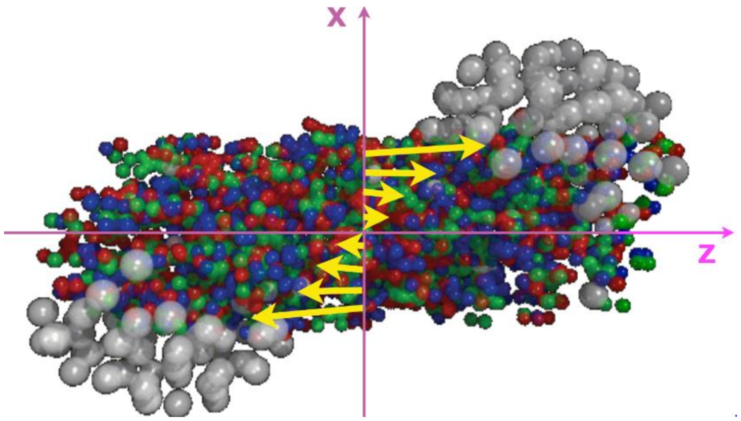
Workshop on AMPT for Relativistic Heavy Ion Collisions

The Global Λ Polarization in HIC



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arXiv: 1704.01507

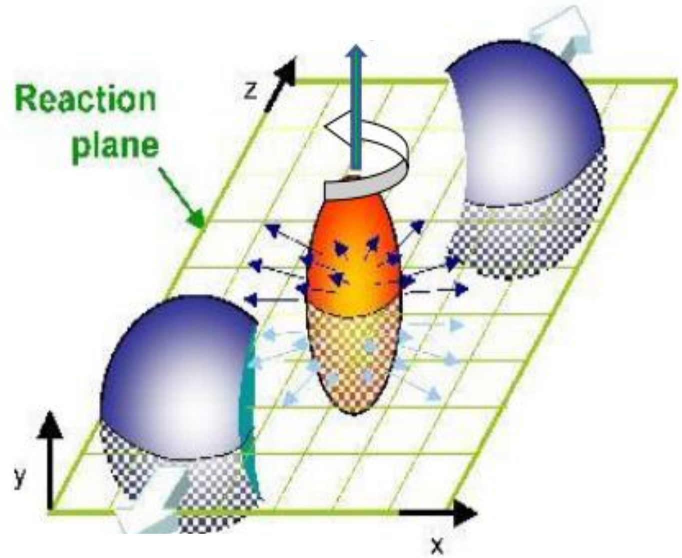
Outline

- Introduction
- Lambda polarization from vorticity
- Numerical results and discussion
- Summary

Introduction

- Strong magnetic field

  Skokov, et.al. 2009, 2011
  Deng, Huang 2012
  Tuchin 2013
  Zhong, Yang, Cai, Feng 2014
  Gursoy, Kharzeev, Rajagopal 2014
  Li, Sheng, Wang 2016 …



- Large angular momentum

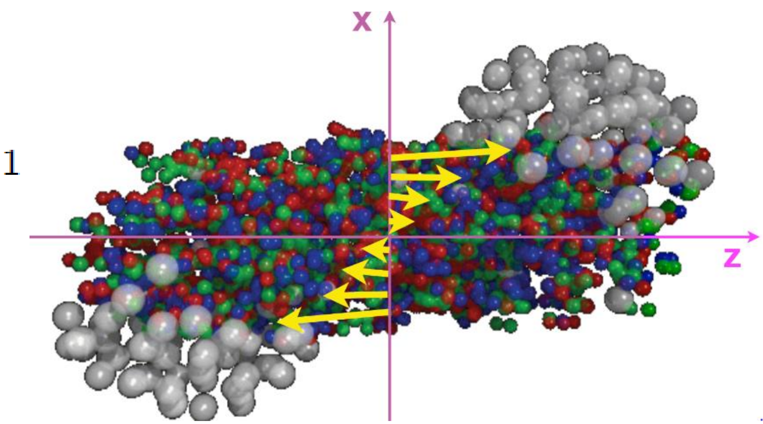
  && vorticity

  Jiang, Lin, Liao 2016
  Deng, Huang 2016

$$eB_y \sim m_\pi^2$$

$$J_y \sim 10^5 \hbar$$

$$\langle \omega_y \rangle \sim 0.01 \mathrm{fm}^{-1}$$



- CME, CMW, CVE, CVW, Polarization …

Introduction

EM vector Field	$\mathbf{A}$	$\mathbf{V}$	Fluid velocity field
Magnetic Field	$\mathbf{B} = \nabla \times \mathbf{A}$	$\boldsymbol{\omega} = \nabla \times \mathbf{V}$	Vortical Field
Lorentz Force	$\mathbf{F} = q\mathbf{v} \times \mathbf{B}$	$\mathbf{F}_{col} = 2m\mathbf{v} \times \boldsymbol{\omega}$	Coriolis Force

Spin-magnetic coupling

$$\mathbf{S} \cdot \mathbf{B}$$

Magnetic induced polarization

Spin-vorticity coupling

$$\mathbf{S} \cdot \boldsymbol{\omega}$$

Vorticity induced polarization

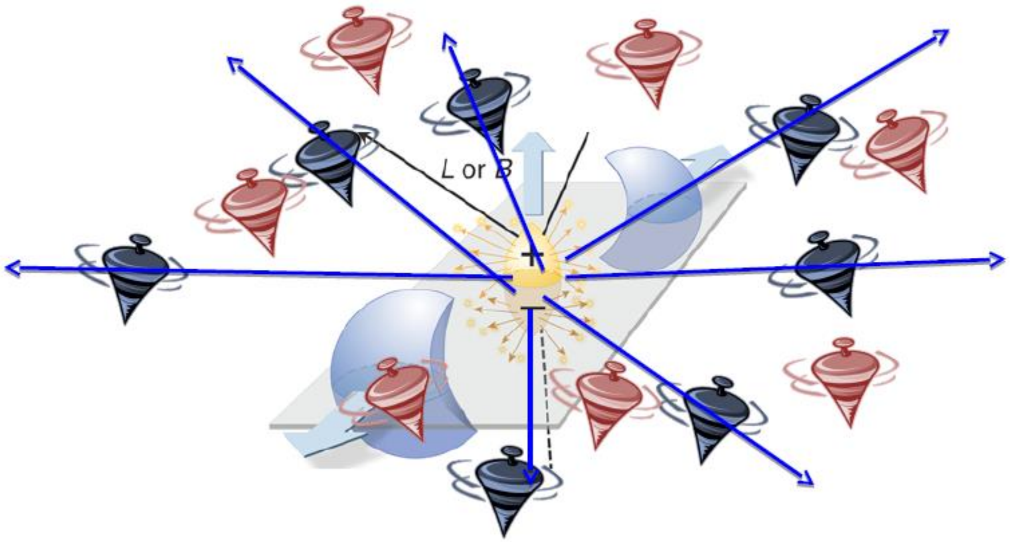
Spin-orbit coupling

Liang, Wang, PRL 94,102301(2005)
Voloshin, nucl-th/0410089
Betz, Gyulassy, Torrieri, PRC 76, 044901(2007)

Probe the vorticity and magnetic field

Global polarization along angular momentum

Global Λ polarization probes B and ω



$$P_\Lambda \simeq \frac{1}{2}\frac{\omega}{T} + \frac{\mu_\Lambda B}{T}$$

$$P_{\bar{\Lambda}} \simeq \frac{1}{2}\frac{\omega}{T} - \frac{\mu_\Lambda B}{T}$$

Becattini, Karpenko, Lisa, Upsal, Voloshin 2016

- Spin-orbit coupling:

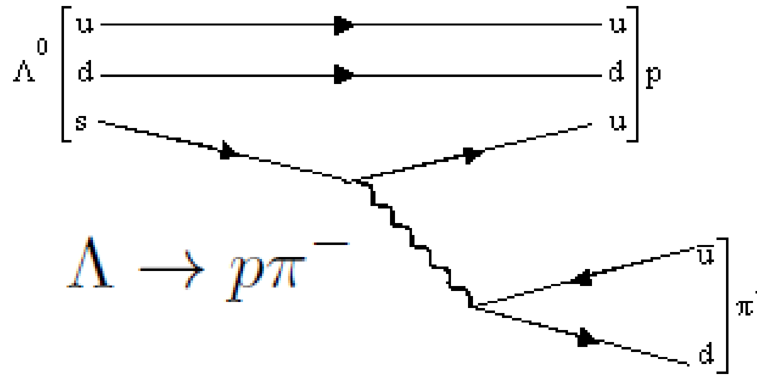
Λ and anti-Λ spins aligned with L

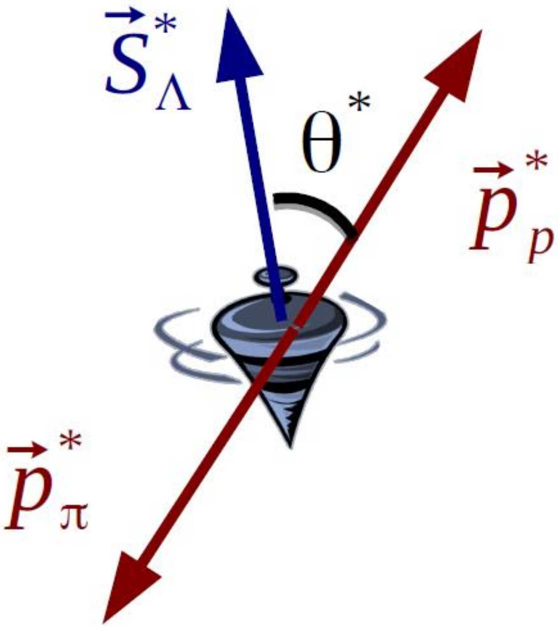
Liang, Wang 2004; Voloshin 2004; …

- Λ spin anti-aligned along B
- anti-Λ spin aligned along B

How to measure it?

- Λ is “self-analyzing”



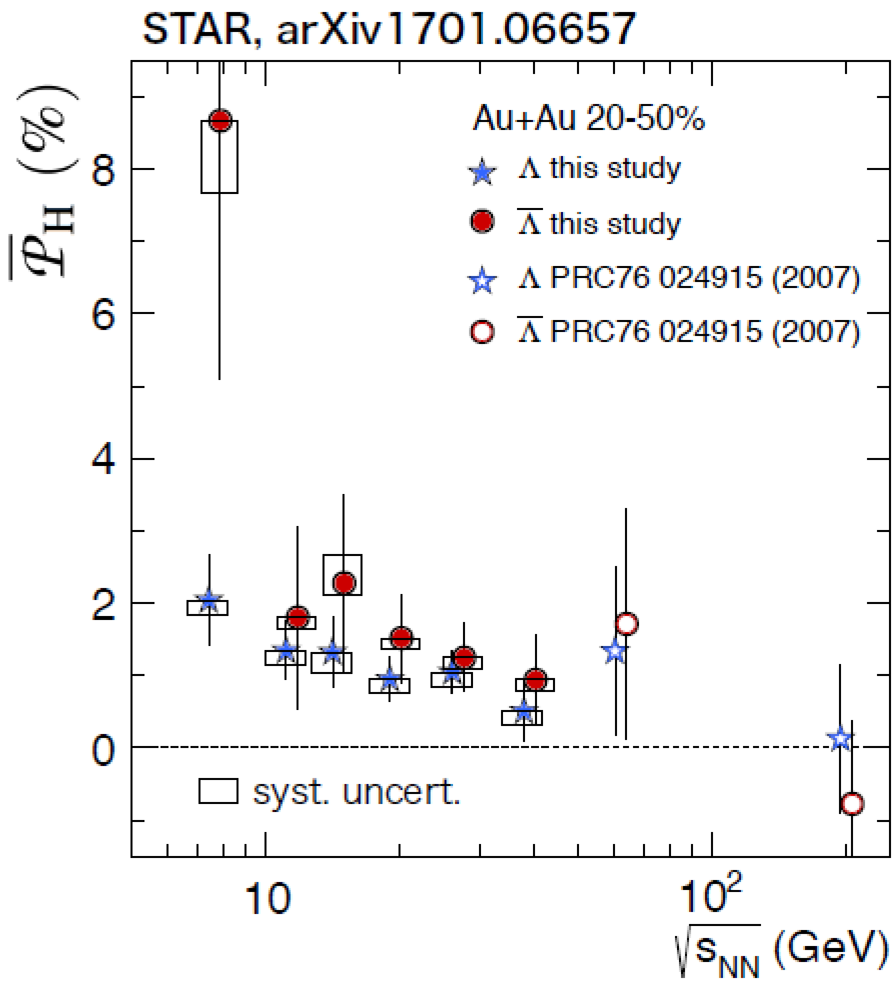


$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}\left(1 + \alpha_H |\vec{\mathcal{P}}_H| \cos\theta^*\right)$$

$$\alpha_\Lambda = -\alpha_{\overline{\Lambda}} = 0.642 \pm 0.013$$

$$\overline{\mathcal{P}}_H \equiv \langle \vec{\mathcal{P}}_H \cdot \hat{J}_{sys} \rangle = \frac{8}{\pi\alpha_H} \frac{\left\langle \cos\left(\phi_p^* - \phi_{\hat{J}_{sys}}\right)\right\rangle}{R_{EP}^{(1)}}$$

STAR measurement



|η|<1

- Positive signals: vorticity
- P(anti-Λ) > P(Λ): B-field

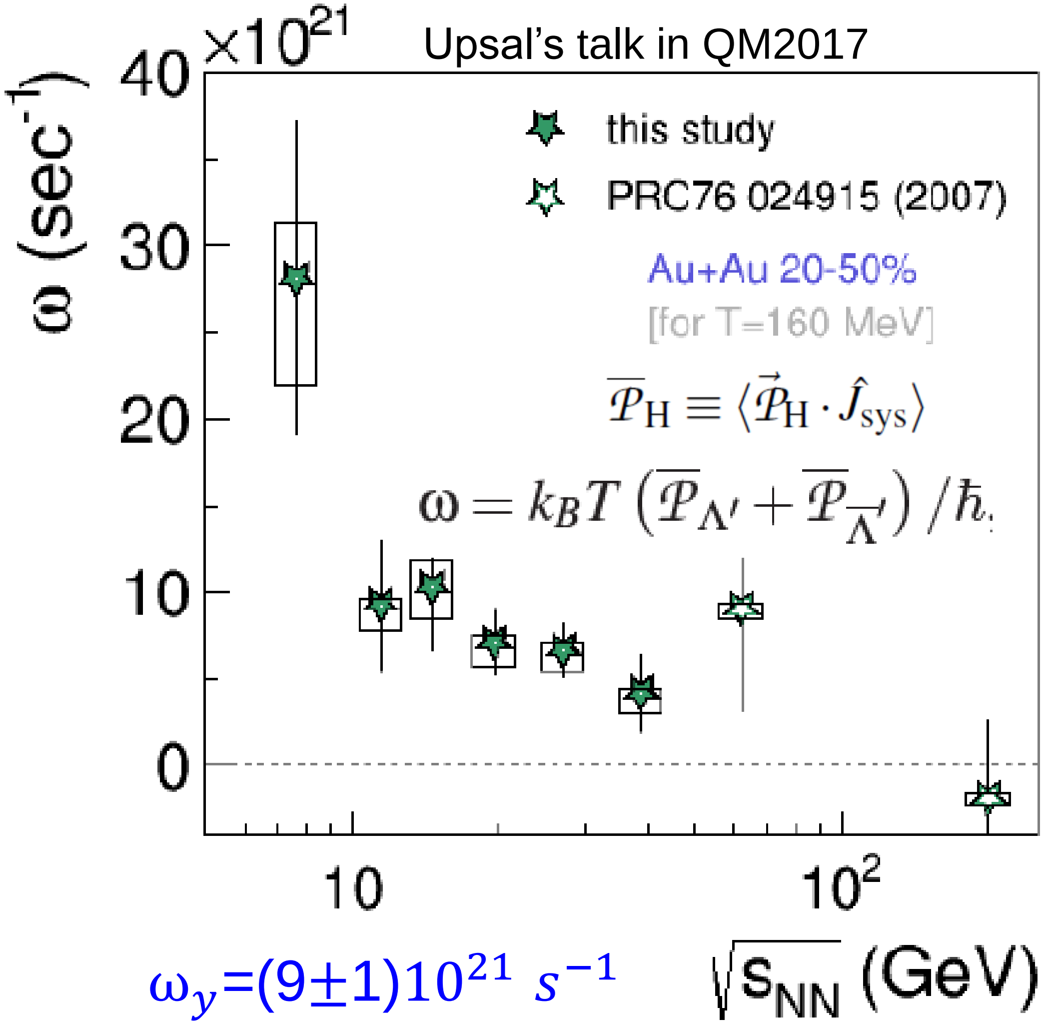
$$P_\Lambda \simeq \frac{1}{2}\frac{\omega}{T} + \frac{\mu_\Lambda B}{T}$$

$$P_{\bar{\Lambda}} \simeq \frac{1}{2}\frac{\omega}{T} - \frac{\mu_\Lambda B}{T}$$

- Λ spin anti-aligned along B
- anti-Λ spin aligned along B

Introduction

Upsal's talk in QM2017



$$\overline{\mathcal{P}}_{\mathrm{H}} \equiv \langle \vec{\mathcal{P}}_{\mathrm{H}} \cdot \hat{J}_{\mathrm{sys}} \rangle$$

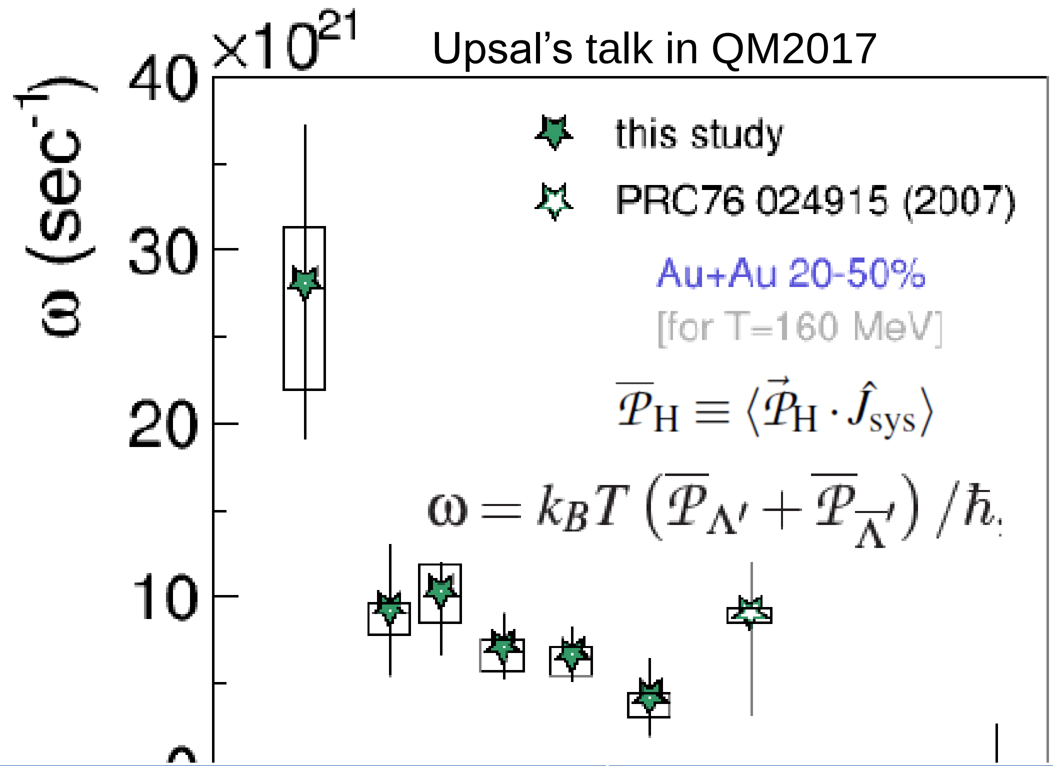
$$\omega = k_B T \left(\overline{\mathcal{P}}_{\Lambda'} + \overline{\mathcal{P}}_{\overline{\Lambda}'} \right) / \hbar,$$

$\omega_y = (9 \pm 1) 10^{21}\ s^{-1}$

RHIC produces the fluid with highest vorticity!

STAR Collab.,1701.06657

Introduction



Solar subsurface flow	$10^{-7}\ s^{-1}$
Supercell tornado cores	$10^{-1}\ s^{-1}$
Rotating soap bubbles	$10^{2}\ s^{-1}$
Super Fluid	$10^{7}\ s^{-1}$

RHIC produces the fluid with highest vorticity!

STAR Collab.,1701.06657

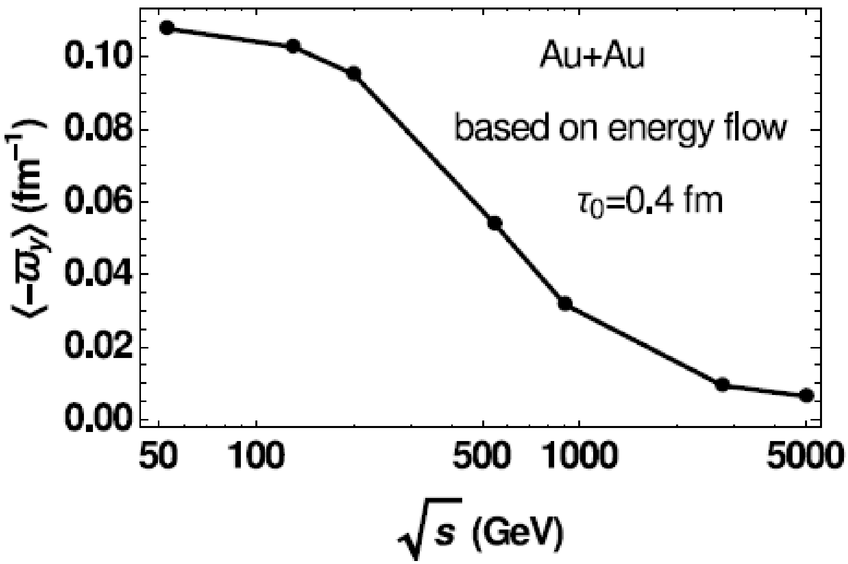
Introduction

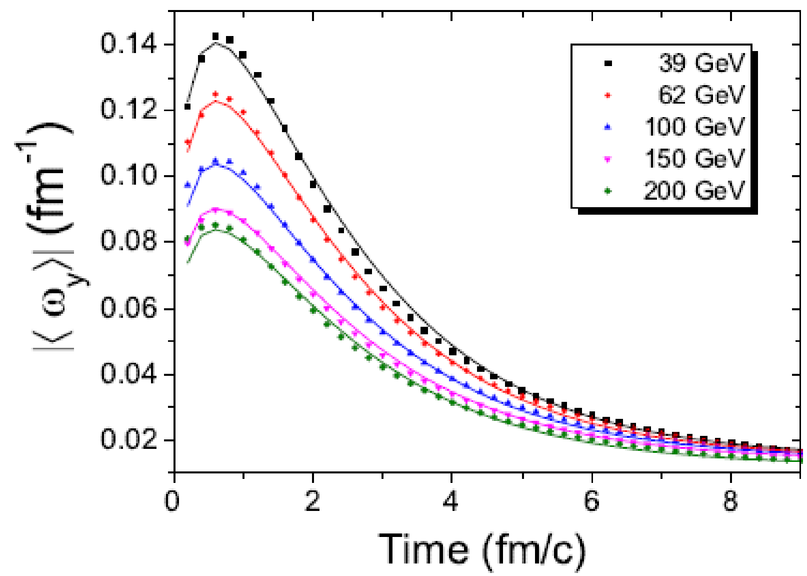
Properties of vorticity field

$$\bar{\omega} \equiv \frac{\int d^2\boldsymbol{x}_\perp \varepsilon(\boldsymbol{x}_\perp)\boldsymbol{\omega}(\boldsymbol{x}_\perp)}{\int d^2\boldsymbol{x}_\perp \varepsilon(\boldsymbol{x}_\perp)}$$

$$\langle \omega_y \rangle = \frac{\int d^3\vec{r}\, [\mathcal{W}(\vec{r})]\, \omega_y(\vec{r})}{\int d^3\vec{r}\, [\mathcal{W}(\vec{r})]}$$

$$\mathcal{W}(\vec{r}) = \quad \epsilon(\vec{r})$$





Jiang, Lin, Liao, Phys.Rev. C94 (2016)
Deng, Huang, Phys.Rev. C93 (2016)

Spin and polarization in relativistic case

Classical Lagrangian formulation

$$L = \frac{1}{2}m\left(\mathbf{v}_r + \boldsymbol{\omega} \times \mathbf{r}\right)^2 - U\left(r\right)$$

$$\mathbf{p} = \frac{\partial L}{\partial \mathbf{v}_r} = m\left(\mathbf{v}_r + \boldsymbol{\omega} \times \mathbf{r}\right)$$

$$H = \mathbf{p} \cdot \mathbf{v}_r - L = \frac{\mathbf{p}^2}{2m} - \boldsymbol{\omega} \cdot \mathbf{L} + U\left(r\right)$$

Dirac Lagrangian in rotating frame

$$\mathcal{L}_D = \bar{\psi}\left(i\gamma^\mu\left(\partial_\mu + \Gamma_\mu\right) - m\right)\psi$$

$$\Gamma_\mu = \frac{1}{4} \times \frac{1}{2}\left[\gamma^a, \gamma^b\right]\Gamma_{abc}$$

$$H = \gamma^0\left(\boldsymbol{\gamma} \cdot \mathbf{p} + m\right) - \boldsymbol{\omega} \cdot \left(\mathbf{x} \times \mathbf{p} + S\right)$$
$$= H_0 - \boldsymbol{\omega} \cdot \mathbf{J}$$

Density matrix

$$\hat{\rho} = \frac{1}{Z}exp\left(-\beta\hat{H} + \beta\nu\hat{Q} + \beta\boldsymbol{\omega} \cdot \hat{\mathbf{J}}\right)$$

$$\beta=\frac{1}{T} \qquad O = tr\left(\rho\hat{O}\right)$$

$$\mathbf{S} = tr\left(\hat{\rho}\hat{S}\right) = \frac{1}{2}\tanh\left(\frac{\omega}{2T}\right) \sim \frac{\omega}{4T}$$

Spin and polarization in relativistic case

Non-relativistic case: $\hat{\rho} = \frac{1}{Z} exp\left(-\beta\hat{H} + \beta\nu\hat{Q} + \beta\boldsymbol{\omega}\cdot\hat{\mathbf{J}}\right)$ $\beta{=}\frac{1}{T}$ $O = tr\left(\rho\hat{O}\right)$

Spin vector $\mathbf{S} \sim \frac{\omega}{4T}$

Relativistic case:

$$\hat{\rho} = \frac{1}{Z} exp\left[-\beta u_\nu \hat{P} + \frac{1}{2}\beta\hat{J}^{\nu\rho}\omega_{\nu\rho} + \beta\xi\hat{Q}\right] \qquad \hat{J}^{\nu\rho} = \hat{J}_L^{\nu\rho} + \hat{J}_S^{\nu\rho}$$

Spin vector (Pauli-Lubanski) $S^\mu = Tr\left(\hat{\rho}\hat{S}^\mu\right)$

Spin ½ particle

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

Statistical-hydro model

Becattini, et.al., 2008, 2013

Wigner function method

Fang, Pang, Wang, Wang, 2016

Chiral kinetic equation

Sun, Ko, 2017

Lambda polarization from vorticity

Spin vector of a spin ½ particle

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

Thermal vorticity

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

$$\beta^\mu = \frac{u^\mu}{T}$$

$$1 - n_F \simeq 1$$

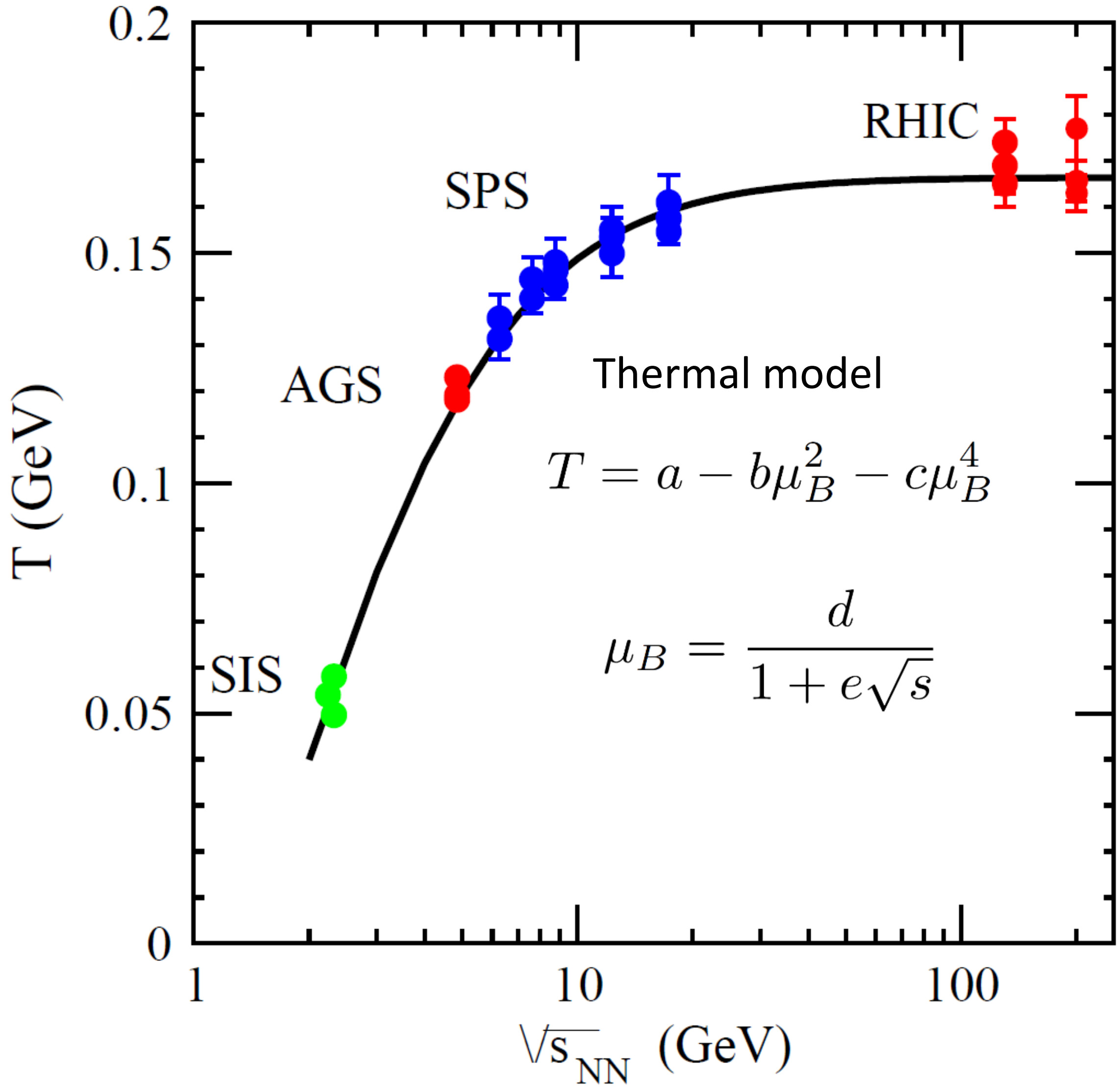
- Boltzmann limit

Relativistic vorticity

$$\Omega_{\mu\nu} = \frac{1}{2}(\partial_\nu u_\mu - \partial_\mu u_\nu)$$

$$S^\mu(x,p) = -\frac{1}{8mT}\epsilon^{\mu\nu\rho\sigma}p_\nu\Omega_{\rho\sigma}(x)$$

Lambda polarization from vorticity



STAR: J.Cleymans, et al PRC 73,034905

Lambda polarization from vorticity

$$S^{\mu}(x,p) = -\frac{1}{8mT}\epsilon^{\mu\nu\rho\sigma}p_{\nu}\Omega_{\rho\sigma}(x)$$

$$\mathbf{\Omega}_S = (\Omega_{yz}, \Omega_{zx}, \Omega_{xy}) = \frac{1}{2}\nabla\times\mathbf{u},$$

$$\mathbf{\Omega}_T = (\Omega_{0x}, \Omega_{0y}, \Omega_{0z}) = \frac{1}{2}(\nabla\gamma + \partial_t\mathbf{u})$$

C.M. Frame

$$S^0(x,p) = \frac{1}{4mT}\mathbf{p}\cdot\mathbf{\Omega}_S,$$

$$\boxed{\mathbf{S}(x,p) = \frac{1}{4mT}(E_p\mathbf{\Omega}_S + \mathbf{p}\times\mathbf{\Omega}_T)}$$

In Lambda's rest frame

$$S^{*\mu}_{\Lambda} = (0, \mathbf{S}^*_{\Lambda})$$

$$\boxed{\mathbf{S}^*_{\Lambda} = \mathbf{S}_{\Lambda} - \frac{\mathbf{p}\cdot\mathbf{S}_{\Lambda}}{E_p(m+E_p)}\mathbf{p}}$$

dominated by

$$\mathbf{S} \simeq \frac{\gamma_{\Lambda}\mathbf{\Omega}_S}{4T}$$

classic limit

$$\mathbf{S} \simeq \frac{\boldsymbol{\omega}}{4T}$$

Numerical method

Transport process:

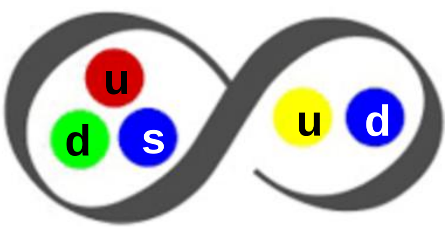
Participants

Initial conditions — **HIJING** + Zhang's Parton Cascade — **ZPC** + A Relativistic Transport Model — **ART**

excited strings into partons → till partons freeze out → nearest partons coalesce into hadrons (resonance decay)

Spectators

- Track the partons' and hadrons' position and momentum information
- Find final-state particles (Λ hyperons)



Lin, Ko, Li, Zhang, Pal, Phys. ReV. C 72, 064901 (2005)

Numerical method

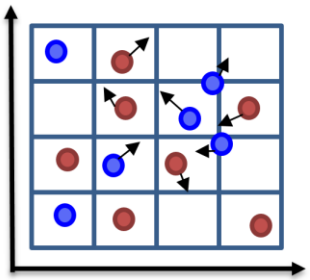
- Velocity:
  - averaging in cell (size: d)

$$\mathbf{v}(t, \mathbf{x}) = \frac{\sum_i \mathbf{p}_i}{\sum_i E_i}$$

  - Gaussian smearing (width: σ)

$$\mathbf{v}(t, \mathbf{x}) = \frac{\sum_i \mathbf{p}_i G(\mathbf{x}_i - \mathbf{x})}{\sum_i E_i G(\mathbf{x}_i - \mathbf{x})}$$

- sum is over both particles and events
- 10^5 events, totally 10TB disk used



comparable if $\frac{d^2}{12} = \sigma^2$

Compare different methods:
Oliinychenko, Petersen 2016
Deng, Huang 2016

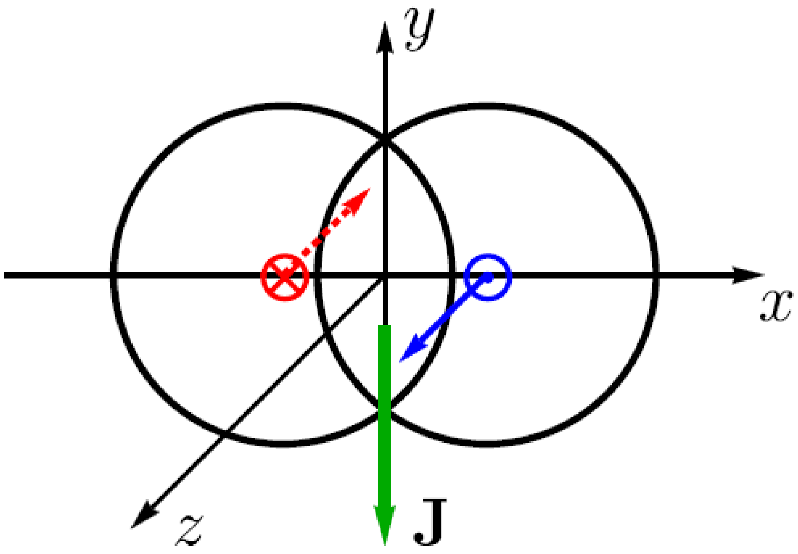
- Vorticity: finite-difference method

Numerical method

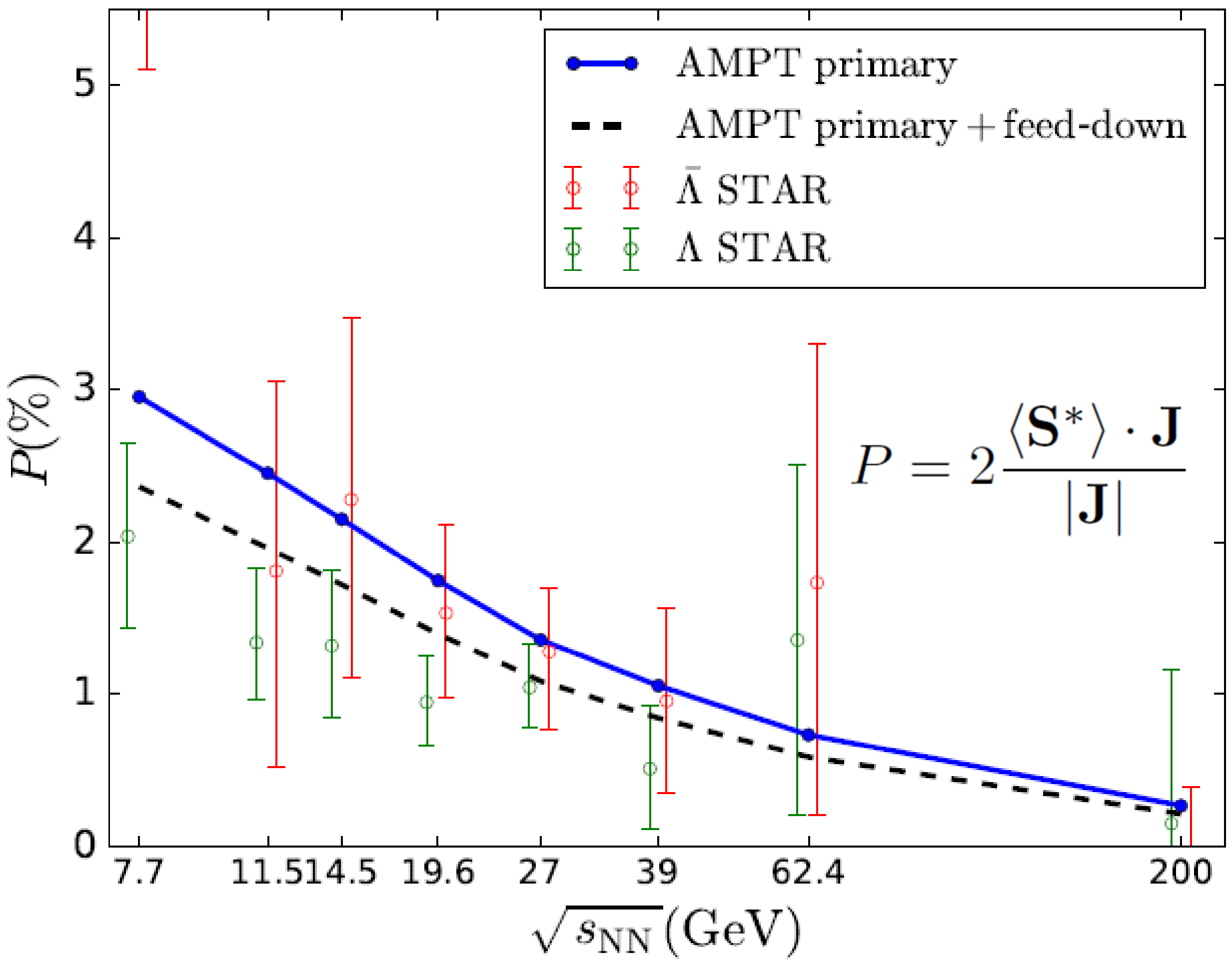
- Polarization: averaging over Lambdas |η|<1

$$\langle \mathbf{S}^* \rangle = \frac{1}{N} \sum_{i=1}^{N} \mathbf{S}^* (x, p)$$

$$P = 2 \frac{\langle \mathbf{S}^* \rangle \cdot \mathbf{J}}{|\mathbf{J}|}$$

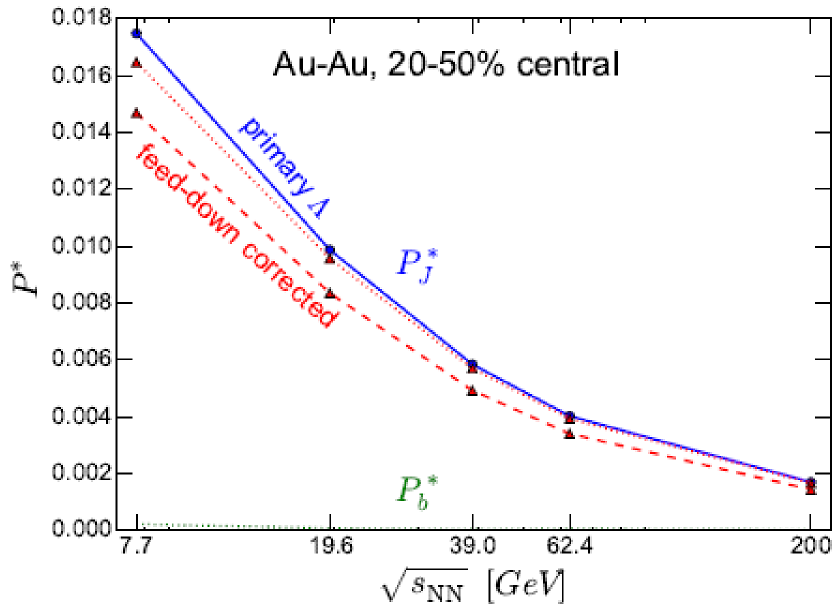


Global polarization from AMPT

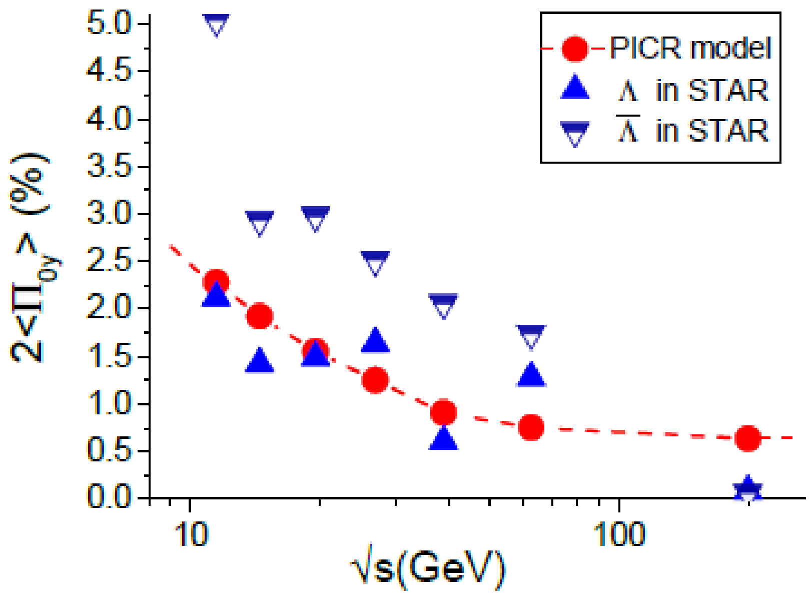


Au-Au 20%-50% with feed-down contribution

Global polarization in other models

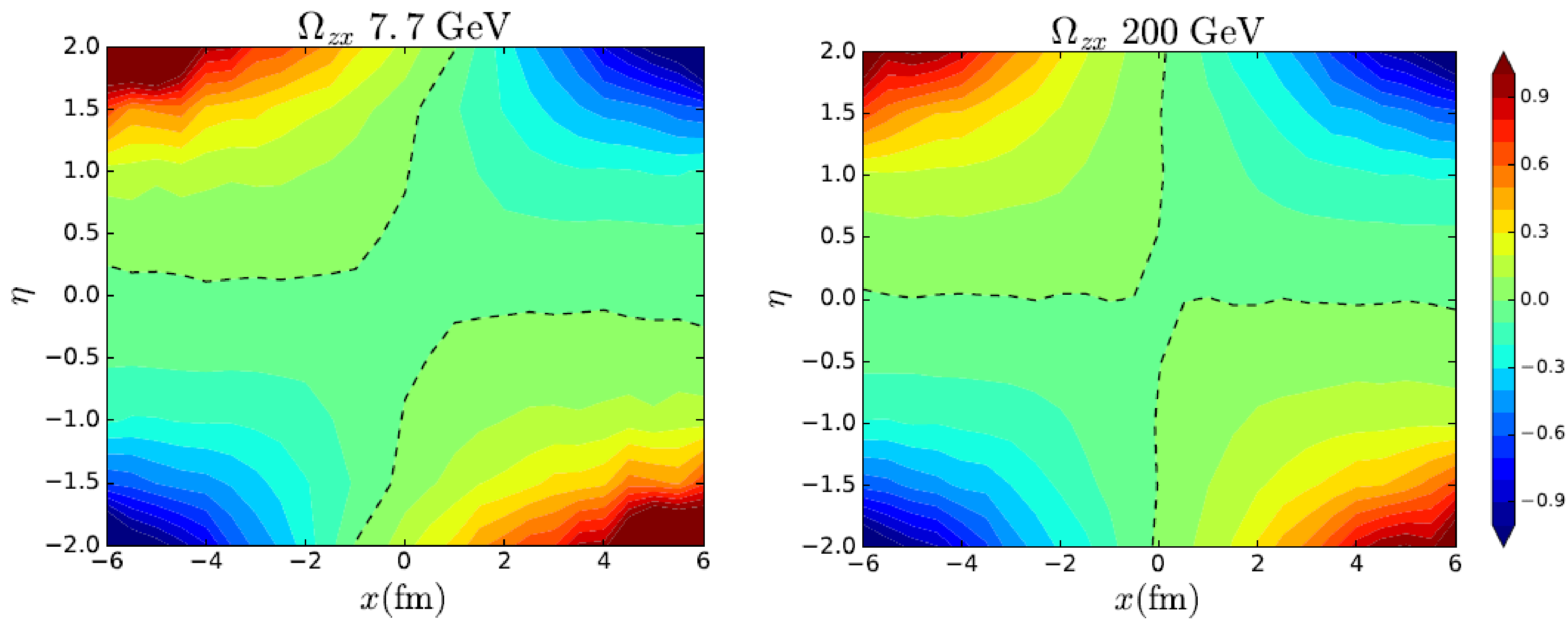


Karpenko, Becattini, EPJC 77, 2017
UrQMD + vHLLE hydro



Xie, Wang, Csernai, PRC 95, 2017
PICR hydro

Vorticity



$$\langle \mathbf{S}^* \rangle \sim \int d^4x f_\Lambda(x) \Omega_{zx}(x)$$

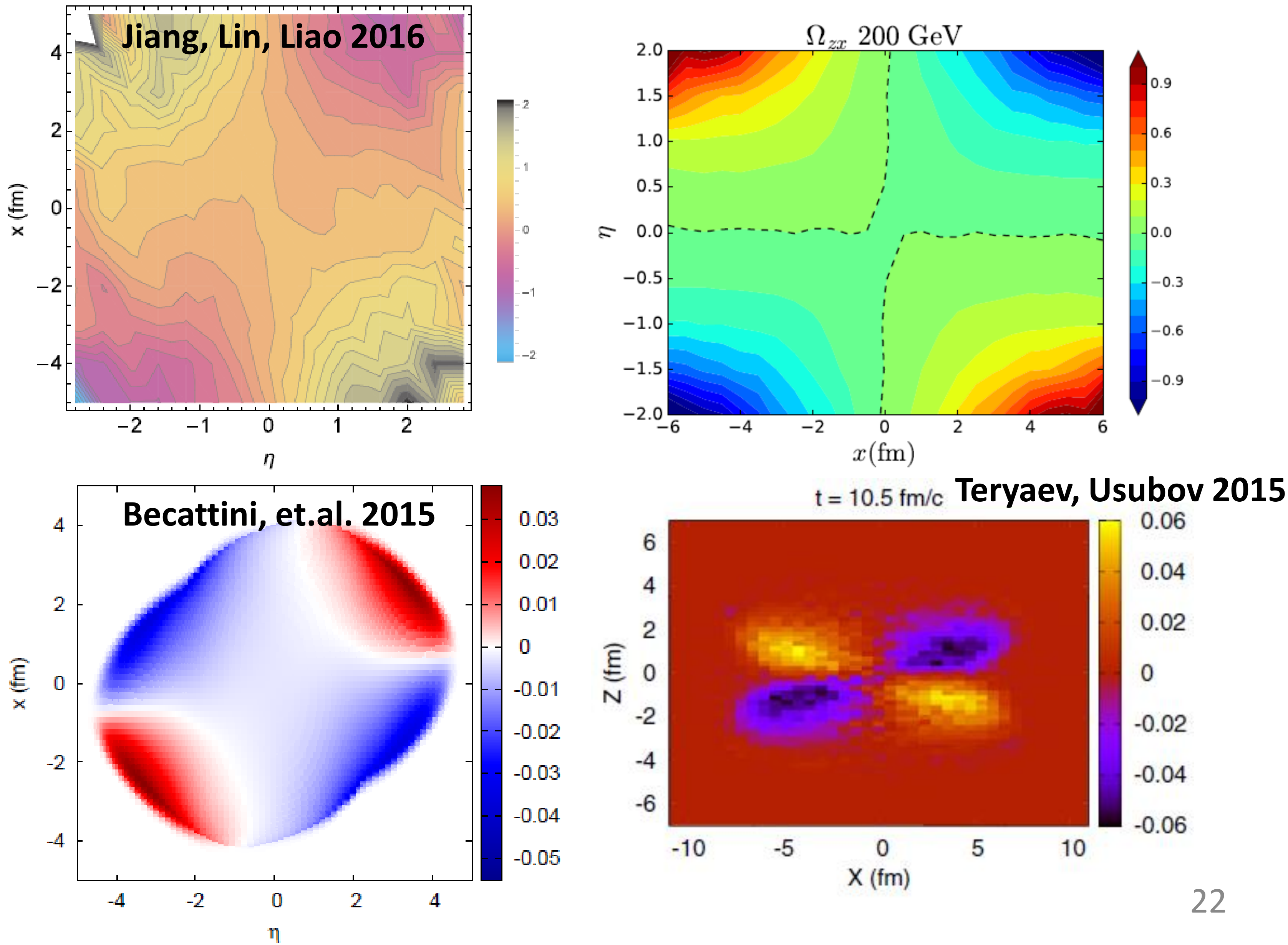
Vorticity on reaction plane

- Nearly odd function of x and η
- Less odd-symmetric at lower energy

$$\Omega_{zx} = \partial_z u^x - \partial_x u^z$$

$$\omega_y = \partial_z v^x - \partial_x v^z$$

Vorticity

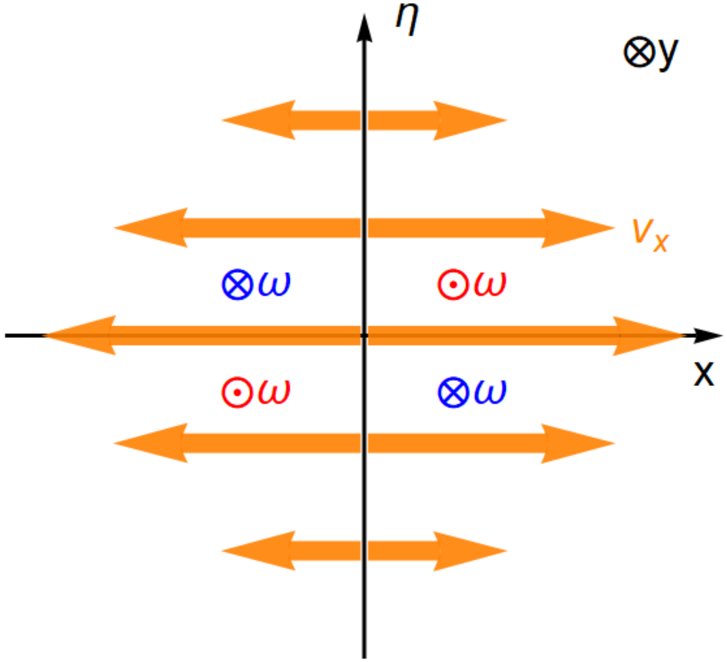


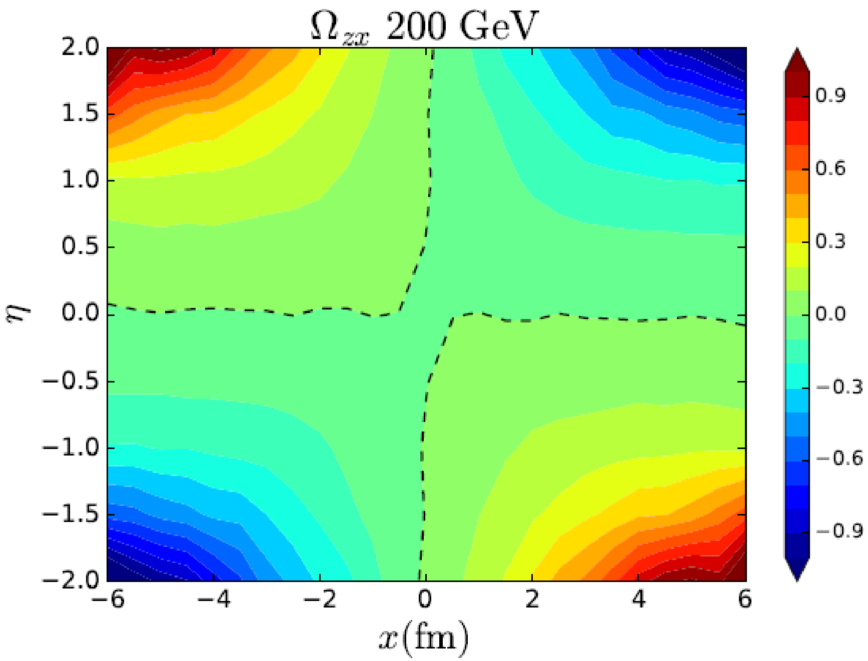
Jiang, Lin, Liao 2016
x (fm)
η
Ω_{zx} 200 GeV
η
x (fm)
Becattini, et.al. 2015
x (fm)
η
t = 10.5 fm/c
Teryaev, Usubov 2015
Z (fm)
X (fm)

Vorticity and radial flow

- The odd-symmetry can be understood by the **radial flow**

Jiang, Lin, Liao 2016



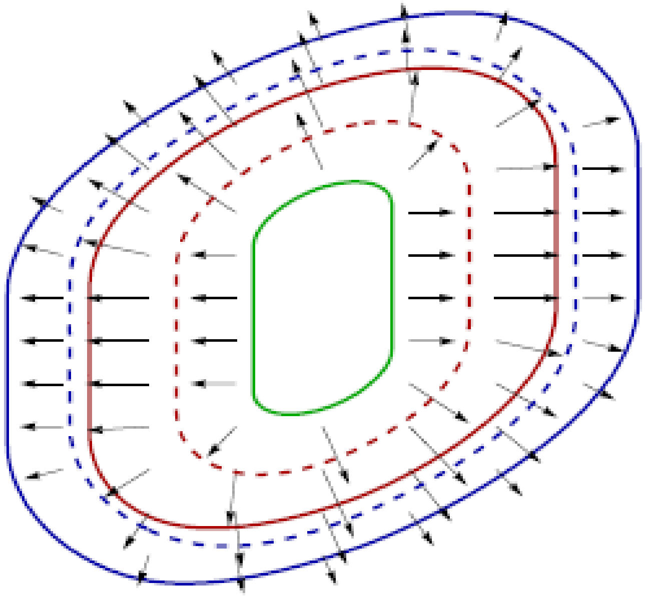


$$\Omega_{zx} = \partial_z u^x - \partial_x u^z$$

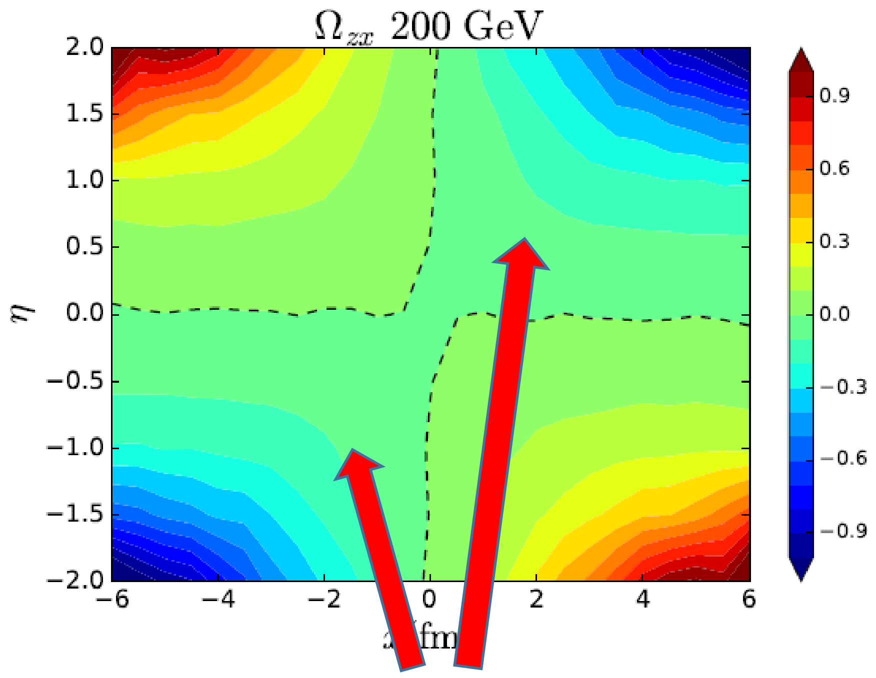
$$\langle \mathbf{S}^* \rangle \sim \int d^4x f_\Lambda(x) \Omega_{zx}(x)$$

Angular momentum

- Angular momentum is NOT zero because of fireball's tilt.



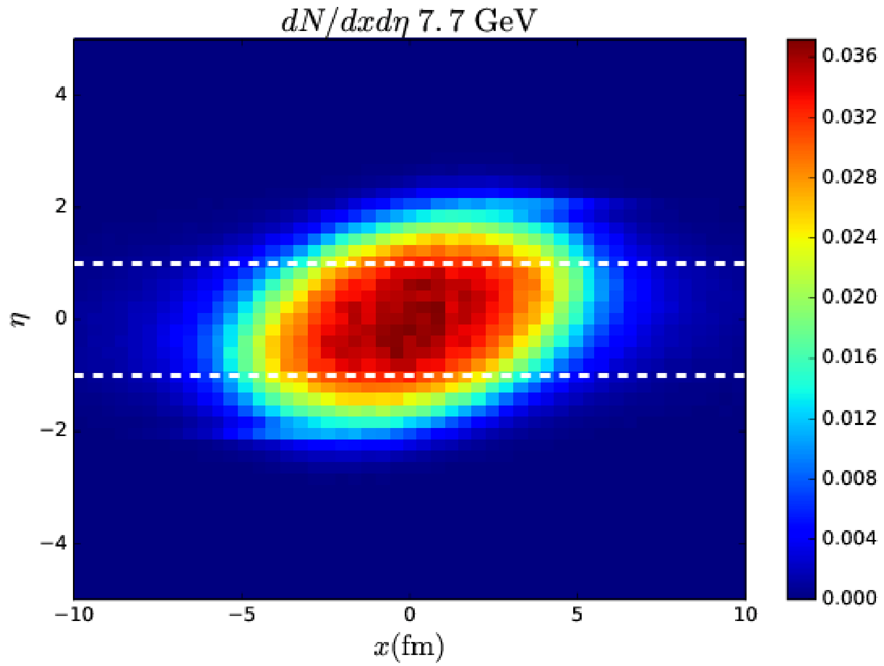
Bozek, Wyskiel 2010

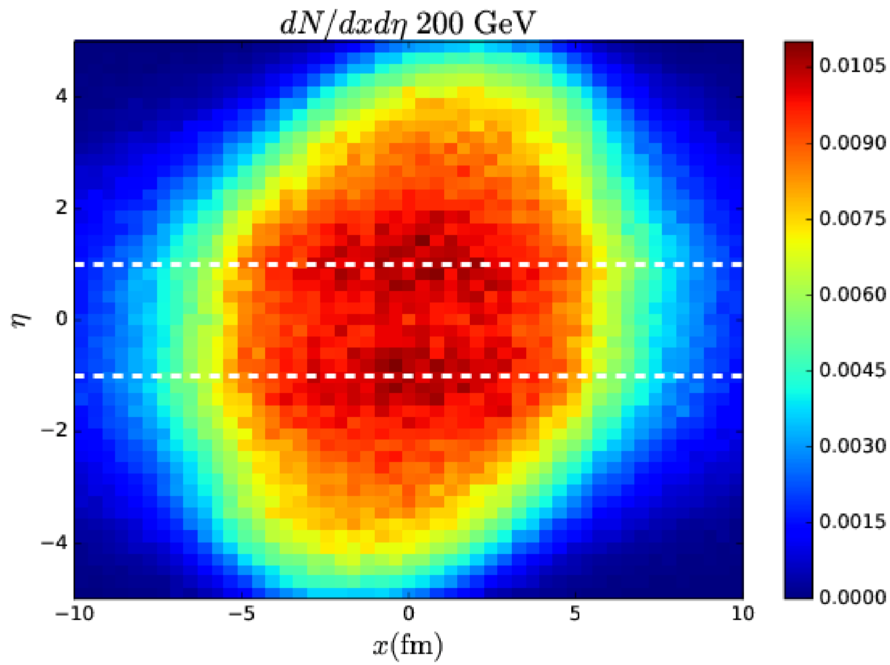


Λ distribution

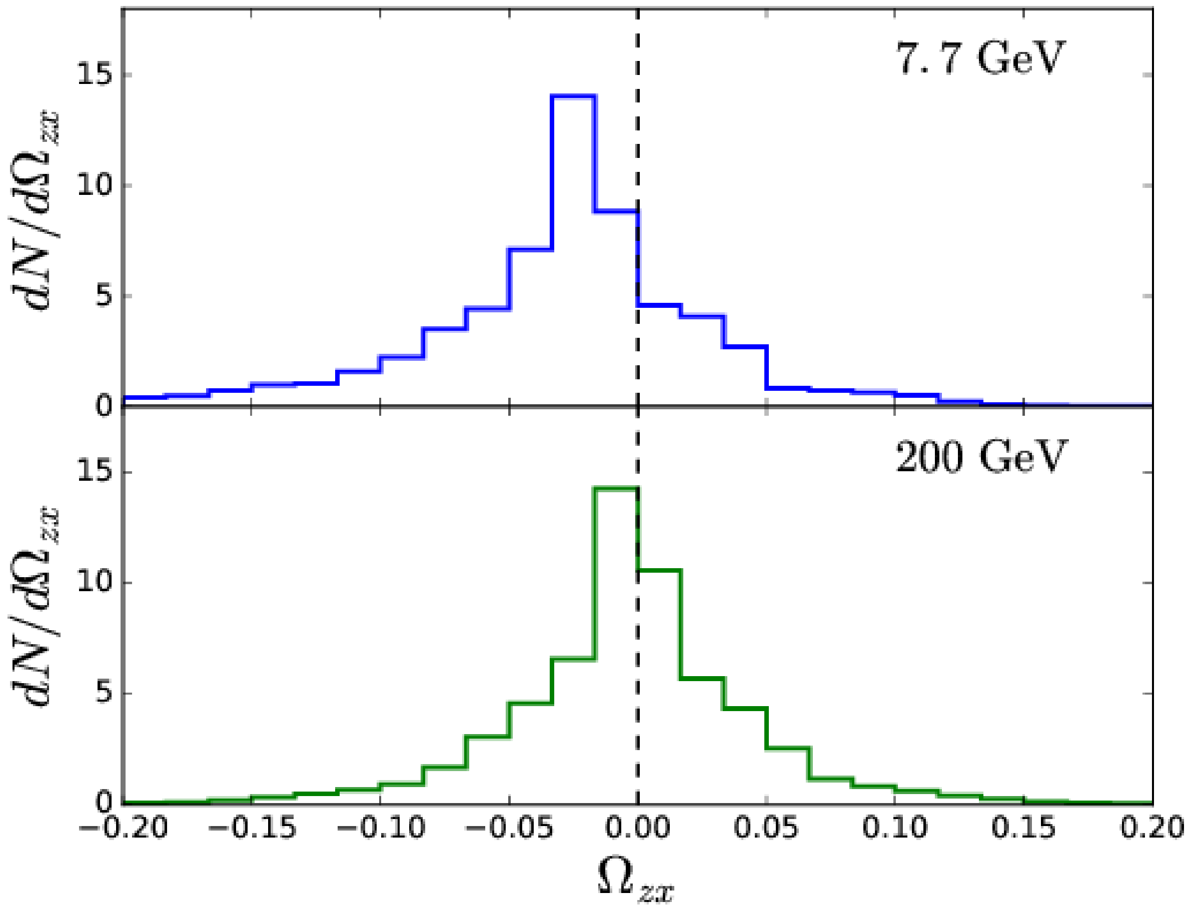
$$\langle \mathbf{S}^* \rangle \sim \int d^4x f_\Lambda(x) \Omega_{zx}(x)$$

- Tilt at 7.7 GeV
- Symmetric at 200 GeV due to the rapid expansion





Λ distribution



Summary and outlook

- We calculated the vorticity induced **global Λ polarization** with AMPT. The result agrees with the experimental data within error-bars.
- The polarization energy dependence can be understood by the asymmetry between the forward- and backward-going participants at low energy.

✓ Direct probe of the vorticity and magnetic field of the rotational fluid

✓ Study the energy behavior of the global polarization signal

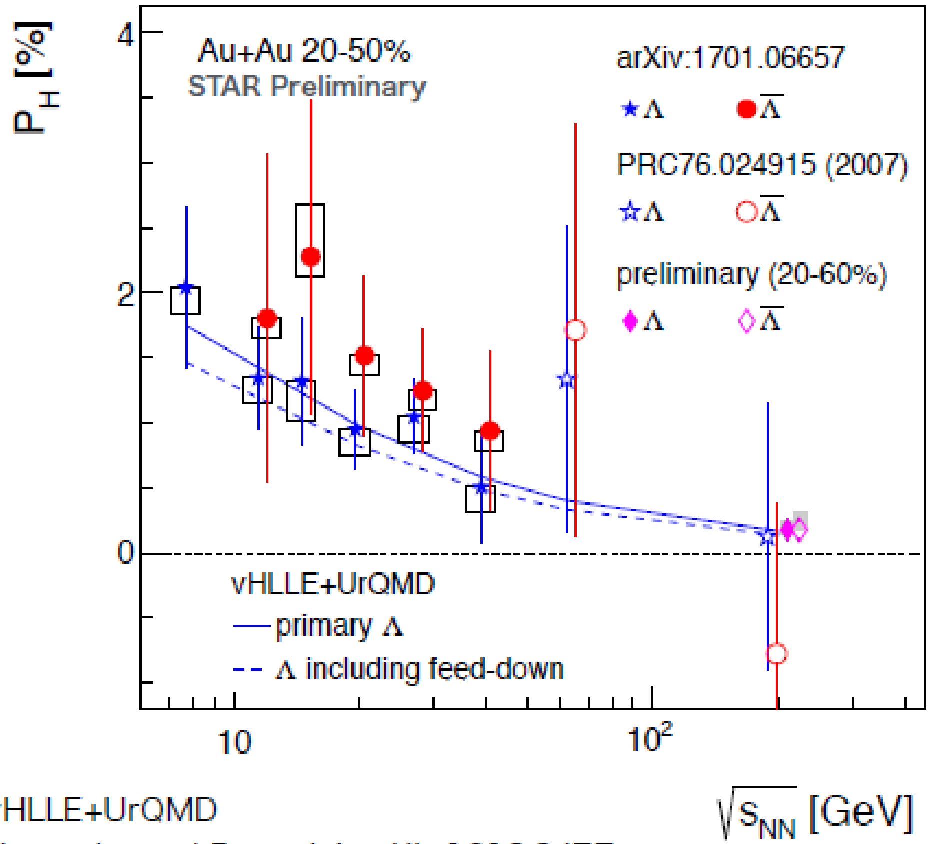
- More studies on magnetic/vorticity field are called.

Thanks for your attention!

buckup

New data at 200 GeV

Niida's talk at UCLA QCD Chirality workshop 2017



vHLLE+UrQMD
Karpenko and Becattini, arXiv:1610.0477

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Vorticity distribution at freeze-out

Karpenko, Becattini 2017

|η|<0.3