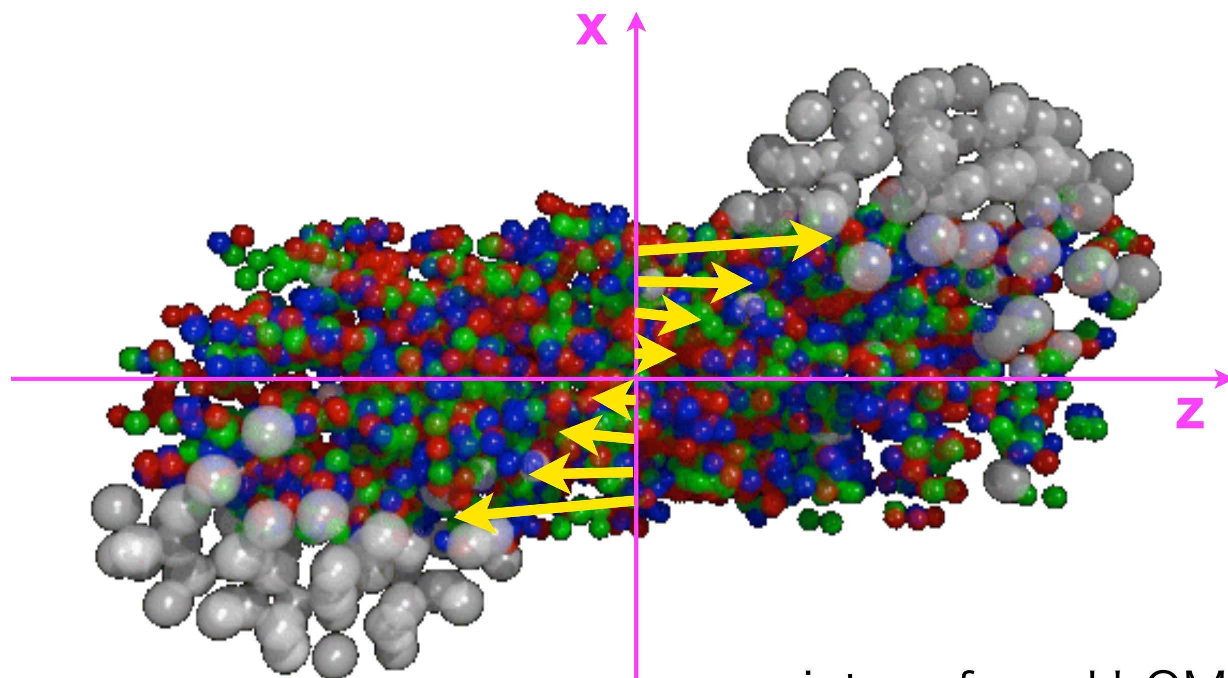
Polarization measurements in STAR

Takafumi Niida
for the STAR Collaboration

Wayne State University

Workshop on Chirality, Vorticity, and Magnetic Field in HIC 2018, Florence

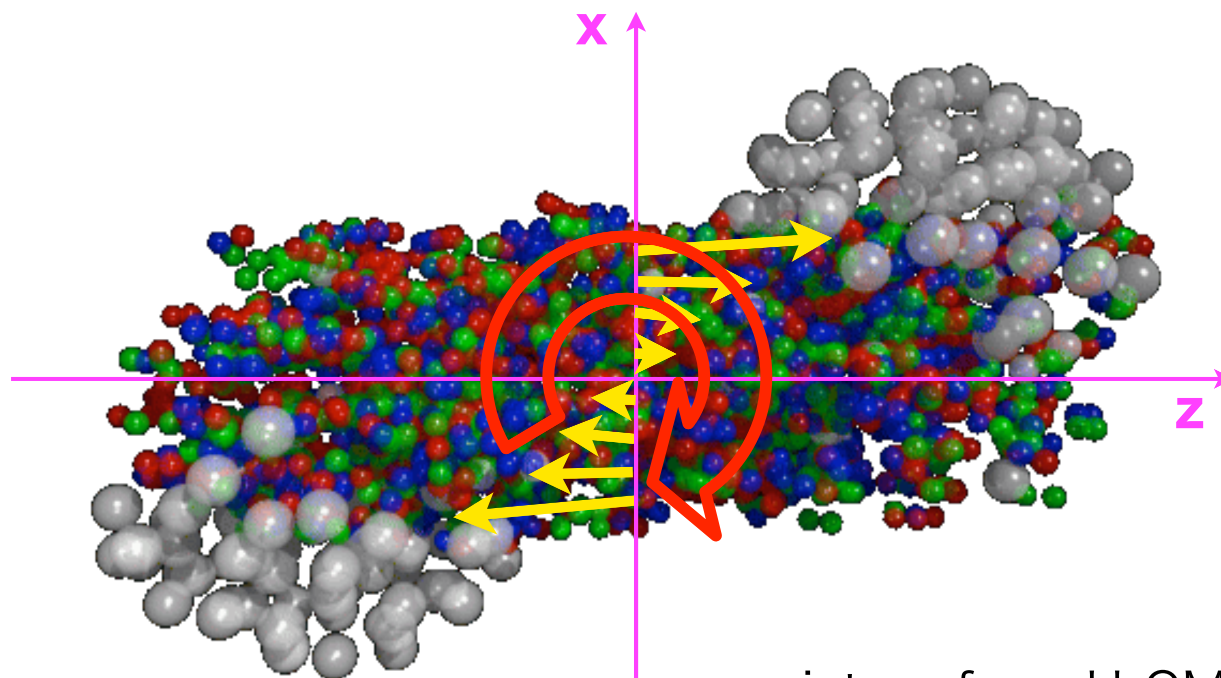
Vorticity in HIC



picture from UrQMD

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

Vorticity in HIC



picture from UrQMD

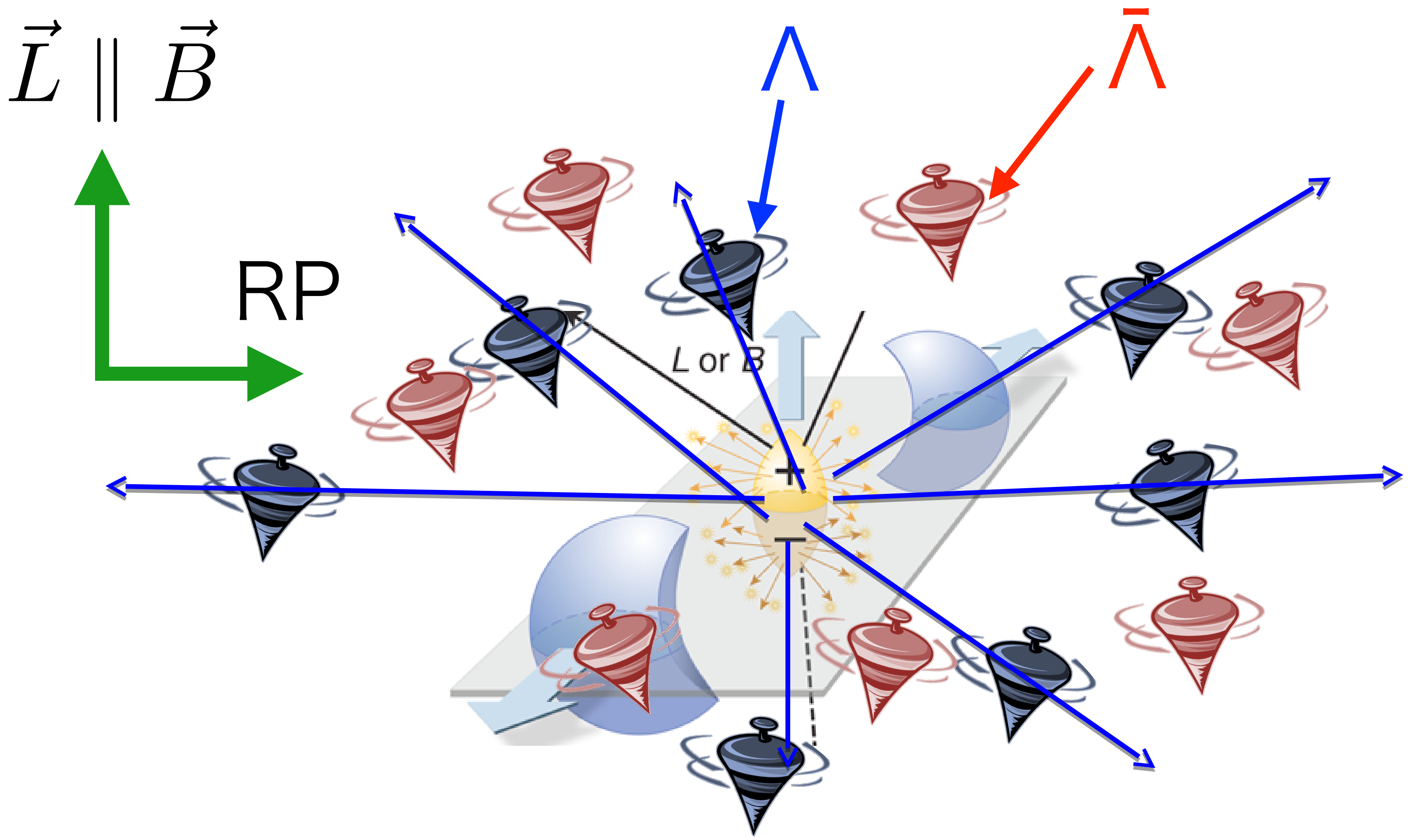
In non-central collisions, the initial collective longitudinal flow velocity depends on x, which makes the initial angular momentum.

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

Global Polarization

★ Non-zero angular momentum transfers to polarization of particles

- Globally polarized quark-gluon plasma in non-central A+A collisions
  Z.-T. Liang and X.-N. Wang, PRL94, 102301 (2005)
- Polarized secondary particles in unpolarized high energy hadron-hadron collisions?
  S. Voloshin, nucl-th/0410089 (2004)



∗direction of ***B*** is the same as ***L***

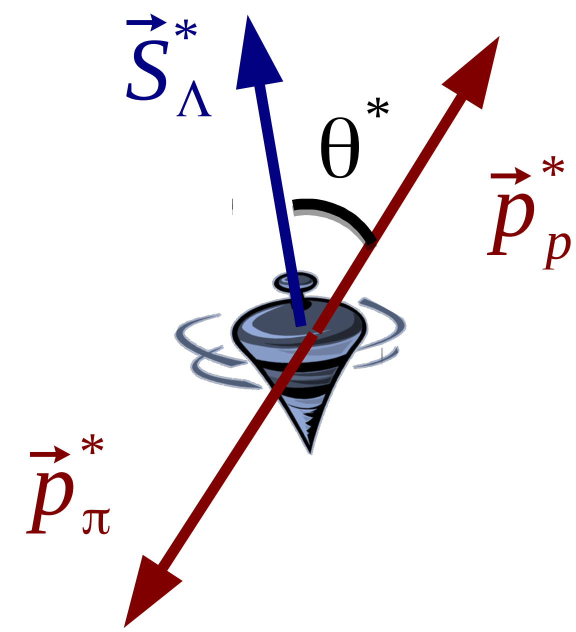
- spin-orbit coupling
  - Λ and anti-Λ's spin are aligned with angular momentum ***L***
- spin alignment by B-field
  - Λ's spin anti-aligned along ***B*** & anti-Λ's spin aligned along ***B***

*Λ has negative magnetic moment

How to measure the polarization?

parity-violating decay of hyperons

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



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

α: Λ decay parameter (=0.642±0.013)
P_Λ: Λ polarization
p_p^*: proton momentum in Λ rest frame

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

(BR: 63.9%, cτ~7.9 cm)

strong decay of vector mesons

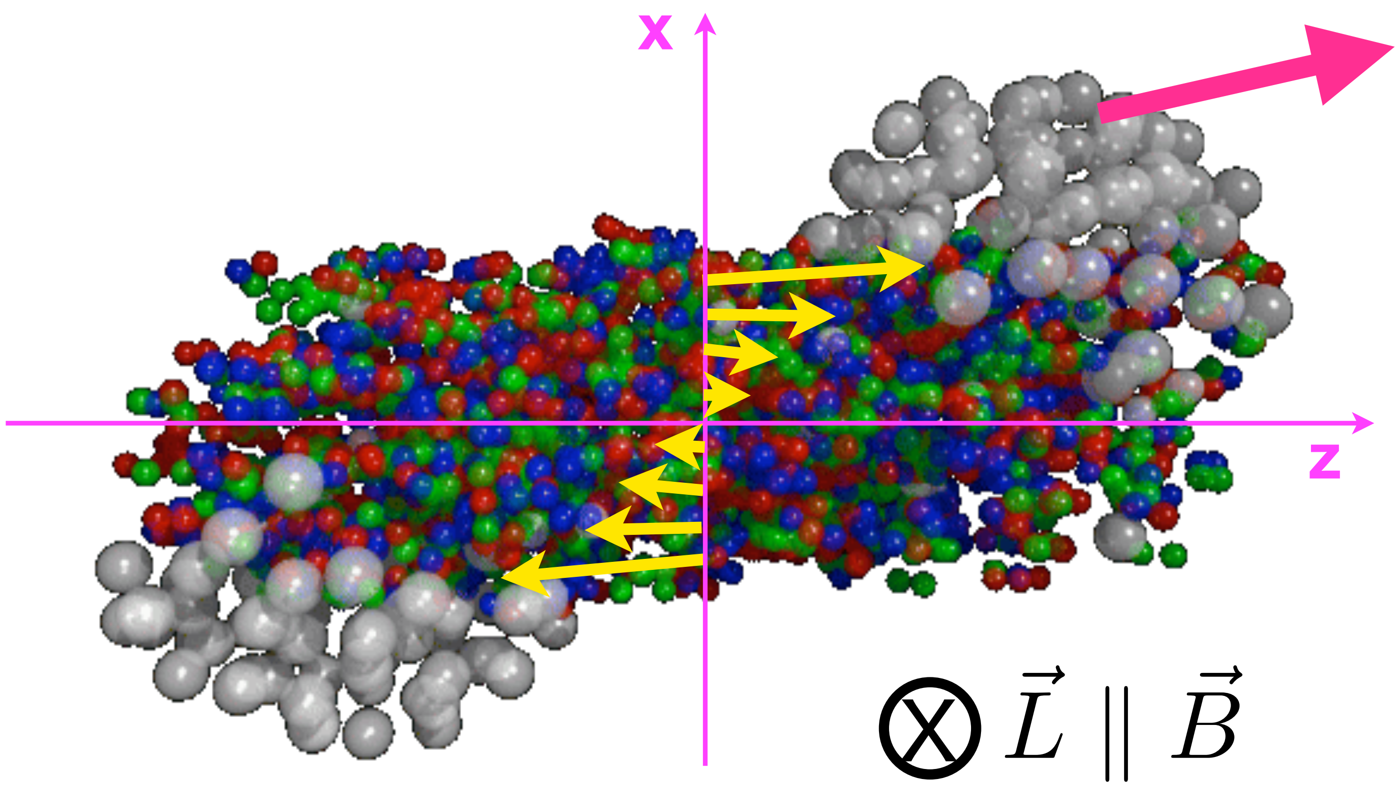
->See talk by Aihong Tang

Deviation from 1/3 in a diagonal element of spin density matrix, ρ_{00}.
(e.g. ϕ->K^++K^-, K^*->π+K)

$$\frac{dN}{d\cos\theta^*} \propto (1 - \rho_{00}) + (3\rho_{00} - 1)\cos^2\theta^*$$

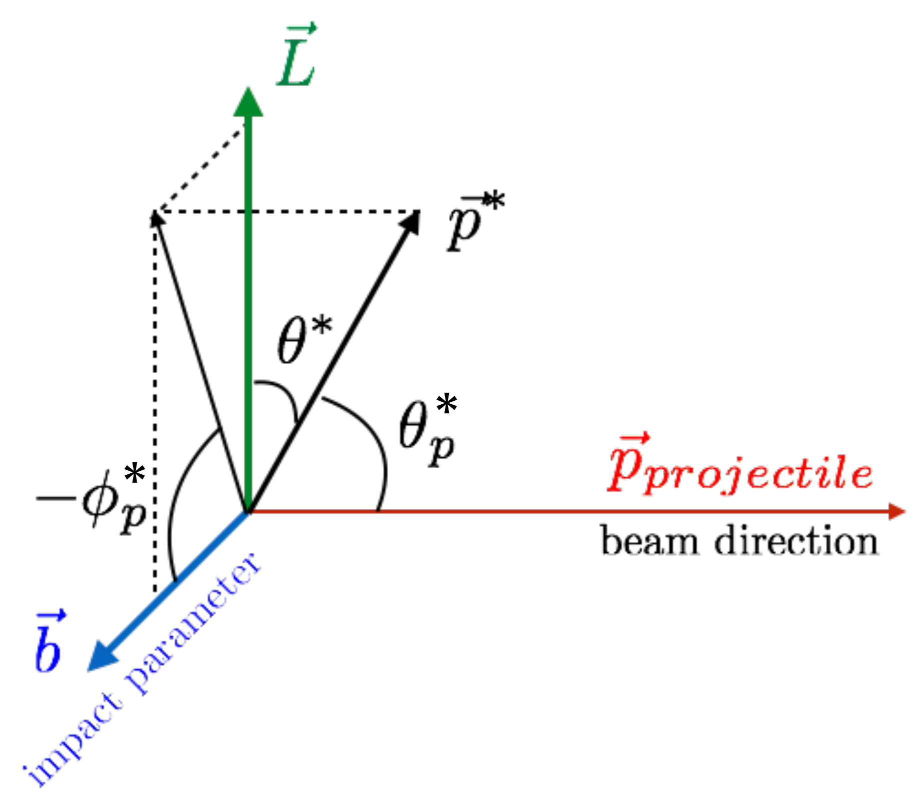
Measurement relative to R.P.

impact parameter



Spectators deflect outwards!

S. Voloshin and TN, PRC94.021901(R)(2016)



Projected onto transverse plane:

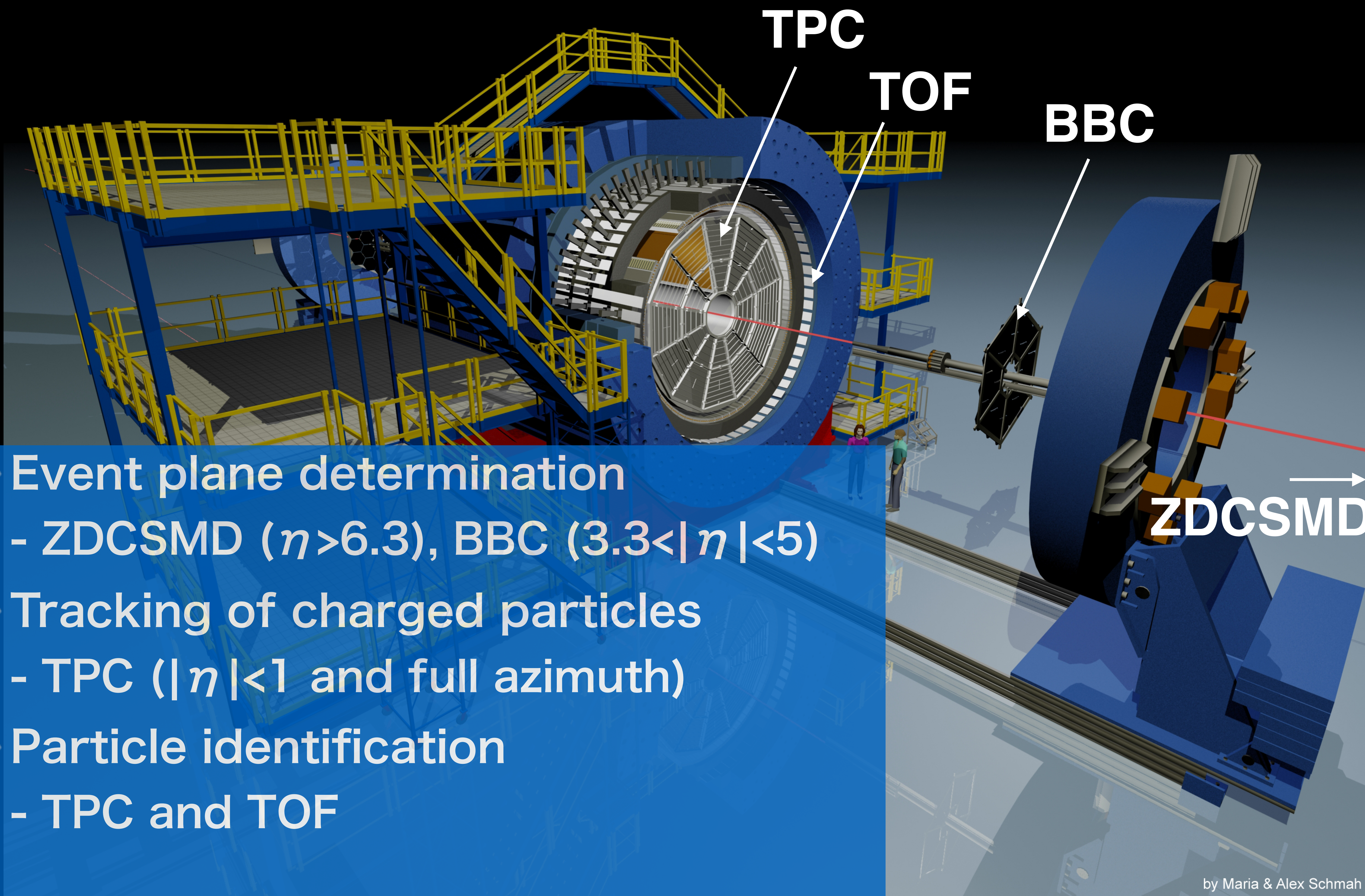
$$P_H = \frac{8}{\pi\alpha} \frac{\langle \sin(\Psi_1 - \phi_p^*) \rangle}{\mathrm{Res}(\Psi_1)} \mathrm{sgn}_\Lambda$$

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

sgn_Λ: 1 for Λ, -1 for anti-Λ

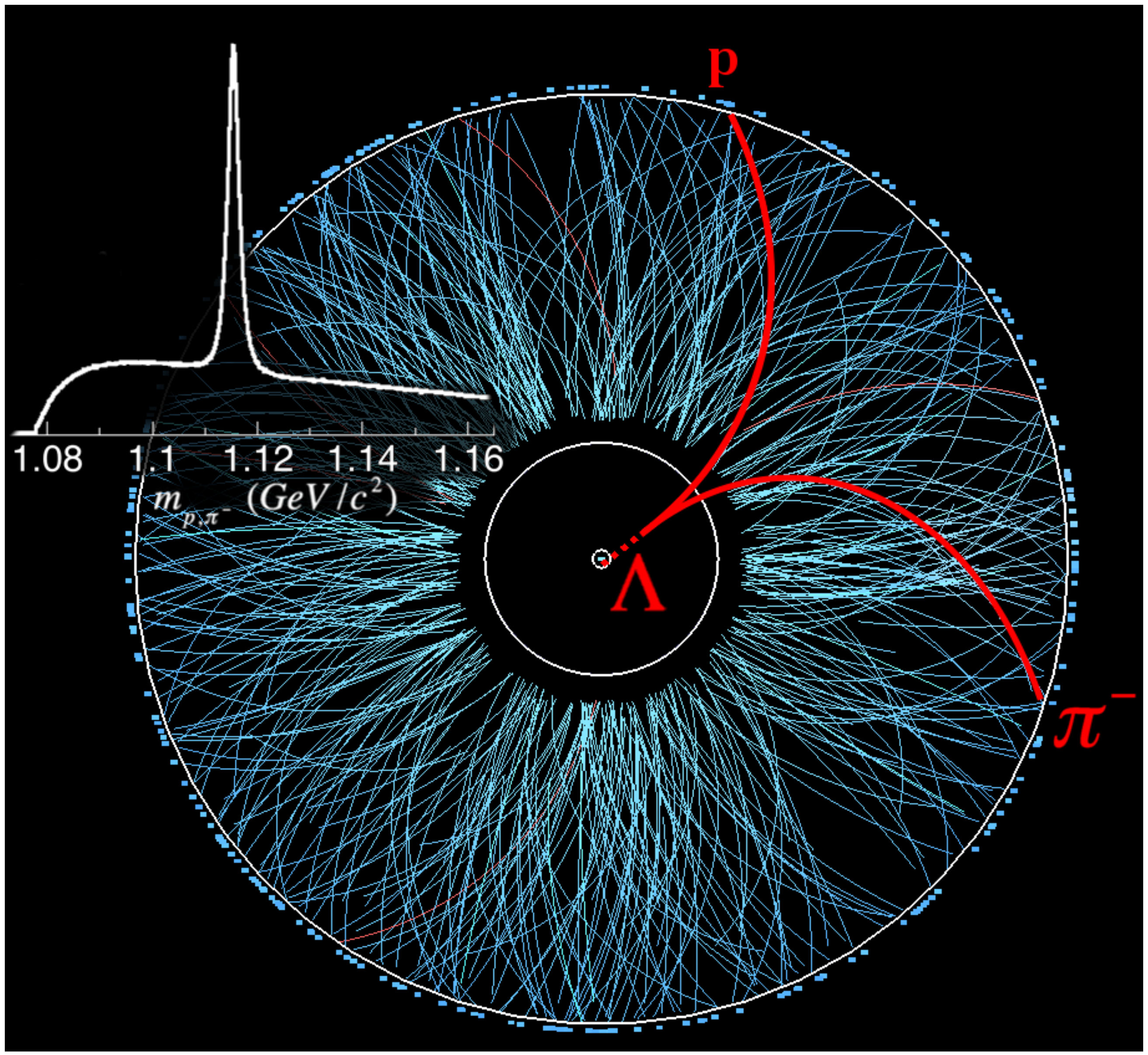
STAR, PRC76, 024915 (2007)

Solenoidal Tracker At RHIC (STAR)



- Event plane determination
  - ZDCSMD (η>6.3), BBC (3.3<$|\eta|$<5)
- Tracking of charged particles
  - TPC ($|\eta|$<1 and full azimuth)
- Particle identification
  - TPC and TOF

Λ reconstruction



- Λ reconstruction
  - identify daughters (π, p) with TPC and TOF and calculate the invariant mass
  - use the information on decay topology to reduce the combinatorial background
- Background level to Λ signal is below 30%
- The number of Λs per event
  - ~1.0 for 10-20% centrality at 200 GeV (raw counts, depends on centrality, efficiency, and cuts used)

Systematic uncertainties

Case of 200 GeV as an example

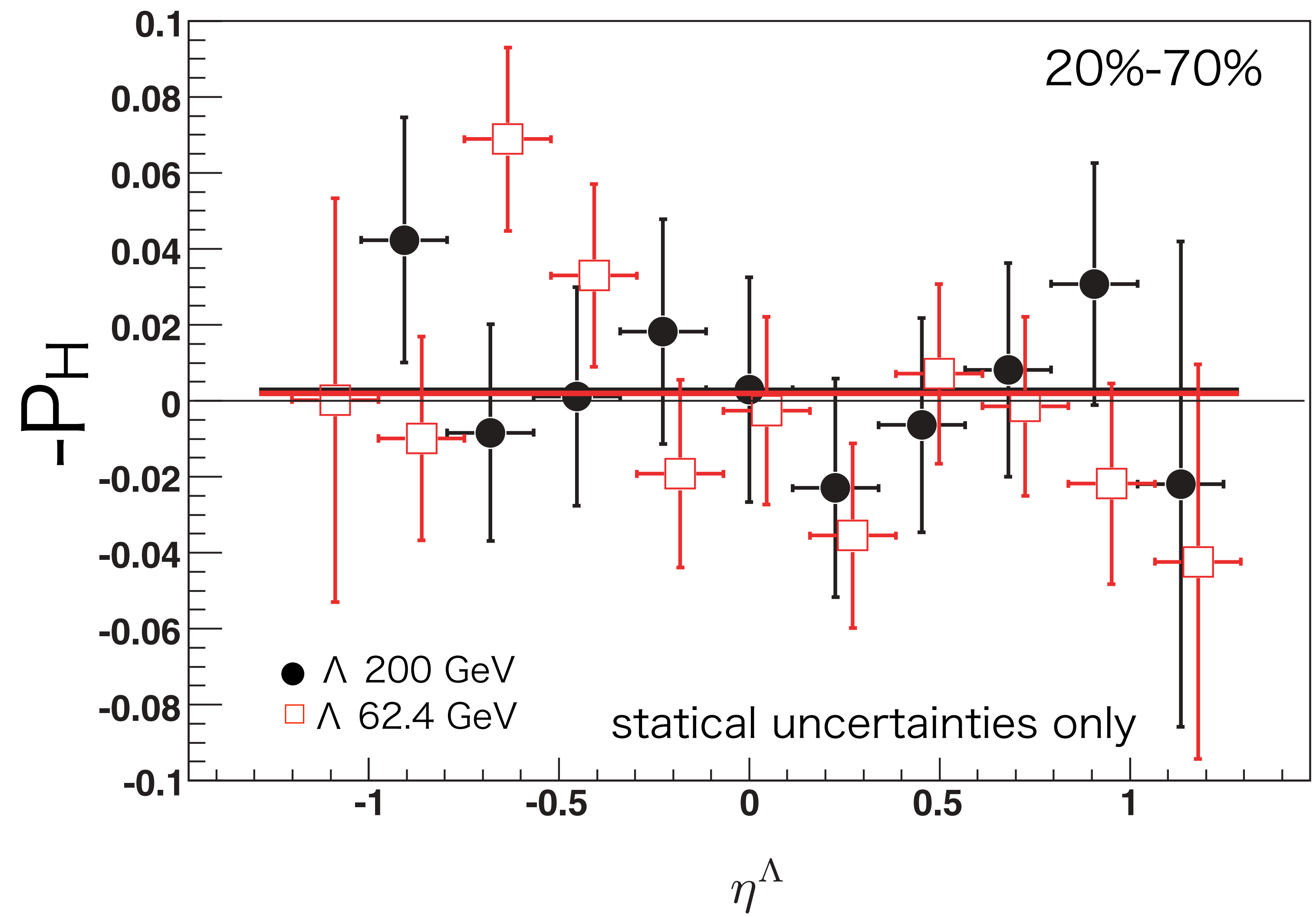
- Event plane determination: ~22%
- Methods to extract the polarization signal: ~21%
- Possible contribution from the background: ~13%
- Topological cuts: <3%
- Uncertainties of the decay parameter: ~2% for Λ, ~9.6% for anti-Λ
- Extraction of Λ yield (BG estimate): <1%

Also, the following studies were done to check if there is no experimental effect:

- Two different polarities of the magnetic field for TPC
- Acceptance effect
- Different time period during the data taking
- Efficiency effect

First paper on Λ polarization from STAR in 2007

STAR, PRC76, 024915 (2007)

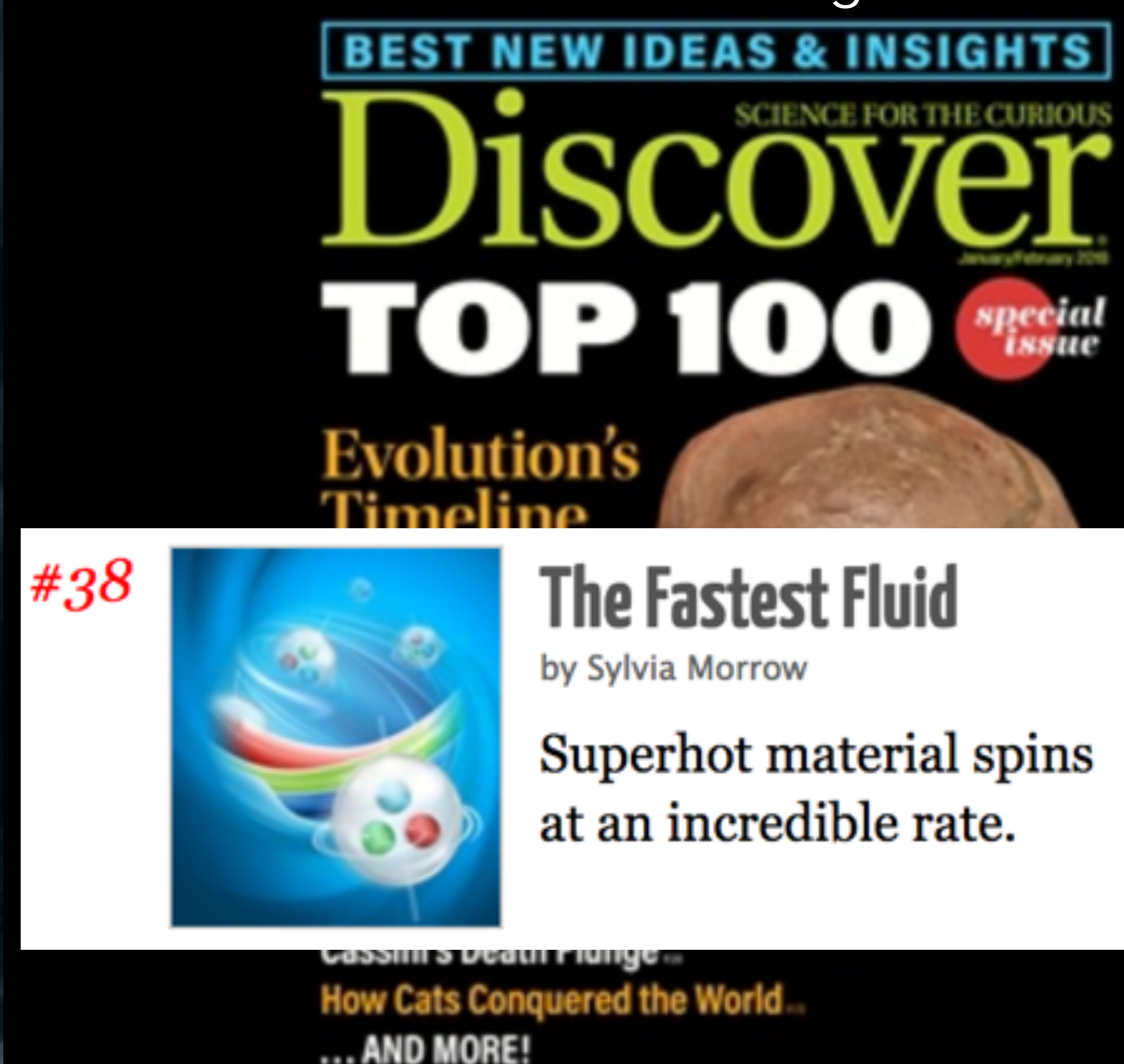


constant fit for 200 GeV
P_H = (-0.28±0.96)%

Results were consistent with zero, giving an upper limit of 2%.
~10M events (from 2004 data) was not sufficient.

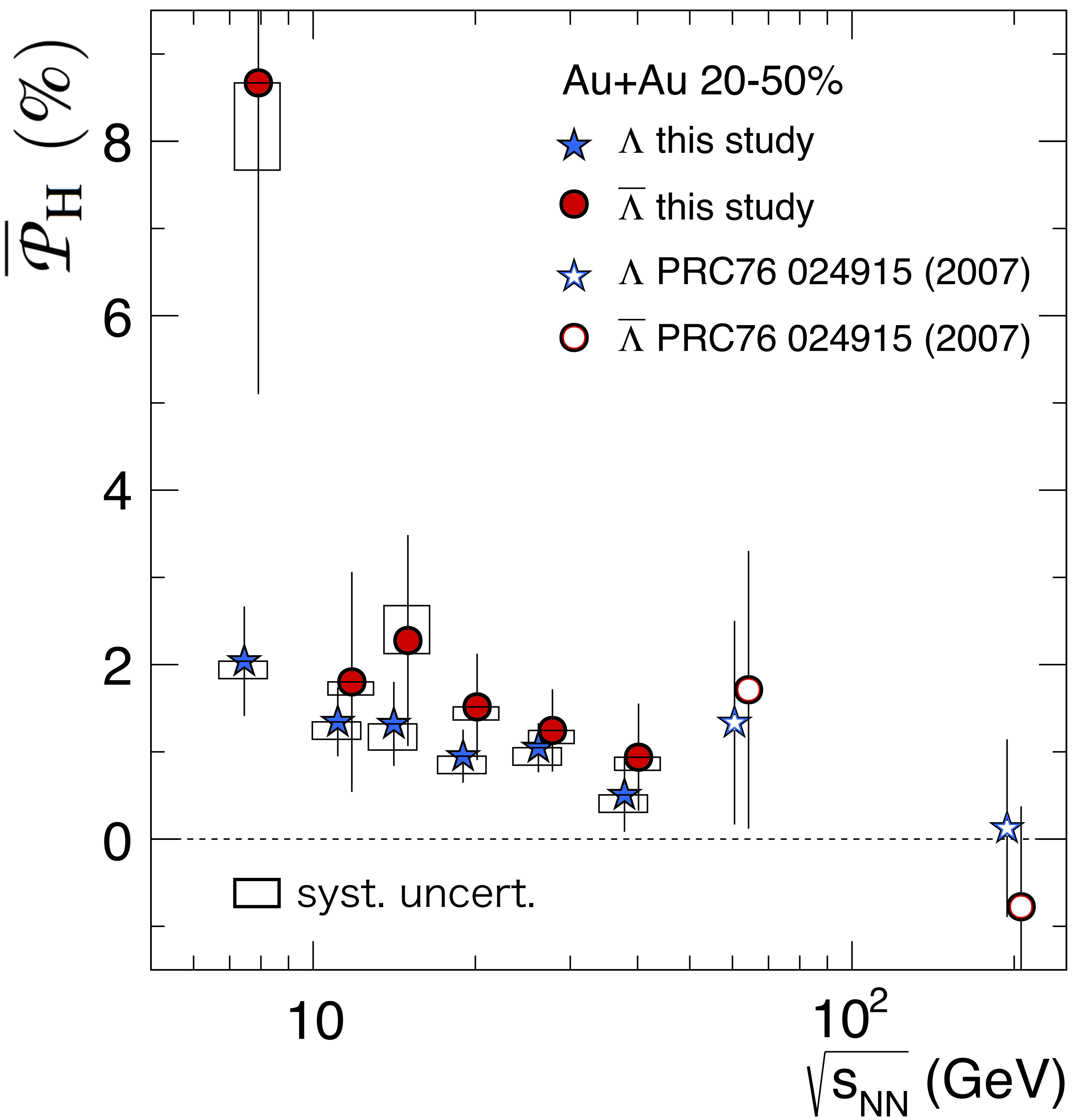
First observation of
fluid vortices formed by HIC

#38 of top100, 2017
Discover Magazine



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

STAR, Nature 548.62 (2017)



- Positive signals in $\sqrt{s_{NN}}$=7.7-39 GeV
  - indication of thermal vorticity!

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

- $P_H(\Lambda) < P_H(\text{anti-}\Lambda)$ systematically

For small thermal vorticity,

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

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

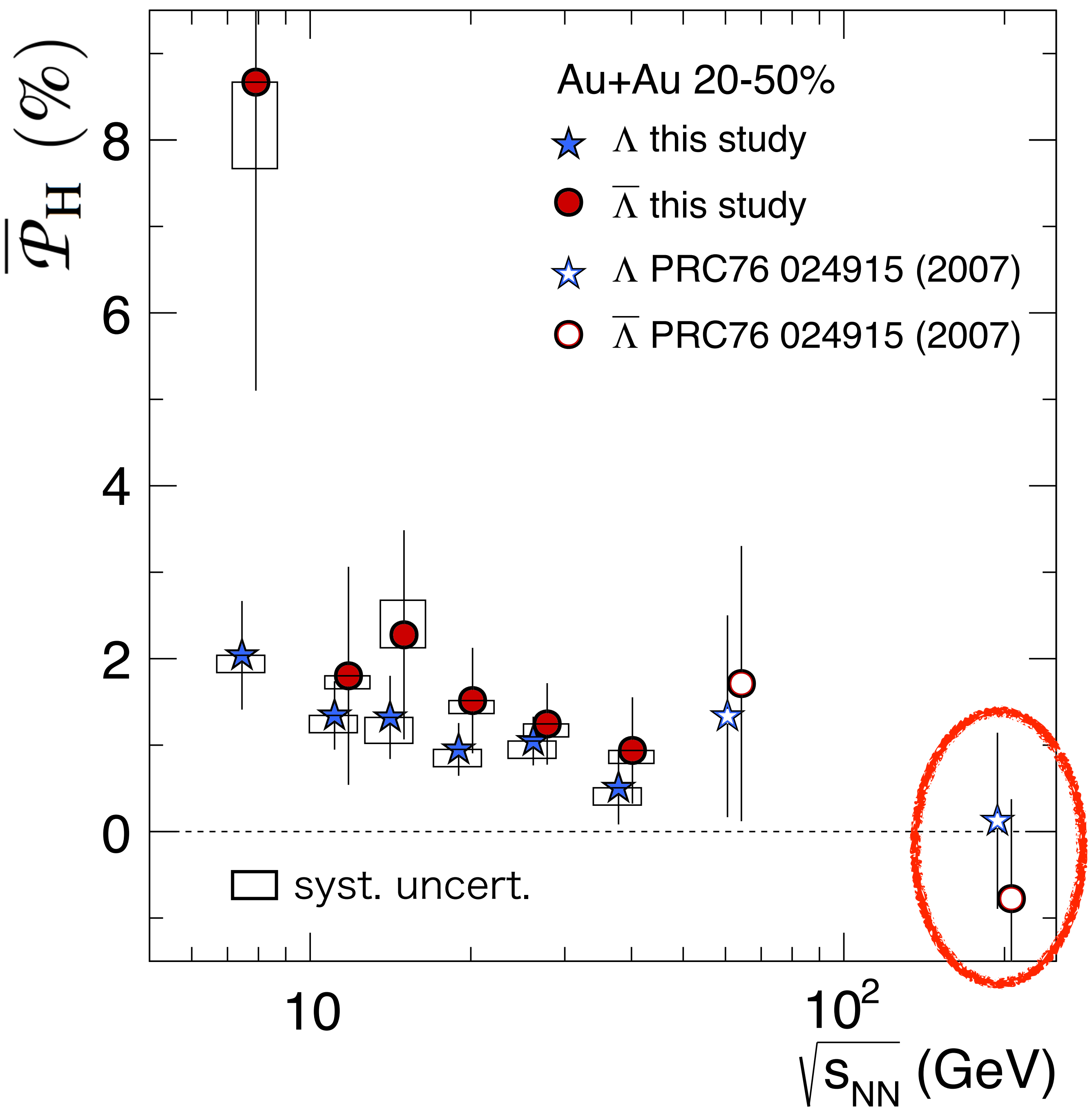
Becattini, Karpenko, Lisa, Upsal, and Voloshin, PRC95.054902 (2017)

- implying a contribution from B-field

->More details in Mike Lisa's talk

Revisiting 200 GeV

STAR, Nature 548.62 (2017)

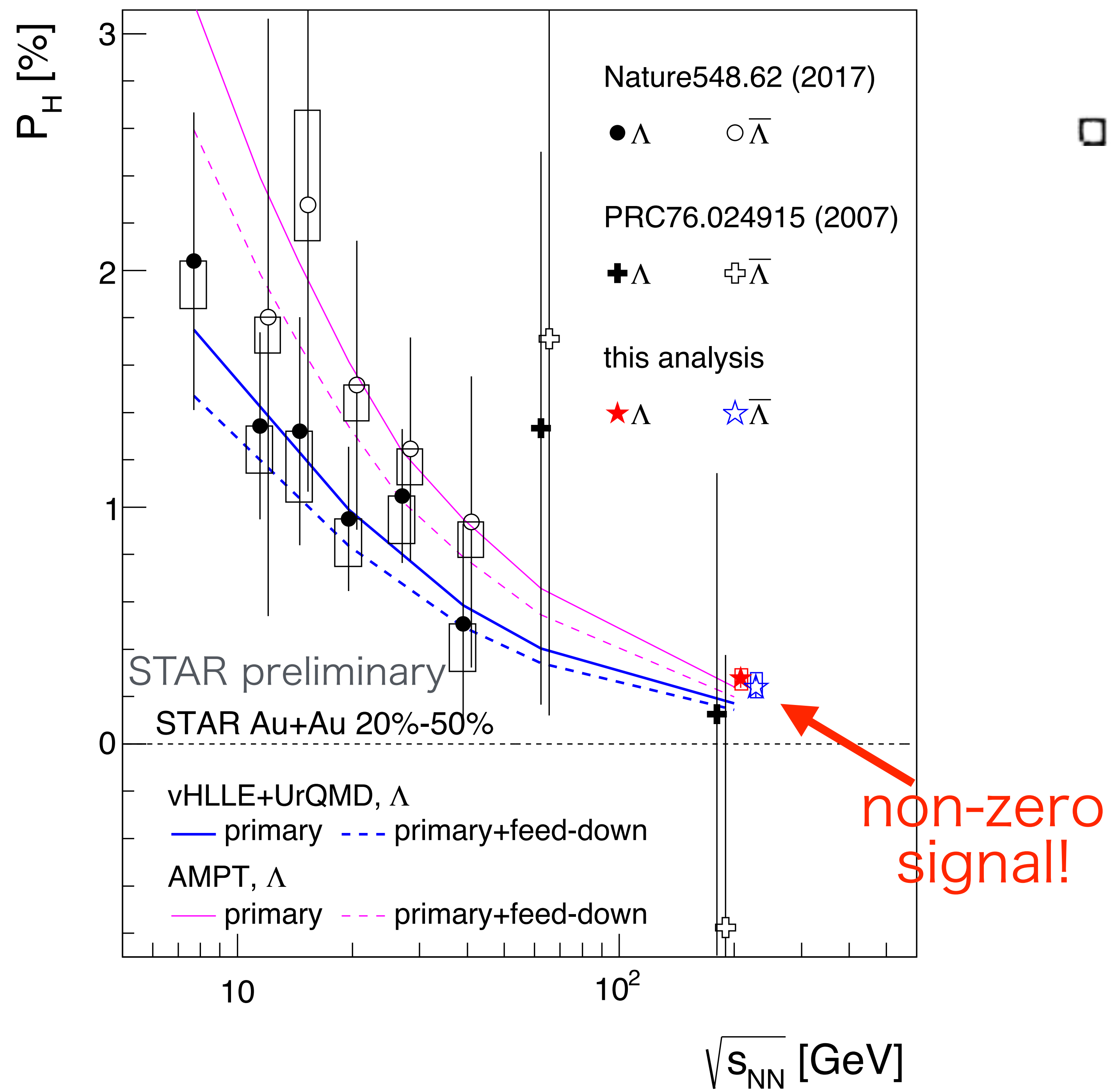


- Previous STAR results at 200 GeV were consistent with zero
  →Can we see the signal when using recent data with more statistics?

- 2007 publication
  - year 2004 data ~**10M** events
- Recent preliminary study
  - year 2010 data ~**200M** events
  - year 2011 data ~**350M** events
  - year 2014 data ~**1B** events

Let's revisit 200 GeV with ~150 times more events!

Λ global polarization vs √sNN



vHLLE+UrQMD: Y. Karpenko and F. Becattini, EPJC(2017)77:213
AMPT: H. Li et al., Phys. Rev. C 96, 054908 (2017)

- Observed finite signal at √sNN = 200 GeV

$$P_H(\Lambda)\ [\%] = 0.277 \pm 0.040(\mathrm{stat}) \pm^{0.039}_{0.049}(\mathrm{sys})$$
$$P_H(\bar{\Lambda})\ [\%] = 0.240 \pm 0.045(\mathrm{stat}) \pm^{0.061}_{0.045}(\mathrm{sys})$$

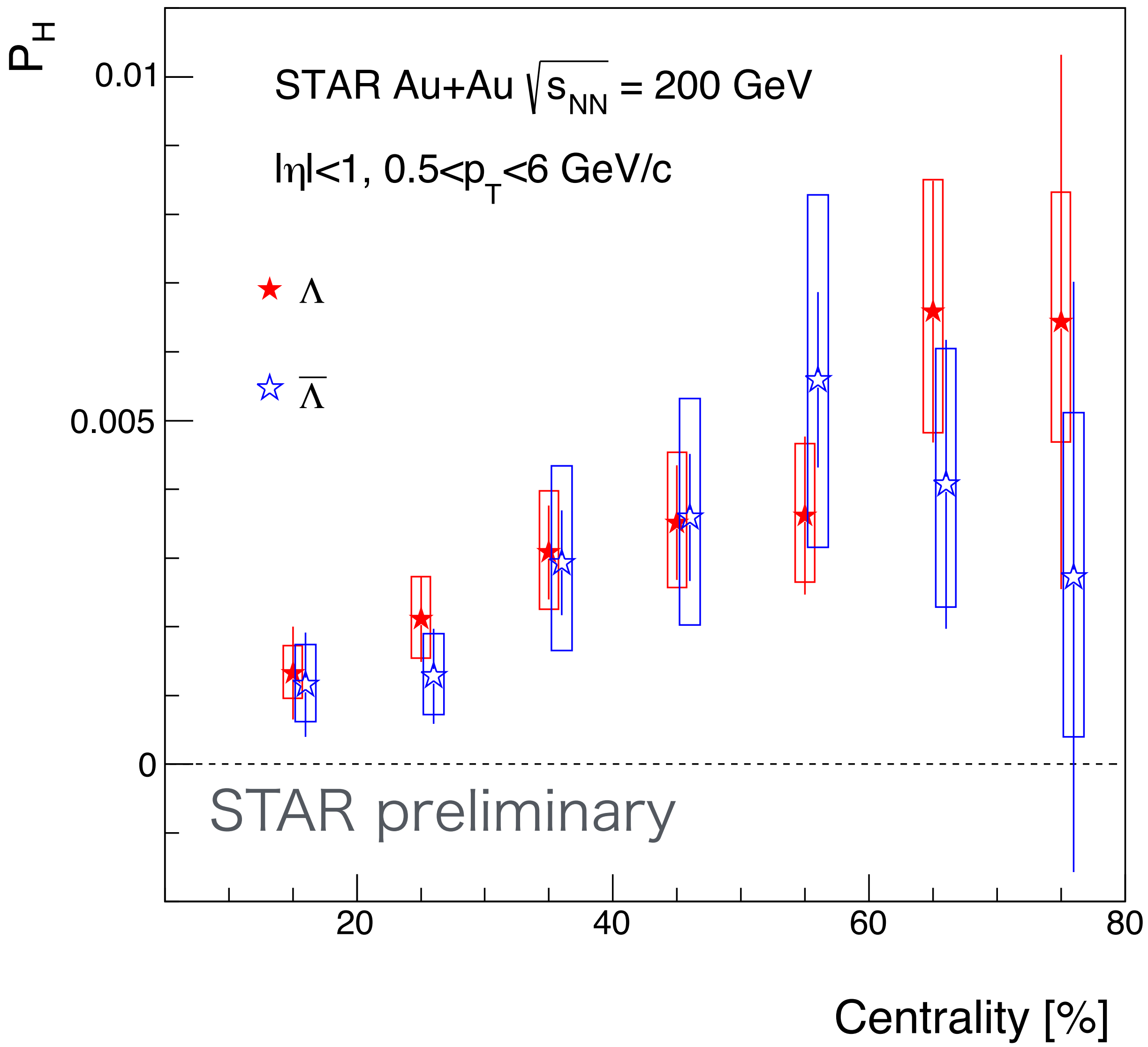
  - ~15% dilution of the signal due to feed-down effect (model-dependent estimation)
  - Following the trend of BES data and close to viscous-hydro+UrQMD and AMPT predictions in all energies
  - No significant difference between Λ and anti-Λ

Go to differential measurements

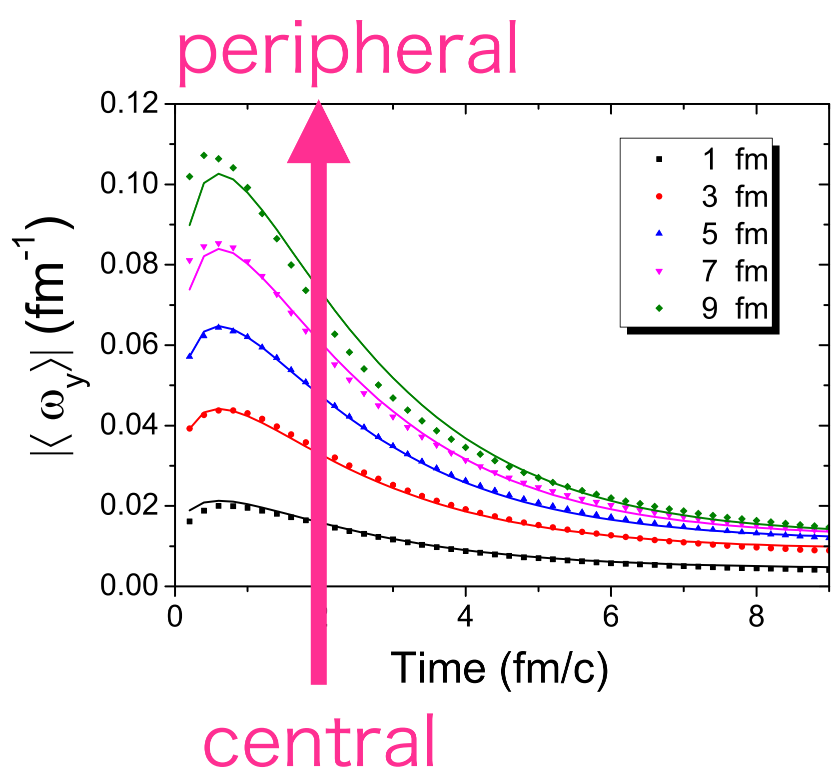
- Any centrality dependence?
- Any p_T dependence?
- Any rapidity dependence?
- Anything else we expect?

Let's look at P_H more differentially for 200 GeV!

Centrality dependence

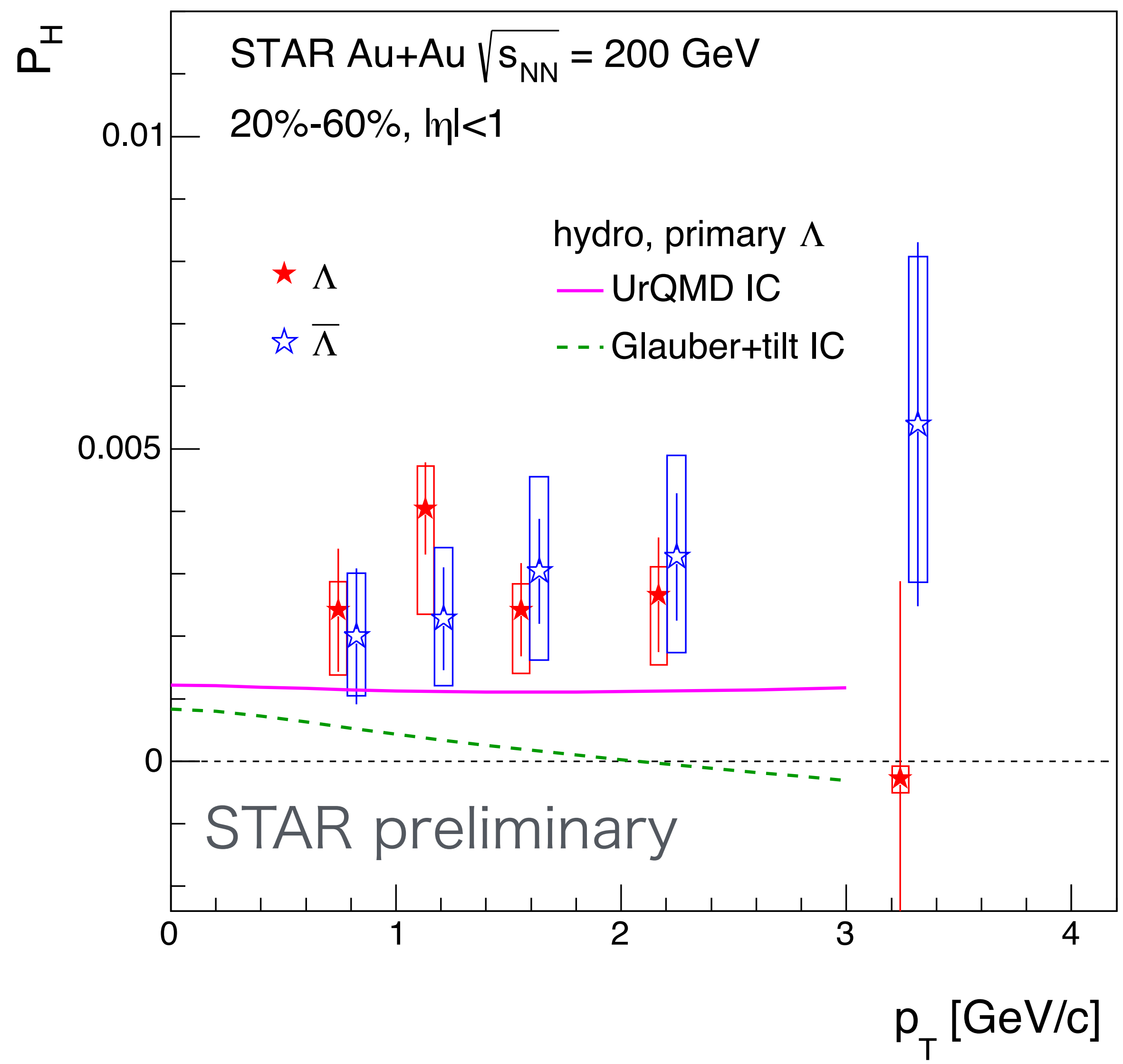


AMPT model,
Y. Jiang et al., PRC94, 044910 (2016)



- Slightly increasing in more peripheral events
  - qualitatively consistent with AMPT calculations
- Not clear if there is a saturation or decrease in most peripheral

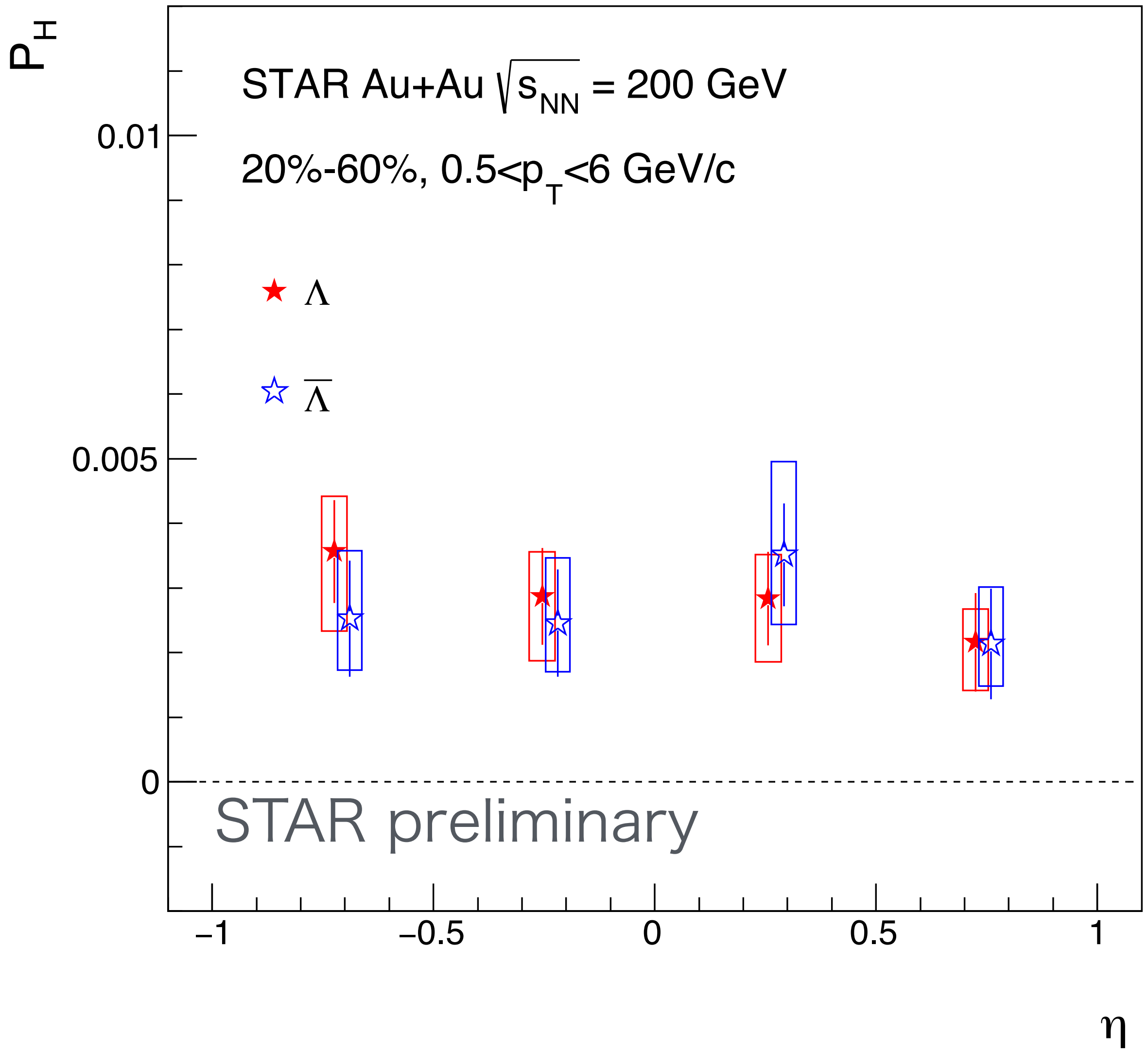
p_T dependence



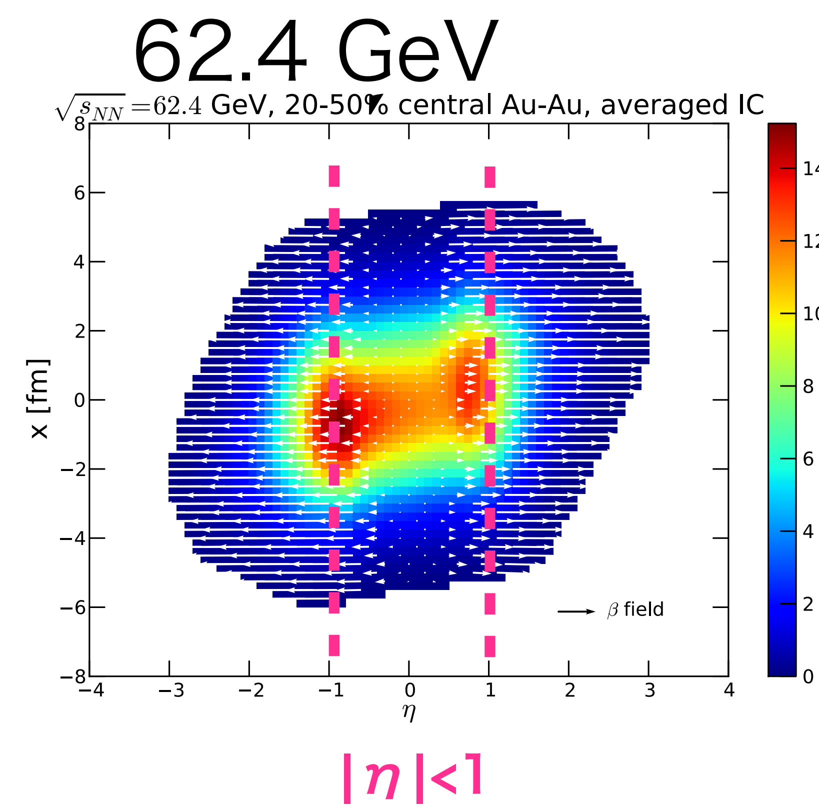
3D viscous hydro-model
F. Becattini and I. Karpenko, PRL120.012302 (2018)

- No significant p_T dependence, as expected from the initial angular momentum of the system
- Qualitatively agrees with hydrodynamic model. Initial conditions affect the magnitude and dependency on p_T

η dependence



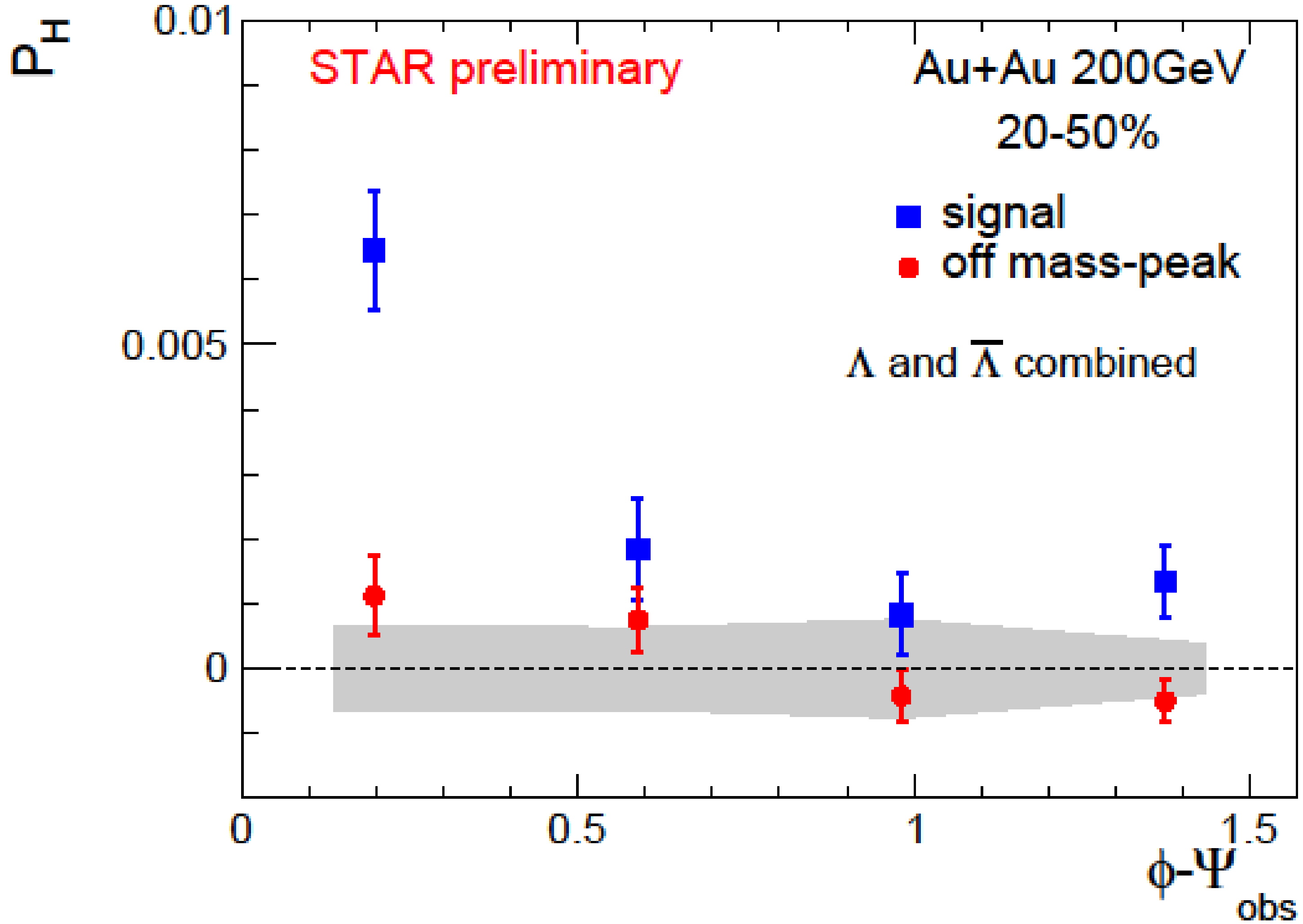
vHLLE+UrQMD,
Karpenko and Becattini, EPJC(2017)77:213

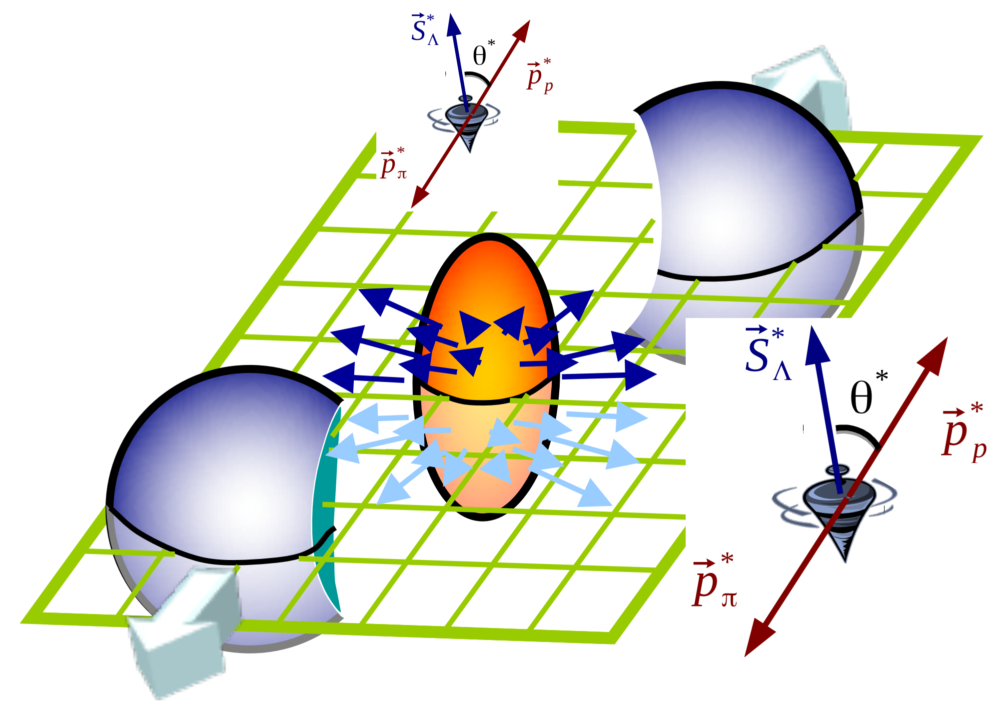


- No significant η dependence
  - a smaller shear flow structure at mid-rapidity than at forward (backward) rapidity due to baryon transparency at higher energy
- More interesting at lower energies or at the LHC energy for forward rapidity

Azimuthal angle dependence

B. Tu, for the STAR Collaboration, SQM2017





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

- Larger signal in in-plane than that in out-of-plane direction

Azimuthal angle dependence

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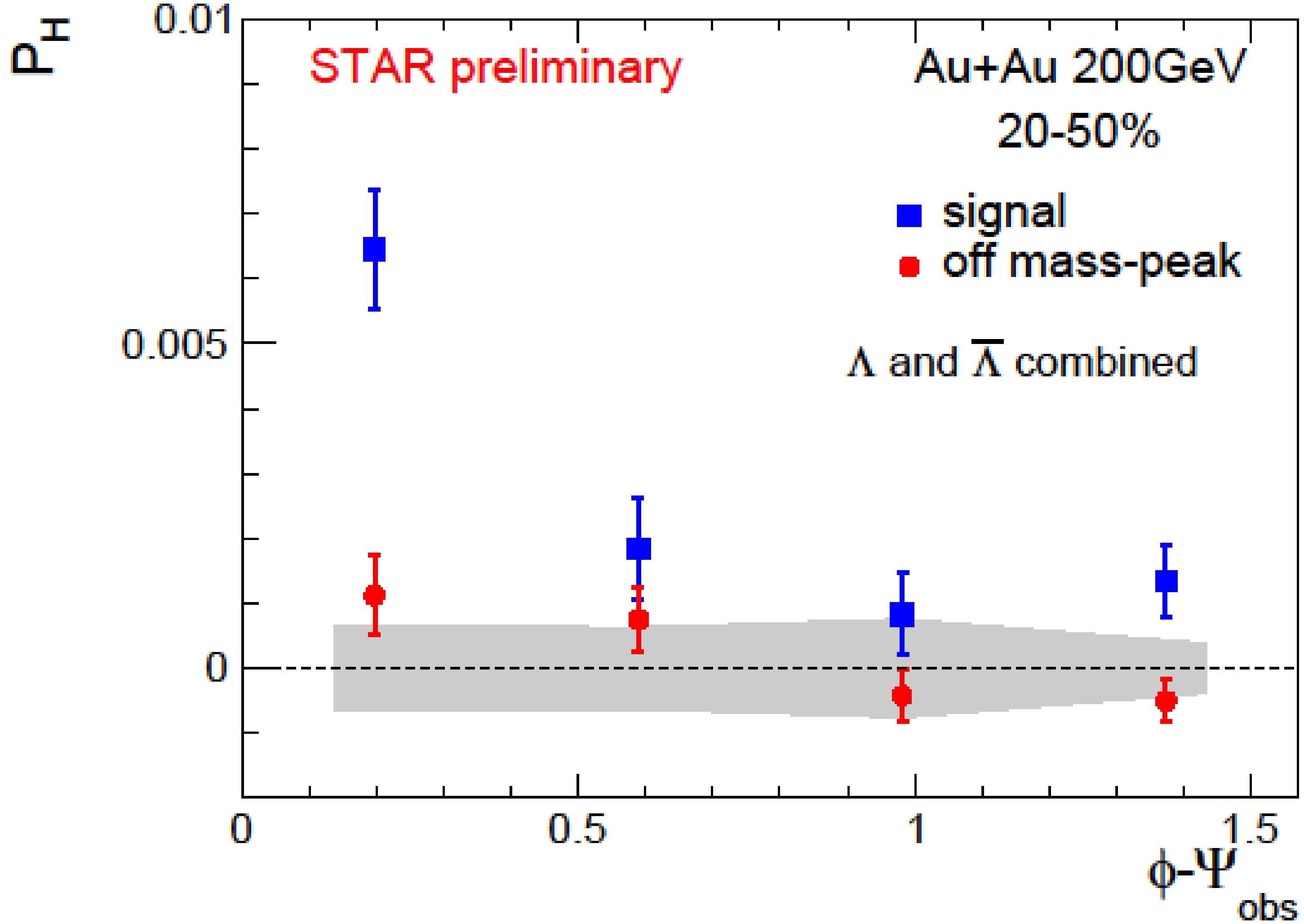
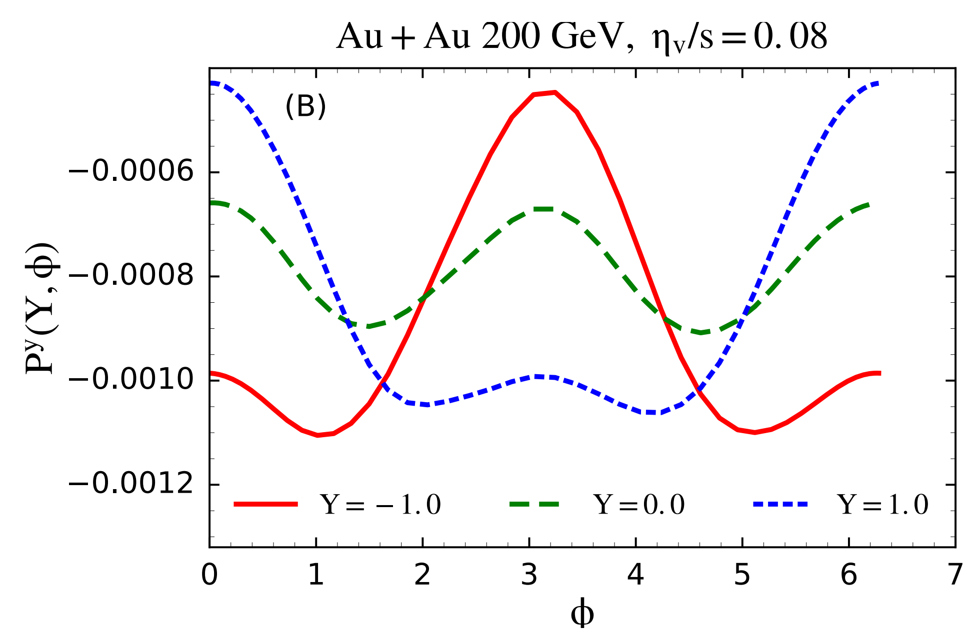


(3+1)D vicious hydro + AMPT IC
L.-G. Pang, QM17

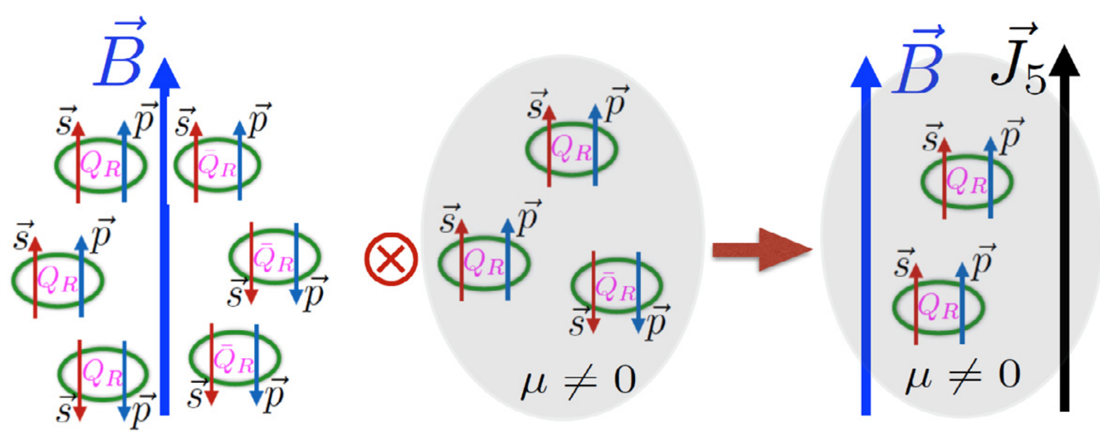


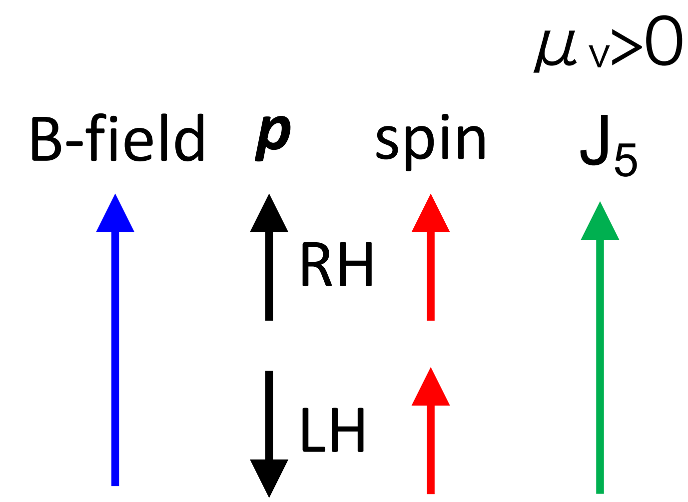
* Correction on EP resolution (for x-axis) is not applied here

- Larger signal in in-plane than that in out-of-plane direction
- Similar trend to the hydrodynamic calculation

Λ polarization vs charge asymmetry?

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

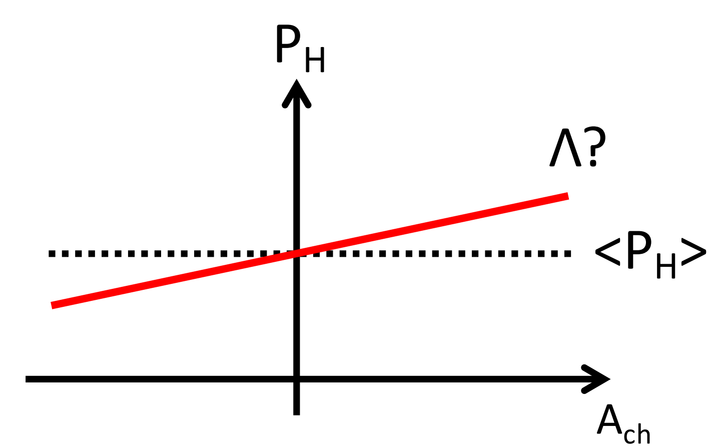




- Λ polarization may have a contribution from the axial current J_5 induced by B-field (Chiral Separation Effect), S. Schlichting and S. Voloshin, in preparation
- Use charge asymmetry A_{ch} instead of $\mu_{\rm v}$

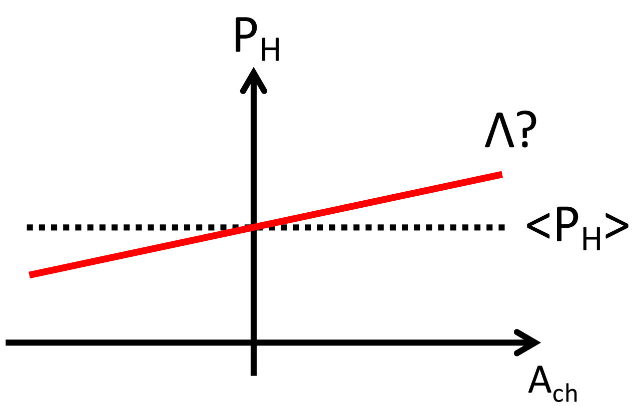
$$\mu_{\rm v}/T \propto \frac{\langle N_+ - N_- \rangle}{\langle N_+ + N_- \rangle} = A_{\rm ch}$$

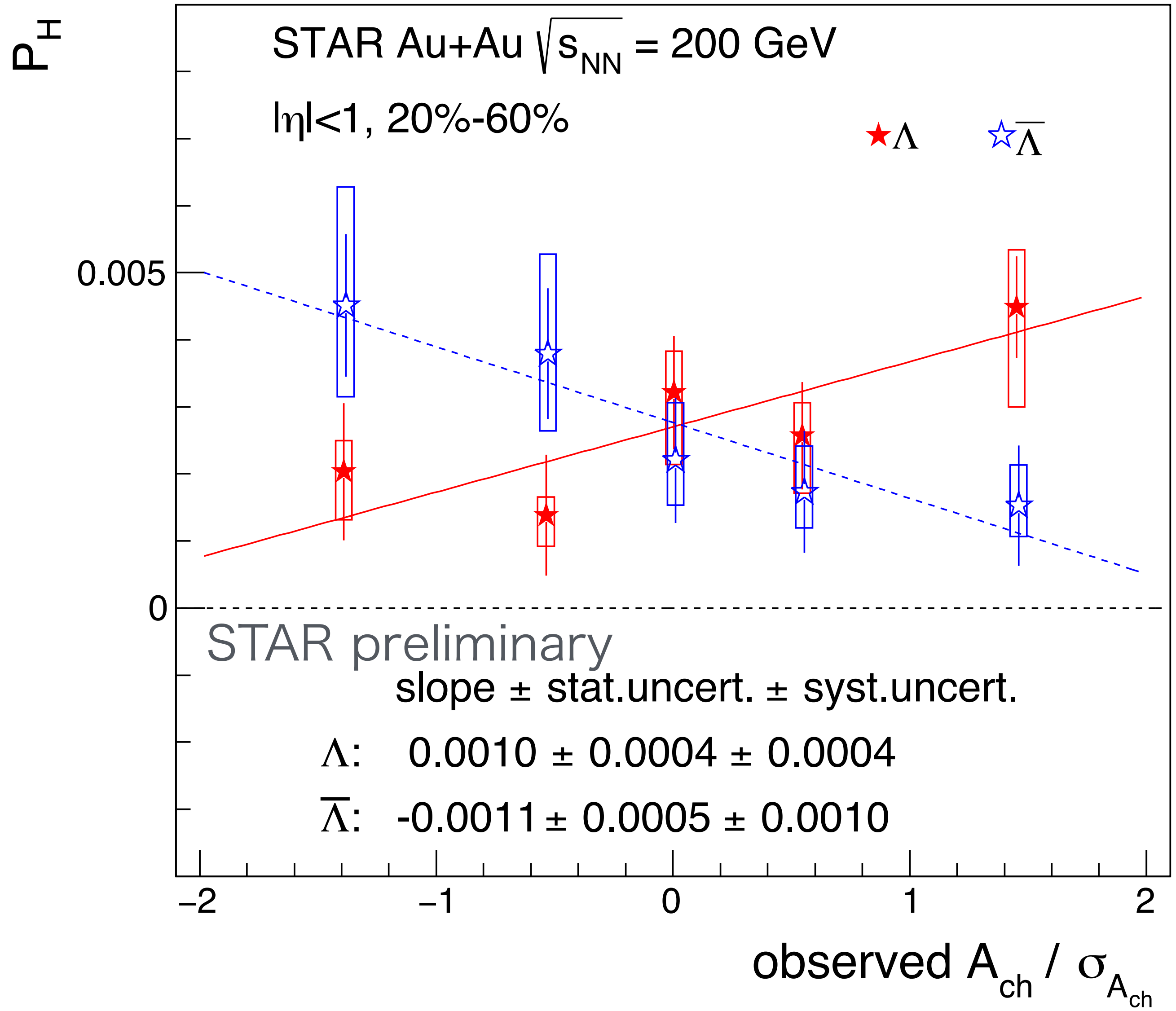
what's the expectation?
true for u-quark but also for Λ?



Charge asymmetry dependence

naive expectation?

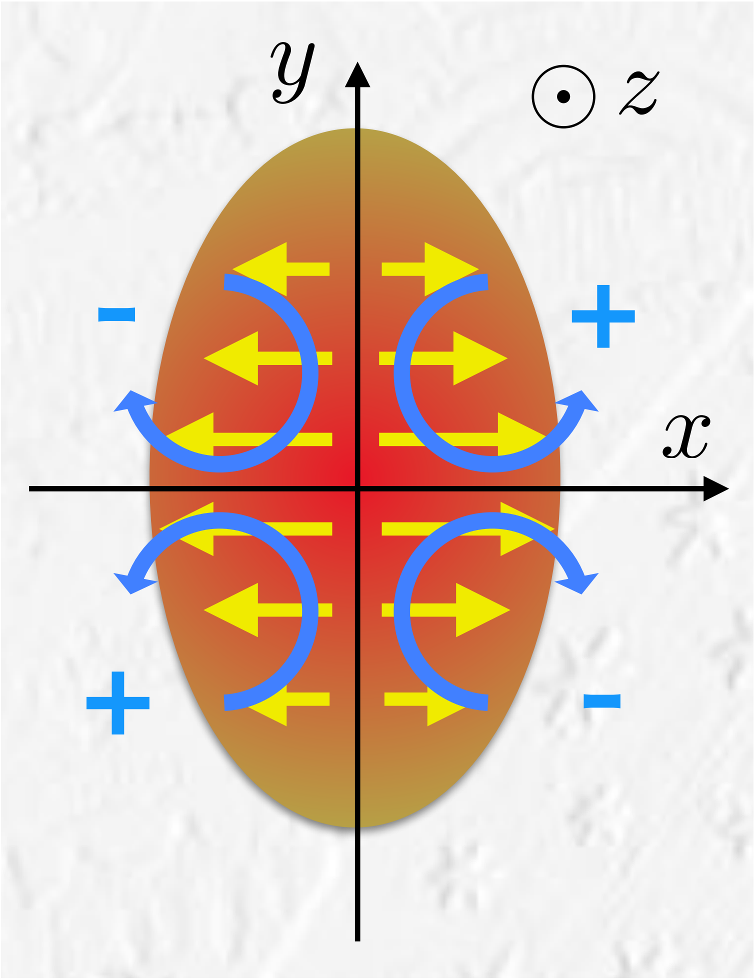




Slopes of Λ and anti-Λ seem to be different.

Possibly a contribution from the axial current?

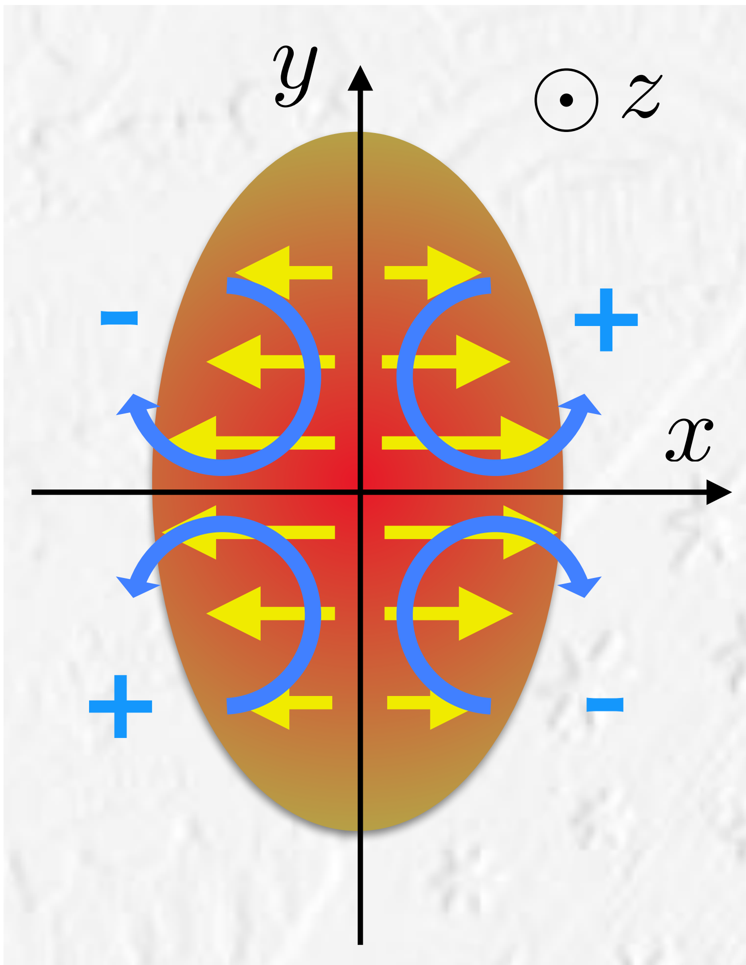
Local vorticity from elliptic flow?



F. Becattini and I. Karpenko, PRL120.012302 (2018)
S. Voloshin, arXiv:1710.08934

Stronger flow in in-plane than in out-of-plane could make local polarization along beam axis!

Local vorticity from elliptic flow?



F. Becattini and I. Karpenko, PRL120.012302 (2018)
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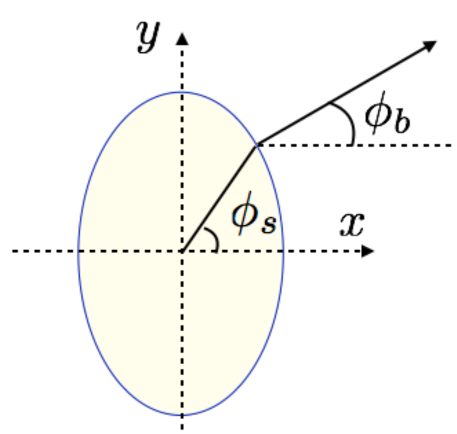
Stronger flow in in-plane than in out-of-plane could make local polarization along beam axis!

S. Voloshin, arXiv:1710.08934

<u>Blast-wave parameterization</u>

$$r_{max} = R[1 - a\cos(2\phi_s)],$$
$$\rho_t = \rho_{t,max}[r/r_{max}(\phi_s)][1 + b\cos(2\phi_s)] \approx \rho_{t,max}(r/R)[1 + (a+b)\cos(2\phi_s)].$$

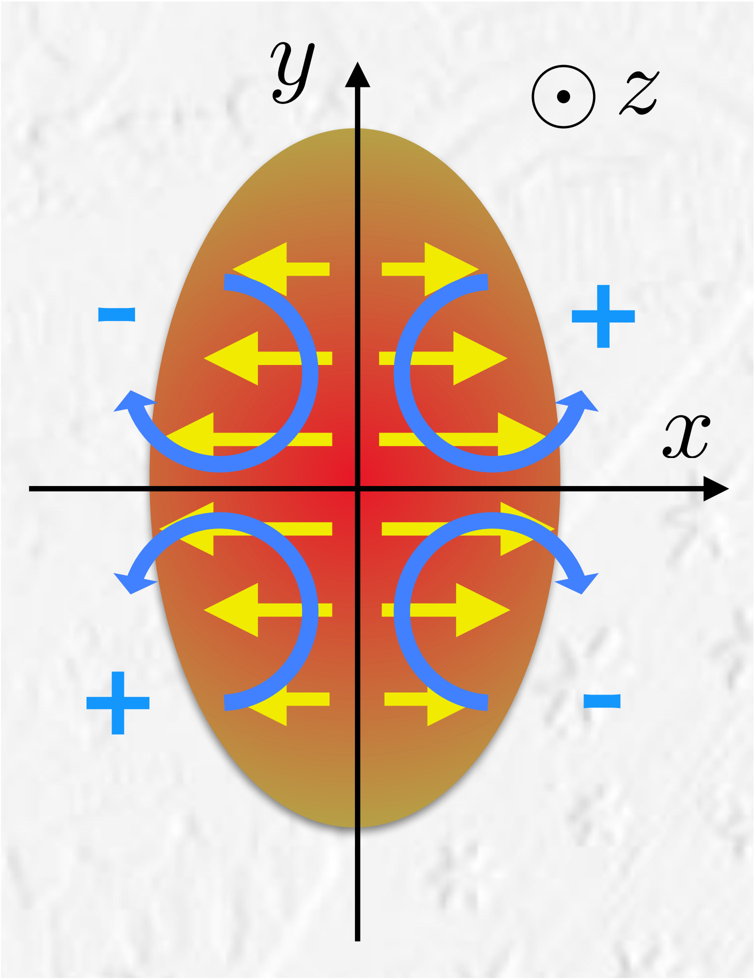


$$\underline{\omega_z} = 1/2(\nabla \times \mathbf{v})_z \approx (\rho_{t,nmax}/R)\,\underline{\sin(n\phi_s)[b_n - a_n]}.$$

a_n: spatial anisotropy, b_n: flow anisotropy

Quadruple or sine structure of ω_z is expected.

Local vorticity from elliptic flow?



F. Becattini and I. Karpenko, PRL120.012302 (2018)
S. Voloshin, arXiv:1710.08934

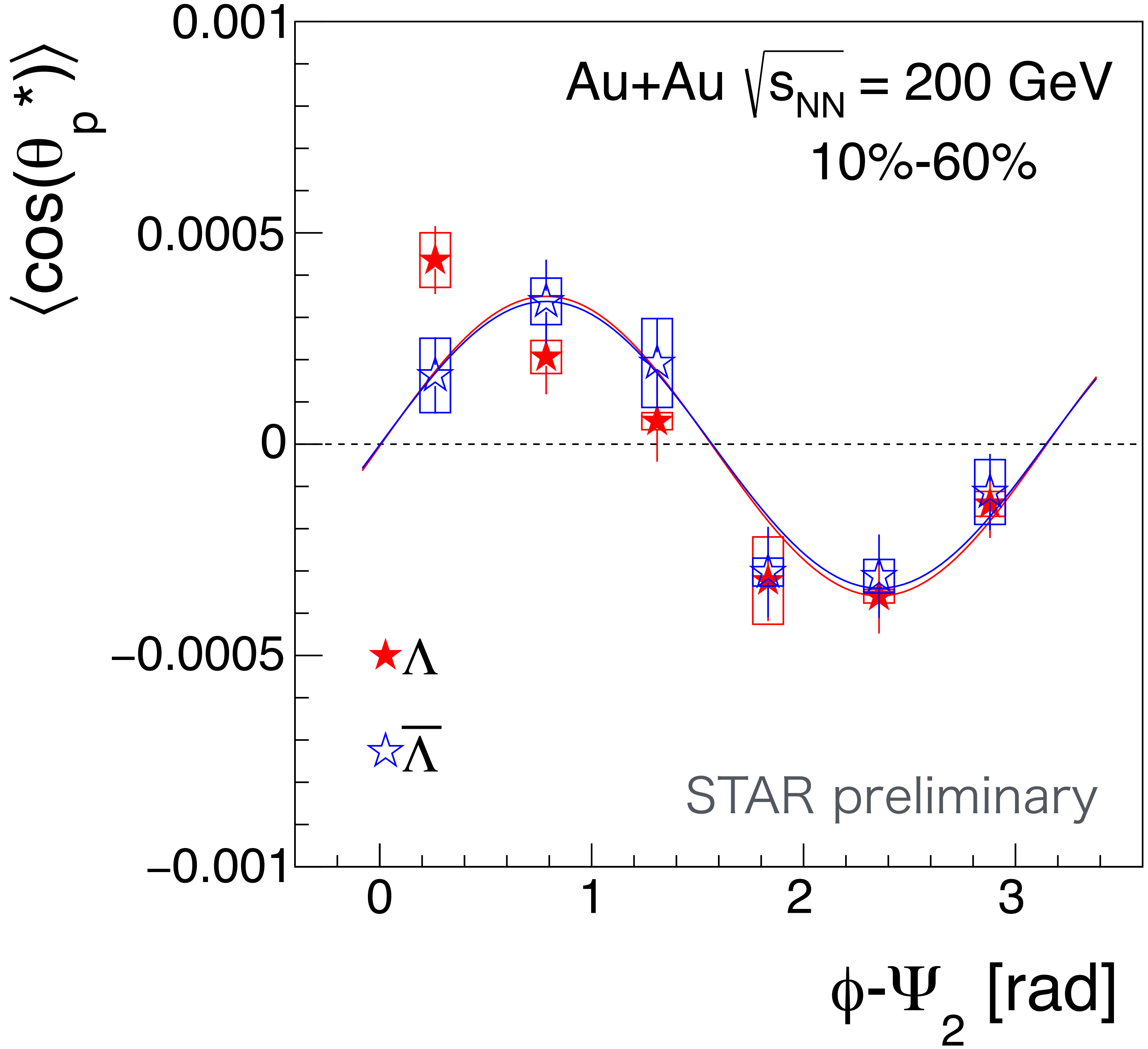
Stronger flow in in-plane than in out-of-plane could make local polarization along beam axis!

θ_p^*: polar angle of daughter proton in Λ rest frame

$$P_H^z \sim \langle \cos(\theta_p^*) \rangle$$

- z-component of polarization
- No need for the 1st-order EP (just need the 2nd-order EP)

Polarization along beam direction



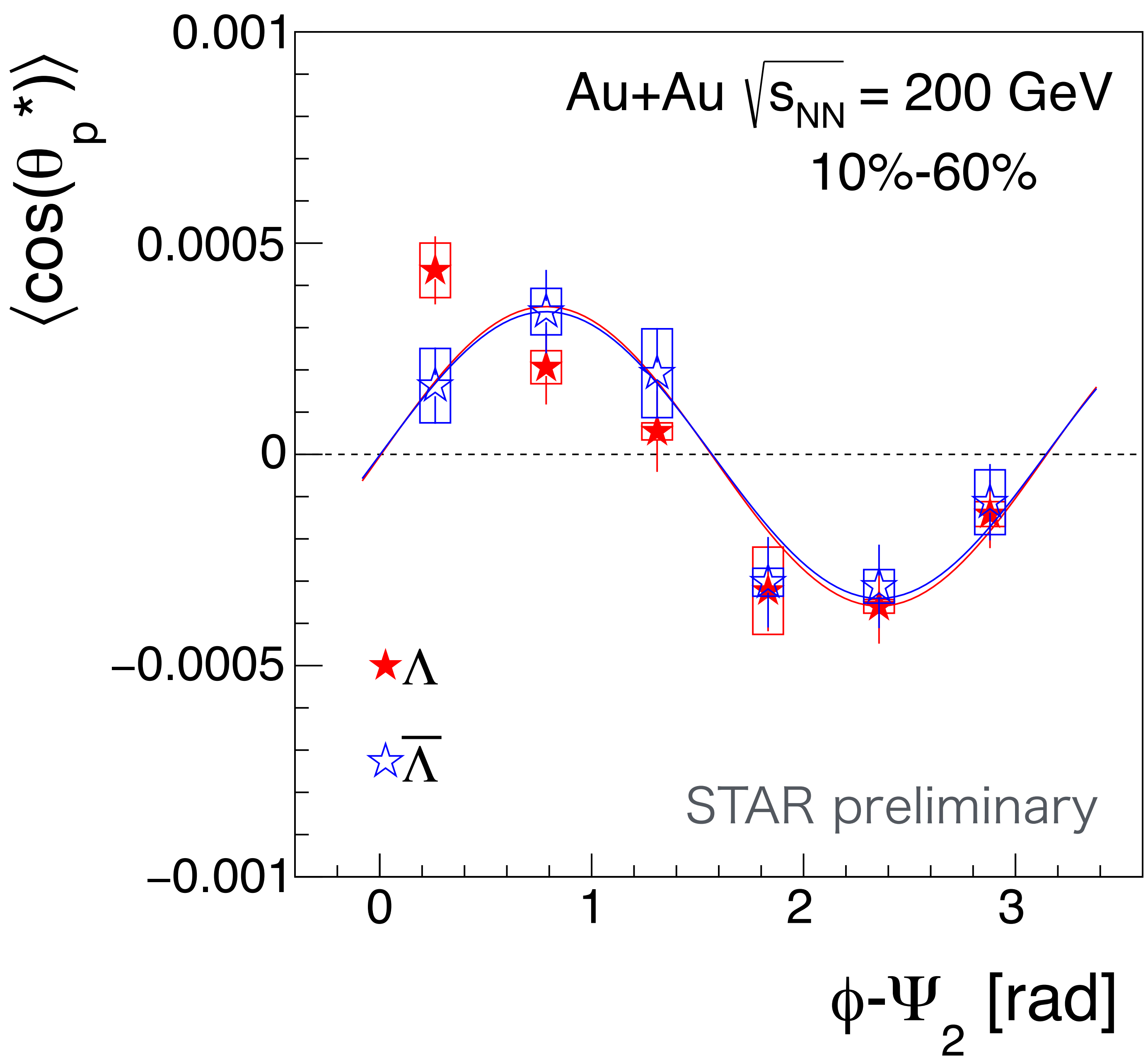
$$P_H^z \sim \langle \cos(\theta_p^*) \rangle$$

- Applied acceptance correction so that average of ω_y over $\Delta\phi$ should be zero due to symmetry

As expected from the elliptic flow, the sine structure can be seen!

* Effect of Ψ_2 resolution is not corrected here. Only the magnitude of the oscillation is affected.

Polarization along beam direction



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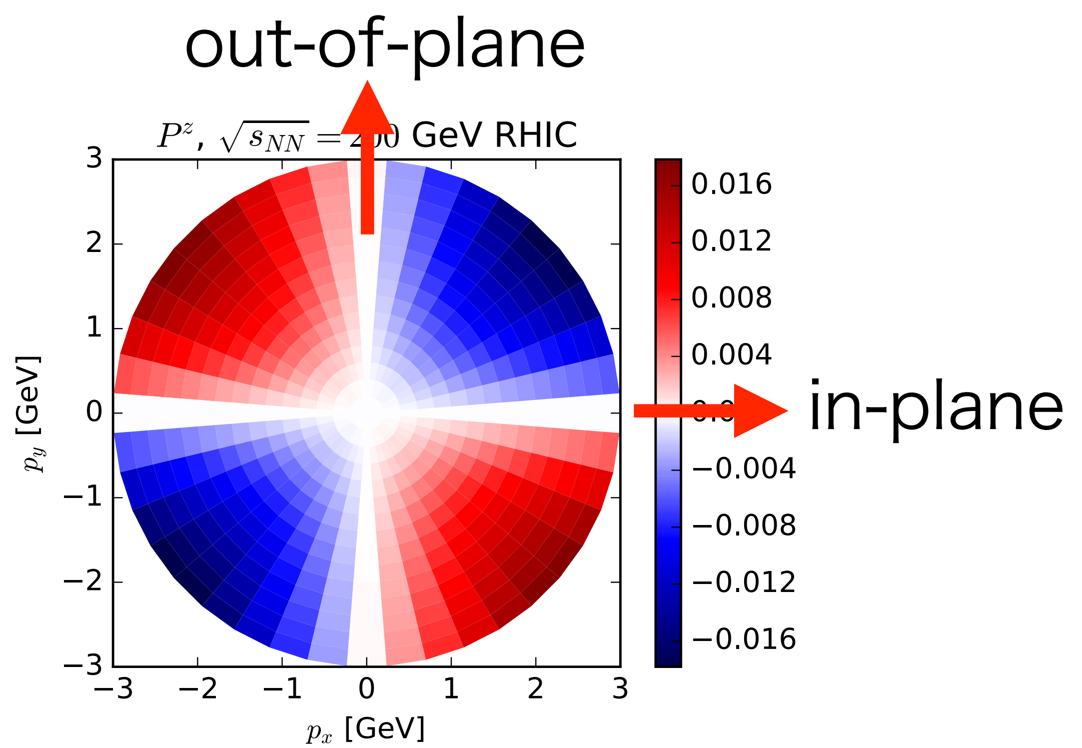
Only the magnitude of the oscillation is affected.

$$P_H^z \sim \langle\cos(\theta_p^*)\rangle$$



F. Becattini and I. Karpenko, PRL.120.012302 (2018)

- Different trend to hydrodynamic model.
- Depends on the relation between flow and spatial anisotropy according to BW

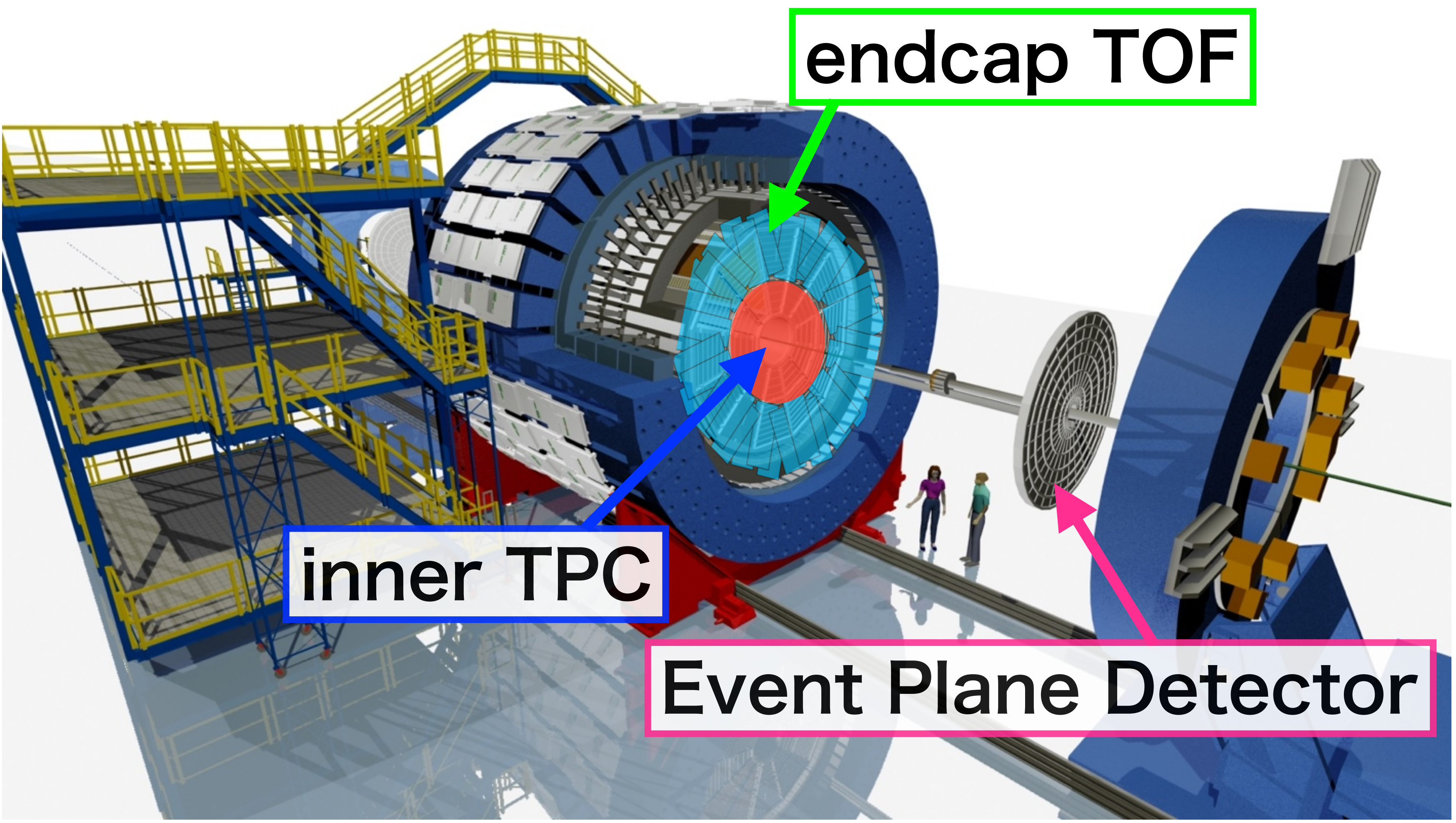
$$\omega_z = 1/2(\nabla \times \mathbf{v})_z \approx (\rho_{t,nmax}/R)\sin(n\phi_s)[b_n - a_n].$$

a_n: spatial anisotropy, b_n: flow anisotropy

Summary

- First observation of Λ global polarization at $\sqrt{s_{NN}}$ = 7.7-39 GeV
- Preliminary studies show non-zero signals 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
  - Centrality and azimuthal angle dependence were observed and no significant dependence on p_T and η.
  - A hint of charge-asymmetry dependence (~2σ level) with a possible relation to the axial current induced by B-field
- Local vorticity along the beam direction
  - Sine structure of the polarization along the beam direction was observed, as expected from the elliptic flow
  - More detailed study is ongoing

Outlook



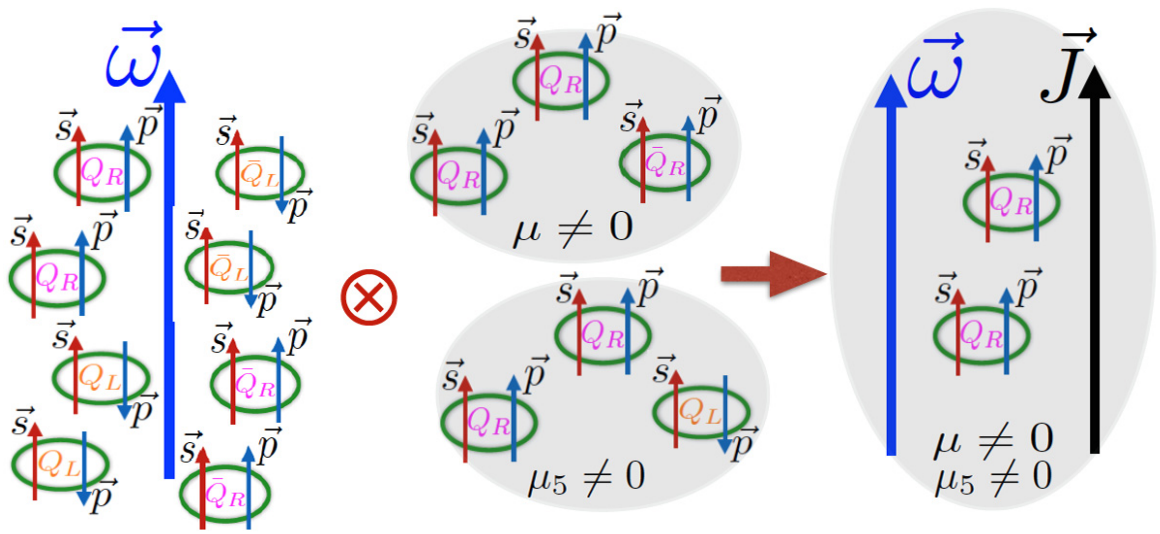
EPD upgrade installed
- $2.1<|\eta|<5.1$
- Improves EP resolution
- Independent trigger

iTPC upgrade ready in 2019
- $p_T>60$ MeV/c
- Extension from $|\eta|<1$ to $|\eta|<1.5$
- Improvement of dE/dx resolution

eTOF upgrade ready in 2019
- $-1.6<\eta<-1.1$
- Extends forward PID capability

- Isobaric collisions and Au+Au 27 GeV in 2018 (Just started last week!)
  - ~1B events for each with EPD (better EP resolution)
  - Any splitting of Λ and anti-Λ? Any difference btw Ru+Ru and Zr+Zr?
- Beam Energy Scan II (2019-2020?)
  - 7.7-19.6 GeV (10 times larger events than BES I) + Fixed target program with iTPC and eTOF (wider η coverage)

Chiral vortical effect



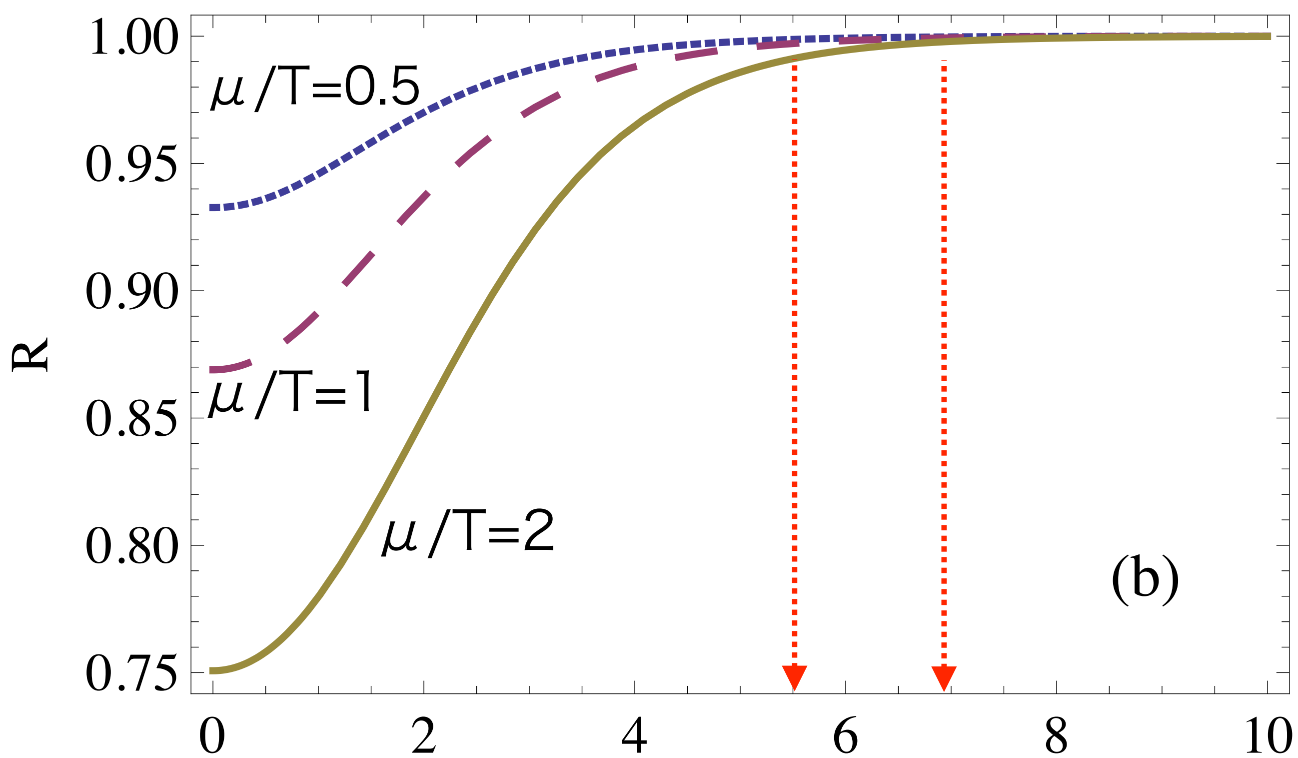
$$\vec{J}_5 = \left[\frac{1}{2\pi^2}(\mu^2 + \mu_5^2) + \frac{1}{6}T^2\right]\vec{\omega}$$

Observed polarization may get an offset from CVE

Effect of non-zero chemical potential?

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

R=P$_\Lambda$/P$_{\text{anti-}\Lambda}$

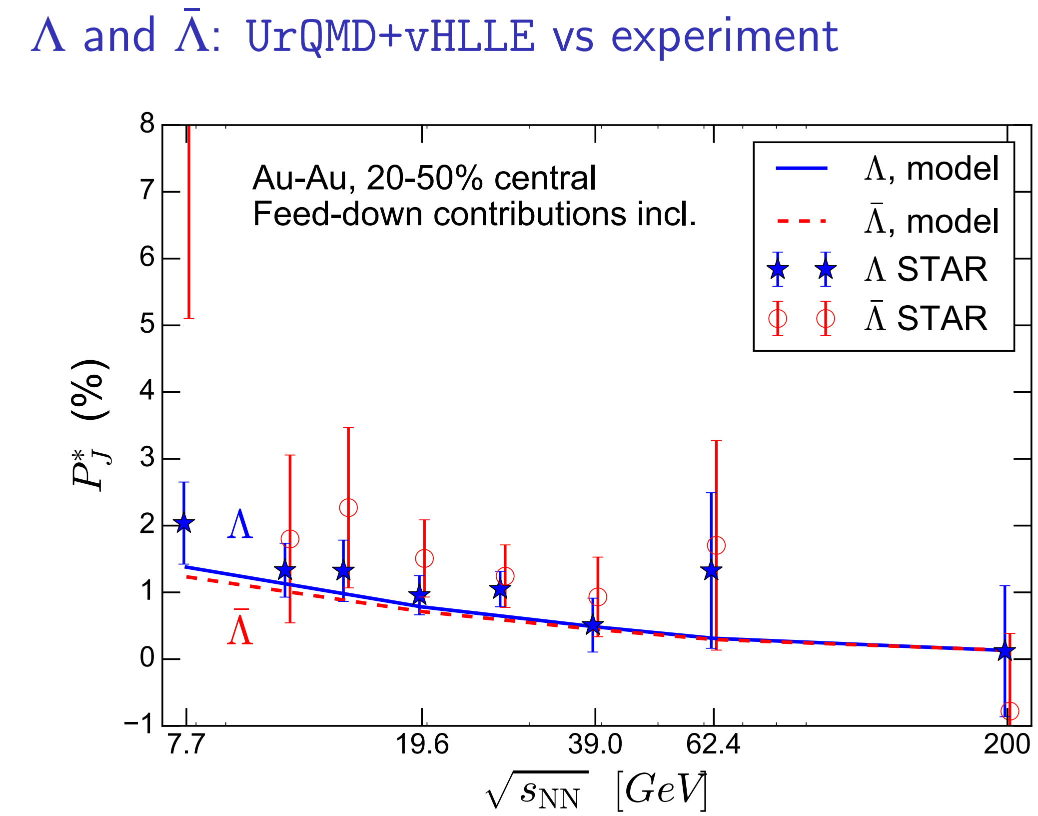


βm = m/T

~ 1.1GeV/(160-200)MeV

~ 5.5-6.8

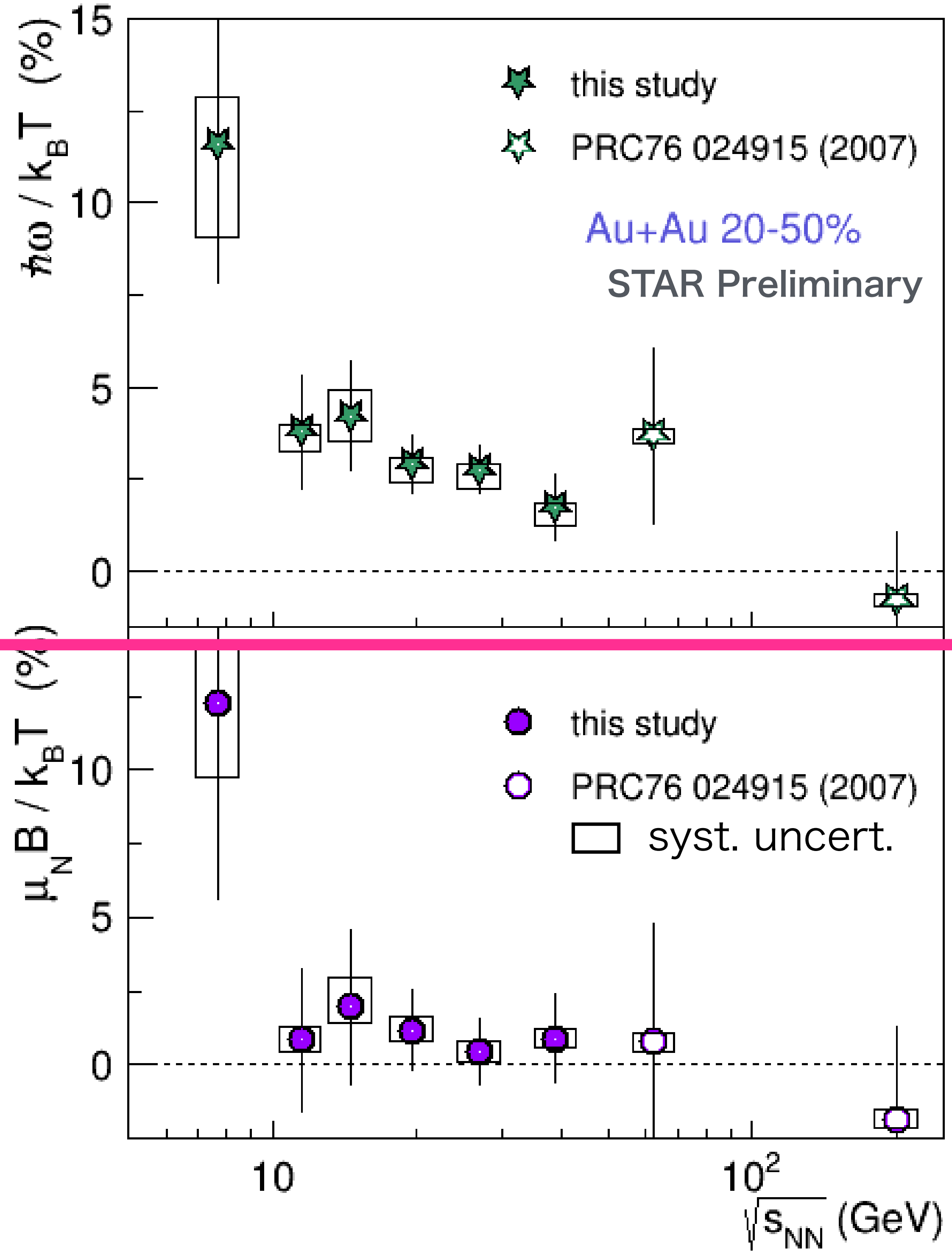
Y. Karpenko, sQM2017



only μ_B effect in model

Non-zero chemical potential makes difference in polarization between Λ and anti-Λ, but the effect seems to be small.

Extracted vorticity



- Vorticity

$$\omega = (P_\Lambda + P_{\bar{\Lambda}})k_B T/\hbar$$
$$\sim 0.02\text{-}0.09\ \mathrm{fm}^{-1}$$
$$\sim 0.6\text{-}2.7 \times 10^{22}\mathrm{s}^{-1}$$

(for T=160 MeV)

Jiang et al., PRC94, 044910 (2016)

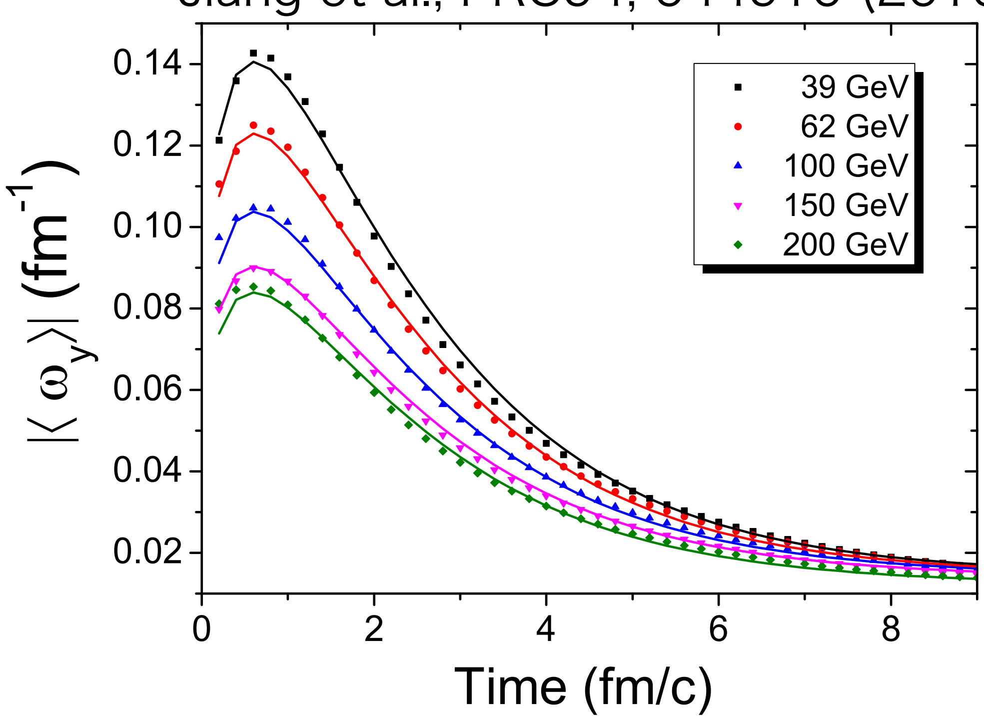
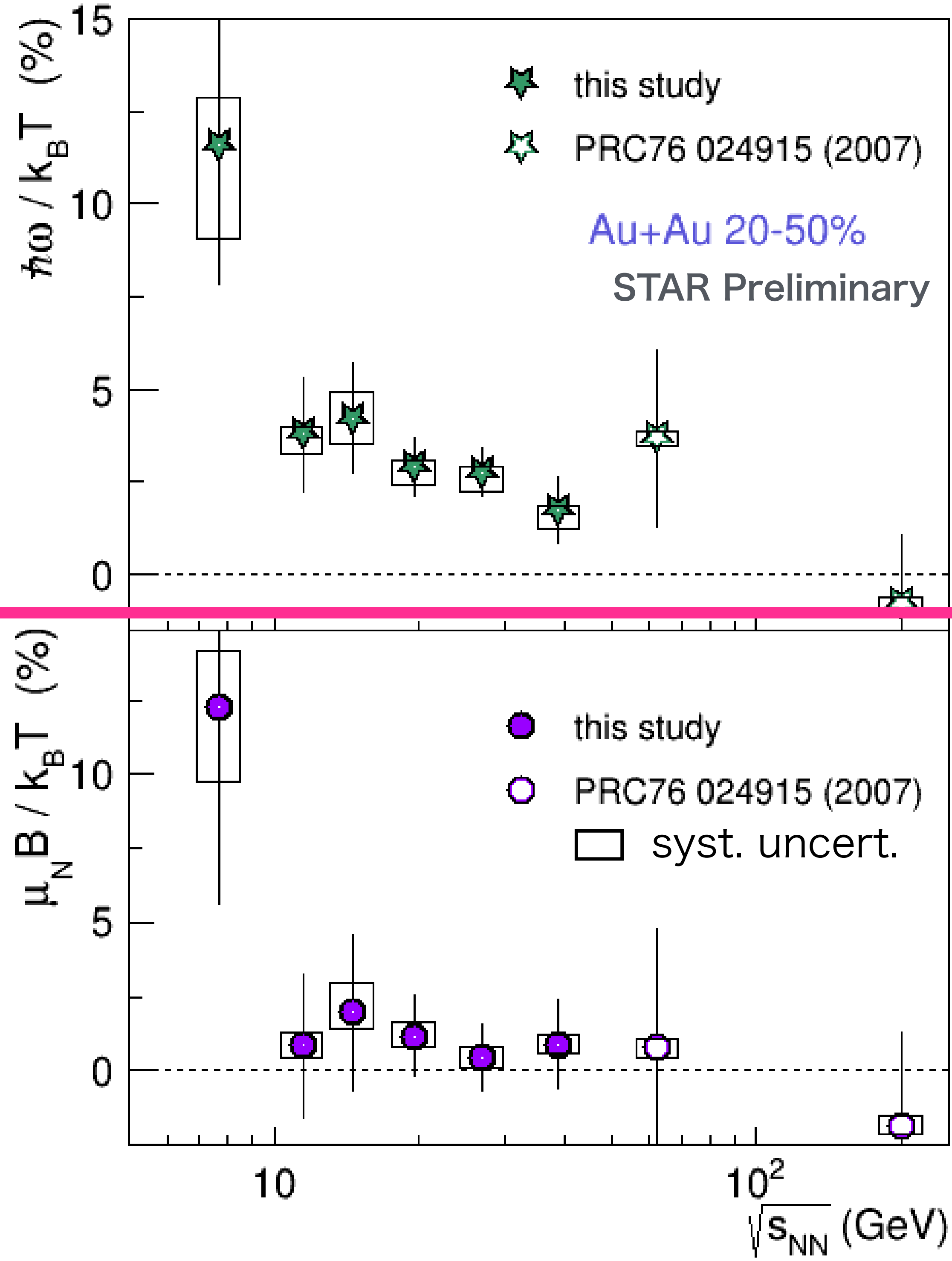


FIG. 12. Averaged vorticity $\langle \omega_y \rangle$ from the AMPT model as a function of time at varied beam energy $\sqrt{s_{NN}}$ for fixed impact parameter $b = 7$ fm. The solid curves are from a fitting formula (see text for details).

Extracted magnetic field



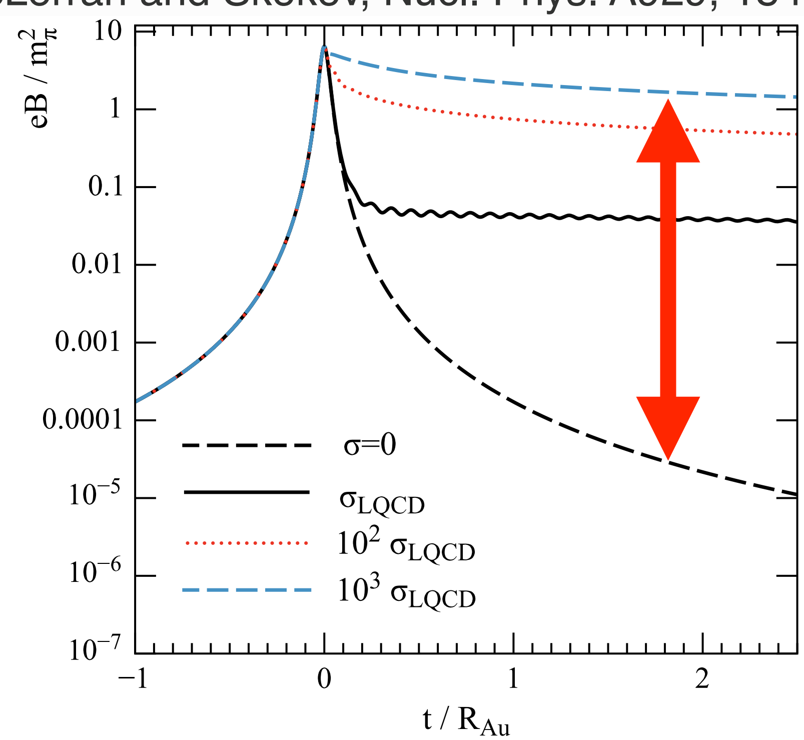
- Magnetic field

$$B = (P_\Lambda - P_{\bar{\Lambda}}) k_B T / \mu_{\rm N}$$

$$\sim 5.0 \times 10^{13} \text{ [Tesla]} \quad \text{(for T=160 MeV)}$$

  - Though the data are consistent with zero, this could be a possible direct probe of B-field

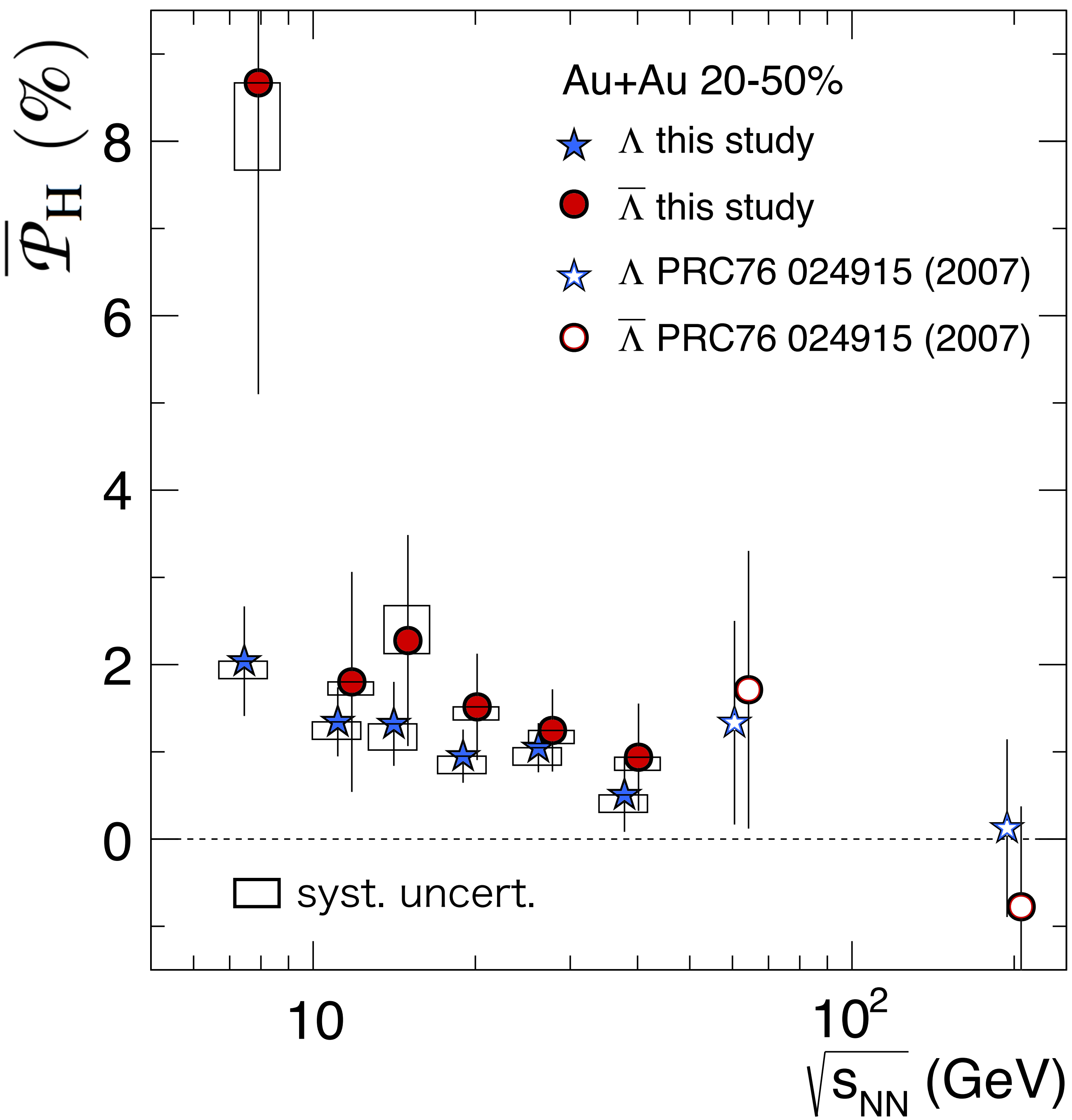
McLerran and Skokov, Nucl. Phys. A929, 184 (2014)



Lifetime of B-field is unknown.
Important for theoretical prediction of CME.

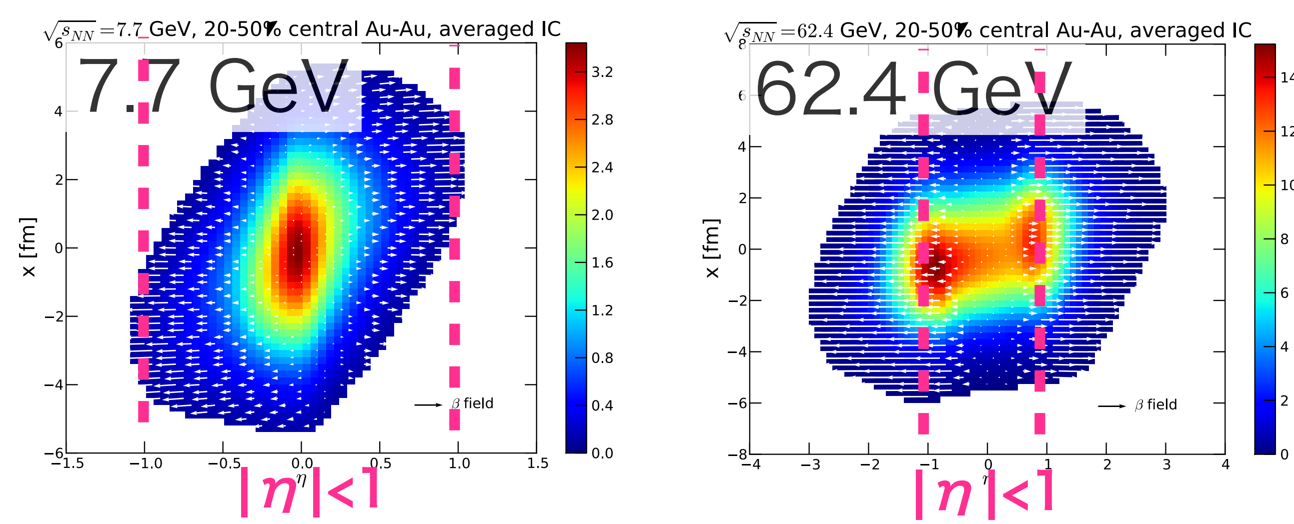
Λ global polarization vs $\sqrt{s_{NN}}$

STAR, Nature 548.62 (2017)



- Positive signals in $\sqrt{s_{NN}}$=7.7-62.4 GeV
  - indication of thermal vorticity!
- Why smaller signal in higher energy?
  - Initial angular momentum is largest at high energy, but…

Karpenko and Becattini, EPJC(2017)77:213



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

Feed-down effect

- Only ~25% of measured Λ and anti-Λ are primary, while ~60% are feed-down from $\Sigma^* \to \Lambda\pi$, $\Sigma^0 \to \Lambda\gamma$, $\Xi \to \Lambda\pi$
- Polarization of parent particle R is transferred to its daughter Λ

$$\mathbf{S}^*_\Lambda = C\mathbf{S}^*_R \qquad \langle S_y \rangle \propto \frac{S(S+1)}{3}\omega$$

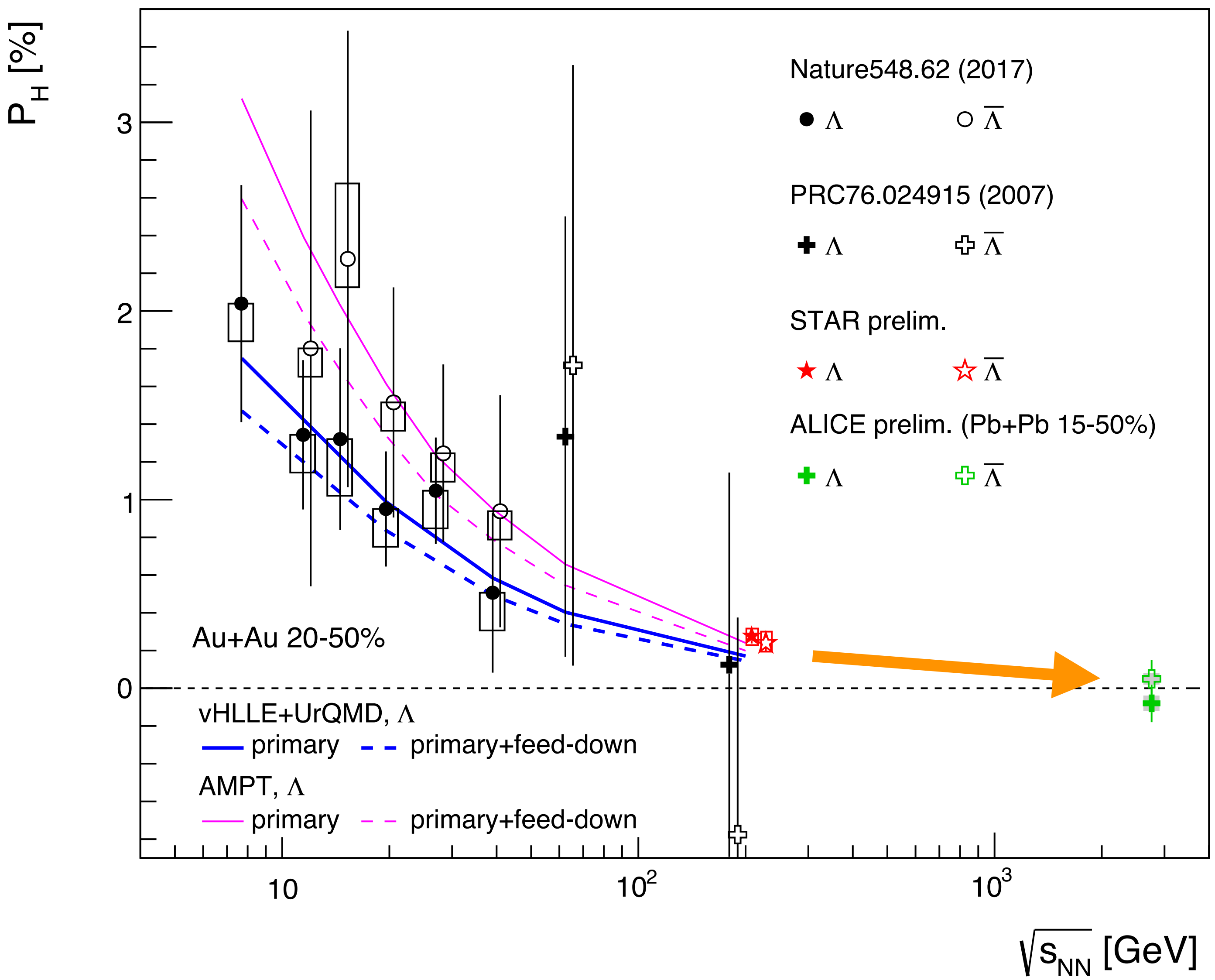
$$\begin{pmatrix} \varpi_c \\ \\ B_c/T \end{pmatrix} = \begin{bmatrix} \frac{2}{3}\sum\limits_R \left(f_{\Lambda R}C_{\Lambda R} - \frac{1}{3}f_{\Sigma^0 R}C_{\Sigma^0 R}\right)\, S_R(S_R+1) & \frac{2}{3}\sum\limits_R \left(f_{\Lambda R}C_{\Lambda R} - \frac{1}{3}f_{\Sigma^0 R}C_{\Sigma^0 R}\right)\,(S_R+1)\,\mu_R \\ \frac{2}{3}\sum\limits_{\overline{R}} \left(f_{\overline{\Lambda R}}C_{\overline{\Lambda R}} - \frac{1}{3}f_{\overline{\Sigma^0}\overline{R}}C_{\overline{\Sigma^0}\overline{R}}\right)\, S_{\overline{R}}(S_{\overline{R}}+1) & \frac{2}{3}\sum\limits_{\overline{R}} \left(f_{\overline{\Lambda R}}C_{\overline{\Lambda R}} - \frac{1}{3}f_{\overline{\Sigma^0}\overline{R}}C_{\overline{\Sigma^0}\overline{R}}\right)\,(S_{\overline{R}}+1)\,\mu_{\overline{R}} \end{bmatrix}^{-1} \begin{pmatrix} P^{\text{meas}}_\Lambda \\ \\ P^{\text{meas}}_{\overline{\Lambda}} \end{pmatrix}$$

$f_{\Lambda R}$: 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

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

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

Go to the LHC energy



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

$$P_H(\Lambda)[\%] = -0.08 \pm 0.10\ (\mathrm{stat}) \pm 0.04\ (\mathrm{syst})$$
$$P_H(\bar{\Lambda})[\%] = \quad 0.05 \pm 0.10\ (\mathrm{stat}) \pm 0.03\ (\mathrm{syst})$$

ALICE preliminary
M. Konyushikhin, QCD Chirality Workshop 2017

- Need at least ~50 times larger statistics for meaningful results

vHLLE+UrQMD: Y. Karpenko and F. Becattini, EPJC(2017)77:213
AMPT: H. Li et al., Phys. Rev. C 96, 054908 (2017)