Experimental overview of spin polarization signatures

Takafumi Niida

筑波大学
University of Tsukuba

WAYNE STATE UNIVERSITY

筑波大学
宇宙史研究センター
Tomonaga Center for the History of the Universe

U.S. DEPARTMENT OF ENERGY | Office of Science

ECT online workshop, Oct. 5-16, 2020*
Spin and hydrodynamics in relativistic nuclear collisions

Important features in non-central heavy-ion collisions

Strong magnetic field

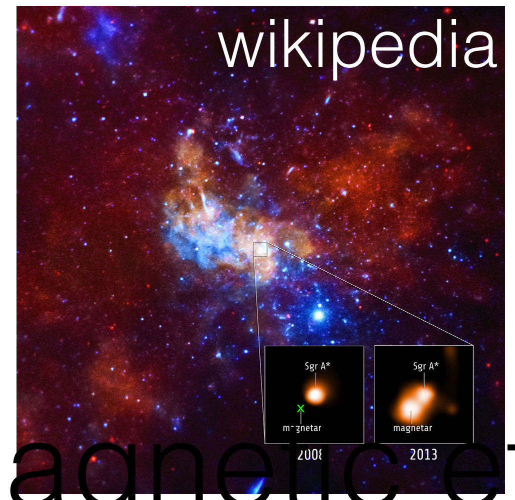
$$B \sim 10^{13}\ \mathrm{T}$$

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

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

typical magnet

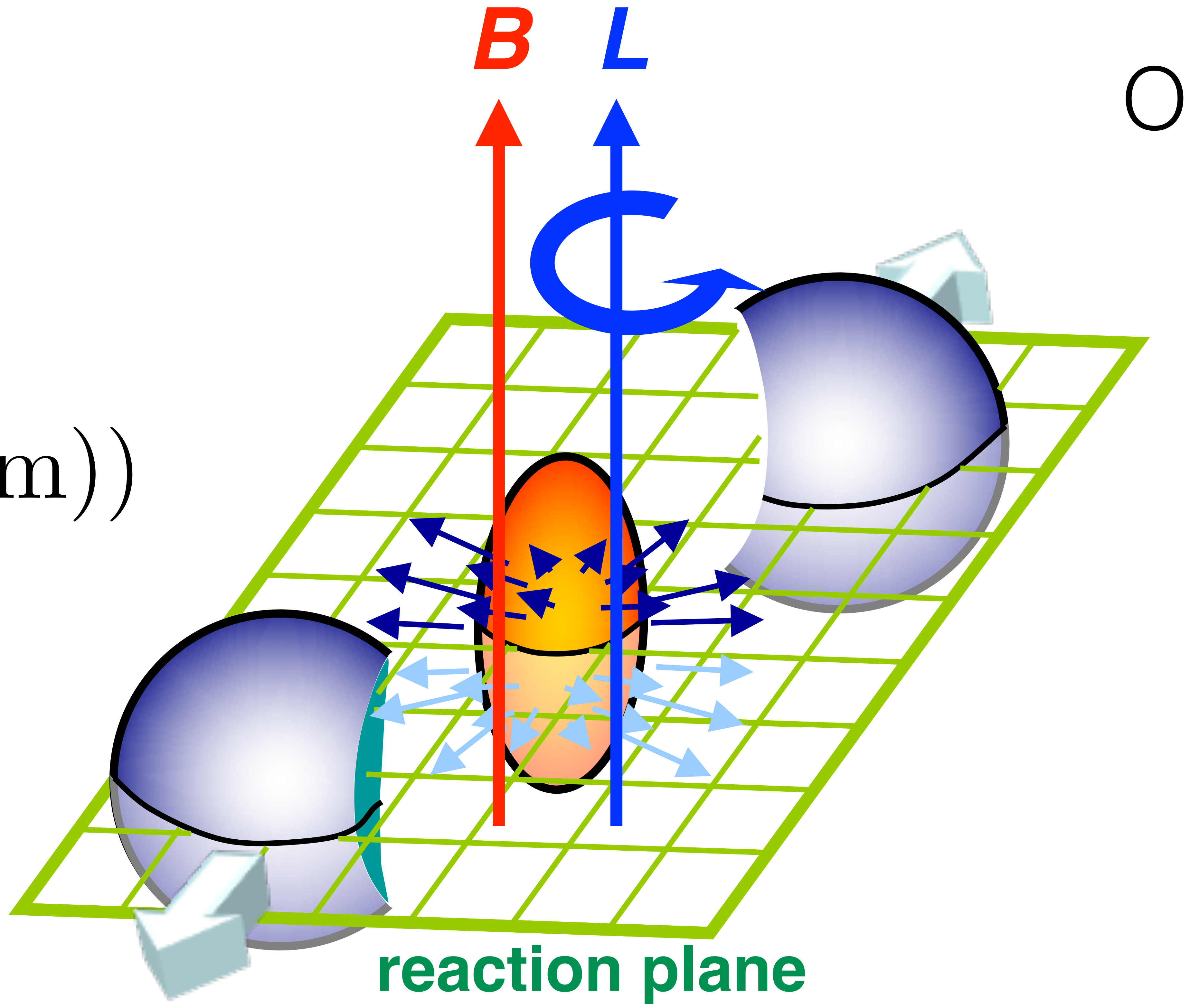
$B \sim 0.1 - 0.5\ \mathrm{T}$



magnetar

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

→Chiral magnetic effect/wave
→**Particle polarization**



Orbital angular momentum

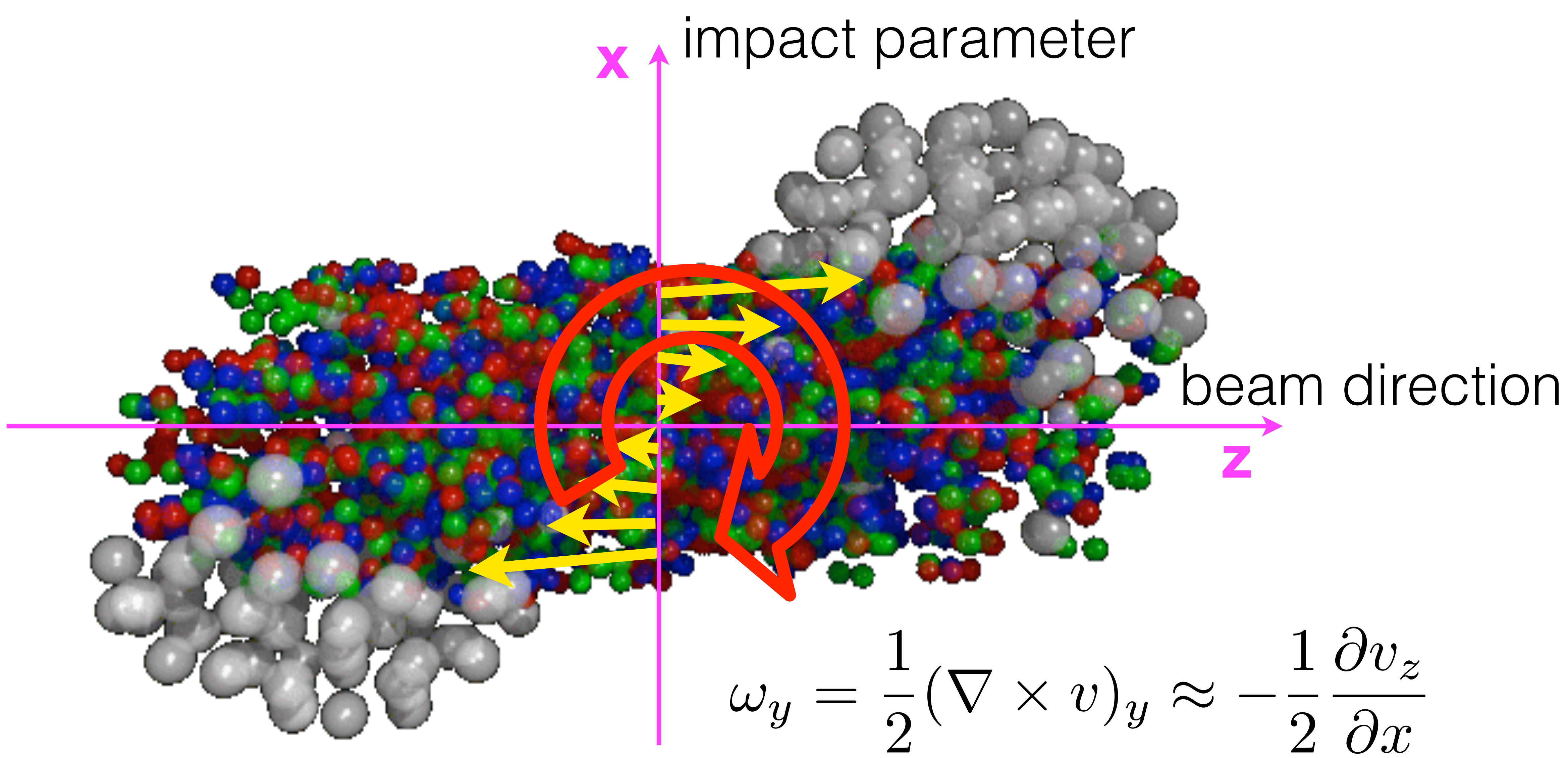
$$\mathbf{L} = \mathbf{r} \times \mathbf{p}$$

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

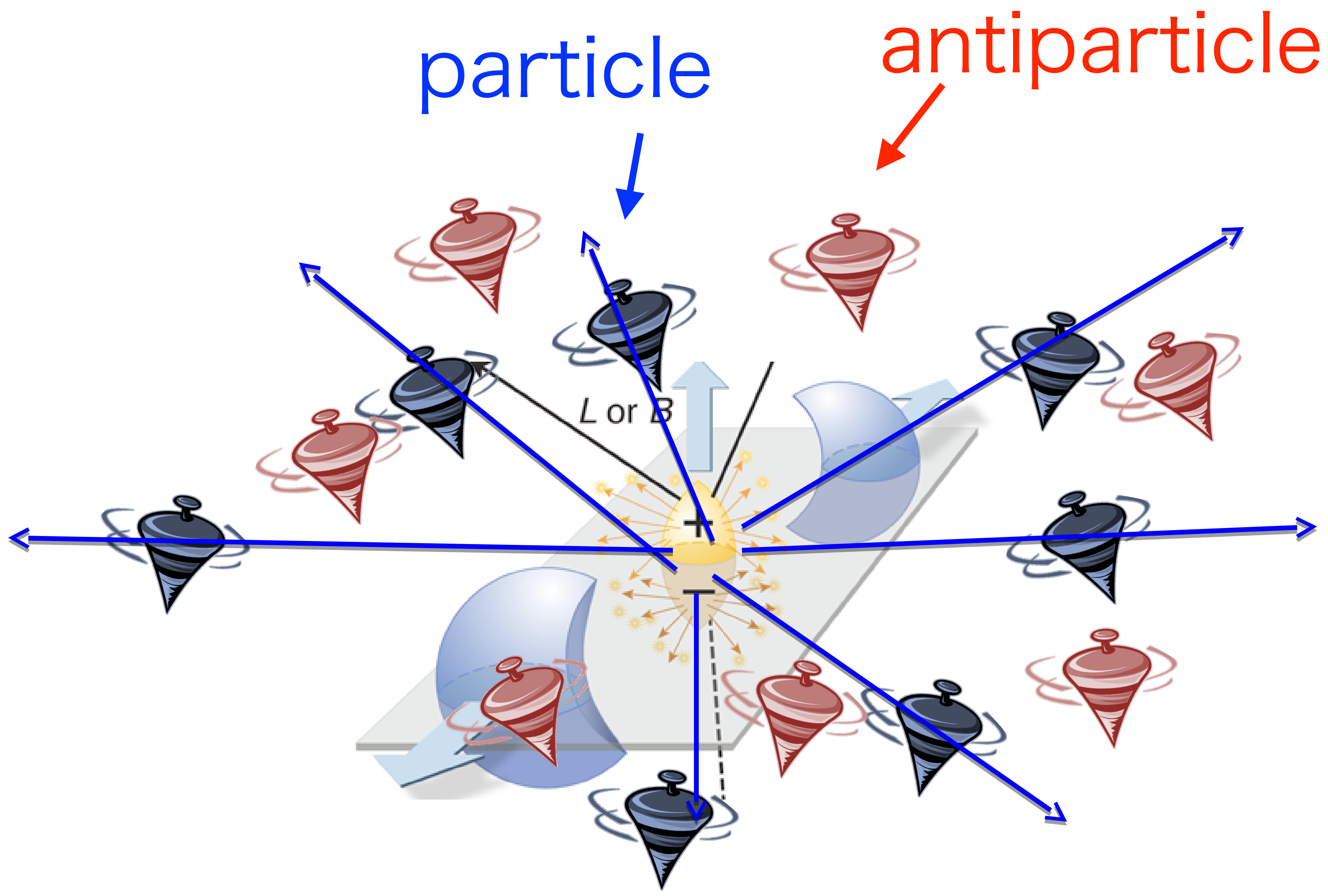
Z.-T. Liang and X.-N. Wang, PRL94, 102301 (2005)

→Chiral 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.

How to measure the polarization?

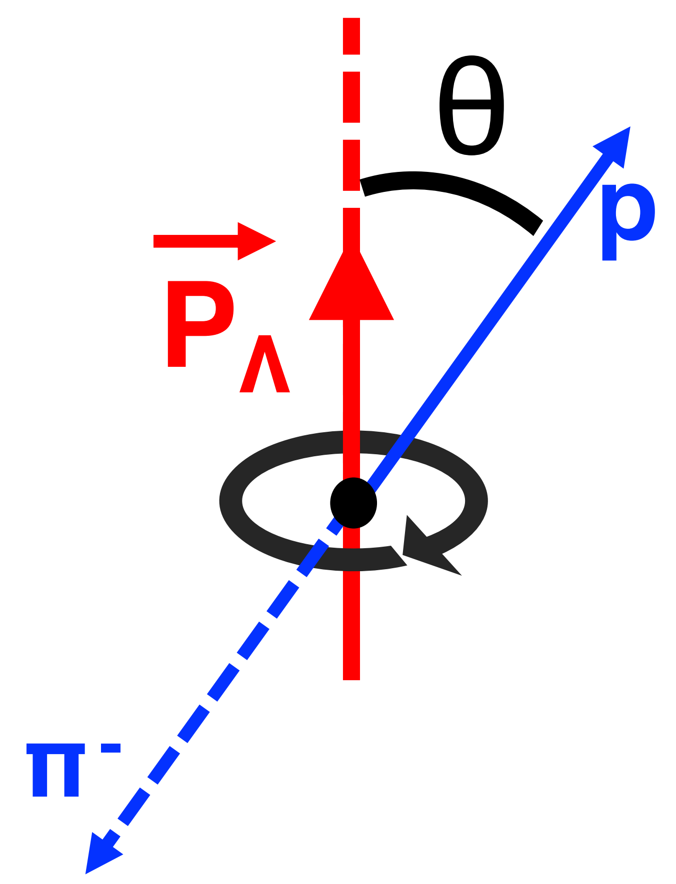
Parity-violating weak decay of hyperons ("self-analyzing")

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

(BR: 63.9%, cτ~7.9 cm)

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

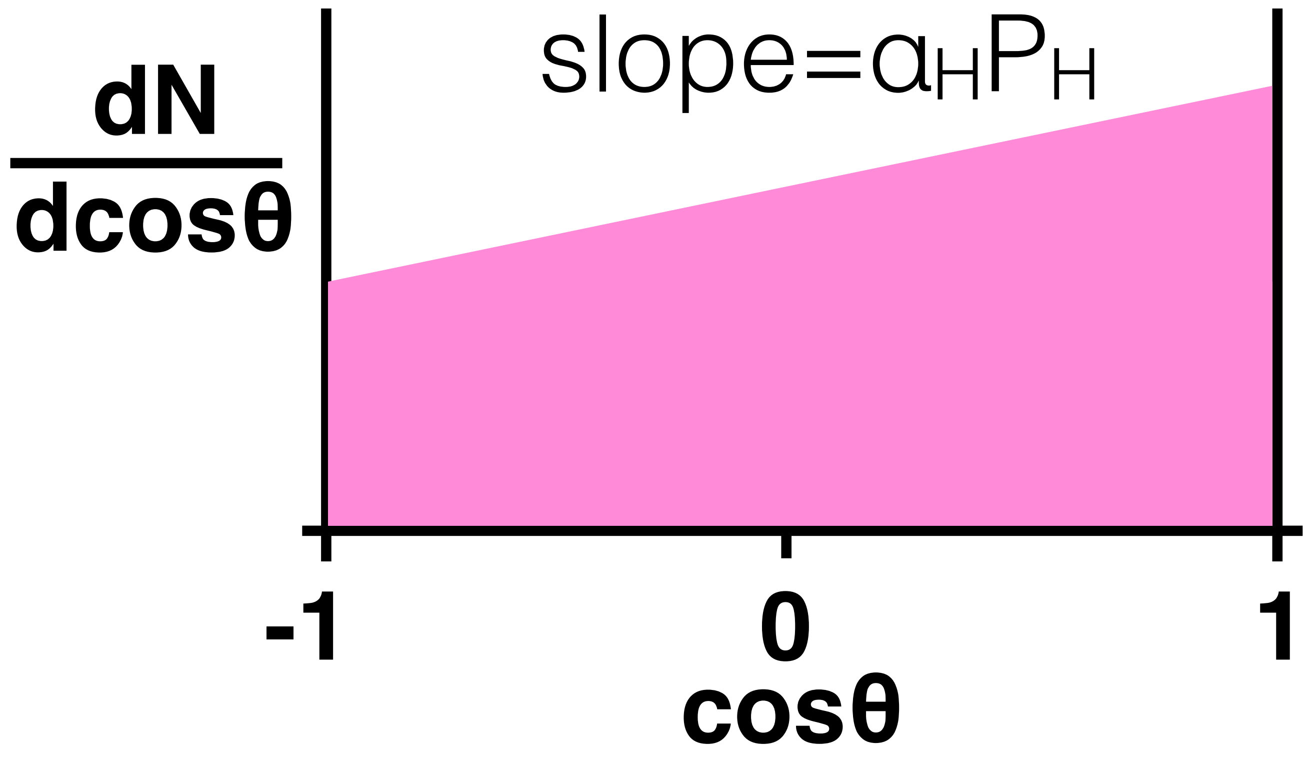
$$\frac{dN}{d\cos\theta^*} \propto 1 + \alpha_H \mathrm{P_H} \cos\theta^*$$



$\mathrm{P_H}$: 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 (BESIII and CLAS)

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

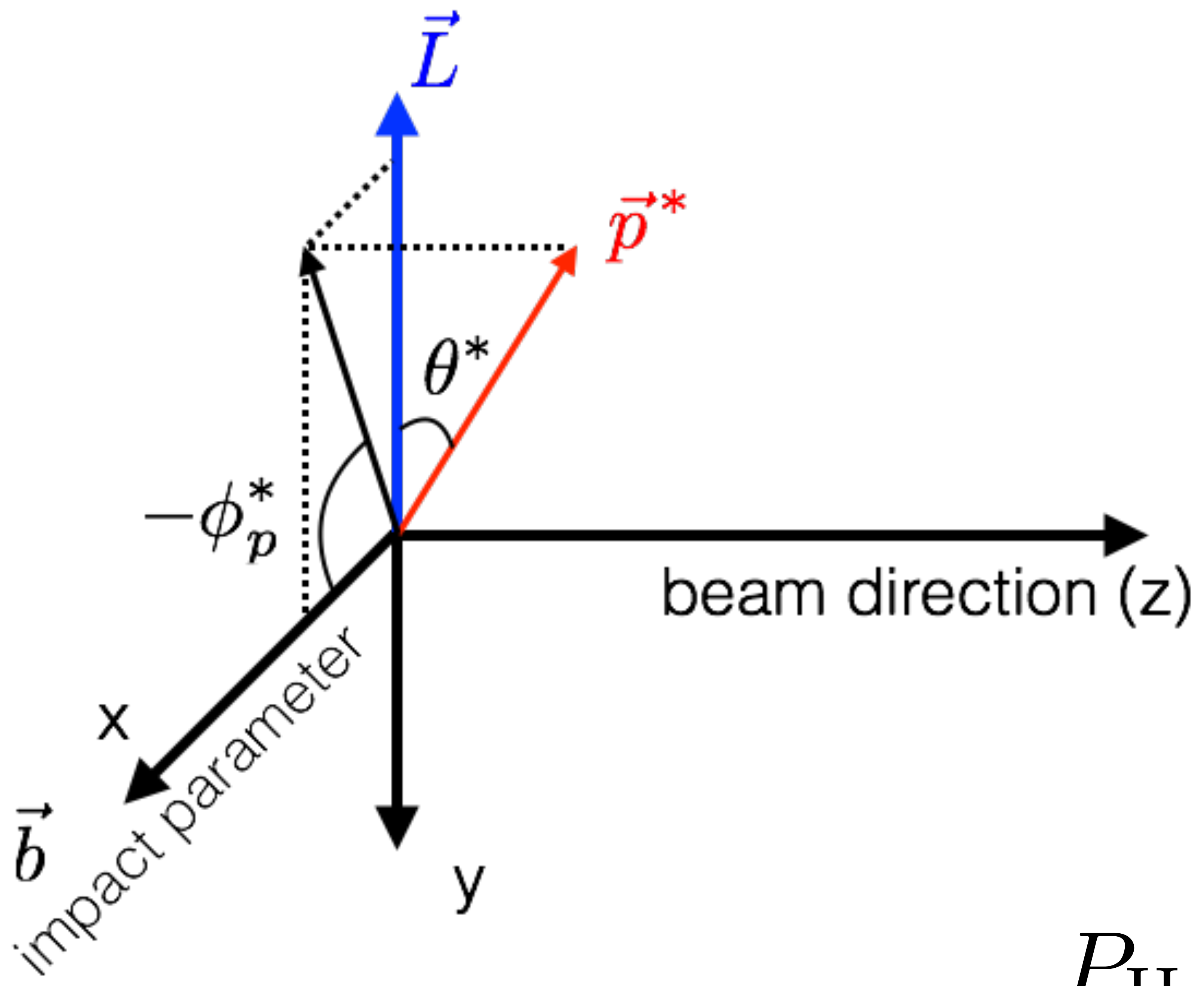
P.A. Zyla et al. (PDG), Prog.Theor.Exp.Phys.2020.083C01

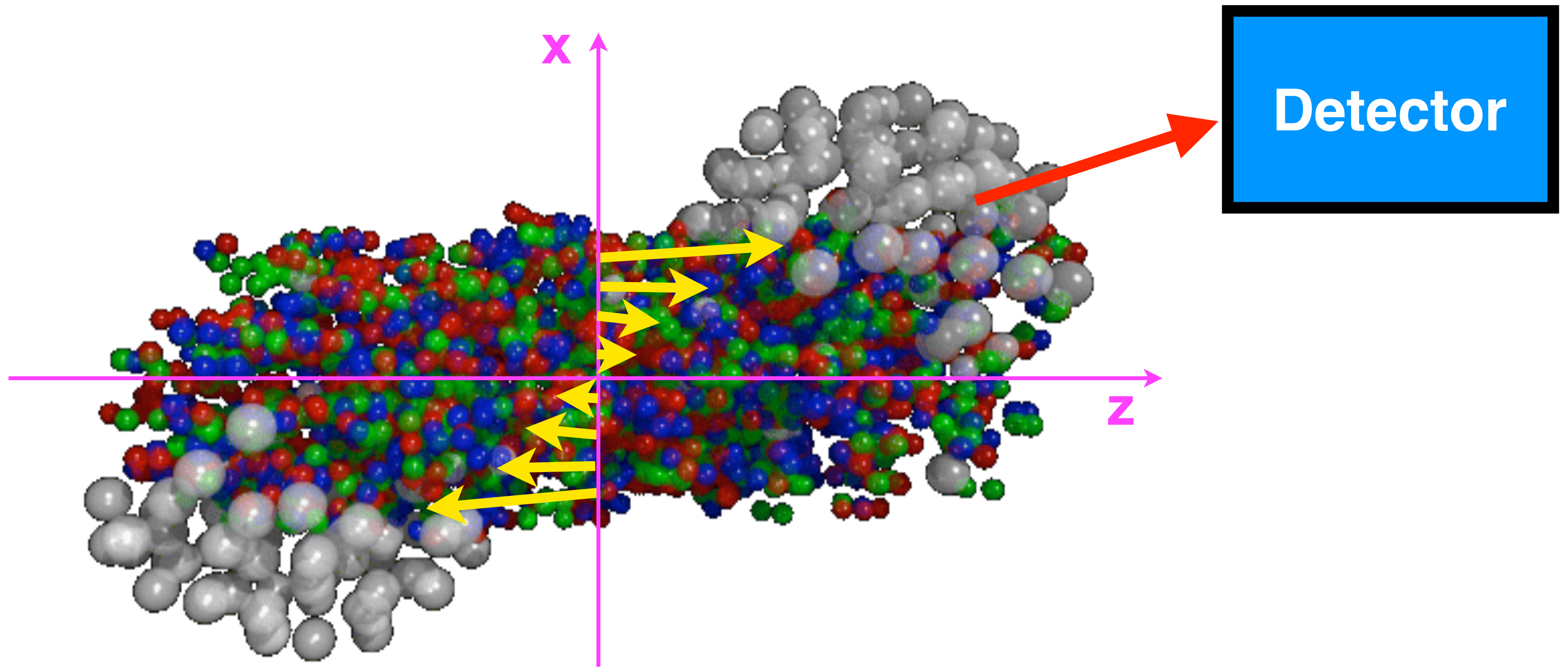
* All plots in this talk are based on α_Λ=-$\alpha_{\bar{\Lambda}}$=0.64±0.013

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)

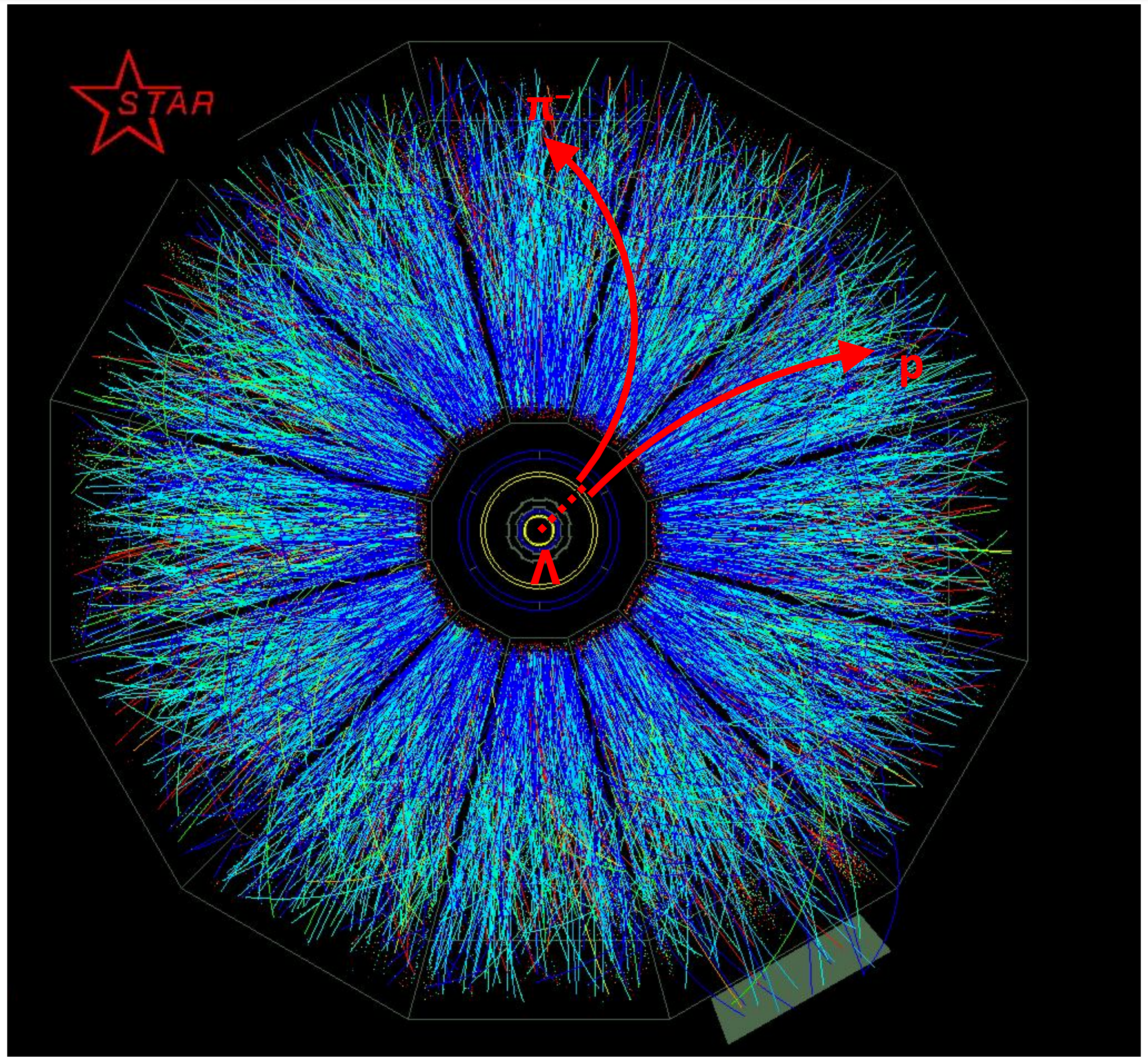
$$P_{\rm H} = \frac{8}{\pi \alpha_{\rm H}} \frac{\langle \sin(\Psi_1 - \phi_p^*) \rangle}{{\rm Res}(\Psi_1)}$$

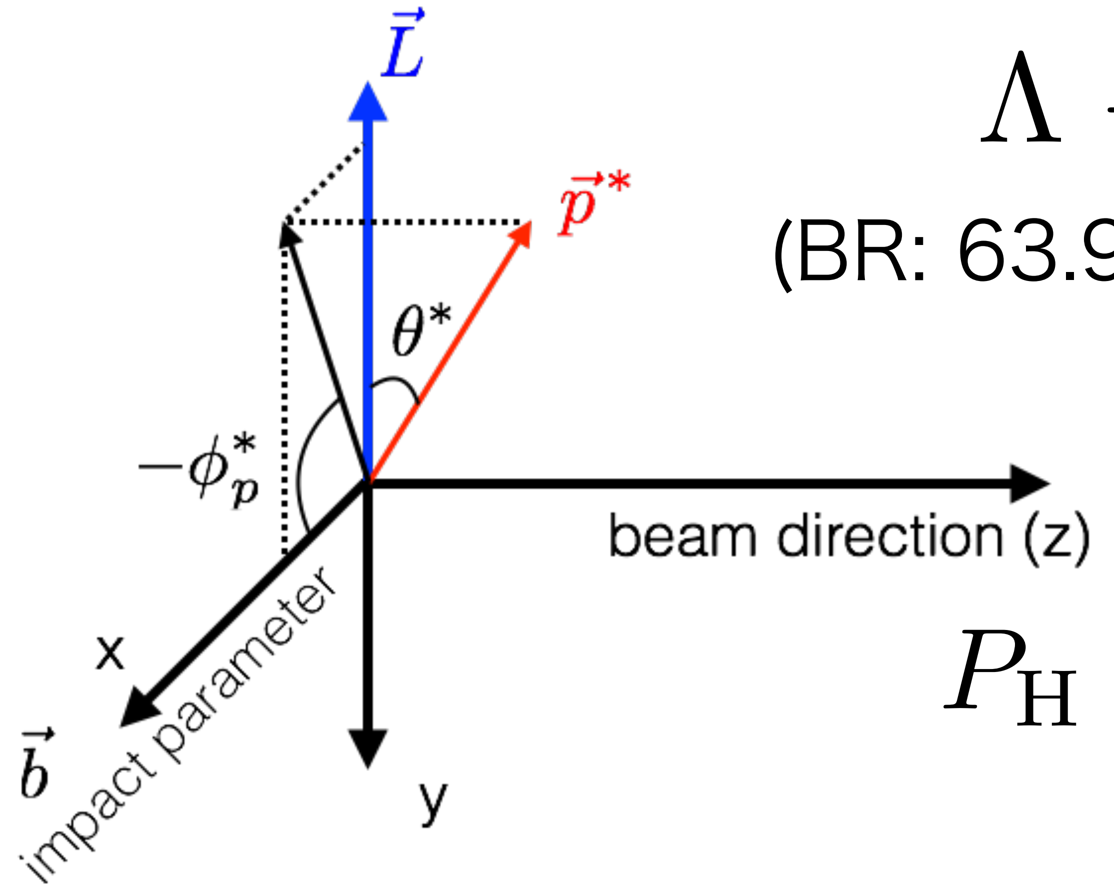
Ψ_1: azimuthal angle of b

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

STAR, PRC76, 024915 (2007)

Signal extraction with Λ hyperons



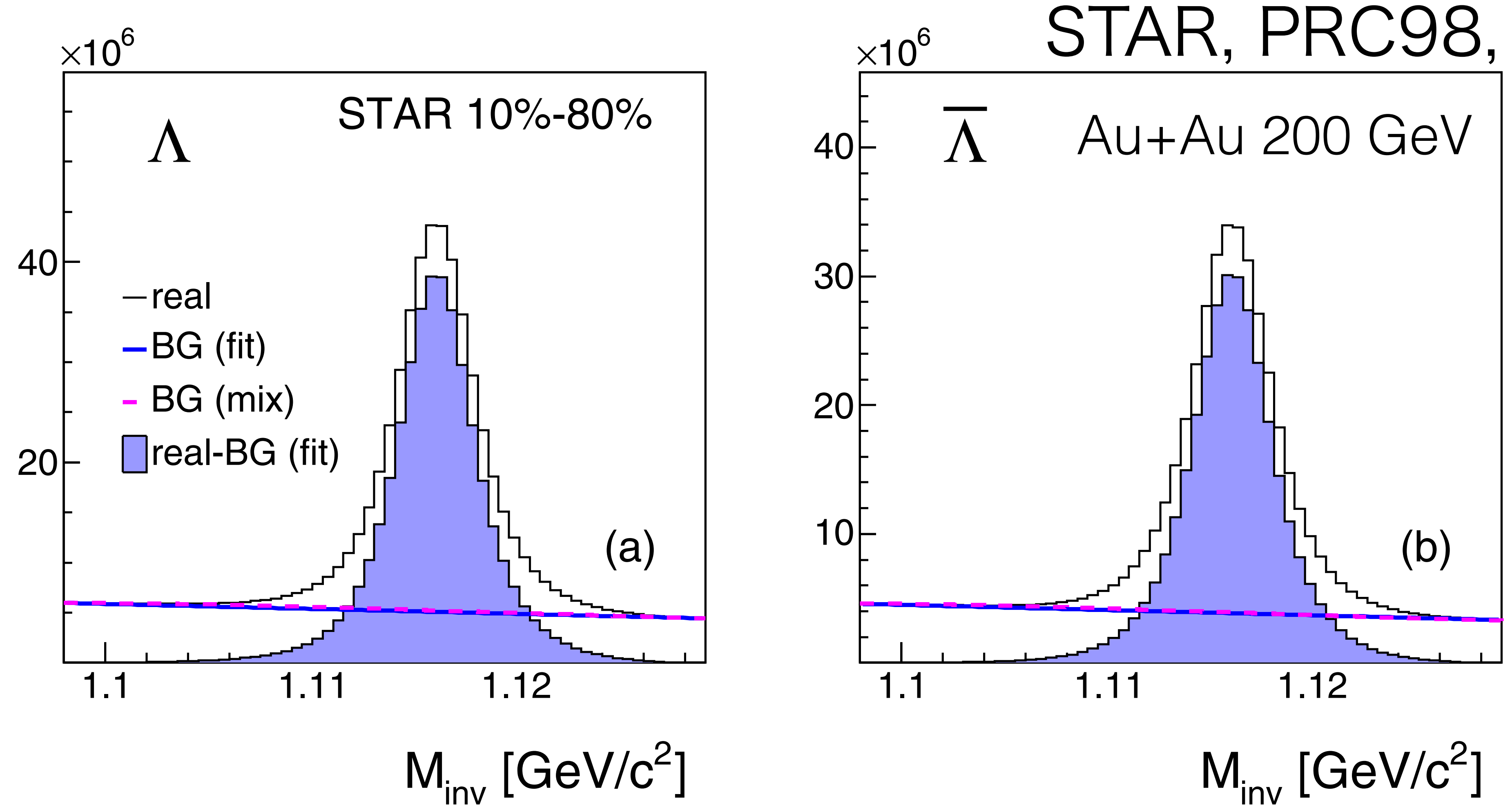


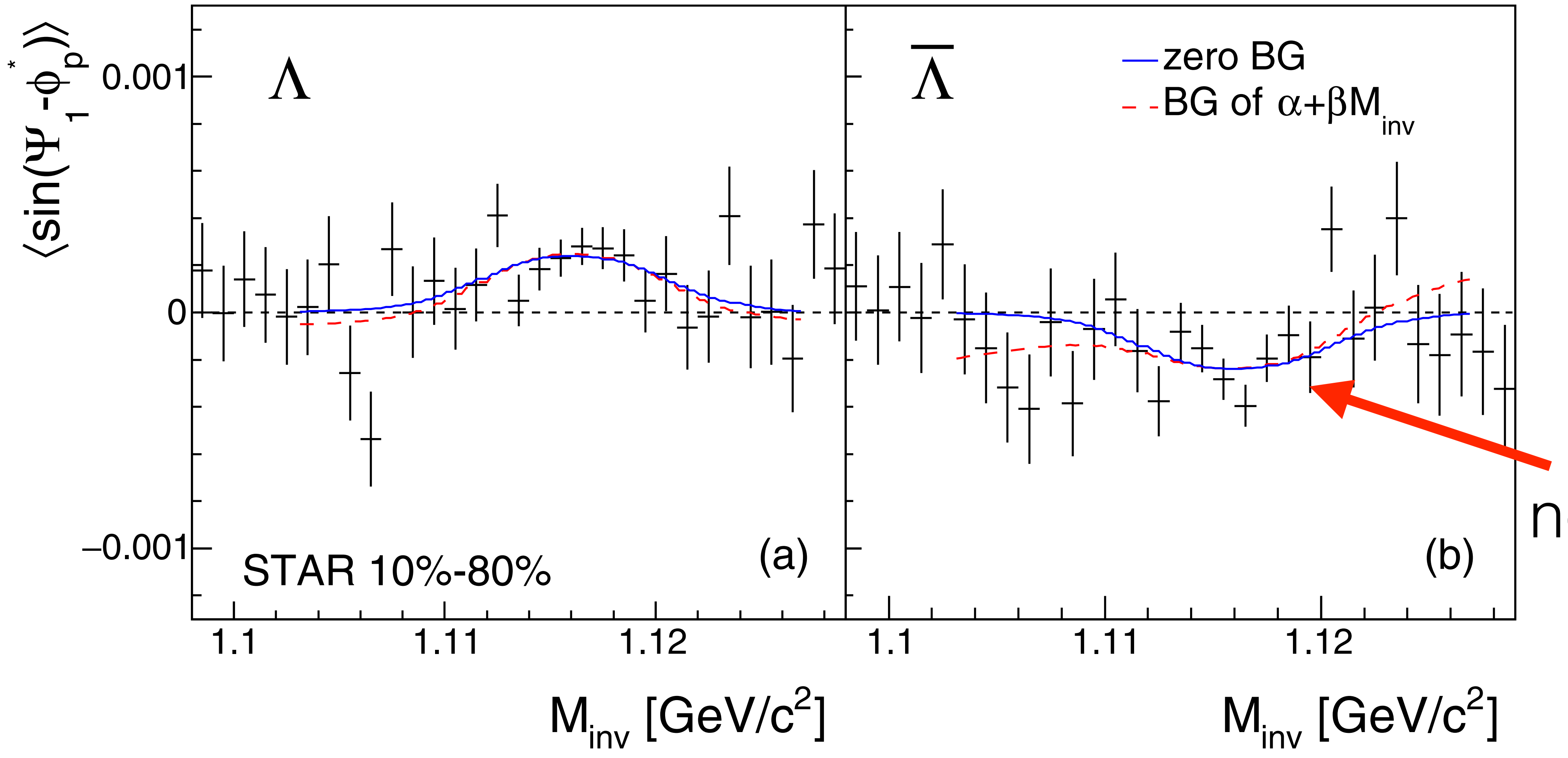
$$\Lambda \rightarrow p + \pi^-$$

(BR: 63.9%, cτ ~7.9 cm)

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

STAR, PRC98, 014910 (2018)





negative for anti-Λ

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

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

Feed-down effect

- ~60% of measured Λ are feed-down from Σ*→Λπ, Σ^0→Λγ, Ξ→Λπ
- 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

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

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

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

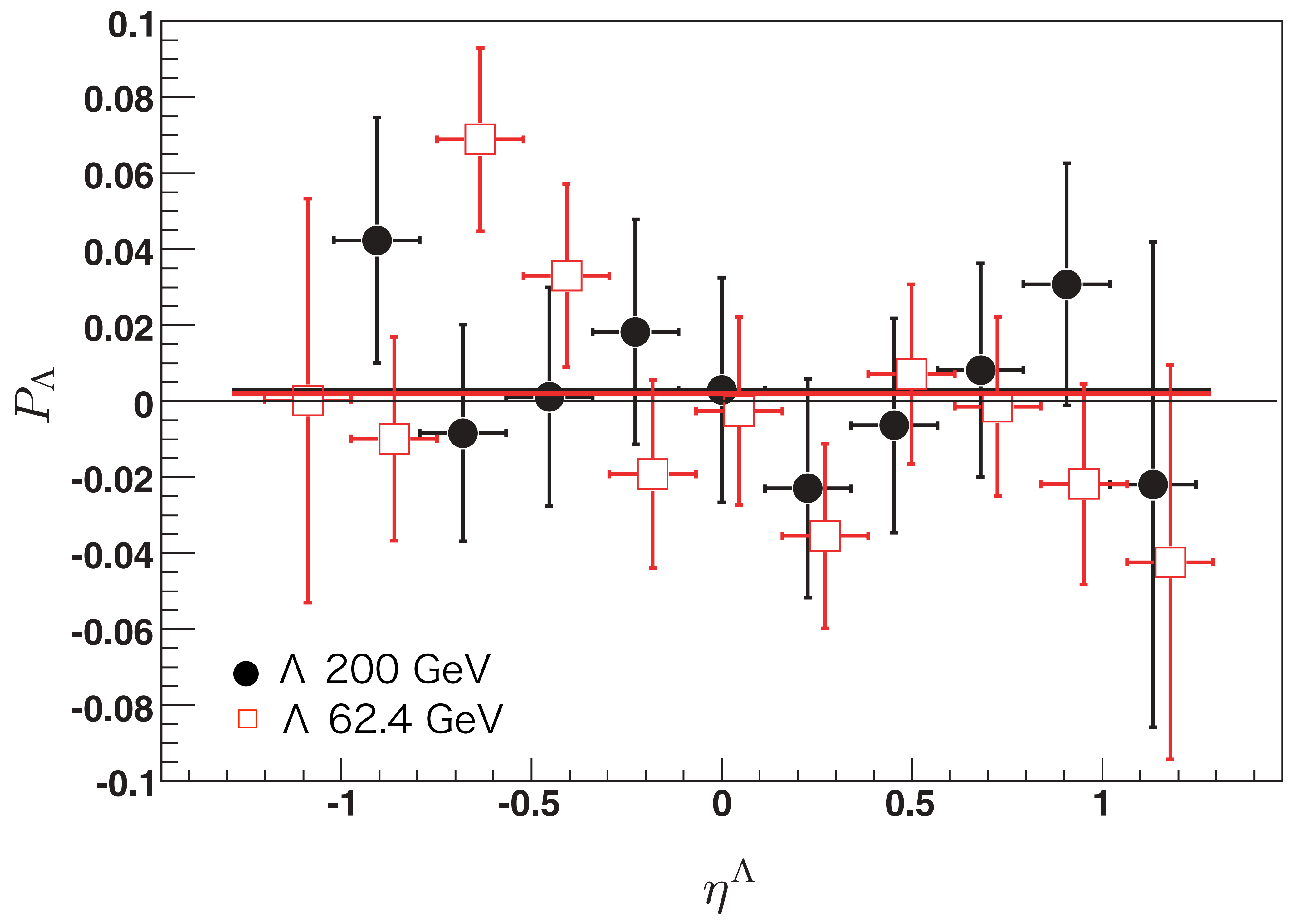
Decay	C
Parity conserving: $1/2^+ \to 1/2^+\ 0^-$	$-1/3$
Parity conserving: $1/2^- \to 1/2^+\ 0^-$	1
Parity conserving: $3/2^+ \to 1/2^+\ 0^-$	1/3
Parity-conserving: $3/2^- \to 1/2^+\ 0^-$	$-1/5$
$\Xi^0 \to \Lambda + \pi^0$	+0.900
$\Xi^- \to \Lambda + \pi^-$	+0.927
$\Sigma^0 \to \Lambda + \gamma$	$-1/3$

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)

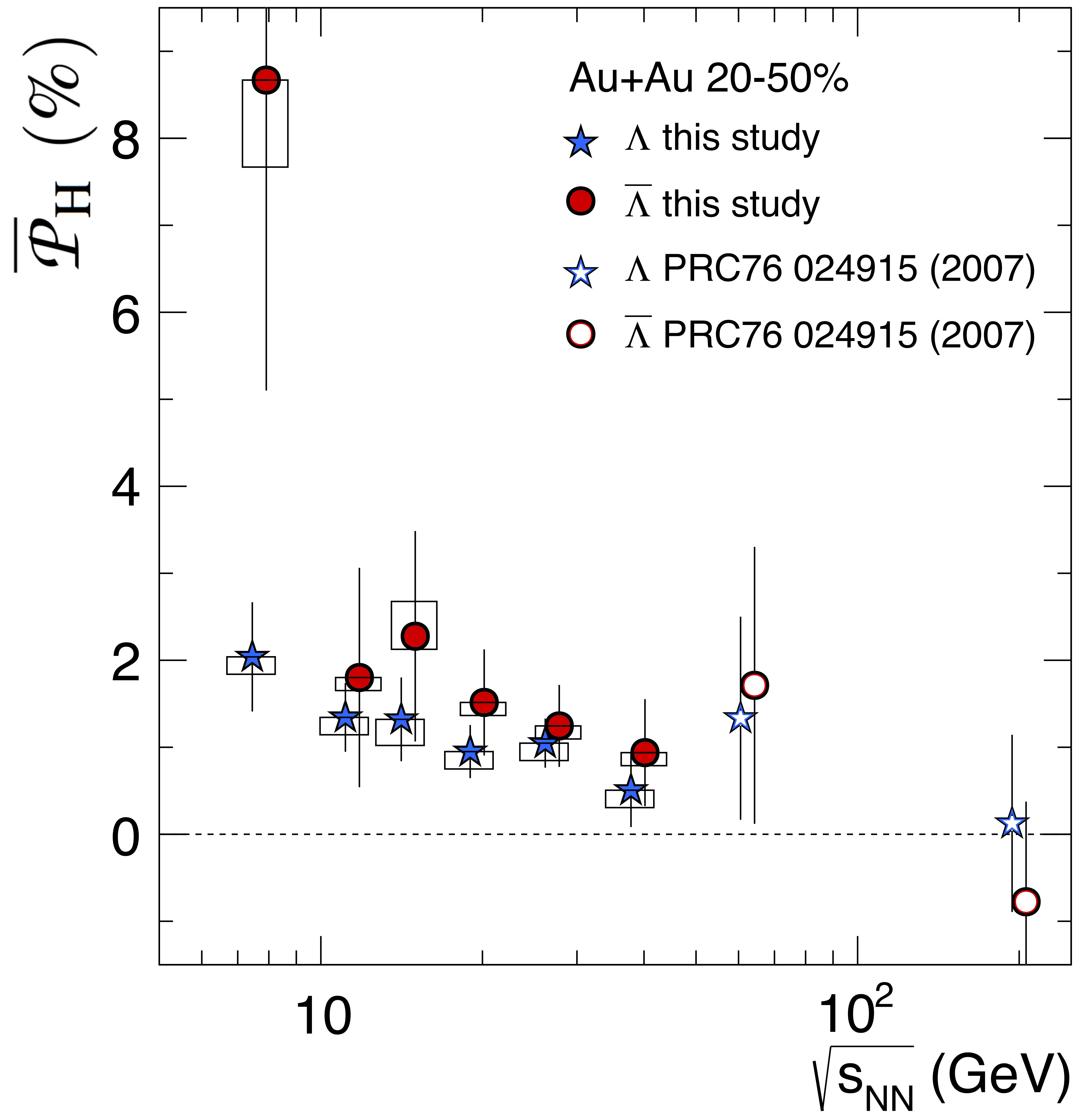
III. CONCLUSION

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)

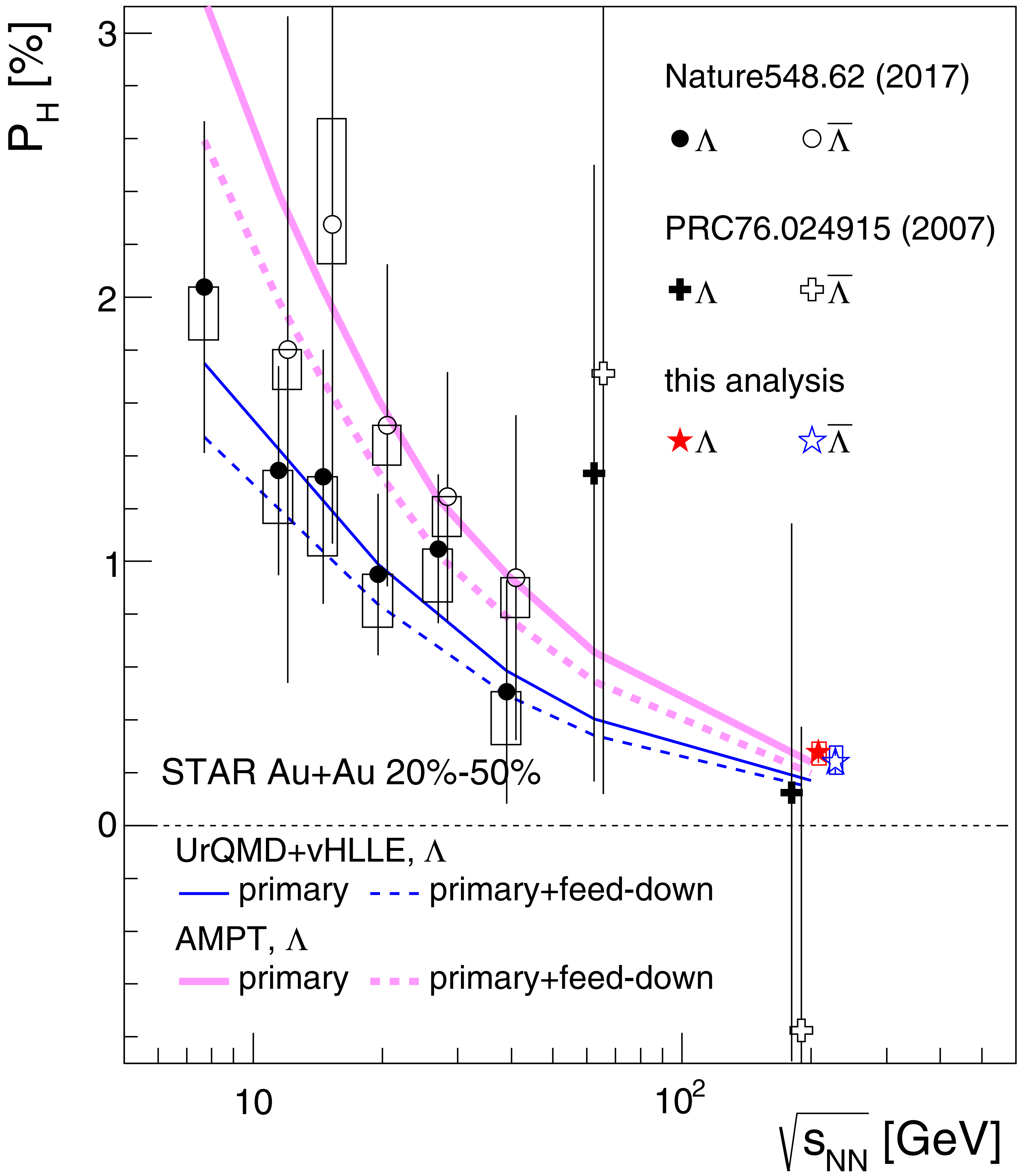
- The most vortical fluid!

Hint of the difference between Λ and anti-Λ P_H

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

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

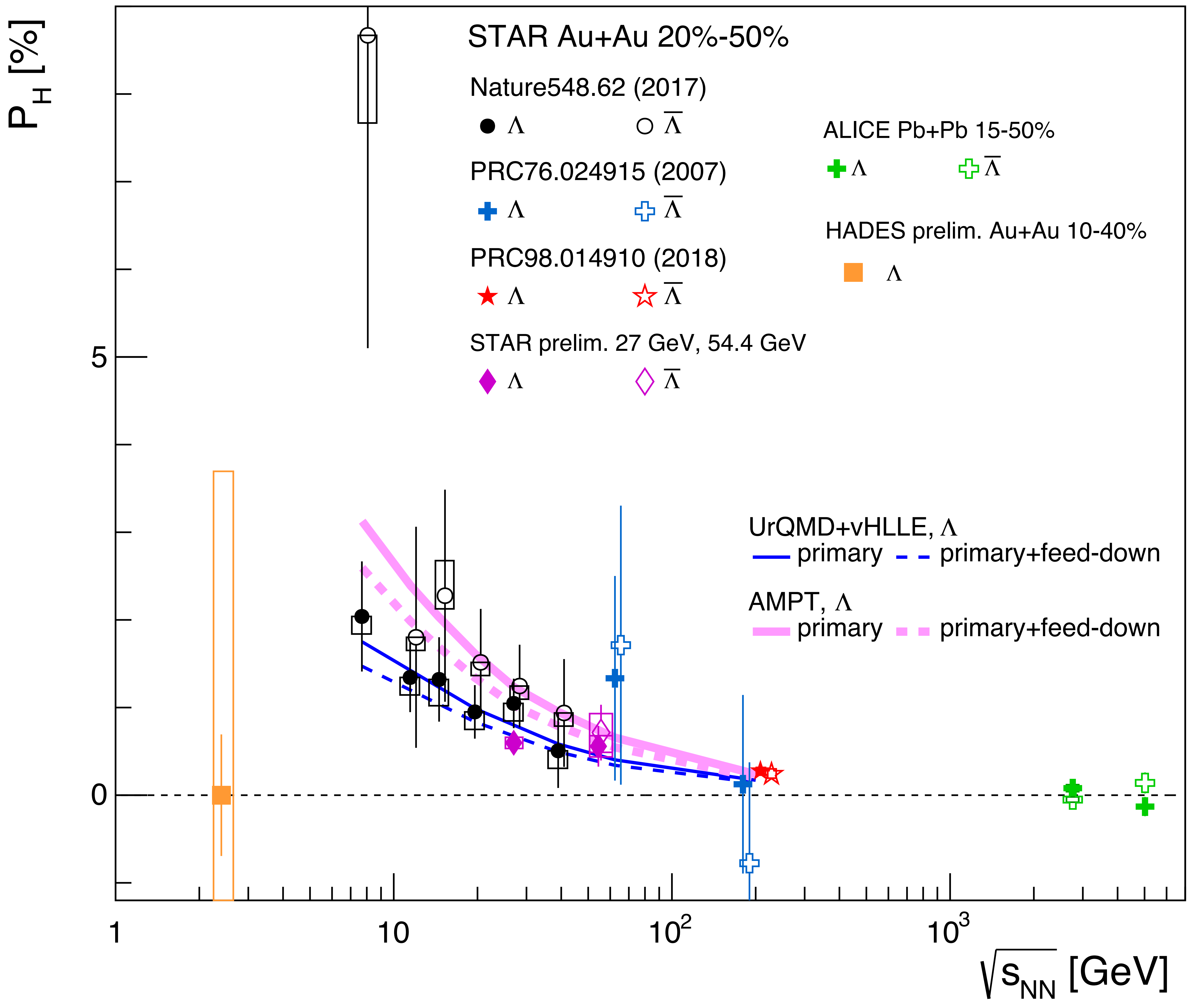
$$P_H(\Lambda)\ [\%] = 0.277 \pm 0.040(\text{stat}) \pm^{0.039}_{0.049}\ (\text{sys})$$
$$P_H(\bar{\Lambda})\ [\%] = 0.240 \pm 0.045(\text{stat}) \pm^{0.061}_{0.045}\ (\text{sys})$$

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

Collection of recent results

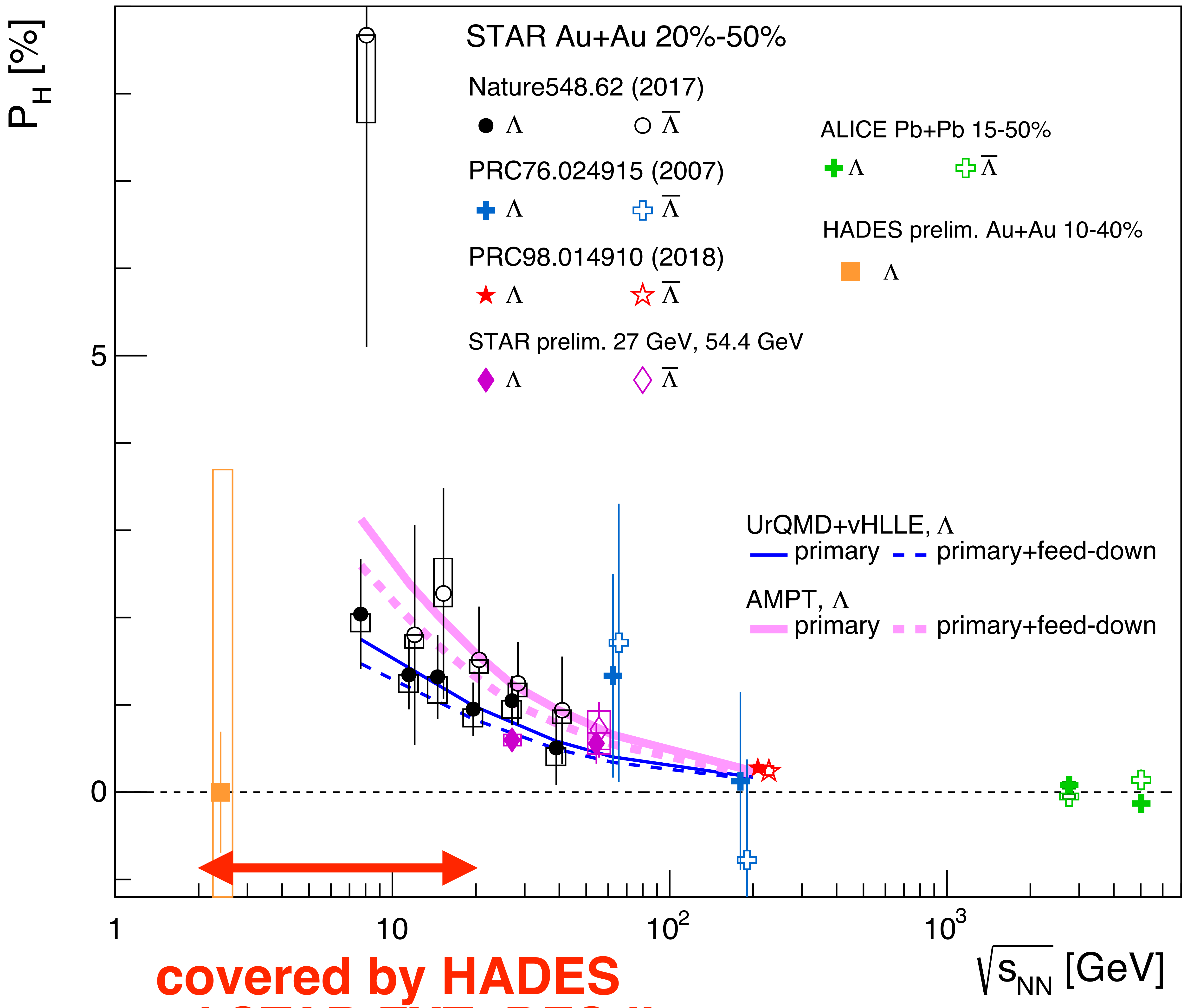
ALICE, PRC101.044611 (2020)
F. Kornas (HADES), SQM2019
J. Adams, K. Okubo (STAR), QM2019



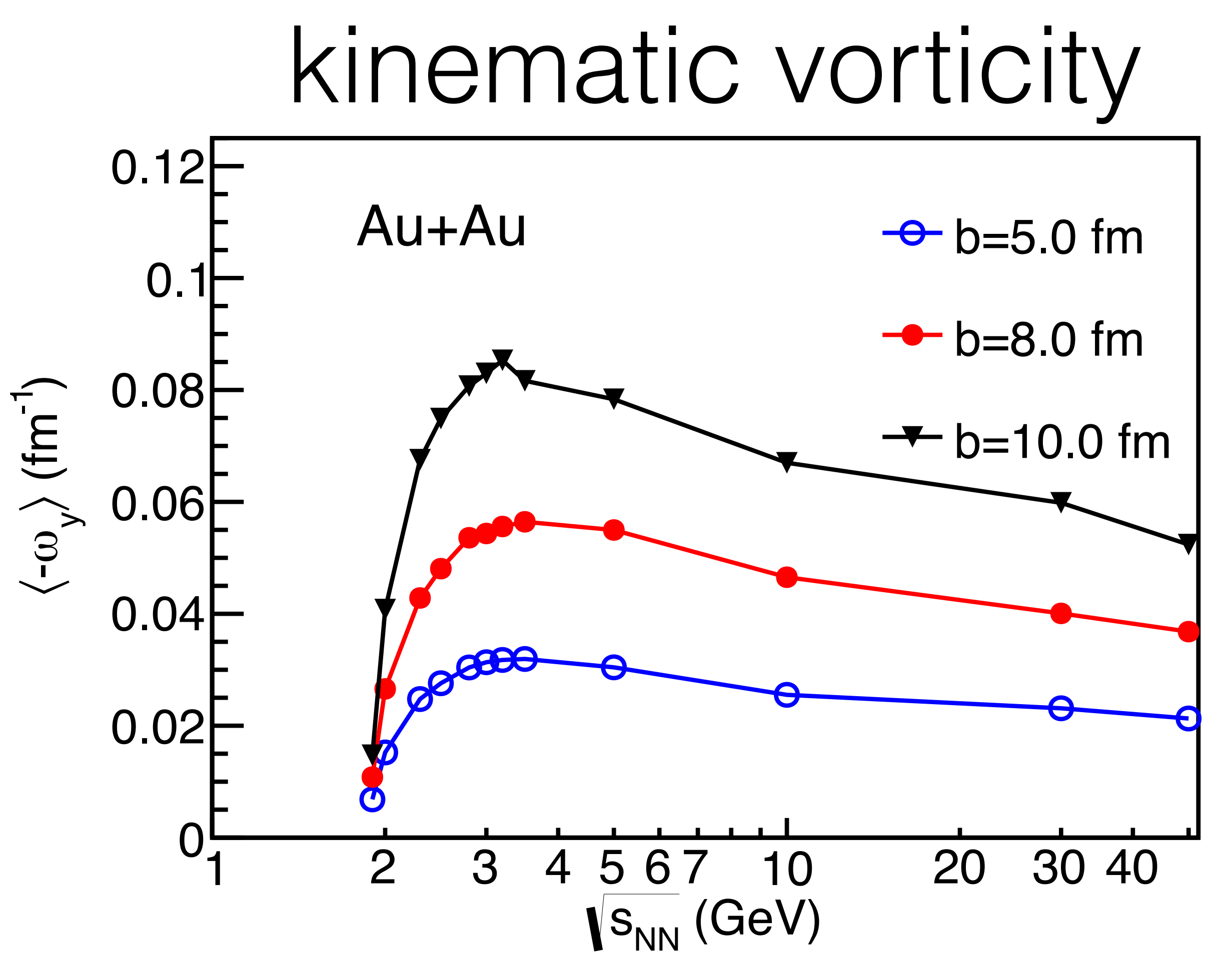
- ALICE at 2.76 and 5.02 TeV
  - Expected signal is of the order of current statistical uncertainty
- HADES at 2.4 GeV
  - still preliminary
  - hopefully reduce systematic uncertainty
- Preliminary of STAR at 27 and 54.4 GeV

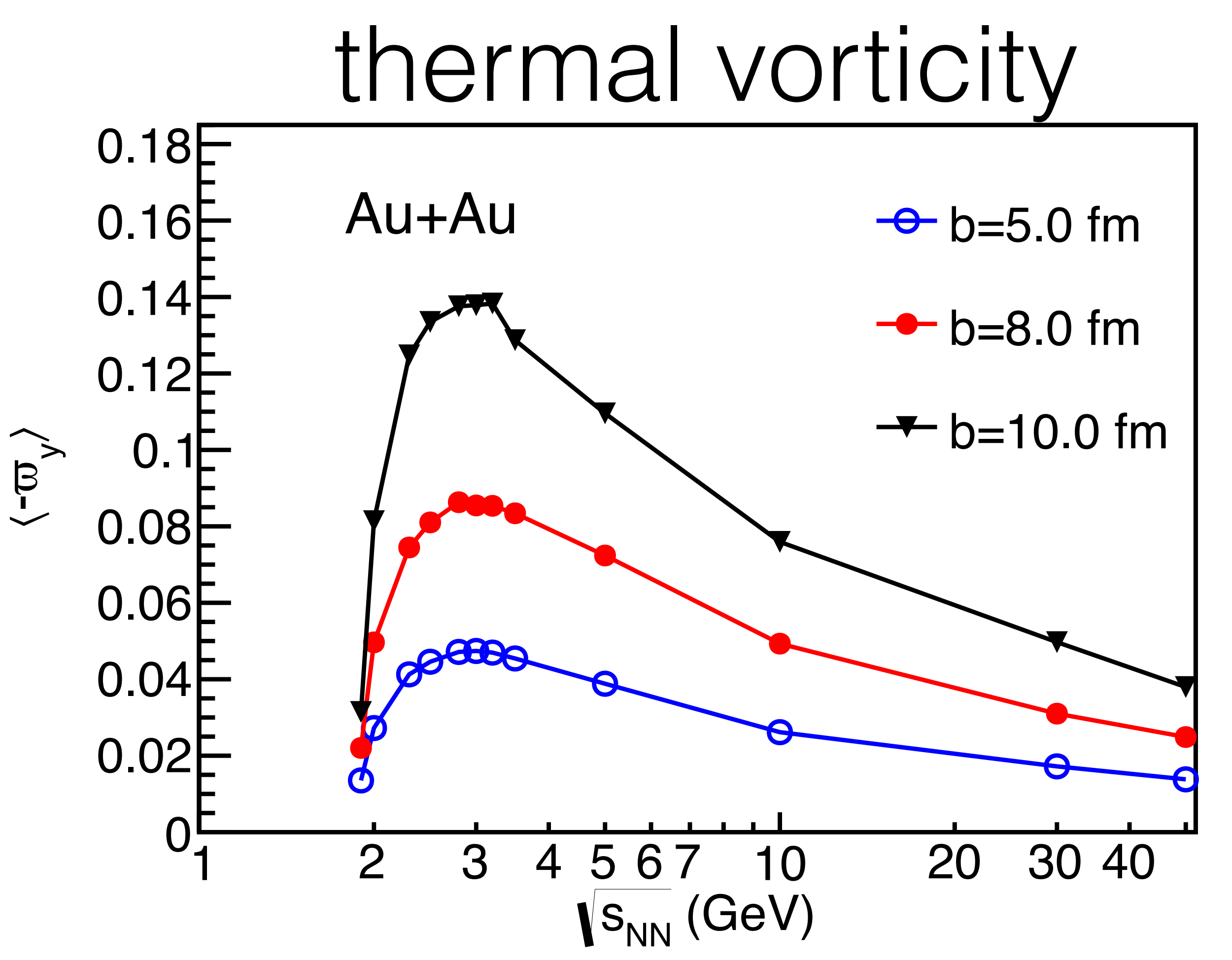
Collection of recent results

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)

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

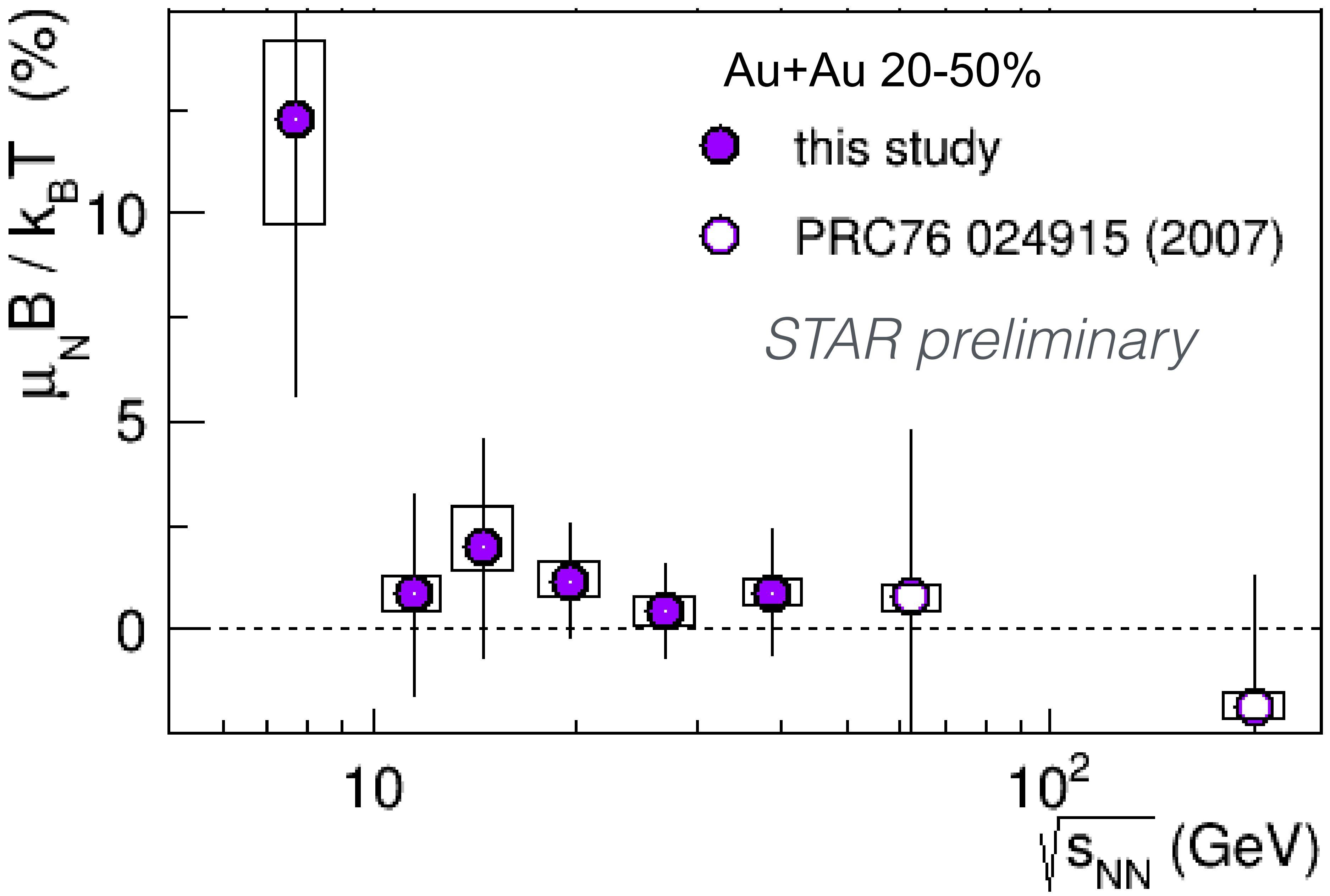
$$P_{\bar{\Lambda}} \simeq \frac{1}{2}\frac{\omega}{T} - \frac{\mu_\Lambda B}{T}$$

μ_Λ: Λ magnetic moment

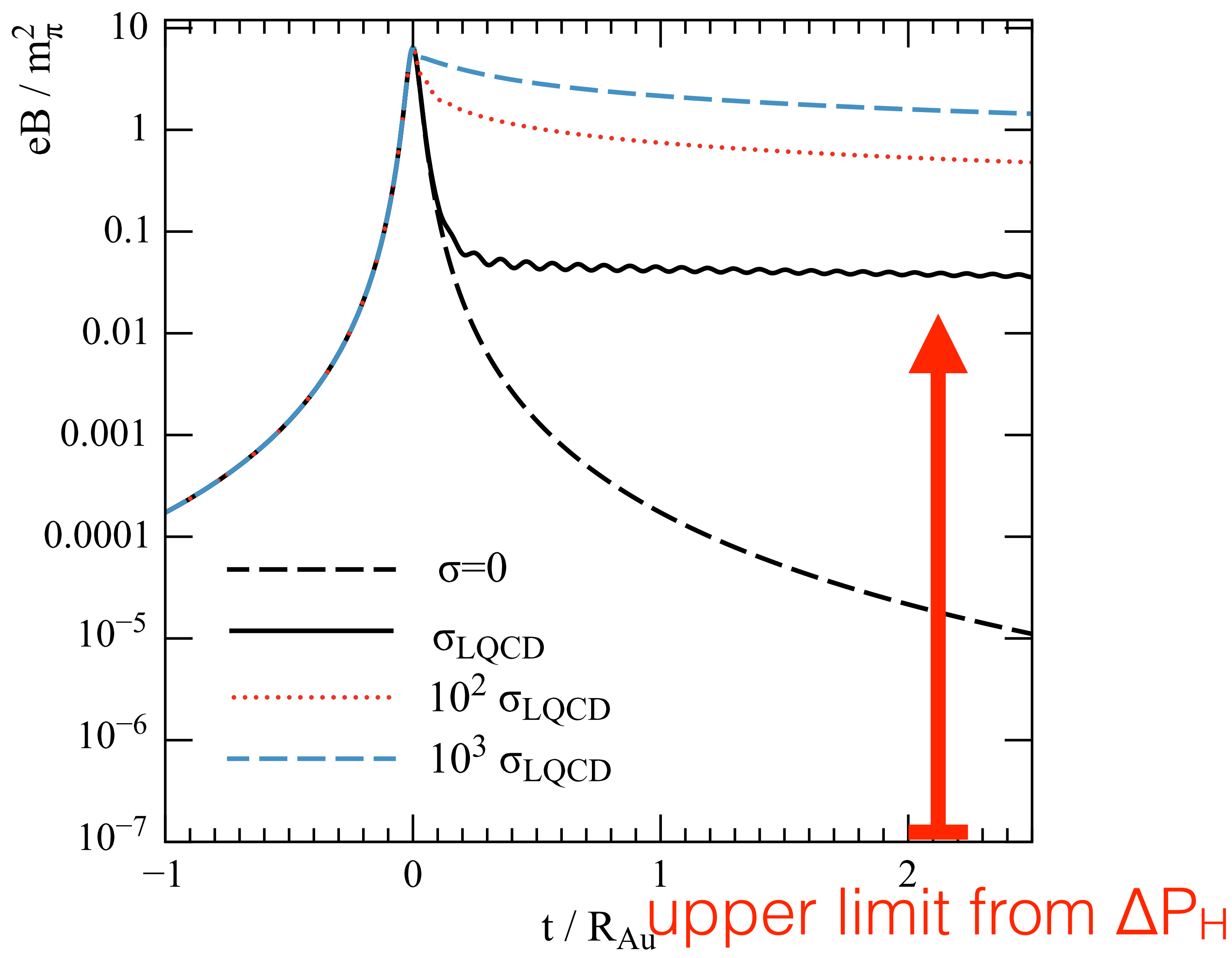
$$B = (P_\Lambda - P_{\bar{\Lambda}})k_B T/\mu_N$$
$$\sim 5.0 \times 10^{13}\ [\mathrm{Tesla}]$$

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

QM17, I. Upsal (STAR)



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

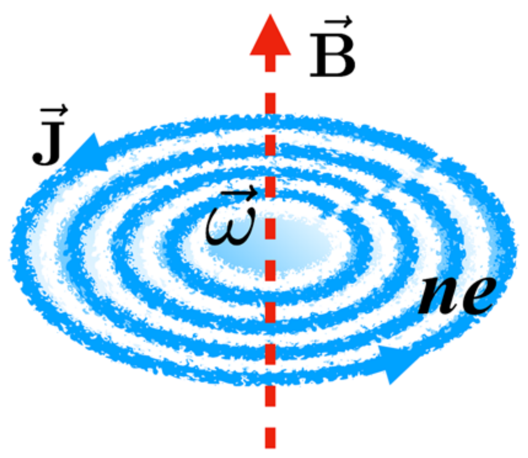


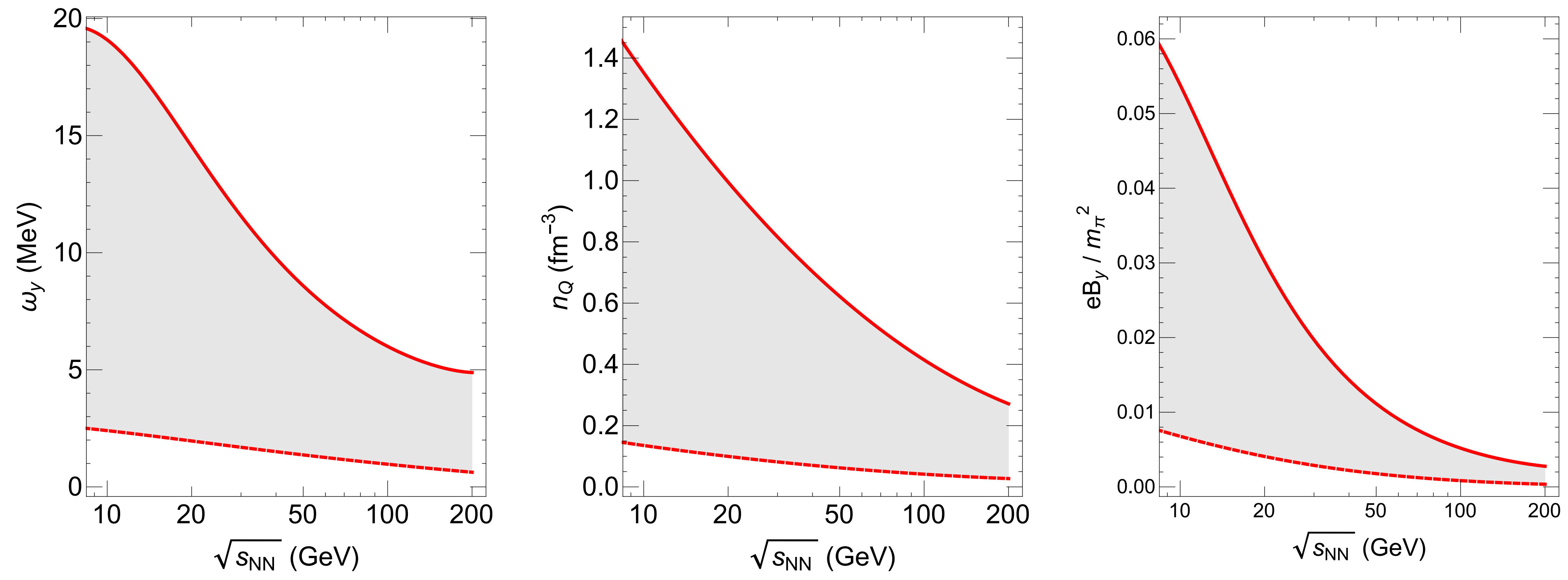
Conductivity increases lifetime.

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

Need caution for the interpretation

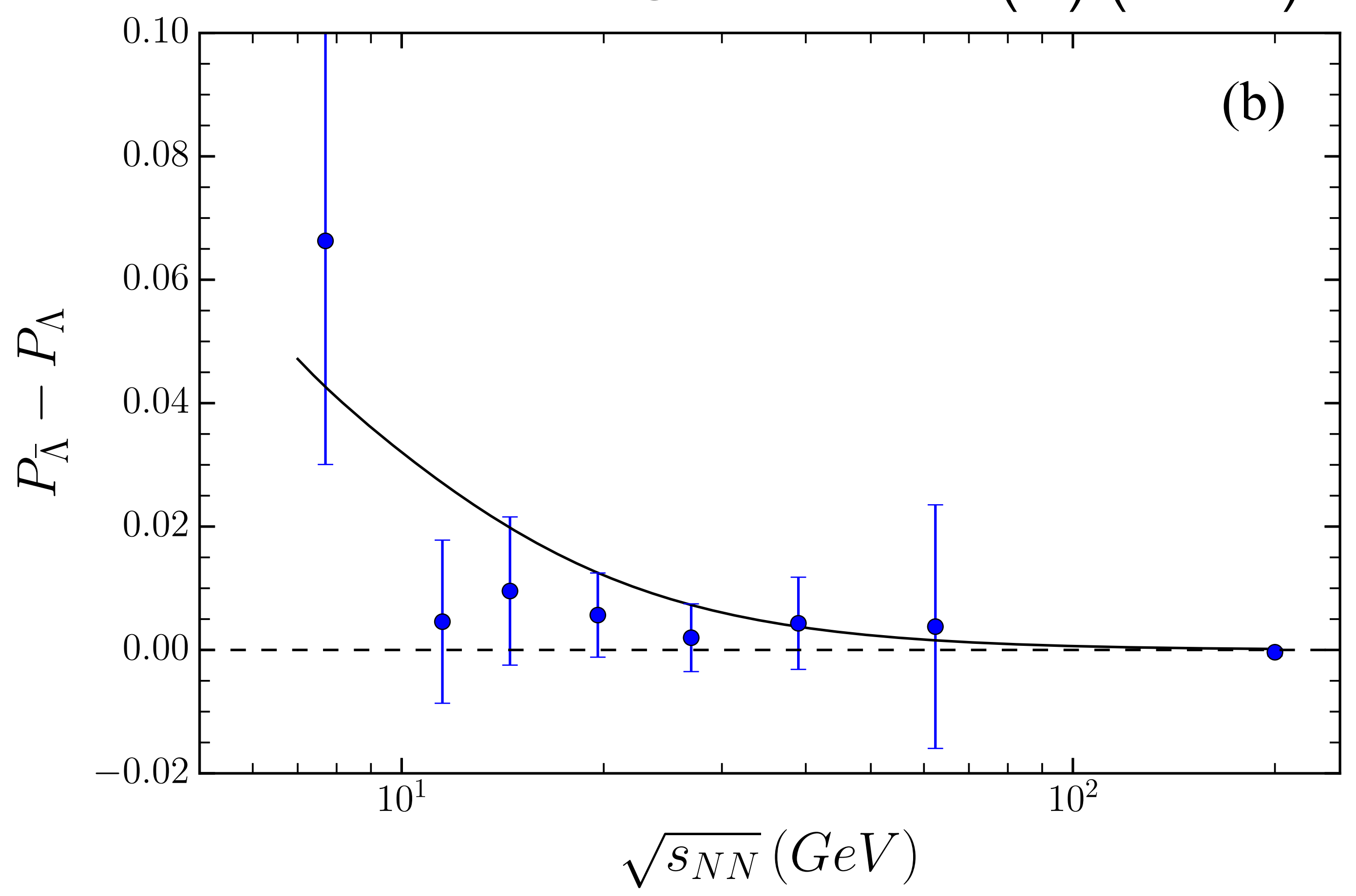
- Initial magnetic field
- Effect of chemical potential (expected to be small)
  R. Fang et al.,, PRC94, 024904 (2016)
- Rotating charged fluid produces B-field with longer lifetime
  X. Guo, J. Liao, and E. Wang, PRC99.021901(R) (2019)
- Spin interaction with the meson field generated by the baryon 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





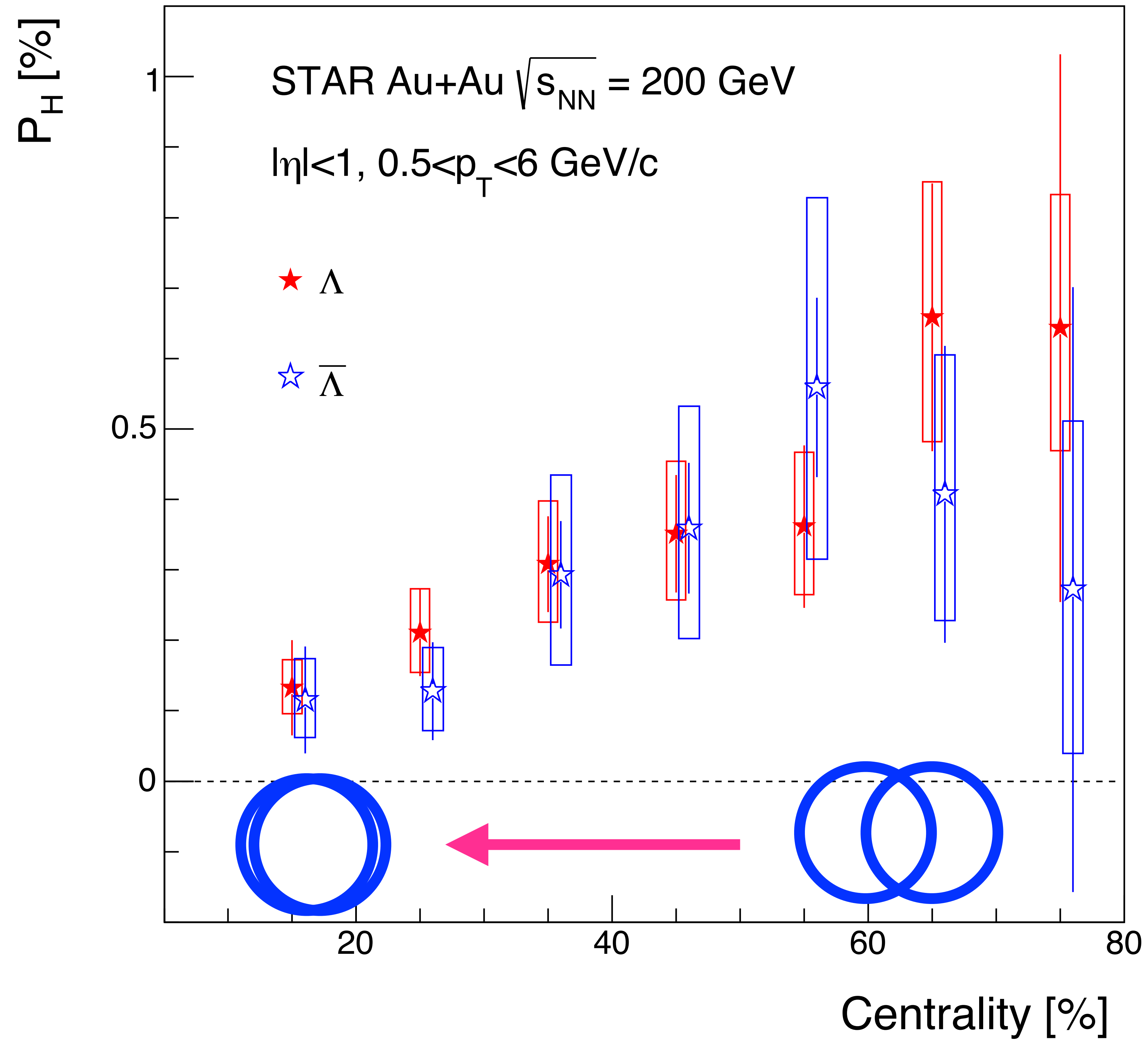
X. Guo, J. Liao, and E. Wang, PRC99.021901(R) (2019)

PRC99.021901(R) (2019)

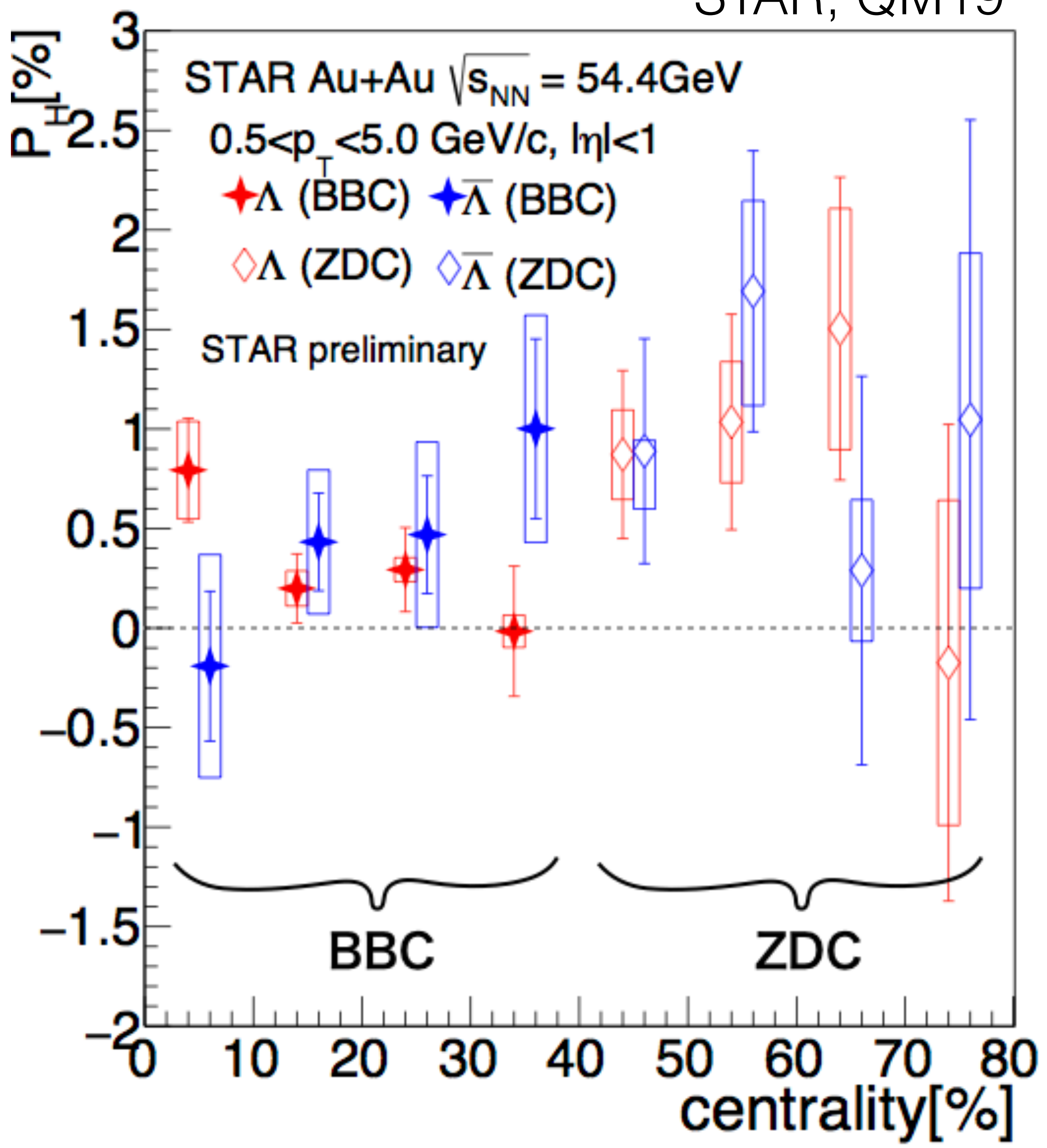


Differential measurements: centrality

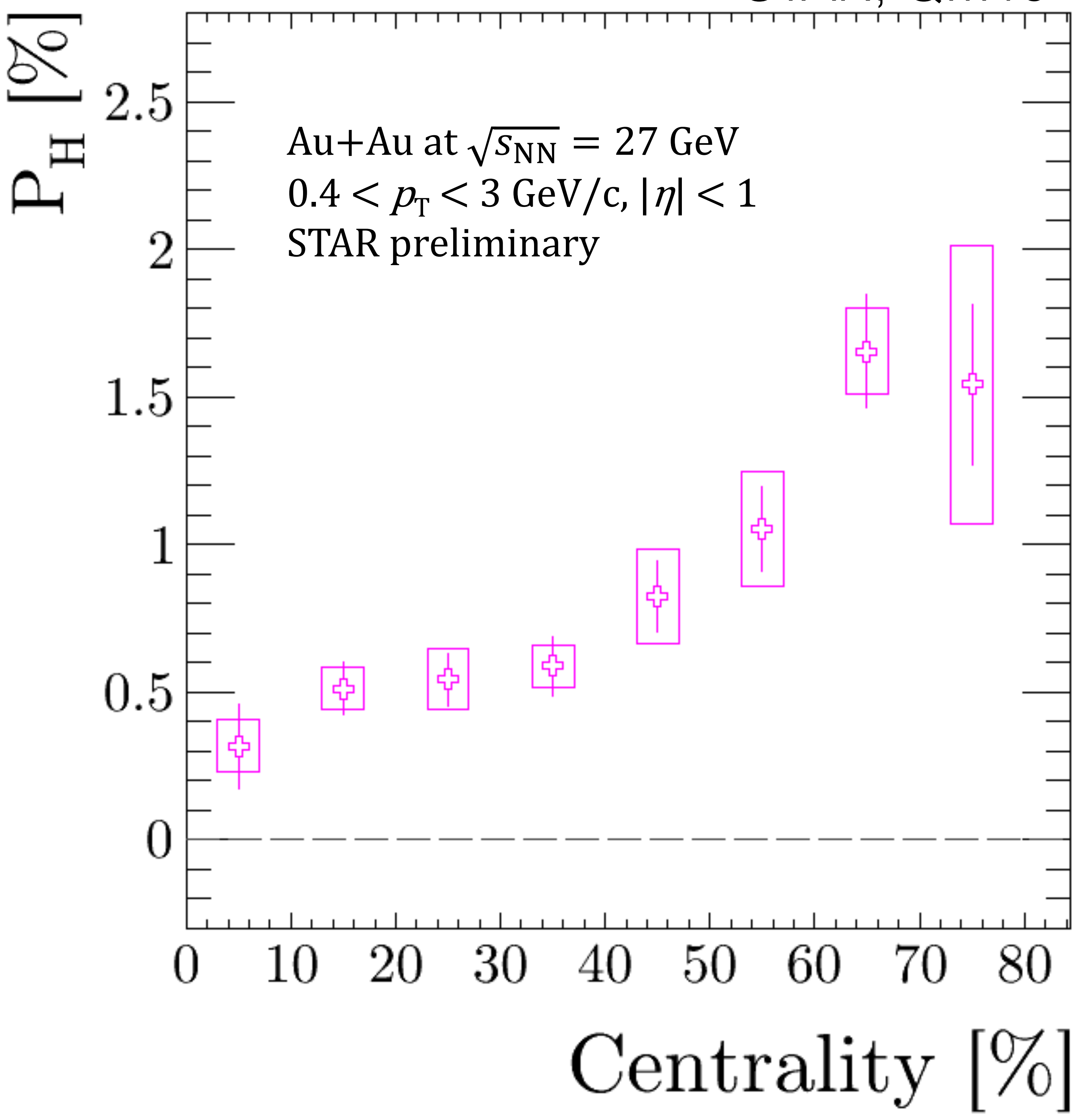
STAR, PRC98, 014910 (2018)



STAR, QM19



STAR, QM19



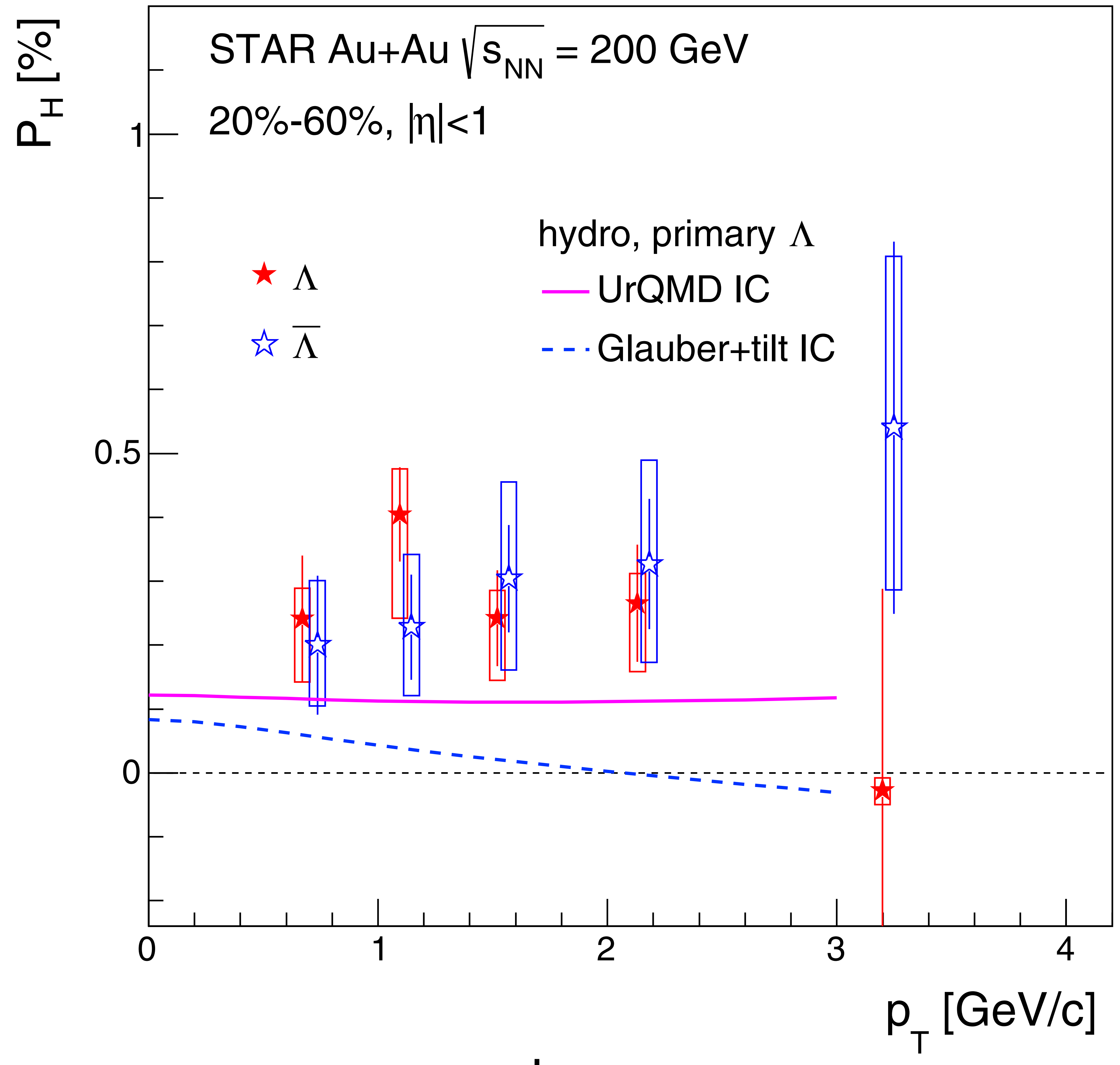
$\sqrt{s_{NN}}$ 200 GeV 54 GeV 27 GeV

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

Similar trend was confirmed at lower energies.

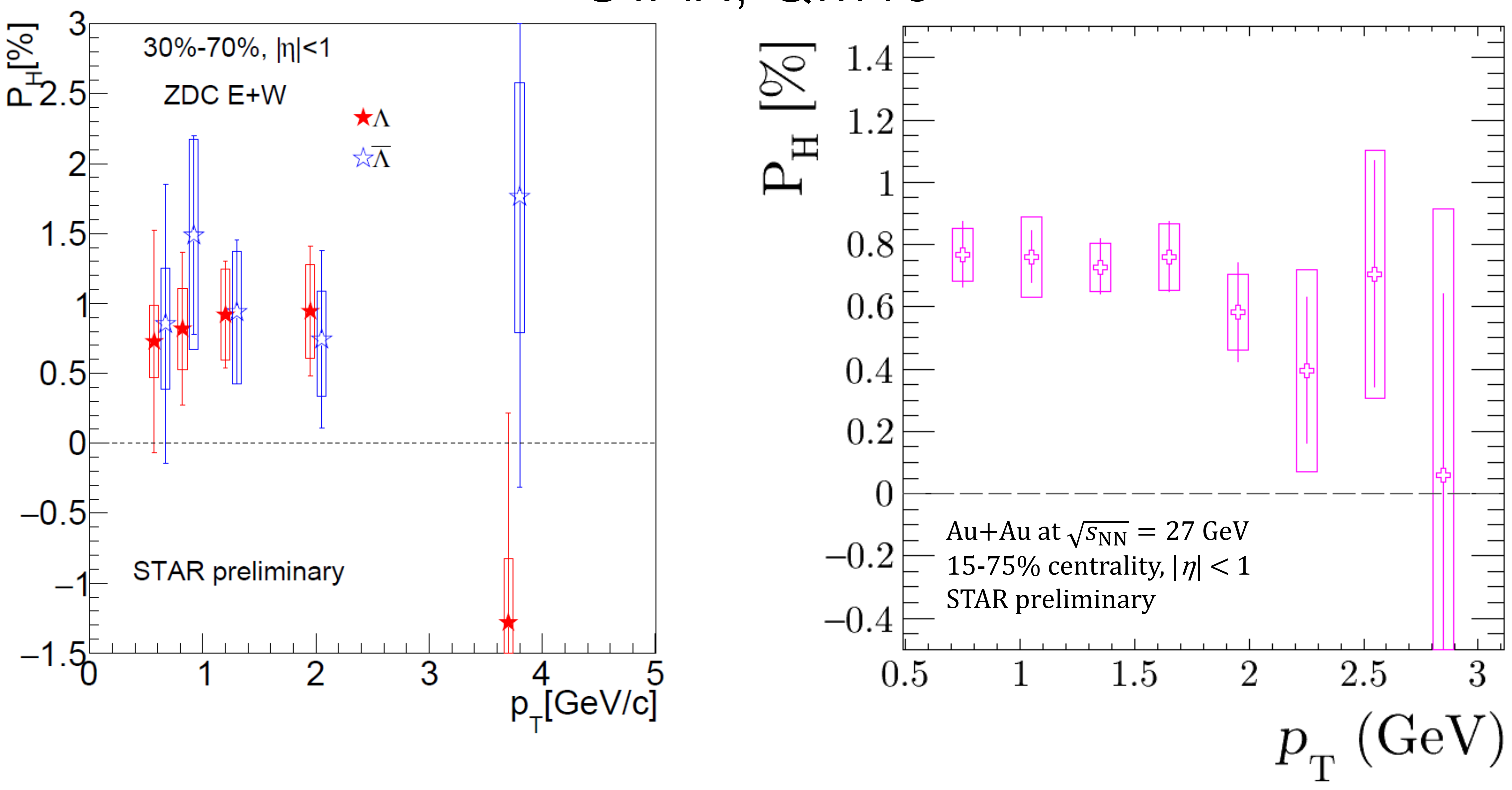
Differential measurements: p_T

STAR, PRC98, 014910 (2018)



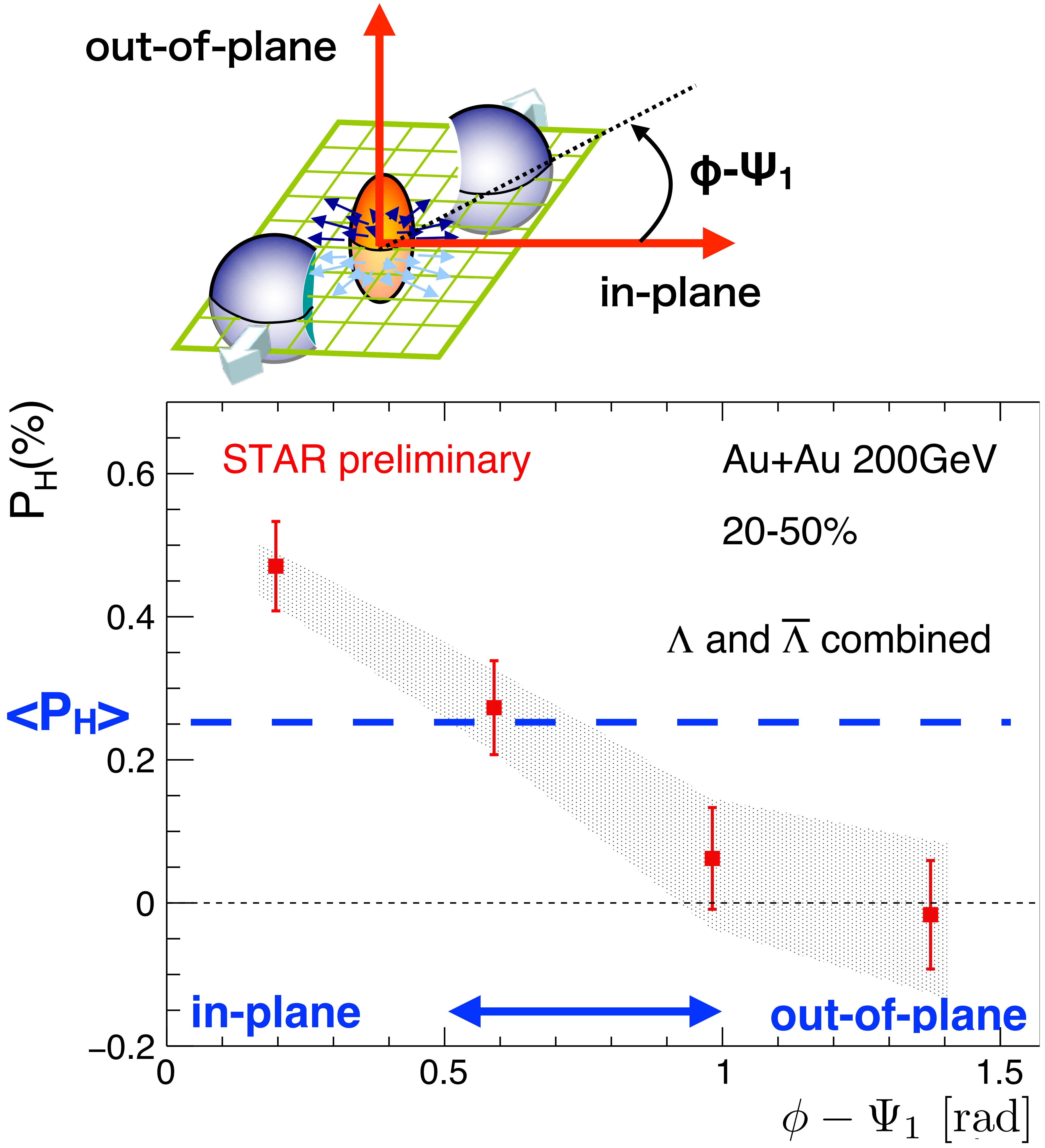
- Naive expectation of smaller P_H due to scattering at low p_T, fragmented at high p_T
- No clear p_T dependence with current precision

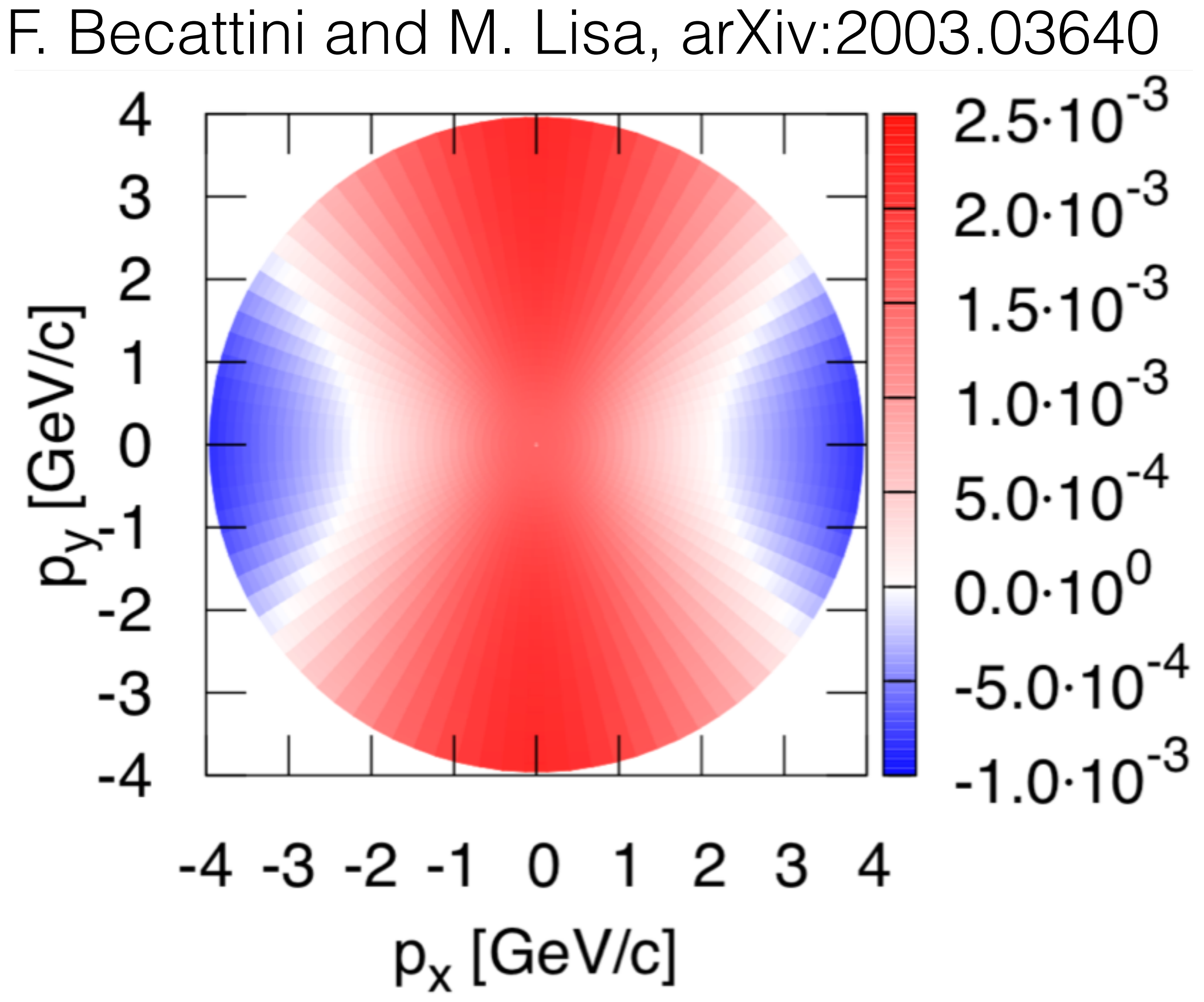
STAR, QM19

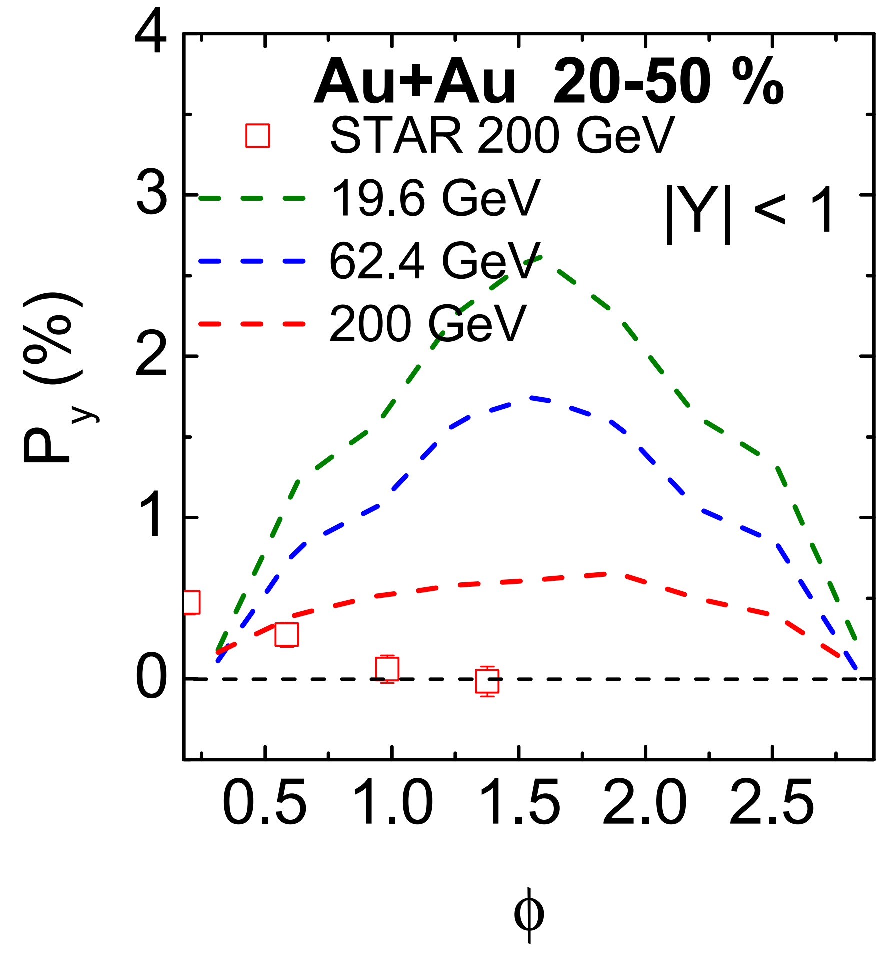


$\sqrt{s_{NN}}$ ← 200 GeV — 54 GeV — 27 GeV

Differential measurements: azimuthal angle





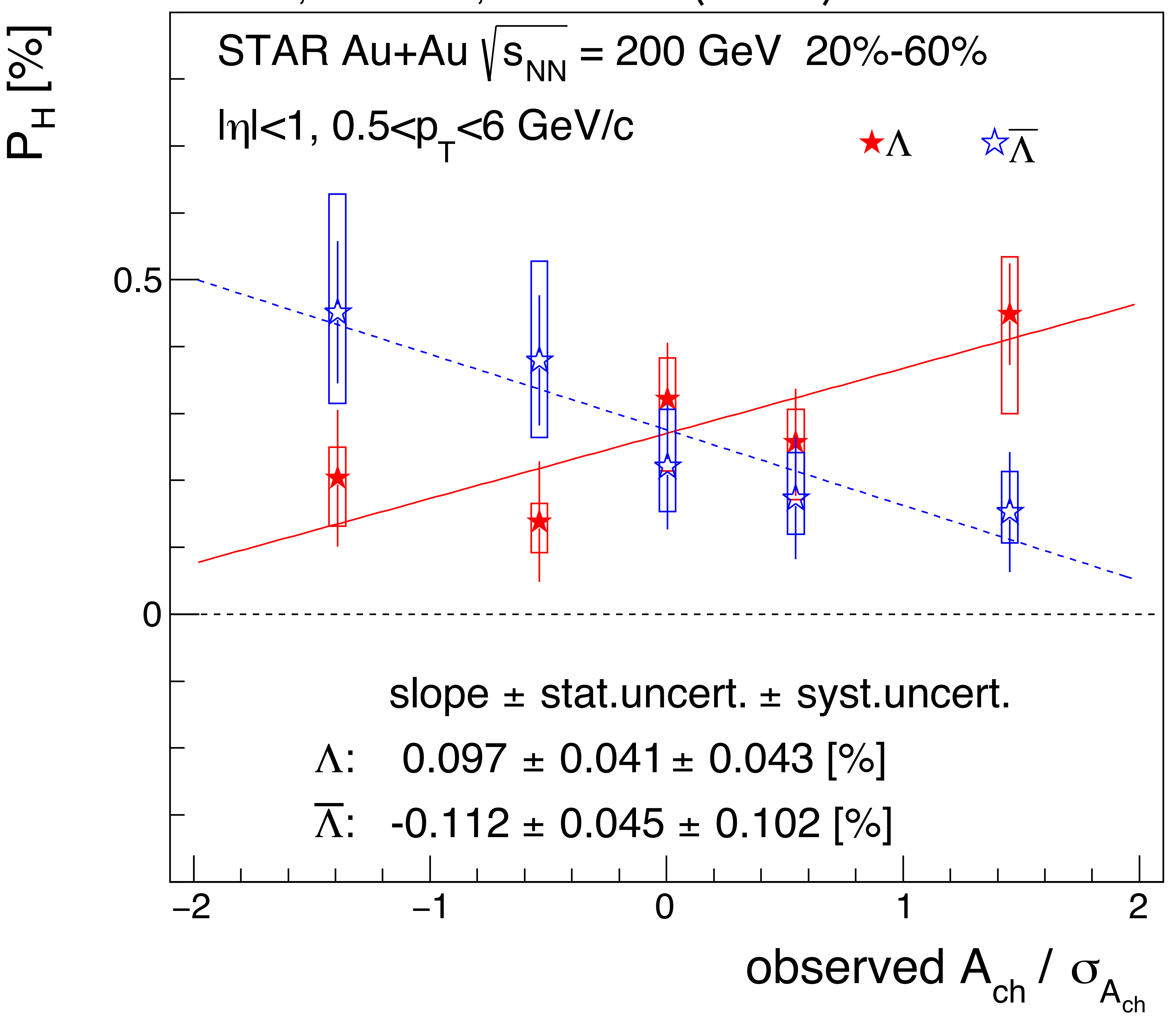


I. Karpenko and F. Becattini, EPJC(2017)77.213
D. Wei, W. Deng, and X. Huang, PRC99.014905 (2019)
H. Wu et al., PR.Research1.033058 (2019)

- 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

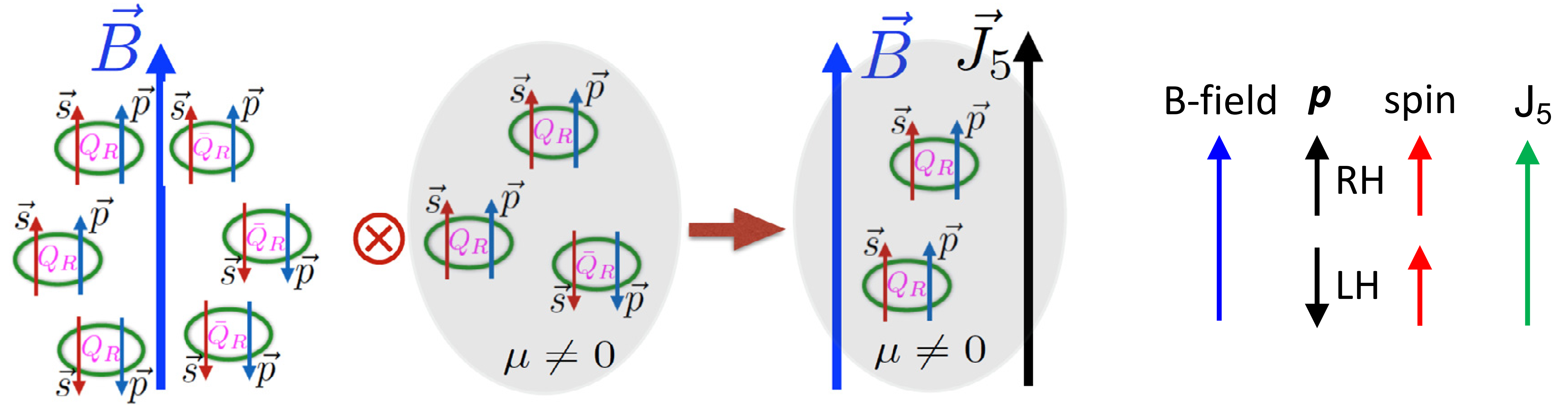
Differential measurements: charge asymmetry

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

Global spin alignment of vector mesons

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%

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)

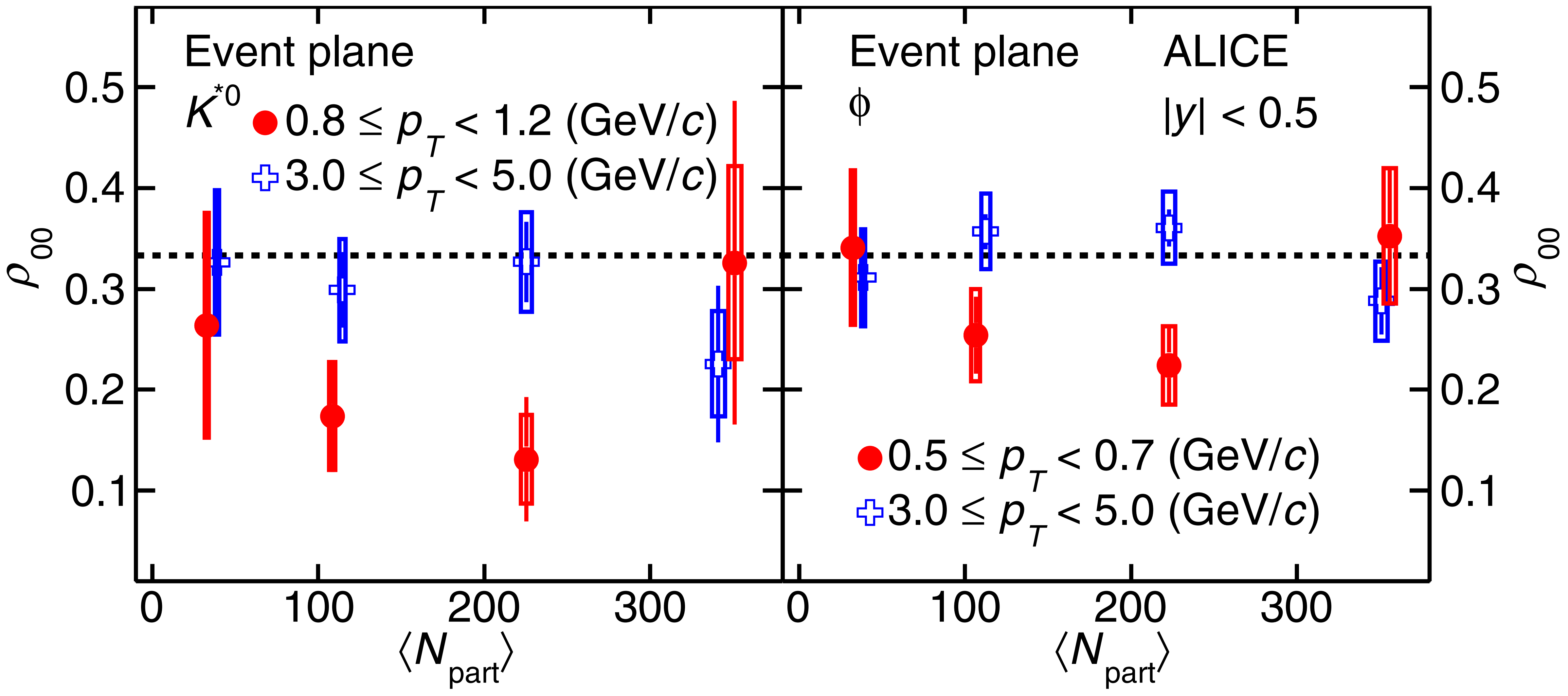
Theoretical expectation for ρ_{00}

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

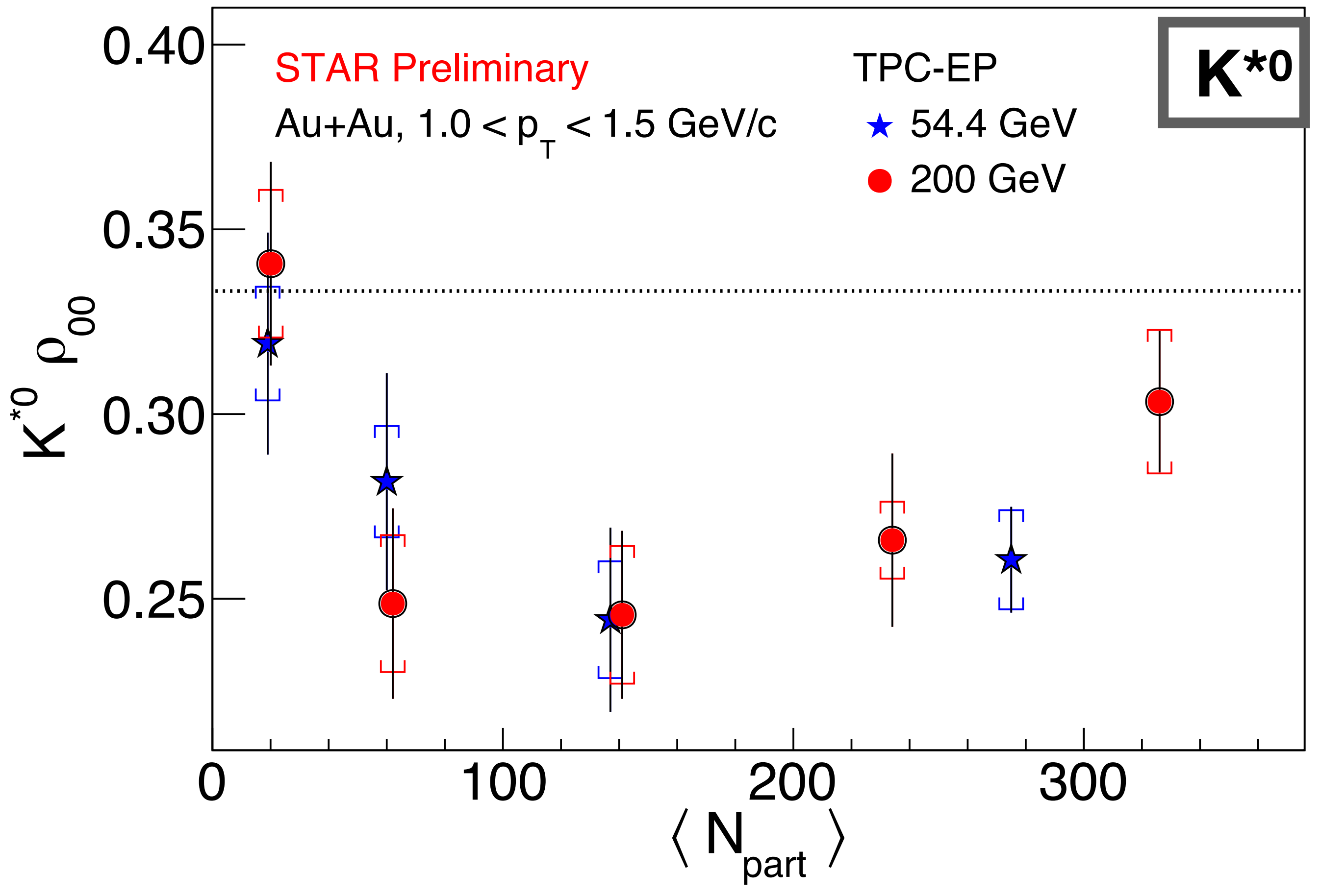
ρ_{00} depends on hadronization process

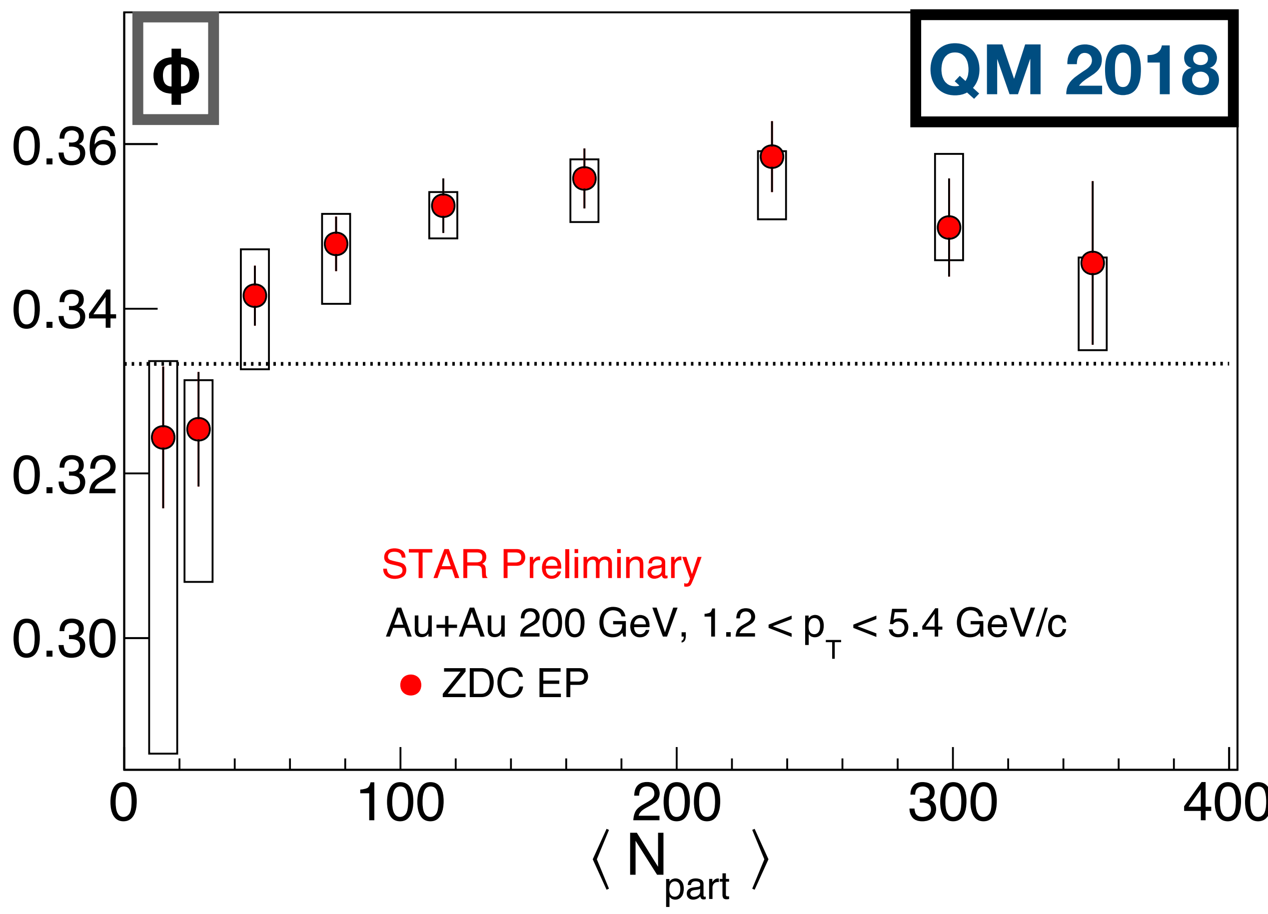
Results from LHC and RHIC

ALICE, PRL125.012301 (2020)



STAR, QM18, QM19





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

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

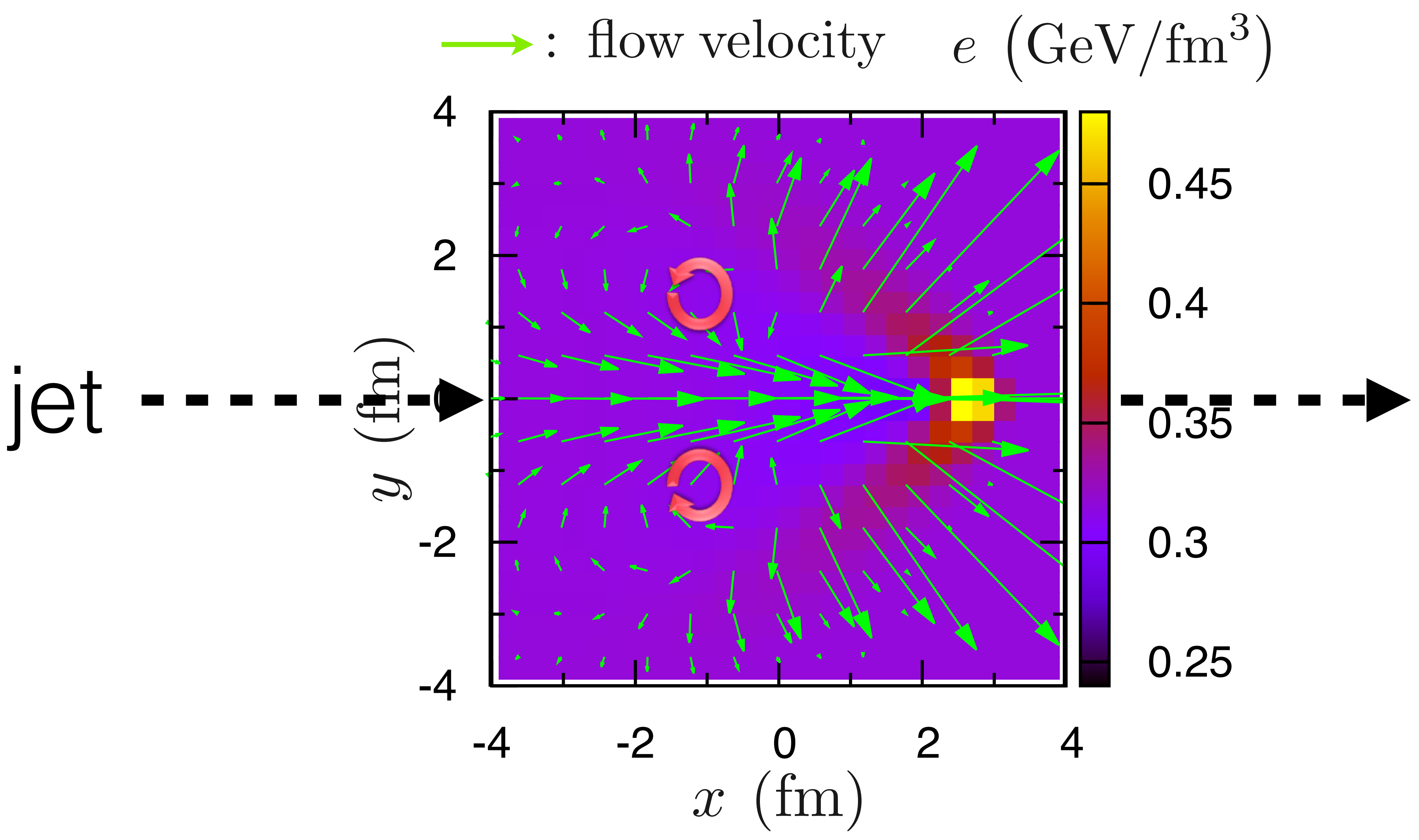
- The deviation in opposite way between:
  - K* and ϕ at RHIC
  - LHC and RHIC for ϕ

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)

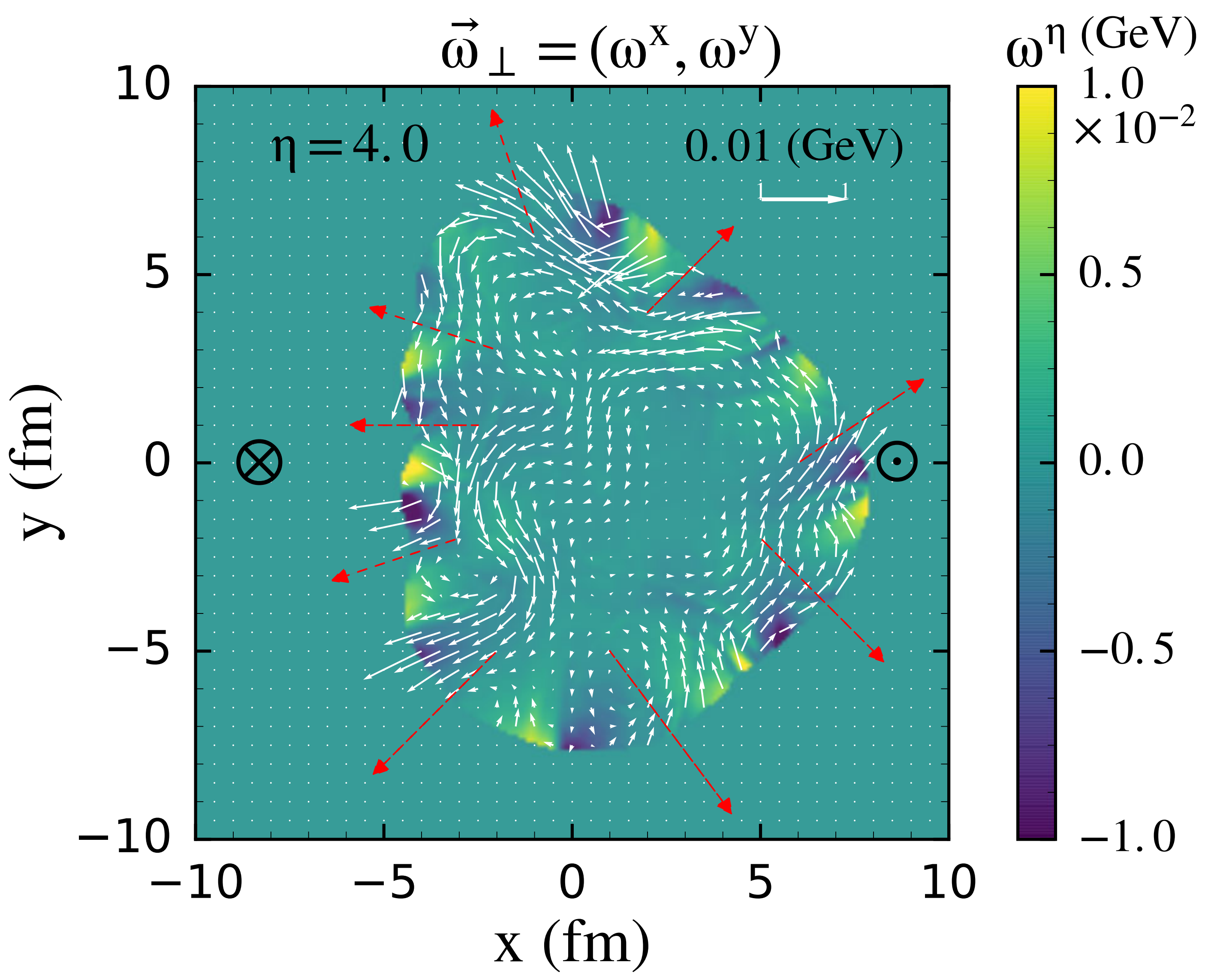
Local vorticity

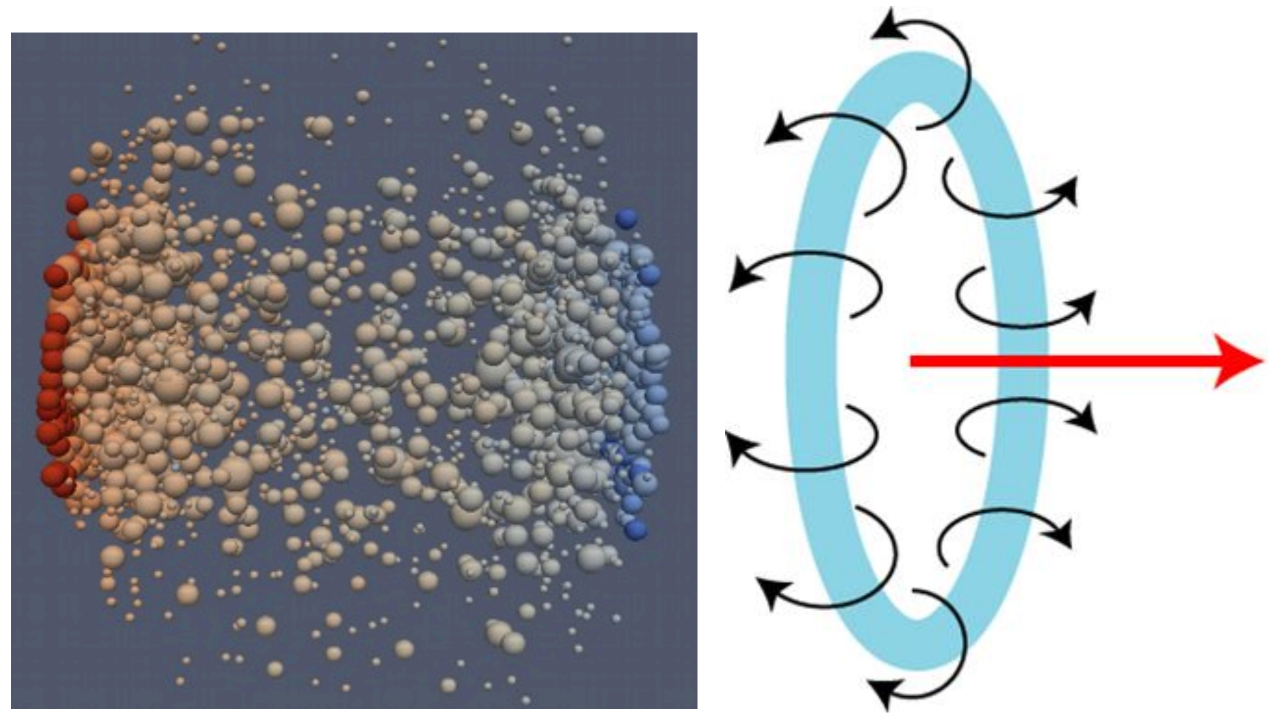
Vortex induced by jet



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

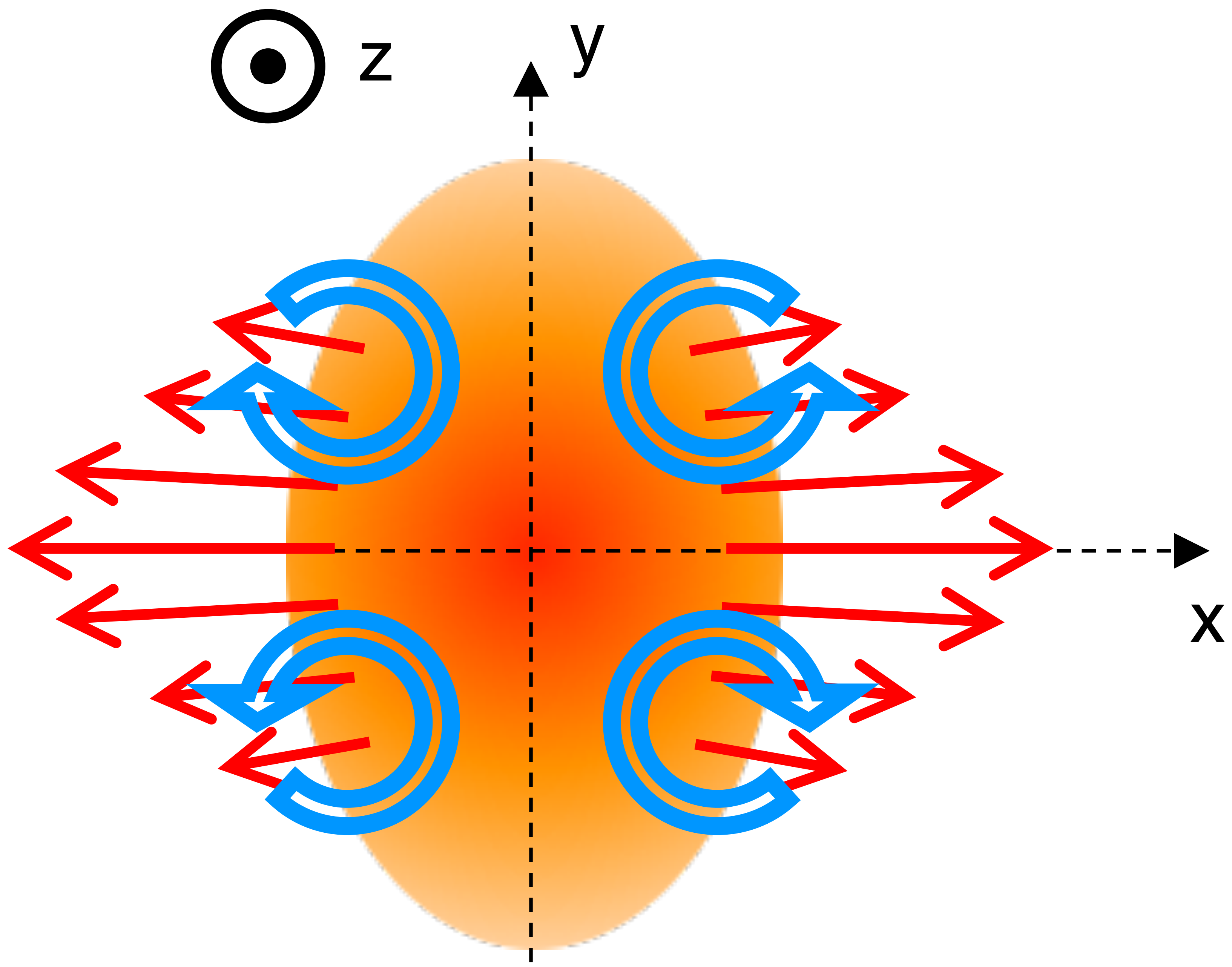


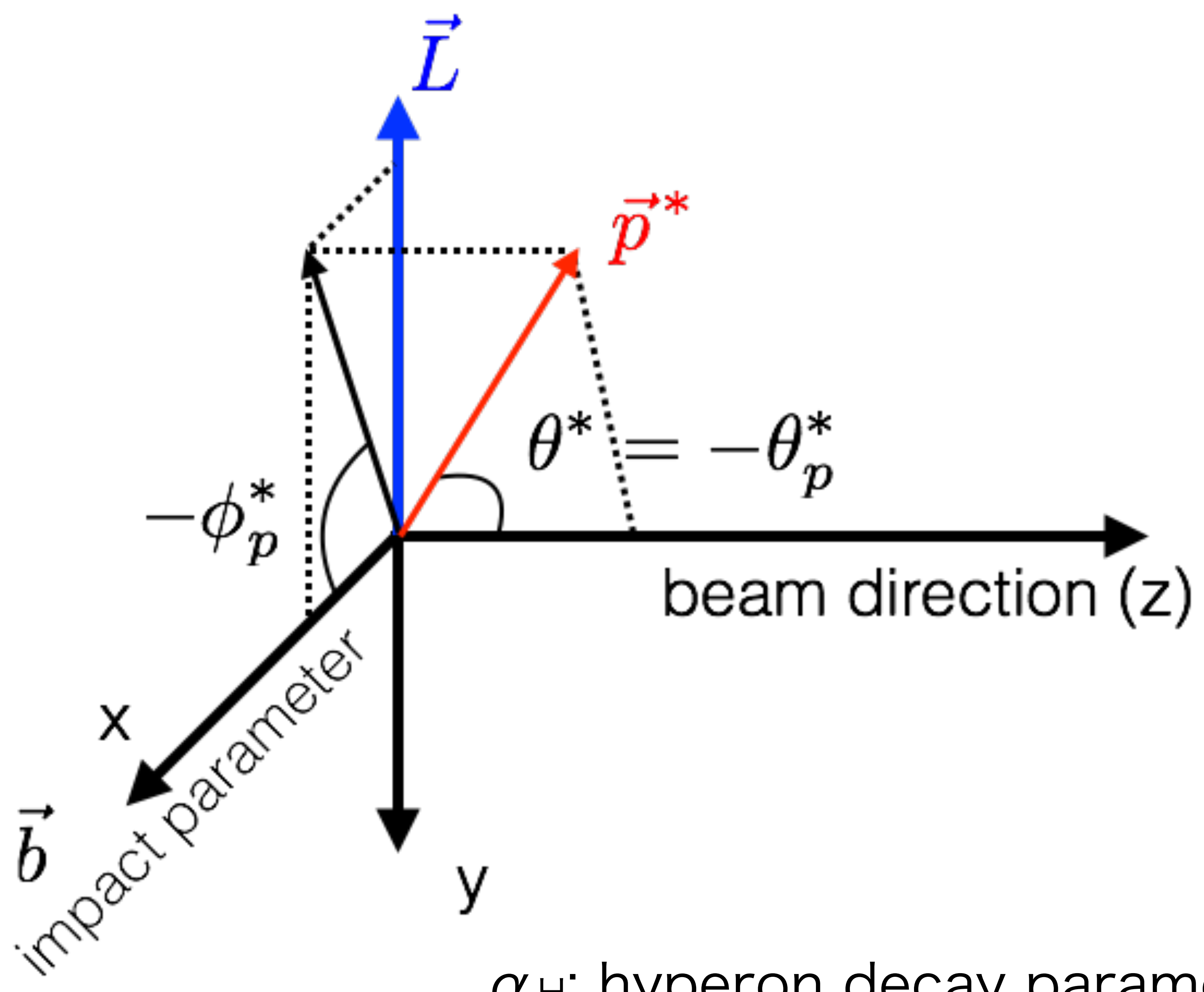


L.-G. Pang, H. Peterson, Q. Wang, and X.-N. Wang, PRL117, 192301 (2016)
F. Becattini and I. Karpenko, PRL120.012302 (2018)
S. Voloshin, EPJ Web Conf.171, 07002 (2018)
X.-L. Xia et al., PRC98.024905 (2018)

Polarization along the beam direction

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





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

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

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

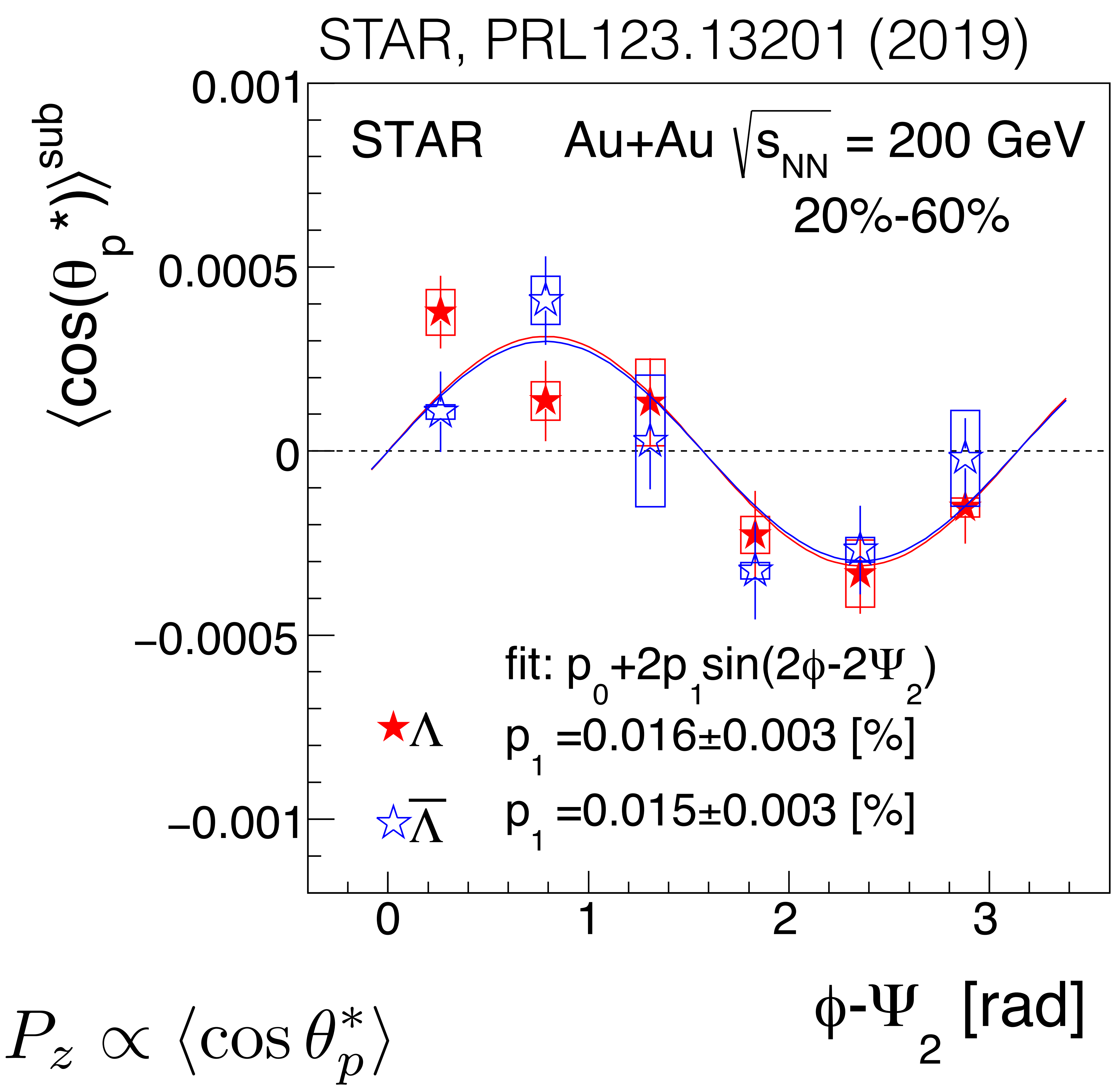
$$\therefore \; P_z = \frac{\langle\cos\theta_p^*\rangle}{\alpha_{\rm H}\langle(\cos\theta_p^*)^2\rangle}$$

$$= \frac{3\langle\cos\theta_p^*\rangle}{\alpha_{\rm H}}$$ (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
could make local vorticity along beam axis, thus polarization

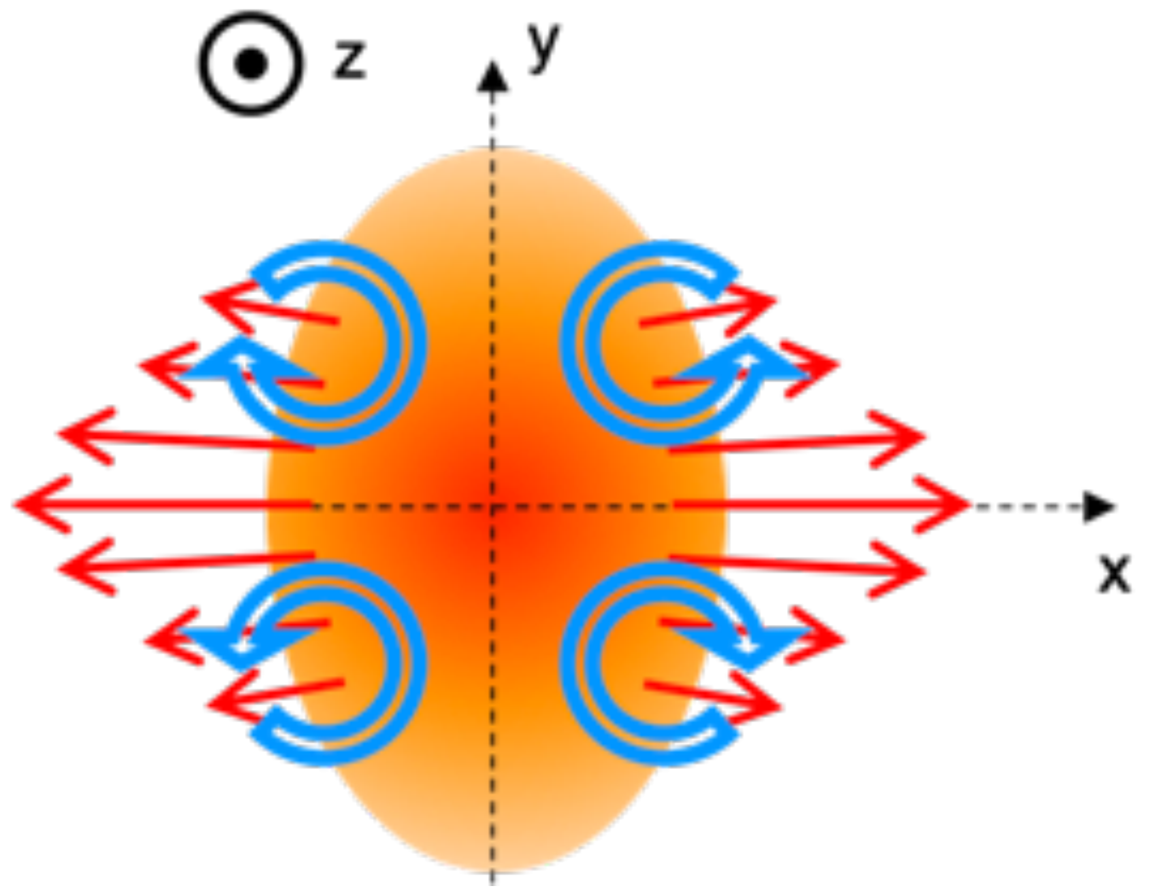
Polarization along the beam direction



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

- 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)

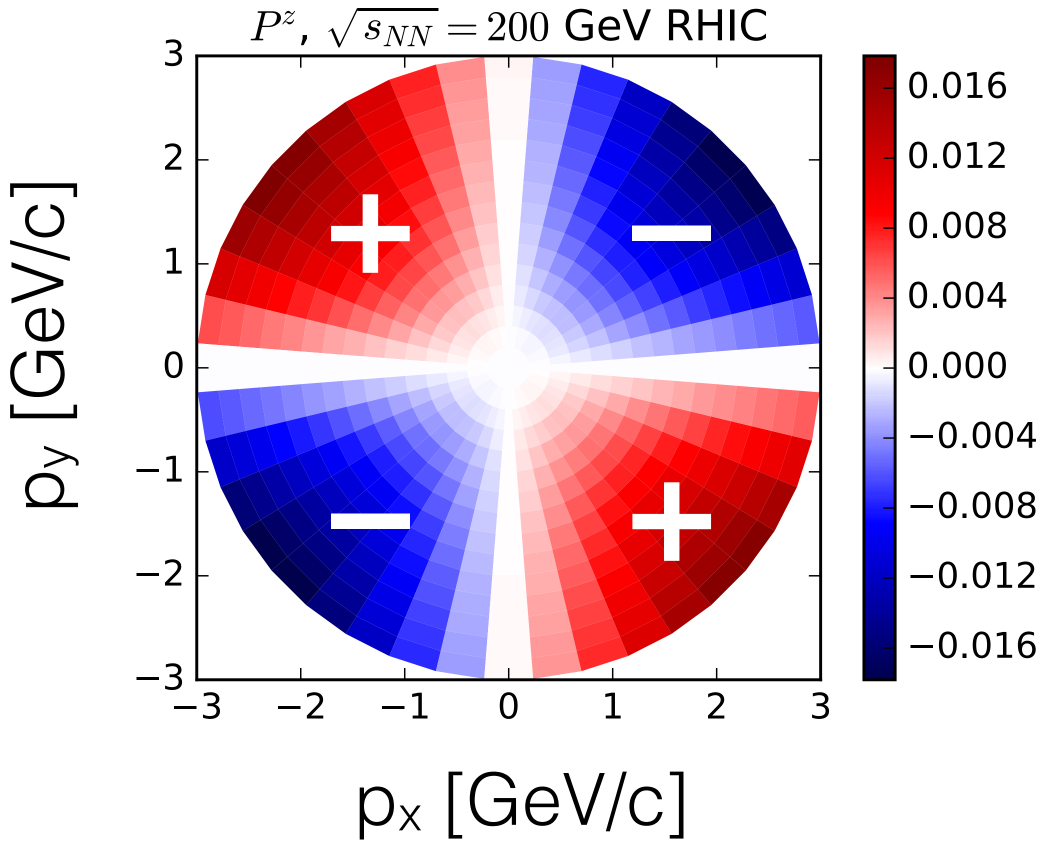
Same sign

- 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

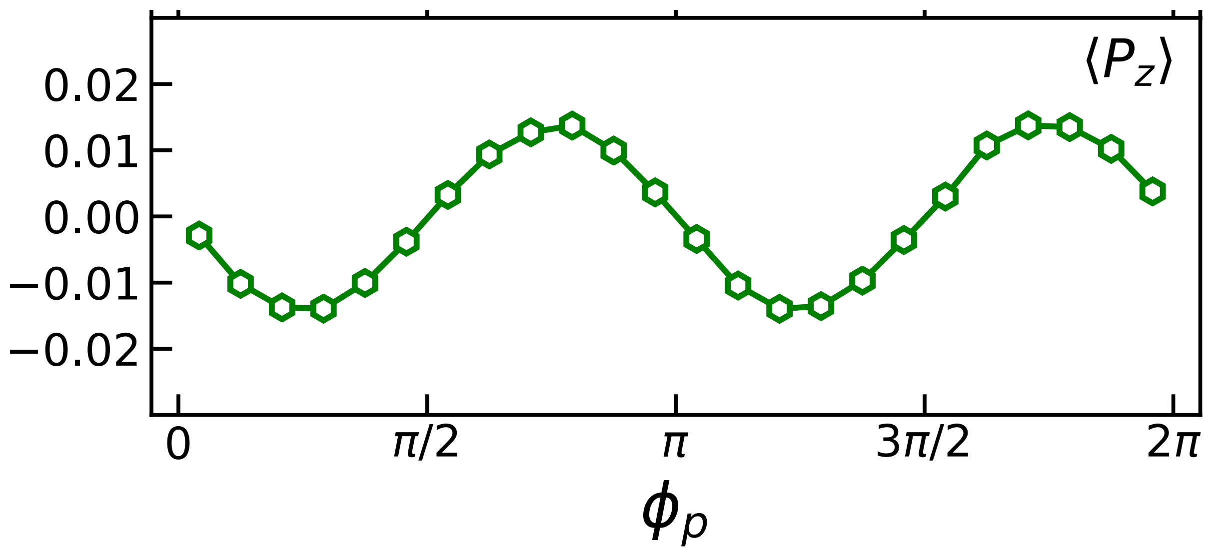
Partly (one of component showing the same sign)

- 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)

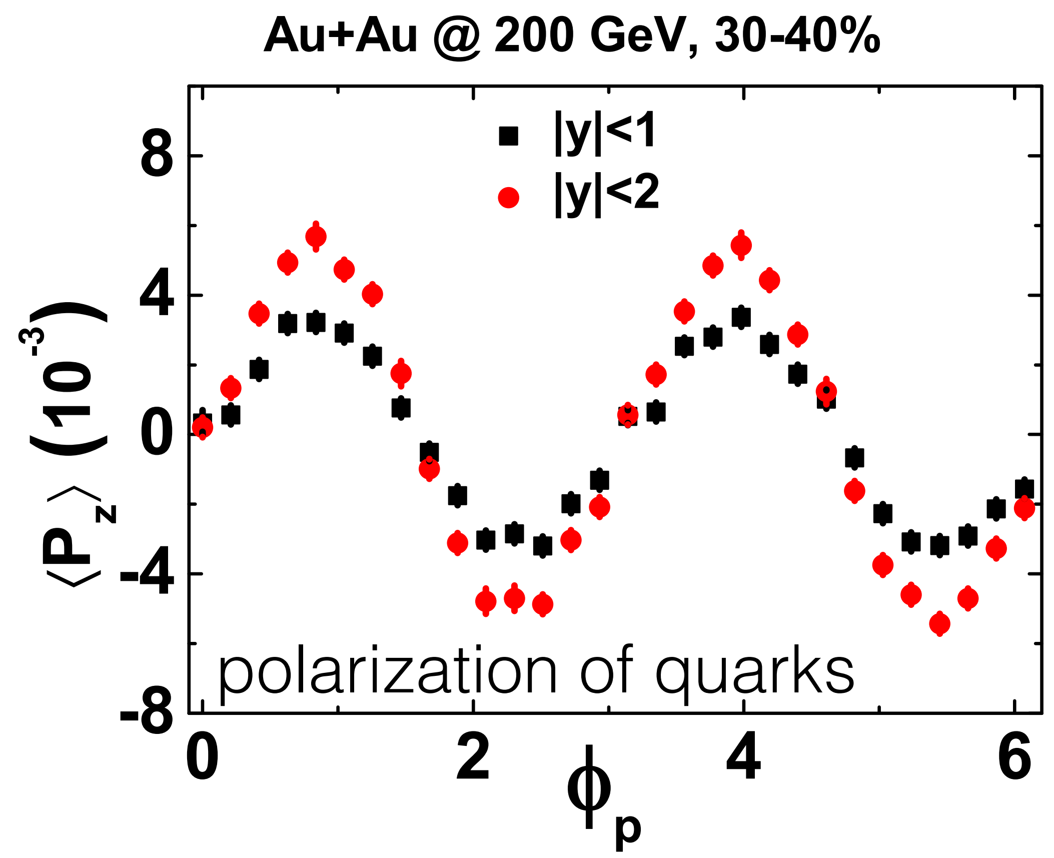
Hydrodynamic model



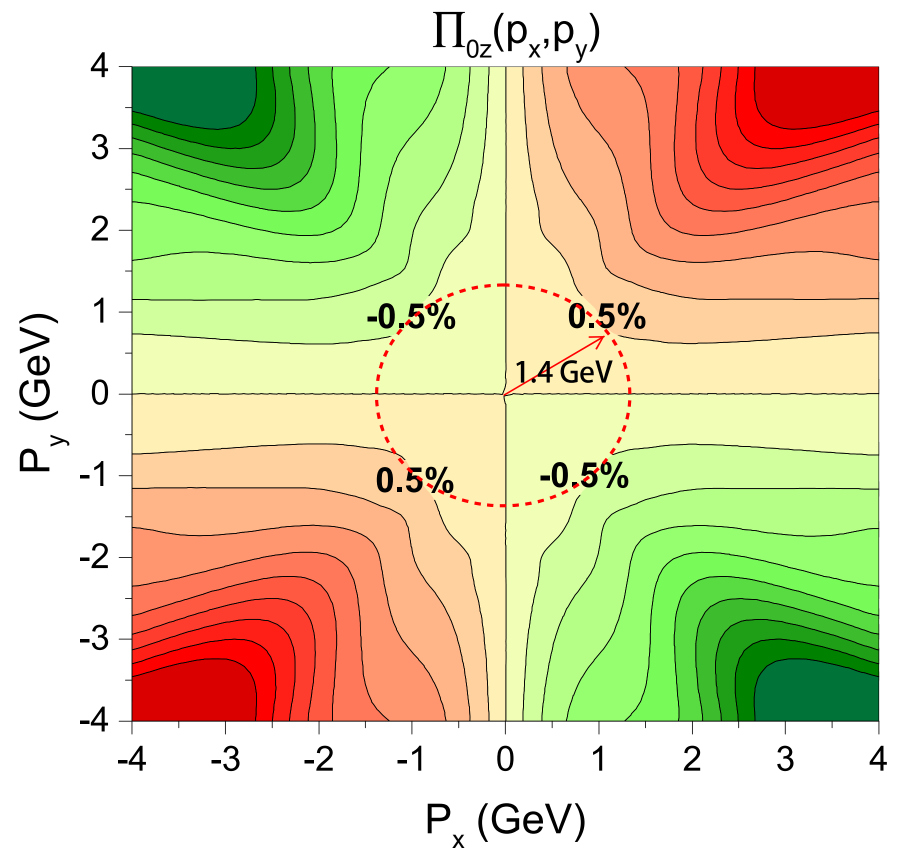
AMPT, Au+Au 200 GeV 20-50%



Chiral kinetic approach



PICR model

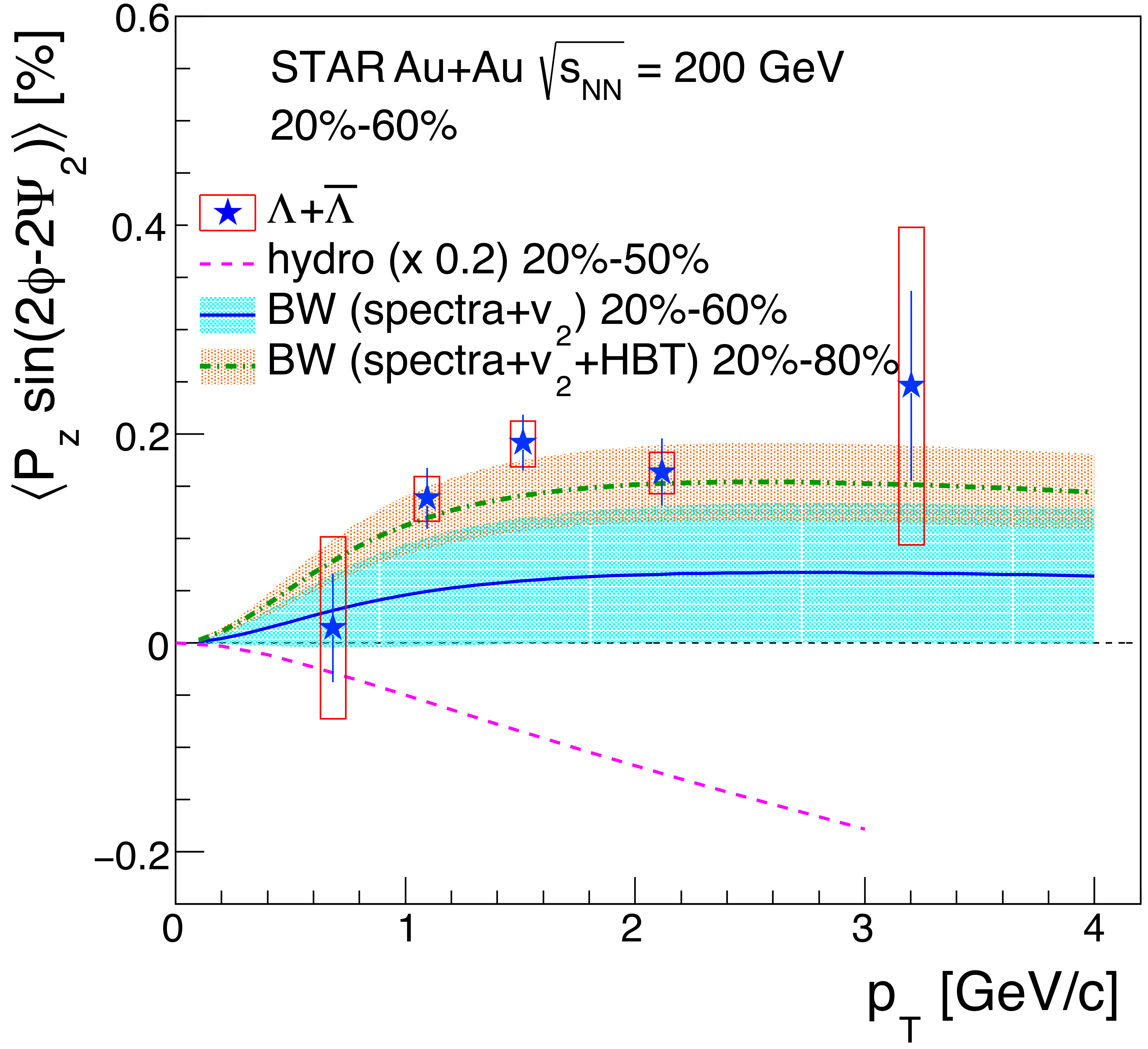


Incomplete thermal equilibrium of spin degree of freedom?

p_T and centrality dependence of P_z modulation

STAR, PRL123.13201 (2019)

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



- Estimate with Blast-wave model
  - Calculate vorticity using the freeze-out parameters extracted from the fits to spectra, v_2, and HBT
  - Convert the vorticity to polarization: $P_z \approx \omega_z/(2T)$

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

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

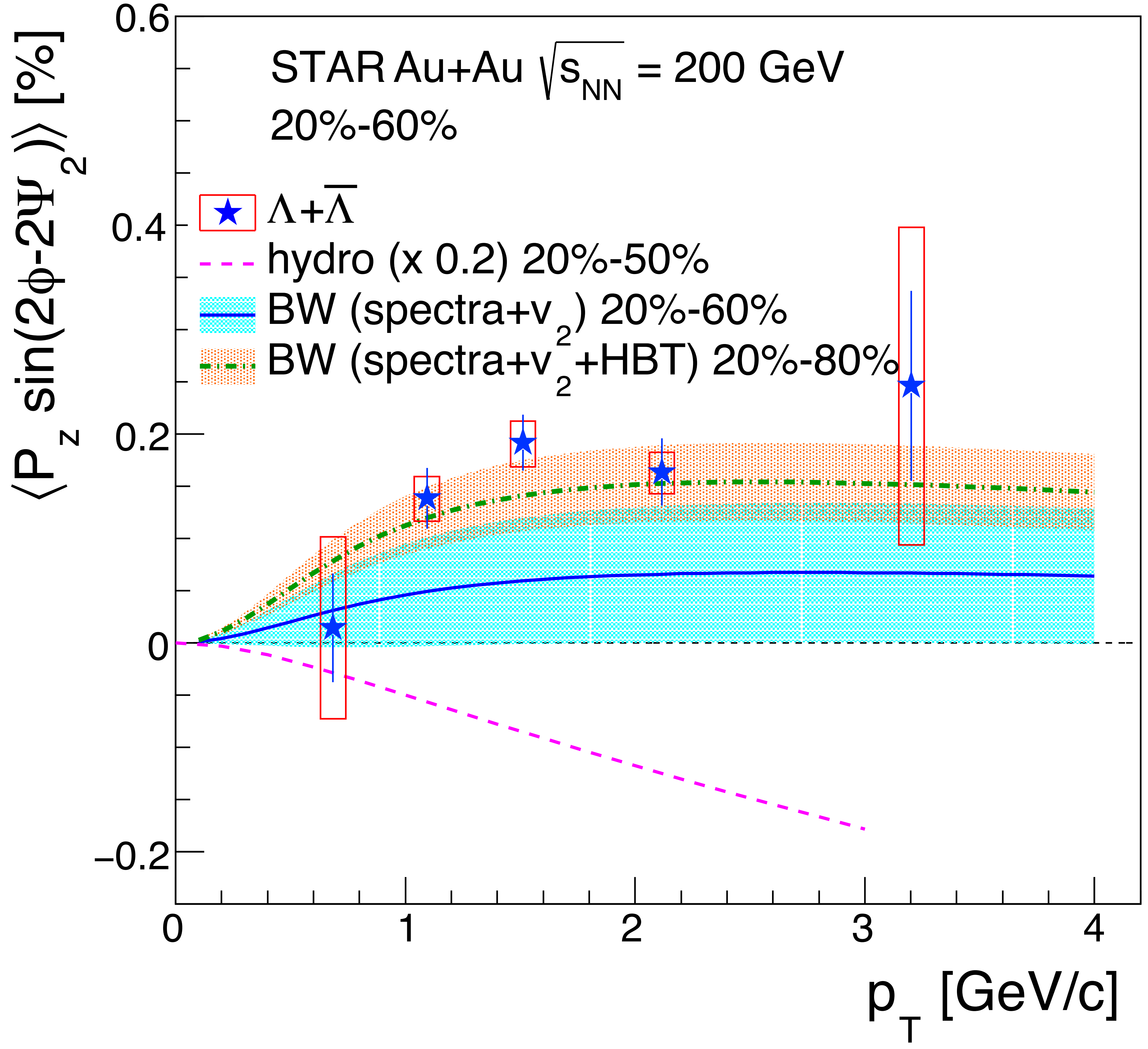
u_i: local flow velocity
ϕ_s: azimuthal angle of the source element
ϕ_b: boost angle perpendicular to the elliptical subshell

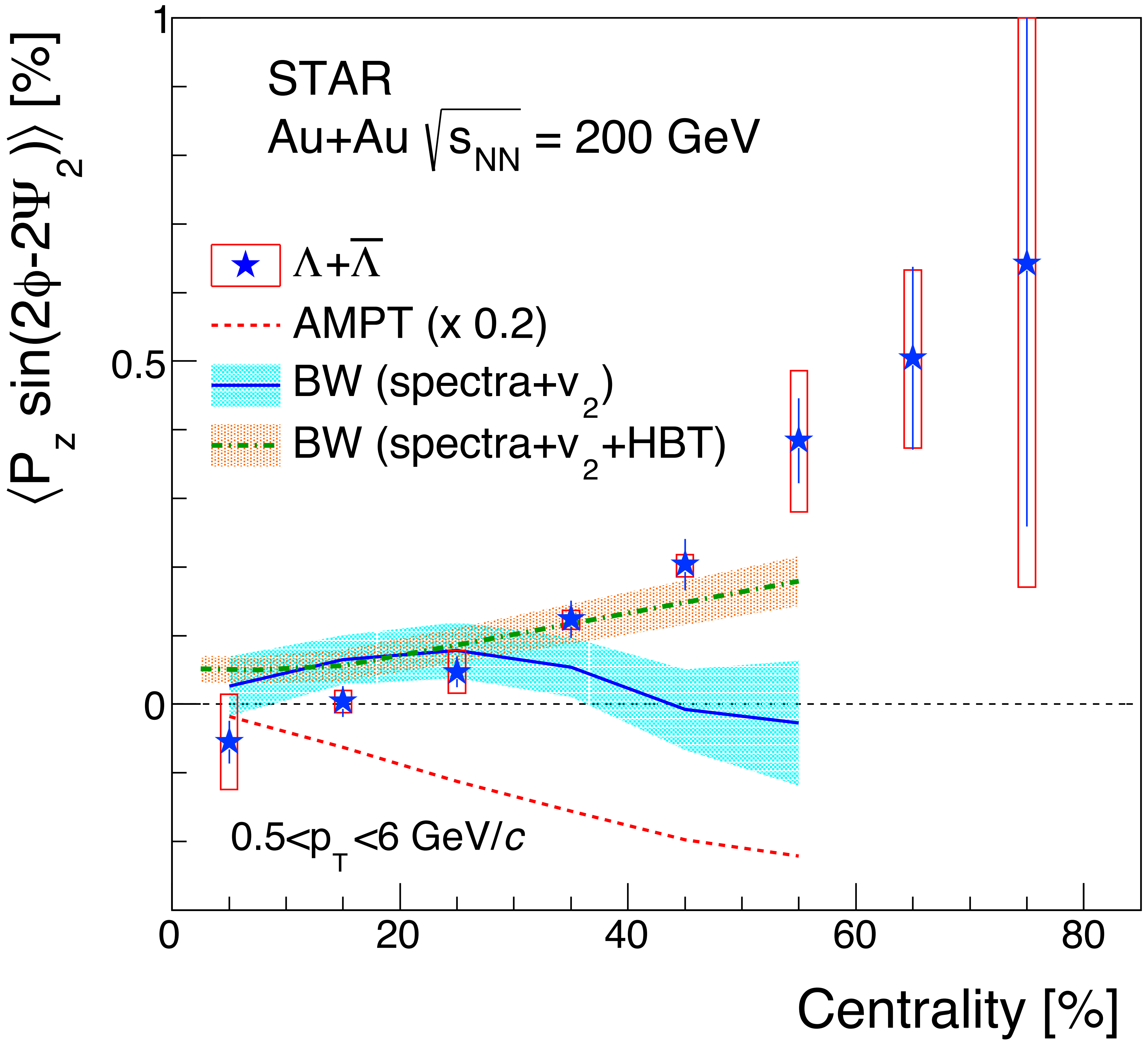
- No strong p_T dependence but a hint of drop-off at p_T<1 GeV/c

p_T and centrality dependence of P_z modulation

STAR, PRL123.13201 (2019)

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



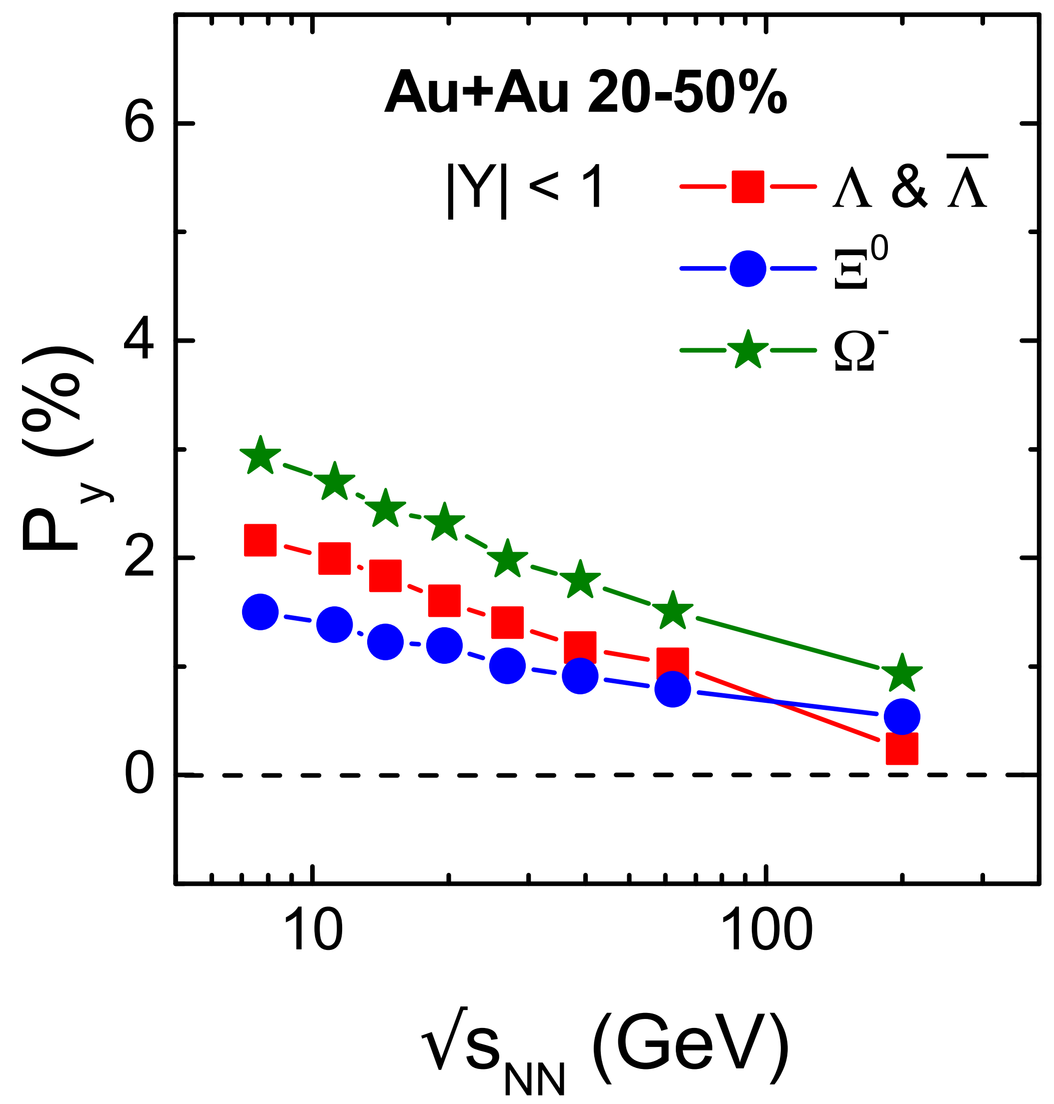


- No strong p_T dependence but a hint of drop-off at p_T<1 GeV/c
- Strong centrality dependence as in v_2
- Blast-Wave model as a simple estimate for kinematic vorticity can describe the data

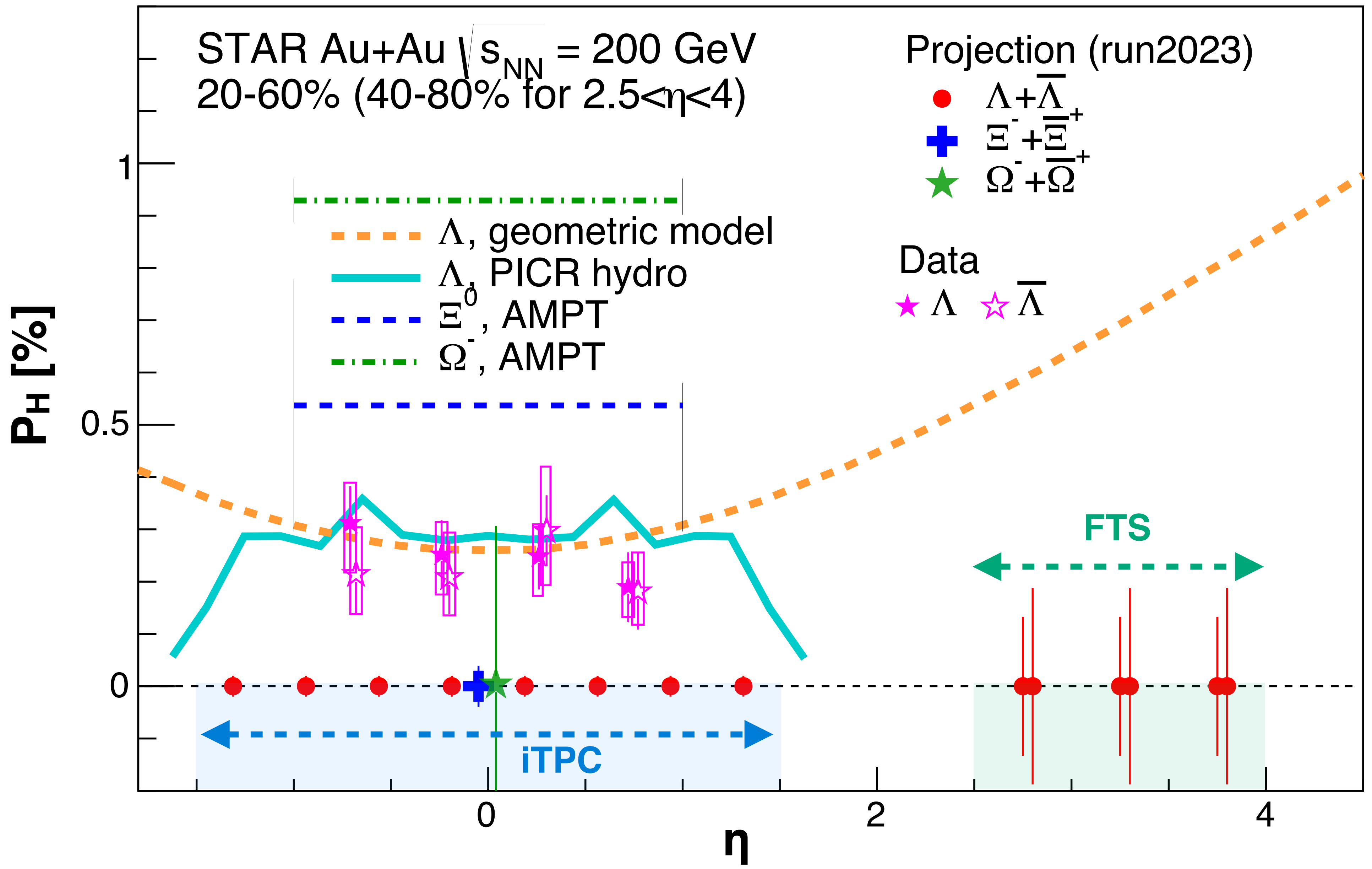
Experimental outlook

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

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



STAR BUR2020



Towards Ξ and Ω polarization measurements

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

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

Polarization of daughter Λ in a weak decay of Ξ (spin 1/2):
(based on Lee-Yang formula)

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

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

$$C_{\Xi^-\Lambda} = +0.927,\ \alpha^2 + \beta^2 + \gamma^2 = 1$$

Similarly, daughter Λ polarization from Ω (spin 3/2):

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

γ_Ω is unknown.
Time-reversal violation parameter β would be small,
the polarization transfer $C_{\Omega\Lambda}$ would be:

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

Several questions arise:
- What about for different spin and magnetic moments?
- Should Λ from Ξ have different polarization? if Ξ is produced at different time?
- What is the polarization transfer of Ω?
- P_Ξ* and daughter P_Λ* are measured in different frames. Are they different?

Also, measuring Ξ and Ω are very challenging in terms of statistics…

$$(dN/dy)_\Lambda \sim 0.1(dN/dy)_{\Xi^-} \sim 0.01(dN/dy)_{\Omega^-}\ \text{(200 GeV)}$$

STAR, PRC108.072301

New results will come soon!

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 fully 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
  - Agreement/disagreement among the data and theoretical calculations in the sign

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

Back up

Blast-wave model parameterization

- Hydro-inspired model parameterized with freeze-out condition assuming the longitudinal boost invariance
  - Freeze-out temperature T_f
  - Radial flow rapidity ρ_0 and its modulation ρ_2
  - Source size R_x and R_y

$$\rho(r, \phi_s) = \tilde{r}[\rho_0 + \rho_2 \cos(2\phi_b)]$$

$$\tilde{r}(r, \phi_s) = \sqrt{(r\cos\phi_s)^2/R_x^2 + (r\sin\phi_s)^2/R_y^2}$$

F. Retiere and M. Lisa, PRC70.044907 (2004)

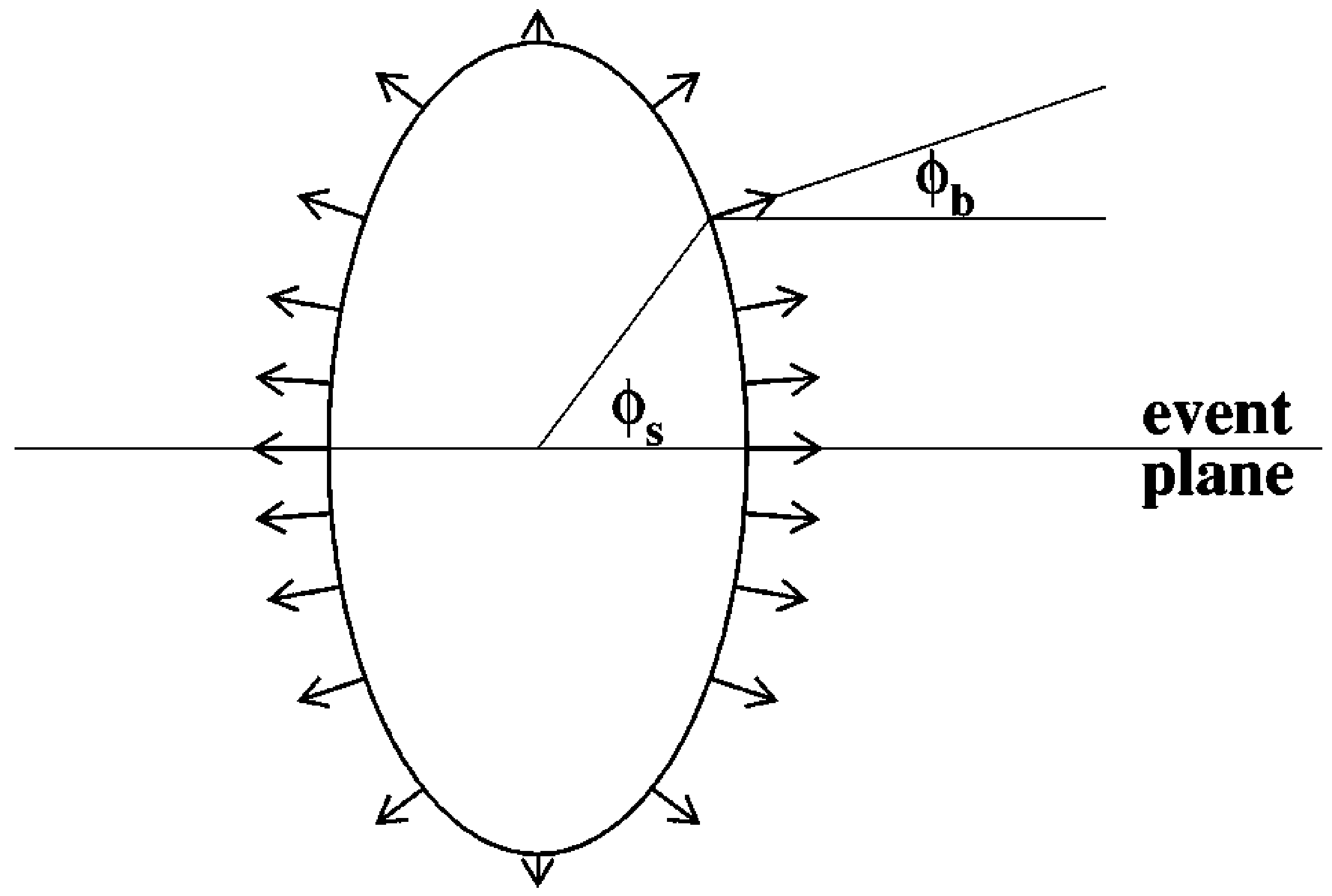


FIG. 2. Schematic illustration of an elliptical subshell of the source. Here, the source is extended out of the reaction plane ($R_y > R_x$). Arrows represent the direction and magnitude of the flow boost. In this example, $\rho_2 > 0$ [see Eq. (4)].

ϕ_s: azimuthal angle of the source element

ϕ_b: boost angle perpendicular to the elliptical subshell

- Calculate vorticity at the freeze-out using the parameters extracted from spectra, v_2, and HBT fit
  -

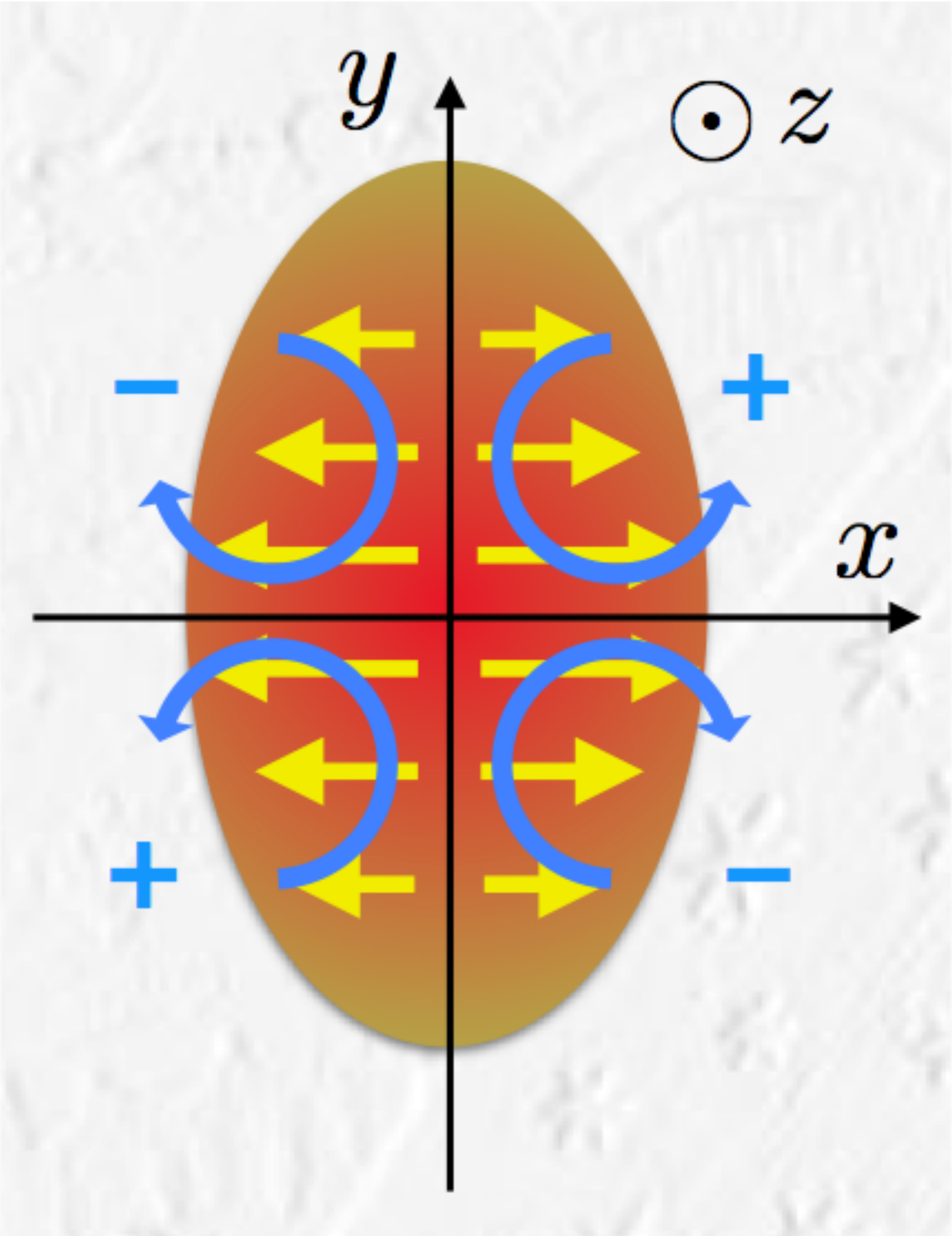
$$\langle \omega_z \sin(2\phi) \rangle = \frac{\int d\phi_s \int r dr\, I_2(\alpha_t) K_1(\beta_t) \omega_z \sin(2\phi_b)}{\int d\phi_s \int r dr\, I_0(\alpha_t) K_1(\beta_t)}$$

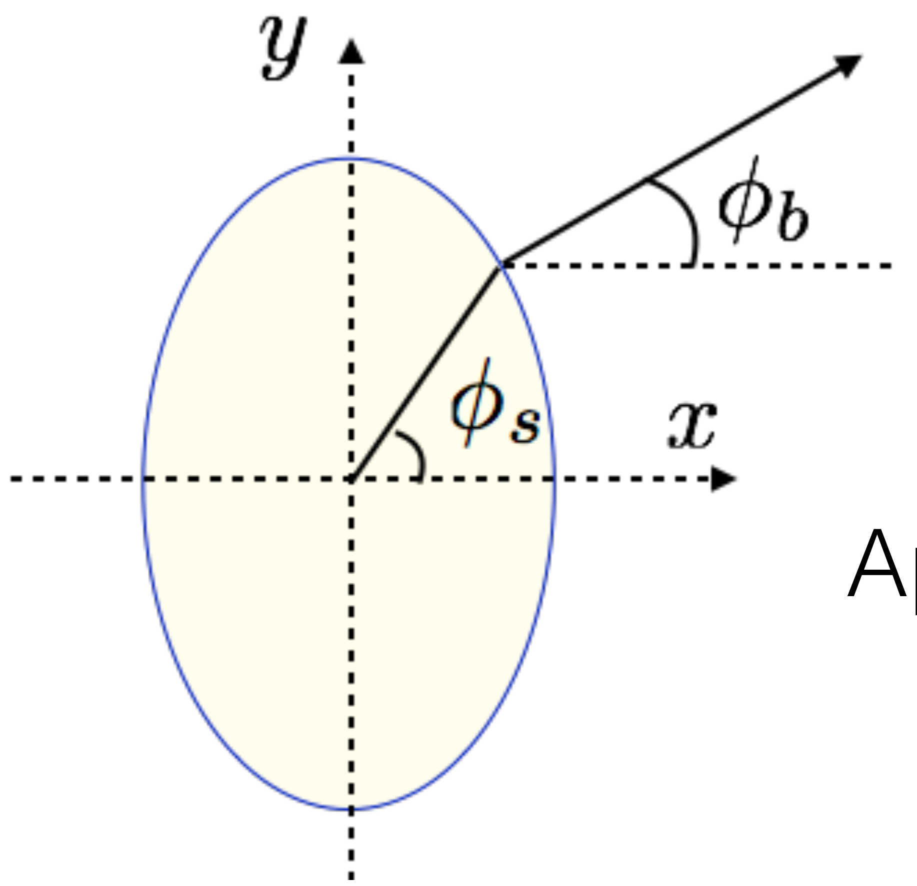
$$\omega_z = \frac{1}{2}\left(\frac{\partial u_y}{\partial x} - \frac{\partial u_x}{\partial y}\right),$$

u: local flow velocity, I_n, K_n: modified Bessel functions

Estimate kinematic vorticity with the blast-wave model

S. Voloshin, SQM2017
EPJ Web Conf.171, 07002 (2018)





R: reference source radius

ρ_t: transverse flow velocity

$$r_{max} = R[1 - a\cos(2\phi_s)],$$

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

Approximation of the kinetic vorticity in the blast-wave model:

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

flow anisotropy

spatial anisotropy

Sine modulation of ω_z is expected with the factor (b_n-a_n).

The sign could be negative depending on the relation of flow and spatial anisotropy.