Vorticity and global polarization in heavy-ion collisions

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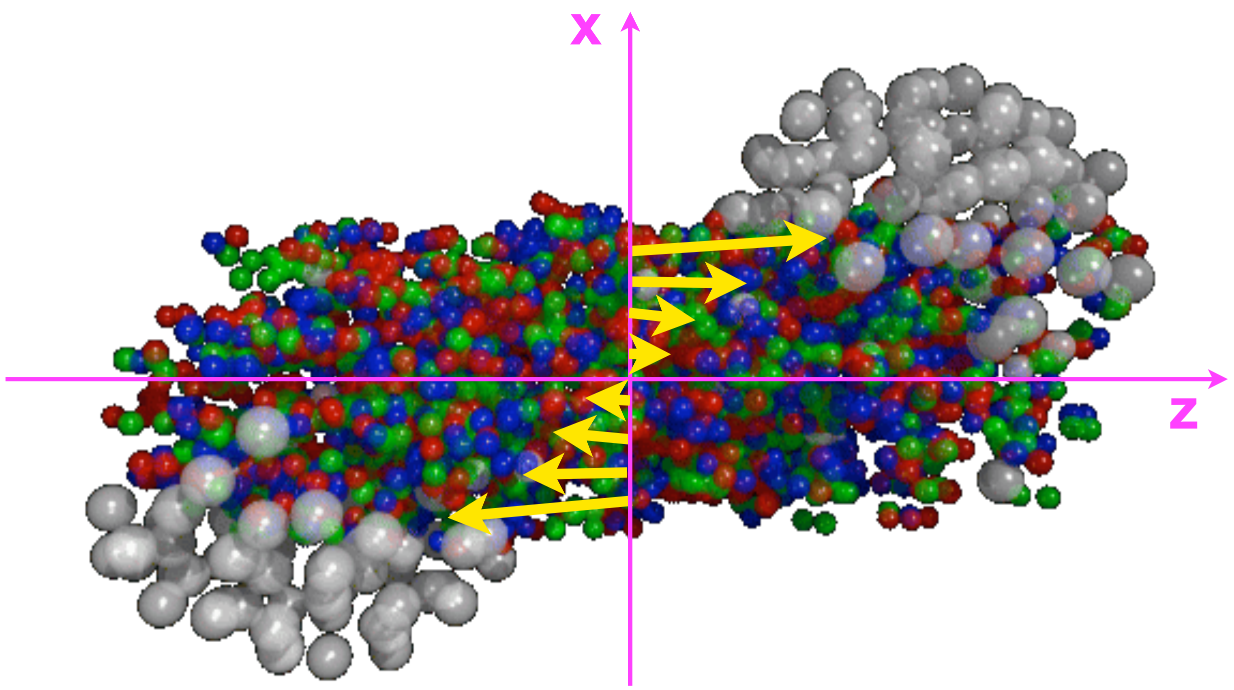
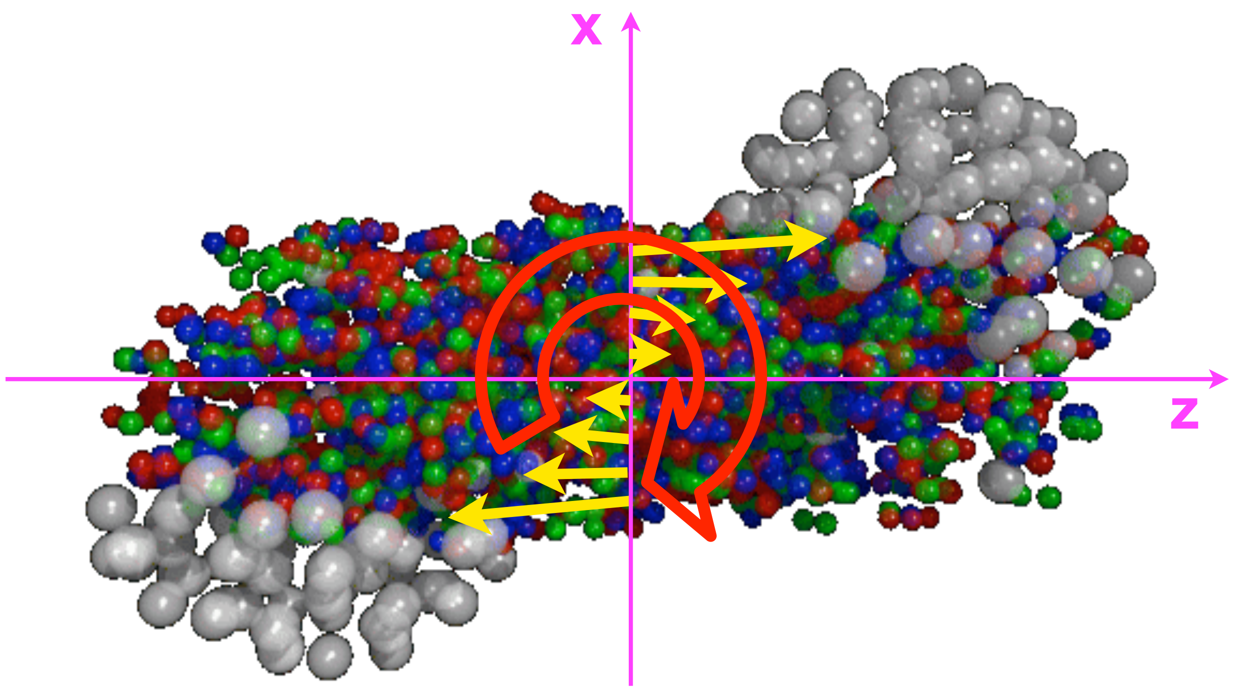
Initial Stages 2017, Kraków, Poland

Vorticity in HIC

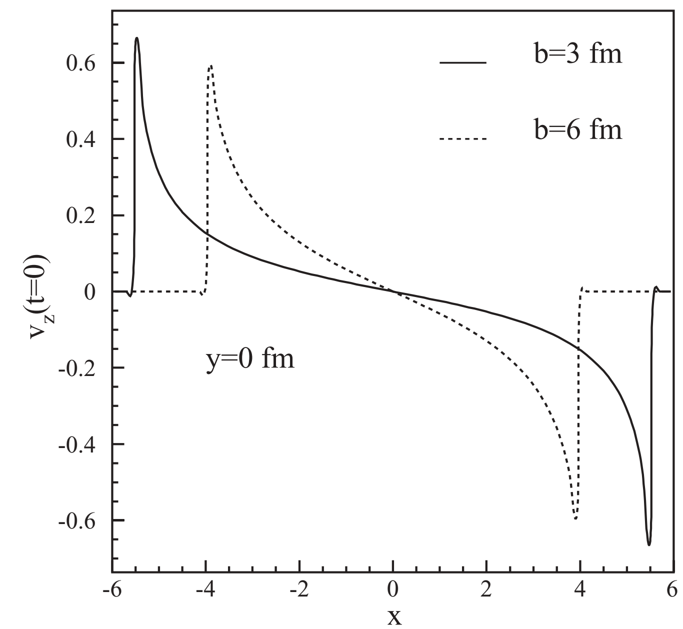


In non-central collisions, the initial longitudinal flow velocity depends on x.

Vorticity in HIC



Becattini et al.,
PRC77, 024906 (2008)



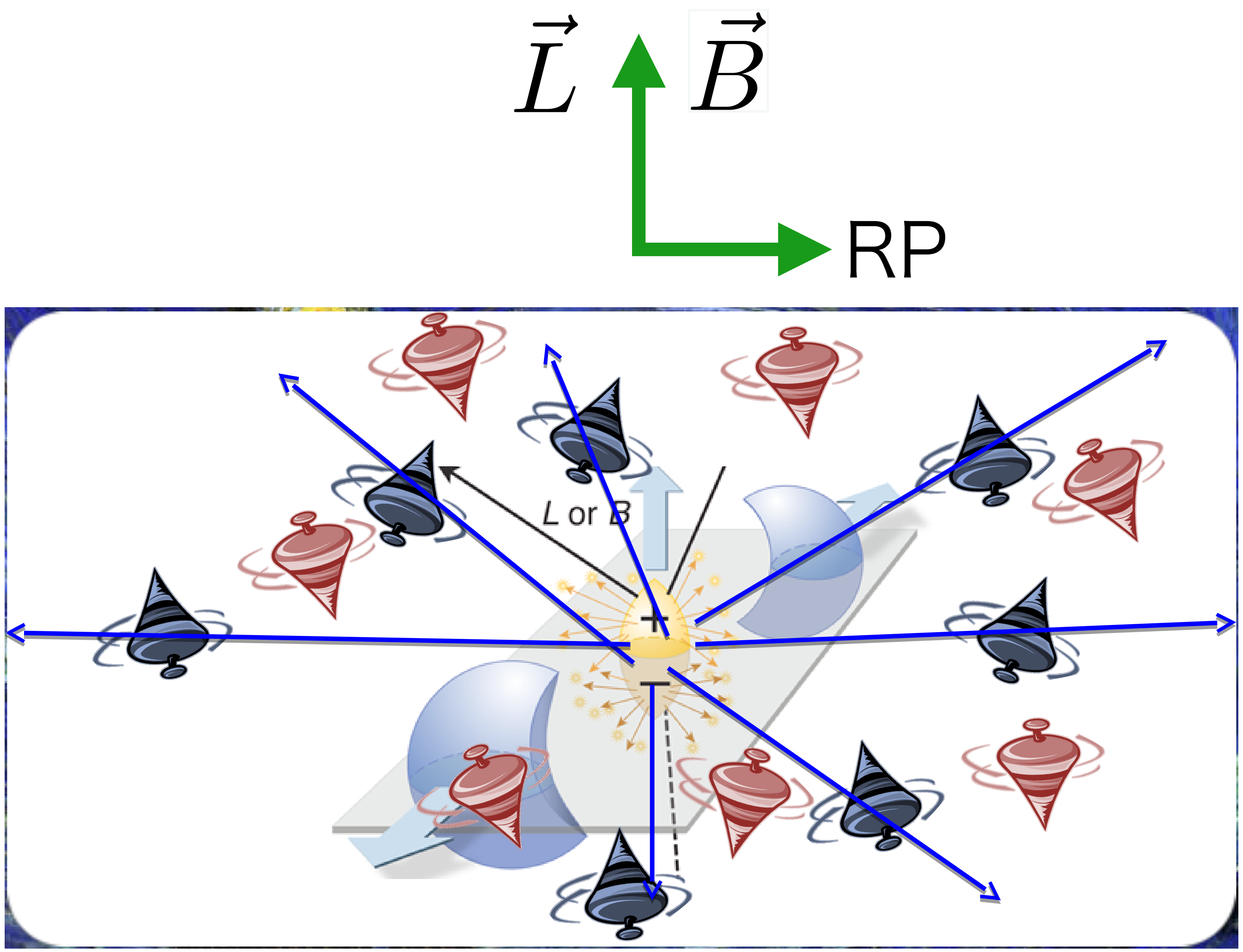
In non-central collisions, the initial longitudinal flow velocity depends on x, which makes the initial angular momentum.

$$\omega_y = (\frac{1}{2}\nabla \times \mathbf{v})_y \approx -\frac{1}{2}\frac{\partial v_z}{\partial x}$$

See F. Becattini's talk!

Global Polarization of Λ

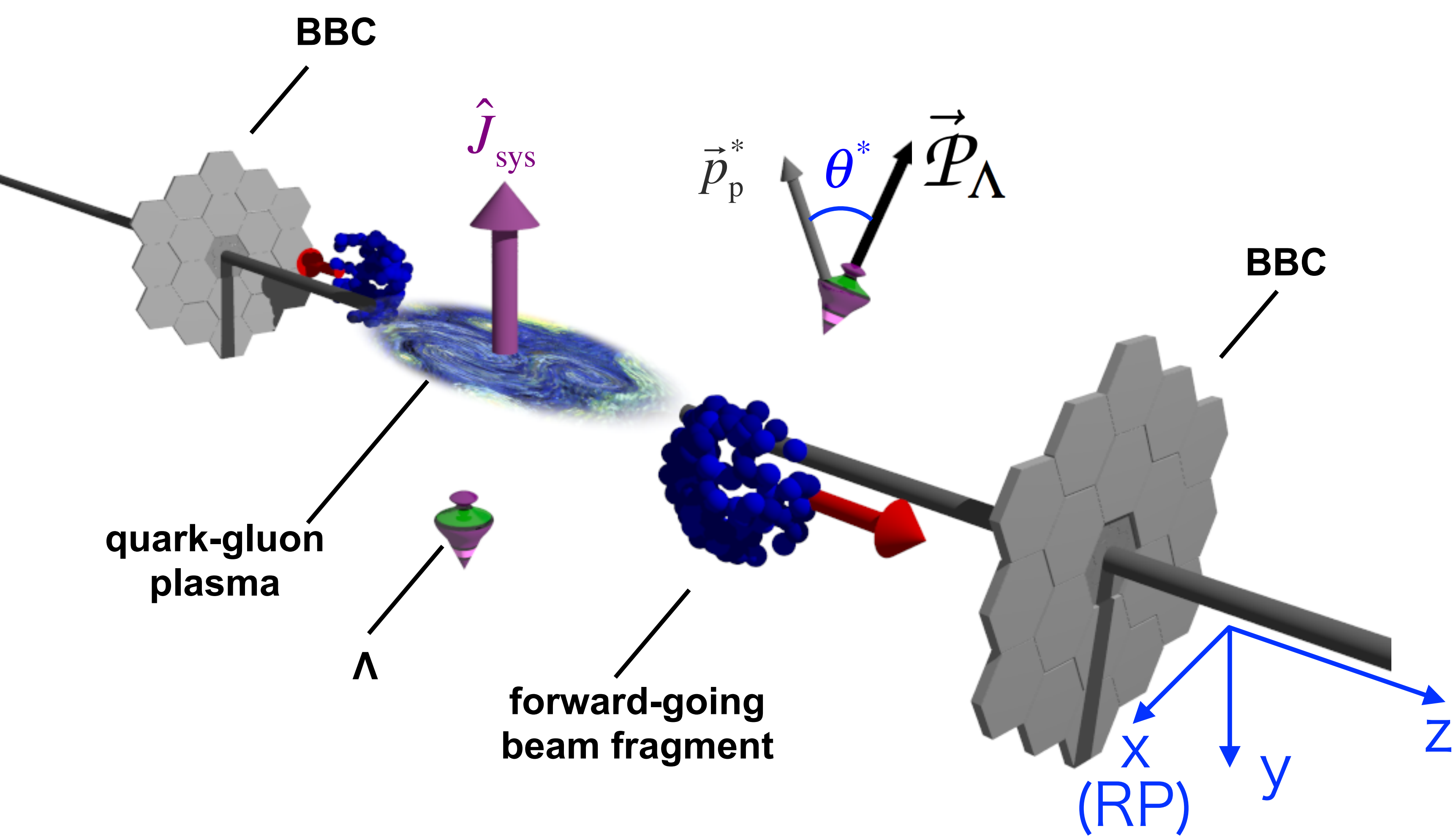
★ Non-zero angular momentum transfers to Λ polarization

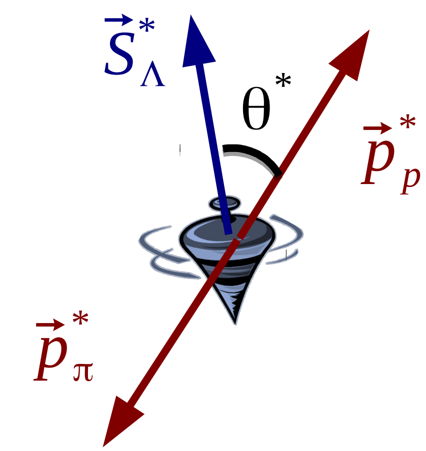


Two effects

- spin-orbit coupling
  - spins of Λ and anti-Λ are aligned with angular momentum ***L***
- spin alignment by B-Field
  - Λ spin anti-aligned along ***B***
  - anti-Λ spin aligned along ***B***

How to measure the polarization?





parity-violating decay

daughter proton preferentially decays in the direction of Λ's spin (opposite for anti-Λ)

$$\frac{dN}{d\Omega} = \frac{1}{4\pi}(1 + \alpha \mathbf{P_\Lambda} \cdot \mathbf{p_p^*})$$

Projected onto transverse plane:

$$P_H = \frac{8}{\pi\alpha} \frac{\langle \sin(\Psi_1 - \phi_p^*) \rangle}{\mathrm{Res}(\Psi_1)} \mathrm{sgn}_\Lambda$$

STAR, PRC76, 024915 (2007)

α: Λ decay parameter (=0.642±0.013)

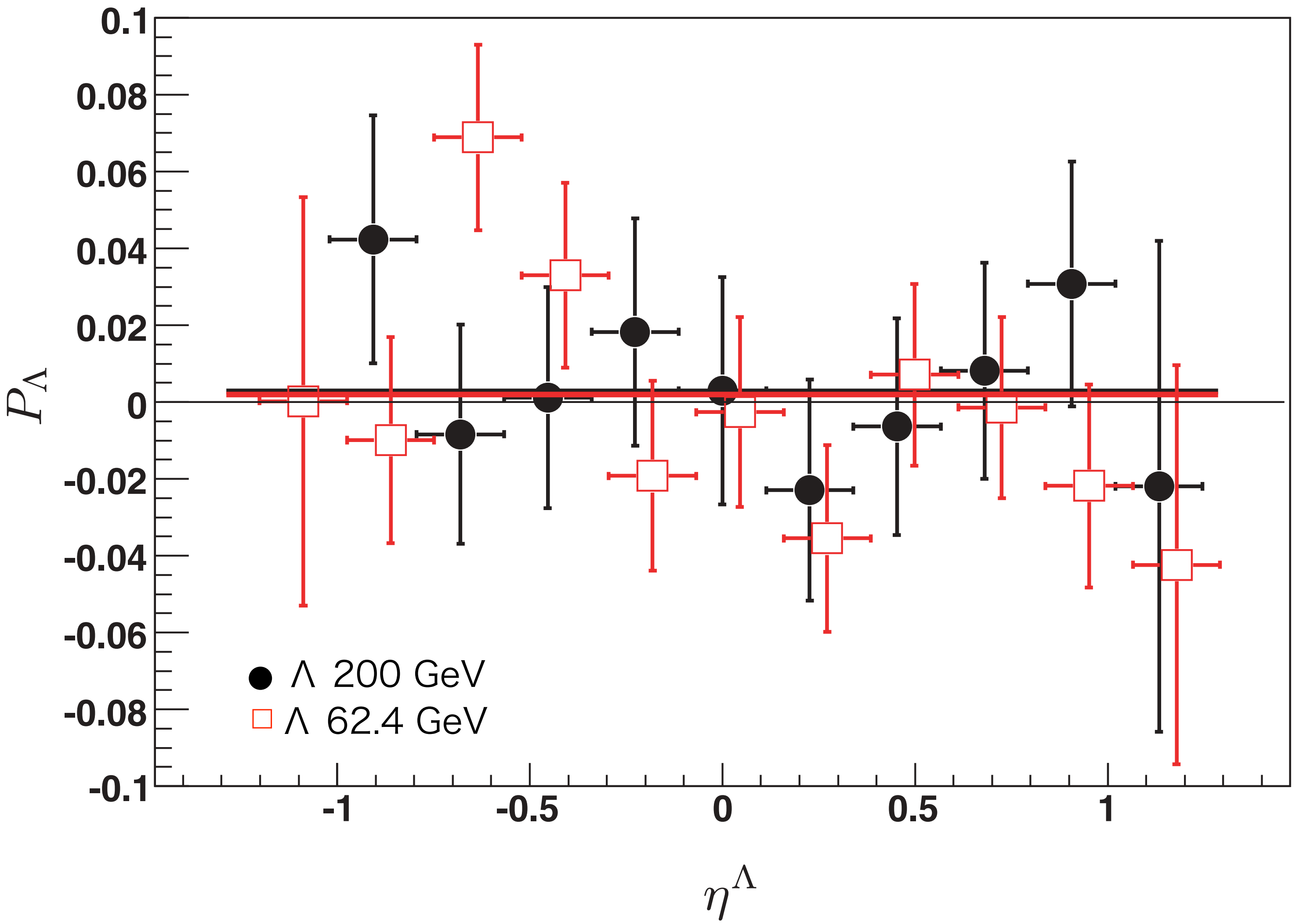
ϕ_p^*: ϕ of daughter proton in Λ rest frame

Ψ_1: 1st-order event plane

sgn_Λ: 1 for Λ, -1 for anti-Λ

First paper on Λ polarization from STAR in 2007

STAR, PRC76, 024915 (2007)

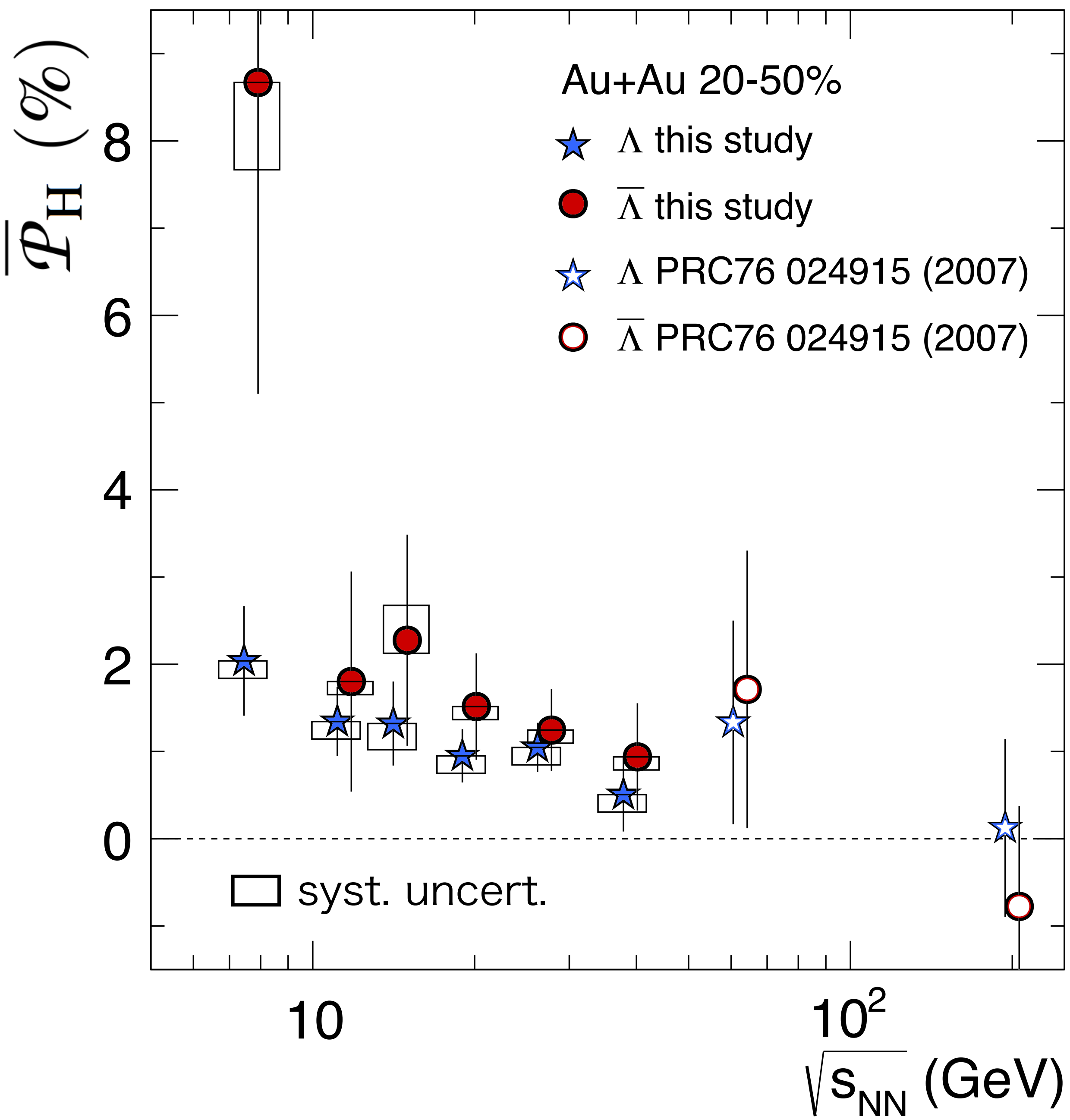


- Results were consistent with zero, giving an upper limit of 0.2%

First observation of
fluid vortices formed by HIC

$\sqrt{s_{NN}}$ dependence of Λ polarization

STAR, Nature 548.62 (2017)

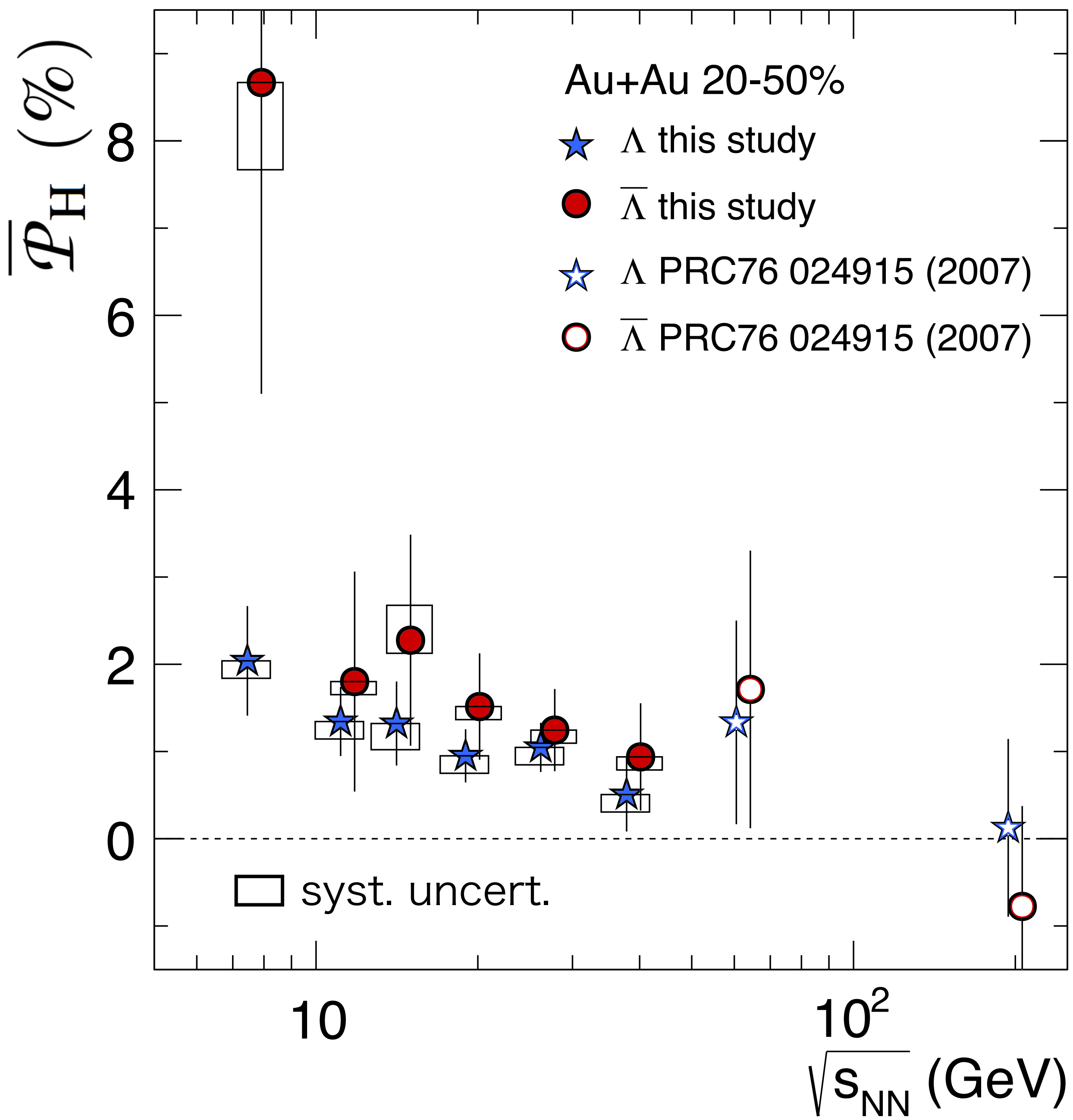


- Positive signals in $\sqrt{s_{NN}}$=7.7-62.4 GeV
  - indication of thermal vorticity!

$$\omega_T = (\frac{1}{2}\nabla \times \mathbf{v}/T)$$

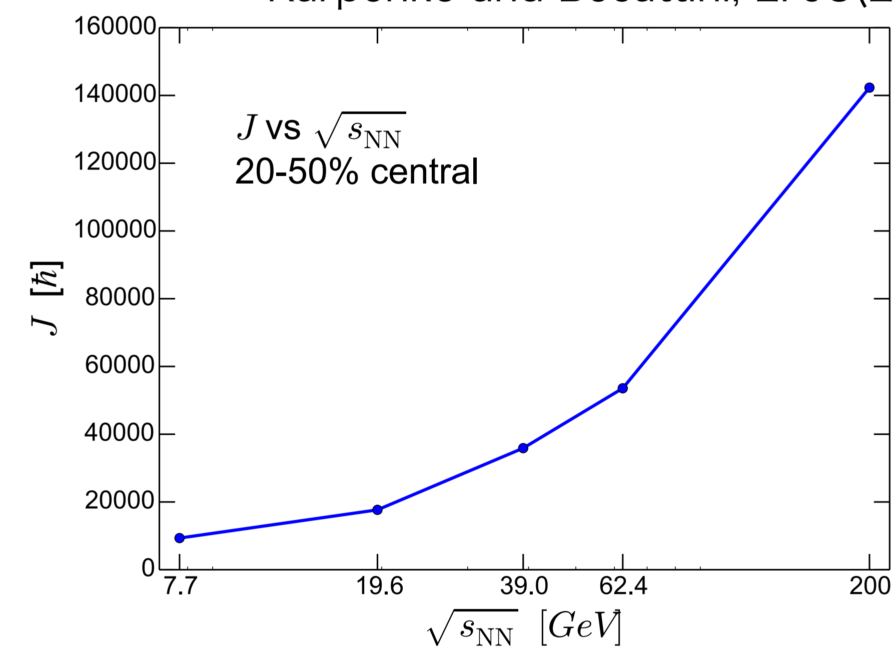
Λ global polarization vs $\sqrt{s_{NN}}$

STAR, Nature 548.62 (2017)



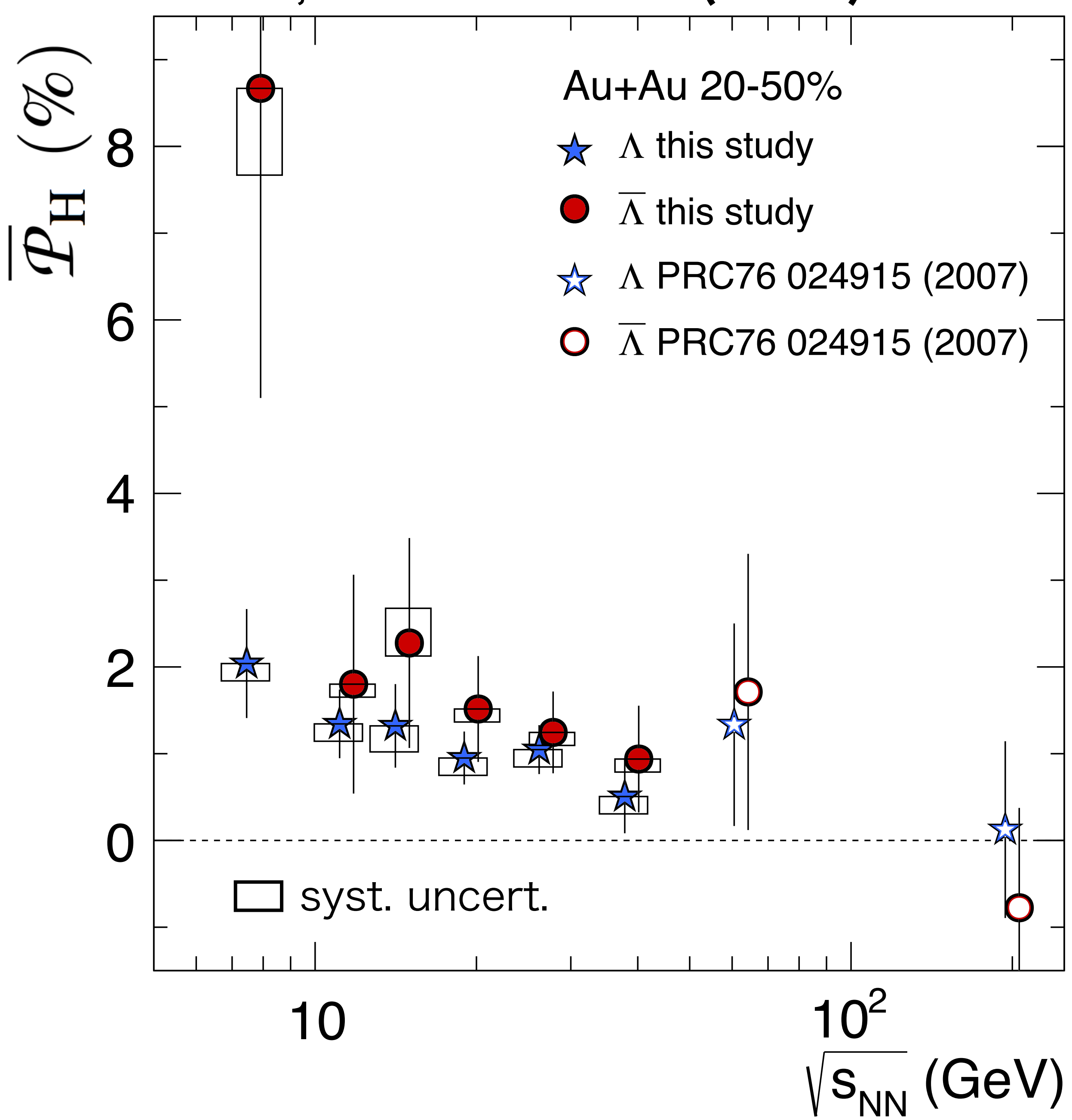
- Why larger signal in lower energy?
  - Initial angular momentum is largest at high energy

Karpenko and Becattini, EPJC(2017)77:213



Λ global polarization vs √sNN

STAR, Nature 548.62 (2017)



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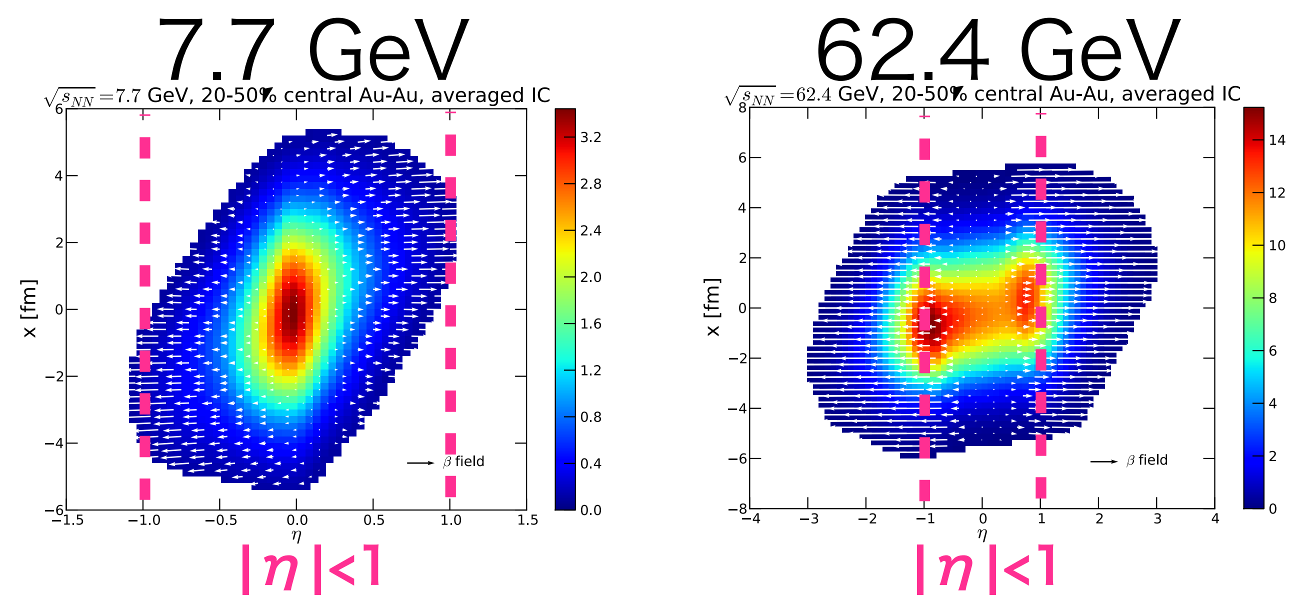


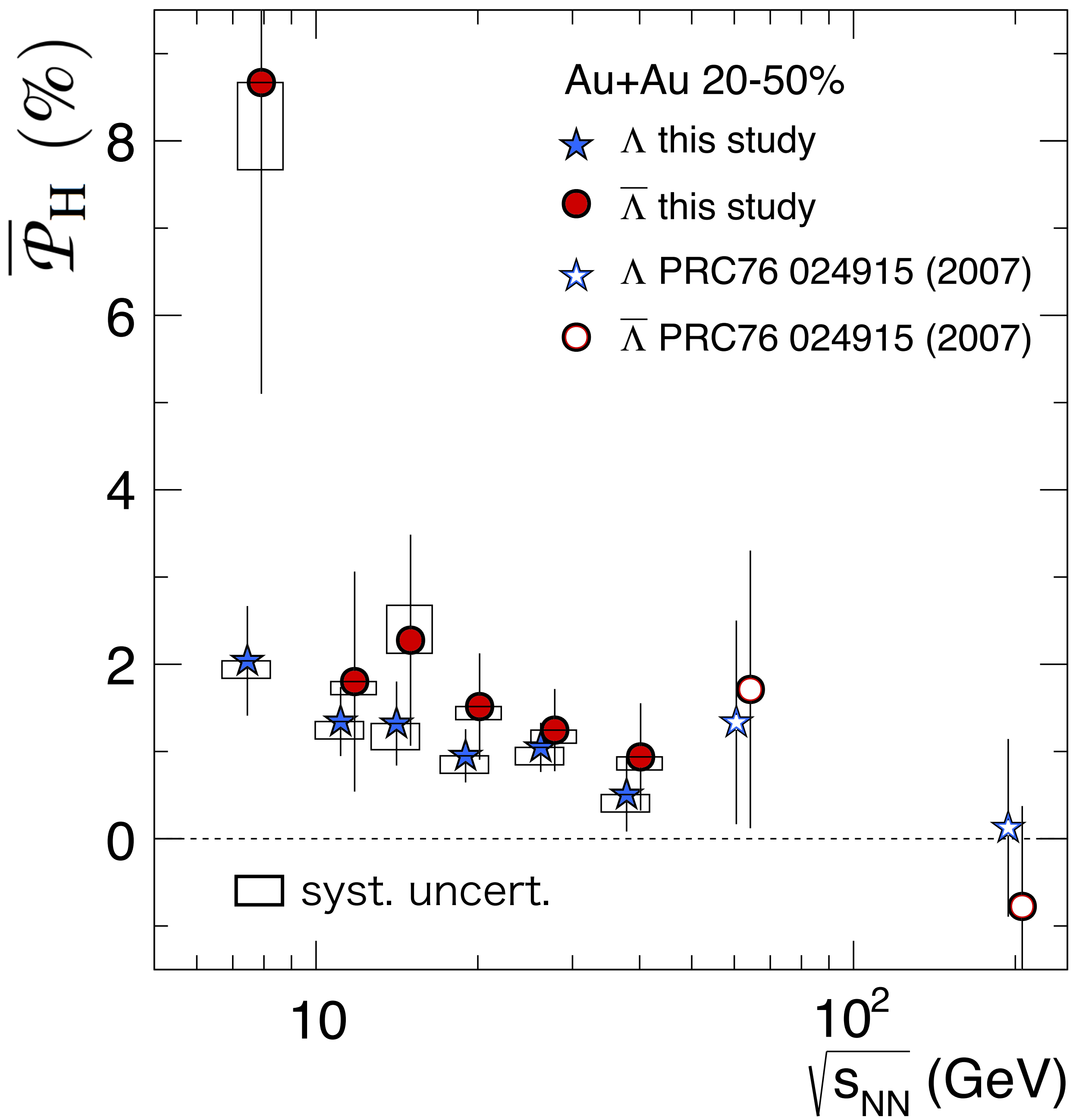
At higher collision energies,

- Smaller shear flow structure at mid-η due to baryon transparency

See I. Karpenko's talk!

Λ global polarization vs $\sqrt{s_{NN}}$

STAR, Nature 548.62 (2017)



- Positive signals in $\sqrt{s_{NN}}$=7.7-62.4 GeV
  - indication of thermal vorticity!

$$\omega_T = (\frac{1}{2}\nabla \times \mathbf{v}/T)$$

- **$P_H(\Lambda) < P_H(\text{anti-}\Lambda)$** systematically
  - implying a contribution from B-field

For small thermal vorticity,

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

Becattini, Karpenko, Lisa, Upsal, and Voloshin
PRC95.054902 (2017)

Accounting for feed-down

- only ~25% of measured Λ and anti-Λ are primary, while ~60% are feed-down from $\Sigma^* \to \Lambda\pi$, $\Sigma^0 \to \Lambda\gamma$, $\Xi \to \Lambda\pi$
- One needs to correct it before extracting physical parameters

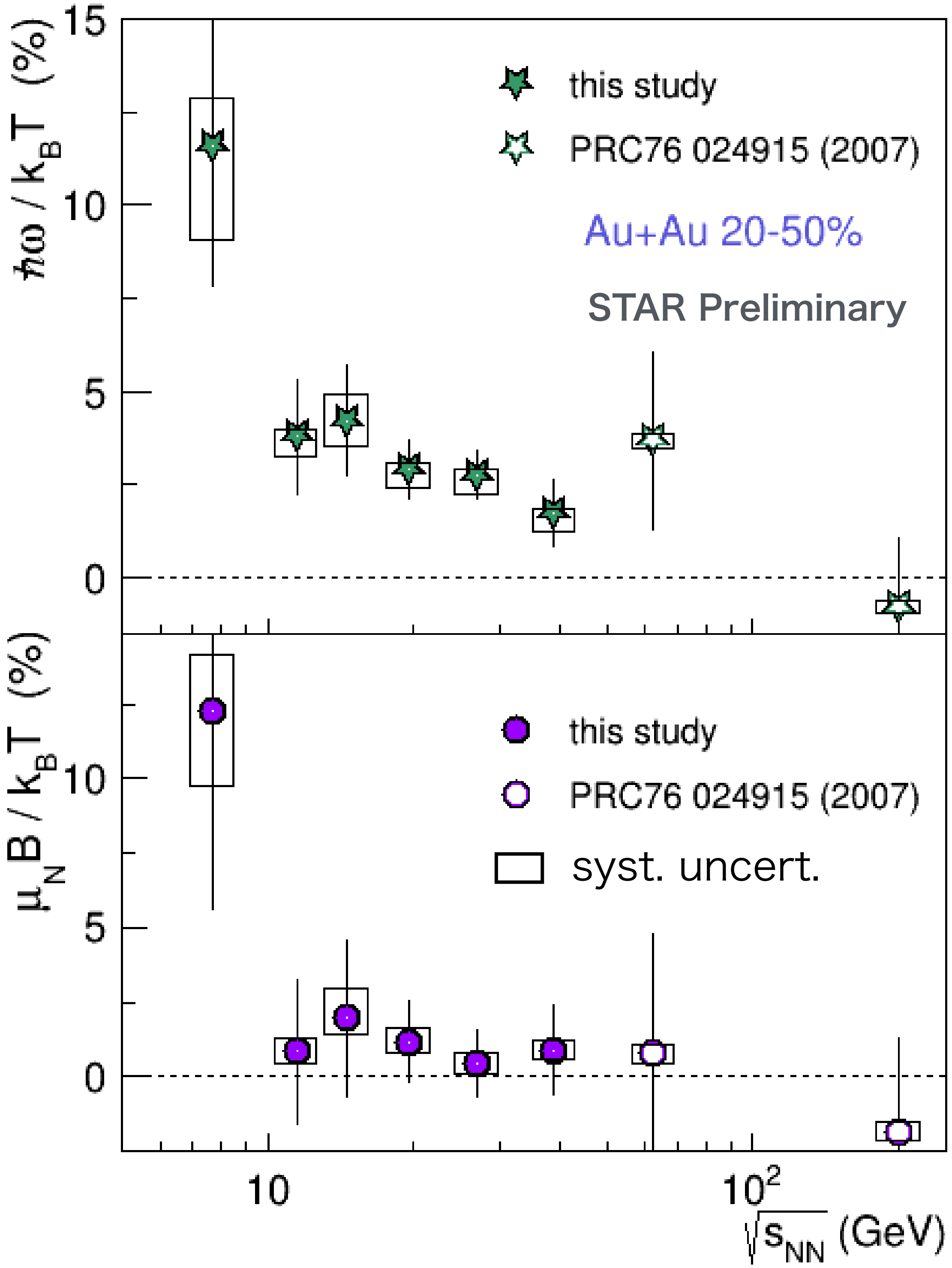
$$\begin{pmatrix} \varpi_c \\ B_c/T \end{pmatrix} = \begin{bmatrix} \frac{2}{3}\sum_R \left(f_{\Lambda R} C_{\Lambda R} - \frac{1}{3} f_{\Sigma^0 R} C_{\Sigma^0 R}\right) S_R(S_R+1) & \frac{2}{3}\sum_R \left(f_{\Lambda R} C_{\Lambda R} - \frac{1}{3} f_{\Sigma^0 R} C_{\Sigma^0 R}\right) (S_R+1)\,\mu_R \\ \frac{2}{3}\sum_{\overline{R}} \left(f_{\overline{\Lambda R}} C_{\overline{\Lambda R}} - \frac{1}{3} f_{\overline{\Sigma}^0 \overline{R}} C_{\overline{\Sigma}^0 \overline{R}}\right) S_{\overline{R}}(S_{\overline{R}}+1) & \frac{2}{3}\sum_{\overline{R}} \left(f_{\overline{\Lambda R}} C_{\overline{\Lambda R}} - \frac{1}{3} f_{\overline{\Sigma}^0 \overline{R}} C_{\overline{\Sigma}^0 \overline{R}}\right) (S_{\overline{R}}+1)\,\mu_{\overline{R}} \end{bmatrix}^{-1} \begin{pmatrix} P_{\Lambda}^{\mathrm{meas}} \\ P_{\overline{\Lambda}}^{\mathrm{meas}} \end{pmatrix}$$

Becattini, Karpenko, Lisa, Upsal, and Voloshin, PRC95.054902 (2017)

$f_{\Lambda R}$: fraction of Λ originating from parent R
$C_{\Lambda R}$: coefficient of spin transfer from parent R to Λ
S_R : parent particle's spin
μ_R : magnetic moment of particle R

~15% dilution of primary Λ polarization
(model-dependent)

Extracted vorticity and B-field



- Vorticity
  - ω/T ~ 2-10% ($\hbar = k_B = 1$)
  - ω~0.02-0.09 fm^{-1} (when assuming T=160 MeV)

Jiang et al., PRC94, 044910 (2016)

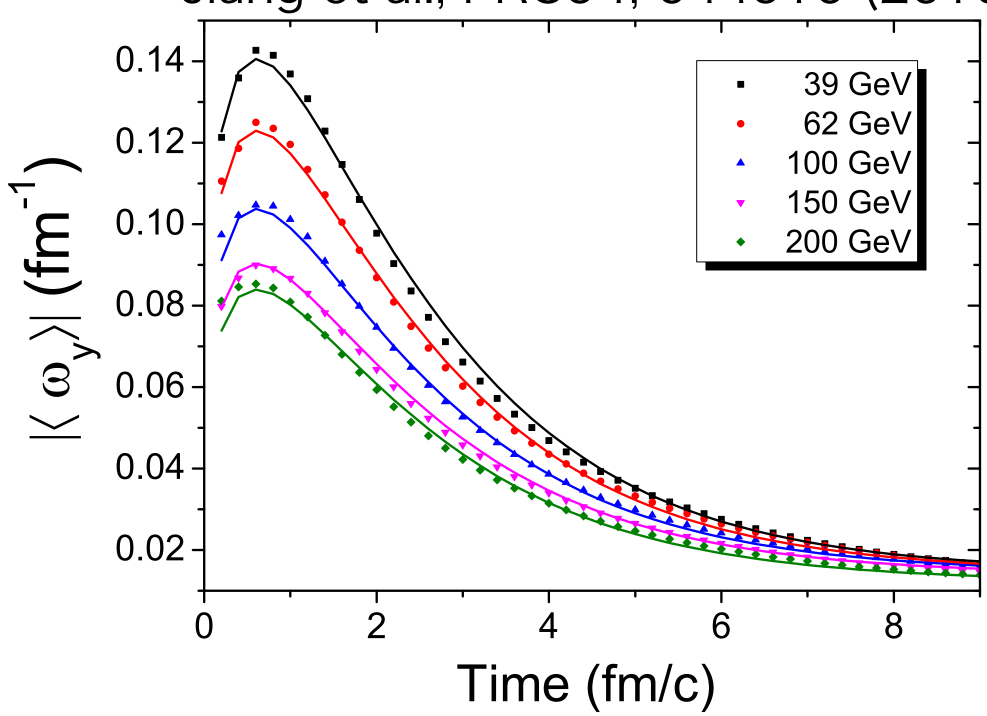
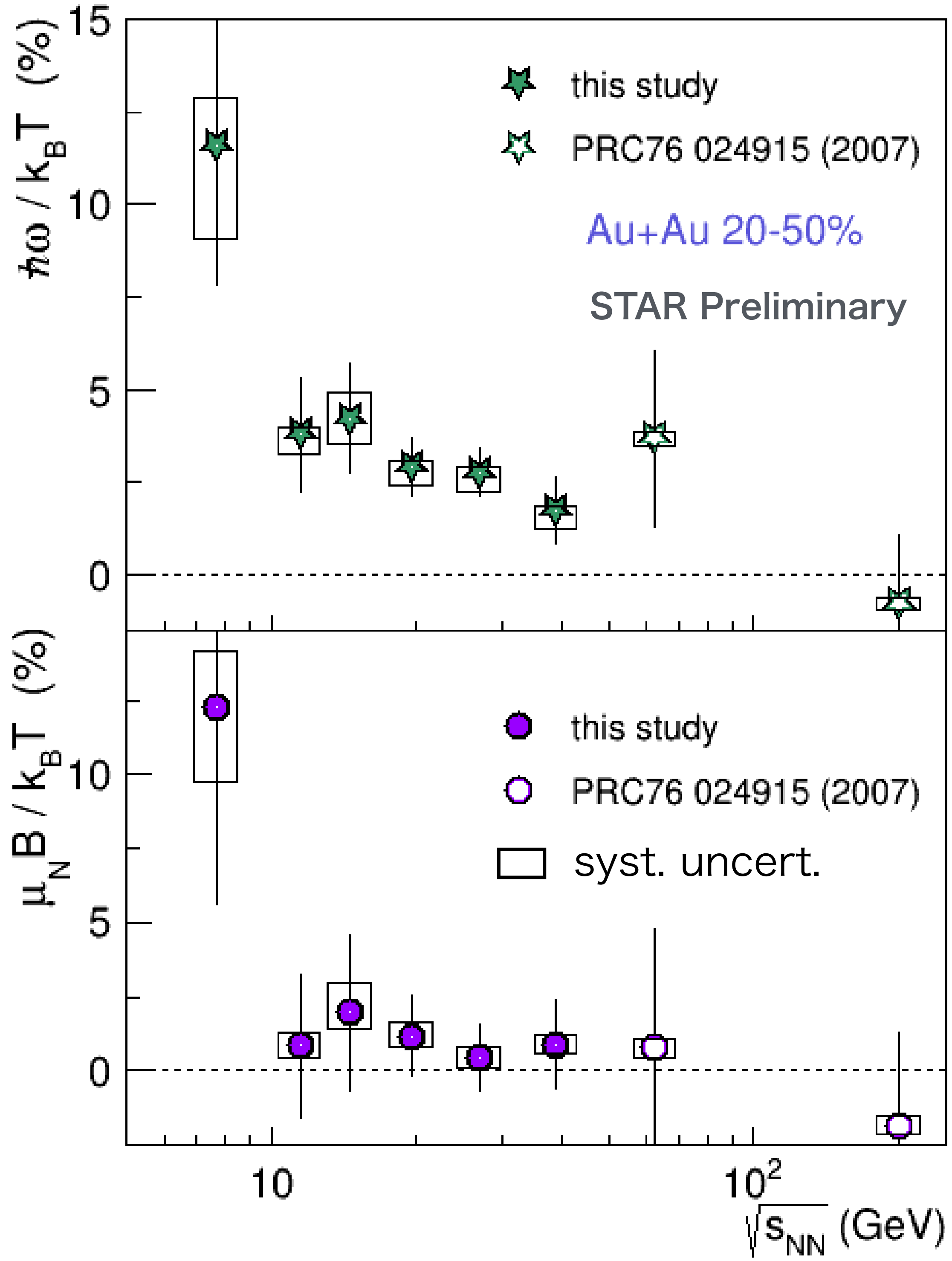


FIG. 12. Averaged vorticity $\langle \omega_y \rangle$ from the AMPT model as a function of time at varied beam energy $\sqrt{s_{NN}}$ for fixed impact parameter $b = 7$ fm. The solid curves are from a fitting formula (see text for details).

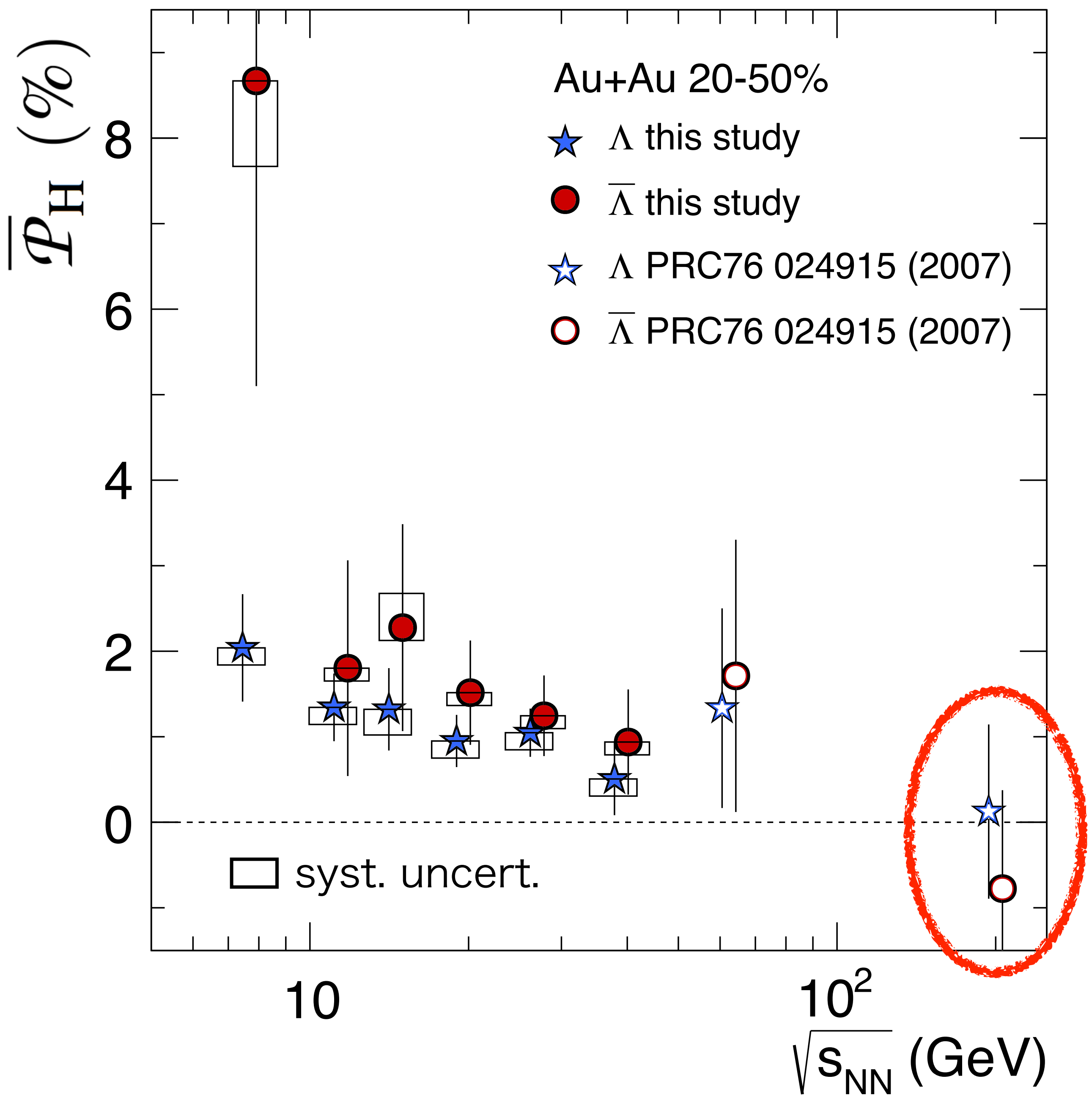
Extract vorticity and B-field



- Vorticity
  - ω/T ~ 2-10% ($\hbar = 1,\ k_B = 1$)
  - ω~0.02-0.09 fm^{-1} (when assuming T=160 MeV)
- Magnetic field
  - Data are consistent with zero, but a possible direct probe of B-field
  - Looking forward to BES II

Back to Λ polarization results

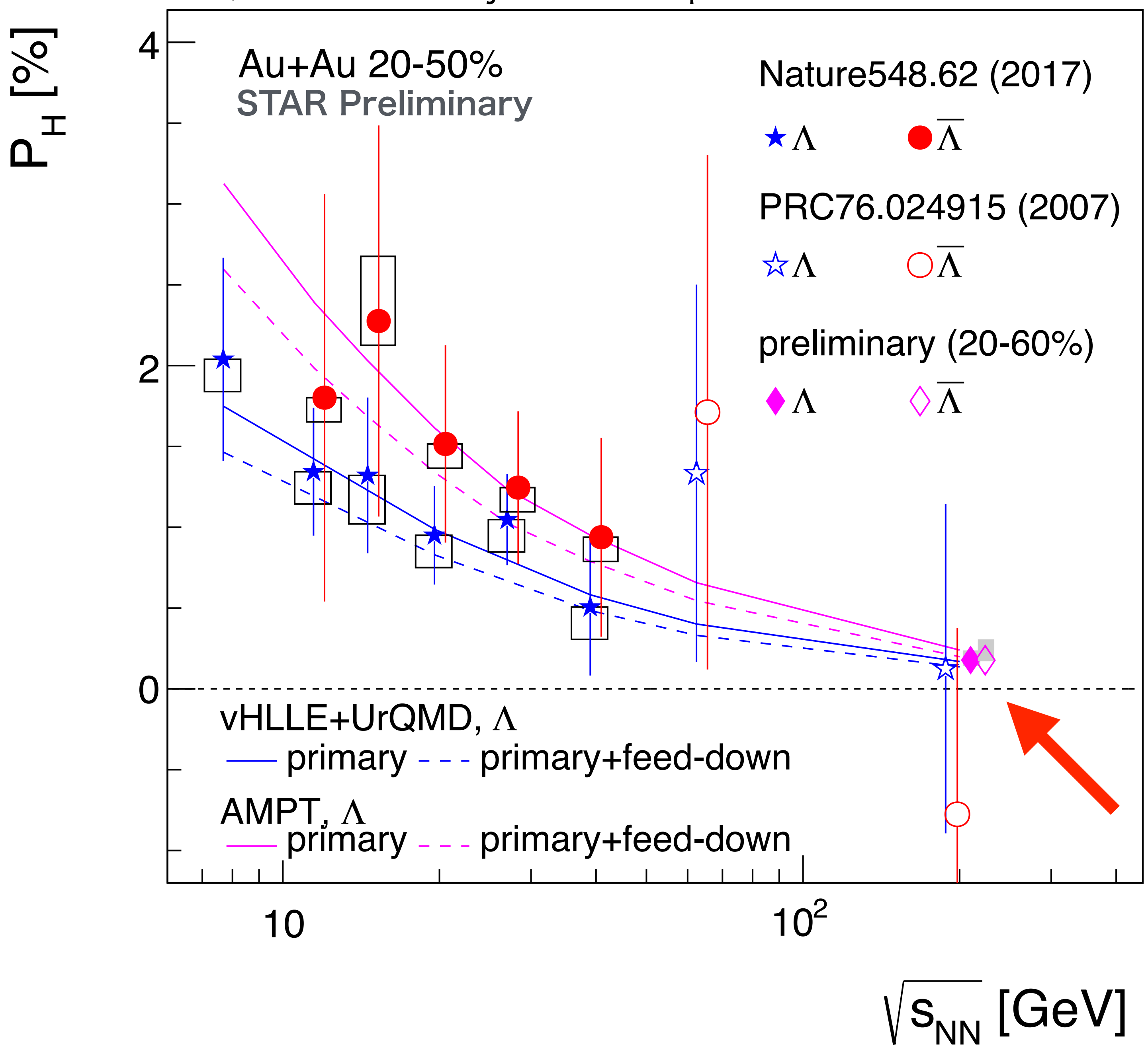
STAR, Nature 548.62 (2017)



- Previous STAR results at 200 GeV were consistent with zero
  →Can we see the signal when using recent data with more statistics?
- 2007 publication
  - year 2004 data ~**9M** events
- Recent preliminary study
  - year 2011 data ~**350M** events

Λ global polarization vs √sNN

TN, QCD Chirality Workshop 2017



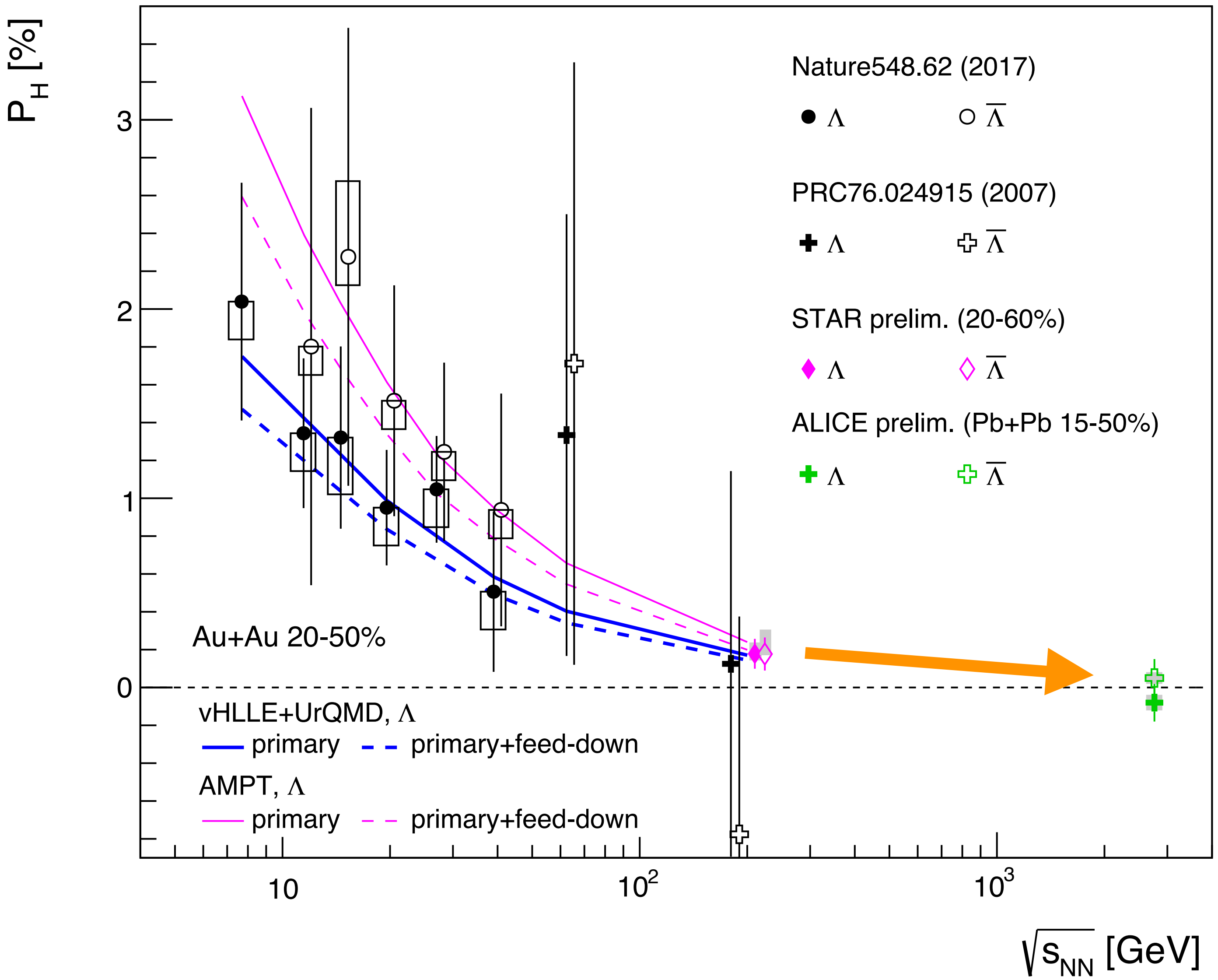
vHLLE+UrQMD: Karpenko and Becattini, EPJC(2017)77:213
AMPT: H. Li et al., arXiv:1704.01507

- Finite signal of P_H at $\sqrt{s_{NN}}$ = 200 GeV

  P_H ~0.18%±0.08±0.06

  - no significant difference between Λ and anti-Λ
  - close to viscous-hydro +UrQMD and AMPT predictions in all energies

Go to the LHC energy

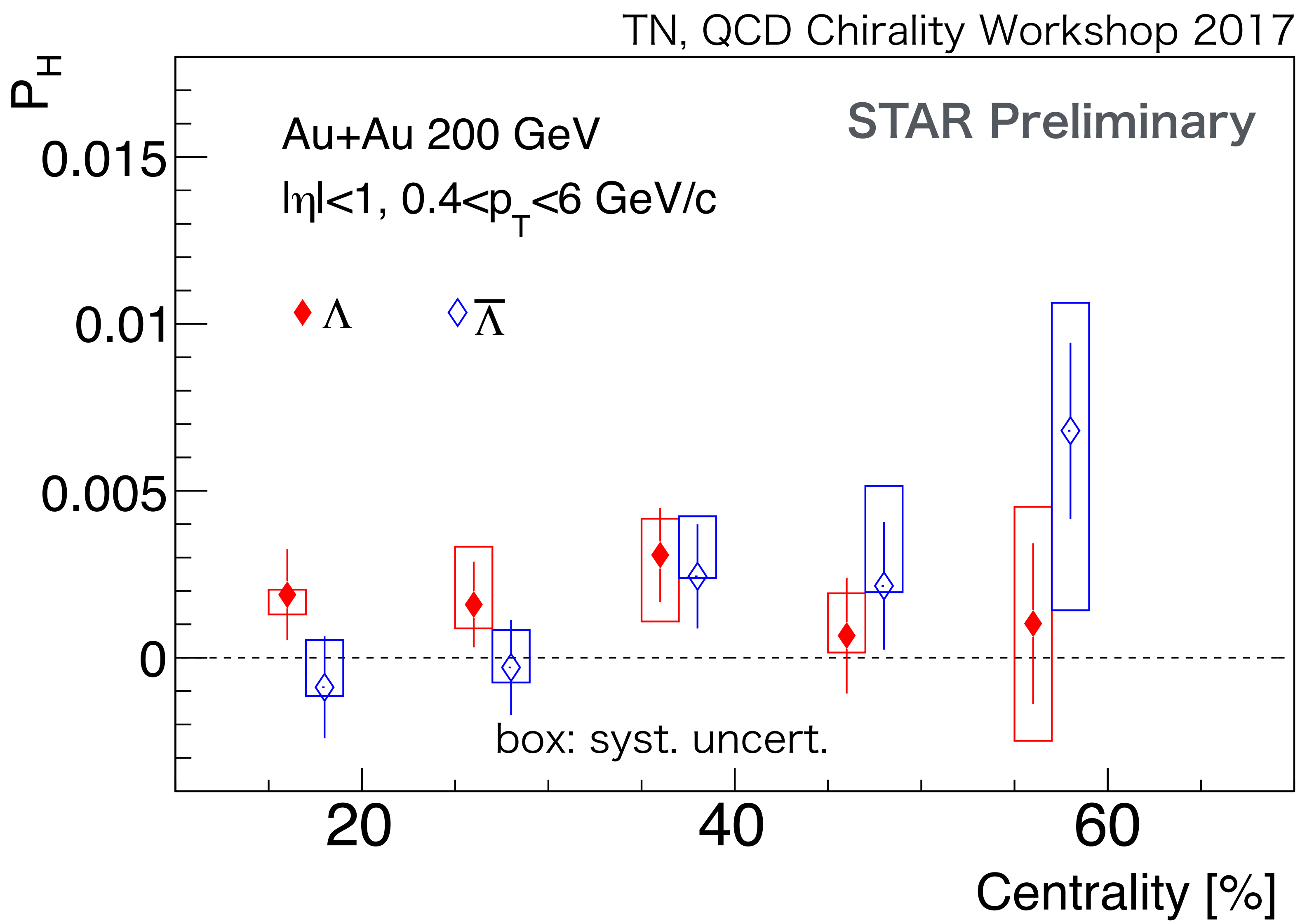


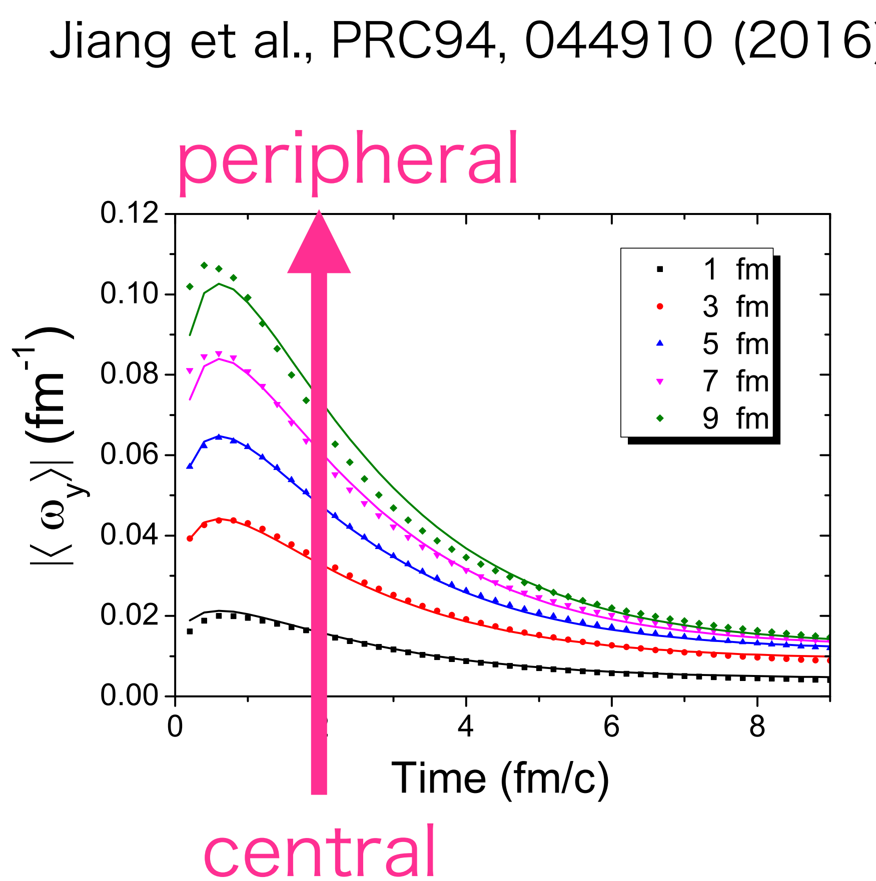
- ALICE preliminary results are consistent with zero, but it seems to follow the global trend
- Need more events!

vHLLE+UrQMD: Karpenko and Becattini, EPJC(2017)77:213
AMPT: H. Li et al., arXiv:1704.01507
ALICE prelim: M. Konyushikhin, QCD Chirality Workshop 2017

Further detailed study at 200 GeV

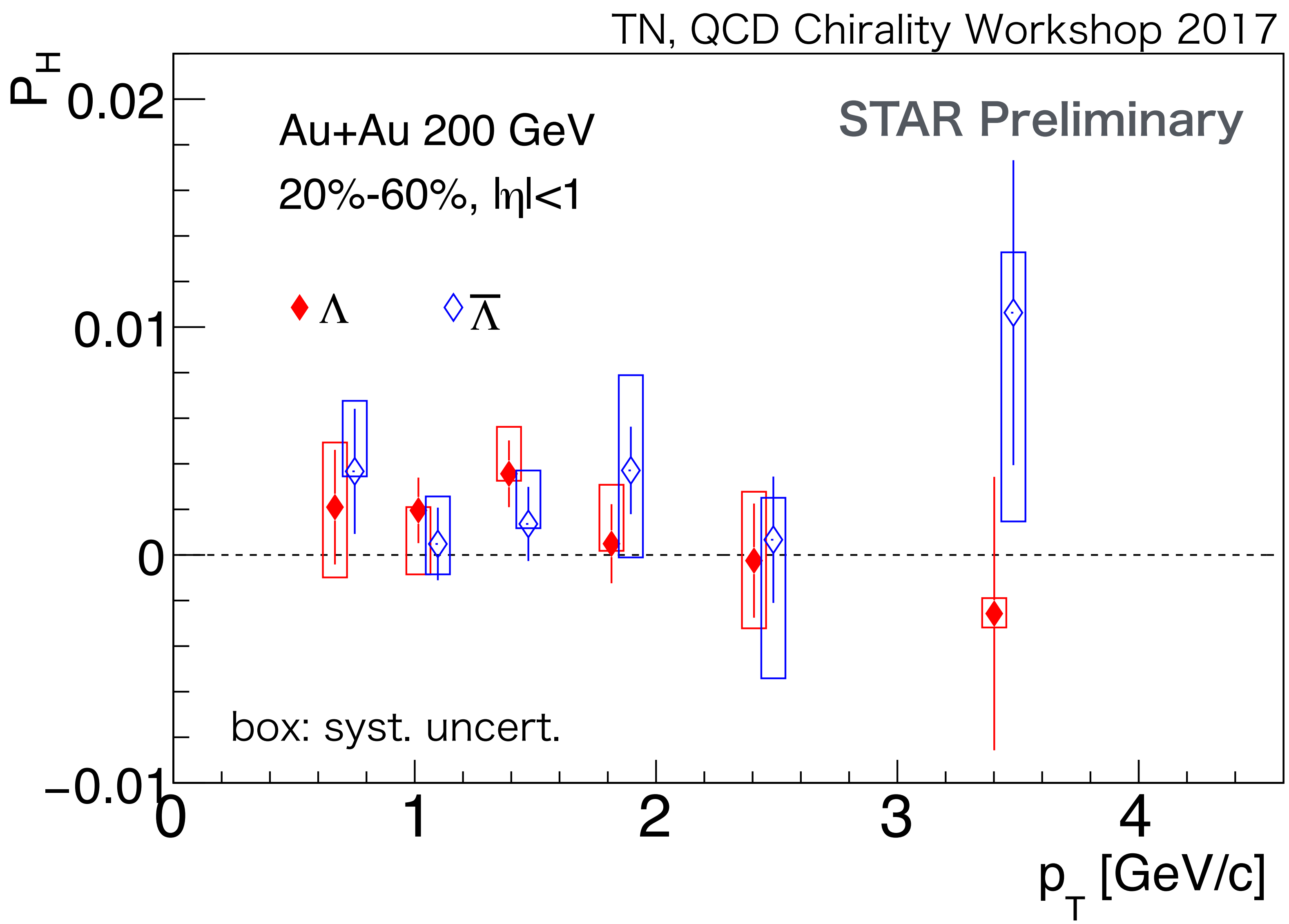
Centrality dependence





- Slight increase in peripheral events for anti-Λ?
- Not enough statistics for now (year2011 data), but recent data (year2014-2016) will allow to make it clear.

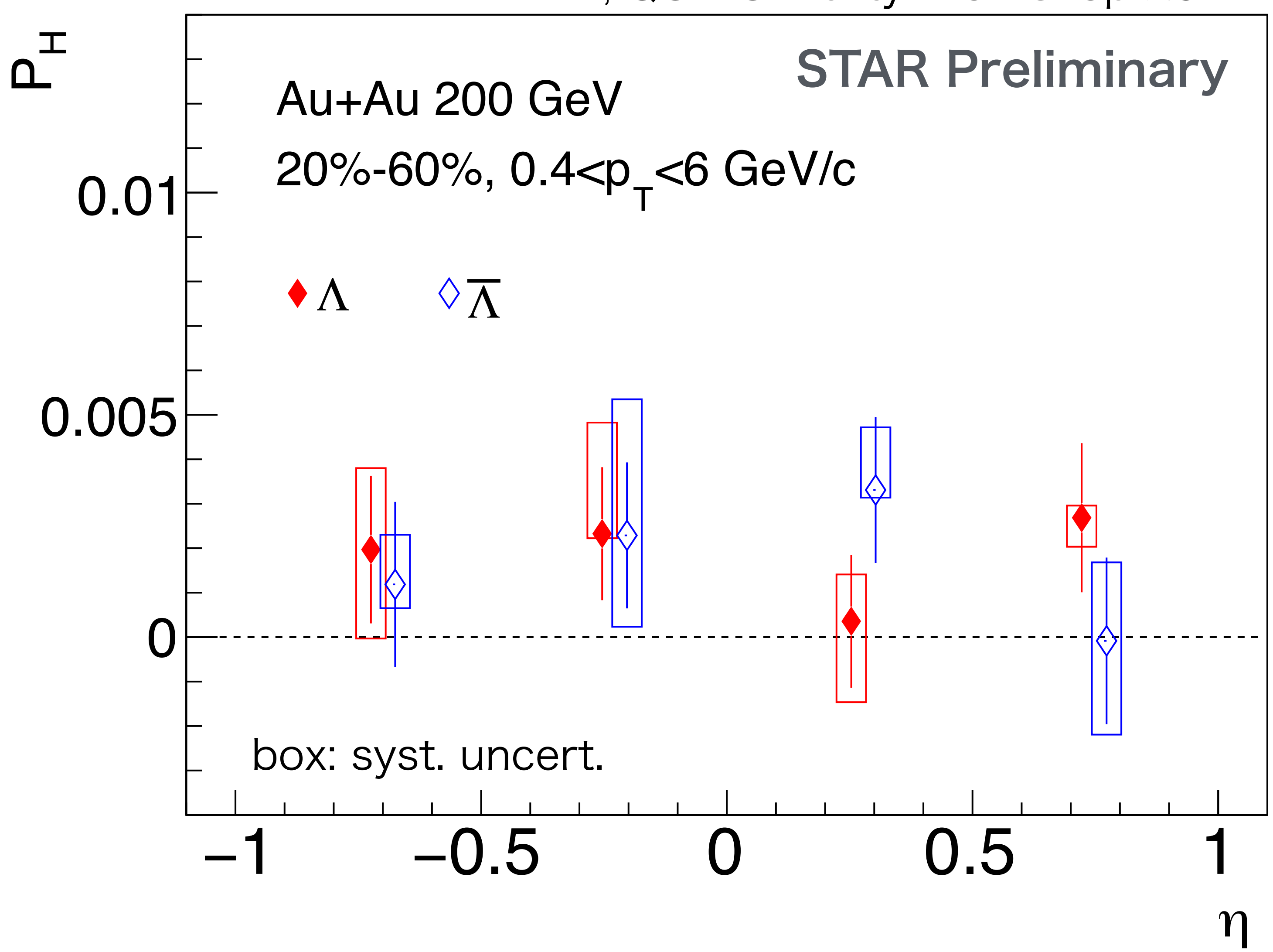
p_T dependence



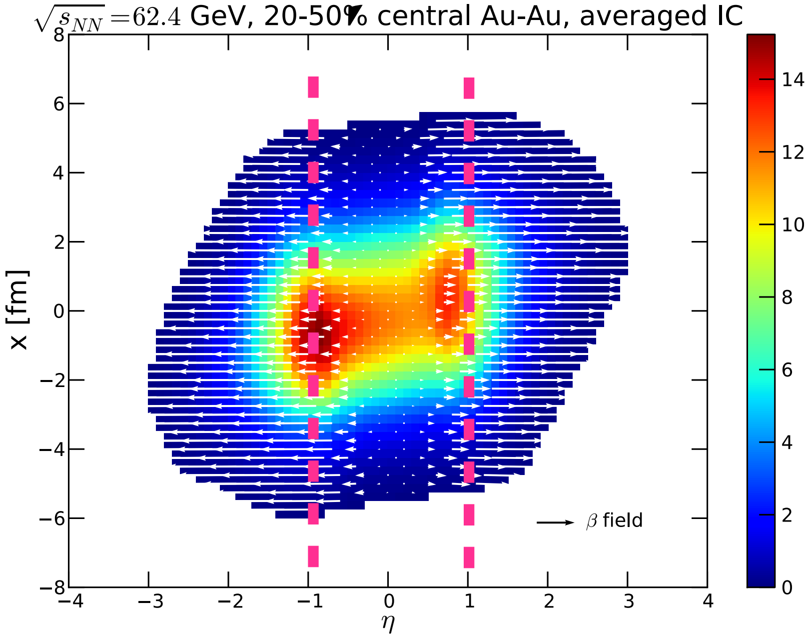
- No significant p_T dependence was observed within current uncertainties

η dependence

TN, QCD Chirality Workshop 2017



62.4 GeV

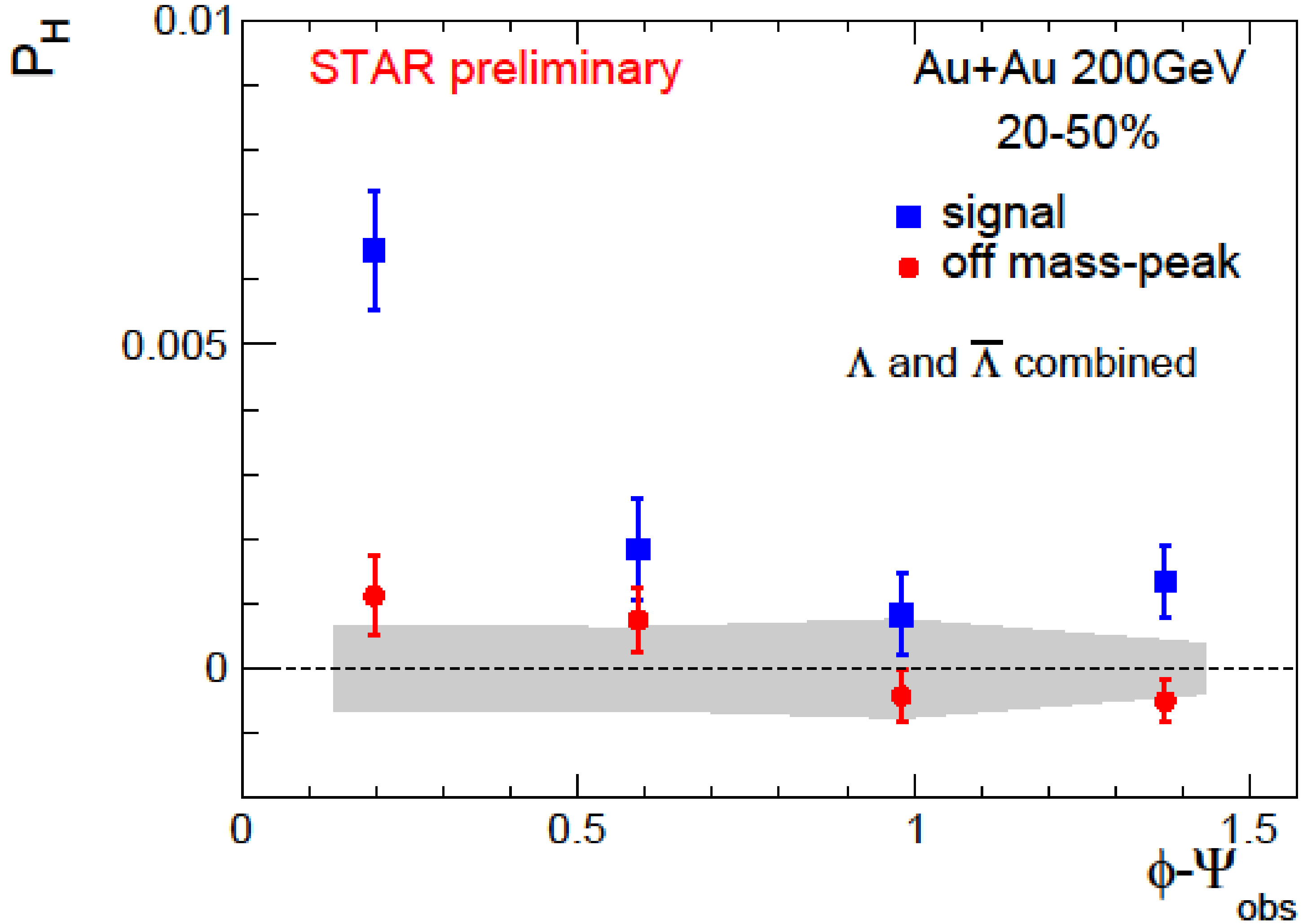


|η|<1

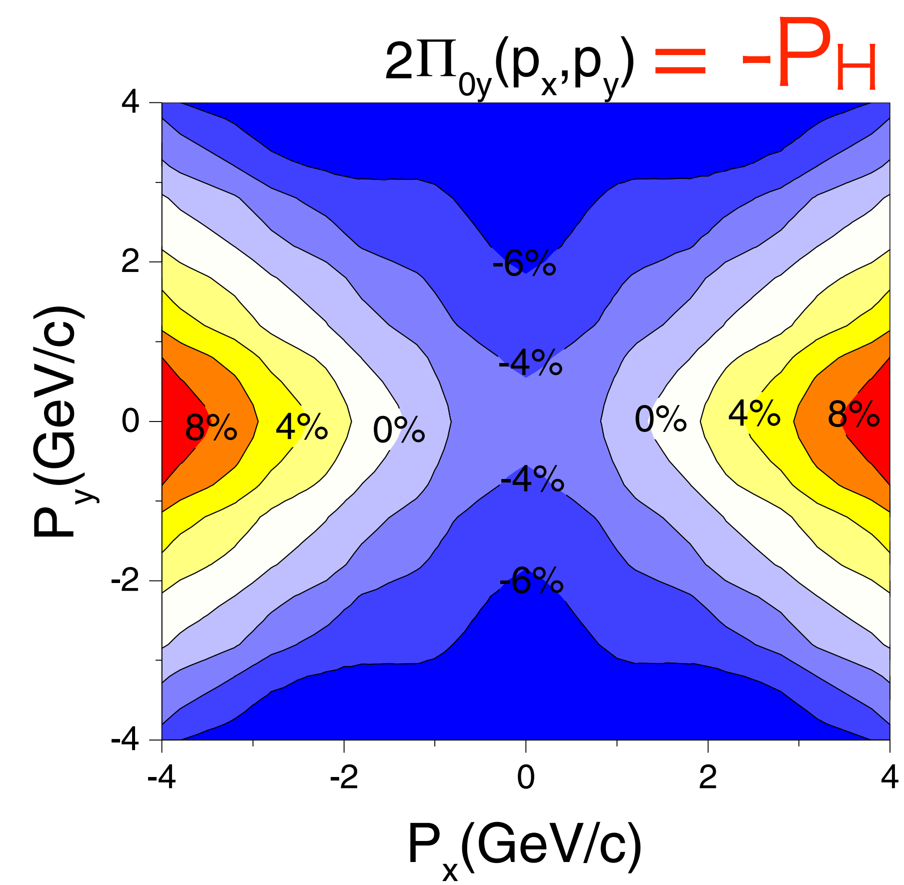
- No significant η dependence (as expected) within uncertainties
- Lower energies or LHC energy with wider η acceptance (CMS&ATLAS) would be more interesting to see

Azimuthal angle dependence

B. Tu, sQM2017



Becattini et al., PRC88.034905 (2013)

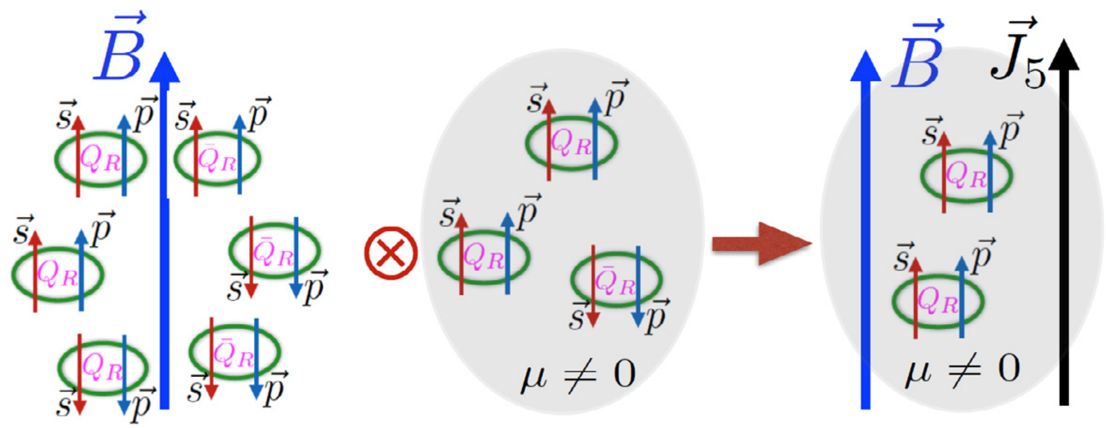


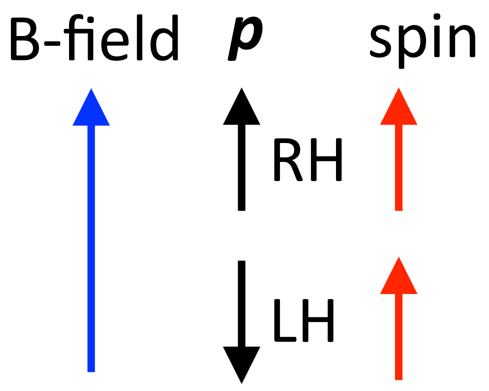
* EP resolution correction (on x-axis) is not applied here

- Larger signal in in-plane direction
- Opposite trend to hydrodynamical calculations?

Λ polarization vs charge asymmetry?

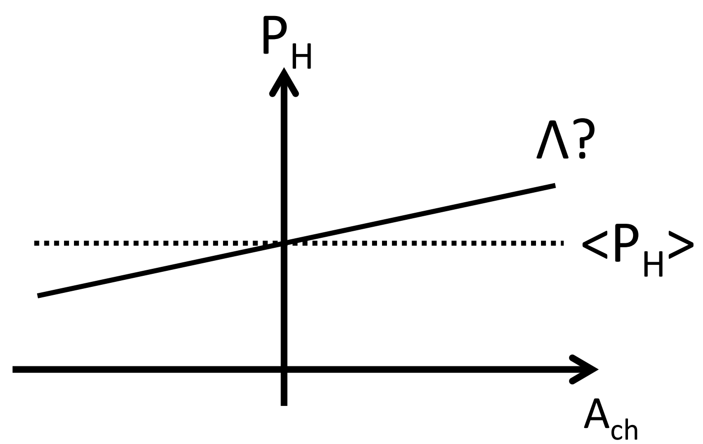
$$\mathbf{J}_5 \propto \mu_{\rm v}\mathbf{B}$$



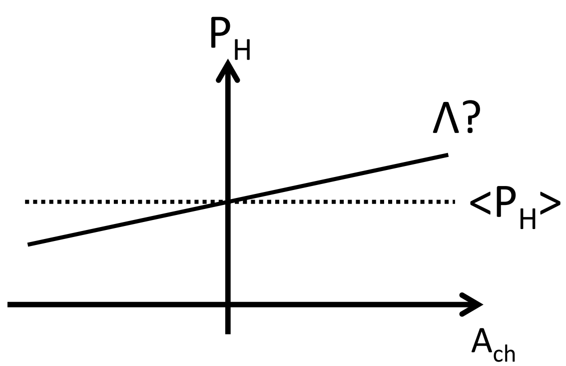


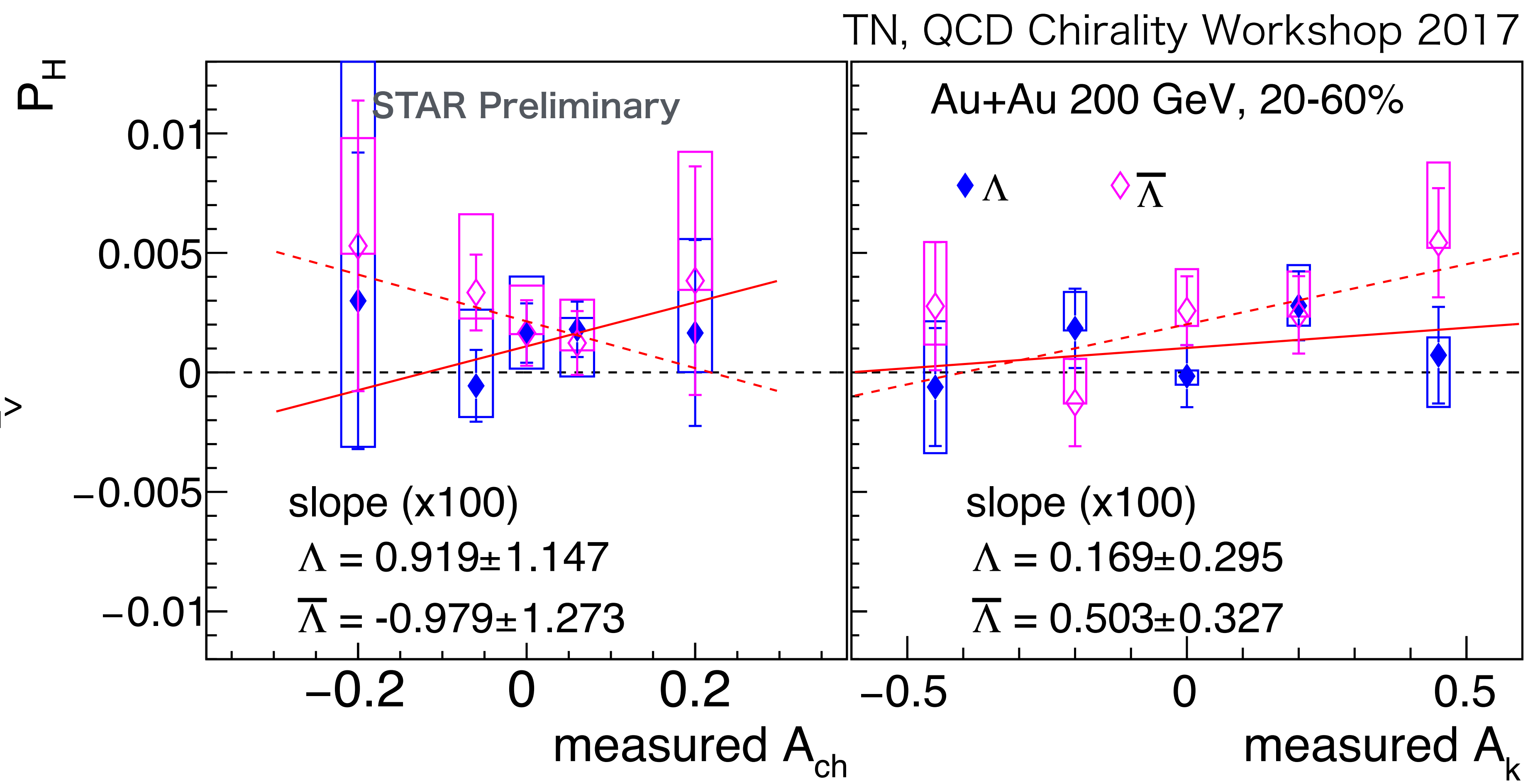
- Λ polarization may be related to the axial current J_5 induced by B-filed (Chiral Separation Effect), S. Shlichting and S. Voloshin, in preparation
- Use (kaon) charge asymmetry instead of $\mu_{\rm v}$

$$\mu_{\rm v}/T \propto \frac{\langle N_{+} - N_{-}\rangle}{\langle N_{+} + N_{-}\rangle} \quad \text{or} \quad \mu_{\rm v}/T \propto \frac{\langle N_{K+} - N_{K-}\rangle}{\langle N_{K+} + N_{K-}\rangle}$$



Charge asymmetry dependence



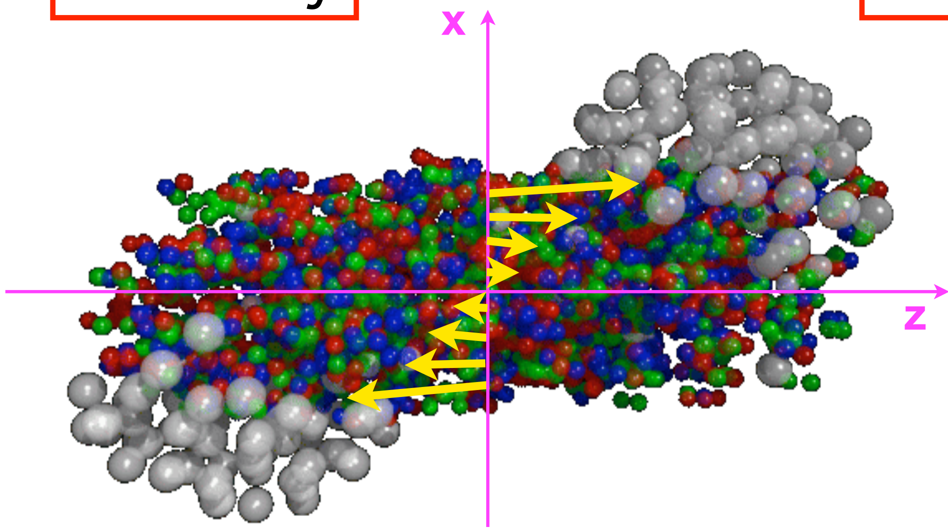


No clear trend within current uncertainties.

Need more events…

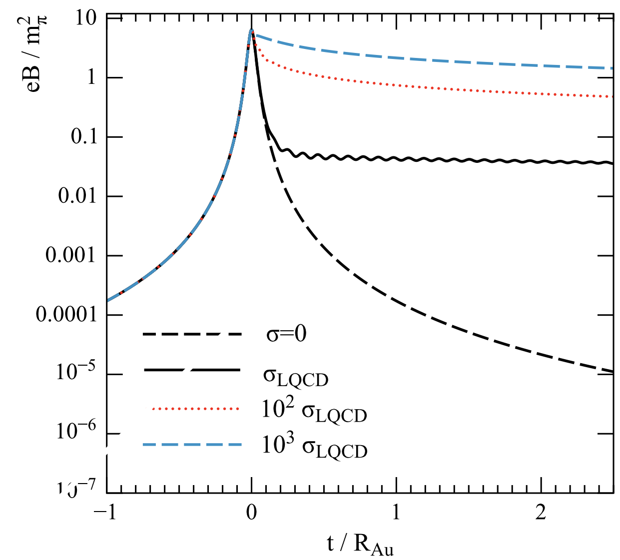
Possible relation to other observables

Vorticity



B-field, conductivity, CME/CSE/CVE

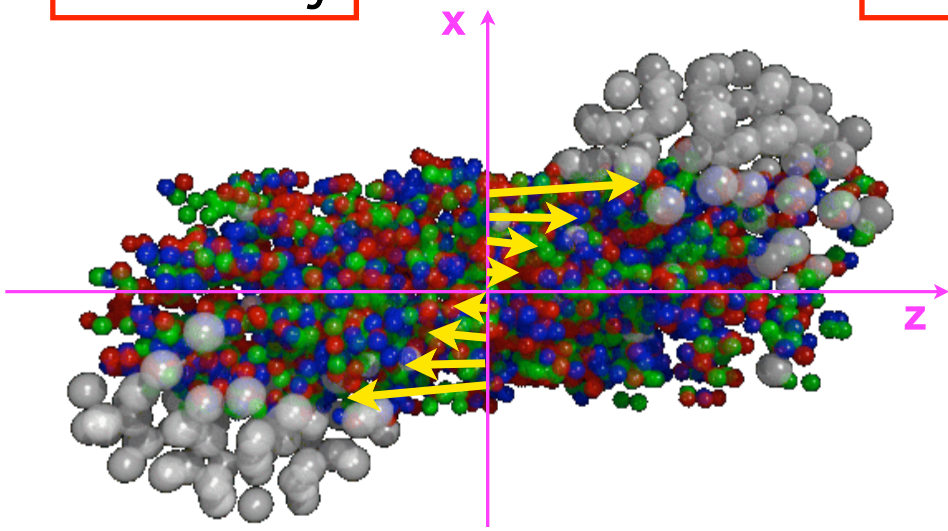
Difference between Λ and anti-Λ



McLerran and Skokov,
Nucl. Phys. A929, 184 (2014)

Possible relation to other observables

Vorticity



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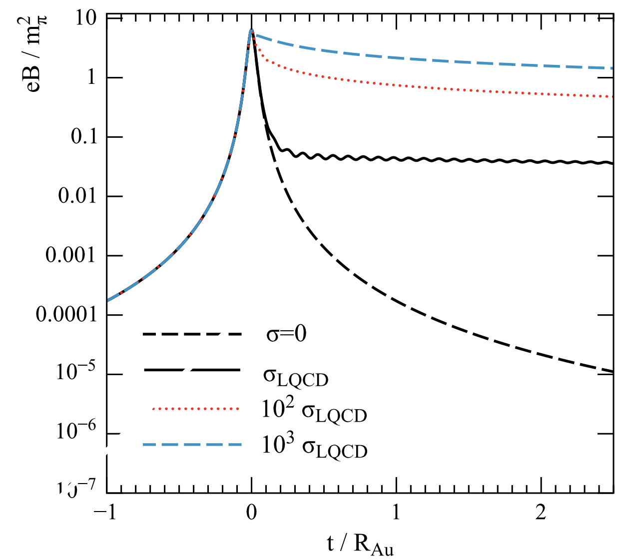
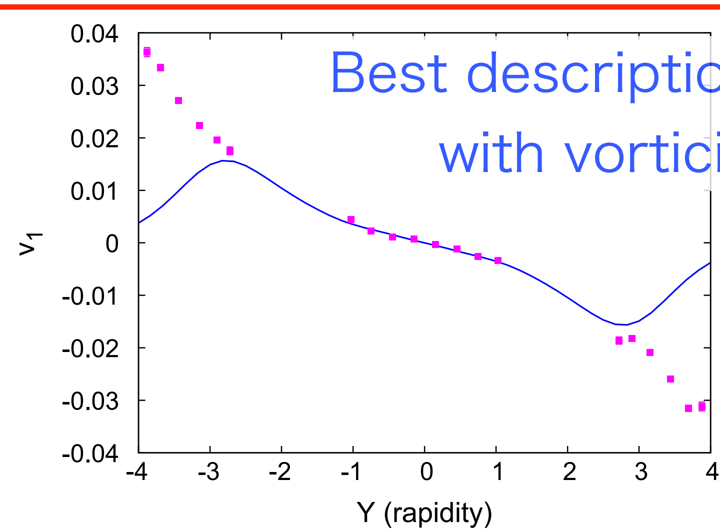


McLerran and Skokov,
Nucl. Phys. A929, 184 (2014)

Directed flow, elliptic flow



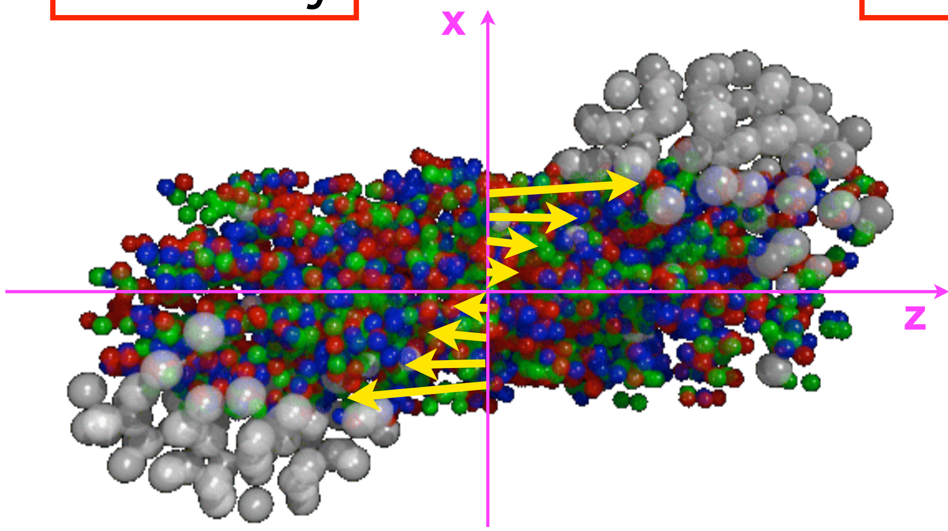
Best description of v
with vorticity!

Fig. 8 Directed flow of pions at $\eta/s = 0.1$ and $\eta_m = 2.0$ compared with STAR data [22]

Becattini et al., Eur. Phys. J. C (2015) 75: 406

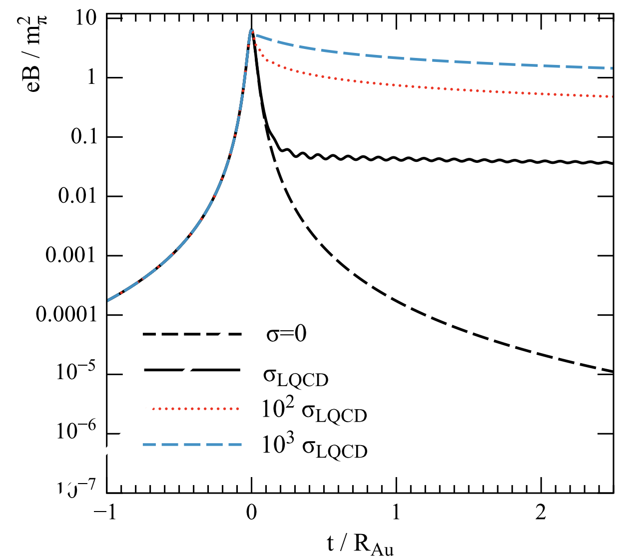
Possible relation to other observables

Vorticity



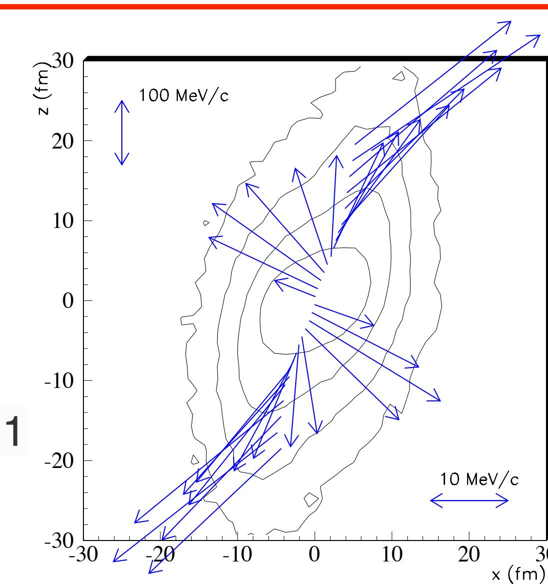
B-field, conductivity, CME/CSE/CVE

Difference between Λ and anti-Λ



McLerran and Skokov,
Nucl. Phys. A929, 184 (2014)

Tilted source via asHBT



Lisa, Heinz, and Wiedemann,
PLB489 (2000) 287
Lisa et al.(E895), PLB496 (2000) 1

Directed flow, elliptic flow

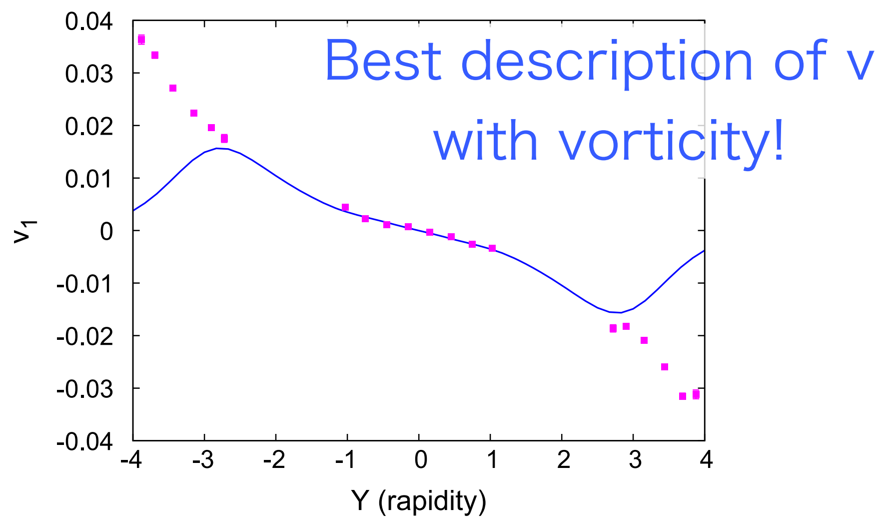
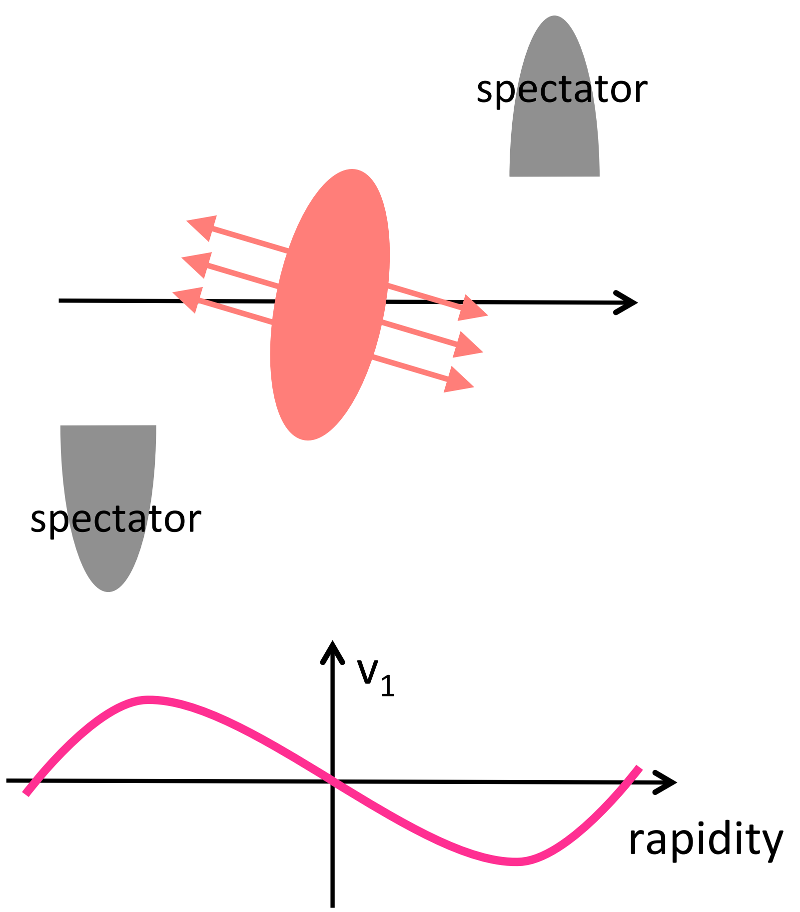


Fig. 8 Directed flow of pions at $\eta/s = 0.1$ and $\eta_m = 2.0$ compared with STAR data [22]

Becattini et al., Eur. Phys. J. C (2015) 75: 406

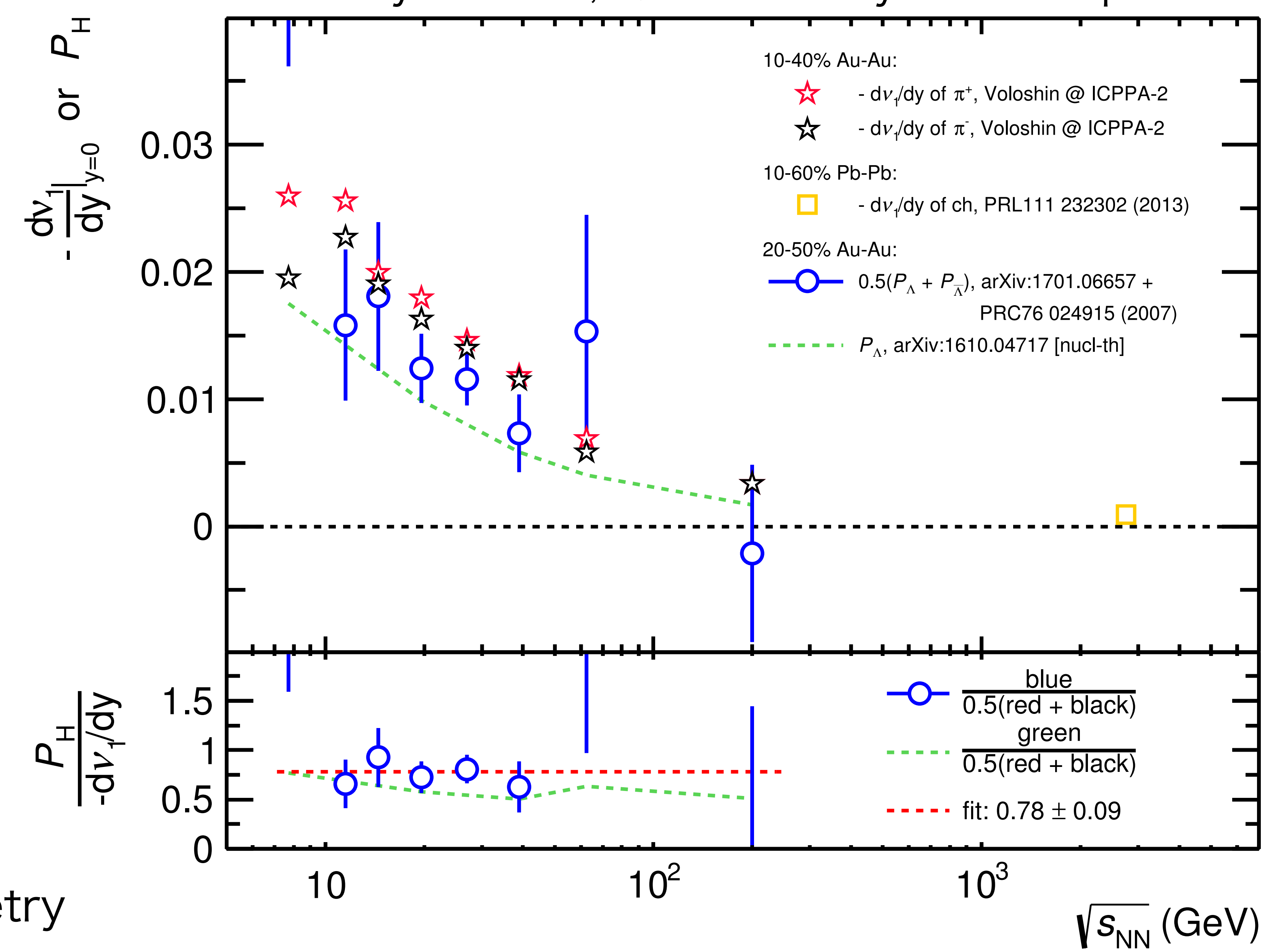
A lot of interesting things!

e.g. Relation to directed flow



S. Voloshin, ICPPA 2016

M. Konyushikhin, QCD Chirality Workshop 2017

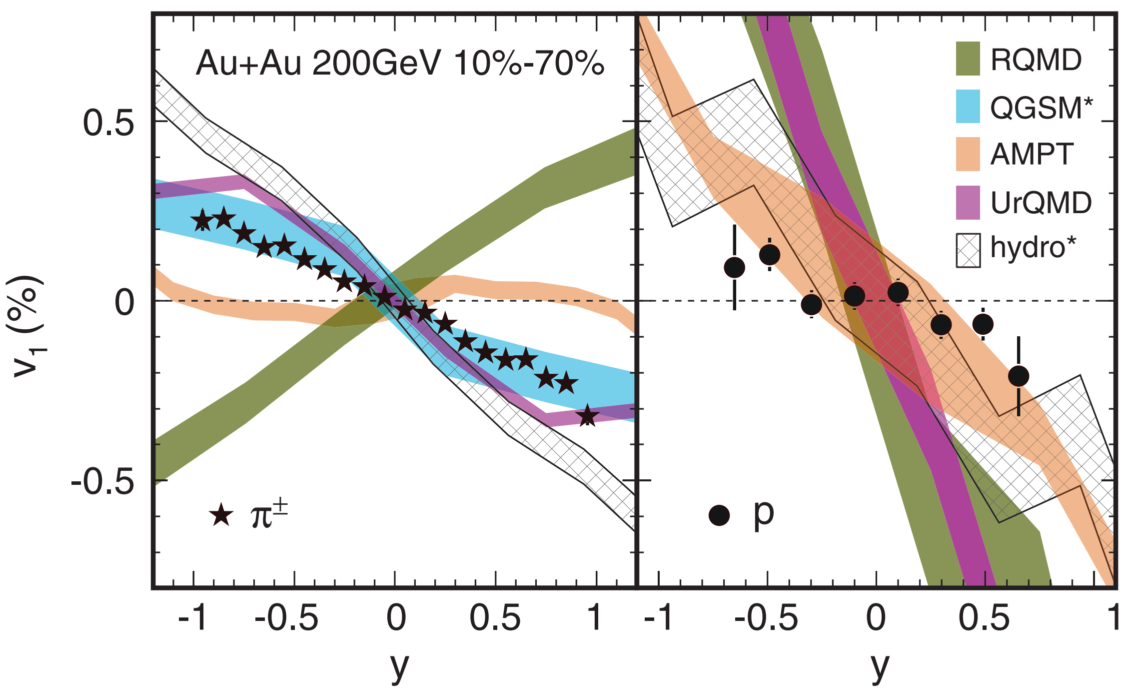


Initial source tilt (or shear flow)
likely contributes v_1 slope
in addition to the density asymmetry

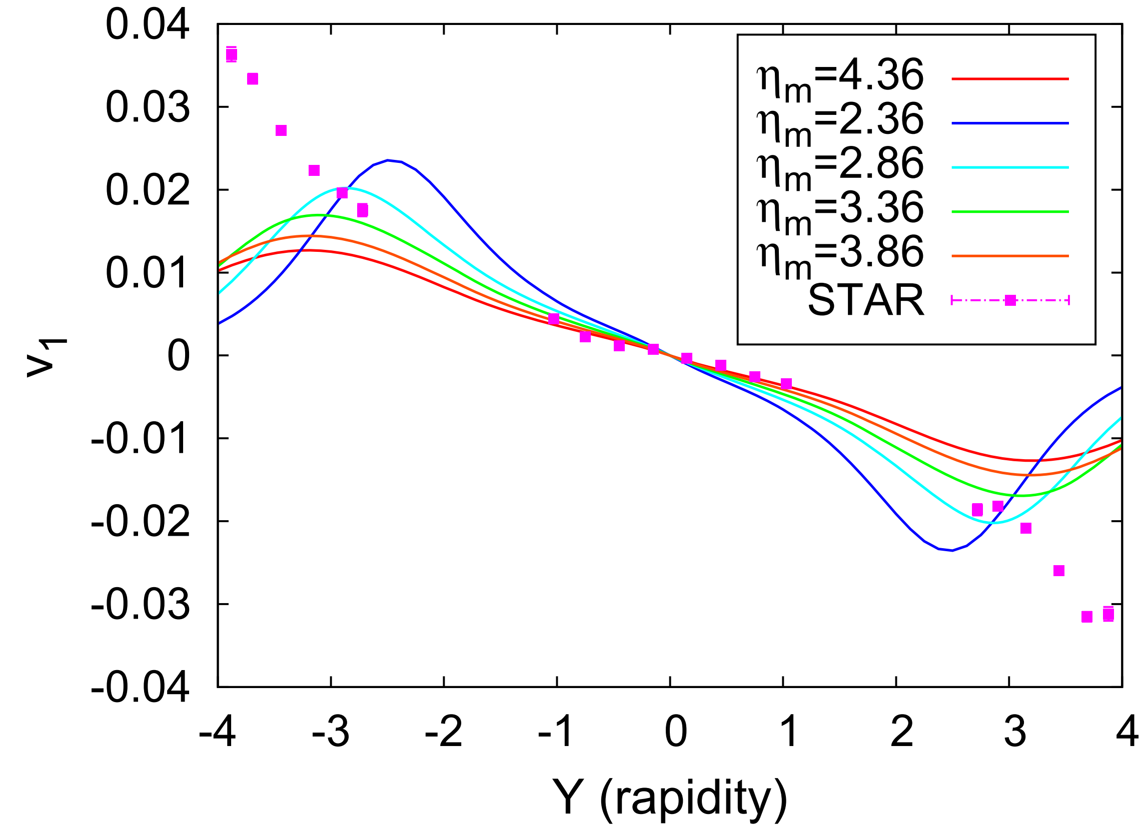
Similar energy dependence of dv_1/dy and polarization!

Directed flow vs models with initial tilt

STAR, PRL108.202301 (2012)



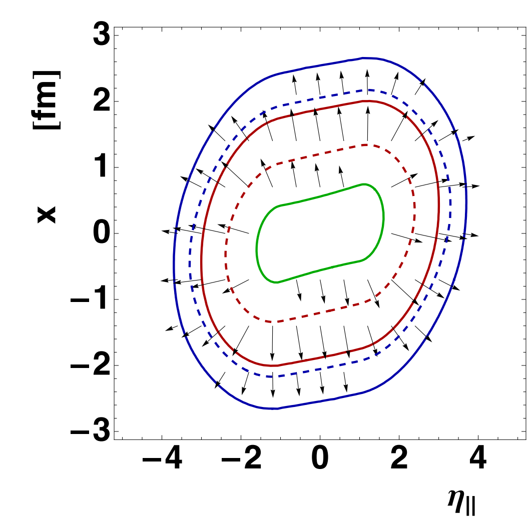
Becattini et al., Eur. Phys. J. C (2015) 75: 406



Many models fail to reproduce v_1

η_m determines the initial tilt

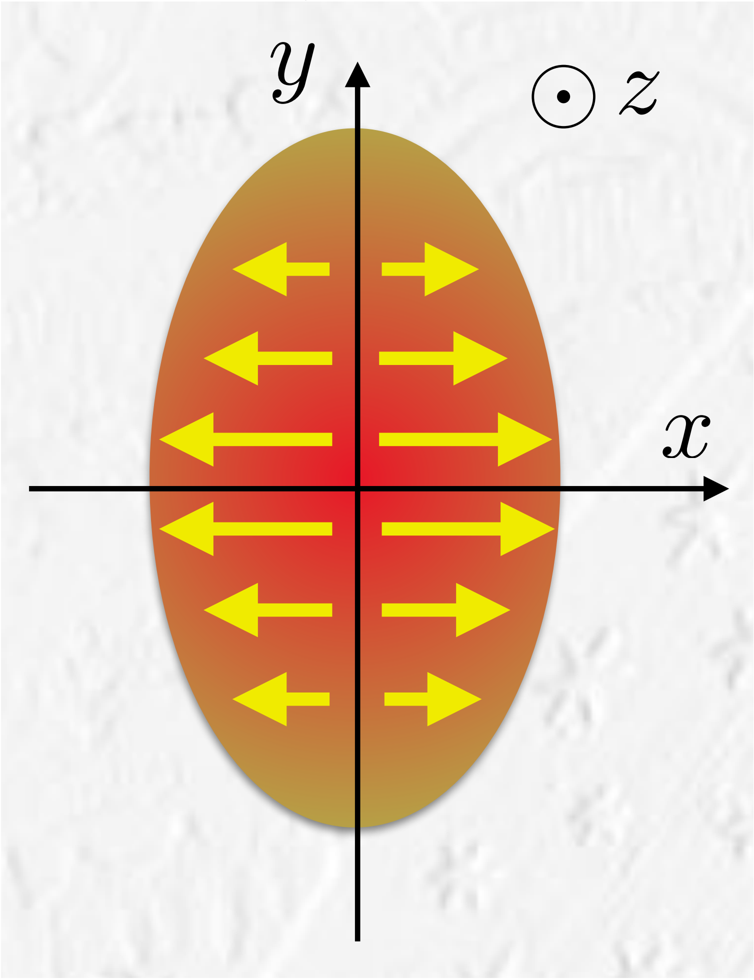
Bozek and Wyskiel, PRC81.054902 (2010)



Better description of v

e.g. Relation to elliptic flow?

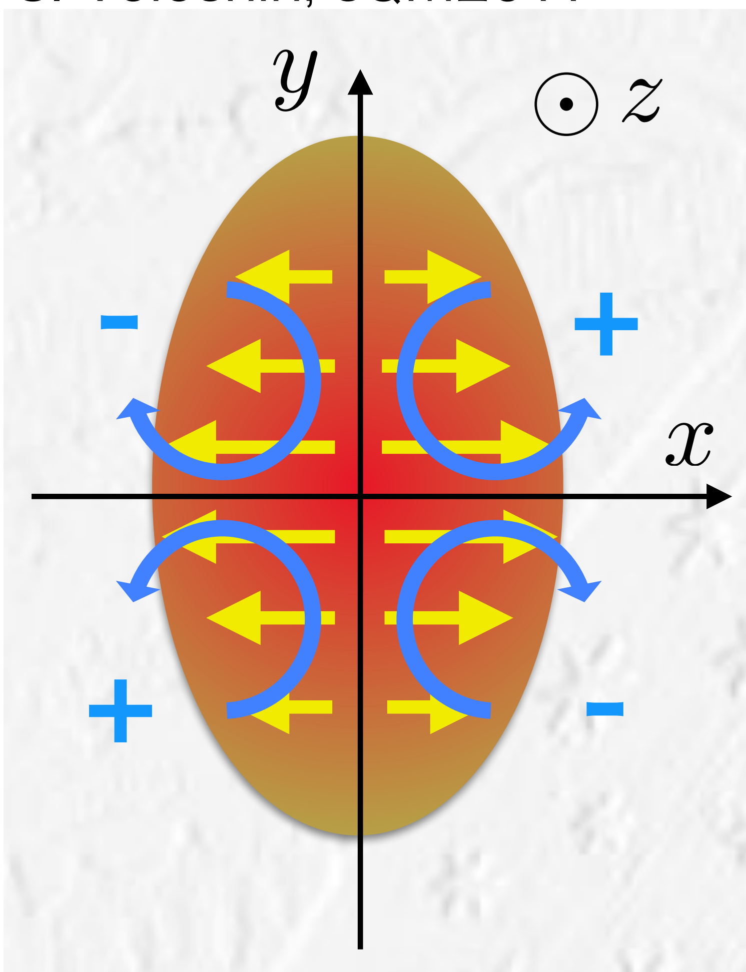
S. Voloshin, sQM2017



Stronger flow in in-plane than in out-of-plane

e.g. Relation to elliptic flow?

S. Voloshin, sQM2017



Polarization along z-direction.

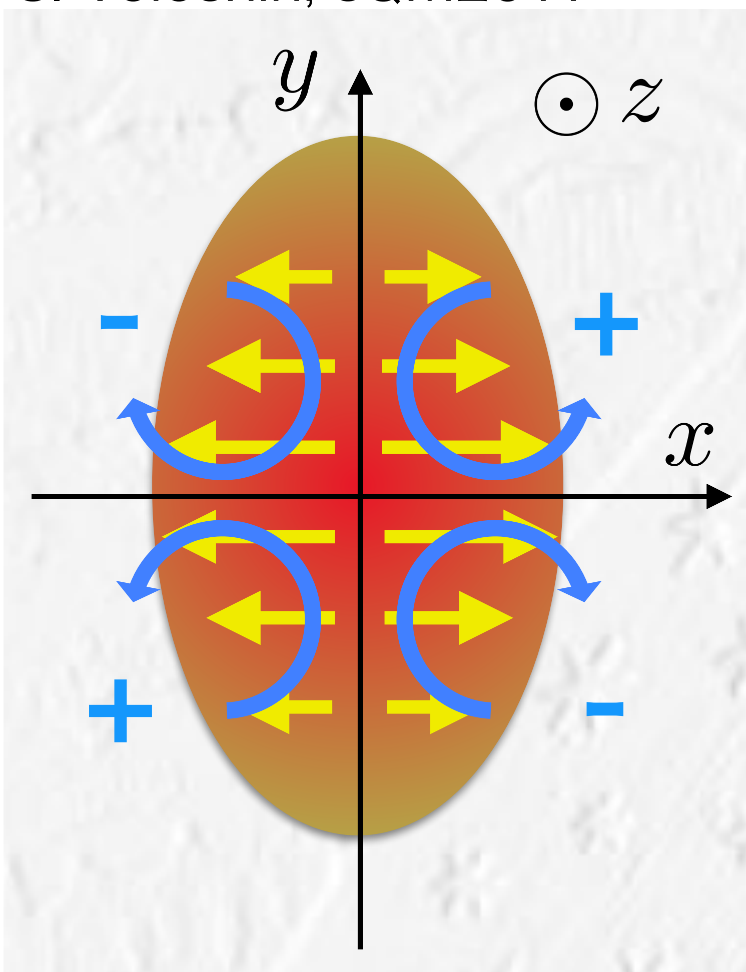
No need for 1st-order EP!

Stronger flow in in-plane than in out-of-plane

There could exist a substructure of vorticity created by elliptic flow (and higher-harmonic flow as well)

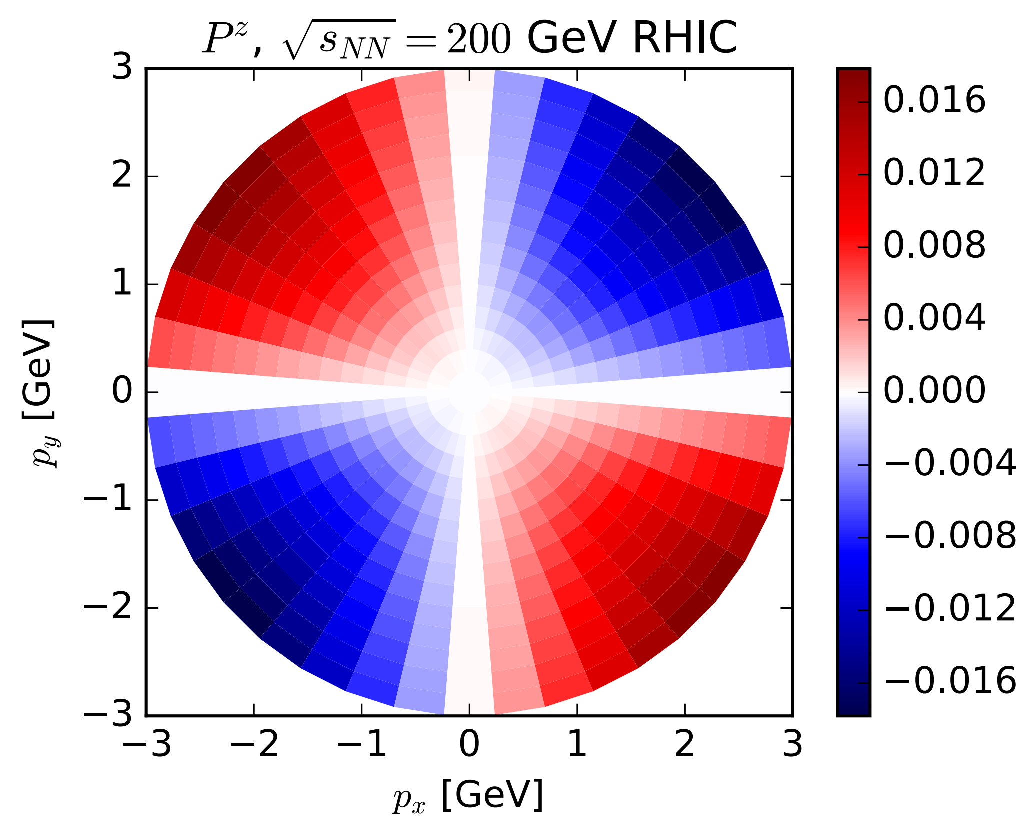
e.g. Relation to elliptic flow?

S. Voloshin, sQM2017



Polarization along z-direction.
No need for 1st-order EP!

Becattini and Karpenko, arXiv:1707.07984

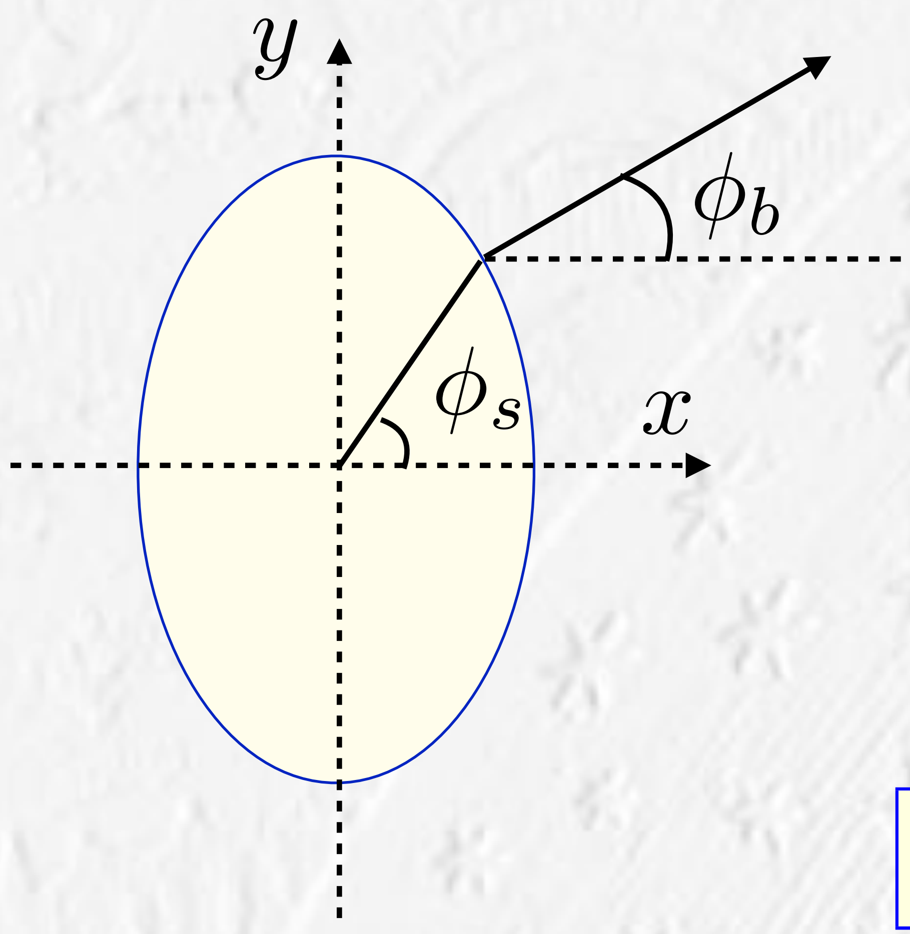


Quadruple structure in hydro model

There could exist a substructure of vorticity created by elliptic flow (and higher-harmonic flow as well)

with Blast-wave parameterization

S. Voloshin, sQM2017



Number of emitting "sources":

$$\propto [1 + 2s_2 \cos(2\phi_b)]$$

Transverse rapidity (boost):

$$\rho_t = \rho_{t,max}[r/r_{max}(\phi_s)][1 + a_2 \cos(2\phi_s)]$$

$$\omega_z \approx \rho_{t,max} \sin(n\phi_s)[a_n - 2s_n]$$

The sign depends on the relation between flow (a_n) and spatial (s_n) anisotropy, similar to as-femptoscopy.

There could exist a substructure of vorticity created by elliptic flow (and higher-harmonic flow as well)

Summary

- First observation of Λ global polarization at $\sqrt{s_{NN}}$ = 7.7-39 GeV at STAR, followed by preliminary studies at $\sqrt{s_{NN}}$ = 200 GeV
  - Indicating a thermal vorticity of the medium in non-central heavy-ion collisions, of the order of a few percent
  - A possible difference between Λ and anti-Λ, which could be due to the initial strong B-field and therefore be a direct probe of the B-field
  - Energy dependence of the polarization can be understood by a shear flow structure within limited acceptance
  - More studies are ongoing, e.g. charge-asymmetry dependence and substructure of the polarization (z-component)

- Possible relation to many other observables (v_1, v_2, HBT, CSE/CVE)

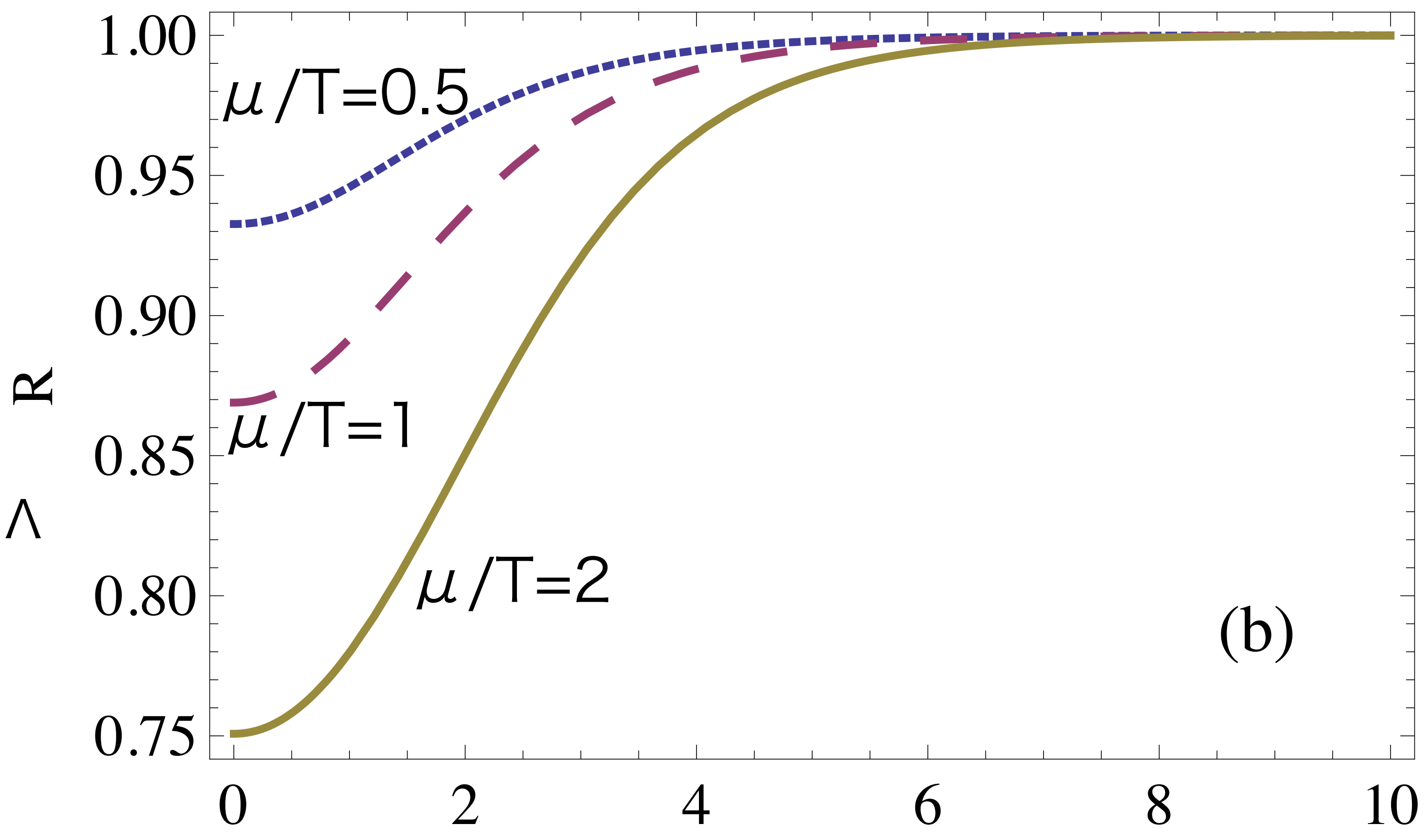
Vorticity is an important piece for further understanding the picture of HIC!

Back up

Effect of non-zero chemical potential

R. Fang, L. Pang, Q. Wang, and X. Wang, PRC94, 024904 (2016)

$R = P_{\Lambda}/P_{anti\text{-}\Lambda}$



$\beta m = m/T$

~ 1.1GeV/(160-200)MeV

~ 5.5-6.8