Vorticity and polarization of hyperons in heavy-ion collisions

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Outline

- Introduction
  - Vorticity in heavy-ion collisions
  - Polarization measurement with hyperons
- Global polarization

  STAR: Nature 548, 62 (2017), PRC98, 014910 (2018), arXiv:2012.13601
- Local polarization

  STAR, PRL123.13201 (2019)
- Summary and Outlook

Important features in non-central heavy-ion collisions

Strong magnetic field

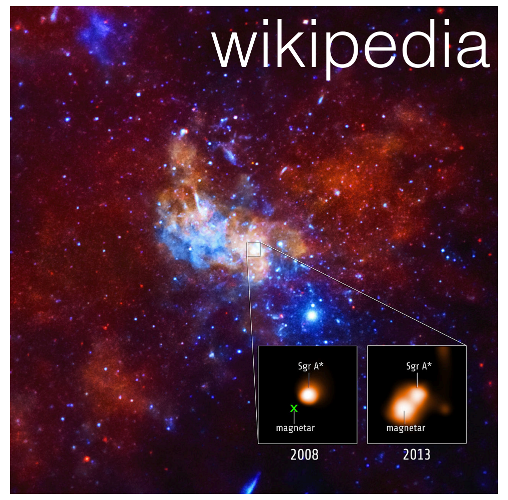
$$B \sim 10^{13}\ \mathrm{T}$$

$$(eB \sim m_\pi^2\ (\tau \sim 0.2\ \mathrm{fm}))$$

D. Kharzeev, L. McLerran, and H. Warringa, Nucl.Phys.A803, 227 (2008)
McLerran and Skokov, Nucl. Phys. A929, 184 (2014)

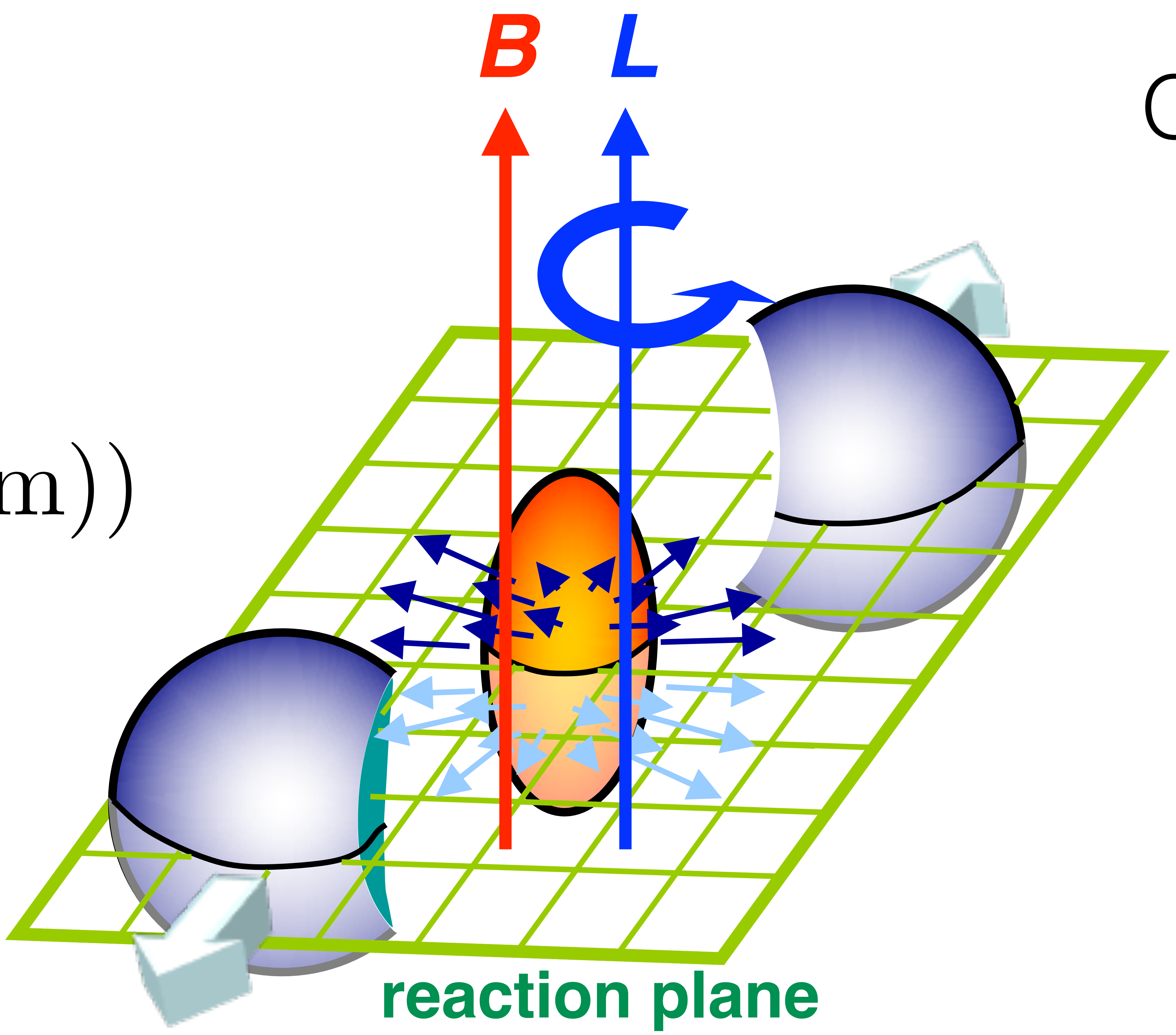
typical magnet

$B \sim 0.1 - 0.5\ \mathrm{T}$



magnetar

$B \sim 10^{11}\ \mathrm{T}$



Orbital angular momentum

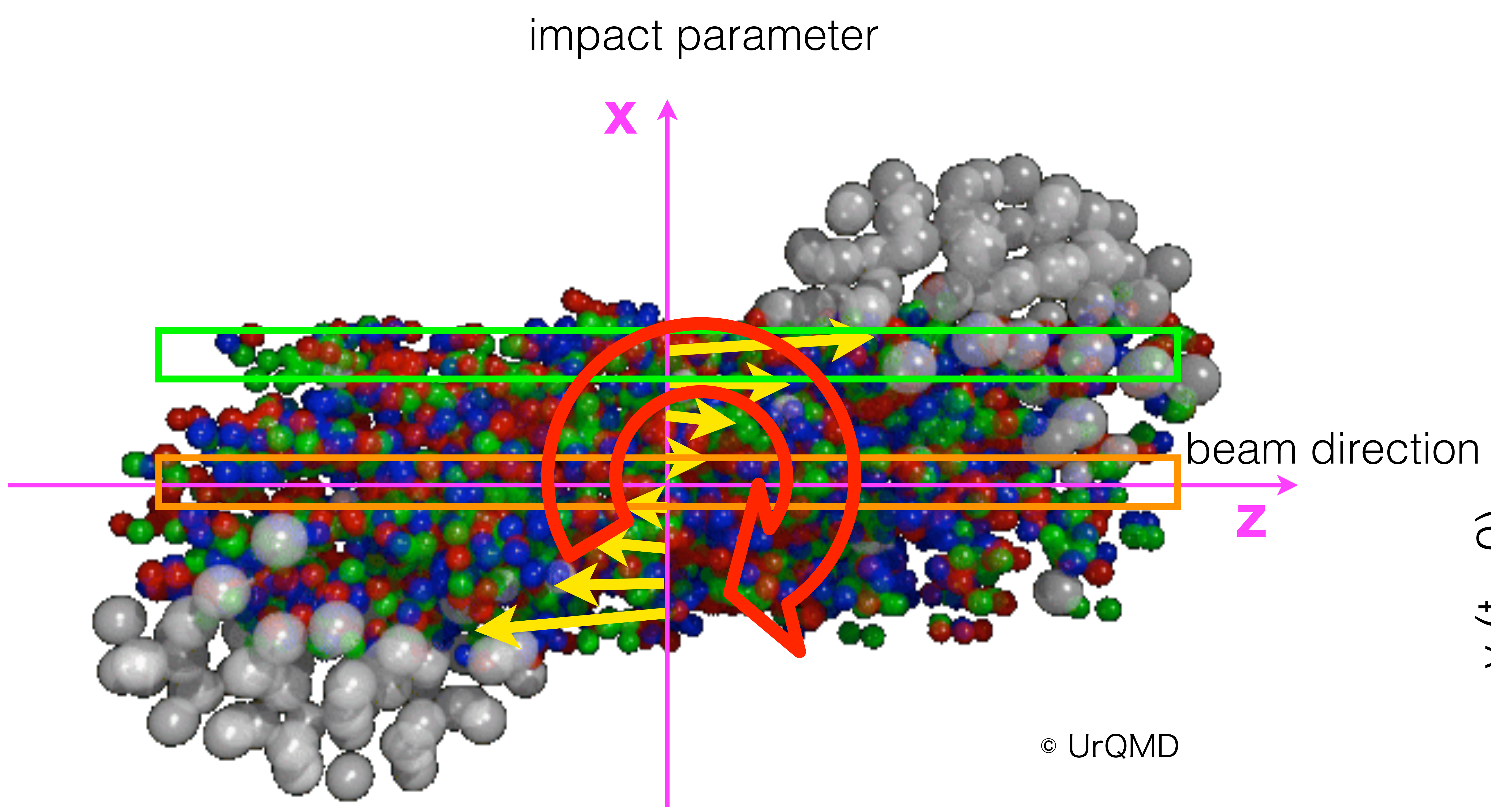
$$\mathbf{L} = \mathbf{r} \times \mathbf{p}$$

$$\sim bA\sqrt{s_{NN}} \sim 10^6\hbar$$

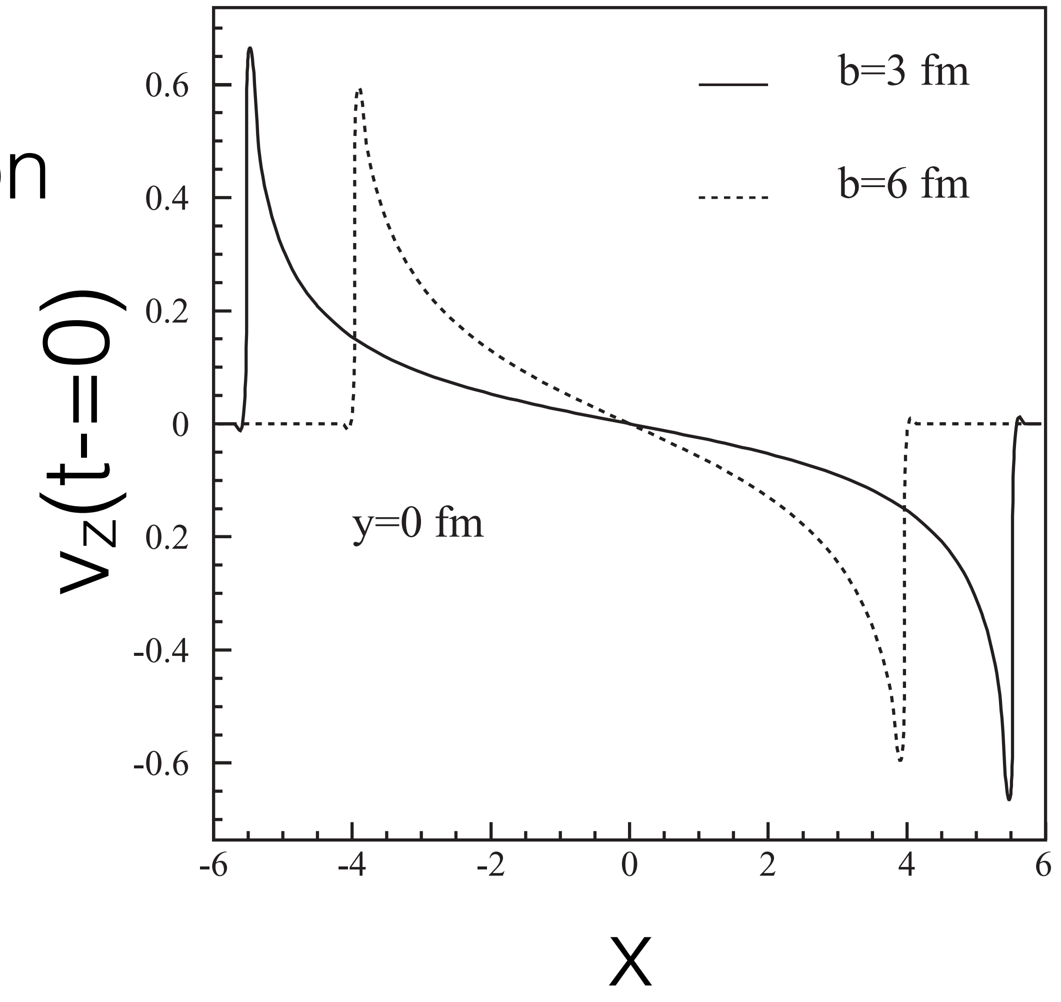
Z.-T. Liang and X.-N. Wang, PRL94, 102301 (2005)

→Chiral magnetic/vortical effects
→**Particle polarization**

Vorticity in HIC



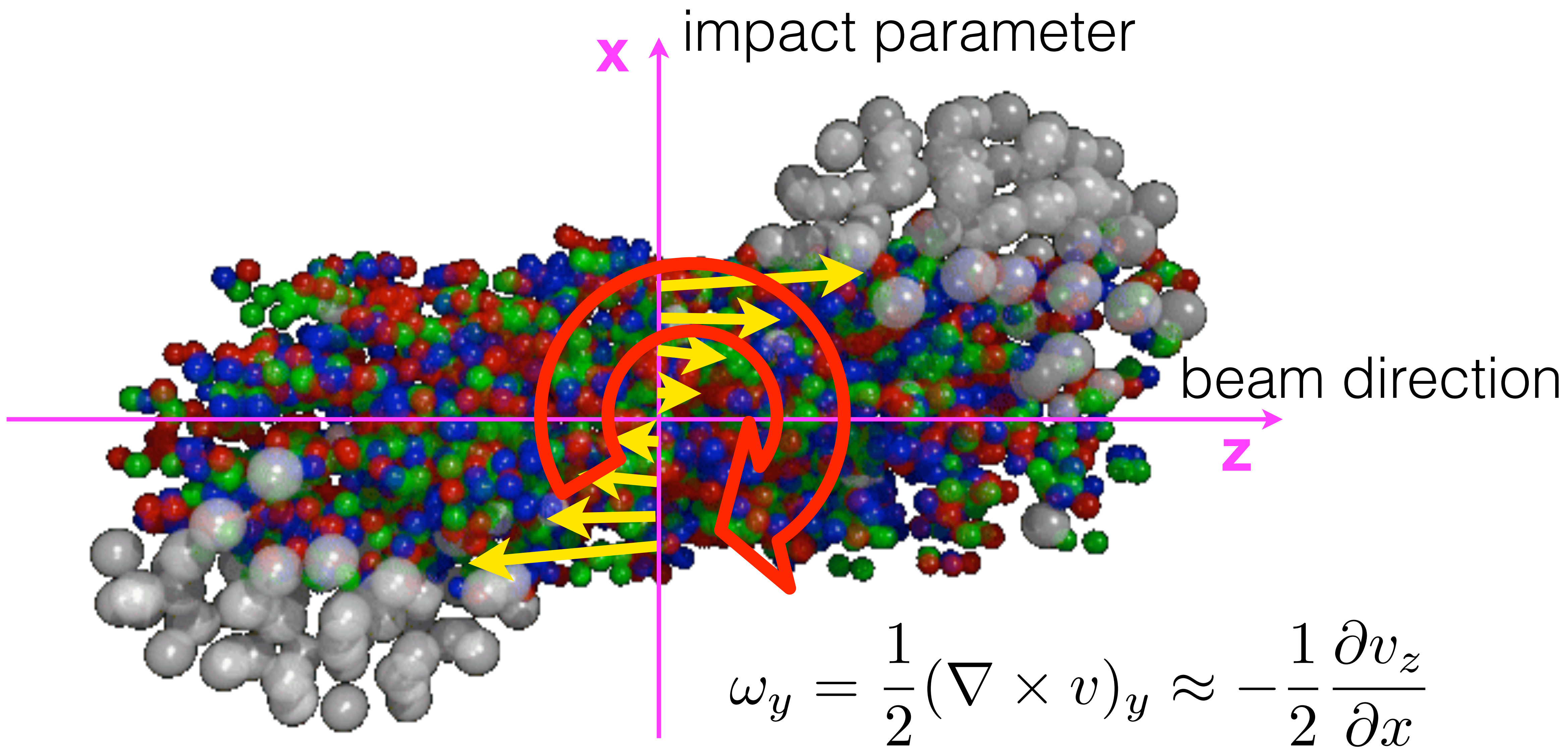
Becattini et al.,
PRC77, 024906 (2008)



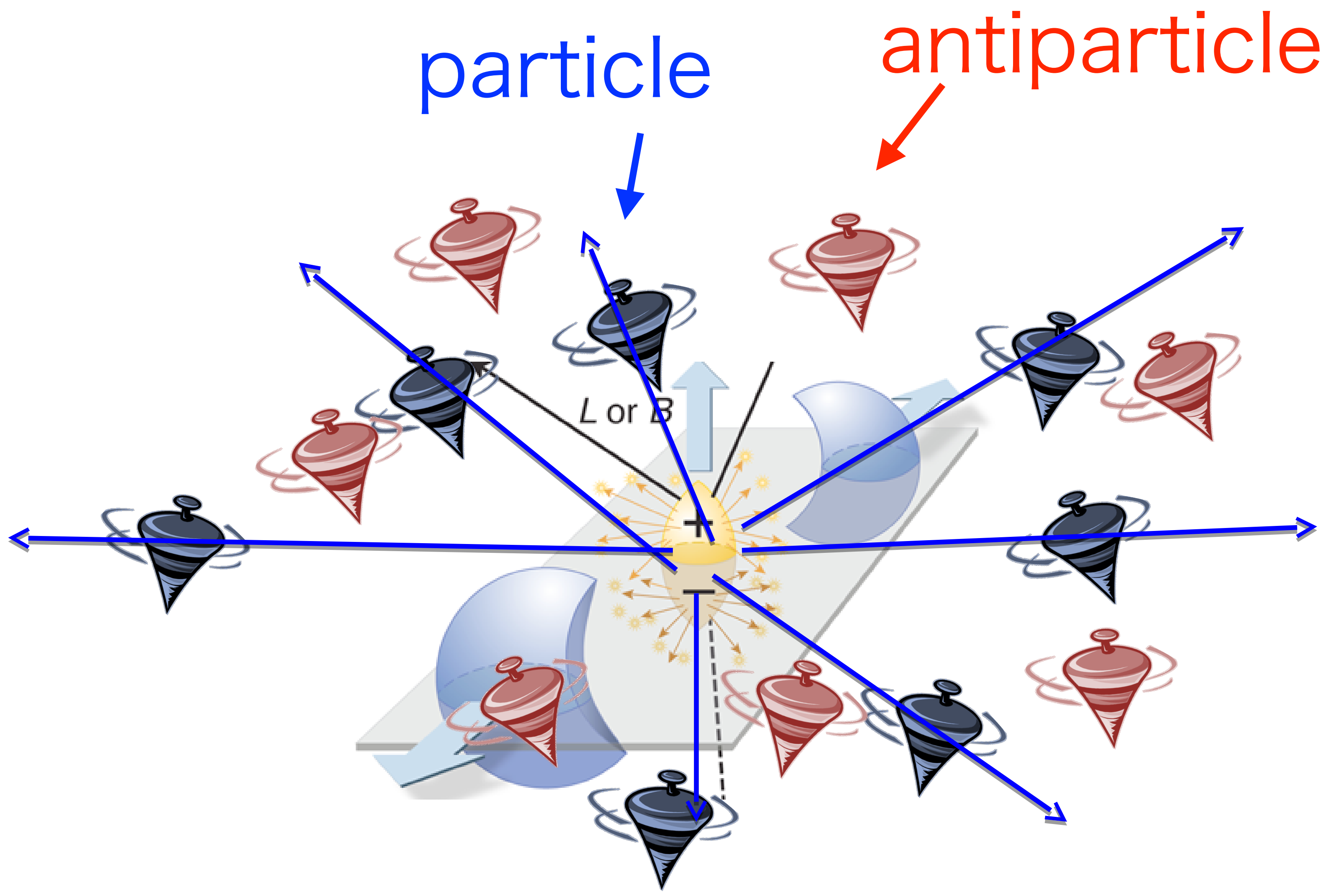
In non-central collisions,
the initial collective longitudinal flow velocity depends on x.

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

Global polarization



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



Z.-T. Liang and X.-N. Wang, PRL94, 102301 (2005)
S. Voloshin, nucl-th/0410089 (2004)

- Orbital angular momentum is transferred to particle spin
  - Particles' and anti-particles' spins are aligned along angular momentum, ***L***
- Magnetic field align particle's spin
  - Particles' and antiparticles' spins are aligned in opposite direction along ***B*** due to the opposite sign of magnetic moment

Produced particles will be "globally" polarized along ***L*** or ***B***.
B might be studied by particle-antiparticle difference.

Rotation vs. Polarization

Barnett effect:

rotation→polarization

Magnetization of an uncharged body when spun on its axis S. Barnett, Phys. Rev. 6, 239 (1915)

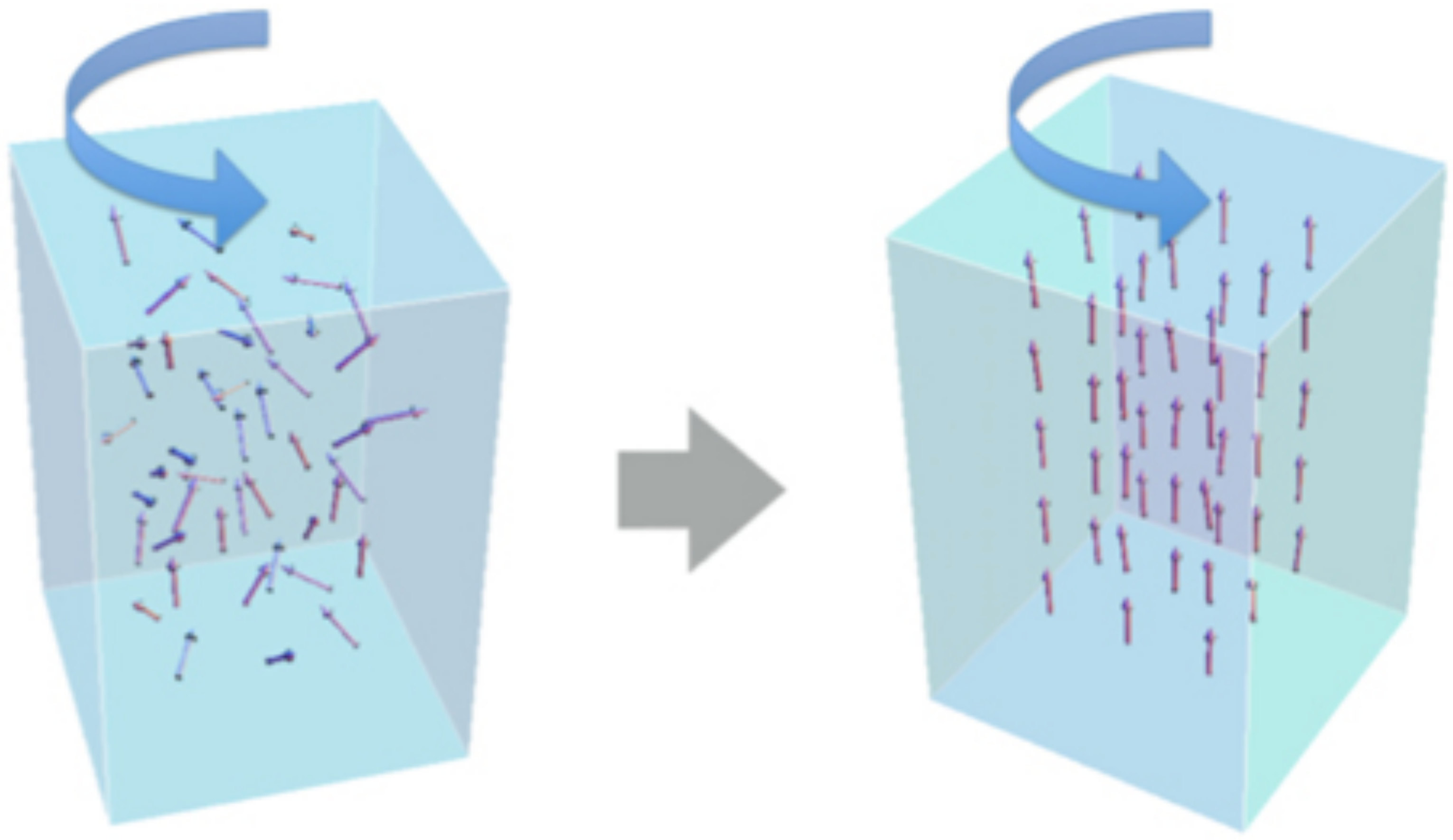


figure: M. Matsuo et al., Front. Phys., 30 (2015)

$$M = \frac{\chi\omega}{\gamma}$$

χ: magnetic susceptibility
γ: gyromagnetic ratio

Einstein-de-Haas effect:

polarization→rotation

Rotation of a ferromagnet under change in the direction/strength of magnetic-field to conserve the total angular momentum.

$$\vec{J} = \vec{L} + \vec{S}$$

A.Einstein, W. J. de Haas,
B.Koninklijke Akademie van Wetenschappen te Amsterdam,
C.Proceedings, 18 I, 696-711 (1915)

"the only experiment by Einstein"

How to measure the polarization?

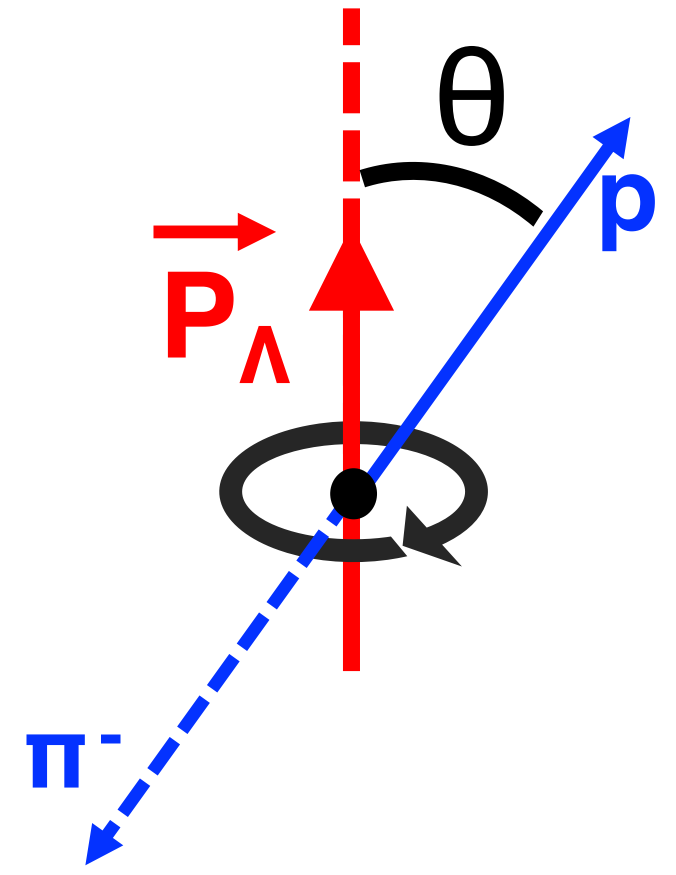
Parity-violating weak decay of hyperons (“self-analyzing”)

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

(BR: 63.9%, $c\tau$ ~7.9 cm)

Daughter baryon is preferentially emitted in the direction of hyperon’s spin (opposite for anti-particle)

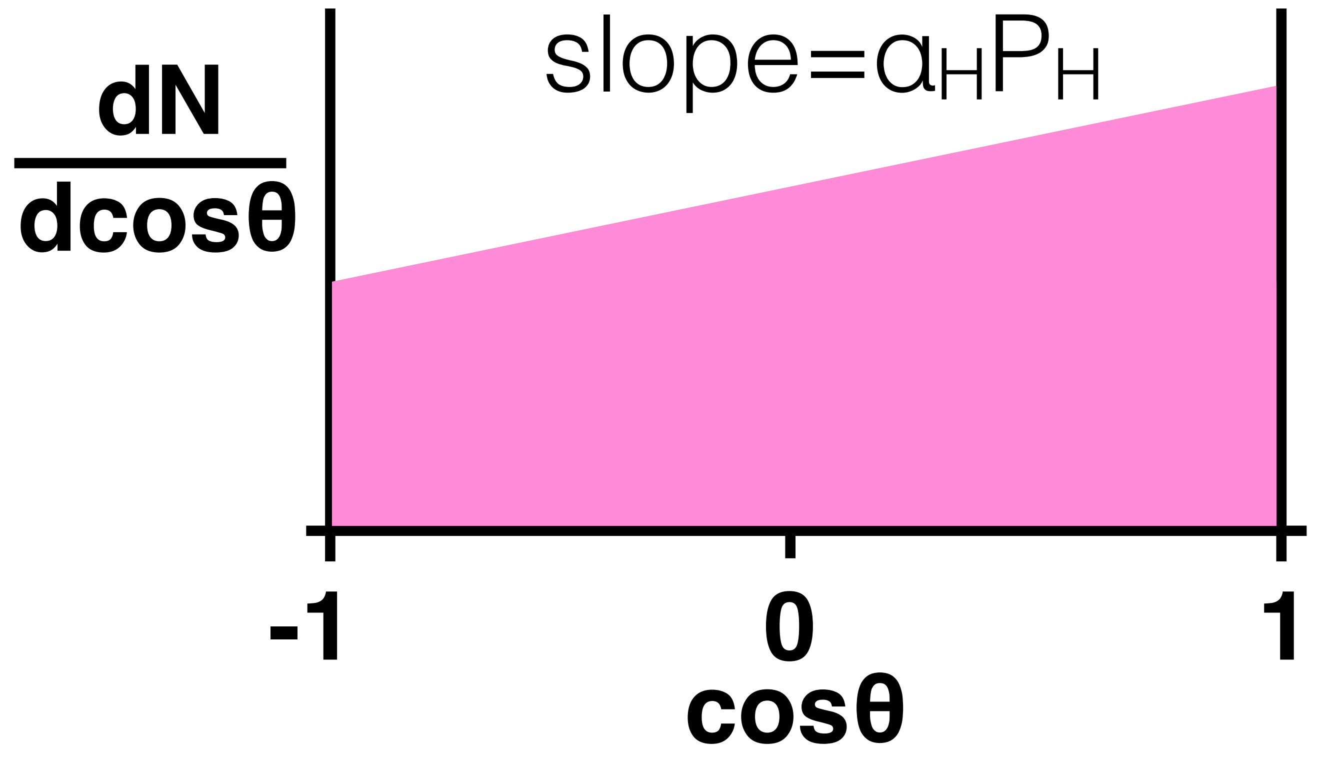
$$\frac{dN}{d\cos\theta^*} \propto 1 + \alpha_H \mathrm{P_H} \cos\theta^*$$



$\mathrm{P_H}$: hyperon polarization

θ^*: polar angle of daughter relative to the polarization direction in hyperon rest frame

α_H: hyperon decay parameter



Note: α_H for Λ recently updated (based on BESIII and CLAS)

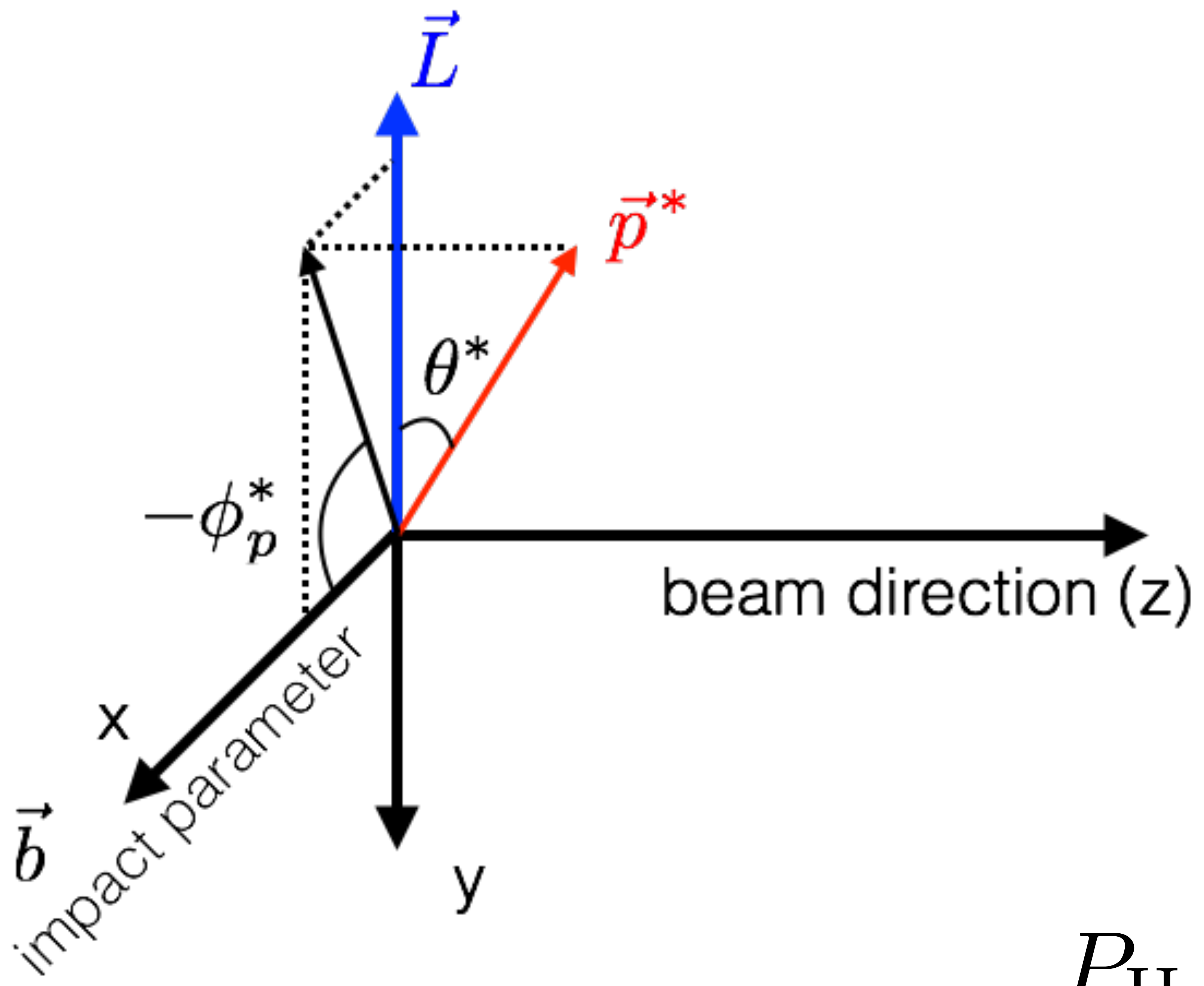
α_Λ=0.642±0.013 → α_Λ=0.732±0.014 P.A. Zyla et al. (PDG), PTEP2020.083C01

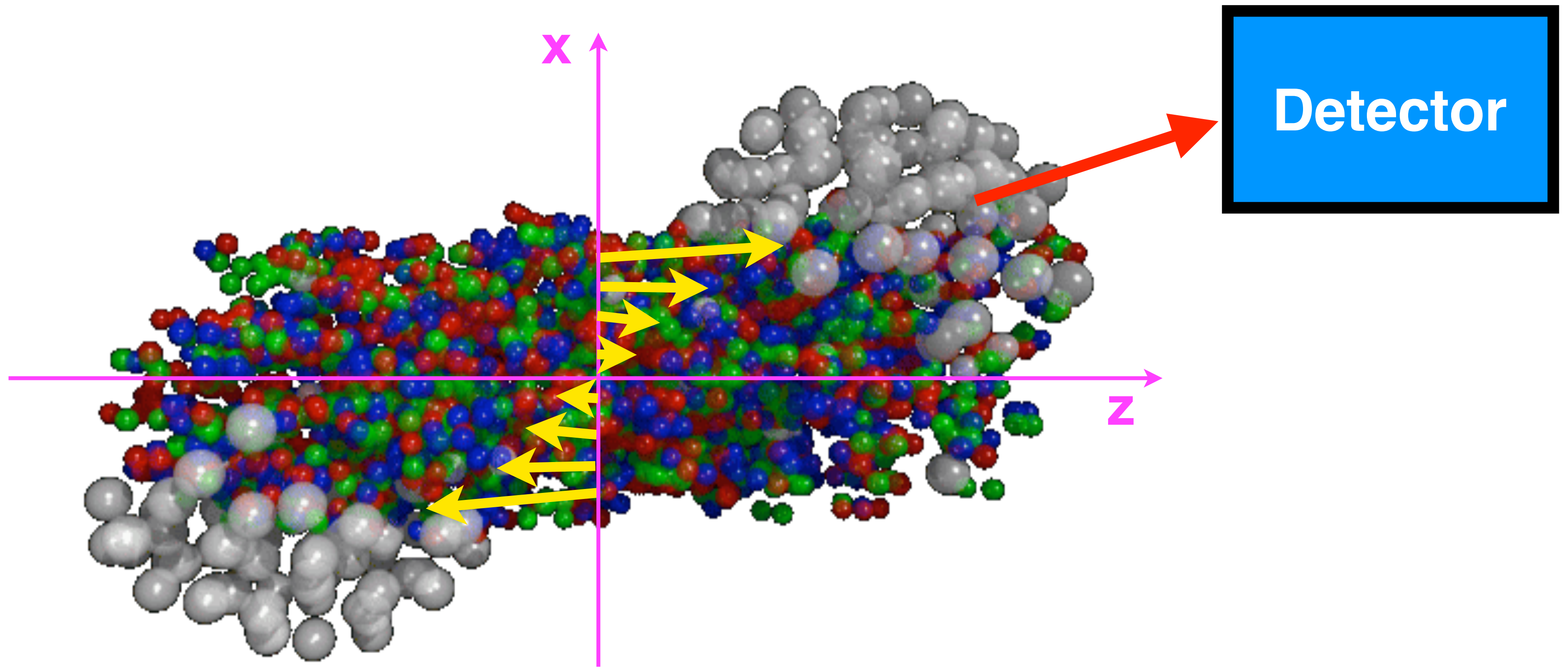
* Published results are based on old parameter. They are scaled by $\alpha_{old}/\alpha_{new}$ when comparing to new results.

How to measure the "global" polarization?

"global" polarization : spin alignment along the initial angular momentum

Projection onto the transverse plane





Angular momentum direction can be determined by spectator deflection (spectators deflect outwards)

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

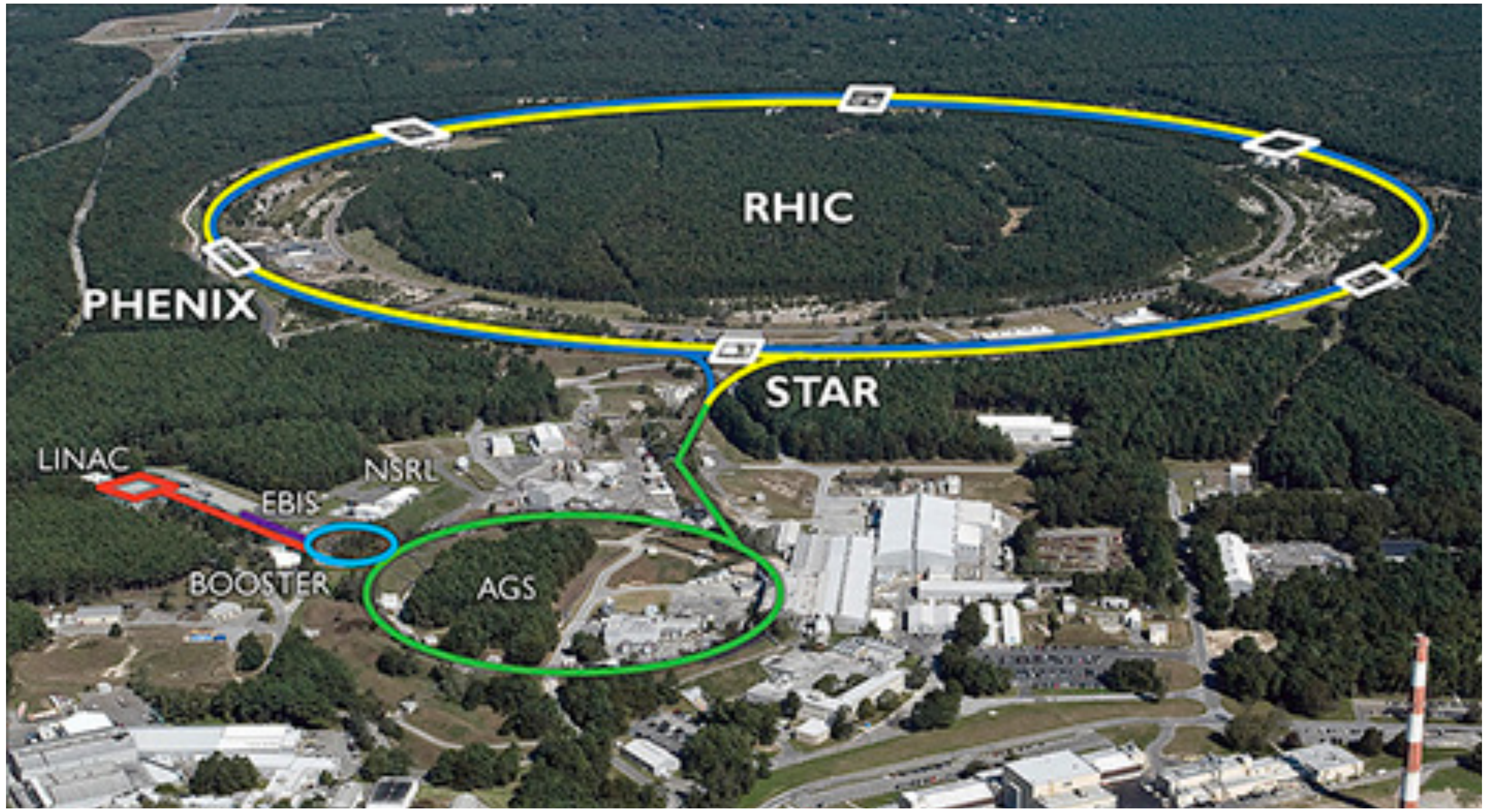
$$P_{\rm H} = \frac{8}{\pi \alpha_{\rm H}} \frac{\langle \sin(\Psi_1 - \phi_p^*) \rangle}{{\rm Res}(\Psi_1)}$$

Ψ_1: azimuthal angle of b

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

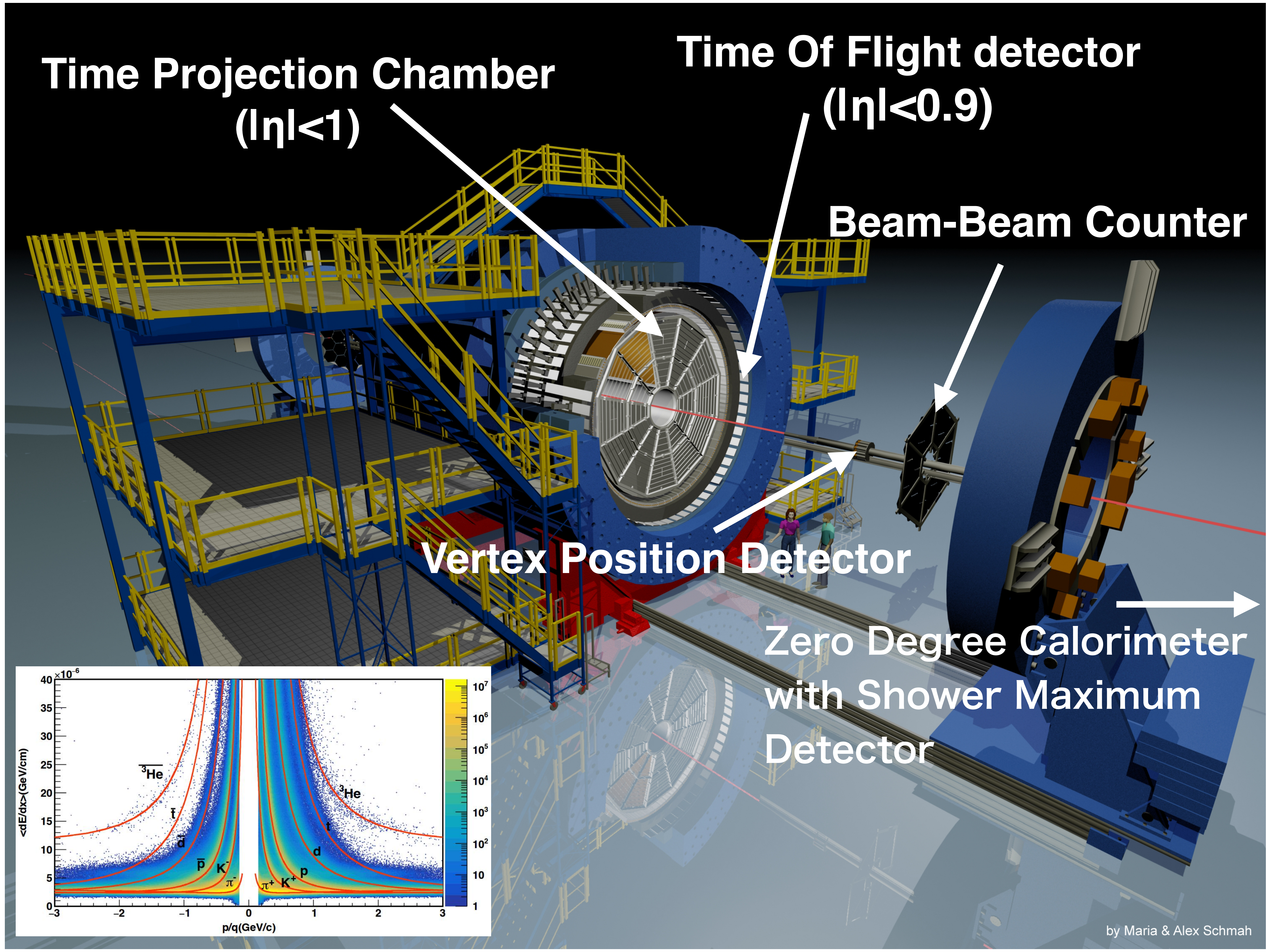
STAR, PRC76, 024915 (2007)

RHIC-STAR experiment



Relativistic Heavy Ion Collider (RHIC)

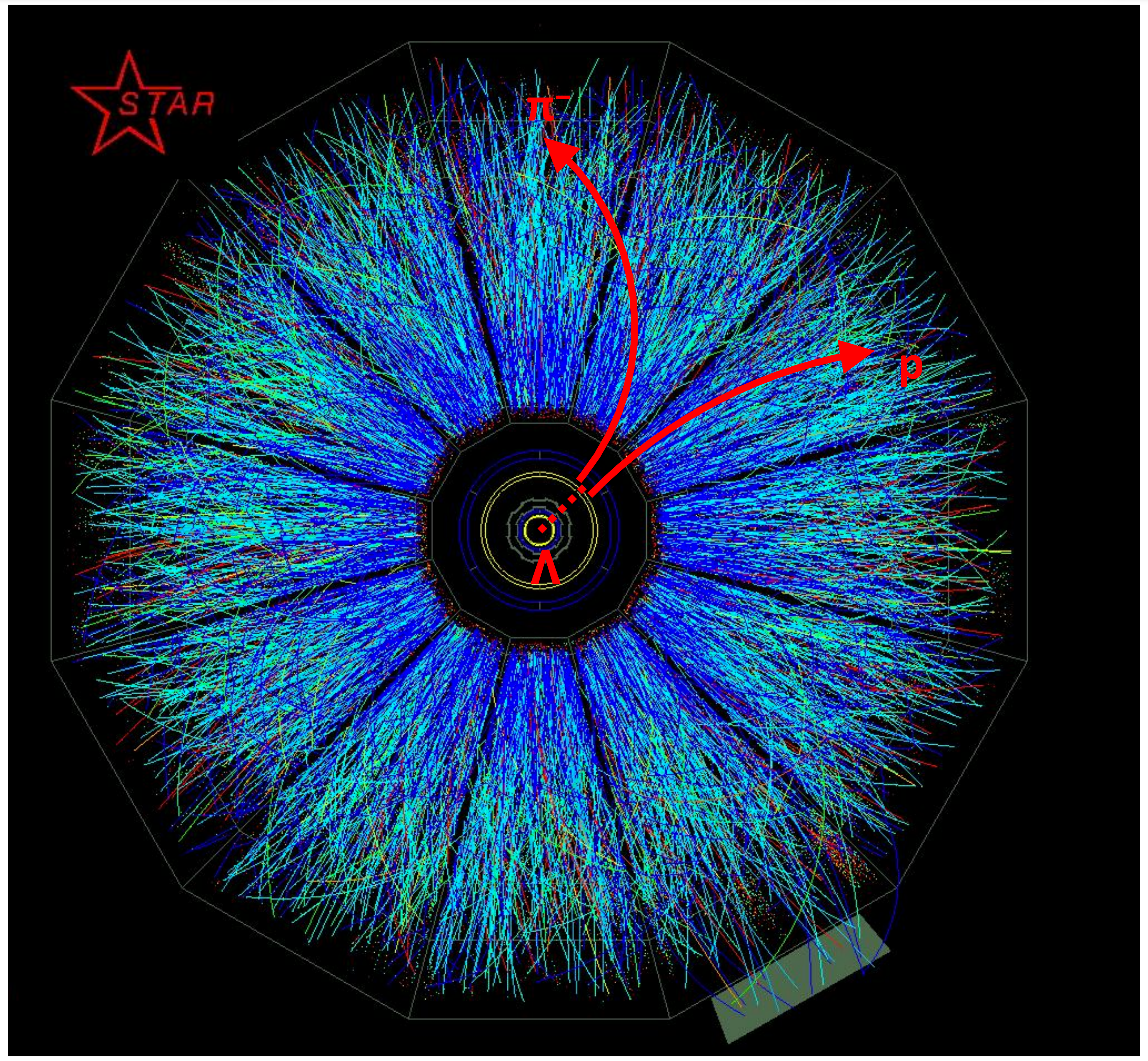
- in Brookhaven National Lab. (NY, USA)
- 3.8 km in circumference
- $\sqrt{s_{NN}}$ = 7.7-200 GeV for A+A
 species: p+p, p(d)+Au, He+Au, Cu+Cu, Cu+Au, A+Au…



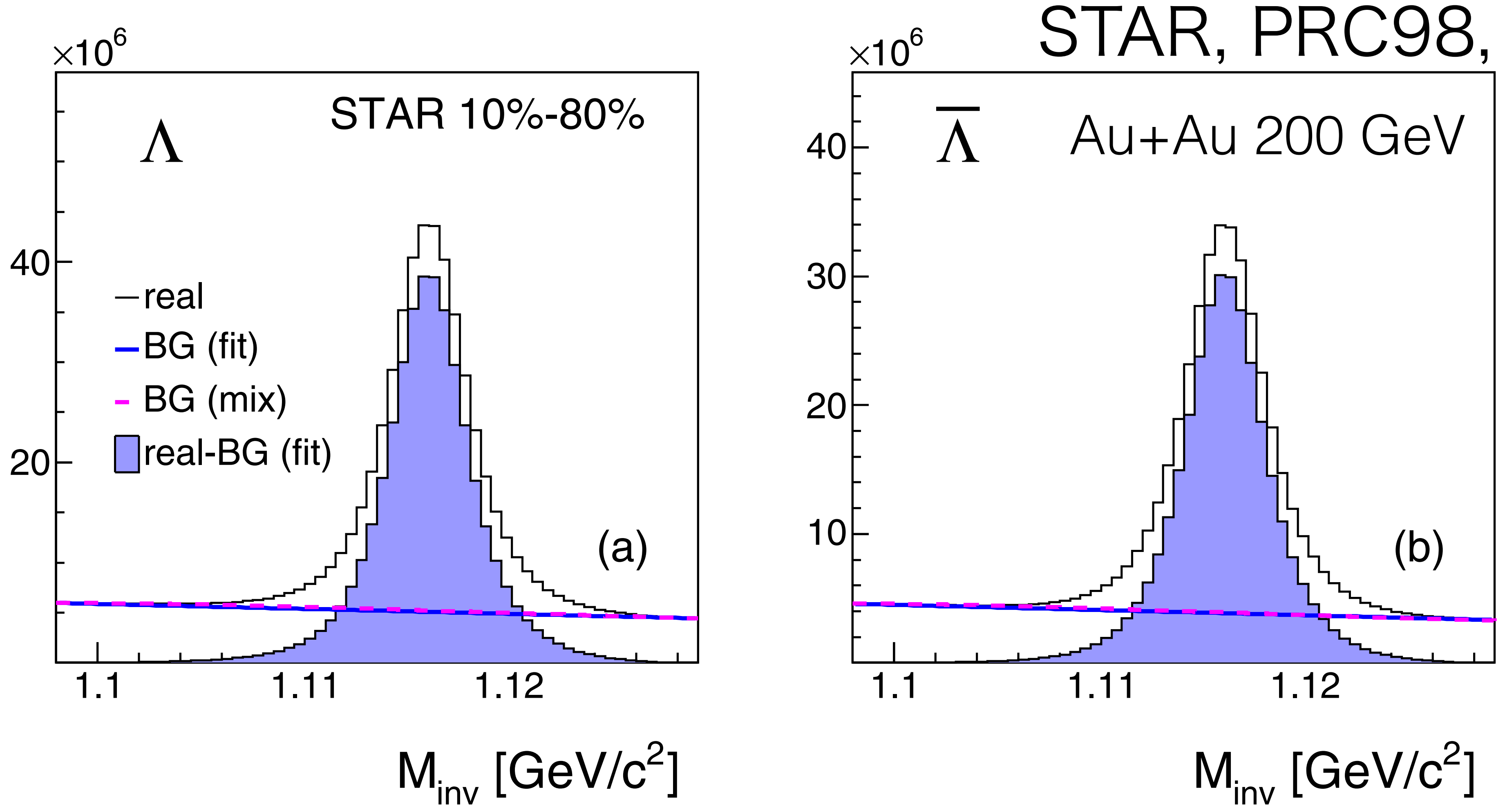
Solenoidal Tracker At RHIC (STAR)

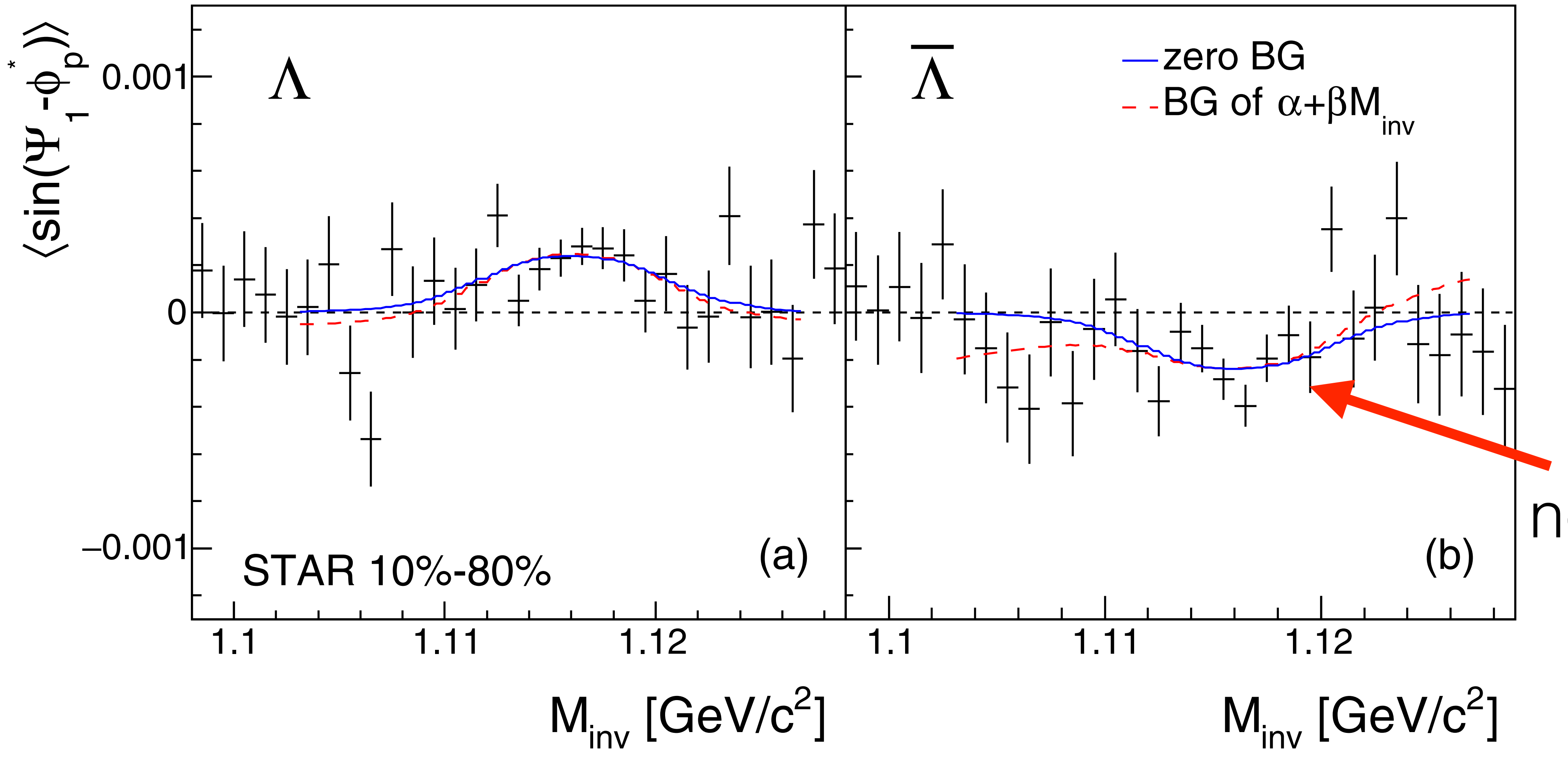
- Full azimuth and wide rapidity coverage
- Excellent particle identification

Signal extraction with Λ hyperons



STAR, PRC98, 014910 (2018)





negative for anti-Λ

$$\alpha_H = -\alpha_{\bar{H}}$$

$$P_{\mathrm{H}} = \frac{8}{\pi\alpha_{\mathrm{H}}} \frac{\langle \sin(\Psi_1 - \phi_p^*)\rangle}{\mathrm{Res}(\Psi_1)}$$

Two methods used to extract the sine F.C.

1. Invariant mass method
2. Bin-counting method

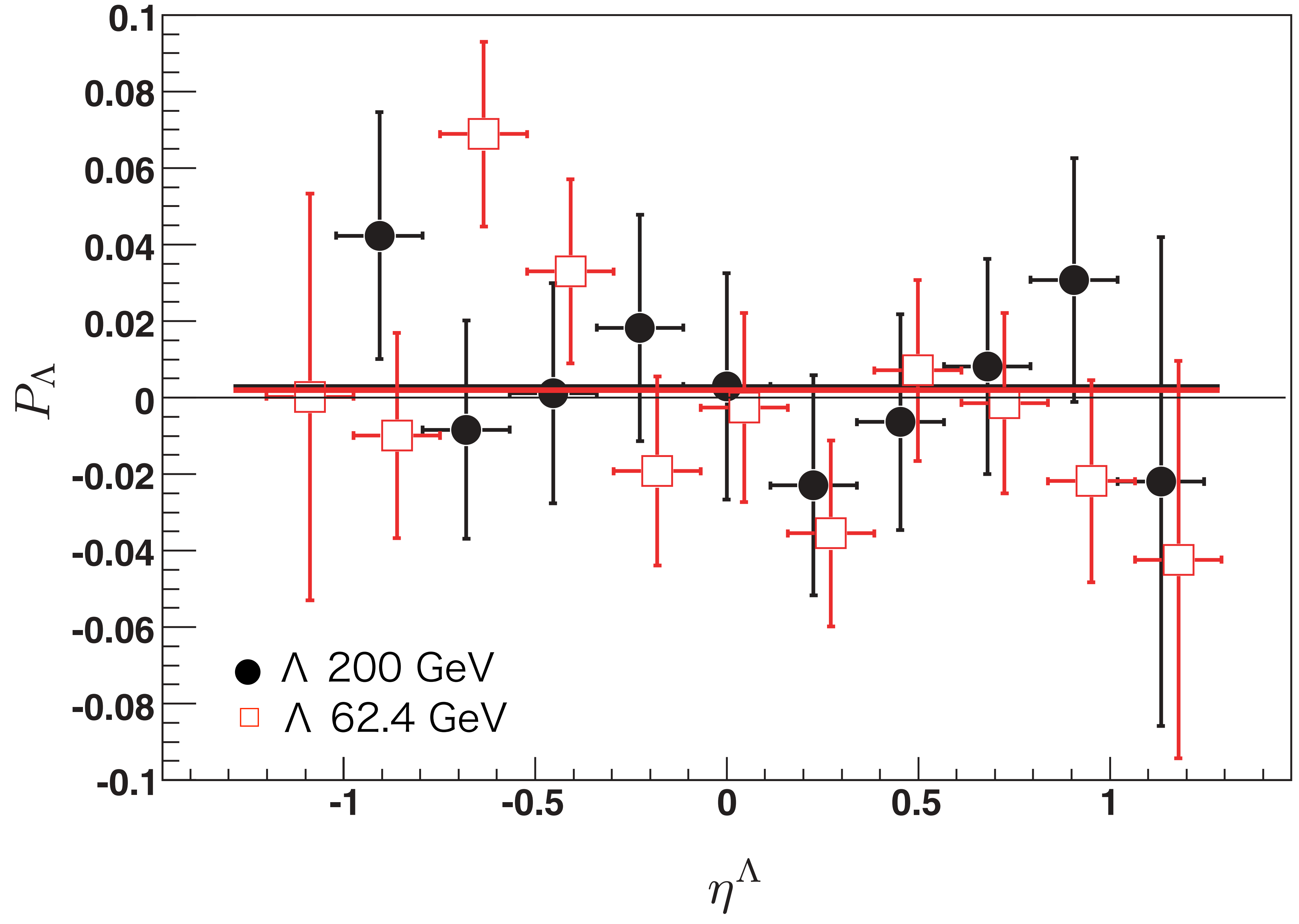
(both give us consistent results)

$$\langle \sin(\Psi_1 - \phi_p^*)\rangle^{\mathrm{obs}} = (1 - f^{\mathrm{Bg}}(M_{\mathrm{inv}}))\langle \sin(\Psi_1 - \phi_p^*)\rangle^{\mathrm{Sg}} + f^{\mathrm{Bg}}(M_{\mathrm{inv}})\langle \sin(\Psi_1 - \phi_p^*)\rangle^{\mathrm{Bg}},$$

First paper from STAR in 2007

PHYSICAL REVIEW C **76**, 024915 (2007)

Global polarization measurement in Au+Au collisions



Au+Au collisions at $\sqrt{s_{NN}}$ = 62.4 and 200 GeV in 2004 with very limited statistics (~9M events)

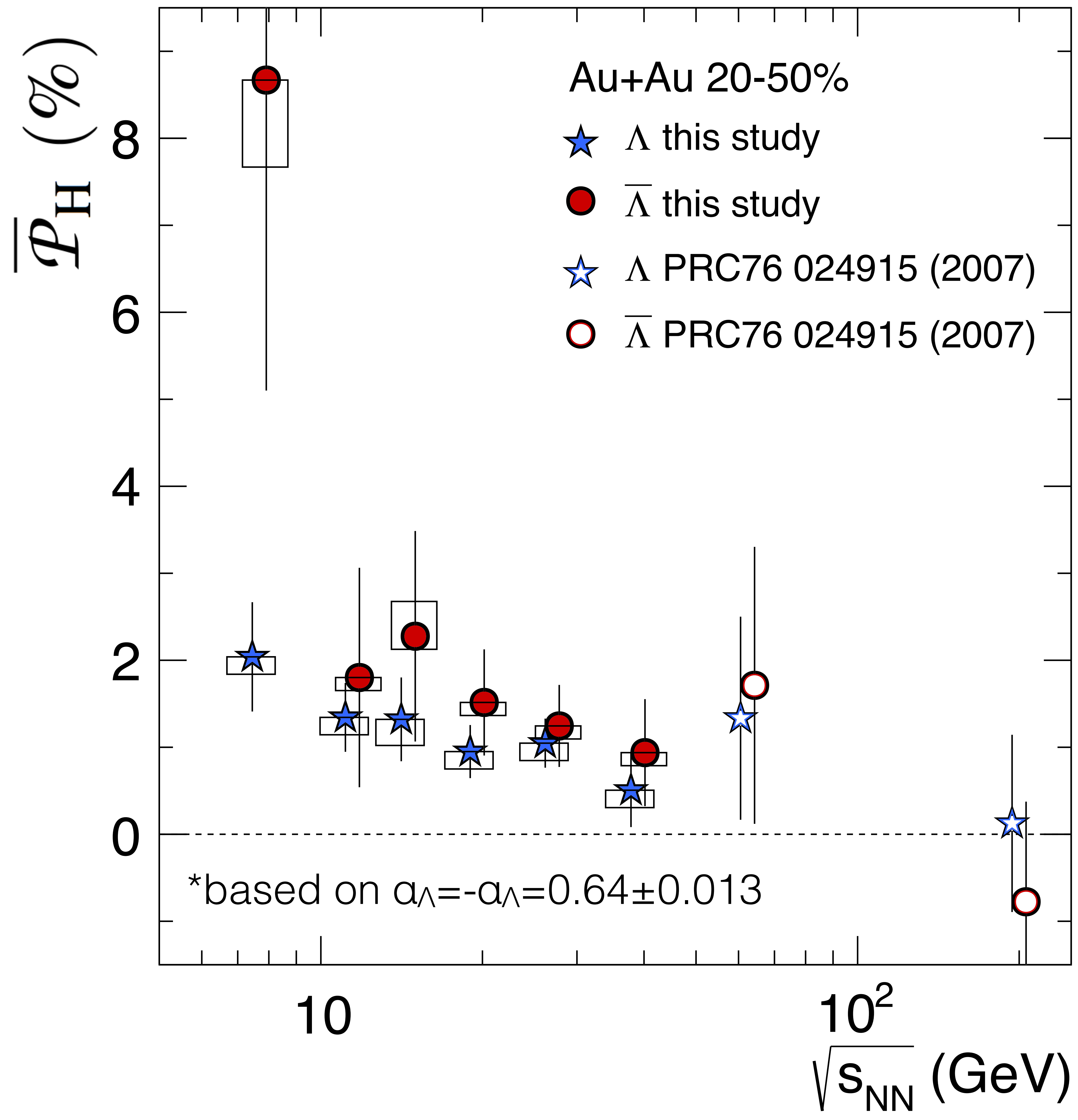
III. CONCLUSION

The Λ and $\bar{\Lambda}$ hyperon global polarization has been measured in Au+Au collisions at center-of-mass energies $\sqrt{s_{NN}} = 62.4$ and 200 GeV with the STAR detector at RHIC. An upper limit of $|P_{\Lambda,\bar{\Lambda}}| \leqslant 0.02$ for the global polarization of Λ and $\bar{\Lambda}$ hyperons within the STAR detector acceptance is

Results were consistent with zero…, giving an upper limit of P_H<2%

First observation in lower energies (2017)

STAR, Nature 548, 62 (2017)



Positive polarization signal at lower energies!

- P_H looks to increase in lower energies

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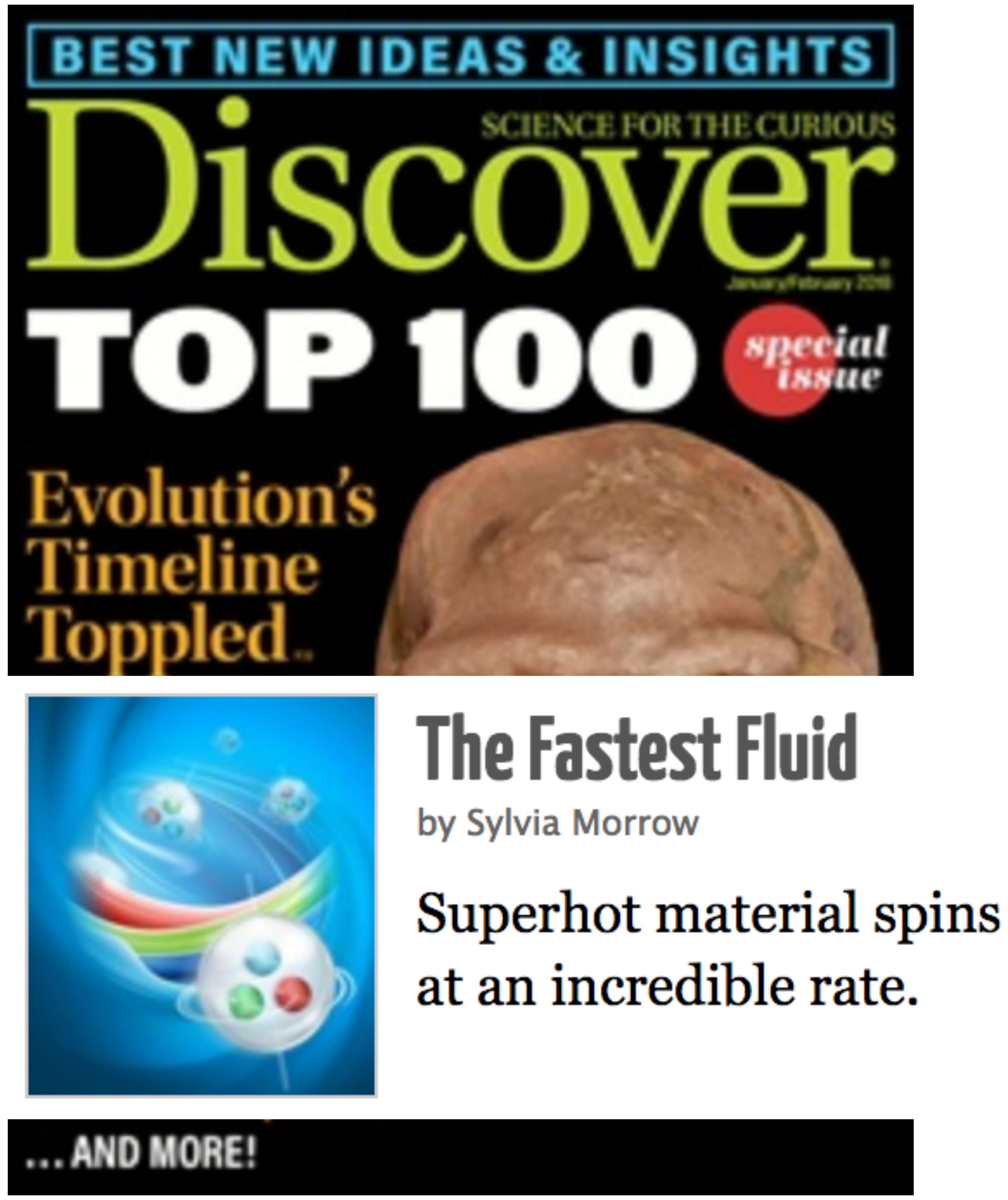
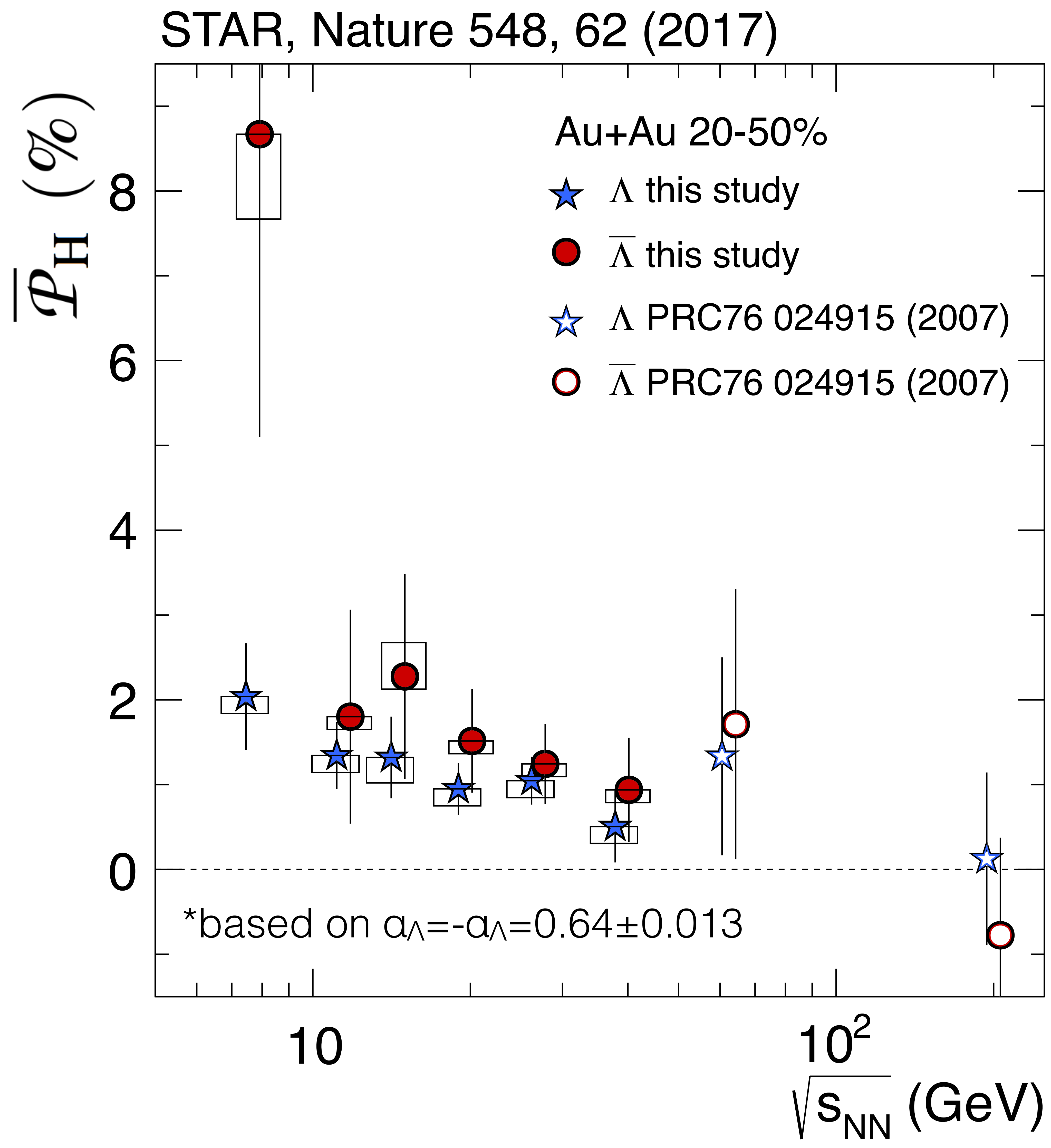


First observation in lower energies (2017)



Positive polarization signal at lower energies!

- P_H looks to increase in lower energies

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

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

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

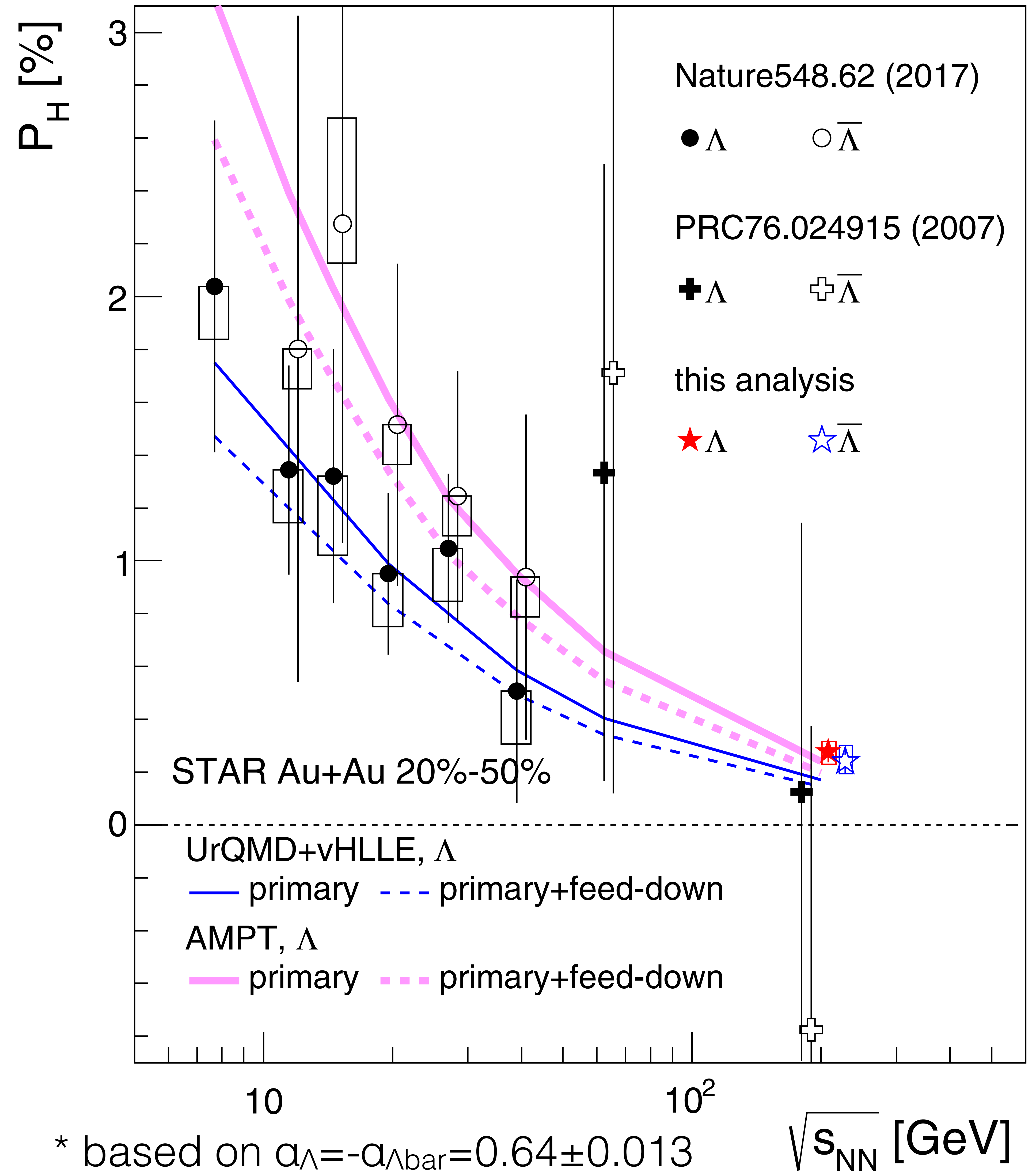
μ_{Λ}: Λ magnetic moment
T: temperature at thermal equilibrium
(T=160 MeV)

- The most vortical fluid!

Hint of the difference between Λ and anti-Λ P_H
- Effect of the initial magnetic field? (discussed later)

Precise measurements at $\sqrt{s_{NN}}$ = 200 GeV

STAR, PRC98, 014910 (2018)



* based on $\alpha_\Lambda = -\alpha_{\Lambda bar} = 0.64 \pm 0.013$

Confirmed energy dependence with new results at 200 GeV

- >5σ significance utilizing 1.5B events
- partly due to stronger shear flow structure at lower $\sqrt{s_{NN}}$ because of baryon stopping

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

Theoretical models can describe the data well

I. Karpenko and F. Becattini, EPJC(2017)77:213, UrQMD+vHLLE
H. Li et al., PRC96, 054908 (2017), AMPT
Y. Sun and C.-M. Ko, PRC96, 024906 (2017), CKE
Y. Xie et al., PRC95, 031901(R) (2017), PICR
D.-X. Wei et al., PRC99, 014905 (2019), AMPT

Feed-down effect

- ~60% of measured Λ 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
  (Polarization transfer could be negative!)

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

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

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

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

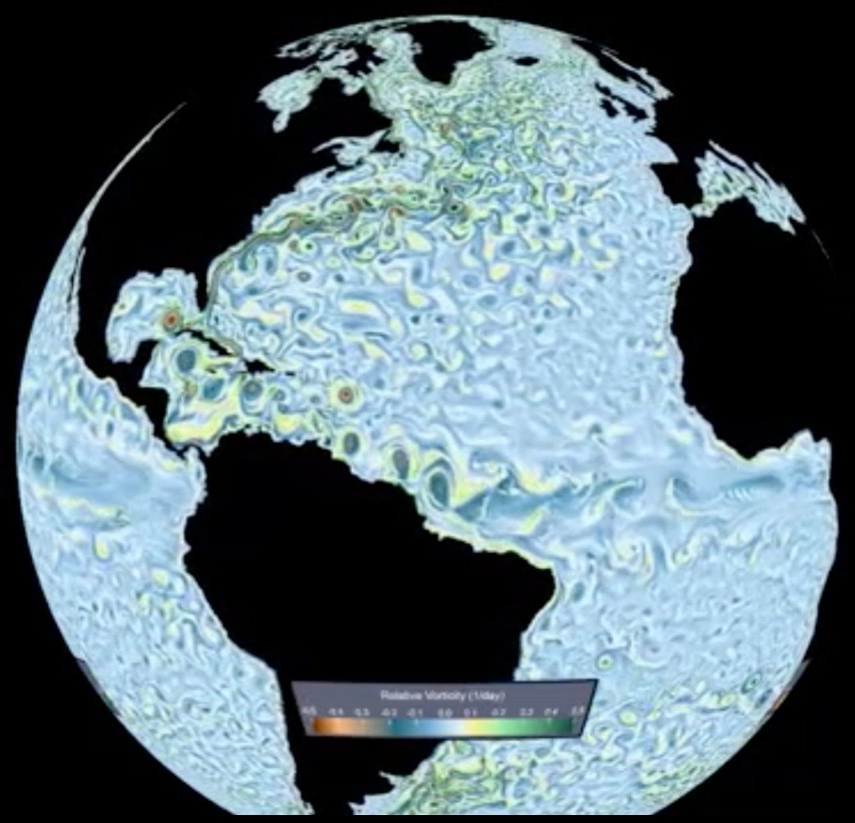
Decay	C
Parity conserving: $1/2^+ \to 1/2^+\ 0^-$	−1/3
Parity conserving: $1/2^- \to 1/2^+\ 0^-$	1
Parity conserving: $3/2^+ \to 1/2^+\ 0^-$	1/3
Parity-conserving: $3/2^- \to 1/2^+\ 0^-$	−1/5
$\Xi^0 \to \Lambda + \pi^0$	+0.900
$\Xi^- \to \Lambda + \pi^-$	+0.927
$\Sigma^0 \to \Lambda + \gamma$	−1/3

Primary Λ polarization will be diluted by 15%-20% (model-dependent)
This also suggests that **the polarization of daughter particles can be used to measure their parent polarization!** e.g. Ξ, Ω

Fastest vorticity

Ocean surface vorticity $\sim 10^{-5}\ s^{-1}$
Jupiter's great red spot $\sim 10^{-4}\ s^{-1}$
Core of supercell tornado $\sim 10^{-1}\ s^{-1}$
Rotating, heated soap bubbles $\sim 10^{2}\ s^{-1}$
Superfluid helium nano droplet $\sim 10^{6}\ s^{-1}$
Matter in heavy ion collisions $\boldsymbol{\sim 10^{22}\ s^{-1}}$

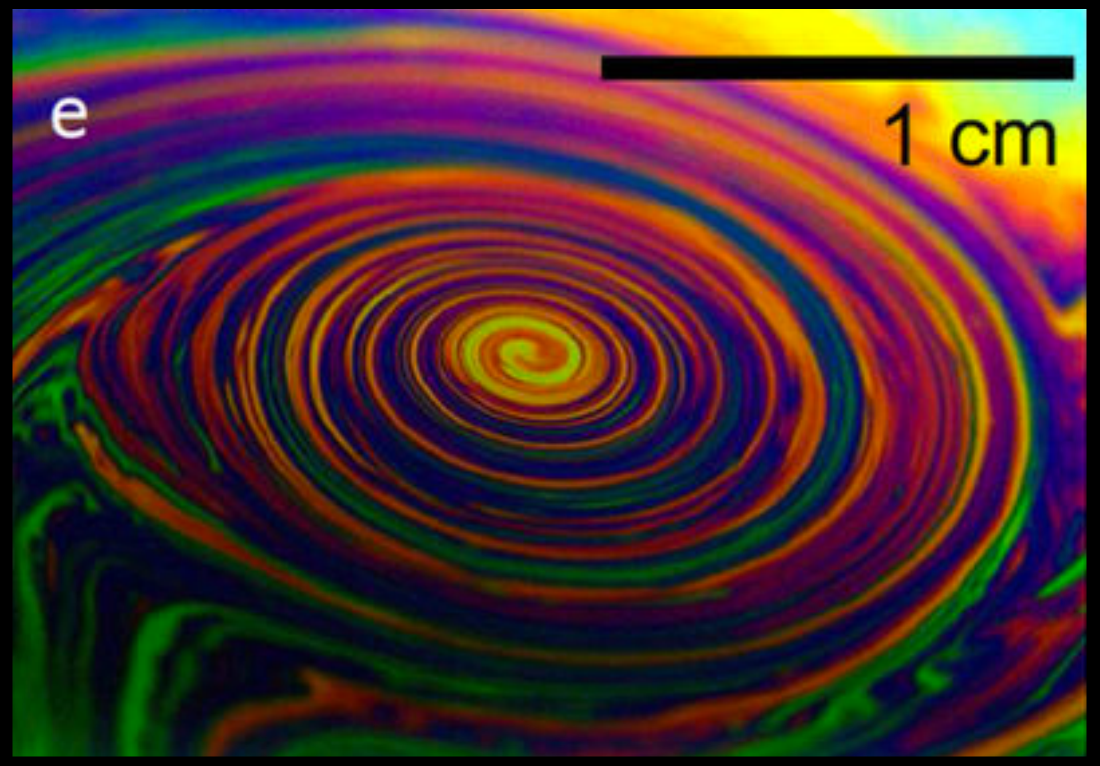
Great red spot of Jupiter (picture: NASA)
6/27, 2019 by Hubble Space Telescope

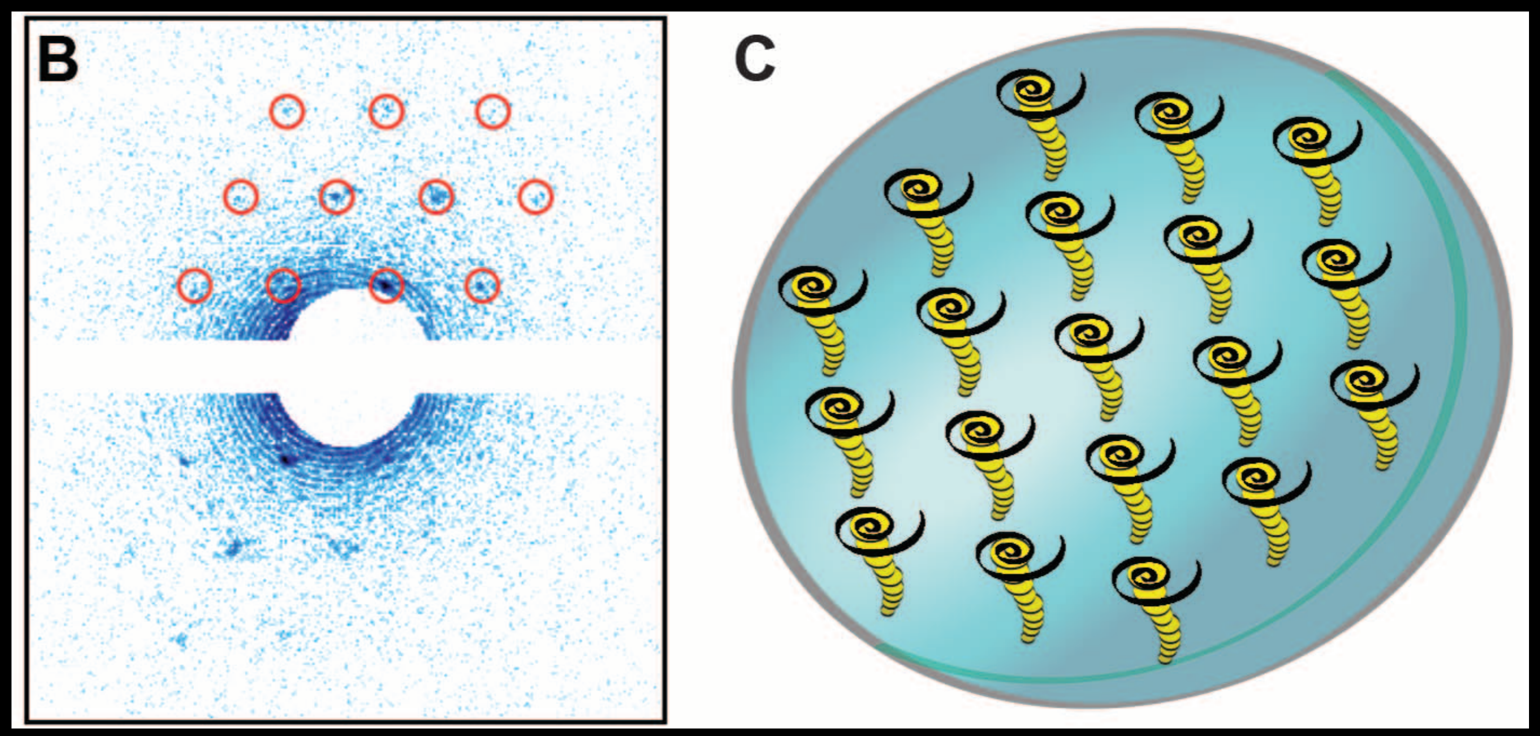


Ocean surface vorticity
https://sos.noaa.gov/datasets/ocean-surface-vorticity/

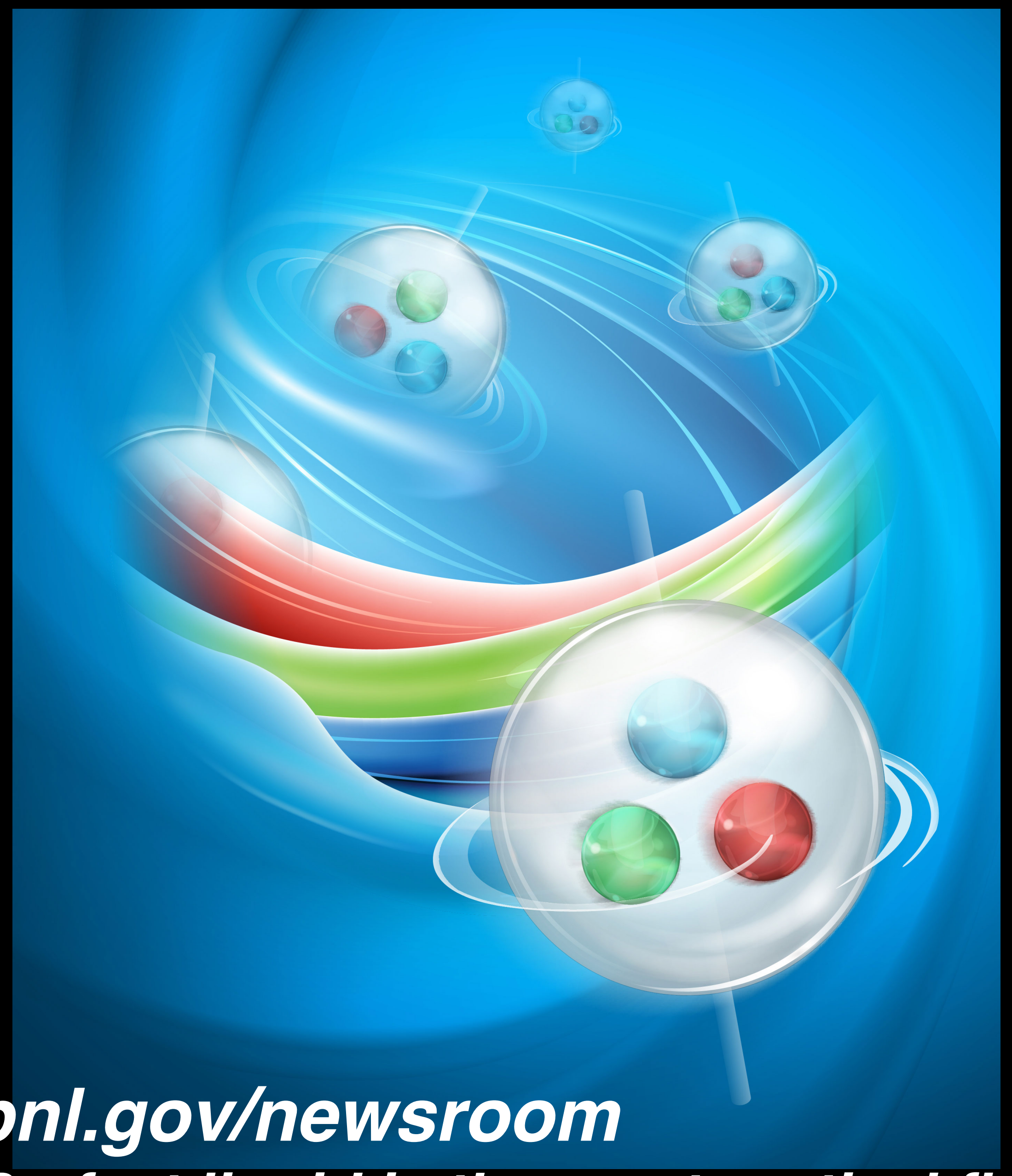
Supercell in Oklahoma (2016)
http://www.silverliningtours.com/tag/tornado/page/3/

vortex of soap bubble
T. Muel et al., Scientific Report 3, 3455 (2013)





vortex aligned to x-ray beam in He droplets
T. Muel et al., Scientific Report 3, 3455 (2013)



bnl.gov/newsroom
Perfect liquid is the most vortical fluid

A possible probe of B-field

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

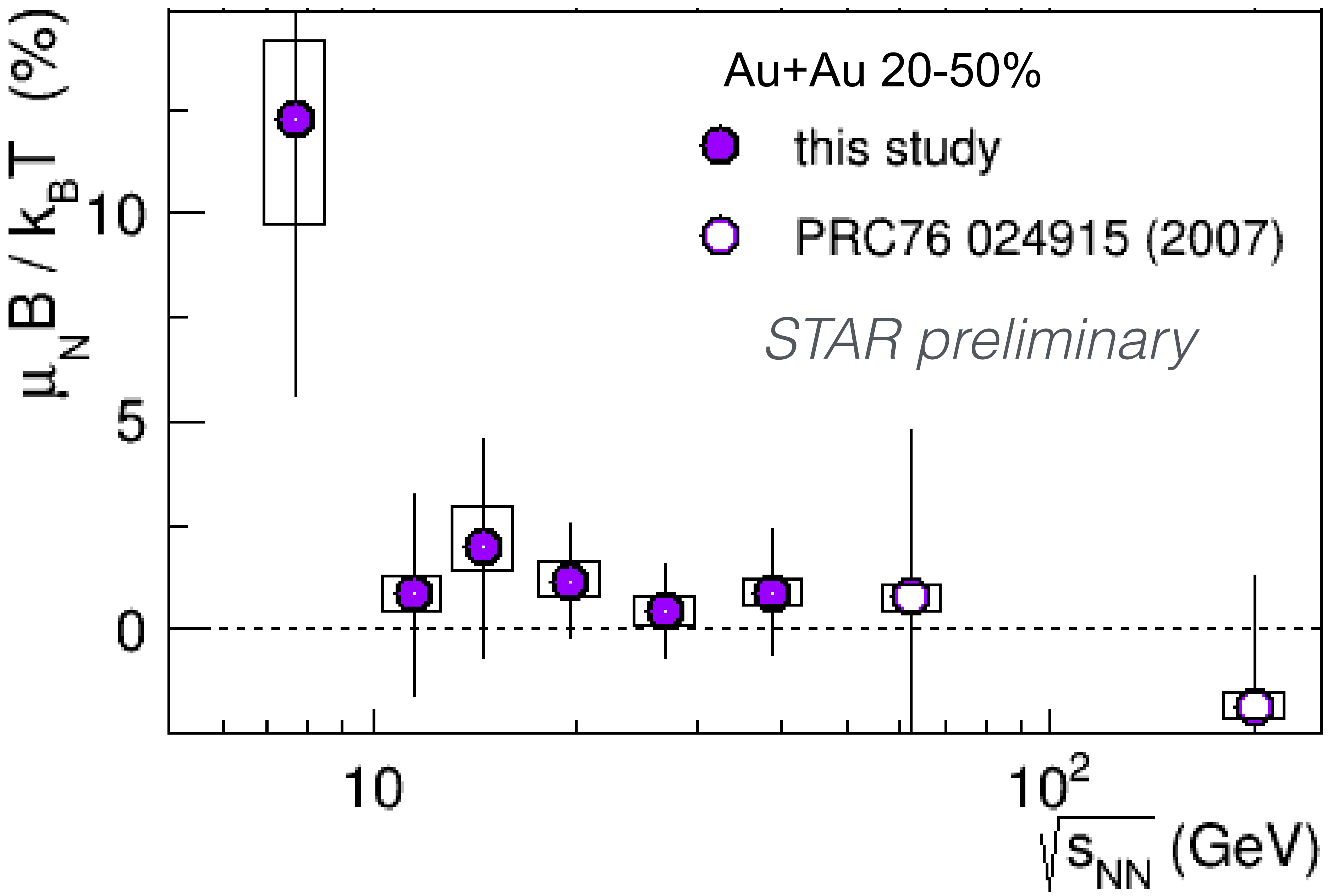
$$P_\Lambda \simeq \frac{1}{2}\frac{\omega}{T} + \frac{\mu_\Lambda B}{T}$$
$$P_{\bar{\Lambda}} \simeq \frac{1}{2}\frac{\omega}{T} - \frac{\mu_\Lambda B}{T}$$

μ_Λ: Λ magnetic moment

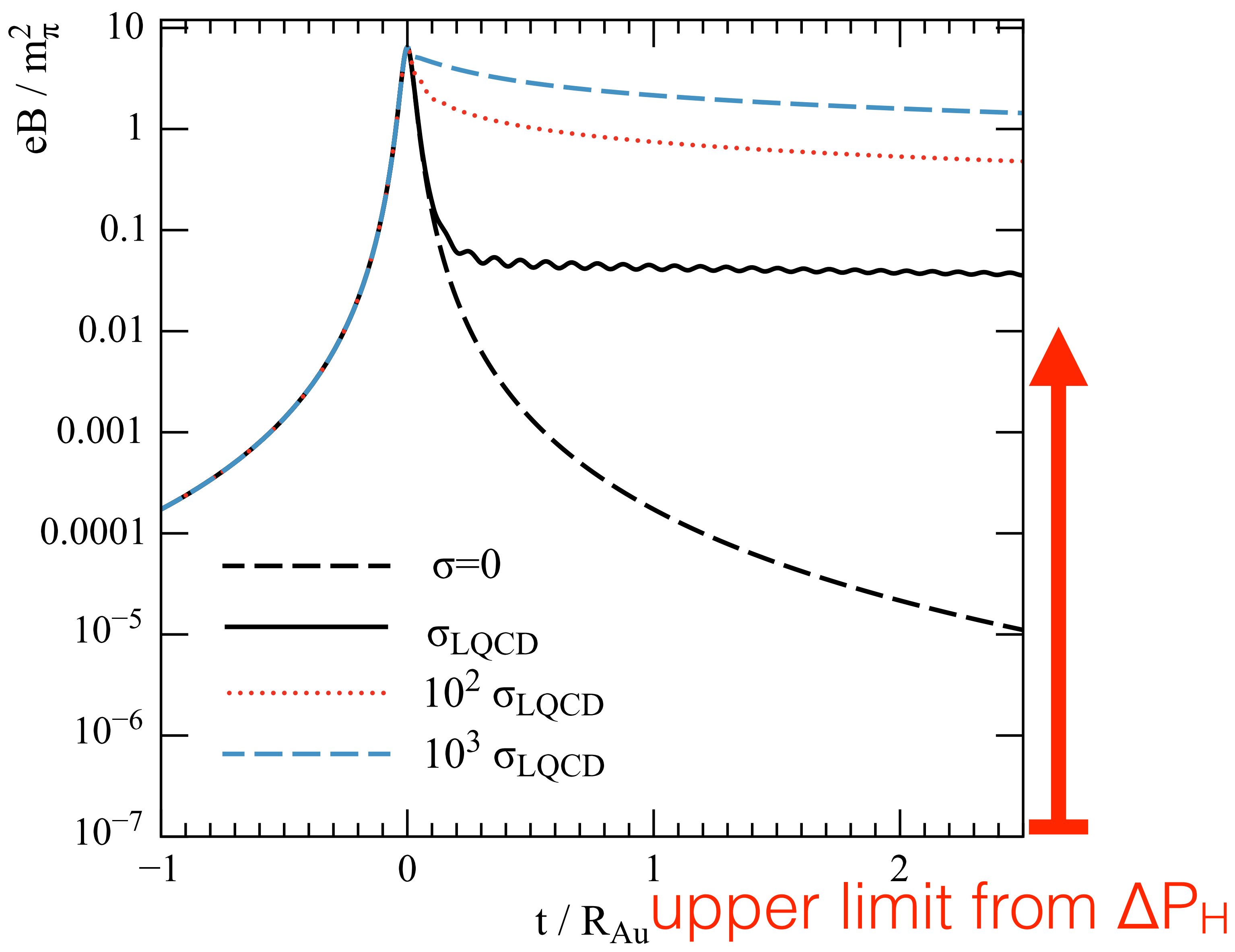
$$B = (P_\Lambda - P_{\bar{\Lambda}})T/(2\mu_\Lambda)$$
$$\sim 2 \times 10^{11} \ [\mathrm{T}]$$
$$eB \sim 10^{-2} \mathrm{m}_\pi^2$$

$\Delta P_\Lambda \sim 0.5\%$, T=160MeV

I. Upsal (STAR), QM17



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

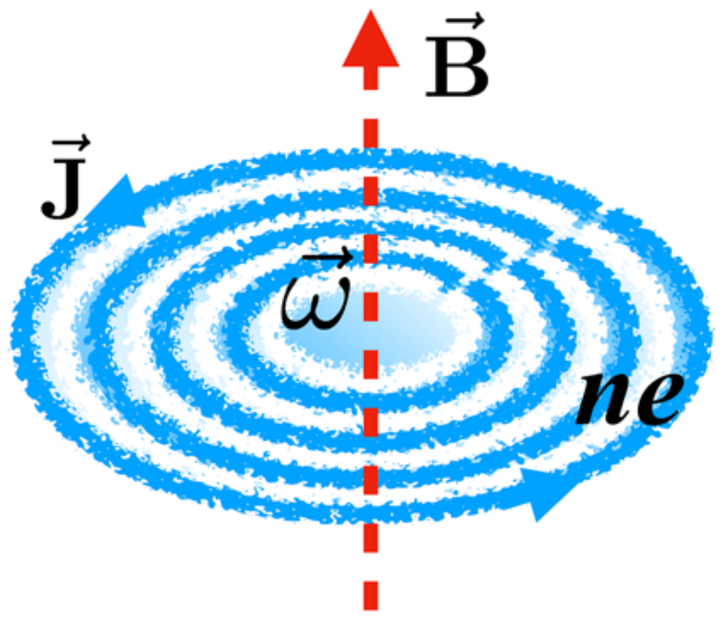


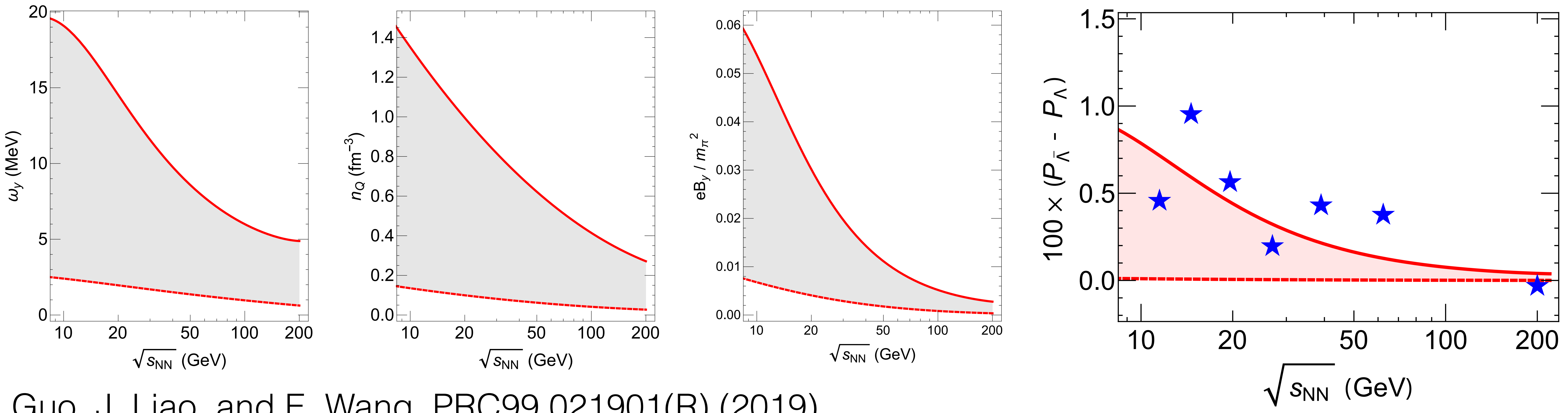
Conductivity increases lifetime.

- Based on thermal model, B-field at kinetic freeze-out could be probed by Λ-antiΛ splitting
  - Current results are consistent with zero (except 7.7 GeV)
- But the splitting could be also due to other effects…

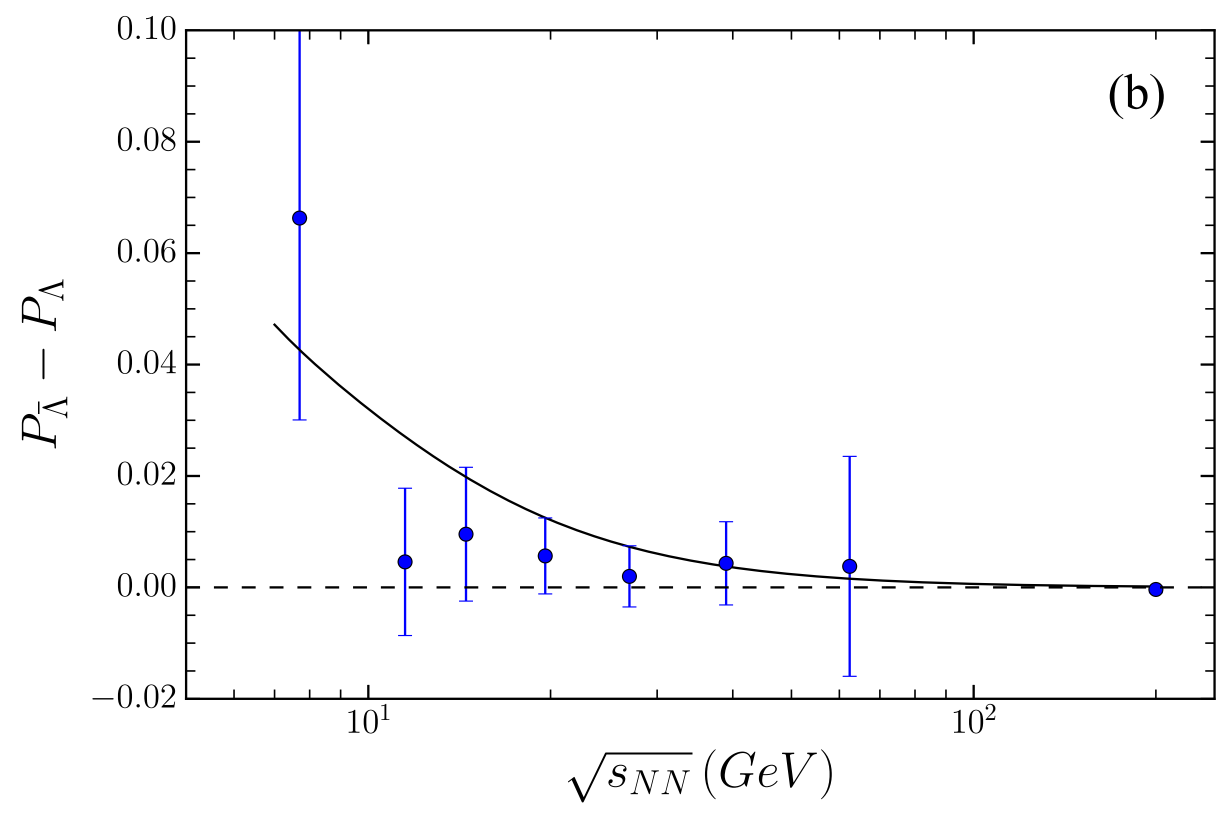
Need caution for the interpretation

- Initial magnetic field
- Effect of chemical potential (expected to be small)
  R. Fang et al.,, PRC94, 024904 (2016)
- Rotating charged fluid produces B-field with longer lifetime
  X. Guo, J. Liao, and E. Wang, PRC99.021901(R) (2019)
- Spin interaction with the meson field generated by the baryon current
  L. Csernai, J. Kapusta, and T. Welle, PRC99.021901(R) (2019)
- Different space time distributions and freeze-out of Λ and antiΛ
  O. Vitiuk, L.Bravina, E. Zabrodin, PLB803(2020)135298





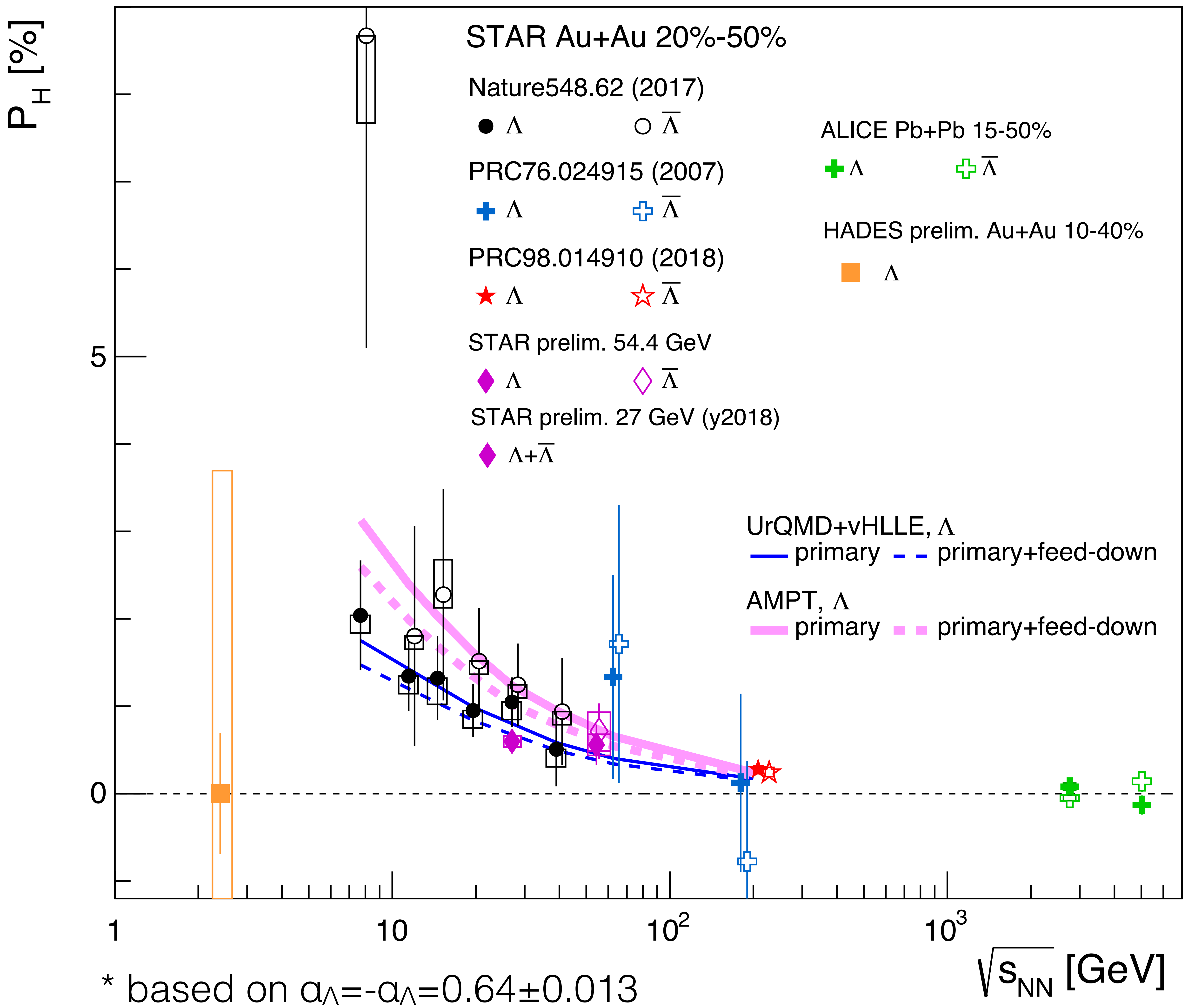
X. Guo, J. Liao, and E. Wang, PRC99.021901(R) (2019)



L. Csernai et al., PRC99.021901(R) (2019)

Complete the energy dependence

ALICE, PRC101.044611 (2020)
F. Kornas (HADES), SQM2019
J. Adams, K. Okubo (STAR), QM2019

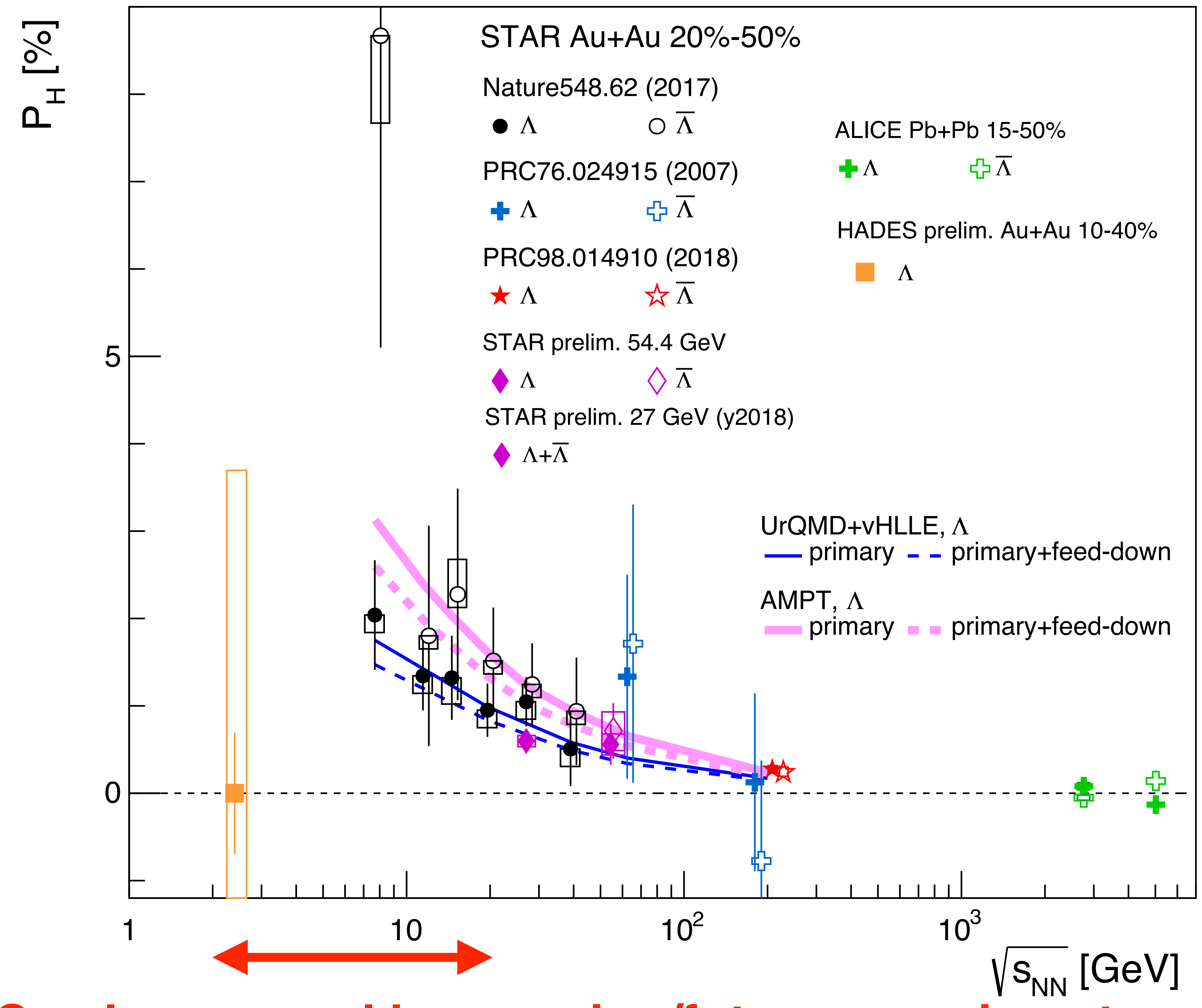


* based on $\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.64 \pm 0.013$

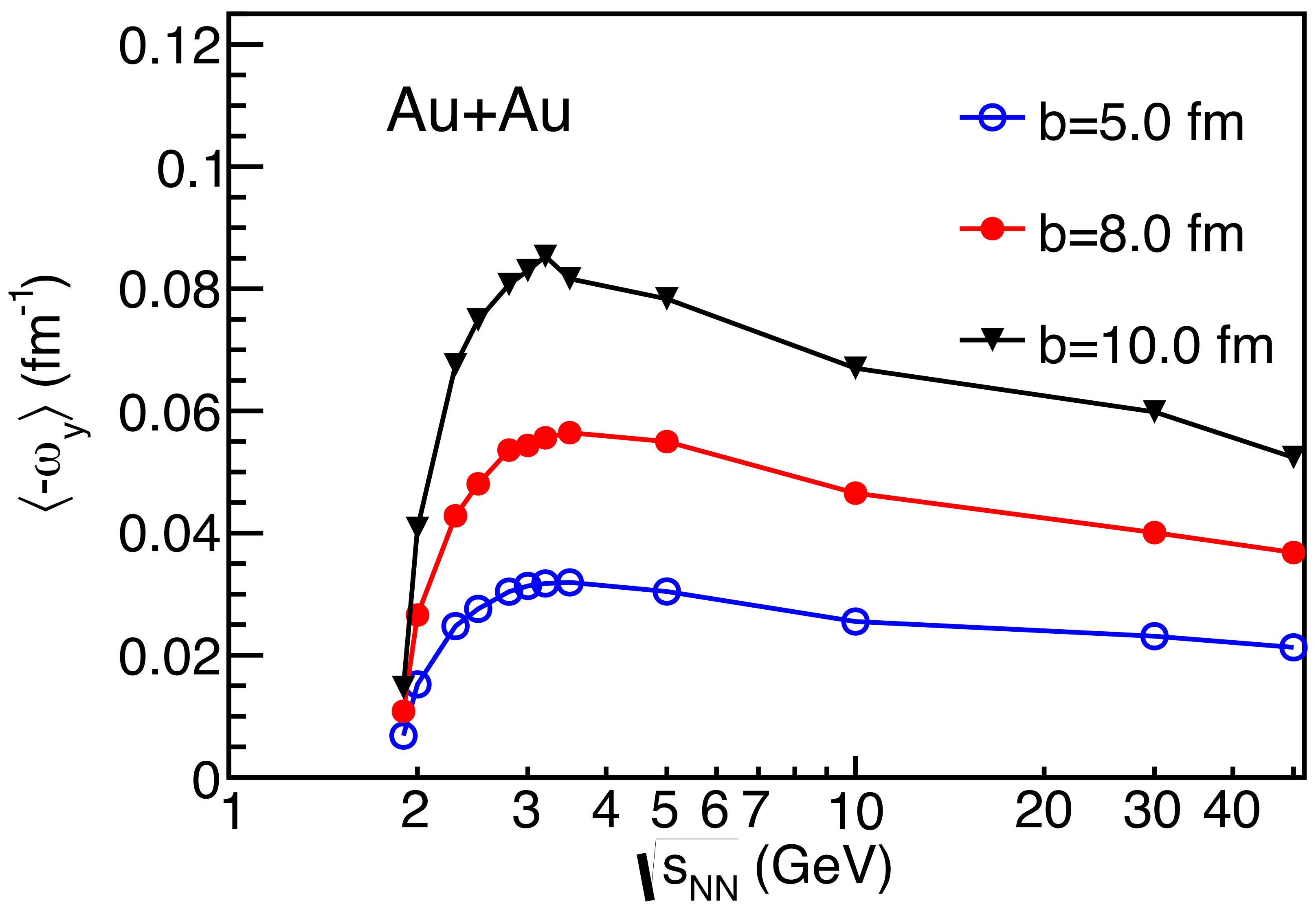
- STAR preliminary at 27 and 54 GeV
- ALICE at 2.76 and 5.02 TeV
  - Expected signal is of the order of current statistical uncertainty
- HADES at 2.4 GeV
  - Large uncertainty but still preliminary
  - Hopefully reduce systematic uncertainty

Complete the energy dependence

ALICE, PRC101.044611 (2020)
F. Kornas (HADES), SQM2019
J. Adams, K. Okubo (STAR), QM2019



Can be covered by ongoing/future experiments

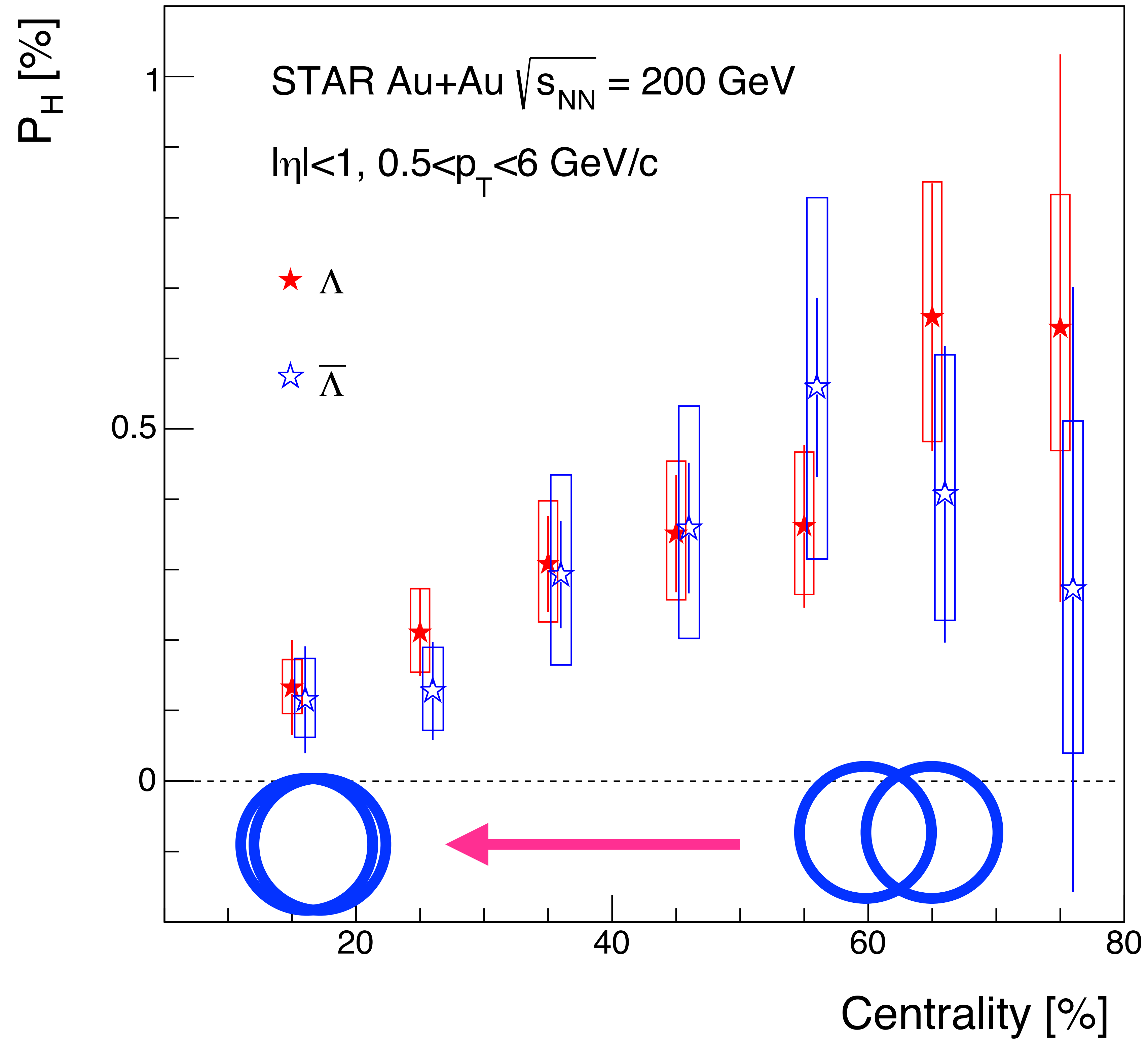


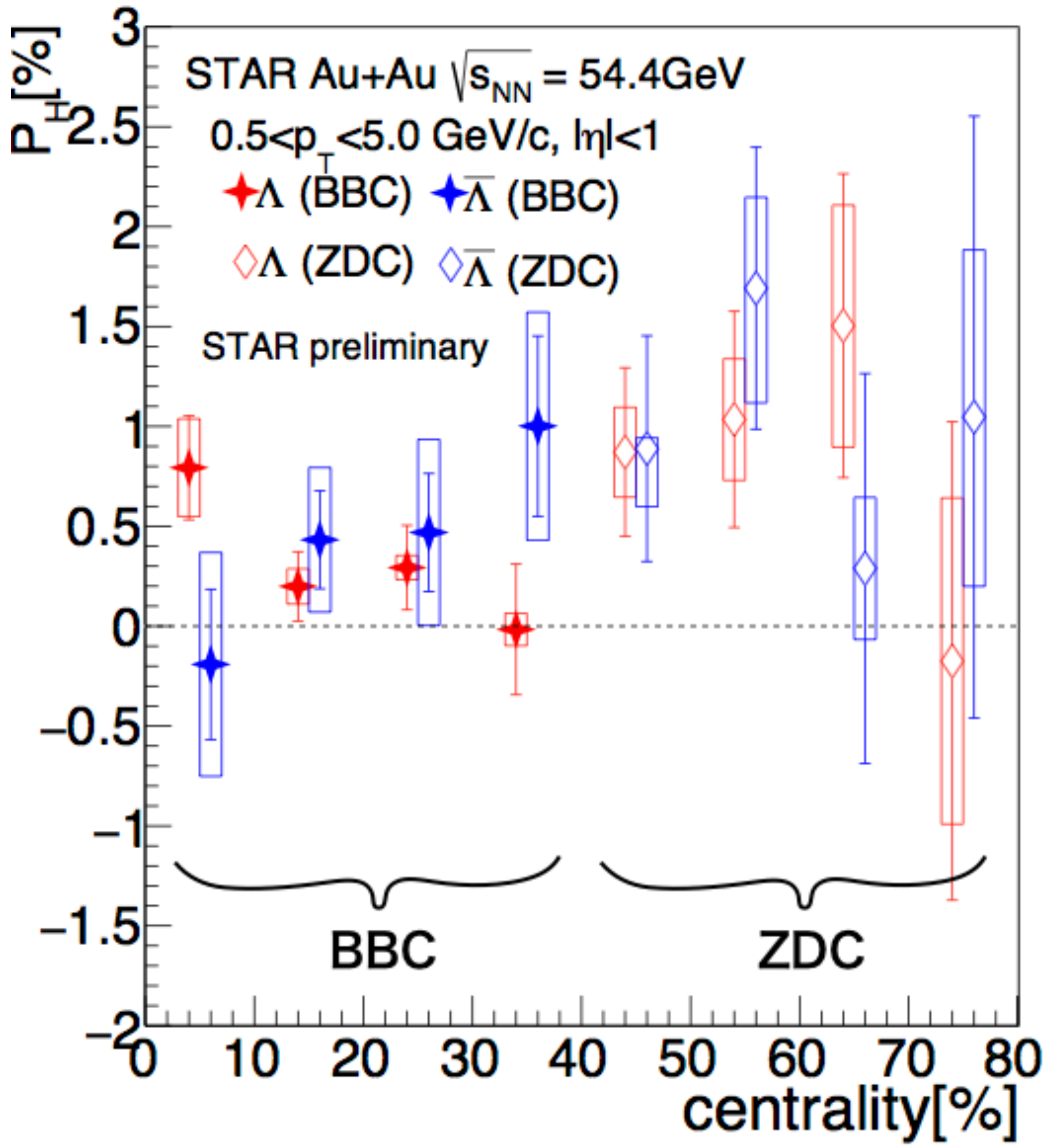
Interesting energy dependence of kinematic vorticity predicted by a transport model (UrQMD)
X.-G. Deng et al., PRC101.064908 (2020)

STAR BES-II+FXT: 3-19 GeV
HADES: 2-3 GeV
NICA: 4-11 GeV
CBM/J-PARC/NA61…

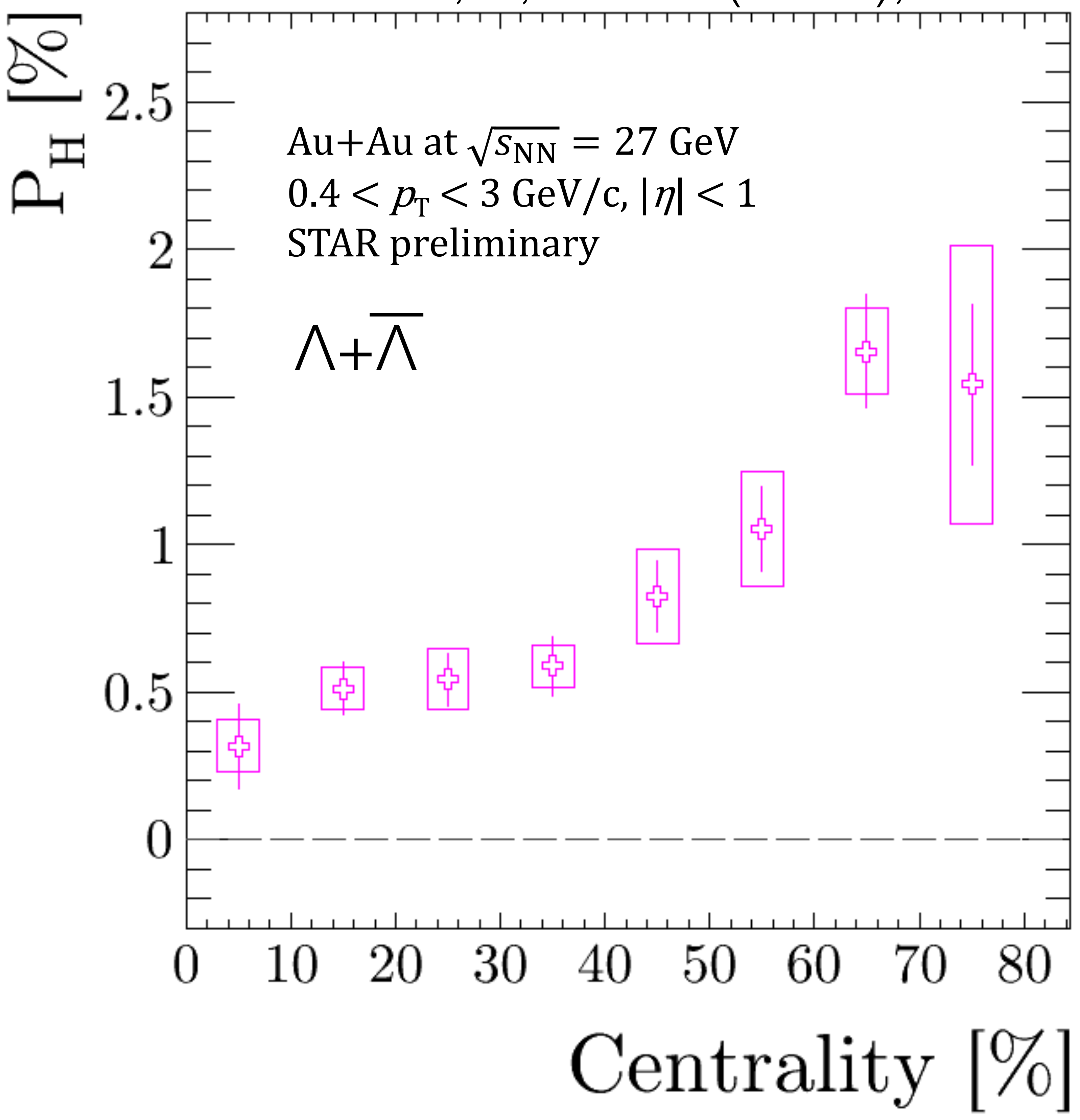
Differential measurements: centrality

STAR, PRC98, 014910 (2018)





J. Adams, K, Okubo (STAR), QM19



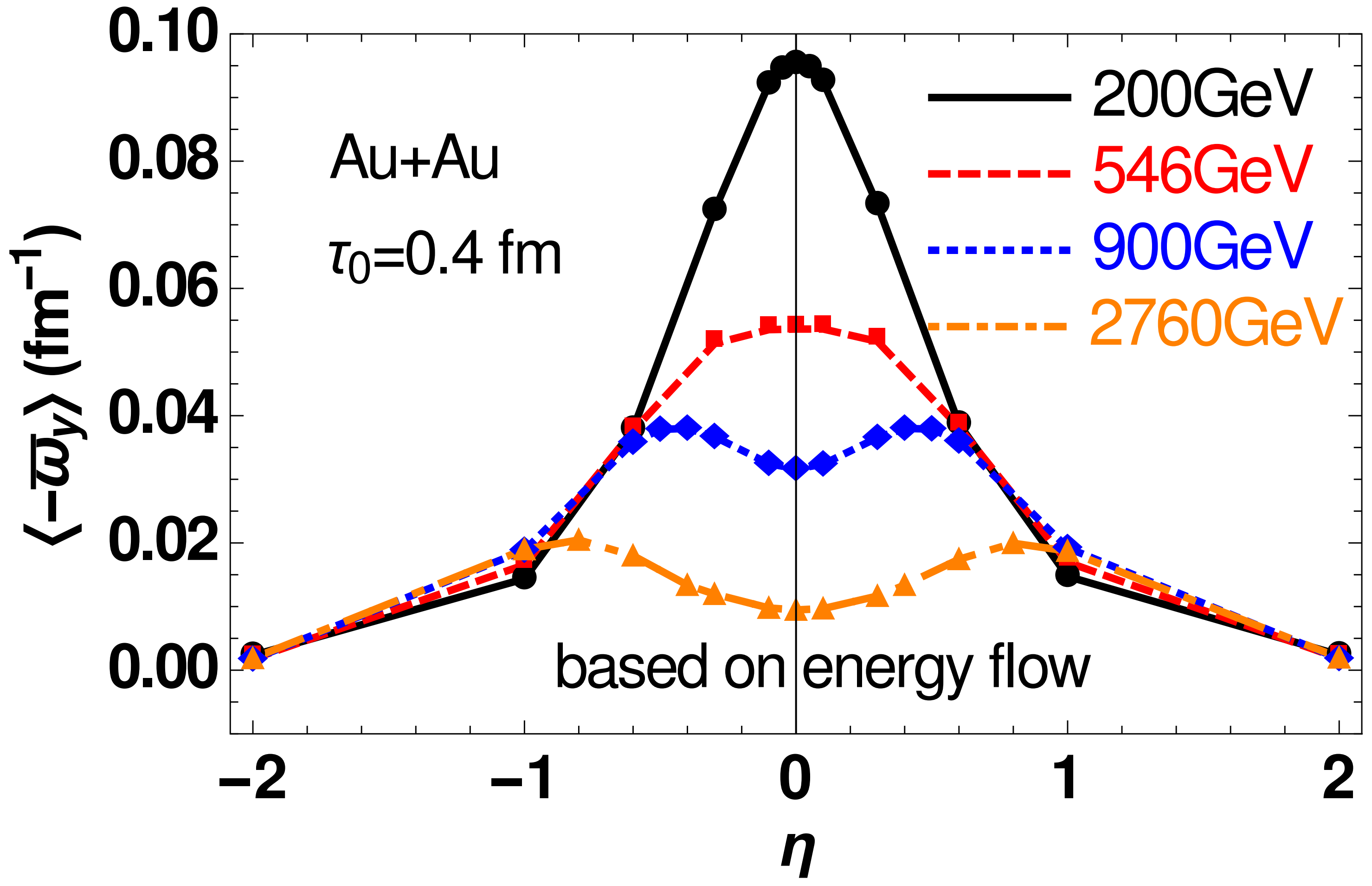
$\sqrt{s_{NN}}$ ← 200 GeV — 54 GeV — 27 GeV

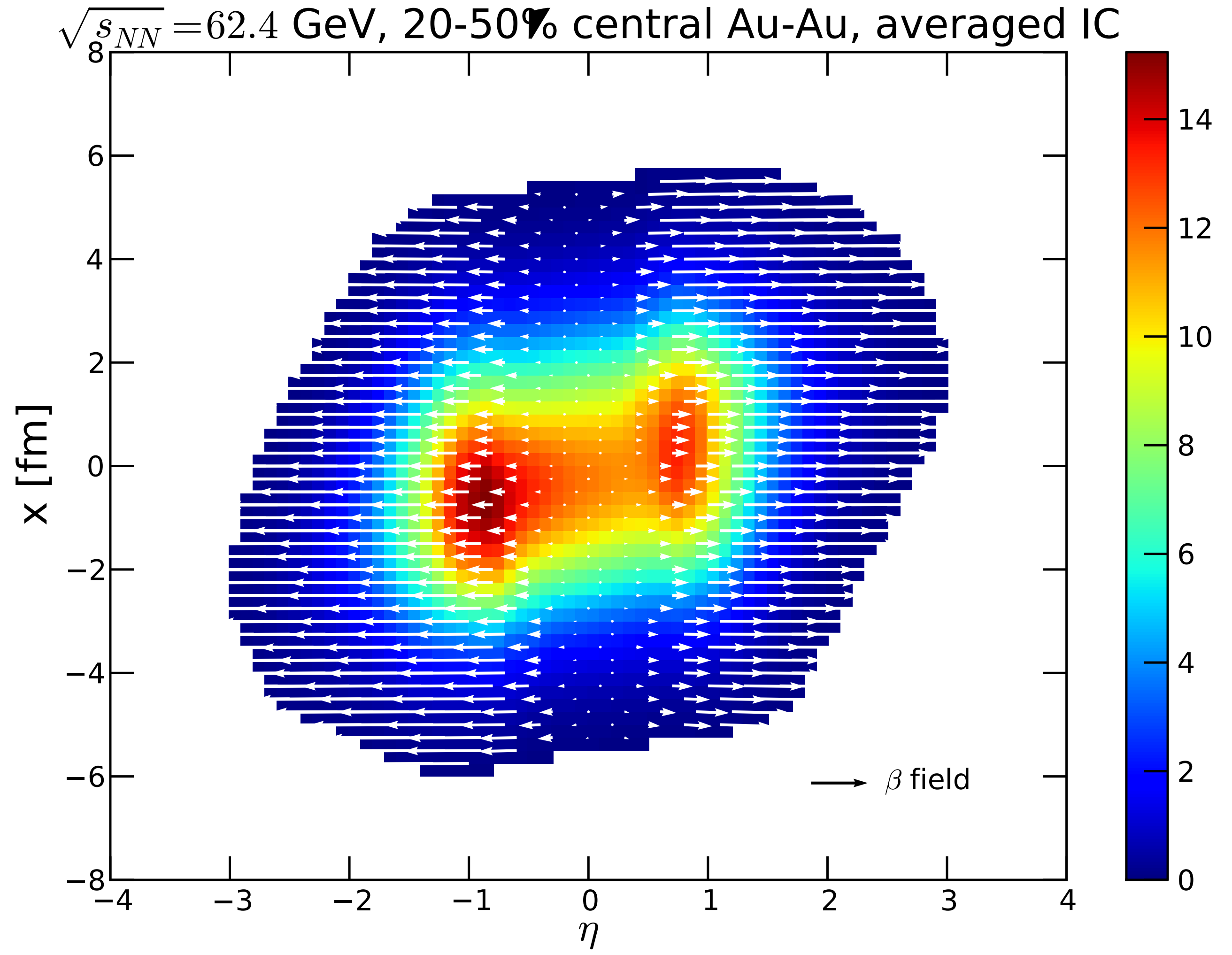
In most central collision → no initial angular momentum
The polarization decreases in more central collisions.

Similar trend was confirmed at lower energies.

Differential measurements: rapidity

W.T.Feng and X.G.Huang, PRC93.064907 (2016)



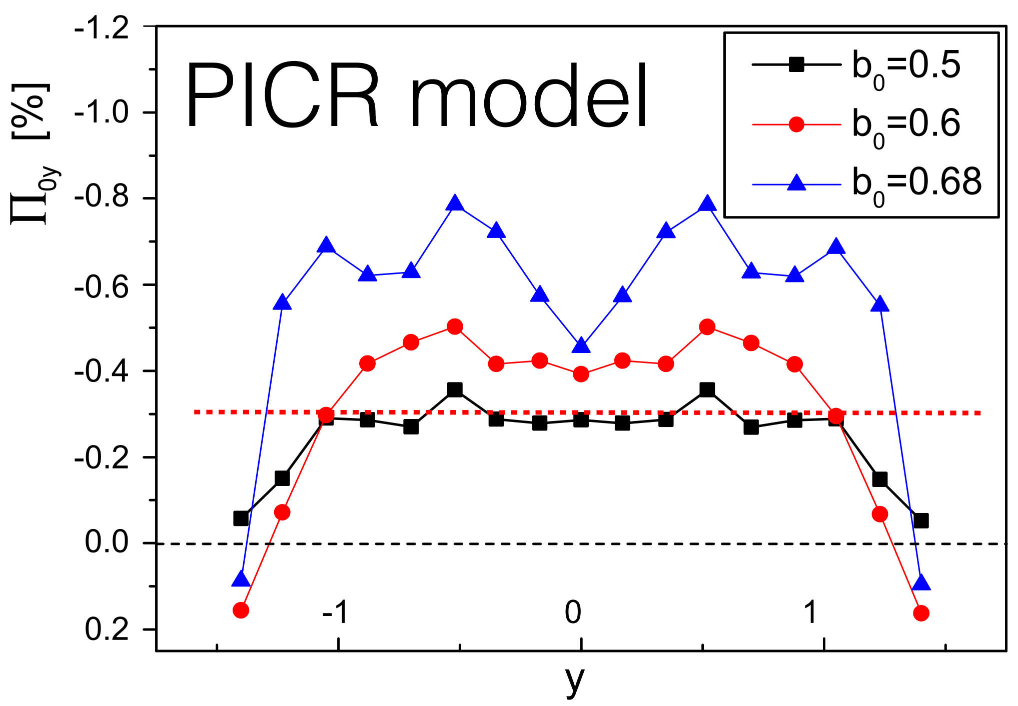


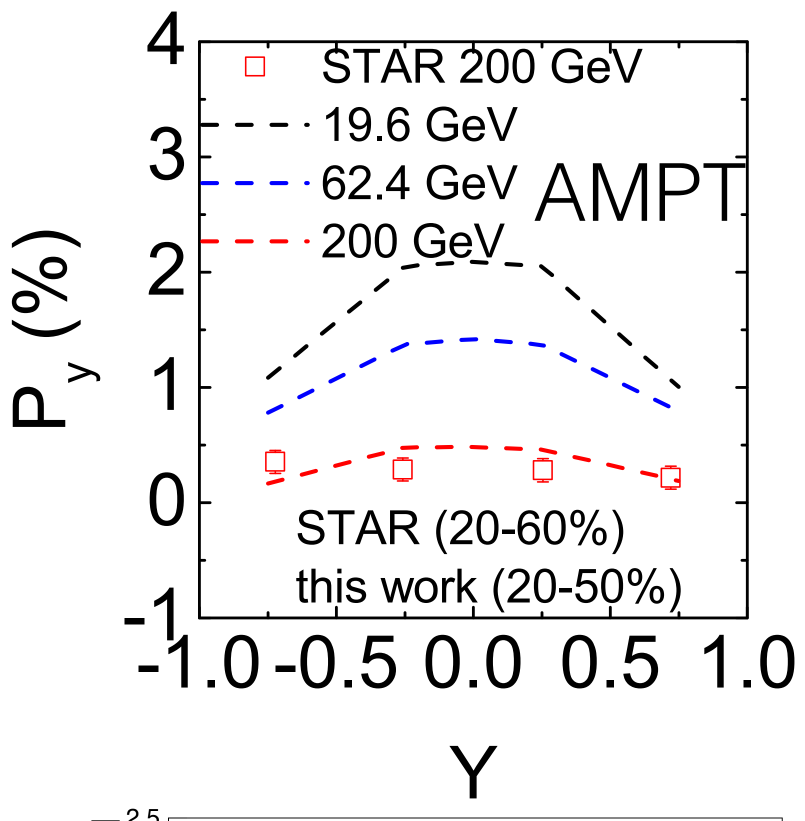
I.Karpenko and F.Becattini, EPJ(2017)77.213

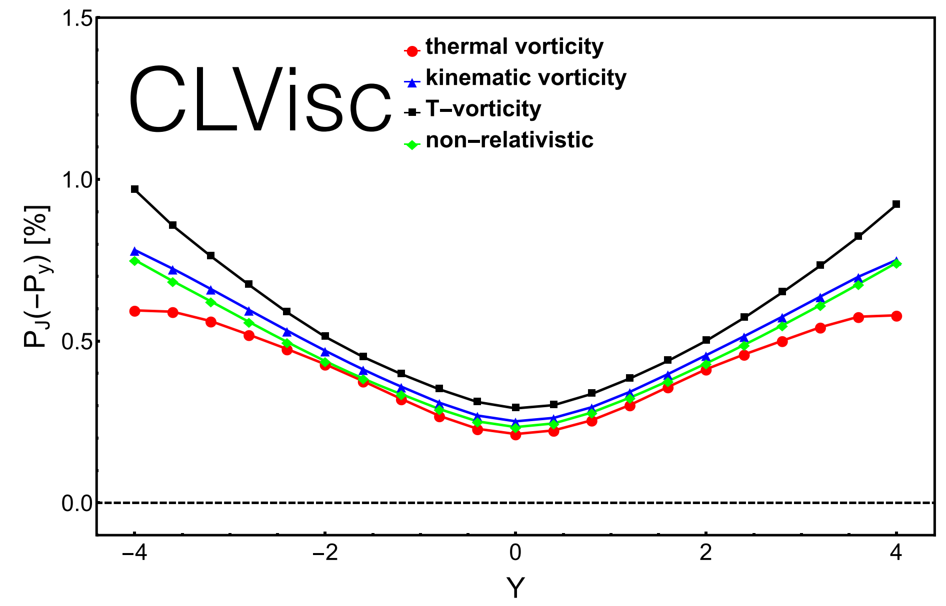
Energy dependence of vorticity vs. rapidity

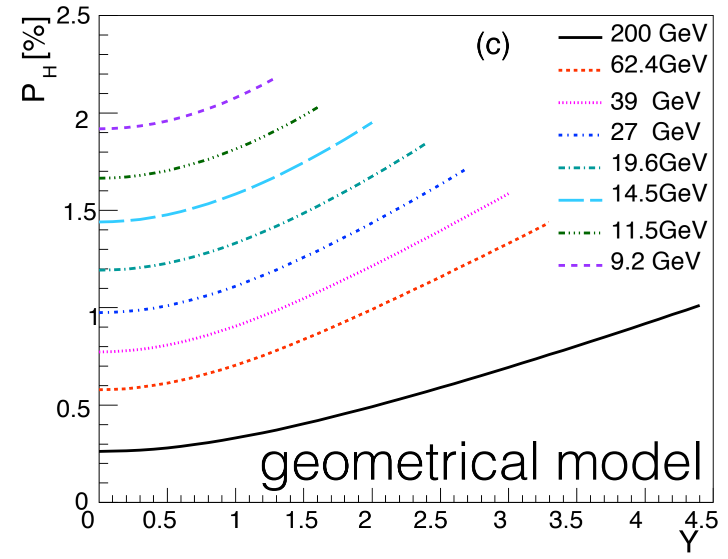
- Baryon stopping and velocity profile in the initial state at given acceptance

But the predicted polarization trend **differs among models**





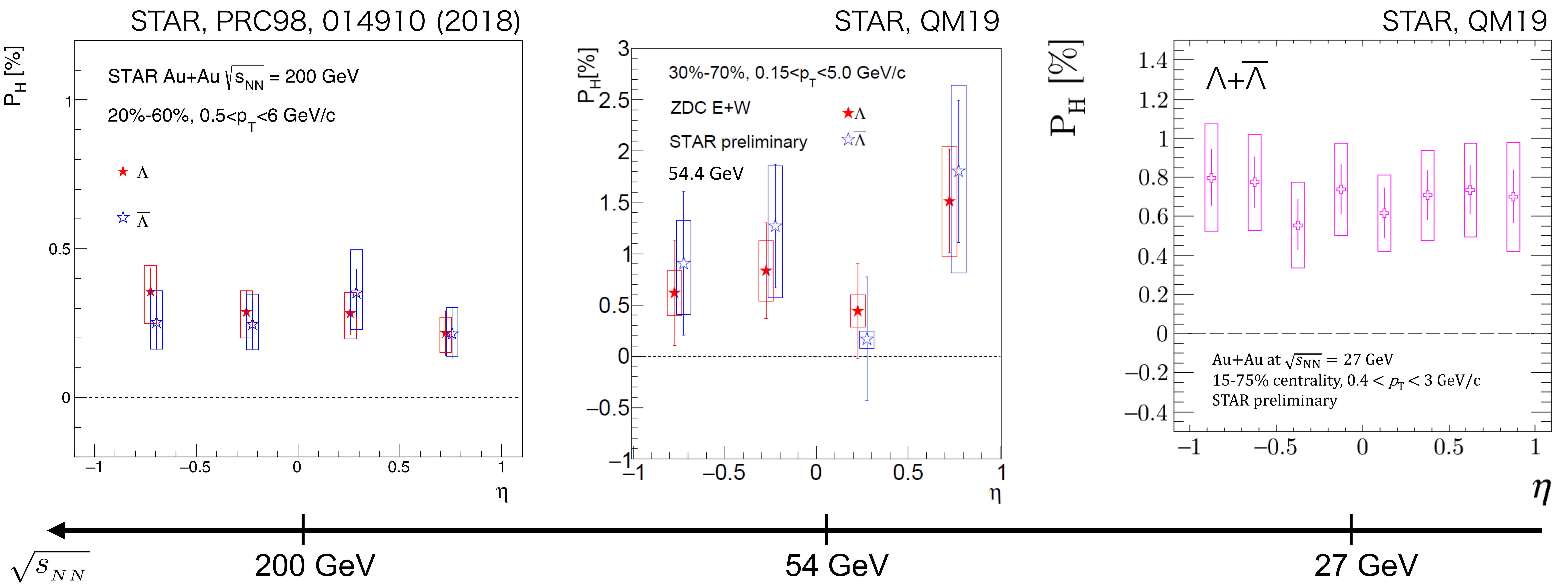




Y.Xie, D.Wang, and L.P.Csernai, RPJ(2020)80:39
H.Z.Wu et al, PRResearch1.033058(2019)

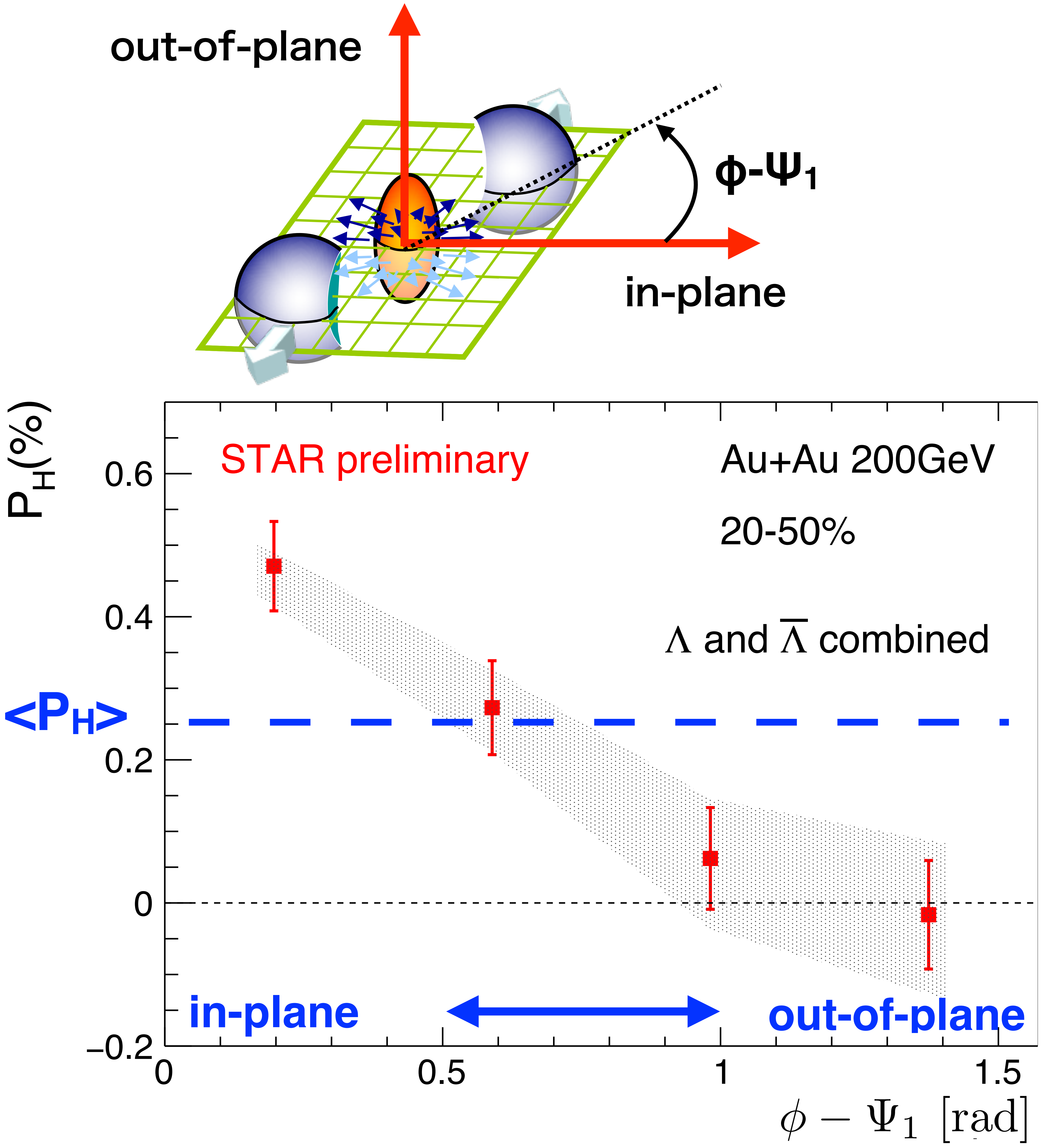
D.X.Wei, W.T.Deng and X.G.Huang, PRC99.014905 (2019)
Z.T.Liang et al., arXiv:1912.10223

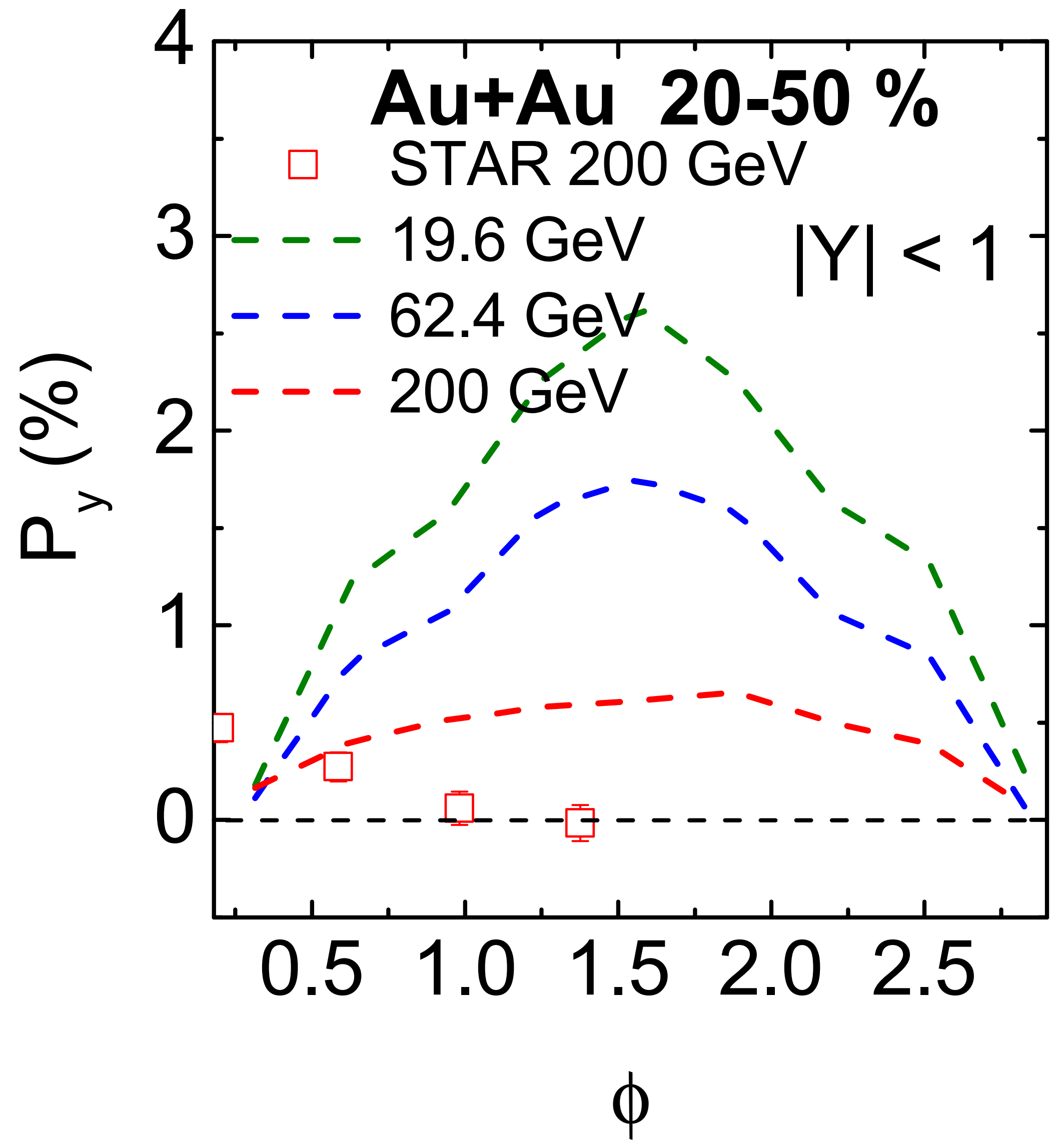
Differential measurements: rapidity

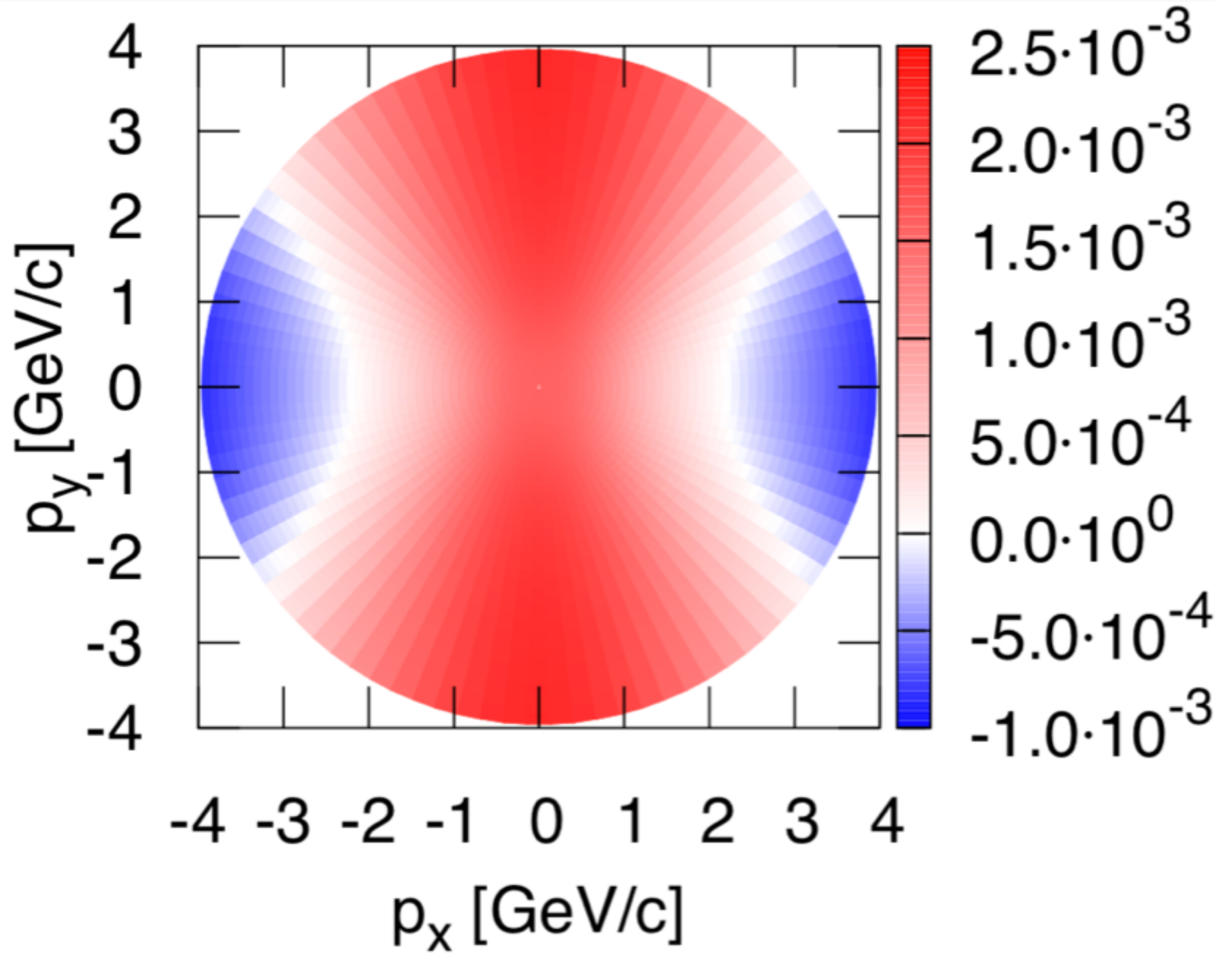


No strong rapidity dependence within |η|<1.
This can be explored further with iTPC(|η|<1.5) and Forward upgrade (2023-).

Differential measurements: azimuthal angle







I. Karpenko and F. Becattini, EPJC(2017)77.213
D. Wei, W. Deng, and X. Huang, PRC99.014905 (2019)

- The data shows larger polarization for in-plane, while many models predict the opposite, i.e. larger for out-of-plane
- **Not fully understood yet**

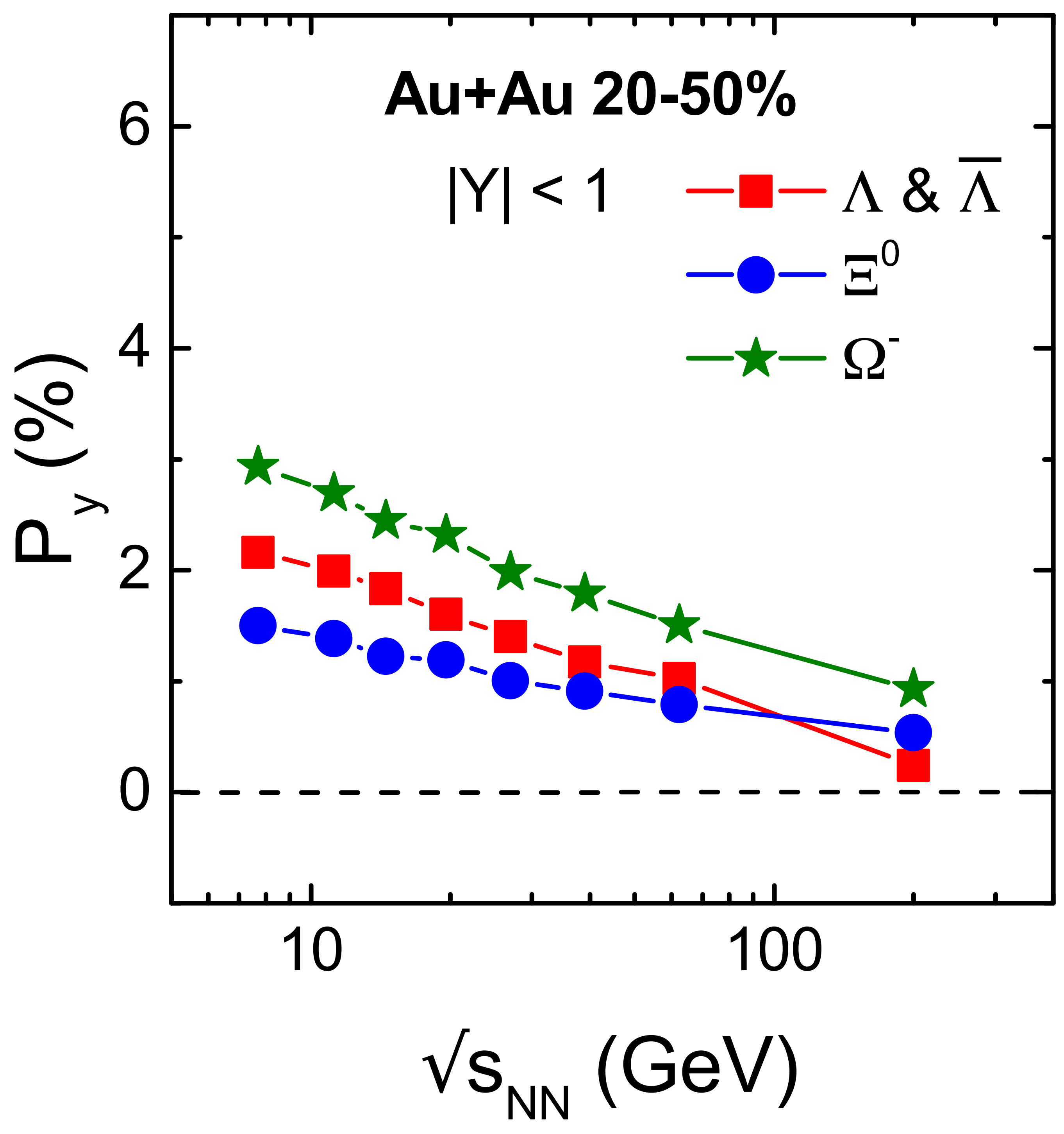
"T-vorticity" may explain the data
H. Wu et al., PR.Research1.033058 (2019)

Other particles to measure polarization?

[P. A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)]

	Mass (GeV/c²)	cτ (cm)	decay mode	decay parameter	magnetic moment (μ_N)	spin
Λ (uds)	1.115683	7.89	Λ->πp (63.9%)	0.732±0.014	−0.613	1/2
Ξ^- (dss)	1.32171	4.91	Ξ^-->$\Lambda\pi^-$ (99.887%)	−0.401±0.010	−0.6507	1/2
Ω^- (sss)	1.67245	2.46	Ω^-->ΛK^- (67.8%)	0.0157±0.002	-2.02	3/2

W.-T. Deng and X.-G. Huang, PRC93.064907 (2016)



Natural candidates would be Ξ and Ω hyperons.

- Different spin and magnetic moments
- Less feed-down in Ξ and Ω compared to Λ
- Could be different freeze-out
- Different valence s-quarks

Based on thermal model:

P(s=1/2) ~ ω/(2T), P(s=3/2) ~ 4 ω/(5T)

F.Becattini et al., PRC95.054902 (2017)

Ξ and Ω polarization measurements

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

Getting difficult due to smaller decay parameter for Ξ and Ω…

$$\alpha_\Lambda = 0.732, \; \alpha_{\Xi^-} = -0.401, \; \alpha_{\Omega^-} = 0.0157$$

spin 1/2

Polarization of daughter Λ in a weak decay of Ξ:
(based on Lee-Yang formula)

T.D. Lee and C.N. Yang, Phys. Rev.108.1645 (1957)

$$\mathbf{P}_\Lambda^* = \frac{(\alpha_\Xi + \mathbf{P}_\Xi^* \cdot \hat{\boldsymbol{p}}_\Lambda^*)\hat{\boldsymbol{p}}_\Lambda^* + \beta_\Xi \mathbf{P}_\Xi^* \times \hat{\boldsymbol{p}}_\Lambda^* + \gamma_\Xi \hat{\boldsymbol{p}}_\Lambda^* \times (\mathbf{P}_\Xi^* \times \hat{\boldsymbol{p}}_\Lambda^*)}{1 + \alpha_\Xi \mathbf{P}_\Xi^* \cdot \hat{\boldsymbol{p}}_\Lambda^*}$$

$$\alpha^2 + \beta^2 + \gamma^2 = 1$$

$$\mathbf{P}_\Lambda^* = C_{\Xi^-\Lambda} \mathbf{P}_\Xi^* = \tfrac{1}{3}(1 + 2\gamma_\Xi)\,\mathbf{P}_\Xi^*.$$

$$C_{\Xi^-\Lambda} = +0.944$$

spin 3/2

Similarly, daughter Λ polarization from Ω:

$$\mathbf{P}_\Lambda^* = C_{\Omega^-\Lambda} \mathbf{P}_\Omega^* = \tfrac{1}{5}(1 + 4\gamma_\Omega)\,\mathbf{P}_\Omega^*.$$

Here **γ_Ω is unknown**.
- Time-reversal violation parameter β_Ω would be small
- α_Ω is very small

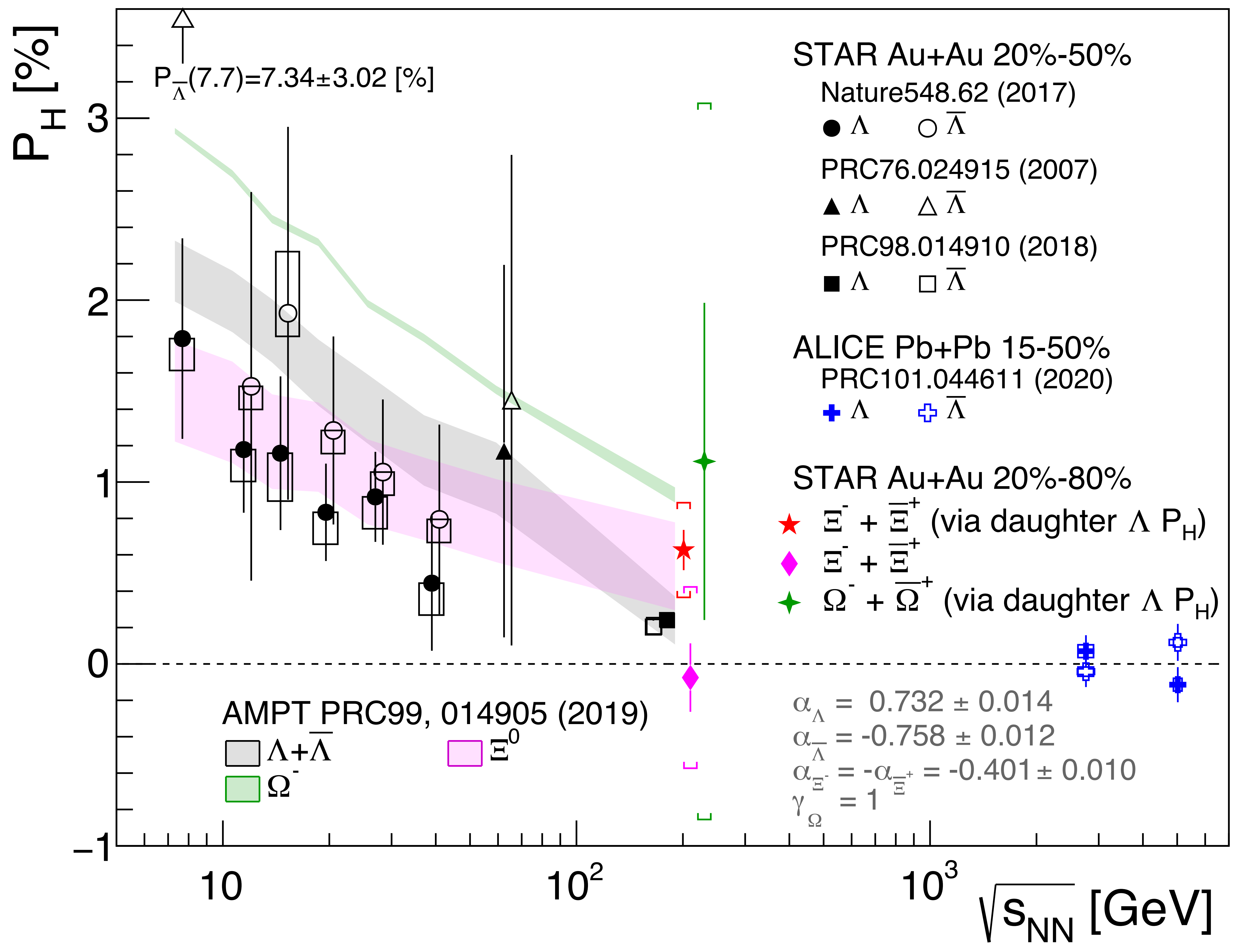
then $\gamma_\Omega \sim \pm 1$ and the polarization transfer $C_{\Omega\Lambda}$ leads to:

$$C_{\Omega\Lambda} \approx +1 \text{ or } -0.6$$

Parent particle polarization can be studied by measuring daughter particle polarization!

Ξ global polarizations at $\sqrt{s_{NN}}$ = 200 GeV

STAR, arXiv:2012.13601



* published results are rescaled by $\alpha_{old}/\alpha_{new}$~0.87

Combined Ξ P_H from the two methods:

$$\langle P_\Xi \rangle = 0.47 \pm 0.10\ (\text{stat.}) \pm 0.23\ (\text{syst.})\ \%$$

cf. $\langle P_{\Lambda+\bar{\Lambda}} \rangle (\%) = 0.24 \pm 0.03 \pm 0.03$

Ξ P_H is larger than Λ P_H

- positive polarization with ~2σ level
- close to AMPT prediction

W.-T. Deng and X.-G. Huang, PRC93.064907 (2016)

Naive expectations for Ξ P_H

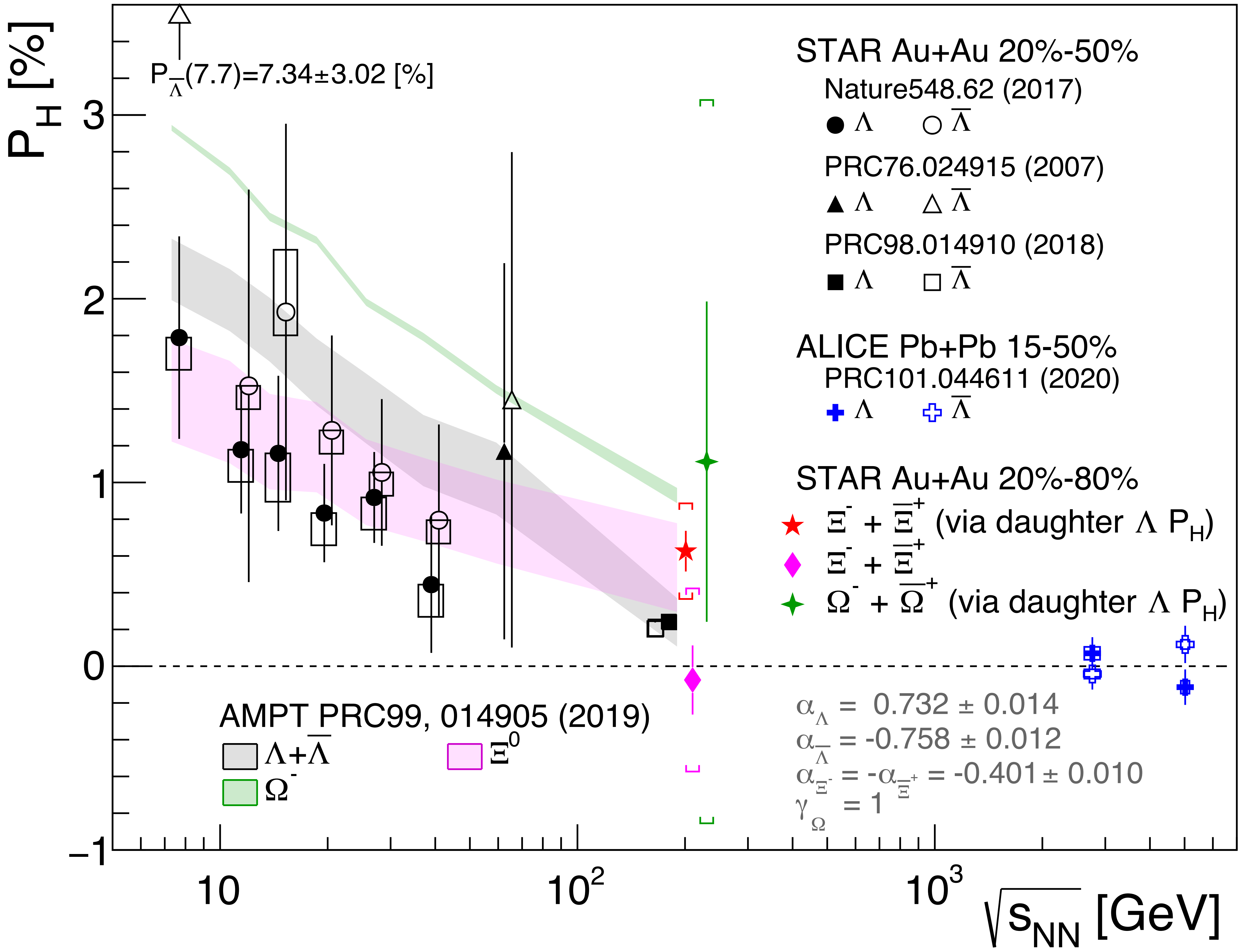
- Thermal model (s=1/2): same P_H (**Ξ=Λ**)
- Lighter particles could be more polarized (**Ξ<Λ**)
- Earlier freeze-out (of multi-strangeness) leads to larger P_H (**Ξ>Λ**)

O.Vitiuk, L.V.Bravina, and E.E.Zabrodin, PLB803(2020)135298

- Feed-down: ~15-20% reduction for primary Λ P_H

Ω global polarizations at $\sqrt{s_{NN}}$ = 200 GeV

STAR, arXiv:2012.13601



* published results are rescaled by $\alpha_{old}/\alpha_{new}$~0.87

Ω P_H via daughter Λ P_H (assuming $C_{\Omega\Lambda}$=+1)

Thermal model (in non-relativistic limit)

$$\mathbf{P} = \frac{\langle \mathbf{s} \rangle}{s} \approx \frac{(s+1)}{3}\frac{\boldsymbol{\omega}}{T}$$

F.Becattini et al., PRC95.054902 (2017)

$P_H(s=3/2) \sim 1.6^* P_H(s=1/2)$

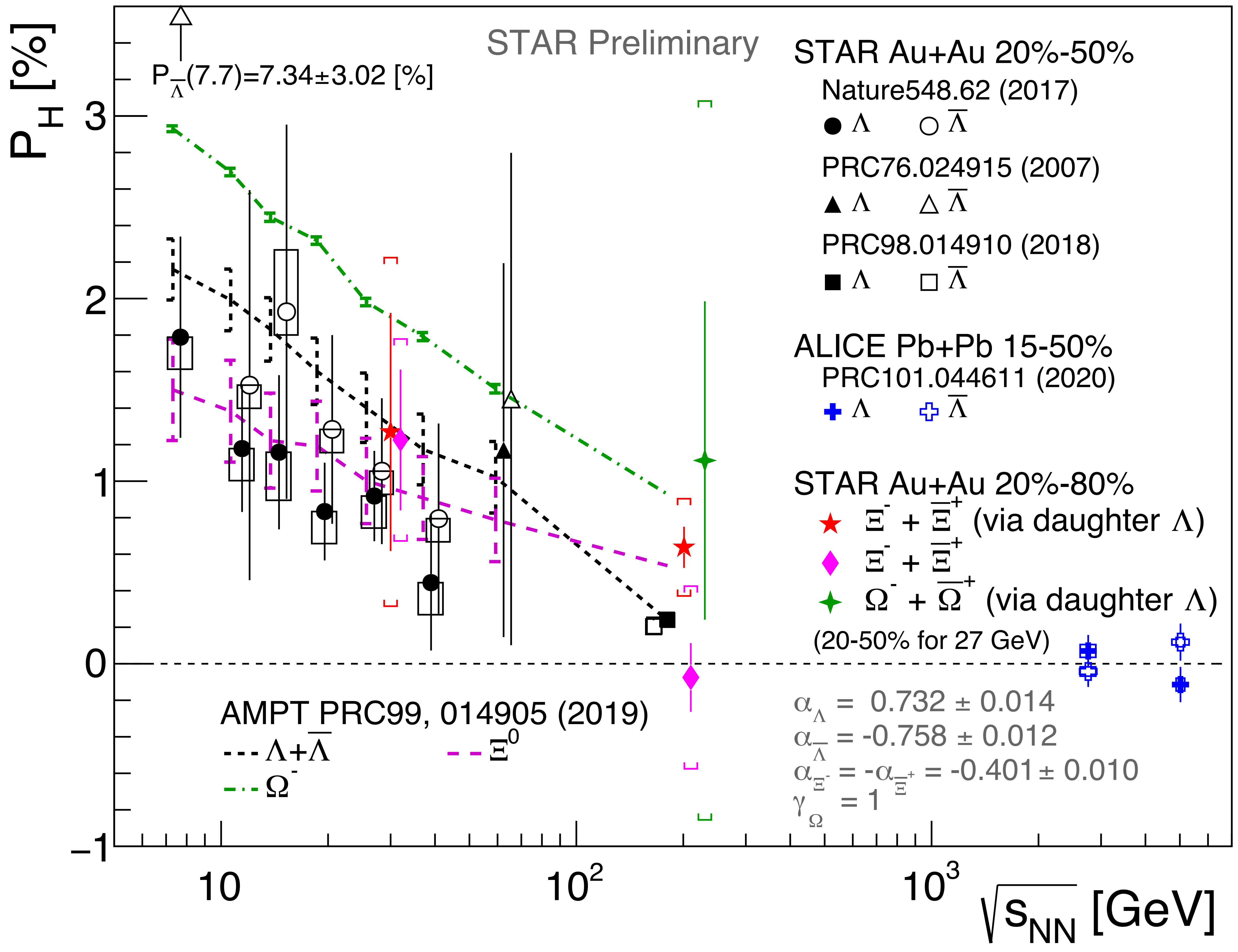
- Large uncertainty, to be improved in future analysis

- Based on the vorticity picture, the data seems to favor γ_Ω=+1($C_{\Omega\Lambda}$=+1) rather than γ_Ω=-1 ($C_{\Omega\Lambda}$=-0.6)

** In other words, γ_Ω can be determined in HIC assuming the global polarization*

Ξ global polarizations at 27 GeV

E. Alpatov (STAR), ICPPA2020
TN (STAR), RHIC&AGS AUM2020



* published results are rescaled by $\alpha_{old}/\alpha_{new}$~0.87

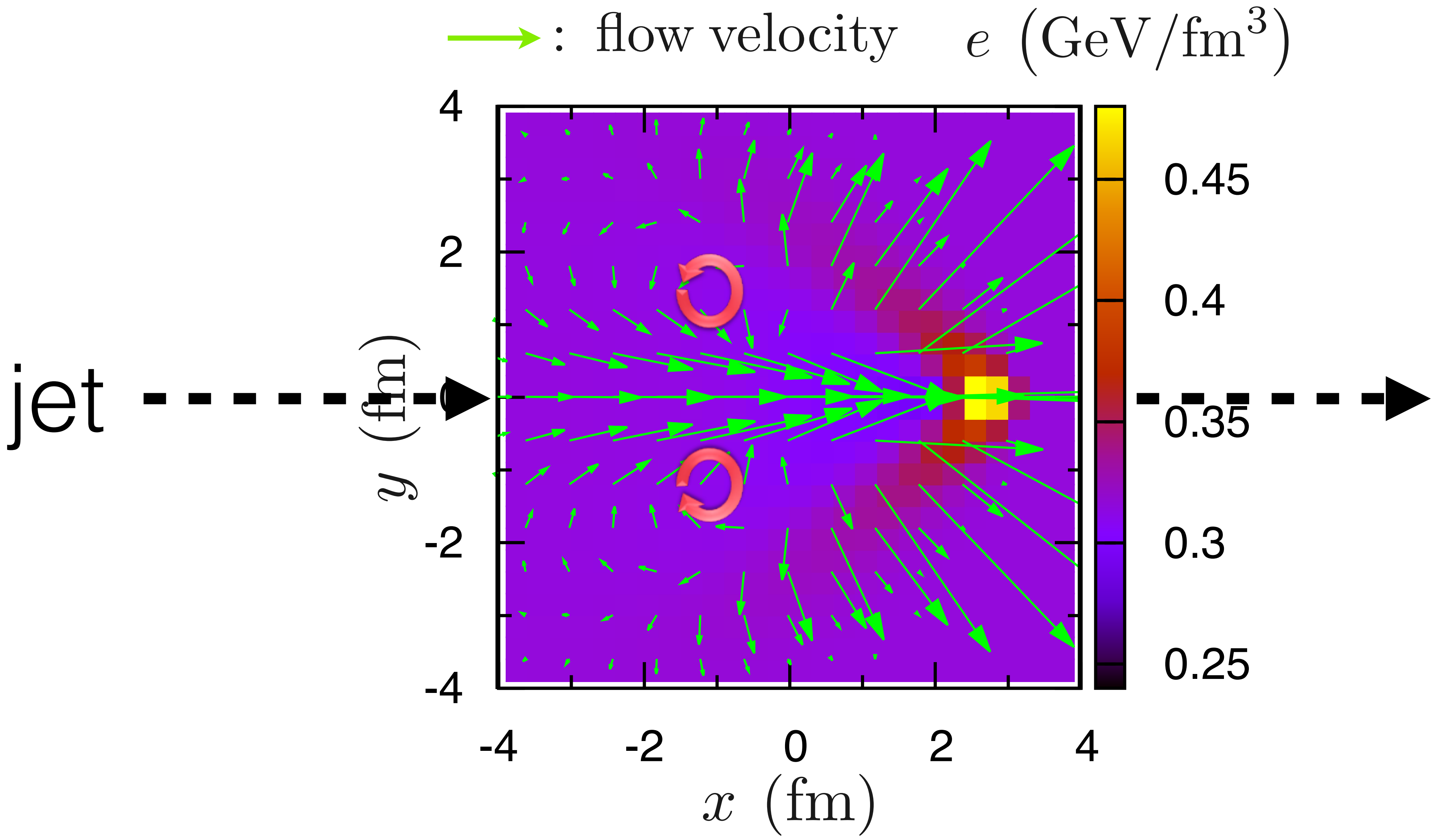
Similarly, positive Ξ P_H is observed at 27 GeV

- Consistent with Λ P_H and AMPT prediction with given large uncertainties

W.-T. Deng and X.-G. Huang, PRC93.064907 (2016)

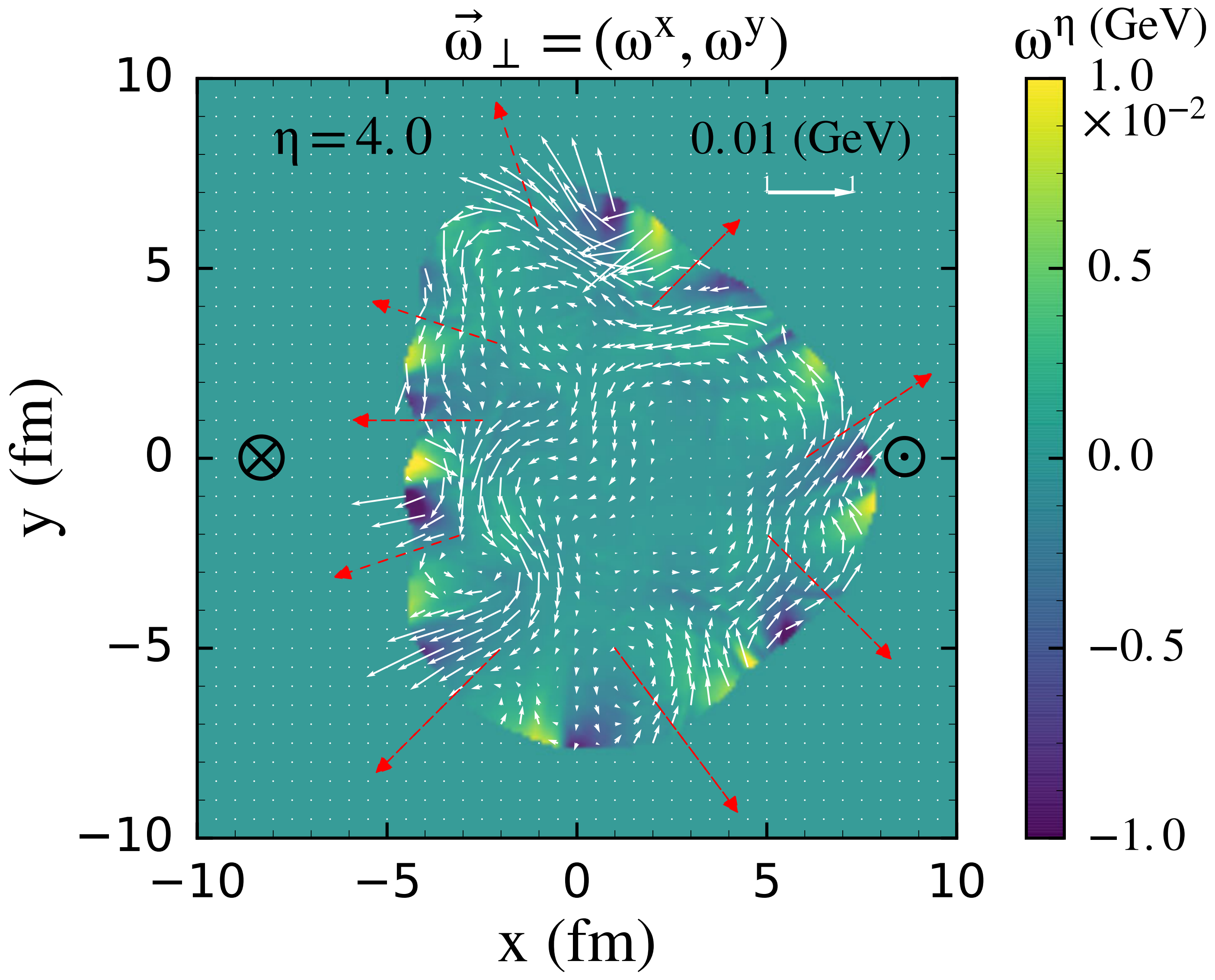
Local vorticity

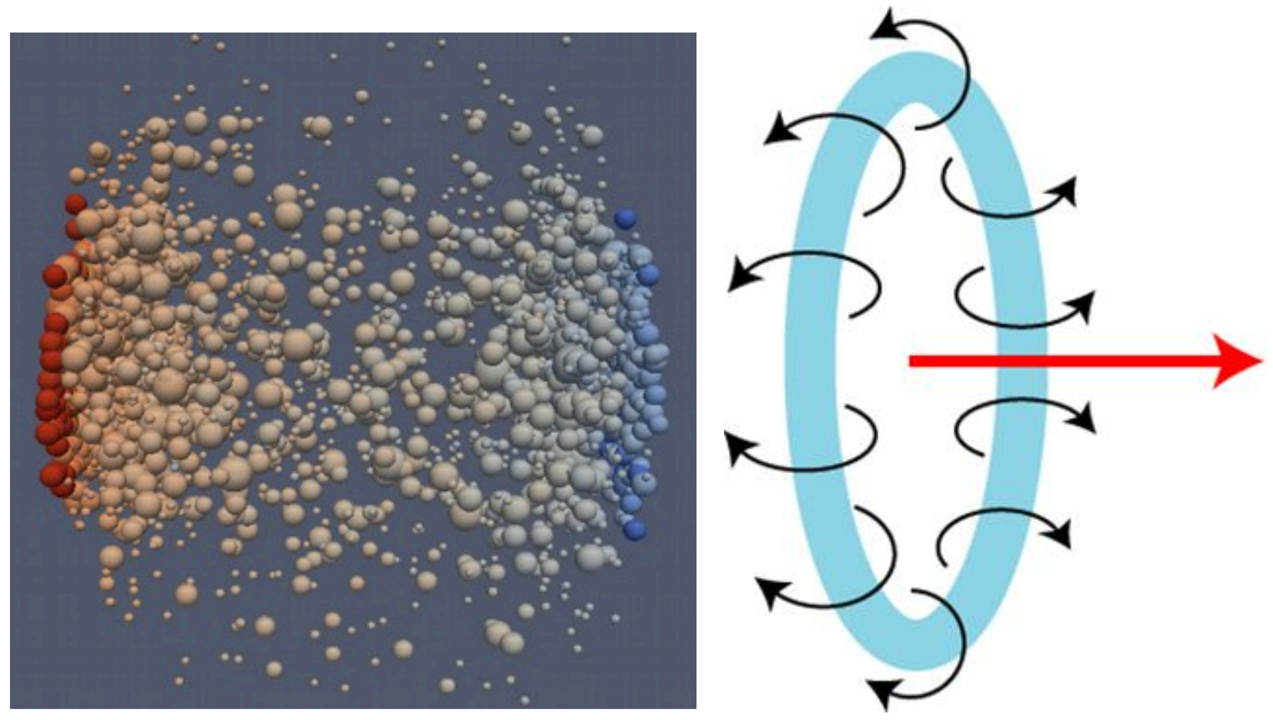
Vortex induced by jet



Y. Tachibana and T. Hirano, NPA904-905 (2013) 1023
B. Betz, M. Gyulassy, and G. Torrieri, PRC76.044901 (2007)

Local vorticity induced by collective flow



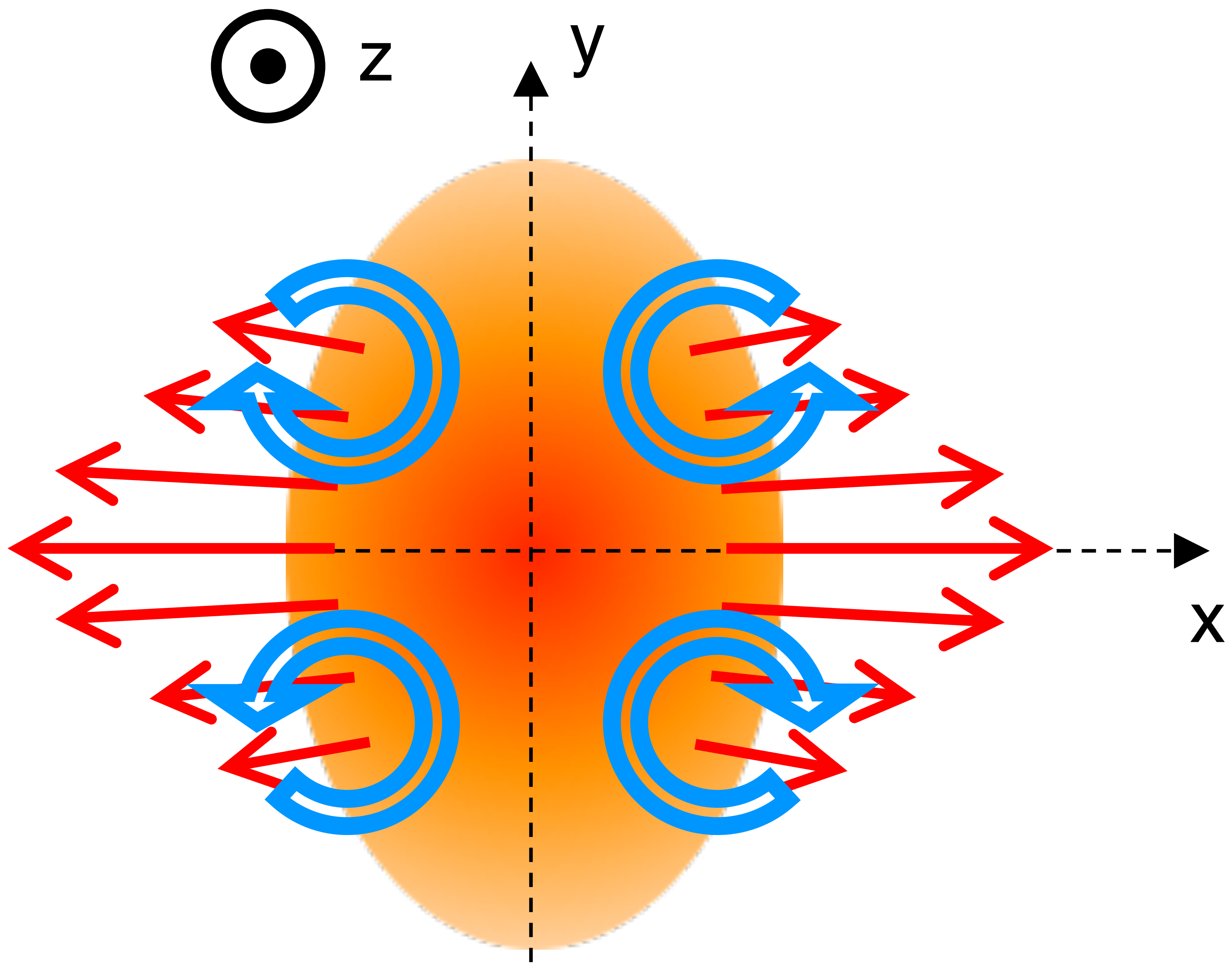


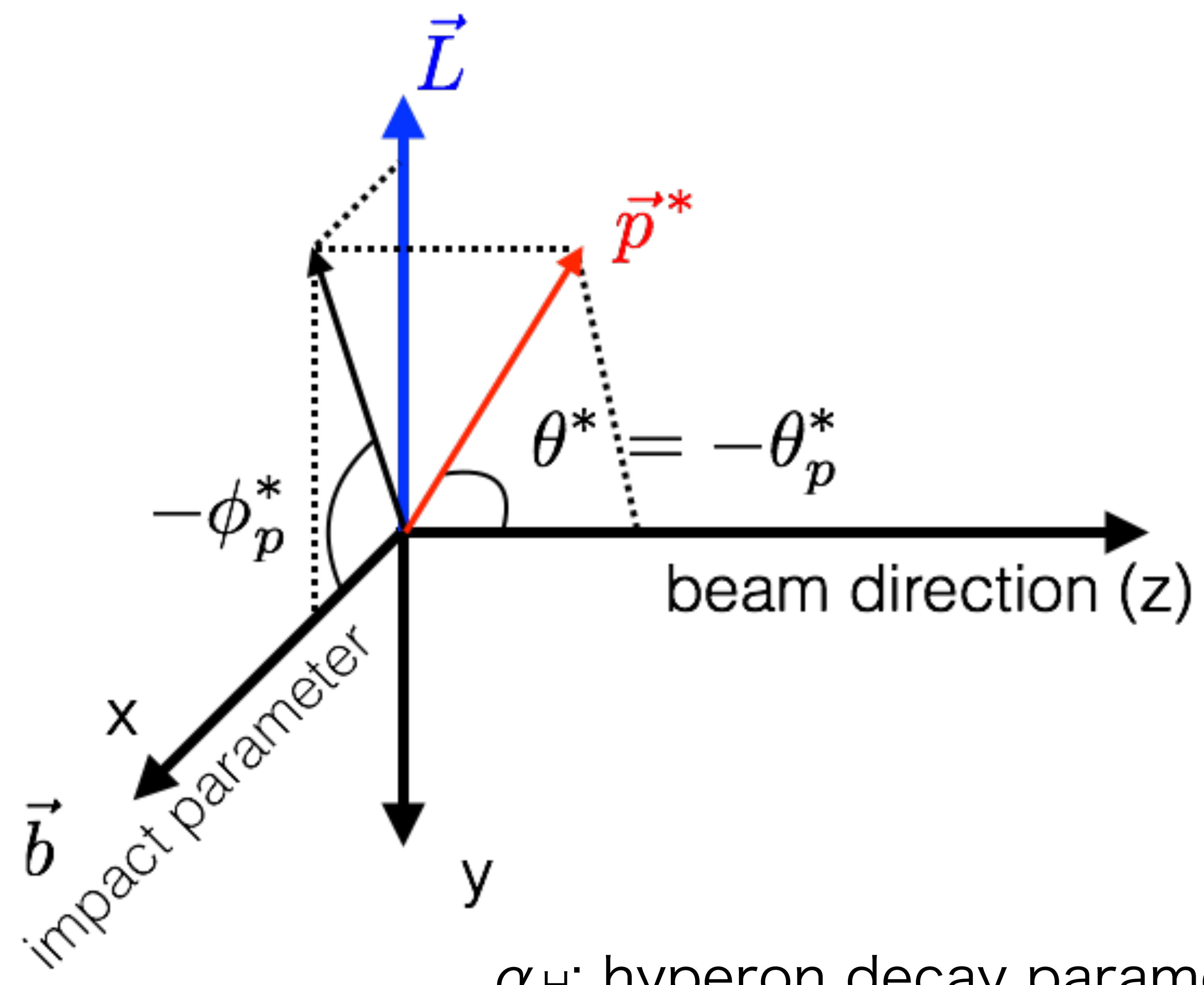
L.-G. Pang, H. Peterson, Q. Wang, and X.-N. Wang, PRL117, 192301 (2016)
F. Becattini and I. Karpenko, PRL120.012302 (2018)
S. Voloshin, EPJ Web Conf.171, 07002 (2018)
X.-L. Xia et al., PRC98.024905 (2018)

Polarization along the beam direction

S. Voloshin, SQM2017

F. Becattini and I. Karpenko, PRL120.012302 (2018)





$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_{\rm H}\mathbf{P_H}\cdot\mathbf{p}_p^*)$$

$$\langle\cos\theta_p^*\rangle = \int \frac{dN}{d\Omega^*}\cos\theta_p^* d\Omega^*$$

$$= \alpha_{\rm H} P_z \langle(\cos\theta_p^*)^2\rangle$$

$$\therefore\ P_z = \frac{\langle\cos\theta_p^*\rangle}{\alpha_{\rm H}\langle(\cos\theta_p^*)^2\rangle}$$

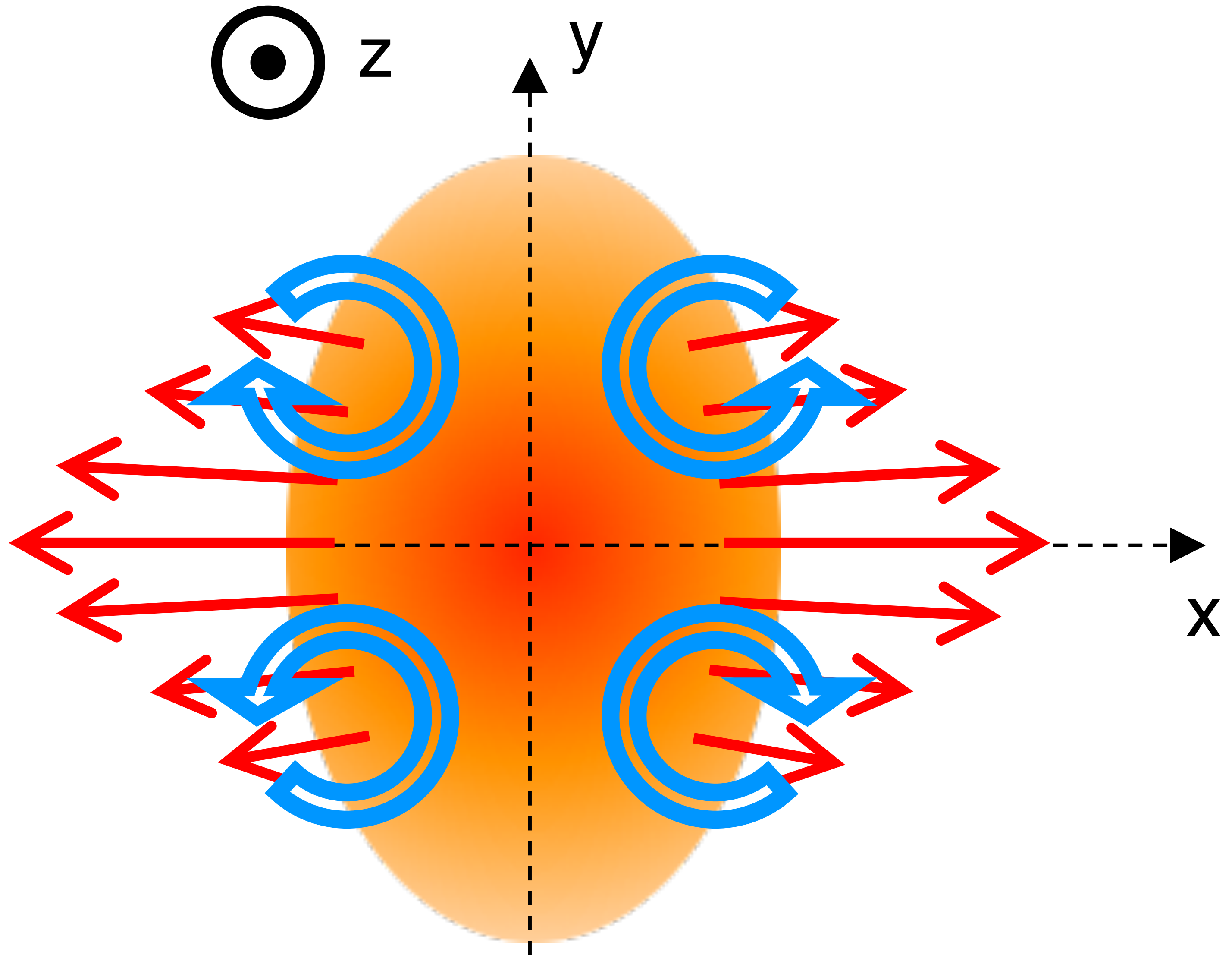
$$= \frac{3\langle\cos\theta_p^*\rangle}{\alpha_{\rm H}}$$ (if perfect detector)

$\alpha_{\rm H}$: hyperon decay parameter

θ_p^*: θ of daughter proton in Λ rest frame

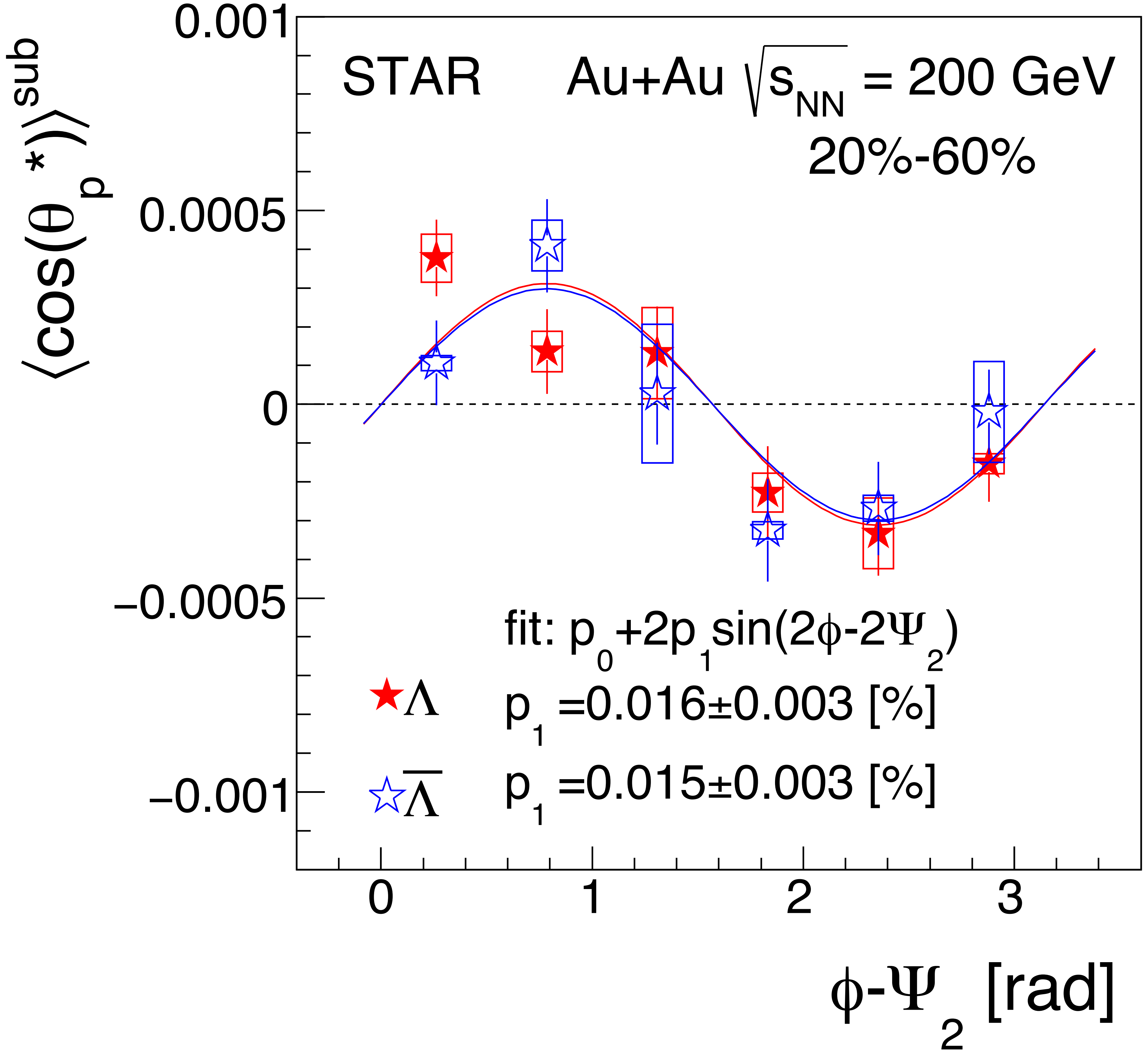
Stronger flow in in-plane than in out-of-plane, known as elliptic flow, makes local vorticity (thus polarization) along beam axis.

"z" polarization



$P_z \propto \langle \cos\theta_p^* \rangle$

STAR, PRL123.13201 (2019)



- Polarization <u>along the beam direction</u> expected from the "elliptic flow"
- Data indeed show such a longitudinal polarization P_z depending on azimuthal angle (sine function)

Disagreement in P_z sign

Opposite sign

- UrQMD IC + hydrodynamic model
  F. Becattini and I. Karpenko, PRL.120.012302 (2018)
- AMPT
  X. Xia, H. Li, Z. Tang, Q. Wang, PRC98.024905 (2018)

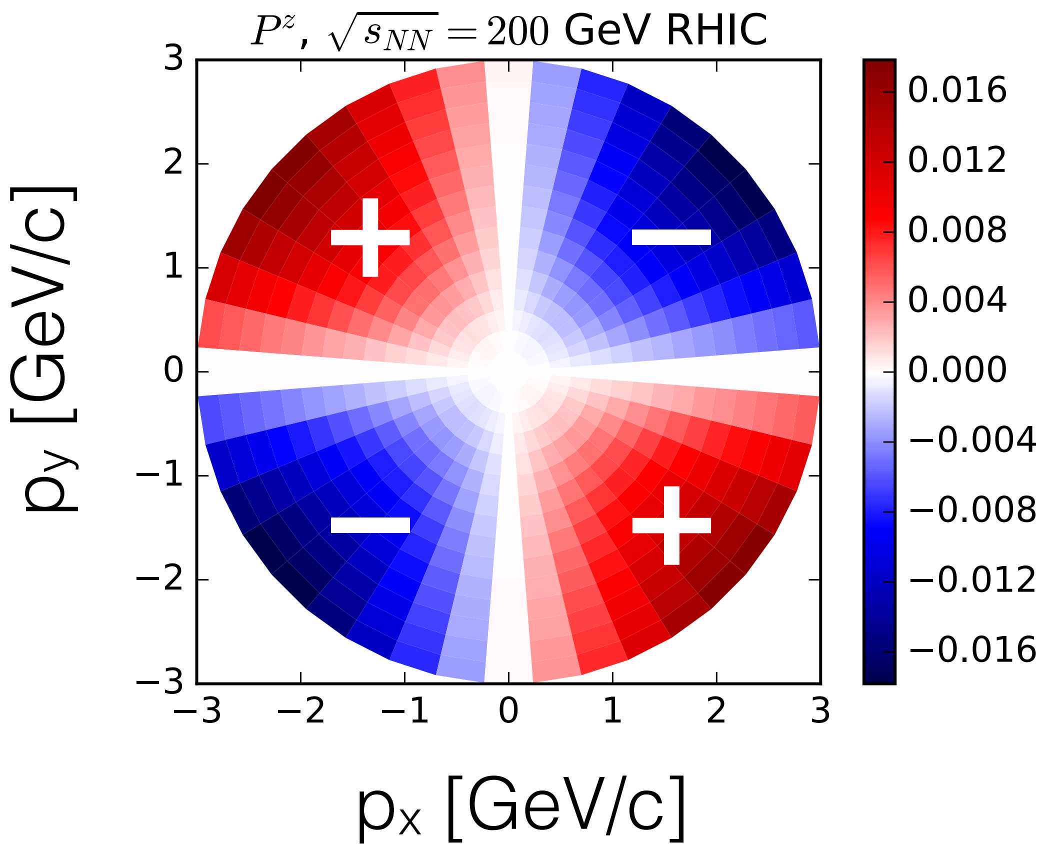
Same sign

- Chiral kinetic approach
  Y. Sun and C.-M. Ko, PRC99, 011903(R) (2019)
- High resolution (3+1)D PICR hydrodynamic model
  Y. Xie, D. Wang, and L. P. Csernai, EPJC80.39 (2020)
- Blast-wave model
  S. Voloshin, EPJ Web Conf.171, 07002 (2018), STAR, PRL123.13201

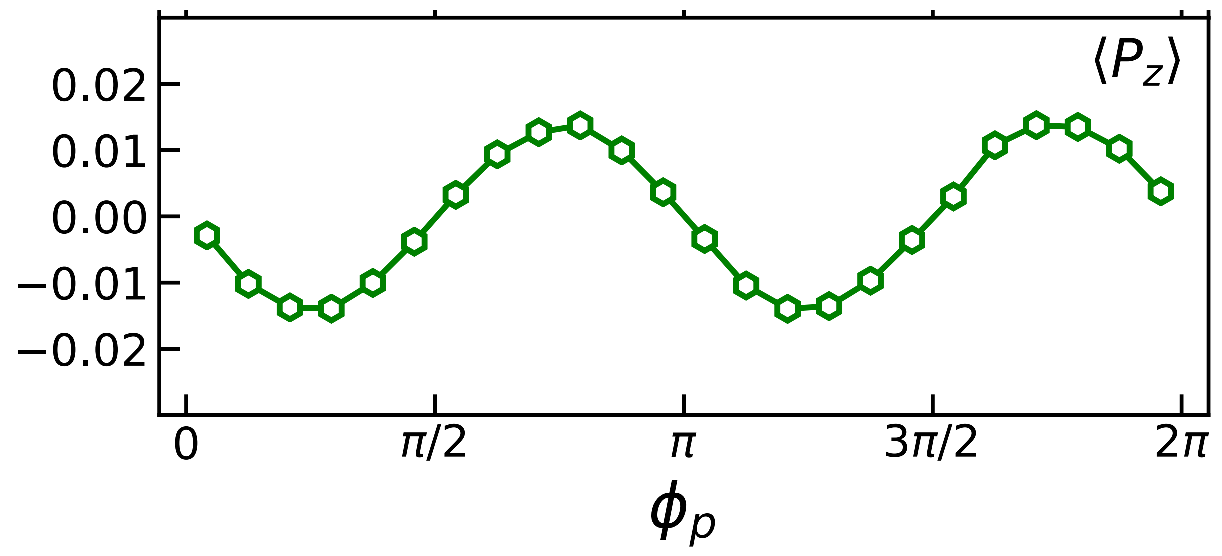
Partly (one of component showing the same sign)

- Glauber/AMPT IC + (3+1)D viscous hydrodynamics
  H.-Z. Wu et al., Phys. Rev. Research 1, 033058 (2019)
- Thermal model
  W. Florkowski et al., Phys. Rev. C 100, 054907 (2019)

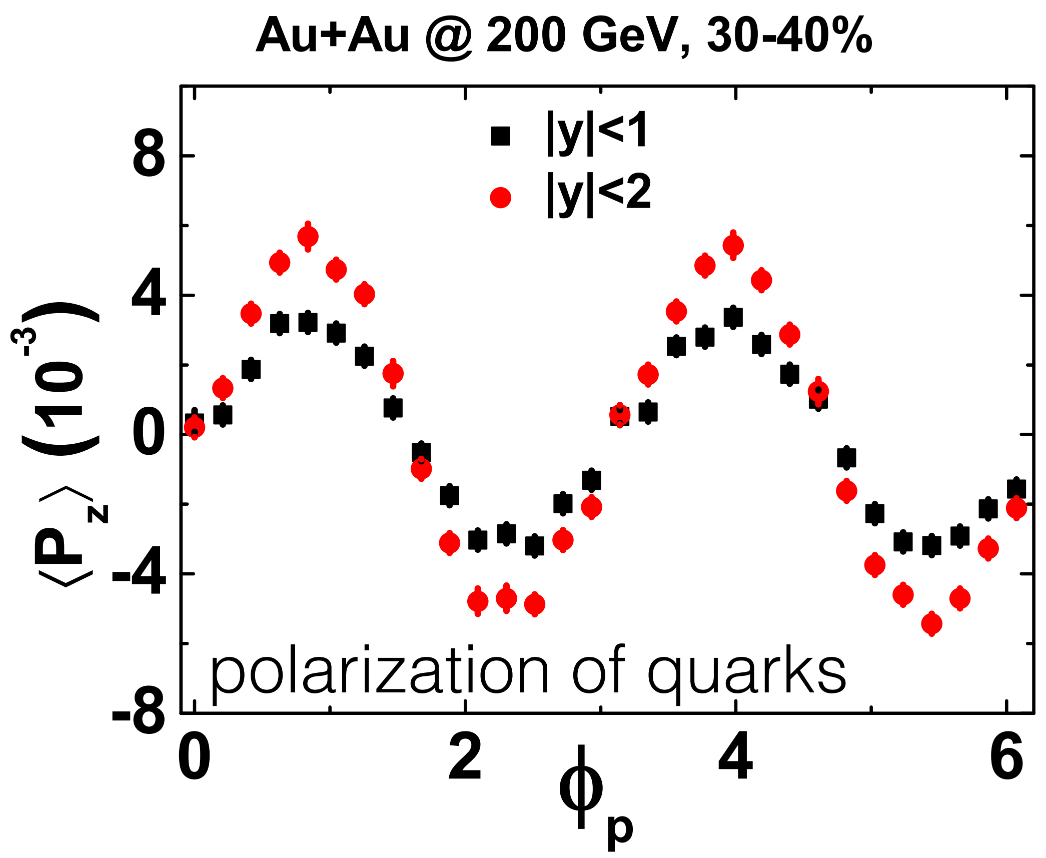
Hydrodynamic model



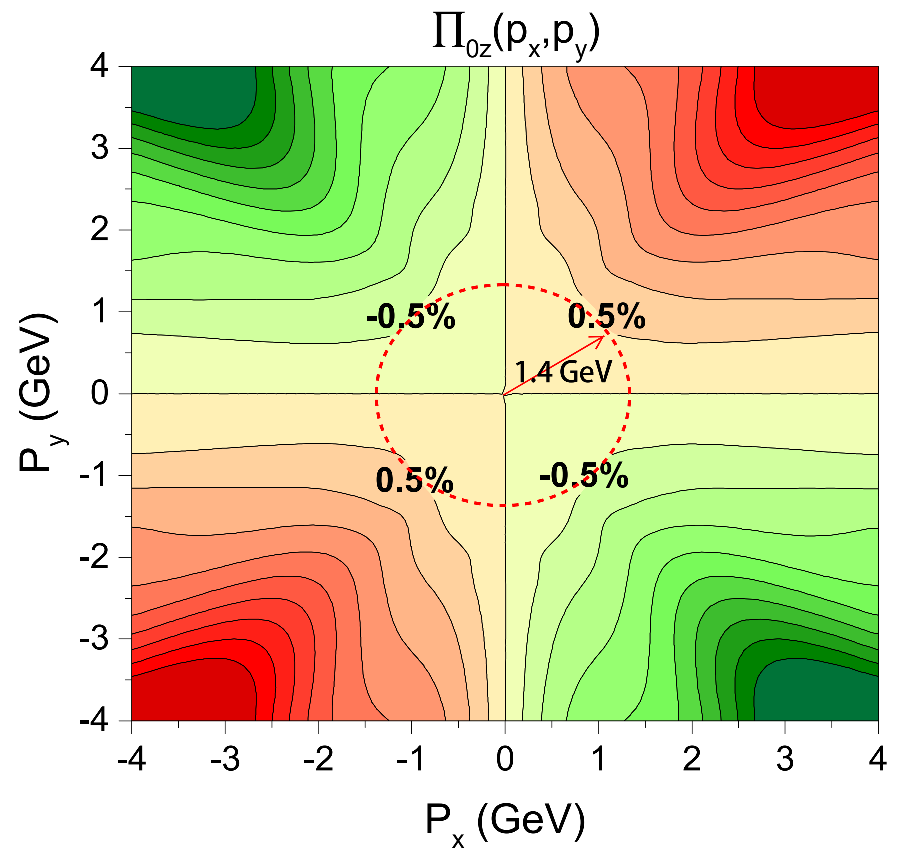
AMPT, Au+Au 200 GeV 20-50%



Chiral kinetic approach



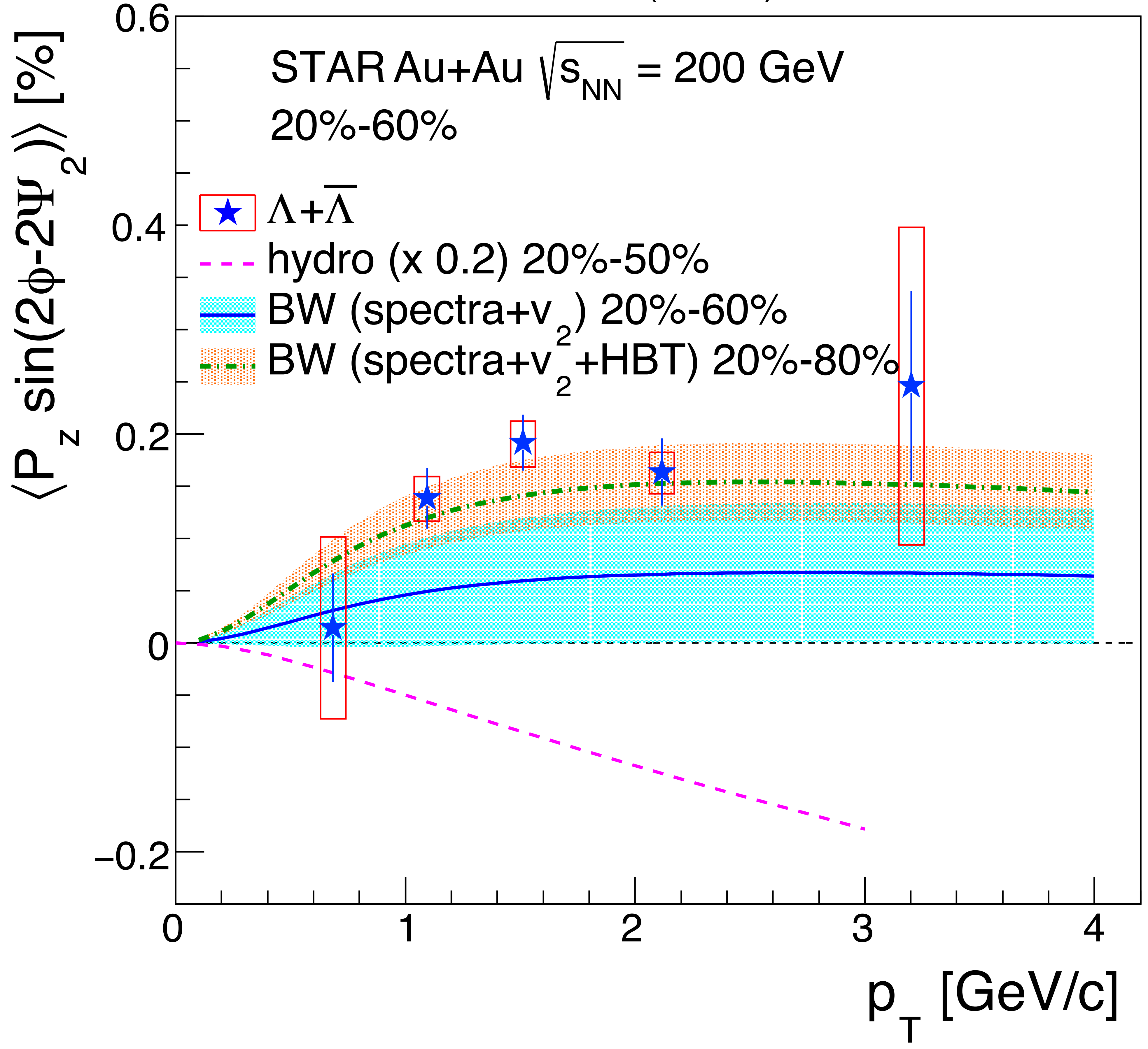
PICR model



Incomplete thermal equilibrium of spin degree of freedom?

P_z modulation

STAR, PRL123.13201 (2019)



- Estimate with Blast-wave model (BW)
  - Calculate vorticity using the freeze-out parameters extracted from the fits to spectra, v_2, and HBT

    BW parameters: STAR, PRC71.044906 (2005)
  - Convert the vorticity to polarization: $P_z \approx \omega_z/(2T)$

$$\langle \omega_z \sin(2\phi) \rangle = \frac{\int d\phi_s \int rdr\, I_2(\alpha_t) K_1(\beta_t) \omega_z \sin(2\phi_b)}{\int d\phi_s \int rdr\, I_0(\alpha_t) K_1(\beta_t)}$$

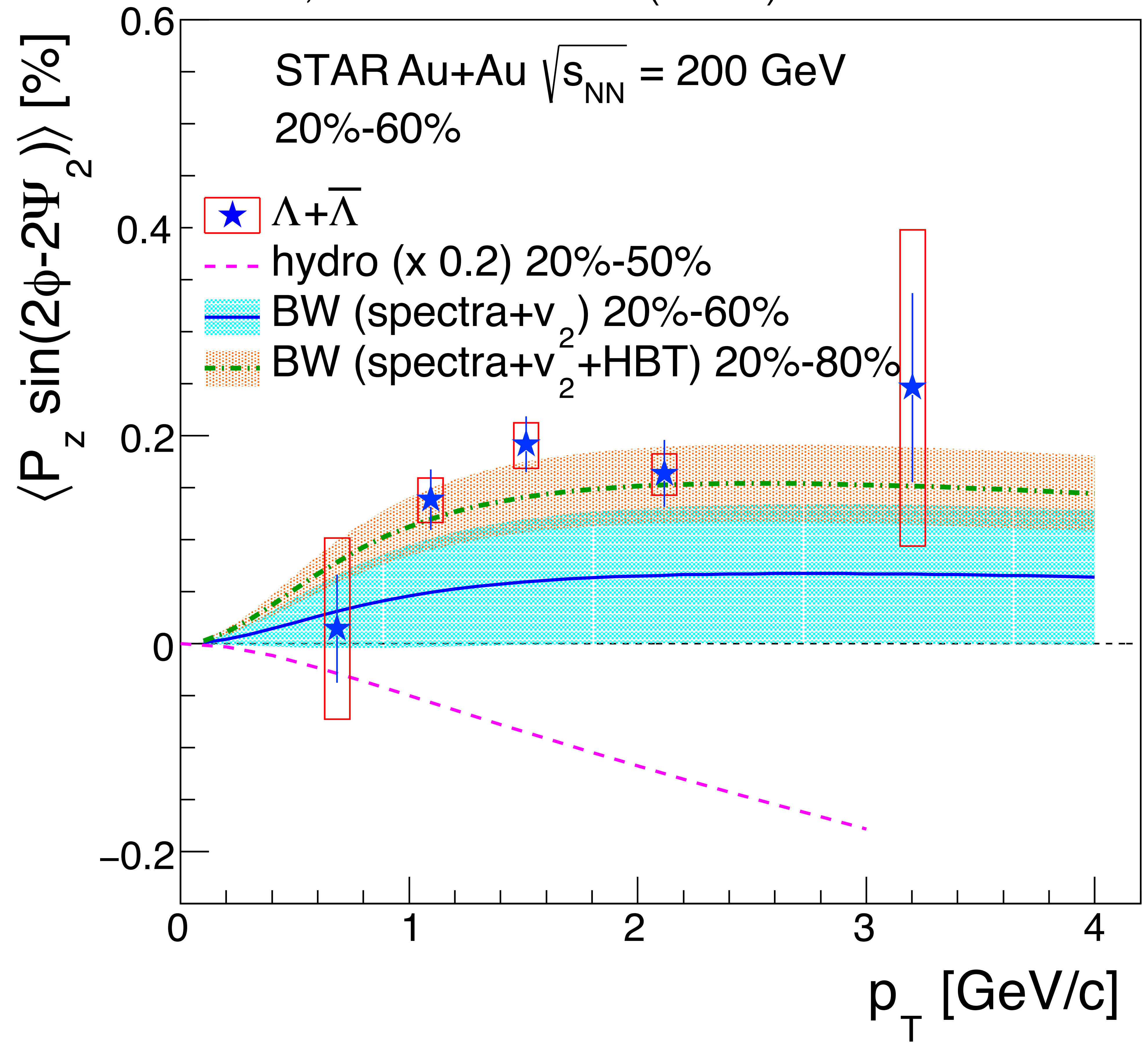
$$\omega_z = \frac{1}{2}\left(\frac{\partial u_y}{\partial x} - \frac{\partial u_x}{\partial y}\right),$$

u_i: local flow velocity
ϕ_s: azimuthal angle of the source element
ϕ_b: boost angle perpendicular to the elliptical subshell

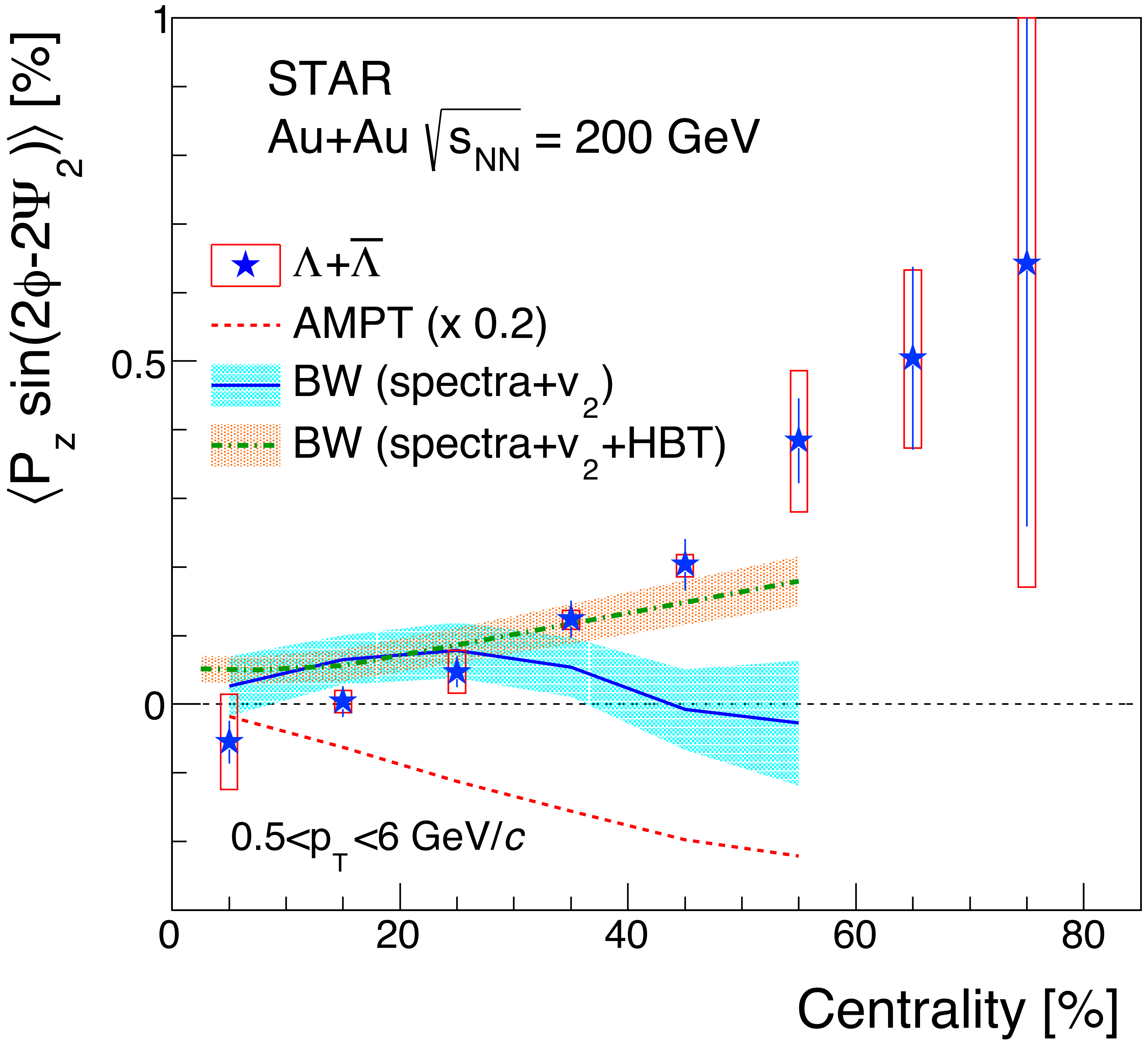
- Hydro-inspired BW model describes the data but more realistic models don’t. Why?
- “T-vorticity" (temperature gradient) may play an important role

P_z modulation

STAR, PRL123.13201 (2019)



BW parameters obtained with HBT: STAR, PRC71.044906 (2005)



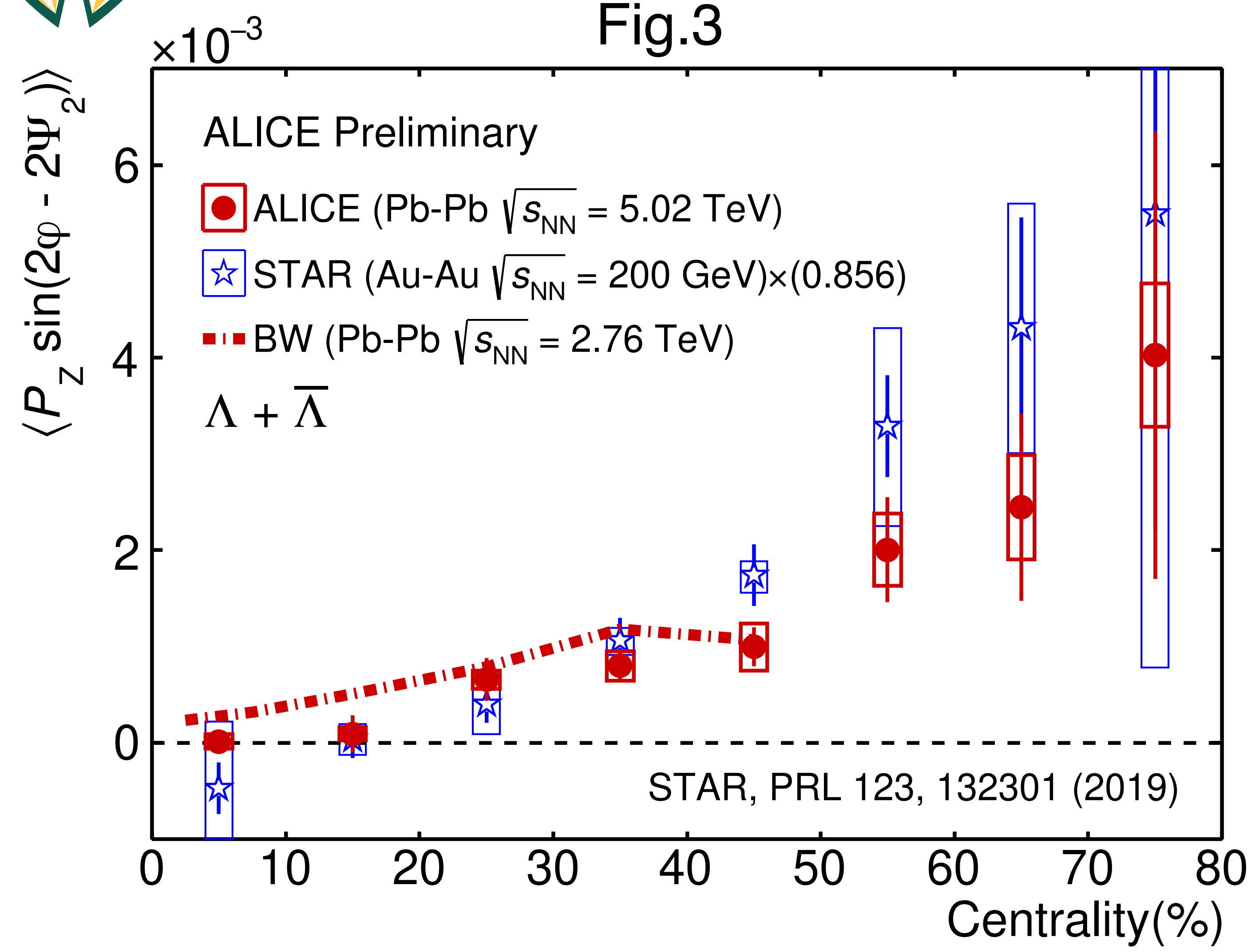
- Blast-Wave model as a simple estimate for kinematic vorticity can describe the data
- Strong centrality dependence as in v_2

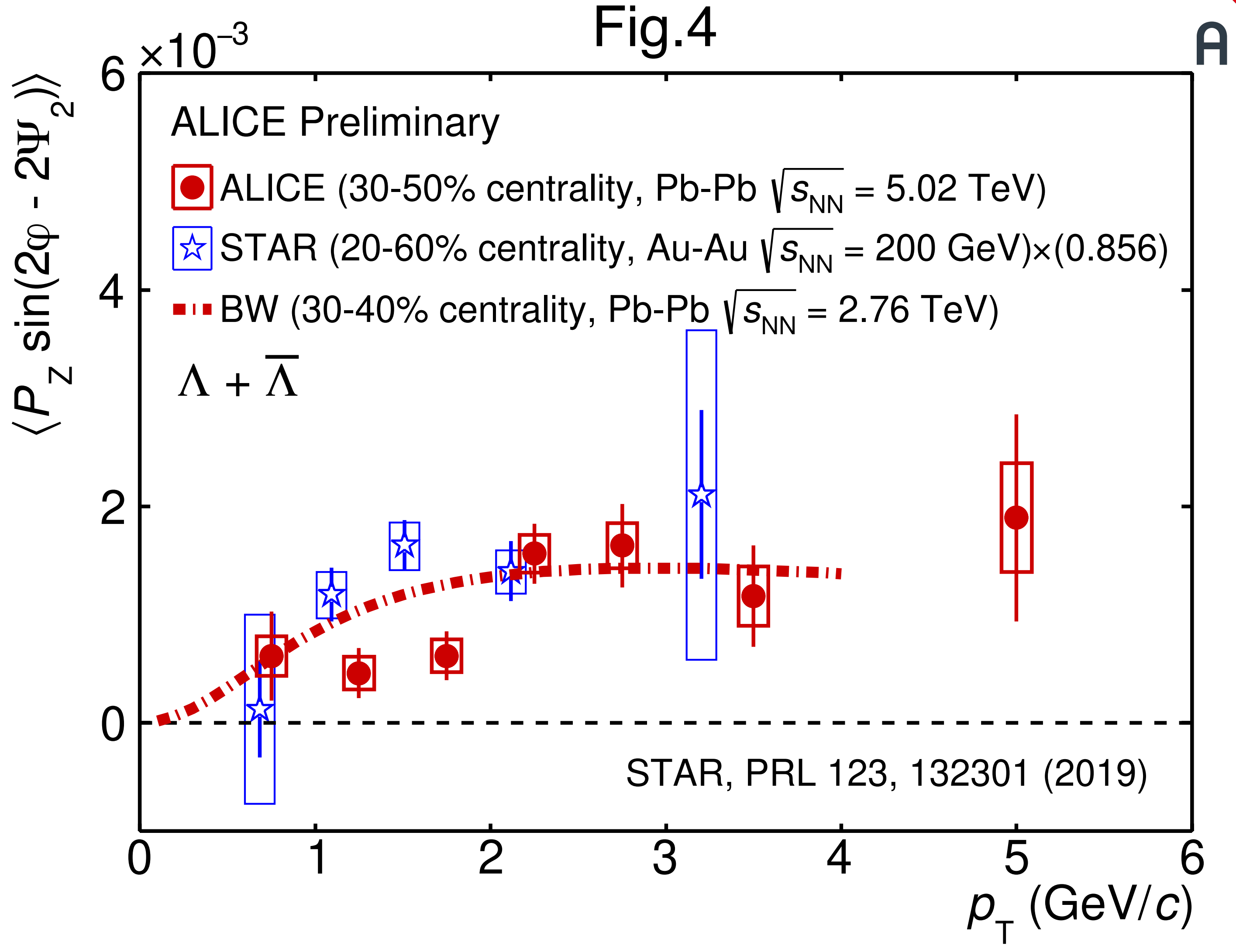
P_z measurement at the LHC

D. Sarkar (ALICE), IS2021

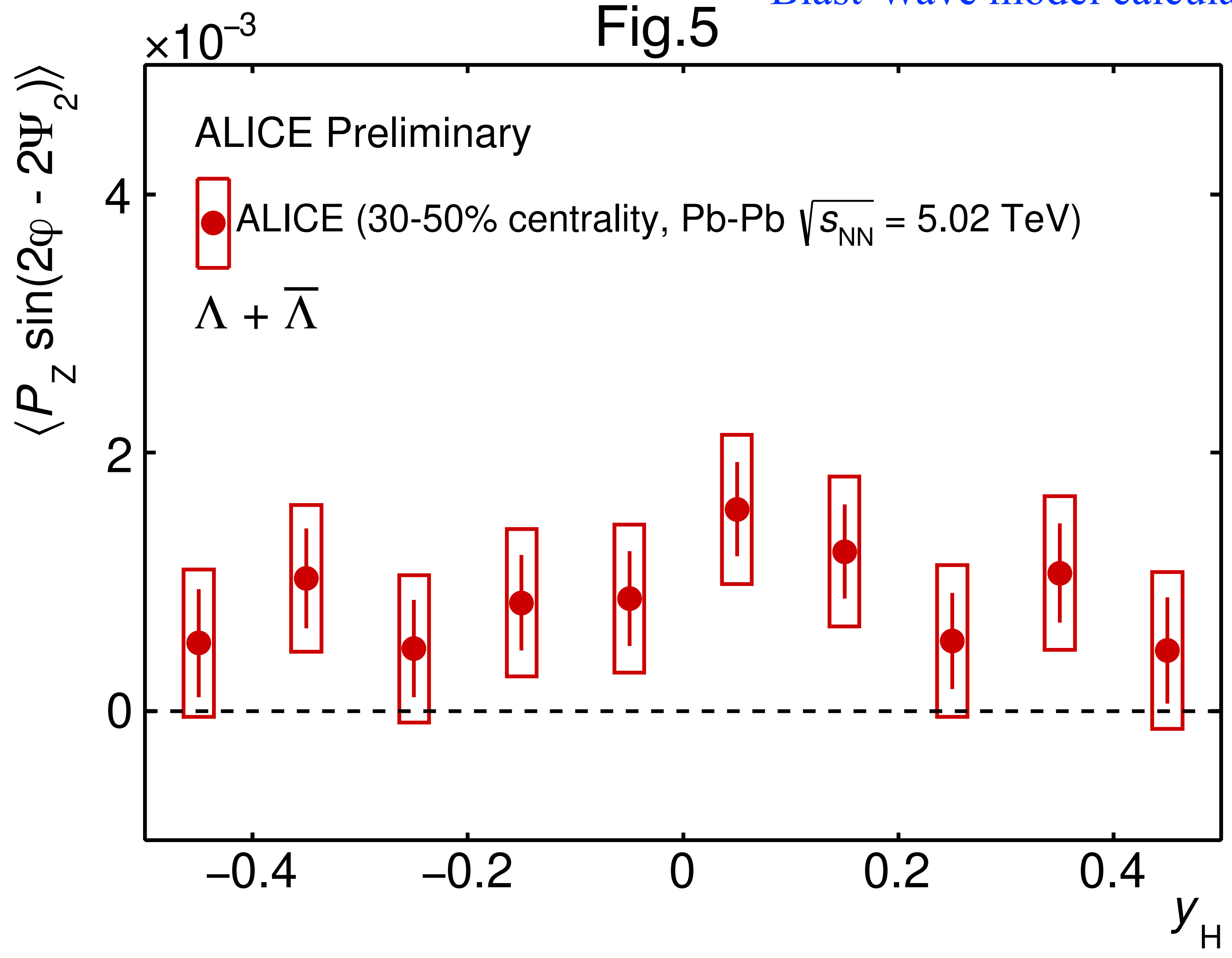
Similar P_z at the LHC!

P_z in Pb-Pb collisions at 5.02 TeV in ALICE





Blast-Wave model calculation: Takafumi Niida and Sergei Voloshin (private communication)



- STAR: α_H= 0.642, ALICE: α_H= 0.750. STAR results are scaled with (0.642/0.750).
- **P_z at the LHC is similar in magnitude (might be somewhat smaller in semi-central and peripheral collisions) compared to P_Z at top RHIC energy.**
- **The sign of phase modulation of P_z is the same at RHIC and the LHC. This is also the same as estimated by the Blast-Wave model.**

if time permits…

Other related observables

spin alignment, **directed flow**, chiral vortical effect…

Global spin alignment of vector mesons

Angular distribution of the decay products can be written with spin density matrix ρ_{nn}.

$$\frac{dN}{d\cos\theta^*} \propto \rho_{0,0}|Y_{1,0}|^2 + \rho_{1,1}|Y_{1,-1}|^2 + \rho_{-1,-1}|Y_{1,1}|^2 \propto \rho_{0,0}\cos^2\theta^* + \frac{1}{2}(\rho_{1,1} + \rho_{-1,-1})\sin^2\theta^*$$

$$\propto (1 - \rho_{0,0}) + (3\rho_{0,0} - 1)\cos^2\theta^*$$

$$\rho_{00} = \frac{1}{3} - \frac{8}{3}\langle\cos[2(\phi_p^* - \Psi_{RP})]\rangle$$

Species	K^{*0}	φ
Quark content	$d\bar{s}$	$s\bar{s}$
Mass (MeV/c²)	896	1020
Lifetime (fm/c)	4	45
Spin (J^P)	1^-	1^-
Decays	Kπ	KK
Branching ratio	**~100%**	66%

Deviation from 1/3 in ρ_{00} indicates spin alignment.

* sign of the polarization cannot be determined. Therefore it's called "spin alignment measurement" rather than "polarization measurement"

Z.-T. Liang and X.-N. Wang, PRL94.102301(2005)
Y. Yang et al., PRC97.034917(2018)

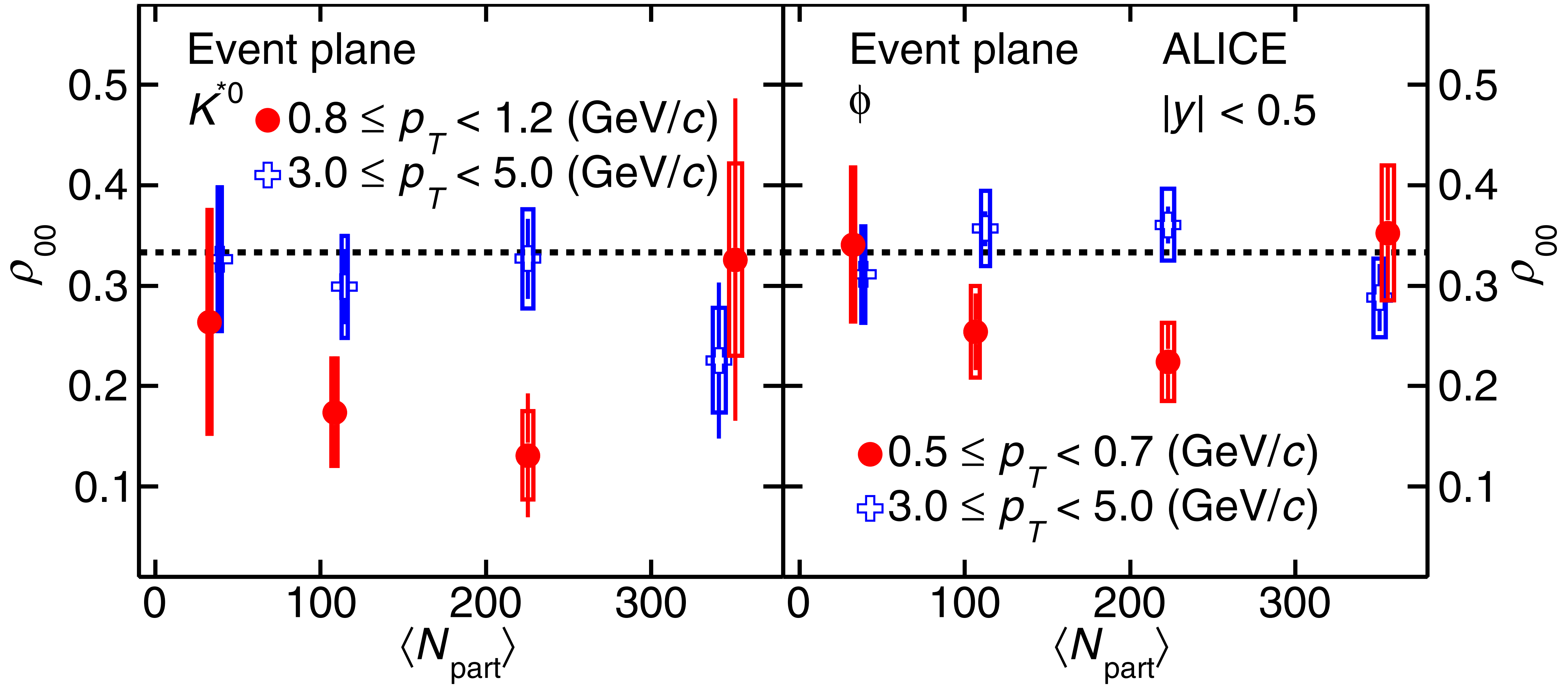
Theoretical expectation for ρ_{00}

Vorticity	
recombination	$\rho_{00} < 1/3$
fragmentation	$\rho_{00} > 1/3$
Magnetic field	$\rho_{00} > 1/3$ (for neutral vector mesons)

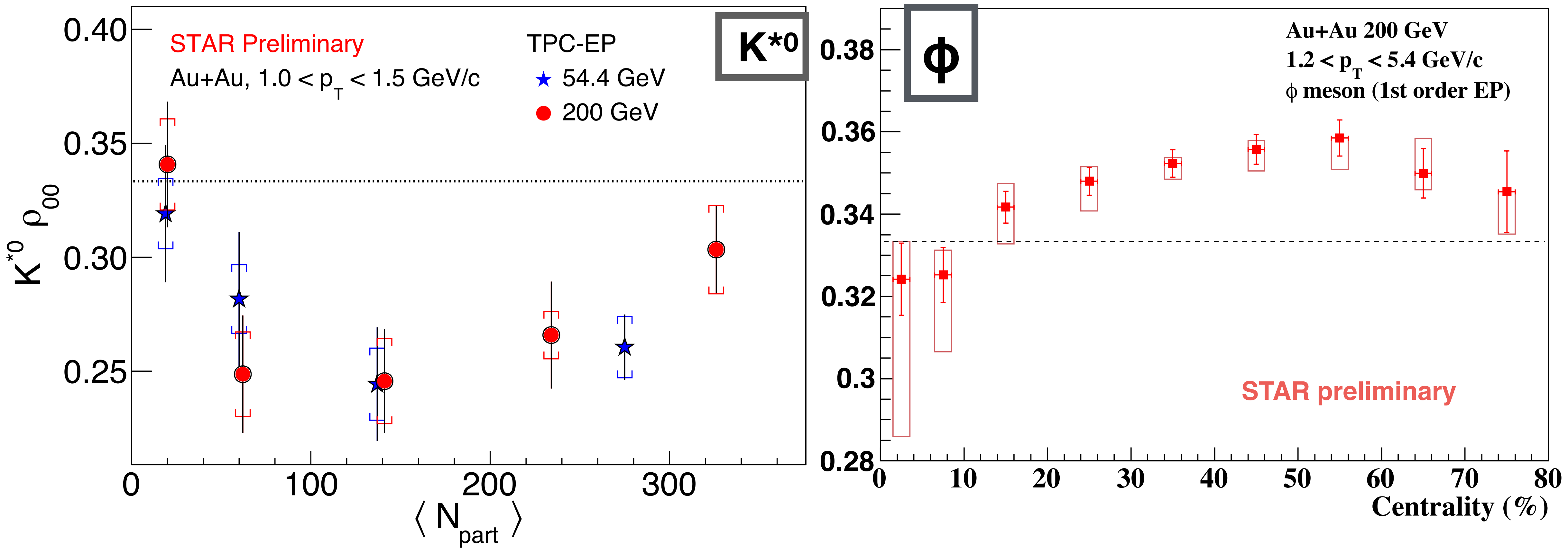
ρ_{00} depends on hadronization process

Spin alignment at the LHC and RHIC

ALICE, PRL125.012301 (2020)



STAR, QM18, QM19



- Large deviation from 1/3 cannot be explained by the vorticity picture

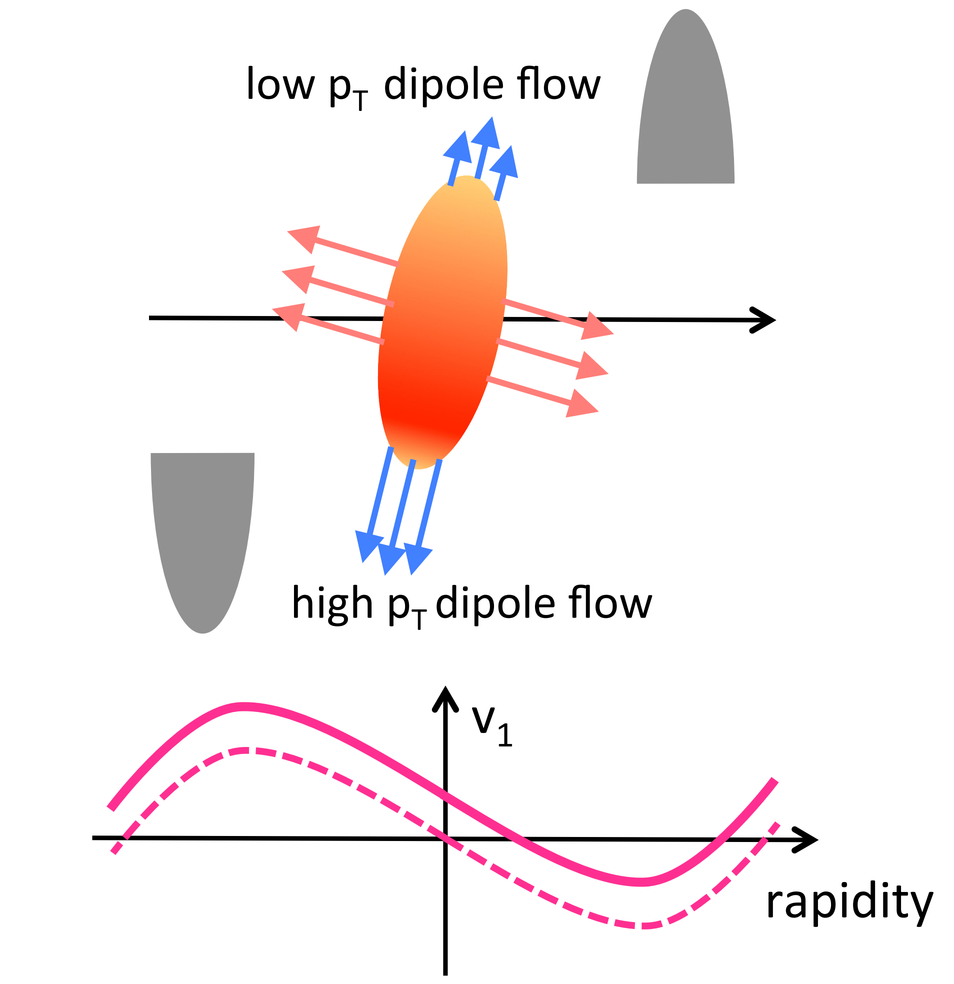
$$\rho_{00} = 1/[3 + (\omega/T)^2].$$

- The deviation in opposite way between:
  - K* and ϕ at RHIC
  - LHC and RHIC for ϕ

Mean field of ϕ meson may play a role?
Does it change from RHIC to LHC only for ϕ?

X. Sheng, L. Oliva, and Q. Wang, PRD101.096005(2020)
X. Sheng, Q.Wang, and X. Wang, PRD102.056013 (2020)

Directed flow and vorticity/global polarization



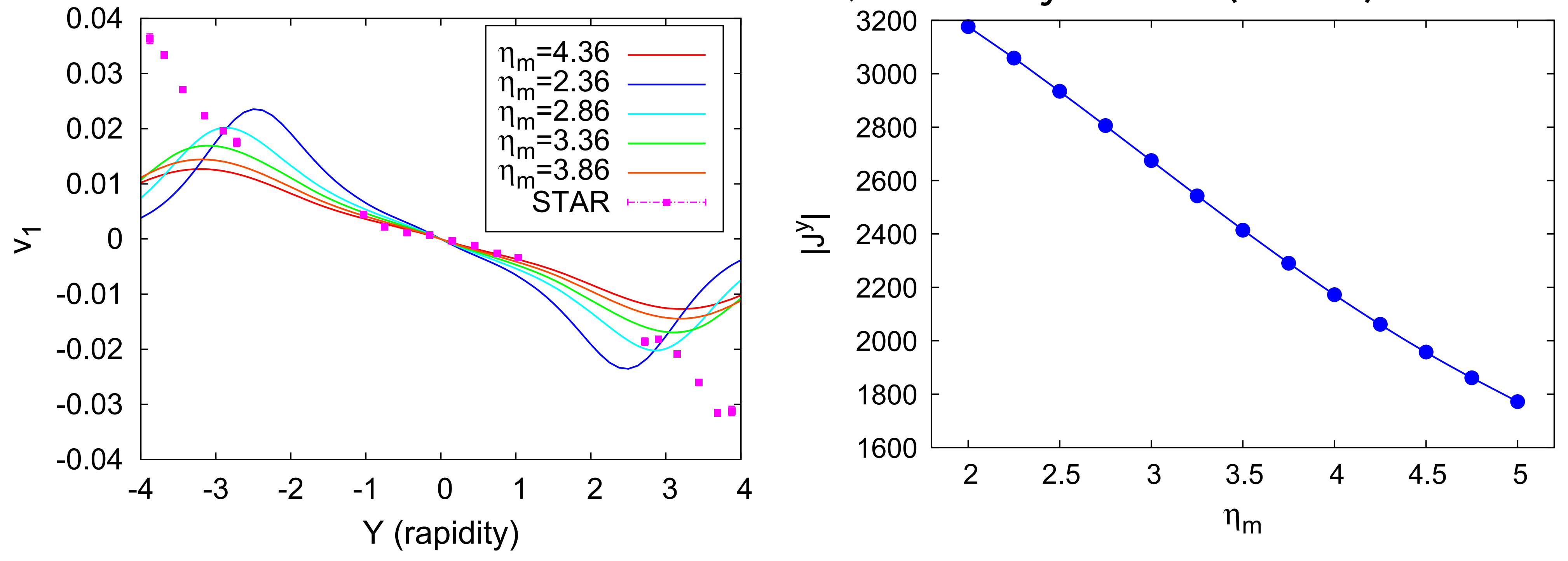
- Two contributions to v_1
  initial tilt + density asymmetry

  P. Bozek and I. Wyskiel, PRC81.054902 (2010)
  U. Heinz and P. Kolb, J.Phys.G30:S1229 (2004)

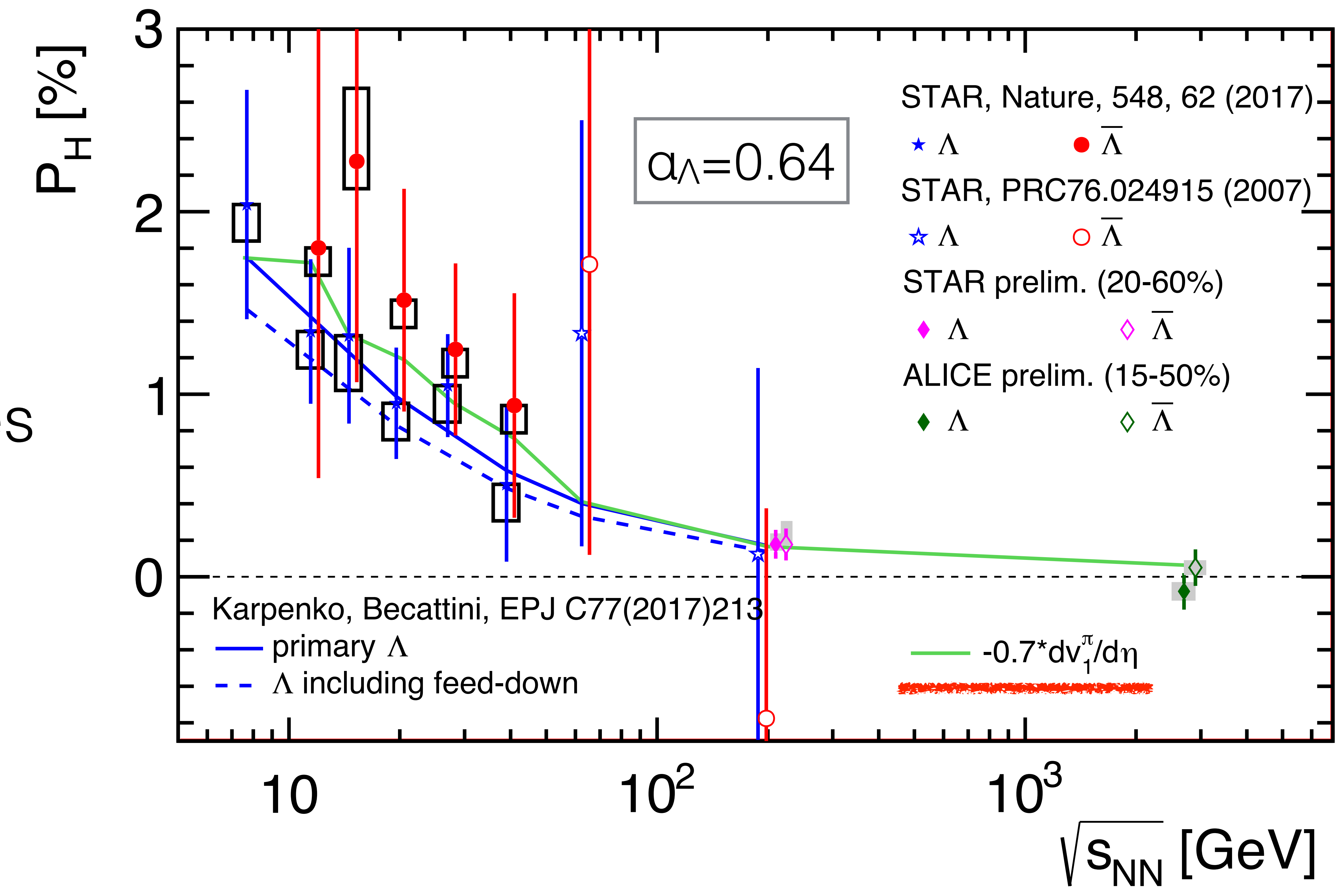
- Relative contribution from the tilt can be studied by $<p_x>$ and v_1 slopes

  STAR, PRC98.014915 (2018)
  ALICE, PRL111.232302 (2013)

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



S. Voloshin, EPJ Web Conf.171, 07002 (2018)



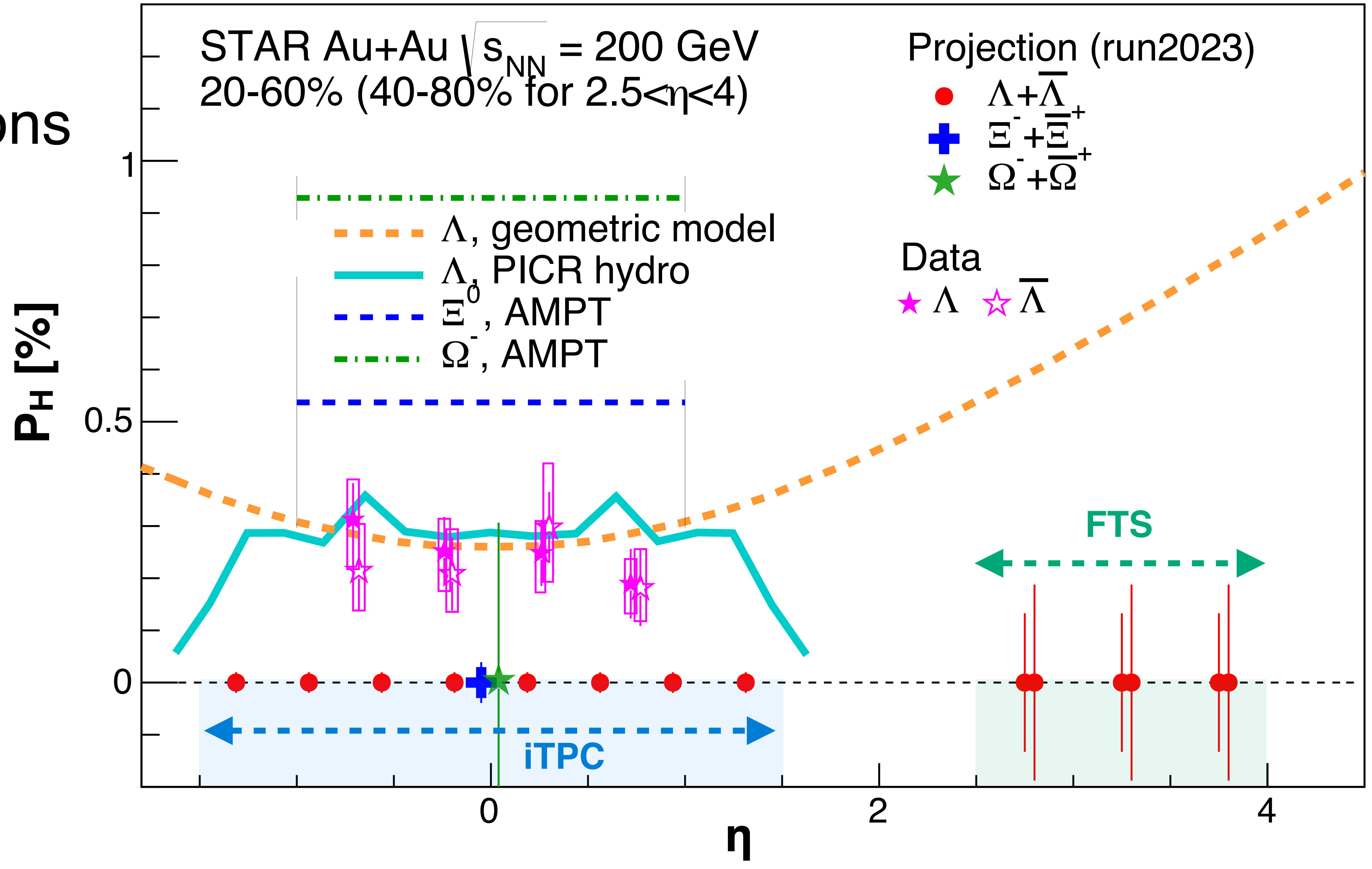
- Better description of v_1 with the tilted source which accounts for vorticity.

- v_1 slope seems to follow the trend of P_H
-> expect P_H(LHC) ~ P_H(RHIC-top)/2

Outlook

- More precise/differential measurements can be done in the coming years
  - High statistics data of BES-II 7.7-19.6 GeV and FXT 3-7.7 GeV (STAR)
  - Isobaric collision data (Ru+Ru, Zr+Zr), ~10% difference in B-field (STAR)
  - Lower energies from STAR-FXT, HADES, CBM, NICA, JPARC-HI…
  - LHC: Ξ/Ω global polarizations, local polarizations
  - STAR forward upgrade in 2023 (200 GeV)

BUR2020, STAR Note SN0755



Summary

- Global and local polarization of Λ hyperons has been observed in heavy-ion collisions
  - Most vortical fluid (ω~10^{21} s^{-1}) created in heavy-ion collisions
  - Energy dependence of global polarization, increasing in lower $\sqrt{s_{NN}}$, is captured well by theoretical models, but there are sign problems to be understood
- First measurements of Ξ(s=1/2) and Ω(s=3/2) global polarizations
  - Positive Ξ polarization, comparable to or slightly higher than Λ and close to AMPT
  - Current result on Ω has large uncertainty, which can be improved in future analysis

There are still many open questions and more precise measurements are needed for better understanding the nature of vorticity and polarization in HIC.

Back up

Variations of model parameters for P_H

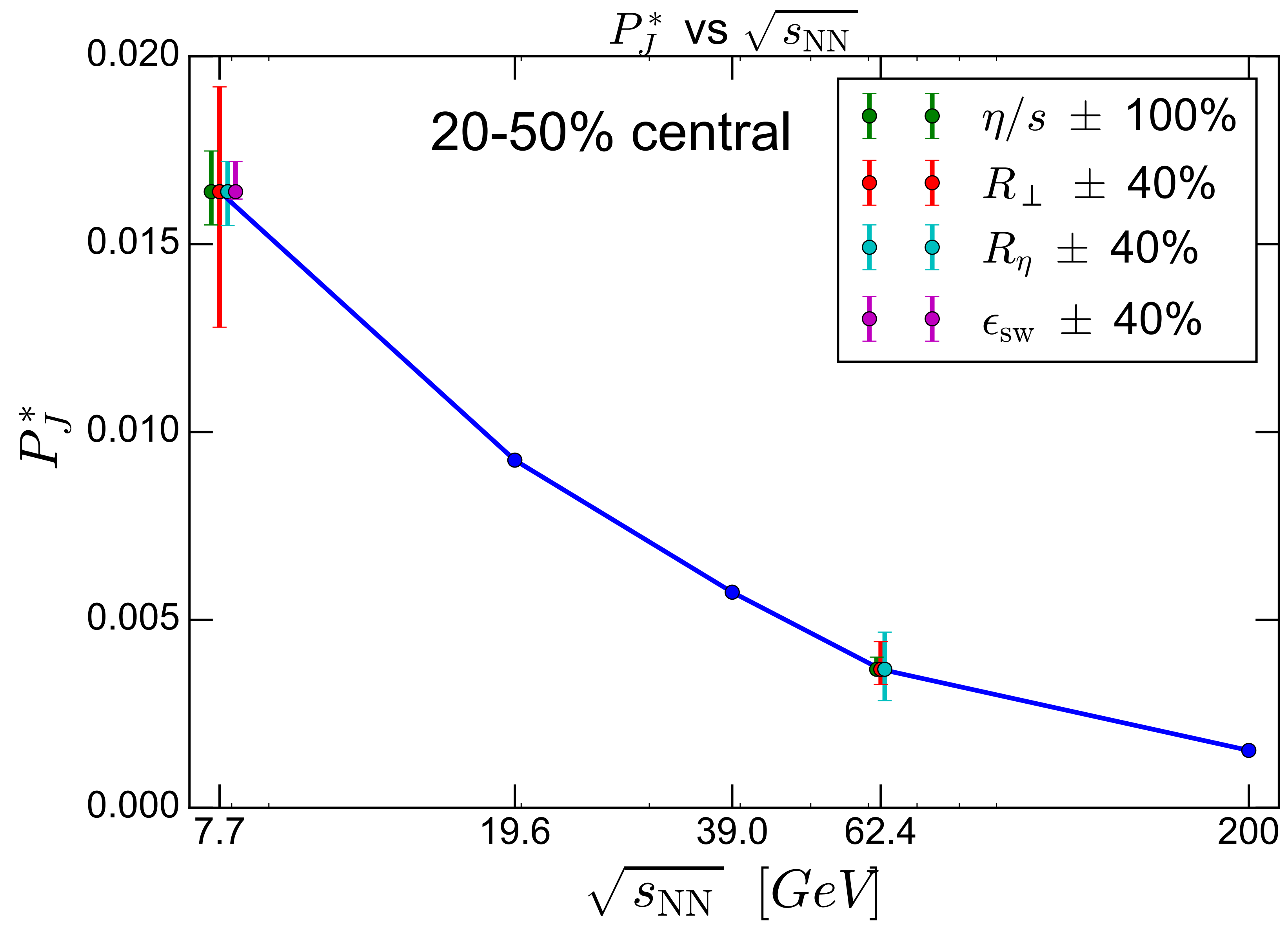
I. Karpenko, QM2017

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

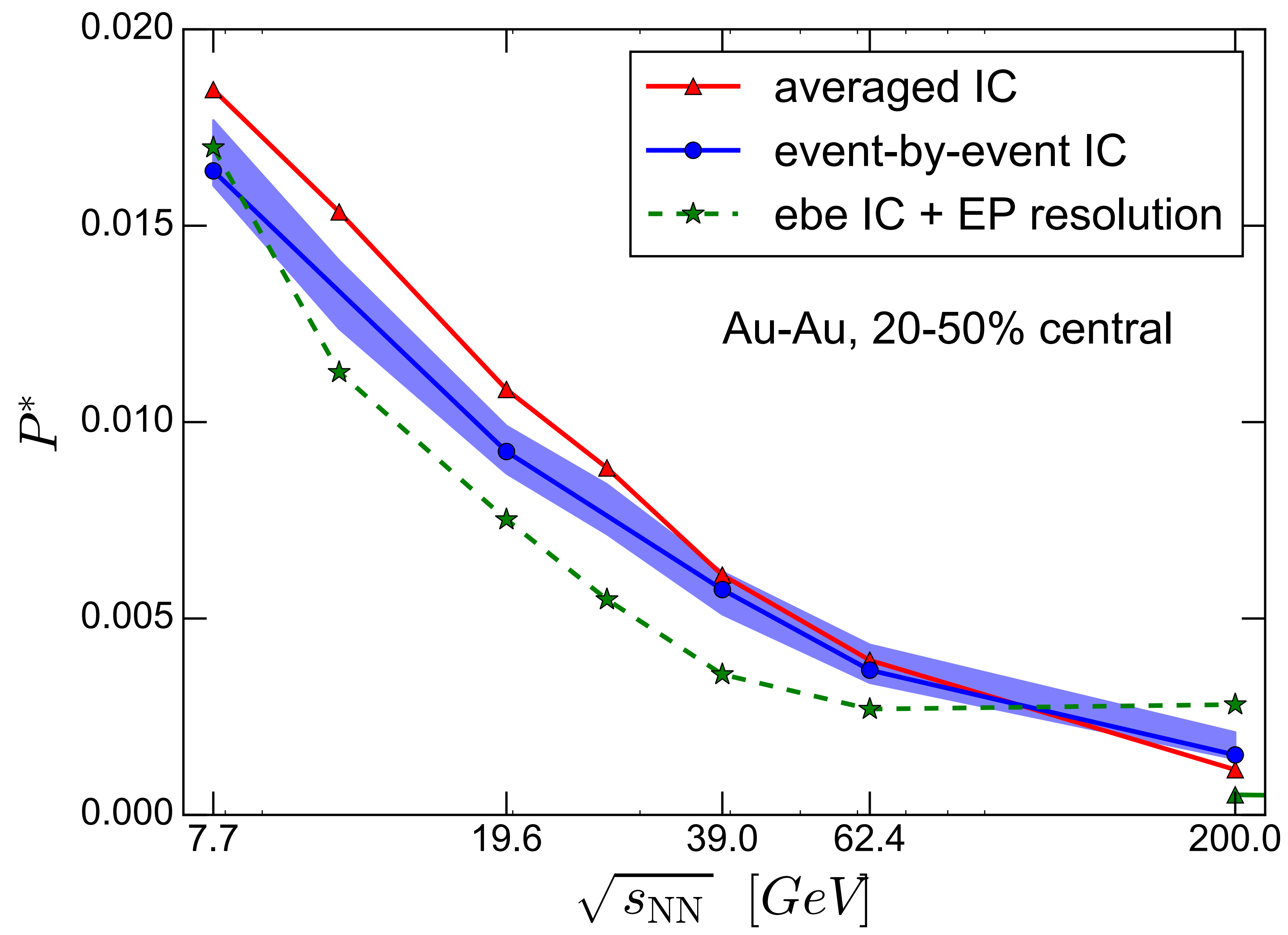
Fluid phase:
η/s: shear viscosity of fluid

Particlization criterion:
$\varepsilon_{sw} = 0.5$ GeV/fm^3

variation of model parameters



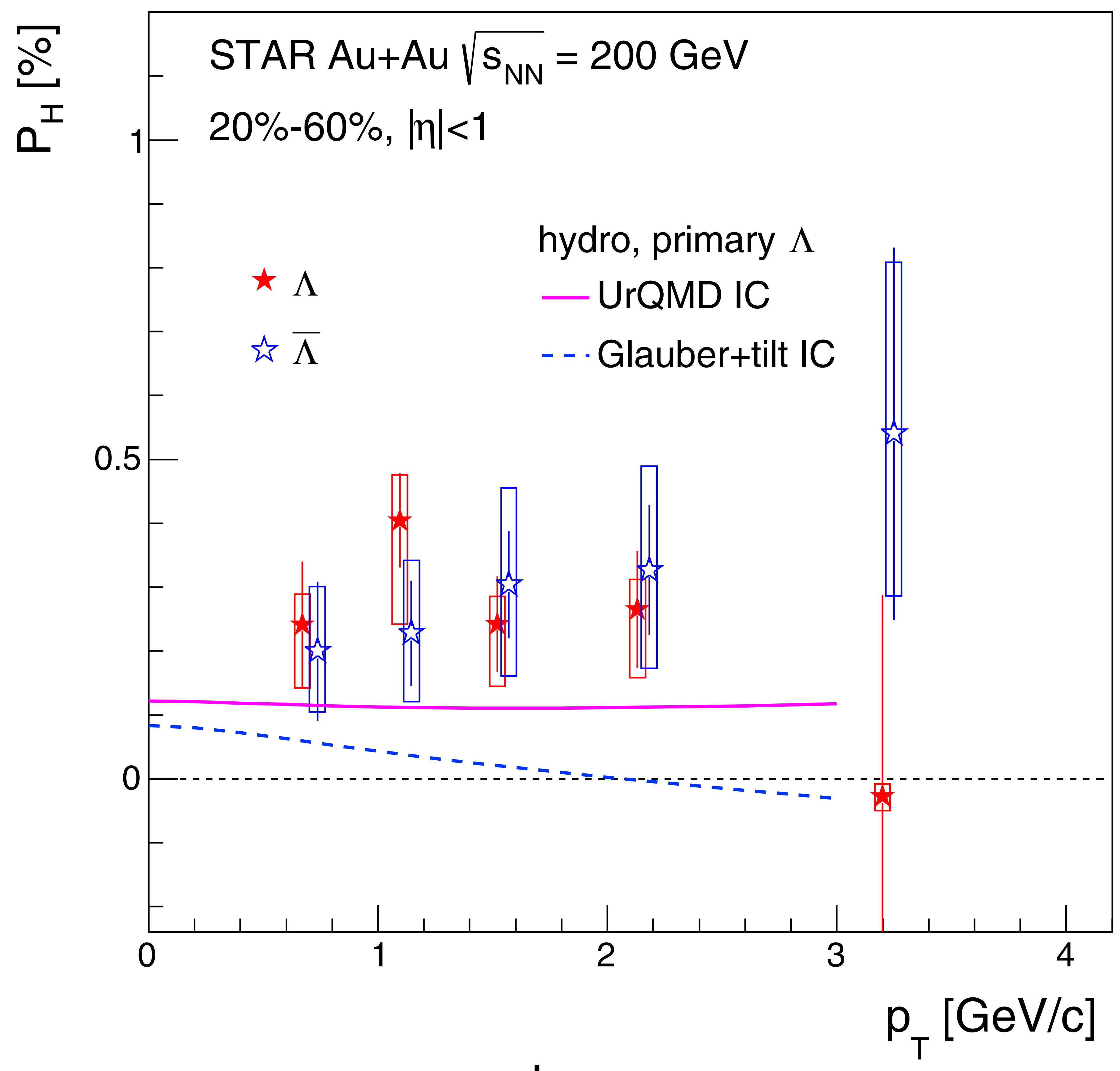
event-by-event vs. averaged



- Collision energy dependence is robust with respect to variation of the parameters of the model.
- There is no big difference between event-by-event and single shot hydrodynamic description.

Differential measurements: p_T

STAR, PRC98, 014910 (2018)



- Naive expectation of smaller P_H due to scattering at low p_T, fragmentation at high p_T
- No clear p_T dependence with current precision

STAR, QM19