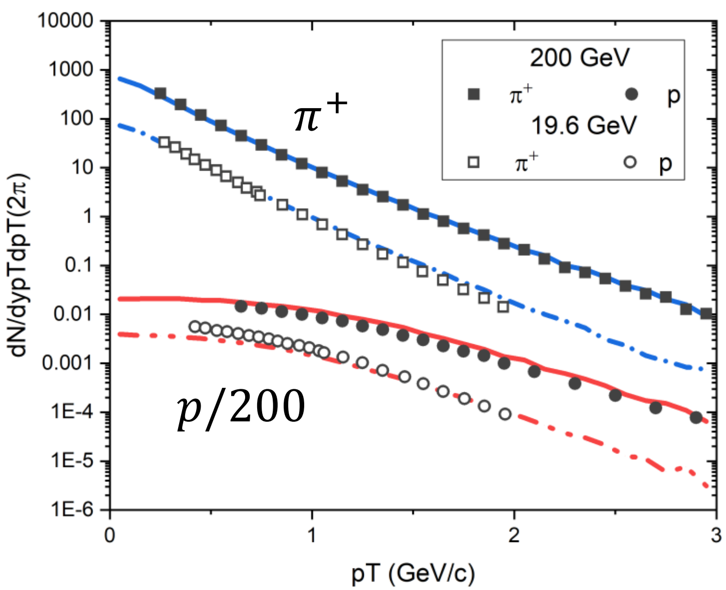
UrQMD: Hadron cascade model

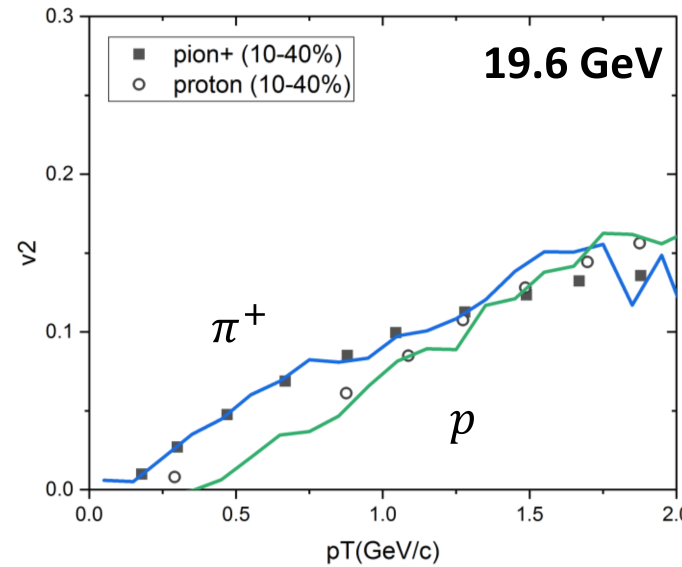
AMPT: Z. Lin, C. Ko, B. Li, B. Zhang and S. Pal, Phys.Rev. C72 (2005) 064901
iSS: ©Zhi Qiu and Chun Shen
MUSIC: B. Schenke, S. Jeon and C. Gale, Phys.Rev. C82 (2010) 014903
UrQMD: M. Bleicher, et al. arXiv:hep-ph/9909407

Bulk hadronic observables:









Soft observables(dN_{ch}/dy, spectra, $v_2(p_T)$)
fit well from top RHIC to BES energies.

From vorticity to polarization:

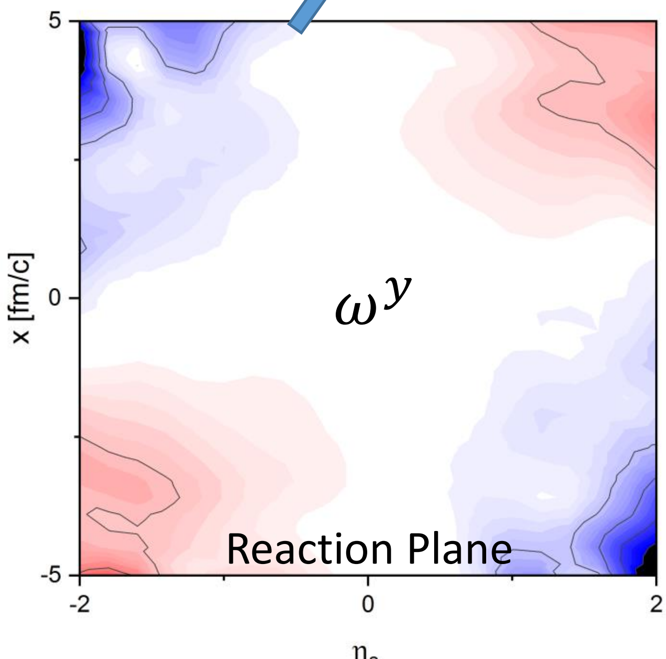
Polarization in the model: integration on the freeze-out surface

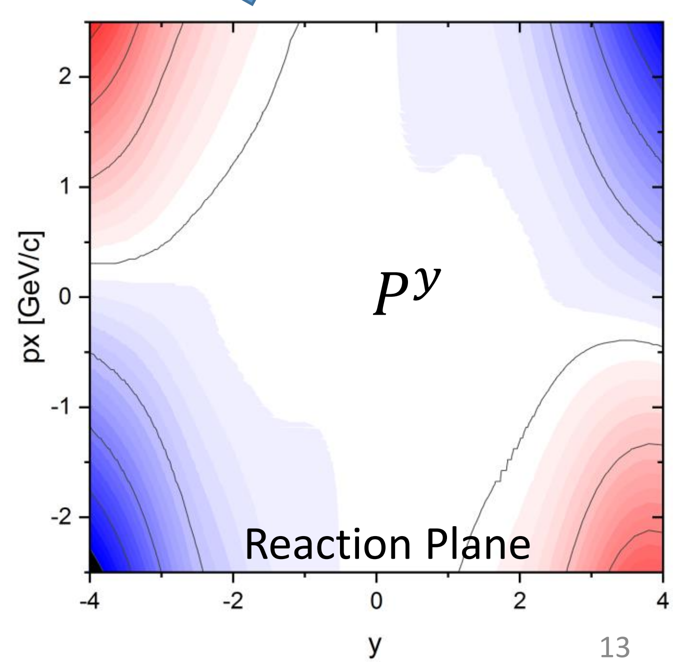
$$P^{\mu}(p) = \frac{1}{N}\int p\cdot d\Sigma \;\; f(x,p)P^{\mu}(x,p) = \frac{1}{4m}\cdot\frac{\int p\cdot d\Sigma \;\; \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}\bar{\omega}_{\sigma\rho}p_{\nu}\; n_F(1-n_F)}{\int p\cdot d\Sigma\; n_F}$$

AMPT → MUSIC → iSS → UrQMD

Vorticity from IC

Polarization on the freeze-out surface





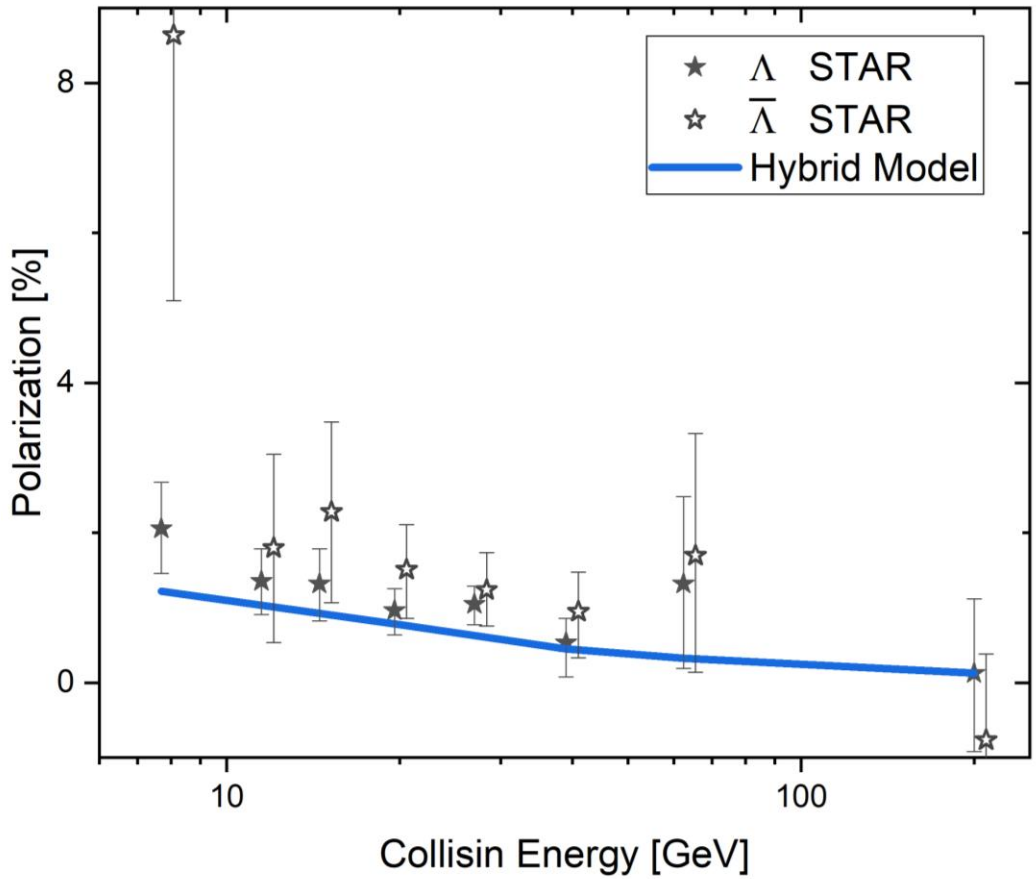
B. Fu, K. Xu, H. Song and X. Huang, in preparation

Λ – polarization results

Global Polarization results:

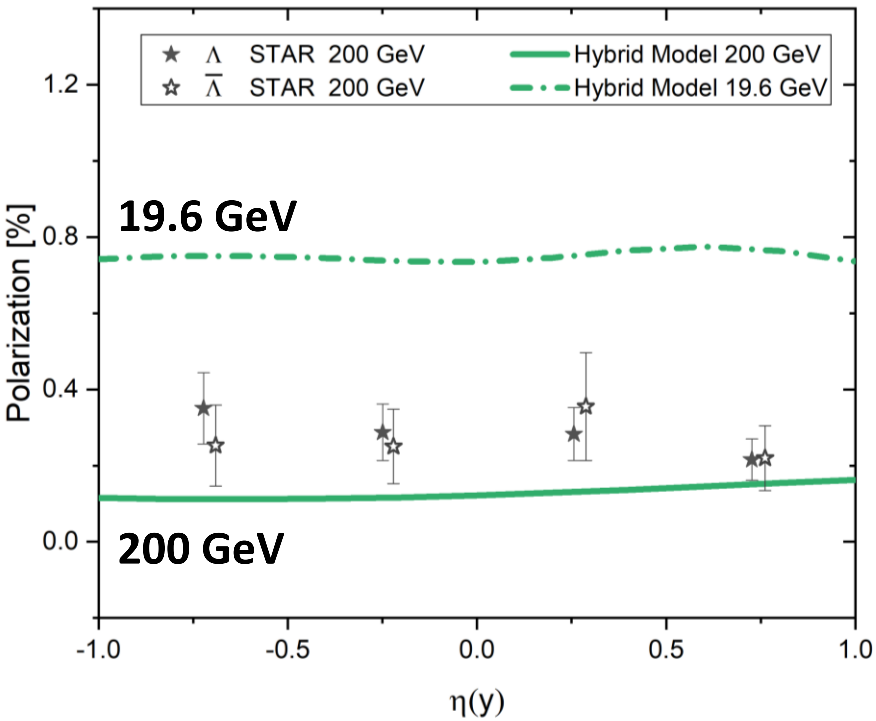
$$P_H = \int p_T dp_T dy d\phi_p \ P_y^*(p_T, \phi_p, y)$$

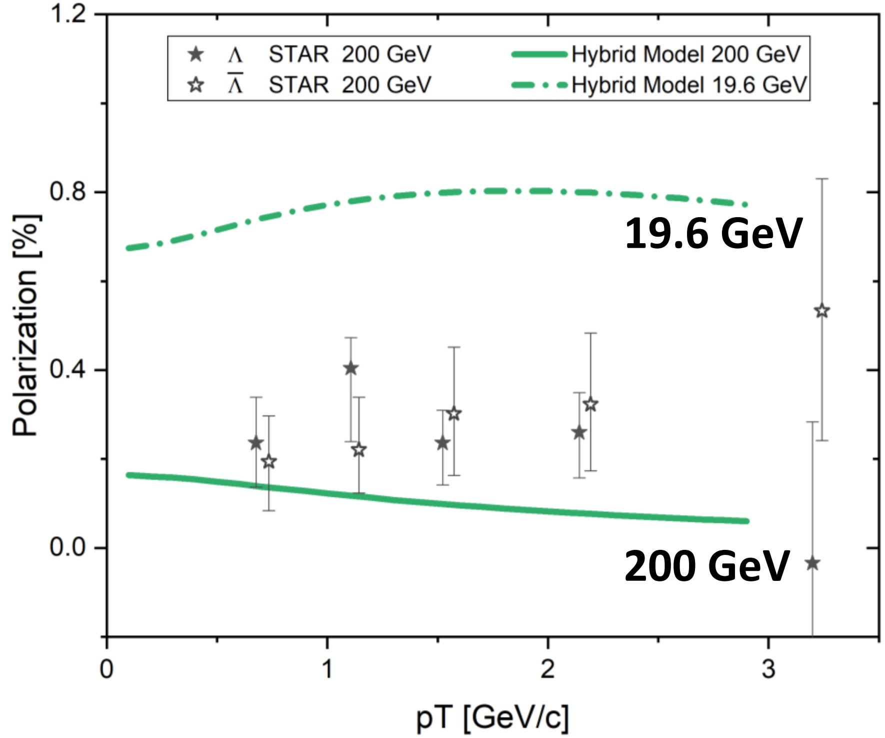
$P^*: boost\ to\ the\ particle's\ rest\ frame$



The trend corresponding to the experiment data

$\eta - dependence$ $p_T - dependence$





$$P_H(y) = \int p_T dp_T d\phi_p \;\; P_y^*(p_T, \phi_p, y)$$

$$P_H(p_T) = \int dy d\phi_p \;\; P_y^*(p_T, \phi_p, y)$$

- At 200 GeV, no significant dependence in the longitudinal and transverse distribution
- At low energies, Hybrid model predicts a similar trend

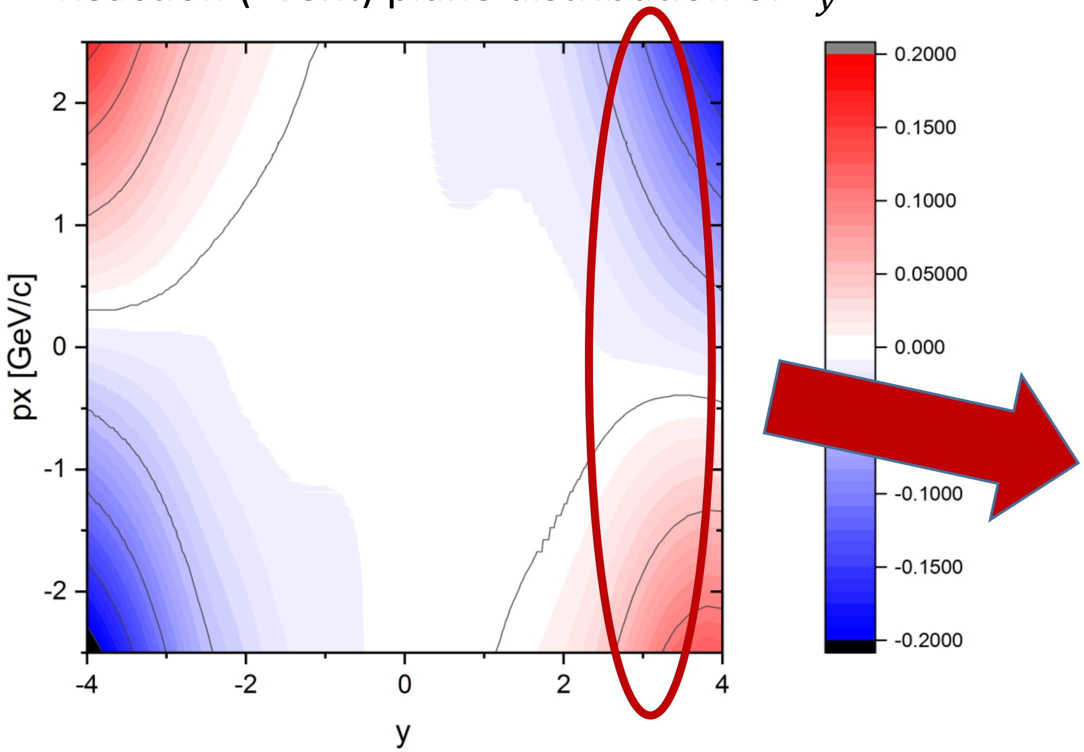
Reaction plane distribution of P^y

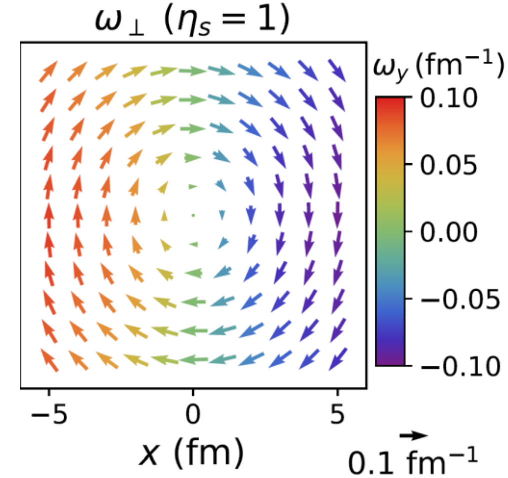
- Circular polarization at finite rapidity region

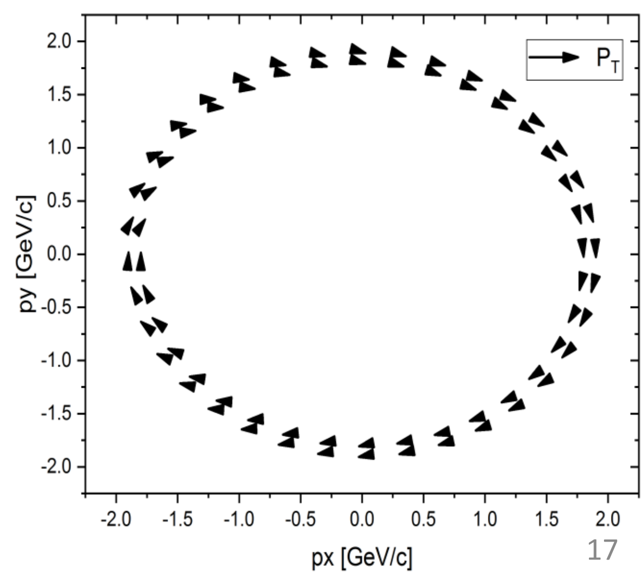
  Same as XiaoLiang's result

X. Xia, et al.
Phys.Rev. C98 (2018) 024905

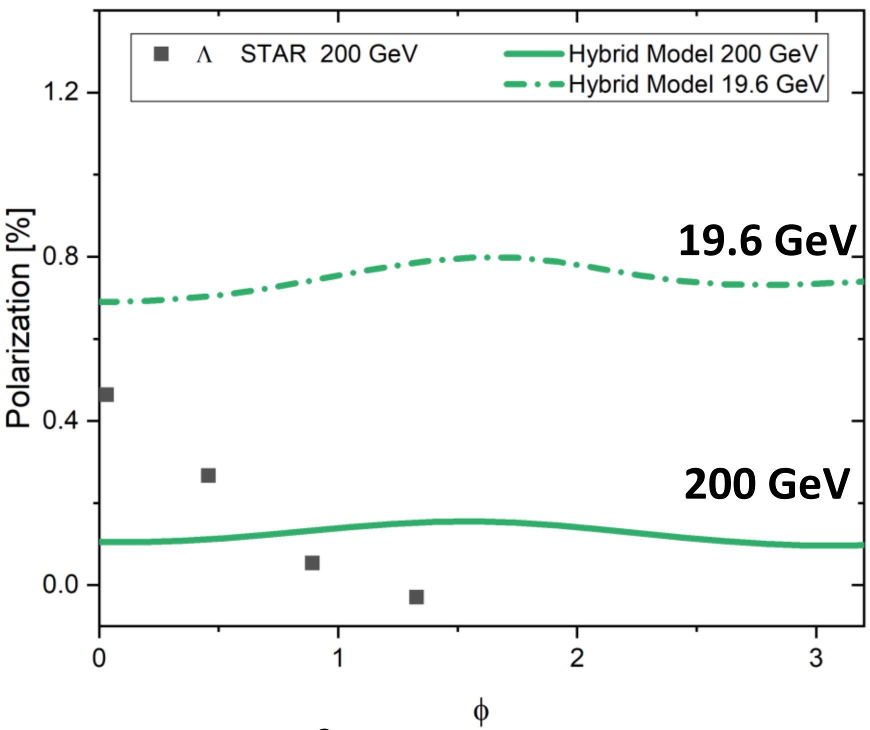
Reaction (Event) plane distribution of P_y



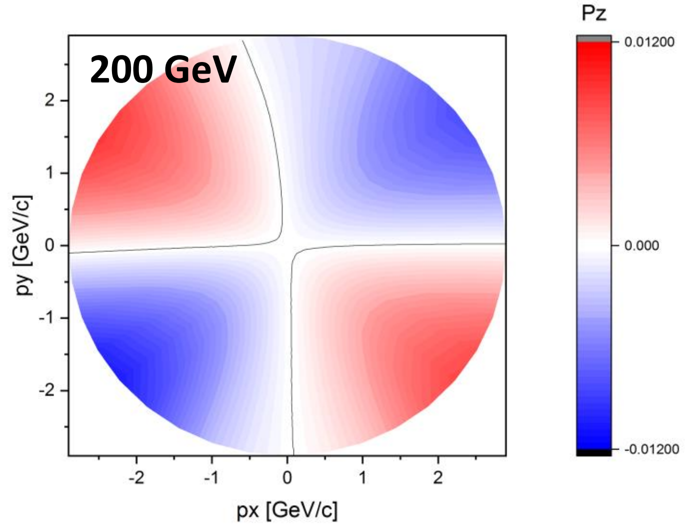


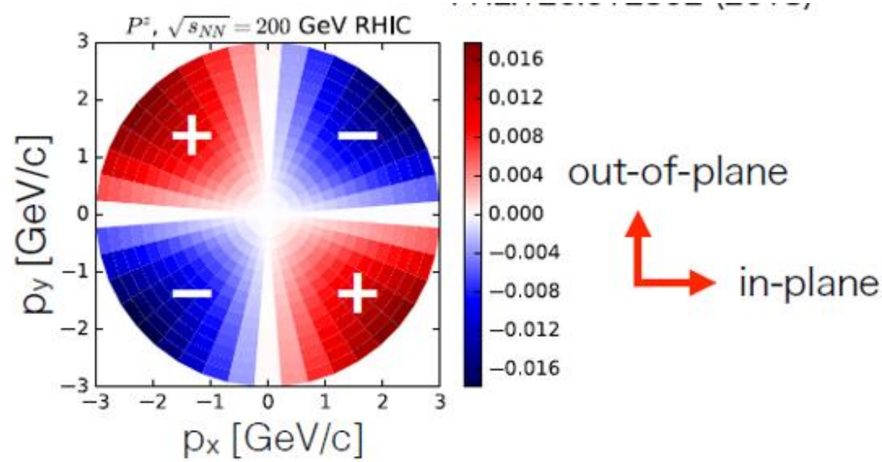


$\phi - dependence$ Transverse P_Z



$$P_H(\phi_p) = \int p_T dp_T dy \; P_y^*(p_T, \phi_p, y)$$



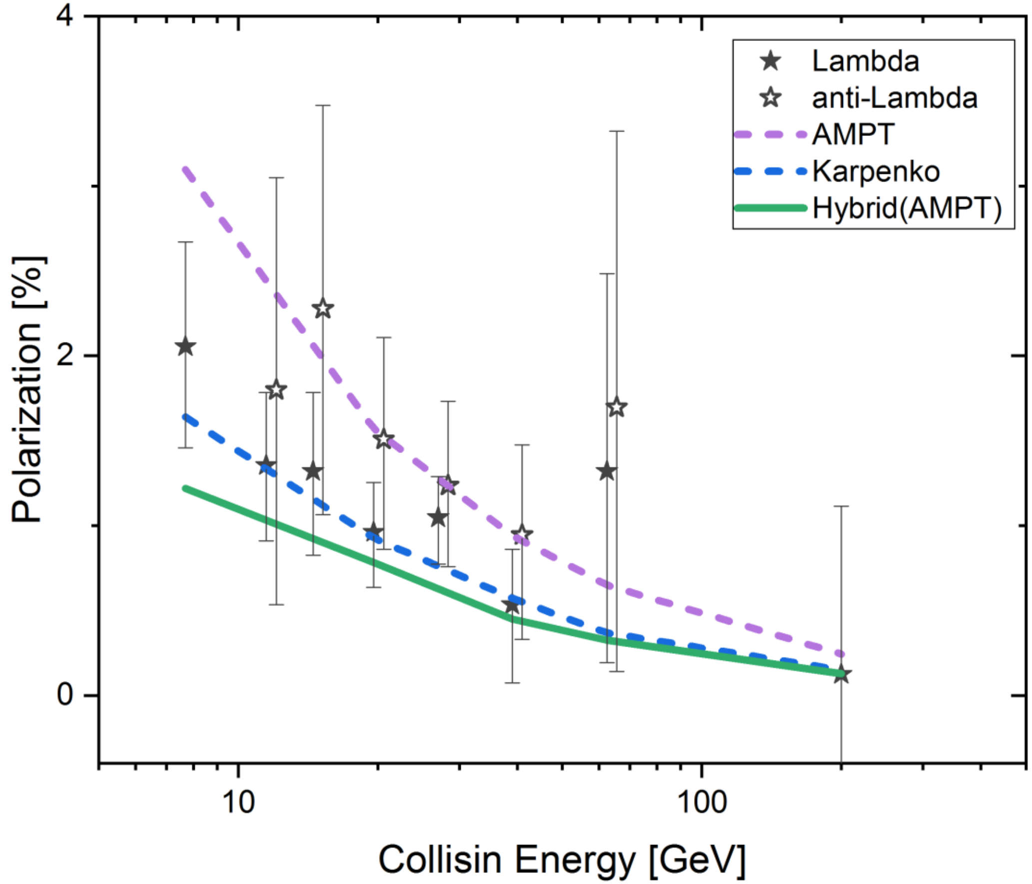


- Similar structure but still with opposite sign

Comparison with other models

Global Polarization results:

AMPT results: Wei, Deng and Huang, Phys.Rev. C99 (2019) no.1, 014905
Vhlle results: Iurii Karpenko, UrQMD + Hydro

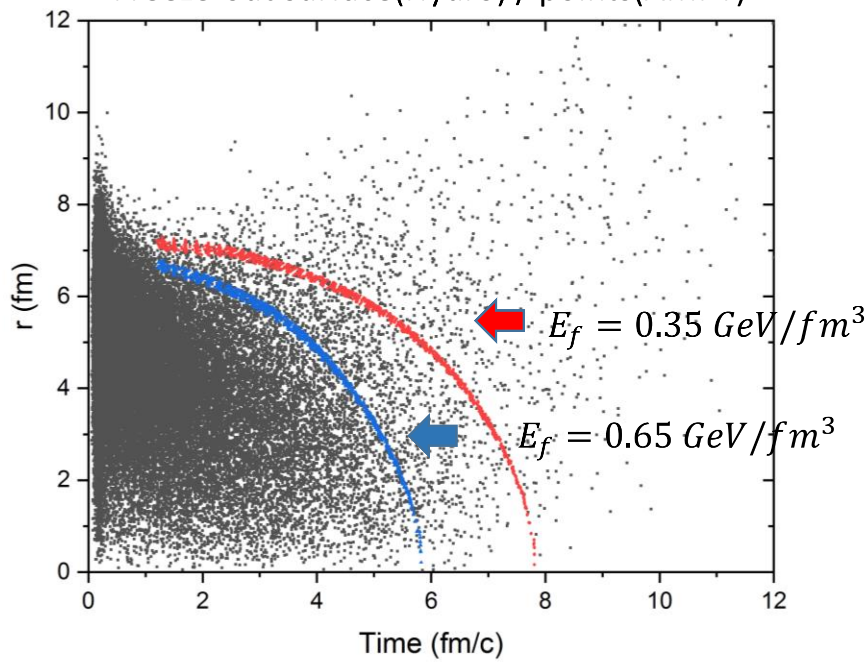


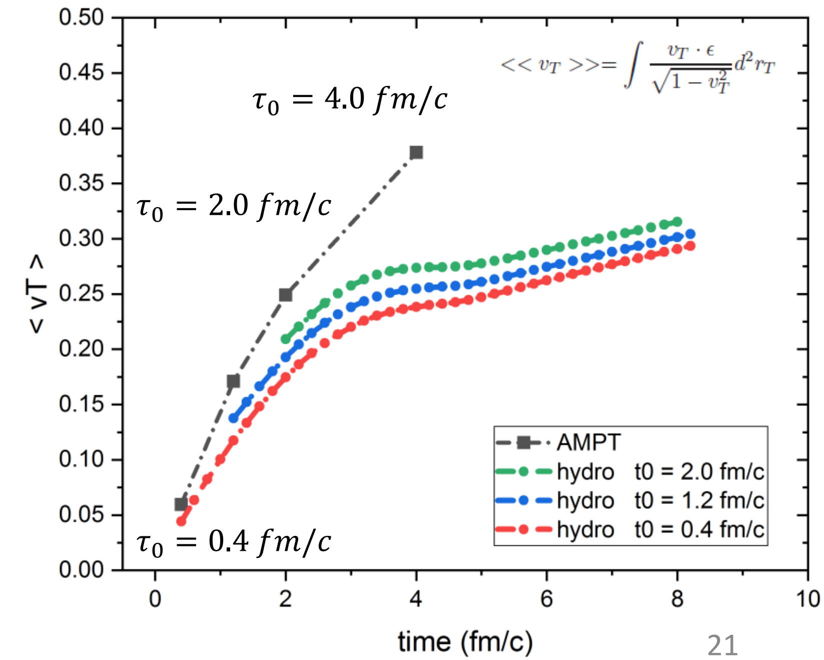
- Like other models, the decreasing trend can be expressed by the our hybrid model, but the magnitude difference exist between different models

Differences between models:

Hybrid model vs. full-AMPT

- Particle emission time is earlier in AMPT
- Averaged velocity difference

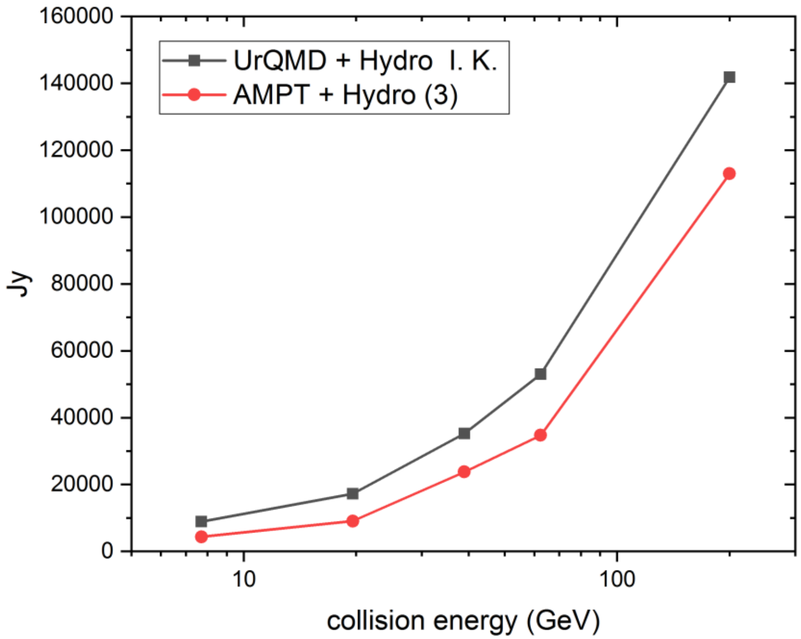


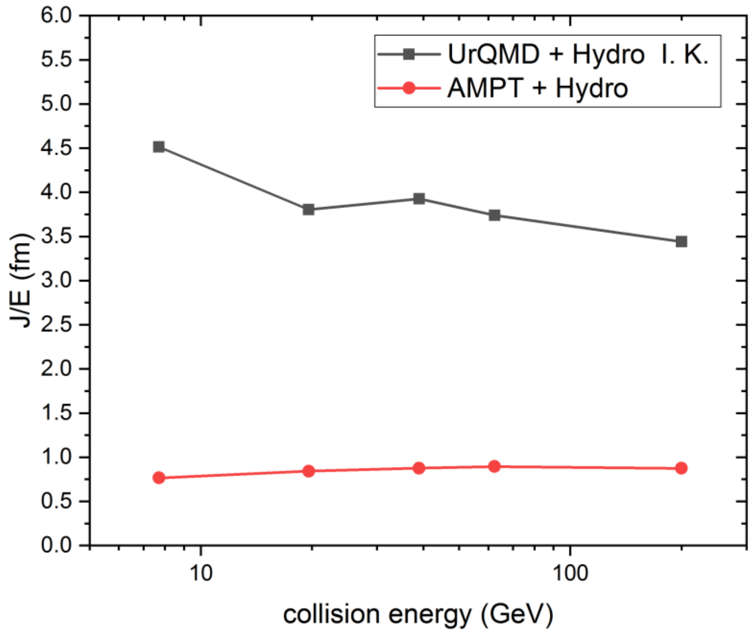


Differences between models:

Hybrid model vs. vhlle (I. K.)

Total/averaged angular momentum





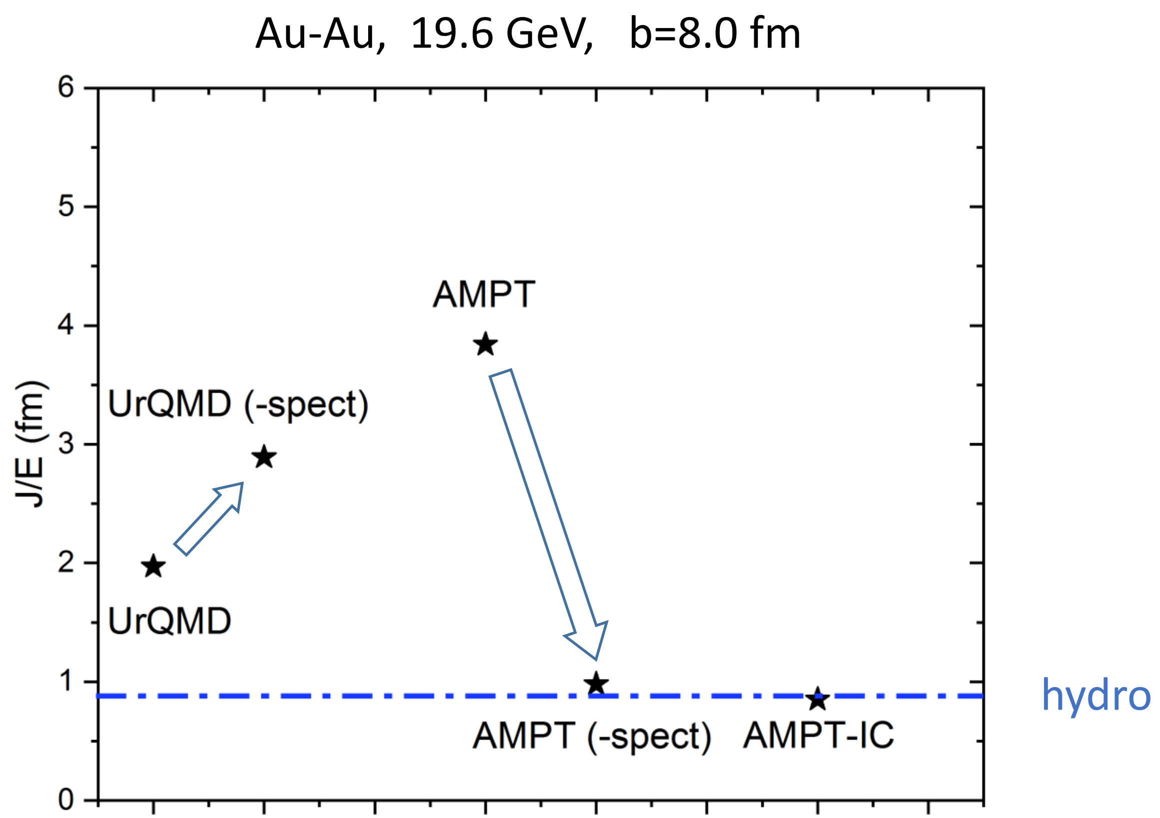
I. Karpenko, et al. Eur.Phys.J. C77 (2017) no.4, 213

- Different (averaged) angular momentum
- We need to check the details further whether the difference comes from the initial condition models UrQMD/AMPT

Differences between models:

1. Spectator particles: (x = y = z = t = 0, UrQMD), (px = py = 0, finite x,y, AMPT)

2. Total angular momentum in the interaction region different



Initial total angular momentum determine the global polarization

Additional comments

The sign puzzle means

F. Becattini, Chirality 2019

$$P^\mu(p) = \frac{1}{N}\int p\cdot d\Sigma \;\; f(x,p)P^\mu(x,p) = \frac{1}{4m}\cdot\frac{\int p\cdot d\Sigma \;\; \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}\bar{\omega}_{\sigma\rho}p_\nu \; n_F(1-n_F)}{\int p\cdot d\Sigma \; n_F}$$

Disagreement with the local equilibrium ansatz
(Spin formula not adequate):

- Resonance decay?
- Dissipative or second order correction?
- Kinetic spin theory?
- Need of a spin tensor?

Disagreement with the hydrodynamic description
(vorticity terms not adequate):

- Hydro model is good enough in the late stage?
- The initial condition correct?

Reaction plane distribution of P^y

Reaction plane distribution $\Leftarrow$ Corresponding vorticity distribution

$$\boxed{P^\mu(p) = \frac{1}{4m} \cdot \frac{\int p \cdot d\Sigma \;\; \tilde{\Omega}^{\mu\nu} p_\nu \; n_F(1-n_F)}{\int p \cdot d\Sigma \; n_F}}$$

$$\tilde{\Omega}^{\mu\nu} \equiv \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}\bar{\omega}_{\sigma\rho} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}(\partial_\rho \beta_\sigma)$$

$$II \Rightarrow \tilde{\Omega}^{yt} p_t + \tilde{\Omega}^{yx} p_x + \tilde{\Omega}^{yz} p_z$$

$$= \boxed{-\tilde{\Omega}^{ty} m_T \cosh y} + \underline{\tilde{\Omega}^{xy} p^x - \tilde{\Omega}^{yz} m_T \sinh y}$$

Dominant term,
non-relativistic

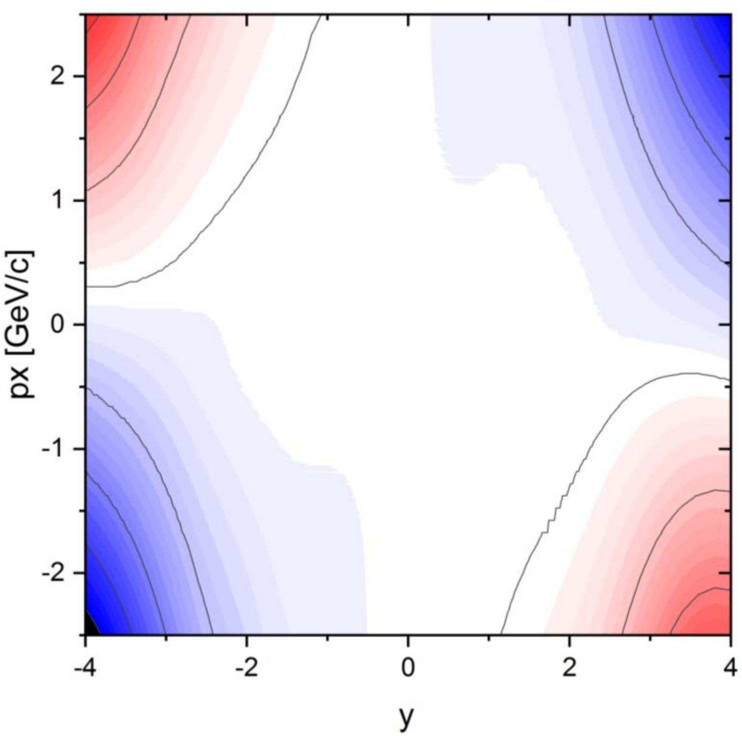
Subordinate terms,
relativistic

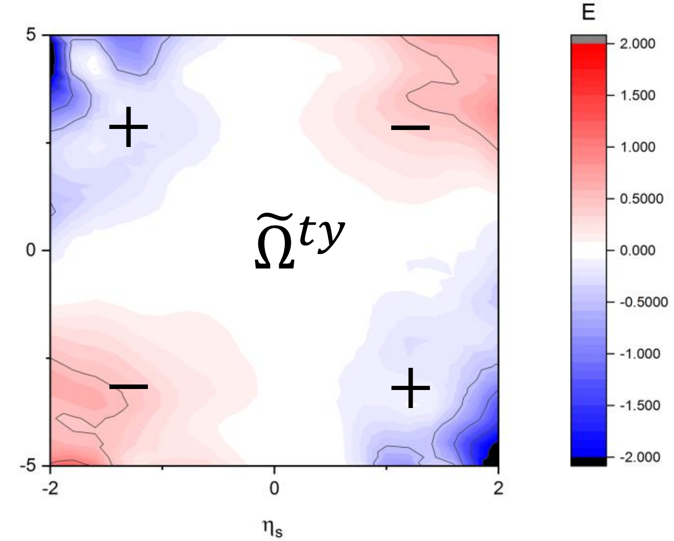
Reaction plane distribution of P^y

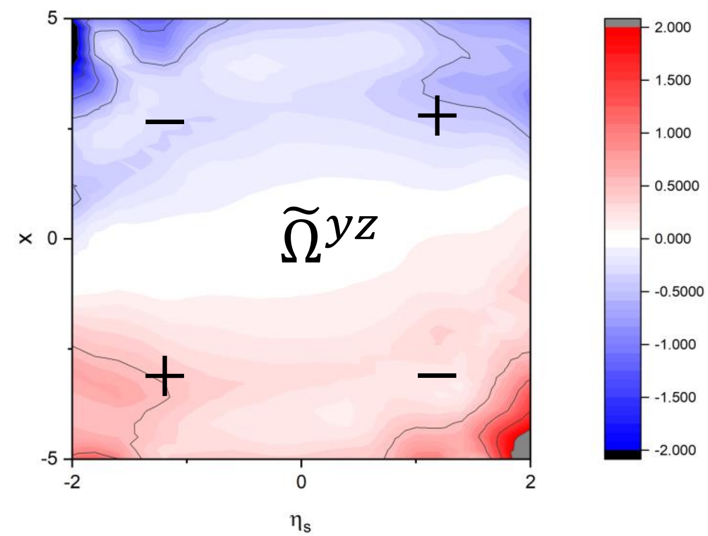
$$II \Rightarrow \tilde{\Omega}^{yt} p_t + \tilde{\Omega}^{yx} p_x + \tilde{\Omega}^{yz} p_z$$

$$= \boxed{-\tilde{\Omega}^{ty} m_T \cosh y} + \tilde{\Omega}^{xy} p^x \boxed{- \tilde{\Omega}^{yz} m_T \sinh y}$$

Reaction (Event) plane distribution of P_y







Initial vorticity structure also affects the expansion so does the local polarization

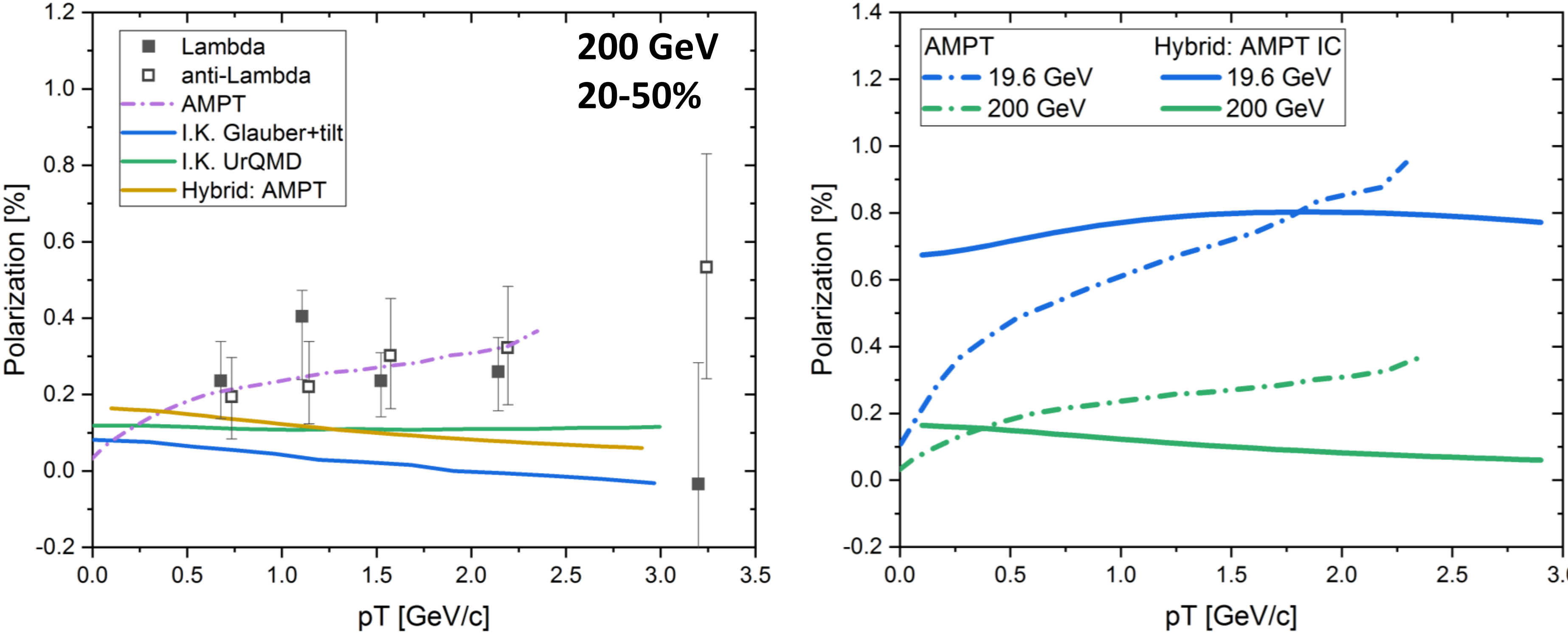
Summary

- Currently, the hybrid model could reproduce lots of soft observables at 7.7-200 GeV
- Based on the hybrid model, the global polarization trend correspond to the experimental data and other model results
- The local polarization might influenced by the less important terms which is determined by the initial models quantitatively.

Backups

$p_T - dependence$

Transverse distribution of the polarization P_y



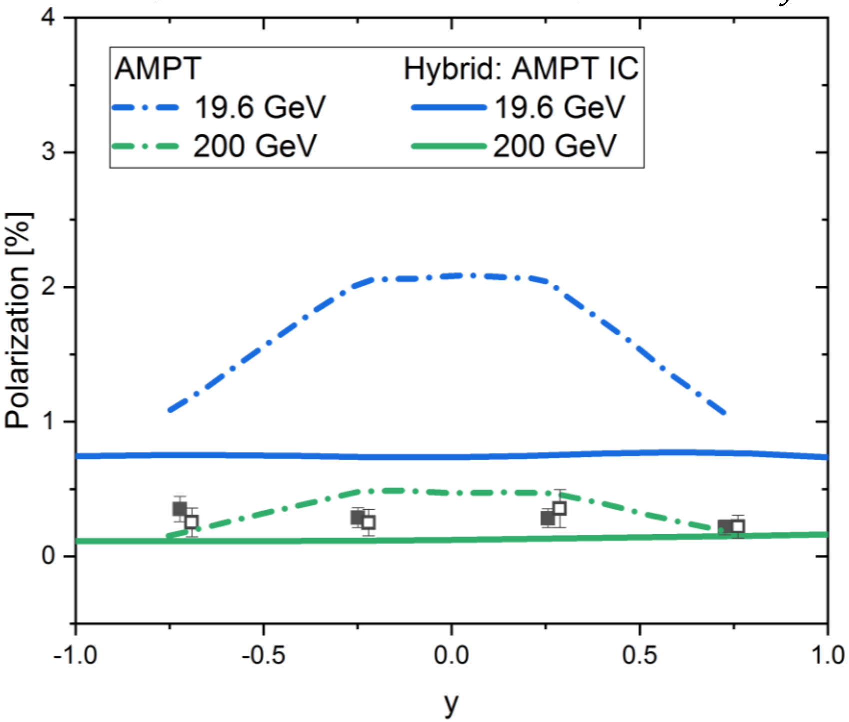
AMPT results: Wei, Deng and Huang, Phys.Rev. C99 (2019) no.1, 014905
Vhlle results: Iurii Karpenko

- At 200 GeV, initial vorticity distribution might makes the difference
- As for the hybrid-AMPT, high energy evolution may dilute the vorticity structure

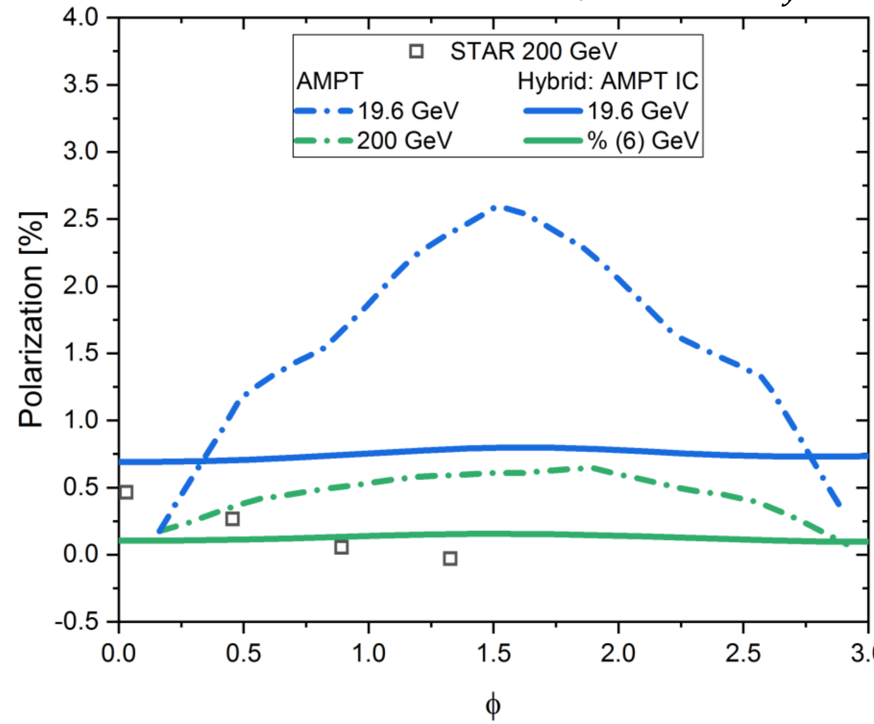
Longitudinal and azimuthal distribution

- For the longitudinal distribution, hybrid model fits well. And again, AMPT results hold larger magnitude and with a plateau in mid-rapidity.
- For the azimuthal distribution, though weakly correlated, hybrid model shows contrary trend with experiments.

longitudinal distribution of the polarization P_y

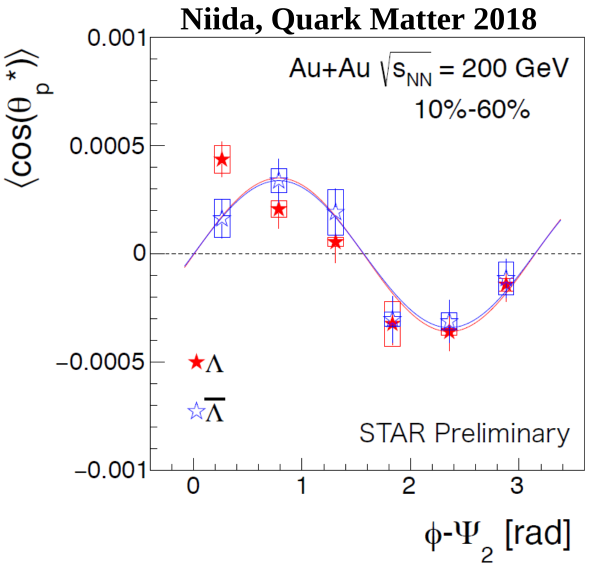


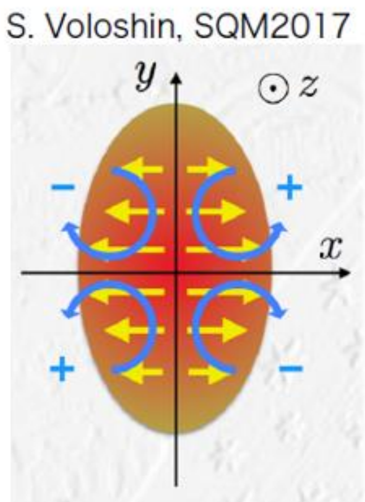
azmuthal distribution of the polarization P_y



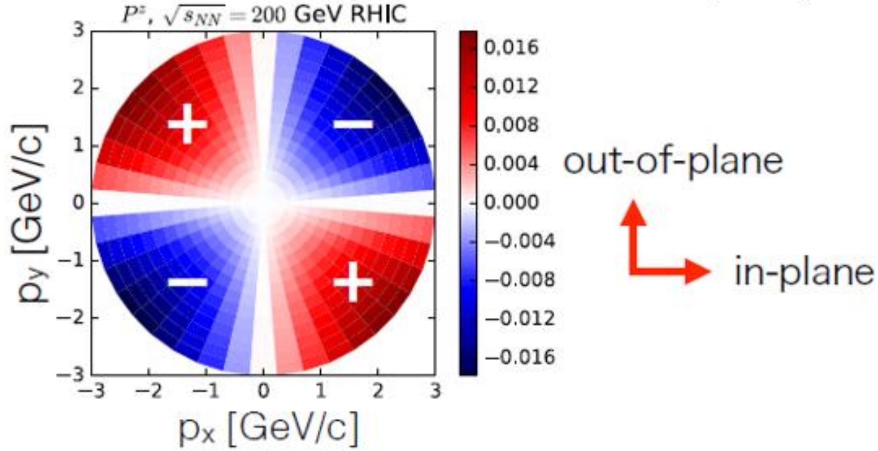
AMPT results: Wei, Deng and Huang, Phys.Rev. C99 (2019) no.1, 014905

Transverse structure: $P^z - puzzle$

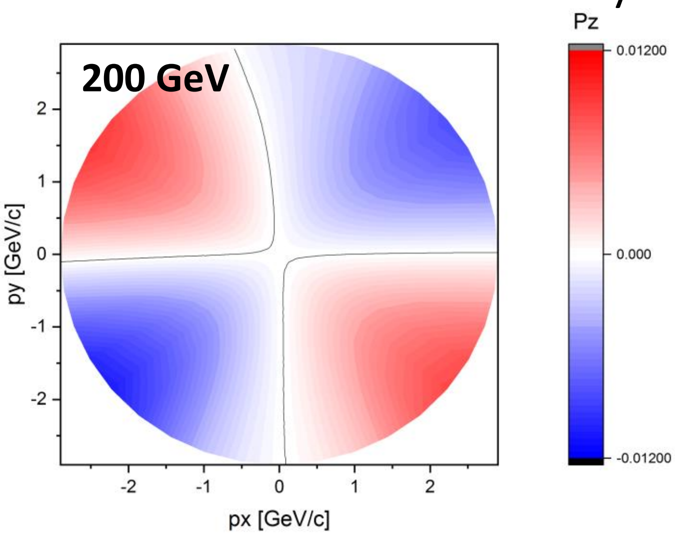


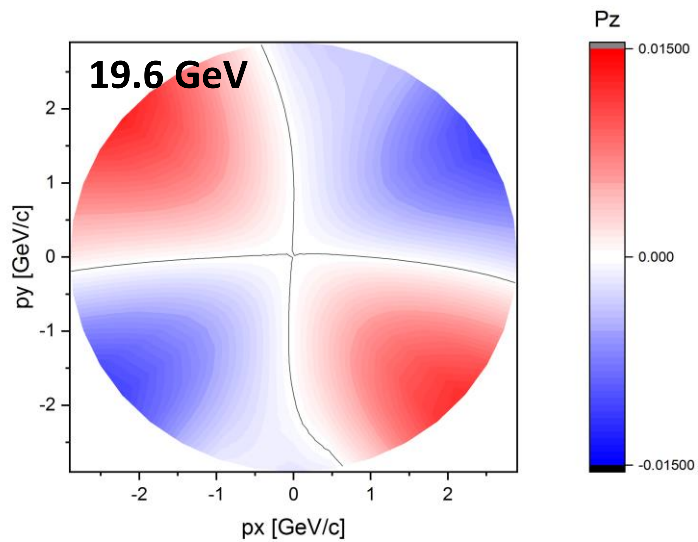


Hydro calculation of Pz
F. Becattini and I. Karpenko,
PRL.120.012302 (2018)



Hybrid-AMPT





Hybrid Model

Model set up

Observables at $\sqrt{s_{NN}} = 7.7 - 62.4\ GeV$

$\Lambda - polarization$

Global polarization

Local polarization

Parameter set:

AMPT → Hydrodynamics → iSS → UrQMD

Parameter in hybrid model at 19.6 GeV 0-5%					
String parm.	a (AMPT)	0.55	Scale factor	S	2.16
String parm.	b (AMPT)	0.15	Shear viscosity	η/s	0.12
Gaussian parm.	σ_η	0.2	Bulk viscosity	ζ/s	$\zeta/s(T)$
Gaussian parm.	σ_r	0.4 fm	Un-equilibrium f	δf_{shear}	Y
Initial EOS	iEOS	S95p-PCE	Un-equilibrium f	δf_{bulk}	N
Initial time	τ_0	1.2 fm/c	Freeze-out energy	E_f	0.65 GeV/fm3
Initial nB	nB	from AMPT	Transform Eq.		L. P.

dN/dy → Scale factor 'K'

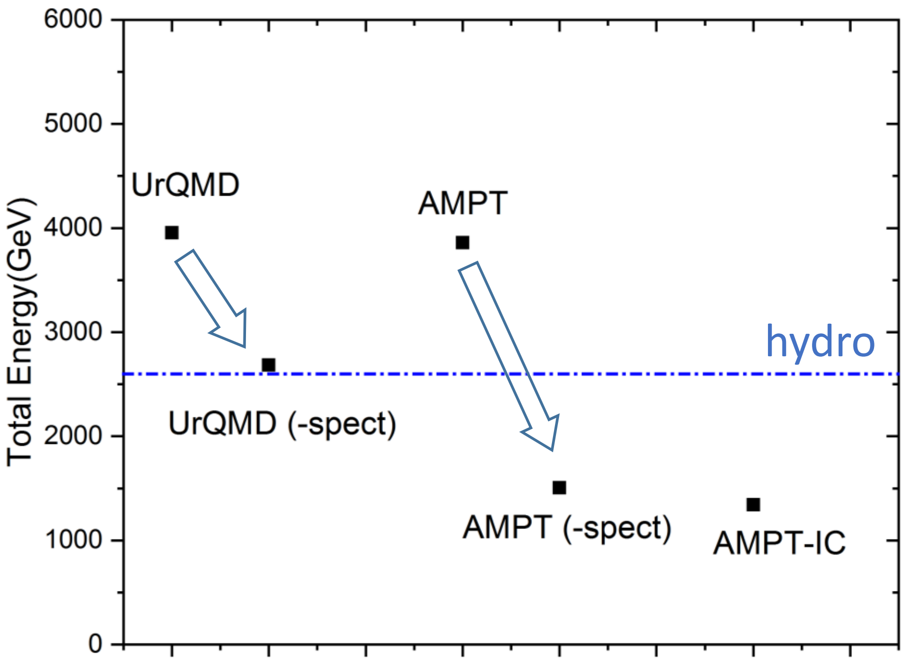
Statistic Model → Freeze-out Temperature

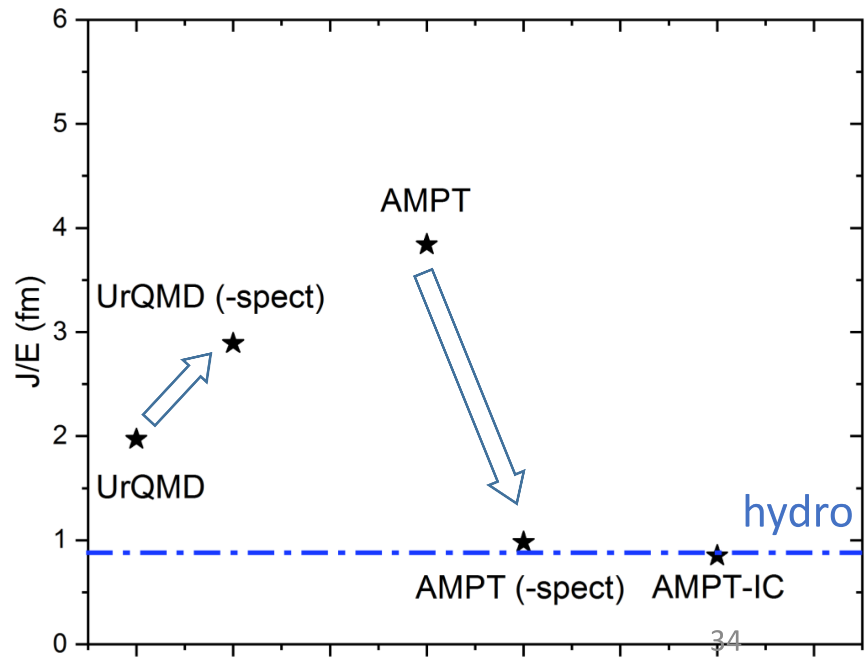
→ Other parameters (spectra/v2) → Polarization

Differences between models:

1. Energy of participant part(QGP) different in AMPT and UrQMD
2. Spectator particles: (x = y = z = t = 0, UrQMD), (px = py = 0, finite x,y, AMPT)
3. Total angular momentum in the interaction region different

Au-Au, 19.6 GeV, b=8.0 fm



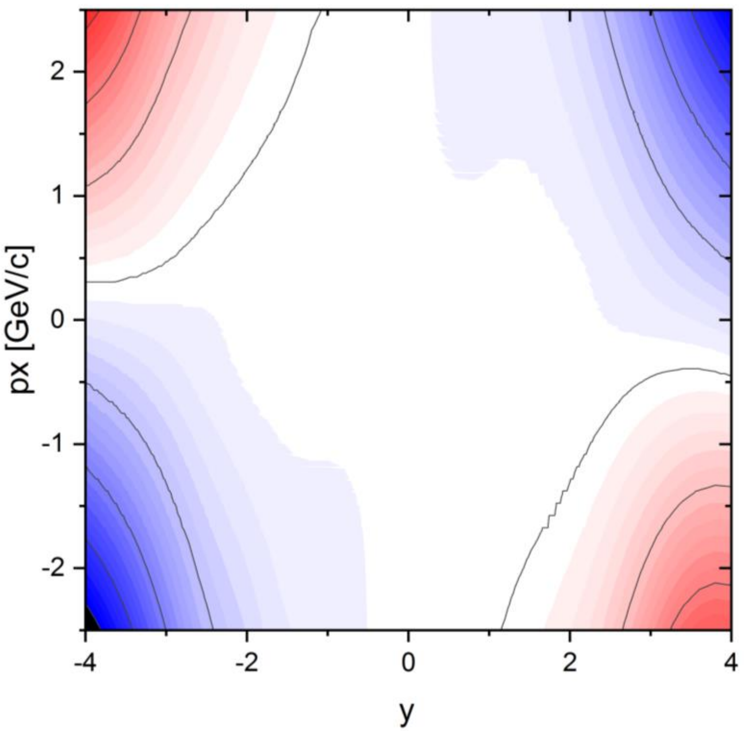


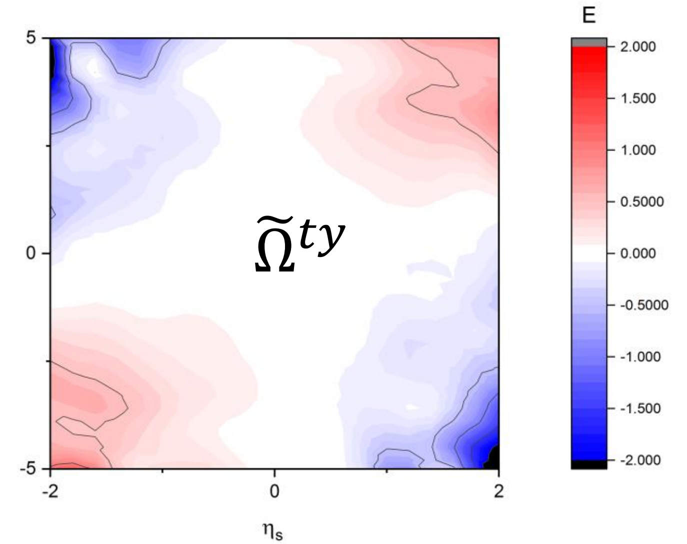
Reaction plane distribution of P^y

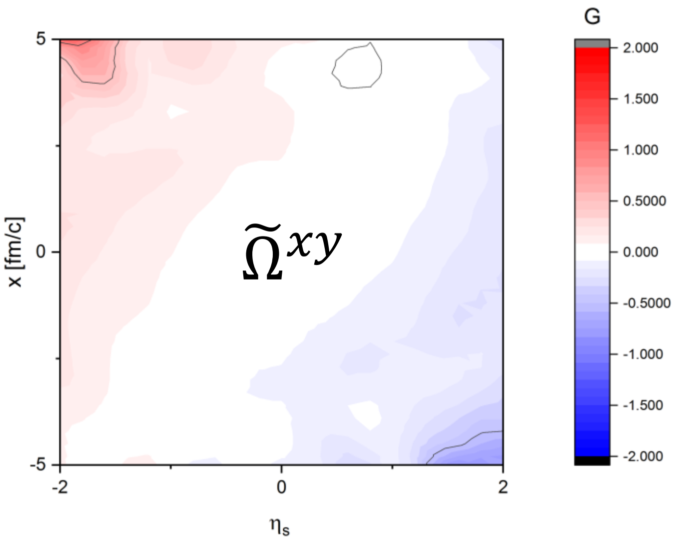
$$II \Rightarrow \tilde{\Omega}^{yt}p_t + \tilde{\Omega}^{yx}p_x + \tilde{\Omega}^{yz}p_z$$

$$= \boxed{-\tilde{\Omega}^{ty}m_T\cosh y} + \boxed{\tilde{\Omega}^{xy}p^x} - \tilde{\Omega}^{yz}m_T\sinh y$$

Reaction (Event) plane distribution of P_y







Initial vorticity structure also affects the expansion
so does the local polarization