Phenomena induced by vorticity and magnetic field in heavy-ion collisions

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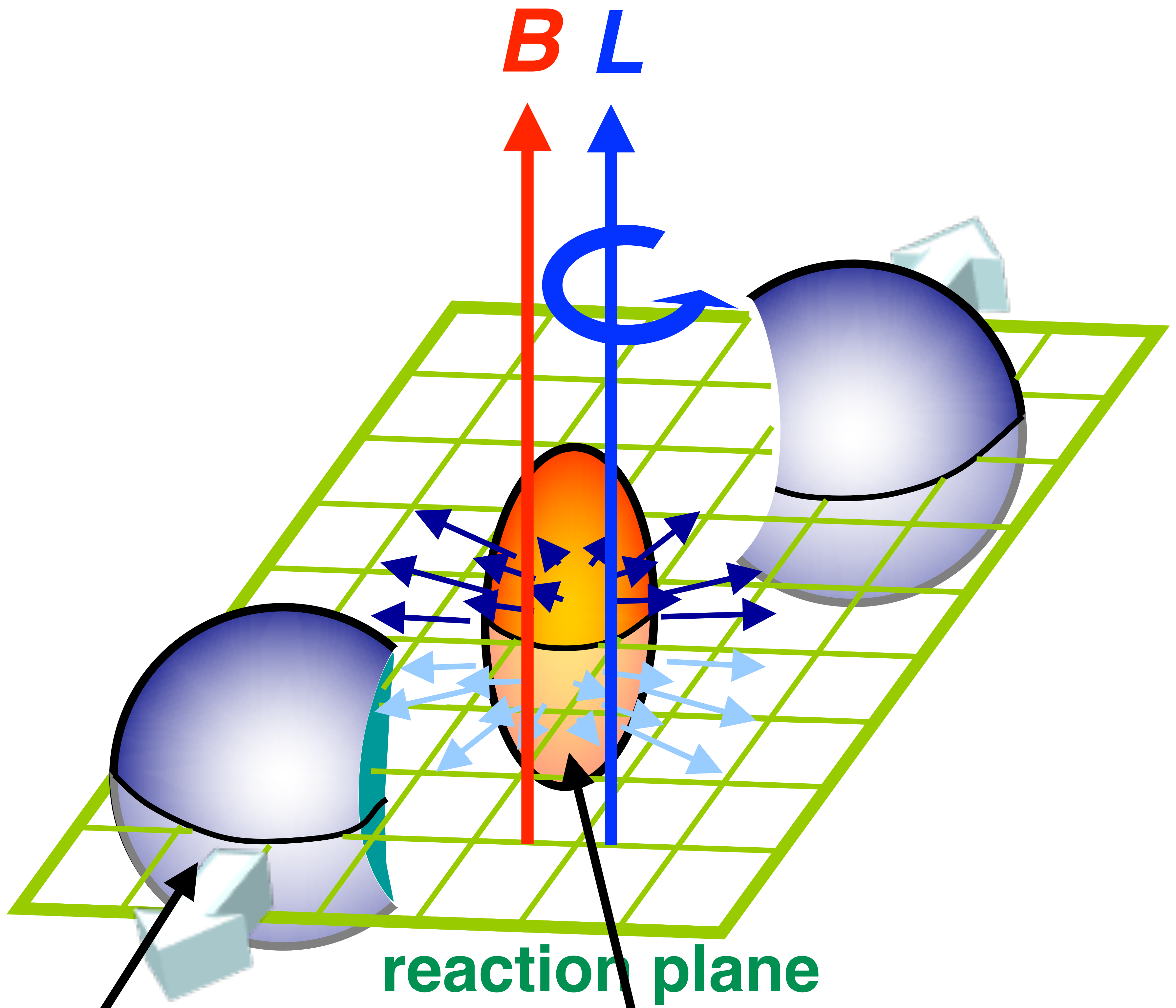
2nd International Workshop on Forward Physics and Forward Calorimeter Upgrade in ALICE

Strong fields in HIC: vorticity and electromagnetic field

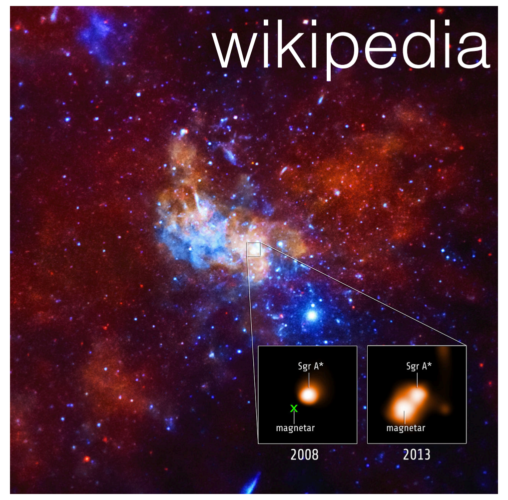


Strong magnetic field

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

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

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



magnetar

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

Orbital angular momentum

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

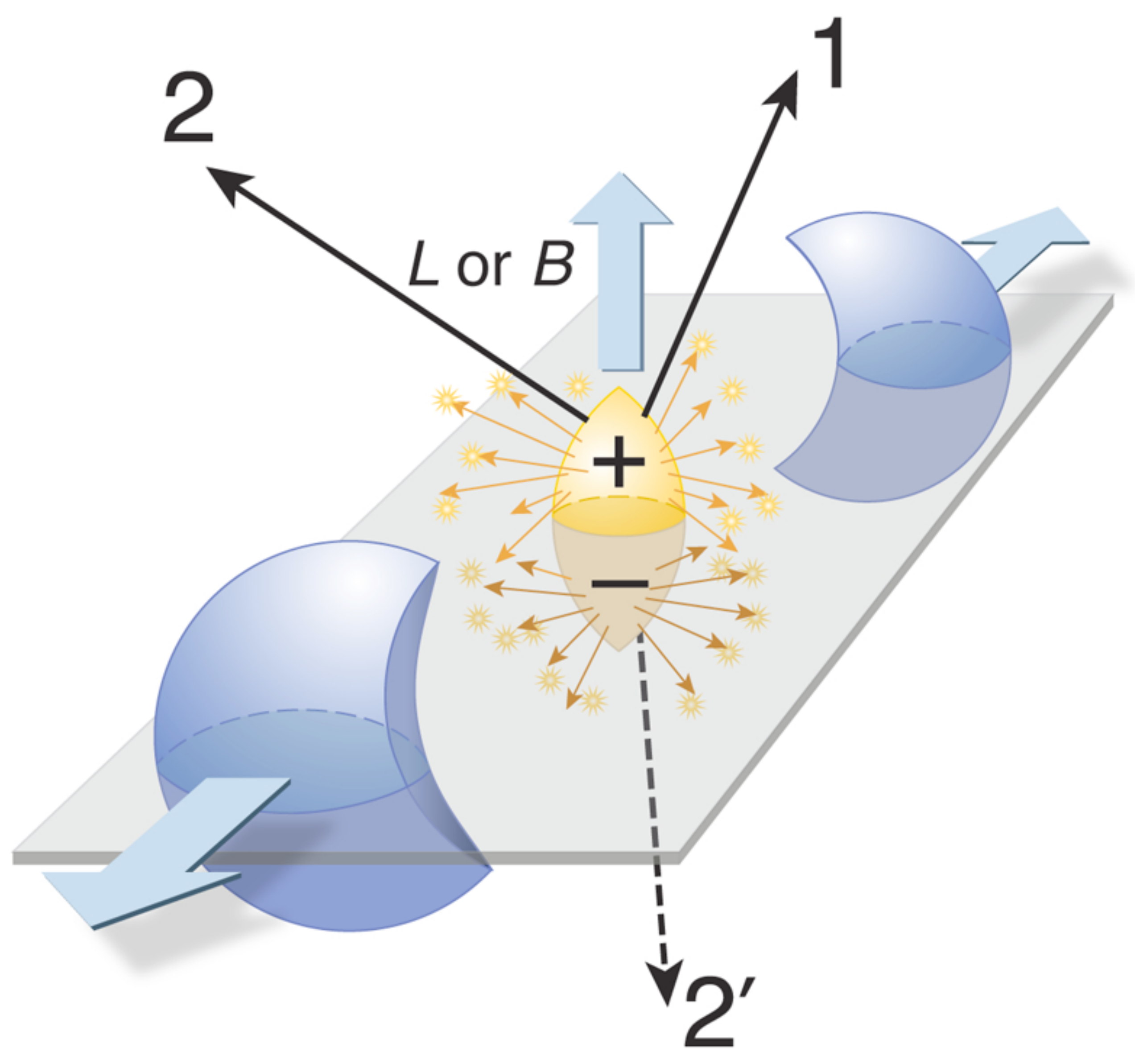
$$\sim bA\sqrt{s_{NN}} \sim 10^6 \hbar$$

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

leading to chiral magnetic/vortical effects, global polarization… etc

Chiral Magnetic Effect (CME)

D. Kharzeev, R. Pisarski, M. Tytgat, PRL81, 512 (1998)
D. Kharzeev, PPNP75(2014)133-151



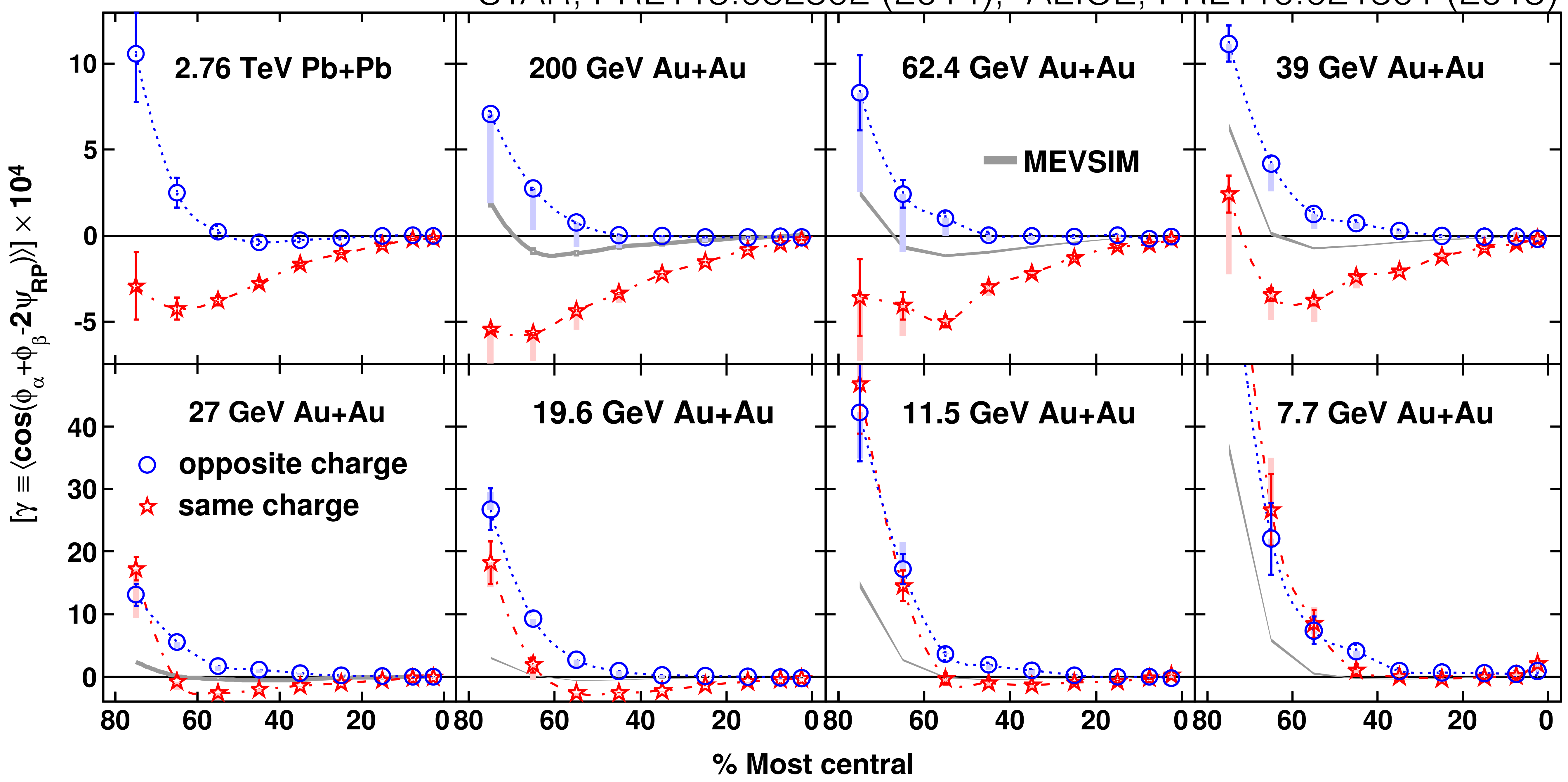
- CME: Electric current along the initial ***B***
  - Massless quarks (chiral symmetry restoration)
  - Chirality imbalance (QCD topological fluctuations)
  - Spin alignment by B-field
- "γ-correlator" often used to study charge separation

$$\gamma_{\alpha\beta} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$$

$$\Delta\gamma = \gamma_{+-} - \gamma_{\pm\pm}$$

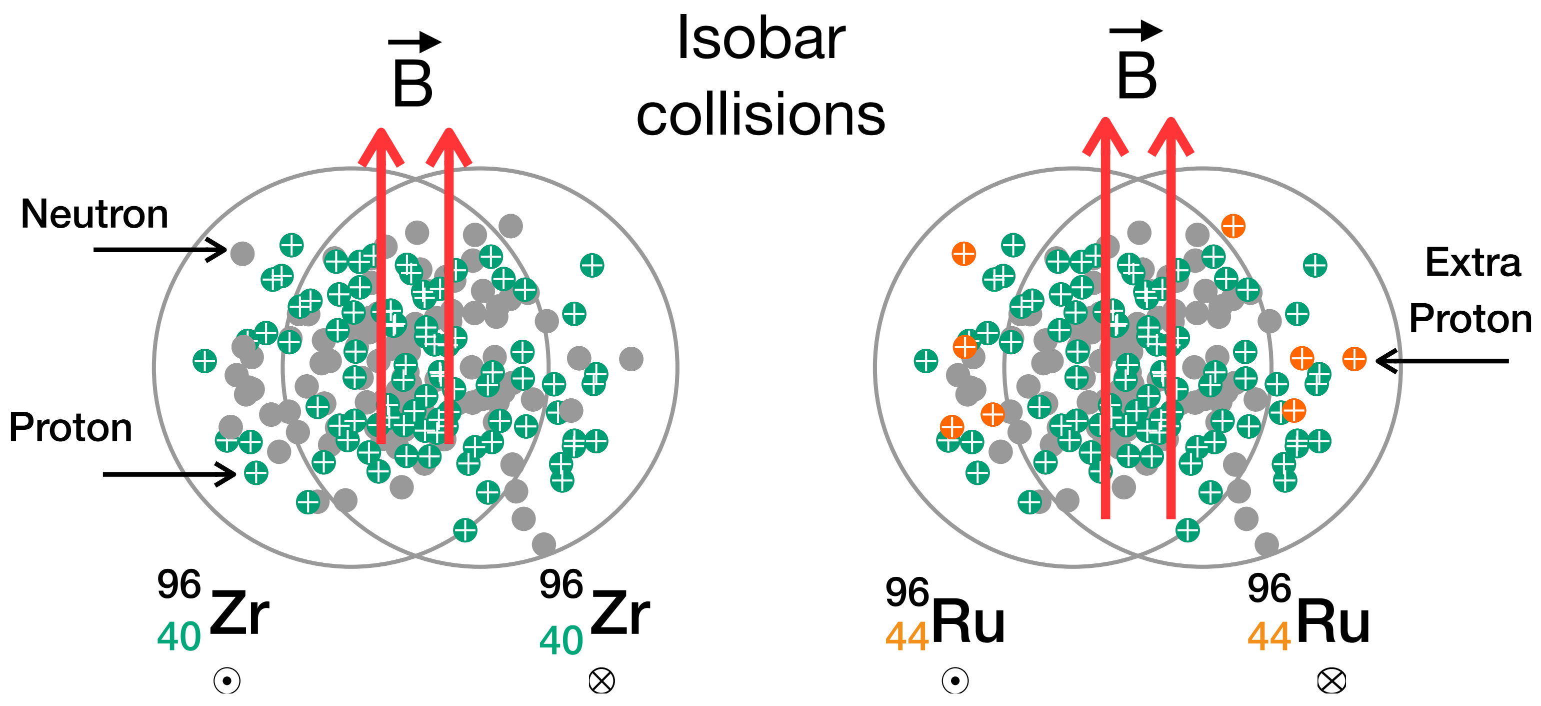
S.Voloshin PRC70, 057901 (2004)

STAR, PRL113.052302 (2014), ALICE, PRL110.021301 (2013)



CME search with isobar collisions

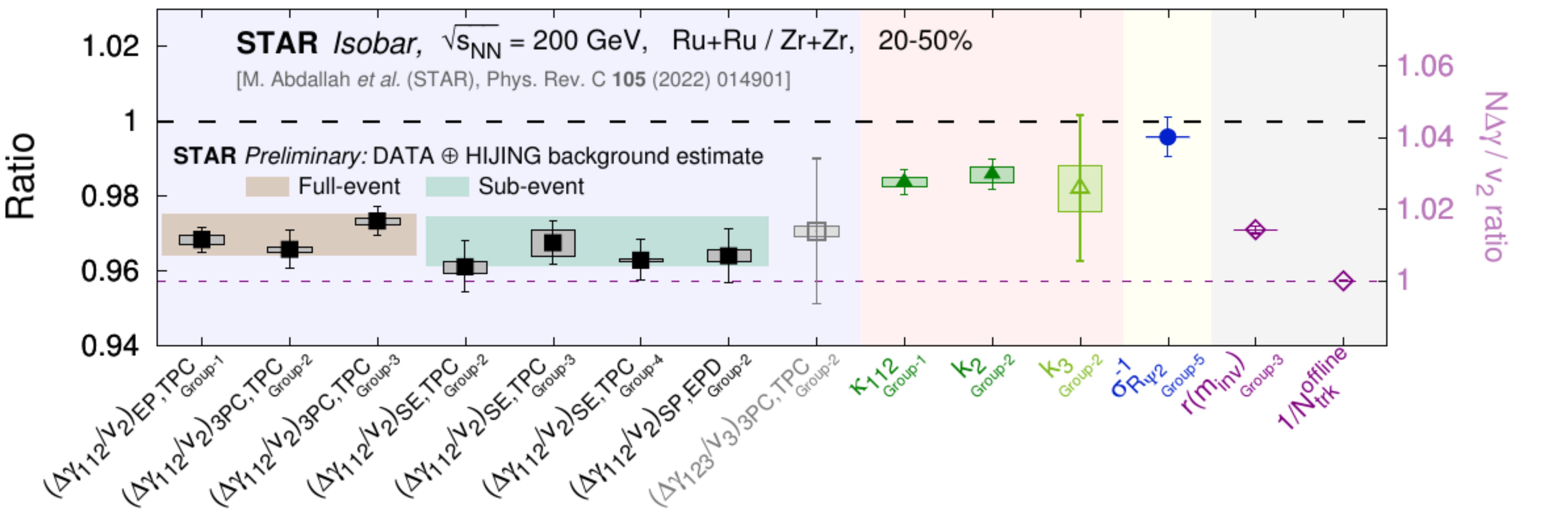
STAR, PRC105.014901 (2022)
STAR, SQM2022 for the updated baseline



$$\frac{(B^2)^{\mathrm{Ru}}}{(B^2)^{\mathrm{Zr}}} \approx 15\%$$

$$\frac{(\Delta\gamma/v_2)^{\mathrm{Ru}}}{(\Delta\gamma/v_2)^{\mathrm{Zr}}} > 1$$

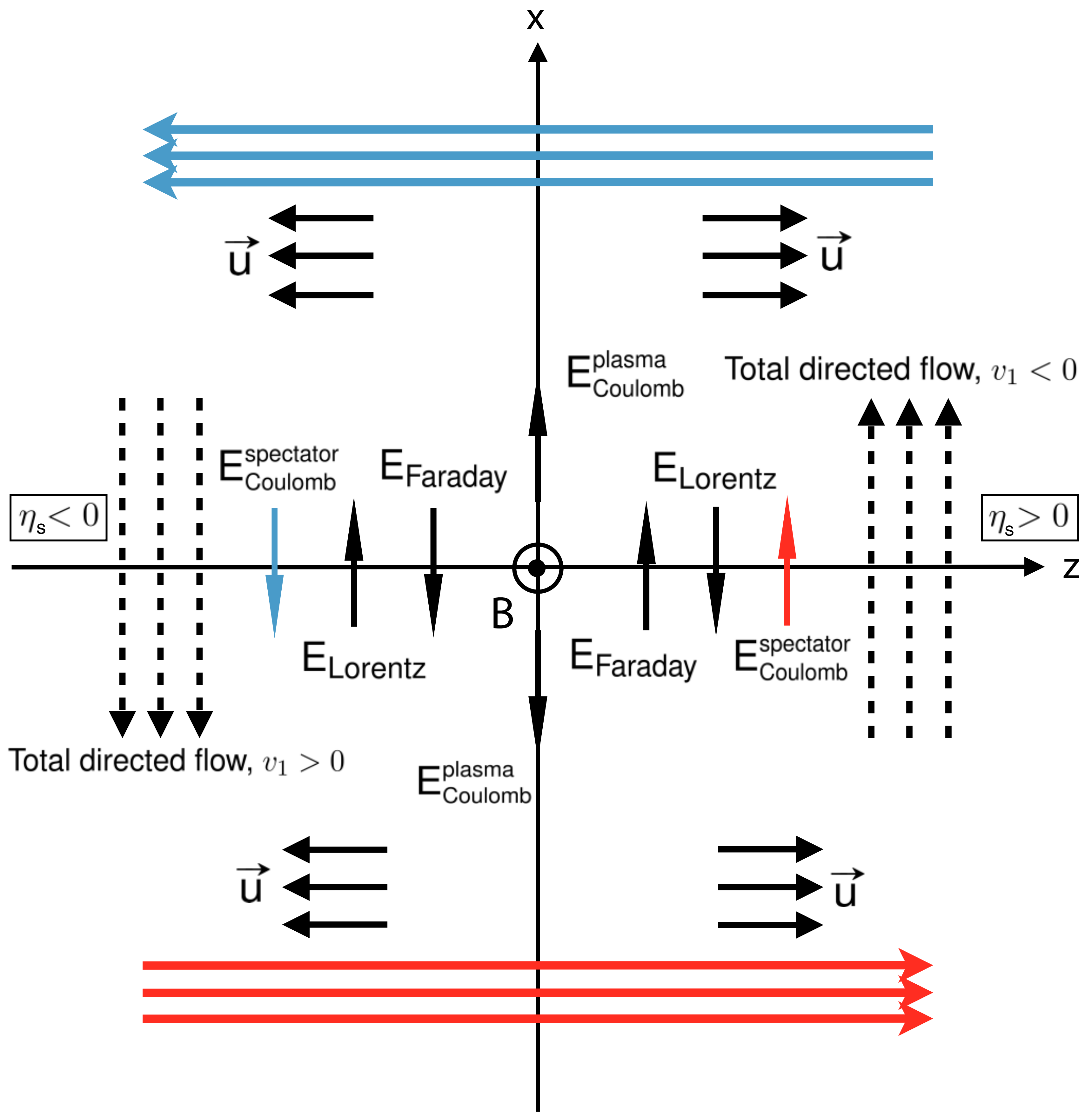
(for case of CME)



- No pre-defined signature of CME was observed in the blind analysis
  - Slight difference in multiplicity due to nuclear deformation
- Estimate of non-flow BG using HIJING, consistent with the data

EM-field effects in directed flow

U. Gürsoy et al., PRC89, 054905 (2014)
U. Gürsoy et al., PRC98, 055201 (2018)



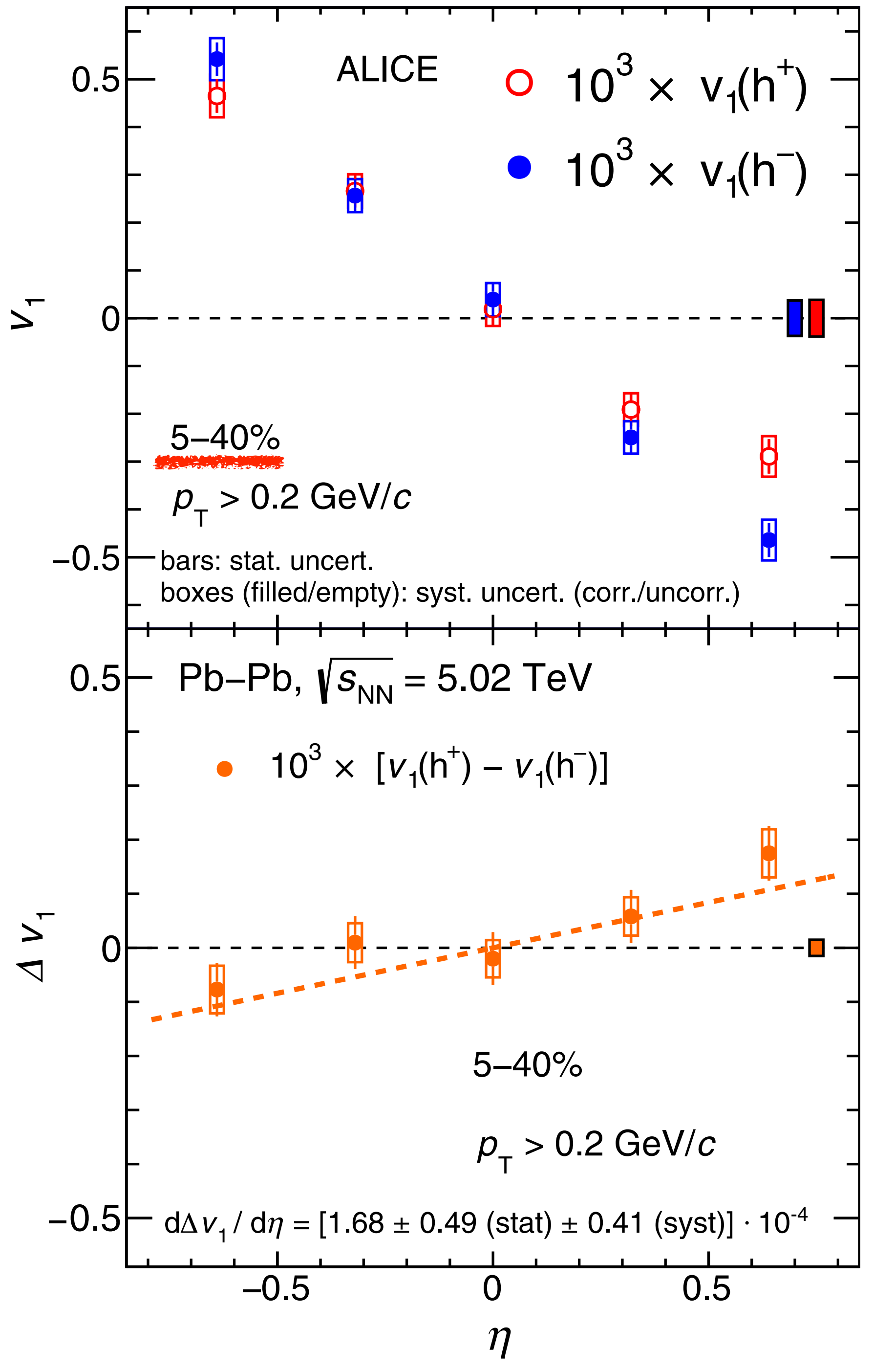
- B-field decreasing with time (Lenz's law, Faraday's law of induction)
- Moving charges feel Lorentz force (Hall effect)
- Coulomb force from spectators

All lead to charge difference of directed flow (v_1)

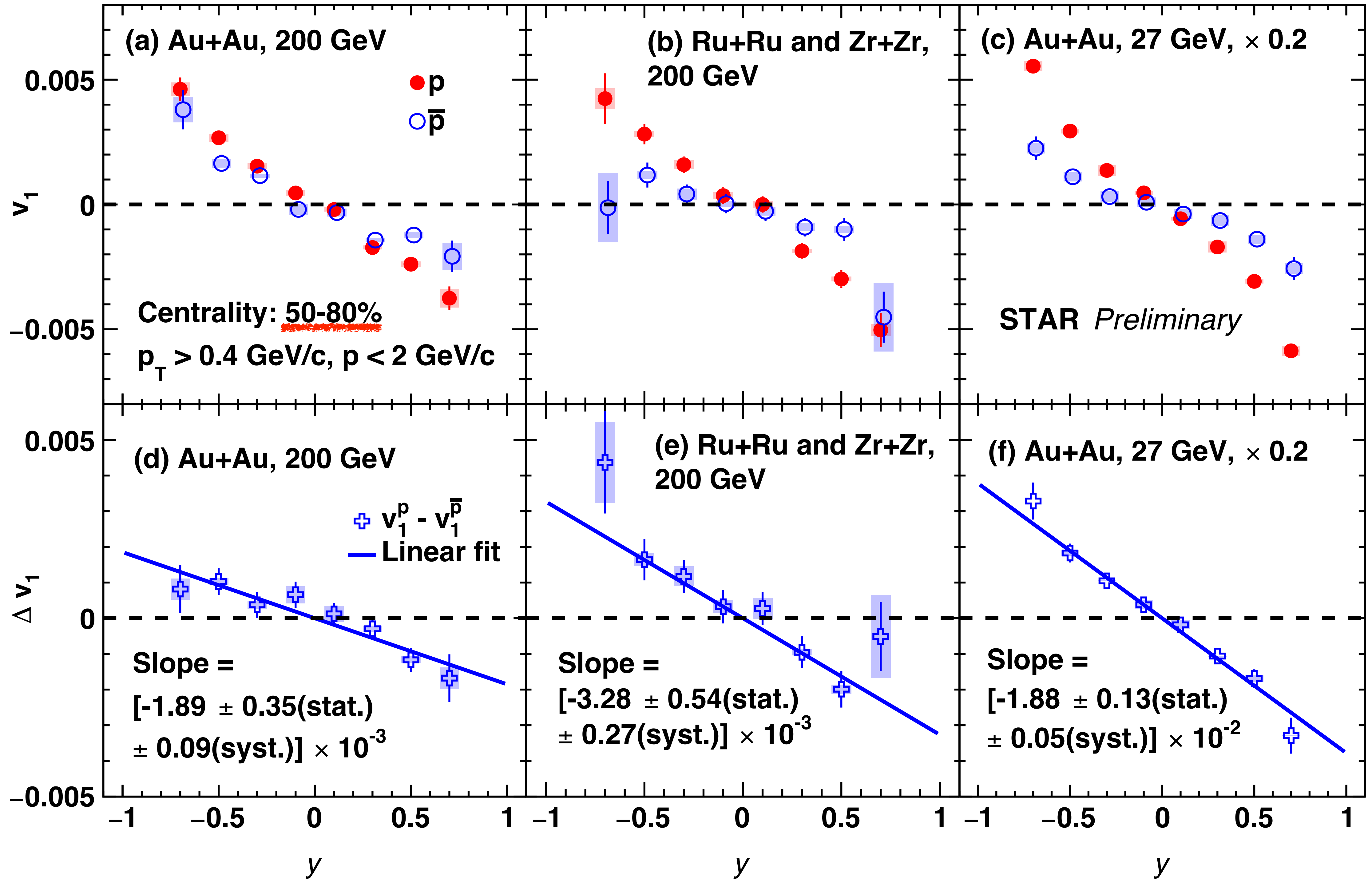
Charge-dependent directed flow

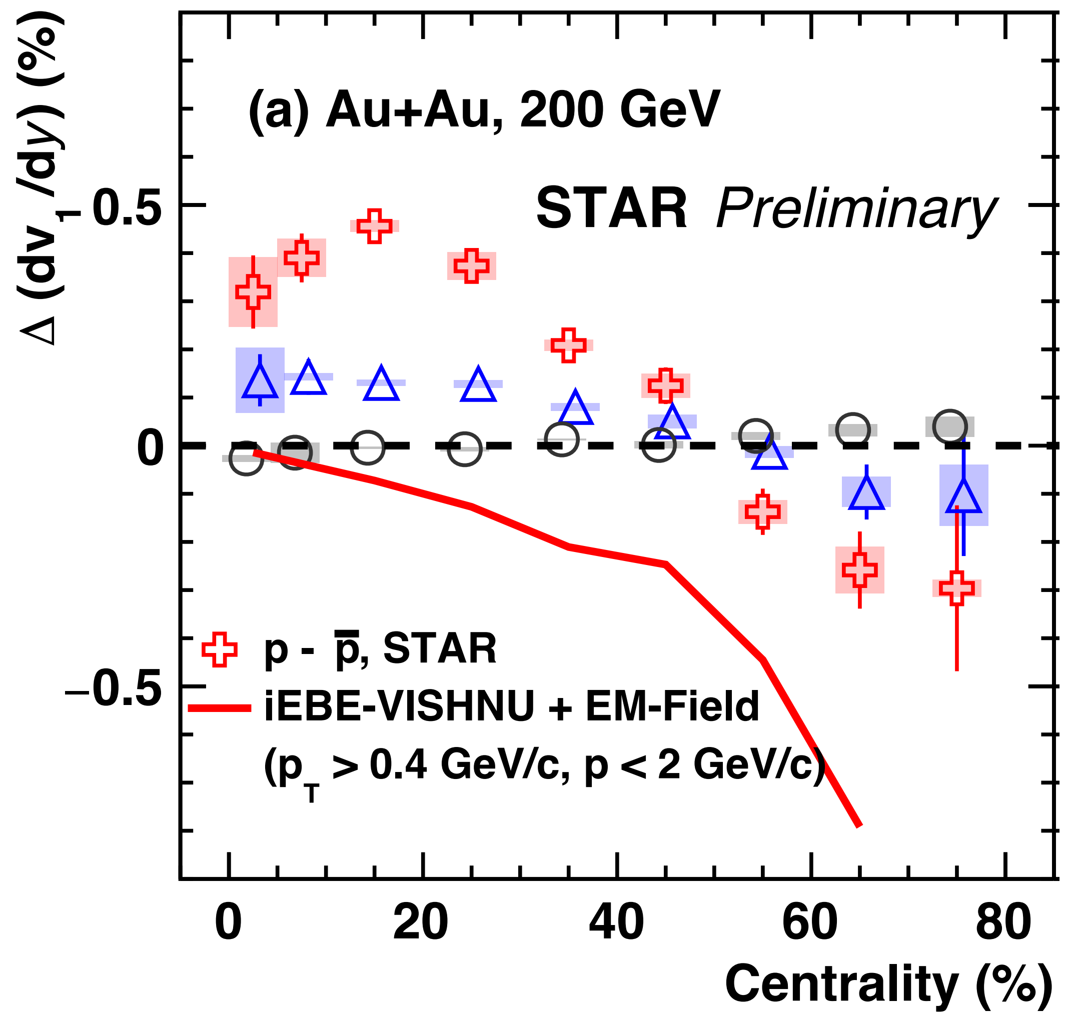
ALICE, PRL125.022301 (2020)
STAR preliminary, QM22

Pb+Pb 5.02 TeV



Au+Au 200 GeV | Isobar 200 GeV | Au+Au 27 GeV

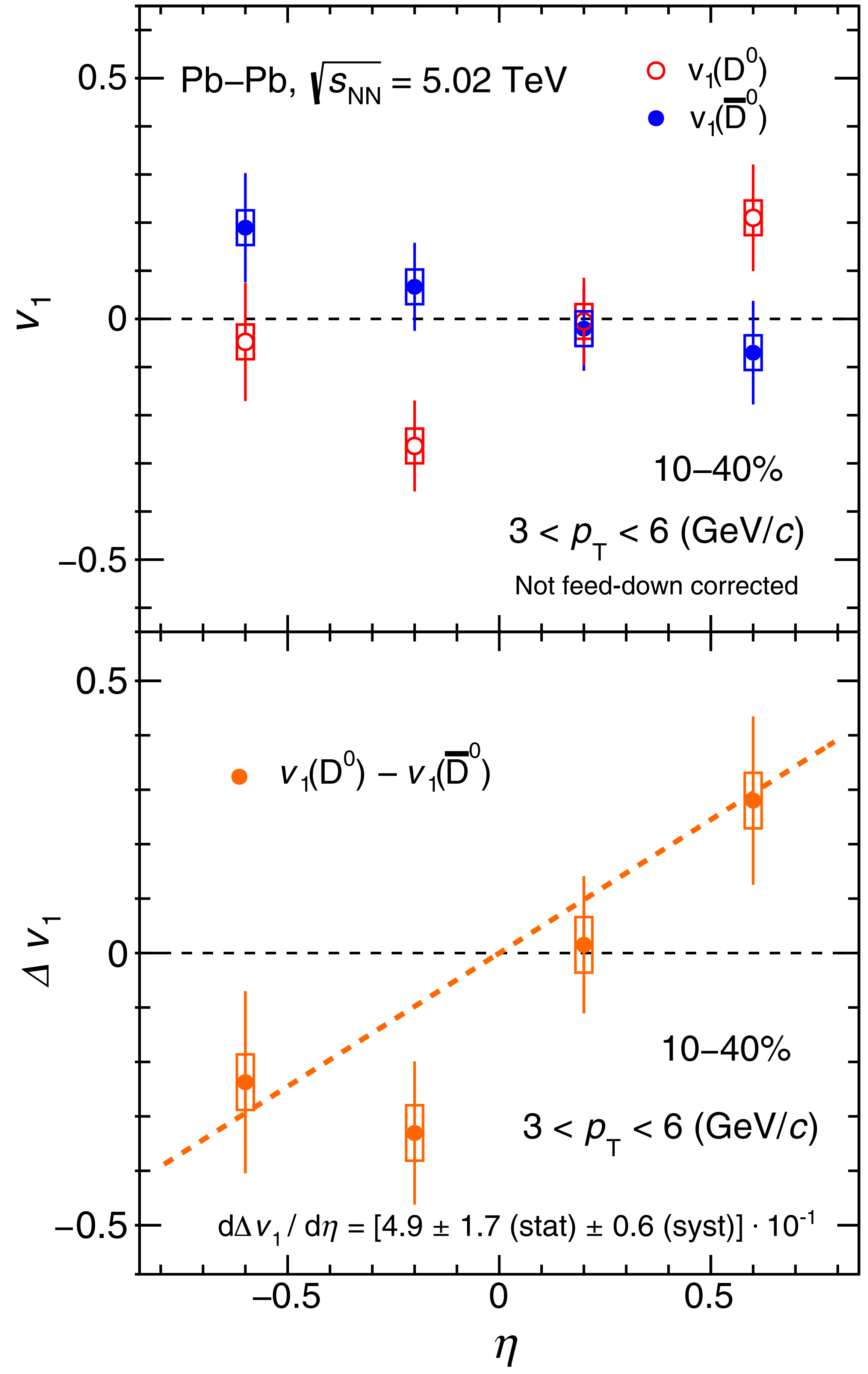


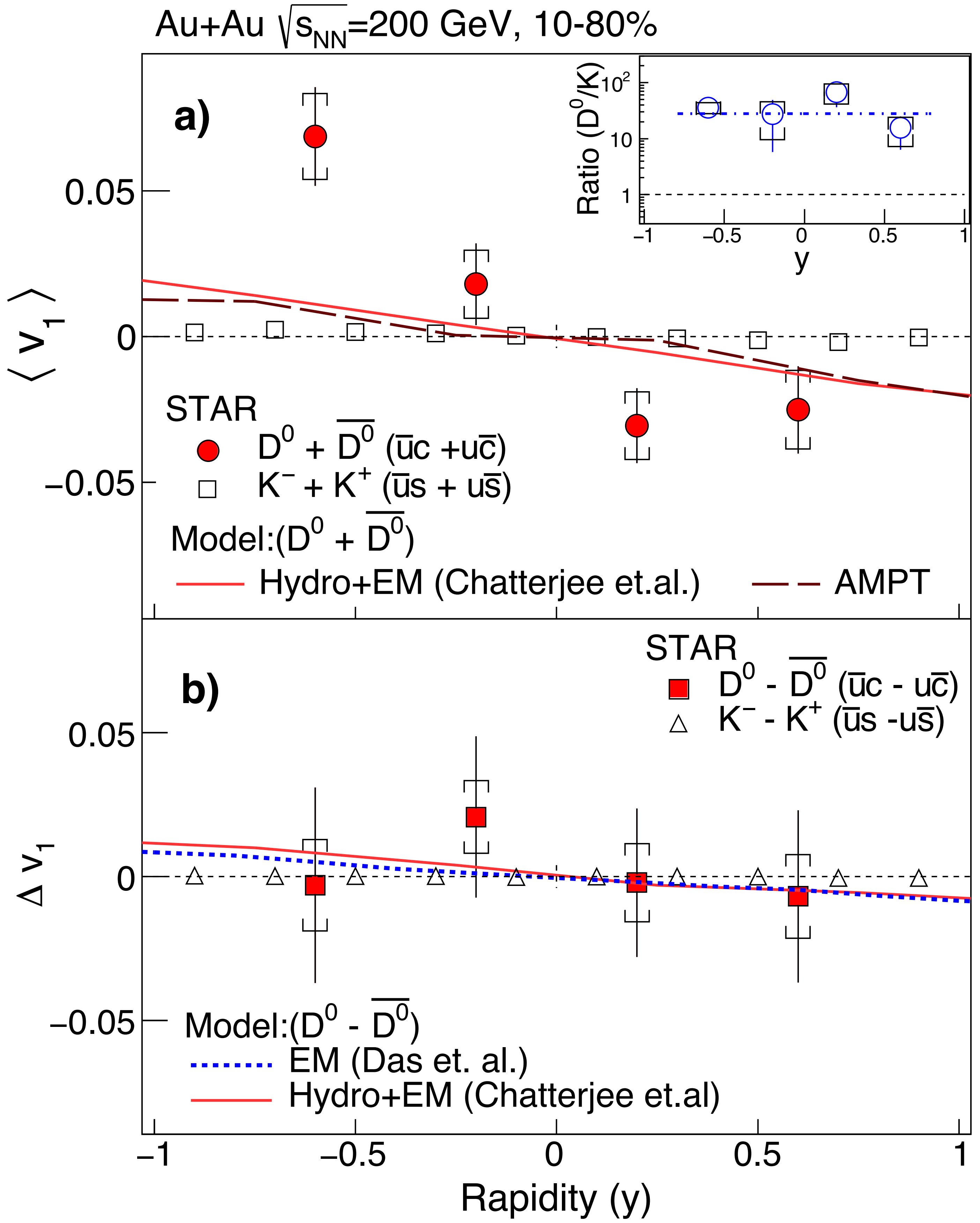


- Δv_1 (positive - negative) depends on collision energy and centrality
  - Competing: Faraday+spectator Coulomb vs. Hall effect in addition to the contribution from transported quarks
  - Negative Δv_1 slope in peripheral collisions, consistent with Faraday+spectator Coulomb
  - Larger signal in lower energy, could be explained by longer lifetime of B-field(?)

Heavy-flavor v1

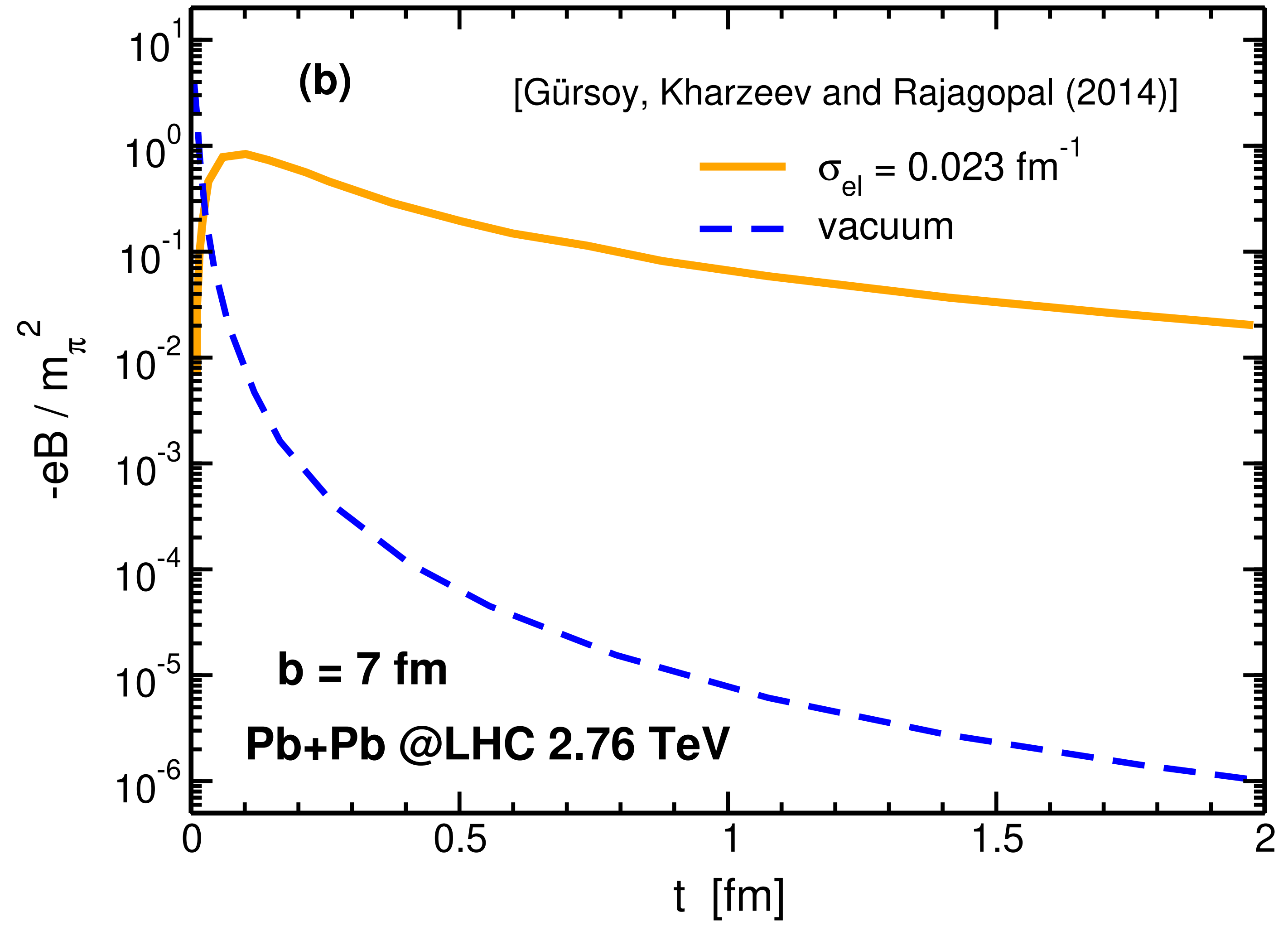
ALICE, PRL125.022301 (2020)
STAR, PRL123.162301 (2019)



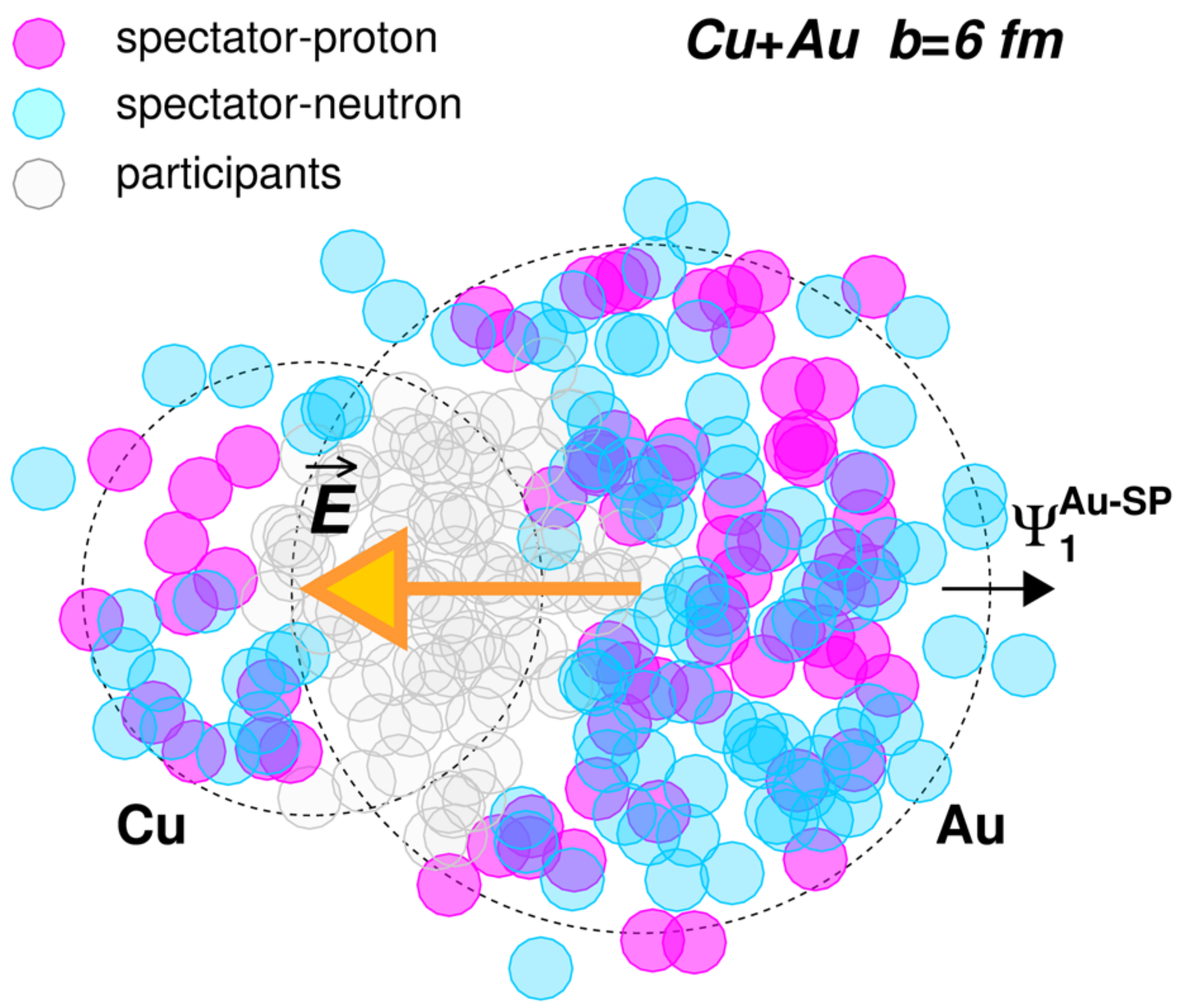


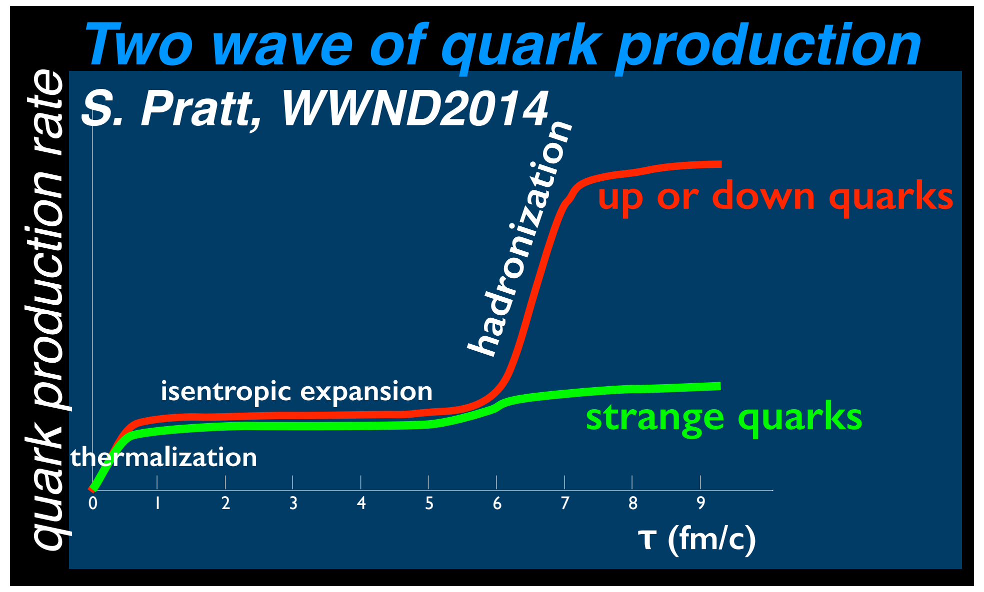
- Better sensitivity to the initial B-field
  - Formation time of heavy quarks ~0.1 fm/c, close to the time when B-field becomes maximum
- Looks opposite slopes at the LHC and RHIC but not so significant

U. Gürsoy et al., PRC89, 054905 (2014)
L. Oliva, EPJA56, 255 (2020)

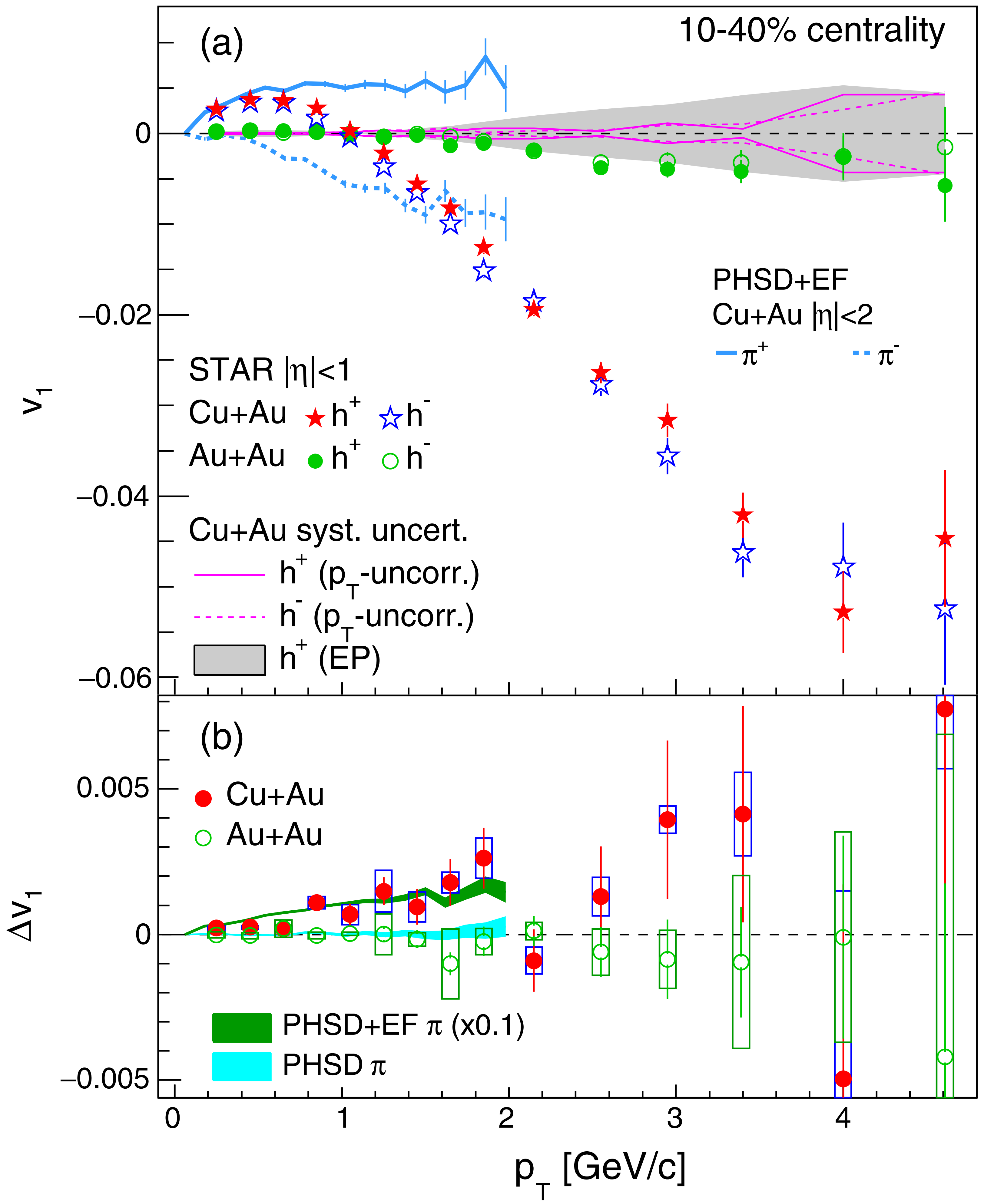


v_1 in asymmetric collisions





STAR, PRL118.012301 (2017)



Charge-dependent v_1 due to the initial E-field

- Sensitive to electric conductivity of QGP

  Y. Hirono, M. Hongo, and T. Hirano, PRC90.021903(R) (2014)

- Sensitive to the quark production time

  V. Voronyuk et al, PRC90.064903 (2014)

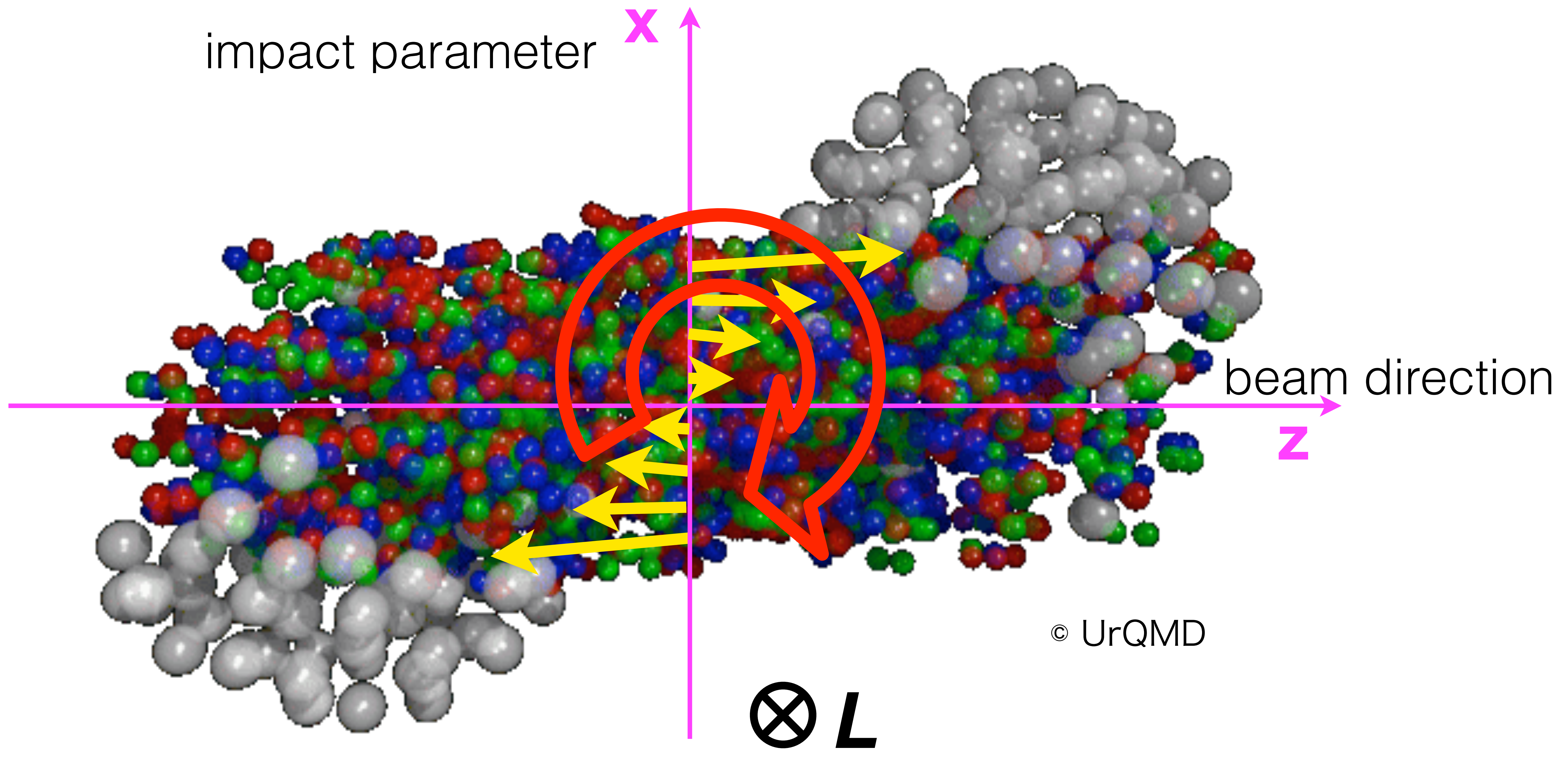
Only ~10% of (anti)quarks are created at the time when E-field is strong (t<0.25 fm/c)

＊based on PHSD model + E-field (assume charge creation at t=0)

Vorticity and "global" polarization

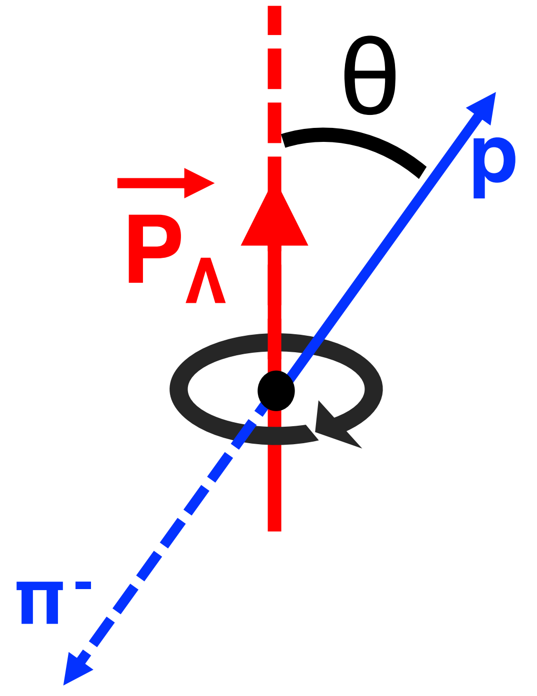
Longitudinal shear flow is produced, where flow velocity v_z depends on x.

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



Particles "globally" polarized along ***L***

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)

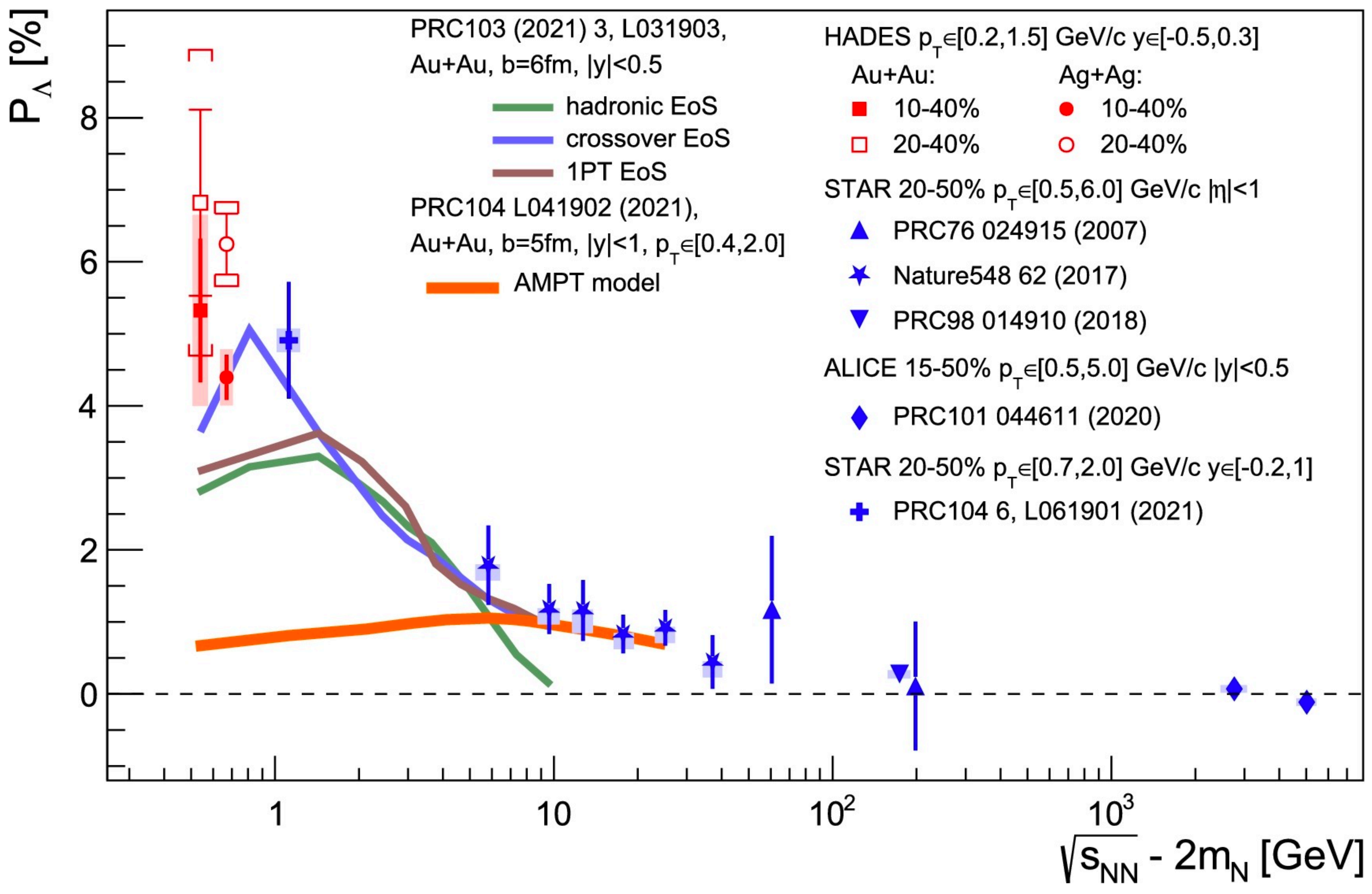


$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_H \mathbf{P}_H^* \cdot \hat{\boldsymbol{p}}_B^*)$$

Parity-violating weak decay of hyperons can be used!

Λ global polarization

STAR, Nature 548, 62 (2017), PRC90, 014910 (2018)
PRC104, L061901 (2021)
ALICE, PRC101, 044611 (2020)
HADES, PLB835, 137506 (2022)



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, PRC103, L031903 (2021), 3FD model
Y. Guo et al., PRC104, L041902 (2021) AMPT

- Continuously increasing down to $\sqrt{s_{NN}}$~2.5 GeV
    - Baryon stopping at mid-rapidity, system lifetime
    - Various models describe the trend

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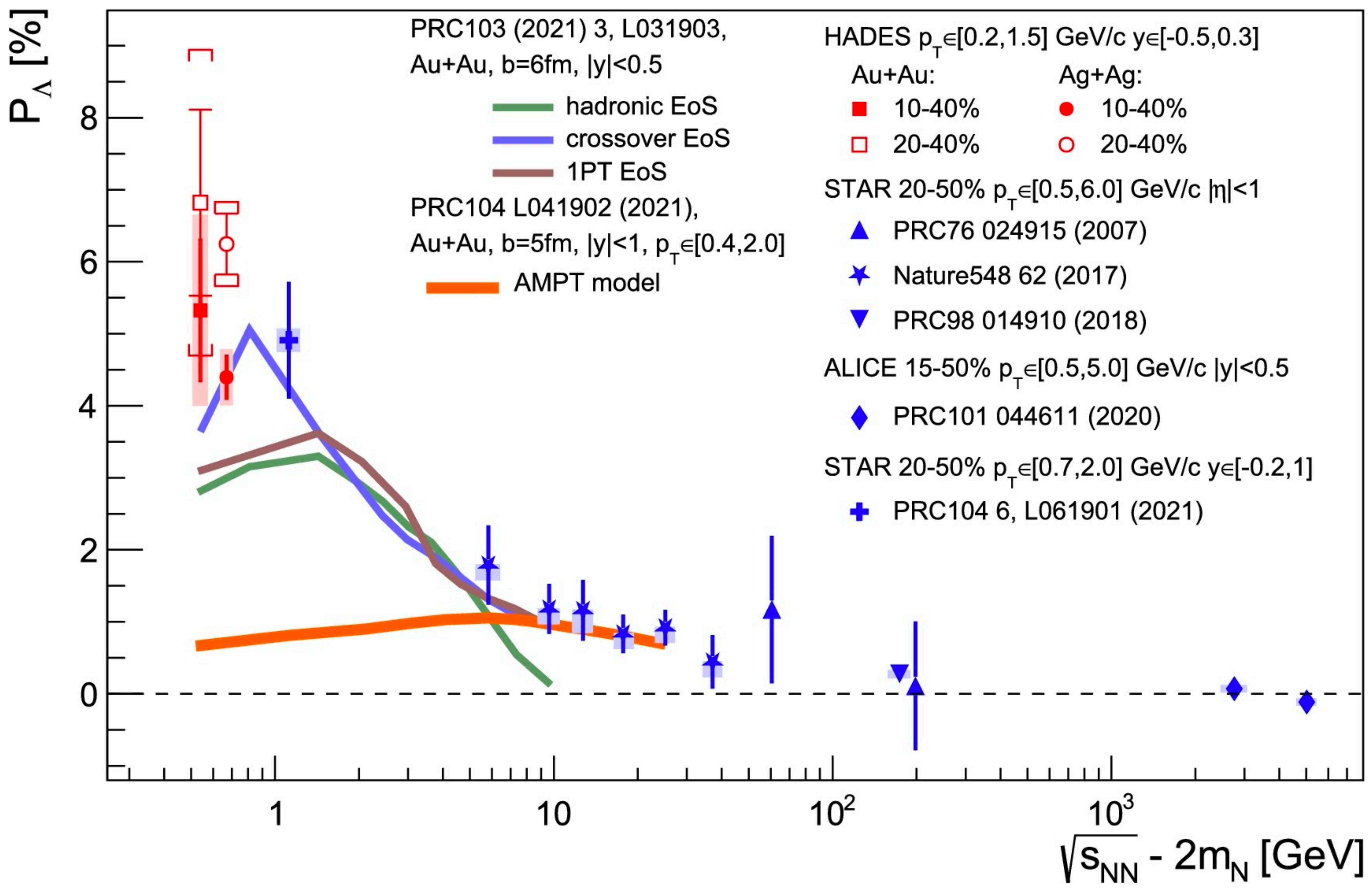

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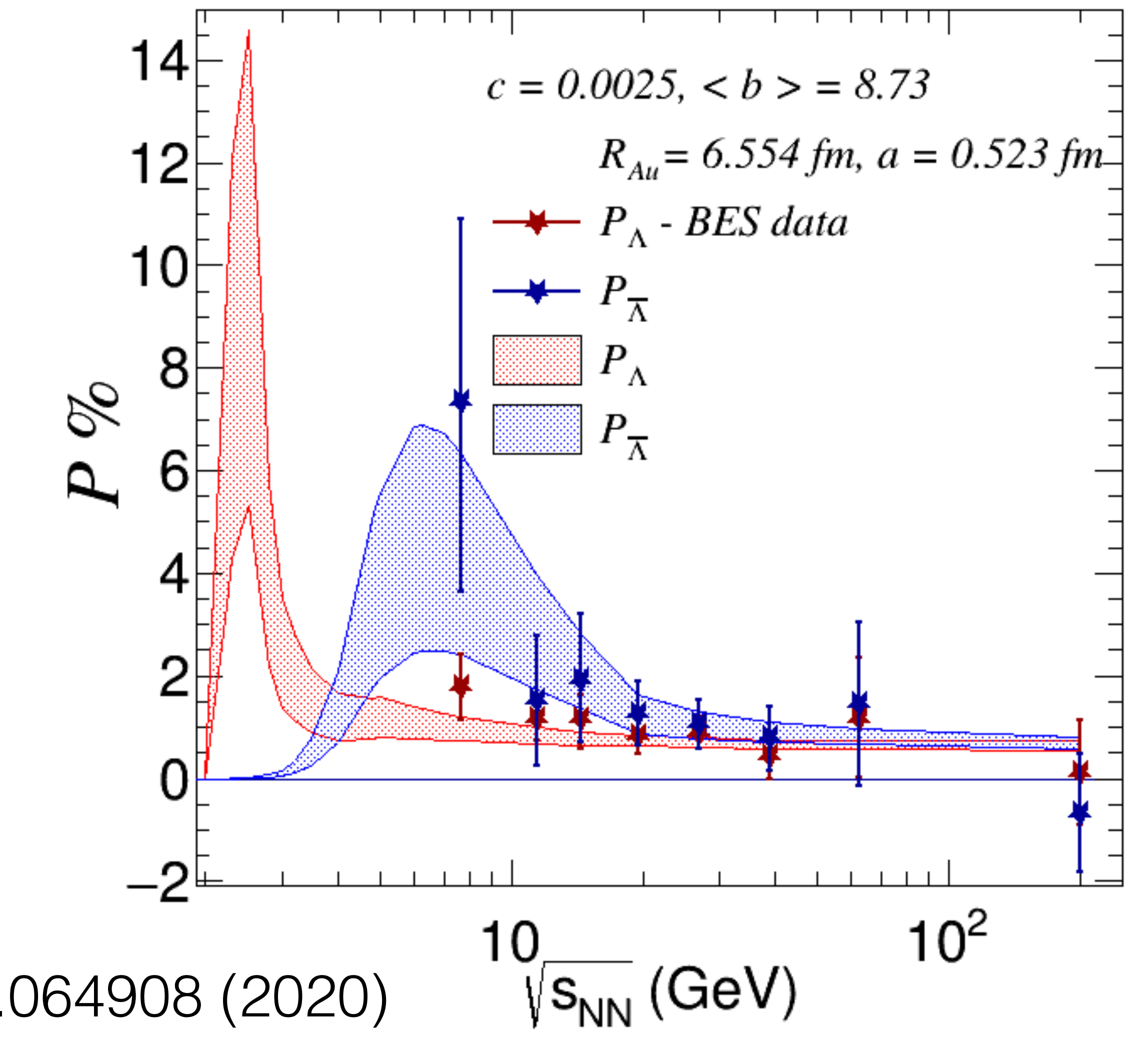

X.-G. Deng et al., PRC101.064908 (2020)
A. Ayala et al., PRC105.034907 (2022)

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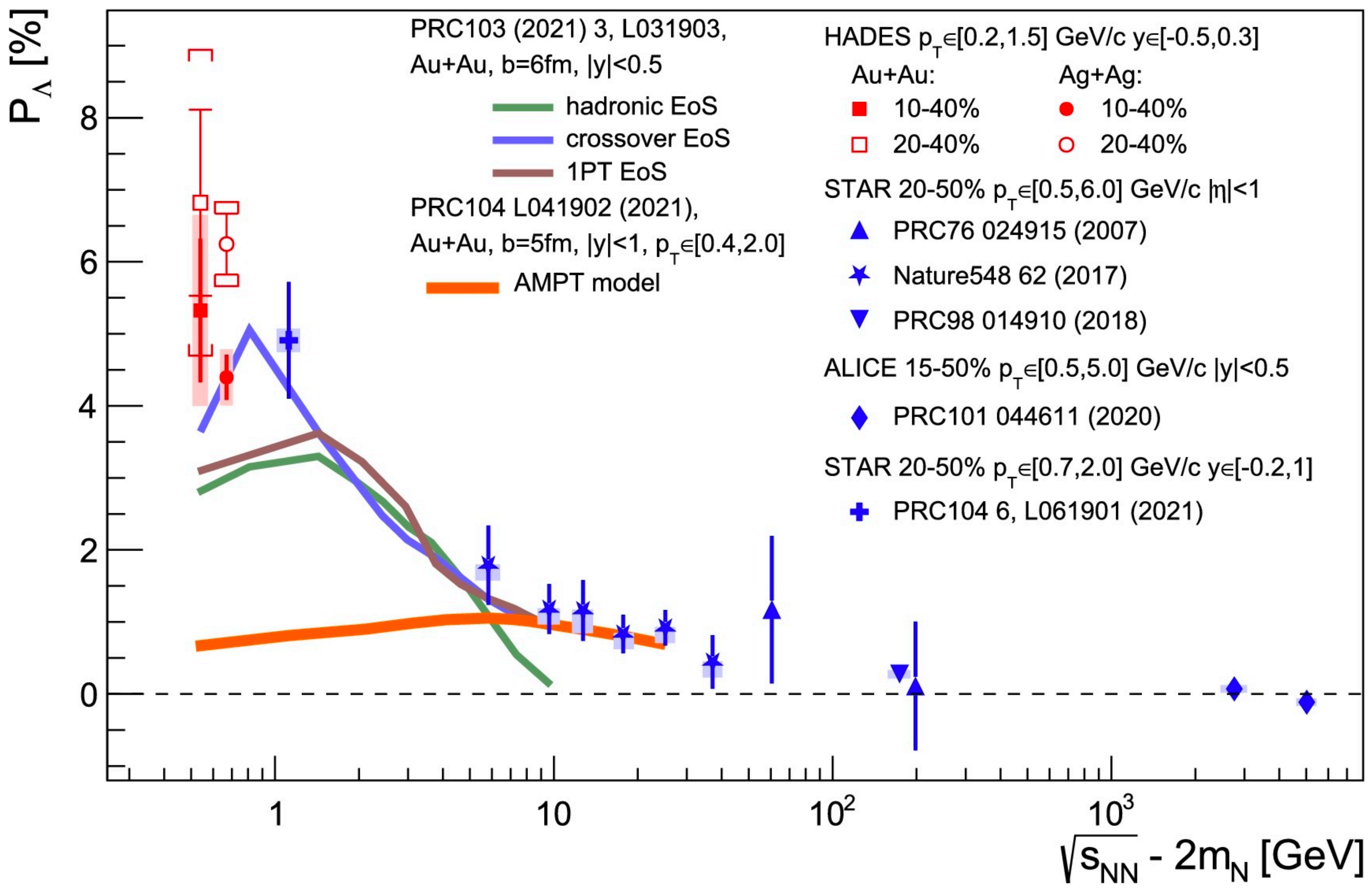

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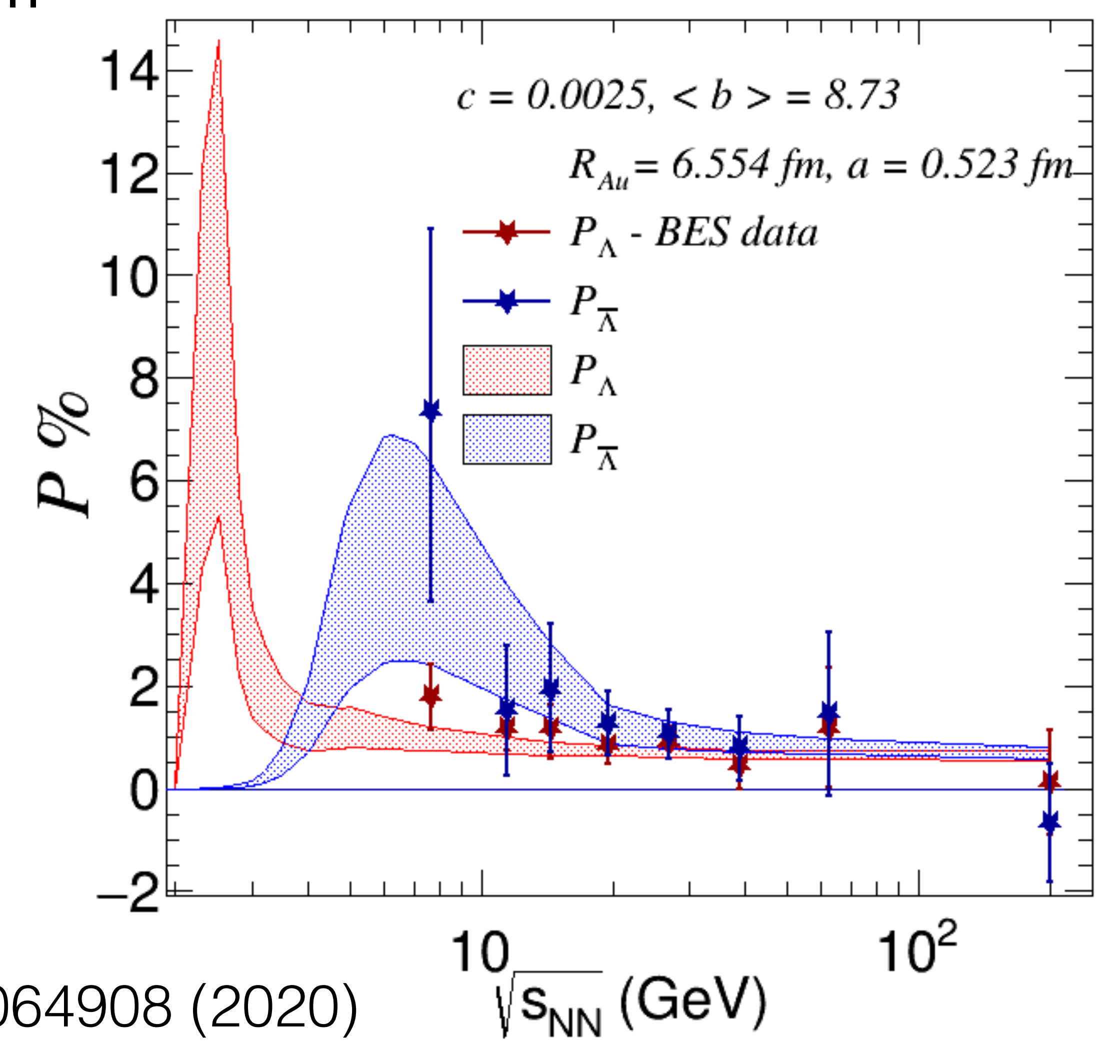
- Continuously increasing down to $\sqrt{s_{NN}}$~2.5 GeV
  - Baryon stopping at mid-rapidity, system lifetime
  - Various models describe the trend
  - Models predict a maximum polarization around $\sqrt{s_{NN}}$ = 3 GeV
  - Possible slope change around $\sqrt{s_{NN}}$~8 GeV, related to change in medium property? i.e. from partonic to hadronic matter
    - More data will come from STAR BES-II



X.-G. Deng et al., PRC101.064908 (2020)
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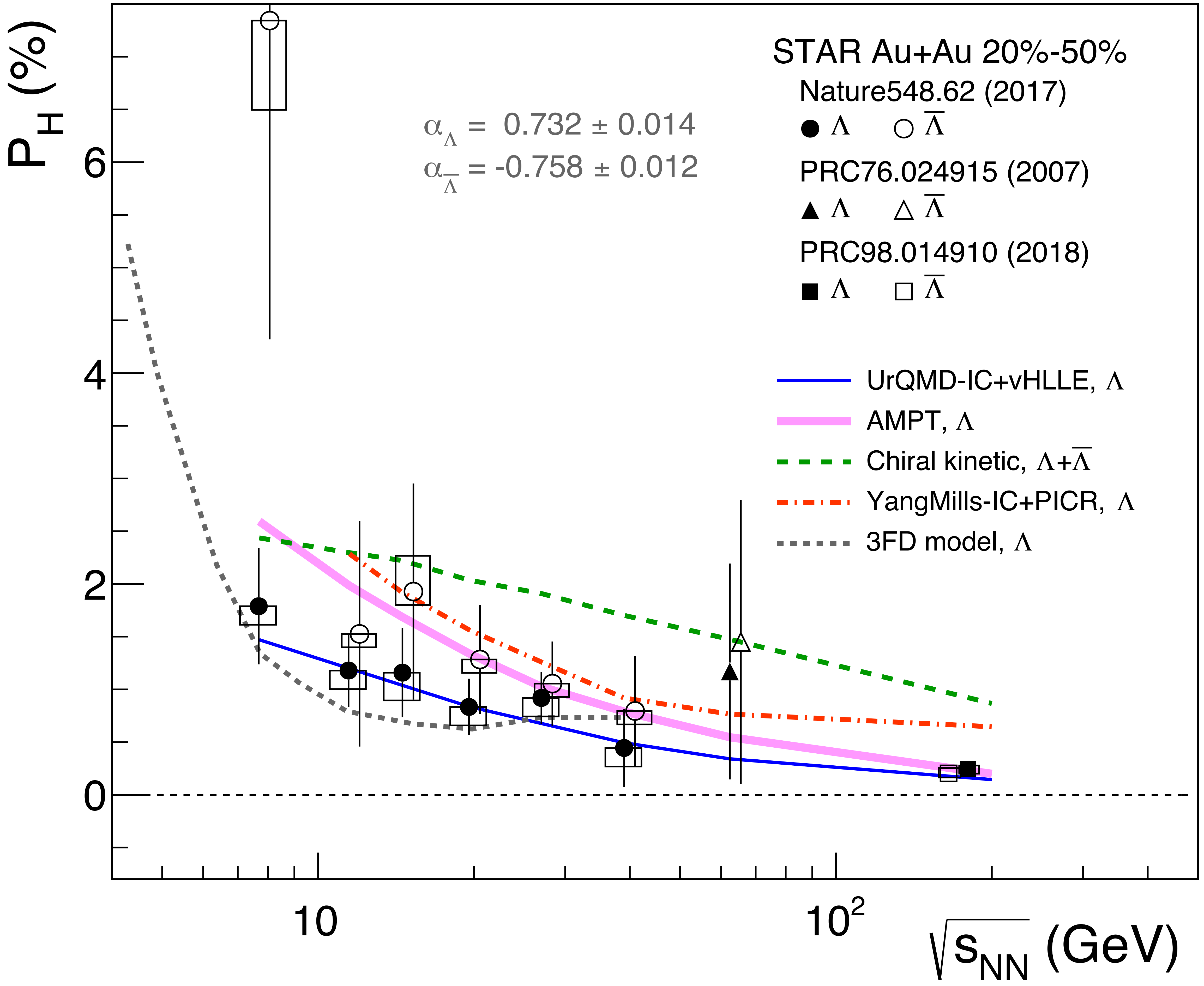
Possible splitting due to B-field?

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



- Possible difference between Λ and anti-Λ
  - s-quarks polarized at early times, then coalesce to Λ
  - Λ at the time of hadronization polarized due to late-time B-field

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

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

μ_Λ: Λ magnetic moment.
Note that $\mu_\Lambda = -\mu_{\Lambda bar}$ and $\mu_\Lambda = -0.613\mu_N$
T: Temperature at thermal equilibrium

- Constraint on the upper limit of later-time B-field

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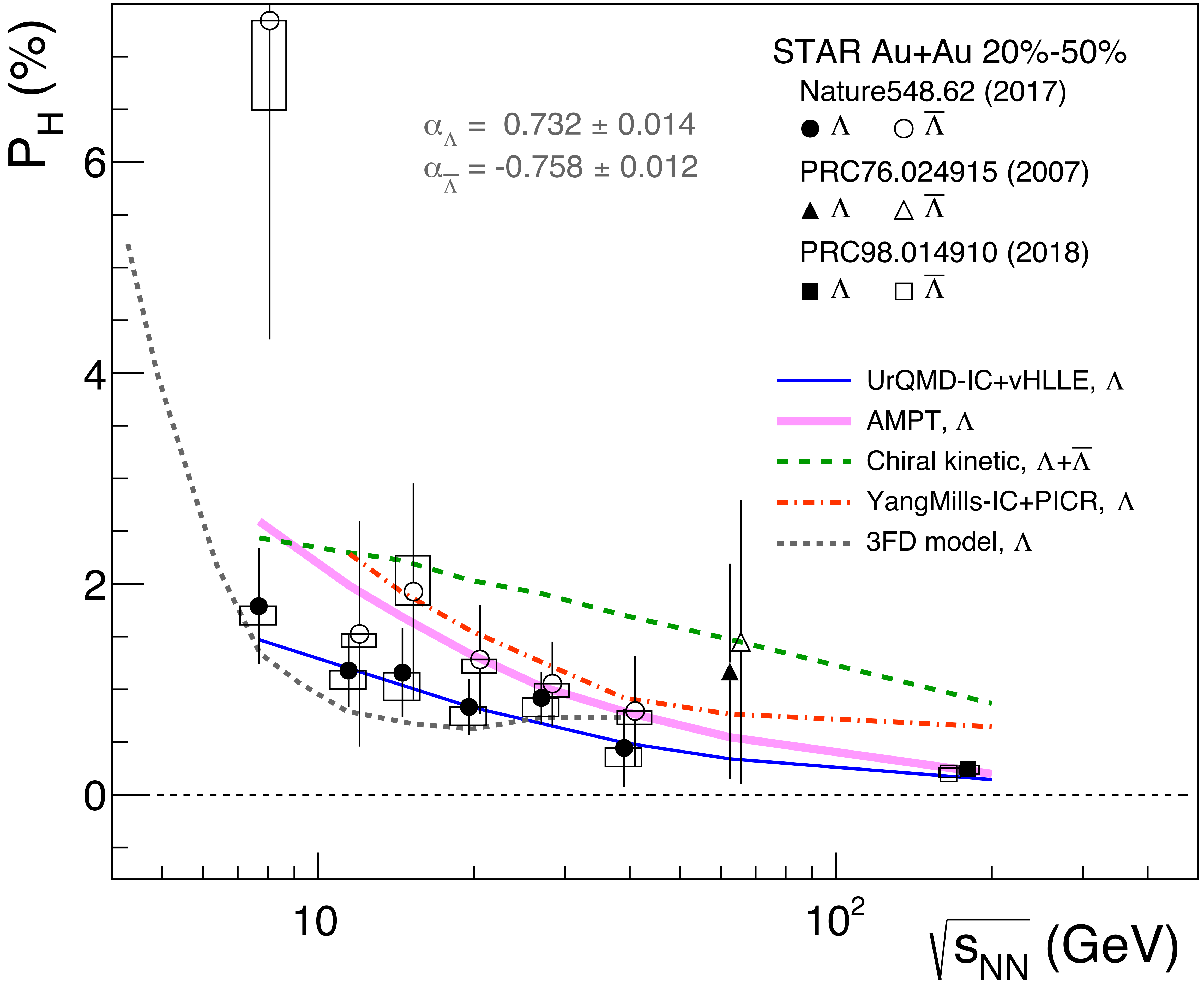

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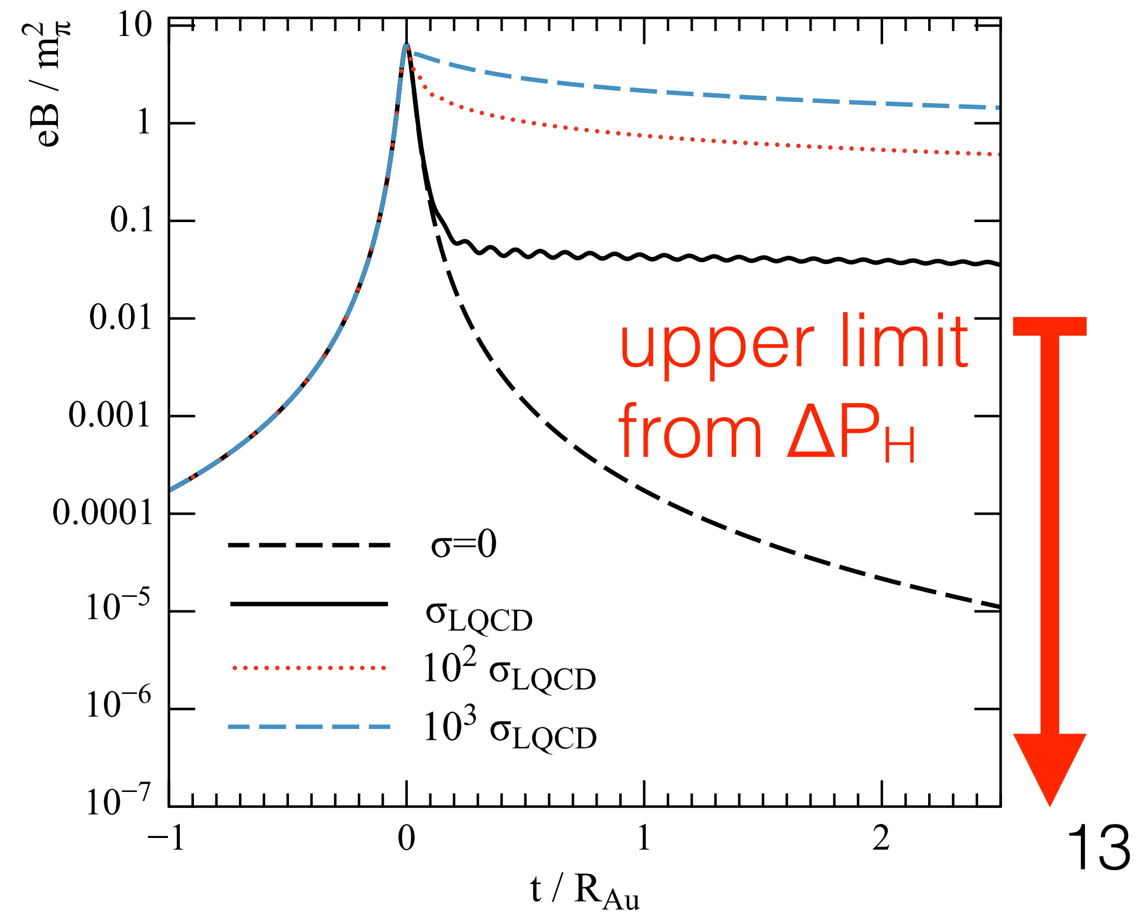
$$|B| = \frac{T_s|\Delta\mathcal{P}|}{2|\mu_\Lambda|} < 8.9 \times 10^{11}\ \mathrm{T}$$

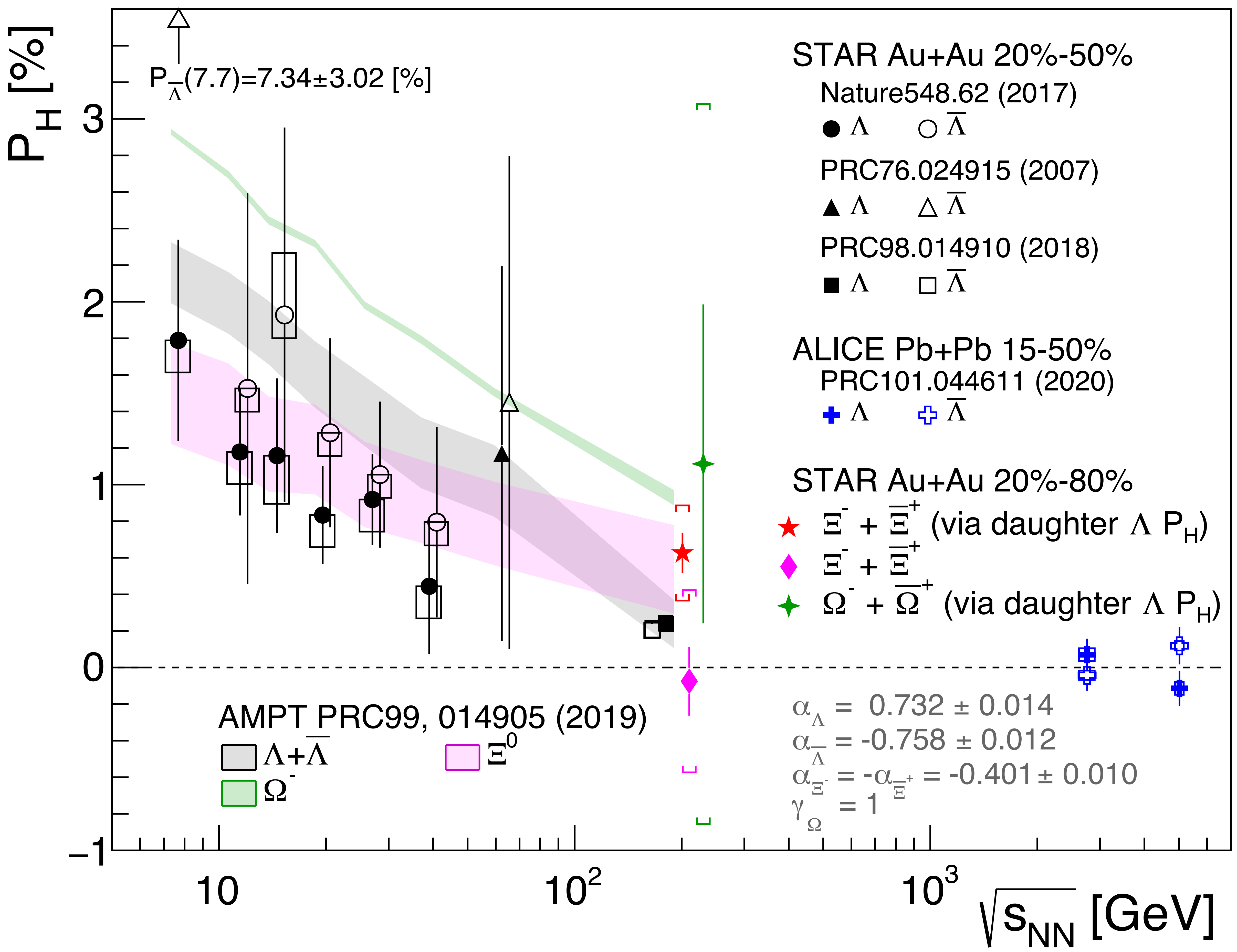
B. Müller and A. Schäfer, PRD98, 071902(R) (2018)

L. McLerran and V. Skokov, NPA929.184 (2014)



Global polarization of multistrangeness

STAR, PRL126, 162301 (2021)



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

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

- Likely hierarchy in P_H, though not significant yet

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

(20-80% centrality)

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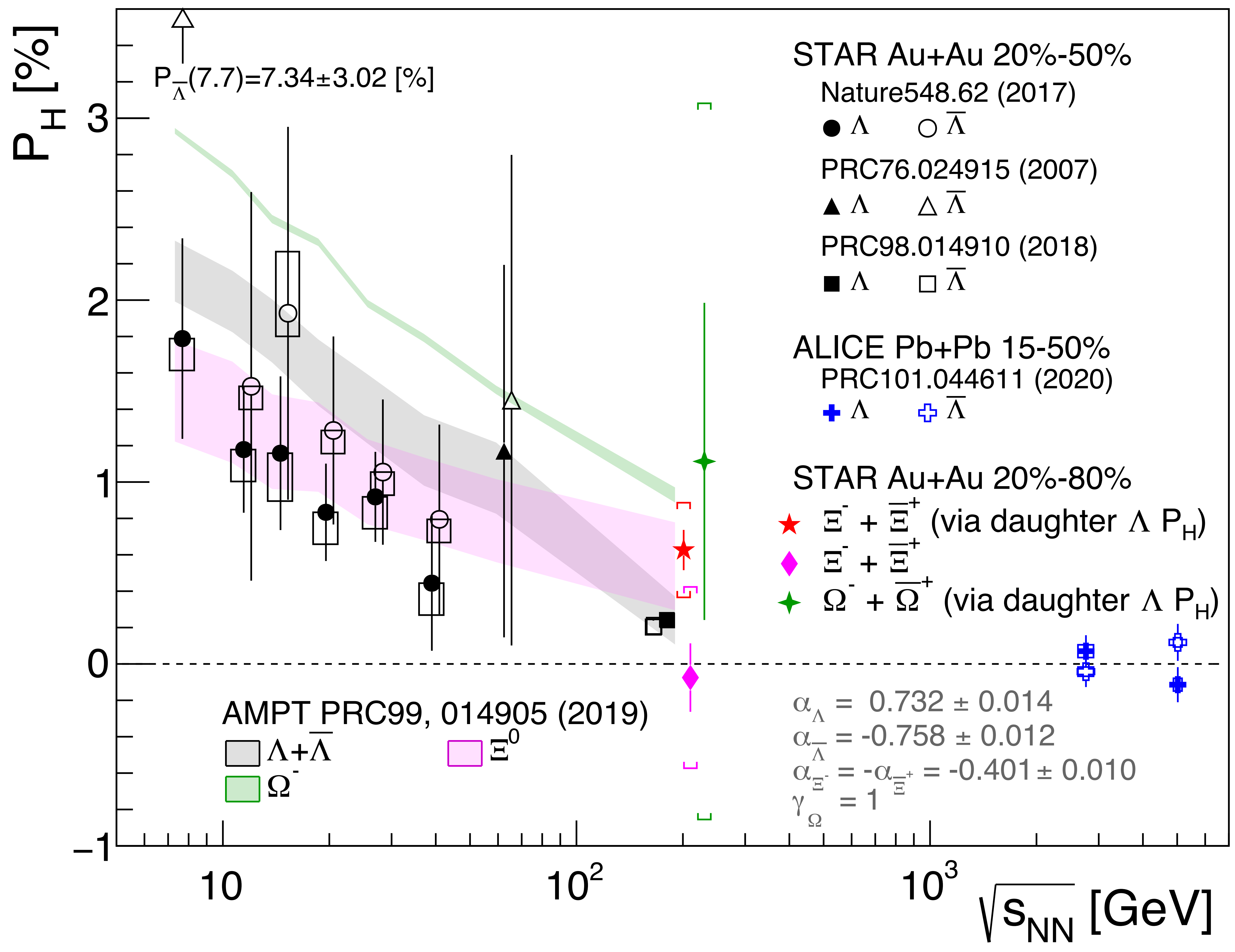

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(20-80% centrality)

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

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

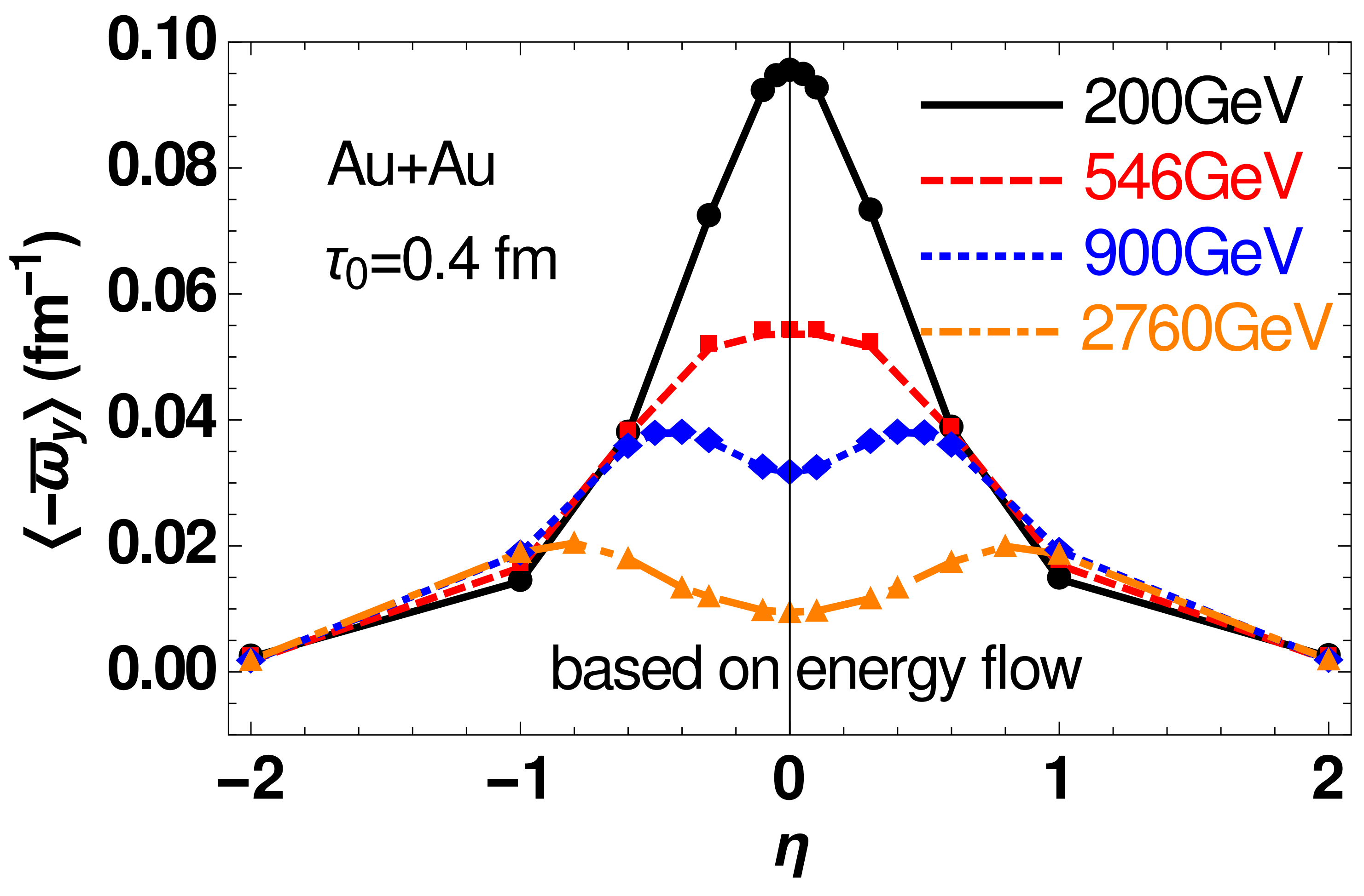
F. Becattini et al., PRC95.054902 (2017)

- Model calculations capture the trend

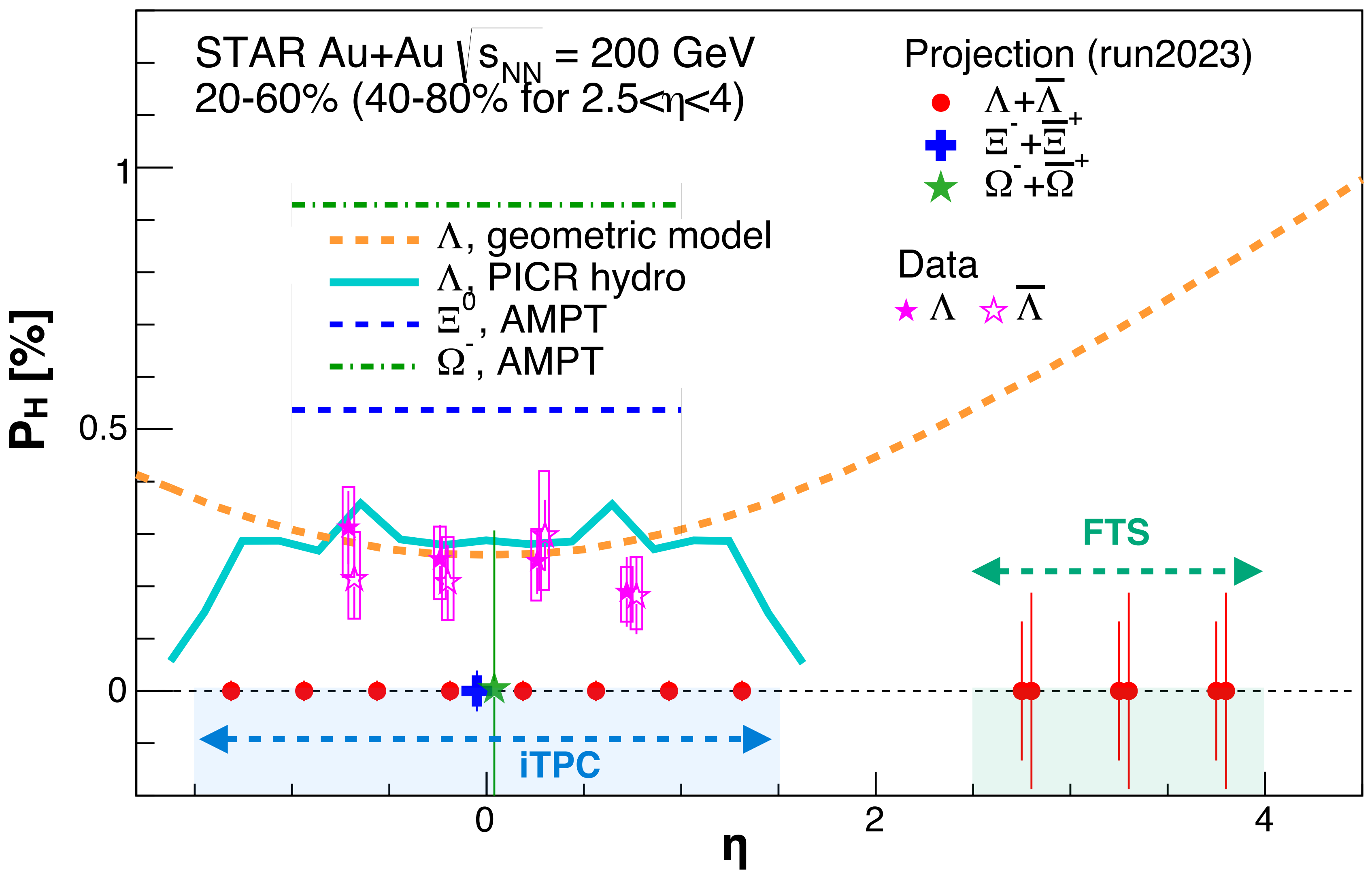
D.-X. Wei, W.-T. Deng, and X.-G. Huang, PRC99.014905 (2019)
B. Fu et al., PRC103.024903 (2021)

Rapidity dependence

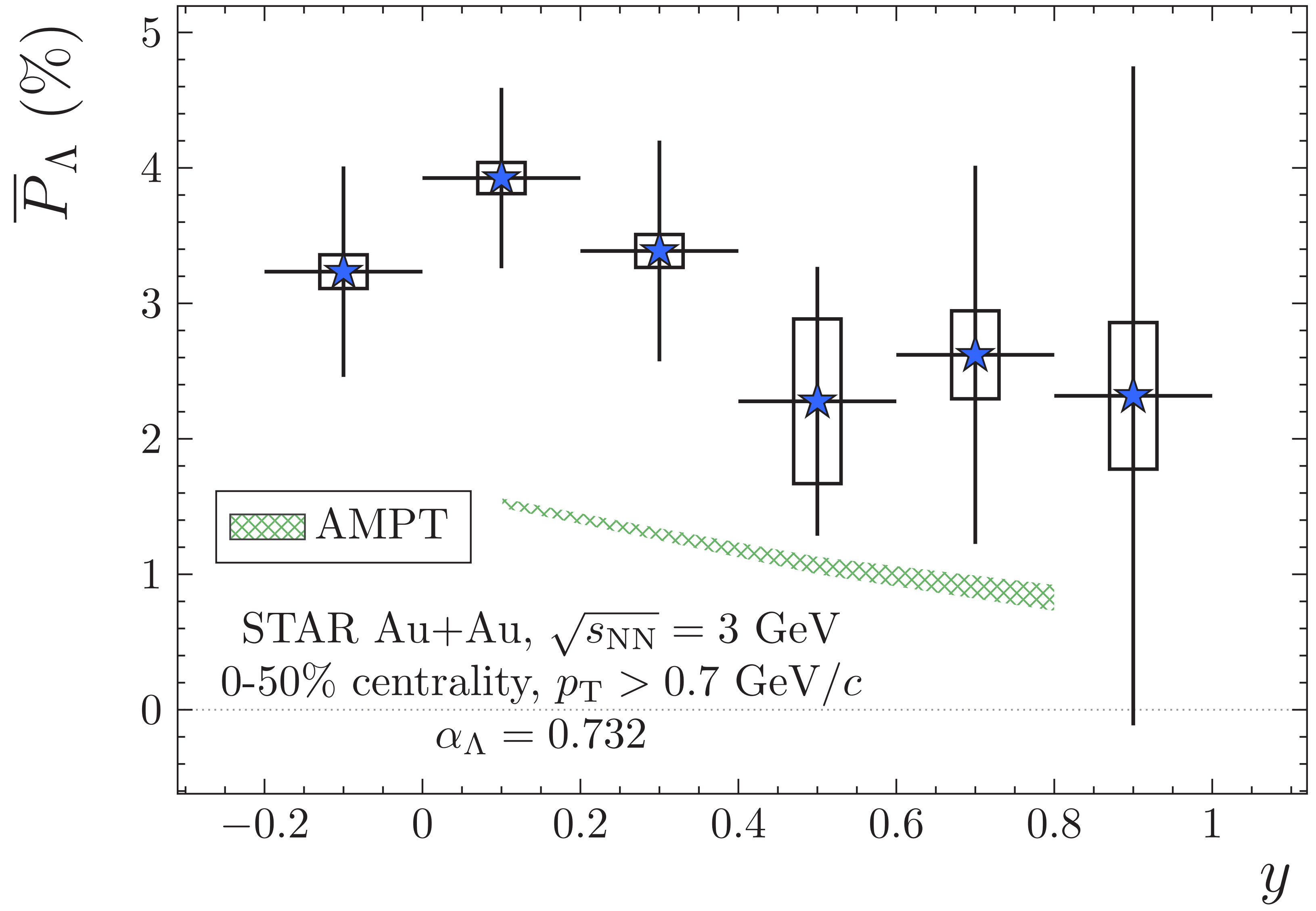
W.T.Feng and X.G.Huang, PRC93.064907 (2016)



BUR2020, STAR Note SN0755



STAR, PRC104, L061901 (2021)

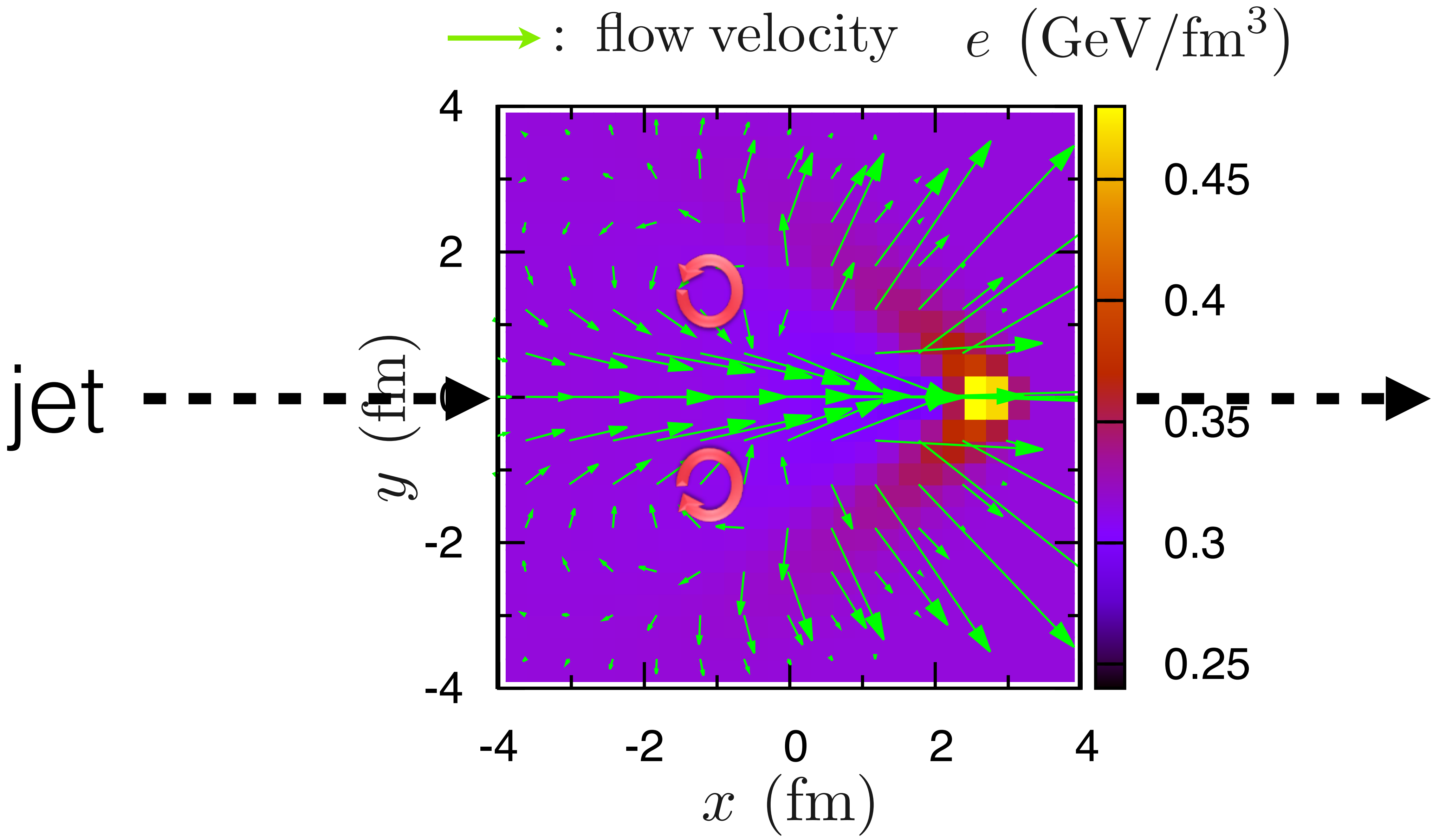


W.T.Feng and X.G.Huang, PRC93.064907 (2016)
D.X.Wei, W.T.Deng and X.G.Huang, PRC99.014905 (2019)
H.Z.Wu et al, PRResearch1.033058 (2019)
Y.Xie, D.Wang, and L.P.Csernai, RPJ (2020) 80:39
Z.T.Liang et al., Chin.Phys.C45, 014102 (2021)

- Models predict the rapidity dependence differently
- So far no strong dependence within acceptance. In lower energies, the measurement close to the beam rapidity (y_{beam} ~1 at $\sqrt{s_{NN}}$ = 3 GeV) didn't show strong dependence but with large uncertainty

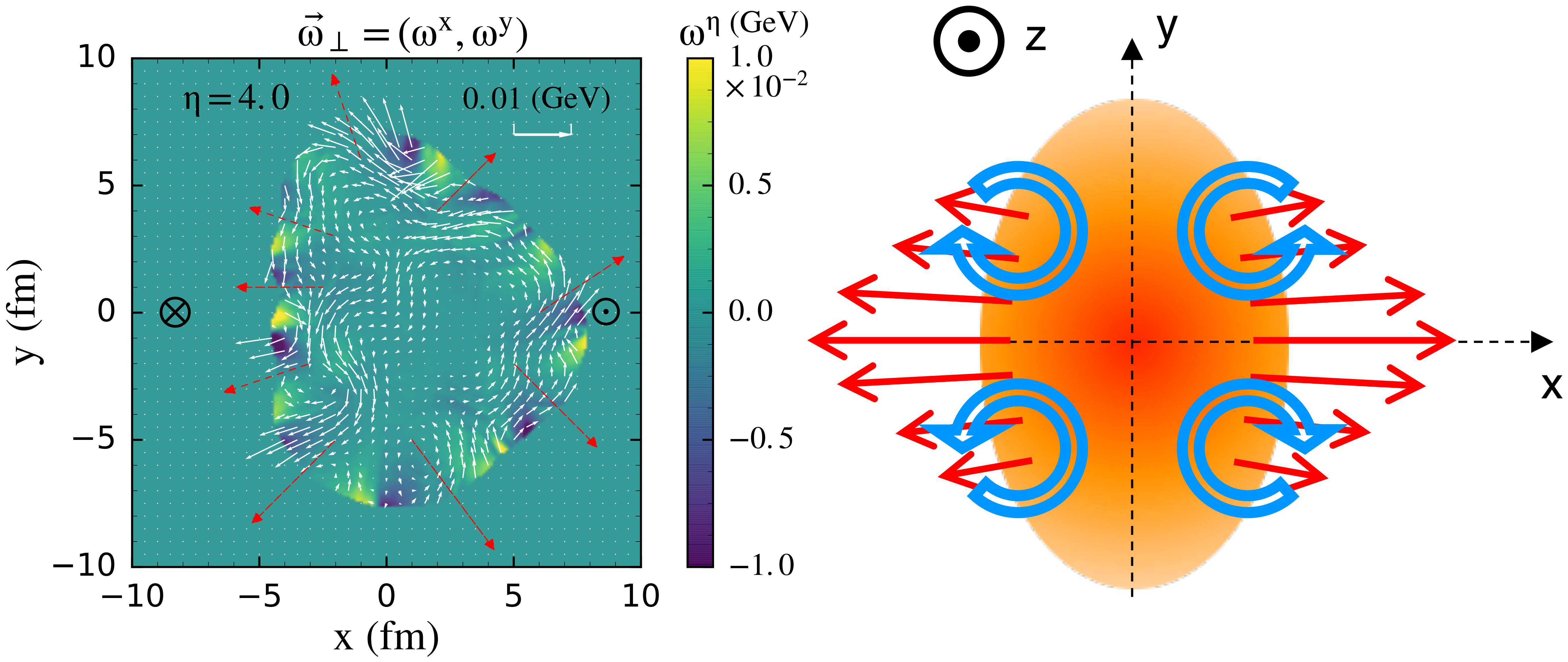
Local vorticity

Vortex induced by jet



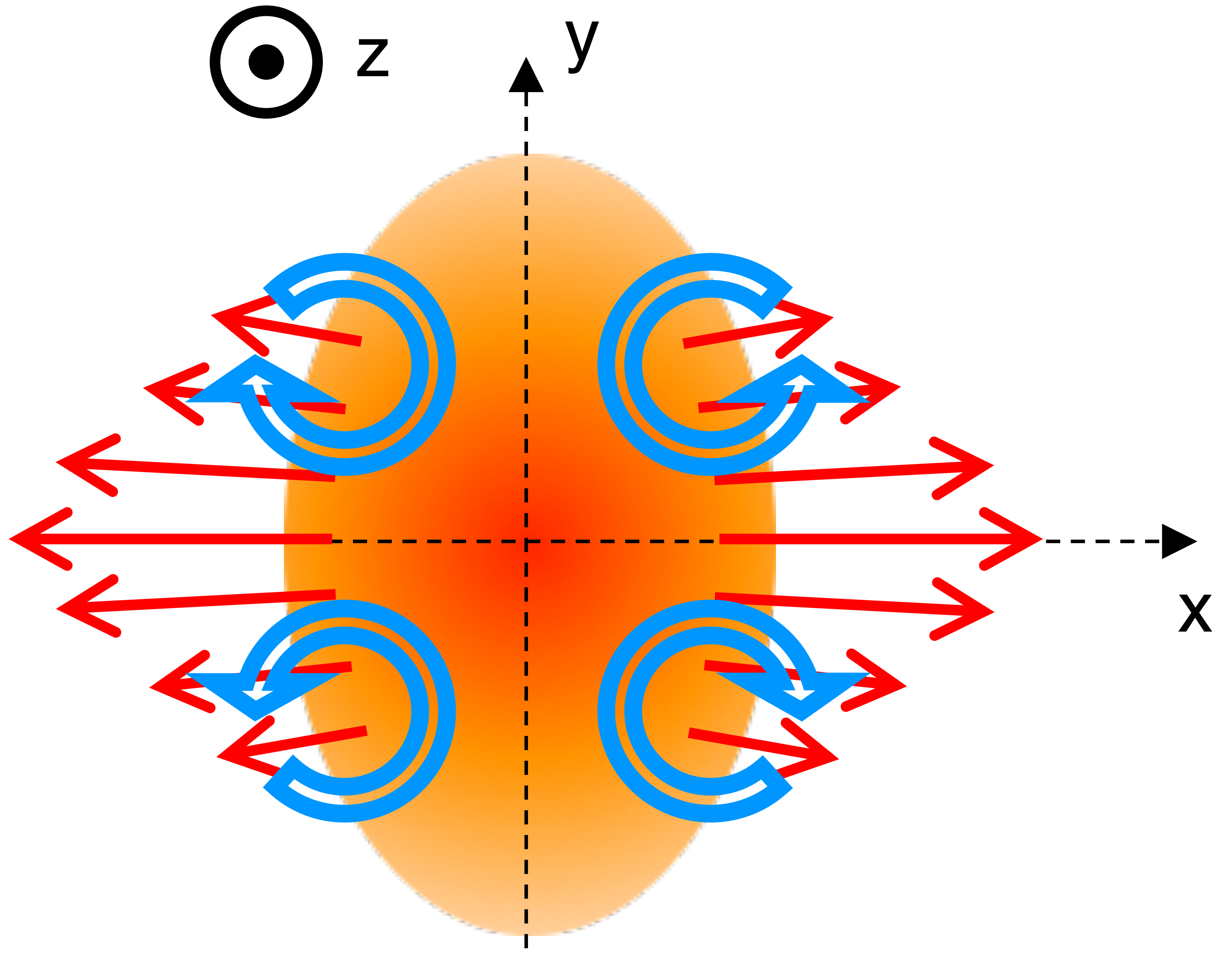
Y. Tachibana and T. Hirano, NPA904-905 (2013) 1023
B. Betz, M. Gyulassy, and G. Torrieri, PRC76.044901 (2007)

Local vorticity induced by collective flow



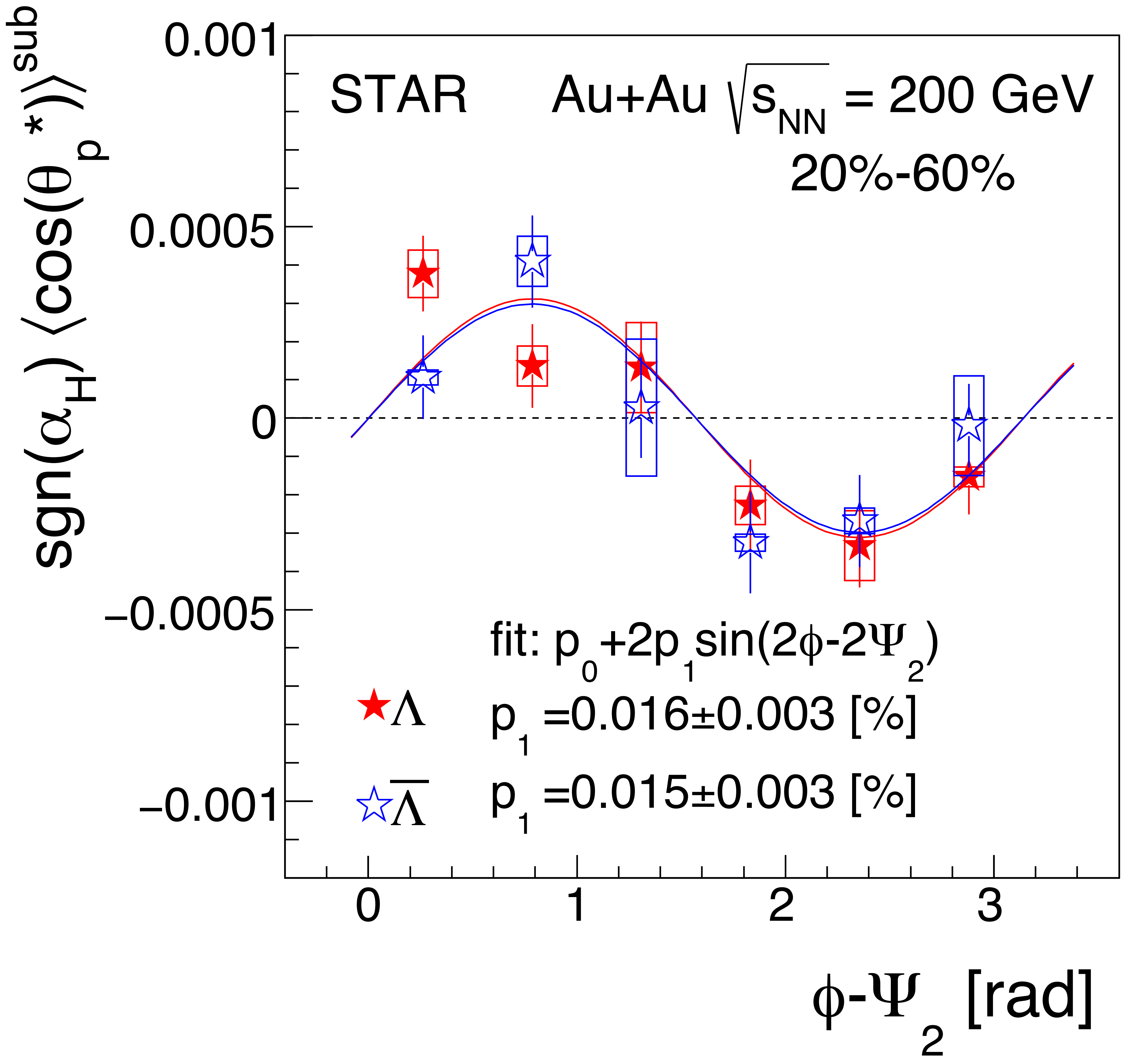
L.-G. Pang, H. Peterson, Q. Wang, and X.-N. Wang, PRL117, 192301 (2016)
F. Becattini and I. Karpenko, PRL120.012302 (2018)
S. Voloshin, EPJ Web Conf.171, 07002 (2018)
X.-L. Xia et al., PRC98.024905 (2018)

"z-component" of polarization: P_z



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

STAR, PRL123.13201 (2019)



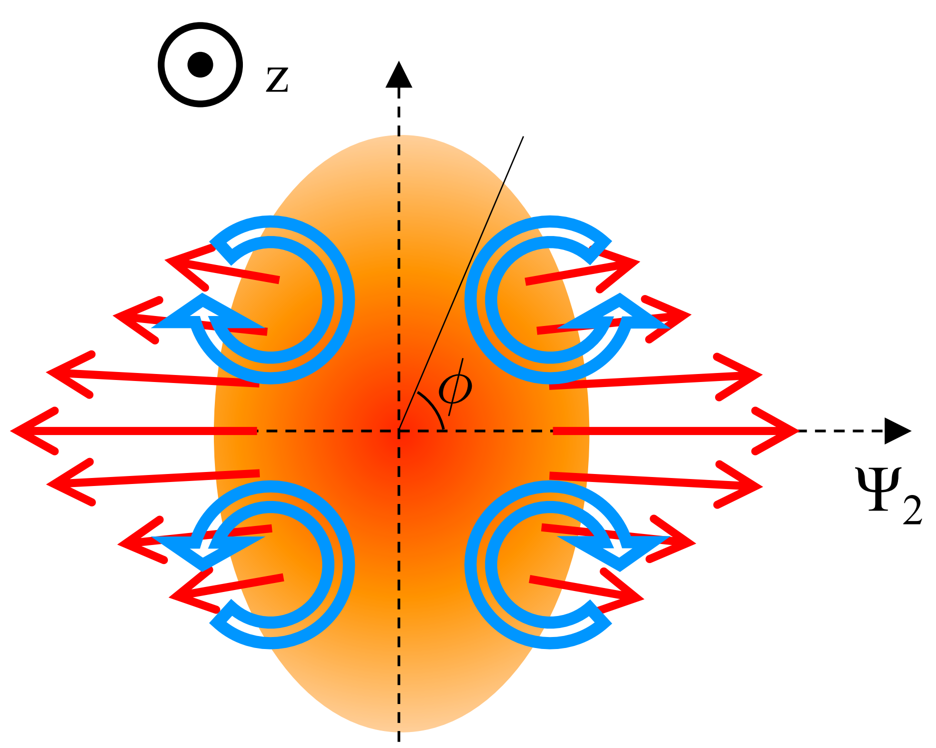
- Polarization <u>along the beam direction</u> expected from "elliptic flow"
- The data indeed show such a longitudinal polarization P_z depending on azimuthal angle (sine function)

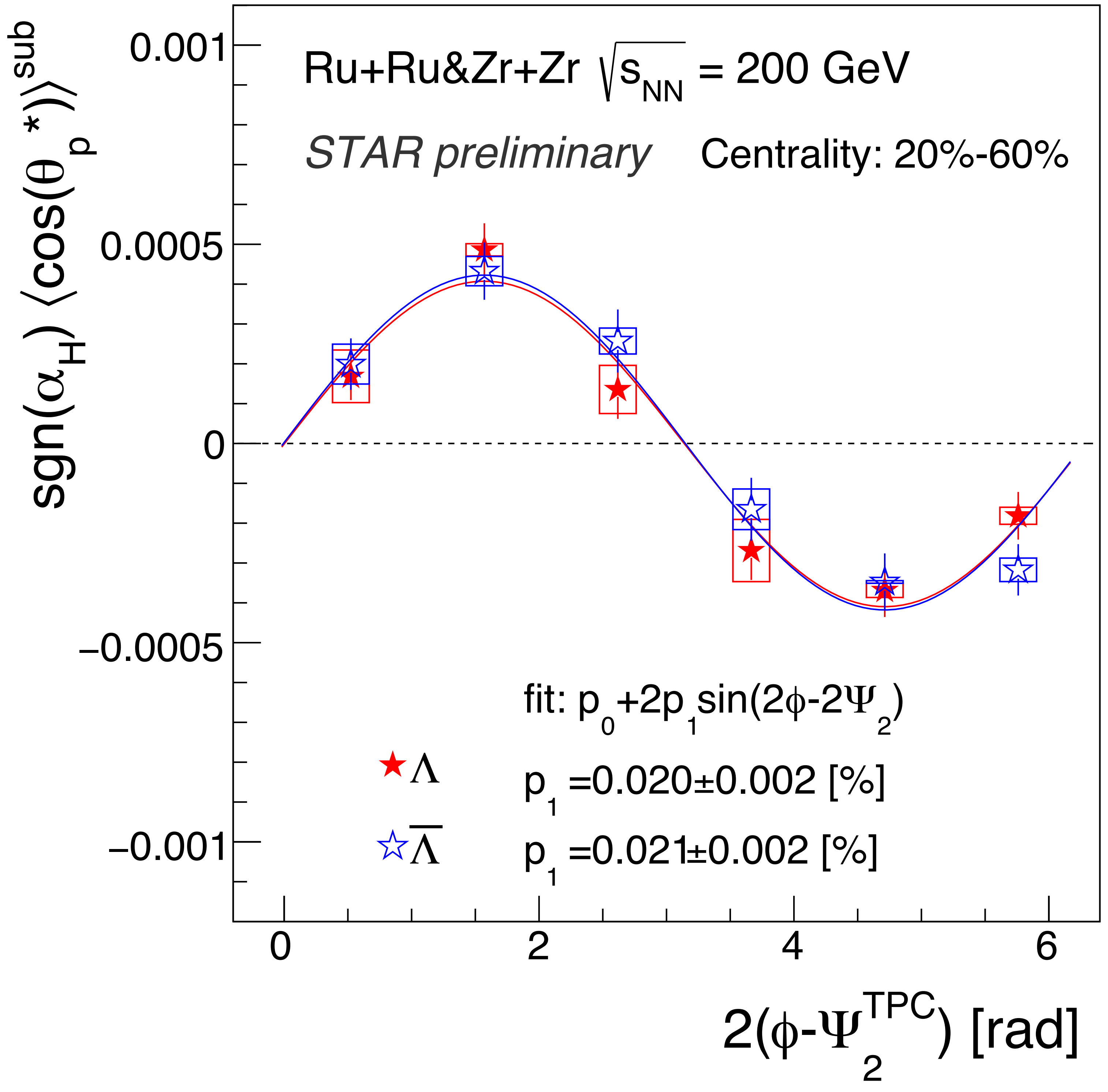
Flow-driven polarization!

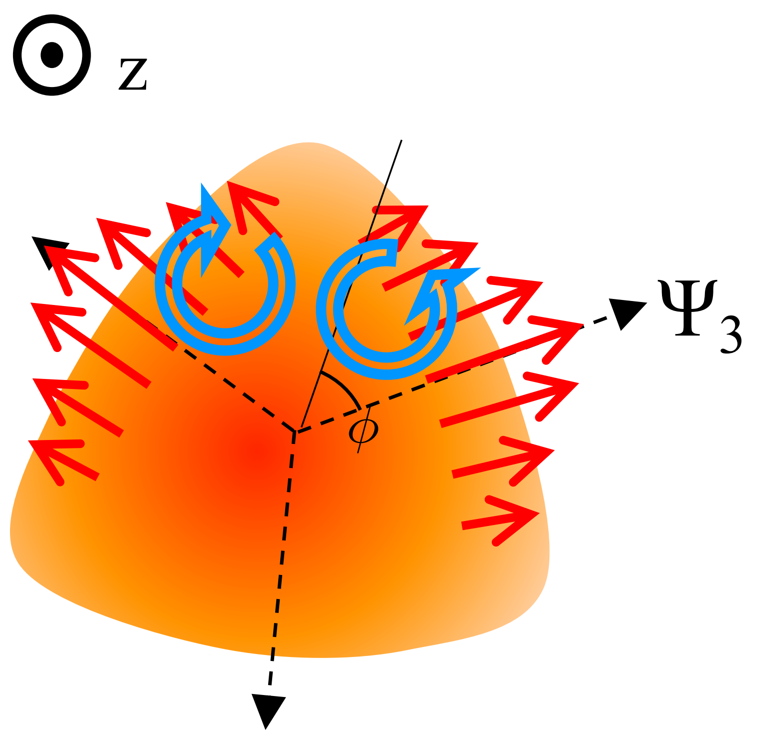
v_3-driven polarization

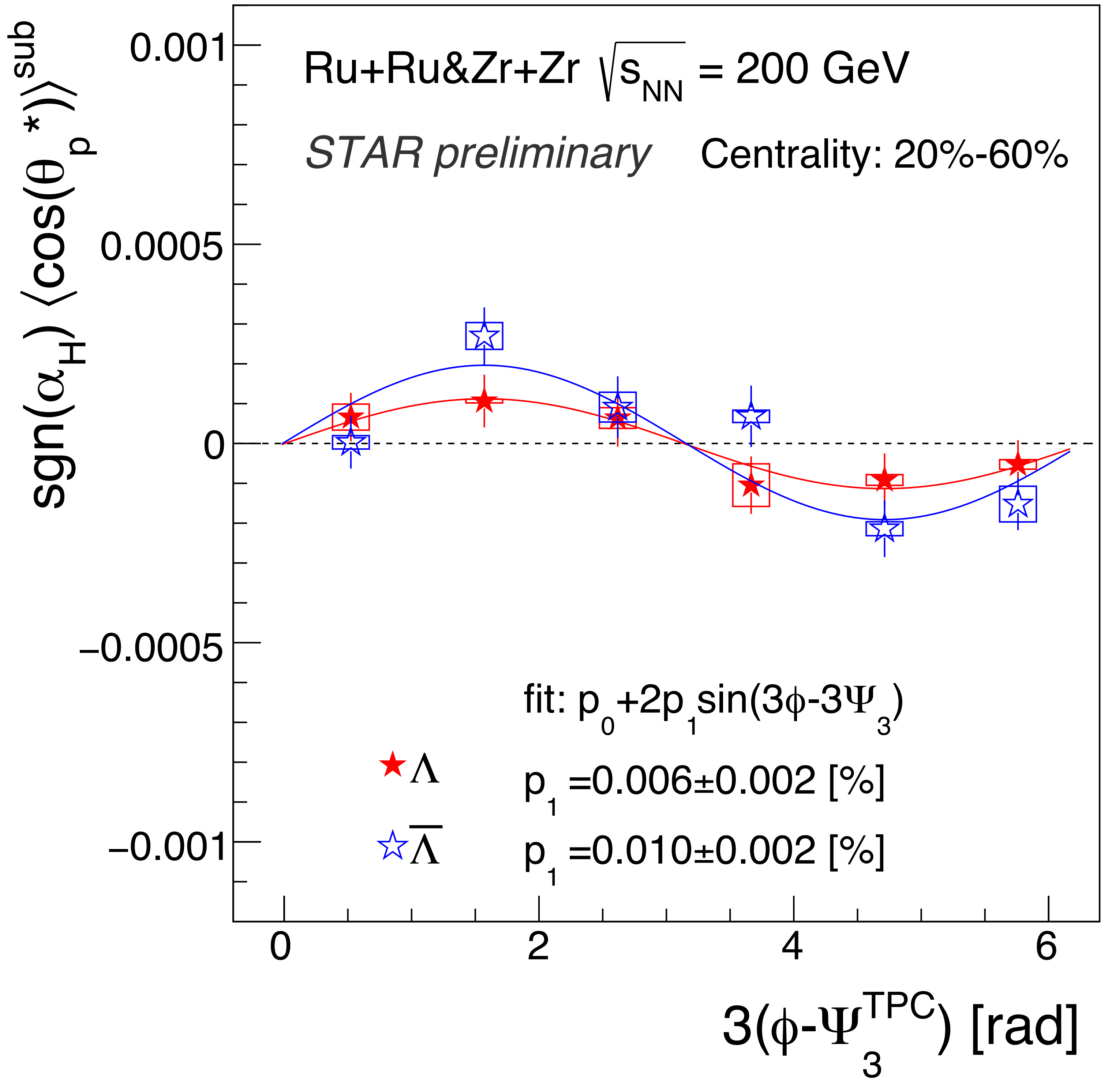
TN (STAR), QM2022

*Not accounted for EP resolution and decay parameter





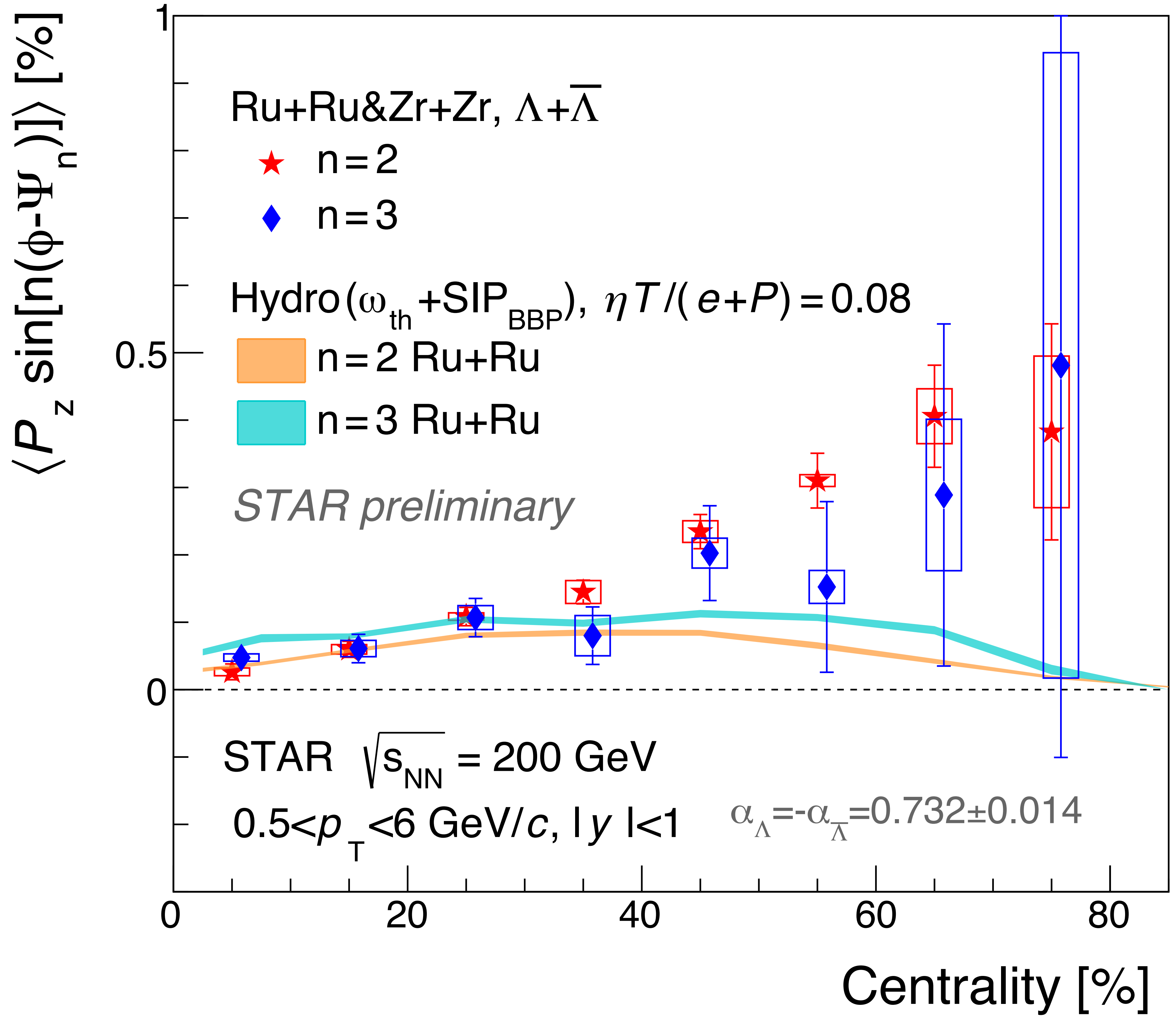




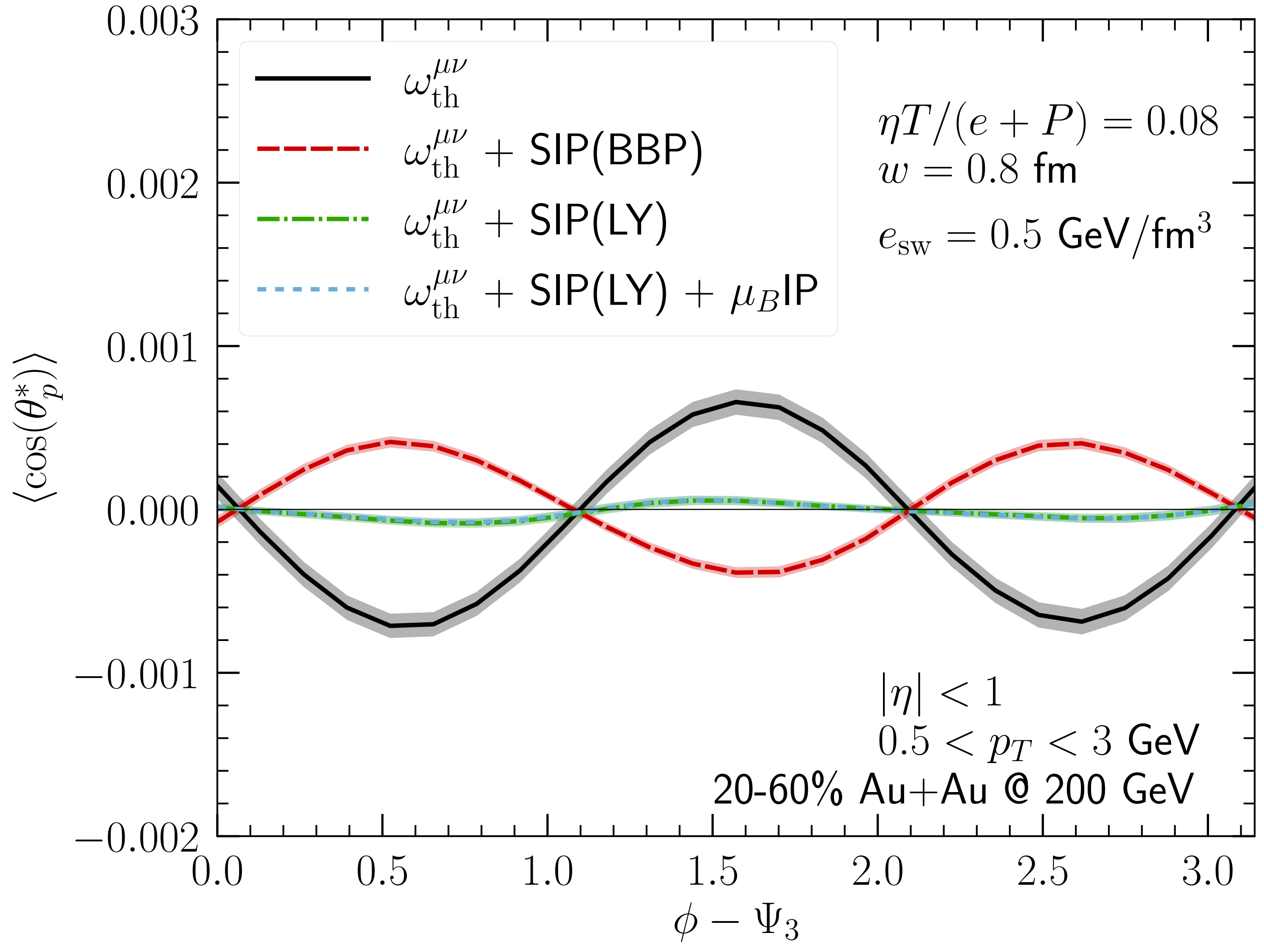
- Further study for the 3rd-order with high statistics data of isobar collisions
- First measurement relative to the 3rd-order event plane Ψ_3!
  - Similar pattern to the 2nd-order, indicating v_3-driven polarization

Centrality dependence of P_z sine modulation

TN (STAR), QM2022



S. Alzharani, S. Ryu, and C. Shen, PRC106, 014905 (2022)

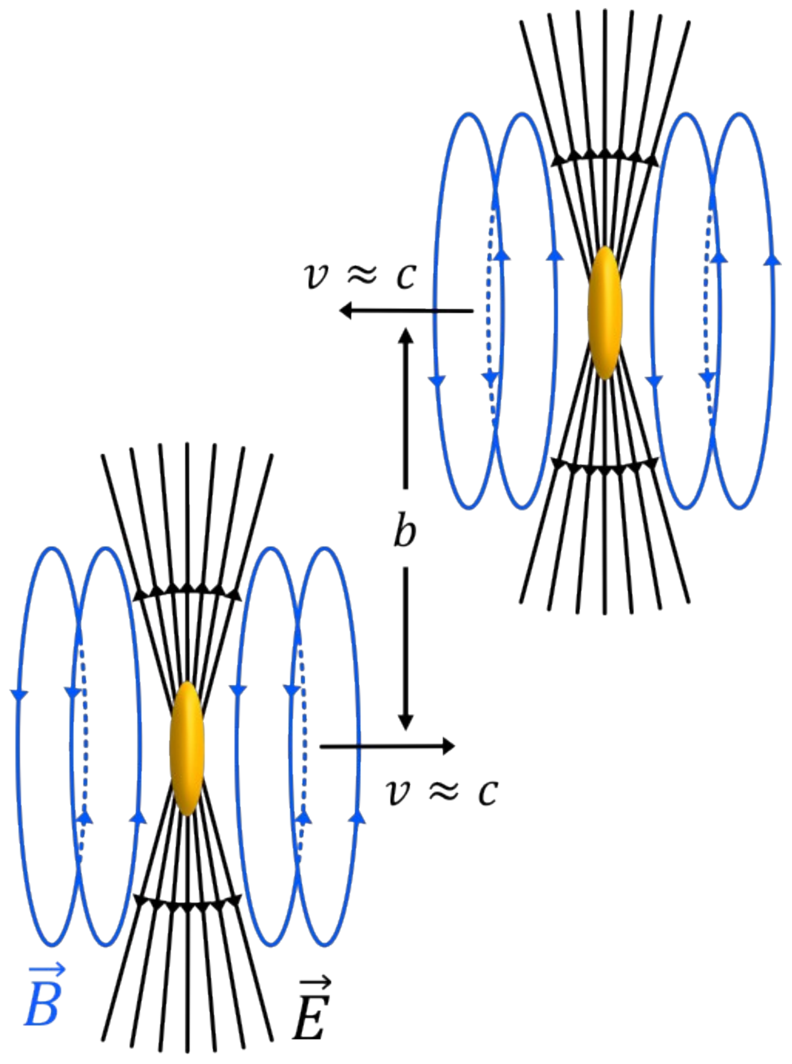


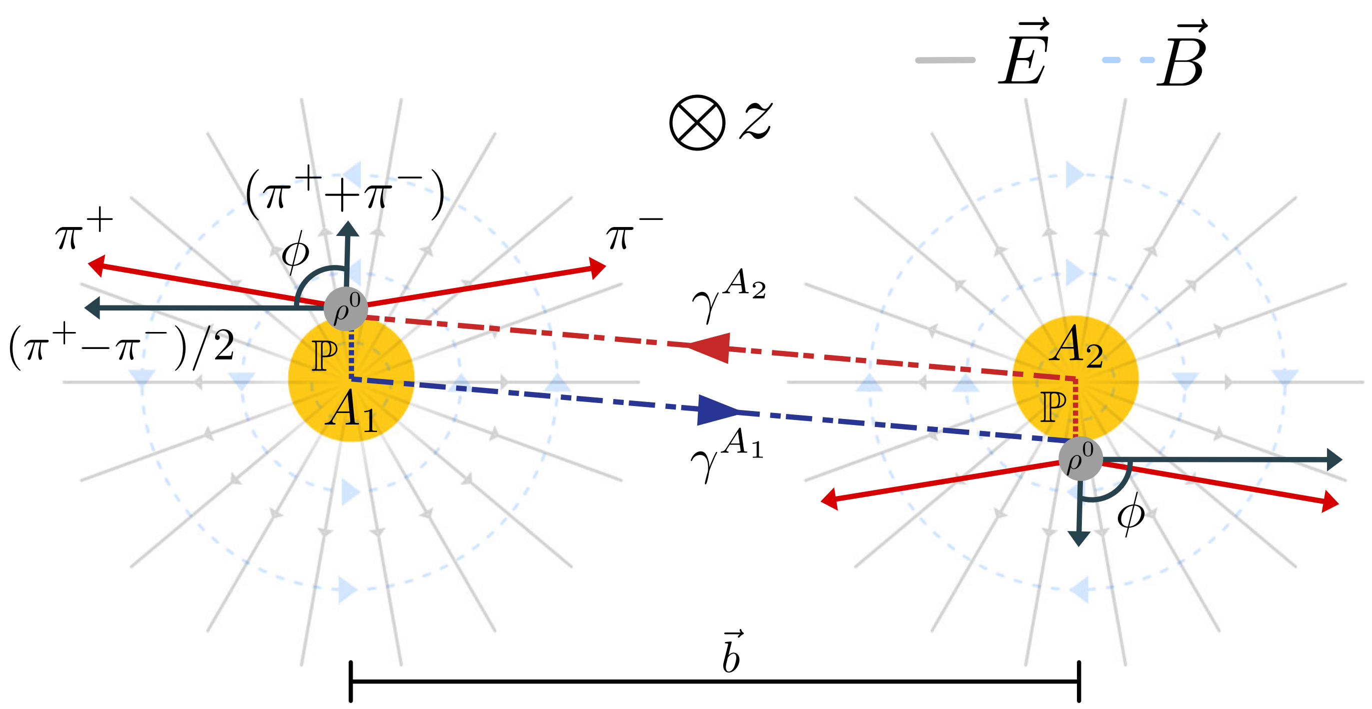
vorticity: $\omega_{\rho\sigma} = \frac{1}{2}(\partial_\sigma u_\rho - \partial_\rho u_\sigma)$

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

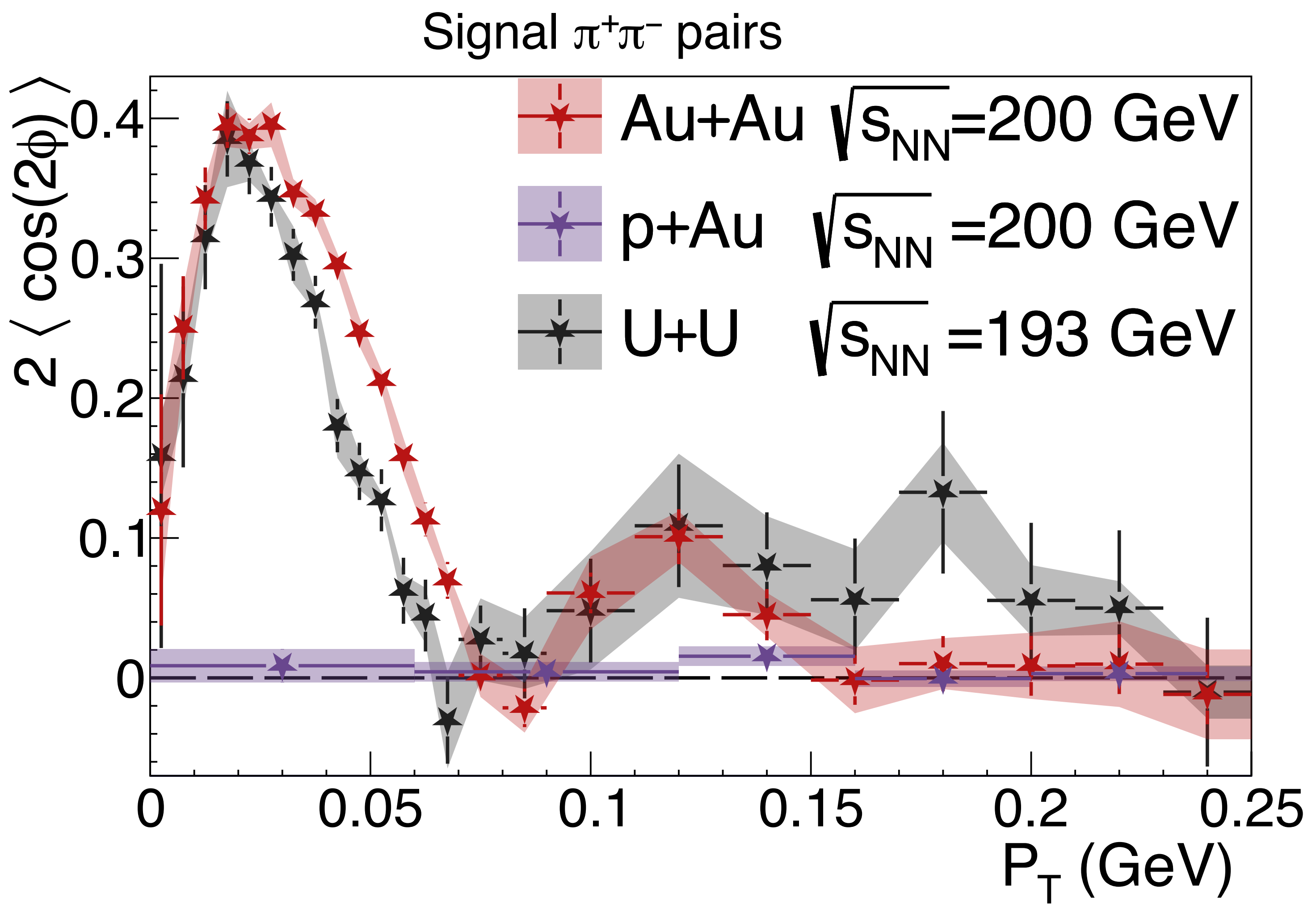
- Comparable 2nd and 3rd order sine coefficients of P_z, especially in most central events
- Hydrodynamic model with “shear term” reasonably describes the data for central but not for peripheral collisions. Still need more investigation on how to implement the shear

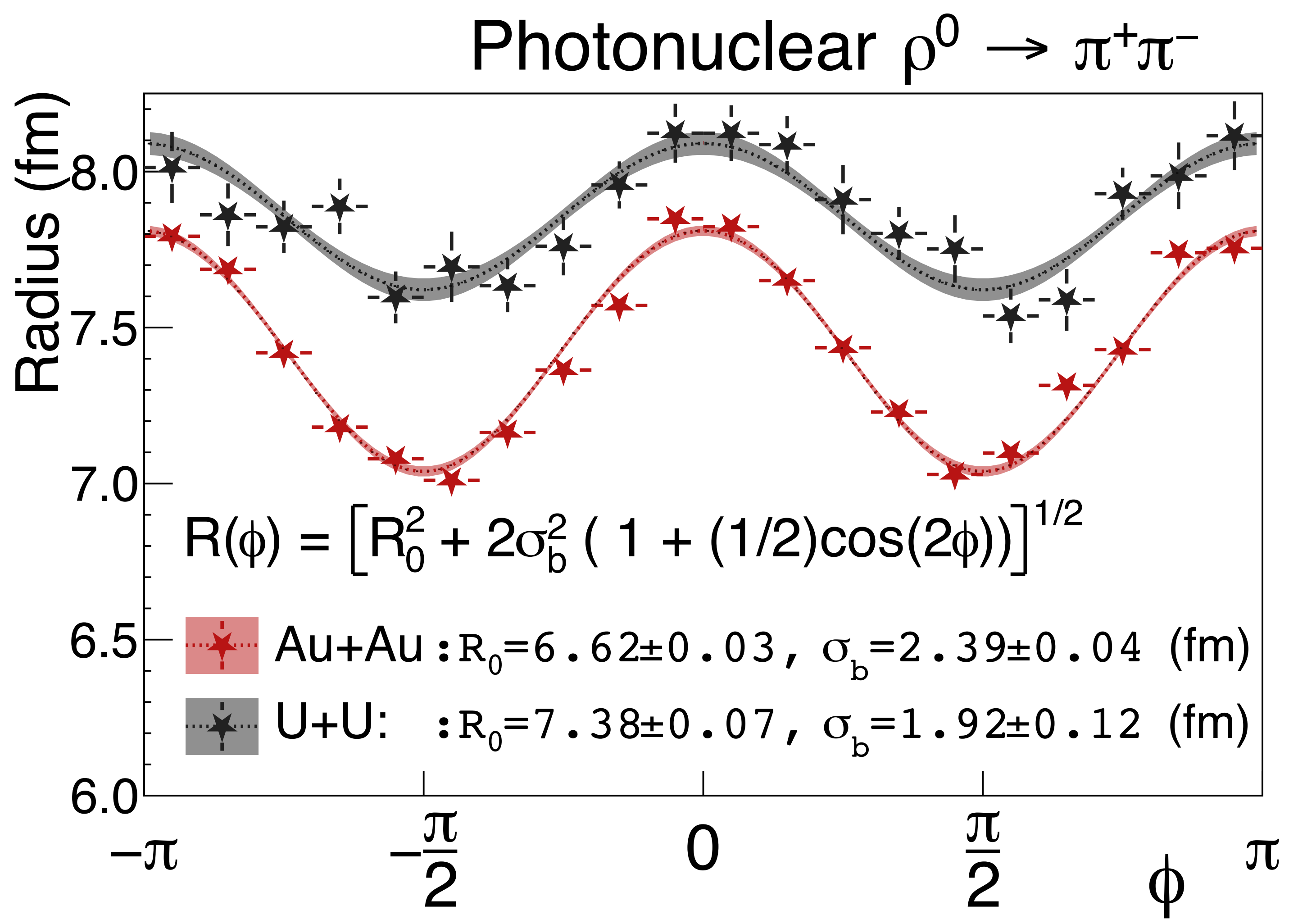
Tomography of nuclei with photon induced process





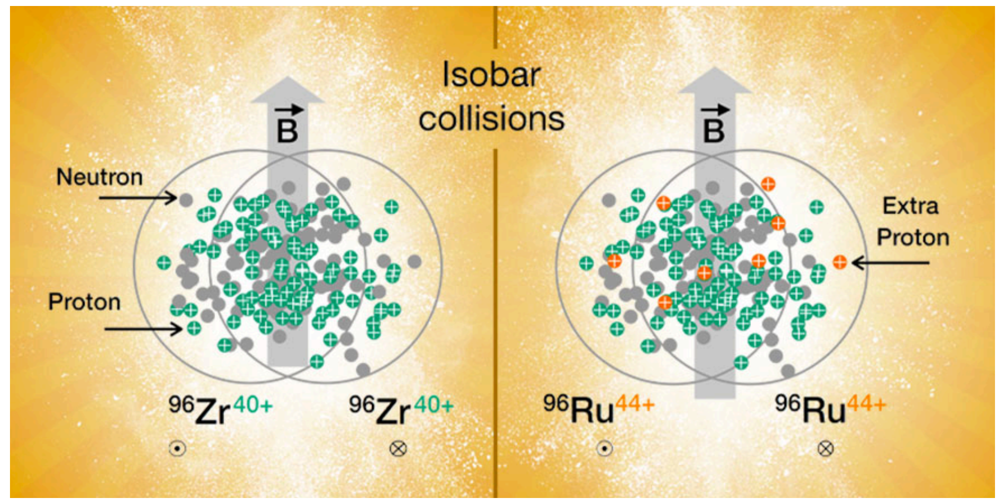
- Transverse linearly polarized photons due to Lorentz contracted EM-field
- Photonuclear production of vector mesons in UPC, e.g. $\gamma\mathbb{P} \rightarrow \rho^0 \rightarrow \pi^+\pi^-$
- Quantum interference with the polarized photons leads to cos(2ϕ) modulation of final state $\pi^+\pi^-$ cf. double slit experiment
- Sensitive to nuclear mass (strong-interaction) radius

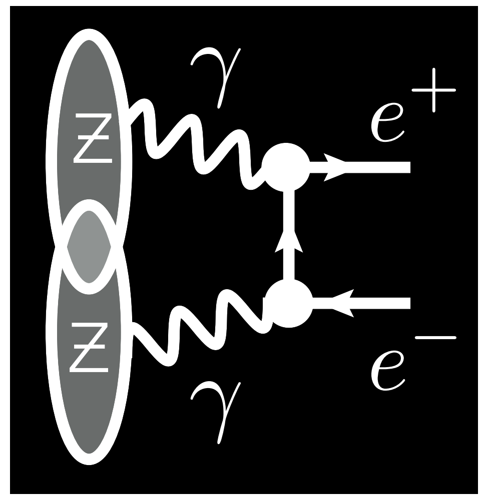




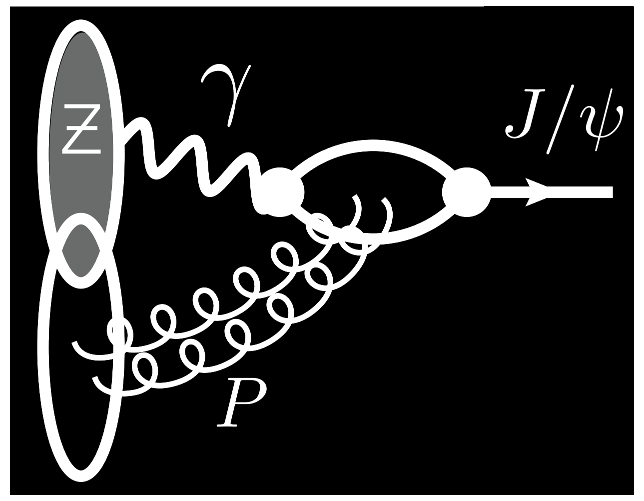
STAR, Sci.Adv.9 (2023)1, eabq3903
arXiv:2204.01625

Probing EM-field difference in isobars via γγ/γA reactions

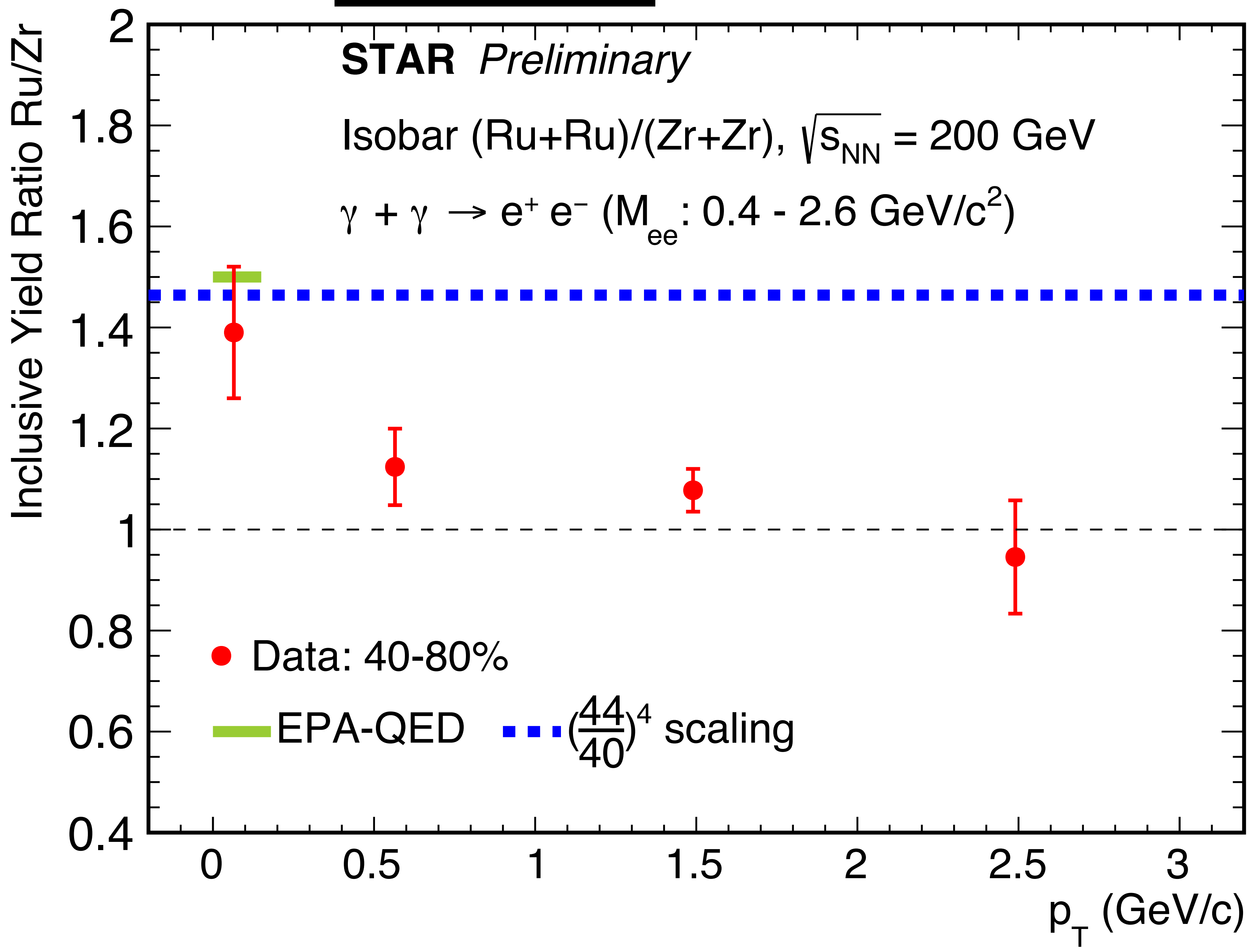




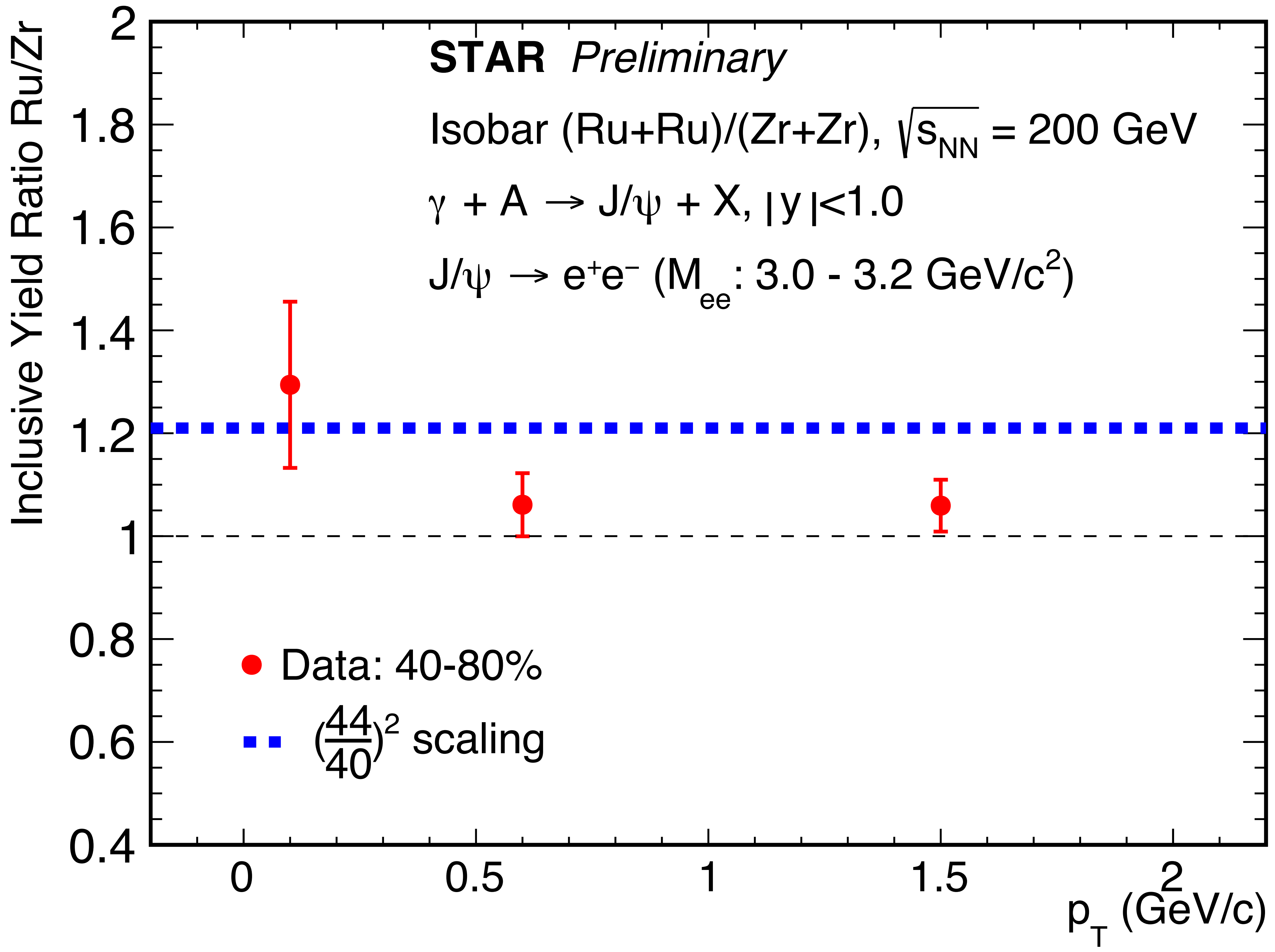
$\sigma(\gamma\gamma \to e^+e^-) \sim Z^4$



$\sigma(\gamma A \to J/\psi A) \sim Z^2$



$\left(\frac{44}{40}\right)^4$



$\left(\frac{44}{40}\right)^2$

- Dilepton (J/Ψ) production at very low p_T is dominated by γγ (γA) reactions
- The data suggest "Z" scaling due to EM-field difference in isobars as expected

W. Zha et al., PLB789(2019)238

Summary

- Interesting physics related to electromagnetic field and vorticity
  - Search for Chiral Magnetic Effect: not conclusive yet, upper limit of CME fraction <10%
  - EM-field effect in directed flow: charge difference clearly seen
  - Global polarization in a wide range of $\sqrt{s_{NN}}$ = 2.4 GeV - 5.02 TeV: most vortical fluid, ΔP_H?
  - Flow-induced polarization along the beam direction: Rich vortical structures, velocity field
  - Photon-induced process: new tool to study nuclear mass radius, probing EM-field

Back up

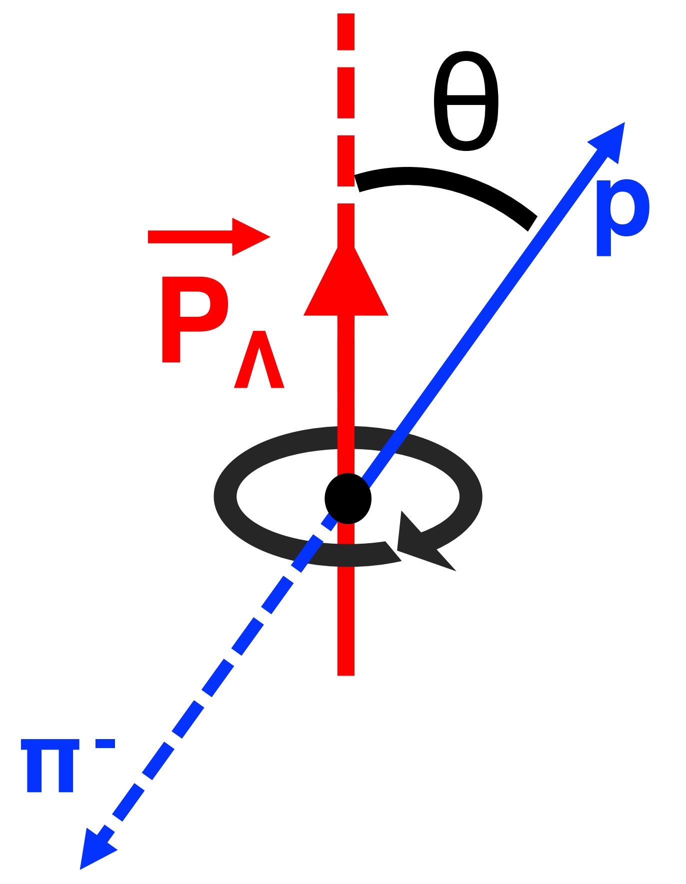
Global polarization measurement

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

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

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

$\mathbf{P}_H$: hyperon polarization
$\hat{\mathbf{p}}_B$: unit vector of daughter baryon momentum
α_H : hyperon decay parameter   * denotes in hyperon rest frame



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

(BR: 63.9%, cτ~7.9 cm)

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

P.A. Zyla et al., PDG2021

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

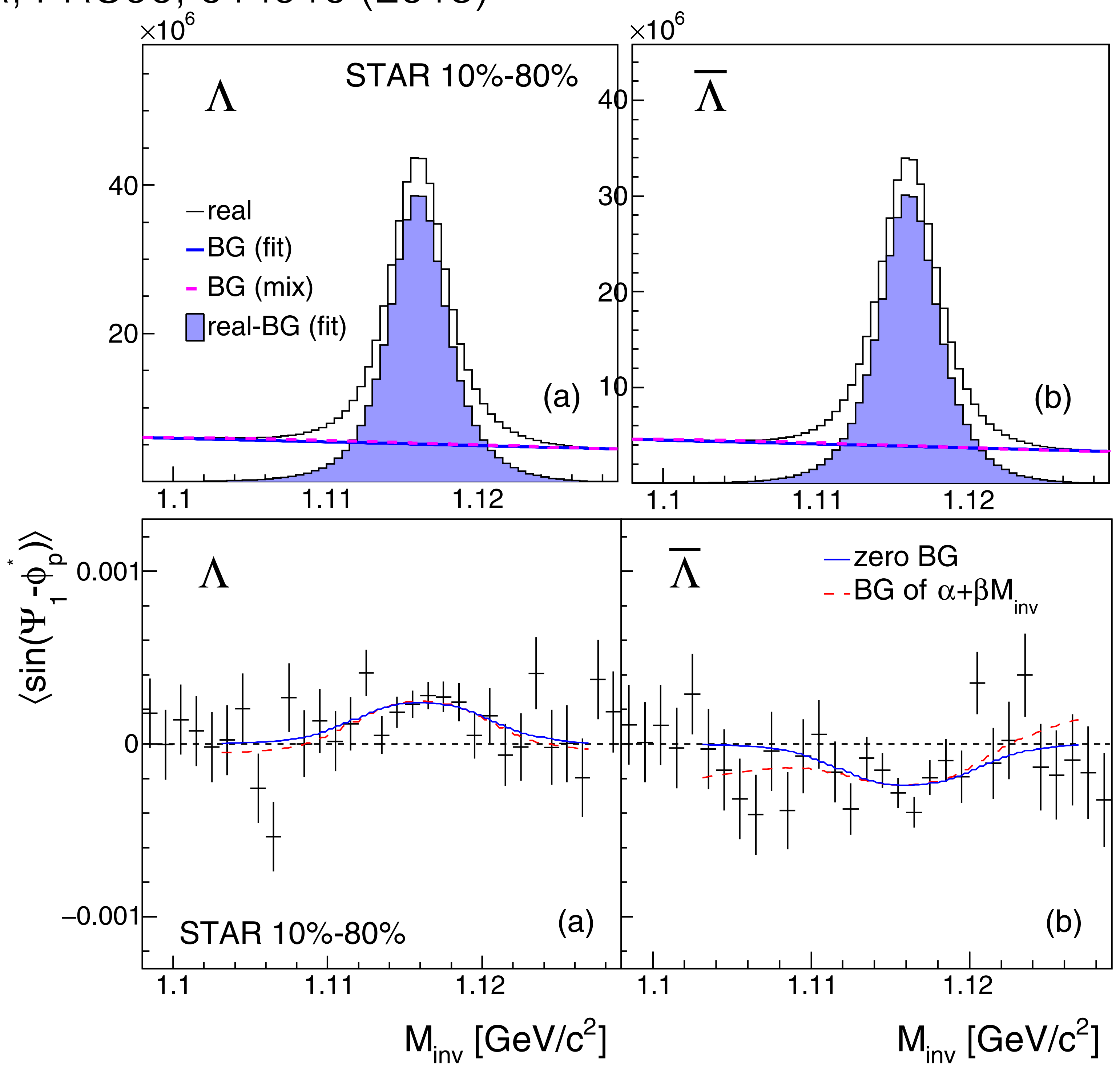
Global polarization measurement

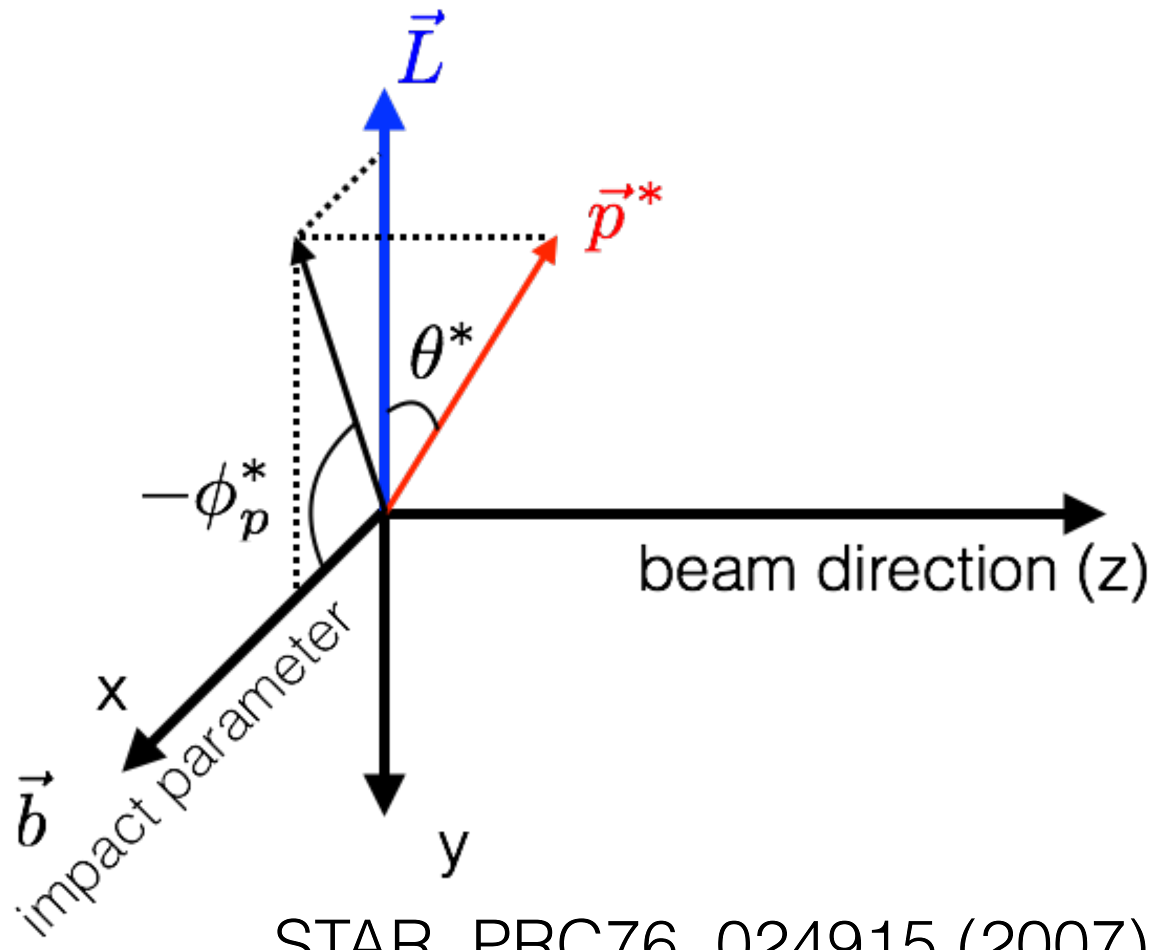
Projection onto the transverse plane

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

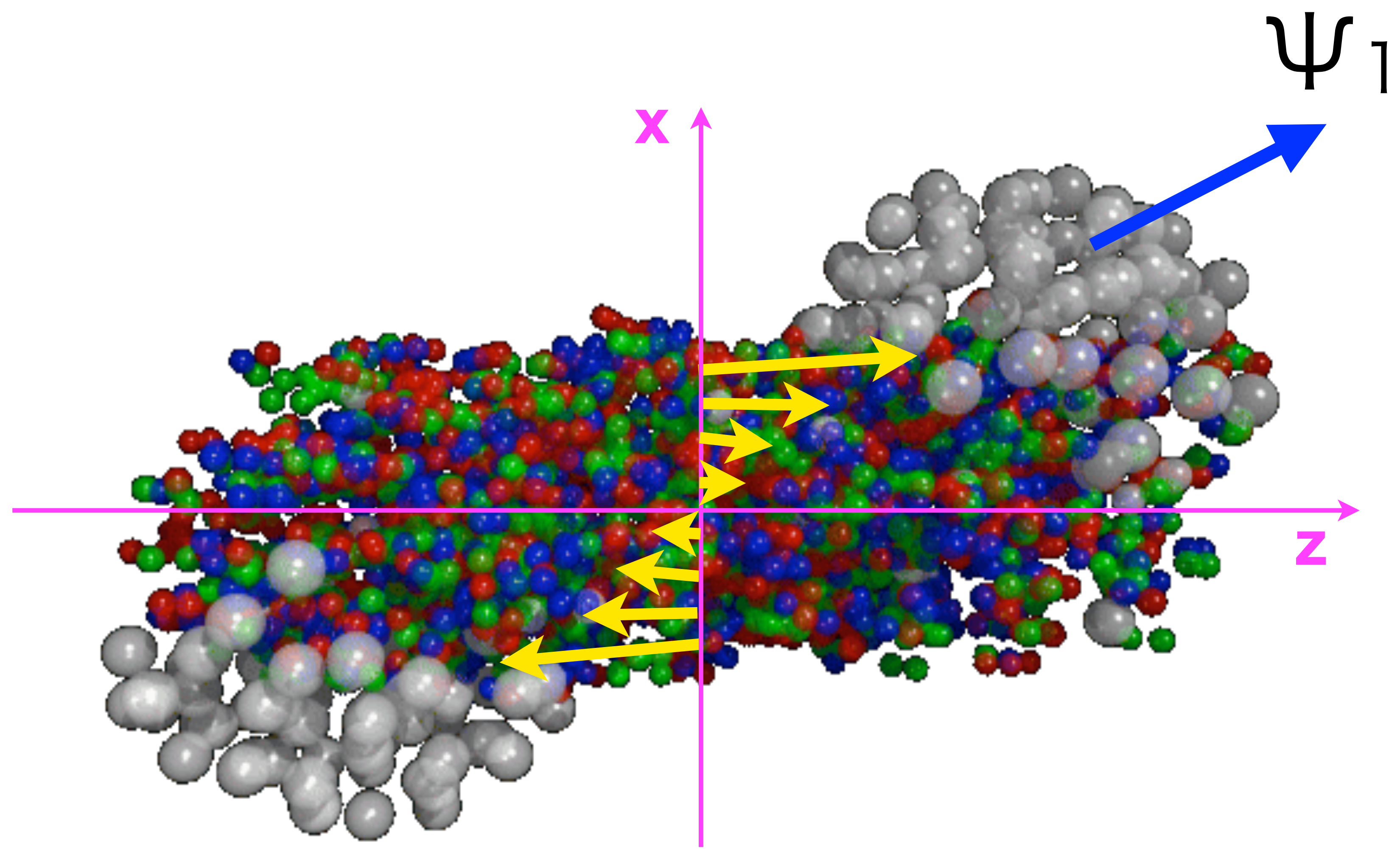
Ψ_1: azimuthal angle of impact parameter

STAR, PRC90, 014910 (2018)





STAR, PRC76, 024915 (2007)



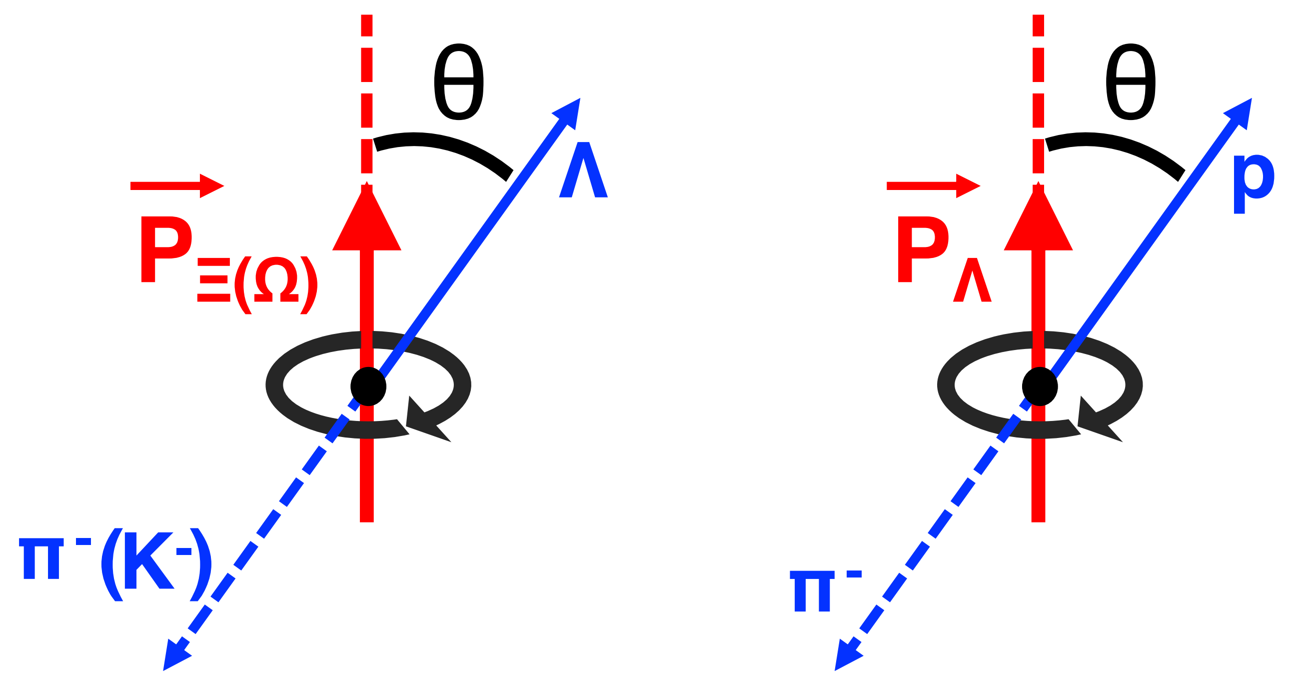
- Impact parameter direction determined by spectator deflection
  S. Voloshin and TN, PRC94.021901(R)(2016)
- COM vs. rest frames, ~3%(10%) reduction at low(higher) p_T
  W. Florkowski and R. Ryblewski, PRC106, 024905 (2022)

Multistrange hyperons: Ξ and Ω

- Extend measurement to Ξ and Ω hyperons
  - ✓ different spin, decay parameter
  - ✓ less feed-down
  - ✓ different freeze-out
  - ✓ # of s-quarks
- Challenge: small α_H (low sensitivity), low production rate

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

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



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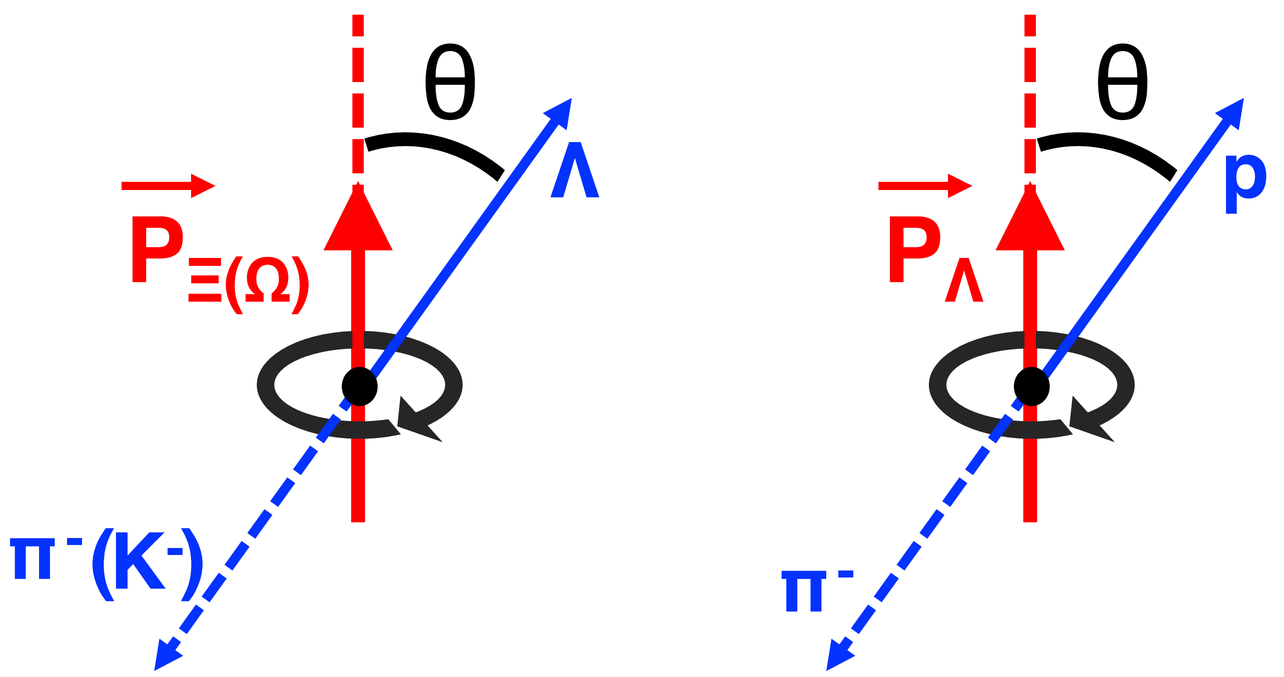

- Polarization of daughter Λ in Ξ and Ω decays

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

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

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

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

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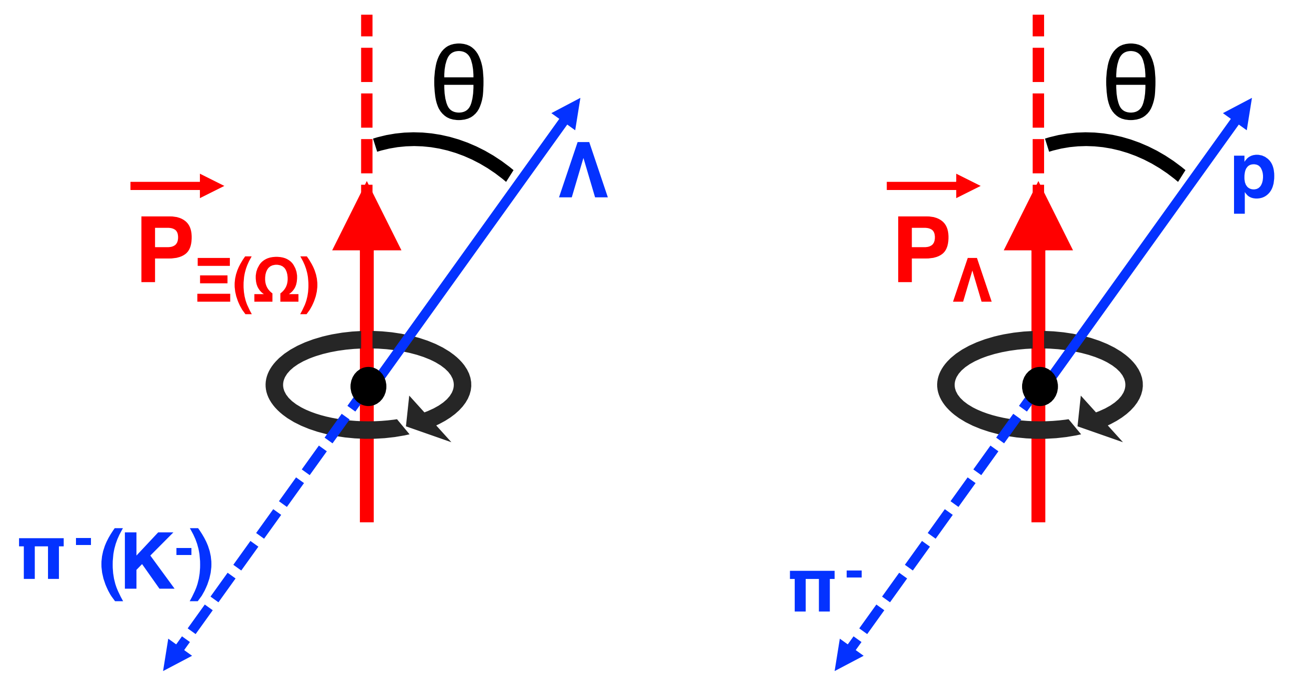

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$$C_{\Xi^-\Lambda} = +0.944$$

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

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

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

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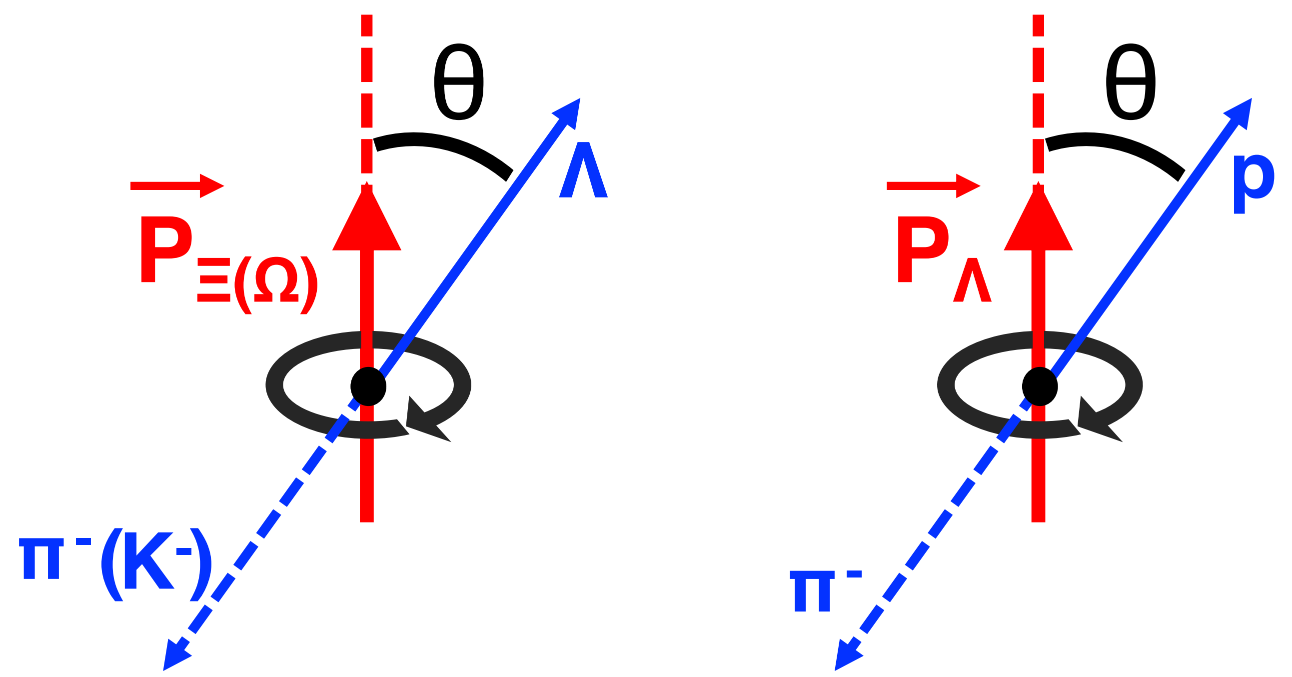

Daughter Λ polarization can be used to know parent particle polarization!

- Polarization of daughter Λ in Ξ and Ω decays

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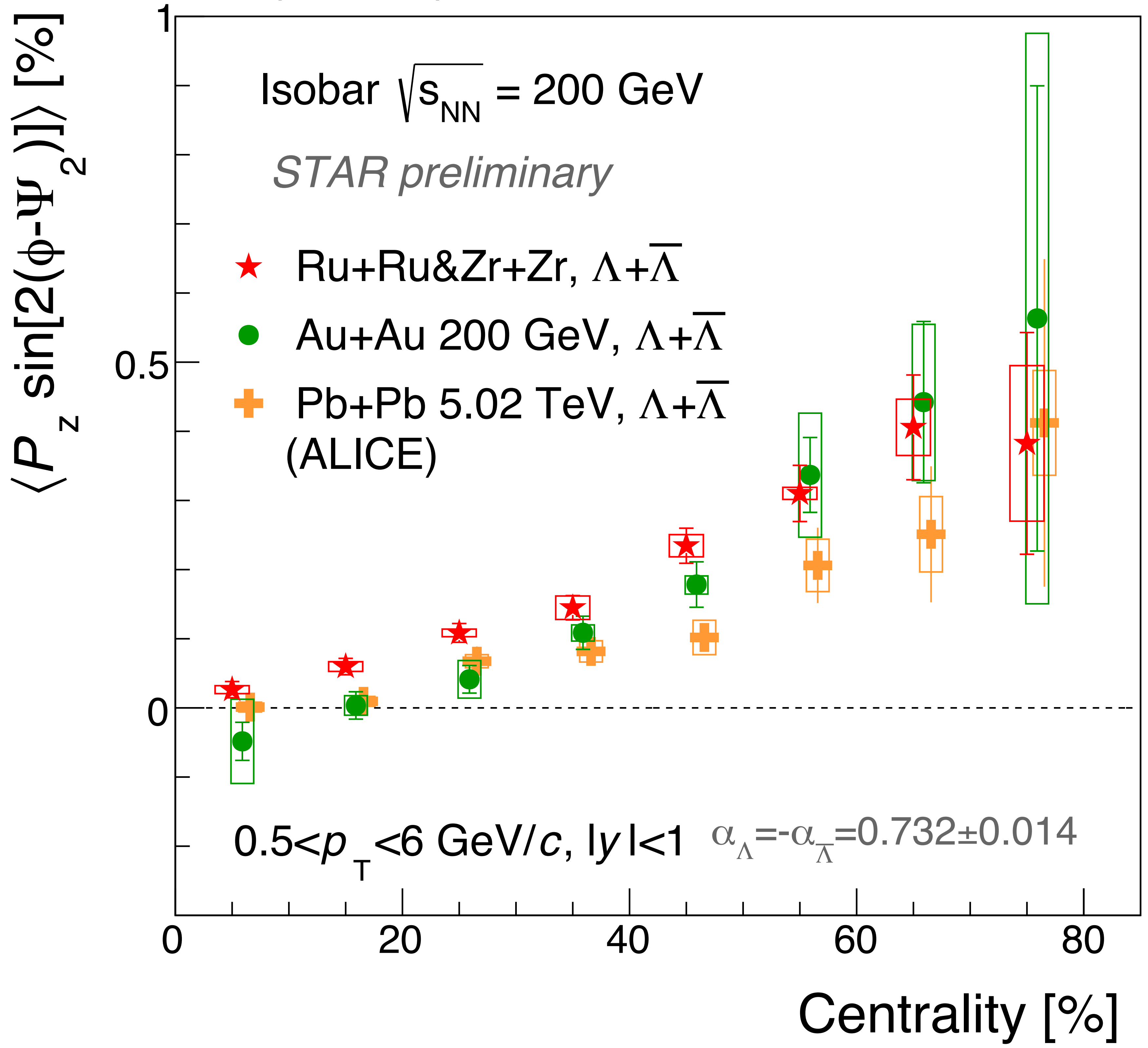
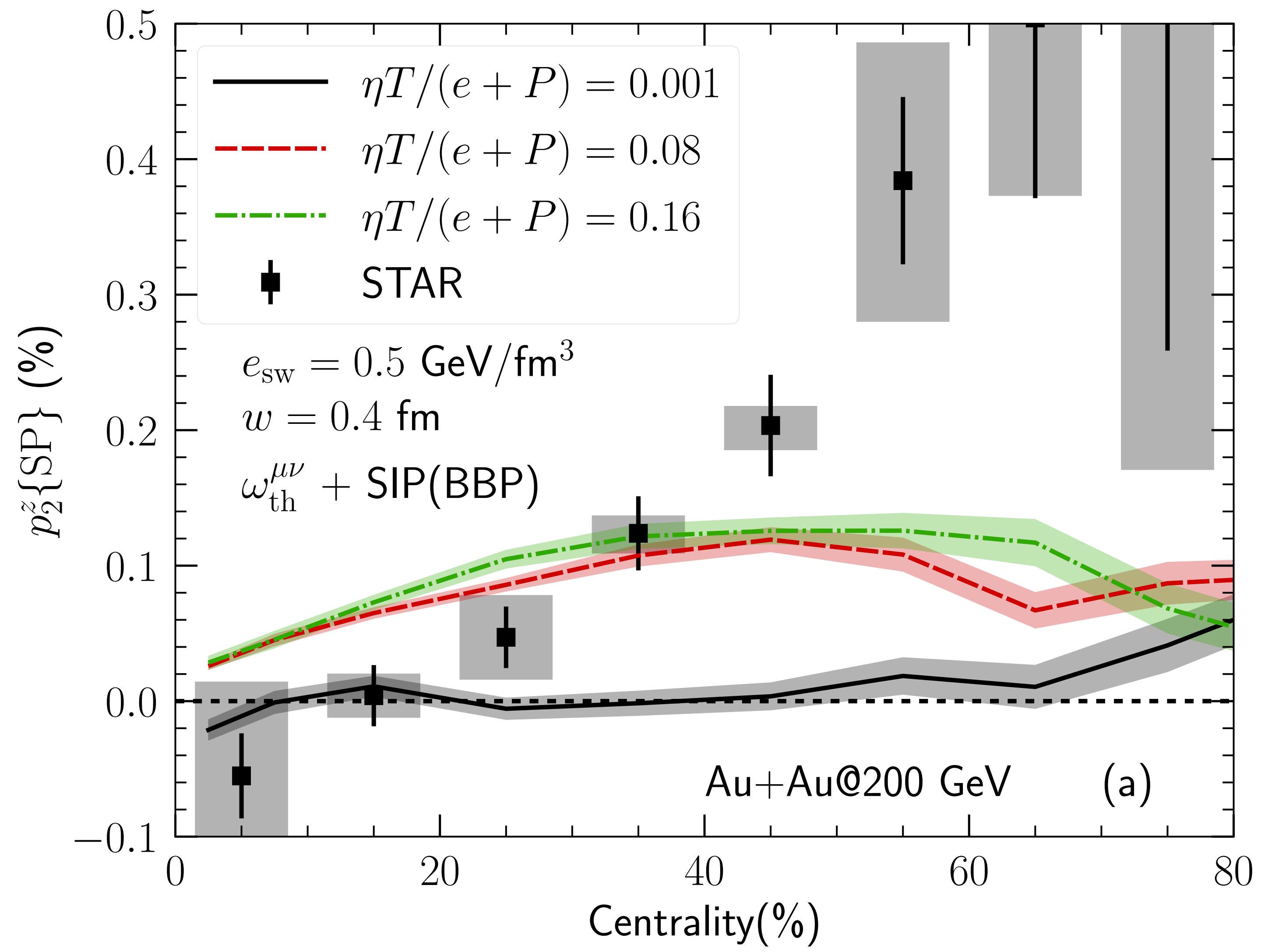
Collision system size dependence of $P_{z,2}$

TN (STAR), QM2022



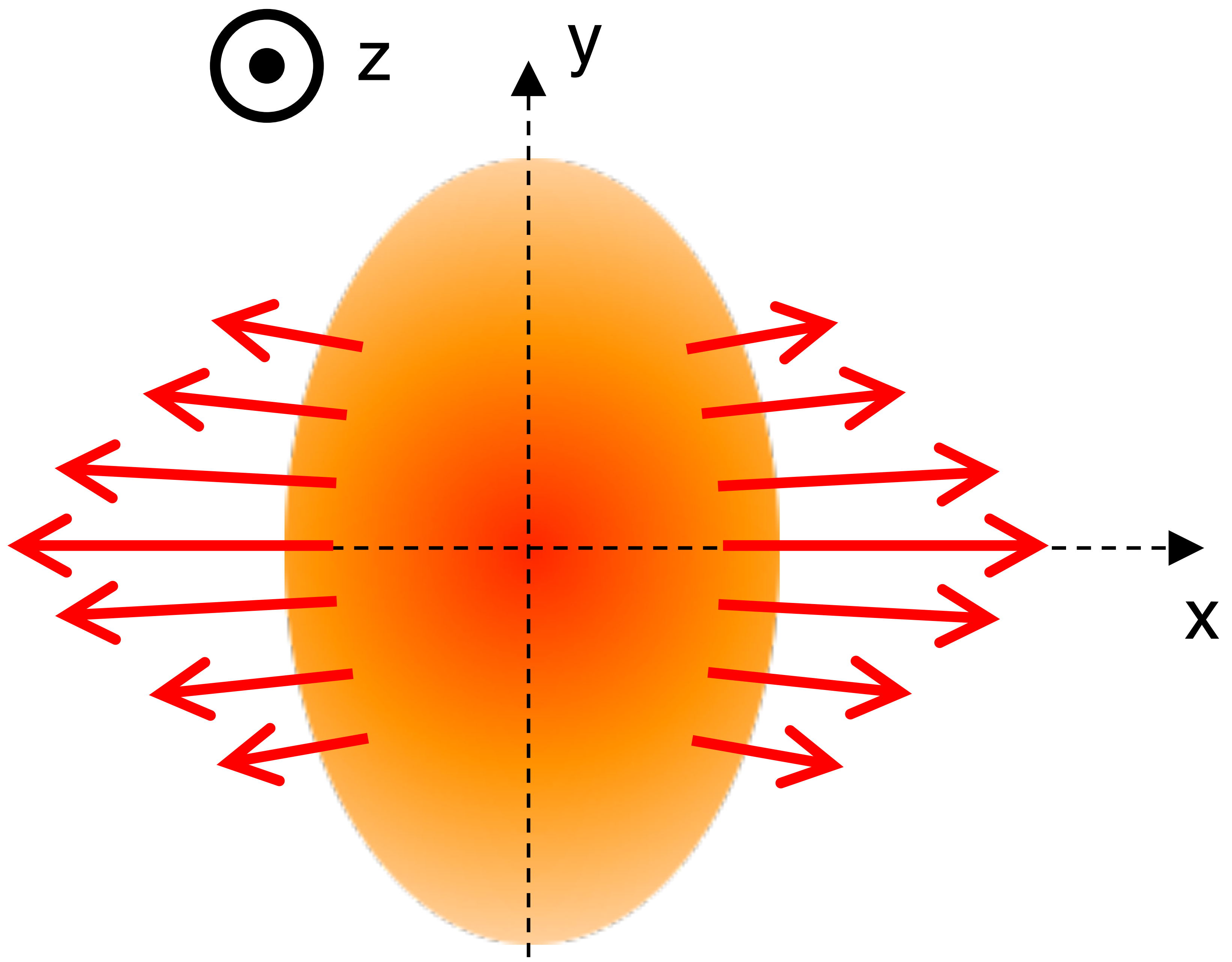
S. Alzharani, S. Ryu, and C. Shen, PRC106, 014905 (2022)

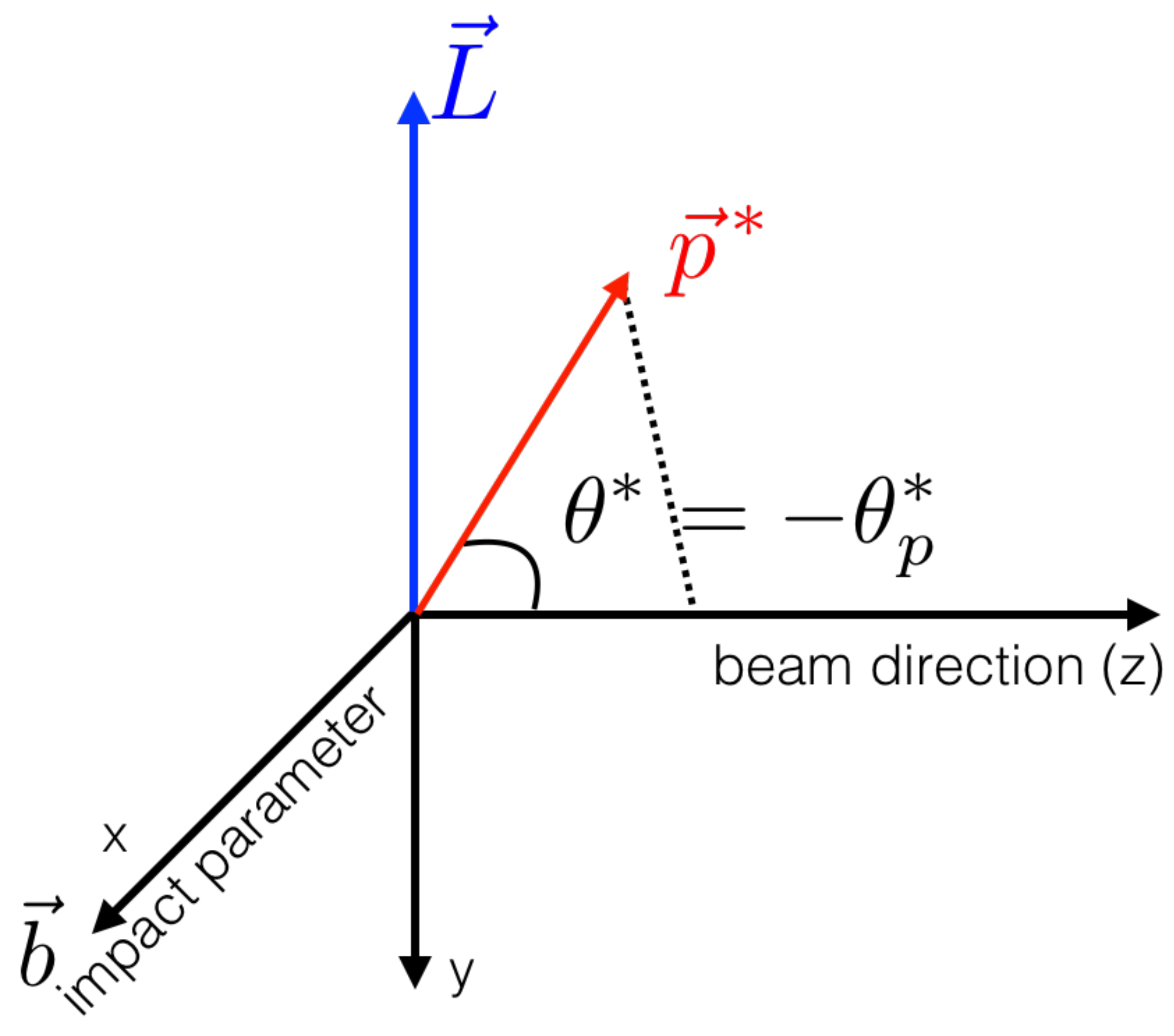


- $P_{z,2}$ from Isobar data comparable to Au+Au and Pb+Pb
  - There may be a small system size dependence, rather than energy dependence
- Additional constraint on the specific shear viscosity

Polarization along the beam direction

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





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

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

$$= \alpha_H P_z \langle (\cos\theta_p^*)^2 \rangle$$

$$\therefore \quad P_z = \frac{\langle \cos\theta_p^* \rangle}{\alpha_H \langle (\cos\theta_p^*)^2 \rangle}$$

$$= \frac{3\langle \cos\theta_p^* \rangle}{\alpha_H} \quad \text{(if perfect detector)}$$

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

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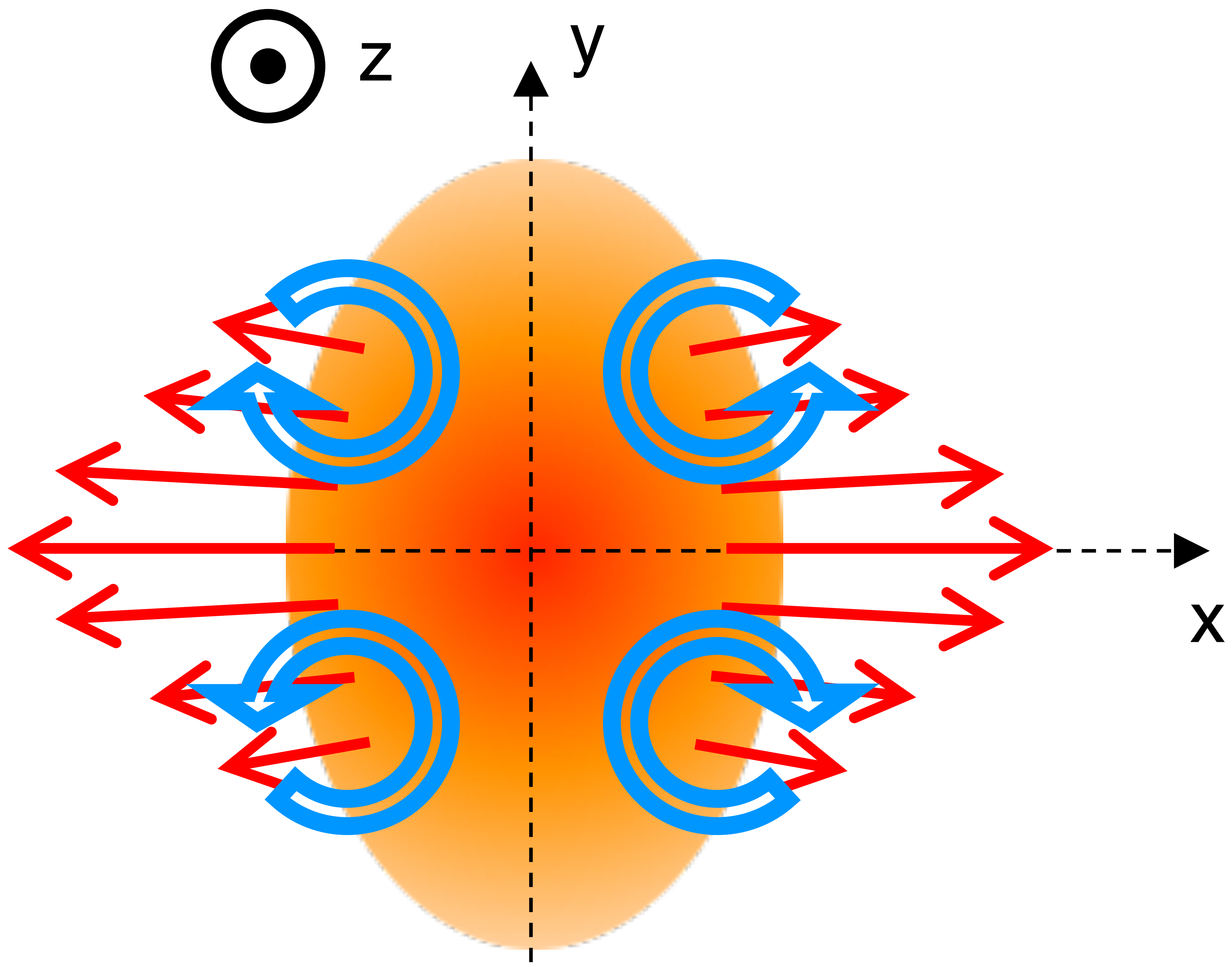

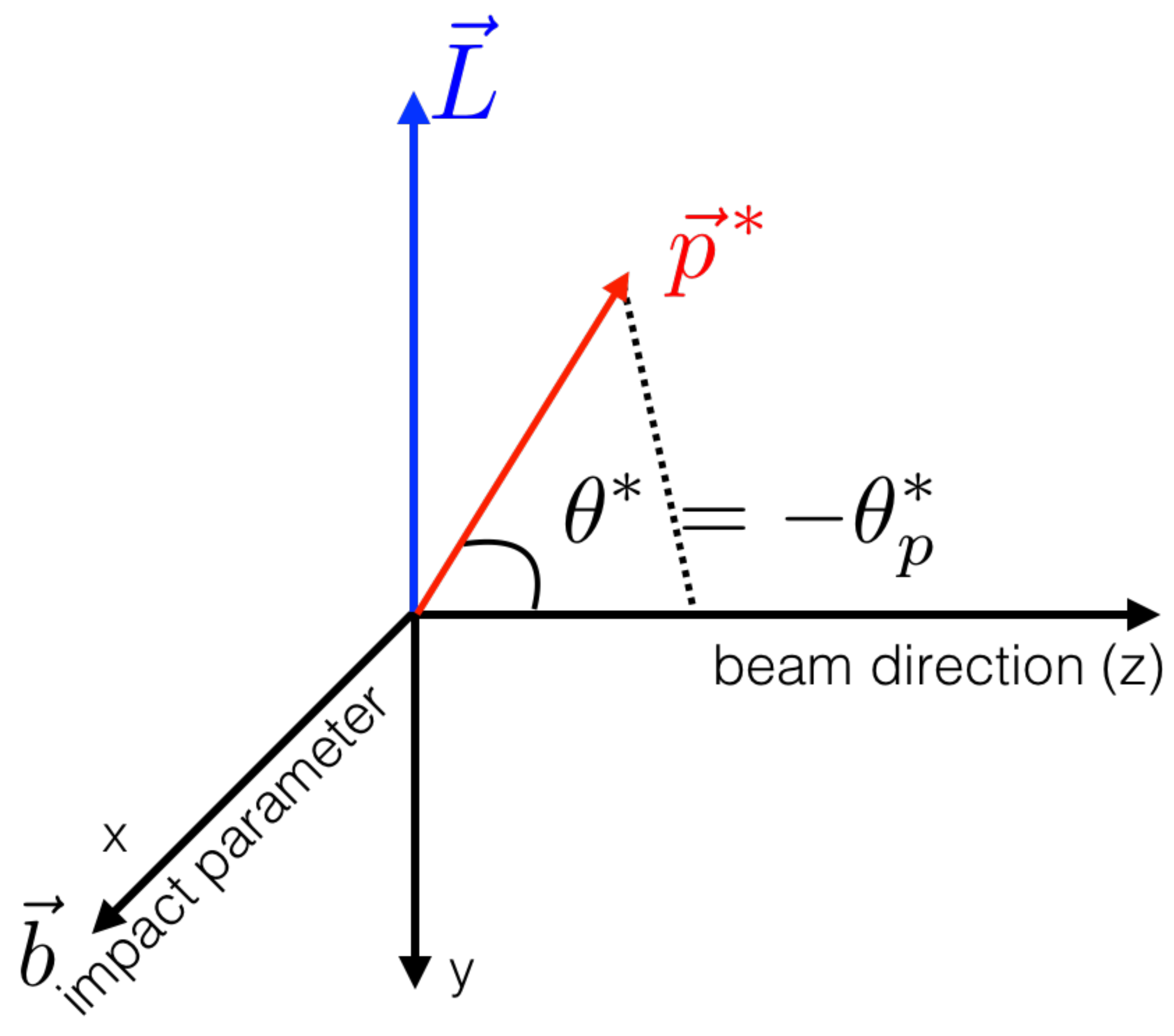

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$$= \alpha_{\rm H} P_z \langle(\cos\theta_p^*)^2\rangle$$

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

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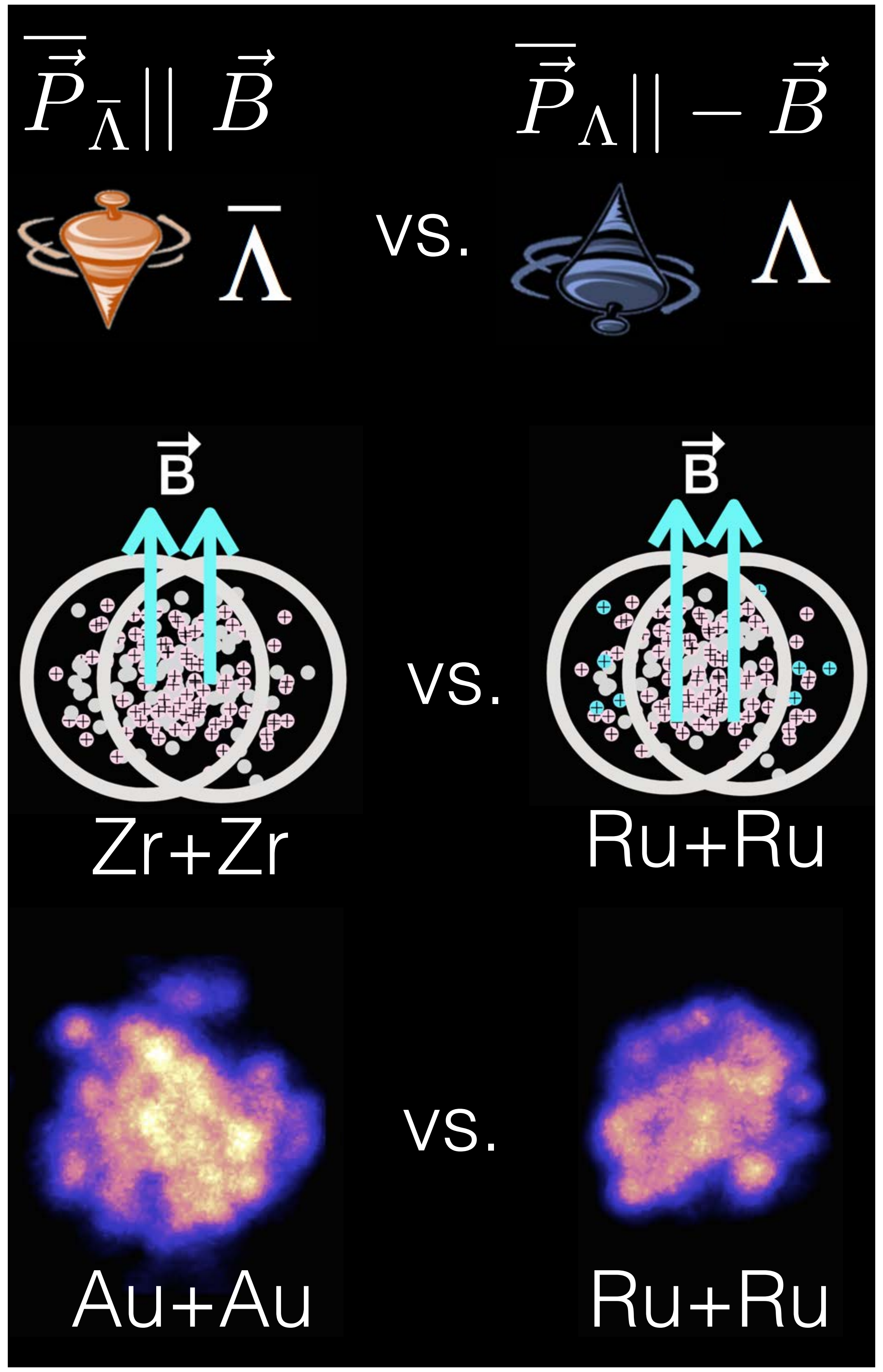
P_H in isobar collisions

picture from P. Tribedy (QM2022)

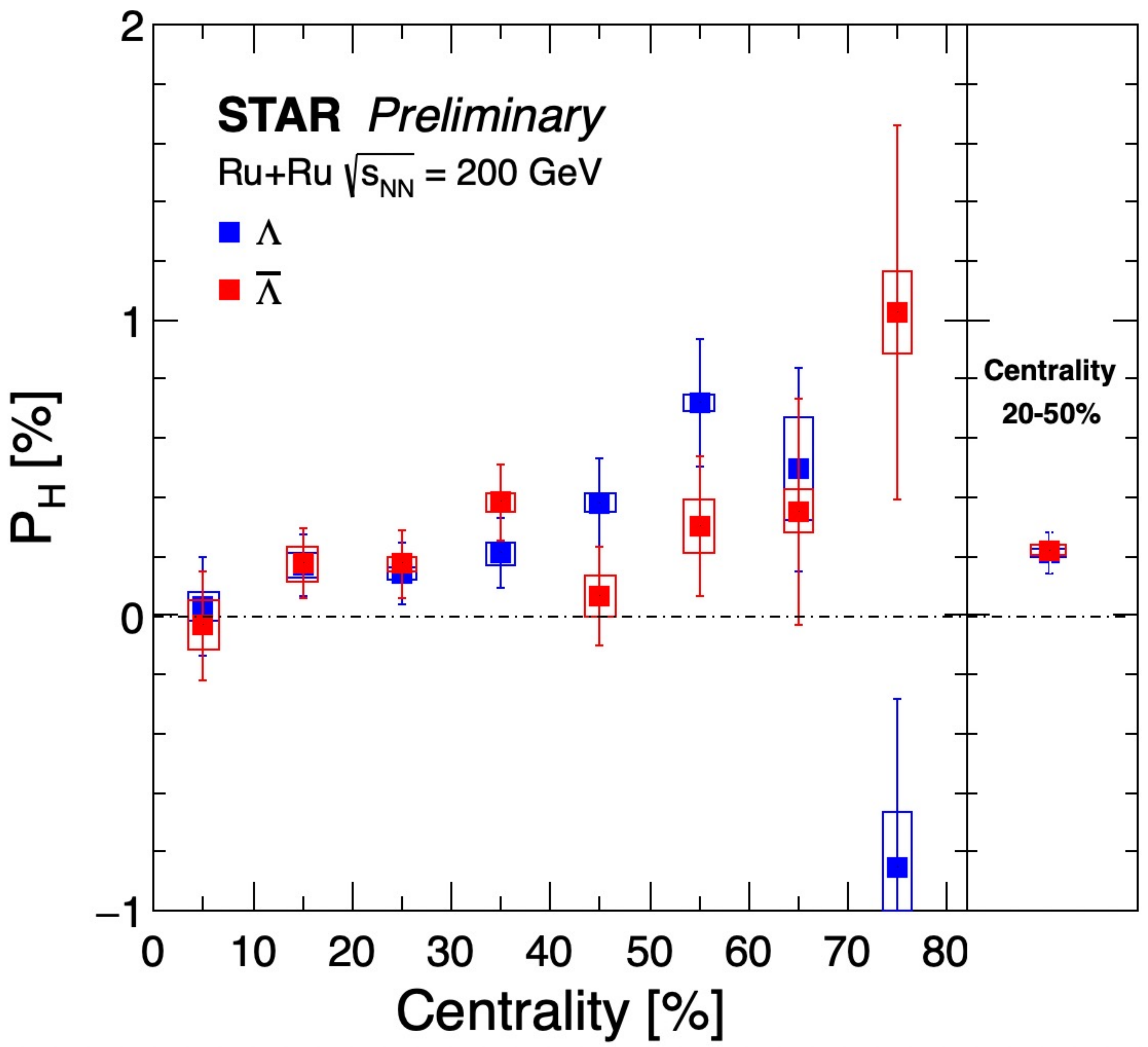


$$P_\Lambda^{\rm Au} < P_\Lambda^{\rm Ru} \approx P_\Lambda^{\rm Zr} < P_\Lambda^{\rm Cu} < P_\Lambda^{\rm O}\ ?$$

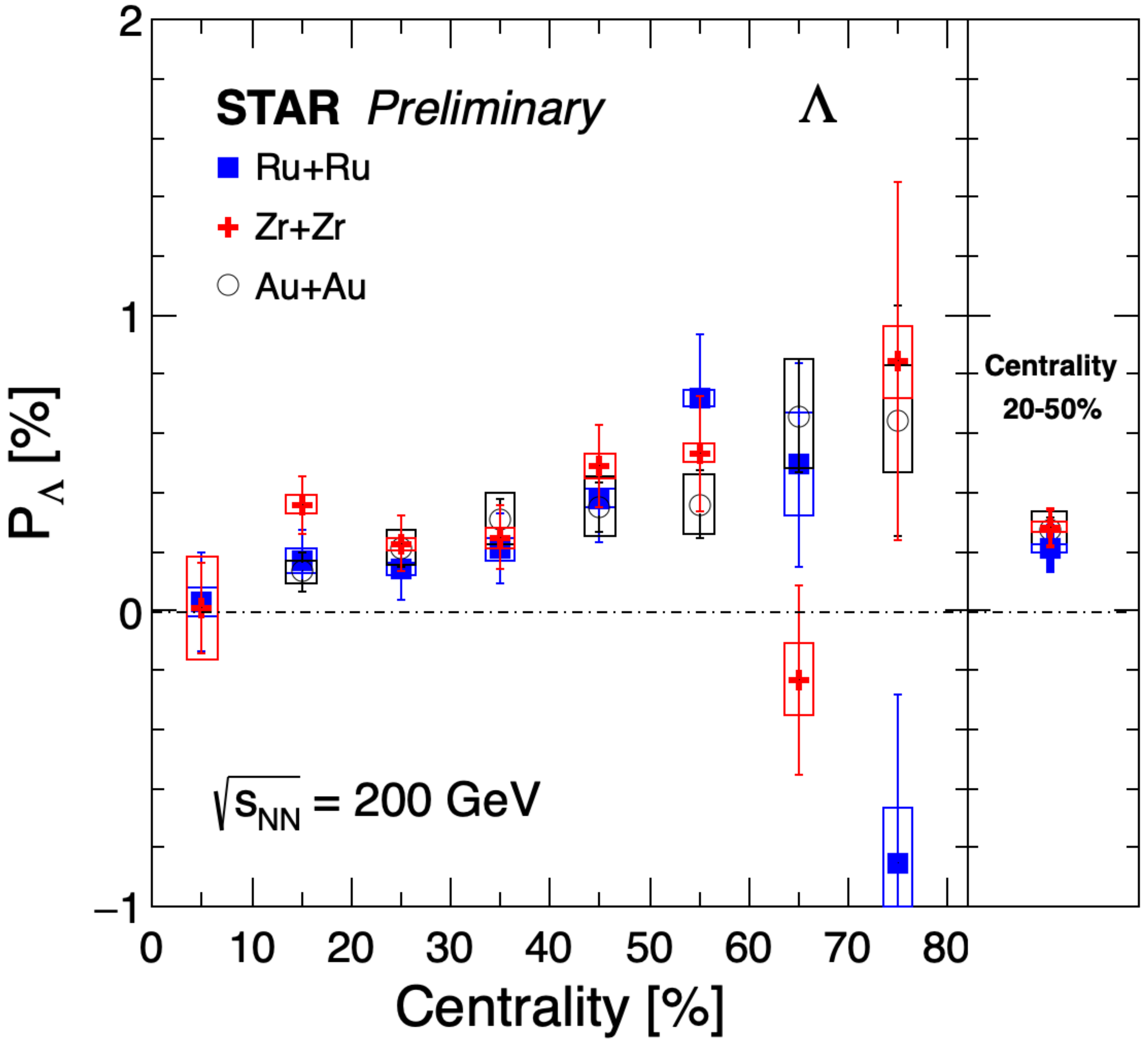
- Initial B-field ($|B|^2$) difference is 10-15% between Ru+Ru and Zr+Zr
- System size dependence predicted: longer lifetime dilutes the vorticity

S. She et al., PLB788(2019)409

Λ vs. anti-Λ in Ru+Ru



Isobar vs. Au+Au for Λ



X. Gou (STAR), QM2022

No significant difference between Λ-antiΛ, isobar vs. Au+Au

A possible probe of B-field

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

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

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

μΛ: Λ magnetic moment

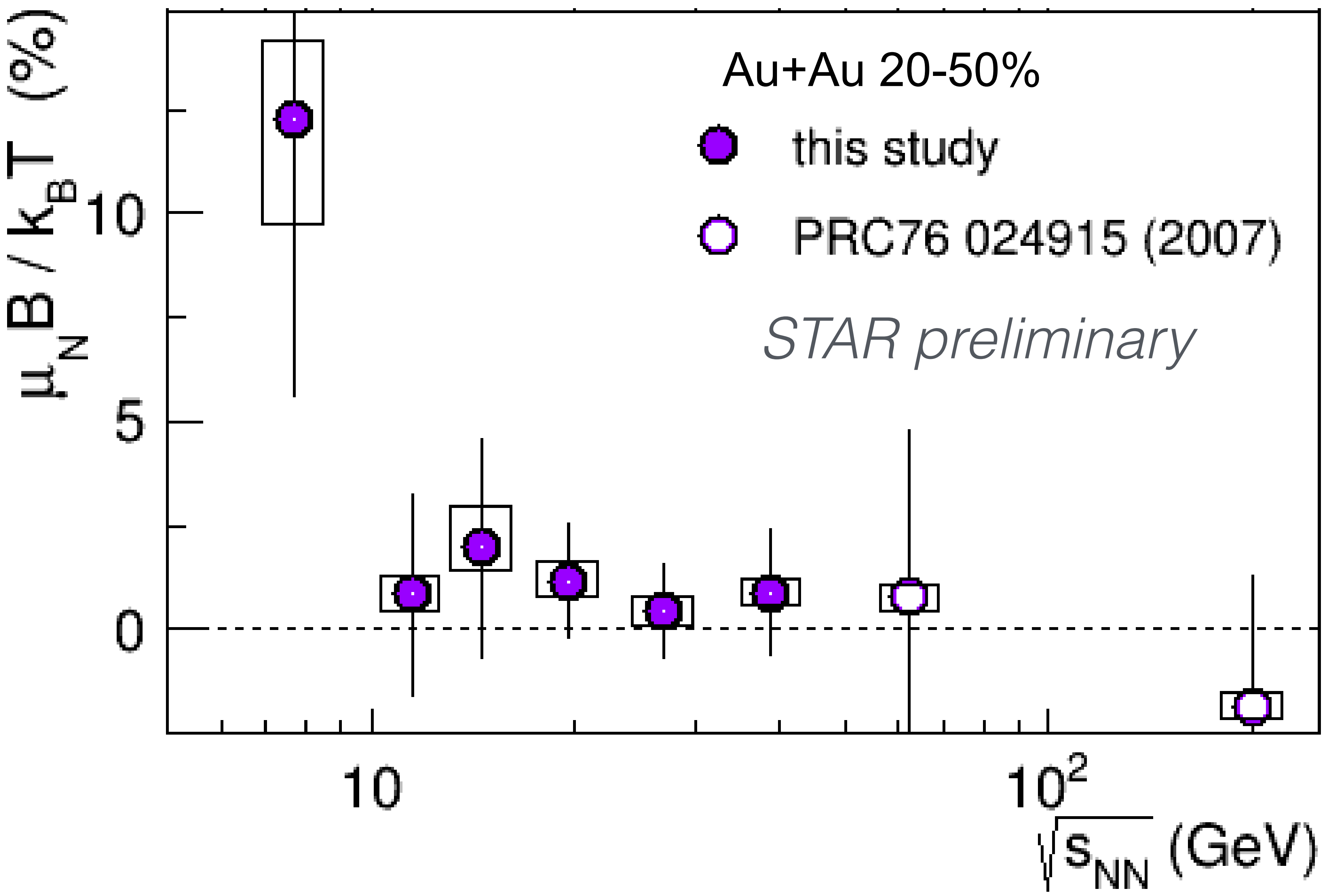
$$B = (P_\Lambda - P_{\bar{\Lambda}})T/(2\mu_\Lambda)$$

$$\sim 2 \times 10^{11}\ [\mathrm{T}]$$

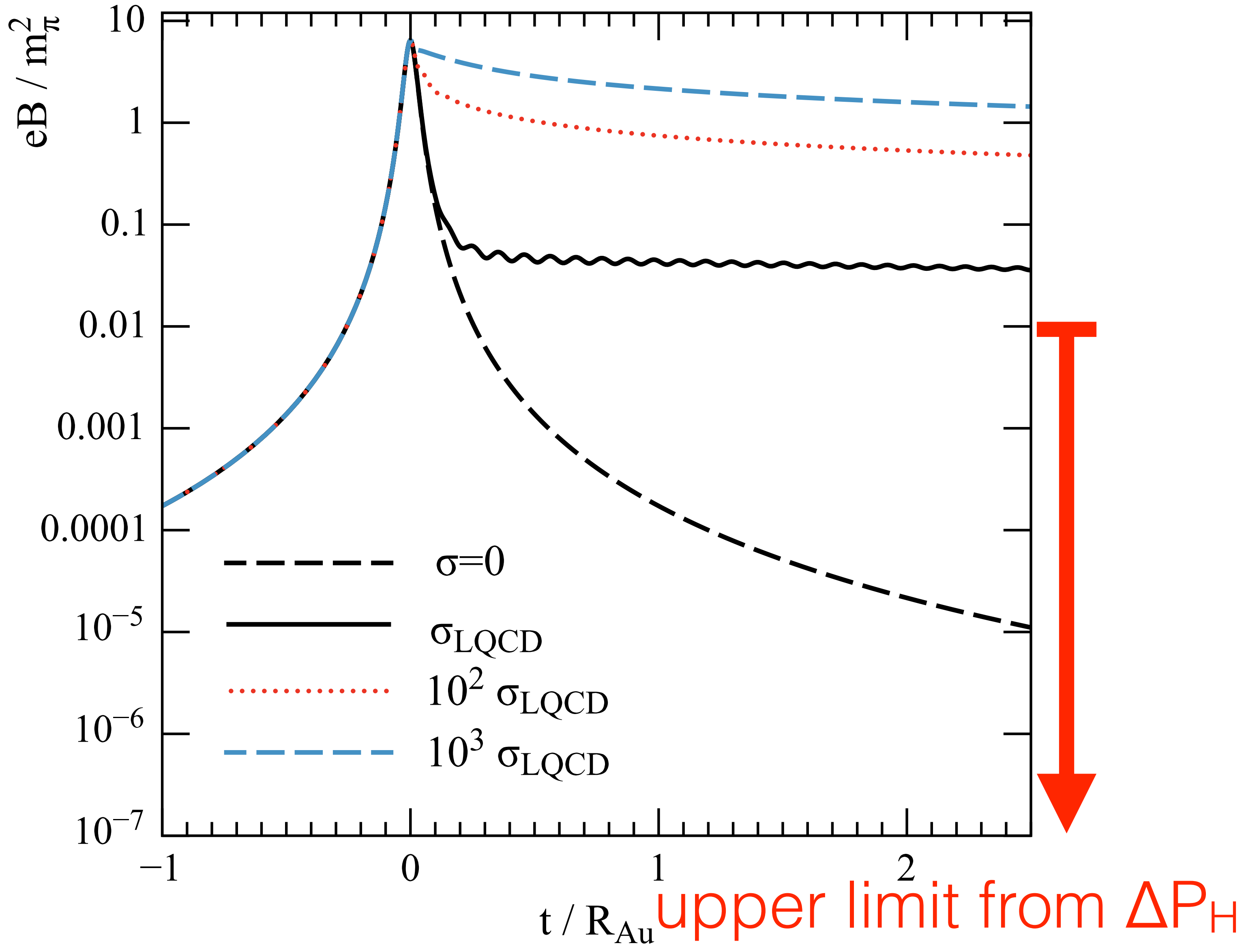
$$eB \sim 10^{-2} \mathrm{m}_\pi^2$$

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

I. Upsal (STAR), QM17



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



Conductivity increases lifetime.

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