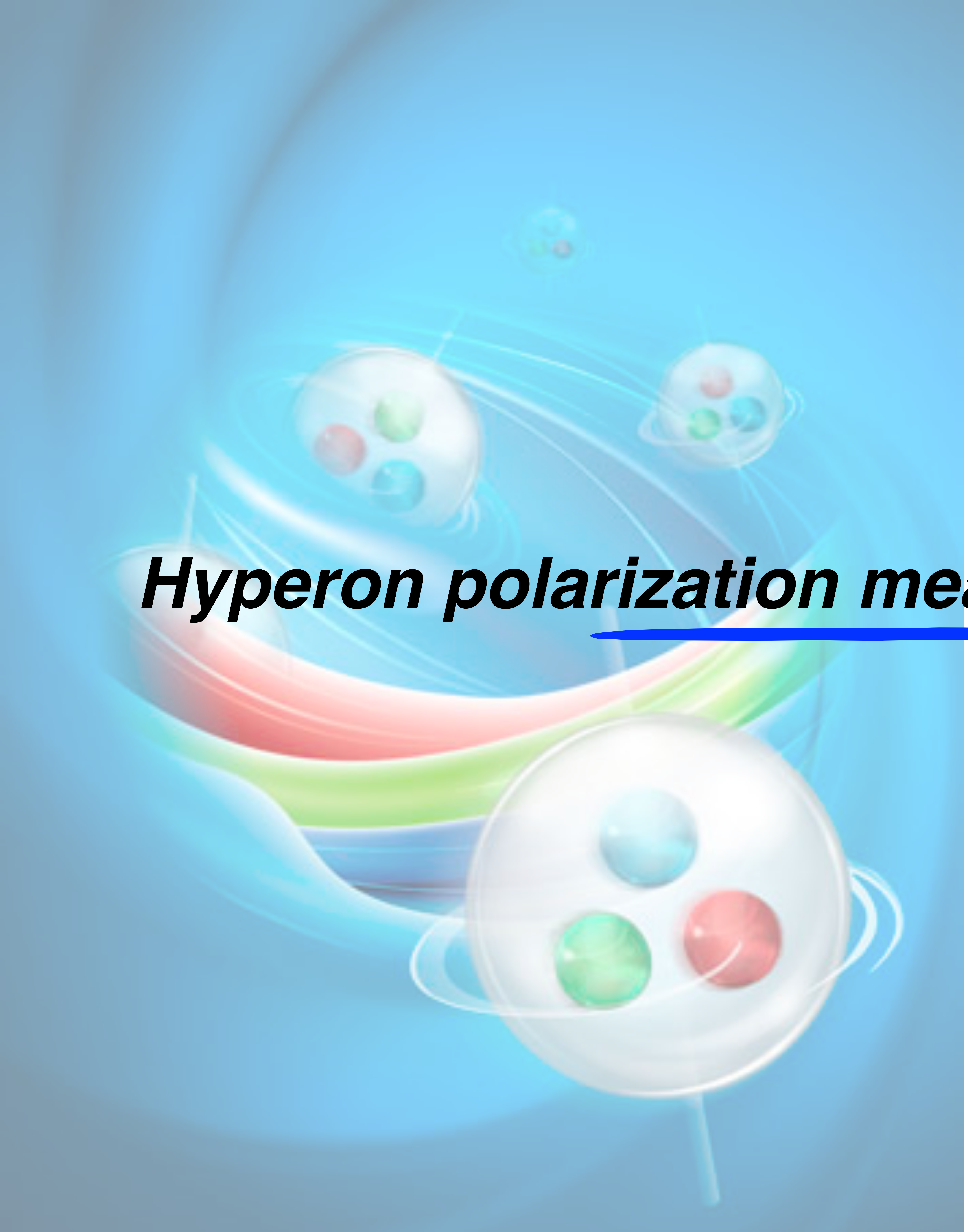


Image from https://www.bnl.gov/newsroom/news.php?a=112068

Hyperon polarization measurements in heavy-ion collisions

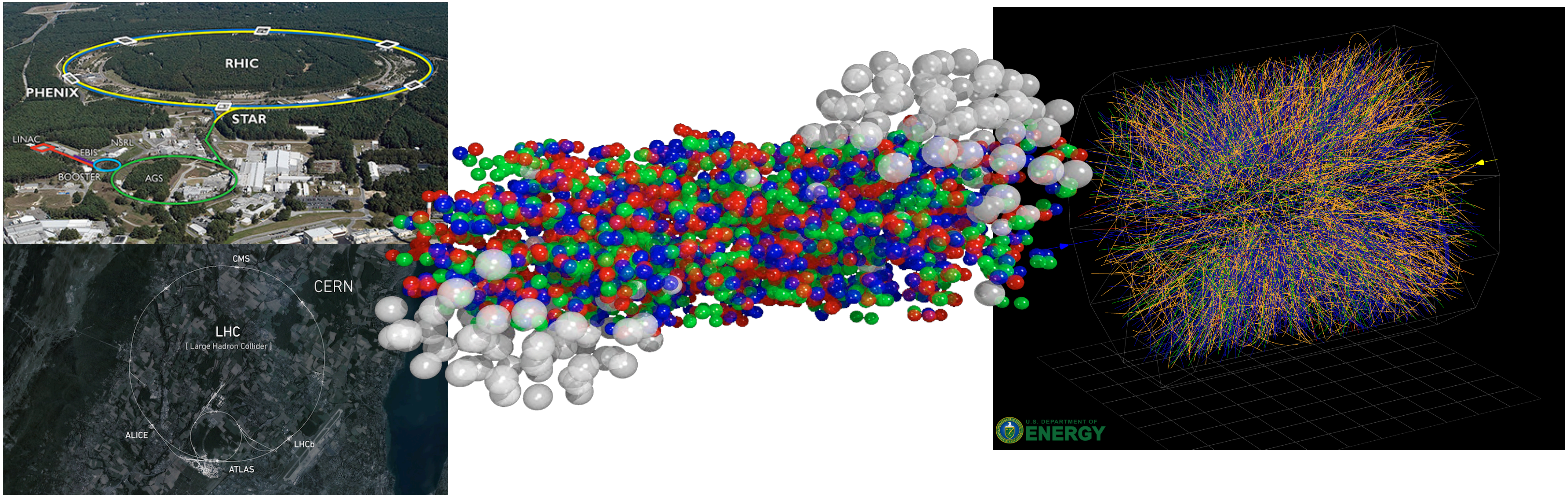
Takafumi Niida

筑波大学
University of Tsukuba

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

25th International Symposium on Spin Physics
Durham, Sep. 24-29/2023

Heavy-ion collision experiment

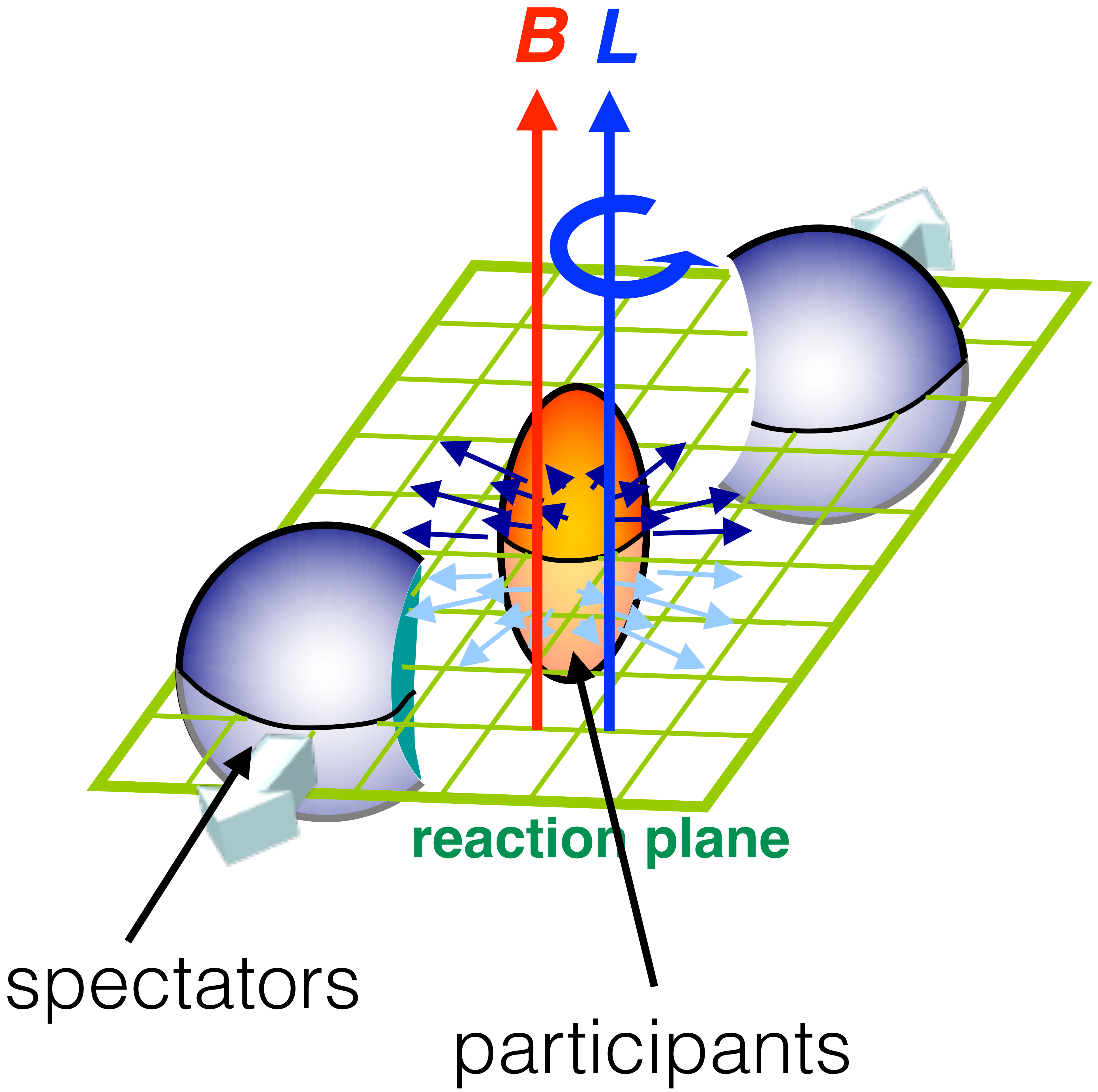


Relativistic heavy-ion collisions at RHIC and the LHC

- Understand properties of quark-gluon plasma
- Explore the QCD phase structure: signatures of QCD critical point and 1st-order phase transition
- Connection to neutron star physics in the high baryon density

Orbital angular momentum / Strong magnetic field

In the initial state of non-central HIC:



Large 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)

typical magnet

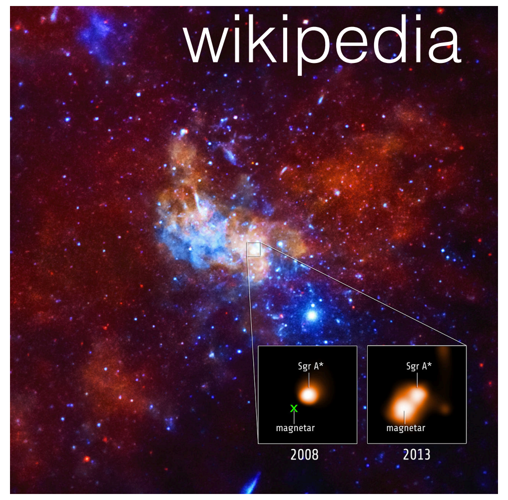
$B \sim 0.1 - 0.5$ T

Strong magnetic field

$$B \sim m_\pi^2/e$$

$$\sim 10^{14}\ \mathrm{T}$$

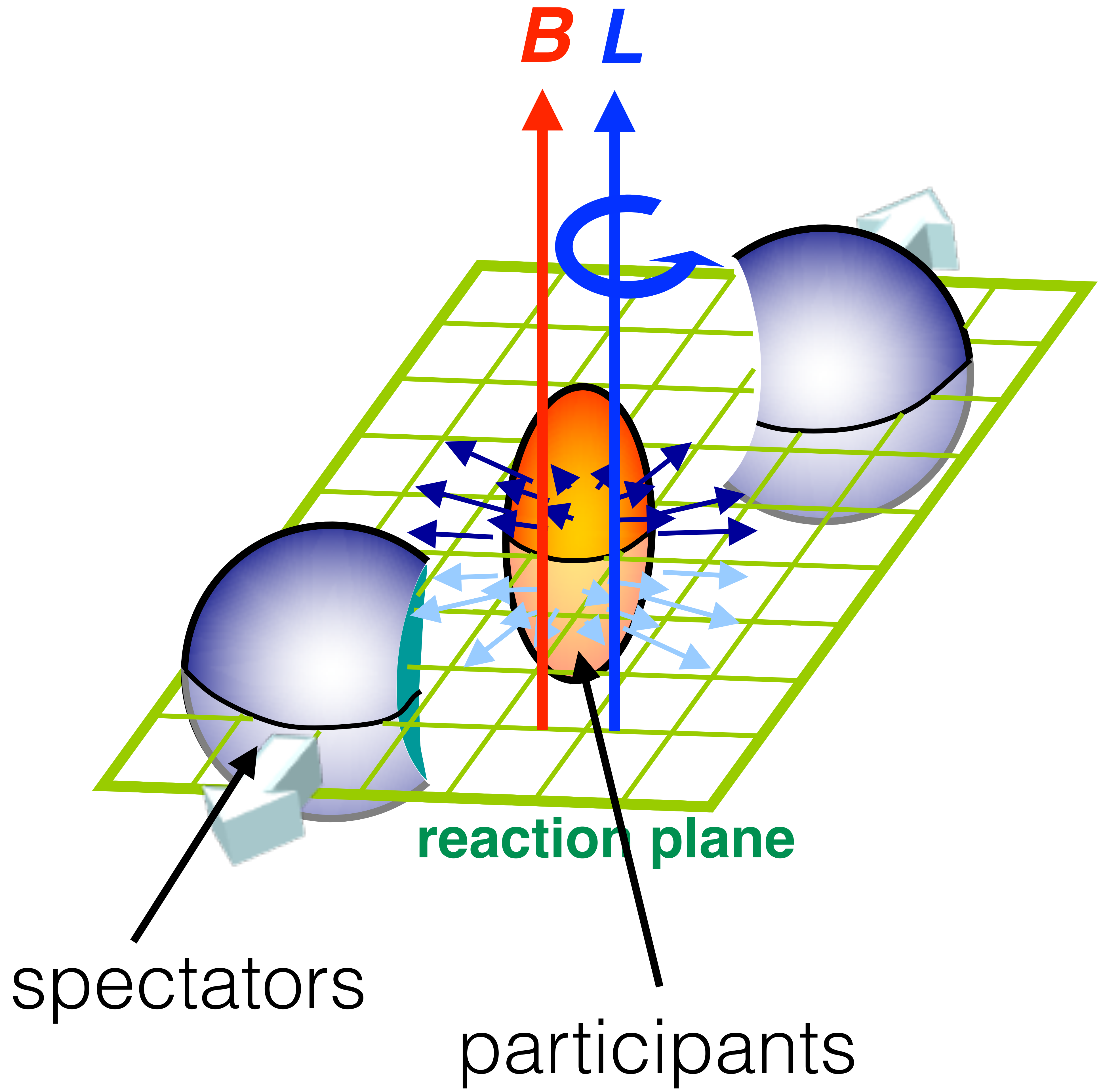
D. Kharzeev et al., Nucl.Phys.A803, 227 (2008)
L. McLerran and V. Skokov, Nucl. Phys. A929, 184 (2014)



magnetar

$B \sim 10^{11}$ T

Orbital angular momentum / Strong magnetic field



Rotating system under strong B-field produces:

- Particles “globally" polarized along ***L or B*** via spin-orbit/spin-magnetic coupling

Z.-T. Liang and X.-N. Wang, PRL94, 102301 (2005)
S. Voloshin, nucl-th/0410089 (2004)
F. Becattini, F. Piccinini, and J. Rizzo, PRC77, 024906 (2008)

- In case of the magnetic coupling, particles and antiparticles are oppositely aligned along ***B***

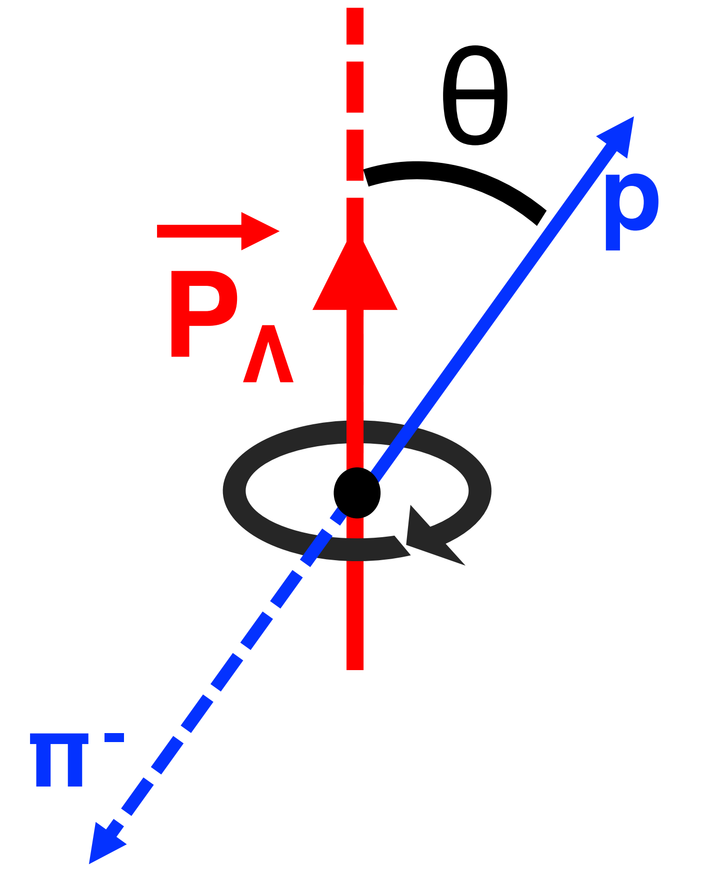
Relativistic version of “Barnett effect”

S. Barnett, Phys. Rev. 6, 239 (1915)
i.e. magnetization of spinning matter (ferromagnet)

Polarization measurement

Parity-violating weak decay of hyperons

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



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

(BR: 63.9%, cτ ~7.9 cm)

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

$\mathbf{P}_H$: hyperon polarization

$\hat{\mathbf{p}}_B$: unit vector of daughter baryon momentum

α_H : hyperon decay parameter

Asterisk* denotes "in hyperon rest frame"

$$\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.732 \pm 0.014$$
$$\alpha_{\Xi^-} = -0.401 \pm 0.010$$
$$\alpha_{\Omega^-} = -0.0157 \pm 0.0021$$

P.A. Zyla et al., PDG2021

Any hyperons can be used but the sensitivity is different, depending on α_H.

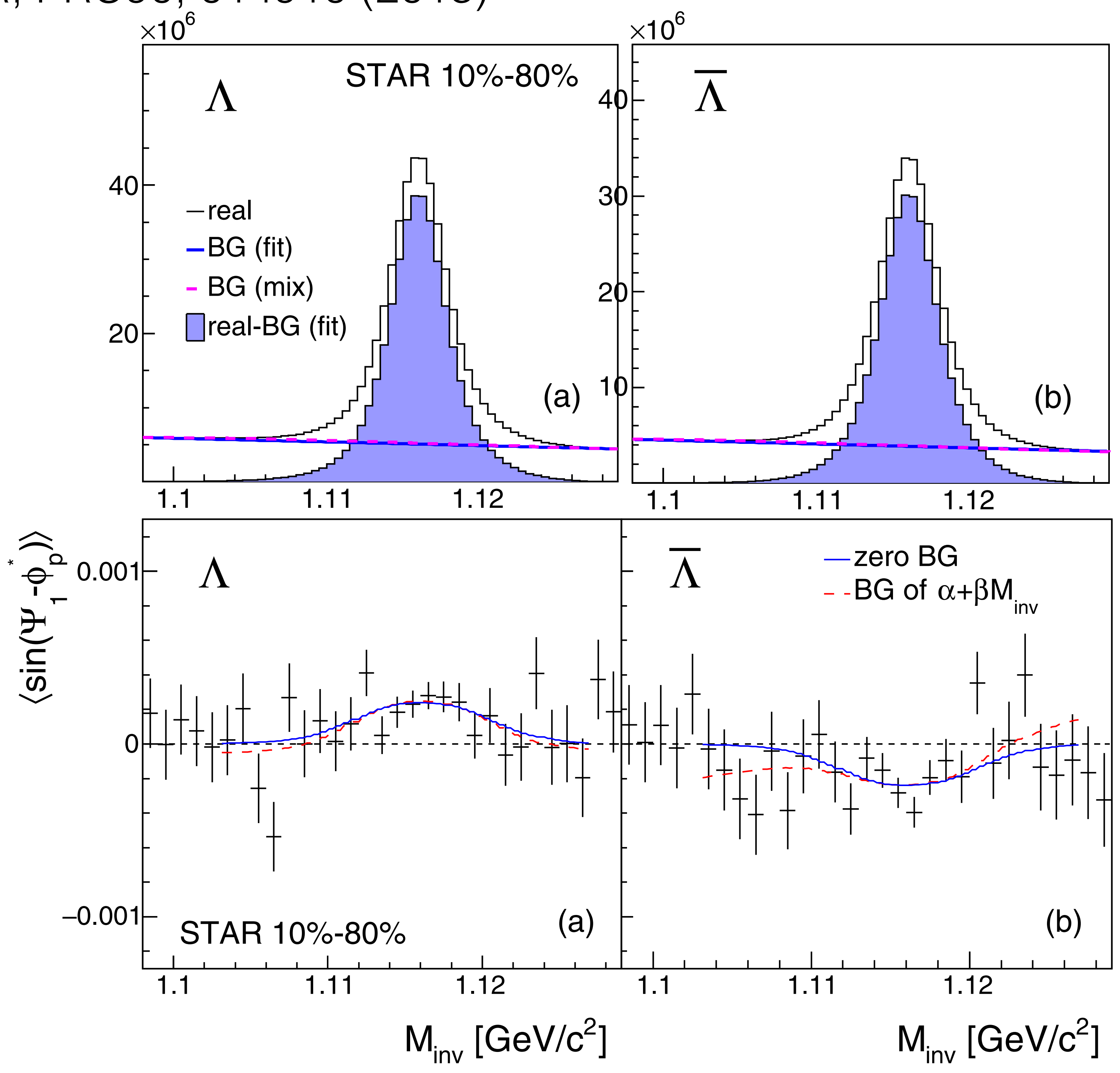
Global polarization measurement

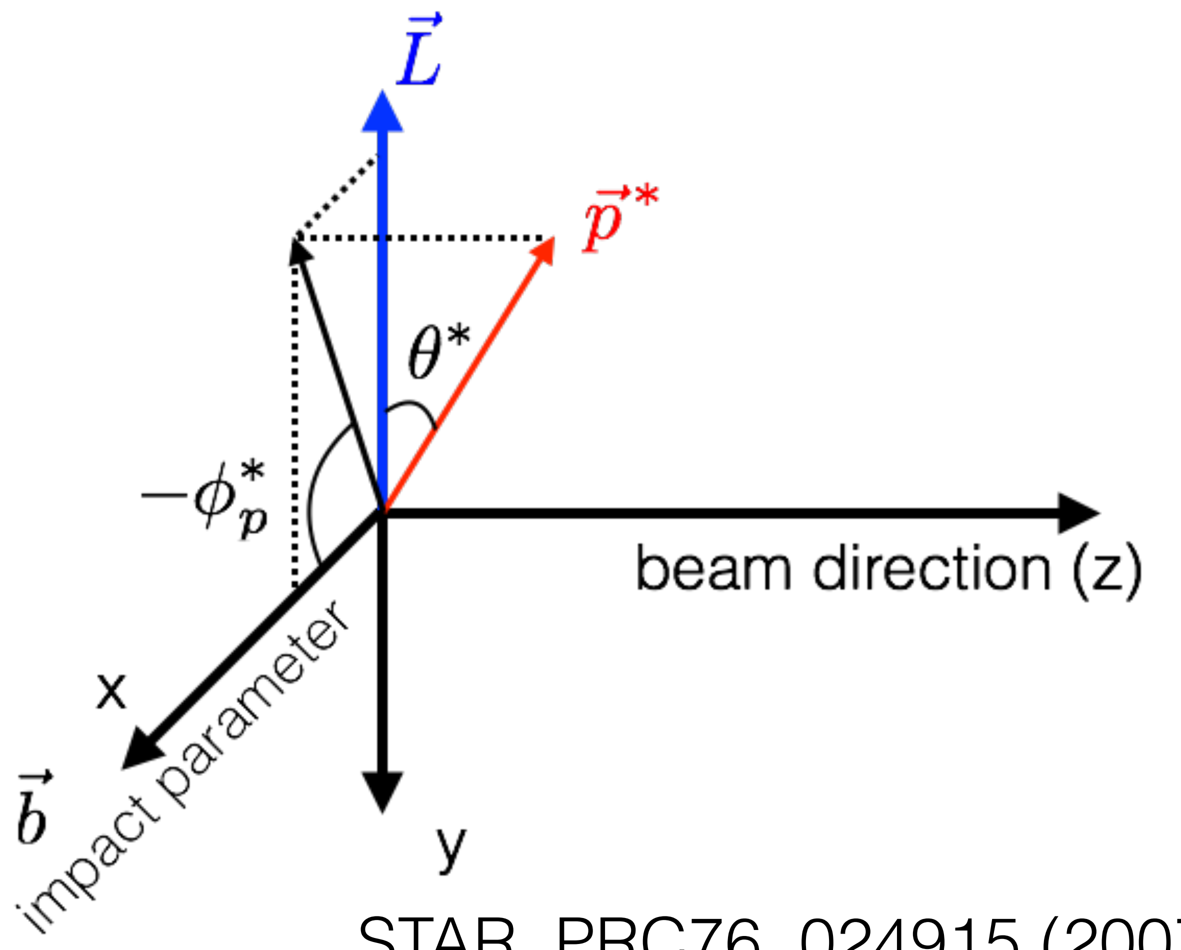
Projection onto the transverse plane

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

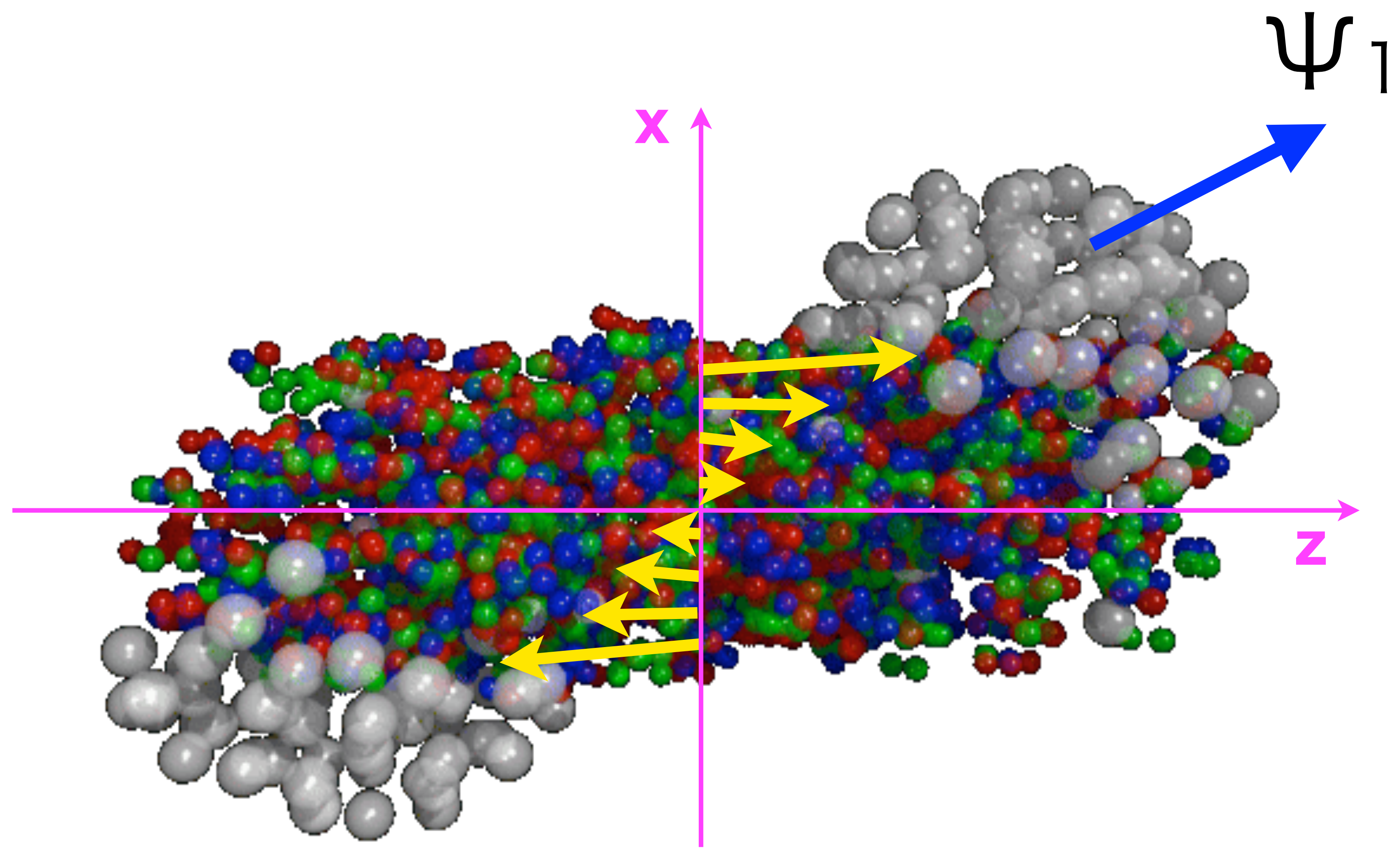
Ψ_1: azimuthal angle of impact parameter

STAR, PRC90, 014910 (2018)





STAR, PRC76, 024915 (2007)



- Impact parameter direction determined by spectator deflection

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

- Feed-down effect: 10-15% dilution of primary Λ P_{H}

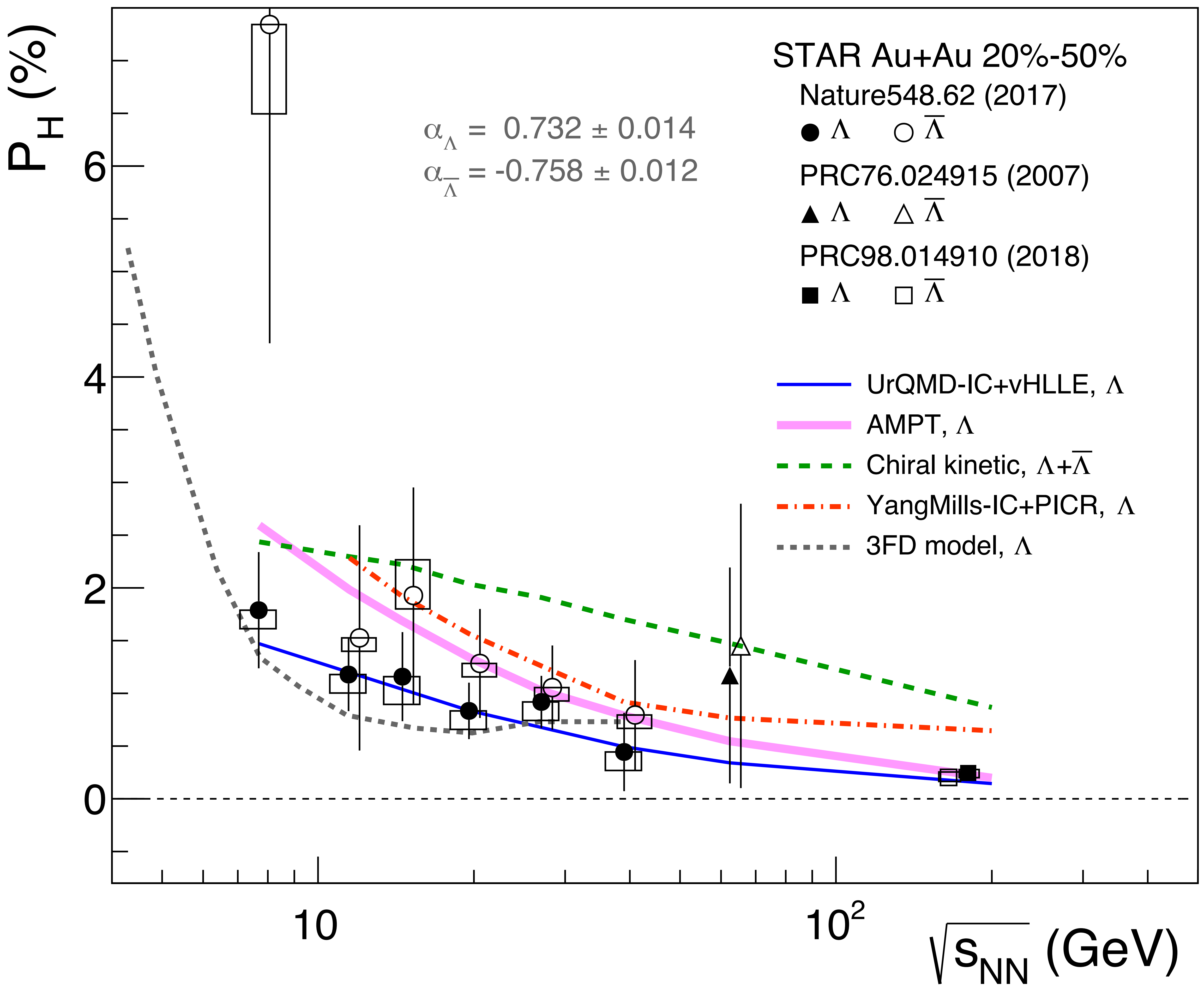
  F. Becattini et al., PRC95.054902 (2017)

- COM vs. rest frames, ~3%(10%) reduction at low(higher) p_{T}

  W. Florkowski and R. Ryblewski, PRC106, 024905 (2022)

Observation of Λ global polarization

STAR, Nature 548, 62 (2017)
STAR, PRC90, 014910 (2018)



- Increasing trend toward lower energies, described well by various theoretical models

  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
  Y. B. Ivanov et al., PRC100, 014908 (2019), 3FD model

- Indication of thermal vorticity

$$P_{\Lambda(\bar{\Lambda})} \simeq \frac{1}{2}\frac{\omega}{T} \pm \frac{\mu_\Lambda B}{T}$$

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

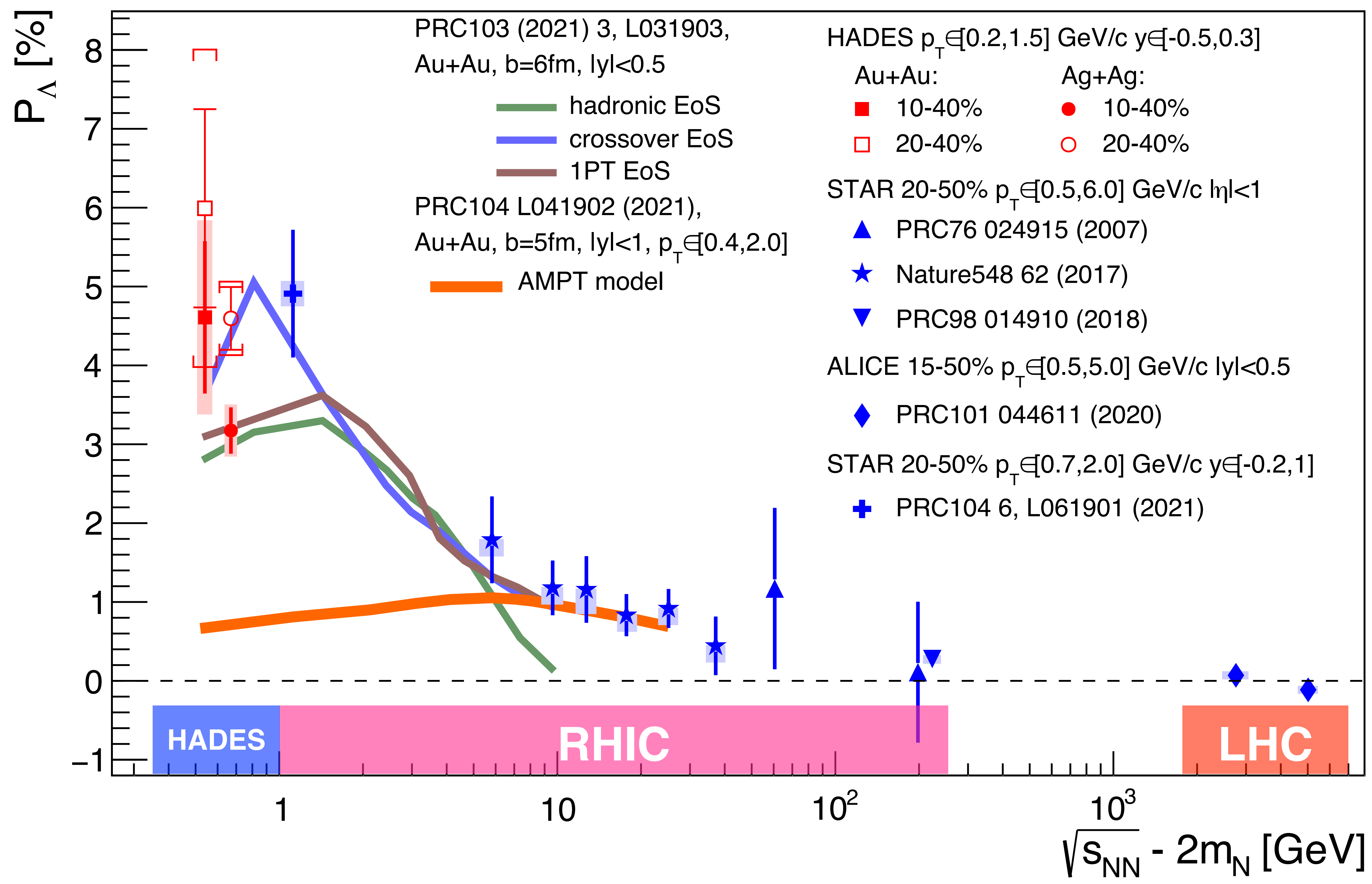
$$\omega = (P_\Lambda + P_{\bar{\Lambda}})k_B T/\hbar \sim 10^{22}\,\mathrm{s}^{-1}$$

μ_Λ: Λ magnetic moment
T: temperature at thermal equilibrium

- Possible difference between Λ and anti-Λ

Λ global polarization at lower energies

STAR, PRC104, L061901 (2021)
HADES, PLB835(2022)137506



- New data from STAR/HADES at lower energies
- Continuous increase down to $\sqrt{s_{NN}}$~2.5 GeV

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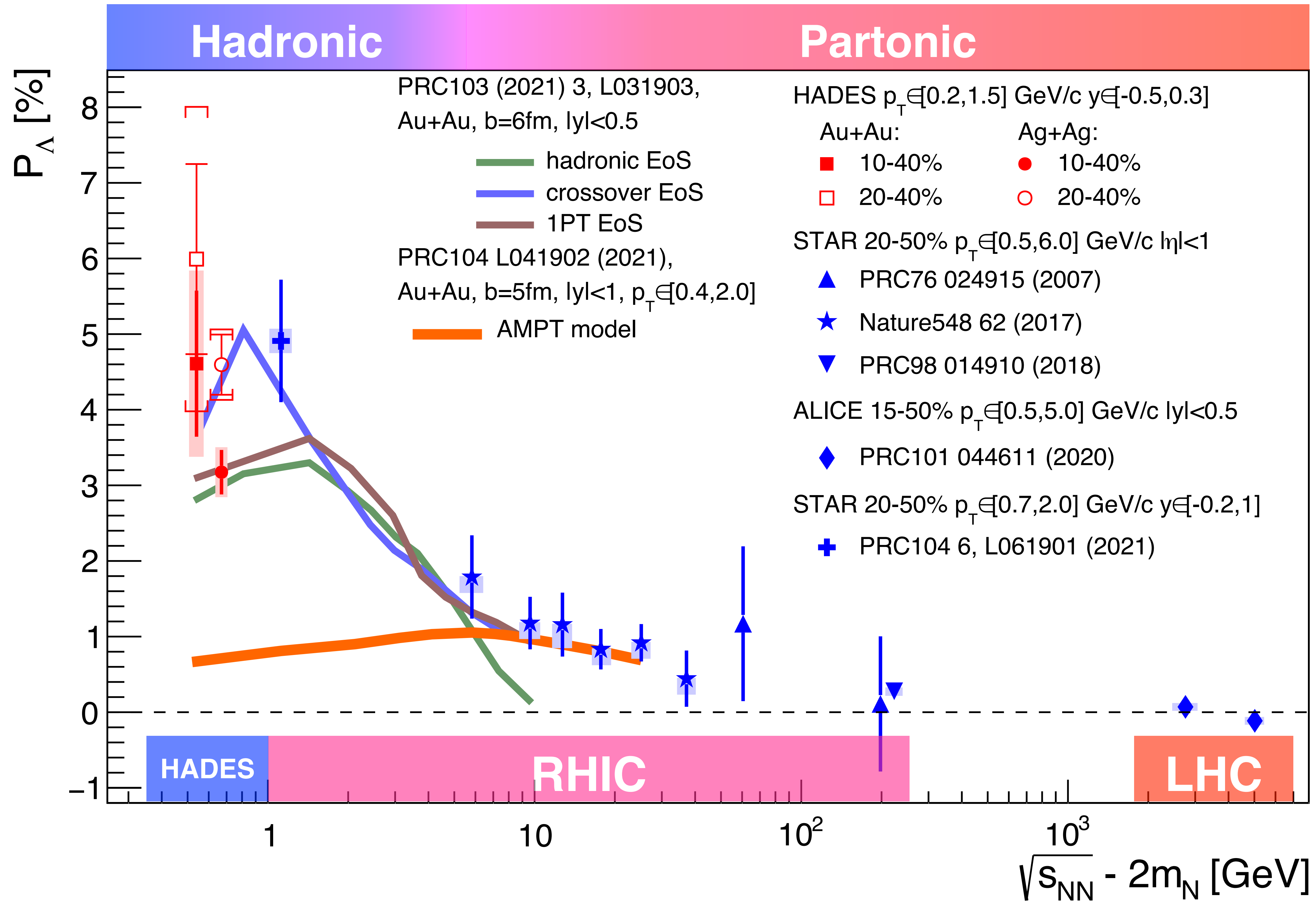
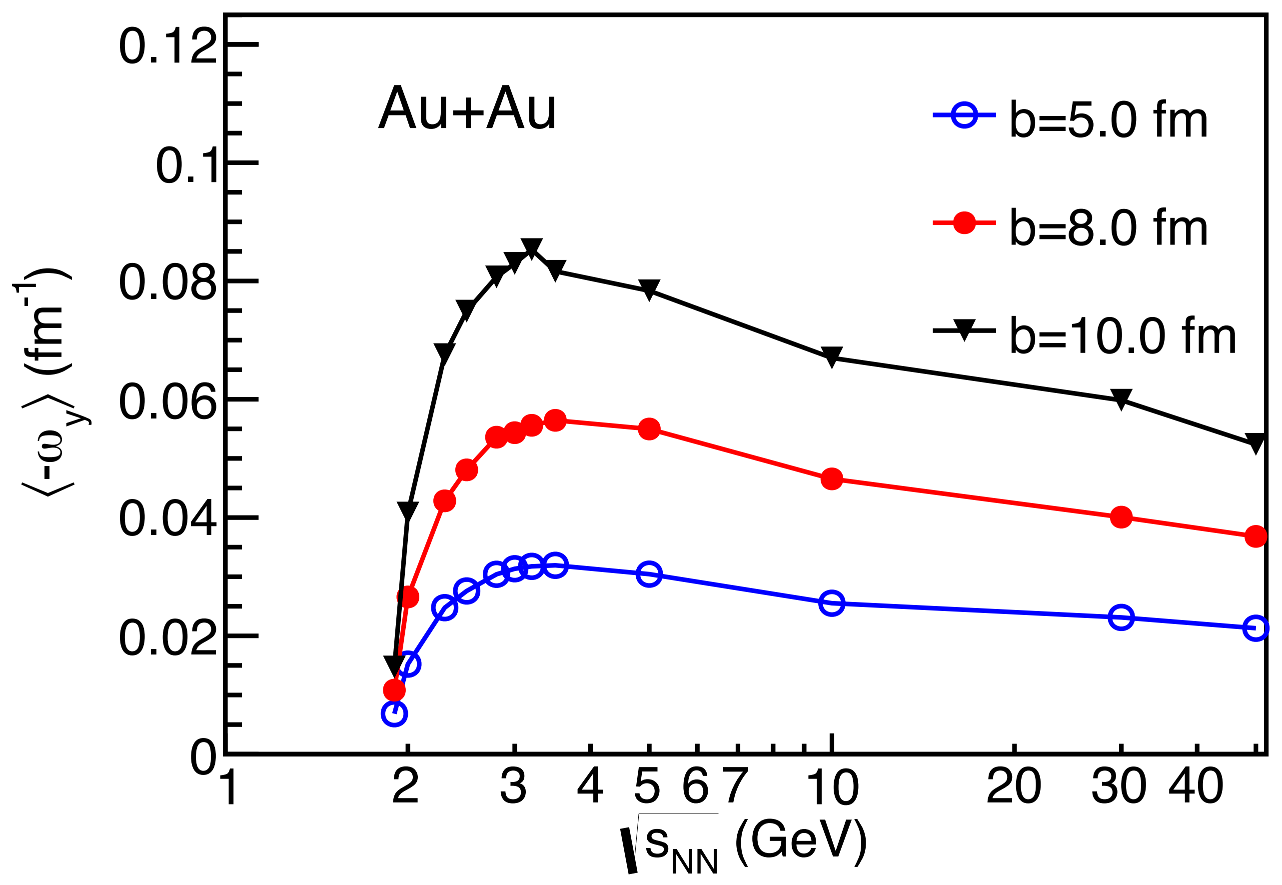
STAR, PRC104, L061901 (2021)
HADES, PLB835(2022)137506

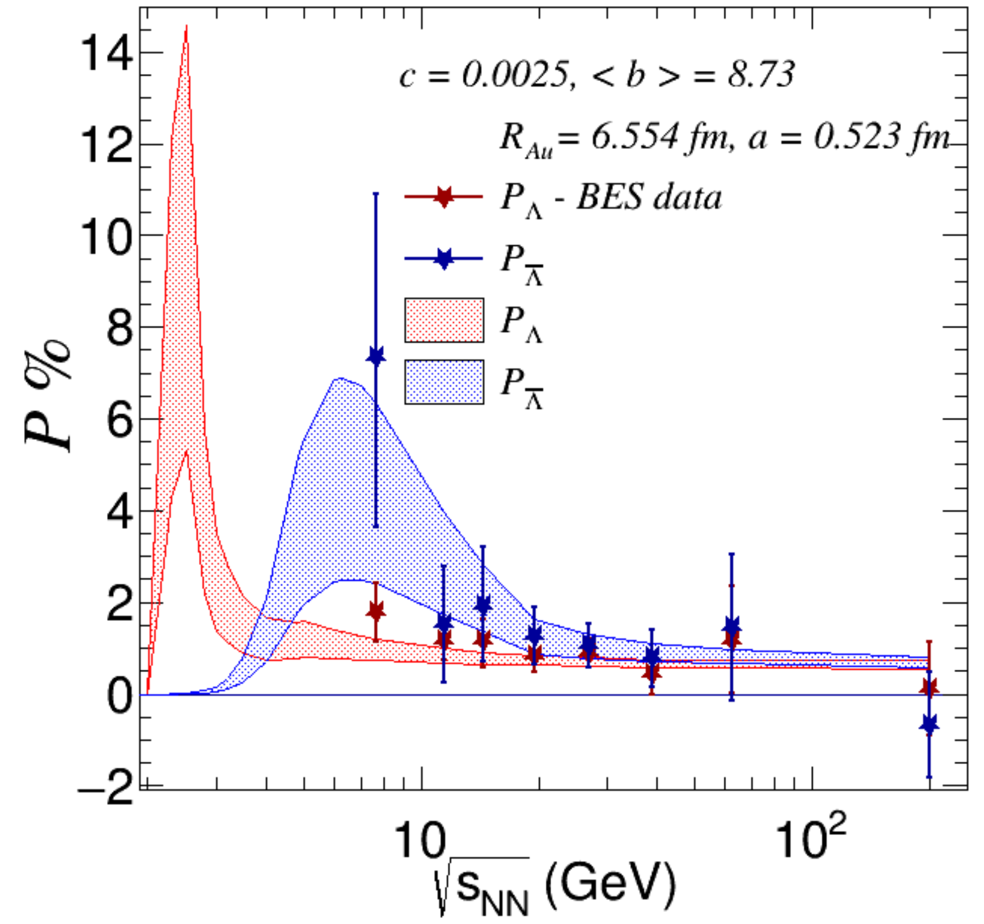


- New data from STAR/HADES at lower energies
- Continuous increase down to $\sqrt{s_{NN}}$~2.5 GeV
    - Predicted to have the maximum around $\sqrt{s_{NN}}$ = 3 GeV
        - Initial L & "stopping" to "transparency" at midrapidity

X.-G. Deng et al., PRC101.064908 (2020)

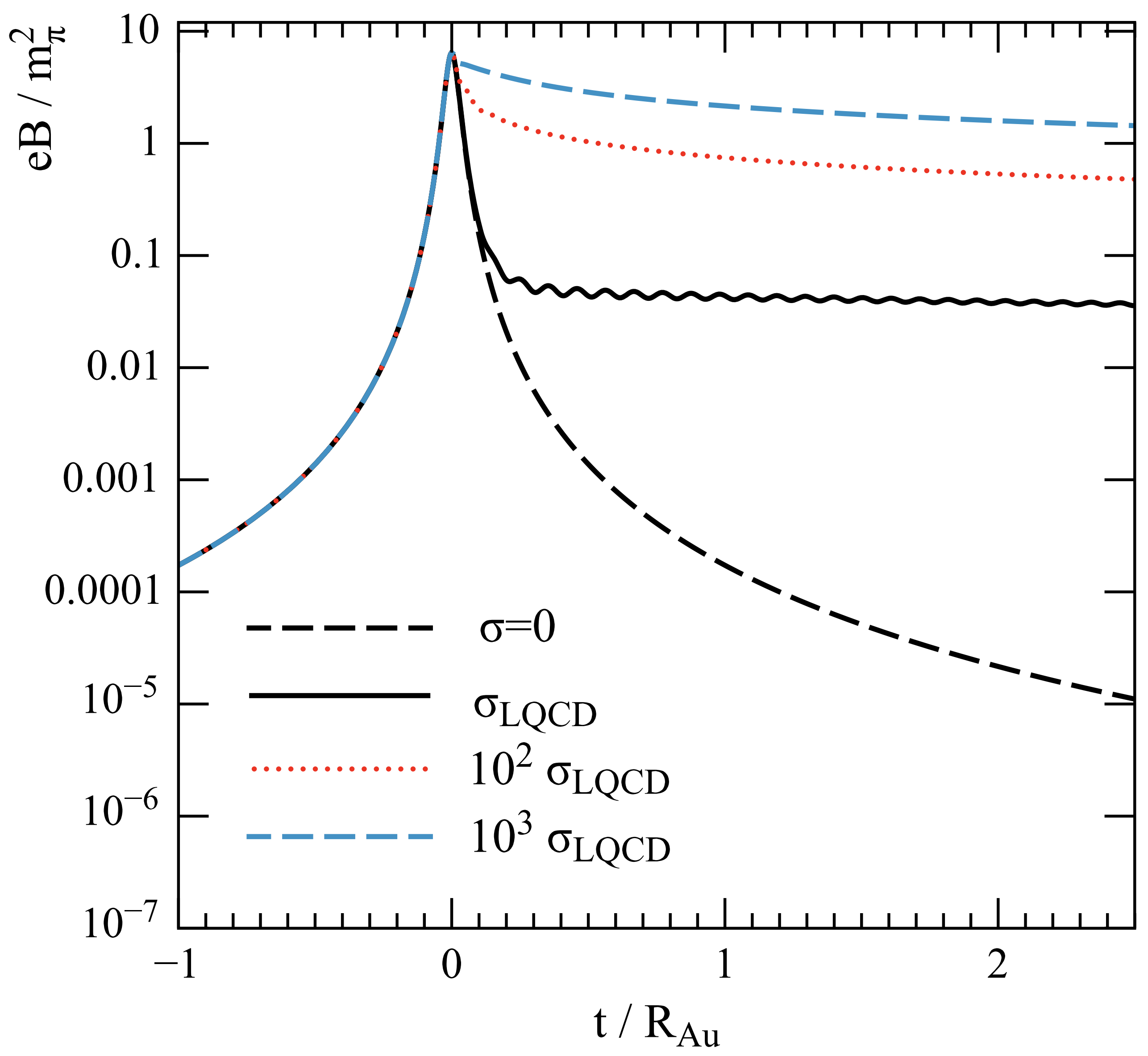


A. Ayala et al., PRC105.034907 (2022)



Λ-$\bar{\Lambda}$ difference?

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



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

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

μ_Λ: Λ magnetic moment

- Lifetime of B-field would be very short (<0.5 fm/c) but could be sustained by QGP depending on its electric conductivity
- Polarization splitting provides an upper limit of the late-stage B-field

F. Becattini et al., PRC95.054902 (2017)
B. Müller and A. Schäfer, PRD98, 071902(R) (2018)
Y. Guo et al., PLB798(2019)134929

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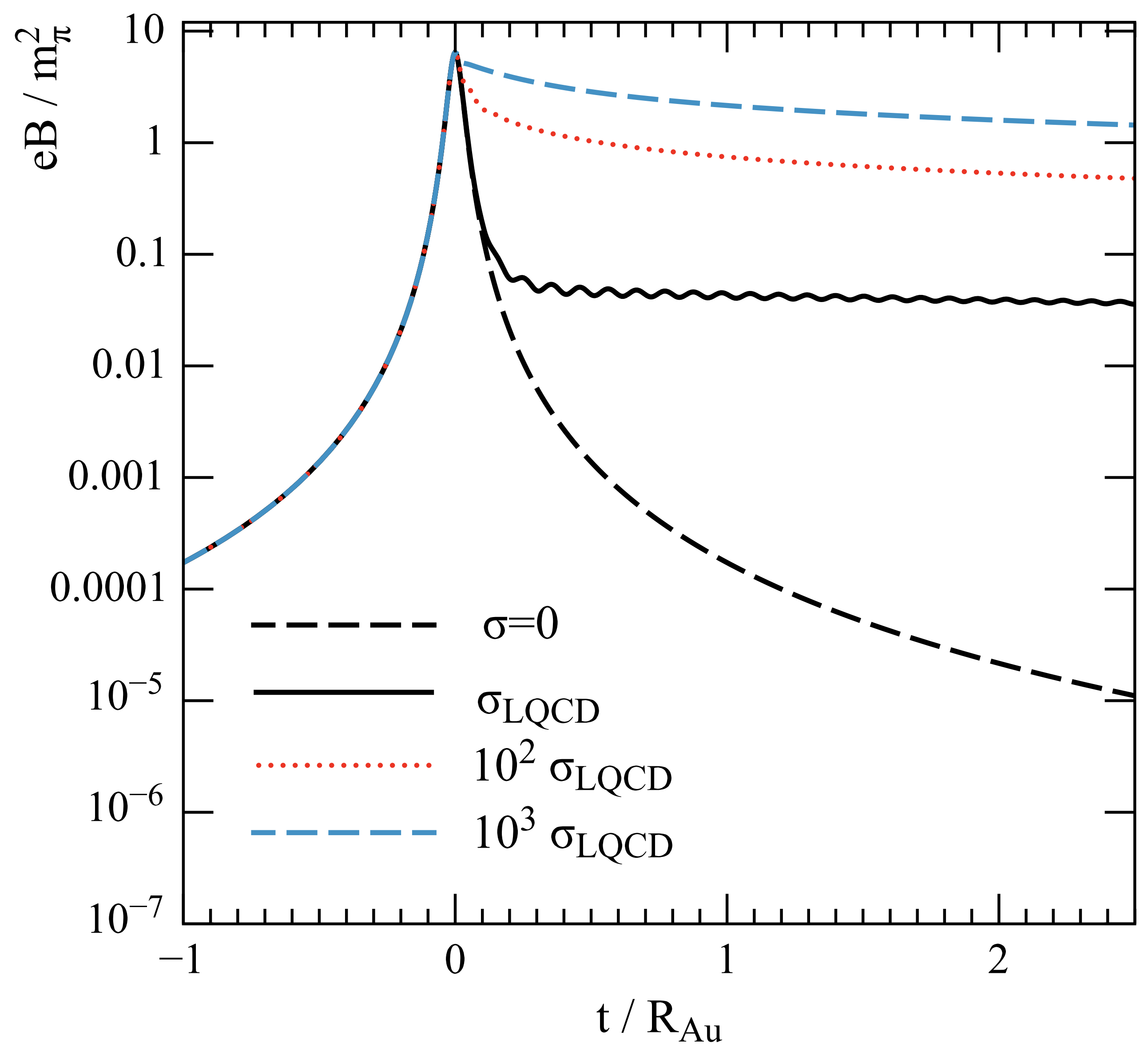

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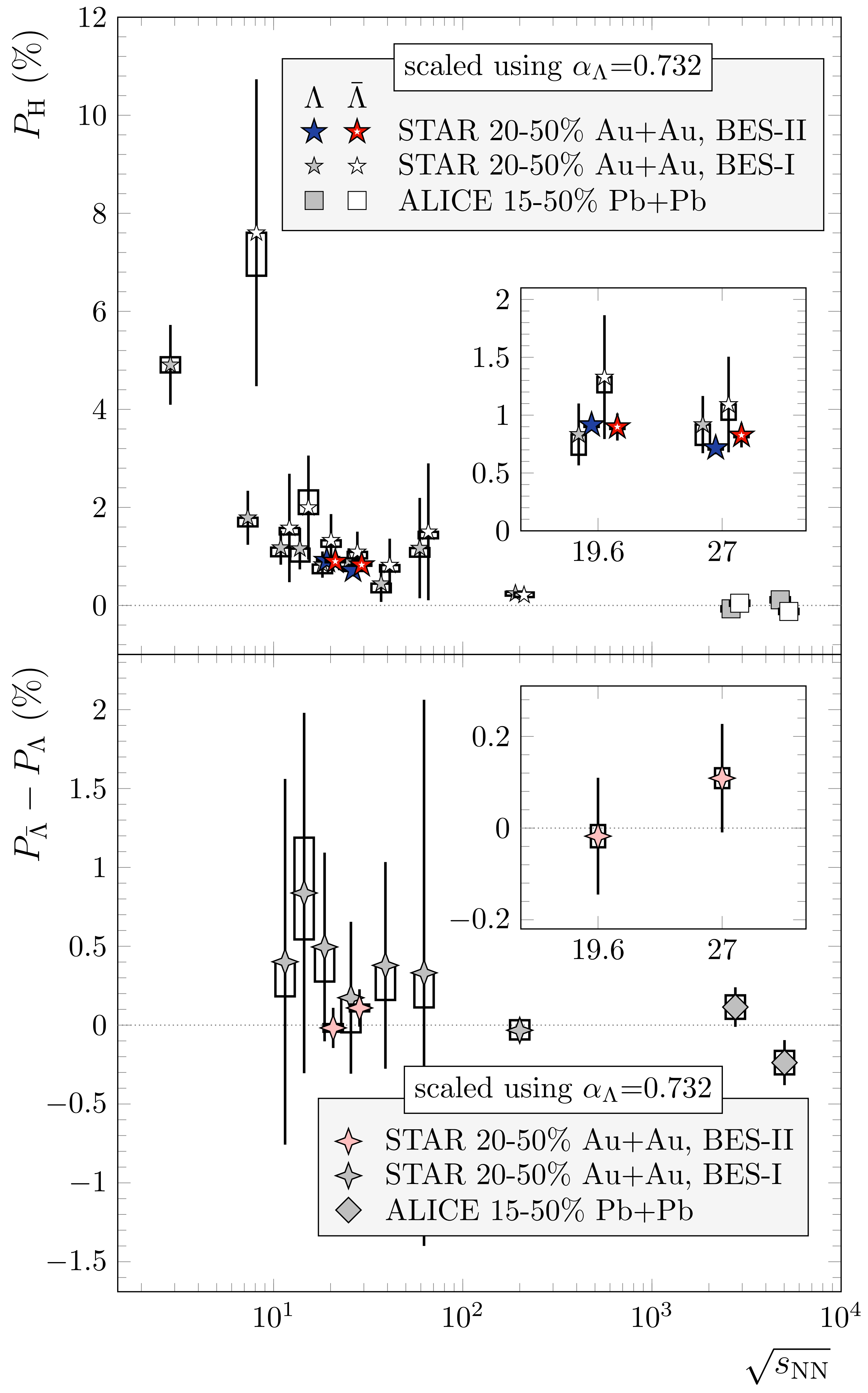
STAR, PRC108, 014910 (2023)



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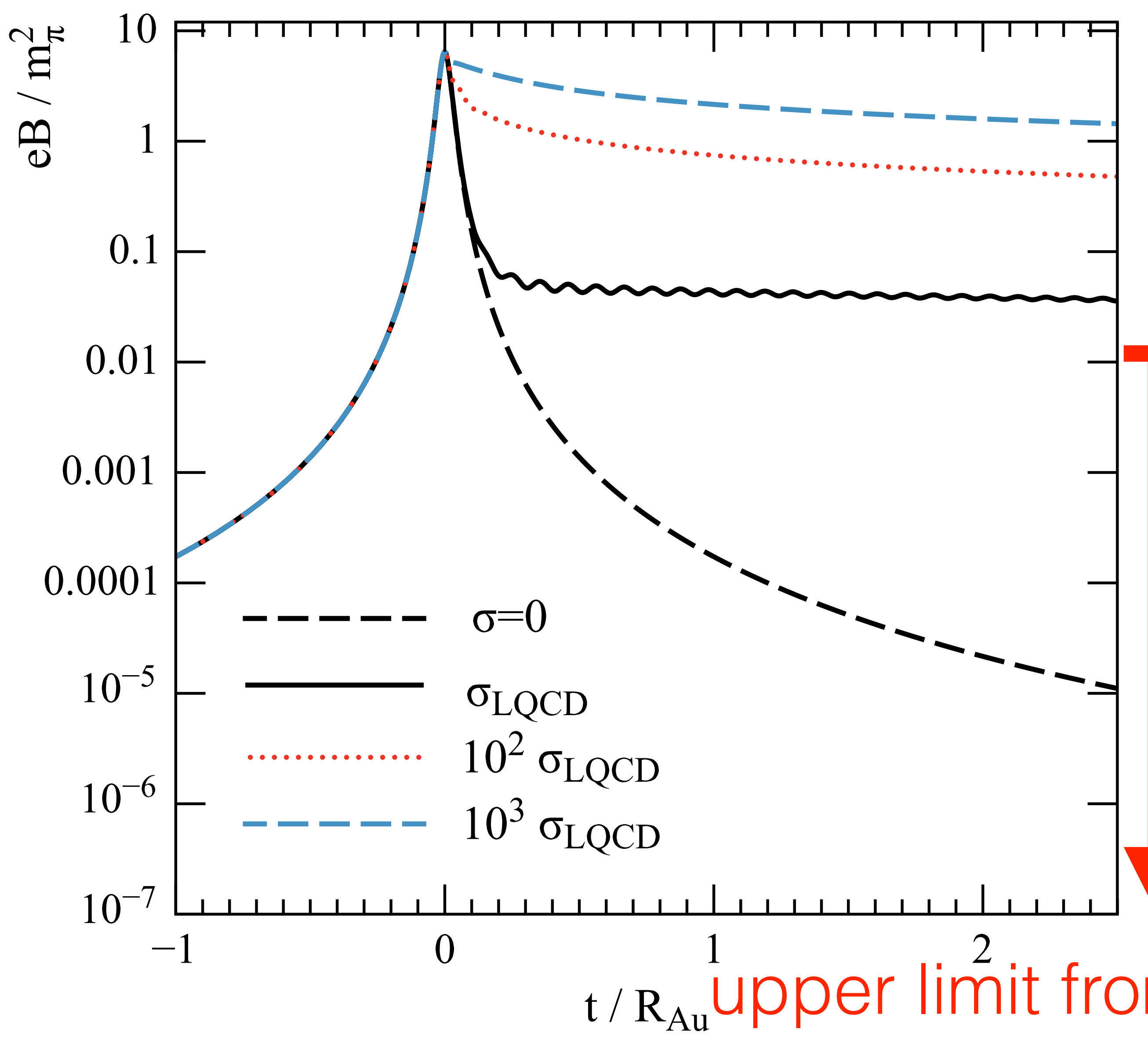


upper limit from ΔP_H

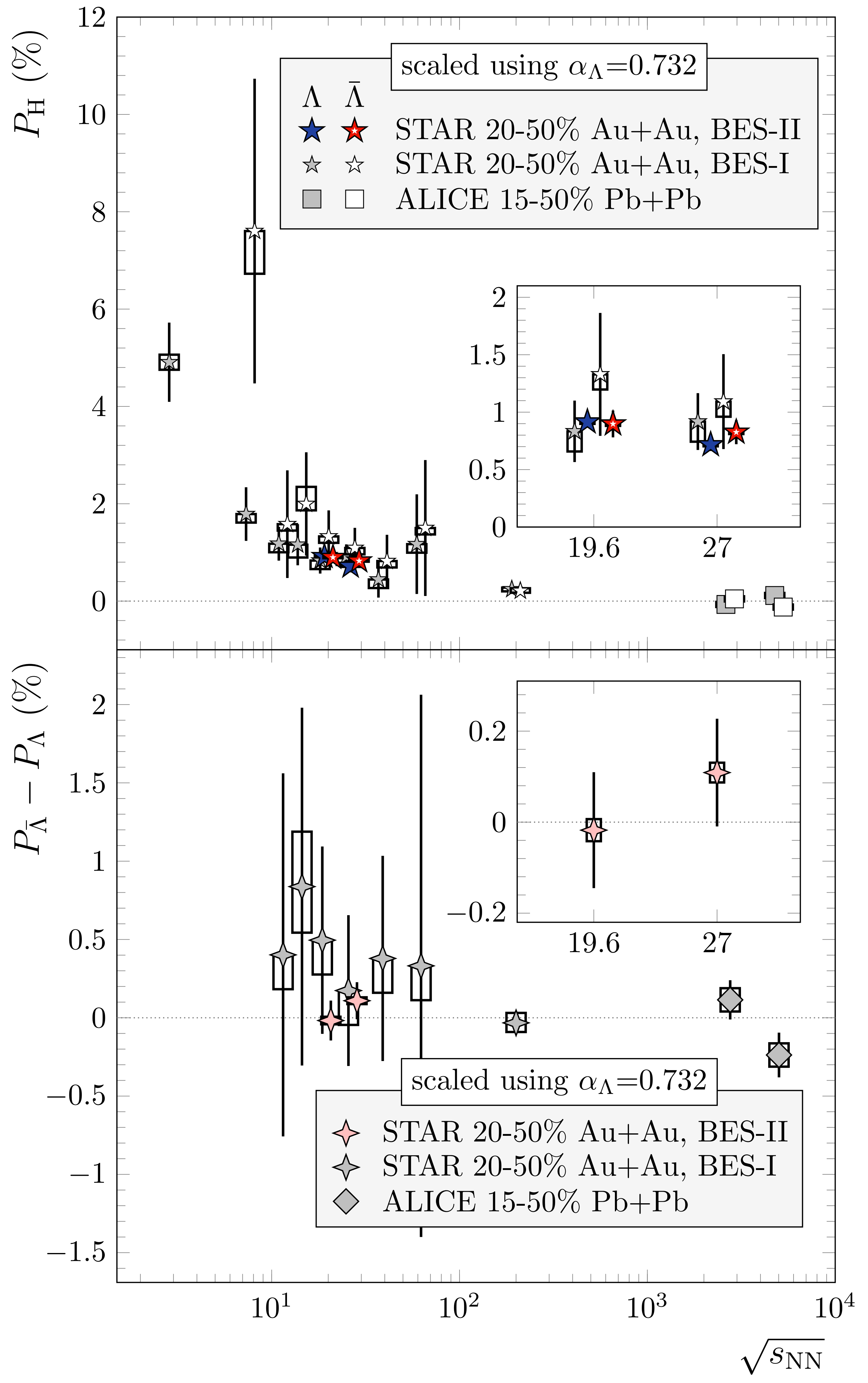
$$P_\Lambda \simeq \frac{1}{2}\frac{\omega}{T} + \frac{\mu_\Lambda B}{T}$$

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

μ_Λ: Λ magnetic moment

$$B = (P_\Lambda - P_{\bar{\Lambda}})T/(2\mu_\Lambda)$$
$$\sim 1.2 \times 10^{13}[\mathrm{T}]$$
$$eB \sim 10^{-2} m_\pi^2$$

for ΔP_Λ~0.3%, T=150 MeV



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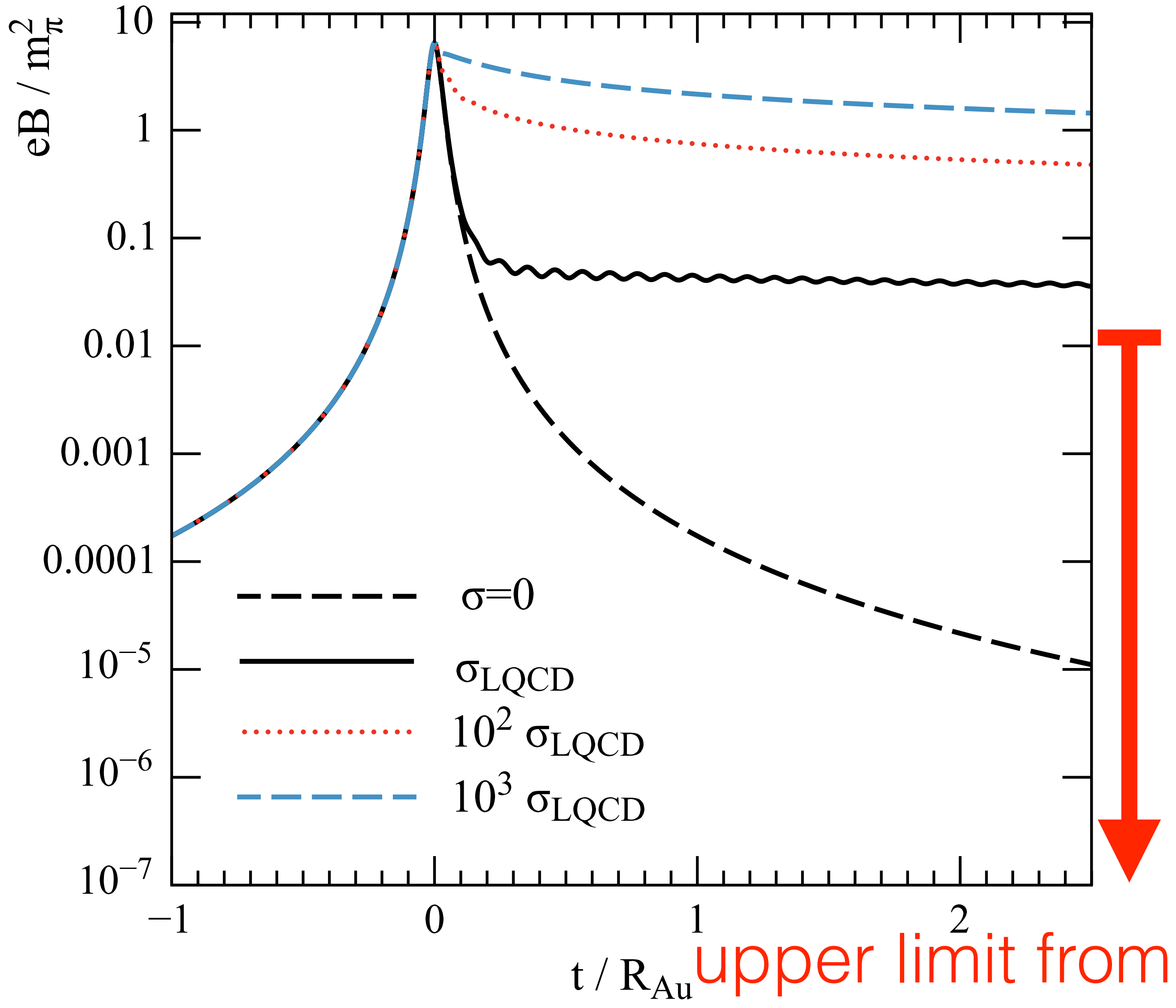
F. Becattini et al., PRC95.054902 (2017)
B. Müller and A. Schäfer, PRD98, 071902(R) (2018)
Y. Guo et al., PLB798(2019)134929

No significant difference in new STAR BES-II results.
An upper limit of the late-stage B-field is B$\lesssim 10^{13}$ T

Λ-$\bar{\Lambda}$ difference?

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



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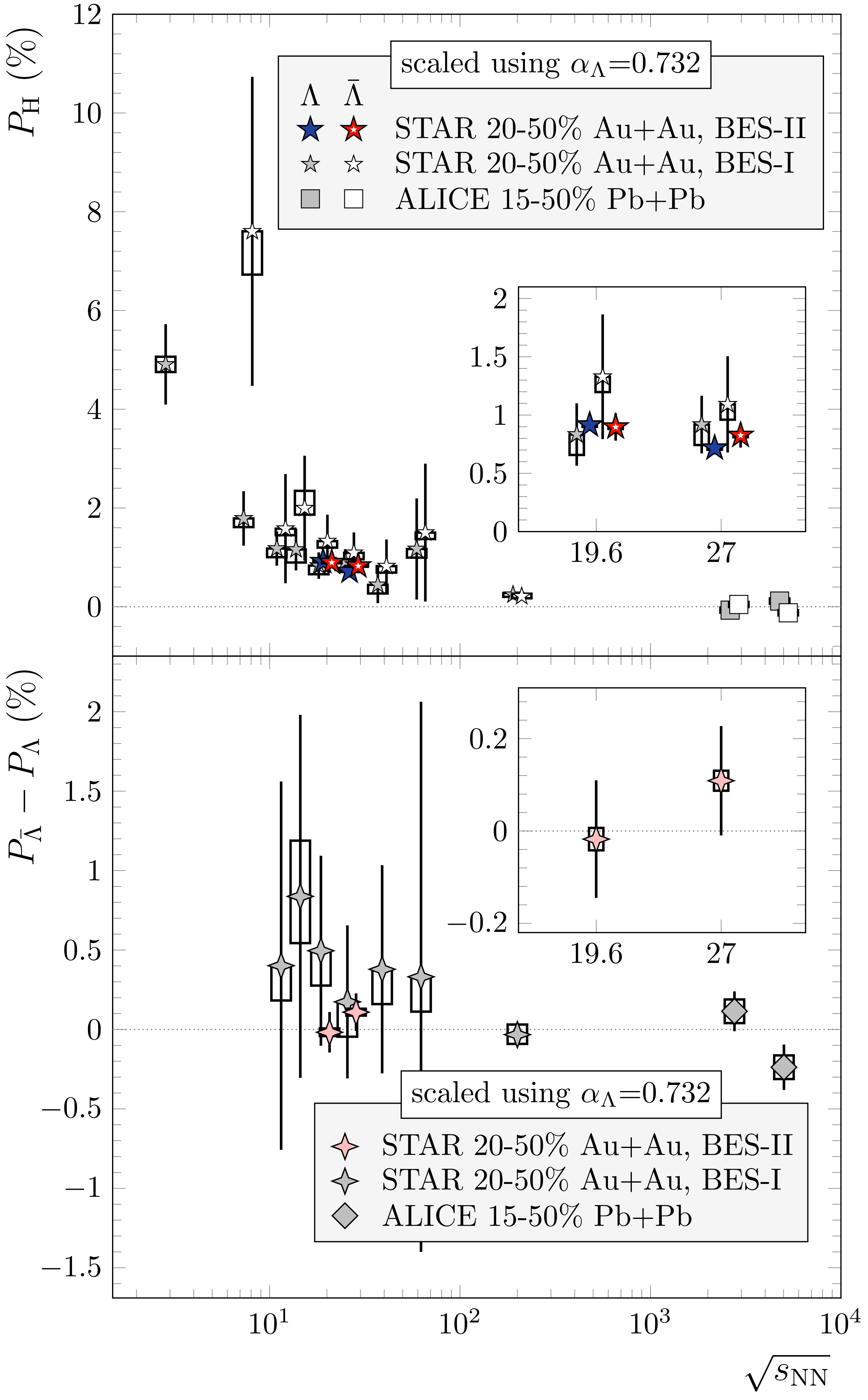
STAR, PRC108, 014910 (2023)



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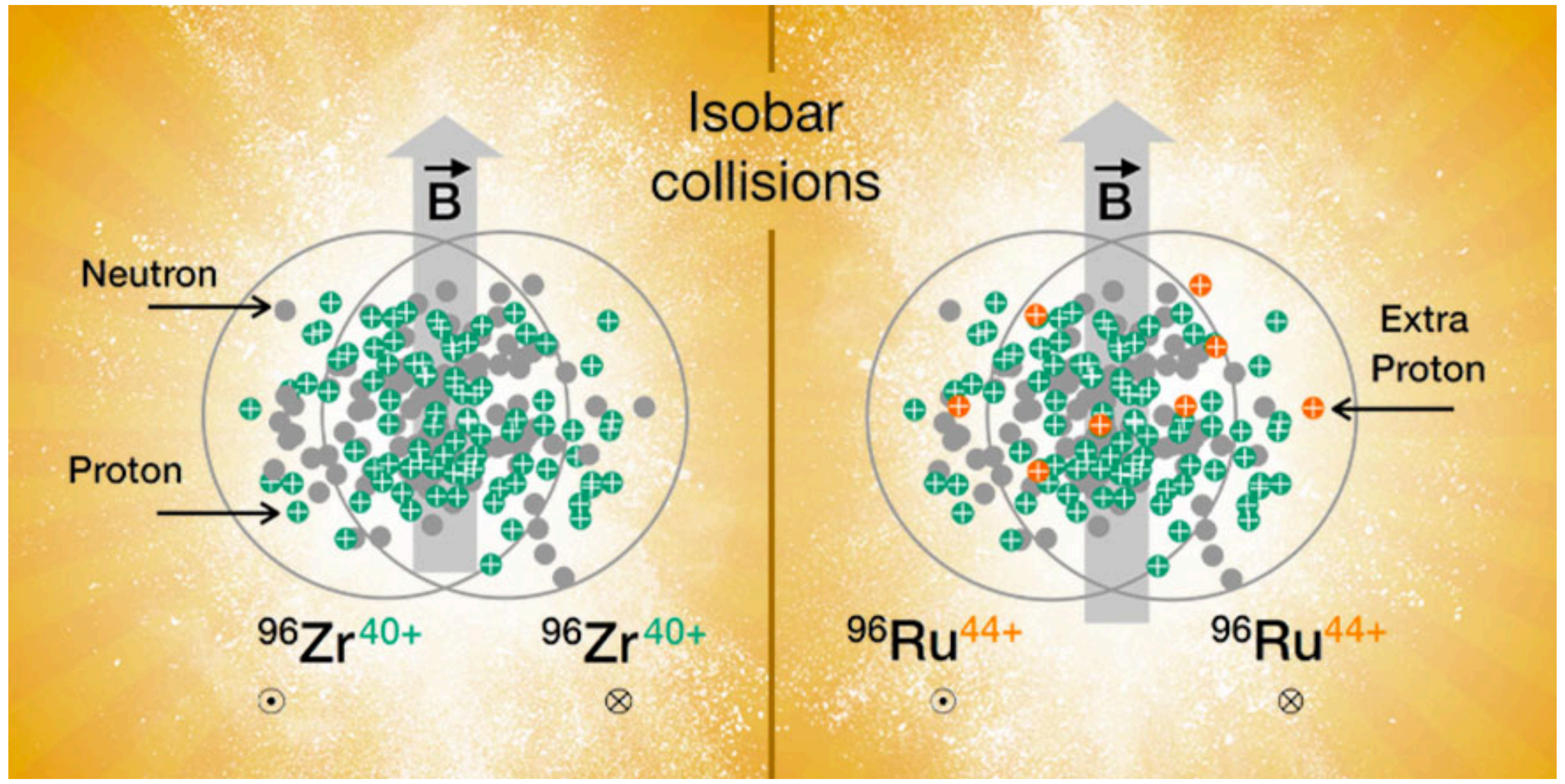
- Polarizati

F. Becatti
B. Müller
Y. Guo et

Caveat: There are other mechanisms to create the polarization difference…
- different emission time/position of Λ and Λbar Vitiuk et al., PLB803(2020)135298
- spin interaction with meson field Csernai et al., PRC99.021901(R) (2019)
- chemical potential Fang et al.,, PRC94, 024904 (2016) …etc

ference in new STAR BES-II results.
the late-stage B-field is B≲10^{13} T

Global polarization in isobar collisions



- Smaller system, larger polarization?

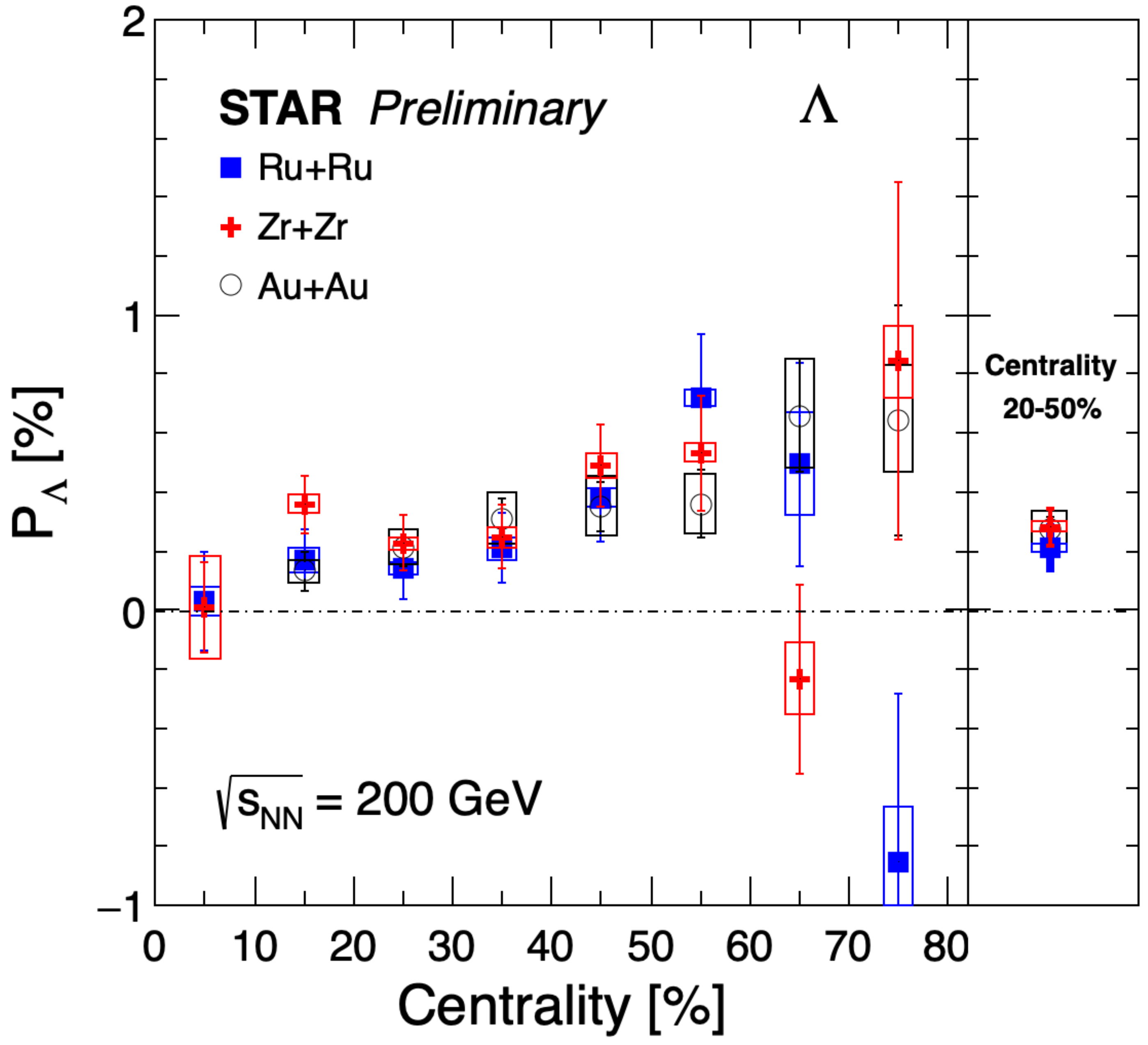
$$P_\Lambda^{\rm Au} < P_\Lambda^{\rm Ru} \approx P_\Lambda^{\rm Zr} < P_\Lambda^{\rm Cu} < P_\Lambda^{\rm O} \ ?$$

S. Shi et al., PLB788(2019)409
S. Alzhrani et al., PRC106, 014905 (2022)

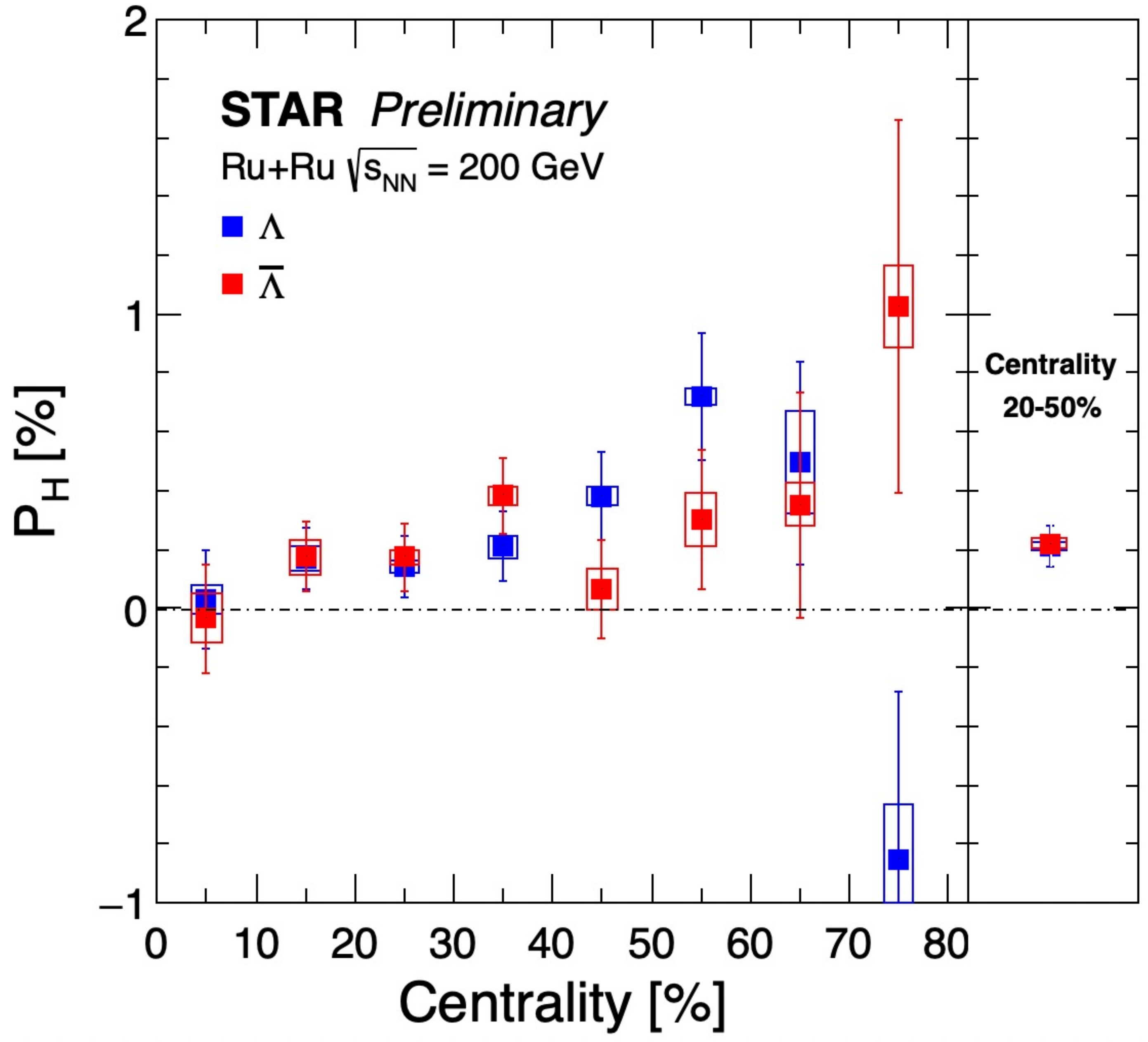
- Larger B-field, larger polarization splitting?

$$\frac{|B^{\rm Ru}|^2}{|B^{\rm Zr}|^2} \approx 15\%$$

Isobar vs. Au+Au for Λ



Λ vs. anti-Λ in Ru+Ru



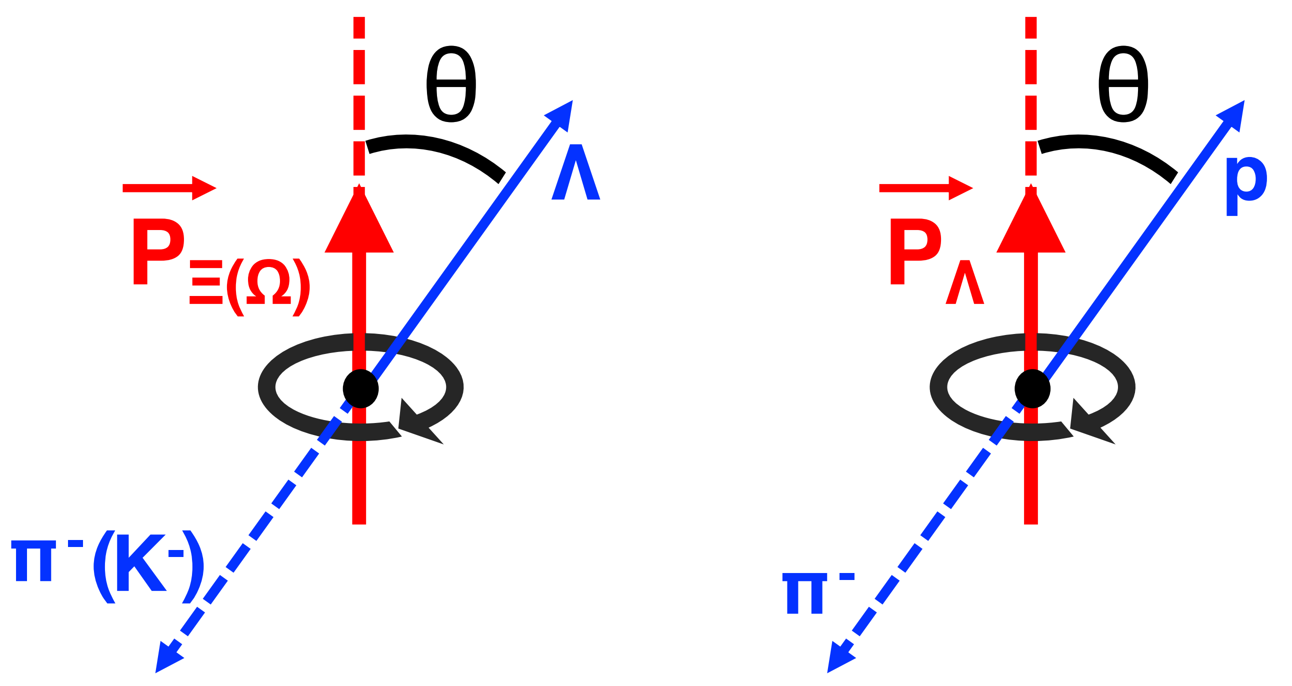
No significant splitting nor system size dependence

See Xingrui Gou's talk

Global polarization of multistrangeness

- Ξ and Ω hyperons
  - ✓ Different spin, decay parameter
  - ✓ Less feed-down
  - ✓ Likely different freeze-out in time
- Challenges: small α_H and low production rate

hyperon	decay mode	α_H	magnetic moment μ_H	spin
Λ (uds)	$\Lambda \to p\pi^-$ (BR: 63.9%)	0.732	-0.613	1/2
Ξ^- (dss)	$\Xi^- \to \Lambda\pi^-$ (BR: 99.9%)	-0.401	-0.6507	1/2
Ω^- (sss)	$\Omega^- \to \Lambda K^-$ (BR: 67.8%)	0.0157	-2.02	3/2



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

- Study Ξ or Ω polarization by measuring daughter Λ polarization

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

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

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

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

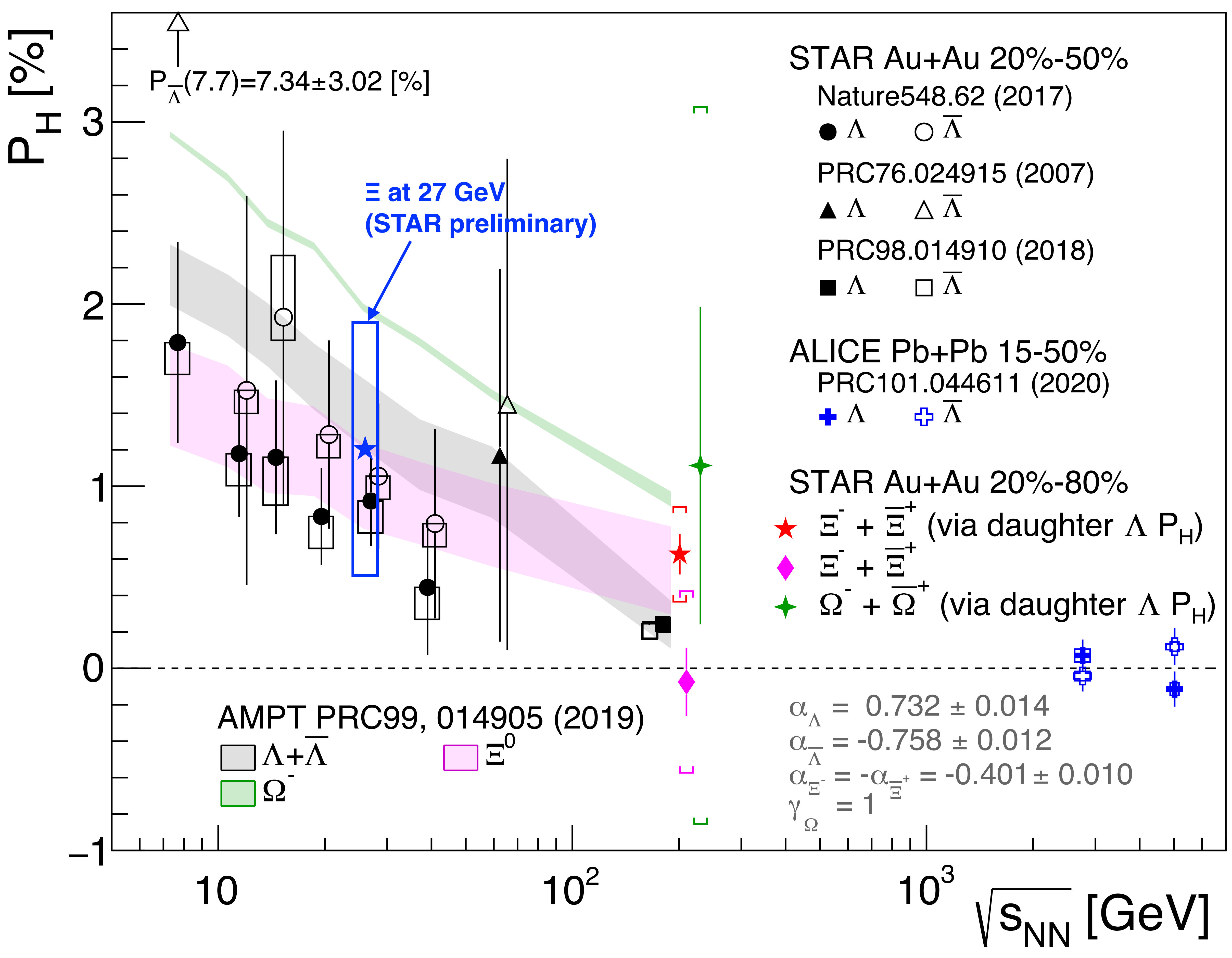
$$\alpha^2 + \beta^2 + \gamma^2 = 1$$

* γ_Ω is unknown $\qquad \alpha_\Omega, \beta_\Omega \ll 1 \to \gamma_\Omega \sim \pm 1$

Polarization transfer factor: $C_{\Omega\Lambda} \approx +1 \text{ or } -0.6$

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

STAR, PRL126, 162301 (2021)



Confirmation of global vorticity picture!

- Hint of hierarchy in P_H but not significant yet

$$\langle P_\Lambda \rangle = 0.24 \pm 0.03 \text{ (stat)} \pm 0.03 \text{ (syst) } \%$$
$$\langle P_\Xi \rangle = 0.47 \pm 0.10 \text{ (stat)} \pm 0.23 \text{ (syst) } \%$$
$$\langle P_\Omega \rangle = 1.11 \pm 0.87 \text{ (stat)} \pm 1.97 \text{ (syst) } \%$$

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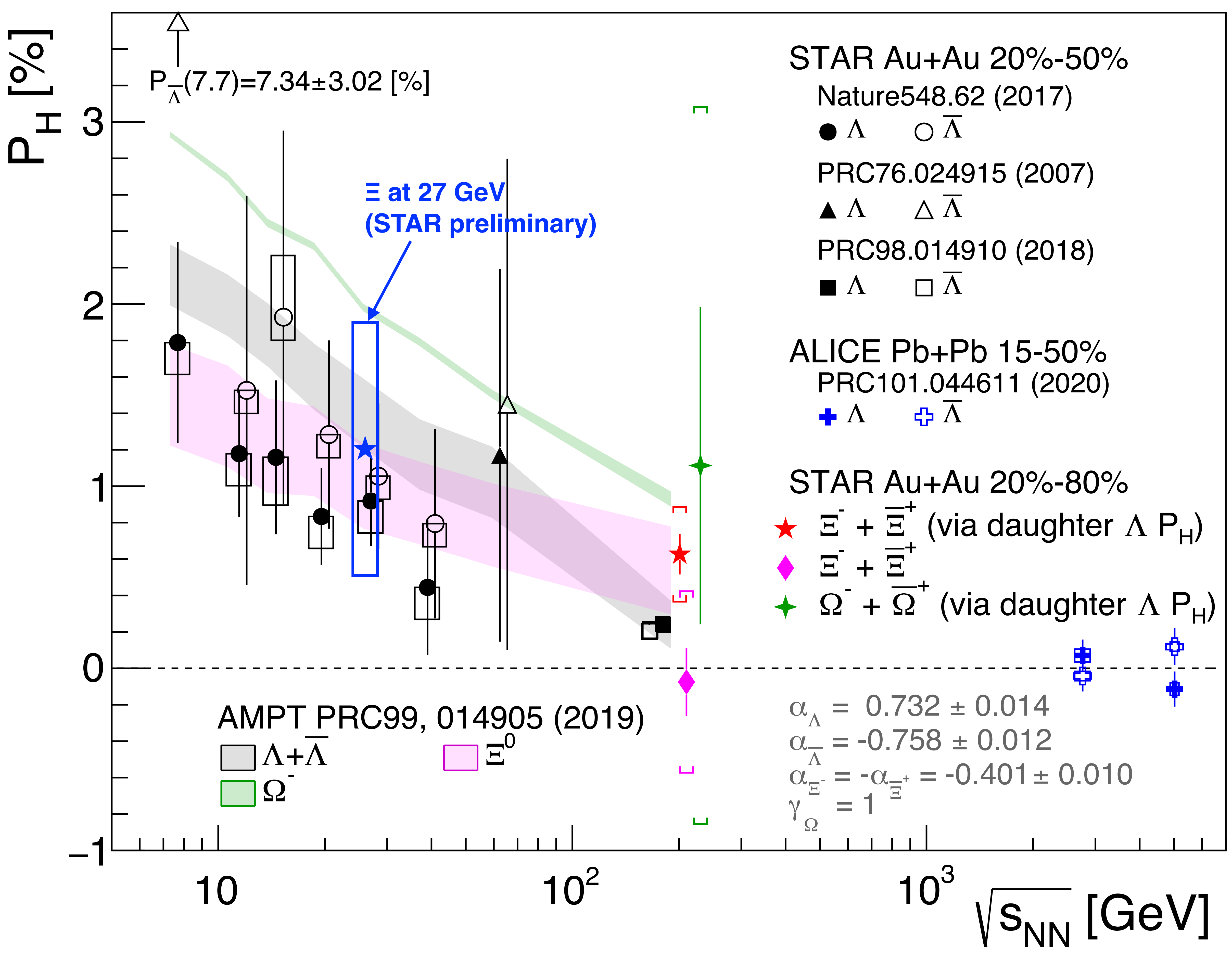

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- Thermal model: $P_\Lambda = P_\Xi = 3/5 * P_\Omega$

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

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

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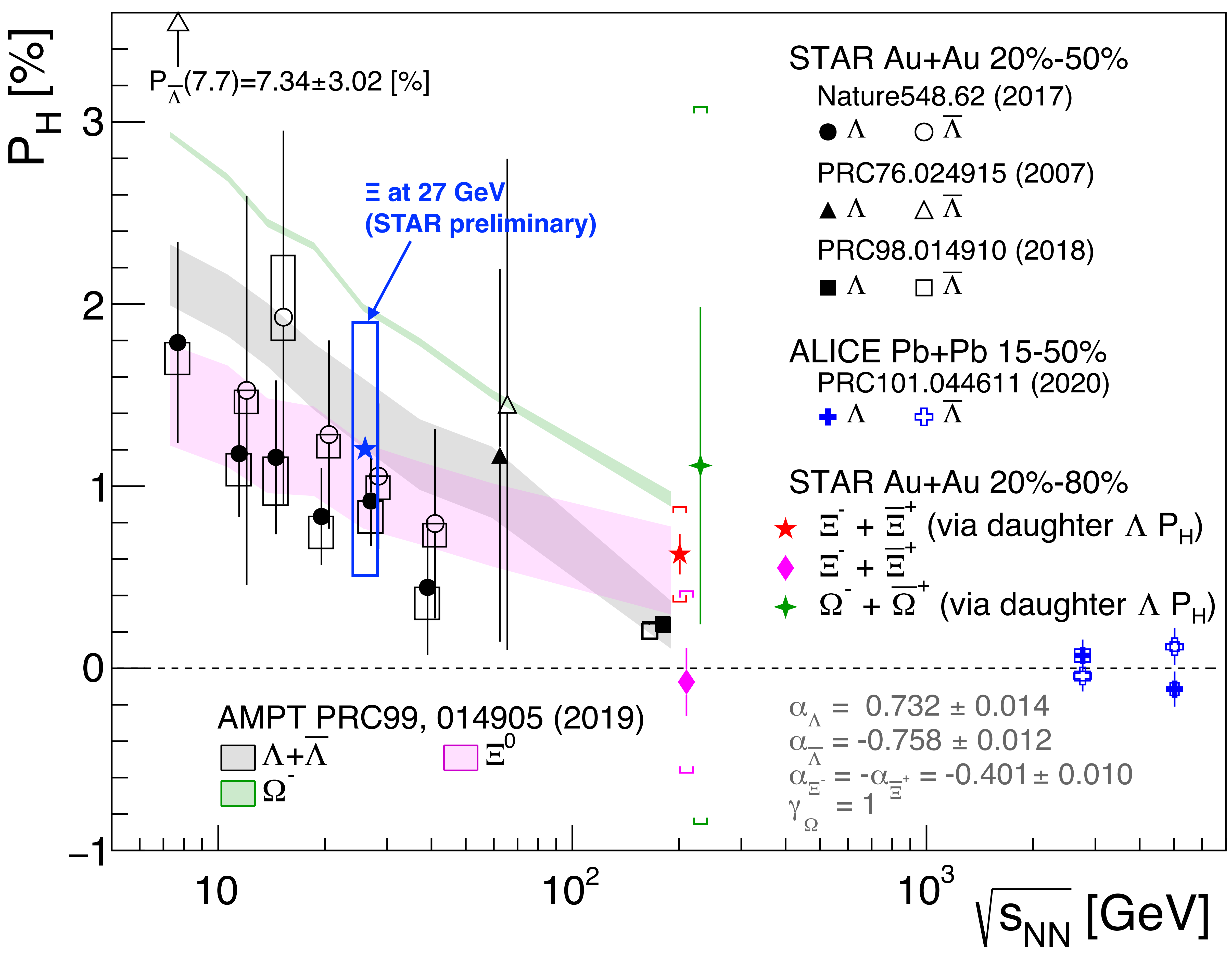

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F. Becattini et al., PRC95.054902 (2017)

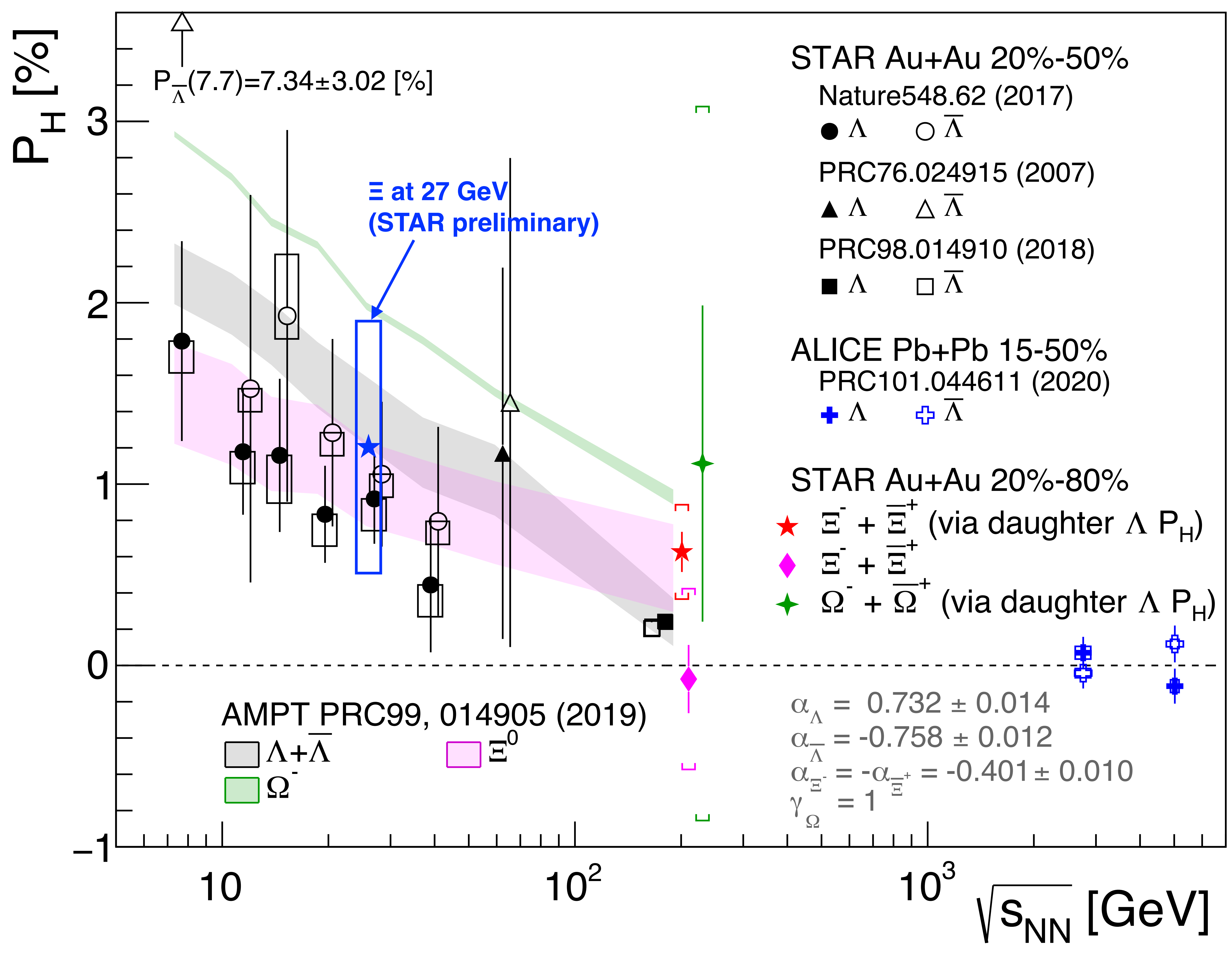
- Earlier freeze-out leads to larger P_H

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

- Feed-down contribution
  - 10-15% reduction of primary Λ P_H F. Becattini, PRC95, 054902 (2017)
  - ~25% increase of primary Ξ P_H H. Li et al., PLB827(2022)136971

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

STAR, PRL126, 162301 (2021)



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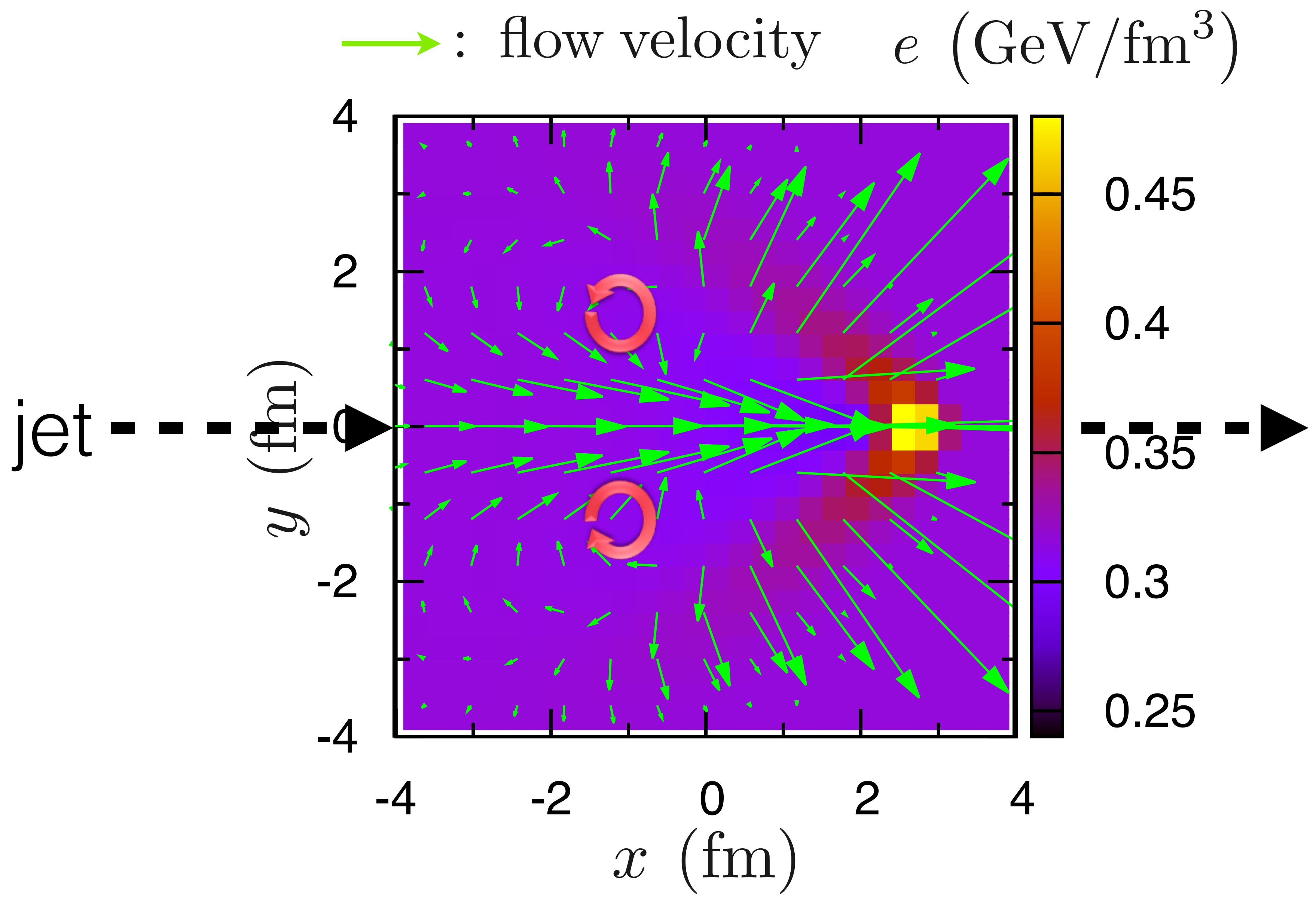
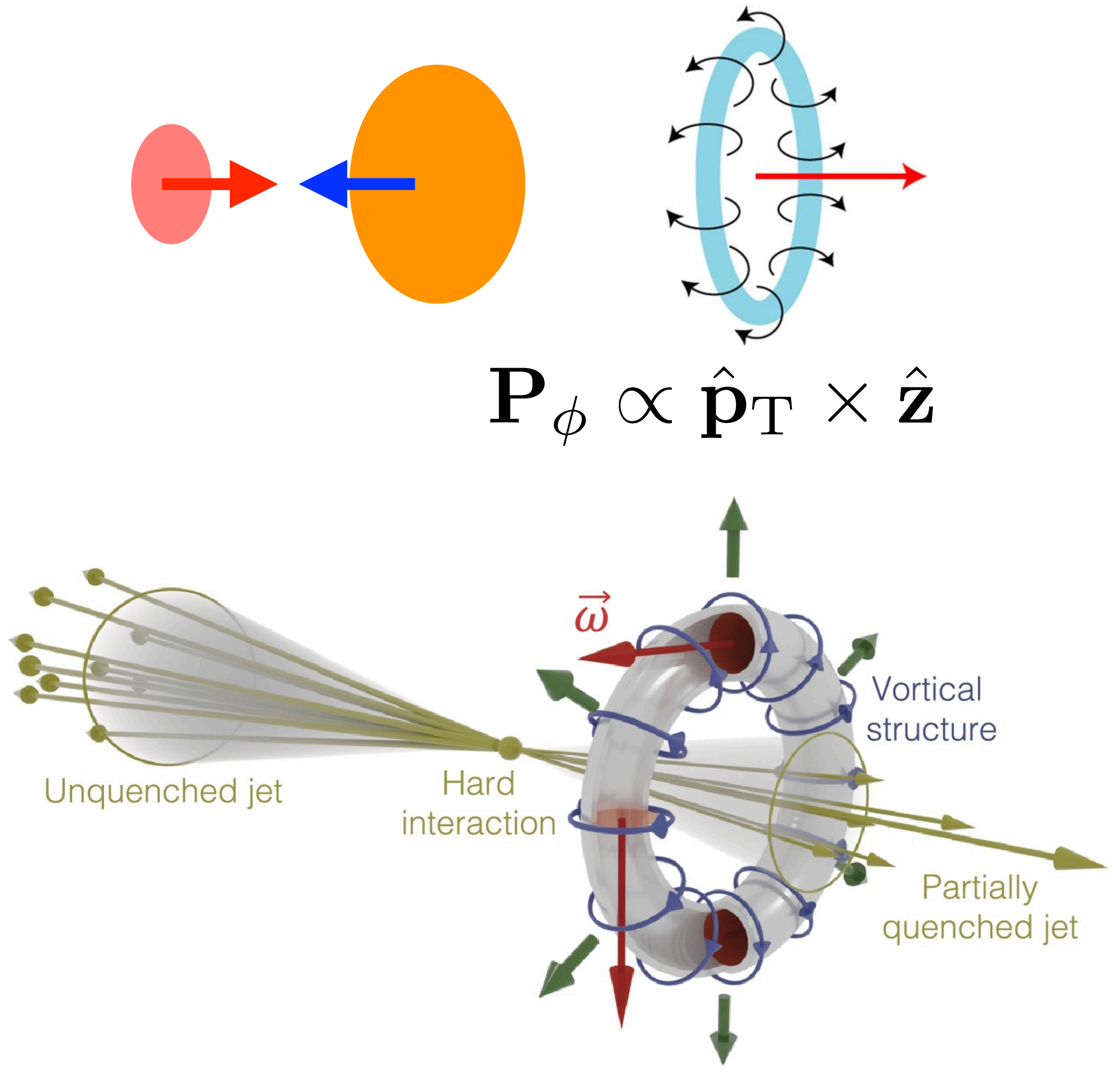
- Explore Ω/antiΩ difference in the coming data for B-field effect $\mu_\Omega \approx 3\mu_\Lambda$

Local vorticity

Vortex induced by jet or in asymmetric collisions

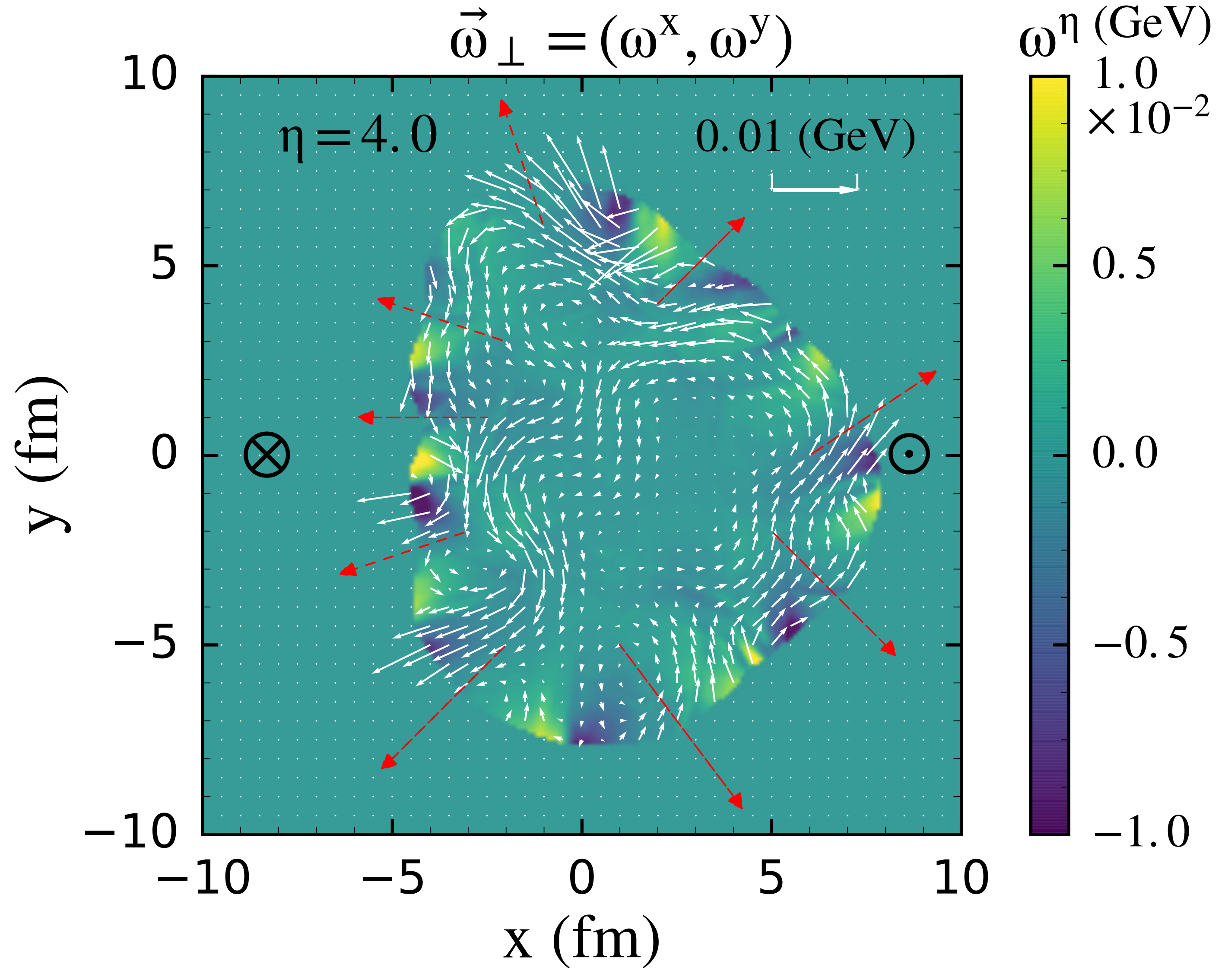




Y. Tachibana and T. Hirano, NPA904-905 (2013) 1023
B. Betz et al., PRC76.044901 (2007)

S. Voloshin, EPJ Web Conf.171, 07002 (2018)
W. M. Serenone et al., PLB820 (2021) 136500
M. Lisa et al., PRC104, L011901 (2021)

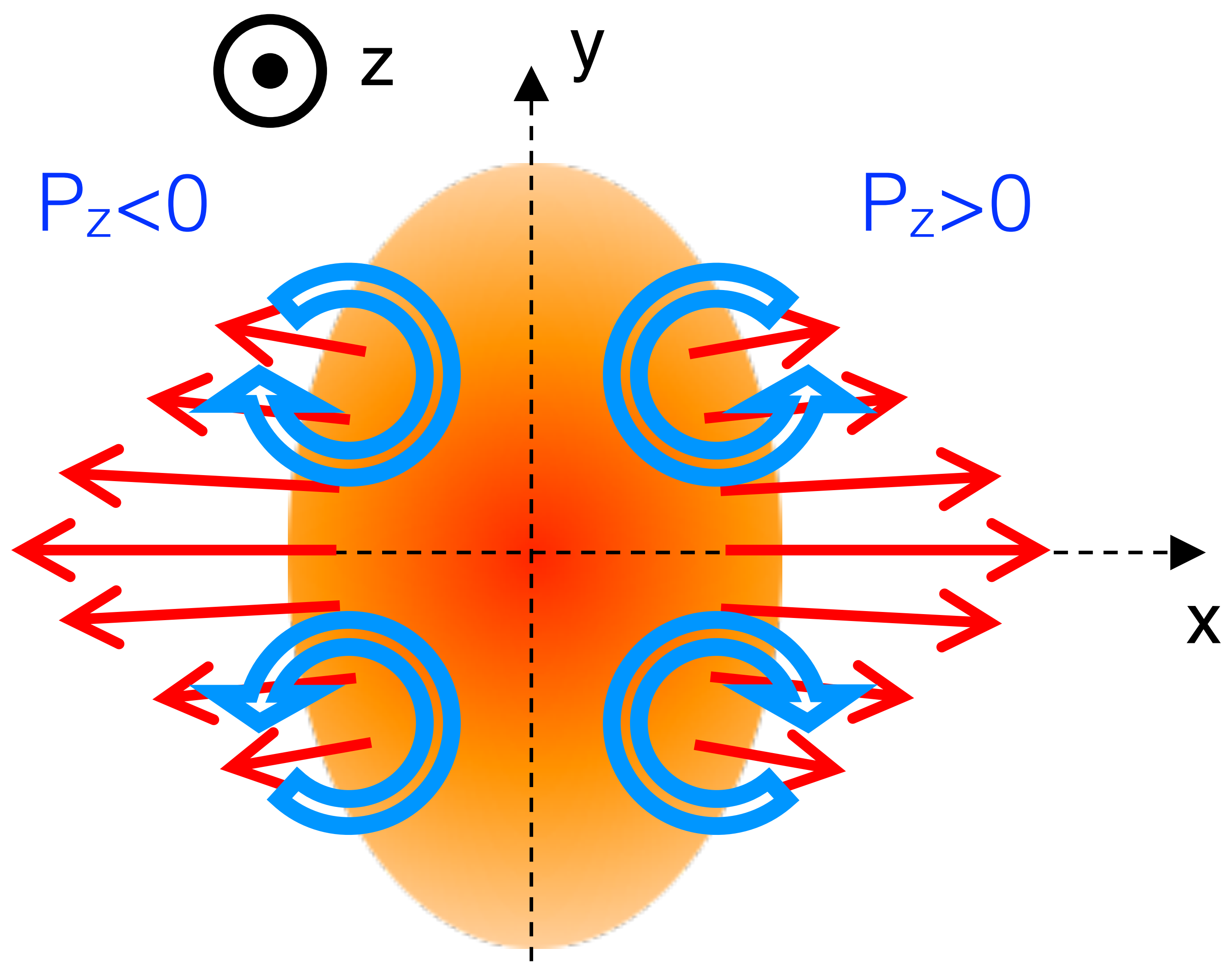
Local vorticity induced by collective expansion with density fluctuations



L.-G. Pang et al., PRL117, 192301 (2016)
X.-L. Xia et al., PRC98.024905 (2018)

Complex vortical structures might be created

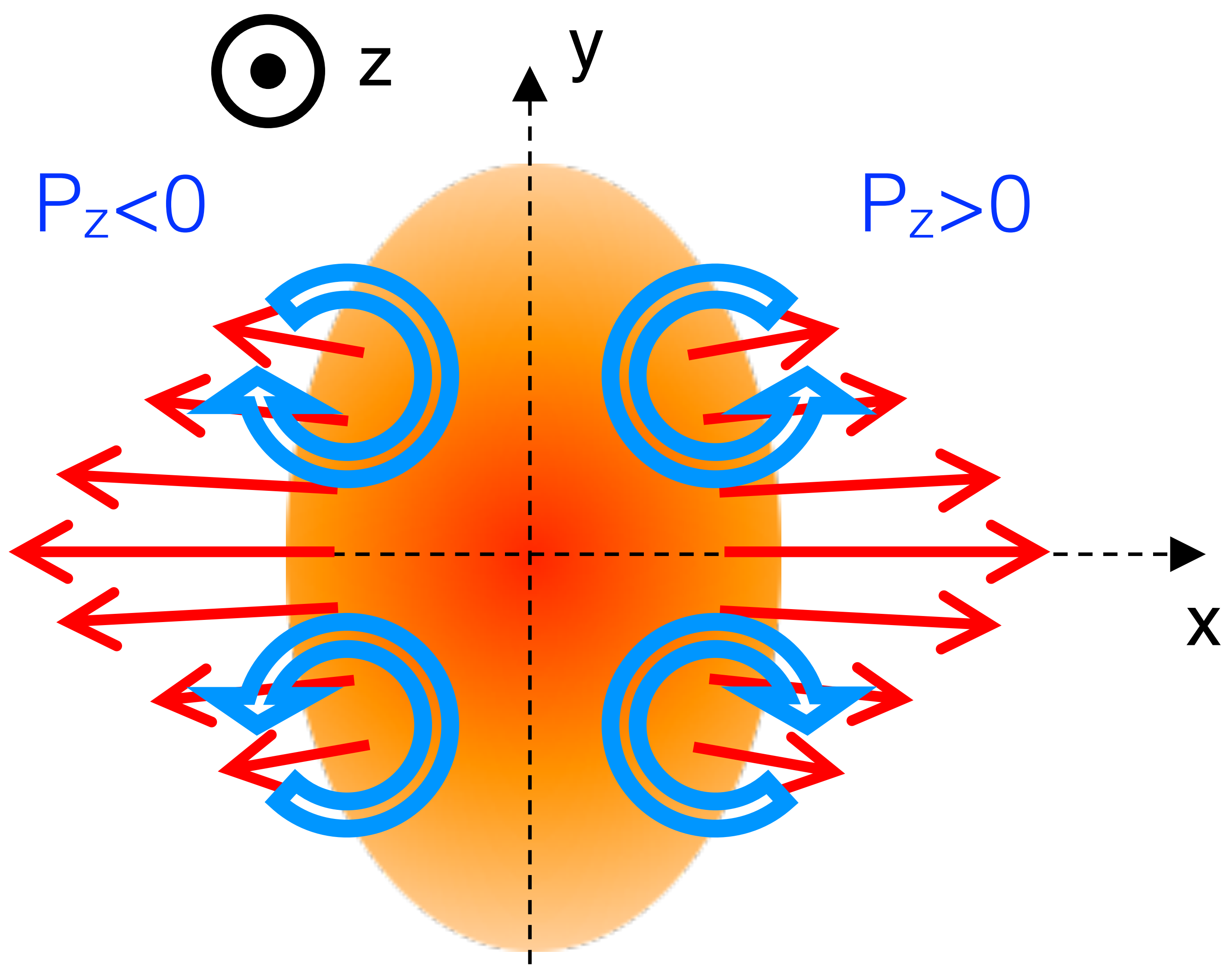
Polarization along the beam direction: P_z



- Polarization along the beam direction expected from the "elliptic flow"

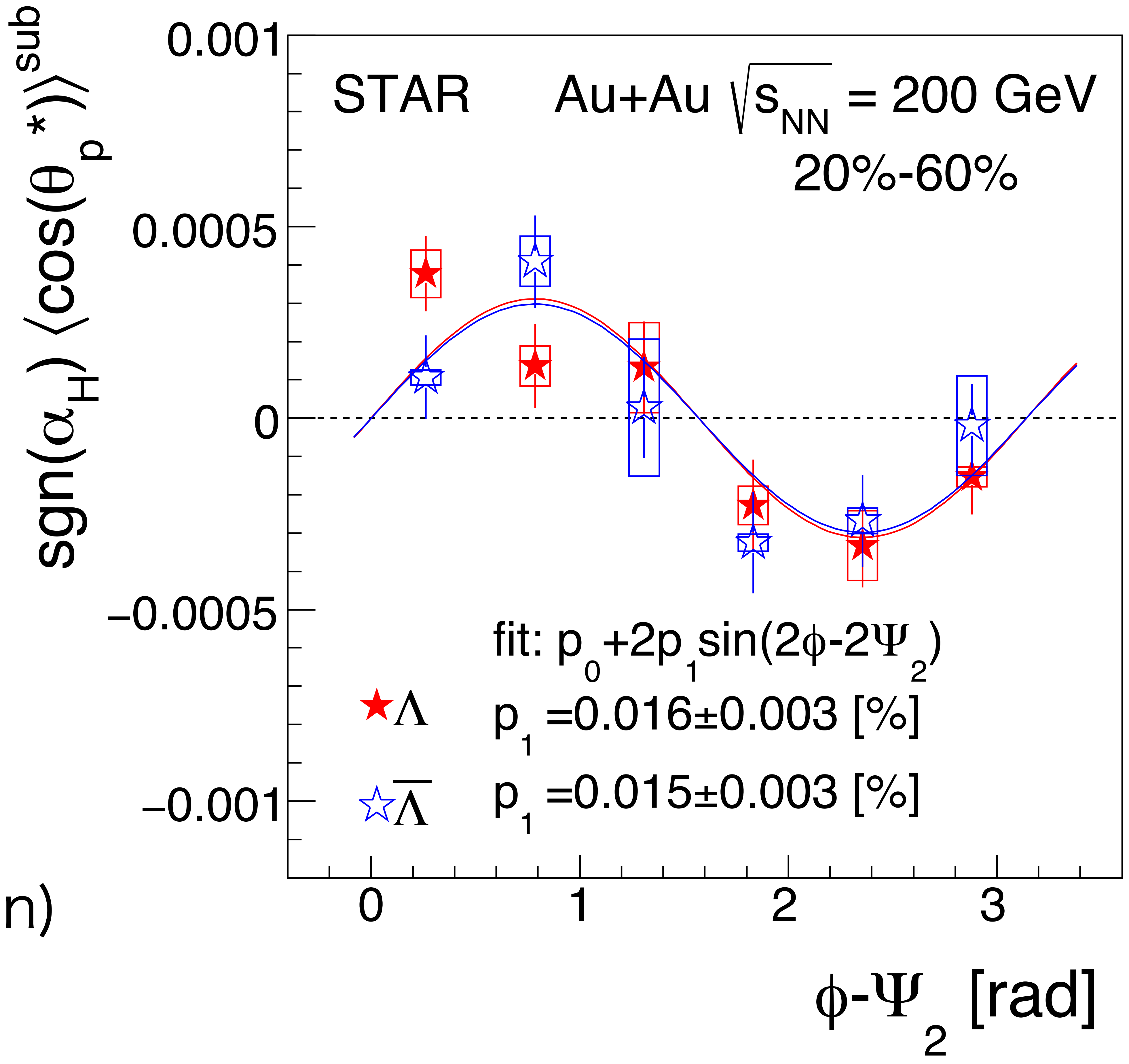
F. Becattini and I. Karpenko, PRL120.012302 (2018)
S. Voloshin, EPJ Web Conf.171, 07002 (2018)

Polarization along the beam direction: P_z



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

STAR, PRL123.13201 (2019)



- Polarization along the beam direction expected from the "elliptic flow"

F. Becattini and I. Karpenko, PRL120.012302 (2018)
S. Voloshin, EPJ Web Conf.171, 07002 (2018)

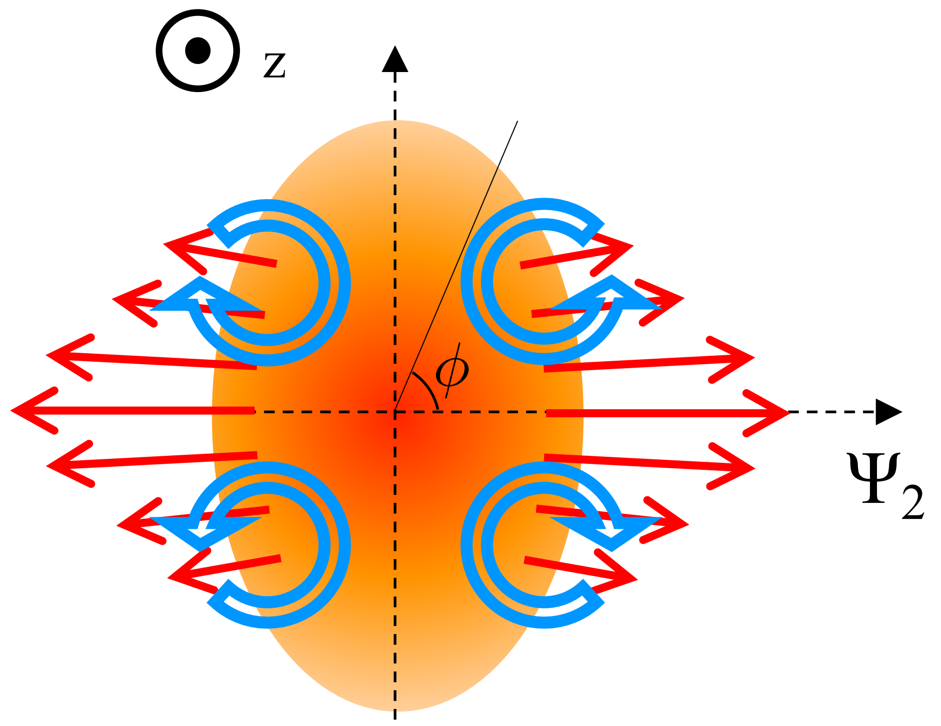
- Data indeed show a quadrupole pattern; the sign of P_z depends on azimuthal angle (~sine function)

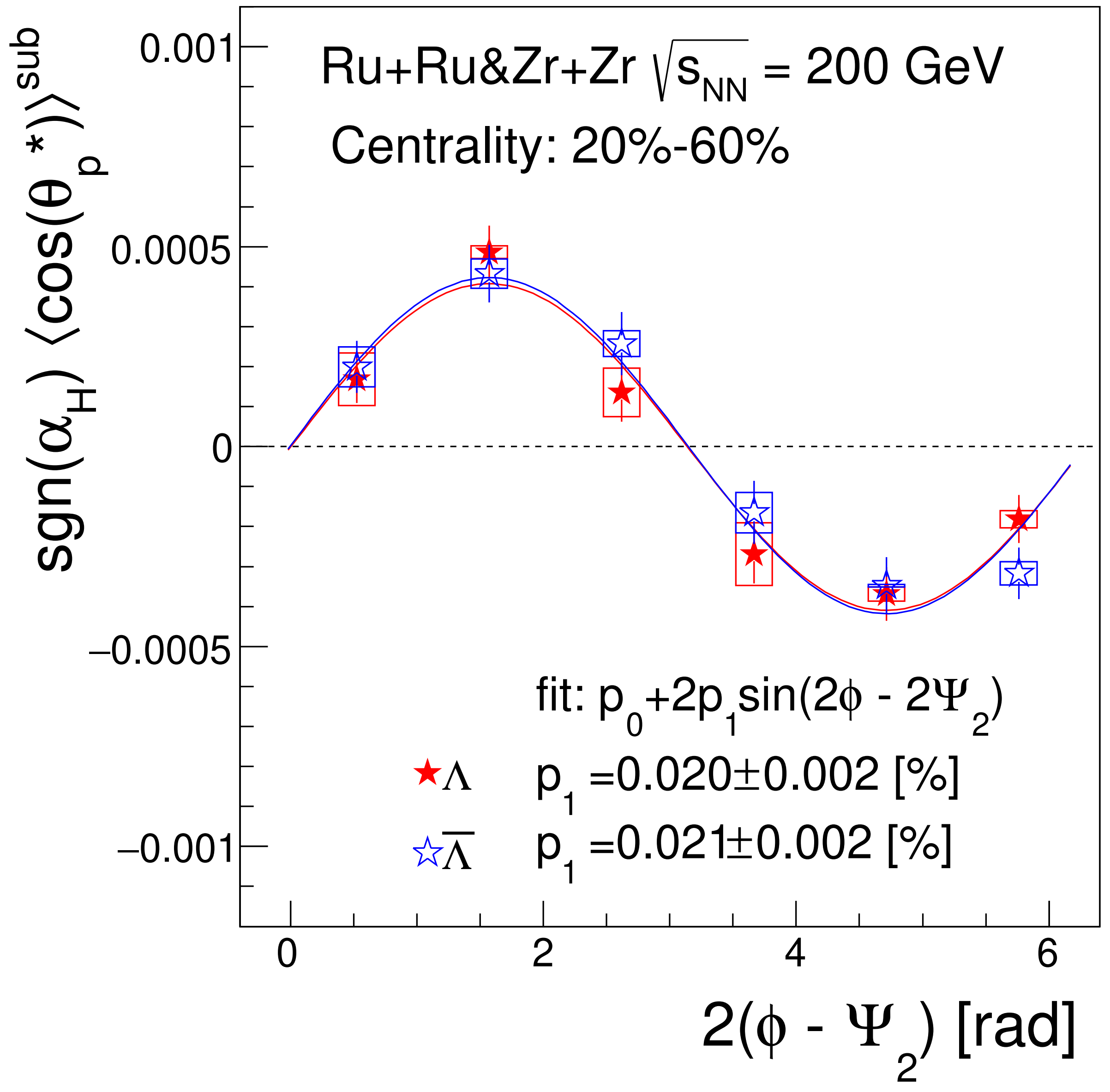
Anisotropic-flow-driven polarization!

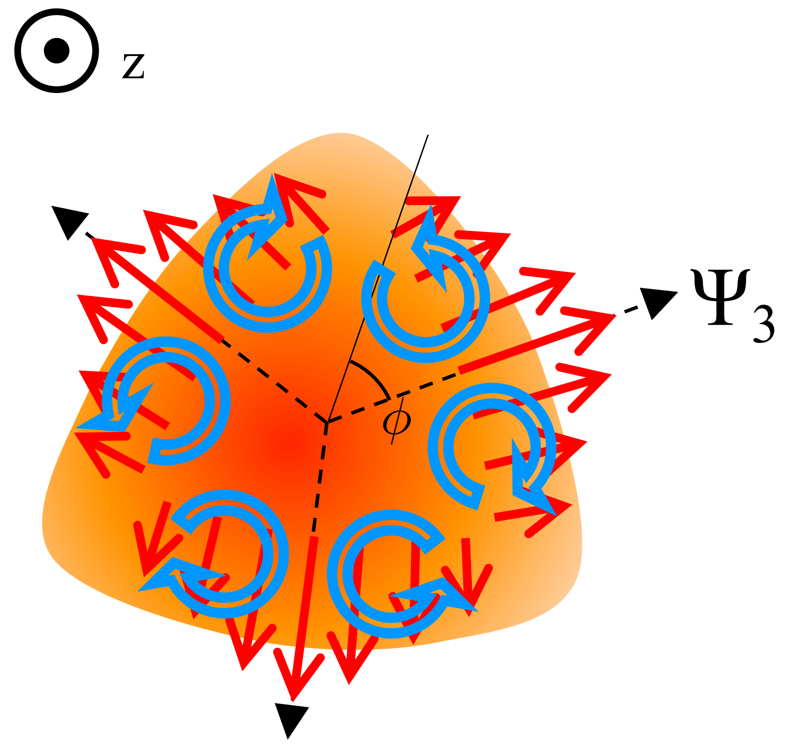
Even due to higher harmonic flow

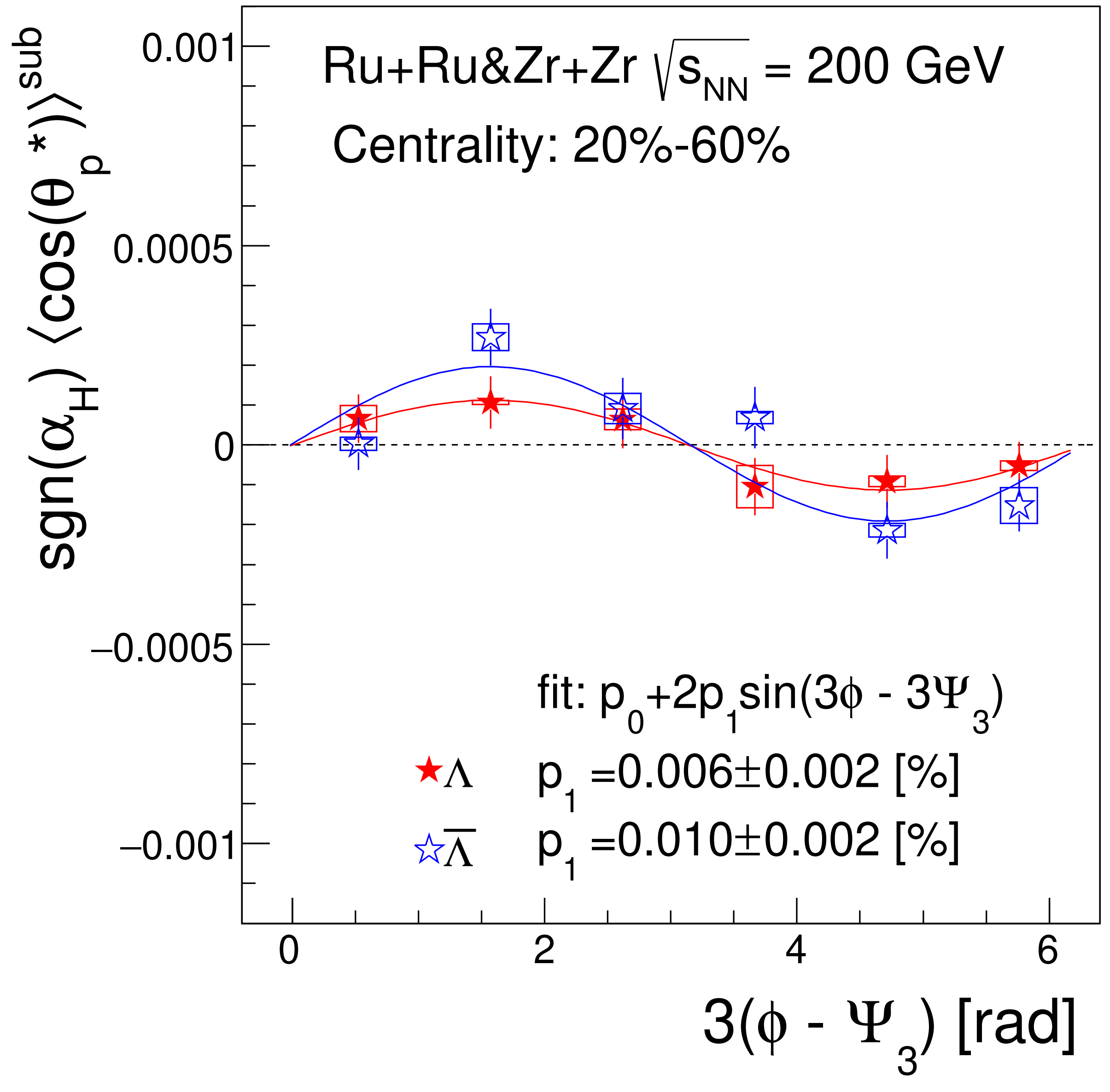
STAR, arXiv:2303.09074

*Not accounted for EP resolution and decay parameter









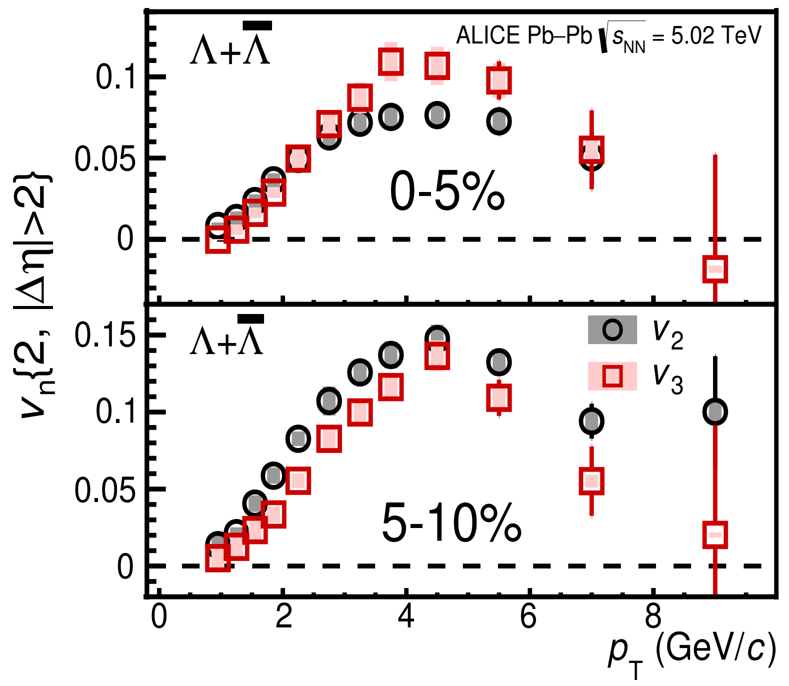
- Recent isobar data (Ru+Ru&Zr+Zr) even show triangular flow plane (Ψ_3) dependence of the polarization
  - Indicating triangular-flow-driven sextupole pattern of vorticity

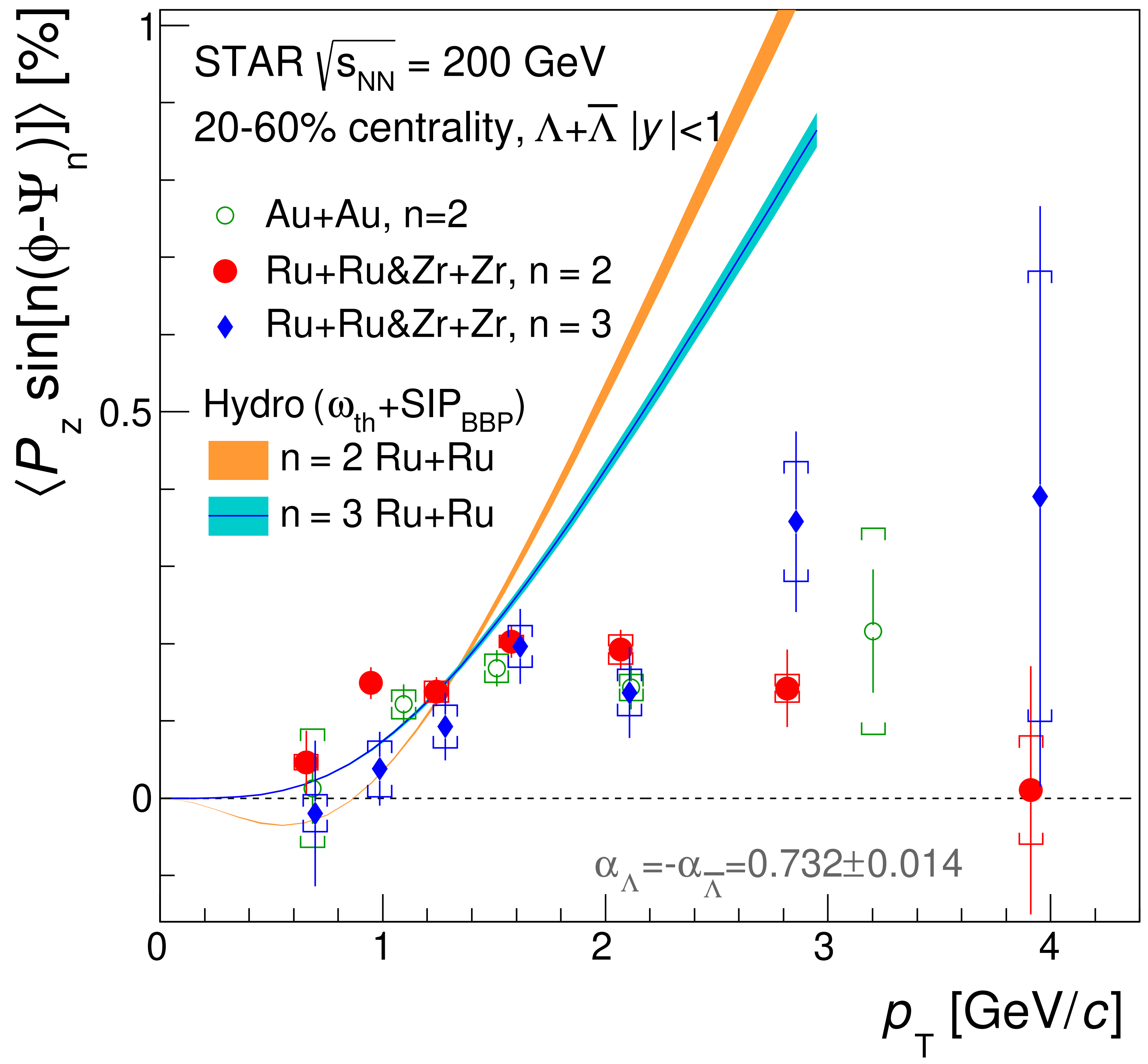
See Xingrui Gou's talk

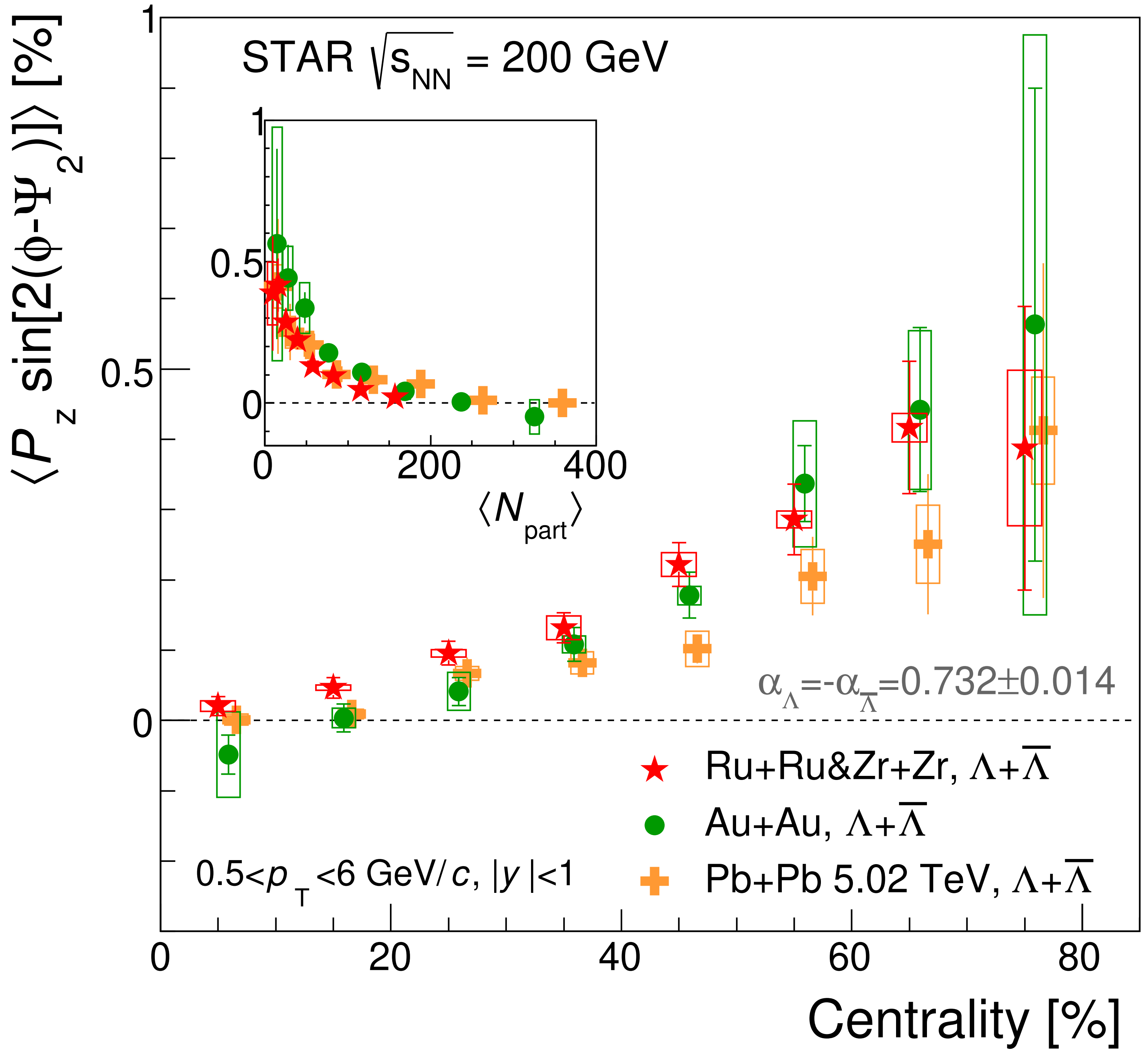
P_z sine modulation

STAR, arXiv:2303.09074

ALICE, JHEP09(2018)006





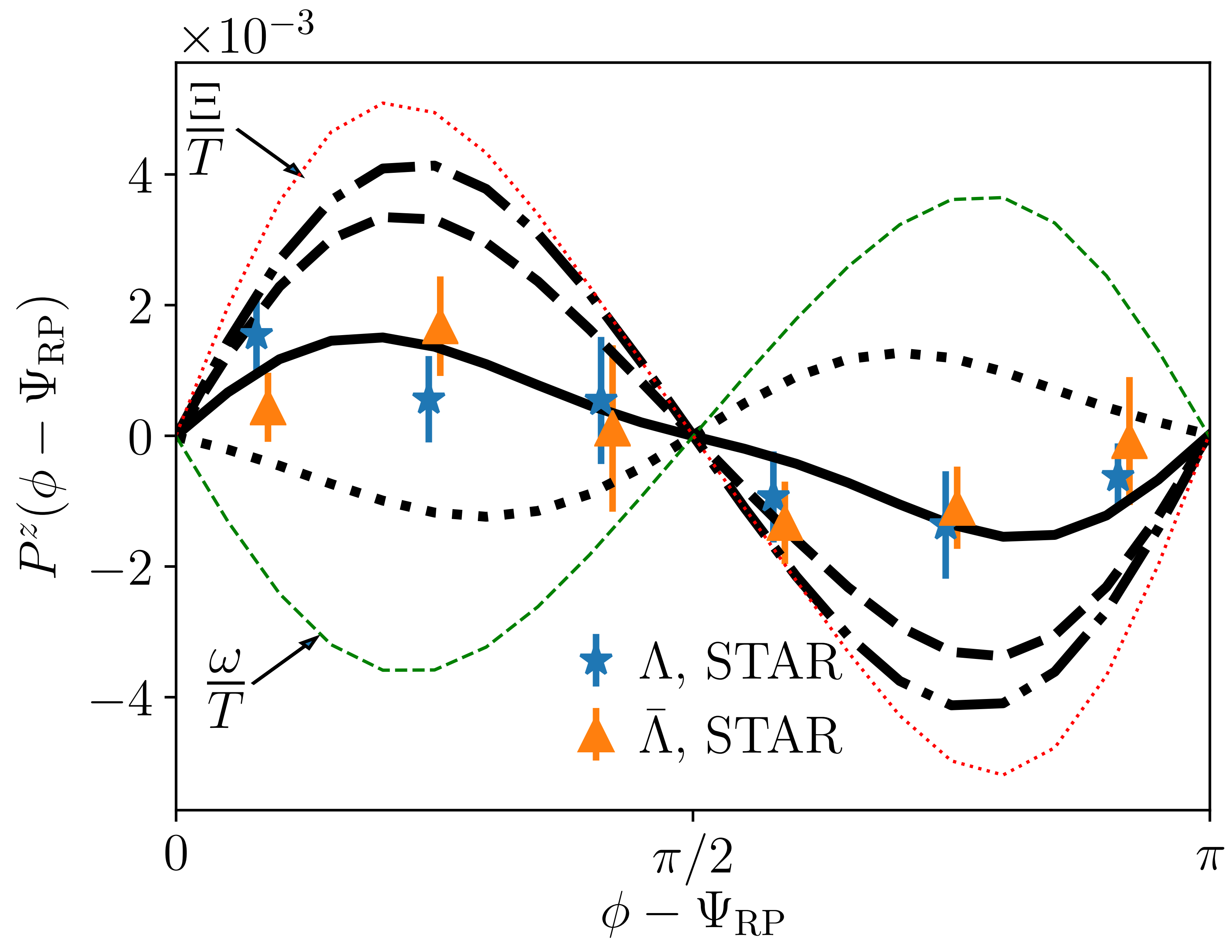


- Similar p_T dependence as v_n, further supporting flow-driven polarization
  - Hydrodynamic model with shear-induced polarization shows a bit different trend
- No significant collision system nor energy dependence
  - Scaling better with N_{part}, suggesting the importance of system size in addition to the geometry?
- Sensitivity to specific shear and bulk viscosities, and the initial state

See Xingrui Gou's talk

S. Alzharani et al., PRC106.014905 (2022)
A. Palermo et al., EPJ Web Conf. 276 (2023) 01026

Spin sign puzzle still remains?

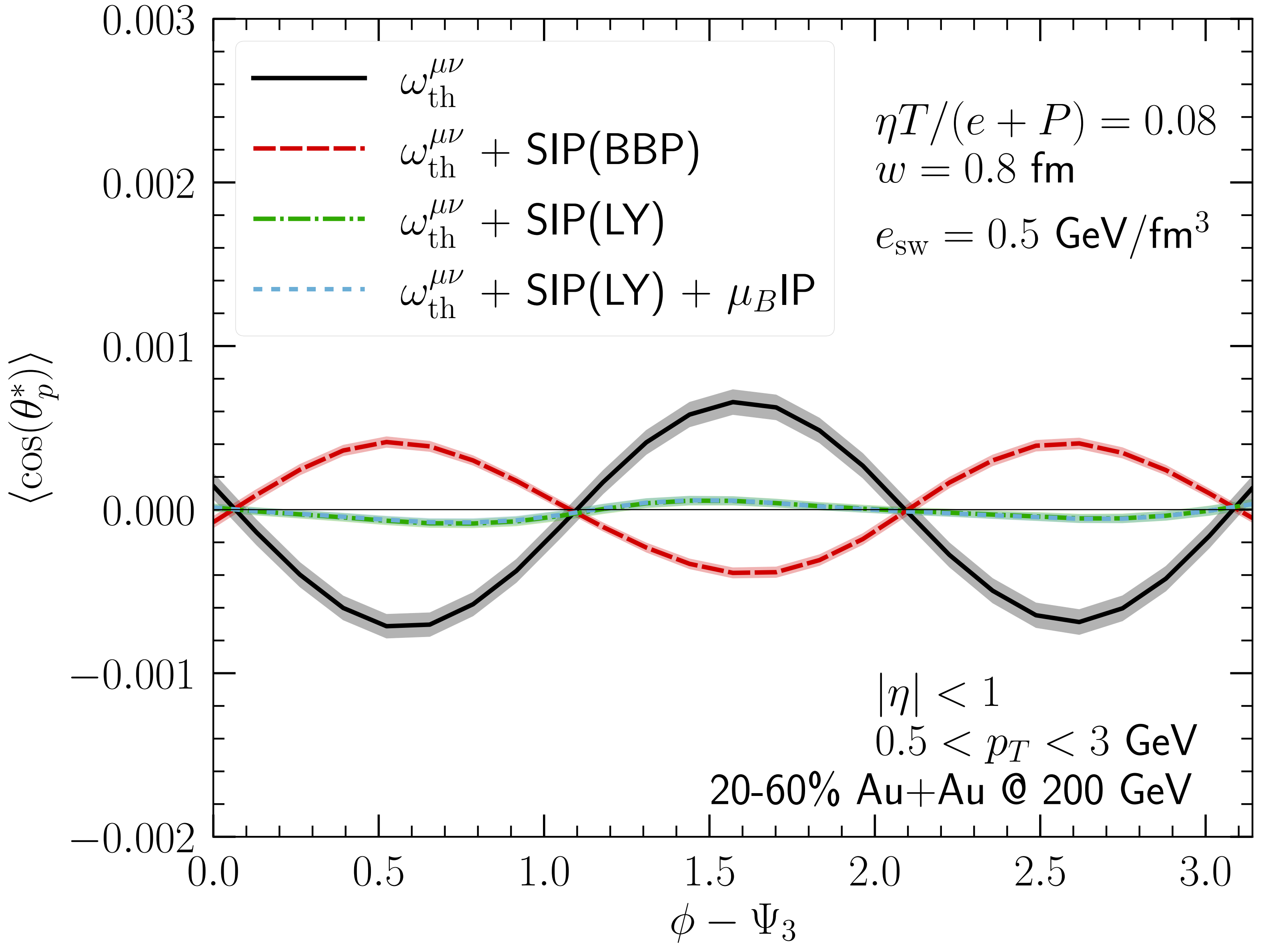


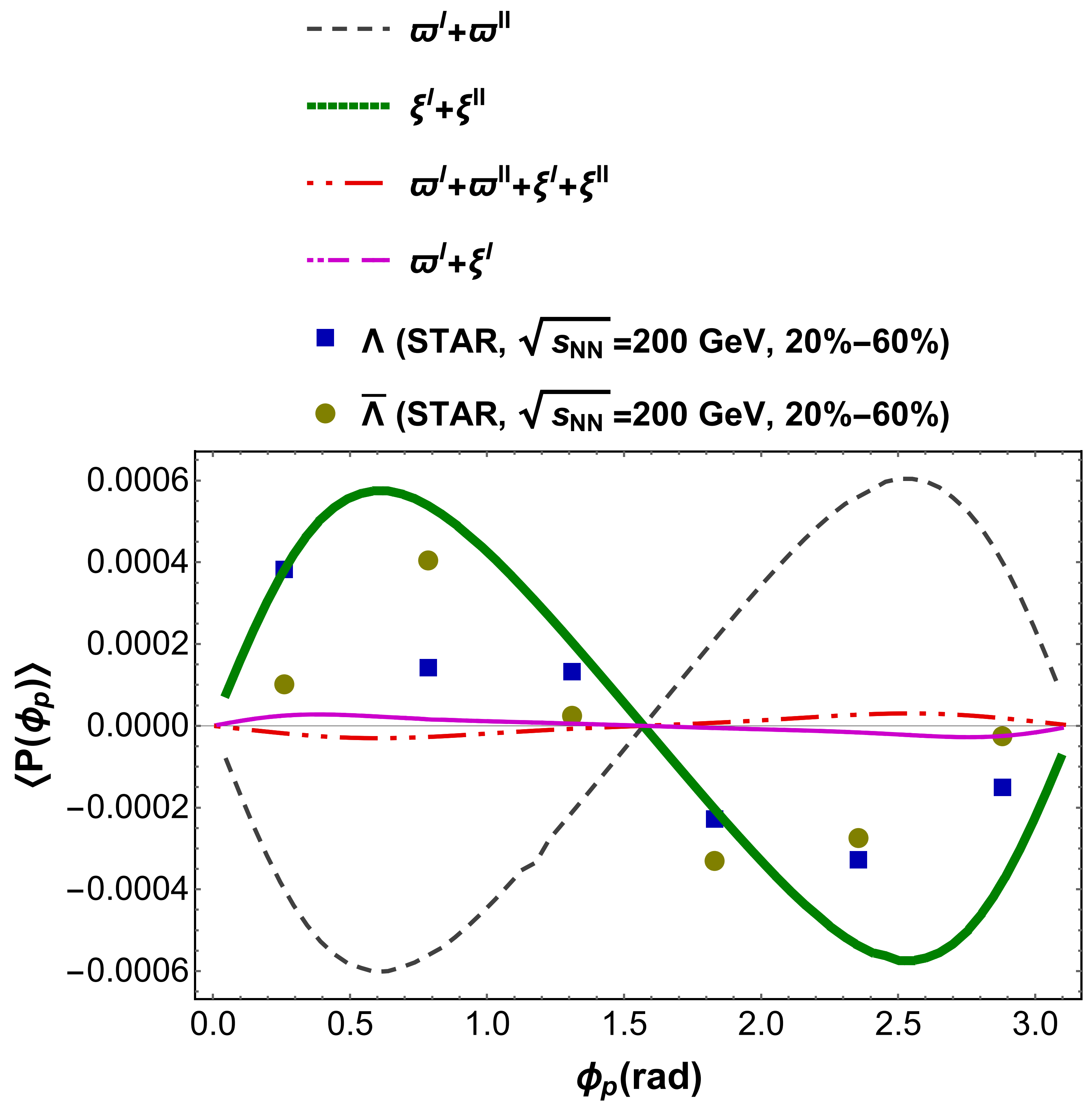
vorticity: $\omega_{\rho\sigma} = \frac{1}{2}(\partial_\sigma u_\rho - \partial_\rho u_\sigma)$

shear: $\Xi_{\rho\sigma} = \frac{1}{2}(\partial_\sigma u_\rho + \partial_\rho u_\sigma)$

S. Liu, Y. Yin, JHEP07(2021)188
B. Fu et al., PRL127, 142301 (2021)
F. Becattini et al., PLB820(2021)136519
F. Becattini et al., PRL127, 272302 (2021)

S. Alzharani et al., PRC106.014905 (2022)
W. Florkowski et al., PRC105, 064901 (2022)
Y. Sun et al., PRC105, 034911 (2022)
C. Yi et al., PRC104, 064901 (2021)



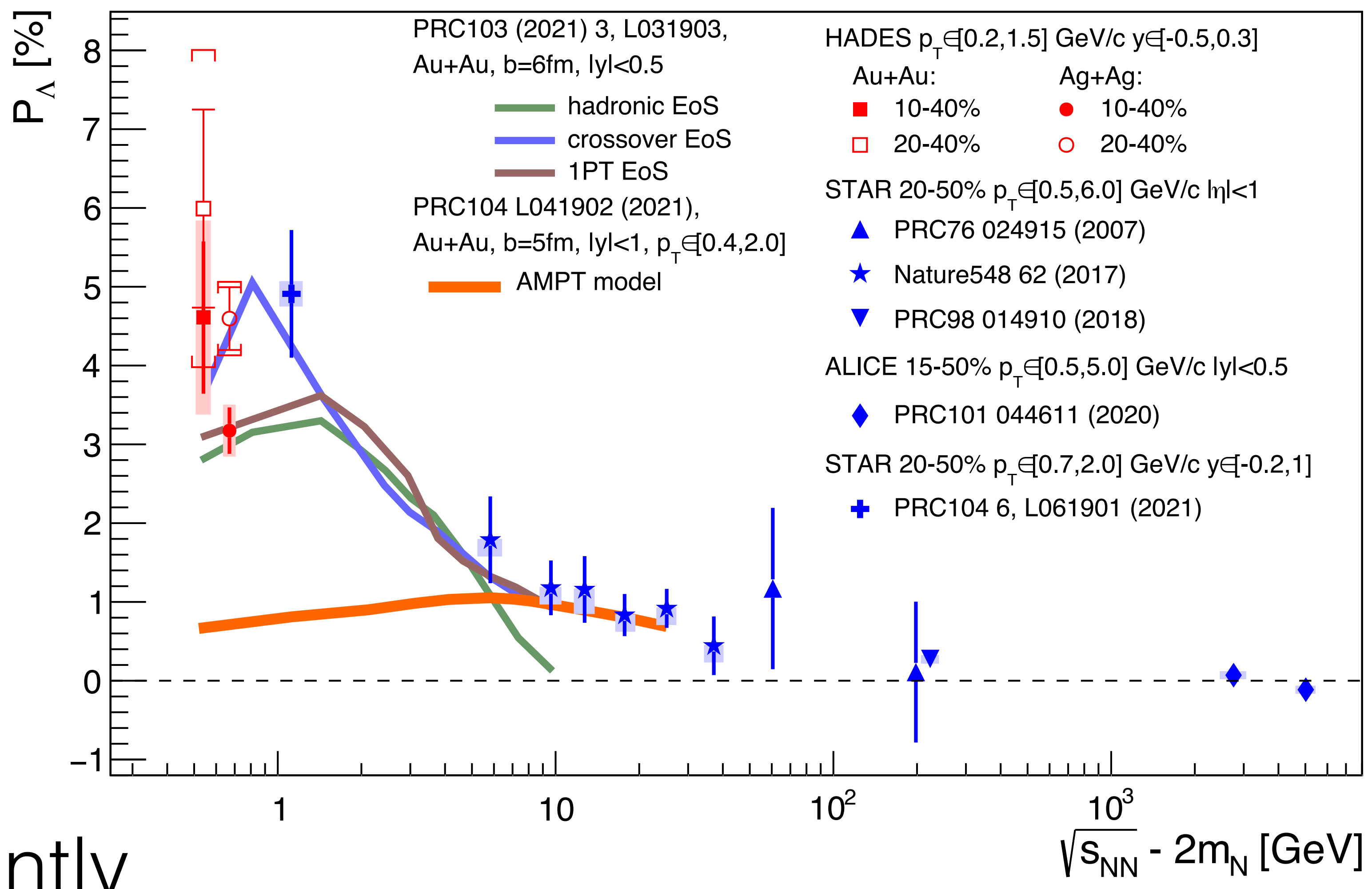


- The sign of P_z is not reproduced by models based on thermal vorticity, referred to as "spin sign puzzle"
  - Spin may not be in equilibrium?
- "Shear tensor" seems to be needed to explain the data but the sign changes depending on the implementation detail
  - Large cancellation of the thermal vorticity and shear contributions

Outlook

- Global polarization
  - Complete the energy dependence filling in $\sqrt{s_{NN}}$ = 3-7.7 GeV
  - Any chance to see P_H splitting? lower energy or Ω hyperon?
  - More precise measurements of Ξ and Ω polarization needed
  - Measurement at forward/backward rapidity where models predict differently

HADES, PLB835(2022)137506

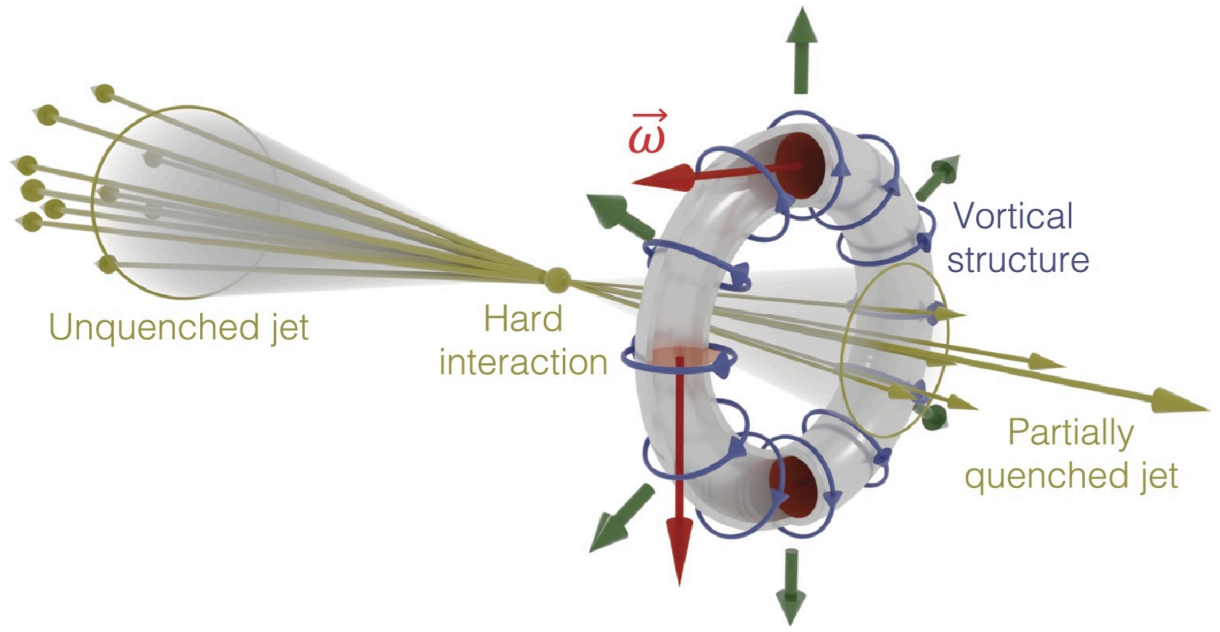


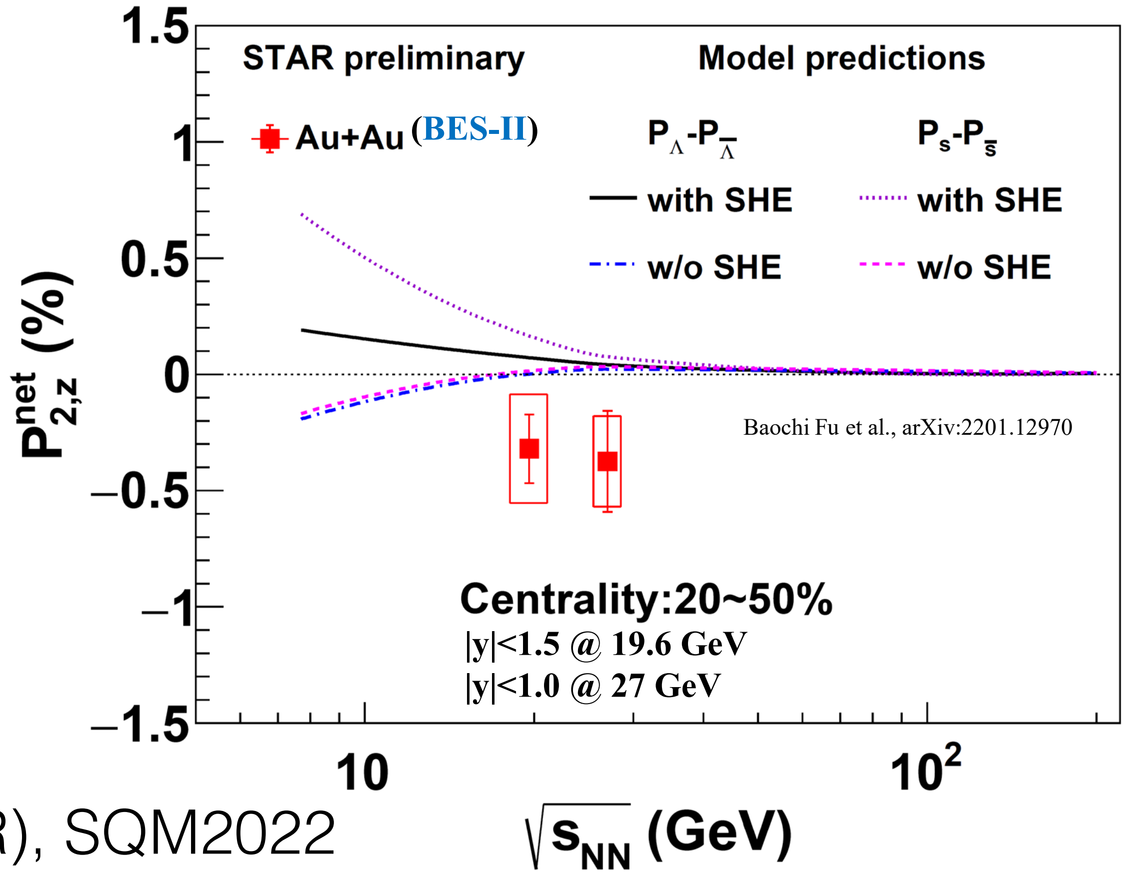
- Local polarization
  - ϕ-polarization (toroidal vortex)
    - due to jet or in *p*+A, Cu+Au, O+Pb(?) collisions
  - Spin Hall Effect?

$$\mathbf{P} = \frac{\langle \mathbf{s} \rangle}{s} \approx \frac{(s+1)}{3}\frac{\omega}{T} \qquad \mu_\Omega \approx 3\mu_\Lambda$$

S. Voloshin, EPJ Web Conf.171, 07002 (2018)
X.-L. Xia et al., PRC98, 024905 (2018)
W. M. Serenone et al., PLB820 (2021) 136500
M. Lisa et al., PRC104, L011901 (2021)

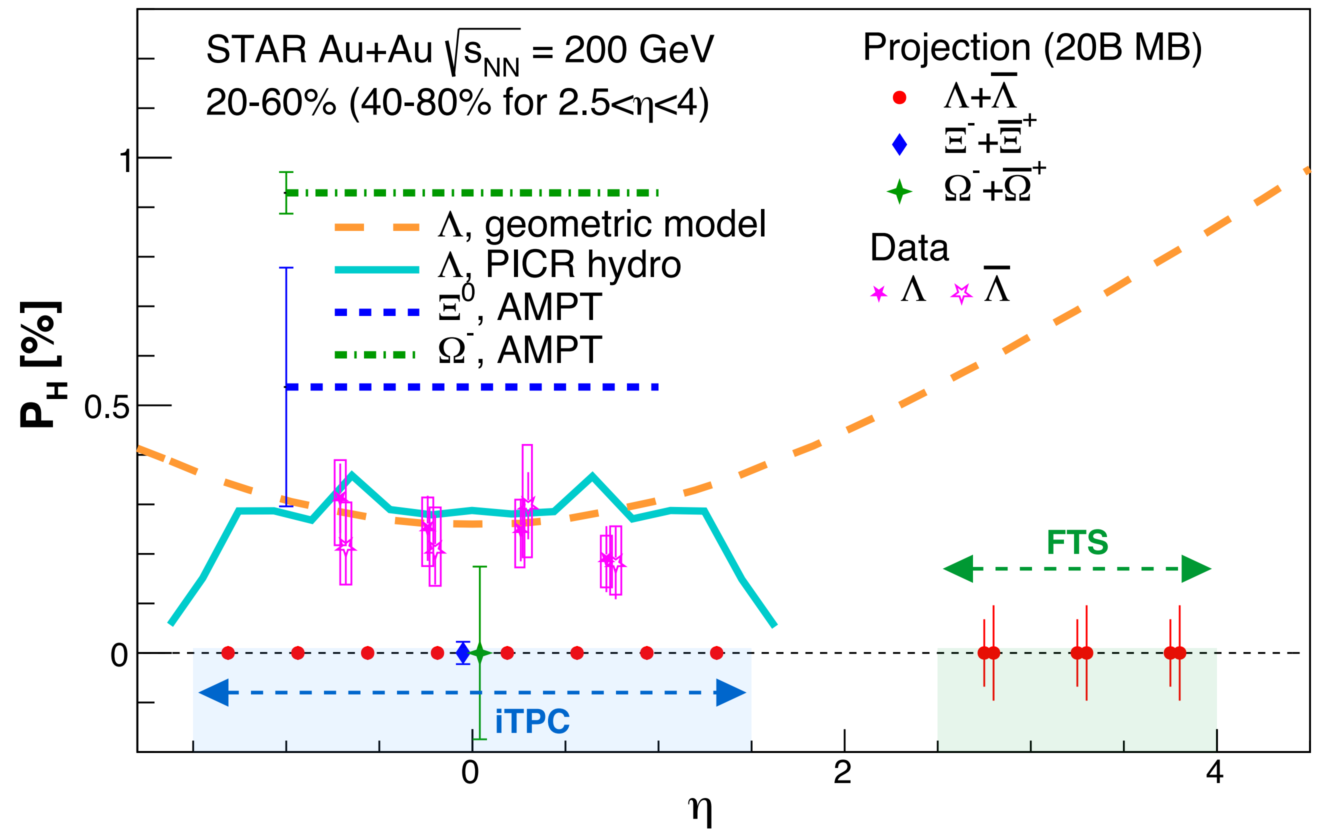
S.Y.F. Liu and Y. Yin, PRD104, 054043 (2021)
B. Fu et al., arXiv:2201.12970





Q. Hu (STAR), SQM2022

BUR2023, STAR Note SN0819



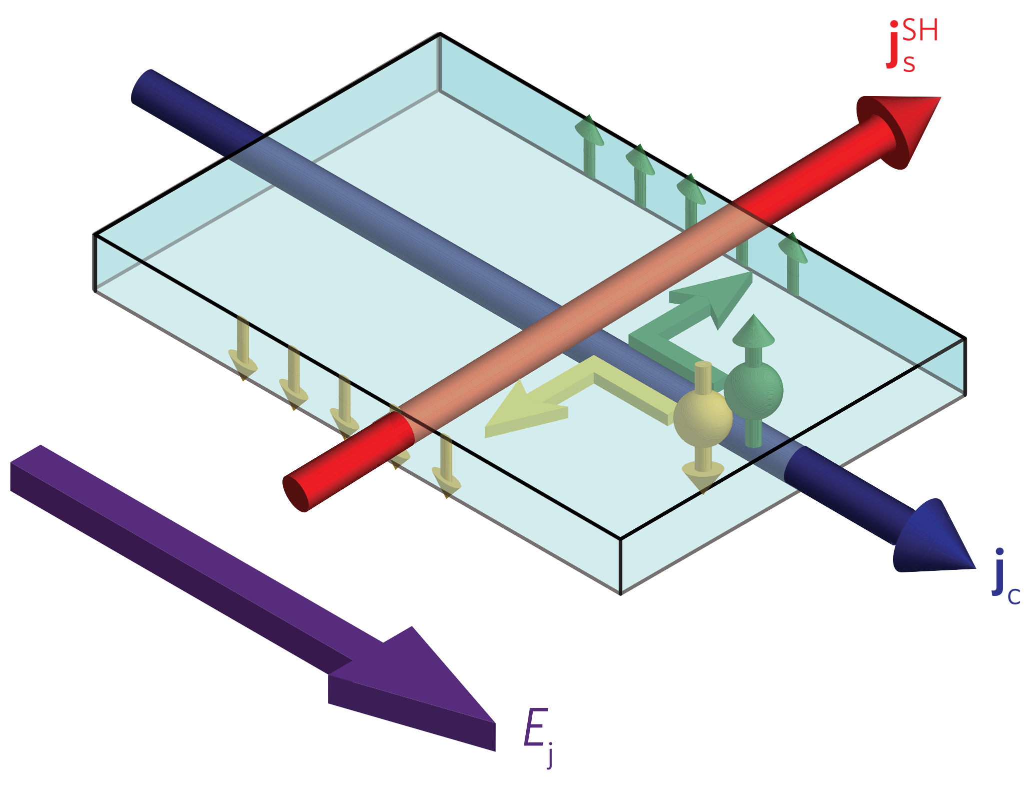
Summary

- Observation of the hyperon polarization open new directions in the study of QCD matter and spin dynamics in heavy-ion collisions

- A lot of progress in the measurements but still some open questions remain
    - Global polarization: energy dependence from a few GeV to TeV, differential measurements, multi-strangeness hyperons
    - Polarization along the beam direction: extended to 3rd-order, importance of the shear term to explain the data but how to implement it?
    - Other predicted phenomena to be explored: vortex ring and spin Hall effect

Backup

Spin Hall effect

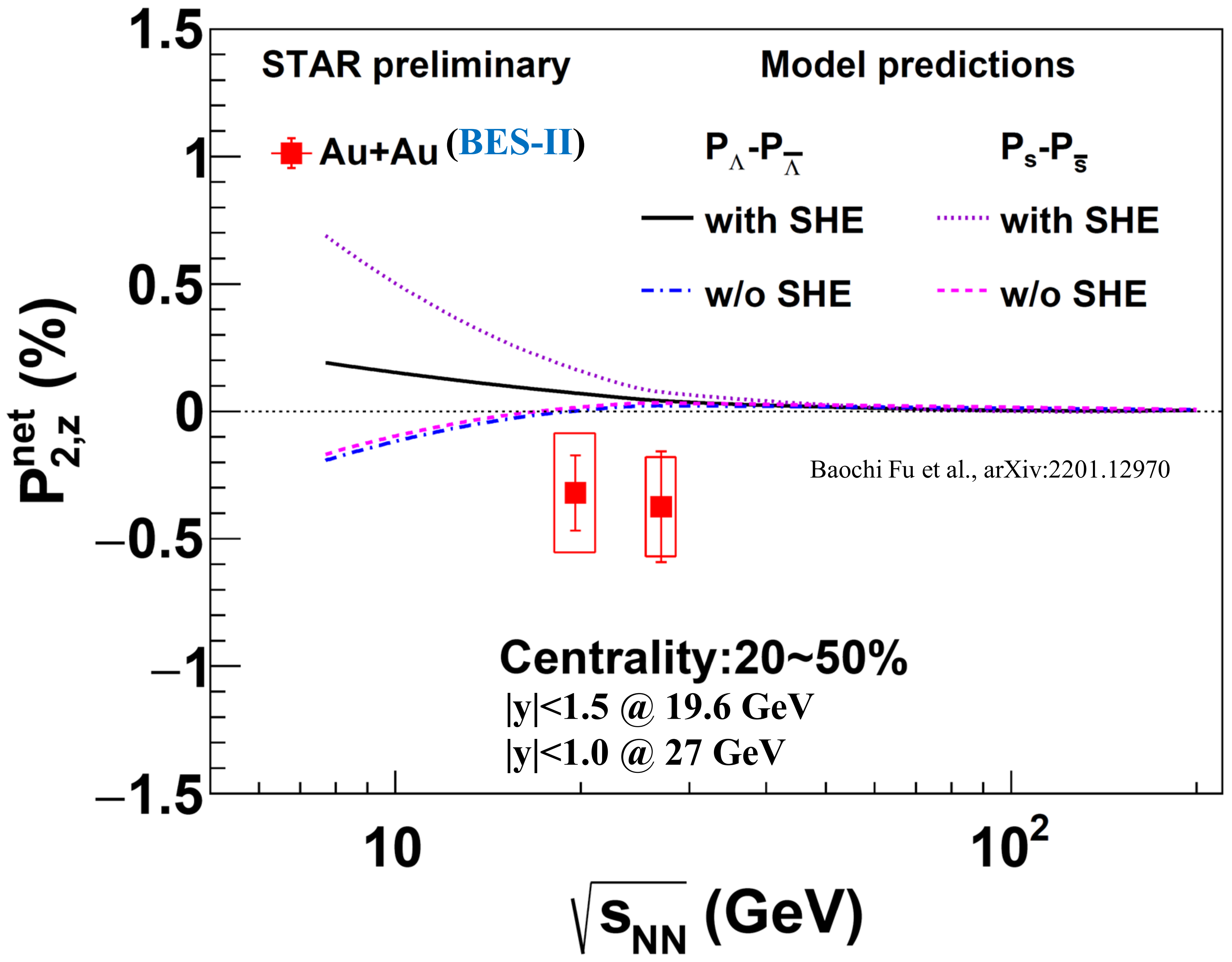


Spin Hall effect, (1972) 2004

S. Meyer et al., Nat. Mater.16, 977 (2017)

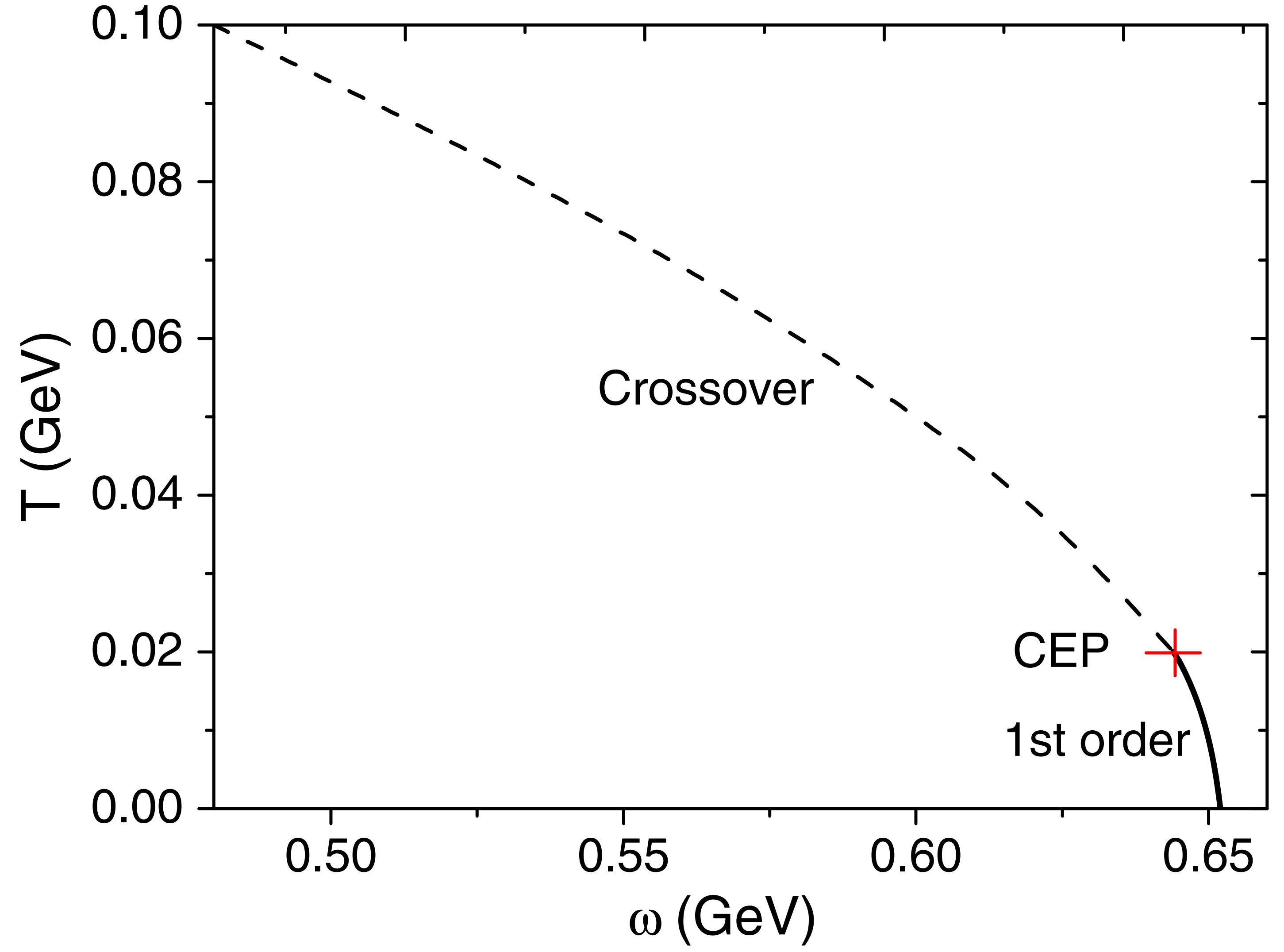
Q. Hu (STAR), SQM2022

S. Liu and Y. Yin, PRD104, 054043 (2021)
B. Fu et al., arXiv:2201.12970

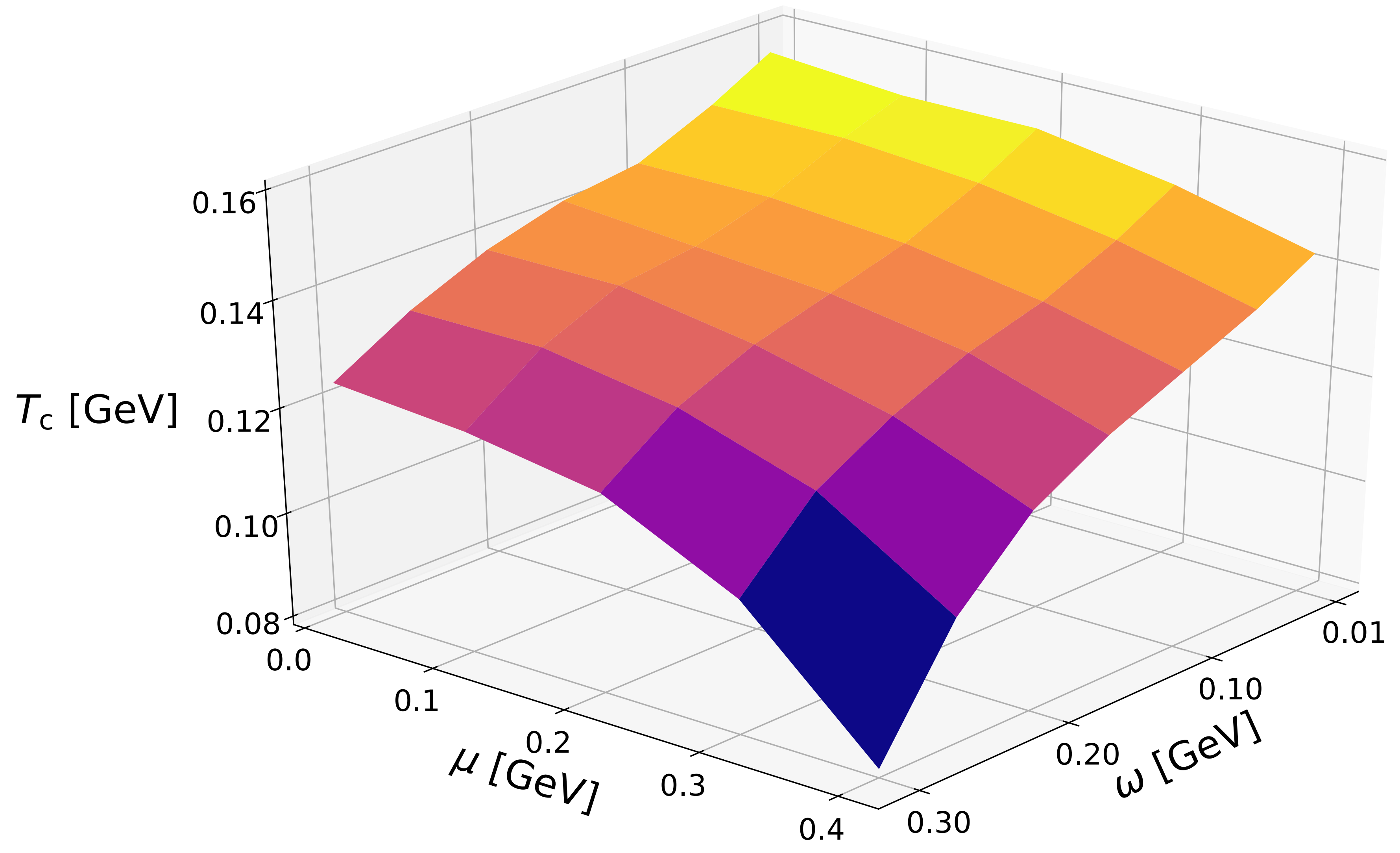


- A hint of Λ-Λbar difference but in the opposite sign to SHE
- Study with BES-II data (lower energies) is ongoing at STAR

Phase diagram of *rotating* nuclear matter



Y. Jiang and J. Liao, PRL117.192302(2016)

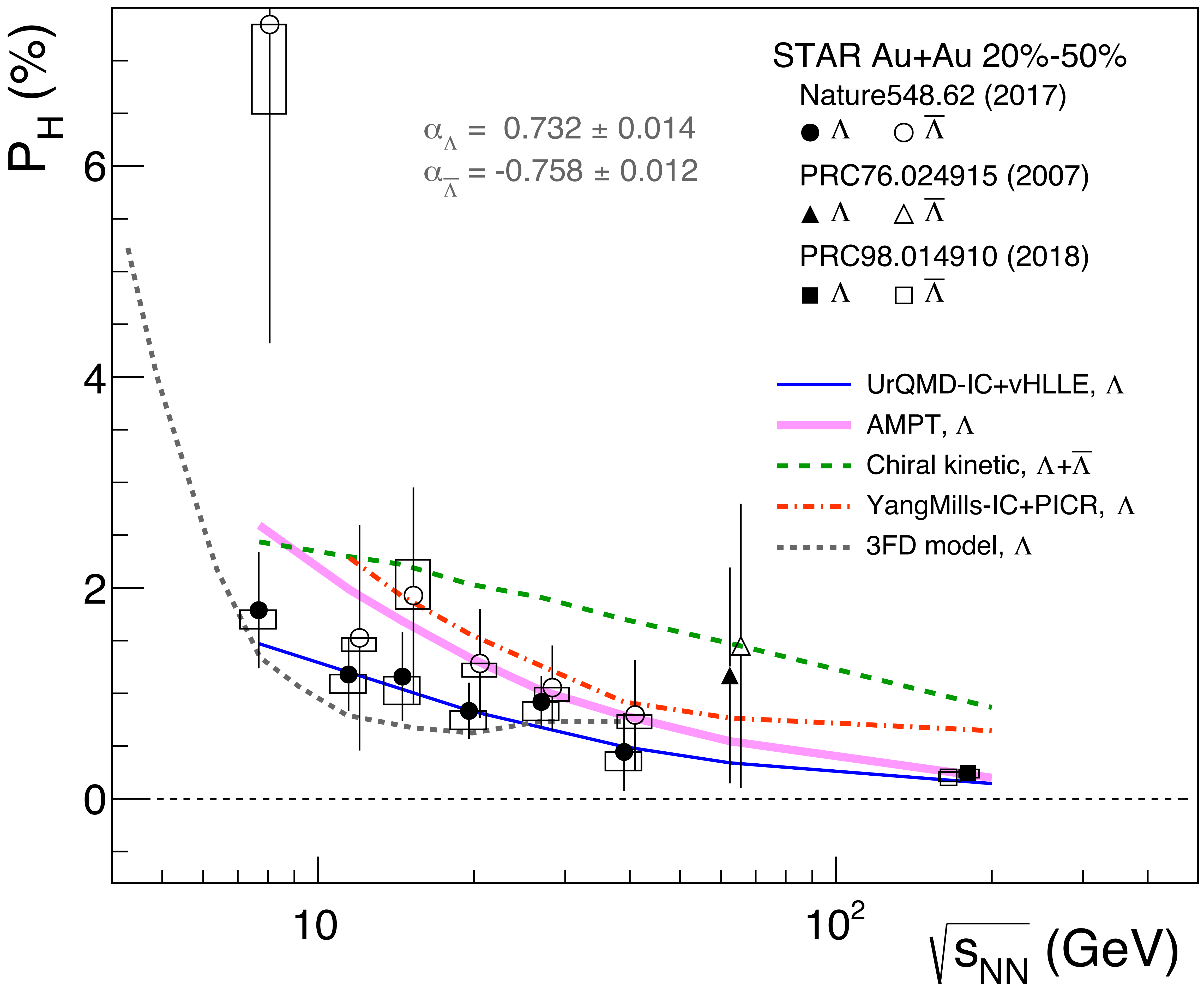


Y. Fujimoto, K. Fukushima, Y. Hidaka, PLB816(2021)136184

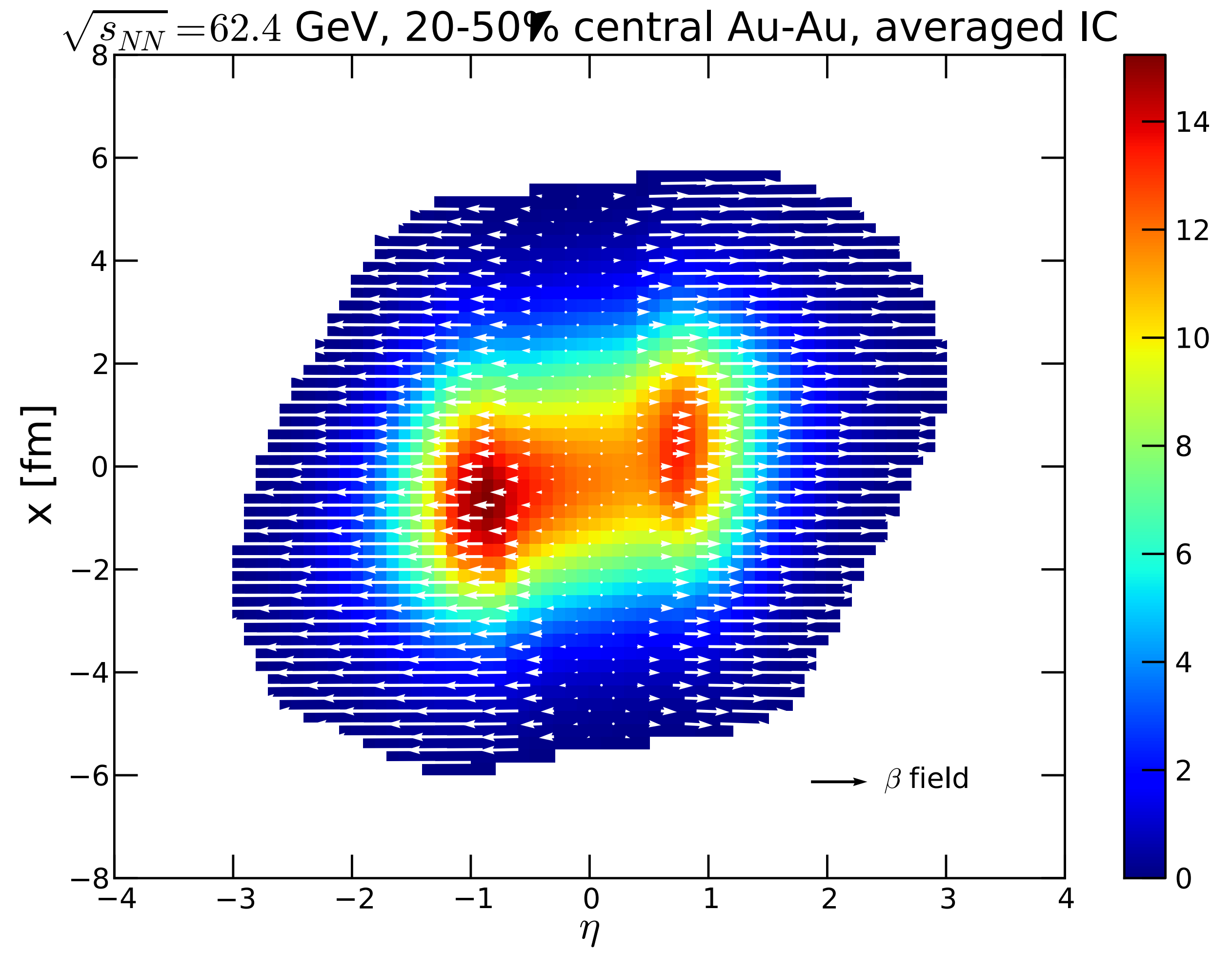
- Vorticity ω acts like baryon chemical potential μ_B and lower deconfinement transition temperature

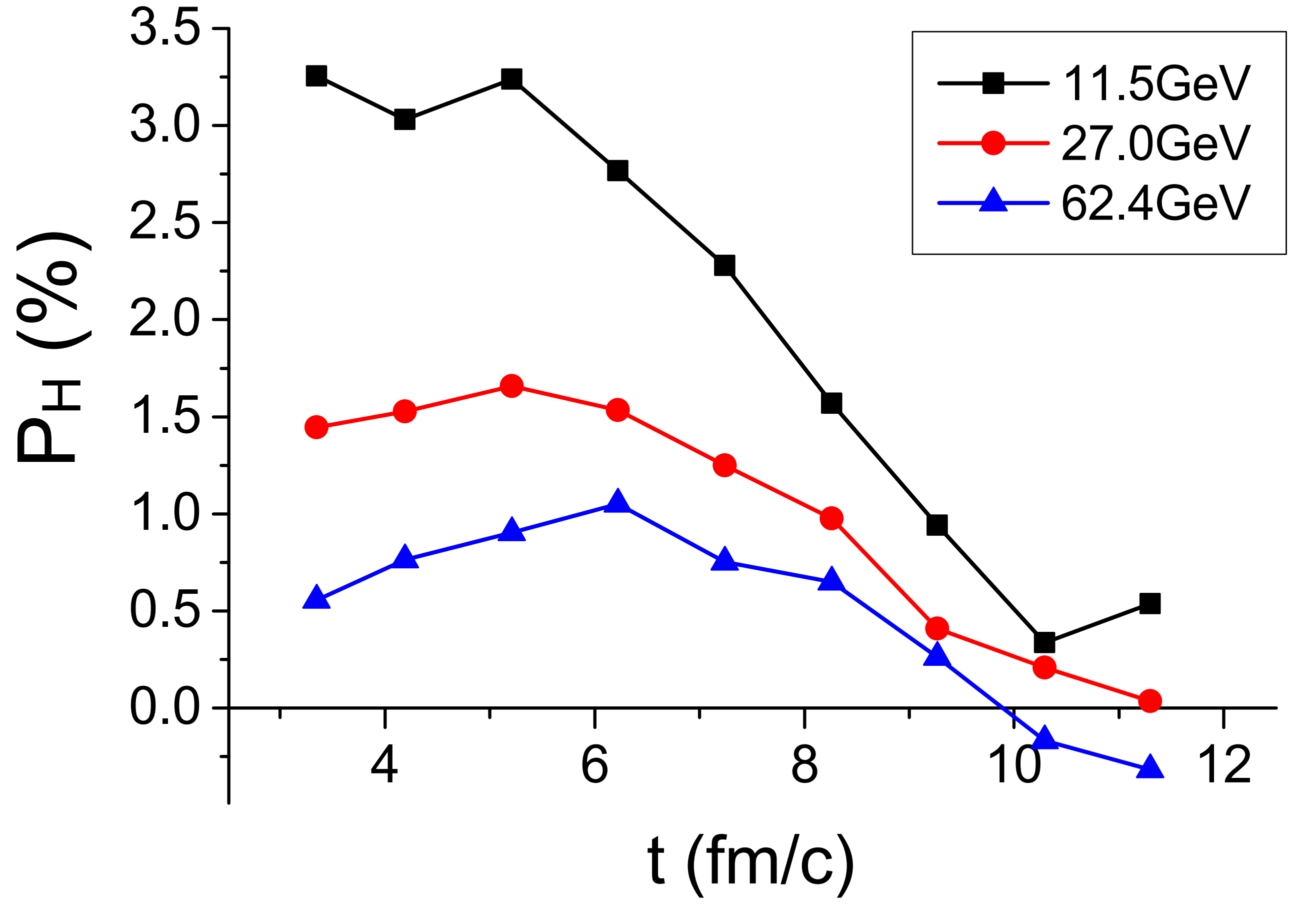
Energy dependence of global polarization

STAR, Nature 548, 62 (2017)
STAR, PRC90, 014910 (2018)



I.Karpenko, F. Becattini, EPJ(2017)77.213
Y. Xie, D. Wang, L. P. Csernai, PRC95, 031901(R) (2017)





- Stronger shear flow in forward (backward) regions + baryon stopping with finite acceptance
- Also related to unknown rapidity dependence
- Longer lifetime of system may dilute the polarization

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

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

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

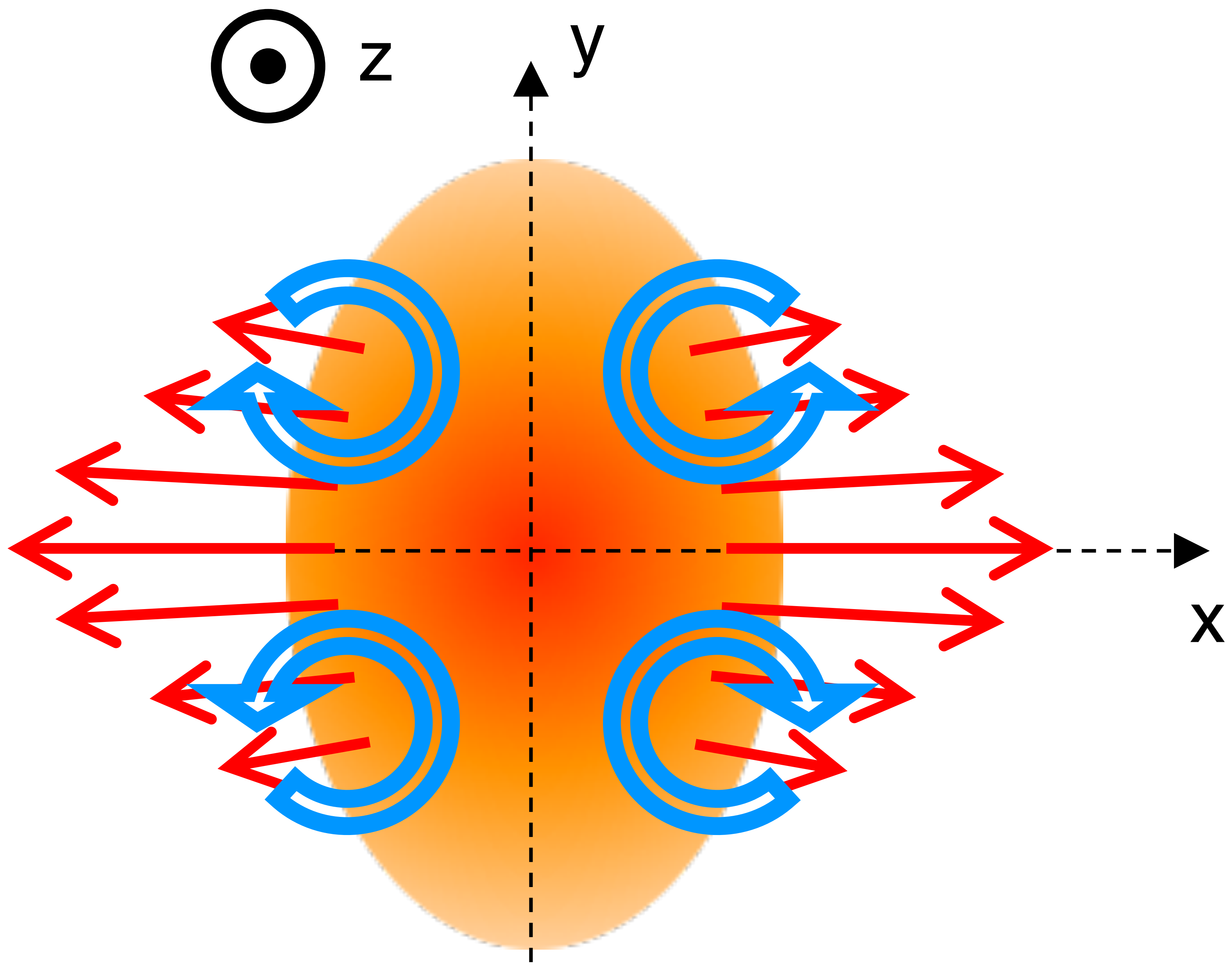
Becattini, Karpenko, Lisa, Upsal, and Voloshin, PRC95.054902 (2017)

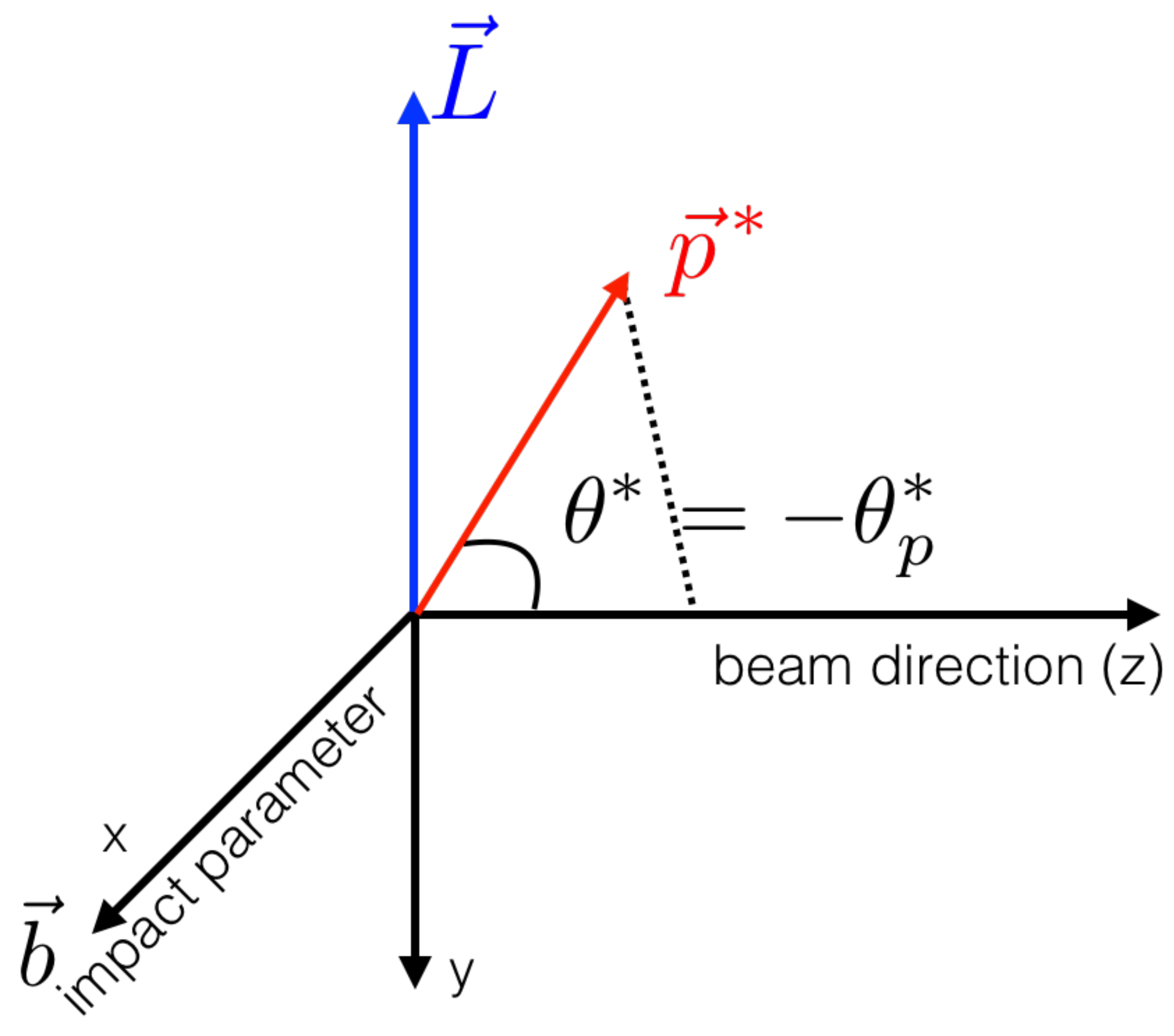
Decay	C
Parity conserving: $1/2^+ \to 1/2^+\ 0^-$	$-1/3$
Parity conserving: $1/2^- \to 1/2^+\ 0^-$	1
Parity conserving: $3/2^+ \to 1/2^+\ 0^-$	$1/3$
Parity-conserving: $3/2^- \to 1/2^+\ 0^-$	$-1/5$
$\Xi^0 \to \Lambda + \pi^0$	$+0.900$
$\Xi^- \to \Lambda + \pi^-$	$+0.927$
$\Sigma^0 \to \Lambda + \gamma$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

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 their parent polarization!** e.g. Ξ, Ω

Polarization along the beam direction

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





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

$$\begin{aligned} \langle \cos\theta_p^* \rangle &= \int \frac{dN}{d\Omega^*} \cos\theta_p^* d\Omega^* \\ &= \alpha_{\mathrm{H}} P_z \langle (\cos\theta_p^*)^2 \rangle \\ \therefore \quad P_z &= \frac{\langle \cos\theta_p^* \rangle}{\alpha_{\mathrm{H}} \langle (\cos\theta_p^*)^2 \rangle} \\ &= \frac{3\langle \cos\theta_p^* \rangle}{\alpha_{\mathrm{H}}} \quad \text{(if perfect detector)} \end{aligned}$$

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, known as elliptic flow, makes local vorticity (thus polarization) along beam axis.