「高エネルギー原子核衝突で生成される渦と偏極」

Vorticity and polarization in heavy-ion collisions

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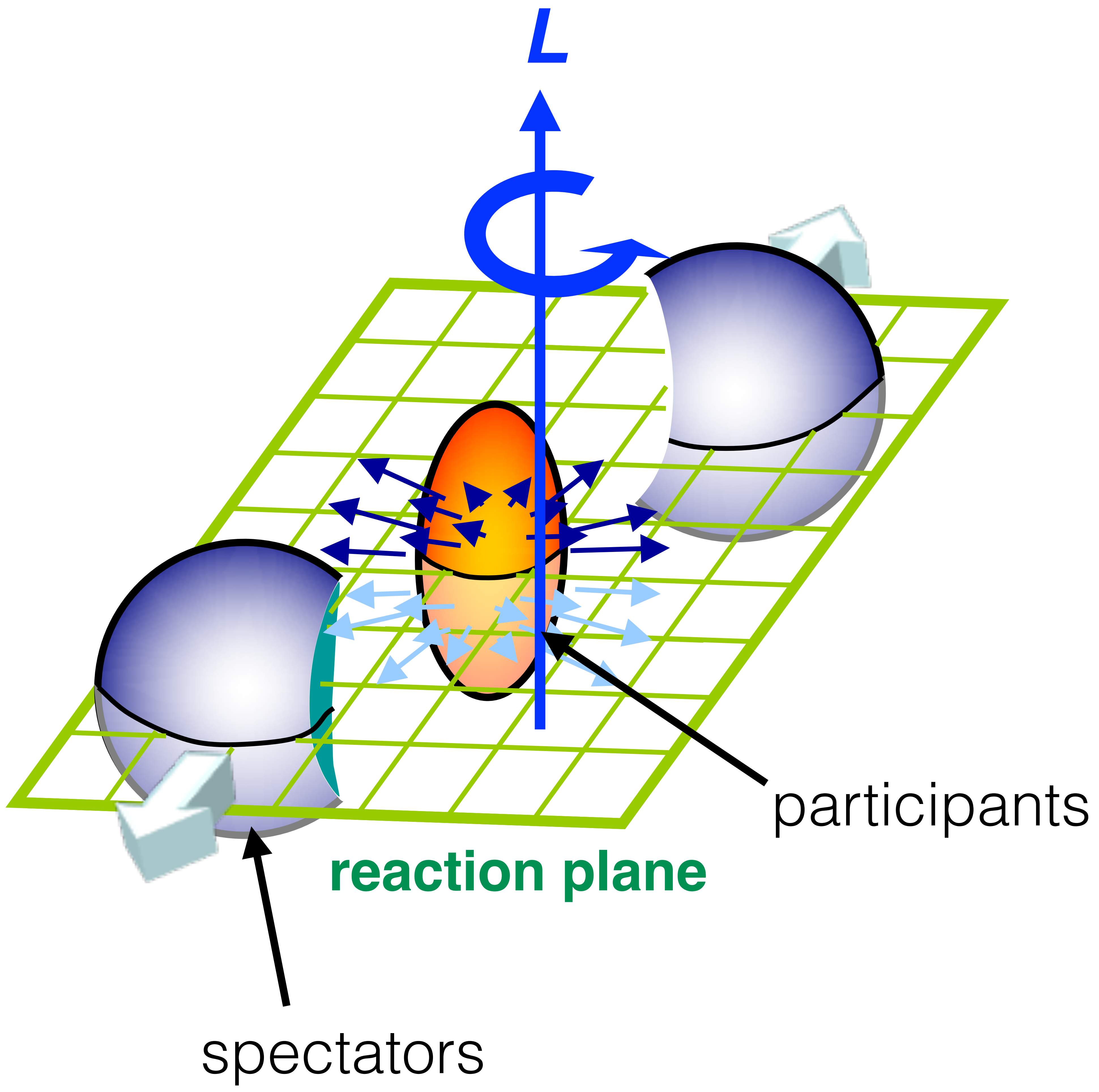
Heavy Ion Pub #31 (online)
September 28, 2020

Outline

- Introduction
  - Initial orbital angular momentum, magnetic field, global polarization…
- Global polarization measurements
- Experimental results and Discussion
  - Global polarization
  - Global spin alignment
  - Local polarization along the beam direction
  - and more if time permits…
- Outlook and Summary

* Slides are prepared in English just in case…

Important features in non-central heavy-ion collisions



Orbital angular momentum **L**

$$\mathbf{L} = \mathbf{r} \times \mathbf{p}$$
$$\sim bA\sqrt{s_{NN}}$$

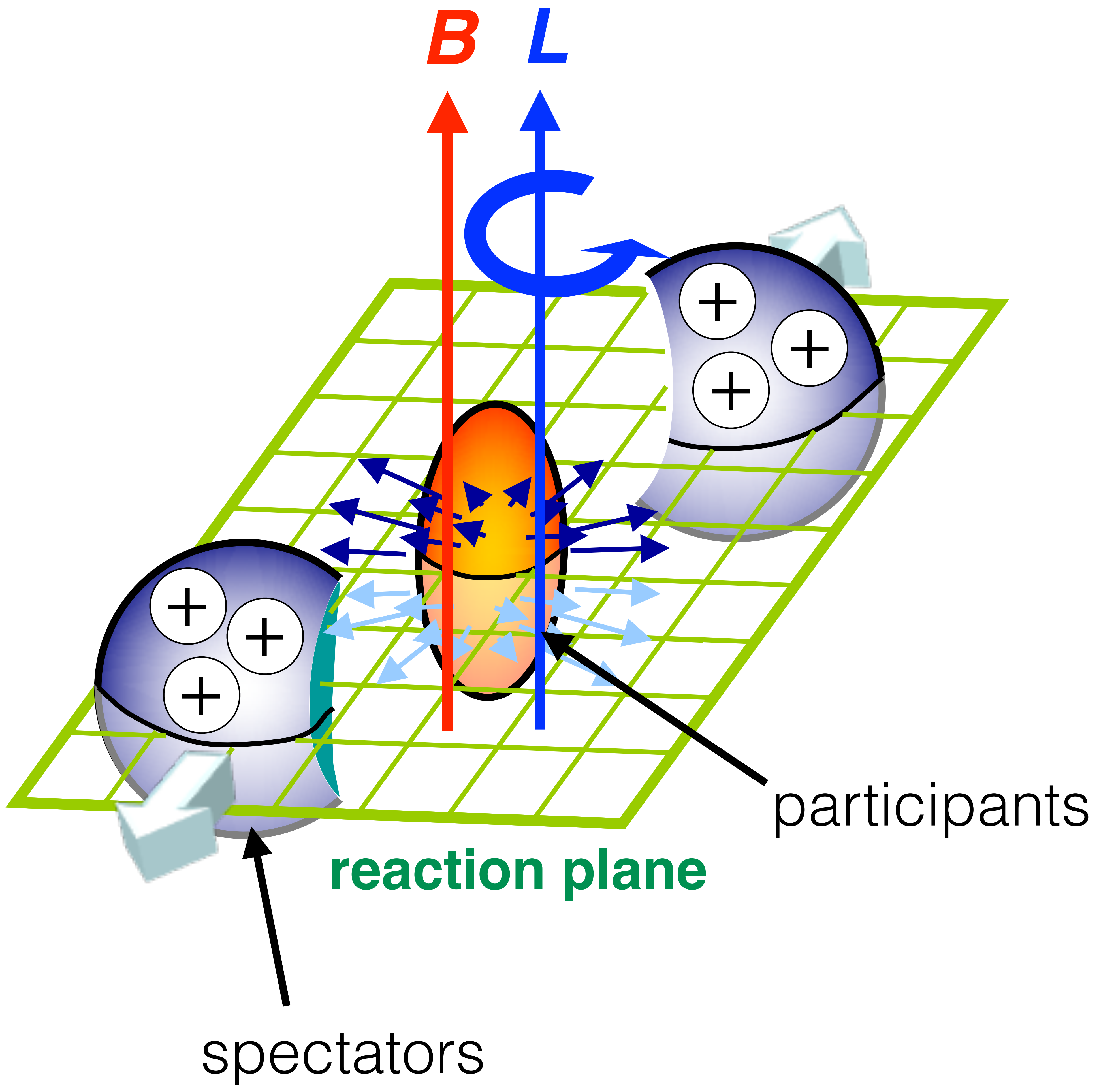
b : impact parameter
(vector connecting the center of two nuclei)
A : mass number

$$\mathbf{L} \sim bA\sqrt{s_{NN}}$$
$$\sim 10\ (\mathrm{fm}) \times 197 \times 200\ (\mathrm{GeV})$$
$$= 2 \times 10^3 \times 197\ (\mathrm{fm} \cdot \mathrm{GeV})$$
$$(\hbar c \sim 197\ \mathrm{MeV} \cdot \mathrm{fm})$$
$$\sim 10^6 \hbar$$

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

Important features in non-central heavy-ion collisions

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



Initial magnetic field B

Approx. Biot-Savart law for a point charge

$$\mathbf{E} = \frac{q}{4\pi\epsilon_0}\frac{1-\beta^2}{(1-\beta^2\sin^2\theta)^{3/2}}\frac{\hat{\mathbf{r}}}{|\mathbf{r}|^2} \sim \frac{q}{4\pi\epsilon_0}\frac{\gamma\hat{\mathbf{r}}}{|\mathbf{r}|^2} \ \text{(at t} \sim 0)$$

$$\mathbf{B} = \frac{1}{c^2}\mathbf{v}\times\mathbf{E}$$

$$B \sim \frac{q\mu_0}{4\pi}\frac{\gamma\mathbf{v}\times\hat{\mathbf{r}}}{|\mathbf{r}|^2} \sim (Z\alpha\hbar/e)(\gamma\beta/r^2)$$

$$eB \sim \hbar Z\alpha\gamma\beta/r^2 \ [1/\mathrm{fm}^2] \ (\text{assume r} \sim 10 \text{ fm}, \ \gamma \sim 106.58)$$

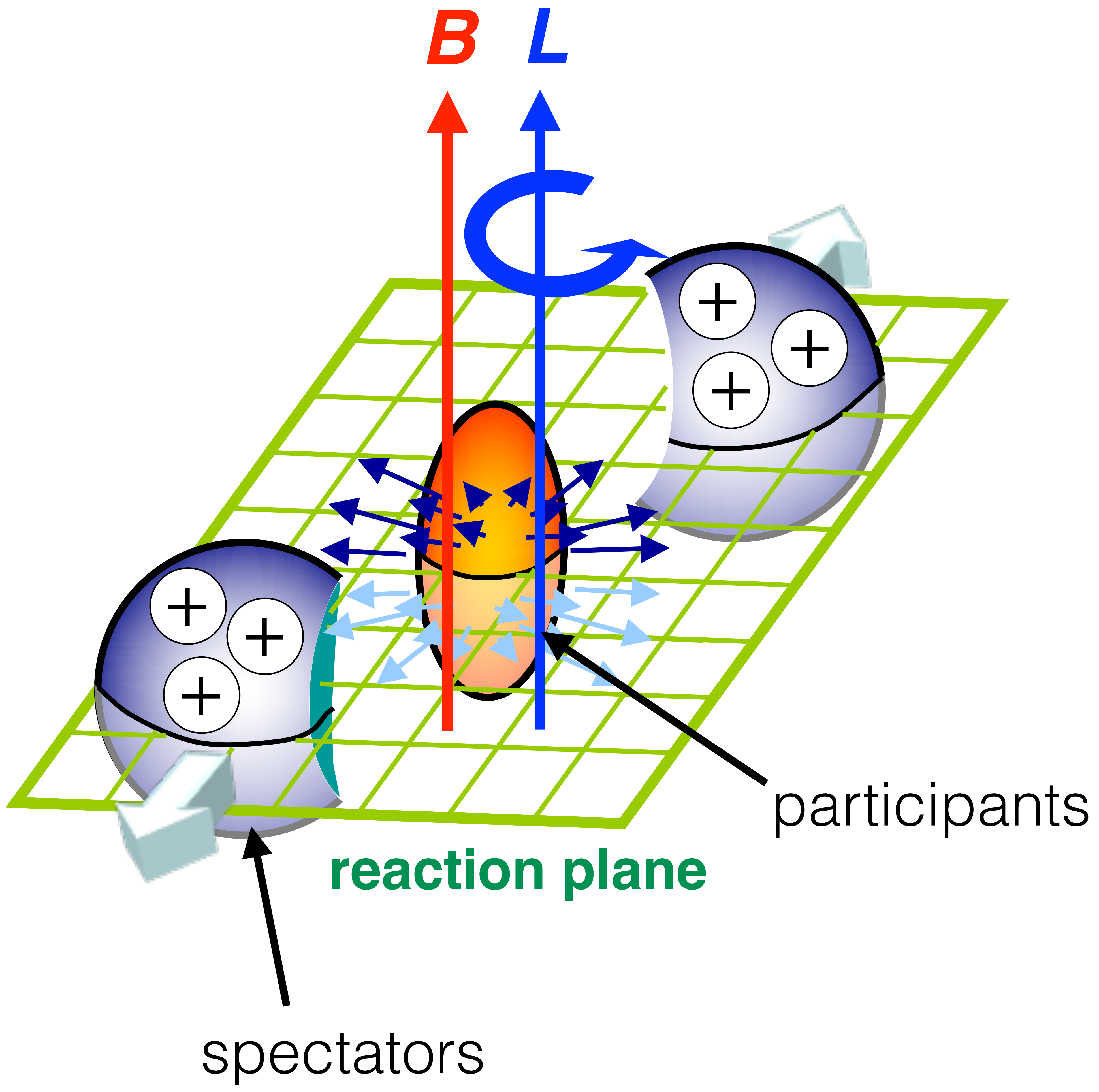
$$\sim \hbar Z\alpha$$

$$\sim m_\pi^2$$

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

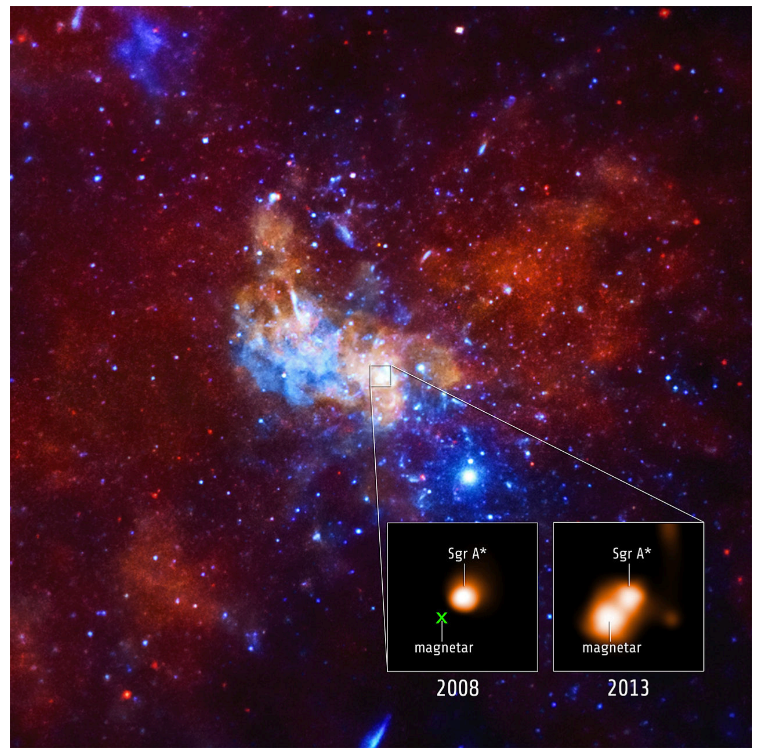
Important features in non-central heavy-ion collisions

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



Initial magnetic field **B**

magnetar, wikipedia



typical magnet	$B \sim 0.1 - 0.5\ \mathrm{T}$
surface on magnetar	$B \sim 10^{11}\ \mathrm{T}$
HI (200 GeV)	$B \sim 10^{13}\ \mathrm{T}$

* Lifetime of B-field is likely short (<0.5 fm/c), depending on conductivity
* Rotating charged fluid also produces the field

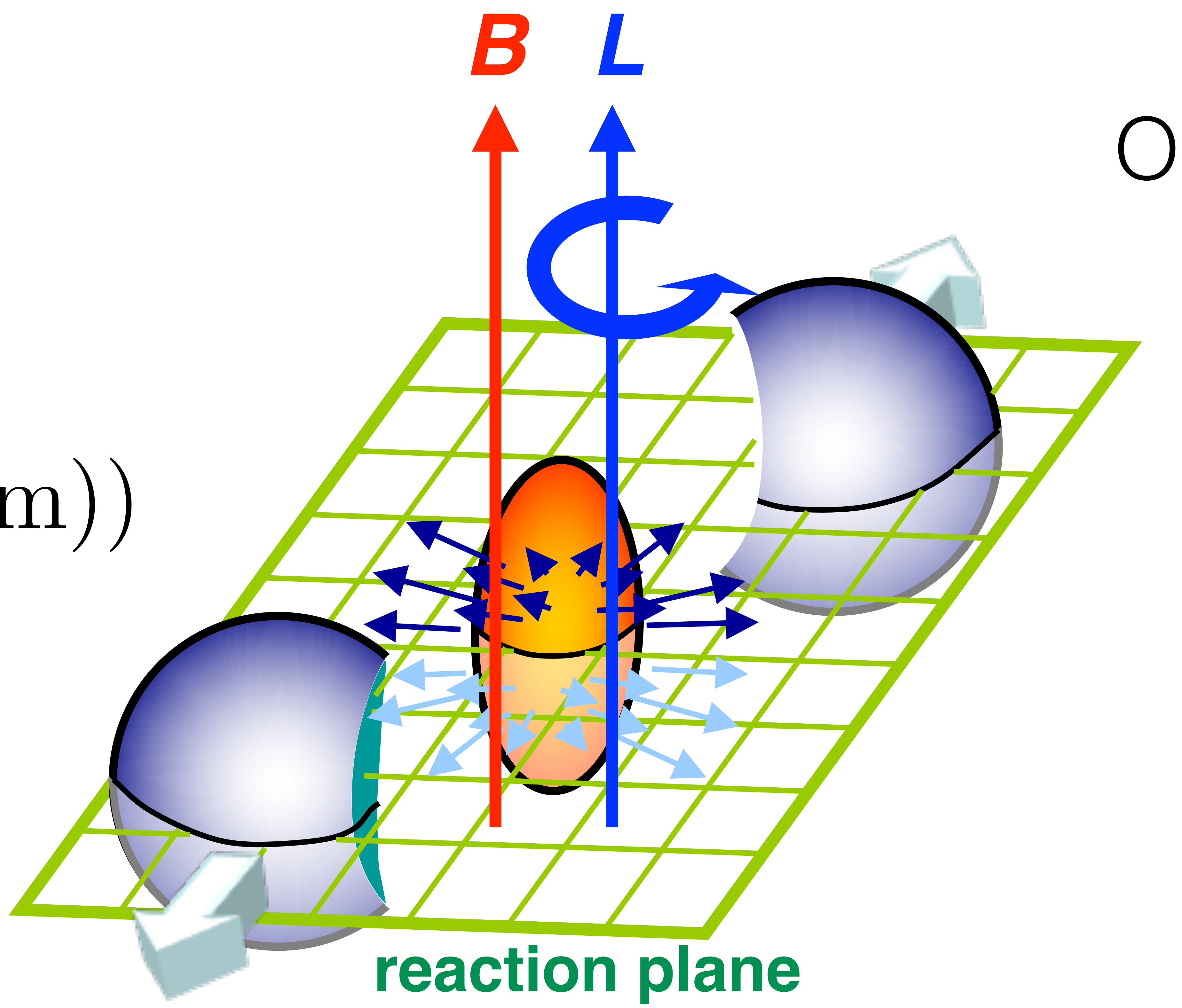
Important features in non-central heavy-ion collisions

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)



Orbital angular momentum

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

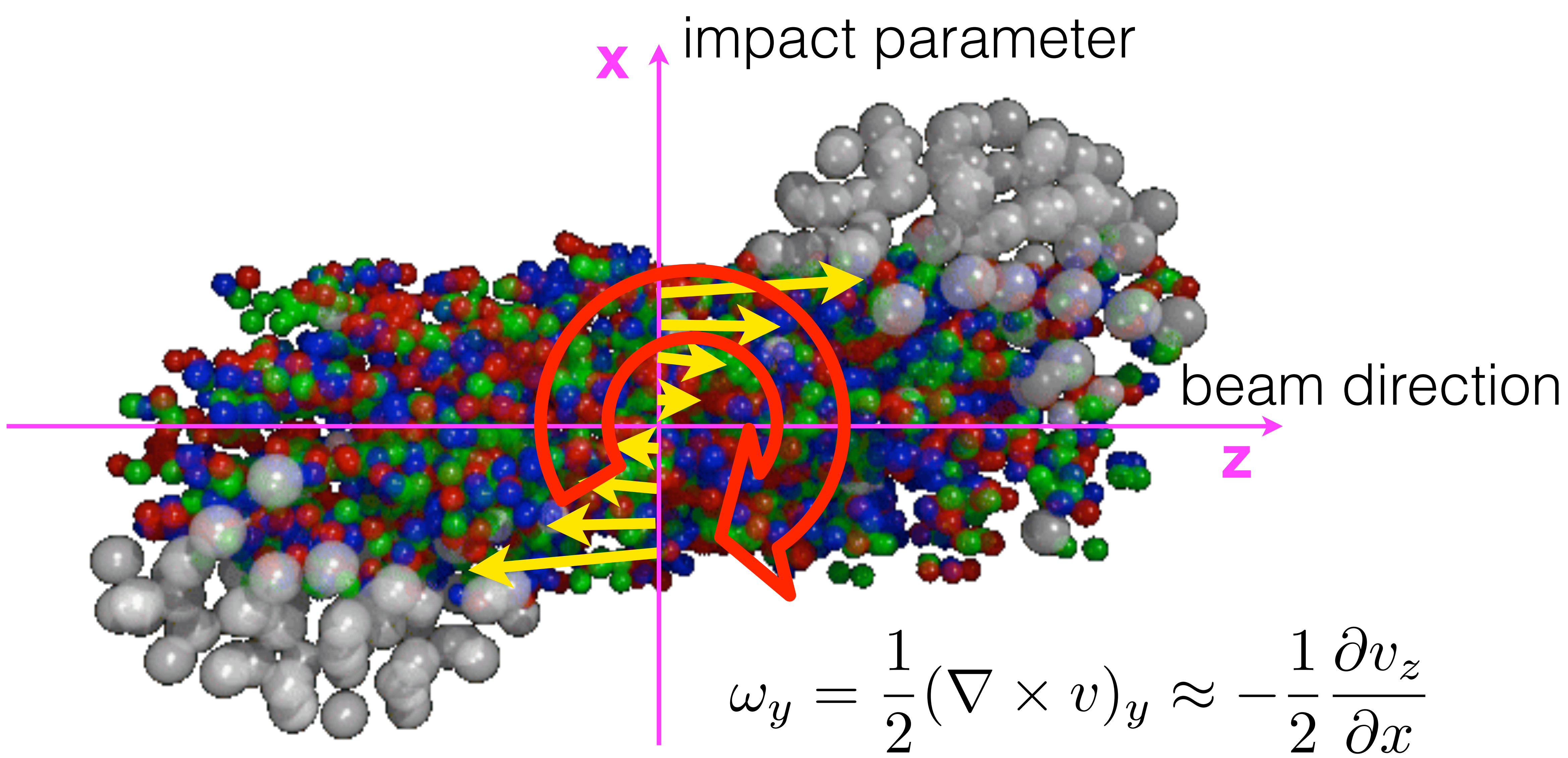
$$\sim bA\sqrt{s_{NN}} \sim 10^6 \hbar$$

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

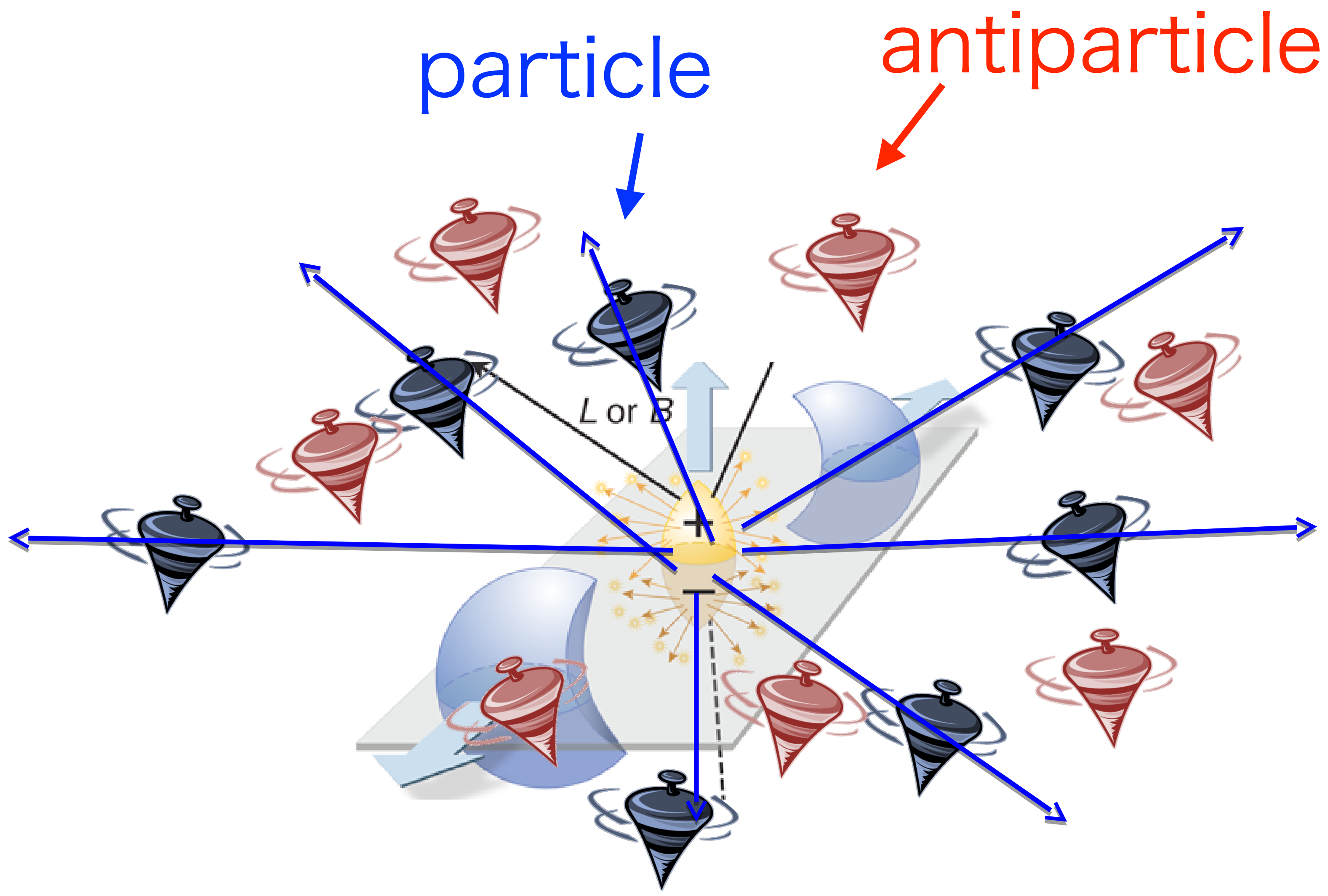
→Chiral magnetic effect
Chiral magnetic wave
Particle polarization

→Chiral vortical effect
→**Particle polarization**

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*** and ***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)

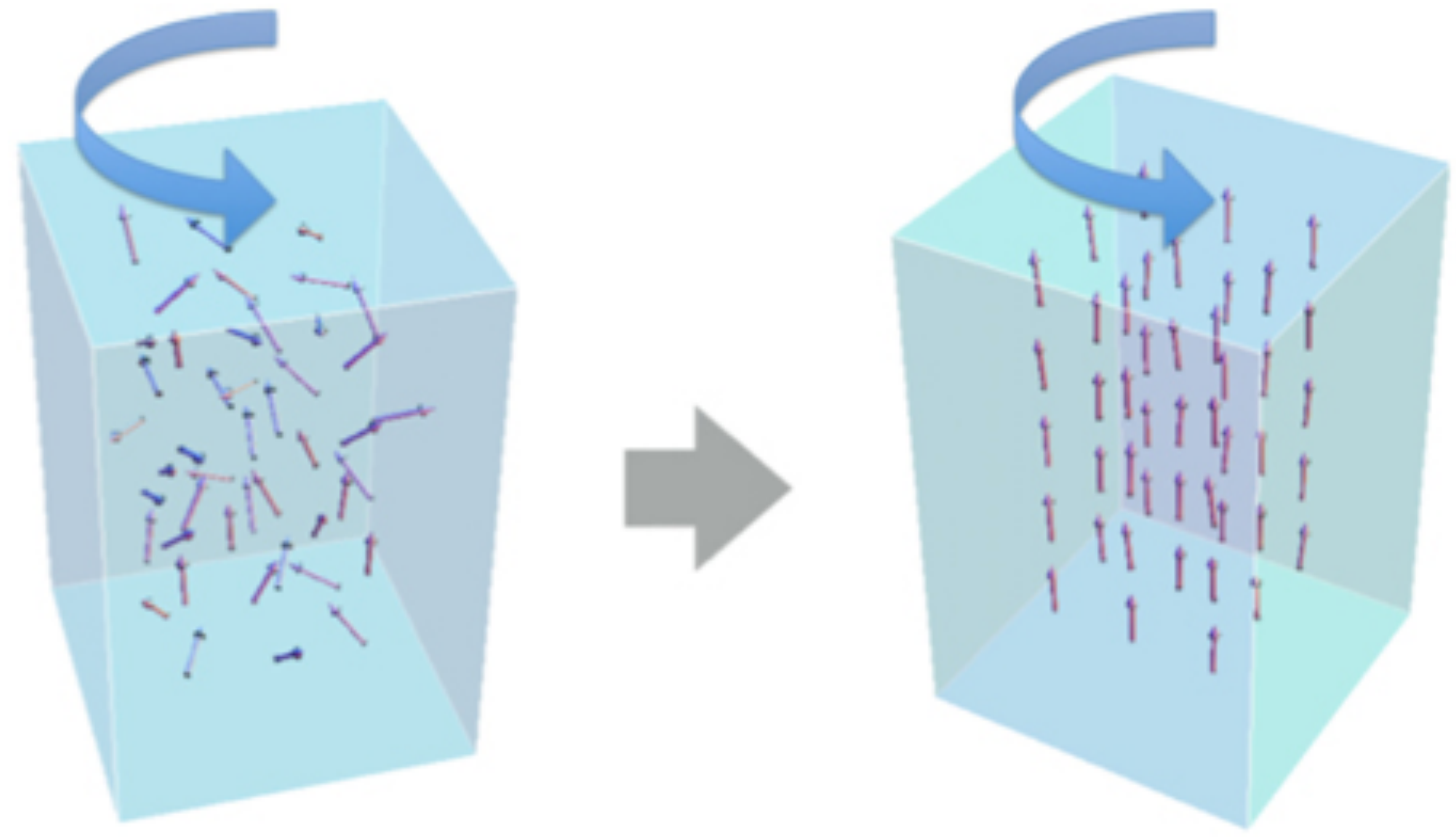


figure: M. Matsuo et al., Front. Phys., 30 (2015)

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

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?

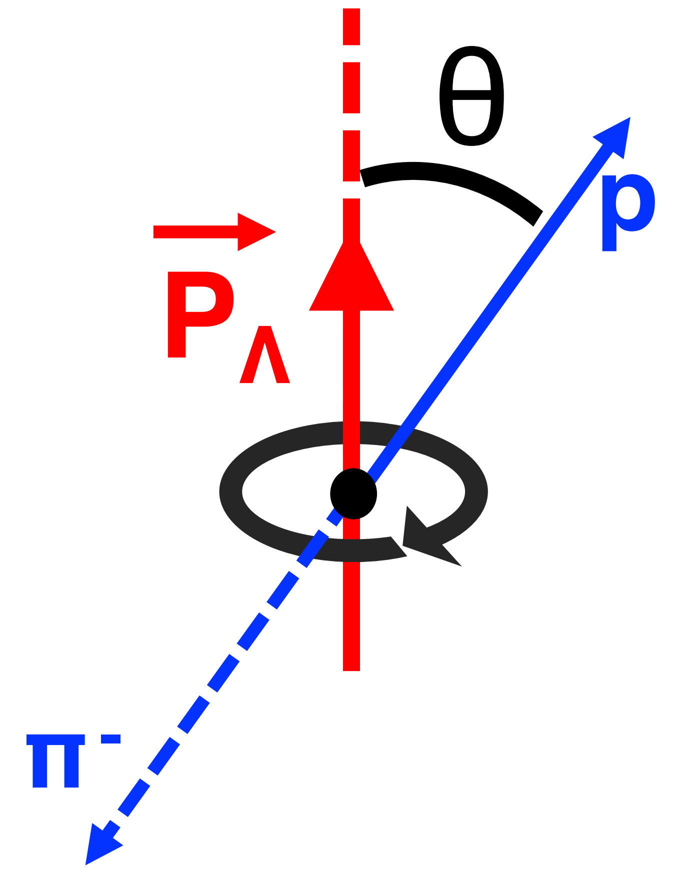
Parity-violating weak decay of hyperons ("self-analyzing")

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

(BR: 63.9%, cτ ~7.9 cm)

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

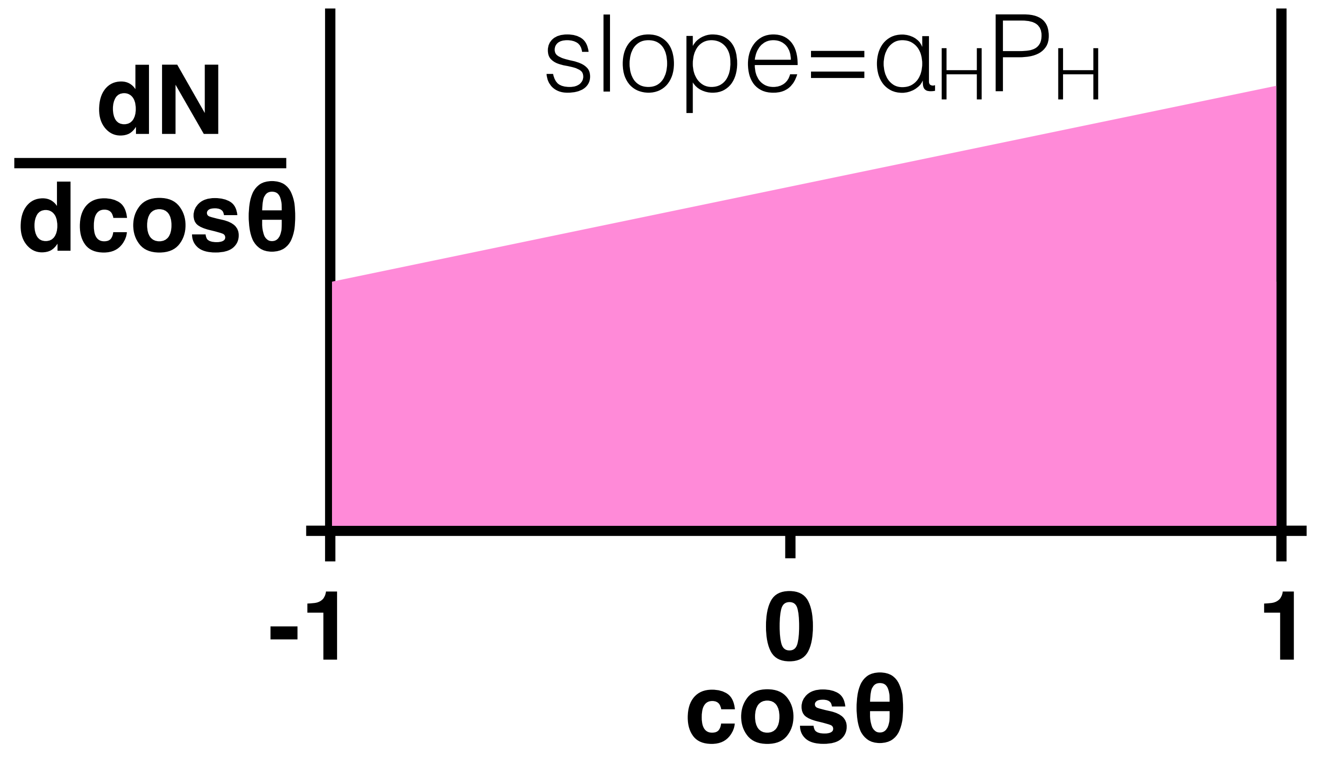
$$\frac{dN}{d\cos\theta^*} \propto 1 + \alpha_H \mathrm{P_H} \cos\theta^*$$



P_H: Λ polarization

θ^*: polar angle of proton relative to the polarization direction in Λ rest frame

α_H: Λ decay parameter



Note: α_H recently updated by BESIII Collaboration

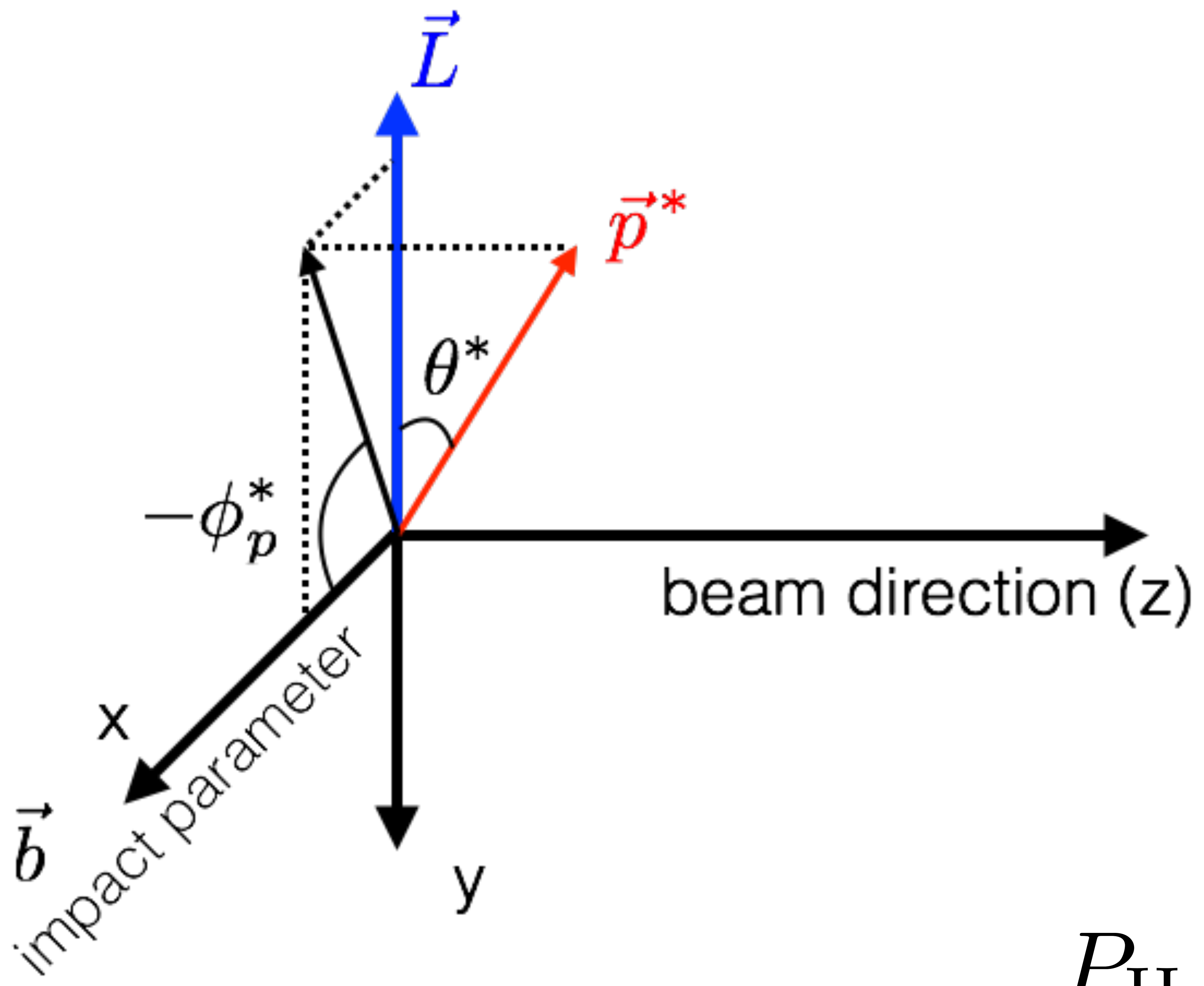
α_Λ=0.732±0.014, $\alpha_{\bar{\Lambda}}$=-0.758±0.012

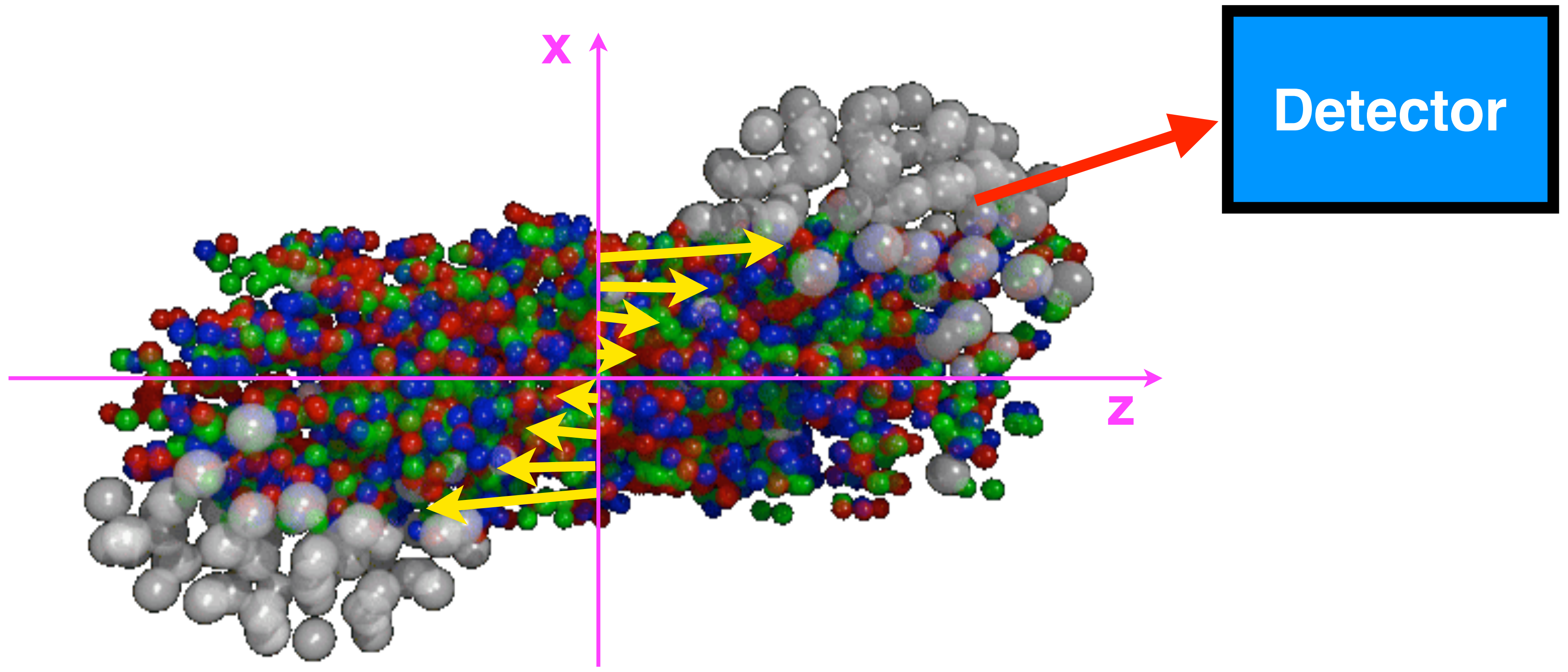
P.A. Zyla et al. (PDG), Prog.Theor.Exp.Phys.2020.083C01

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)

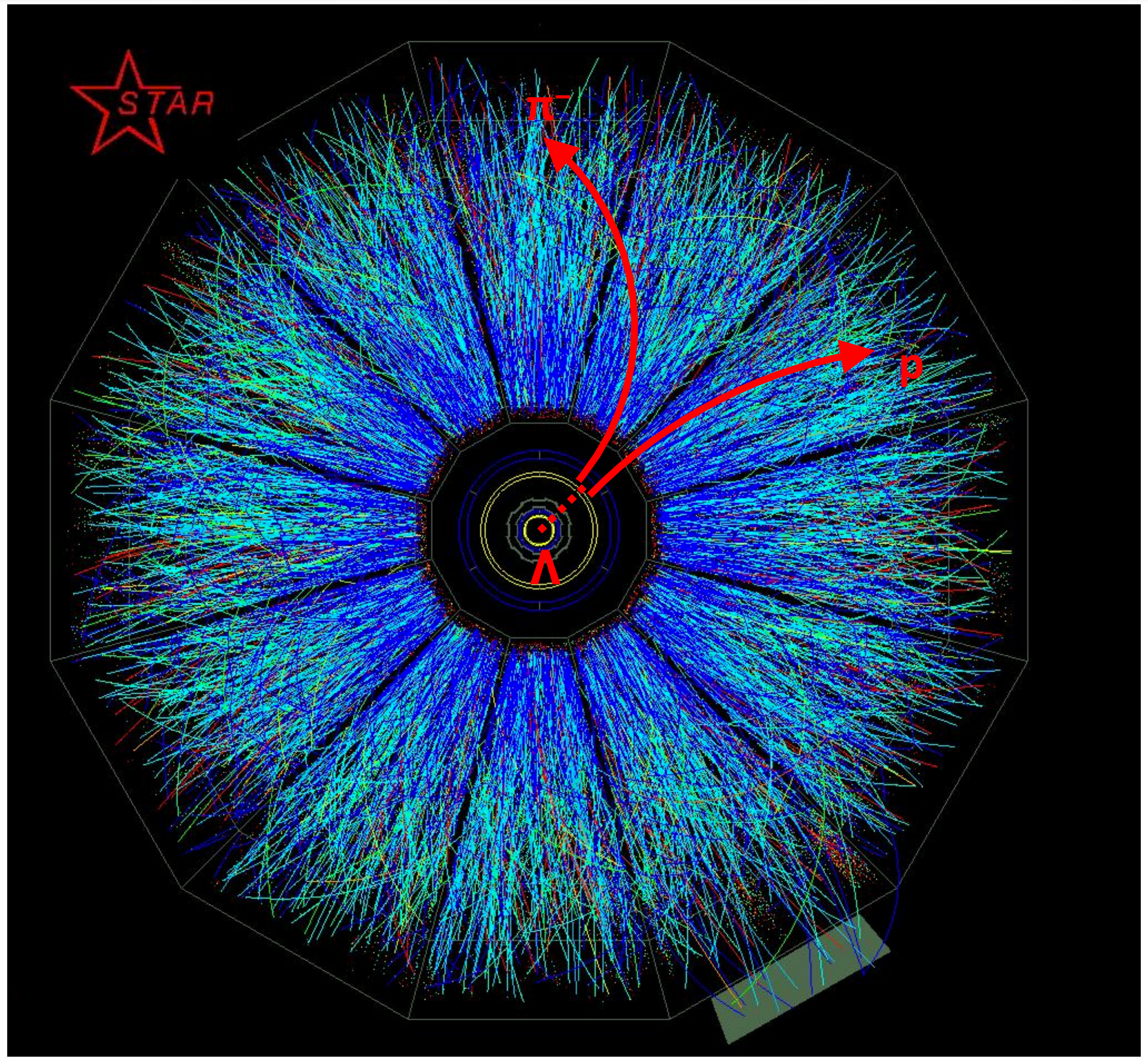
$$P_{\mathrm{H}} = \frac{8}{\pi \alpha_{\mathrm{H}}} \frac{\langle \sin(\Psi_1 - \phi_p^*) \rangle}{\mathrm{Res}(\Psi_1)}$$

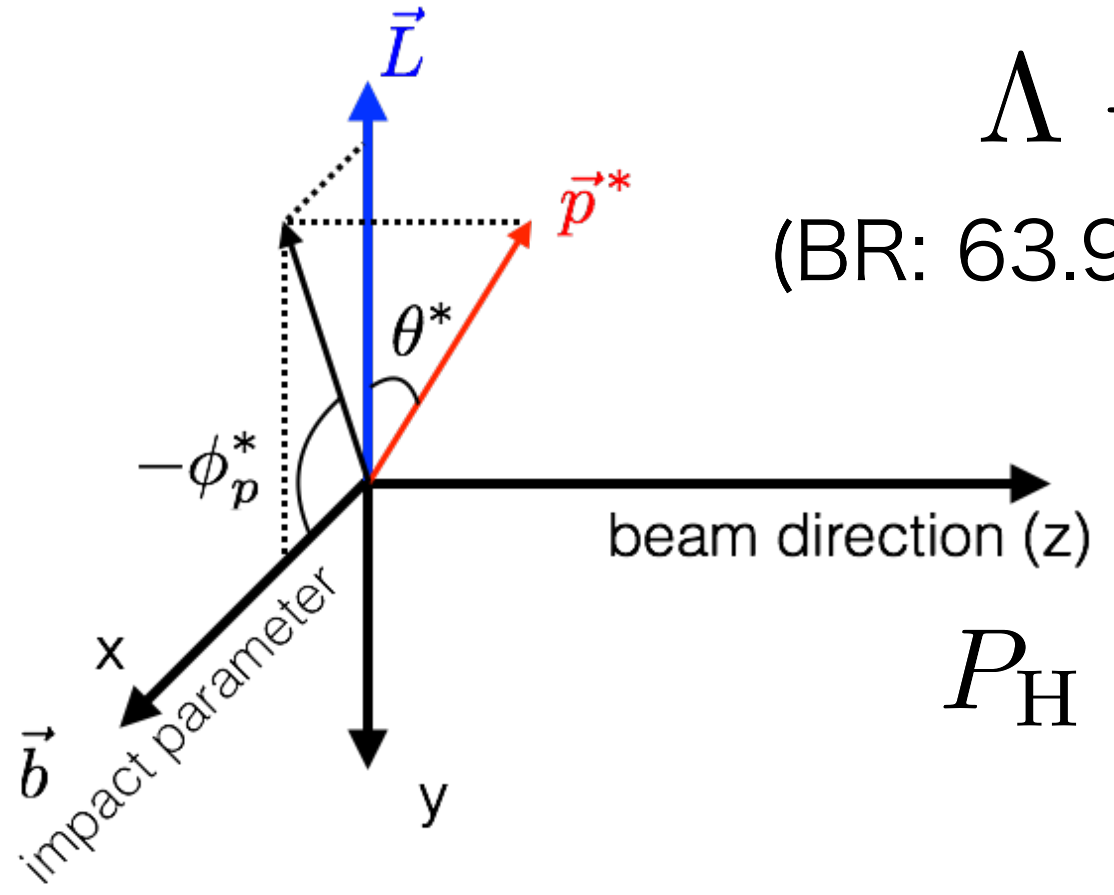
Ψ_1: azimuthal angle of b

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

STAR, PRC76, 024915 (2007)

Signal extraction with Λ hyperons



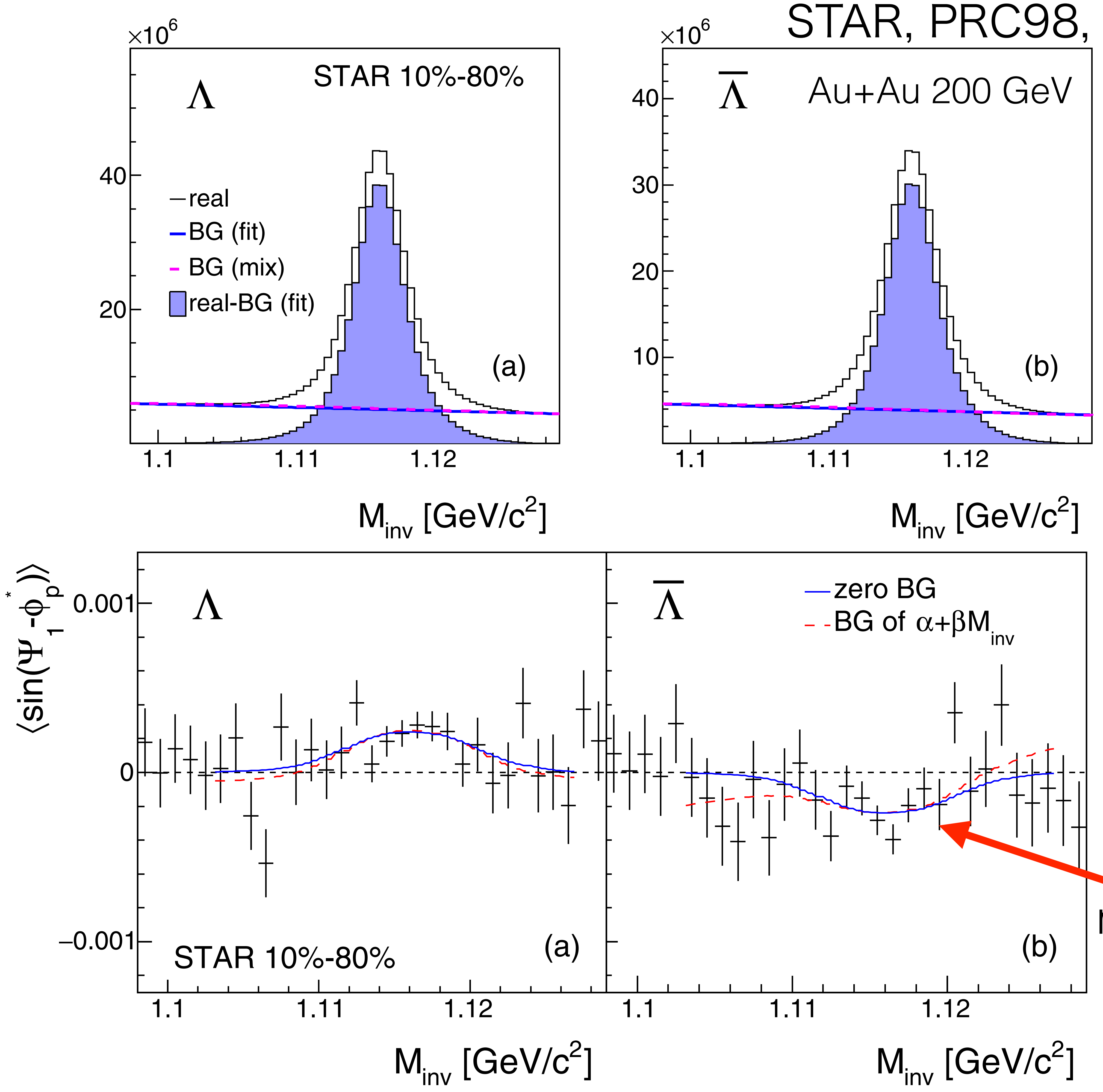


$$\Lambda \rightarrow p + \pi^-$$

(BR: 63.9%, cτ ~7.9 cm)

$$P_H = \frac{8}{\pi \alpha_H} \frac{\langle \sin(\Psi_1 - \phi^*_p) \rangle}{\mathrm{Res}(\Psi_1)}$$

STAR, PRC98, 014910 (2018)



negative for anti-Λ

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

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

T. Niida, HI-Pub 2020

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)

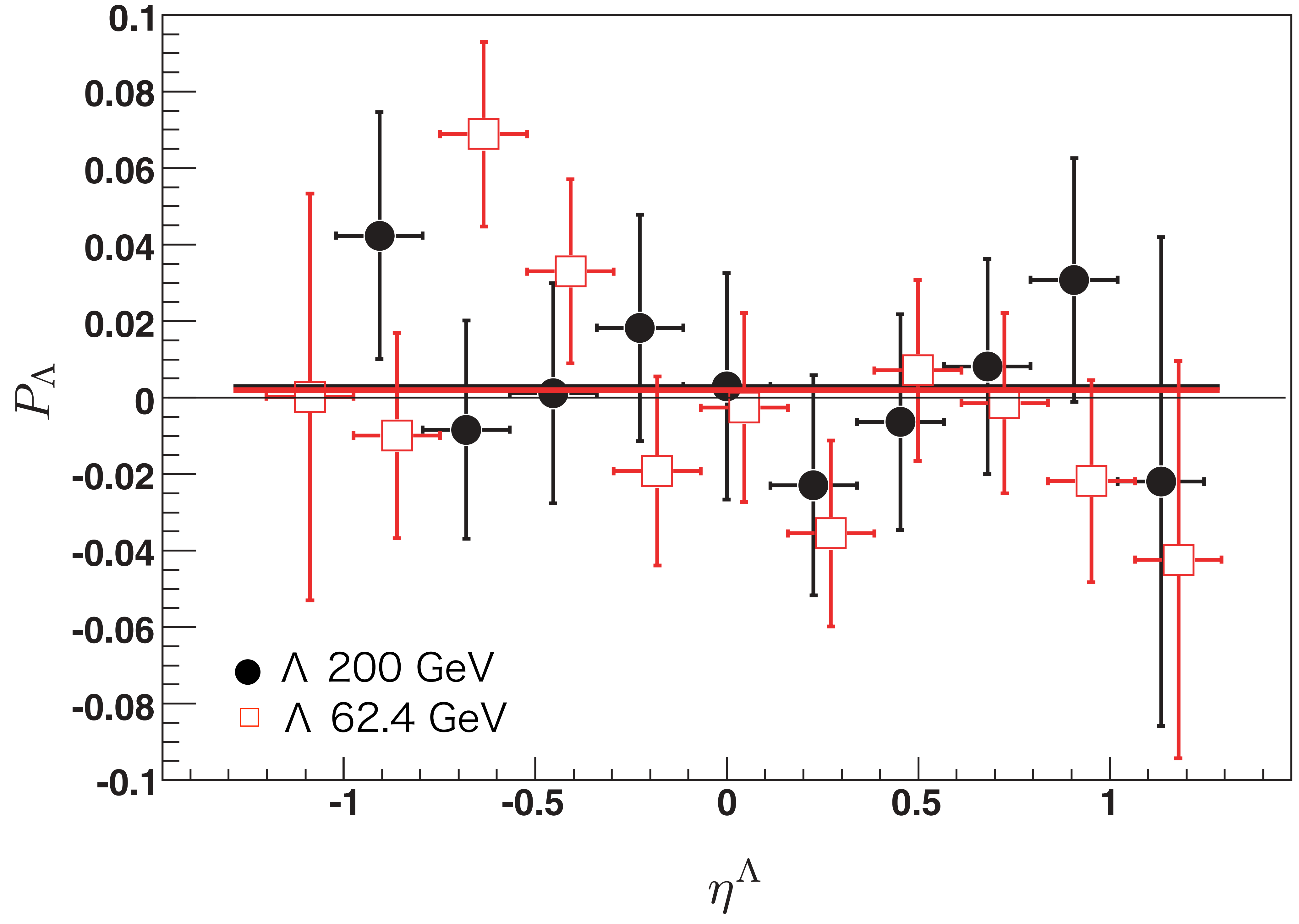
Decay	C
Parity conserving: $1/2^+ \to 1/2^+\ 0^-$	$-1/3$
Parity conserving: $1/2^- \to 1/2^+\ 0^-$	1
Parity conserving: $3/2^+ \to 1/2^+\ 0^-$	1/3
Parity-conserving: $3/2^- \to 1/2^+\ 0^-$	$-1/5$
$\Xi^0 \to \Lambda + \pi^0$	+0.900
$\Xi^- \to \Lambda + \pi^-$	+0.927
$\Sigma^0 \to \Lambda + \gamma$	$-1/3$

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 the polarization of its parent! e.g. Ξ, Ω

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)

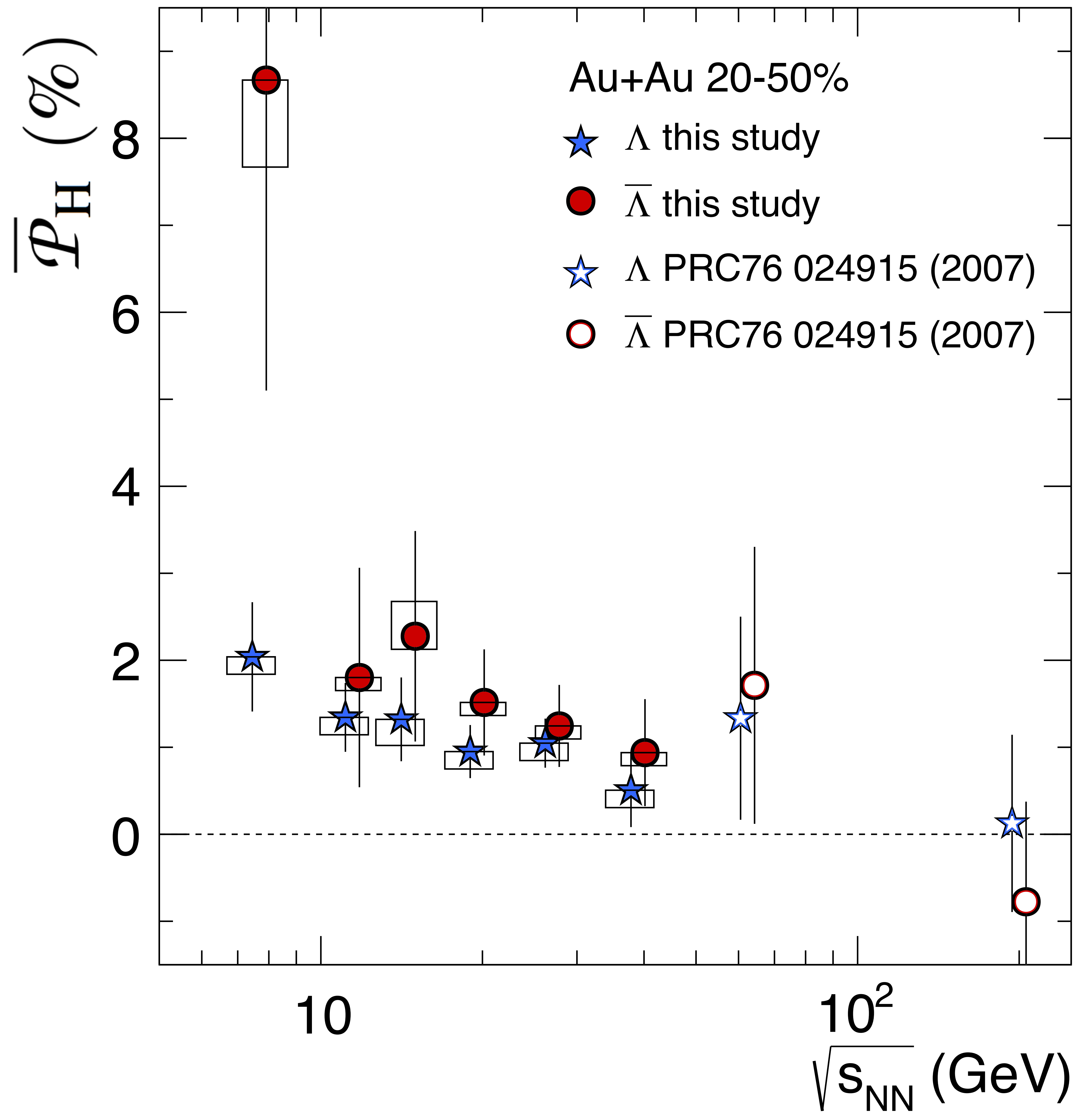
III. CONCLUSION

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 BES-I

STAR, Nature 548, 62 (2017)



Positive polarization signal at lower energies!

- P_H looks to increase in lower energies

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

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

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

$$\omega = (P_\Lambda + P_{\bar{\Lambda}})k_B T/\hbar$$

$$\sim 0.02\text{-}0.09\ \mathrm{fm}^{-1}$$

$$\sim 0.6\text{-}2.7 \times 10^{22}\mathrm{s}^{-1}$$

μ_Λ: Λ magnetic moment

T: temperature at thermal equilibrium (T=160 MeV)

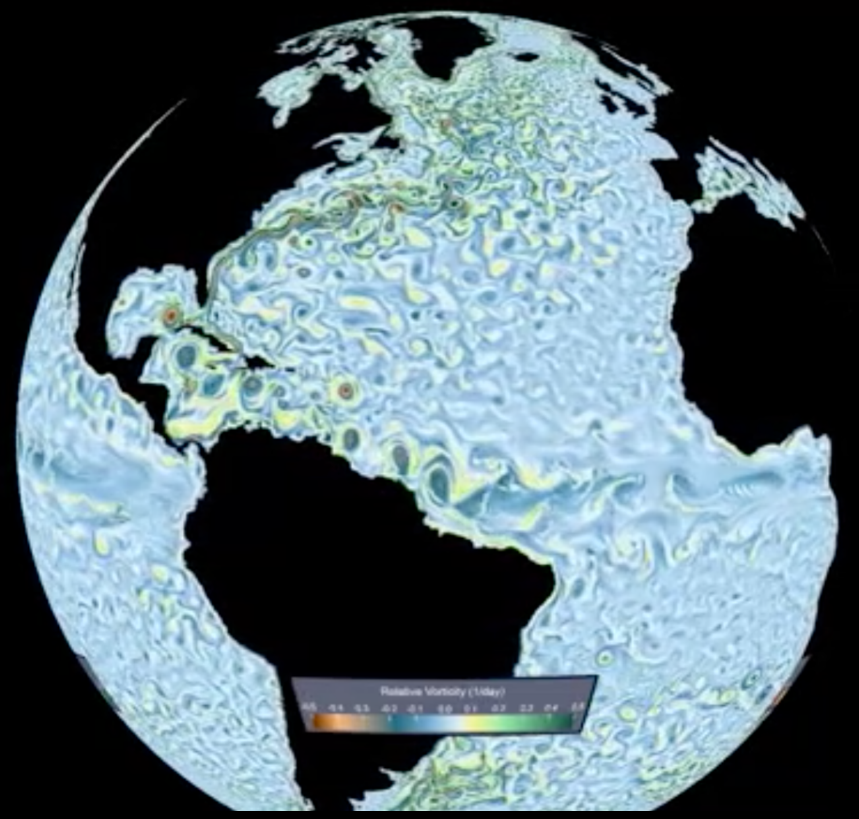
- The most vortical fluid!

Hint of the difference between Λ and anti-Λ P_H

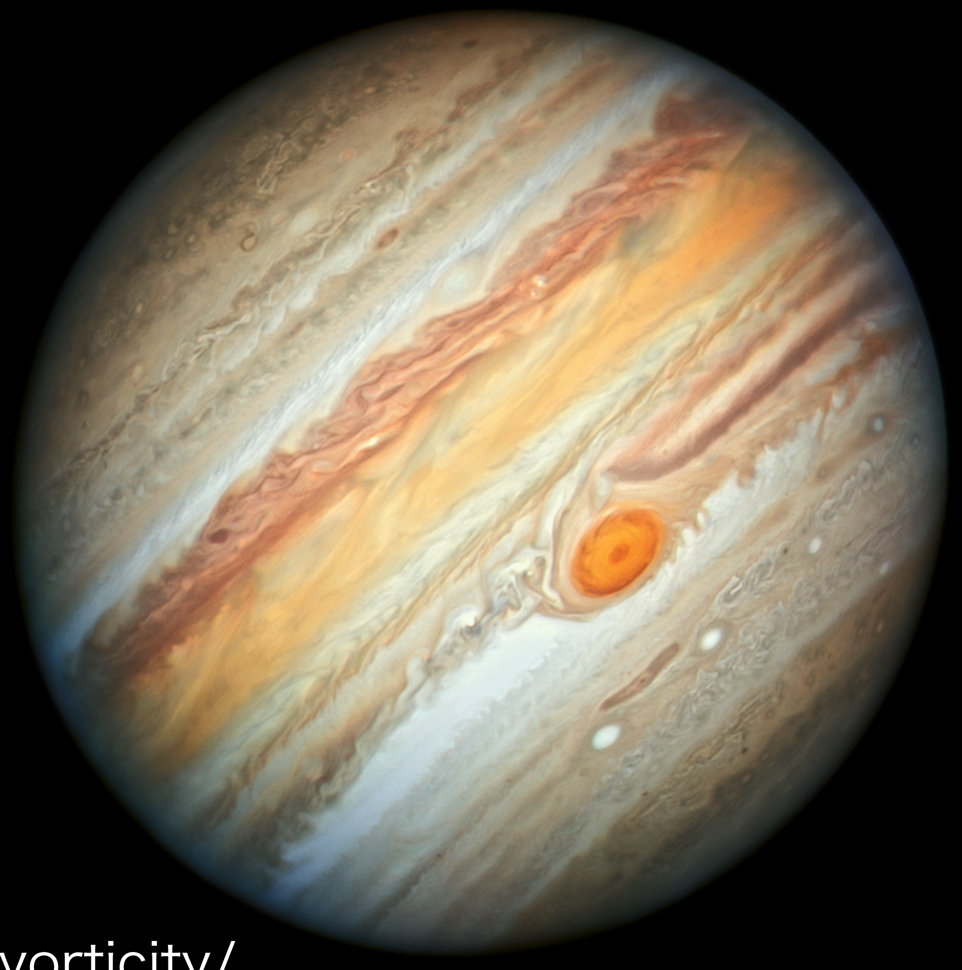
- Effect of the initial magnetic field? (discuss later)

Fastest vorticity

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



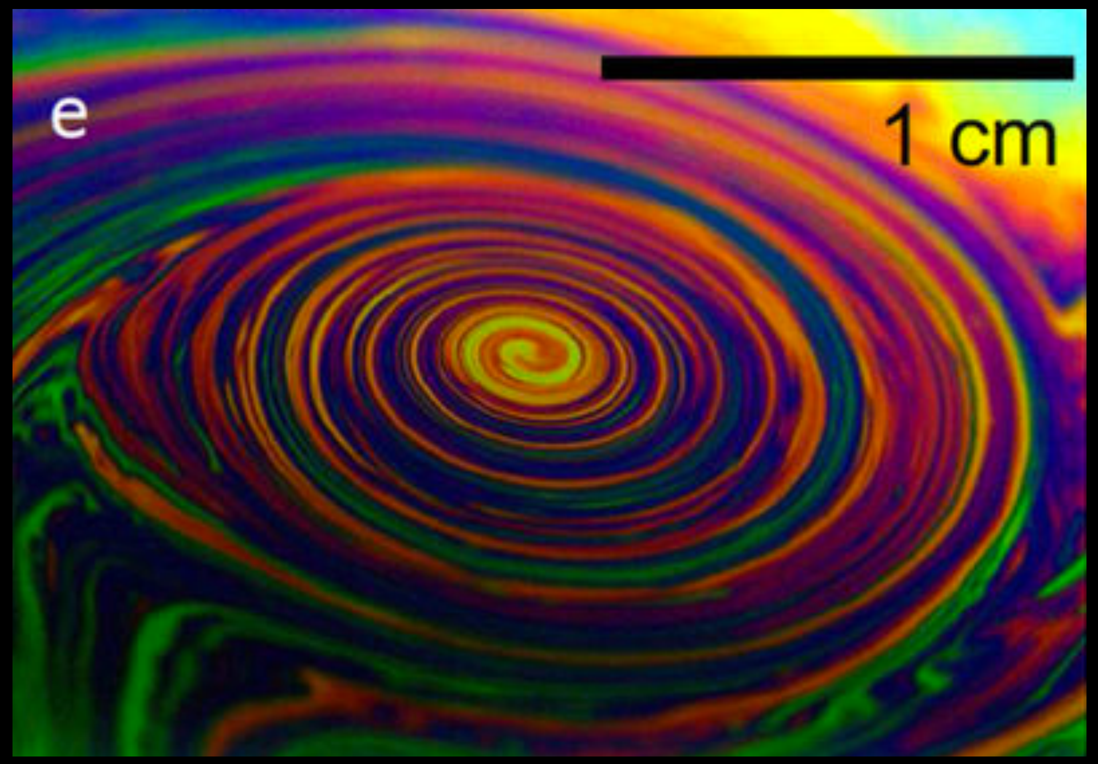
Ocean surface vorticity
https://sos.noaa.gov/datasets/ocean-surface-vorticity/

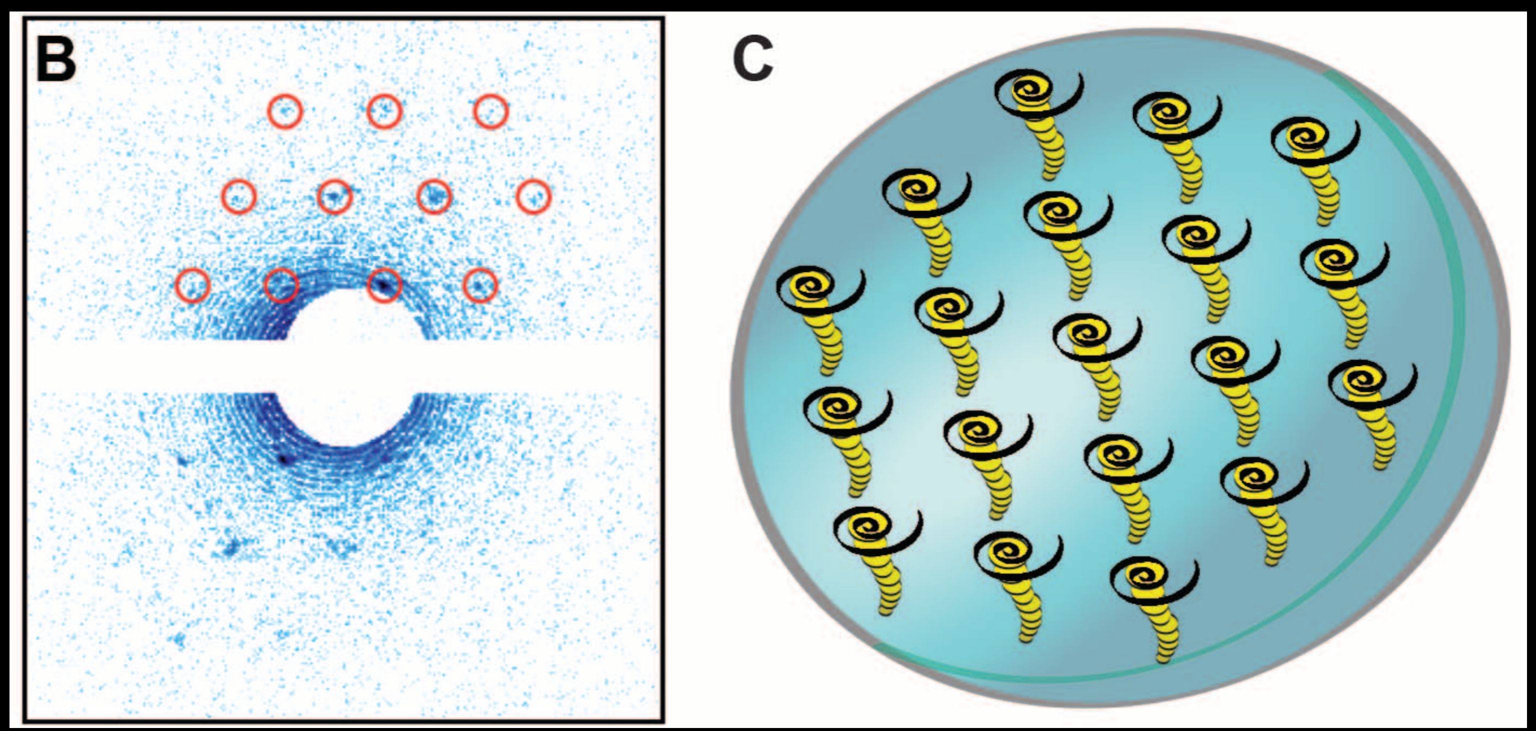


Great red spot of Jupiter (picture: NASA)
6/27, 2019 by Hubble Space Telescope

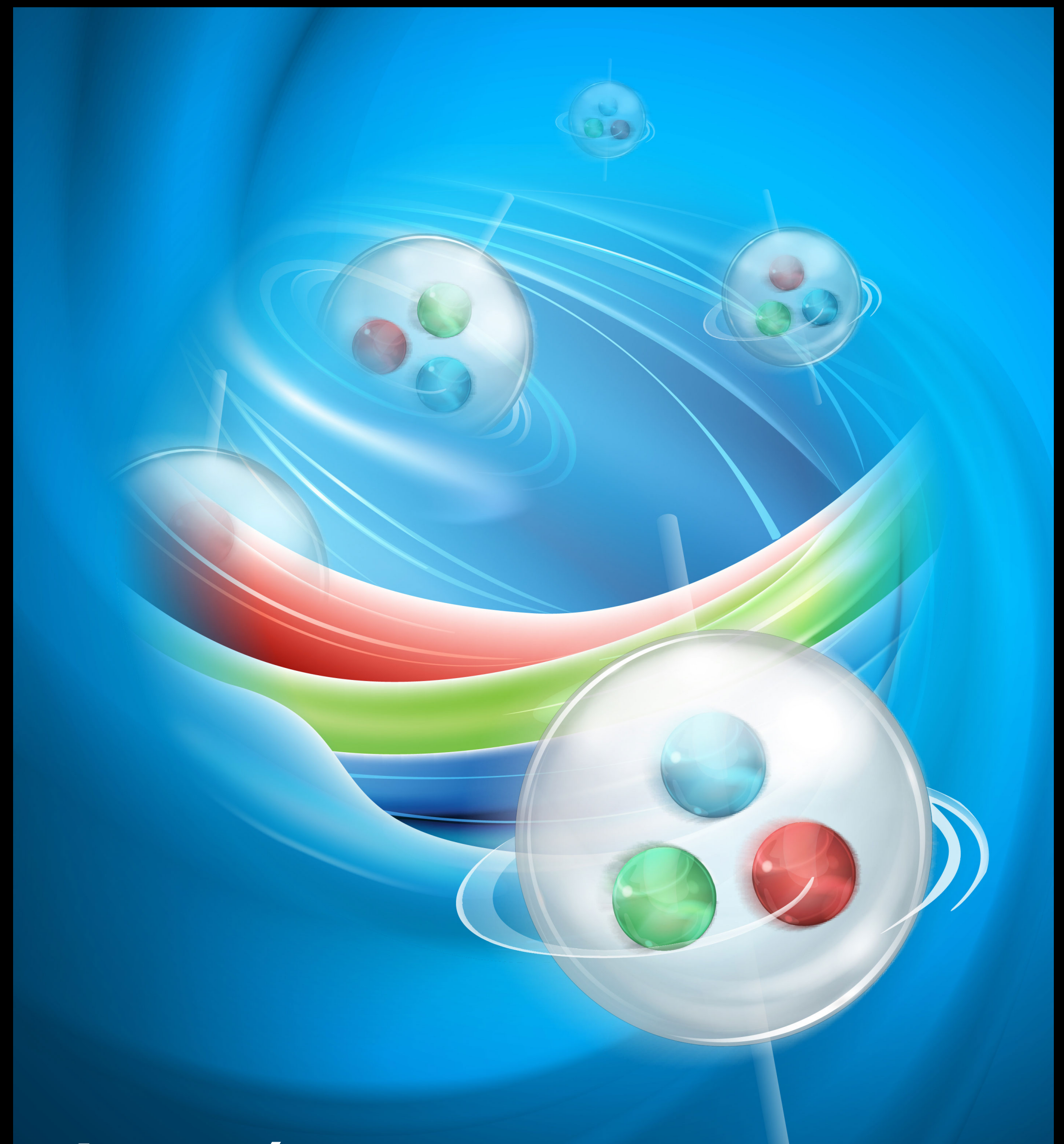
Supercell in Oklahoma (2016)
http://www.silverliningtours.com/tag/tornado/page/3/

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





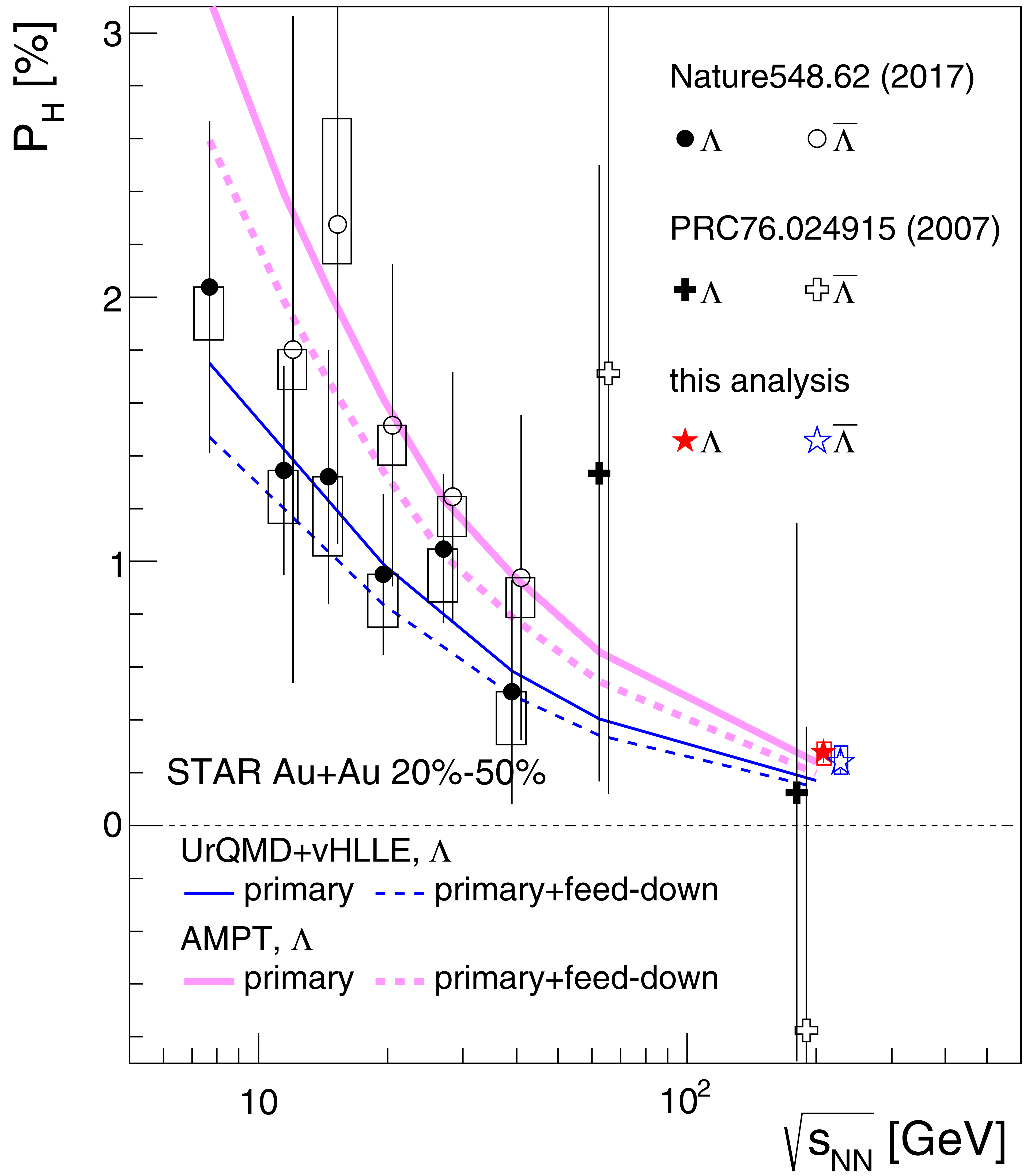
vortex aligned to x-ray beam in He droplets
T. Muel et al., Scientific Report 3, 3455 (2013)



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

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

STAR, PRC98, 014910 (2018)



Confirmed energy dependence with new results at 200 GeV

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

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

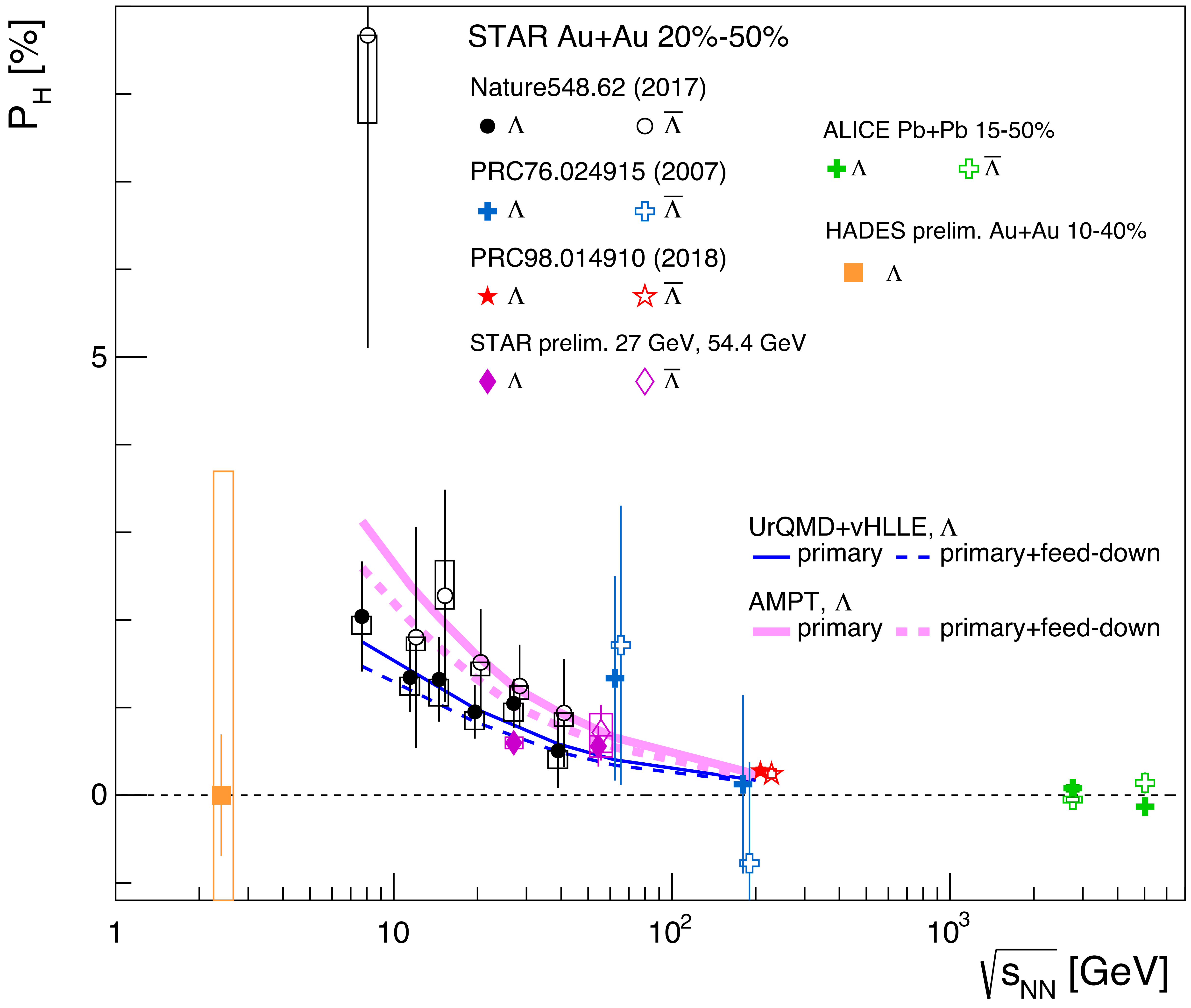
$$P_H(\bar{\Lambda})\ [\%] = 0.240 \pm 0.045(\mathrm{stat}) \pm^{0.061}_{0.045}\ (\mathrm{sys})$$

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

Collection of recent results

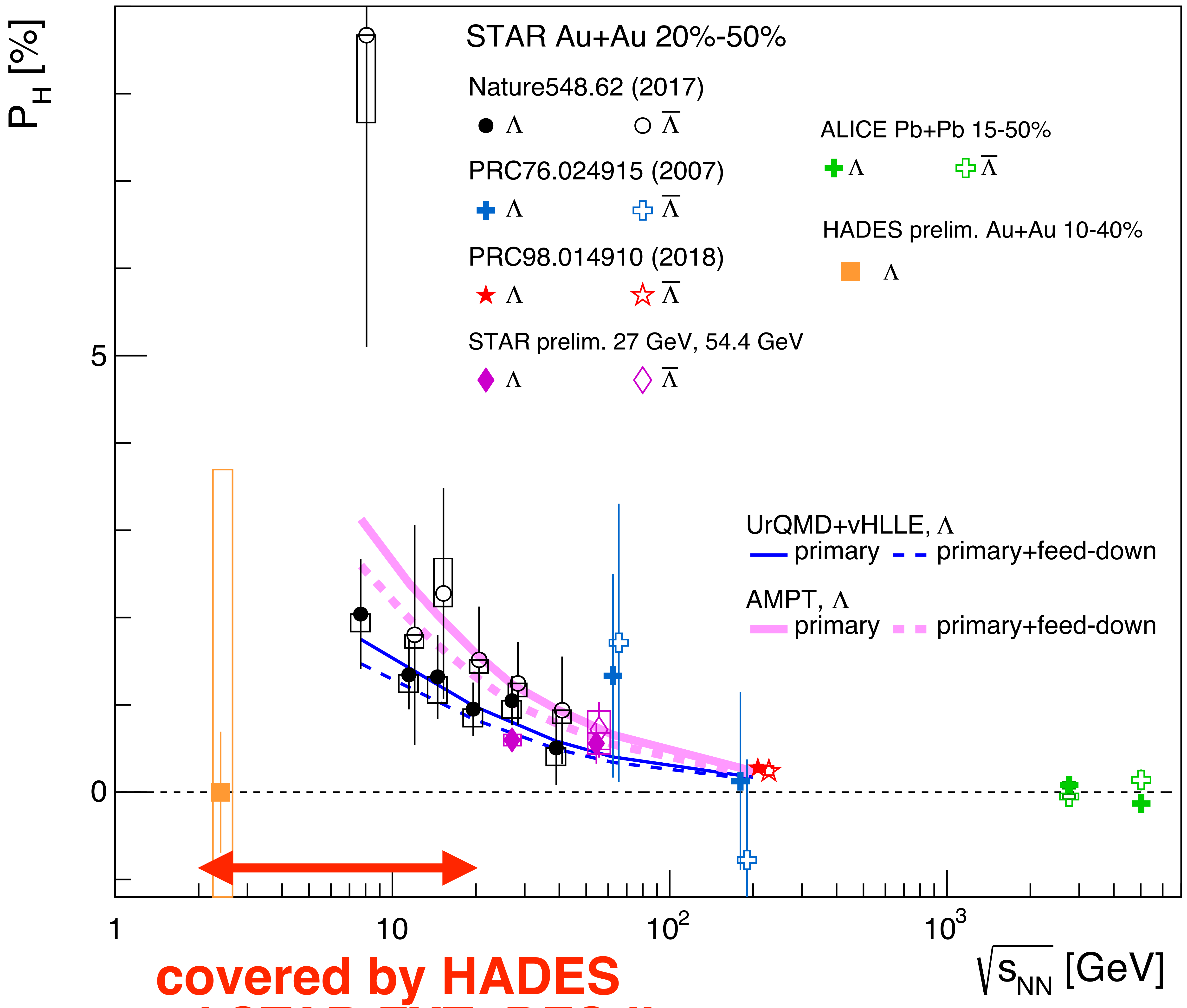
ALICE, PRC101.044611 (2020)
F. Kornas (HADES), SQM2019
J. Adams, K. Okubo (STAR), QM2019



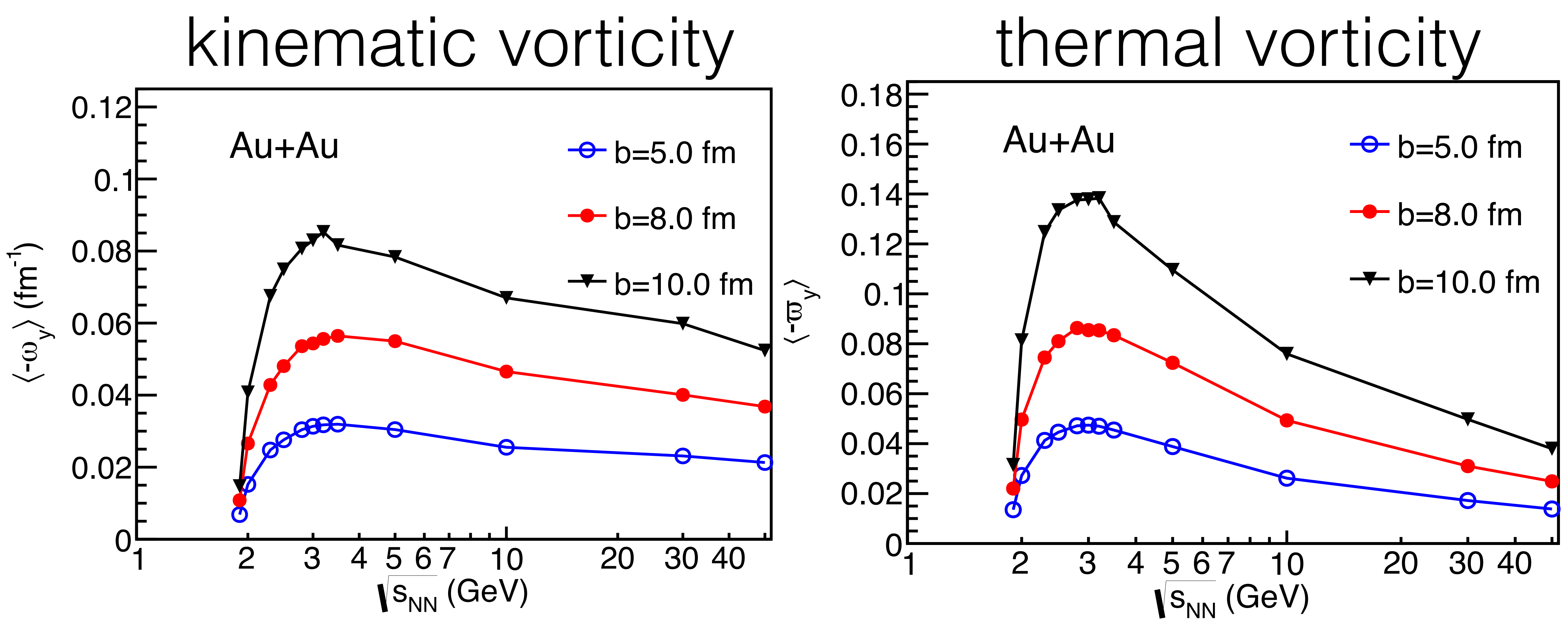
- ALICE at 2.76 and 5.02 TeV
  - Expected signal is of the order of current statistical uncertainty
- HADES at 2.4 GeV
  - still preliminary
  - hopefully reduce systematic uncertainty
- Preliminary of STAR at 27 and 54.4 GeV

Collection of recent results

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



covered by HADES and STAR FXT+BES-II



Energy dependence of kinematic and thermal vorticity with UrQMD
X.-G. Deng et al., PRC101.064908 (2020)

HADES: 2.0-2.4 GeV
STAR FXT: 3-7.7 GeV
STAR BES II: 7.7-19 GeV

A possible probe of B-field

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

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

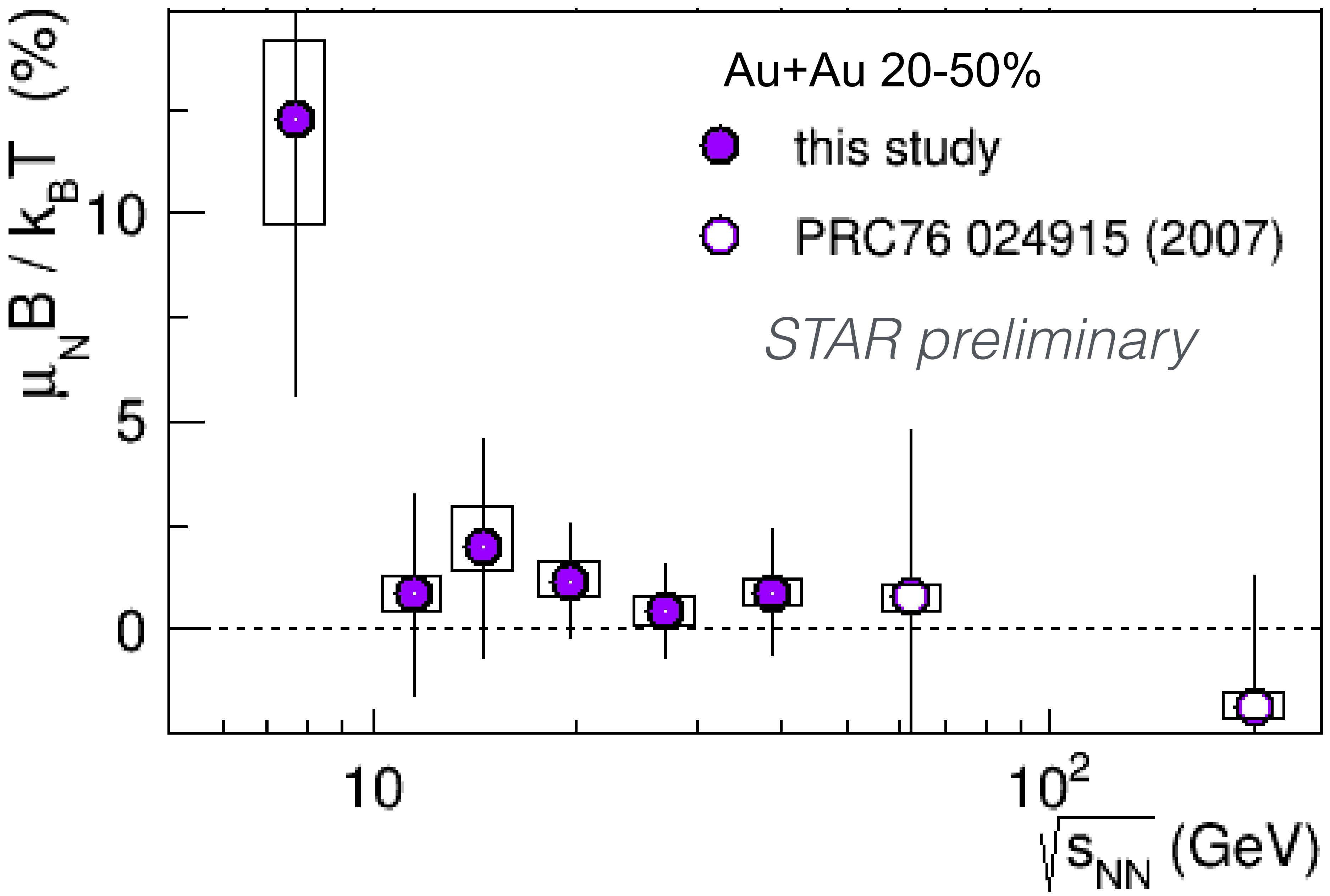
$$P_{\bar{\Lambda}} \simeq \frac{1}{2}\frac{\omega}{T} - \frac{\mu_\Lambda B}{T}$$

μ_Λ: Λ magnetic moment

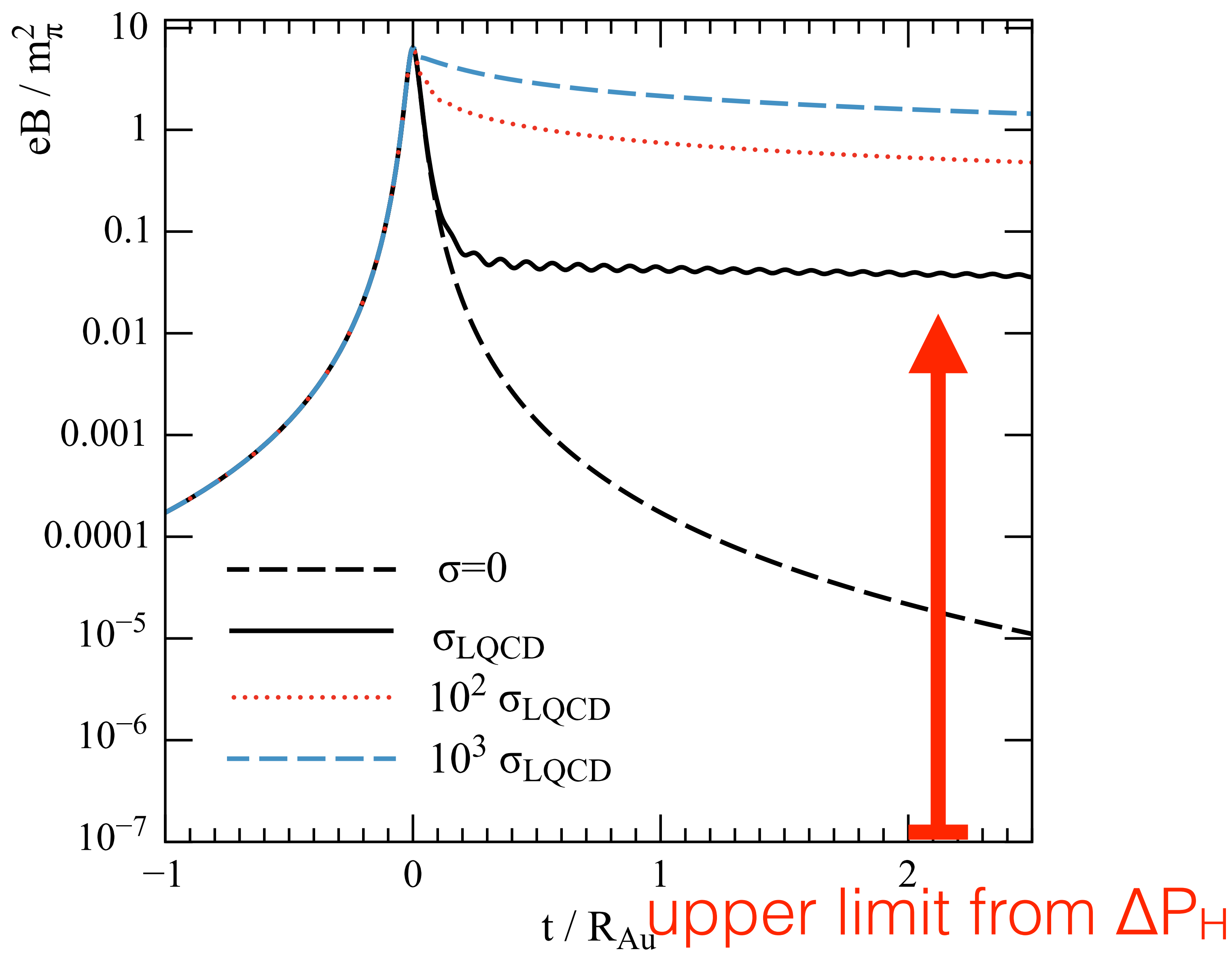
$$B = (P_\Lambda - P_{\bar{\Lambda}})k_B T/\mu_N$$
$$\sim 5.0 \times 10^{13} \text{ [Tesla]}$$

nuclear magneton $\mu_N = -0.613\mu_\Lambda$

QM17, I. Upsal (STAR)



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



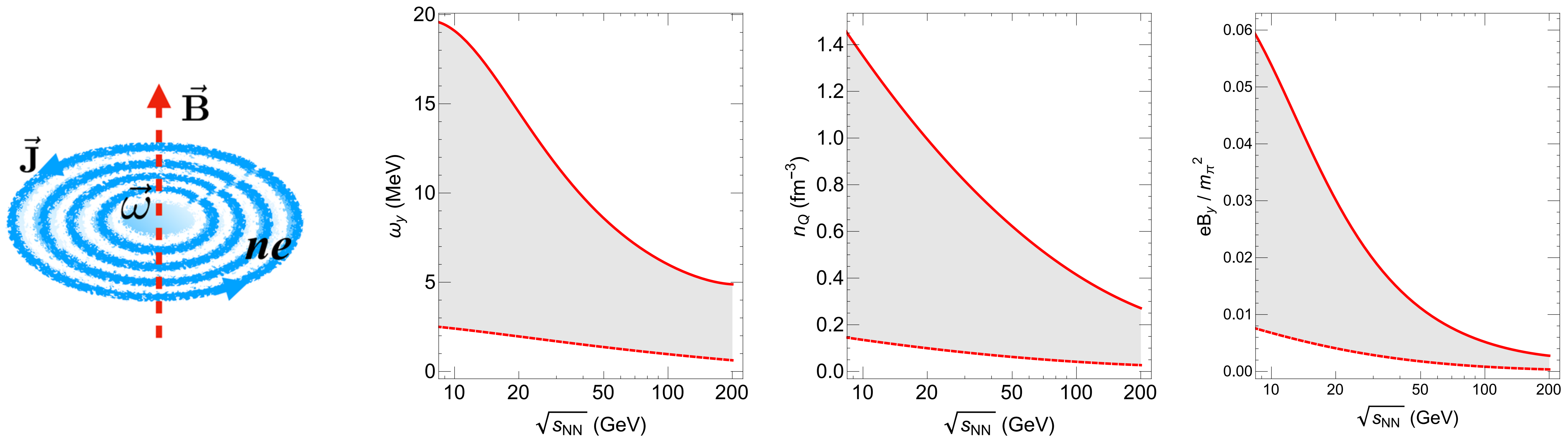
Conductivity increases lifetime.

- B-field at freeze-out could be probed by Λ-antiΛ splitting
  - Current results are consistent with zero (except 7.7 GeV)
- The small splitting could be also due to other effects

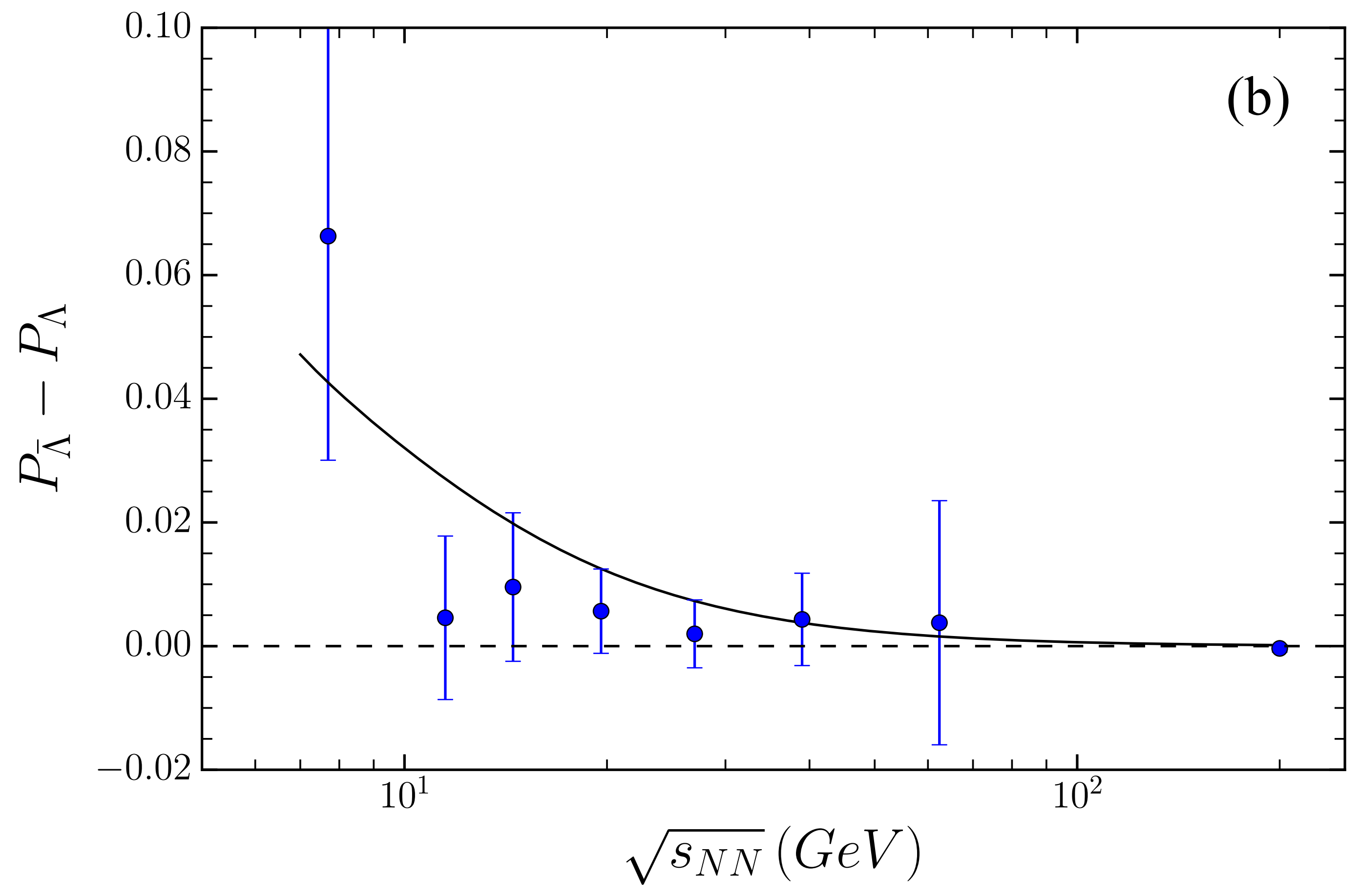
But need caution for the interpretation

Λ-antiΛ P_H splitting could be also due to other effects:

- 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

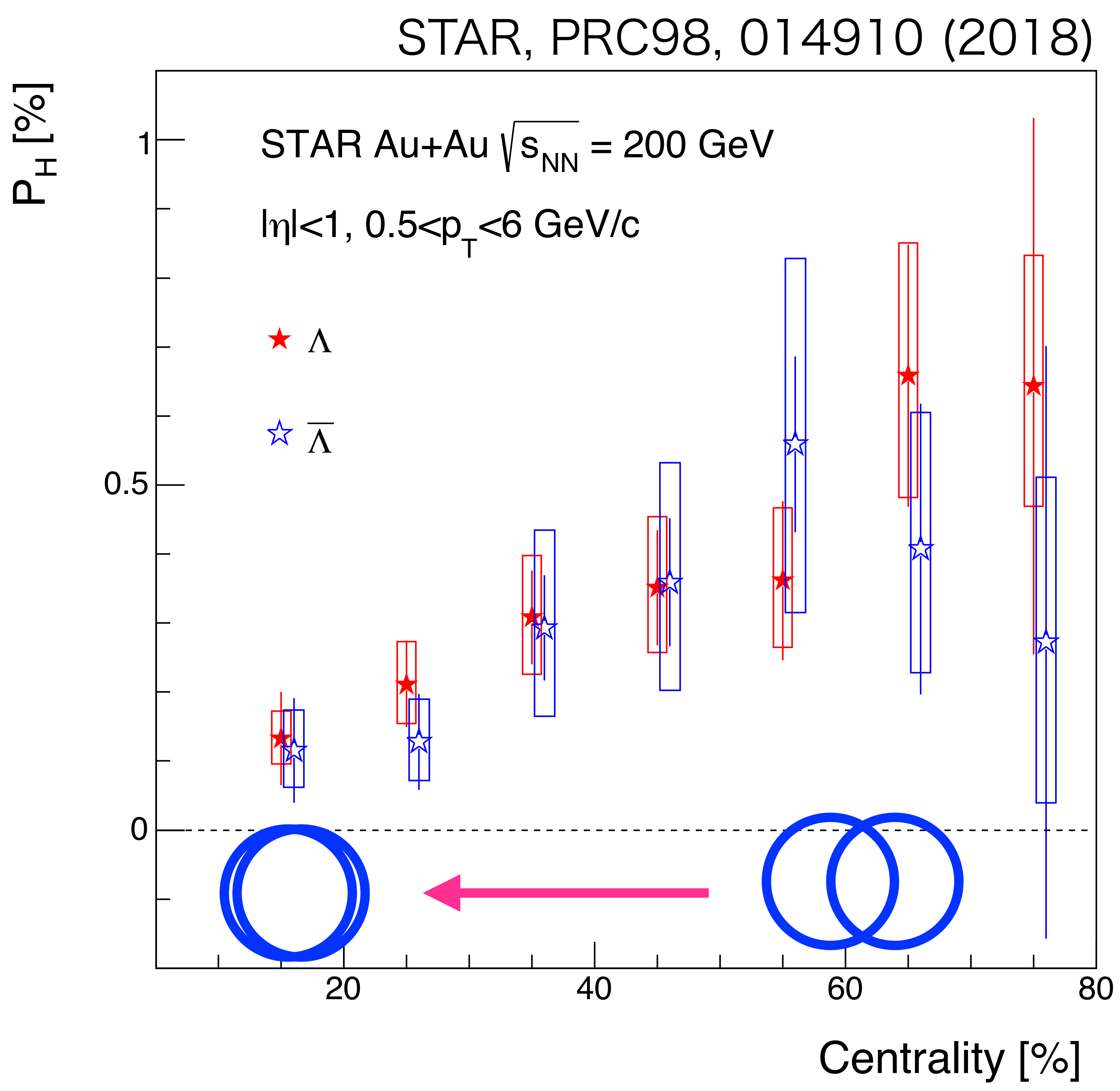


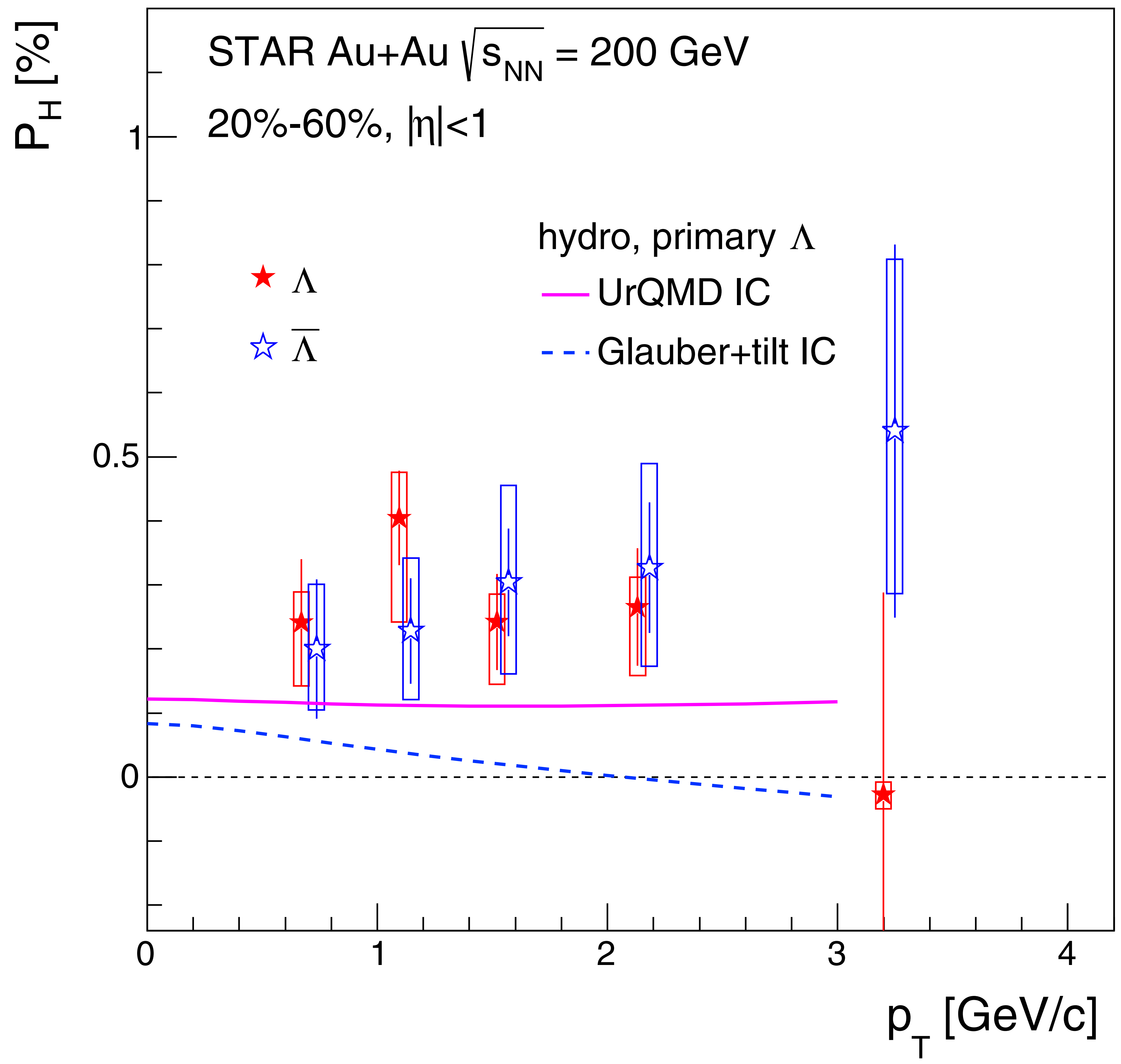
X. Guo, J. Liao, and E. Wang, PRC99.021901(R) (2019)



L. Csernai, J. Kapusta, and T. Welle, PRC99.021901(R) (2019)

Differential measurements: centrality and p_T

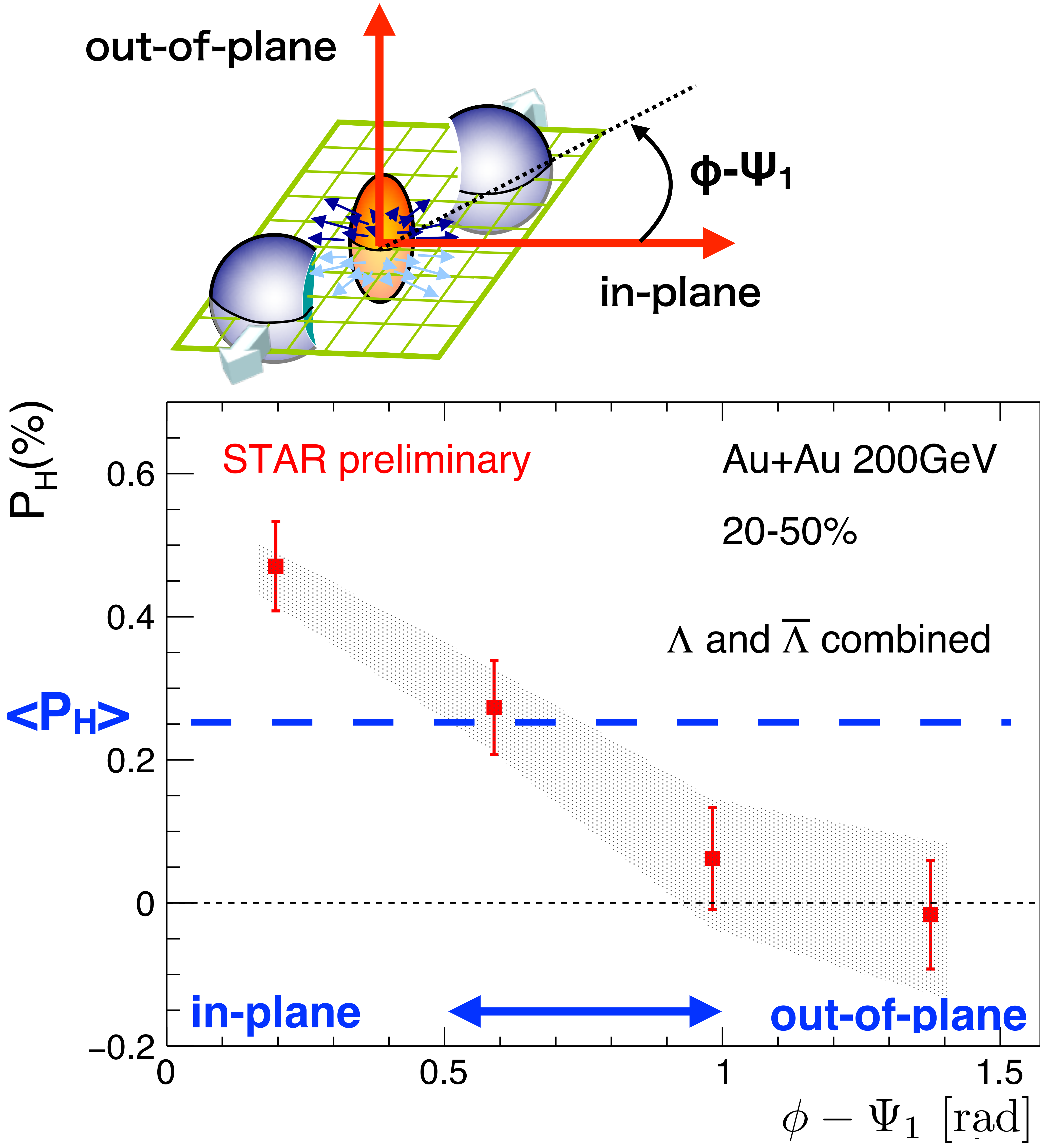


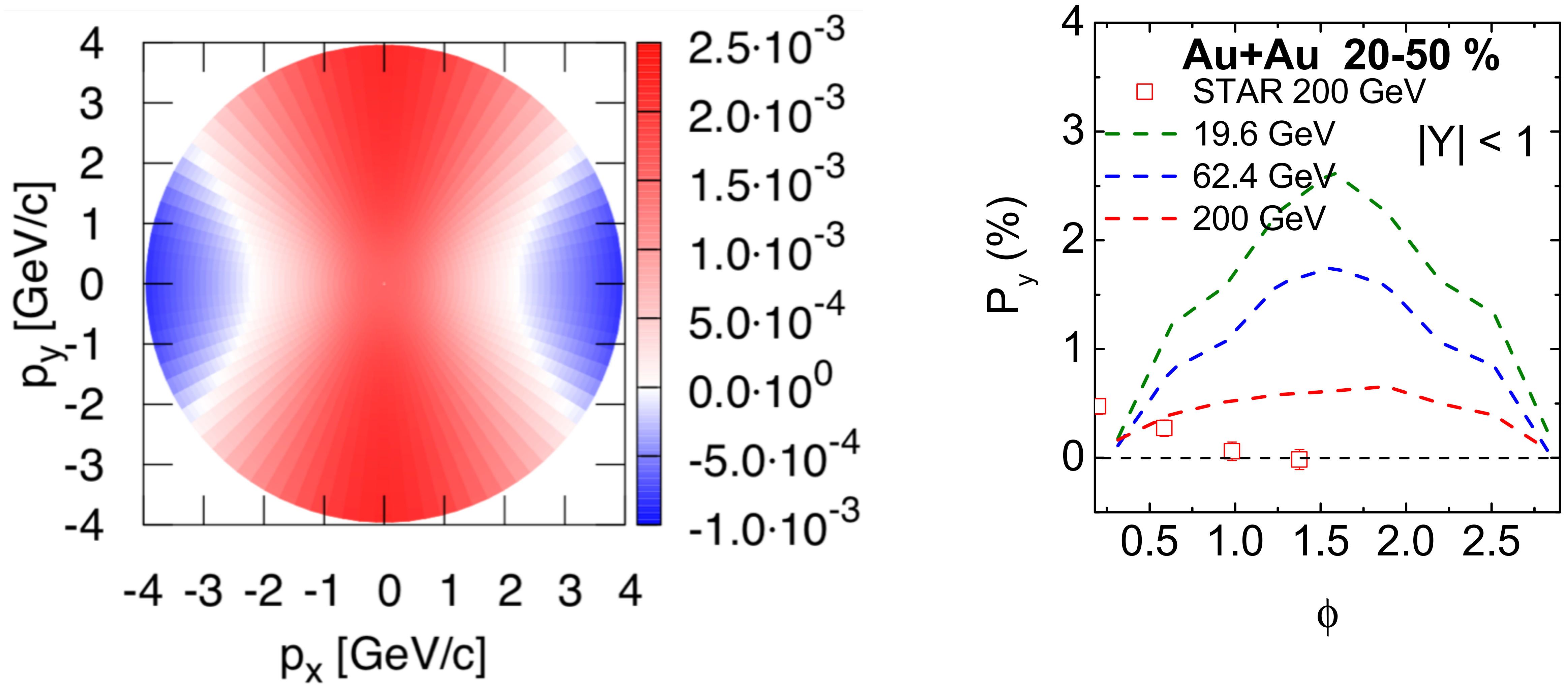


In most central collision → no initial angular momentum
The polarization decreases in more central collisions.

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

Differential measurements: azimuthal angle



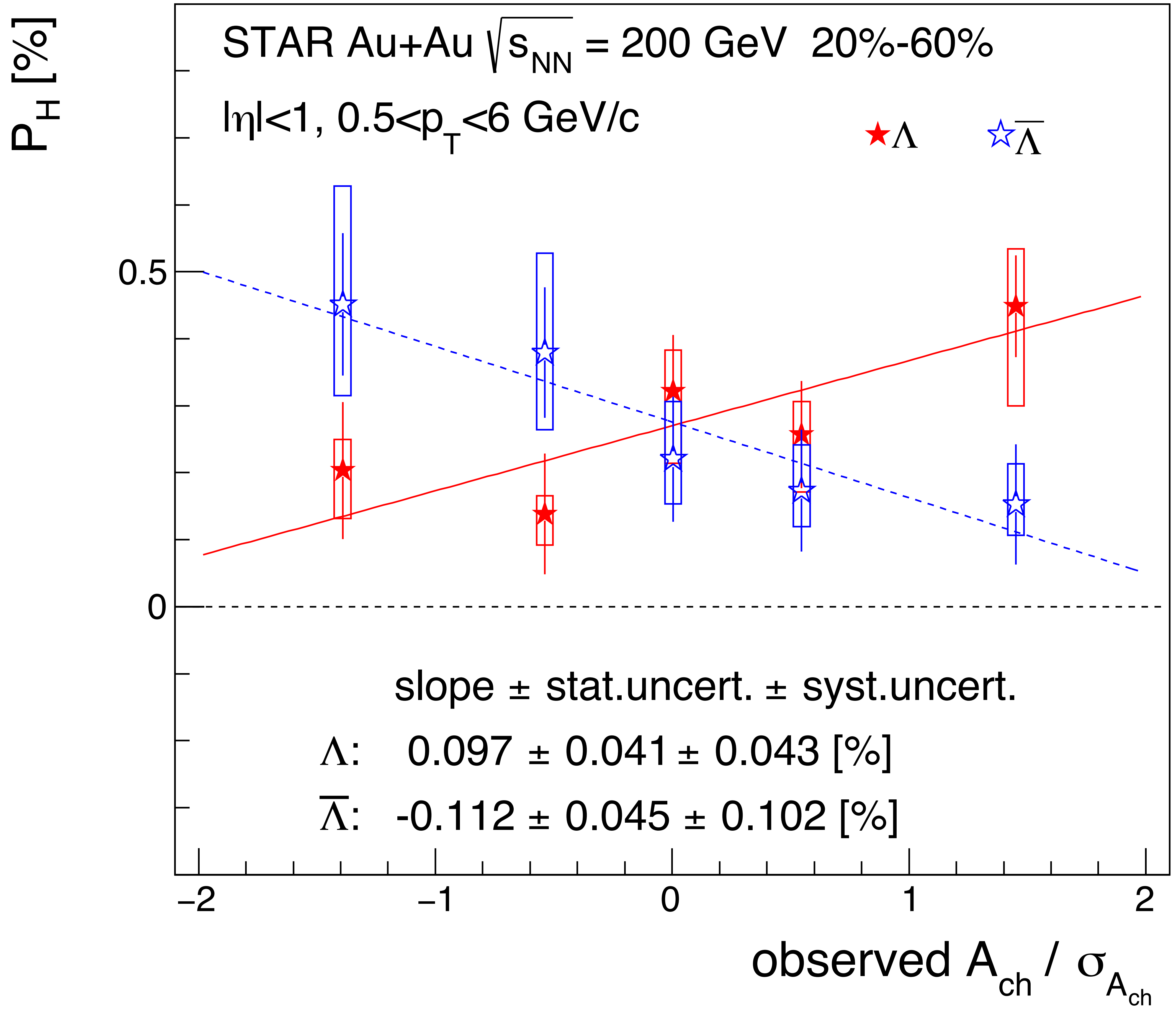


I. Karpenko and F. Becattini, EPJC(2017)77.213
D. Wei, W. Deng, and X. Huang, PRC99.014905 (2019)
H. Wu et al., PR.Research1.033058 (2019)

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

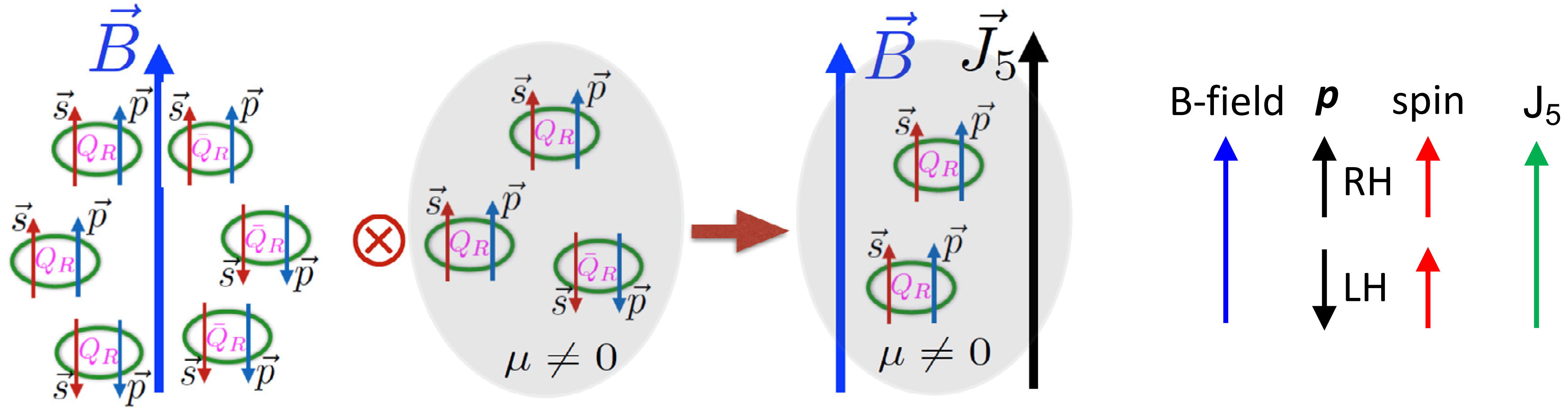
Differential measurements: charge asymmetry

STAR, PRC98, 014910 (2018)



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

Chiral Separation Effect $\mathbf{J}_5 \propto e\mu_v \mathbf{B}$



B-field + massless quarks + non-zero μ_v → axial current J_5

- A_{ch} dependence observed
  - Slopes of Λ and anti-Λ seem to be opposite (~2σ level)
- Possible contribution from axial charge or
- Quark vector chemical potential may explain the data

Sun and Ko, INT20-1-c

Spin alignment of vector mesons

Species	K^{*0}	φ
Quark content	$d\bar{s}$	$s\bar{s}$
Mass (MeV/c^2)	896	1020
Lifetime (fm/c)	4	45
Spin (J^P)	1^-	1^-
Decays	Kπ	KK
Branching ratio	**~100%**	66%

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

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

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

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

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"

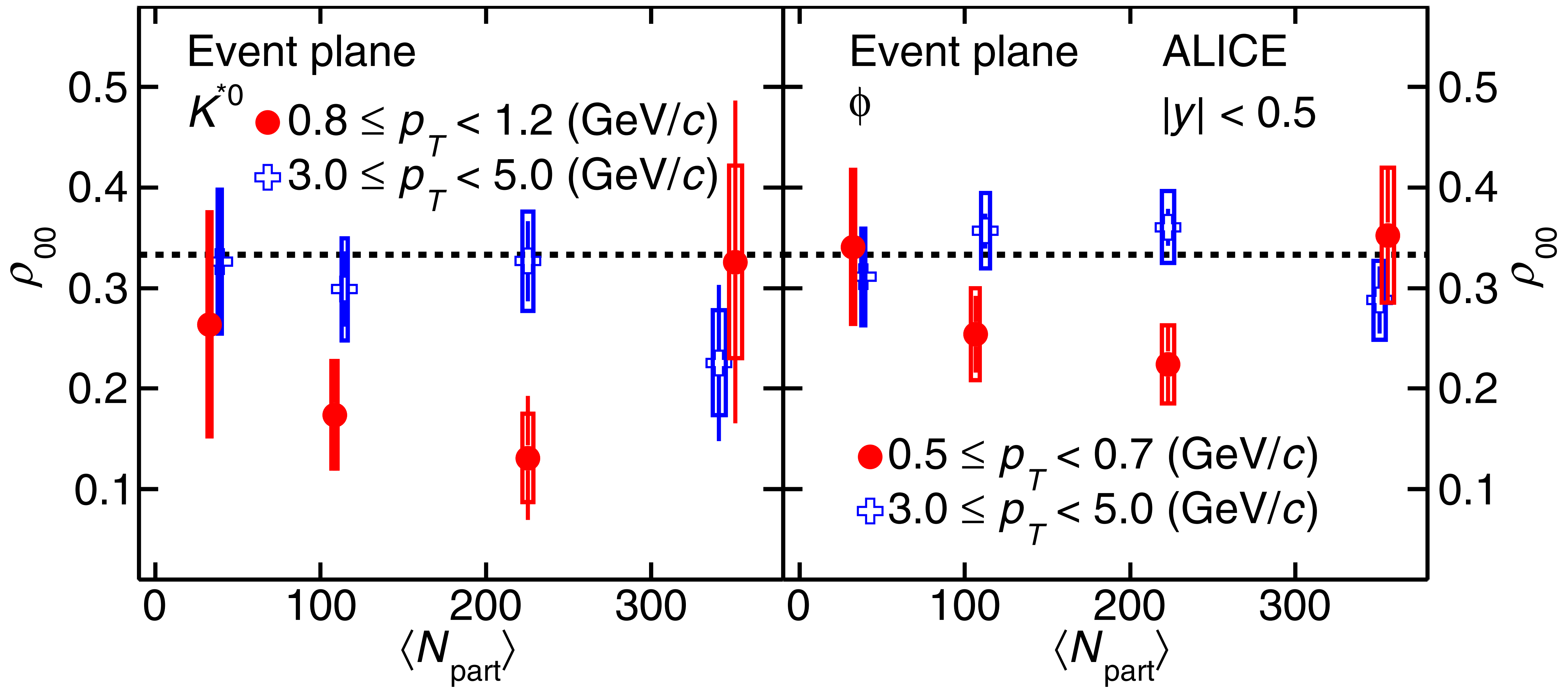
Z.-T. Liang and X.-N. Wang, PRL94.102301(2005)
Y. Yang et al., PRC97.034917(2018)

Theoretical expectation for ρ_{00}

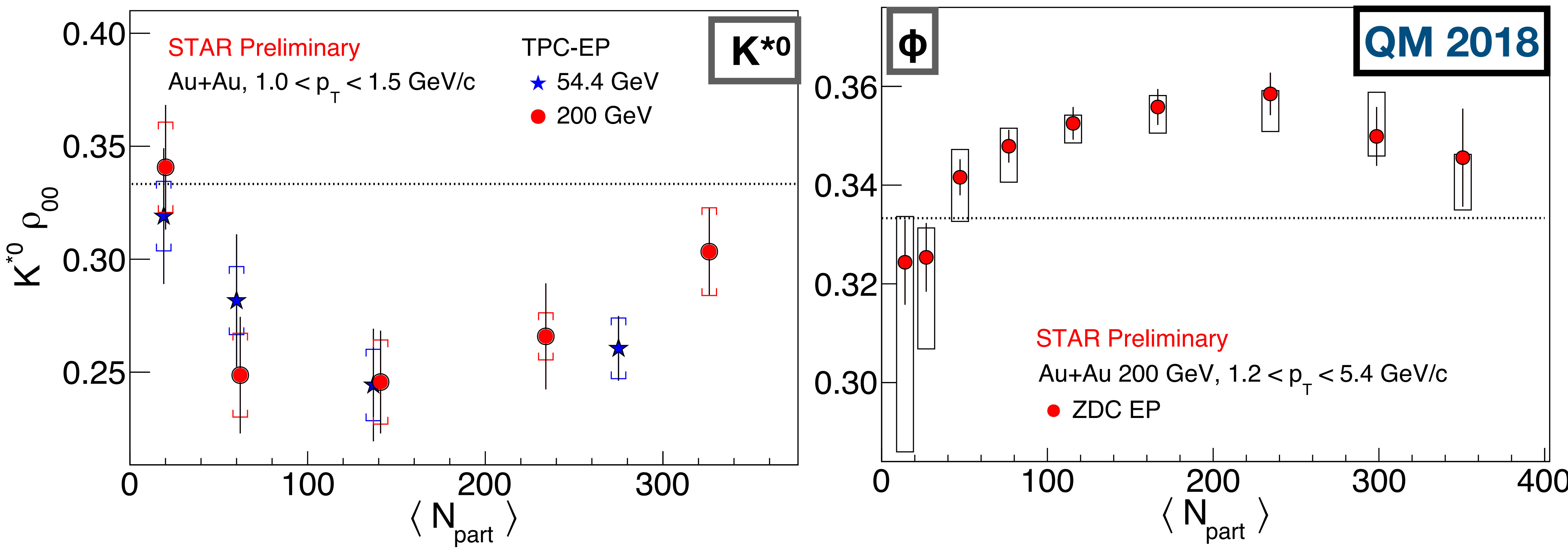
Vorticity	
recombination	$\rho_{00} < 1/3$
fragmentation	$\rho_{00} > 1/3$
Magnetic field	$\rho_{00} > 1/3$ (for neutral vector mesons)

Results from LHC and RHIC

ALICE, PRL125.012301 (2020)



STAR, QM18, QM19



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

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

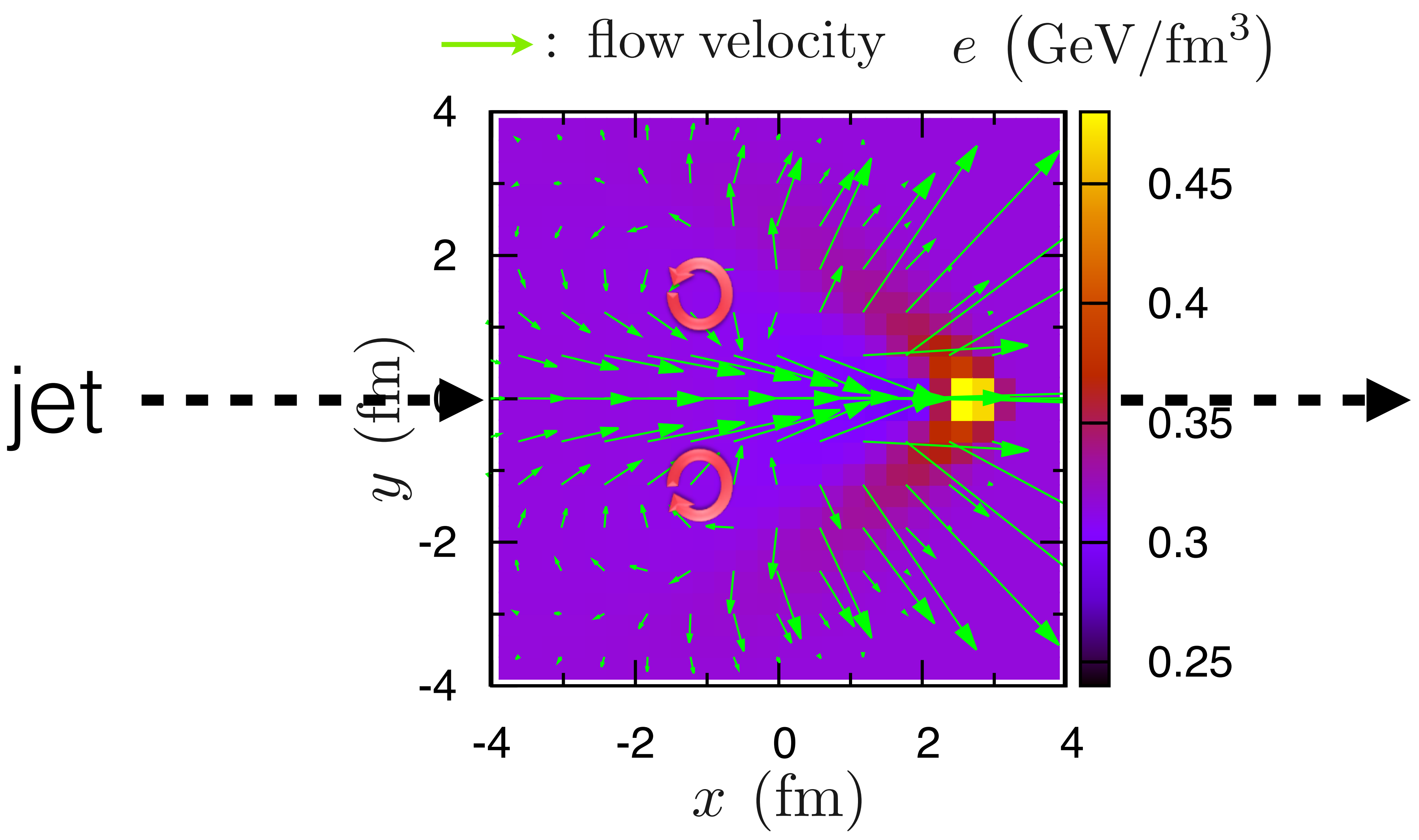
- The deviation in opposite way between:
  - K* and ϕ at RHIC
  - LHC and RHIC for ϕ

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)

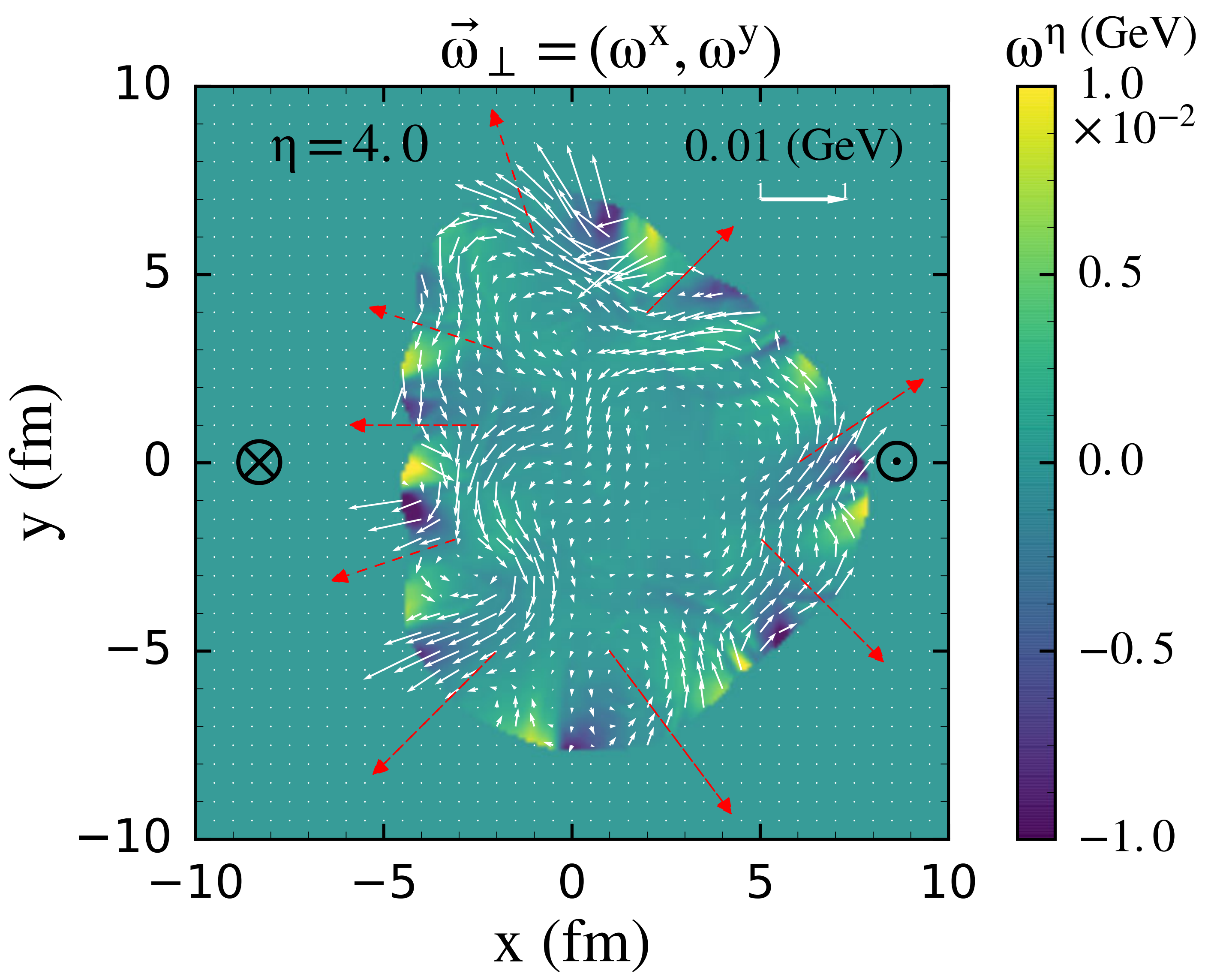
Local vorticity

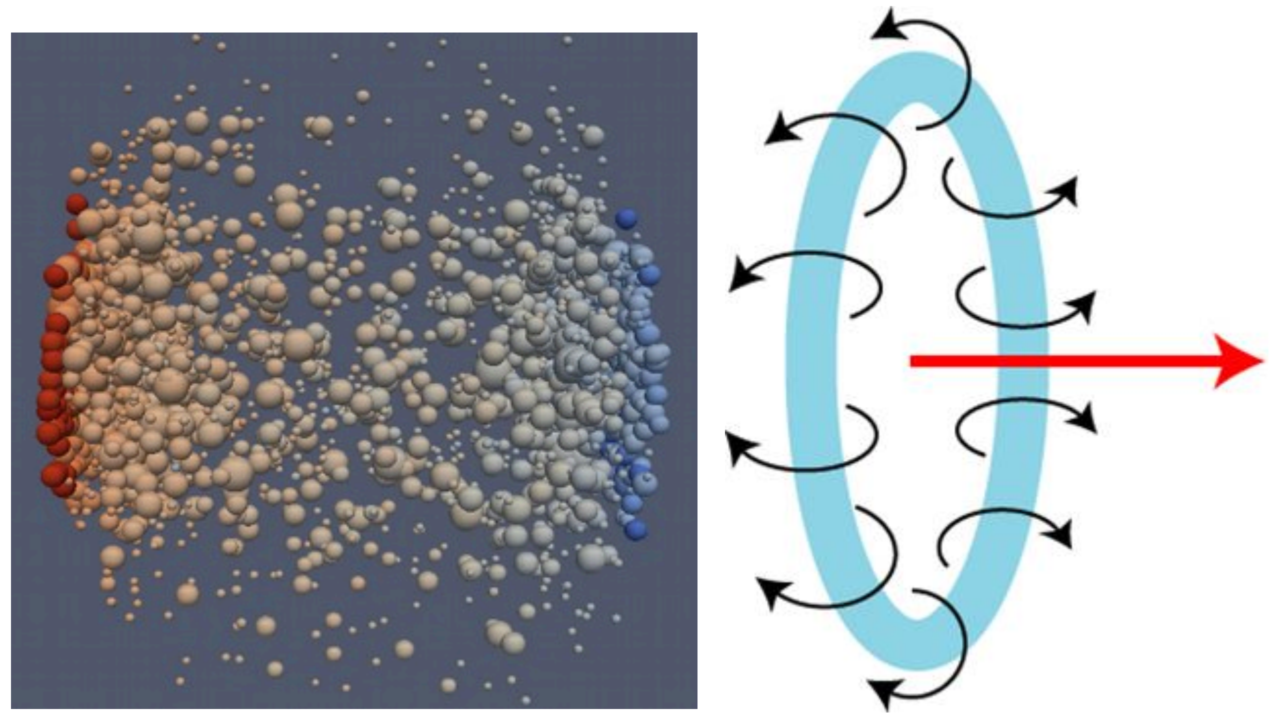
Vortex induced by jet



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

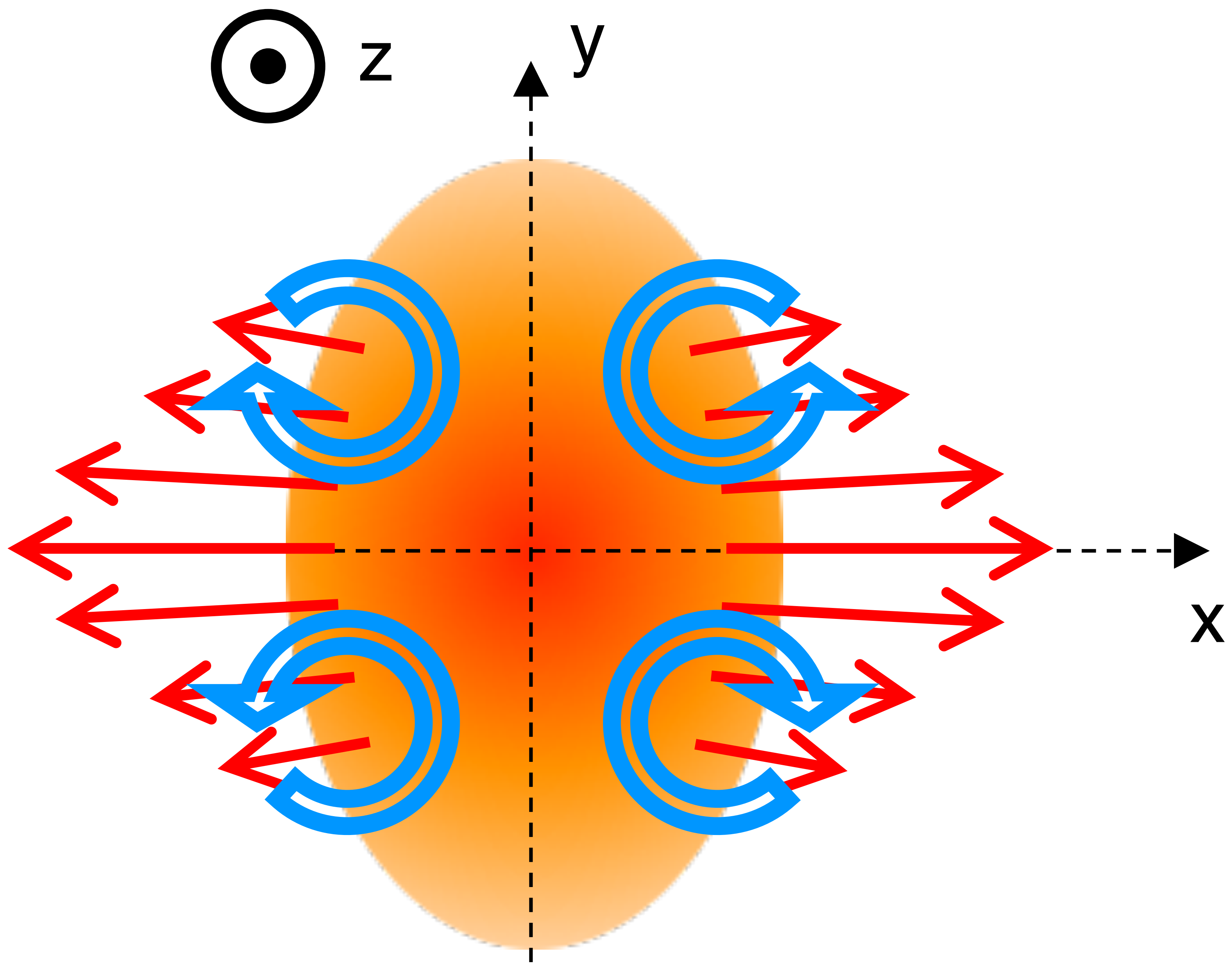


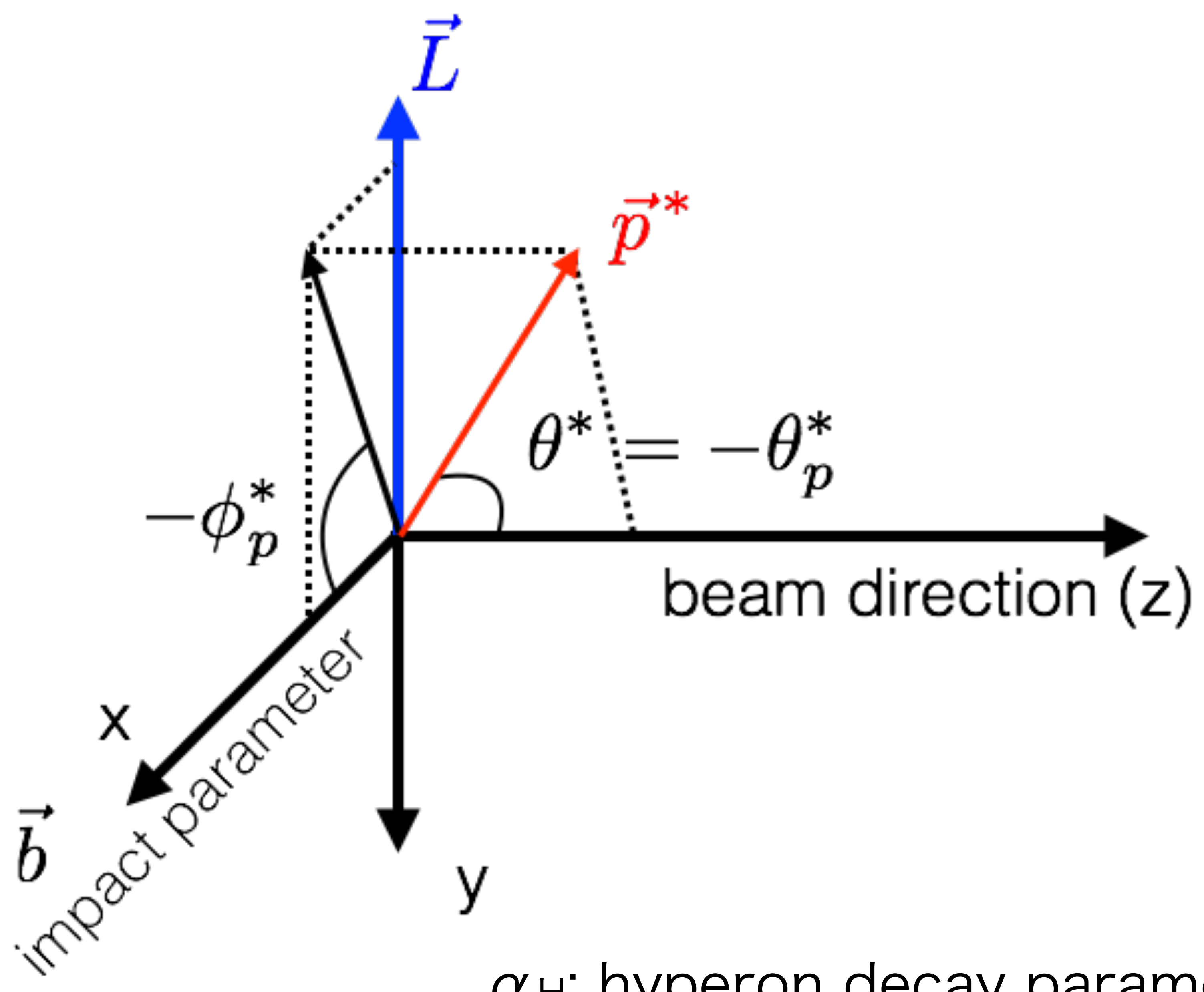


L.-G. Pang, H. Peterson, Q. Wang, and X.-N. Wang, PRL117, 192301 (2016)
F. Becattini and I. Karpenko, PRL120.012302 (2018)
S. Voloshin, EPJ Web Conf.171, 07002 (2018)
X.-L. Xia et al., PRC98.024905 (2018)

Polarization along the beam direction

S. Voloshin, SQM2017
F. Becattini and I. Karpenko, PRL120.012302 (2018)





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

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

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

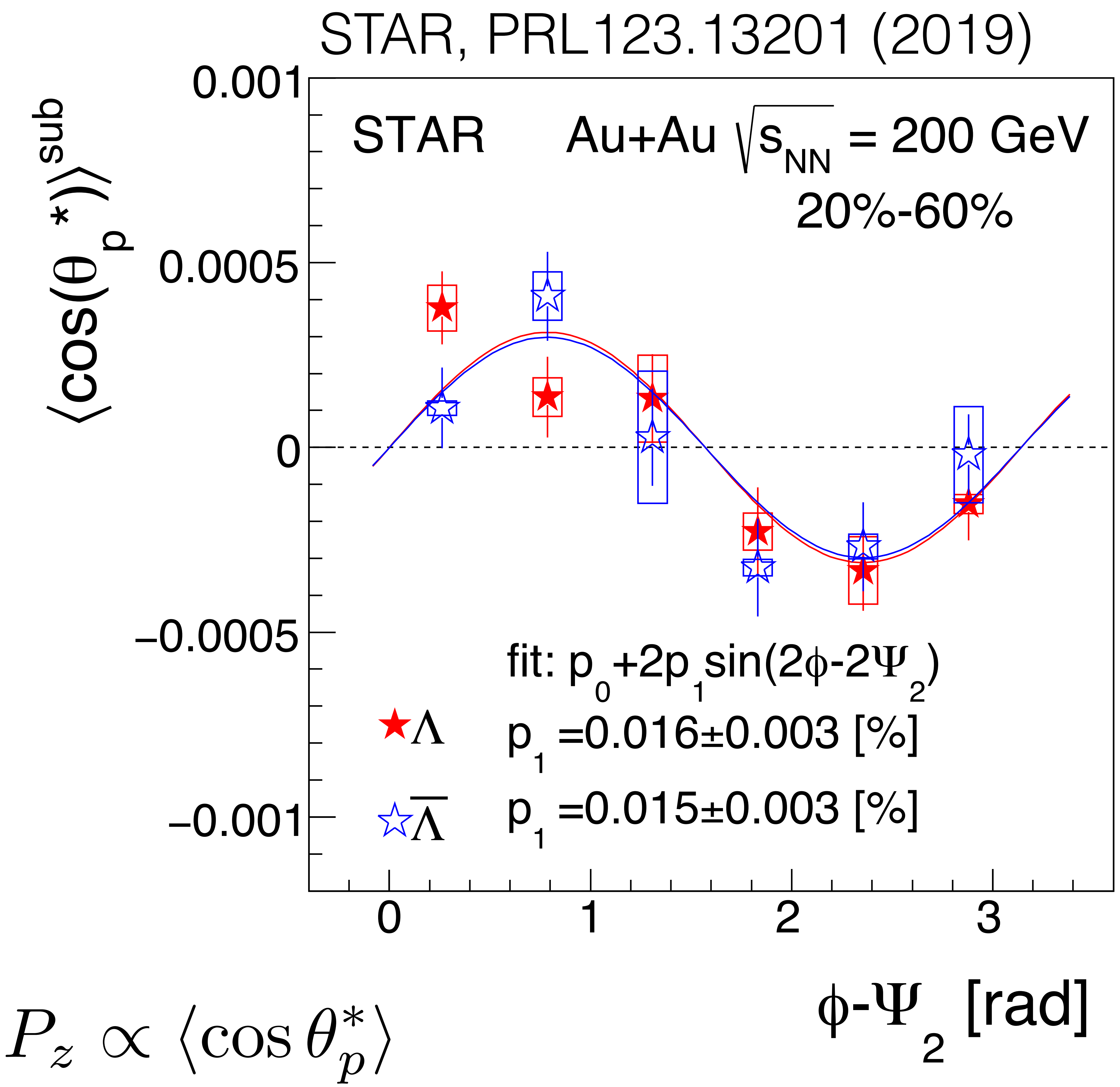
$$\therefore \; P_z = \frac{\langle \cos\theta_p^* \rangle}{\alpha_{\mathrm{H}} \langle (\cos\theta_p^*)^2 \rangle}$$

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

α_{H}: hyperon decay parameter
θ_p^*: θ of daughter proton in Λ rest frame

Stronger flow in in-plane than in out-of-plane
could make local vorticity along beam axis, thus polarization

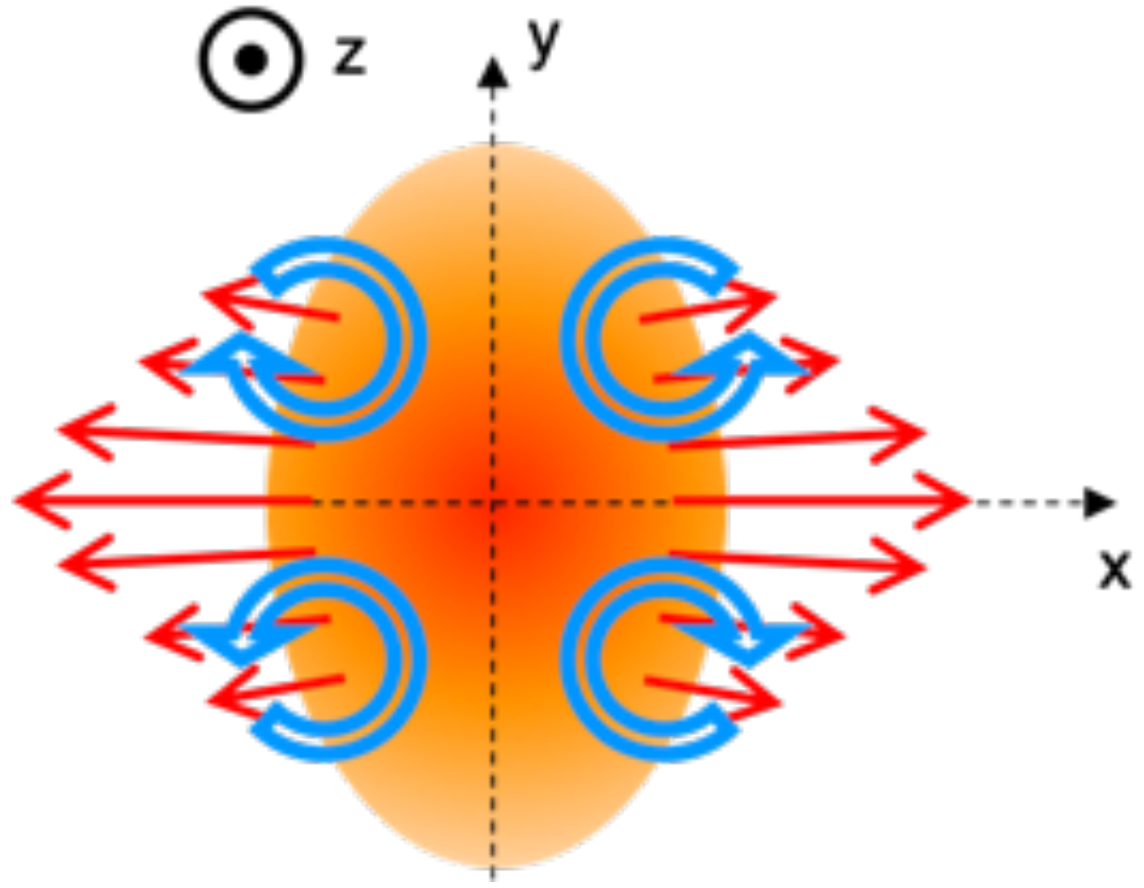
Polarization along the beam direction



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

- Sine structure as expected from the elliptic flow
- Some models cannot describe the sign but some can do. Note that they reasonably describe "global" P_H.

- F. Becattini and I. Karpenko, PRL.120.012302 (2018)
- X. Xia et al., PRC98.024905 (2018)
- Y. Sun and C.-M. Ko, PRC99, 011903(R) (2019)
- Y. Xie, D. Wang, and L. P. Csernai, Eur. Phys. J. C (2020) 80:39
- W. Florkowski et al., Phys. Rev. C 100, 054907 (2019)
- H.-Z. Wu et al., Phys. Rev. Research 1, 033058 (2019)



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)

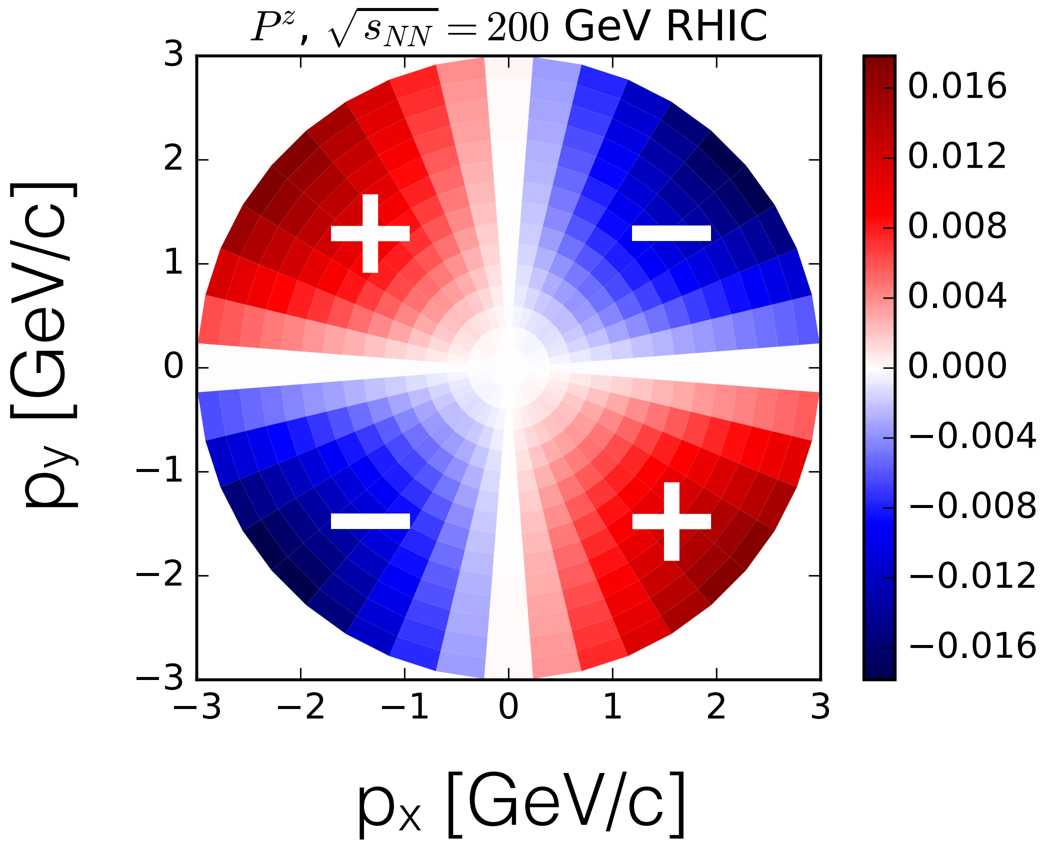
Same sign

- 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

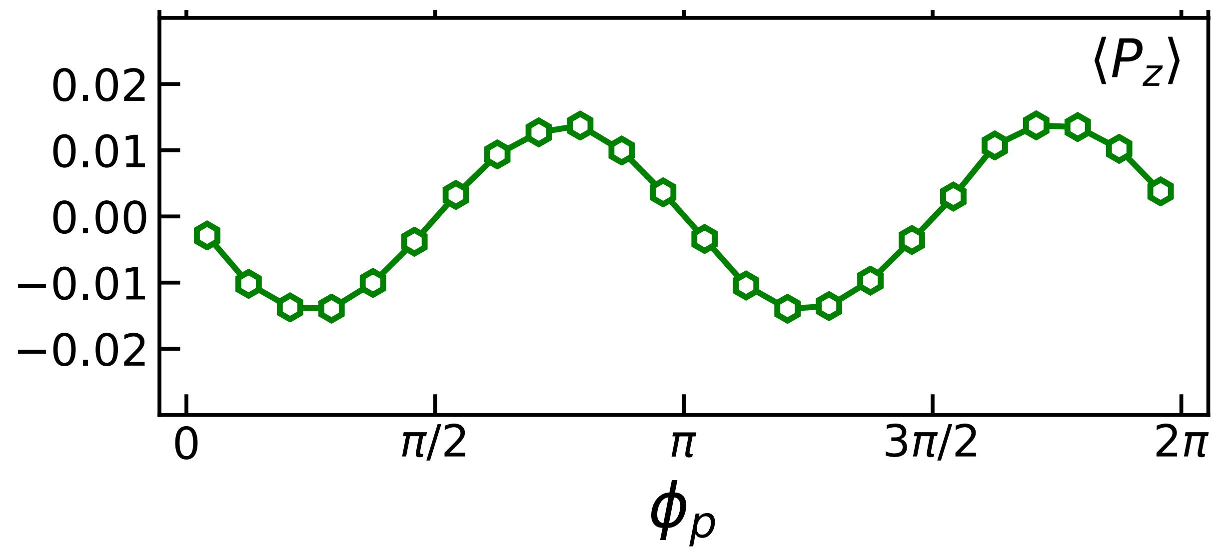
Partly (one of component showing the same sign)

- 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)

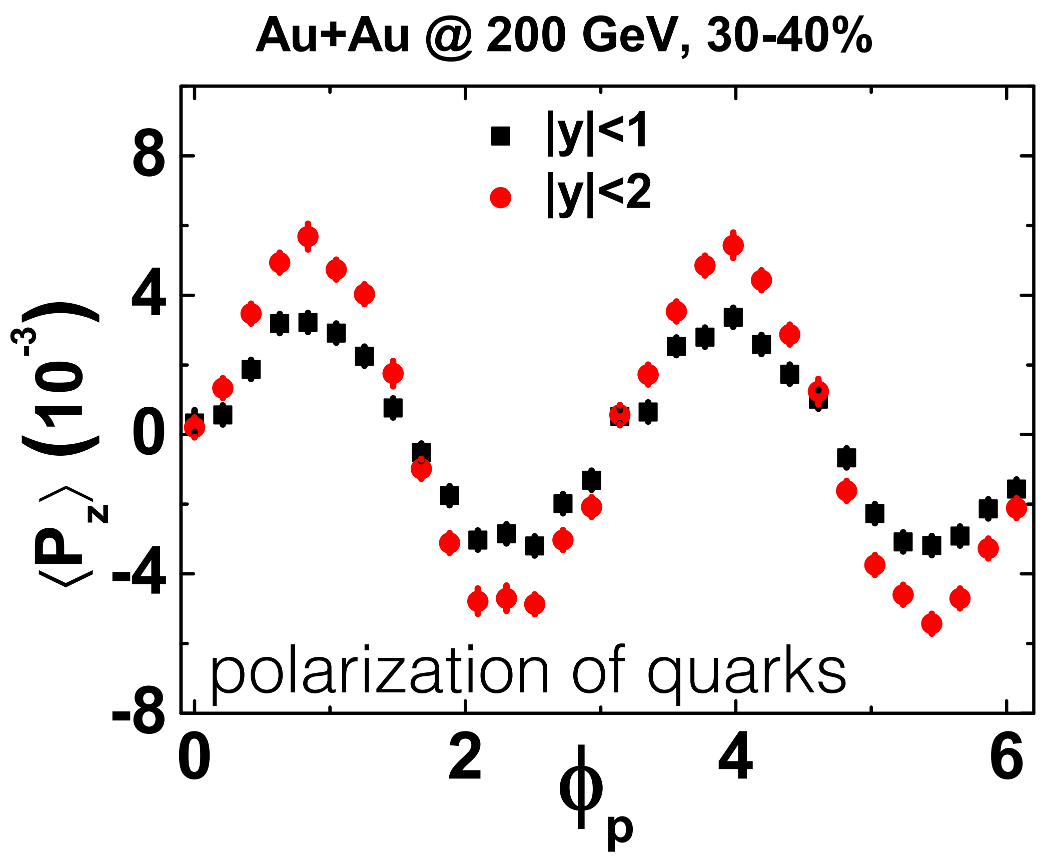
Hydrodynamic model



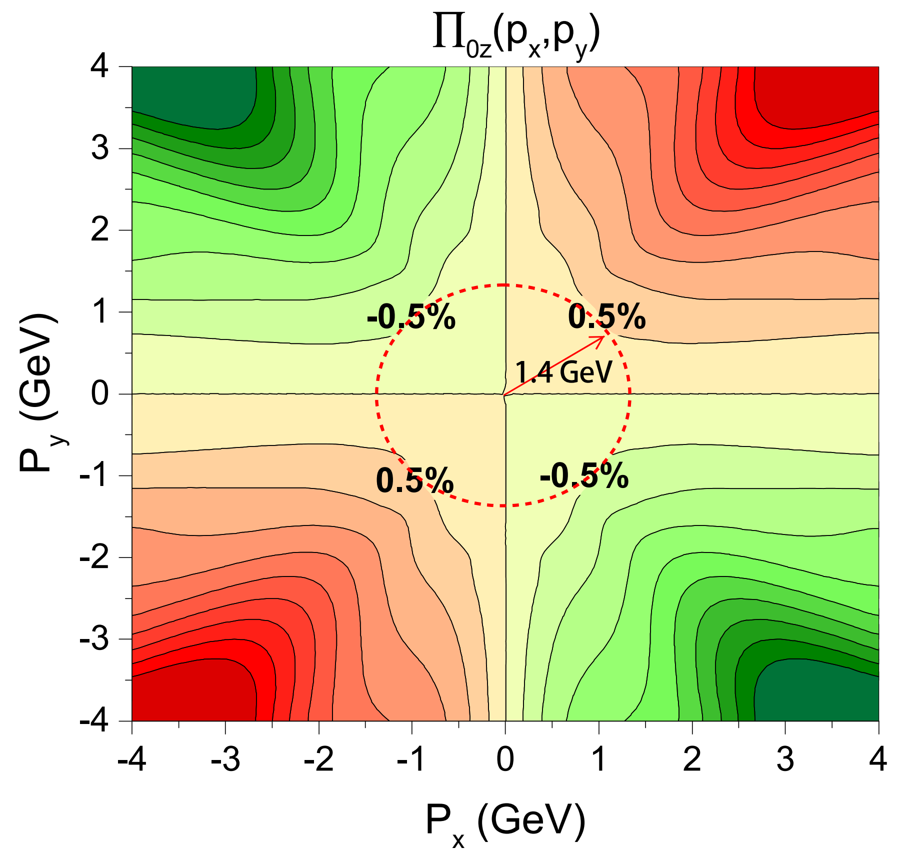
AMPT, Au+Au 200 GeV 20-50%



Chiral kinetic approach



PICR model

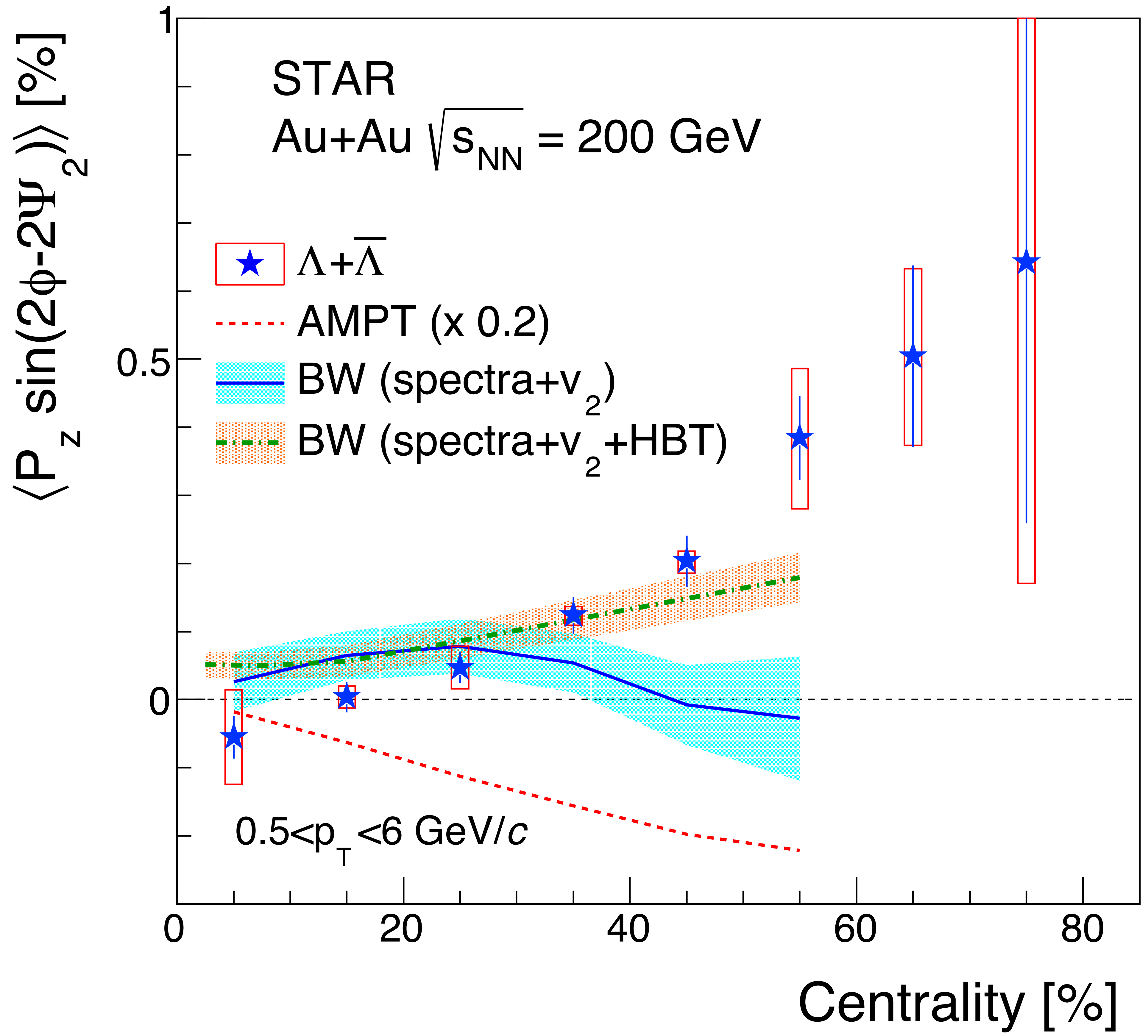


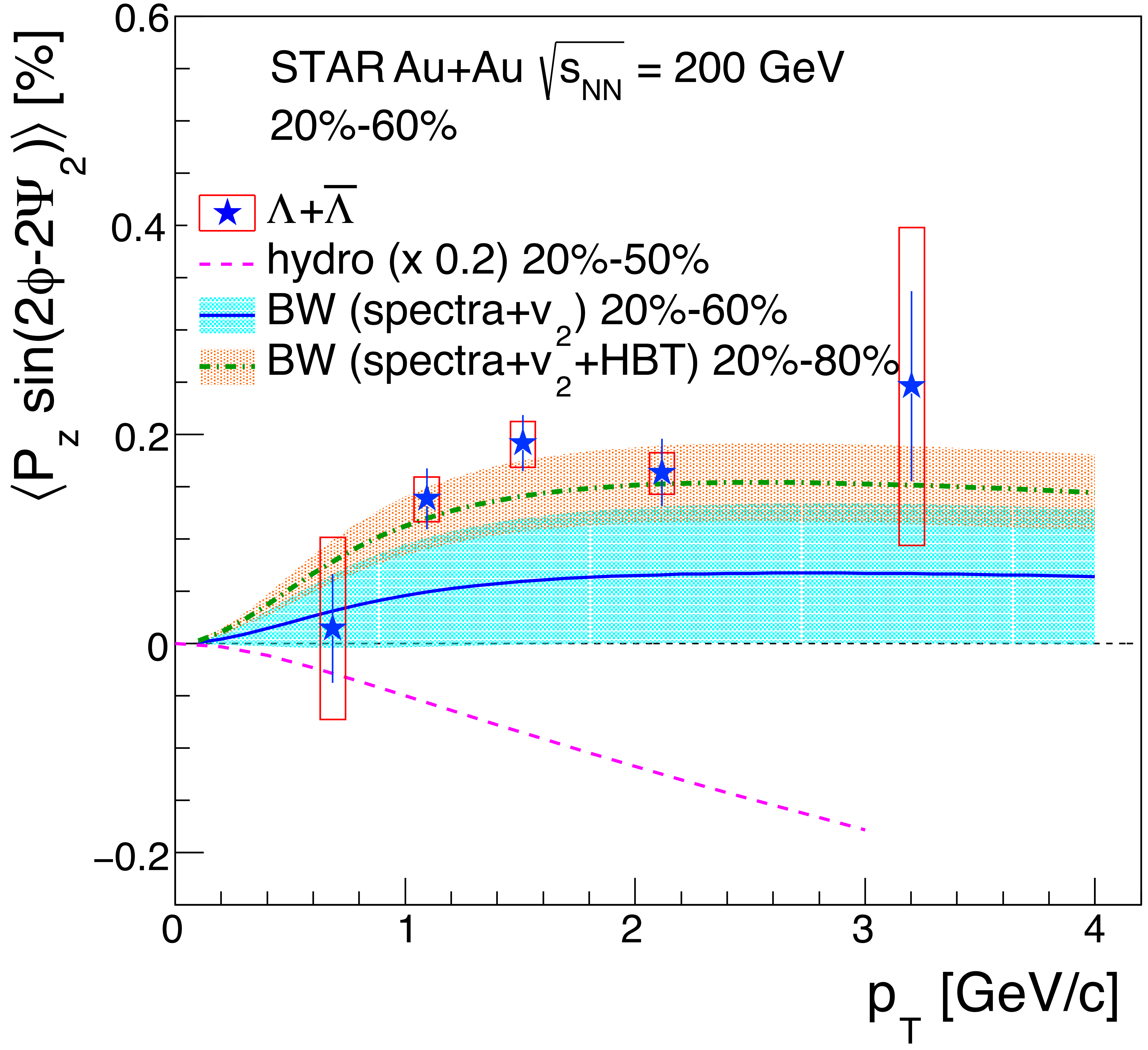
Incomplete thermal equilibrium of spin degree of freedom?

Centrality and p_T dependence of P_z modulation

STAR, PRL123.13201 (2019)

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

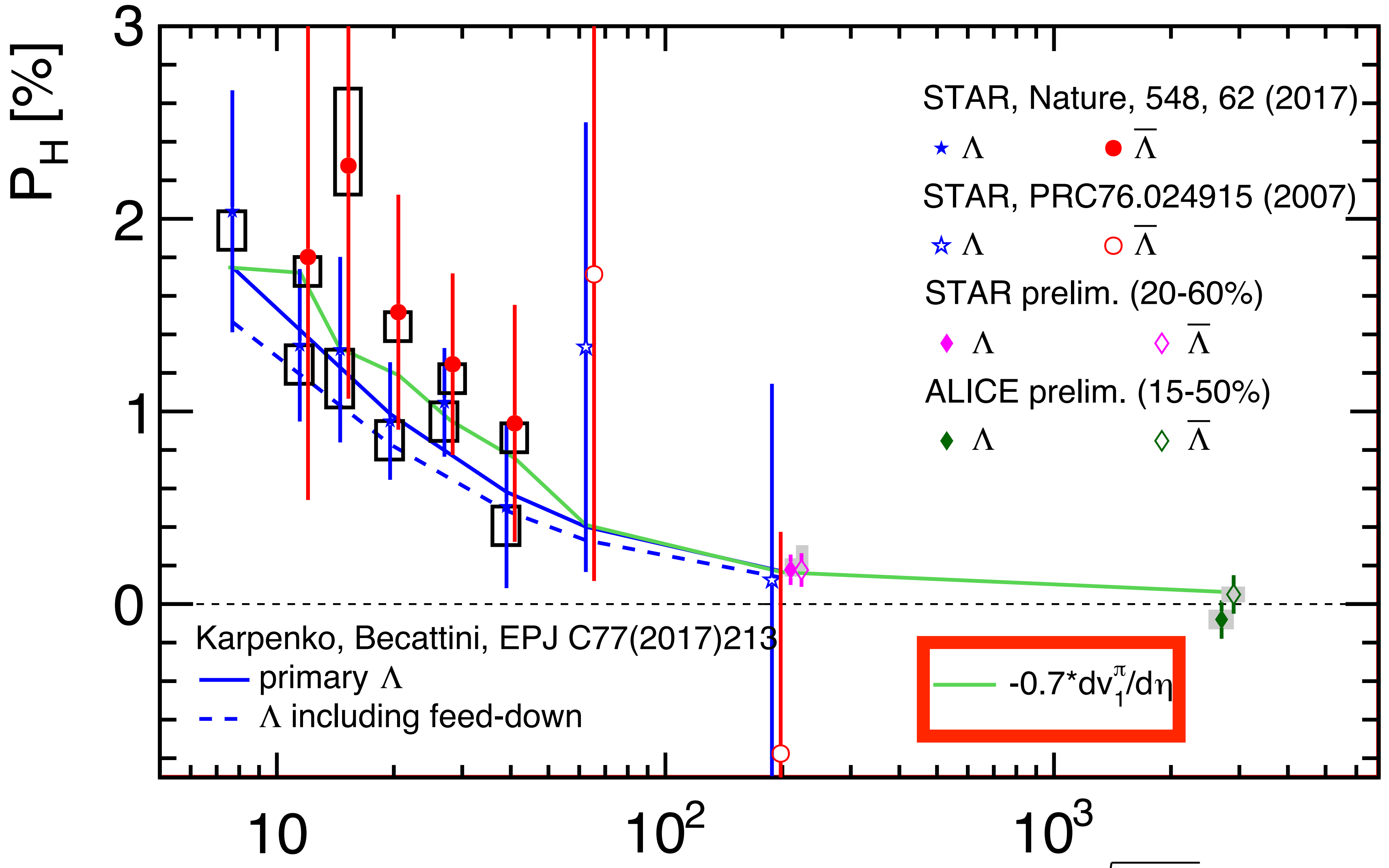




- Strong centrality dependence as in v_2
- No strong p_T dependence but a hint of drop-off at p_T<1 GeV/c
- Blast-Wave model as a simple estimate for kinematic vorticity can describe the data

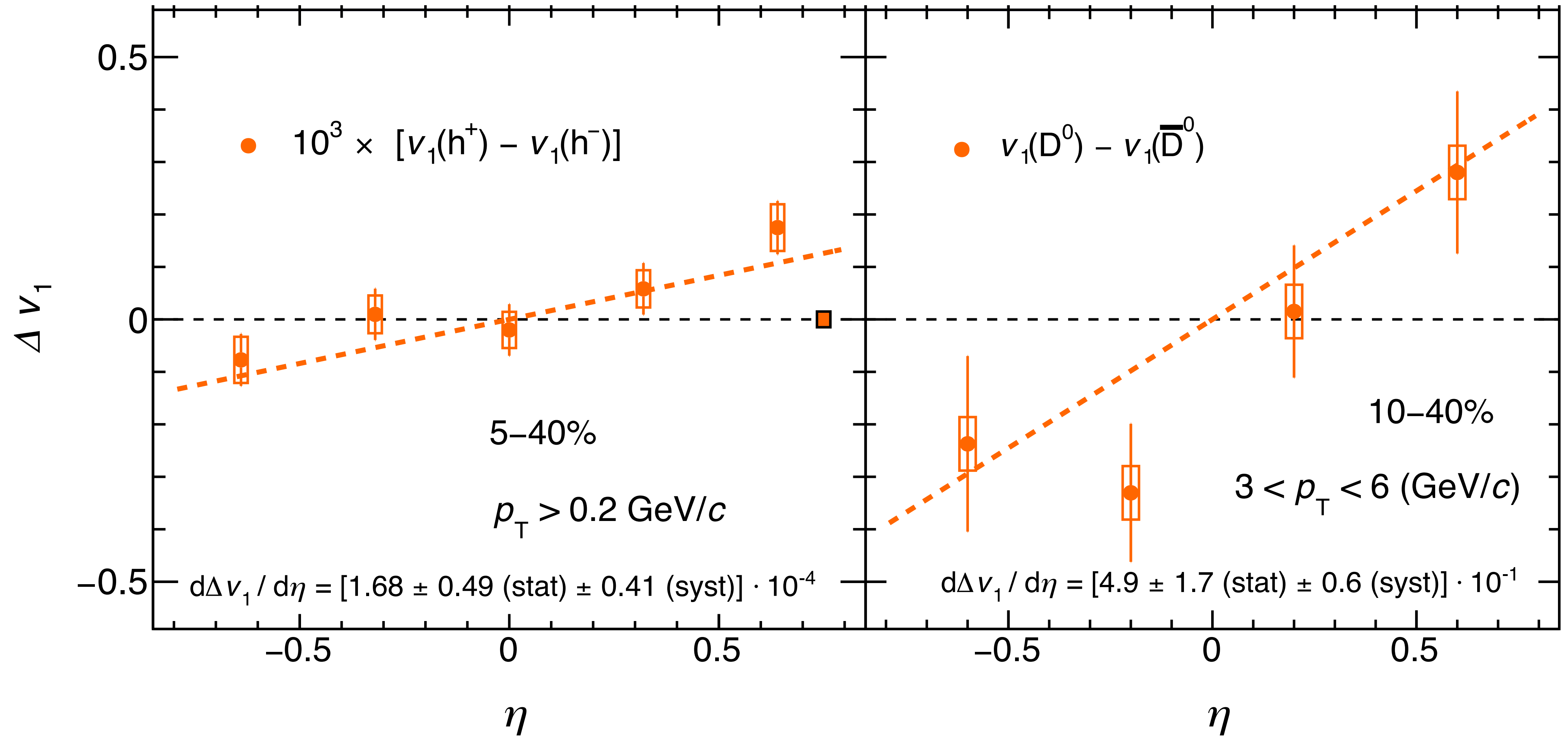
v_1 and vorticity/EM-field

v_1: sensitive to the initial tilt and EM-field



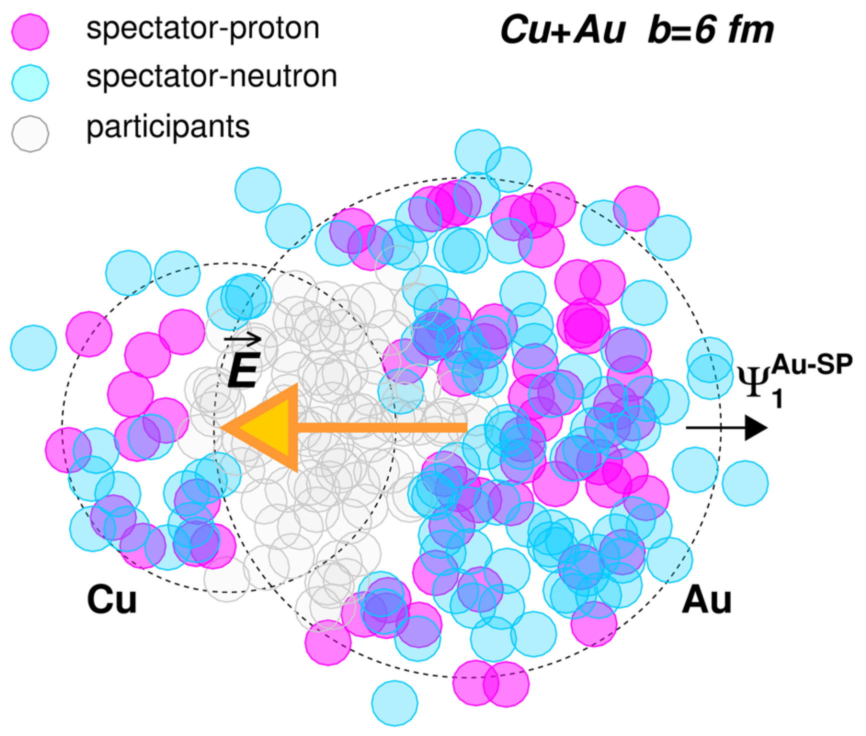
S. Voloshin, EPJ Web Conf.171, 07002 (2018)

ALICE, PRL125.022301 (2020)
Gursoy, Kharzeev, and Rajagopal, PRC89.054905 (2014)
Das et al., PLB768(2017)260

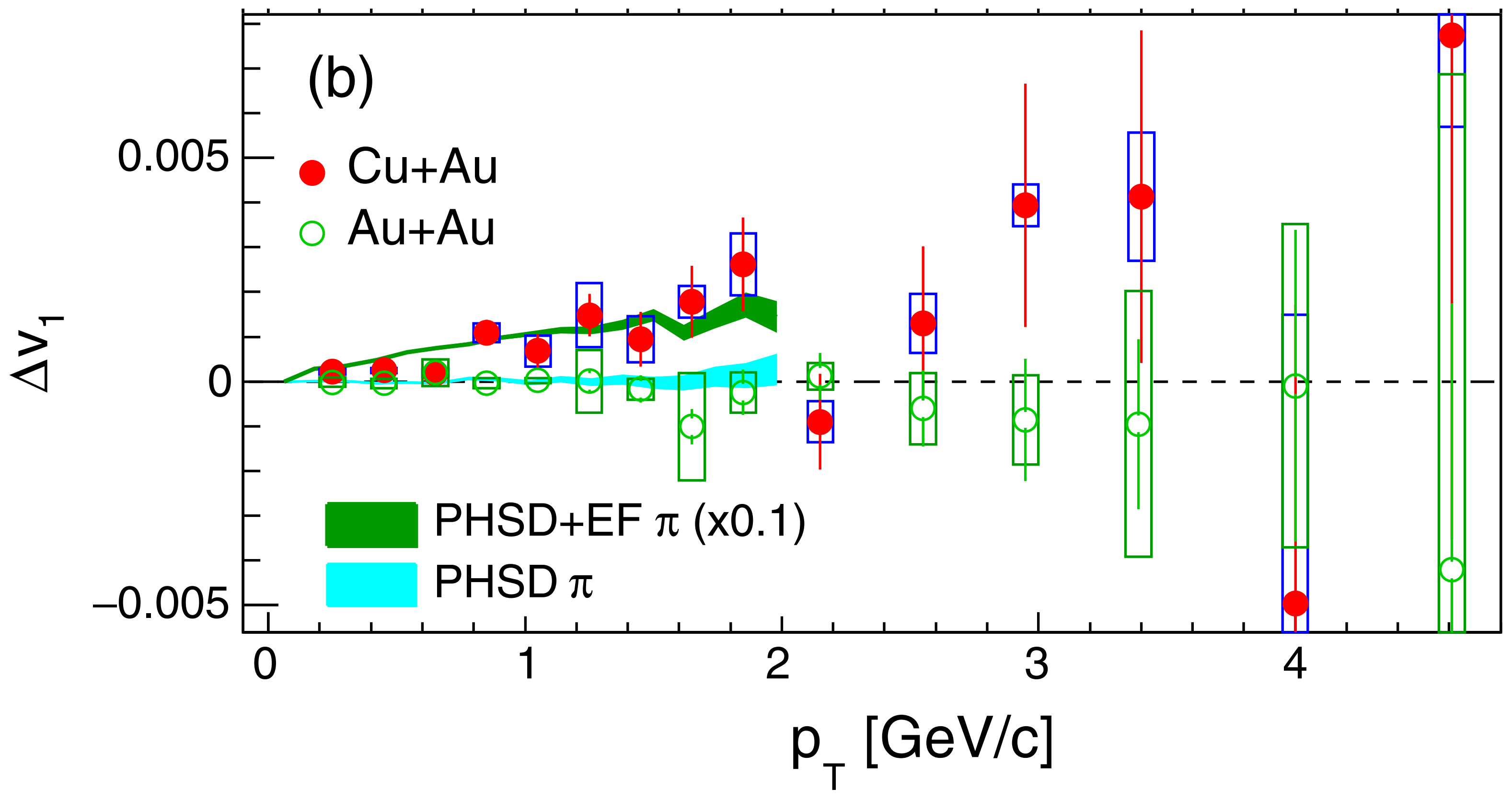


Cu+Au v_1: EM-field lifetime, quark density evolution, conductivity

Y. Hirono, M. Hongo, and T. Hirano, PRC90.021903(R) (2014)
V. Voronyuk et al., PRC90.064903 (2014)



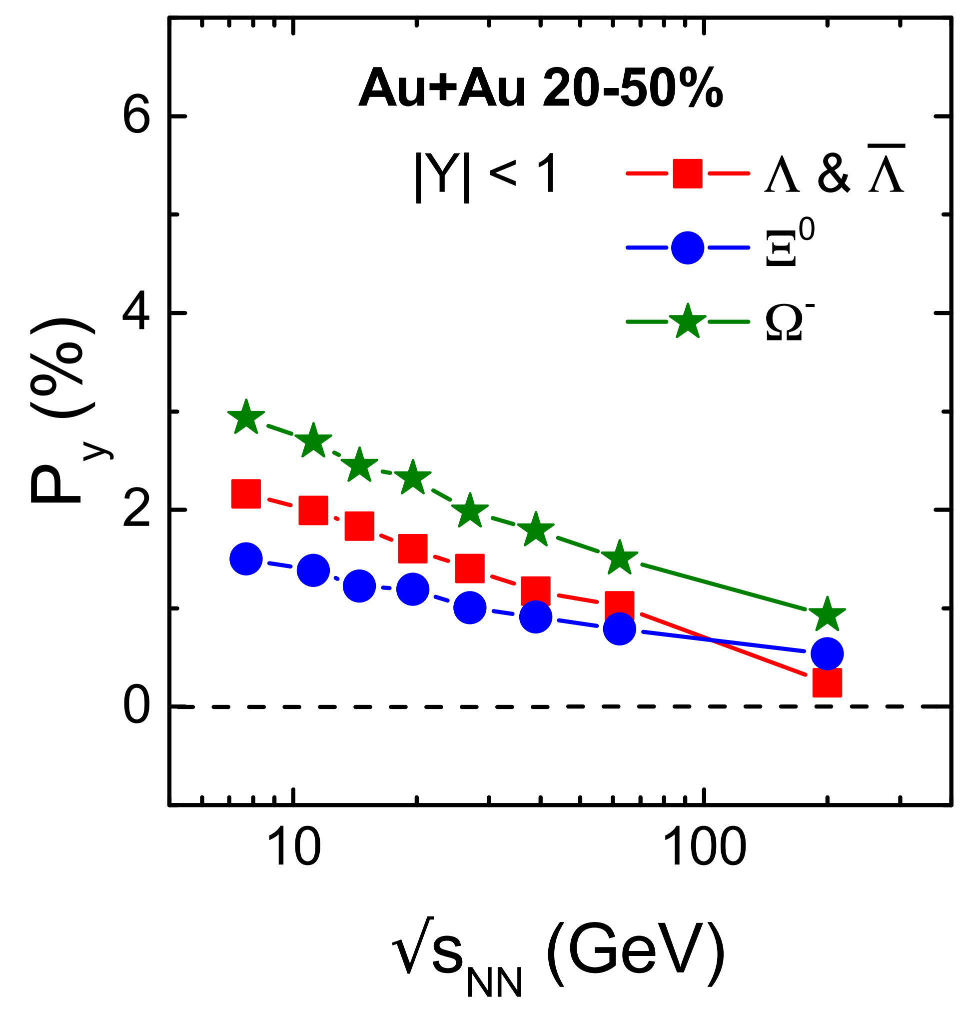
STAR, PRL118.012301 (2017)



Outlook

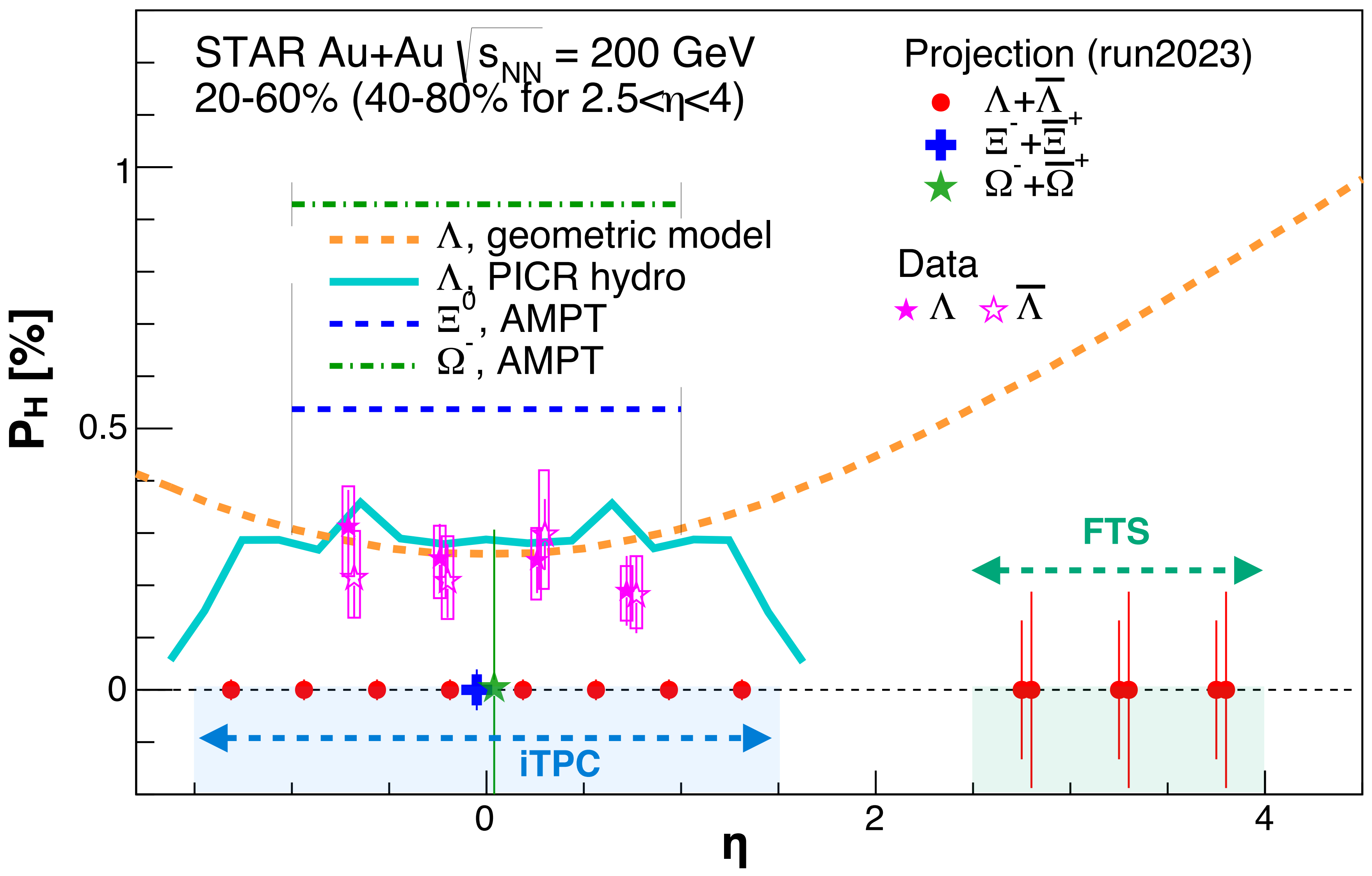
- STAR
  - High statistics data of BES-II 7.7-19.6 GeV and FXT 3-7.7 GeV
  - Isobaric collision data (Ru+Ru, Zr+Zr), ~10% difference in B-field
  - Global polarization of multi-strangeness (Ξ and Ω)
  - Forward upgrade in Run-2023

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



- ALICE/CMS/ATLAS
  - Global/local polarizations at 5.02 TeV in LHC Run3
- HADES
  - Measurements at lowest energies (2-2.4 GeV)
- Future facilities/experiments

STAR BUR2020



T. Niida, HI-Pub 2020

Summary

- Global polarization of Λ has been observed at $\sqrt{s_{NN}}$ = 7.7-200 GeV
  - Most vortical fluid (ω~10^{21} s^{-1}) created in heavy-ion collisions
  - Energy dependence, increasing in lower $\sqrt{s_{NN}}$, is captured well by theoretical models
  - Λ-antiΛ splitting is not significant
  - Azimuthal angle dependence is not understood yet
- Global spin alignment shows larger deviation from 1/3
  - ϕ meson field may explain this large deviation?
  - Different trend between RHIC and LHC ϕ or between ϕ and K* at RHIC
- Polarization along the beam direction has been observed at $\sqrt{s_{NN}}$ = 200 GeV
  - Qualitatively consistent with a picture of the elliptic flow but agreement/disagreement among the data and theoretical calculations in the sign

There are still many open questions and more precise data are needed.