



Spin Physics in Nuclear and Collider Experiments

- Spin as a probe of QCD matter and hadron structure -

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(新井田 貴文)

 **筑波大学**
University of Tsukuba

Contents of this lecture

- ▶ Day-1: The birth of spin physics: Stern-Gerlach to Wu
- ▶ Day-2: Spin structure of nucleon and Transverse spin phenomena
- ▶ Day-3: Spin polarization in relativistic heavy-ion collisions (1)
- ▶ Day-4: Spin polarization in relativistic heavy-ion collisions (2)
- ▶ Day-5: Spin correlations and Future directions

Day-3

Spin polarization in relativistic heavy-ion collisions

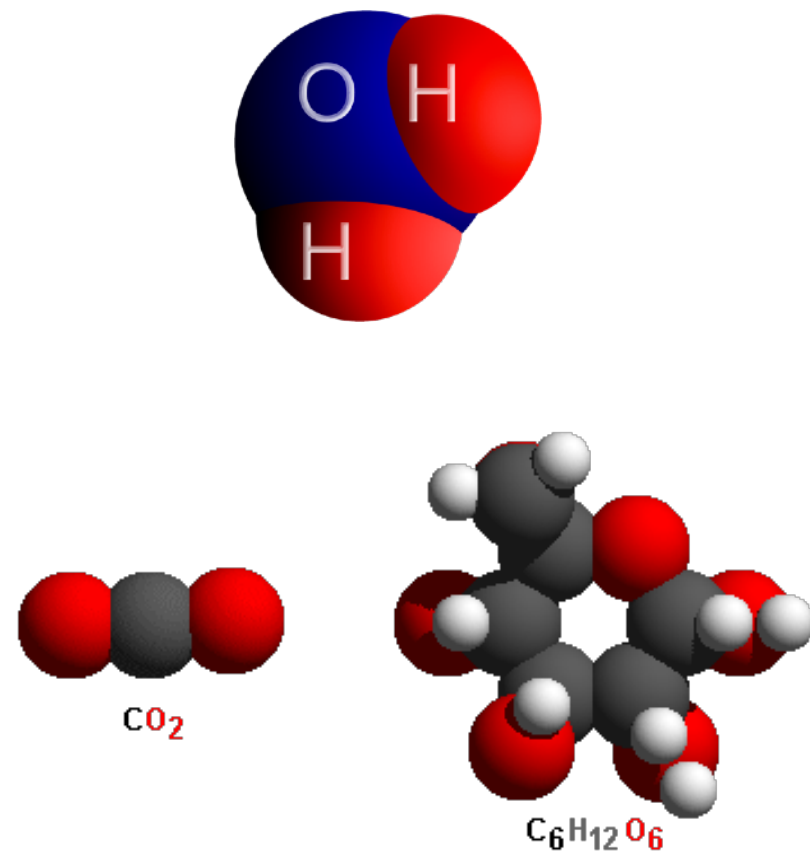
Hierarchy of matter

Matter around us



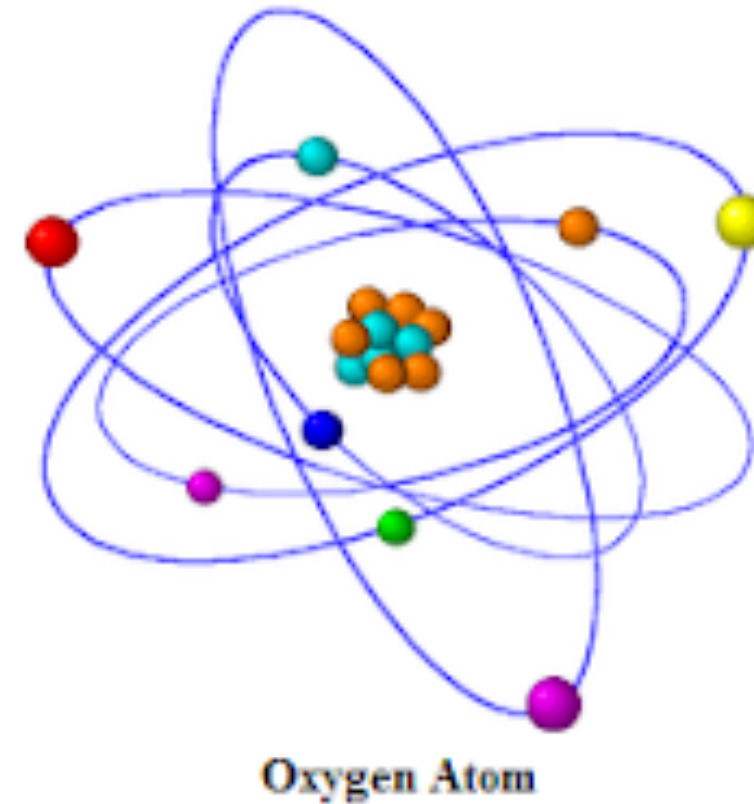
$\sim 10^{-1}$ m

Molecule



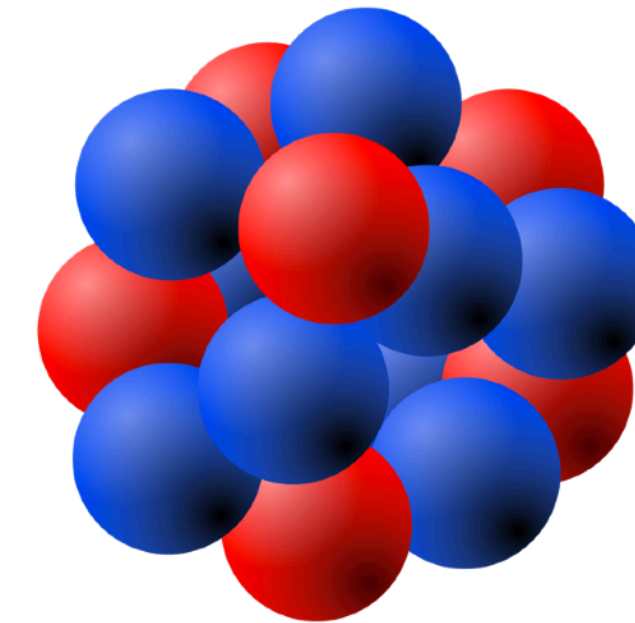
$\sim 10^{-9}$ m

Atom



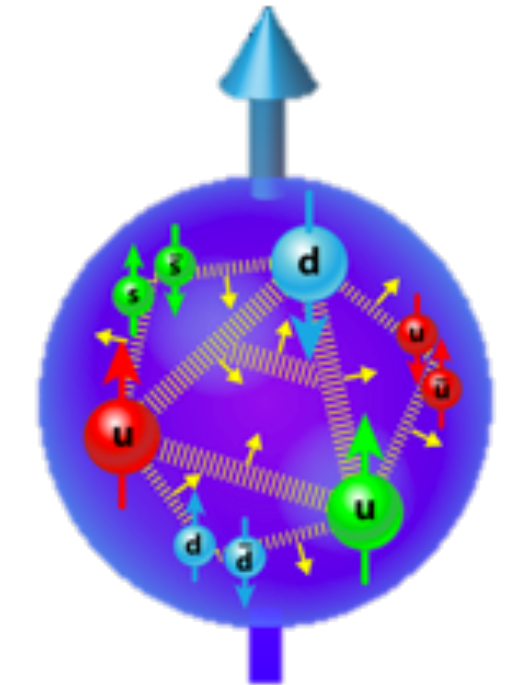
$\sim 10^{-10}$ m

Nucleus



$10^{-14} \sim 10^{-15}$ m

Quarks and Gluons



10^{-15} m = 1 fm (femto-meter)
(also sometimes called "fermi")

Quarks and gluons are elementary particles and building blocks of matter
(no internal structure in quarks and gluons)

Elementary particles

Standard Model of Elementary Particles

	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
QUARKS	u up	c charm	t top	g gluon	H higgs
	$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	d down	s strange	b bottom	γ photon	
LEPTONS	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	e electron	μ muon	τ tau	Z Z boson	
	$< 1.0 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$	
	0	0	0	± 1	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

- Matter particles (fermions, spin-1/2)
- Force carriers (gauge bosons, spin-1).

Strong interaction between quarks mediated by gluons is described by quantum chromodynamics (QCD)

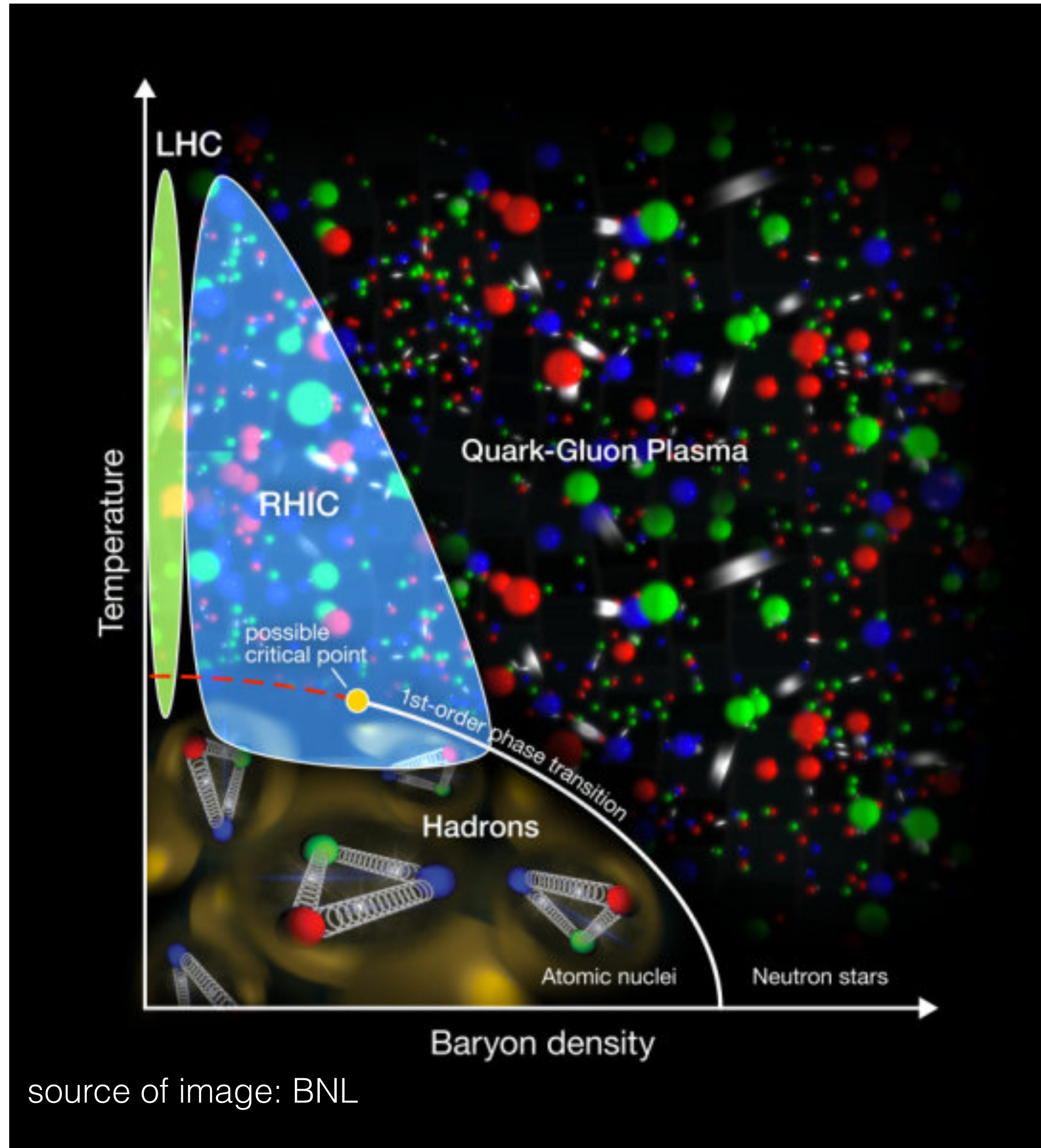
Confinement

- Strong interaction becomes stronger at long distance (low Q)
- Quarks/gluons cannot exist as isolated particles

Asymptotic freedom

- Strong interaction becomes weaker at short distance (high Q)
- Quarks behave almost like free particles

Quark-Gluon Plasma (QGP)



At extremely high temperatures and densities, quarks and gluons become deconfined, forming a new state of matter called quark-gluon plasma (QGP).

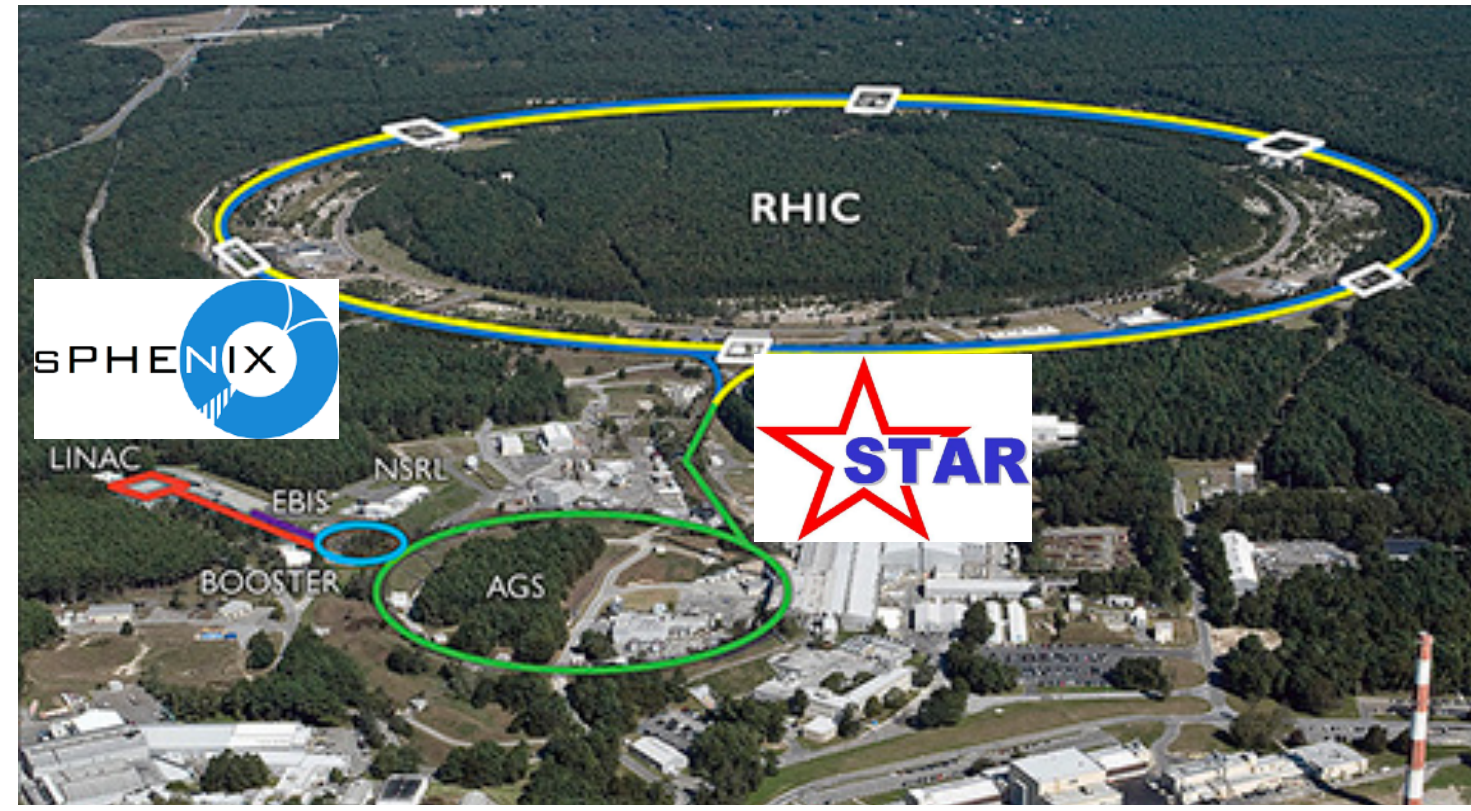
$$\circ T_{pc} \sim 155 \text{ MeV}, \quad \varepsilon_c \sim 0.4 \text{ GeV/fm}^3 \text{ (Lattice QCD)}$$

By colliding heavy nuclei at nearly the speed of light in particle accelerators, hot and dense matter - QGP - can be created in the laboratory

$$1\text{eV} \sim 10^4 \text{ K}, \quad 170 \text{ MeV} \sim 2 \times 10^{12} \text{ K} \sim \text{a few trillion Celsius}$$

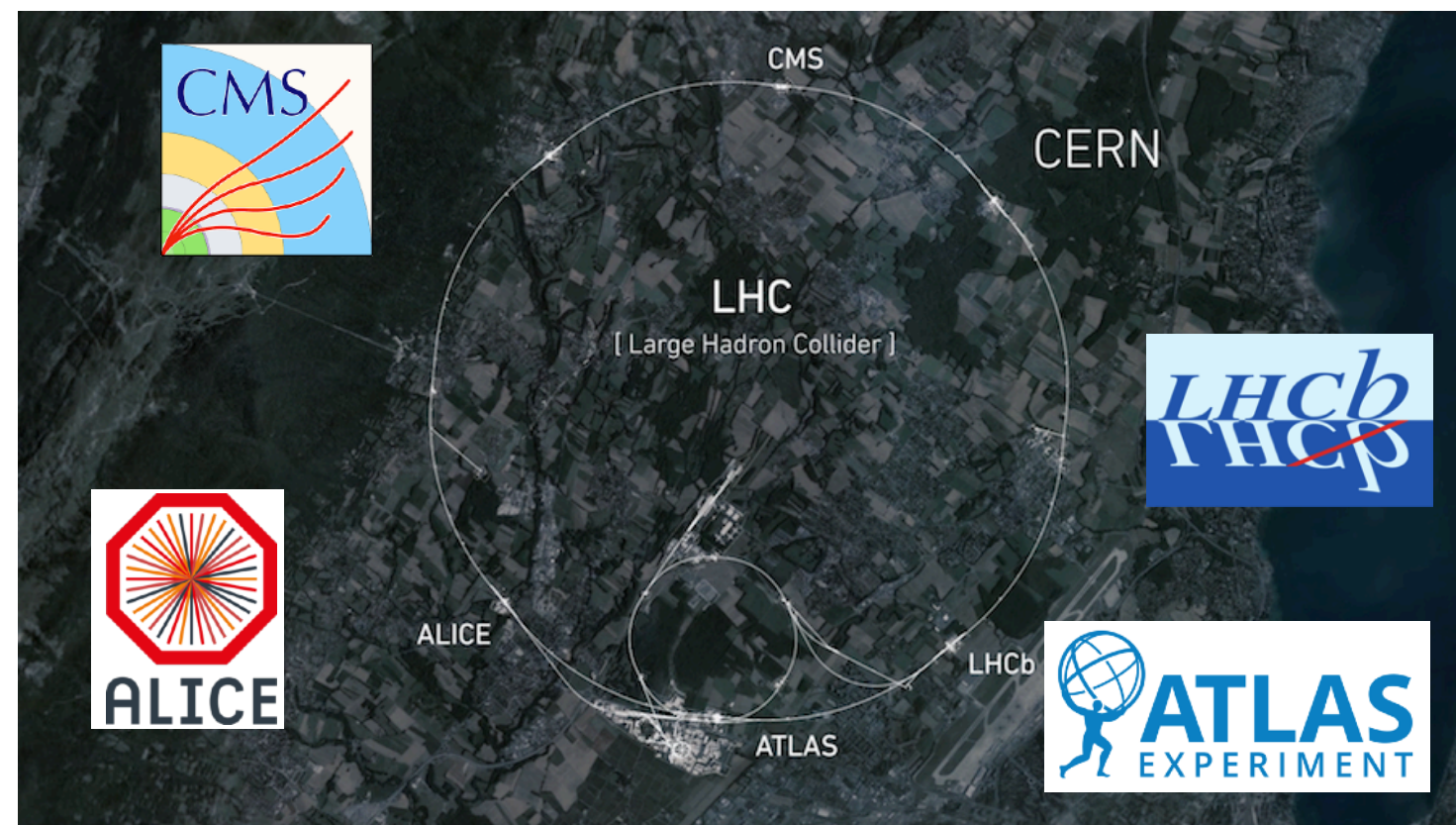
Relativistic Heavy Ion Collisions

Relativistic Heavy Ion Collider at BNL



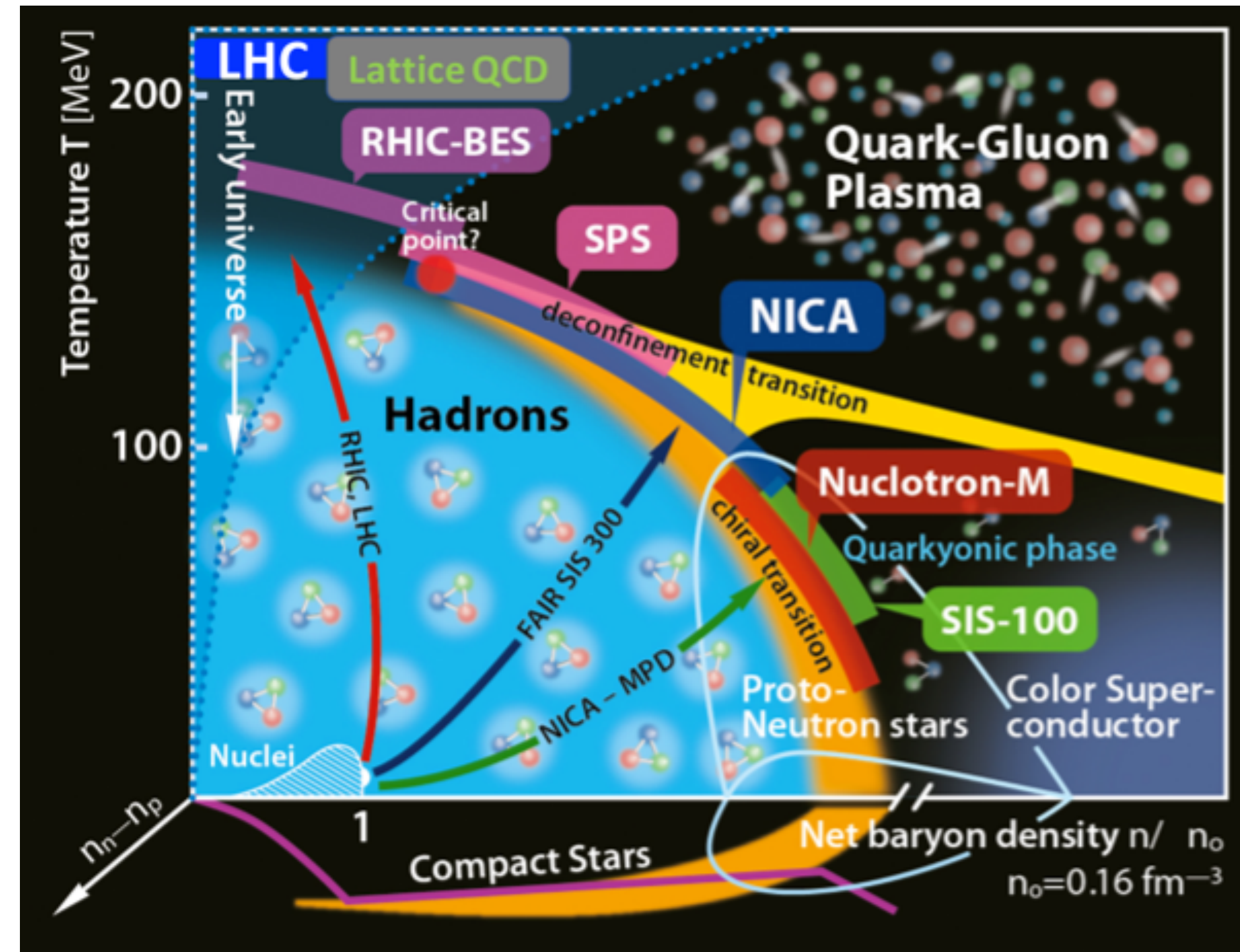
(2000-2026)

Large Hadron Collider at CERN



(First Pb-Pb collisions in 2010)

“Conjectured” QCD phase diagram



- Study properties of a deconfined state of matter, Quark-Gluon Plasma
- Search for QCD critical point and 1st-order phase transition
- Connection to the interior of neutron star at high baryon density

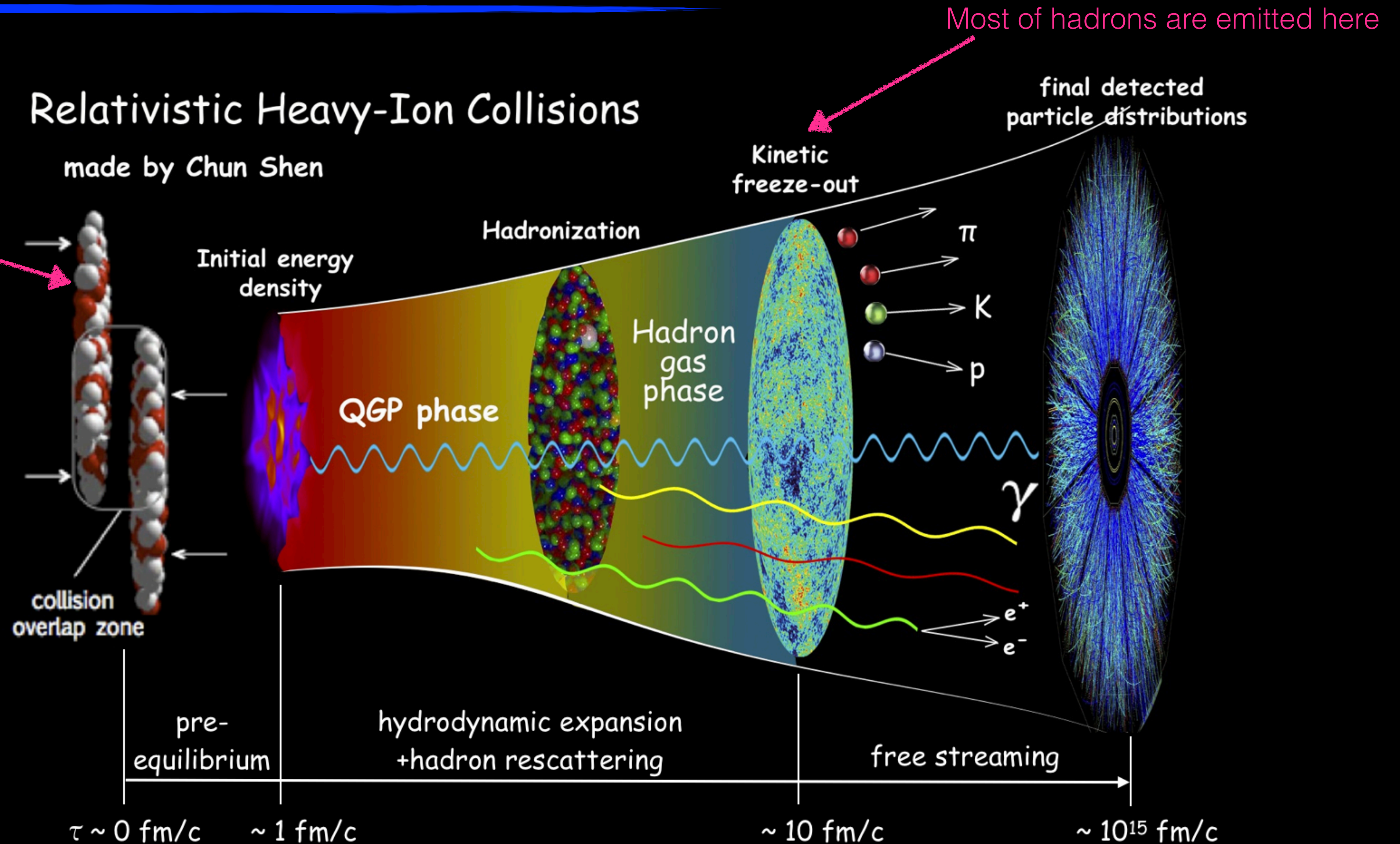
Time evolution of “Little Bang”

Relativistic Heavy-Ion Collisions

made by Chun Shen

Lorentz contracted
 $\gamma \sim 100$ (RHIC)
 $\gamma \sim 2500$ (LHC)

(99.995% the speed of light
at RHIC)



Very short lifetime ~ 10 fm/c $\sim 10^{-23}$ s

Orbital angular momentum / Strong magnetic field

For non-central heavy-ion collisions,

Large orbital angular momentum of the system:

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

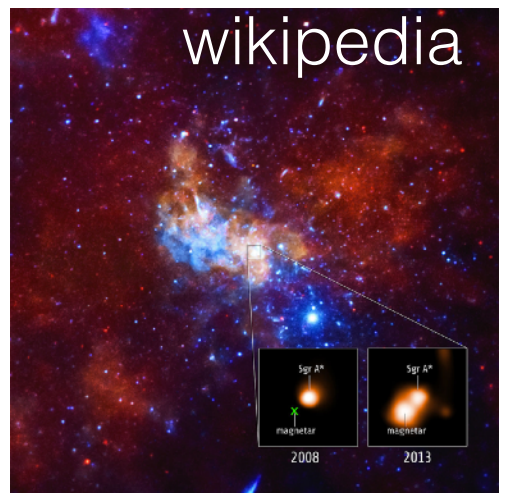
$$\sim bA\sqrt{s_{NN}} \sim 10^6 \hbar$$

Also, strong magnetic field created:

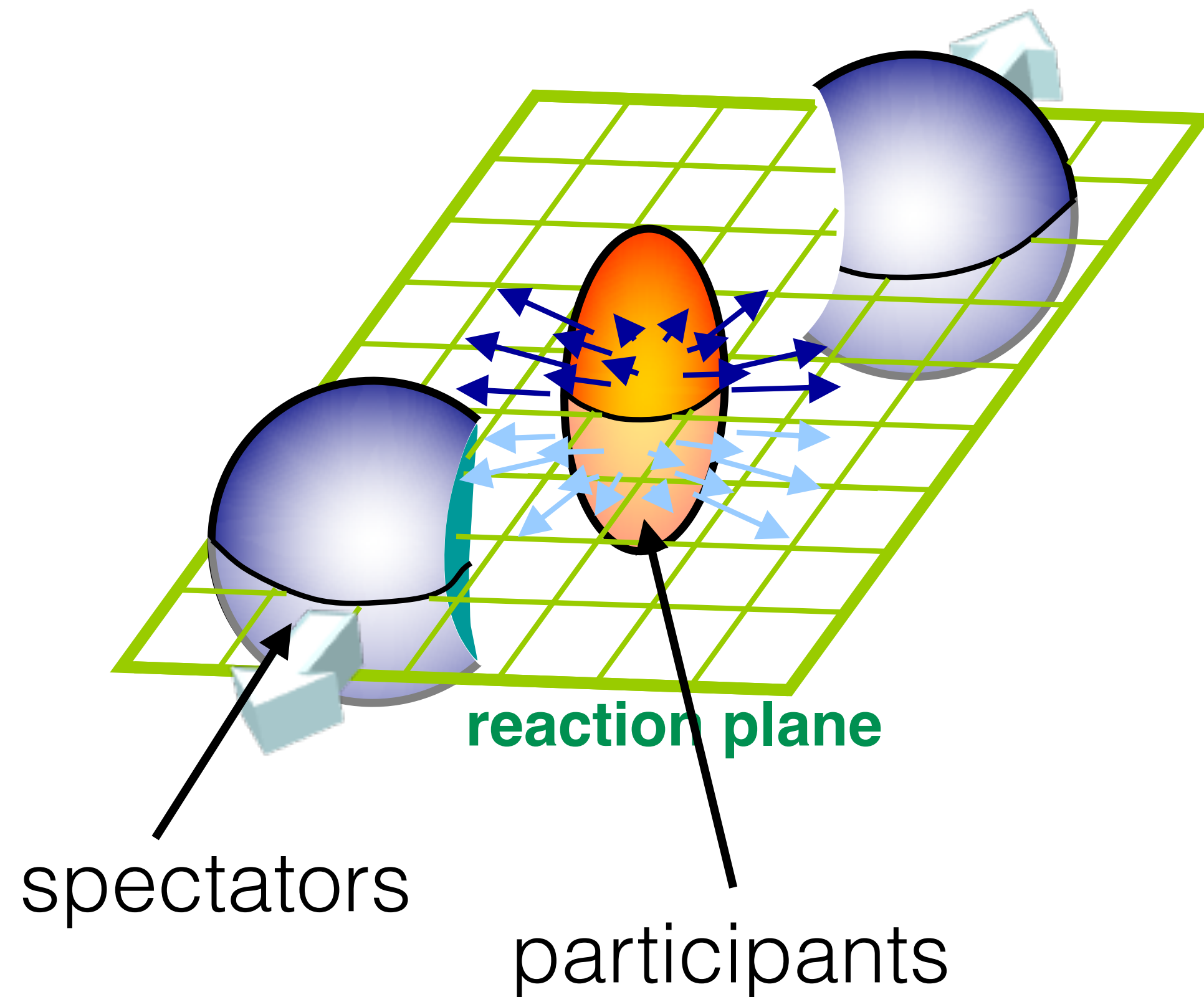
$$B \sim m_{\pi}^2 / e$$
$$\sim 10^{14} \text{ T}$$

D. Kharzeev et al., Nucl.Phys.A803, 227 (2008)

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



c.f. magnetar $B \sim 10^{11} \text{ T}$



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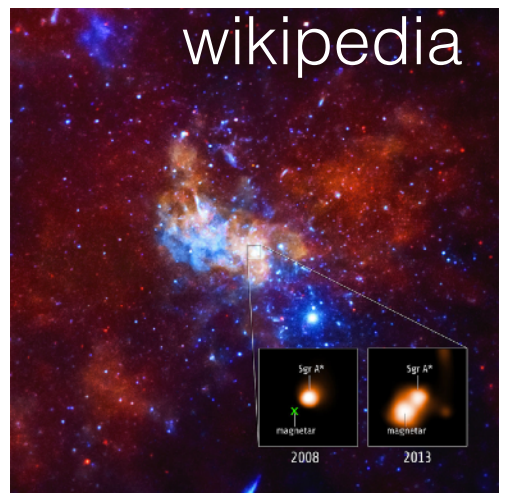
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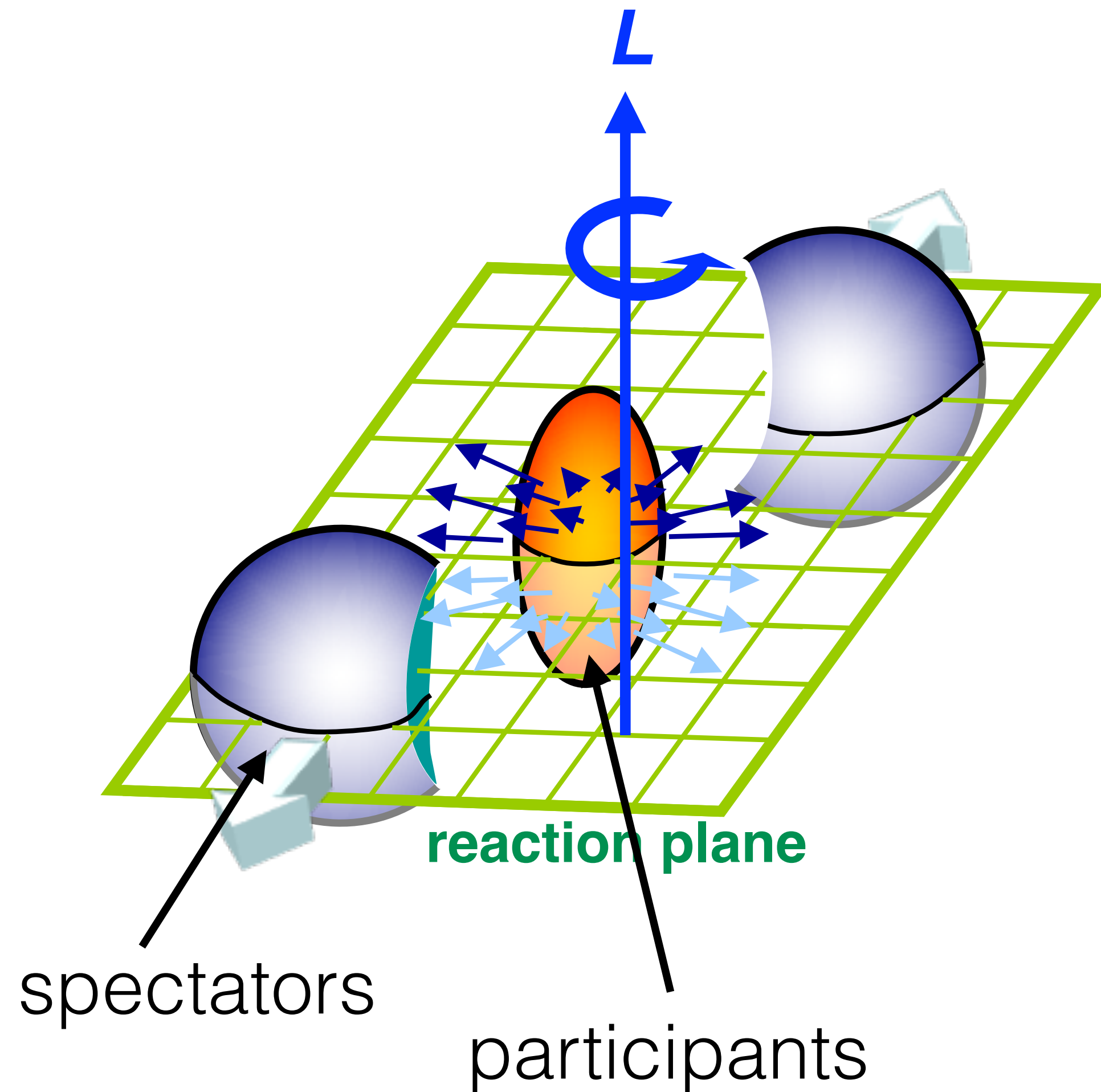
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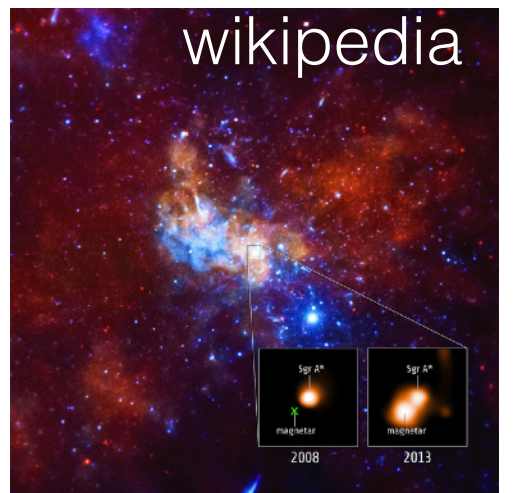
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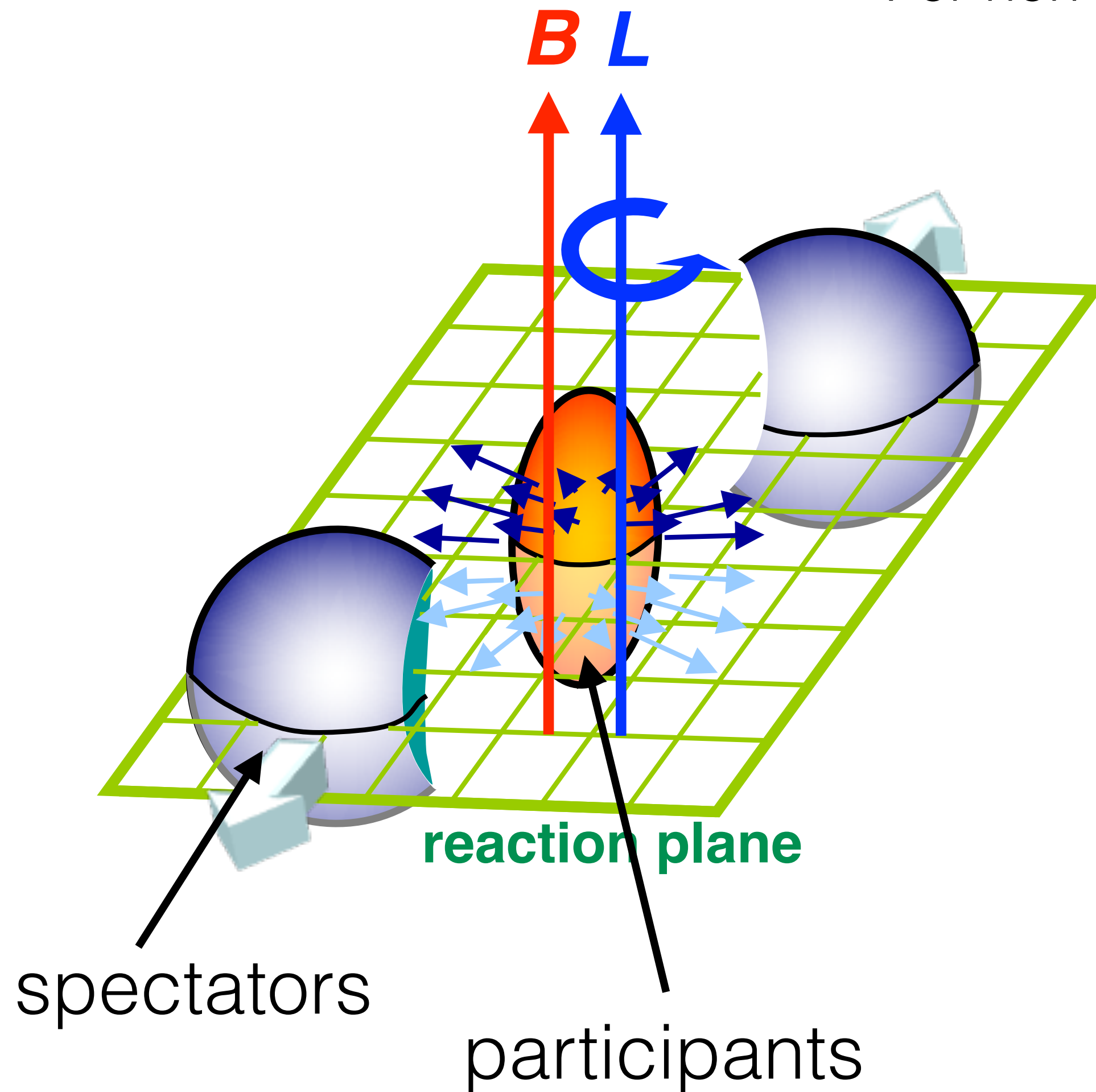
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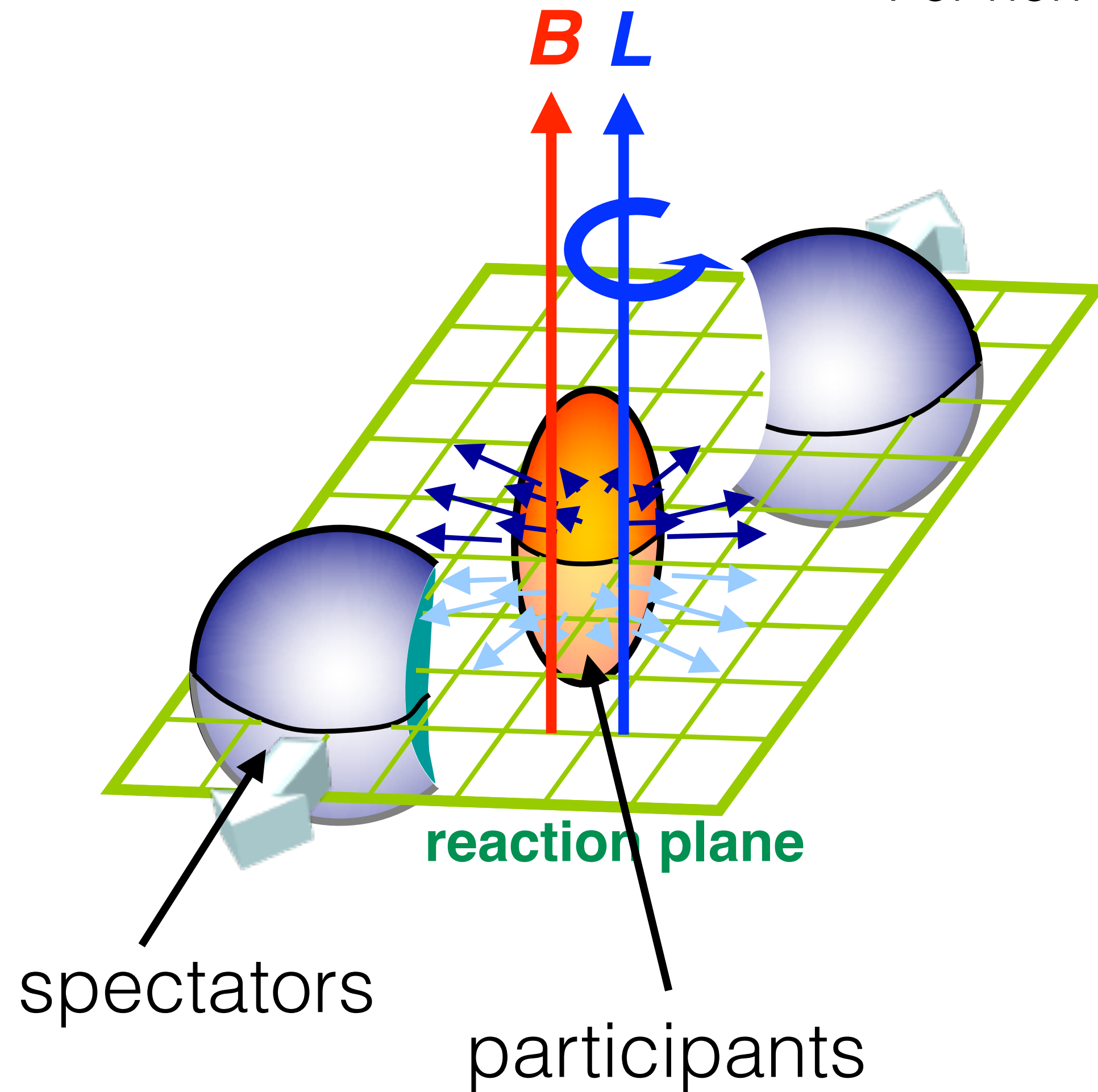
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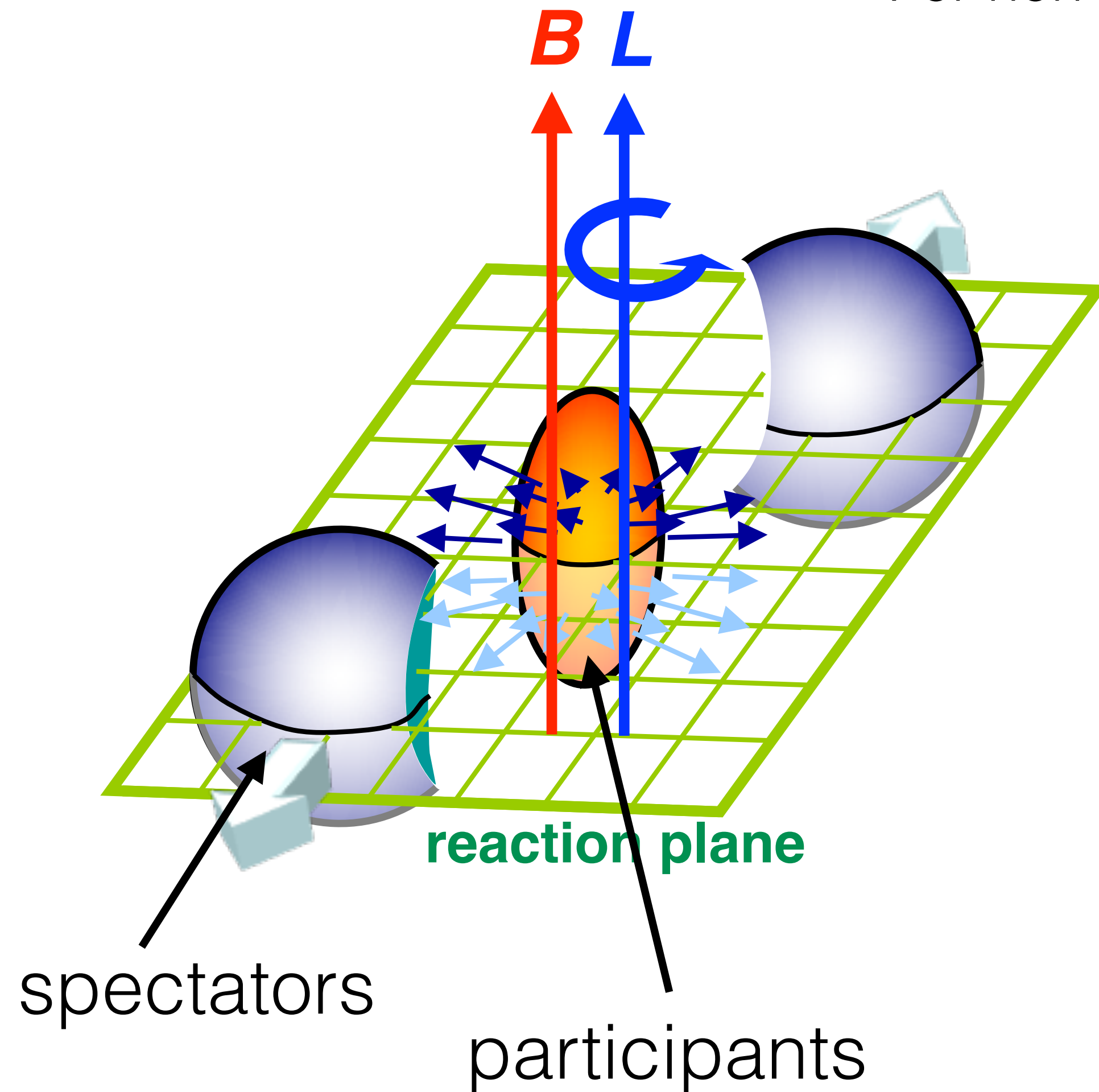
$$\sim 10 \text{ (fm)} \times 197 \times 200 \text{ (GeV)}$$

$$= 2 \times 10^3 \times 197 \text{ (fm} \cdot \text{GeV)}$$

$$(\hbar c \sim 197 \text{ MeV} \cdot \text{fm})$$

$$\sim 10^6 \hbar$$

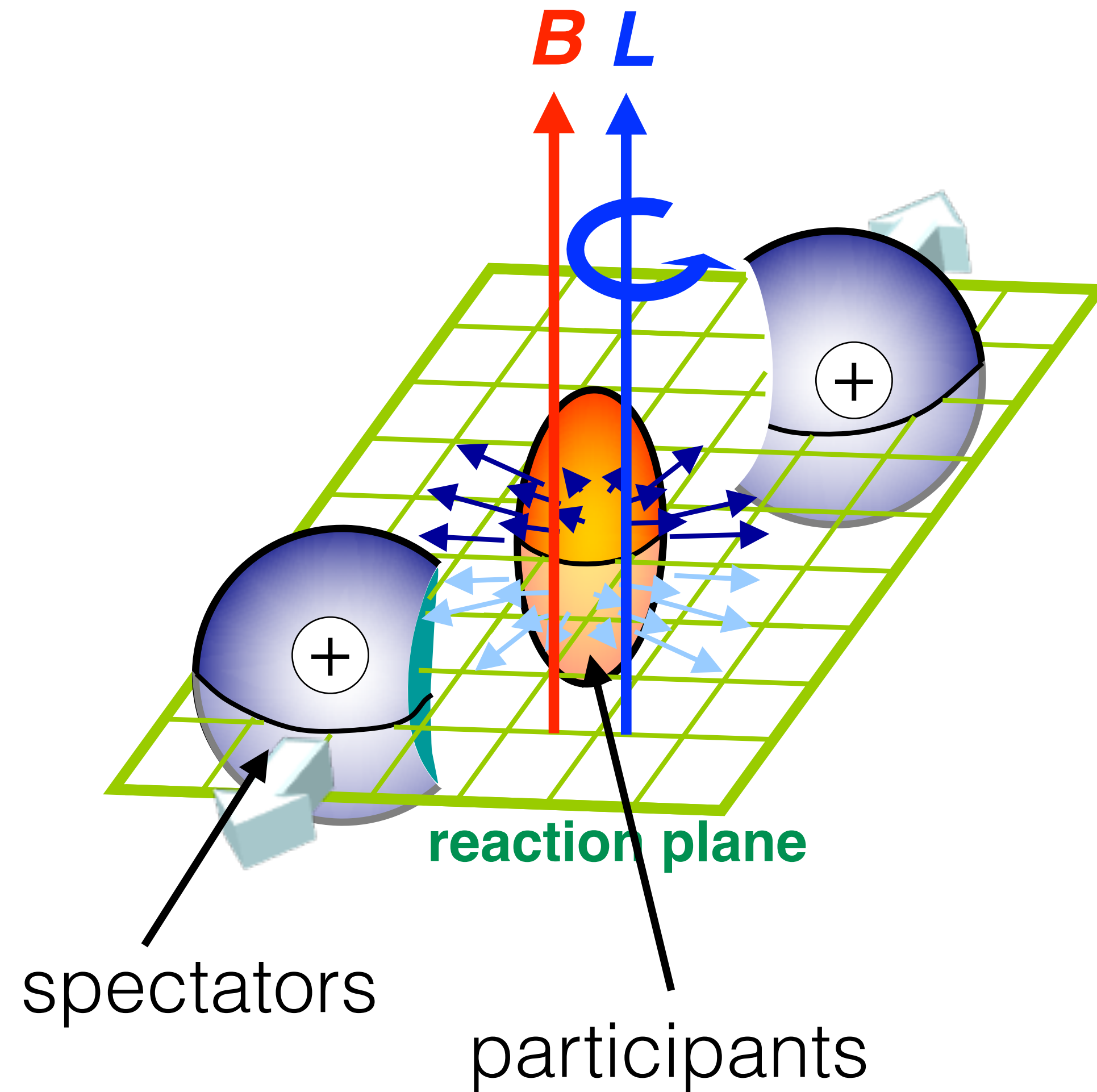
b : impact parameter
 A : mass number



Orbital angular momentum / Strong magnetic field

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

Initial magnetic field

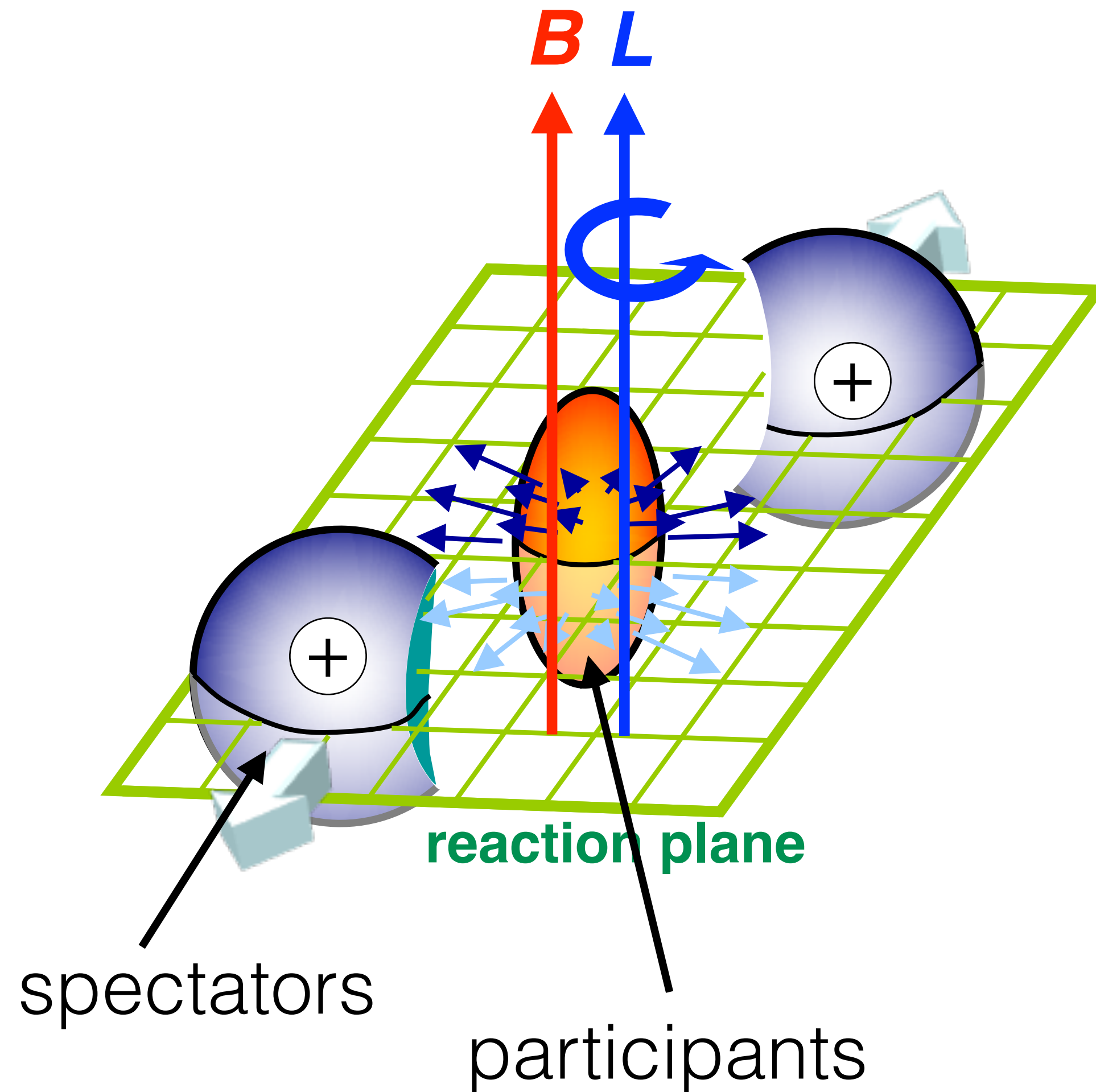


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Initial magnetic field

Assuming point charge and using Bio-Savart's Law



Orbital angular momentum / Strong magnetic field

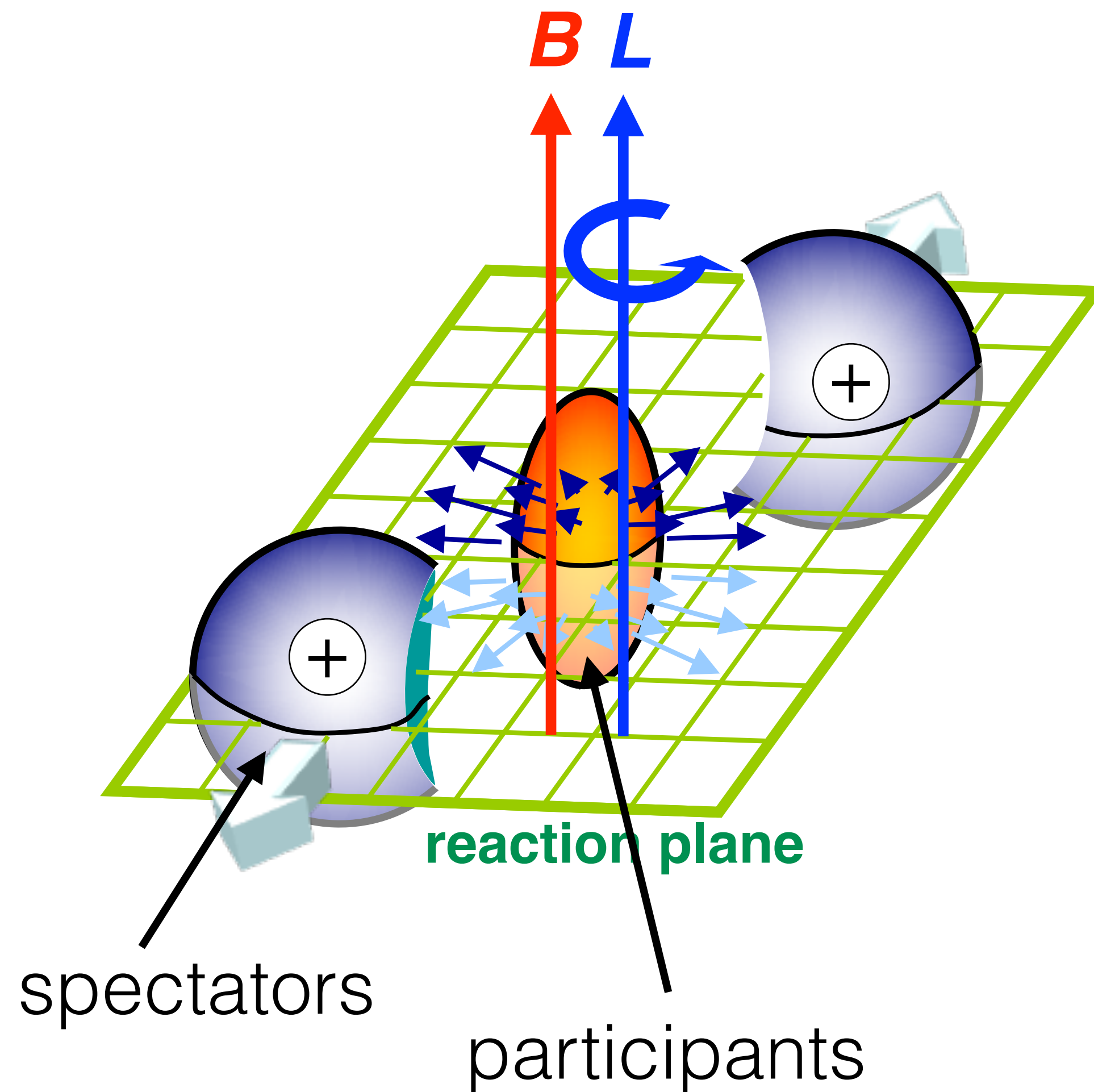
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Initial magnetic field

Assuming point charge and using Bio-Savart's Law

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

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



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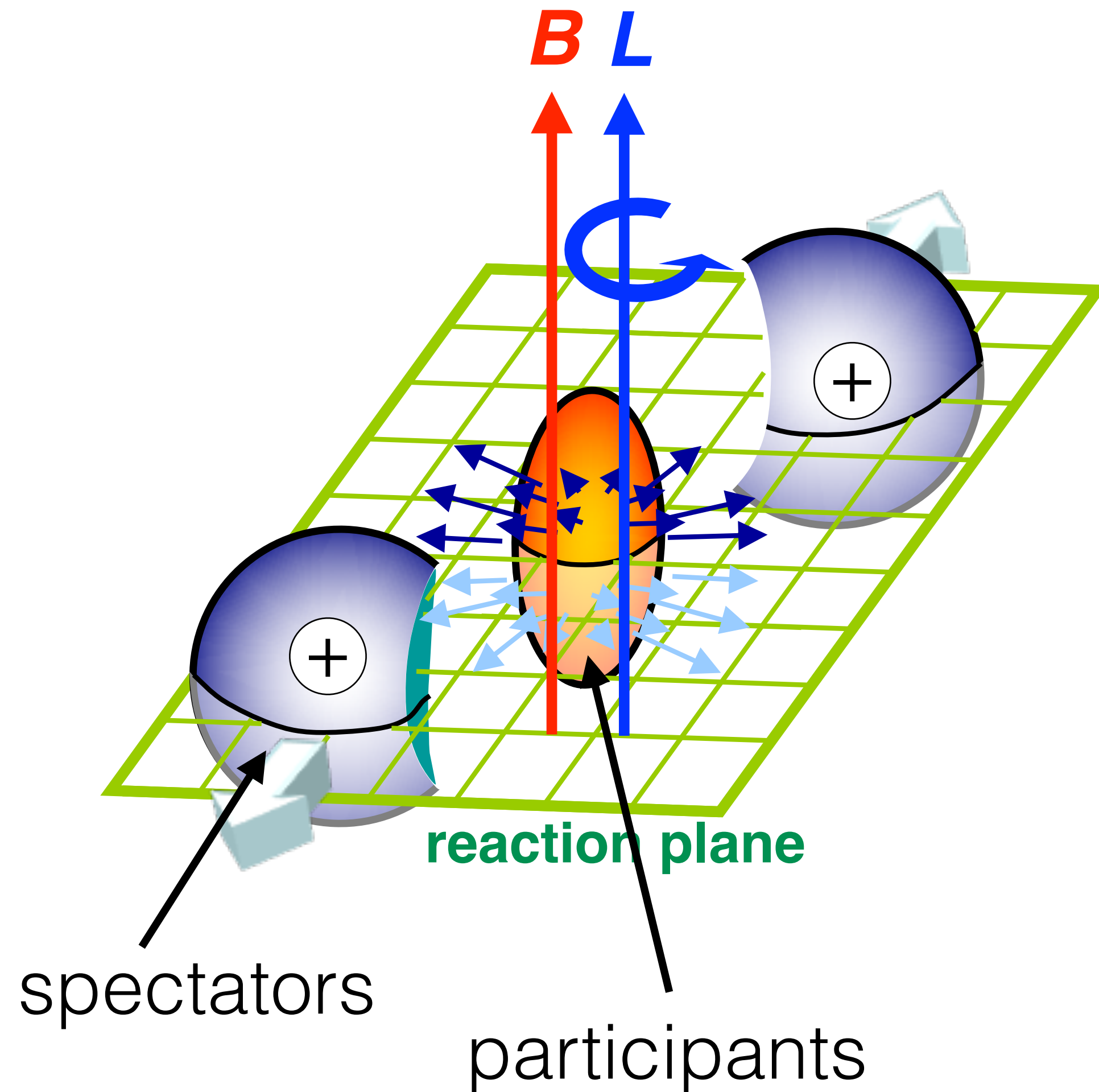
$$B \sim \frac{q\mu_0}{4\pi} \frac{\gamma \mathbf{v} \times \hat{\mathbf{r}}}{|\mathbf{r}|^2} \sim (Z\alpha\hbar/e)(\gamma\beta/r^2)$$

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

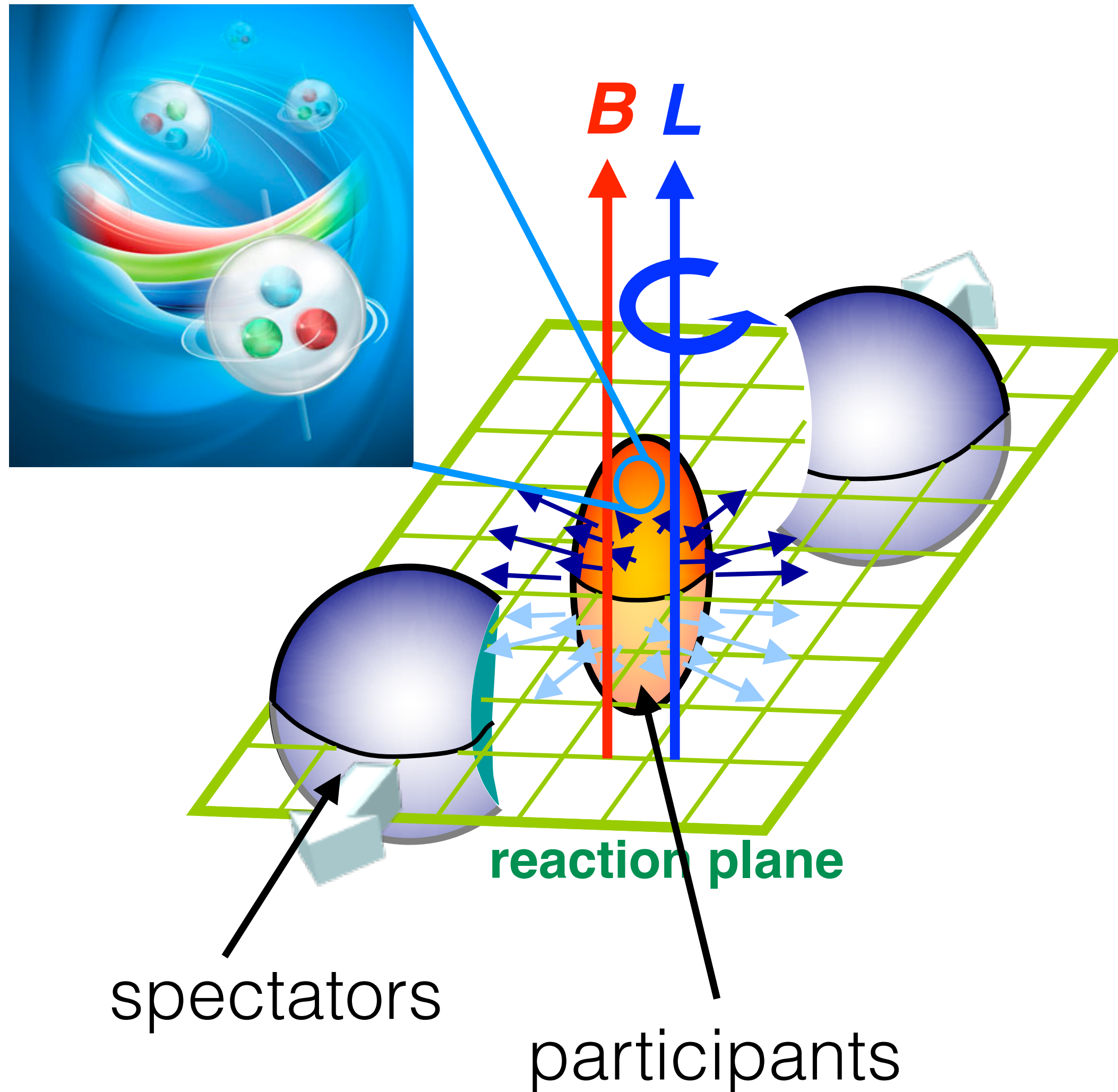
$$\sim \hbar Z\alpha$$

$$\sim m_\pi^2$$

$$B \sim 10^{13} - 10^{14} \text{ T}$$



“Global” polarization



Rotating system under strong B-field:

- Particles are “globally” polarized along L or B via spin-orbit/spin-magnetic couplings
- Particles and antiparticles are oppositely aligned along B

Z.-T. Liang and X.-N. Wang, PRL94,102301(2005), PLB629(2005)20

S. Voloshin, nucl-th/0410089

B. Betz, M. Gyulassy, and G. Torrieri, PRC76, 044901 (2007)

PRL 94, 102301 (2005)

PHYSICAL REVIEW LETTERS

18

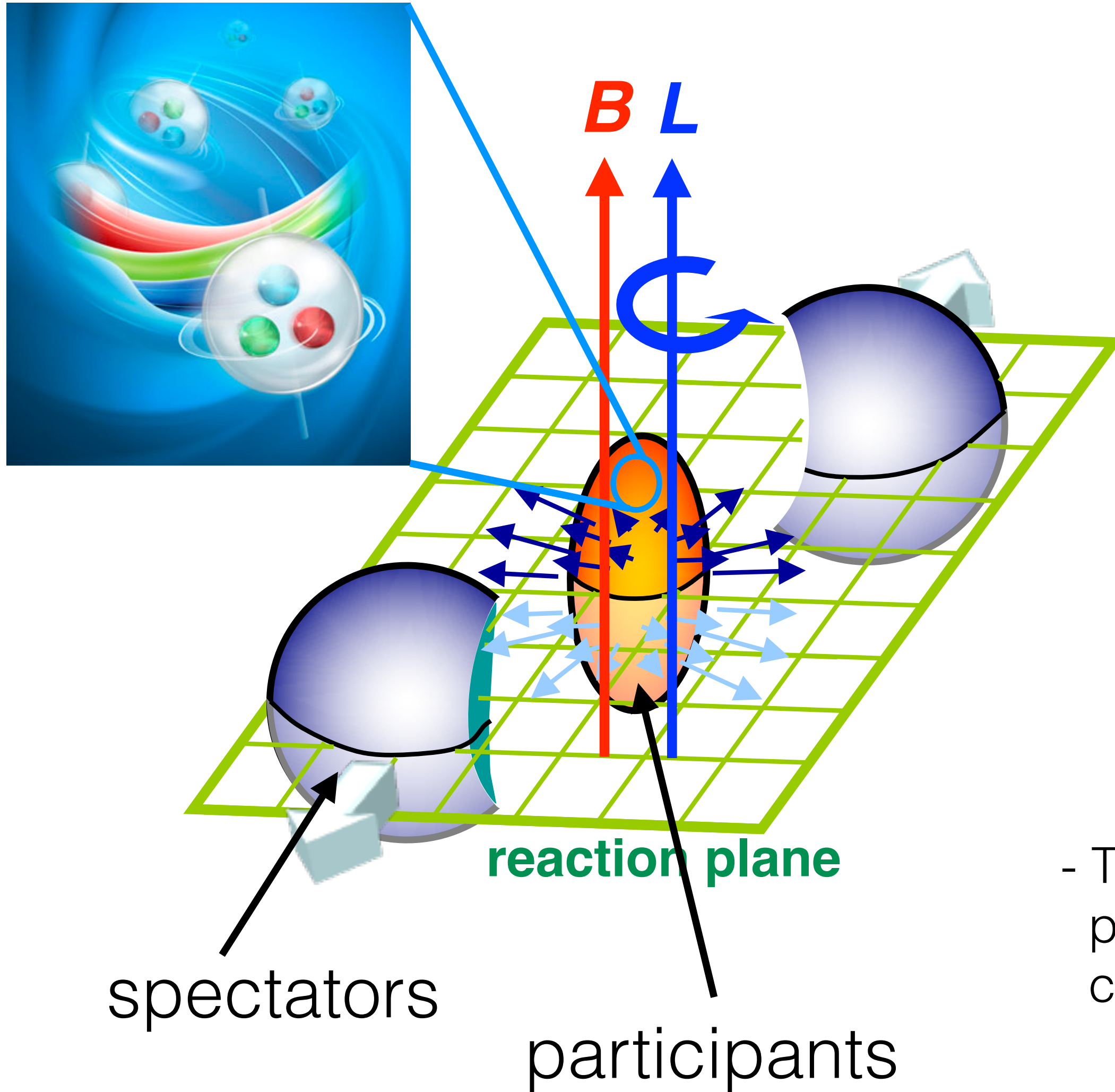
Globally Polarized Quark-Gluon Plasma in Noncentral $A + A$ Collisions

Zuo-Tang Liang¹ and Xin-Nian Wang^{2,1}

“Global polarization”

Average polarization along the orbital angular momentum

“Global” polarization



- Polarization $\mathbf{P}$ in non-relativistic limit assuming a local thermodynamic equilibrium

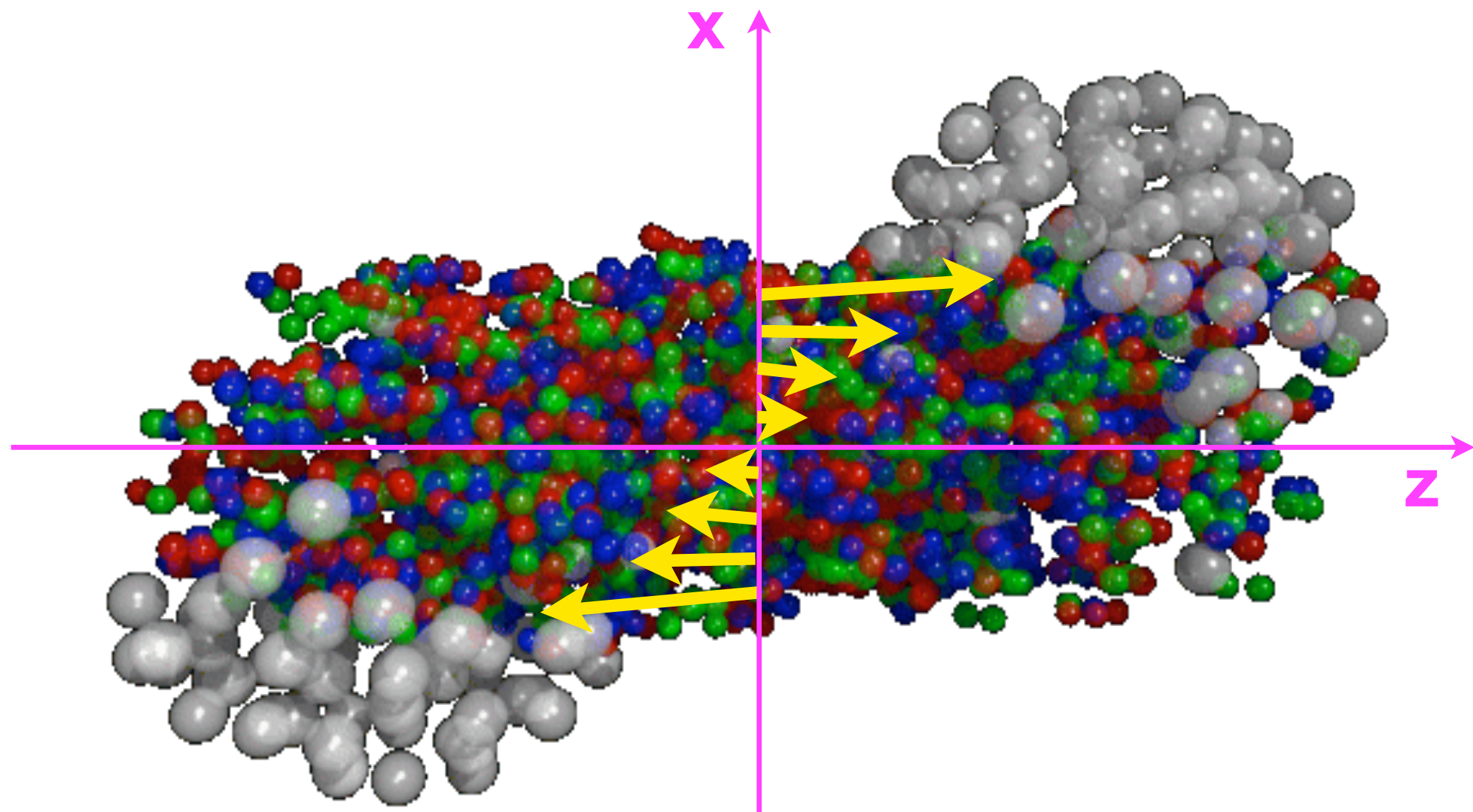
$$\mathbf{P} = \frac{(S + 1)(\boldsymbol{\omega} + \mu \mathbf{B}/S)}{3T}$$

S : particle spin
 ω : vorticity
 B : magnetic field at freeze-out
 μ : magnetic moment

F. Becattini, F. Piccinini, and J. Rizzo, PRC77, 024906 (2008)

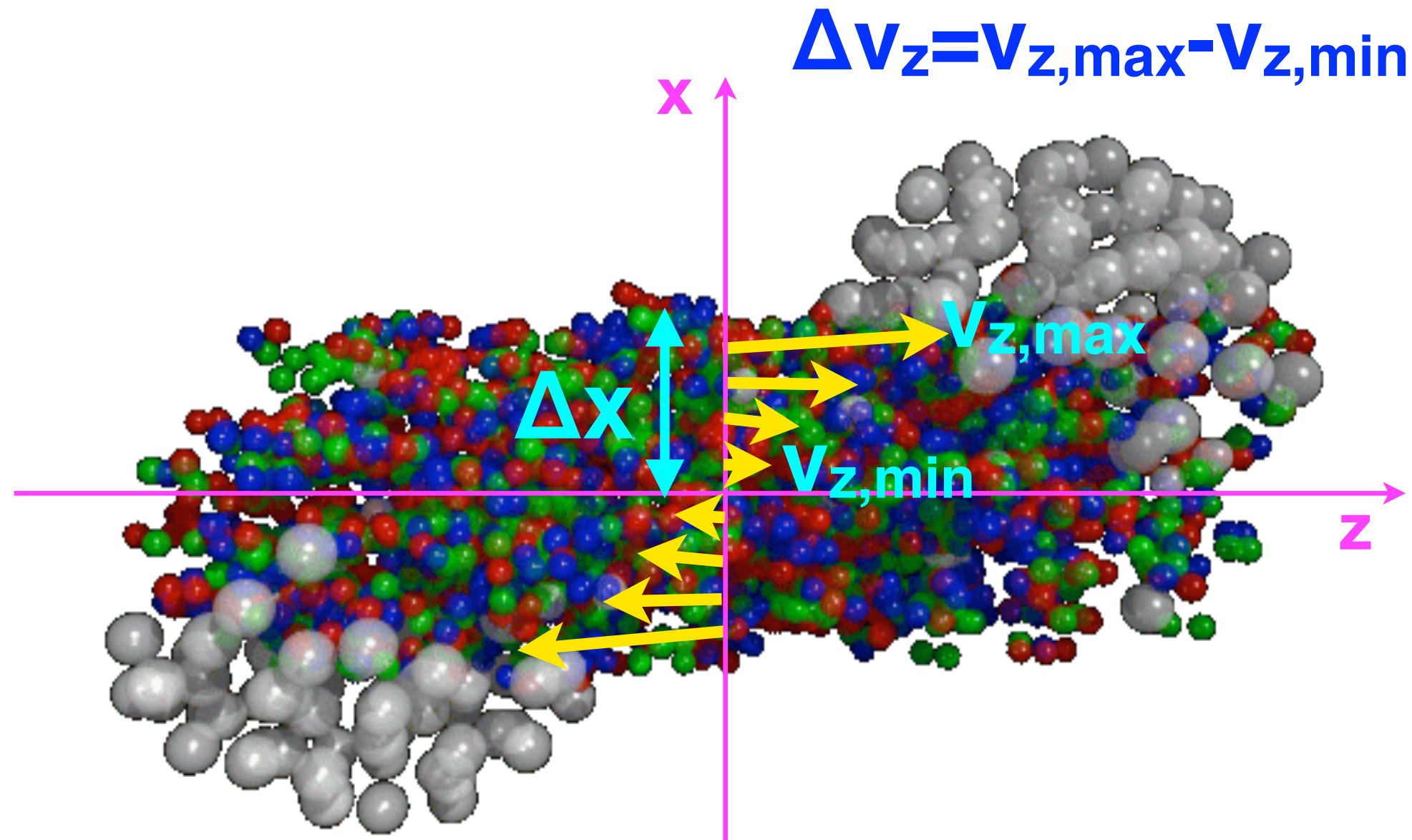
- The sign of magnetic moment is opposite between particle and anti-particle, therefore any difference in the polarization could originate from the magnetic-field contribution

Let's guesstimate vorticity!



$$\begin{aligned}\omega_y &= \frac{1}{2}(\nabla \times v)_y = \frac{1}{2}\left(\frac{\partial v_x}{\partial z} - \frac{\partial v_z}{\partial x}\right) \\ &\approx -\frac{1}{2}\frac{\partial v_z}{\partial x} \approx -\frac{1}{2}\frac{\Delta v_z}{\Delta x}\end{aligned}$$

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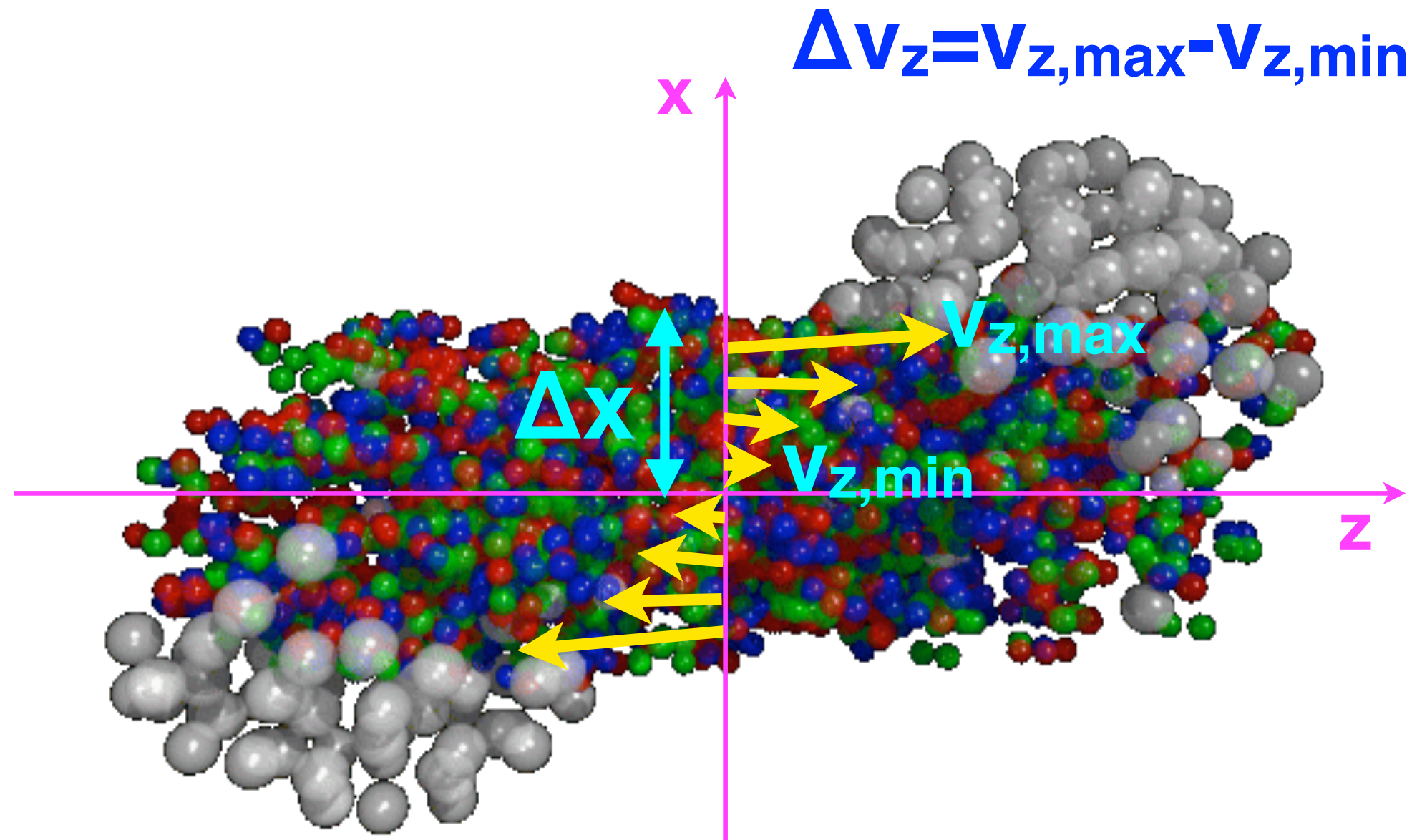


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Q1. What is the radius of a Au nucleus?

Q2. How large would $\Delta v_z/c$ be?

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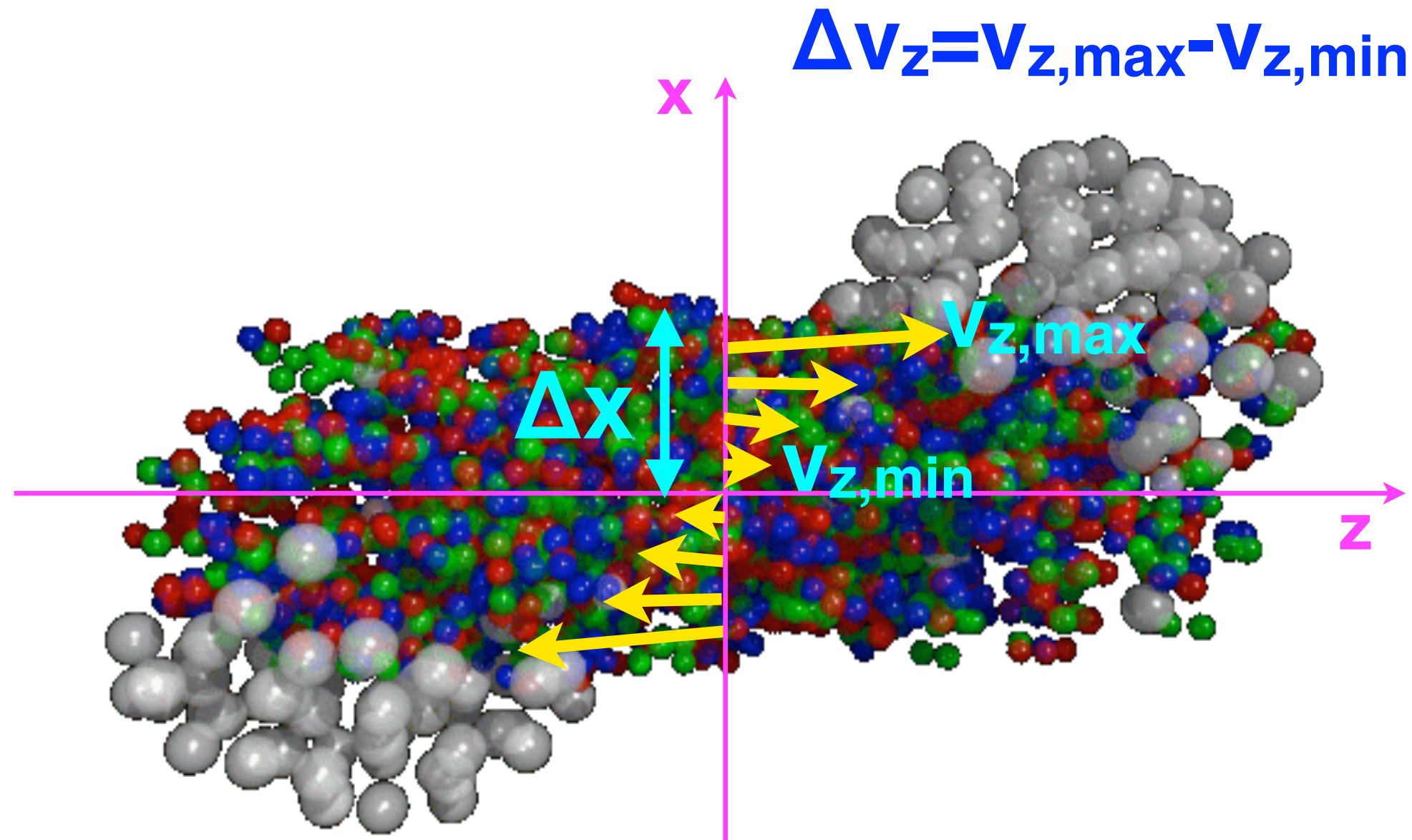
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Let me assume $\Delta x \sim 5$ fm, $\Delta v_z \sim 0.1$ here.

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$$\begin{aligned}\omega_y &\approx -\frac{0.1}{2 \times 5} = -0.01 \text{ [1/fm]} \\ &= -0.01 \times 3 \times 10^8 \times 10^{15} \text{ [1/s]} \\ &= -3 \times 10^{21} \text{ [1/s]}\end{aligned}$$

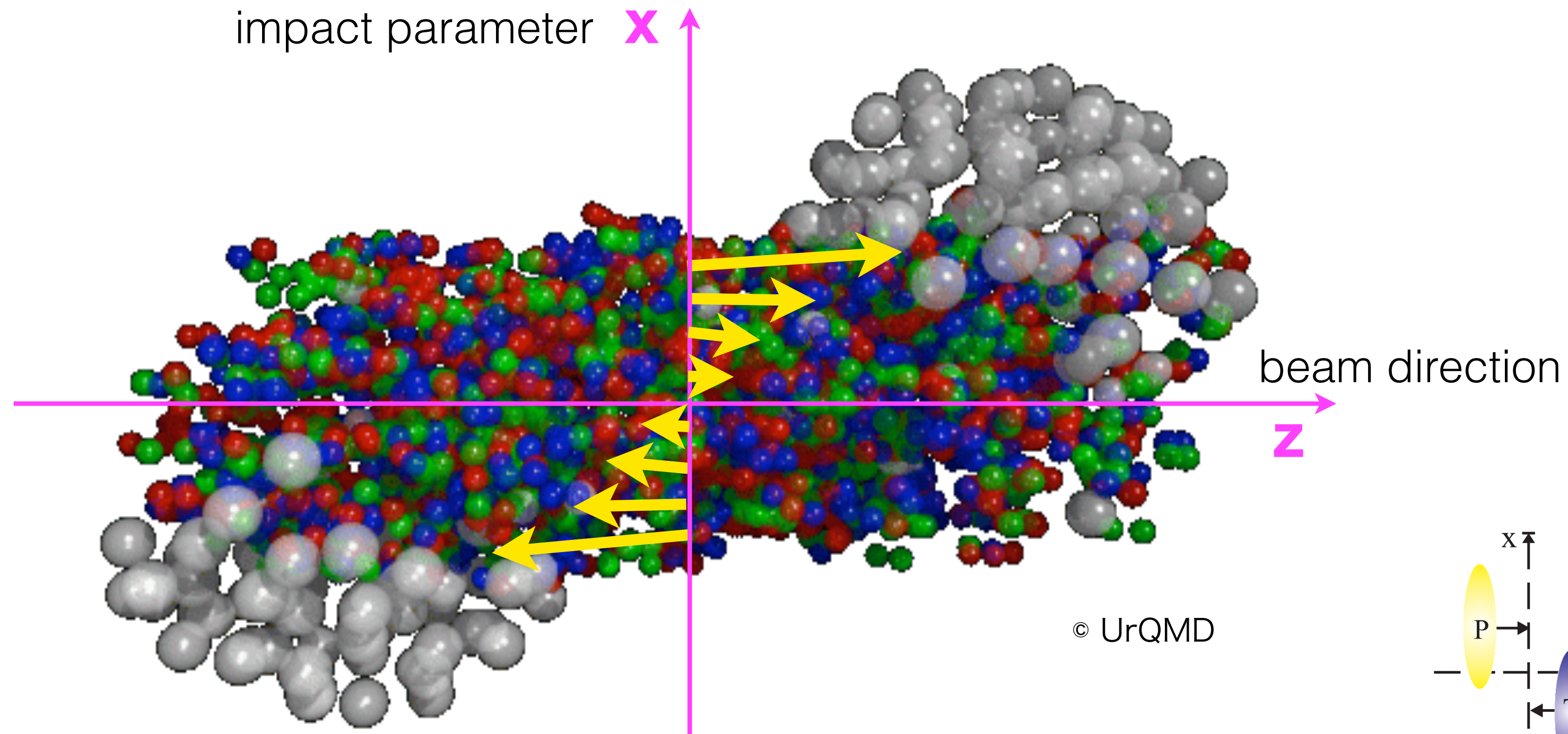
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Vorticity in HIC

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

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



F. Becattini et al.,
PRC77, 024906 (2008)

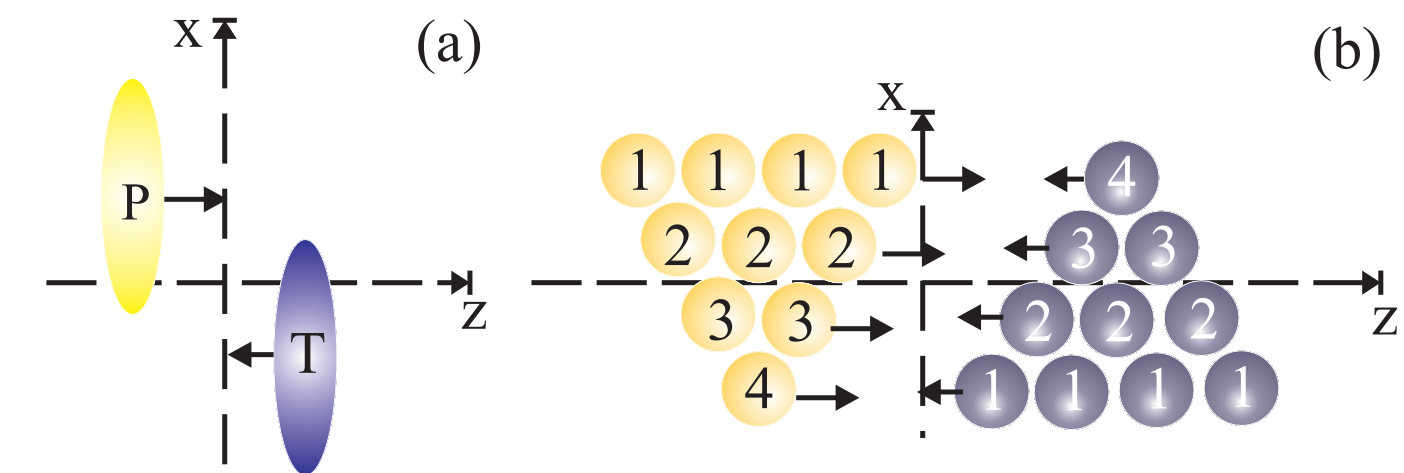
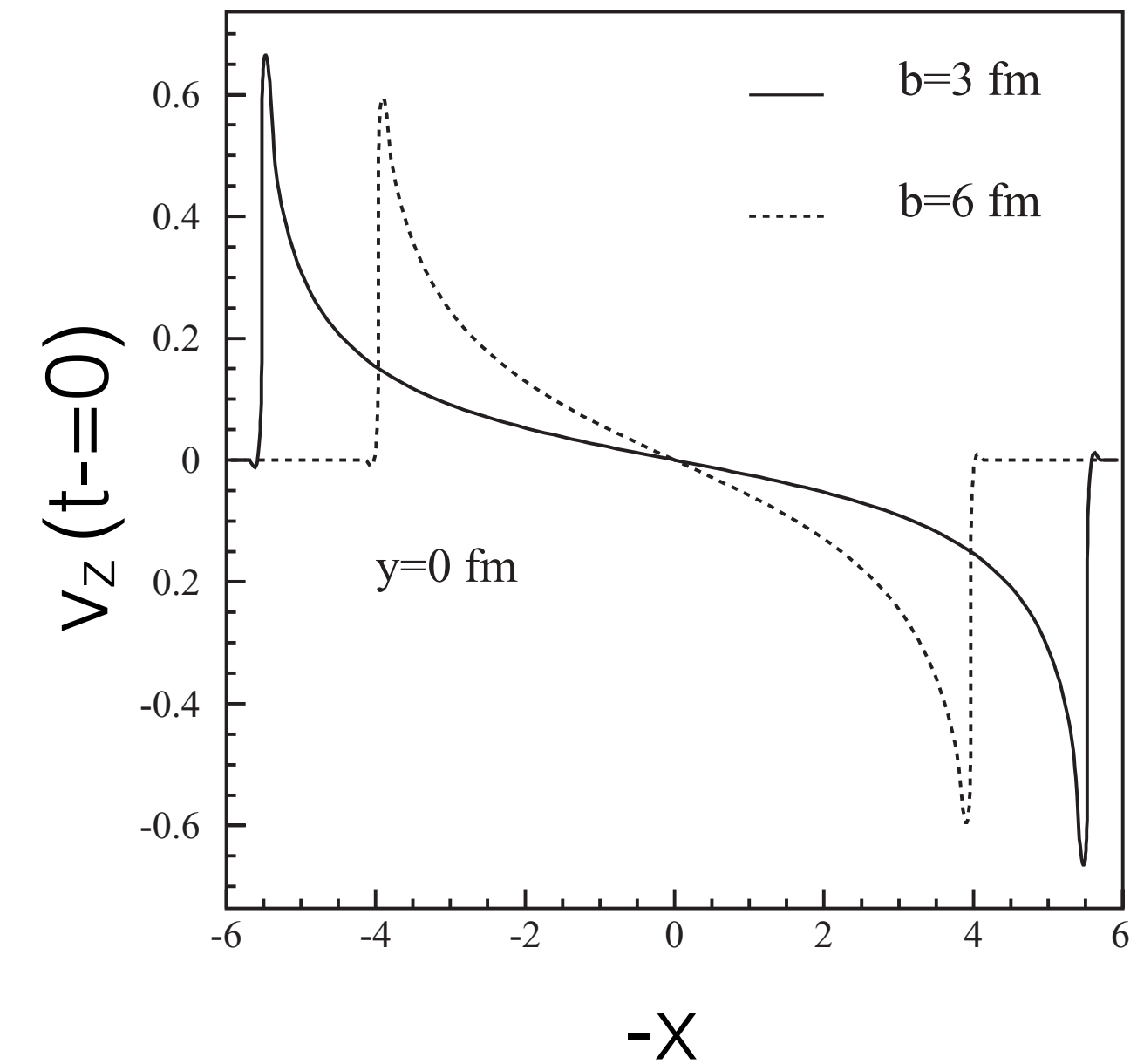
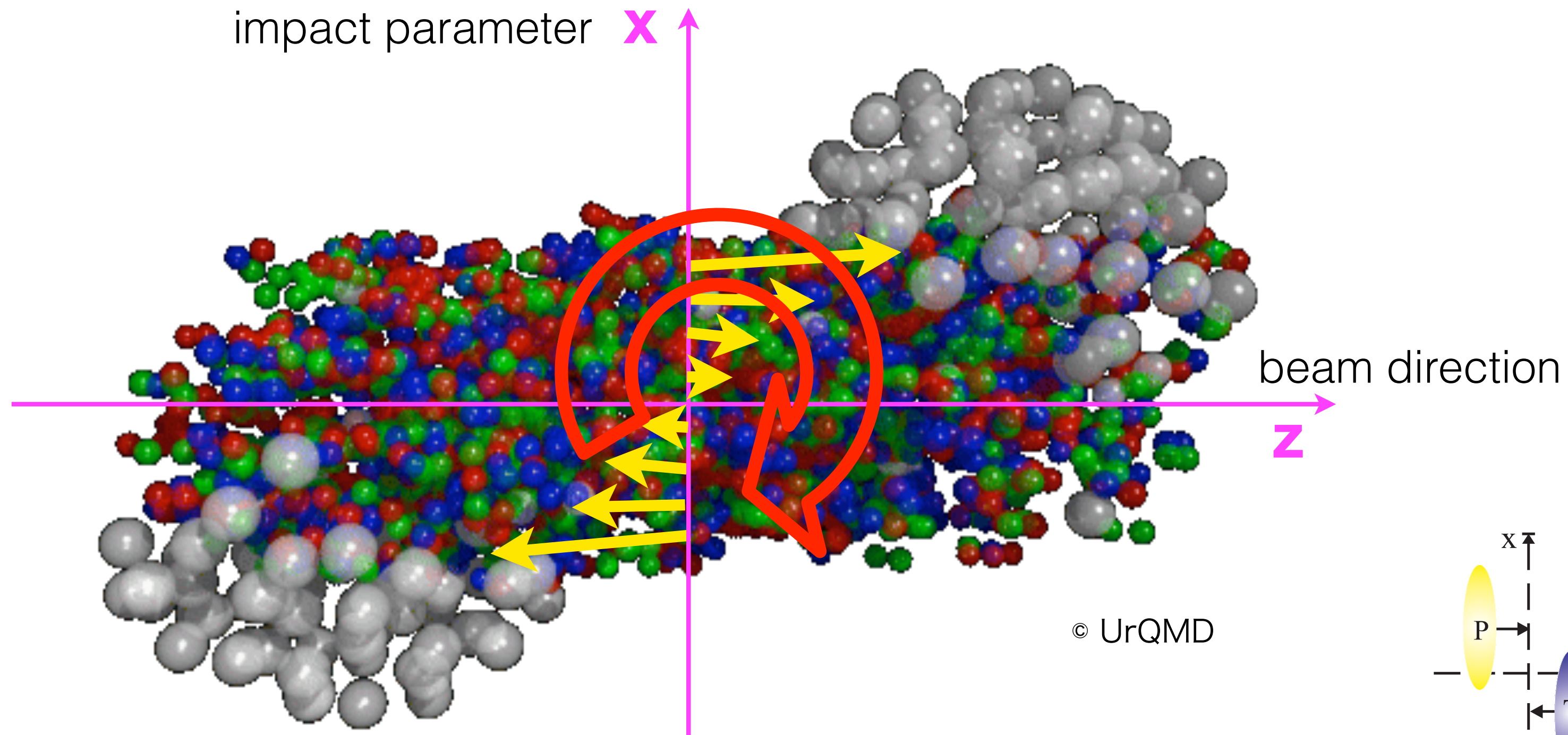


figure from R. Snellings et al., PRL84, 2803(200)

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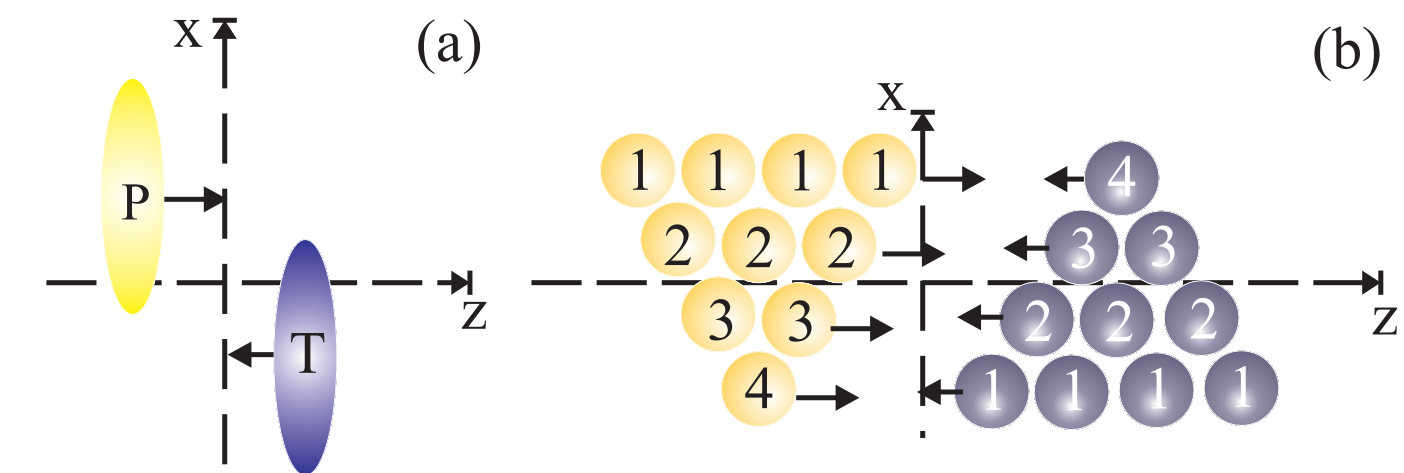
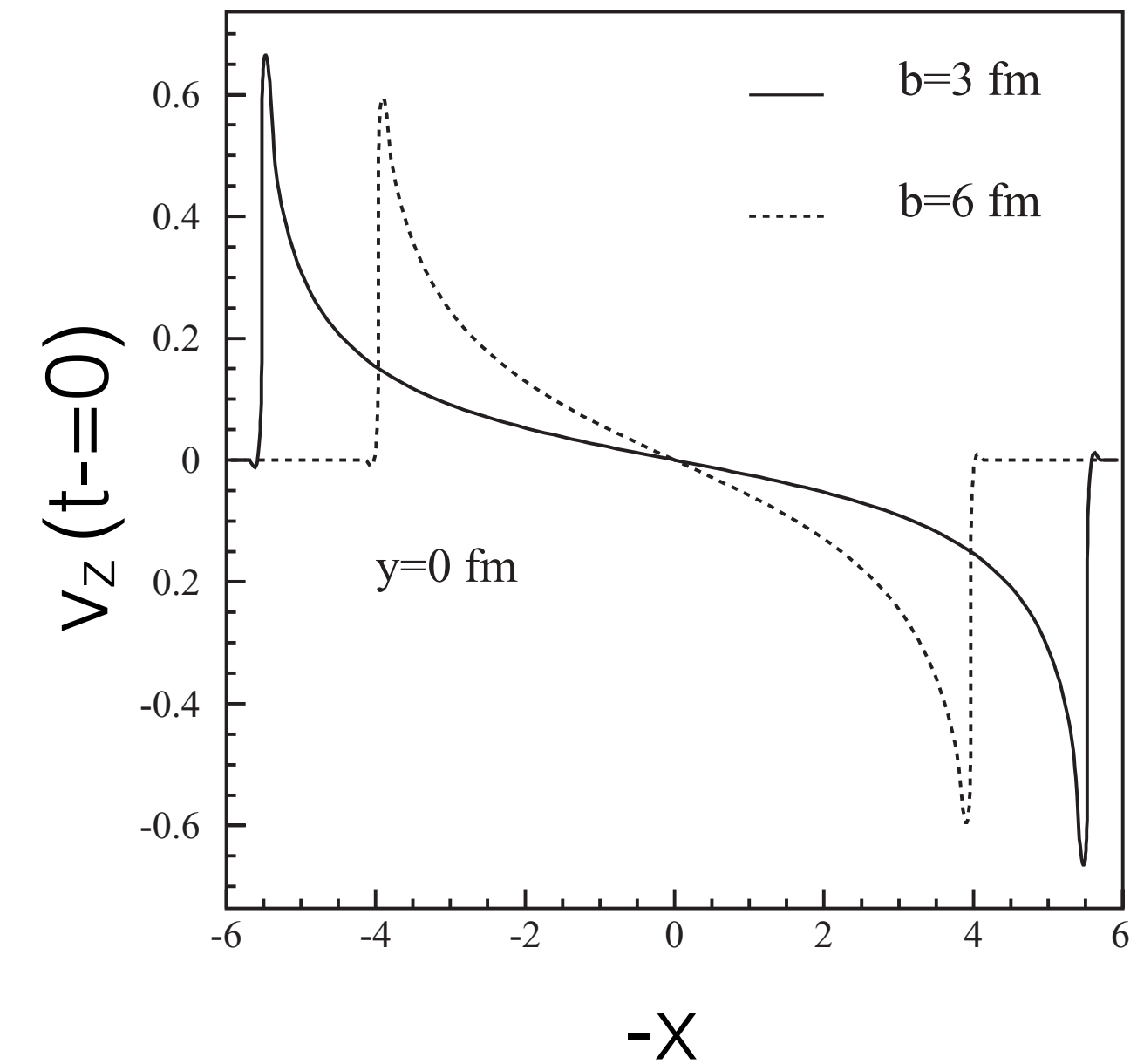


figure from R. Snellings et al., PRL84, 2803(200)

Rotation vs. Polarization

Barnett effect:

rotation→polarization

Magnetization of an uncharged body

when spun on its axis S. Barnett, Phys. Rev. 6, 239 (1915)

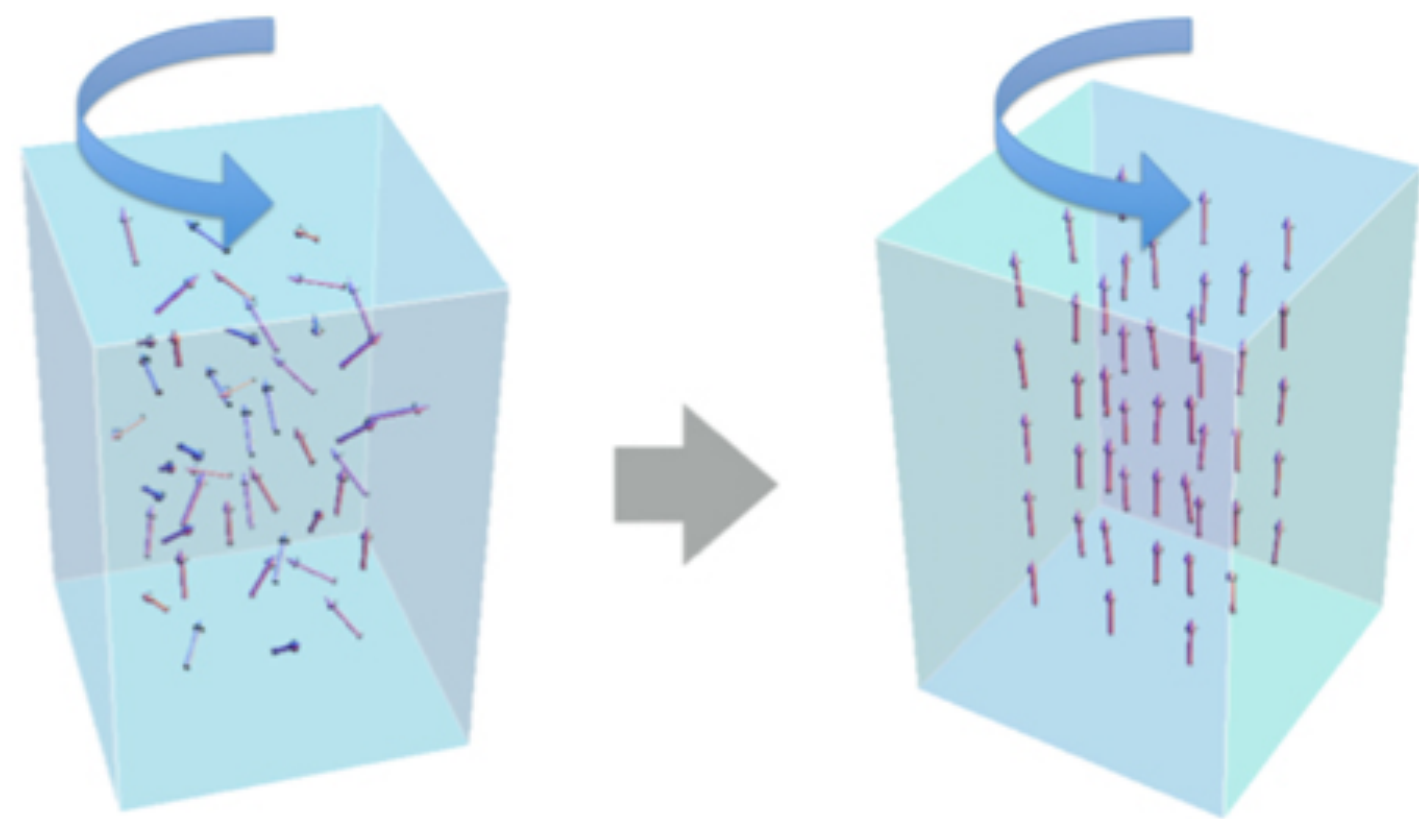


figure: M. Matsuo et al., Front. Phys., 30 (2015)

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

χ : magnetic susceptibility

γ : gyromagnetic ratio

Einstein-de-Haas effect:

polarization→rotation



“the only experiment by Einstein”

Change in the direction/strength
of magnetic-field

-> Rotation of a ferromagnet

Conservation of the total angular
momentum.

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

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

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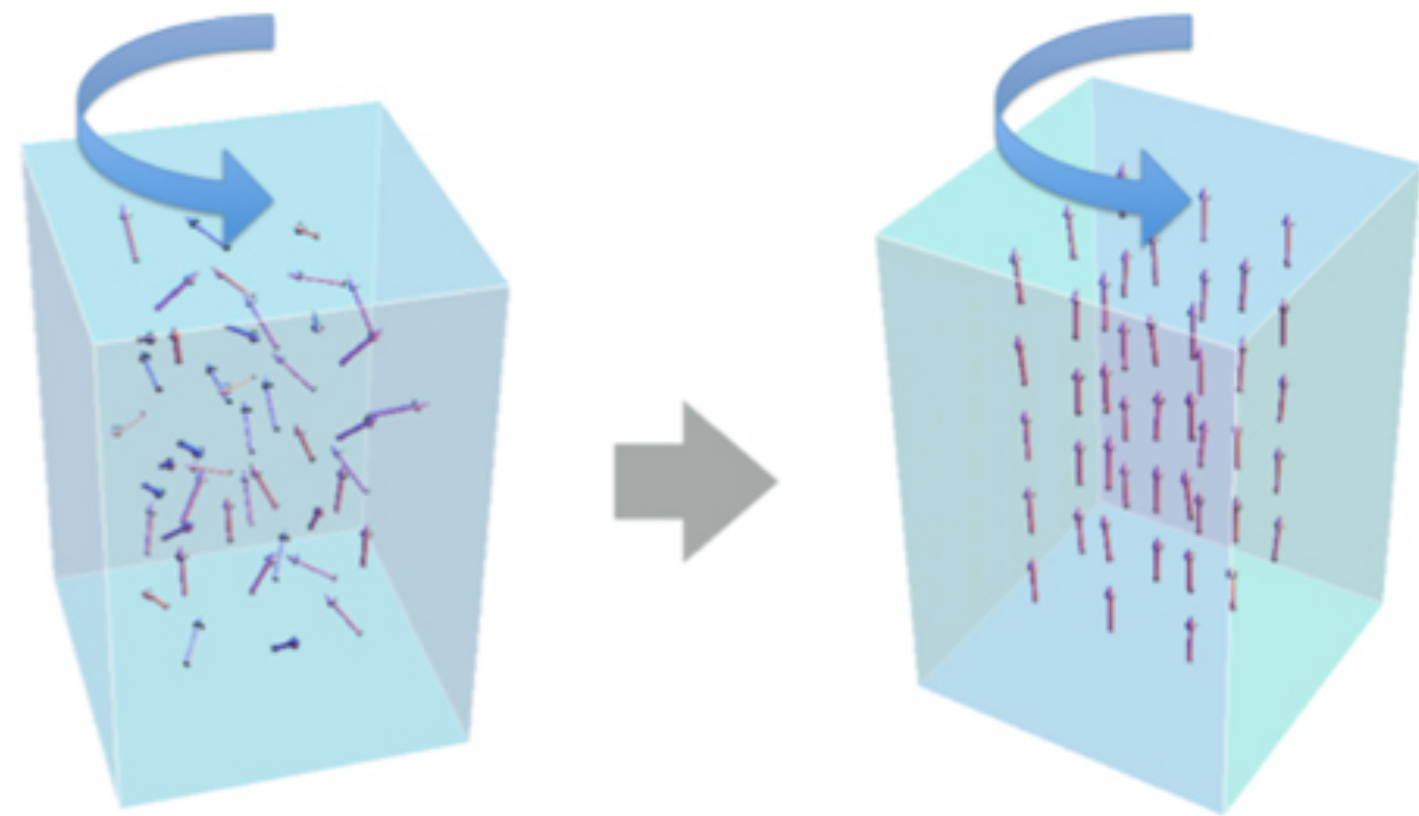


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Global polarization is a relativistic analogue of the Barnett effect

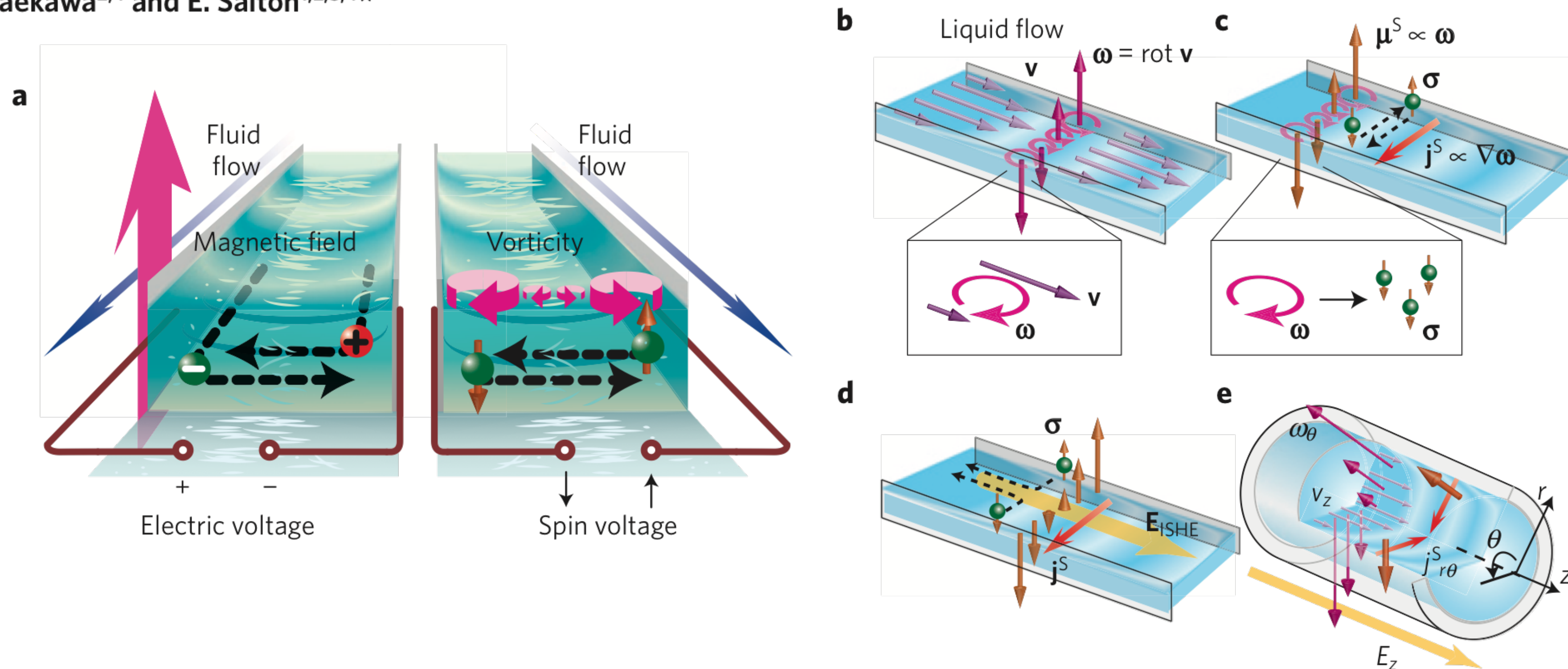
Barnett: Mechanical rotation → spin polarization (magnetization)

HIC: Fluid vorticity → particle spin polarization

Spin hydrodynamic generation

R. Takahashi et al., Nat. Phys. 12, 52-56 (2016)

R. Takahashi^{1,2,3,4★}, M. Matsuo^{2,4}, M. Ono^{2,4}, K. Harii^{2,4}, H. Chudo^{2,4}, S. Okayasu^{2,4}, J. Ieda^{2,4},
S. Takahashi^{1,4}, S. Maekawa^{2,4} and E. Saitoh^{1,2,3,4★}



Fluid vorticity → Electron spin current
Analogy to the heavy-ion case

How do we measure global polarization?

Parity-violating weak decay of hyperons

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

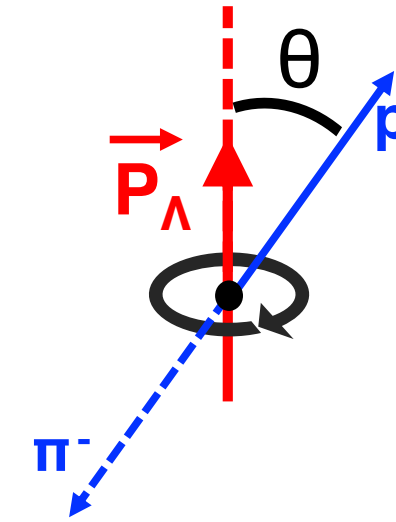
$\mathbf{P}_H$: hyperon polarization

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

α_H : hyperon decay parameter

asterisk(*) denotes “in hyperon rest frame”

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



$$\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.747 \pm 0.009$$

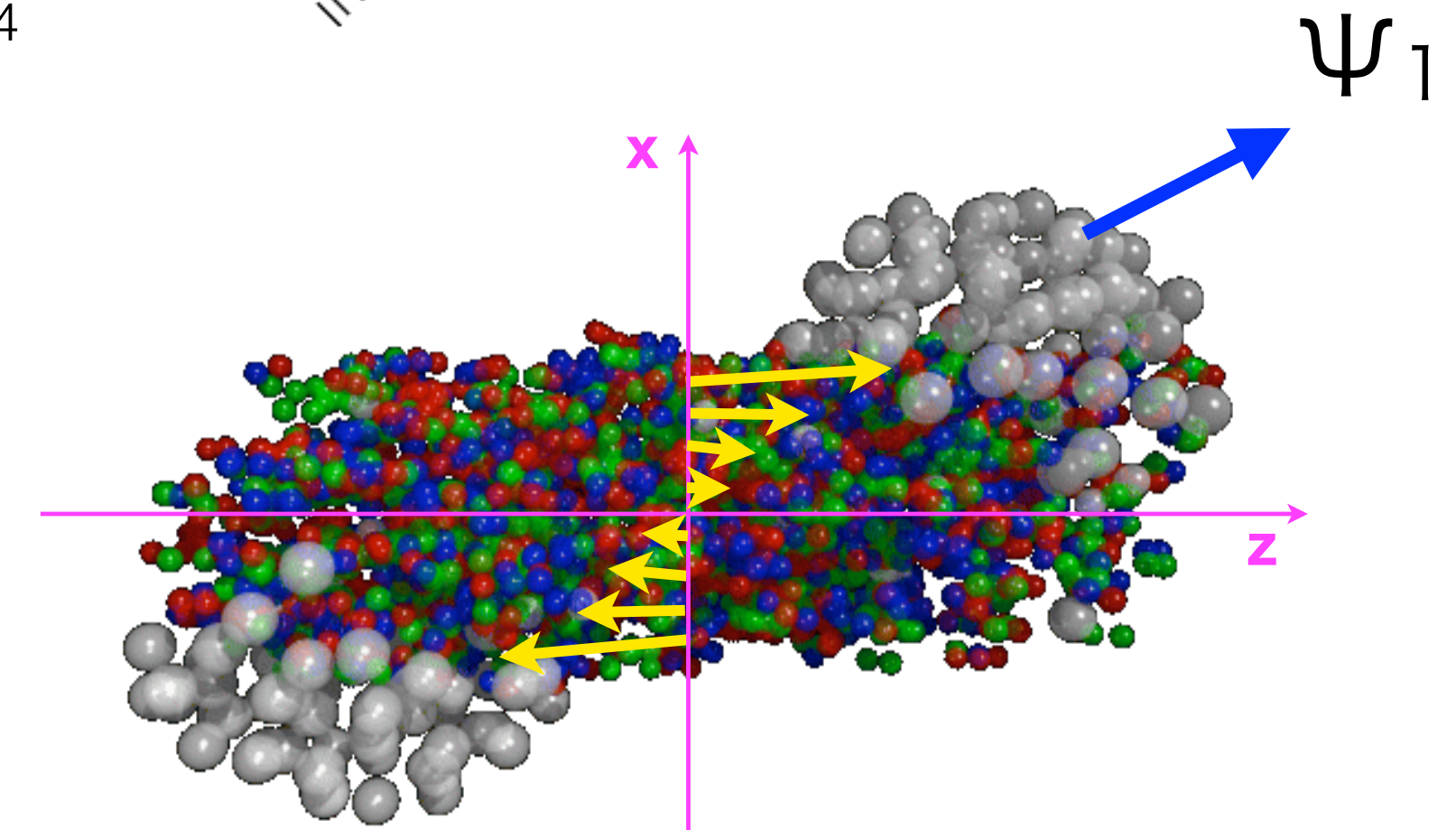
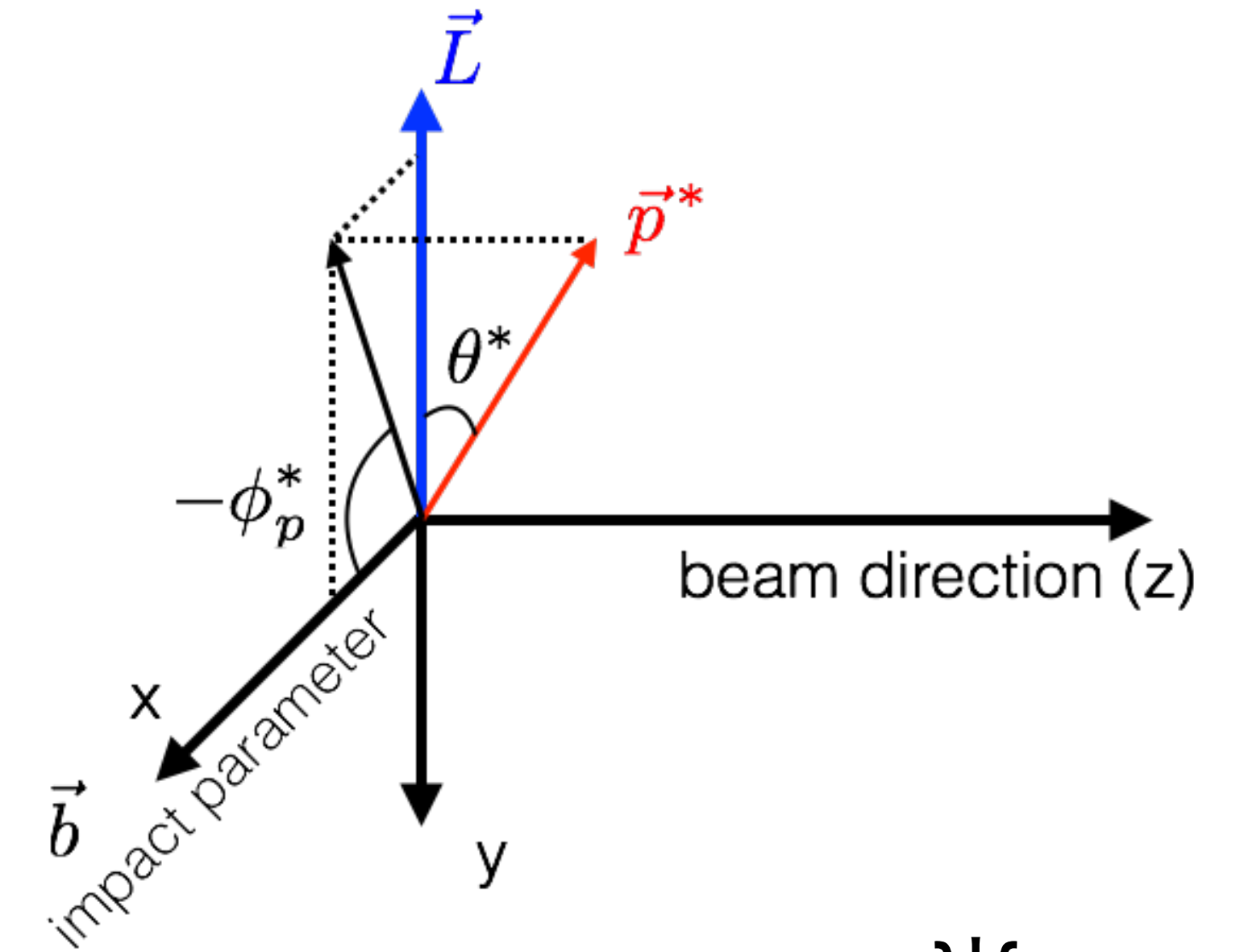
PDG2024

Polarization along the initial L direction

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

Ψ_1 : azimuthal angle of spectator fragment

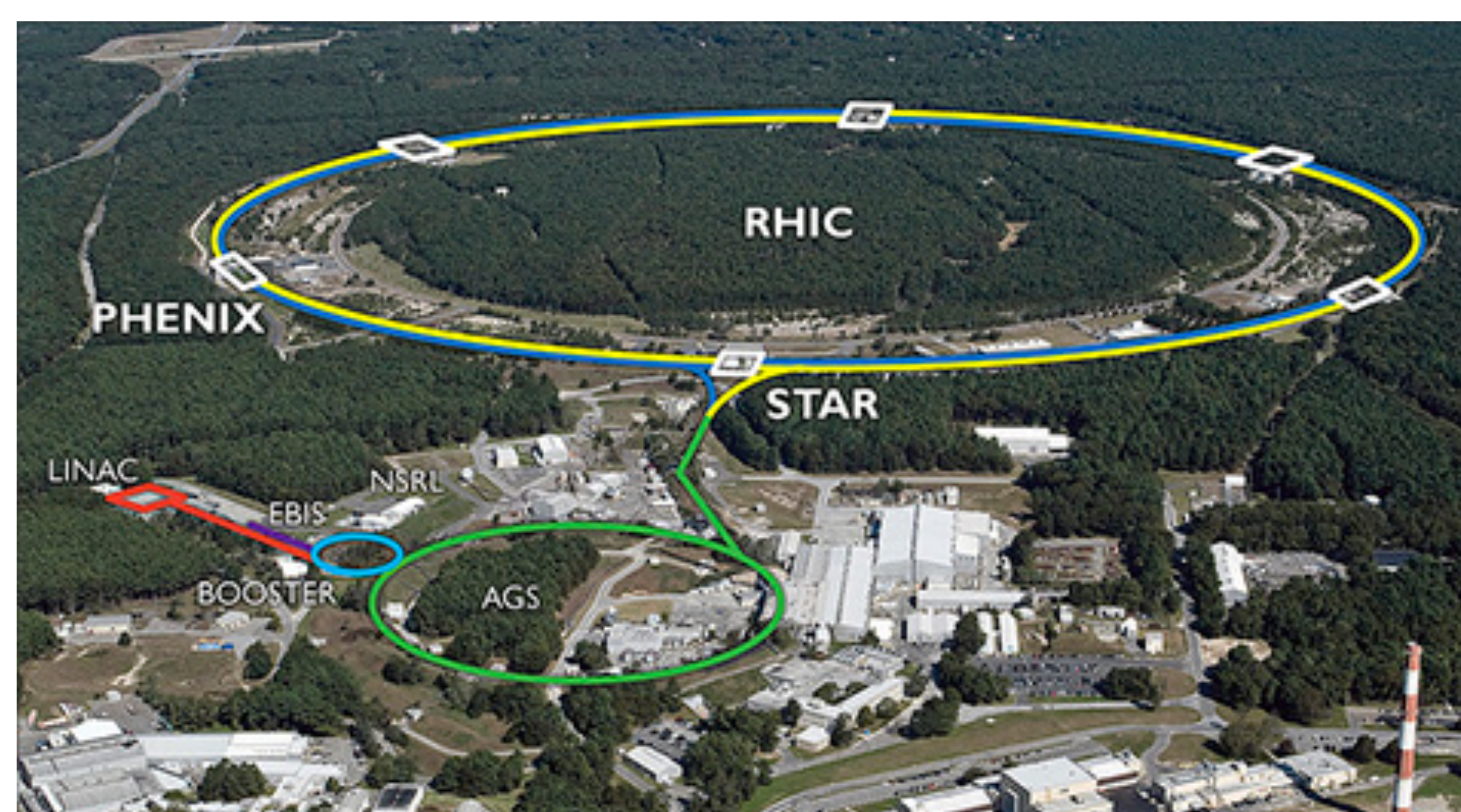
STAR, PRC76, 024915 (2007)



Spectators fly away from the beam axis (at high energy)

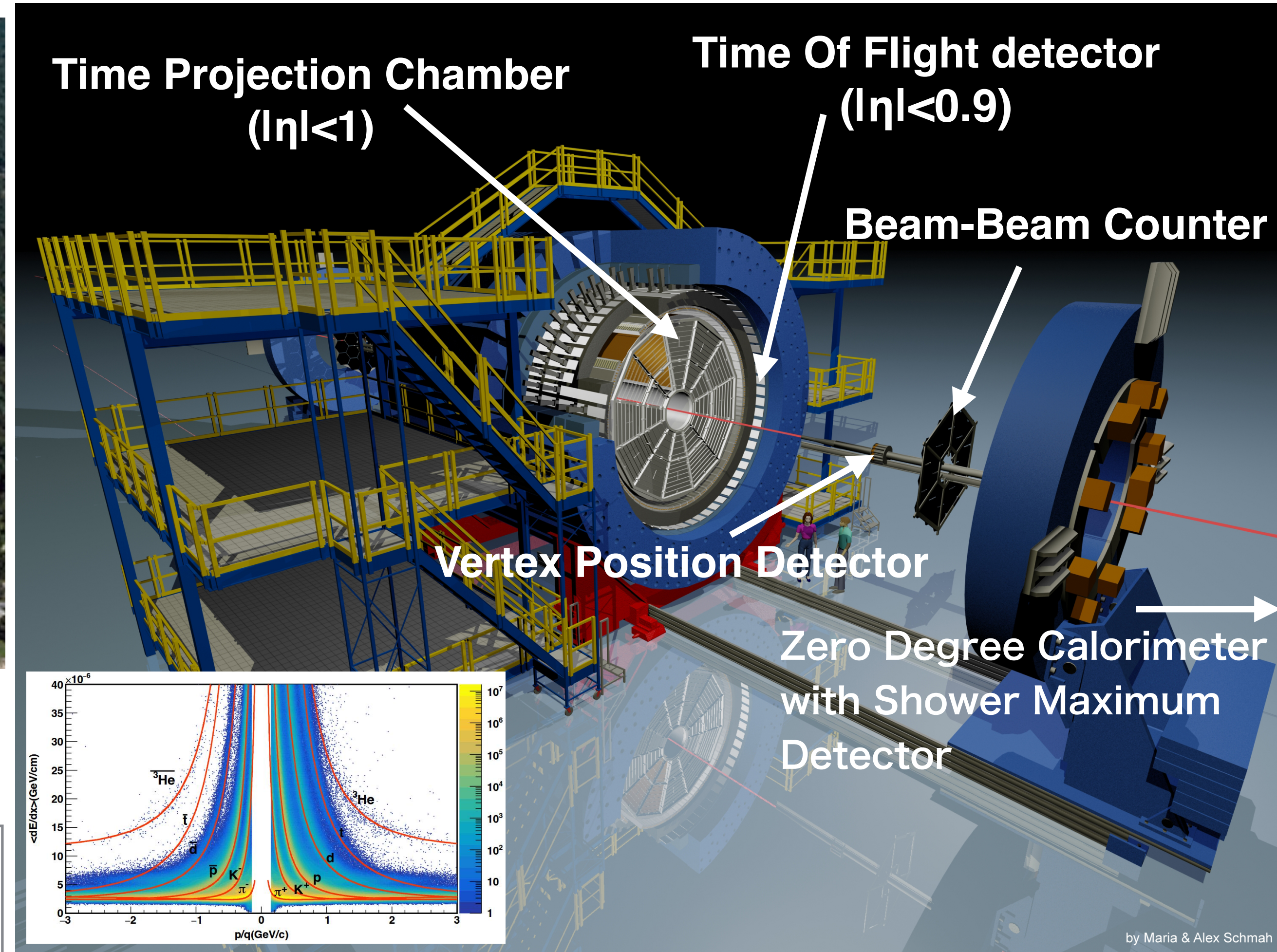
S. Voloshin and TN, PRC94.021901(R) (2016)

RHIC-STAR experiment



Relativistic Heavy Ion Collider (RHIC)

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

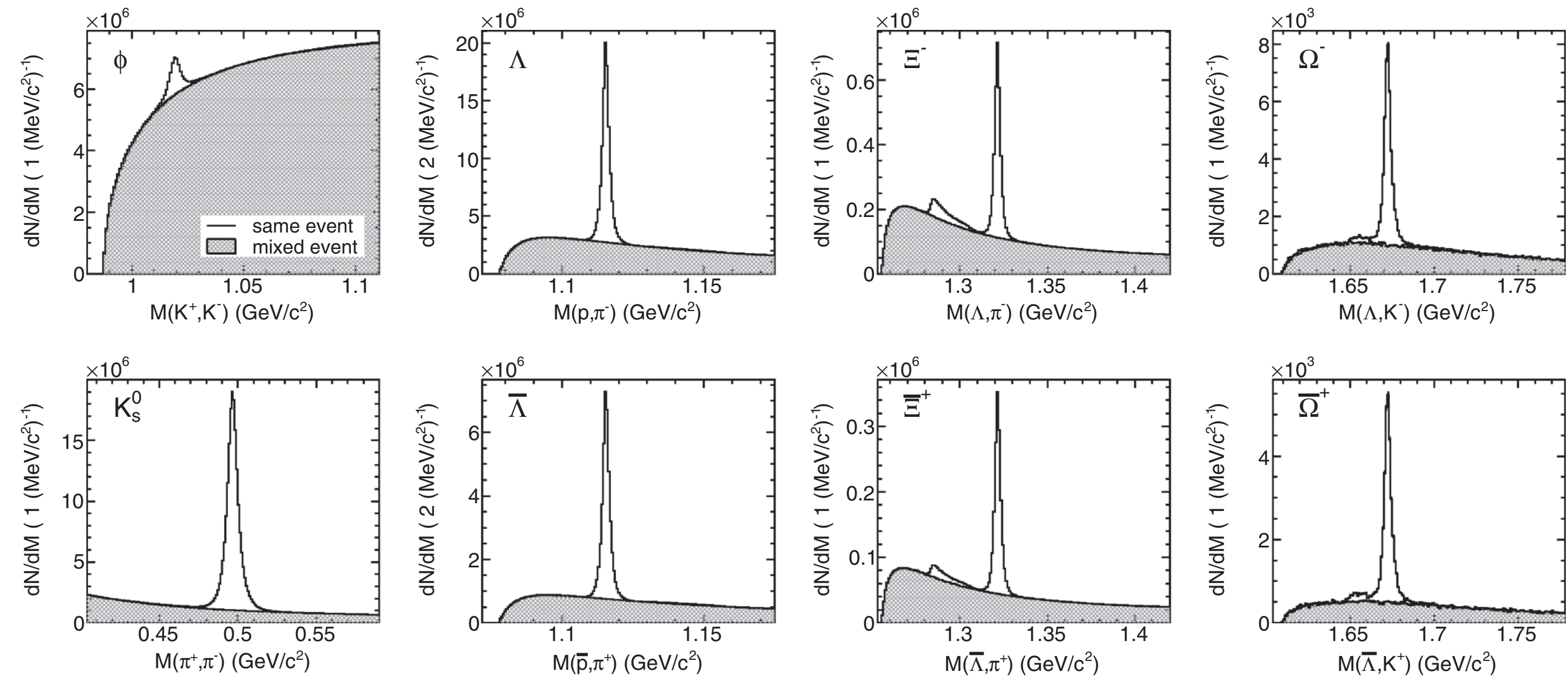
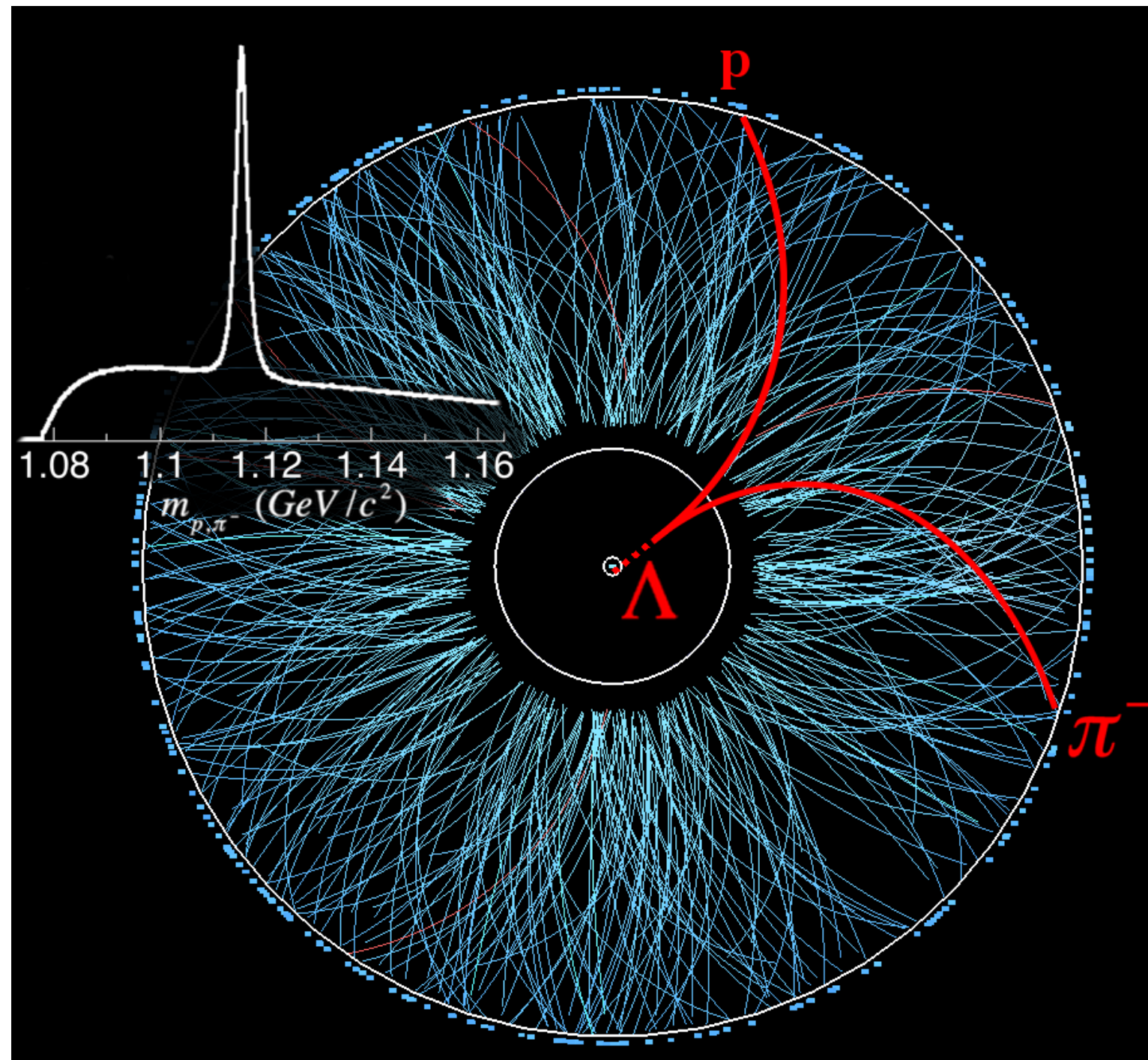


Solenoidal Tracker At RHIC (STAR)

- Full azimuth and wide rapidity coverage
- Excellent particle identification

Identification of (weakly) decaying particles

STAR, PRC88.014902 (2013)



* ϕ -meson decays via strong interaction

Calculate invariant mass from daughter particles

$$M^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$$

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

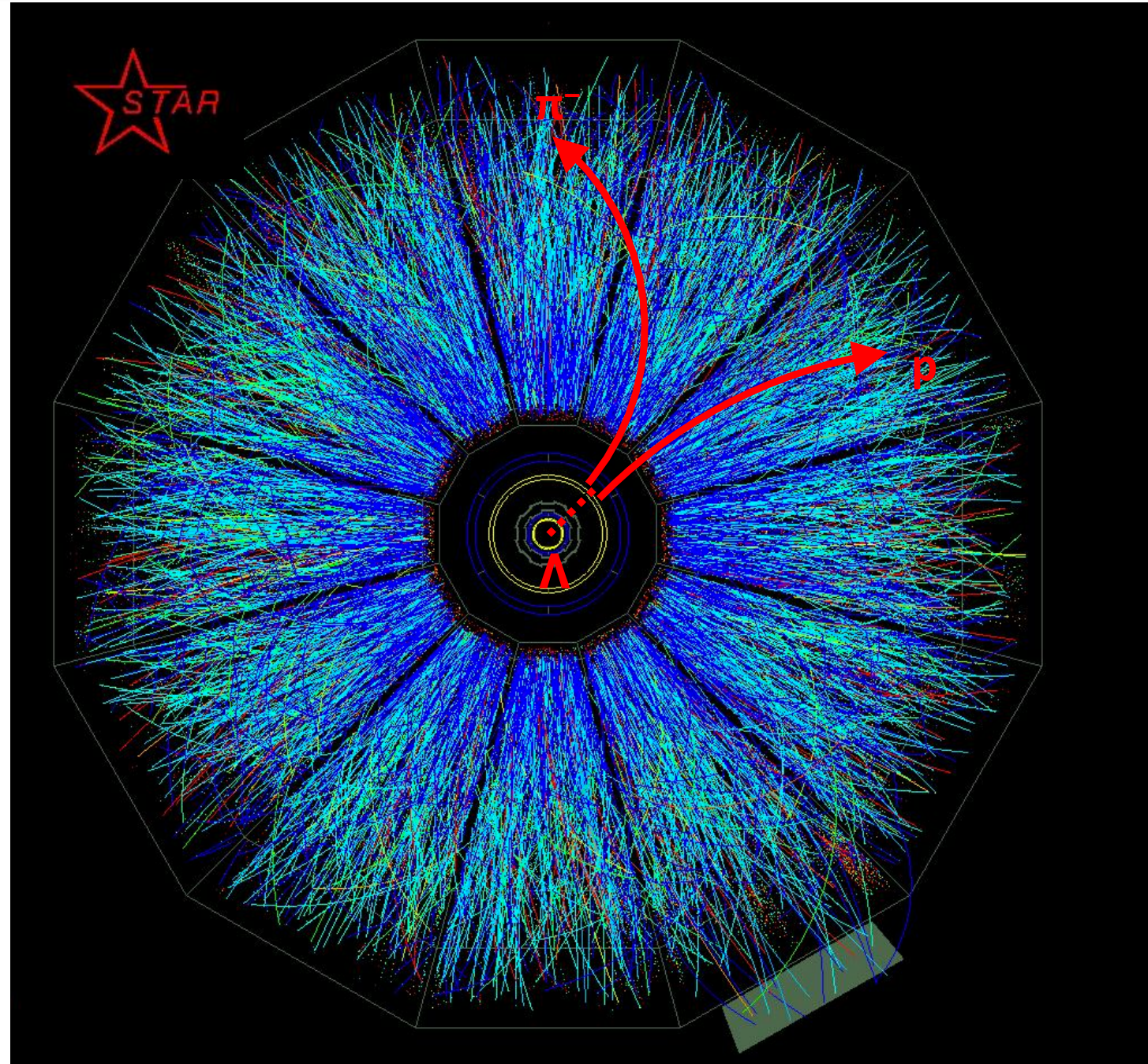
$$K_s^0 \rightarrow \pi^+ + \pi^-$$

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

$$\phi \rightarrow K^+ + K^-$$

$$\Omega^- \rightarrow \Lambda + K^-$$

Signal extraction with Λ hyperons

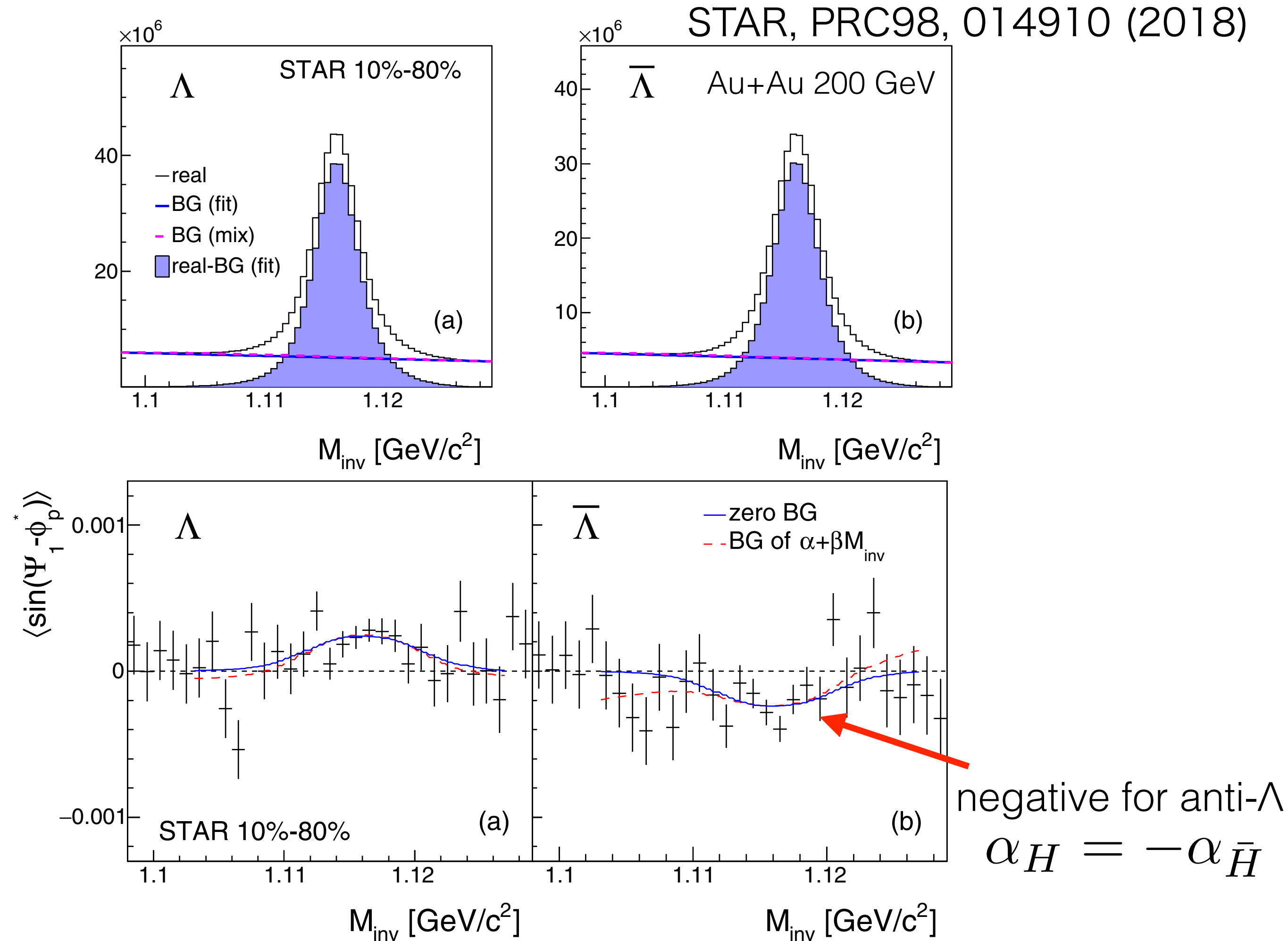


$$P_H = \frac{8}{\pi\alpha_H} \frac{\langle \sin(\Psi_1 - \phi_p^*) \rangle}{\text{Res}(\Psi_1)}$$

Two methods used to extract the sine F.C.

1. Invariant mass method
2. Bin-counting method

(both give us consistent results)

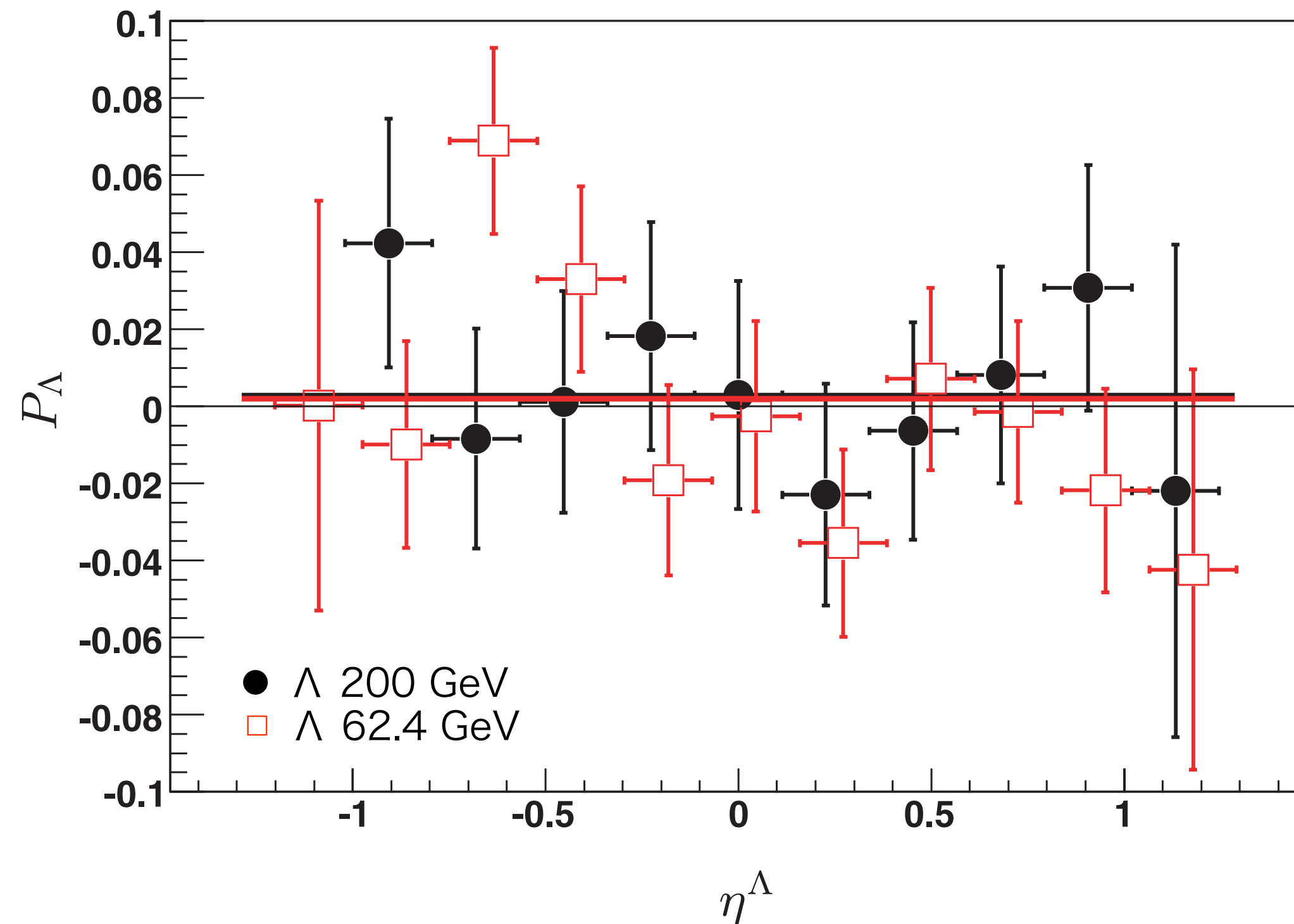


$$\begin{aligned} \langle \sin(\Psi_1 - \phi_p^*) \rangle^{\text{obs}} &= (1 - f^{\text{Bg}}(M_{\text{inv}})) \langle \sin(\Psi_1 - \phi_p^*) \rangle^{\text{Sg}} \\ &+ f^{\text{Bg}}(M_{\text{inv}}) \langle \sin(\Psi_1 - \phi_p^*) \rangle^{\text{Bg}}, \end{aligned}$$

First paper from STAR in 2007

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

Global polarization measurement in Au+Au collisions



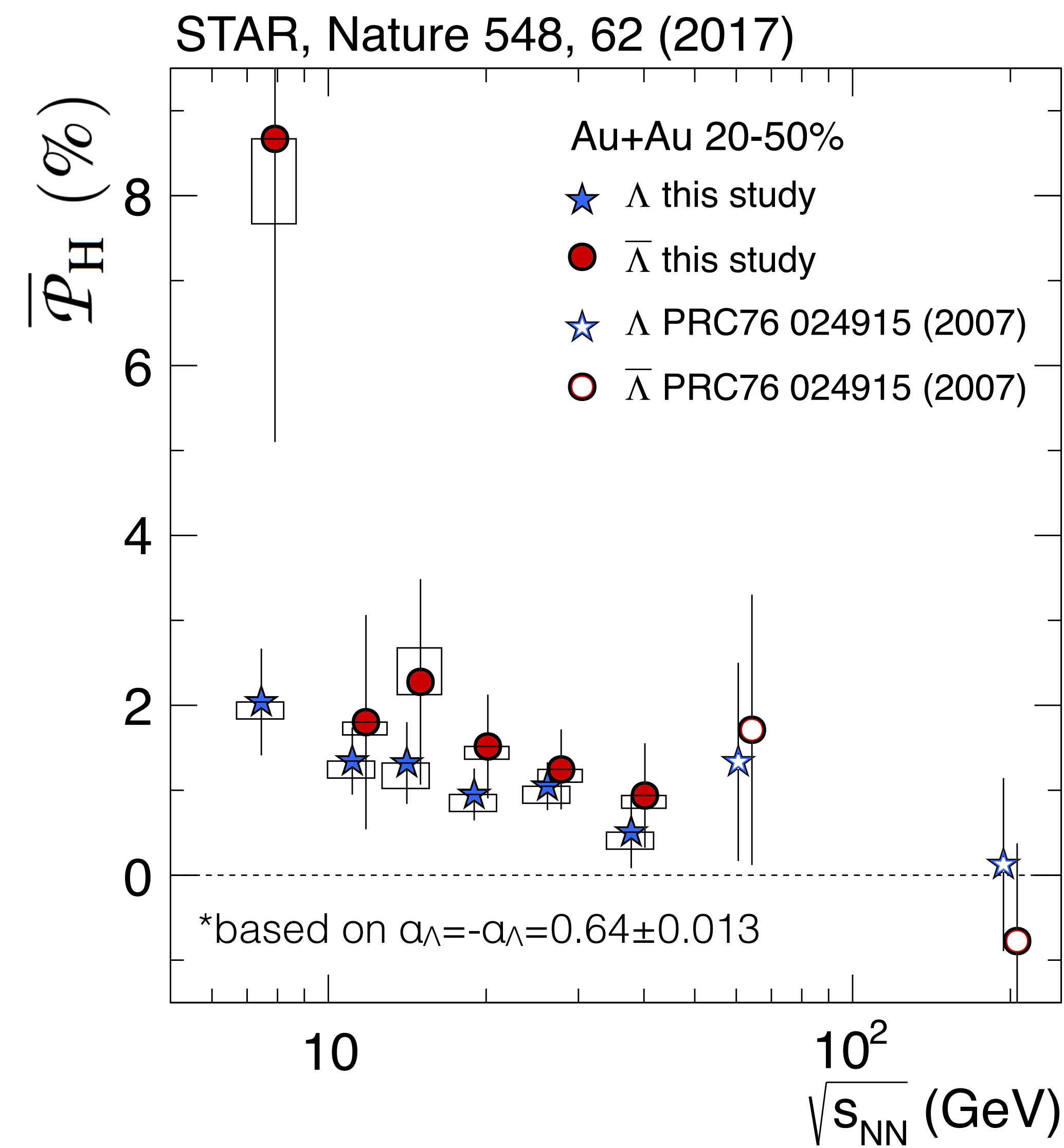
Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ and 200 GeV in 2004 with very limited statistics (~ 9 M events)

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 $|P_{\Lambda, \bar{\Lambda}}| \leq 0.02$ for the global polarization of Λ and $\bar{\Lambda}$ hyperons within the STAR detector acceptance is

Results were consistent with zero..., giving an upper limit of $P_H < 2\%$

First observation in lower energies (2017)



Positive polarization signal at lower energies!
- P_H looks to increase in lower energies



#38

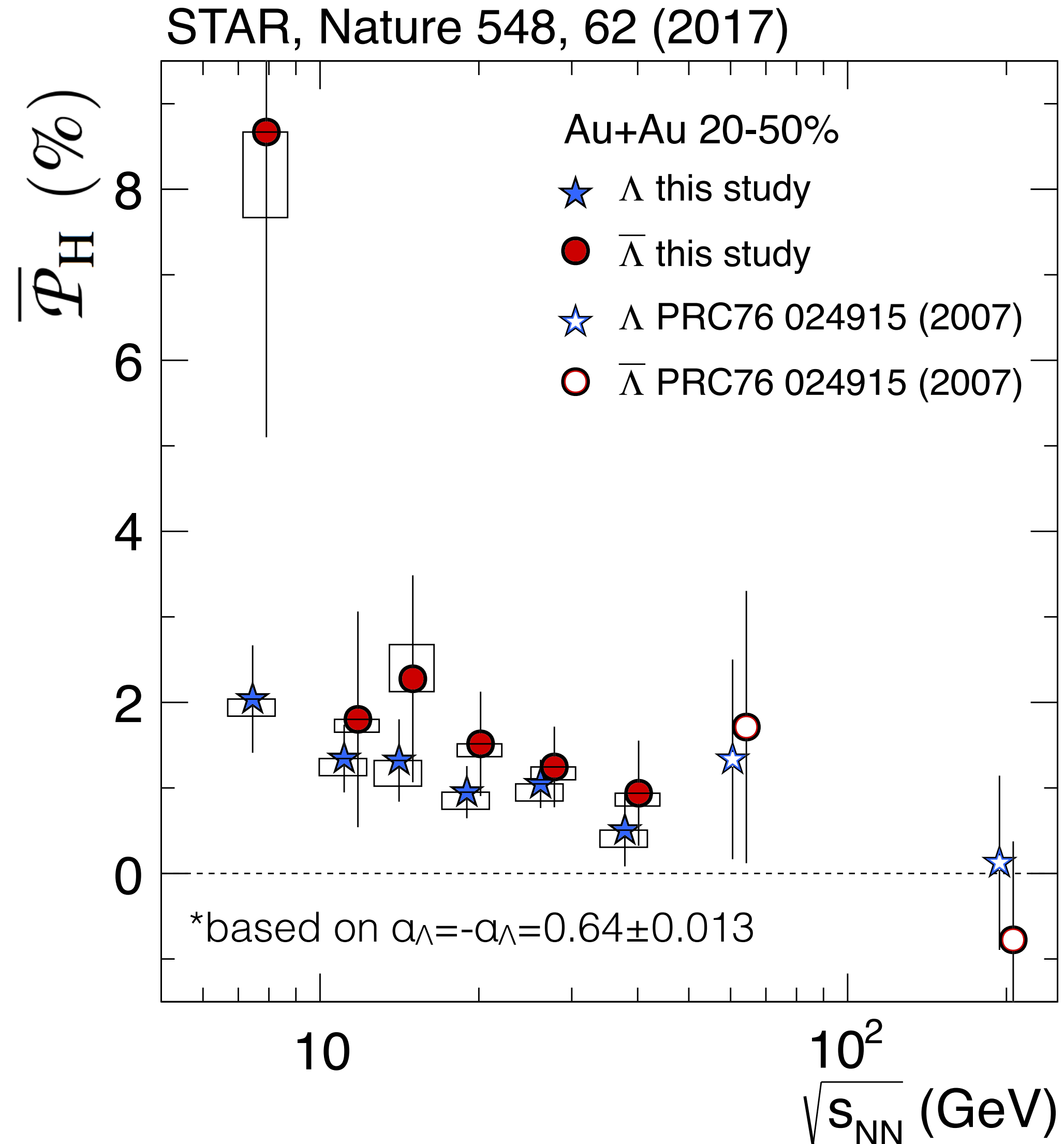
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SCIENCE FOR THE CURIOUS
January/February 2018
TOP 100 special issue

Evolution's Timeline Toppled

The Fastest Fluid
by Sylvia Morrow
Superhot material spins at an incredible rate.

... AND MORE!

First observation in lower energies (2017)



Positive polarization signal at lower energies!

- P_H looks to increase in lower energies

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

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

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

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

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

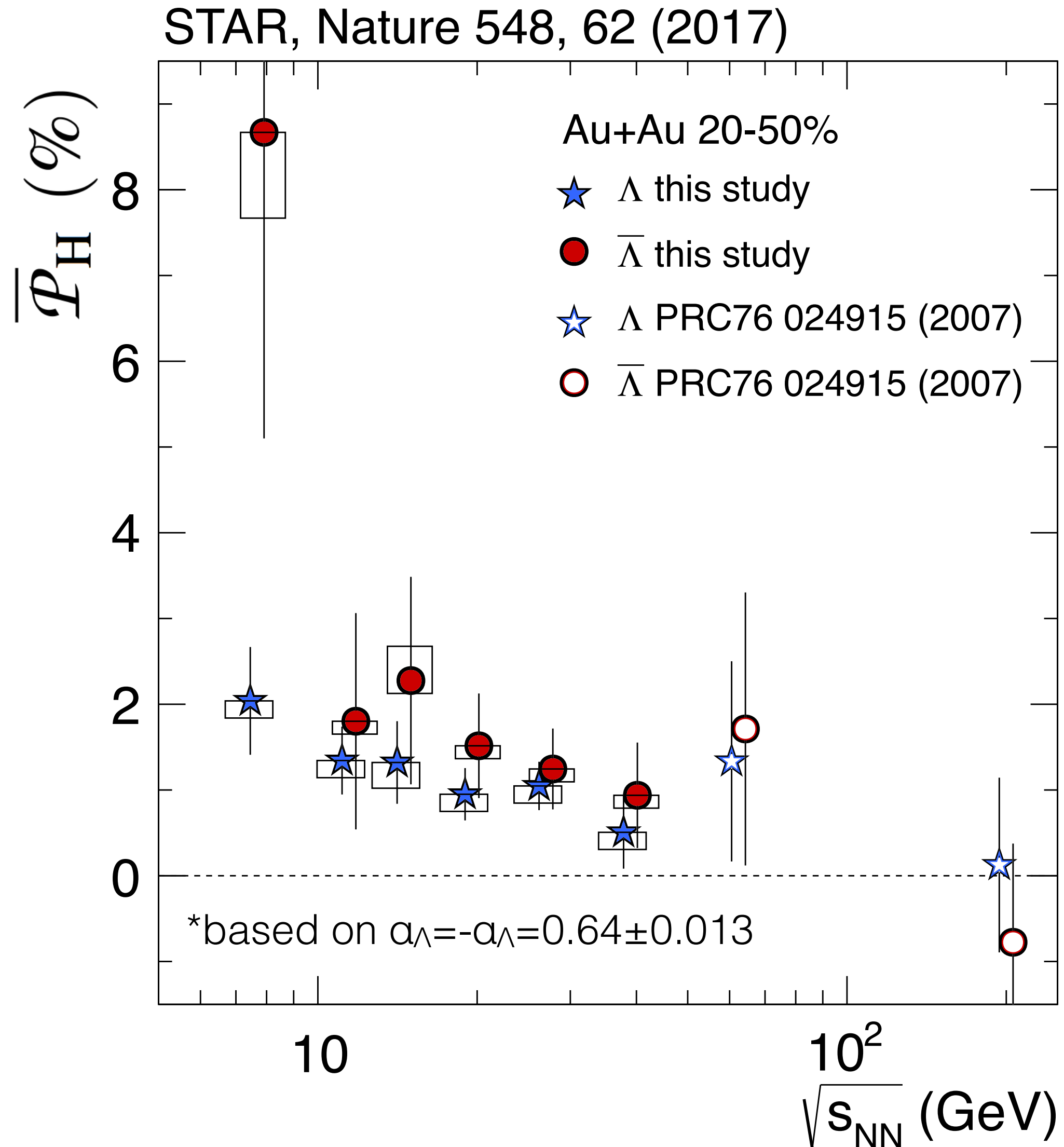
$$\sim 0.6-2.7 \times 10^{22} \text{ s}^{-1}$$

μ_{Λ} : Λ magnetic moment

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

- The most vortical fluid!

First observation in lower energies (2017)



Positive polarization signal at lower energies!

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

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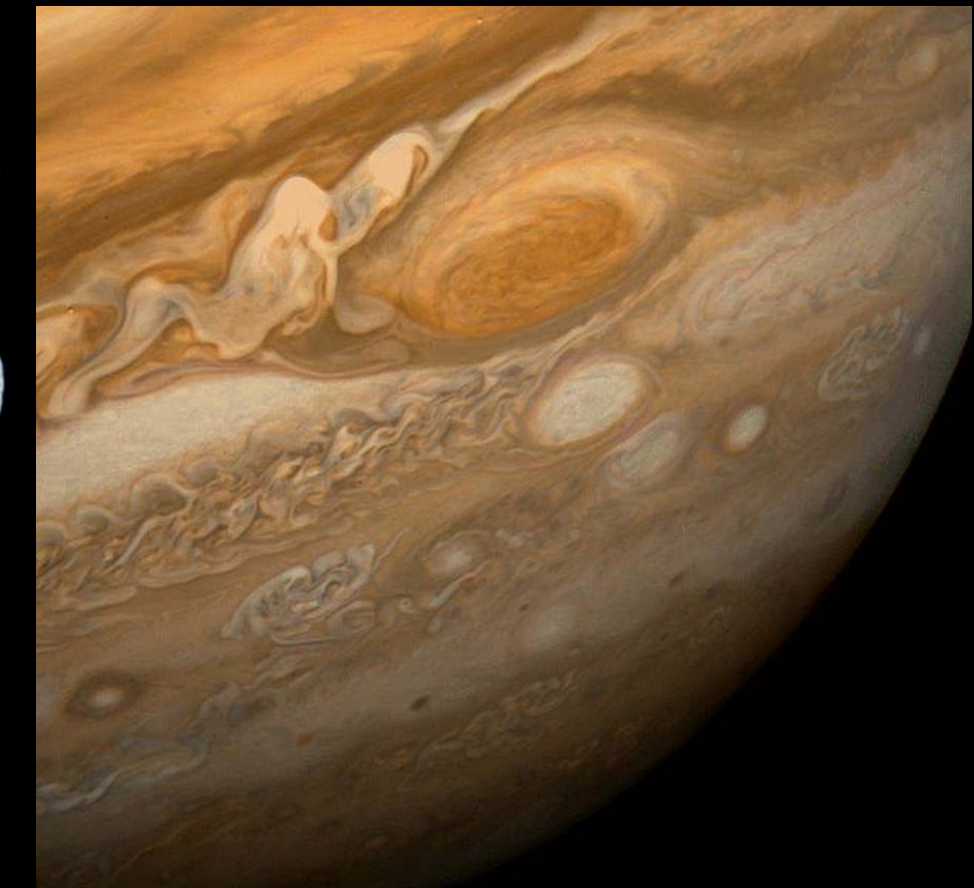
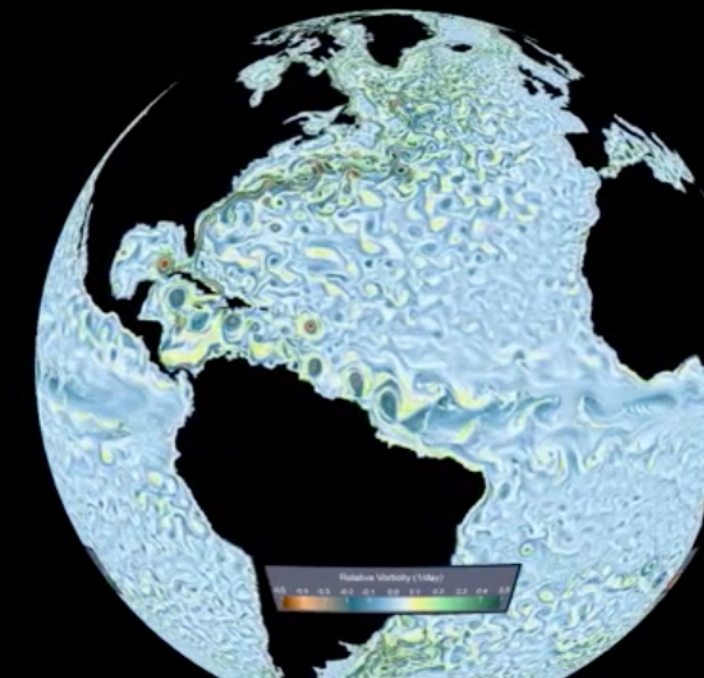
- The most vortical fluid!

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

Vorticity we know

<i>Ocean surface vorticity</i>	$\sim 10^{-5} \text{ s}^{-1}$
<i>Jupiter's great red spot</i>	$\sim 10^{-4} \text{ s}^{-1}$
<i>Core of supercell tornado</i>	$\sim 10^{-1} \text{ s}^{-1}$
<i>Rotating, heated soap bubbles</i>	$\sim 10^2 \text{ s}^{-1}$
<i>Superfluid helium nano droplet</i>	$\sim 10^6 \text{ s}^{-1}$

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

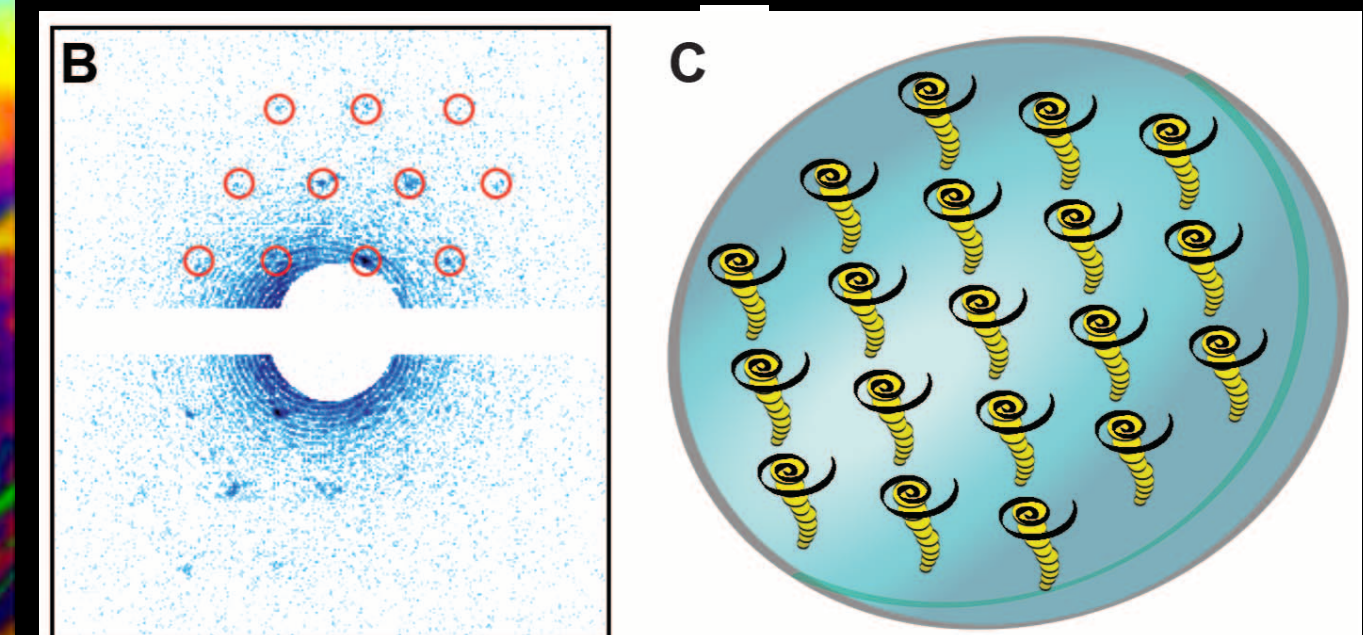
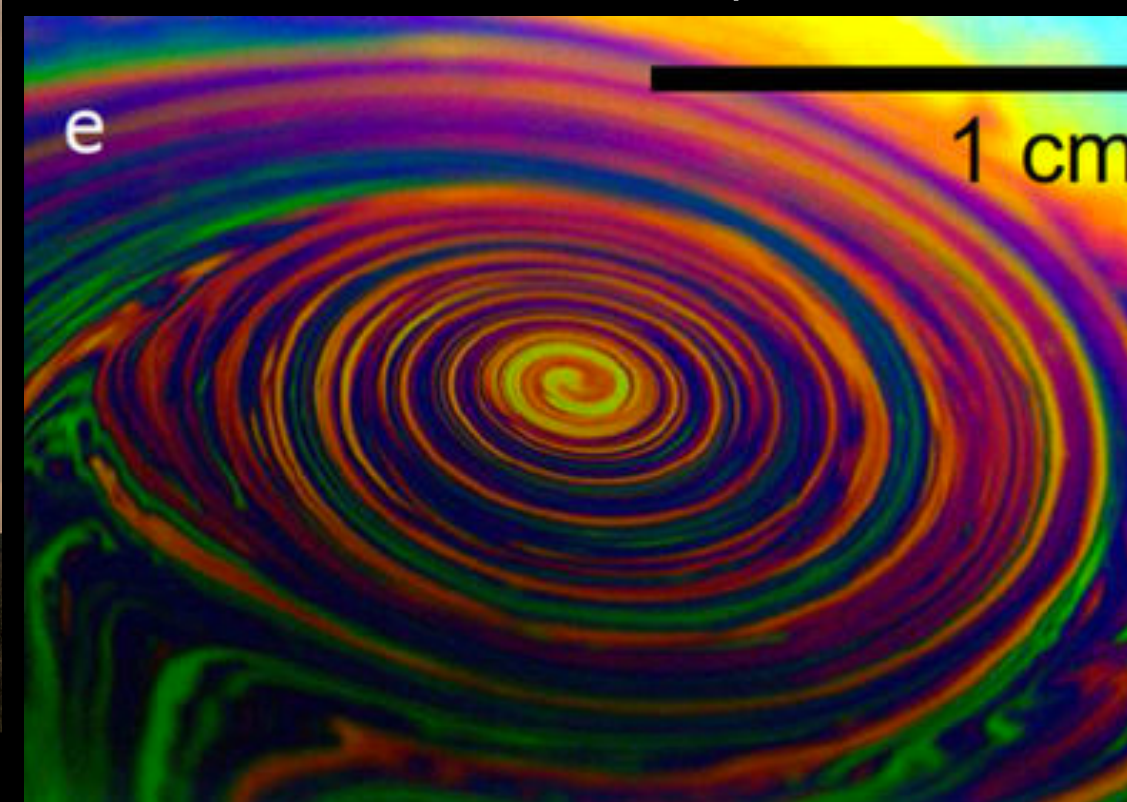


Great red spot of Jupiter
(from wikipedia)



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

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



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

The most vortical fluid!

<i>Ocean surface vorticity</i>	$\sim 10^{-5} \text{ s}^{-1}$
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<i>Rotating, heated soap bubbles</i>	$\sim 10^2 \text{ s}^{-1}$
<i>Superfluid helium nano droplet</i>	$\sim 10^6 \text{ s}^{-1}$
<i>Matter in heavy ion collisions</i>	$\sim 10^{22} \text{ s}^{-1}$

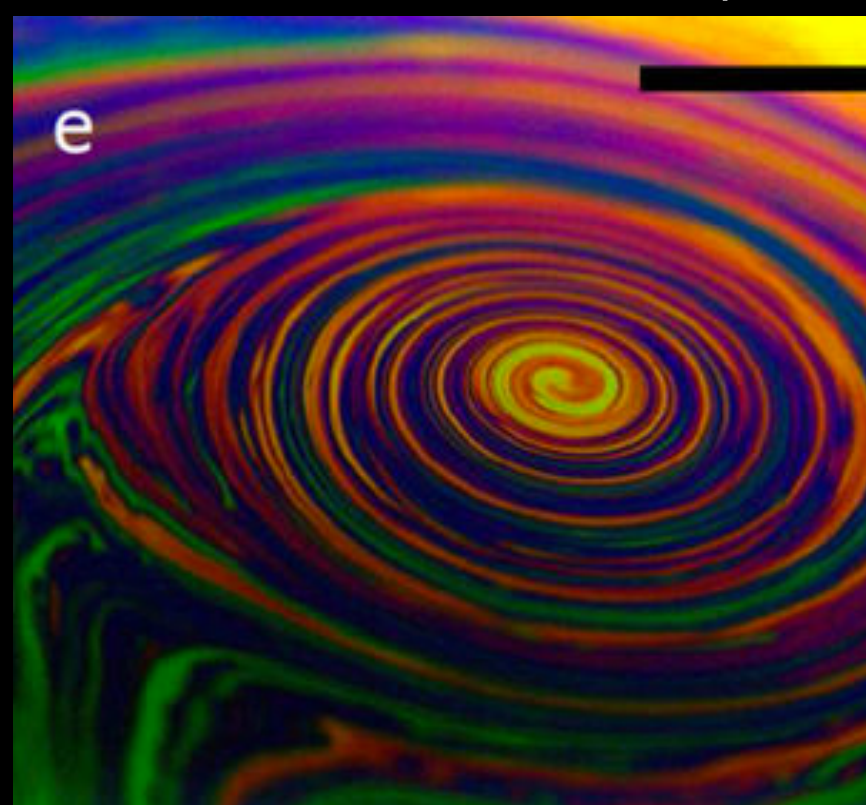
Ocean surface vorticity
<https://sos.noaa.gov/datasets/ocean-surface-vorticity/>



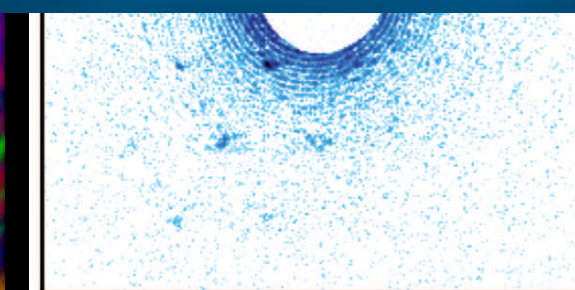
Supercell in Oklahoma (2016)

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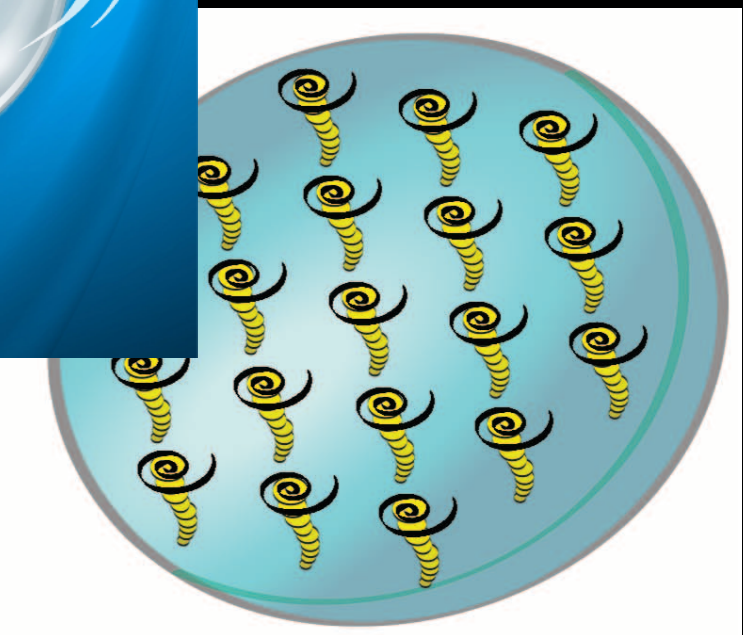
vortex of soap bubble
T. Muel et al., Scientific Report 3



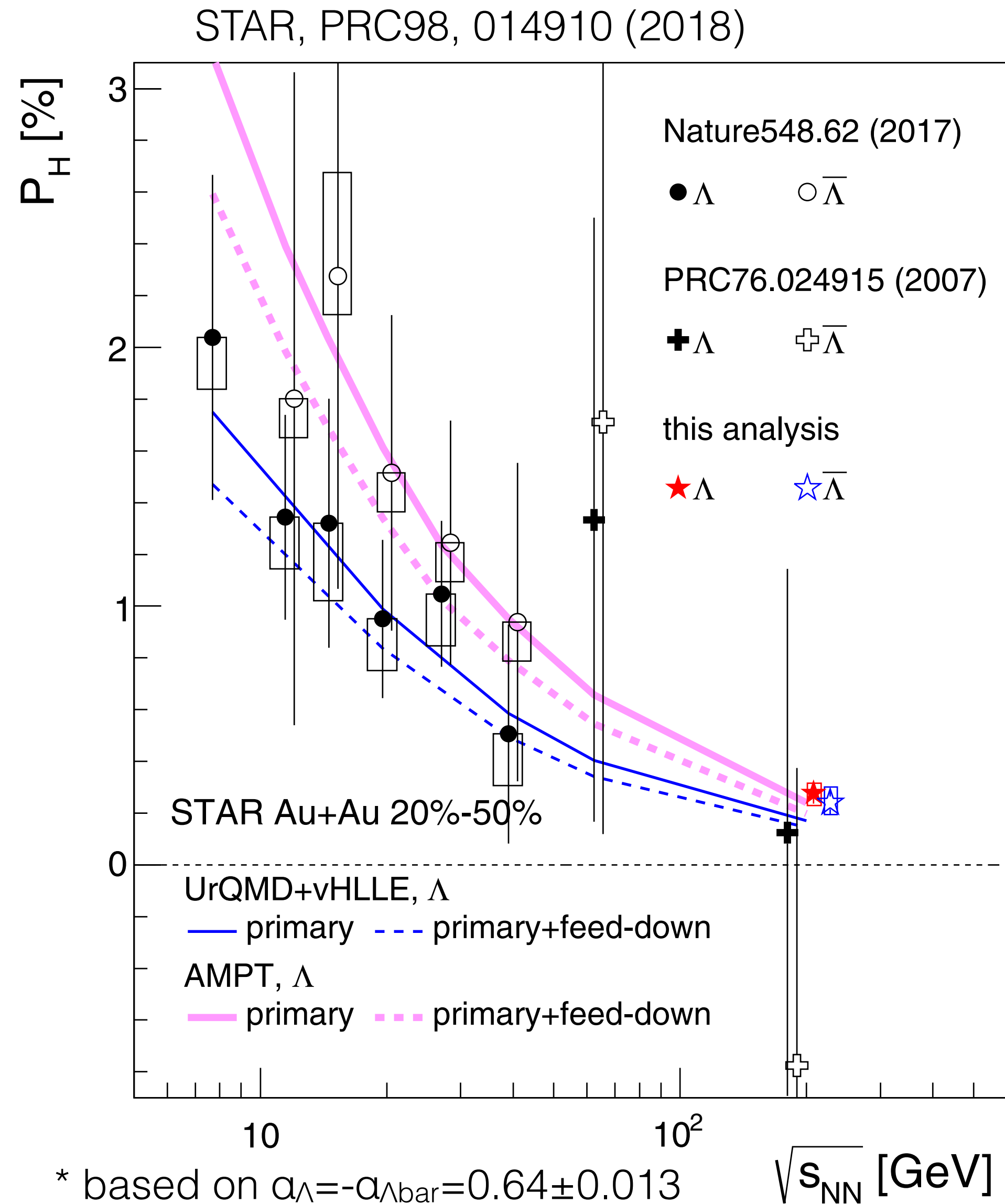
Great Red Spot of Jupiter
(NASA/JPL)



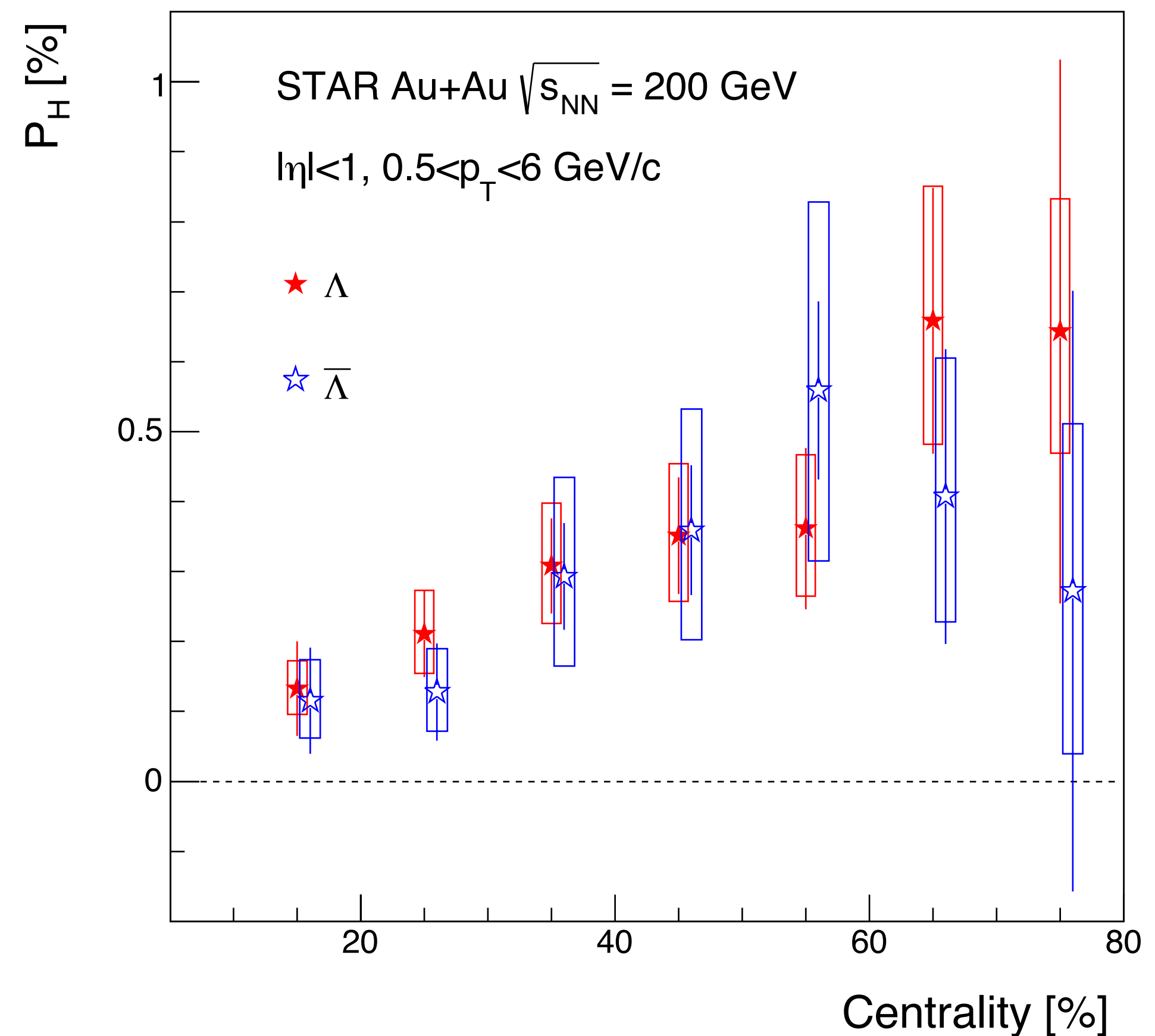
vortex aligned to x-ray beam in He droplets
T. Muel et al., Scientific Report 3, 3455 (2013)



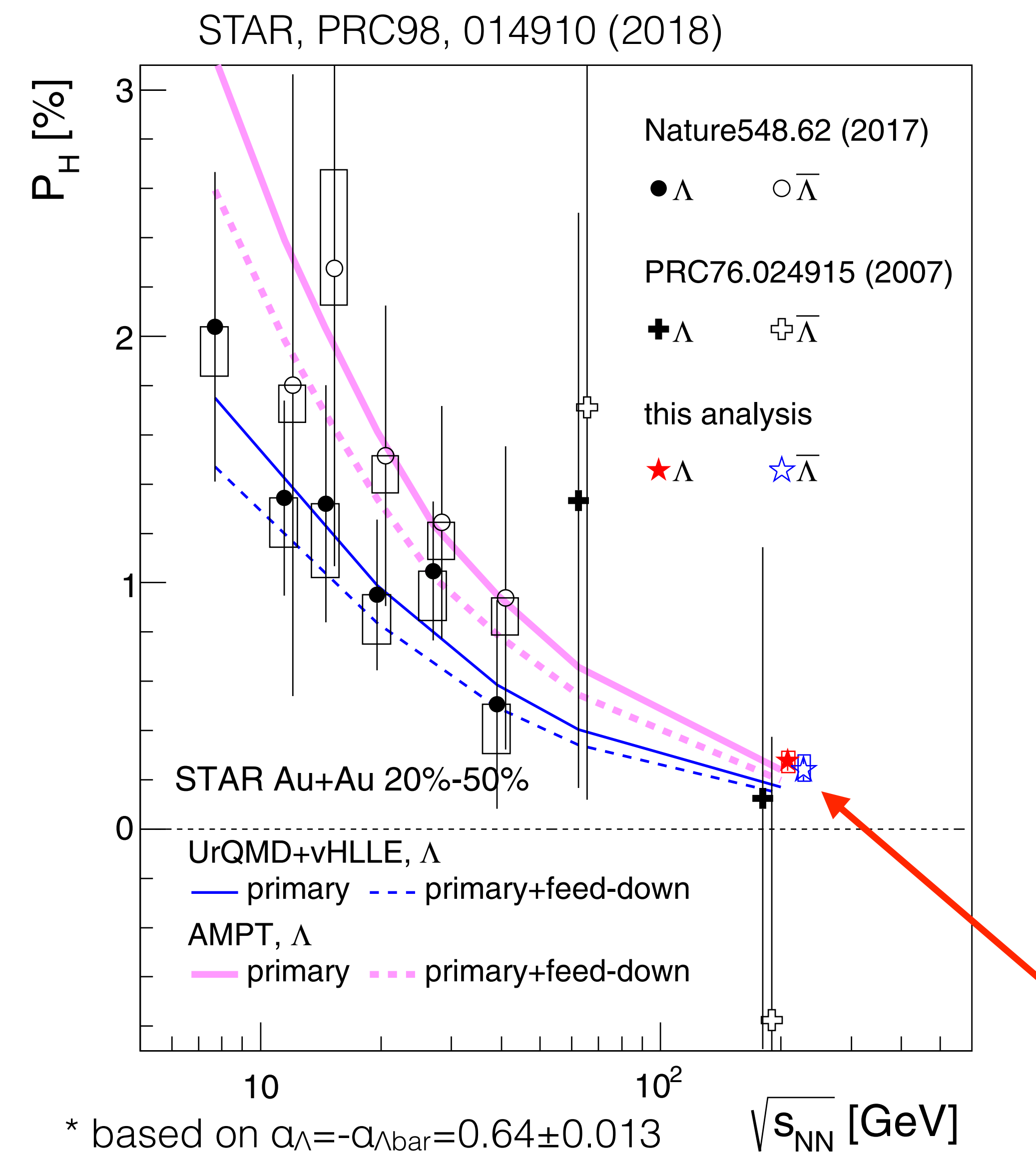
Precise measurements at $\sqrt{s_{NN}} = 200$ GeV (2018)



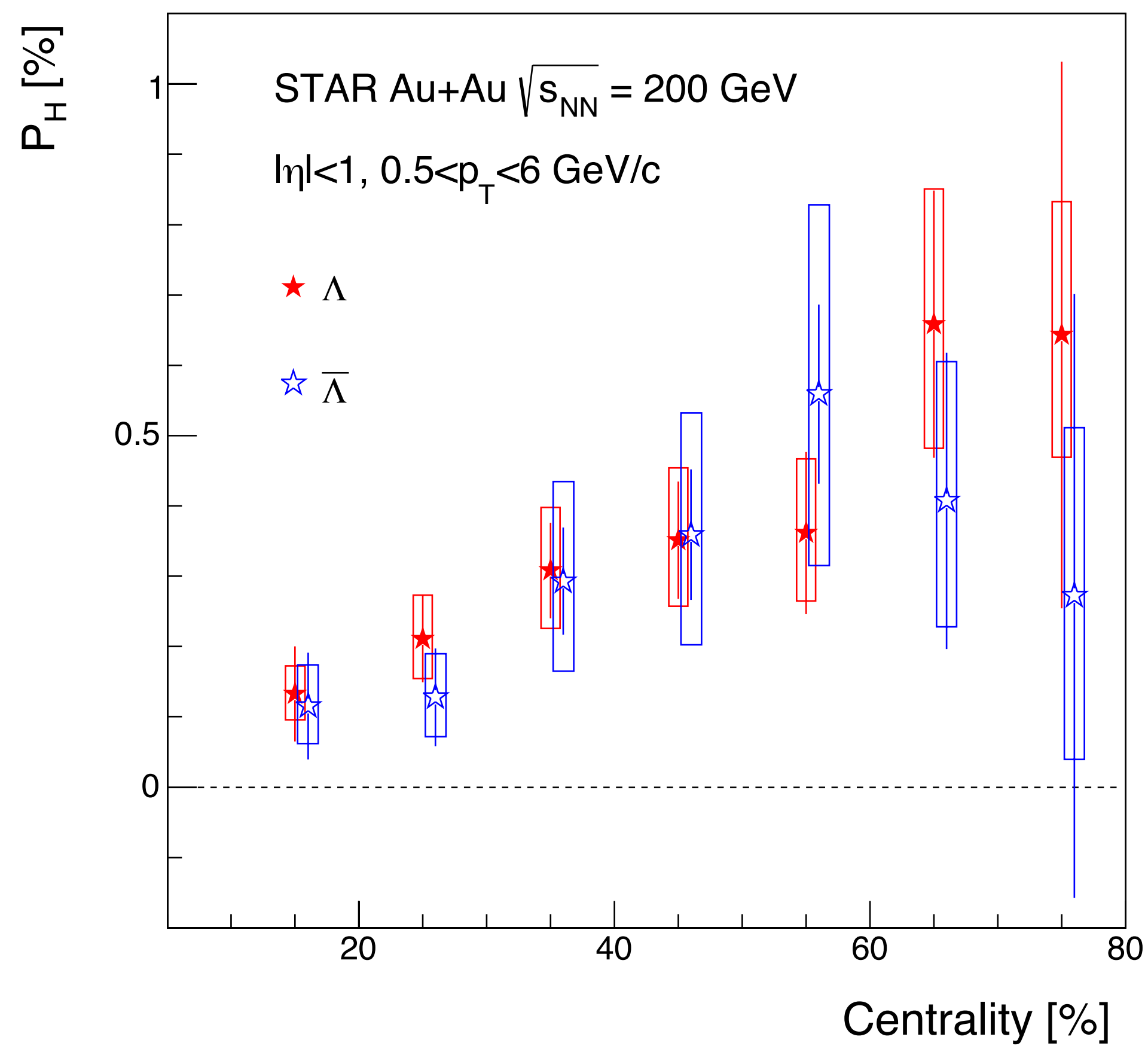
- Confirmed energy dependence with the 200 GeV results
- Centrality dependence was observed as expected



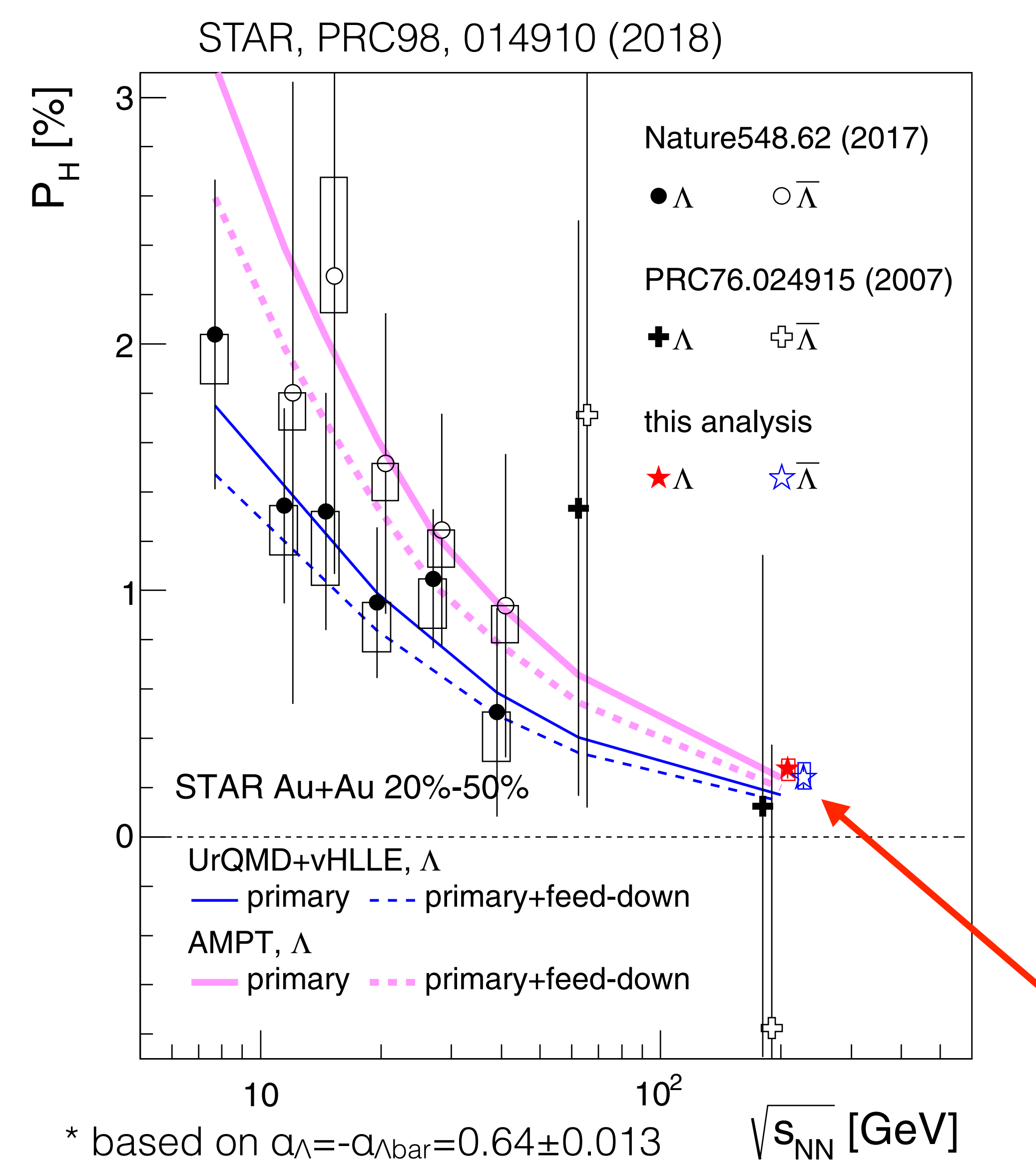
Precise measurements at $\sqrt{s_{NN}} = 200$ GeV (2018)



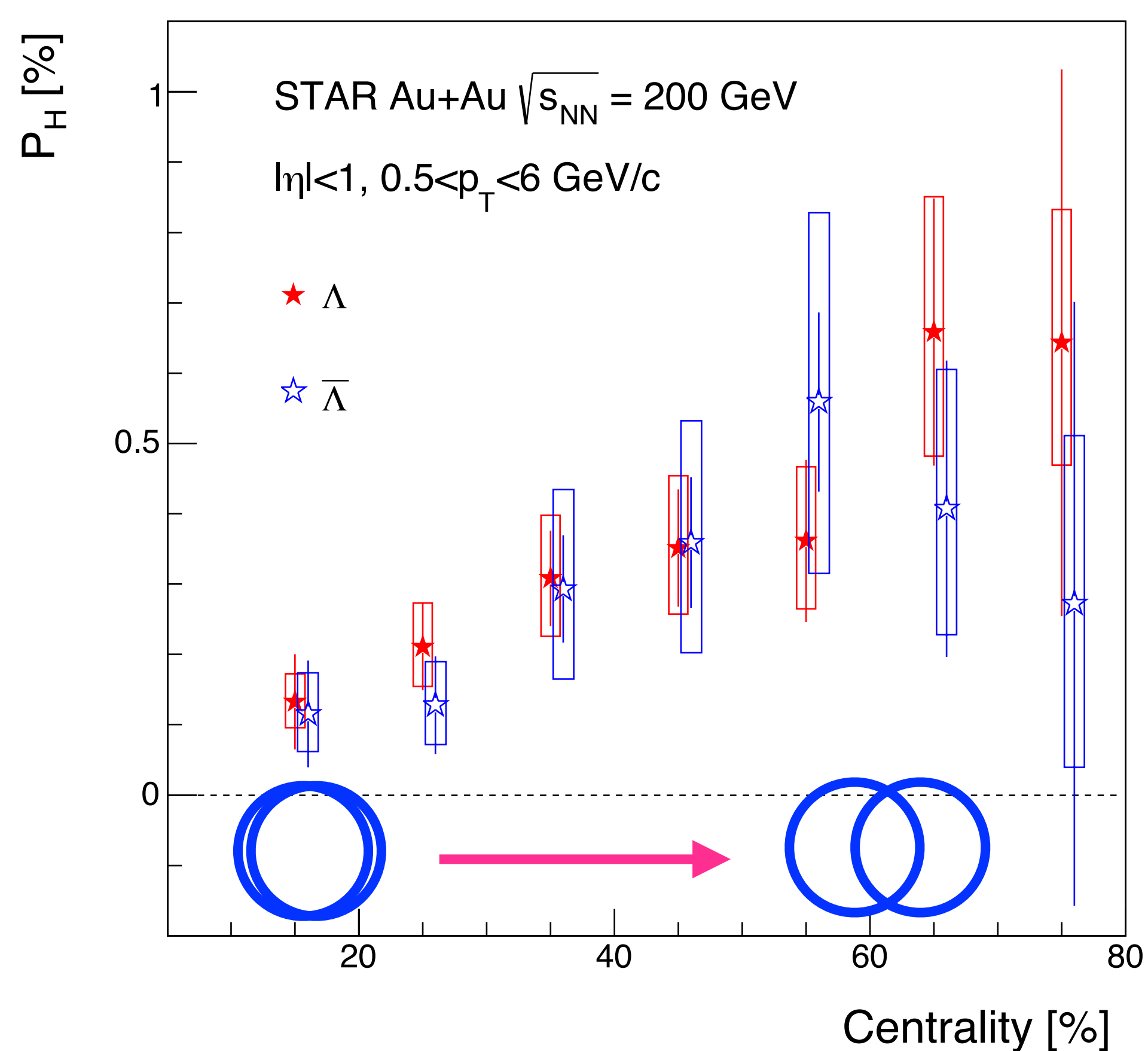
- Confirmed energy dependence with the 200 GeV results
- Centrality dependence was observed as expected



Precise measurements at $\sqrt{s_{NN}} = 200 \text{ GeV}$ (2018)



- Confirmed energy dependence with the 200 GeV results
- Centrality dependence was observed as expected



Rapidly growing topic with new measurements

- Global P_H
- Local polarization (P_z)
- Vector-meson spin-alignment
- Spin-spin correlation
- *Only experimental papers in HIC

Measurement of the J/ψ Polarization with Respect to the Event Plane in Pb-Pb Collisions at the LHC

S. Acharya^{124,131}, D. Adamová⁸⁶, A. Adler⁶⁹, G. Aglieri Rinella³², M. Agnello²⁹, N. Agrawal⁵⁰, Z. Ahammed¹³¹, S. Ahmad¹⁵, S. U. Ahn⁷⁰ et al. (ALICE Collaboration)

Phys. Rev. Lett. 131, 042303 – Published 25 July, 2023

ALICE

Physics Letters B

Volume 846, 10 November 2023, 137920

First measurement of prompt and non-prompt D^{*+} vector meson spin alignment in pPb collisions at $\sqrt{s} = 13$ TeV

ALICE

Evidence of Spin-Orbital Angular Momentum Interactions in Relativistic Heavy-Ion Collisions

S. Acharya¹⁴¹, D. Adamová⁹⁴, A. Adler⁷⁴, J. Adolfsson⁶⁰, M. M. Aggarwal⁹⁹, G. Aglieri Rinella³³, M. Agnello³⁰, N. Agrawal^{10,53}, Z. Ahammed¹⁴¹ et al. (The ALICE Collaboration)

Phys. Rev. Lett. 125, 012301 – Published 30 June, 2020

ALICE

Polarization of Λ and $\bar{\Lambda}$ Hyperons along the Beam Direction in Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV

S. Acharya¹⁴³, D. Adamová⁹⁸, A. Adler⁷⁶, G. Aglieri Rinella³⁵, M. Agnello³¹, N. Agrawal⁵⁵, Z. Ahammed¹⁴³, S. Ahmad¹⁶, S. U. Ahn⁷⁸ et al. (ALICE Collaboration)

Phys. Rev. Lett. 128, 172005 – Published 29 April, 2022

ALICE

nature

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Article | Published: 18 January 2023

Pattern of global spin alignment of ϕ and K^{*0} mesons in heavy-ion collisions

STAR Collaboration

Nature 614, 244–248 (2023) | Cite this article

Polarization of Λ ($\bar{\Lambda}$) Hyperons along the Beam Direction in Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

J. Adam¹³, L. Adamczyk², J. R. Adams³⁷, J. K. Adkins²⁸, G. Agakishiev²⁶, M. M. Aggarwal³⁹, Z. Ahammed⁵⁹, I. Alekseev^{3,33}, D. M. Anderson⁵³ et al. (STAR Collaboration)

Phys. Rev. Lett. 123, 132301 – Published 27 September, 2019

STAR

Global polarization of Λ and $\bar{\Lambda}$ hyperons in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV

S. Acharya¹⁴¹, D. Adamová⁹³, S. P. Adhya¹⁴¹, A. Adler⁷³, J. Adolfsson⁷⁹, M. M. Aggarwal⁹⁸, G. Aglieri Rinella³⁴, M. Agnello³¹, N. Agrawal^{10,48,53} et al. (ALICE Collaboration)

Phys. Rev. C 101, 044611 – Published 20 April, 2020 Erratum Phys. Rev. C 105, 029902 (2022)

ALICE

Hyperon Polarization along the Beam Direction Relative to the Second and Third Harmonic Event Planes in Isobar Collisions at $\sqrt{s_{NN}} = 200$ GeV

M. I. Abdulhamid⁴, B. E. Aboona²⁴, J. Adam¹⁵, J. R. Adams³⁹, G. Agakishiev²⁹, L. Aggarwal⁴⁰, M. M. Aggarwal⁴⁰, Z. Ahammed⁶⁰, A. Altbaev²⁹ et al. (STAR Collaboration)

Phys. Rev. Lett. 131, 202301 – Published 14 November, 2023

STAR

Observation of Λ hyperon local polarization in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV

The CMS Collaboration*

CERN-EP-2024-328 2025/02/13

nature

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

First observation of field vortices formed by heavy-ion collisions

SUBATOMIC SWIRLS

STAR

Physical Review C

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Global polarization of Λ hyperons in Au collisions at $\sqrt{s_{NN}} = 200$ GeV

J. Adam⁹, L. Adamczyk¹, J. R. Adams³¹, J. K. Adkins²¹, G. Agakishiev²³, Z. Ahammed⁵⁶, N. N. Ajitanand⁴⁴, I. Alekseev^{17,28} et al. (STAR Collaboration)

Phys. Rev. C 104, L061901 – Published 21 December, 2021

STAR

Measurement of global polarization of Λ hyperons in few-GeV heavy-ion collisions

M. S. Abdallah⁵, B. E. Aboona⁵⁵, J. Adam⁶, L. Adamczyk², J. R. Adams³⁹, J. K. Adkins³⁰, G. Agakishiev²⁸, M. M. Aggarwal⁴¹, Z. Ahammed⁶¹, I. Alekseev^{3,35}, D. M. Anderson⁵⁵ et al. (STAR Collaboration)

Phys. Rev. Lett. 126, 162301 – Published 22 April, 2021 Erratum Phys. Rev. Lett. 131, 089901 (2023)

STAR

Global Polarization of Ξ and Ω Hyperons in Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

J. Adam⁶, L. Adamczyk², J. R. Adams³⁹, J. K. Adkins³⁰, G. Agakishiev²⁸, M. M. Aggarwal⁴¹, Z. Ahammed⁶¹, I. Alekseev^{3,35}, D. M. Anderson⁵⁵ et al. (STAR Collaboration)

Phys. Rev. Lett. 126, 162301 – Published 22 April, 2021 Erratum Phys. Rev. Lett. 131, 089901 (2023)

STAR

Global polarization of Λ and $\bar{\Lambda}$ hyperons in Au + Au collisions at $\sqrt{s_{NN}} = 19.6$ and 27 GeV

M. I. Abdulhamid⁴, B. E. Aboona⁵⁵, J. Adam¹⁵, L. Adamczyk², J. R. Adams³⁹, L. Aggarwal⁴¹, M. M. Aggarwal⁴¹, Z. Ahammed⁶², E. Alpatov⁶ et al. (STAR Collaboration)

Phys. Rev. C 108, 014910 – Published 27 July, 2023

STAR

Hyperon global polarization in isobar Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}} = 200$ GeV

The STAR Collaboration

Abstract

The polarization of Λ , $\bar{\Lambda}$, Ξ , and Ω hyperons along the angular momentum of the system of Ru+Ru and Zr+Zr at $\sqrt{s_{NN}} = 200$ GeV with the STAR detector at RHIC. The polarization is extracted and found to show an increasing trend in more peripheral collisions. Dependence on rapidity are investigated for Λ and $\bar{\Lambda}$ hyperons, but no significant dependence has been observed for Ξ and Ω hyperons. The results for Λ hyperons measurements are qualitatively consistent with hydrodynamic shear-induced polarization and thermal vorticity, and show no obvious system size dependence in Au+Au collisions. For the first time, the dependence of the polarization on the hyperon's constituent quark spin is extracted in the second harmonic event plane and shows stronger polarization for the in-plane constituent quarks at the level of $\sim 10\%$.

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Measuring spin correlation between quarks during QCD confinement

STAR Collaboration

Nature 650, 65–71 (2026) | Cite this article

29k Accesses | 3 Citations | 686 Altmetric | Metrics

Abstract

The vacuum is now understood to have a rich and complex structure, characterized by fluctuating energy fields and a condensate of virtual quark-antiquark pairs. The

2005 Prediction

2007 First attempt

2017 First observation Λ

2018 Differential meas.

2019 First P_z

2020 ϕ and K^{*0} (LHC)

2025 Ξ and Ω

2026 pPb P_z

D^{*0}

spin-spin (pp)

J/ ψ

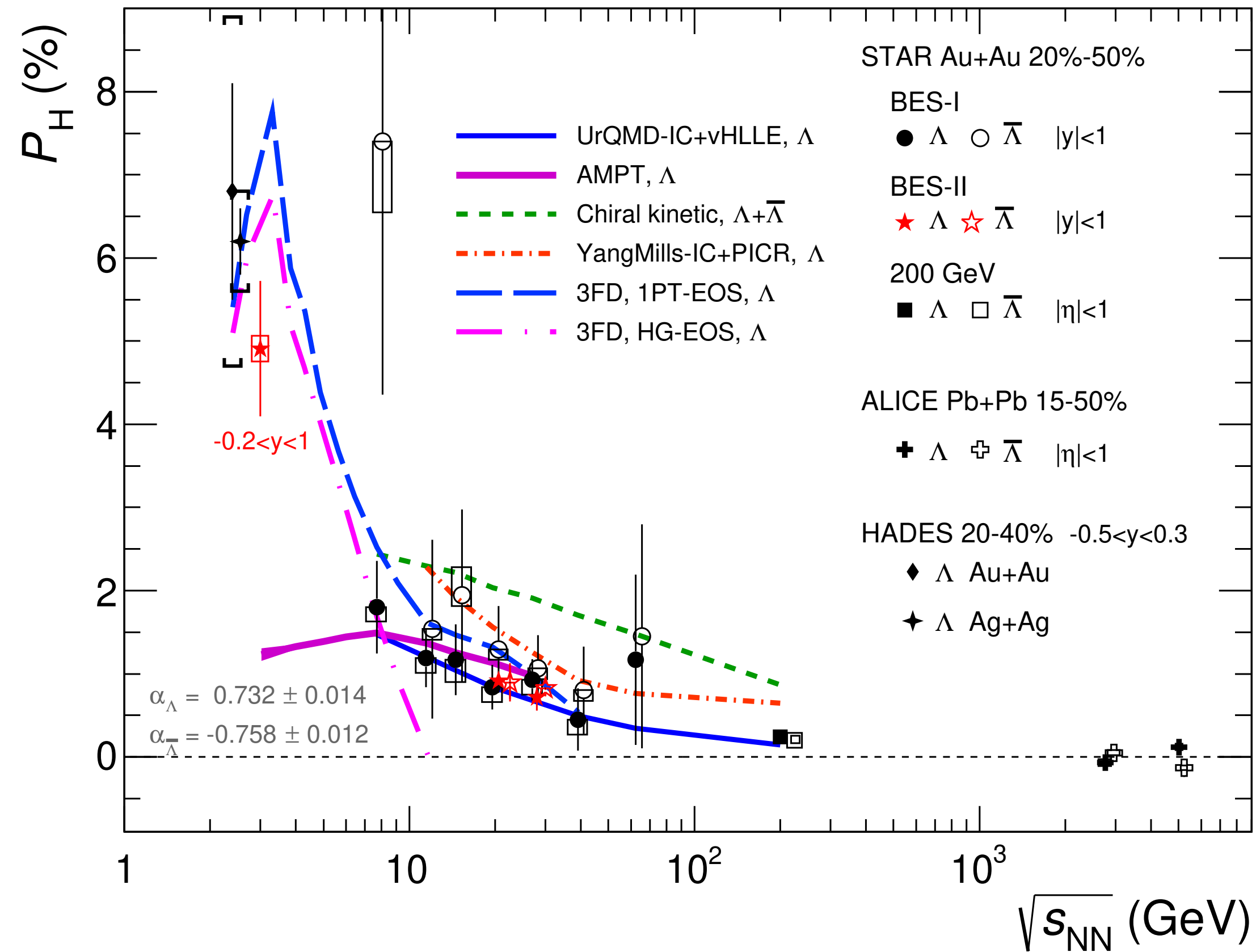
3rd-order P_z

Λ global polarization vs. $\sqrt{s_{NN}}$

Recent reviews

F.Becattini, M.Buzzegoli, TN, S.Pu, A.Tang, Q.Wang, Int.J.Mod.Phys.E33(2024)2430006

TN and S.Voloshin, Int.J.Mod.Phys.E33(2024)2430010



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

I. Karpenko and F. Becattini, EPJC(2017)77:213, UrQMD+vHLL

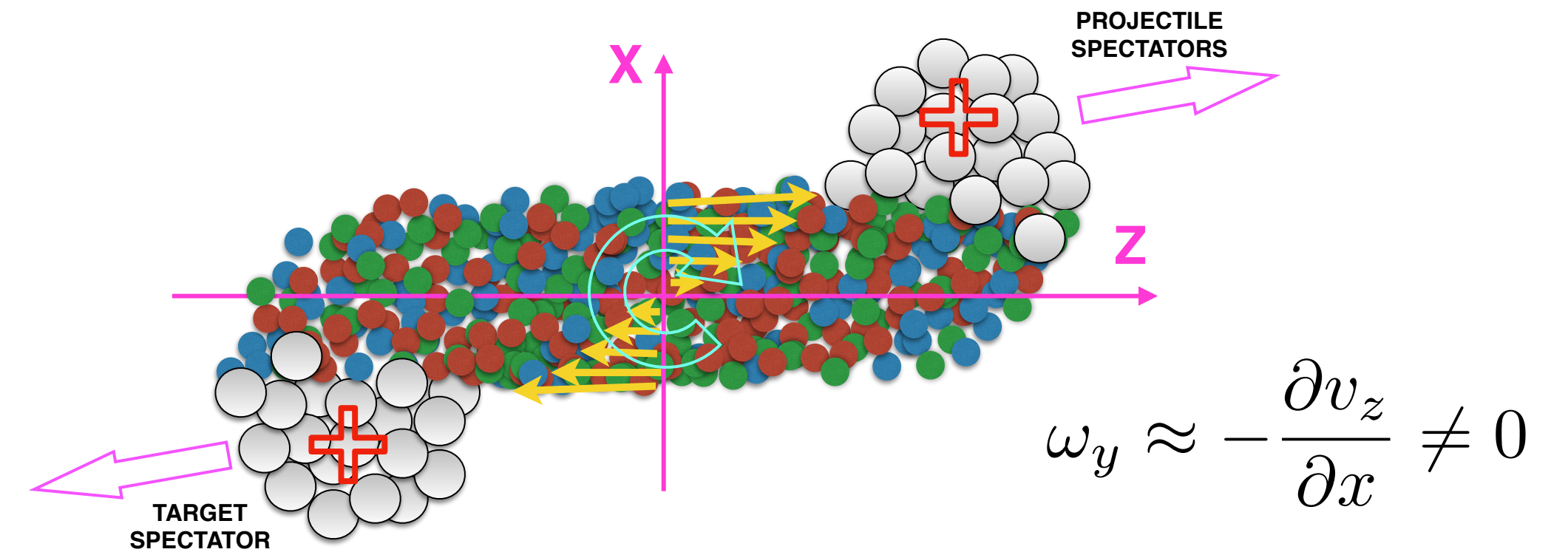
H. Li et al., PRC96, 054908 (2017), AMPT

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

...and more

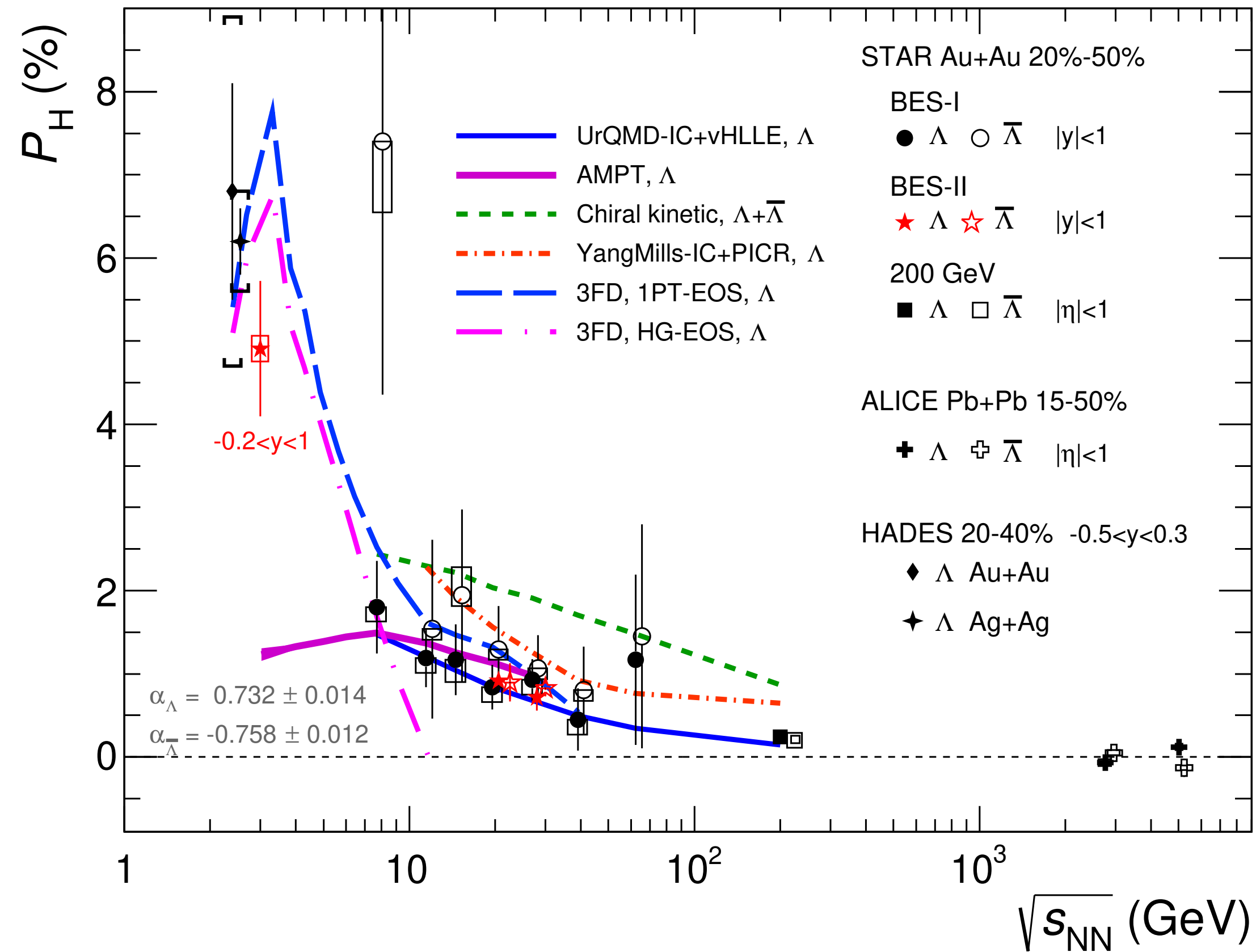


Λ global polarization vs. $\sqrt{s_{NN}}$

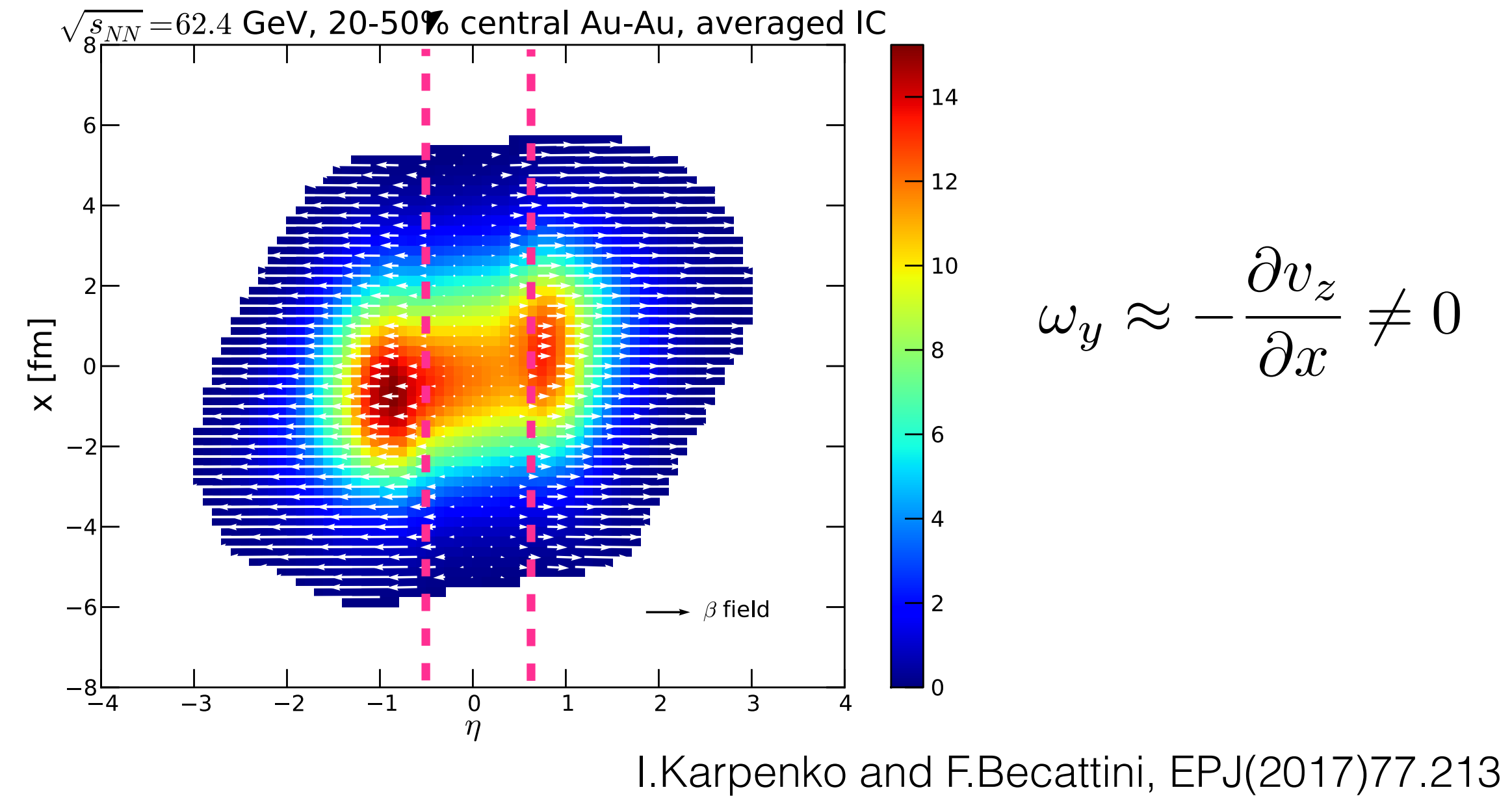
Recent reviews

F.Becattini, M.Buzzegoli, TN, S.Pu, A.Tang, Q.Wang, Int.J.Mod.Phys.E33(2024)2430006

TN and S.Voloshin, Int.J.Mod.Phys.E33(2024)2430010



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



$$\omega_y \approx -\frac{\partial v_z}{\partial x} \neq 0$$

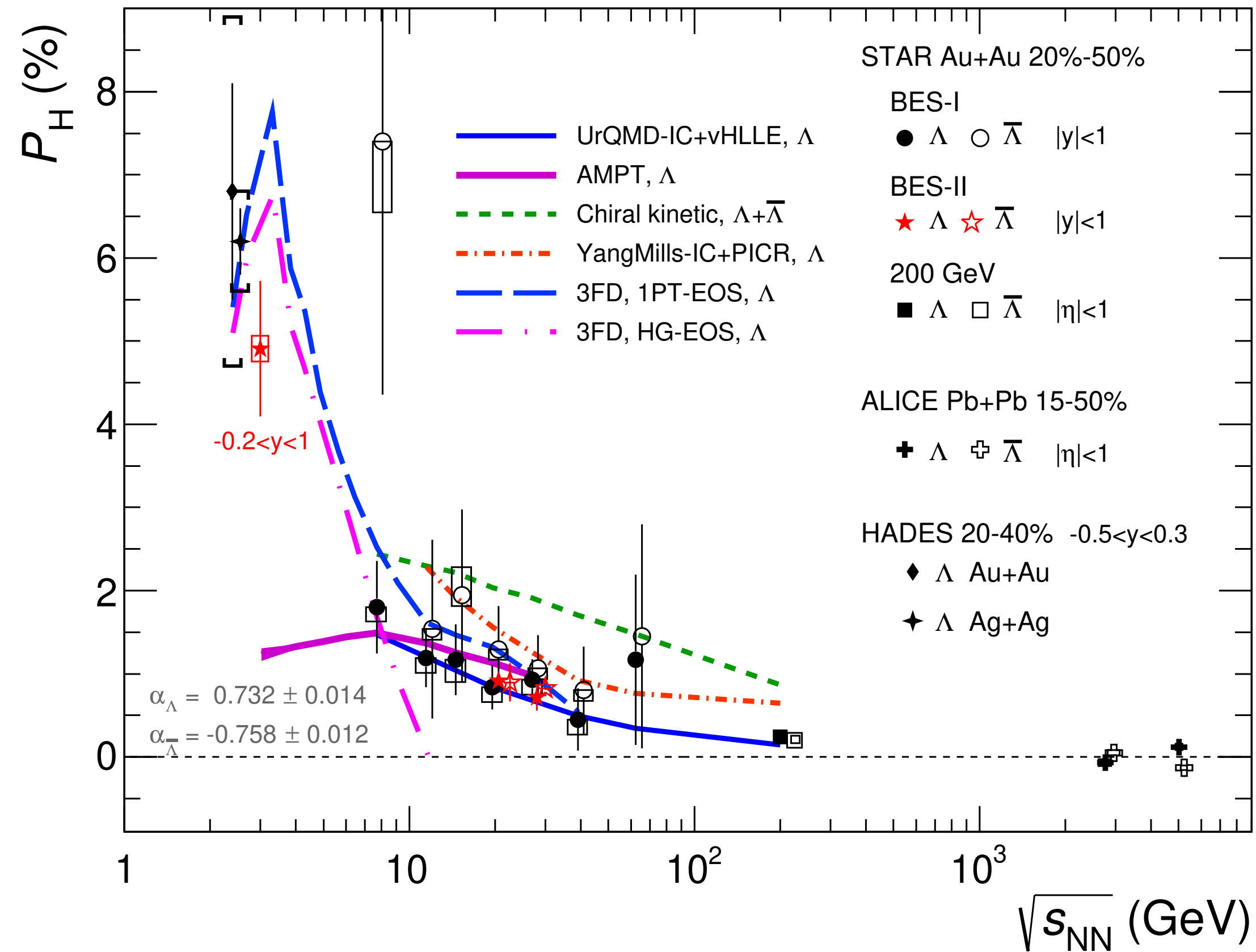
- Velocity shear becomes smaller at higher energy due to longitudinal boost invariance
- Dilution effect due to longer system lifetime

Λ global polarization vs. $\sqrt{s_{NN}}$

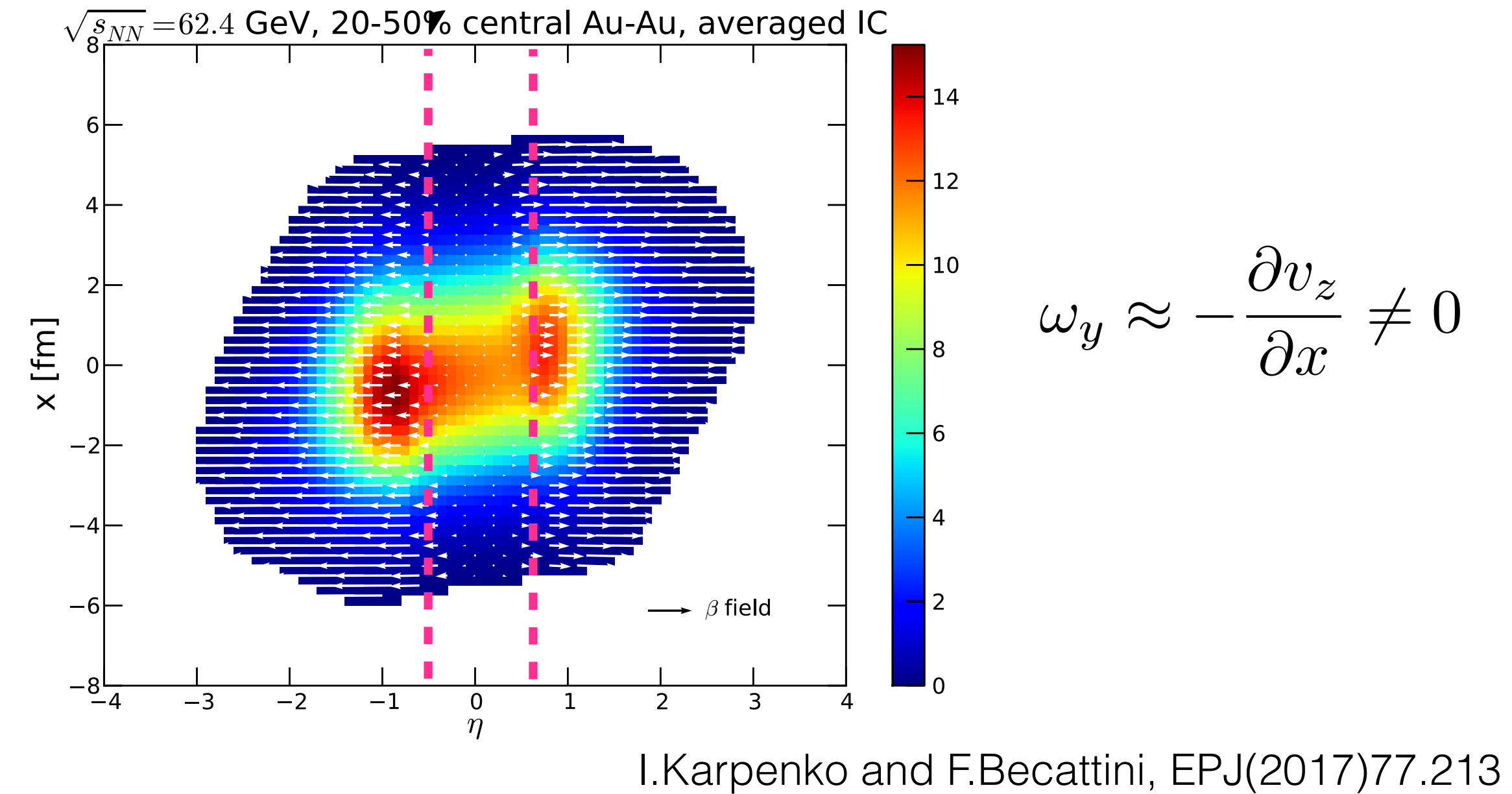
Recent reviews

F.Becattini, M.Buzzegoli, TN, S.Pu, A.Tang, Q.Wang, Int.J.Mod.Phys.E33(2024)2430006

TN and S.Voloshin, Int.J.Mod.Phys.E33(2024)2430010



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



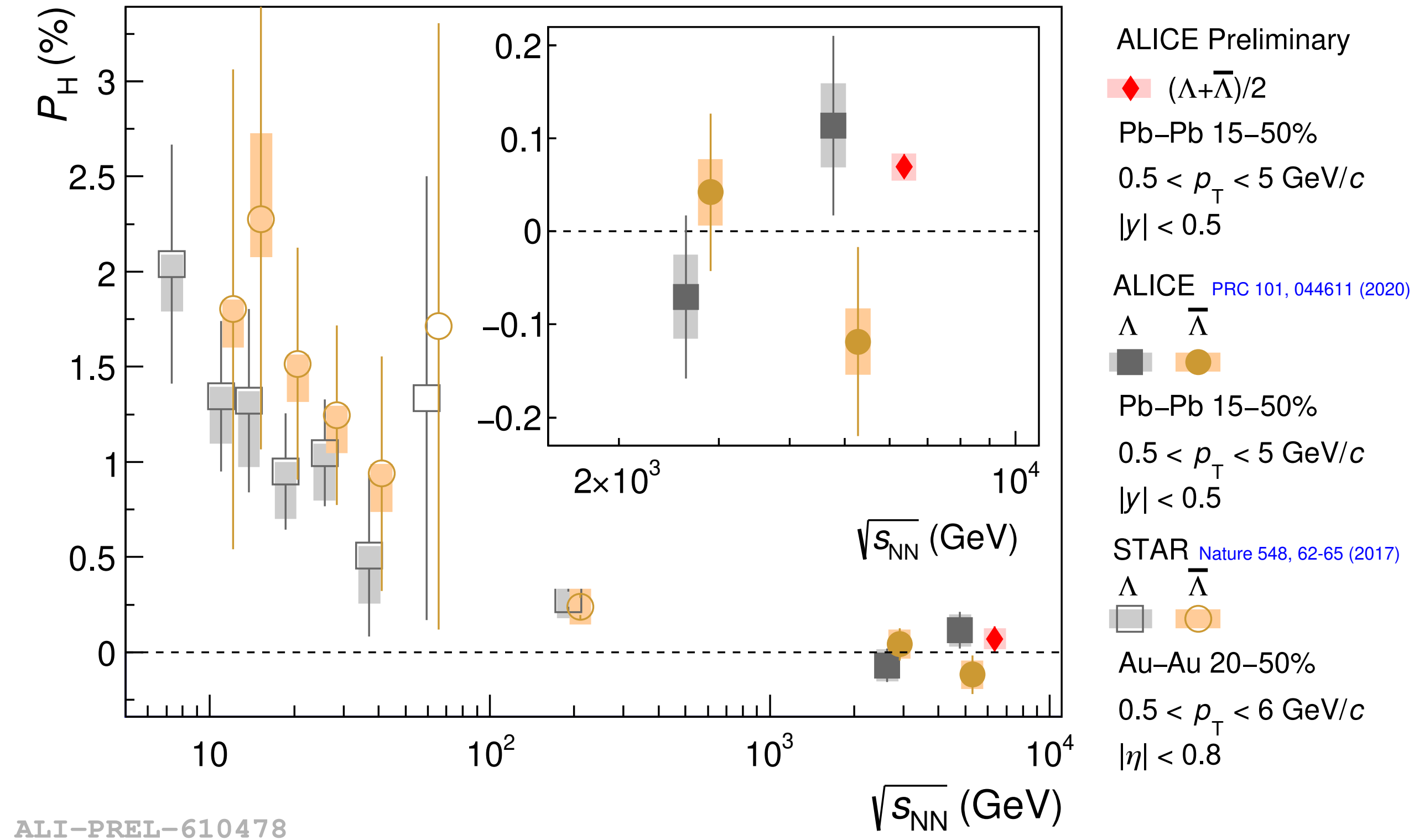
$$\omega_y \approx -\frac{\partial v_z}{\partial x} \neq 0$$

- Velocity shear becomes smaller at higher energy due to longitudinal boost invariance
- Dilution effect due to longer system lifetime

Global polarization is sensitive to the initial velocity profile!

Λ global polarization at the LHC

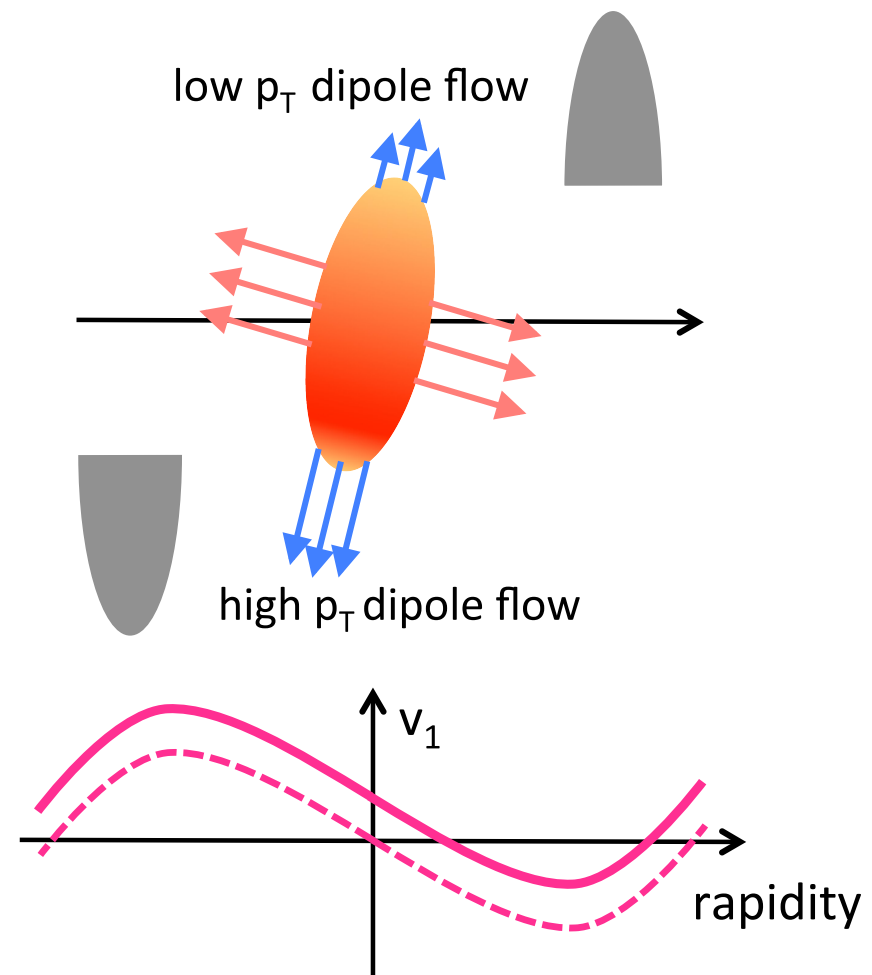
P. Das (ALICE), SPIN2025



- ALICE preliminary result at 5.36 TeV shows $P_\Lambda \sim 0.07\%$ with 5σ significance
 - Implying that the longitudinal boost invariance is (slightly) breaking
- Empirical estimate with directed flow: $P_H^{\text{LHC}} \sim 0.05\text{--}0.1\%$

Relation to directed flow

(b) tilted source
+ asymmetric density gradient



- Two contributions to v_1
initial tilt + density asymmetry

P. Bozek and I. Wyskiel, PRC81.054902 (2010)

U. Heinz and P. Kolb, J.Phys.G30:S1229 (2004)

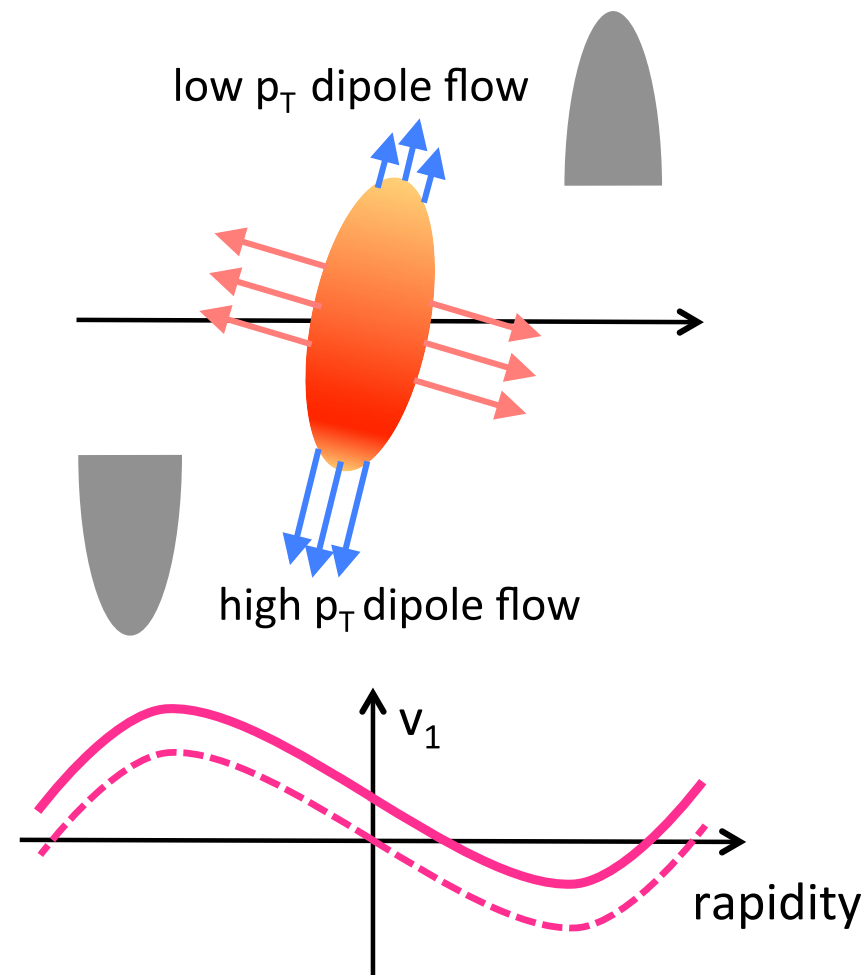
STAR, PRC98.014915 (2018)

ALICE, PRL111.232302 (2013)

$$v_1 = \langle \cos(\phi - \Psi_1) \rangle$$

Relation to directed flow

(b) tilted source
+ asymmetric density gradient



- Two contributions to v_1
initial tilt + density asymmetry

P. Bozek and I. Wyskiel, PRC81.054902 (2010)

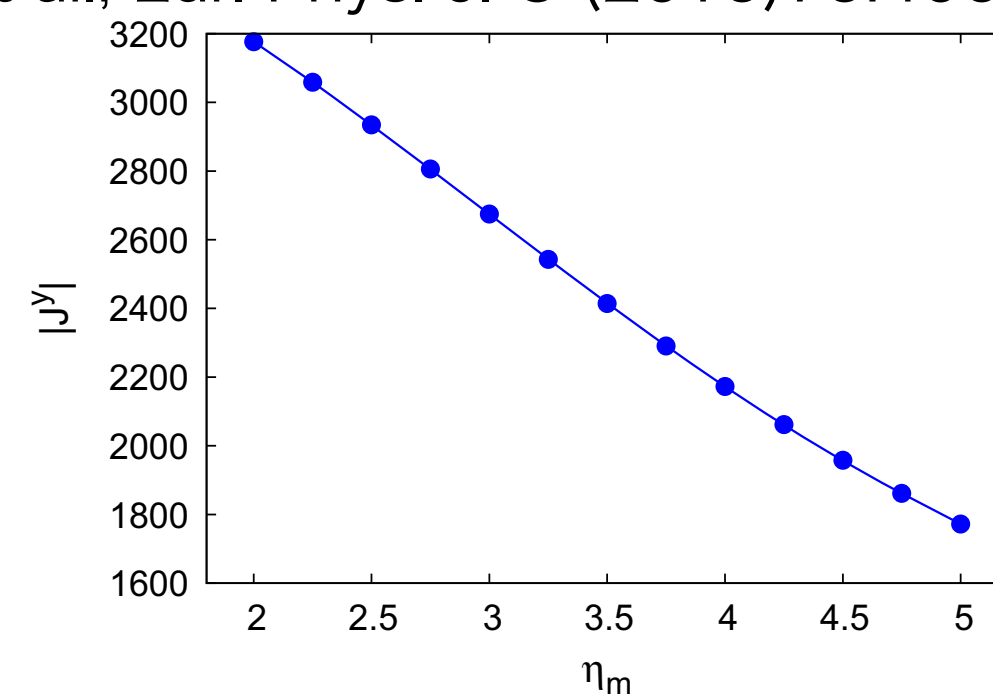
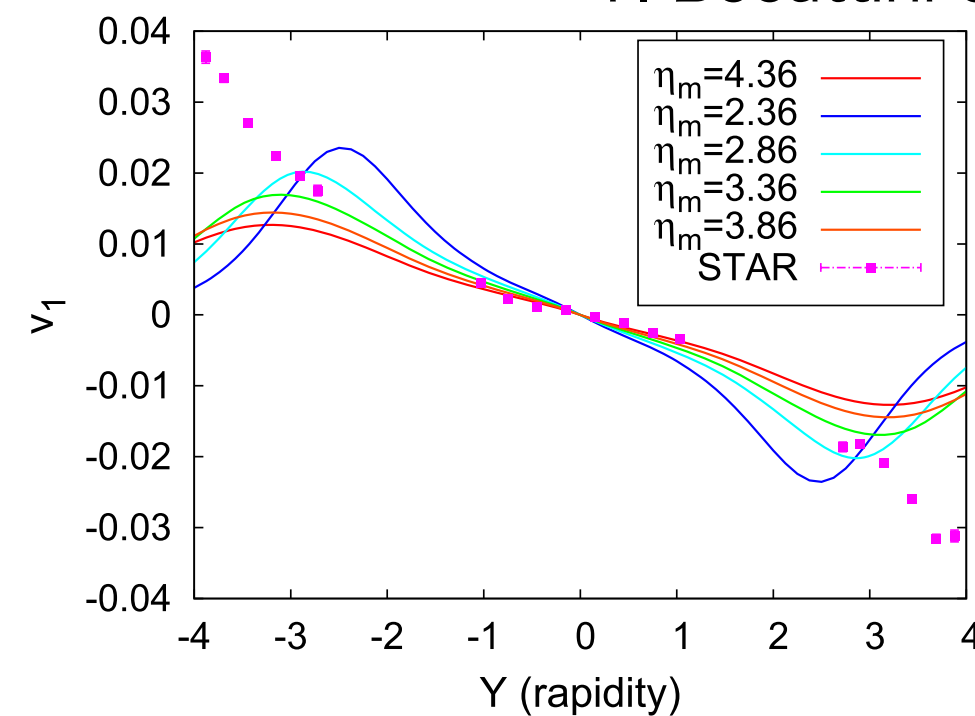
U. Heinz and P. Kolb, J.Phys.G30:S1229 (2004)

STAR, PRC98.014915 (2018)

ALICE, PRL111.232302 (2013)

$$v_1 = \langle \cos(\phi - \Psi_1) \rangle$$

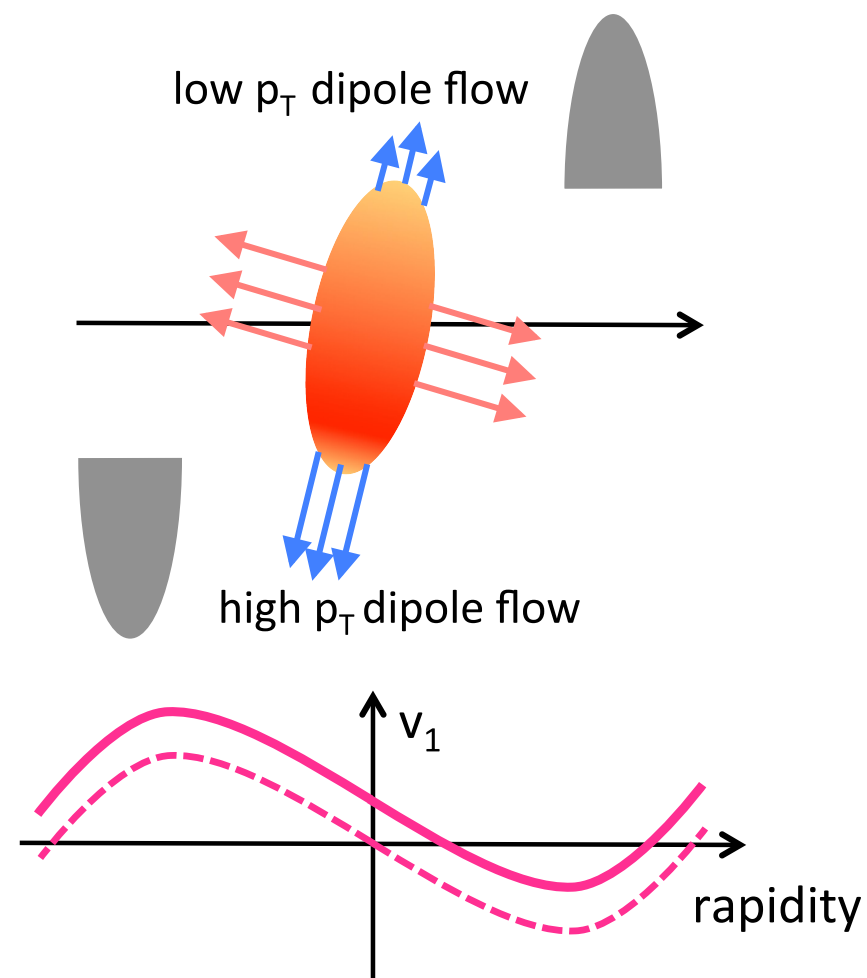
F. Becattini et al., Eur. Phys. J. C (2015)75:406



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

Relation to directed flow

(b) tilted source
+ asymmetric density gradient



- Two contributions to v_1
initial tilt + density asymmetry

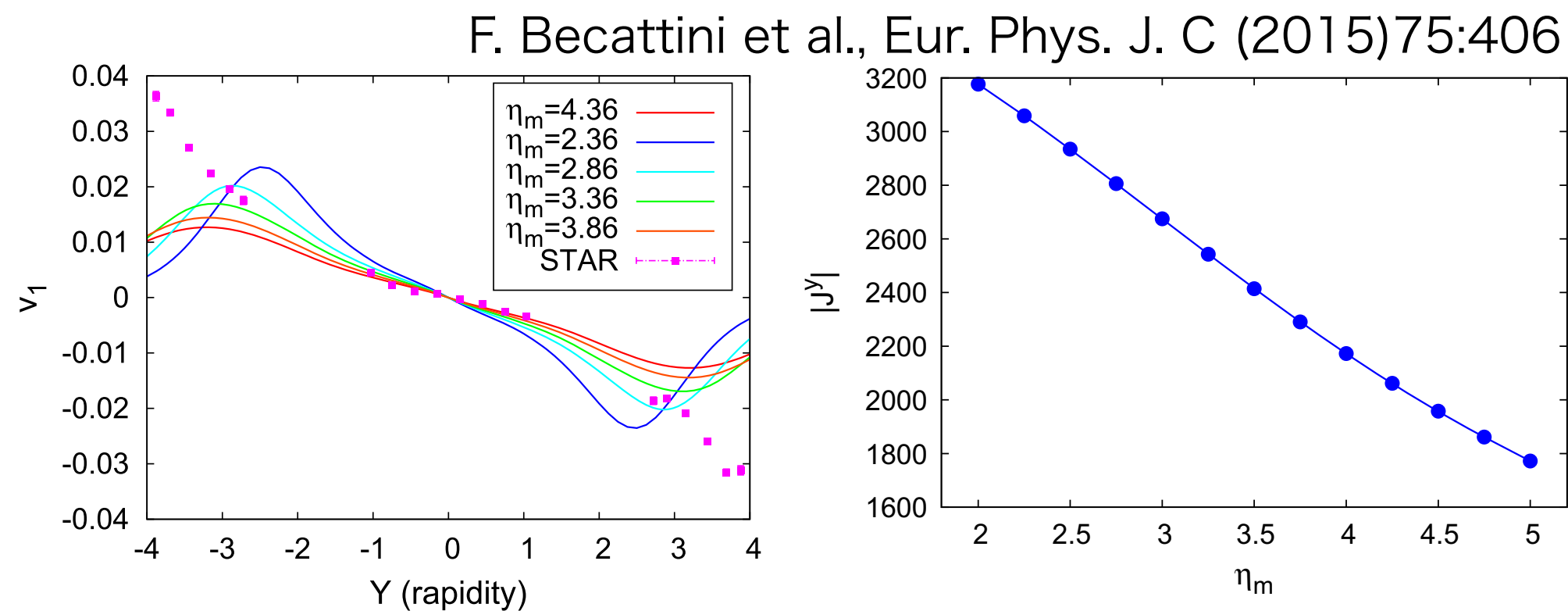
P. Bozek and I. Wyskiel, PRC81.054902 (2010)

U. Heinz and P. Kolb, J.Phys.G30:S1229 (2004)

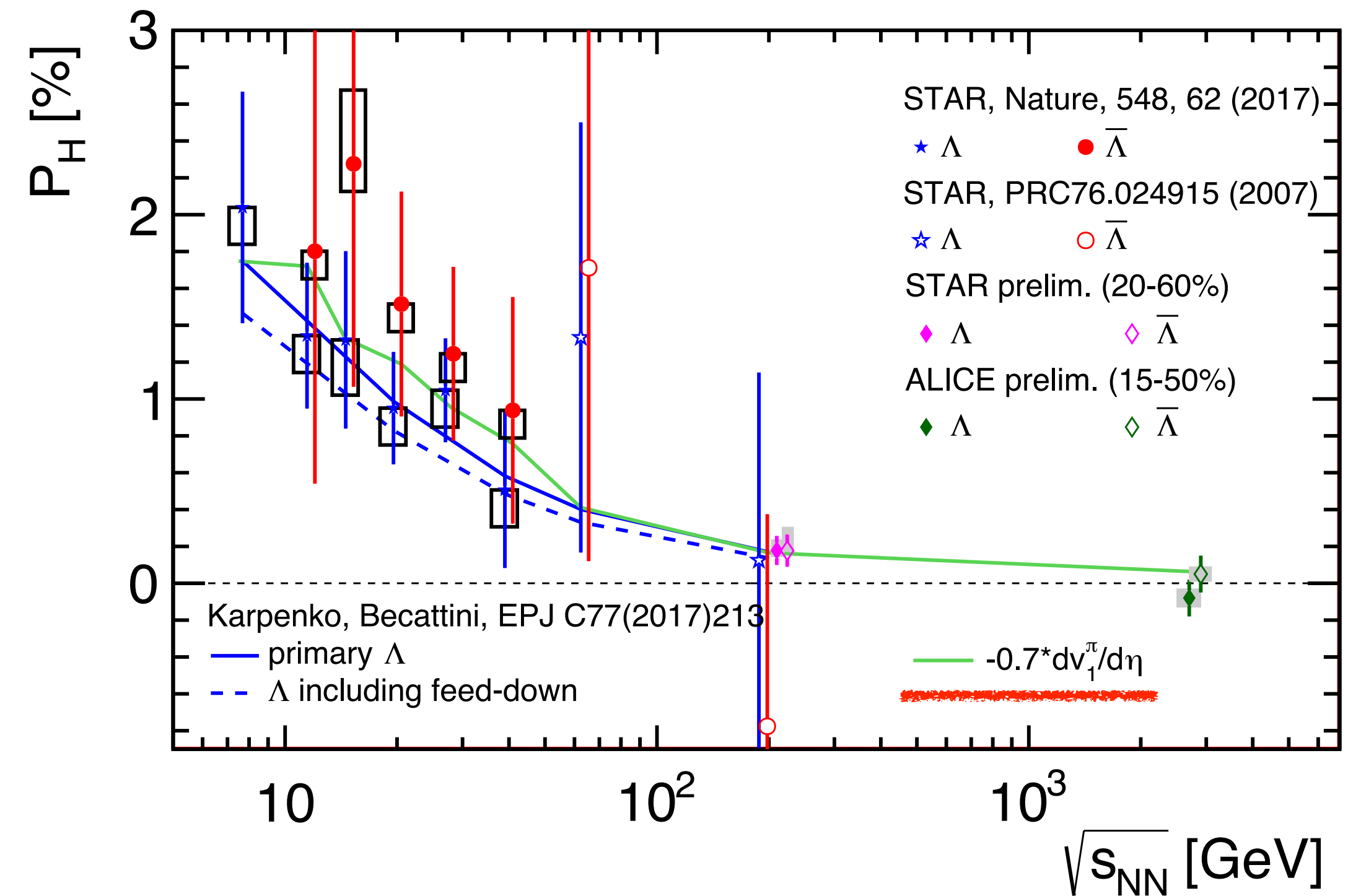
STAR, PRC98.014915 (2018)

ALICE, PRL111.232302 (2013)

$$v_1 = \langle \cos(\phi - \Psi_1) \rangle$$



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

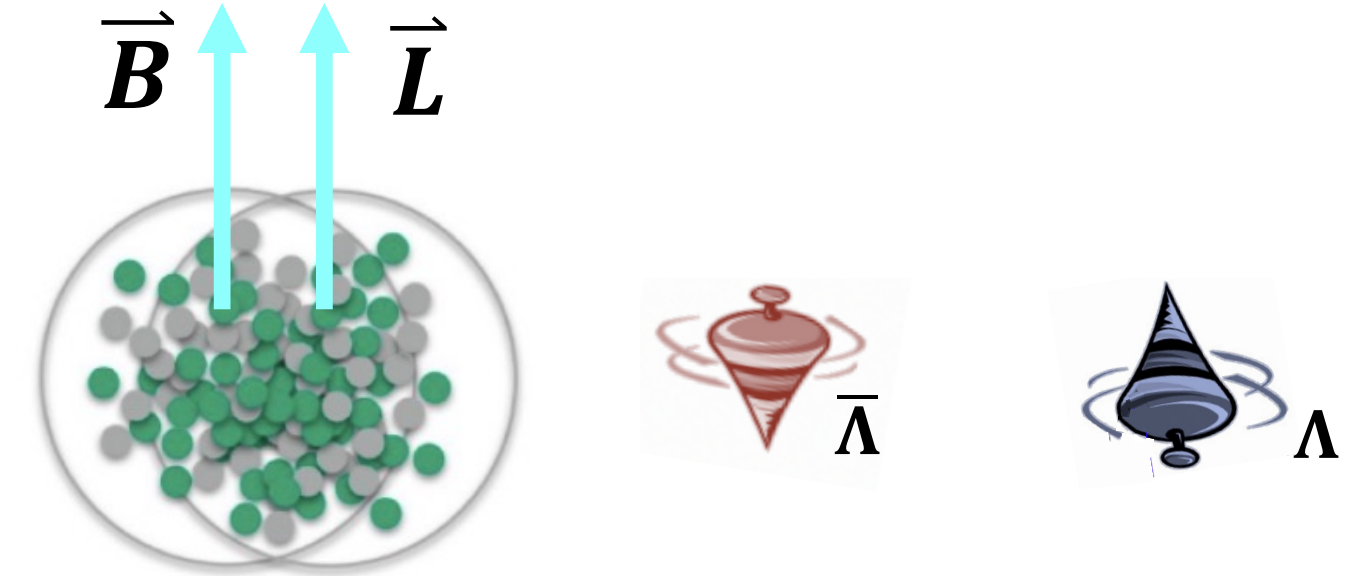
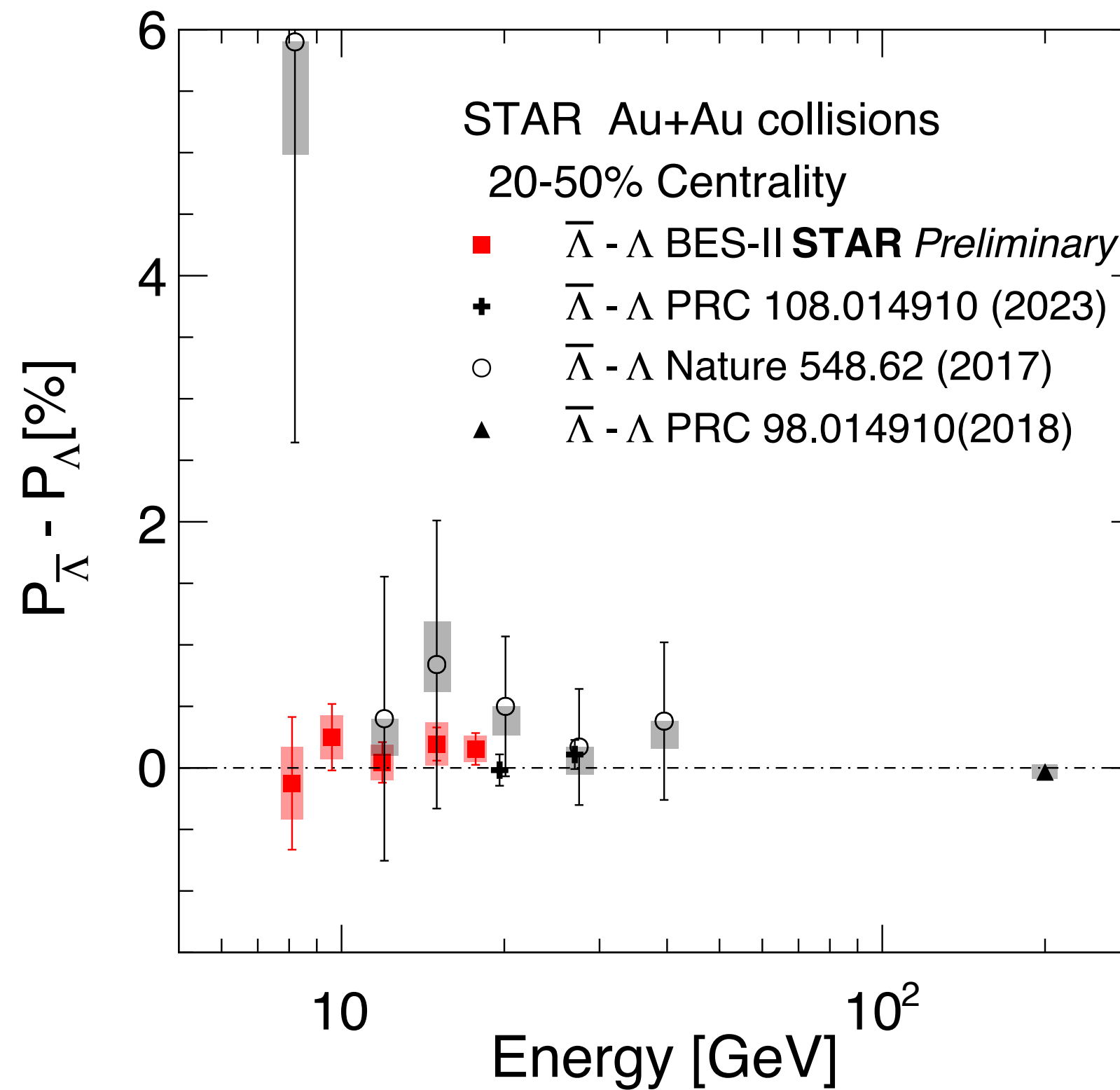
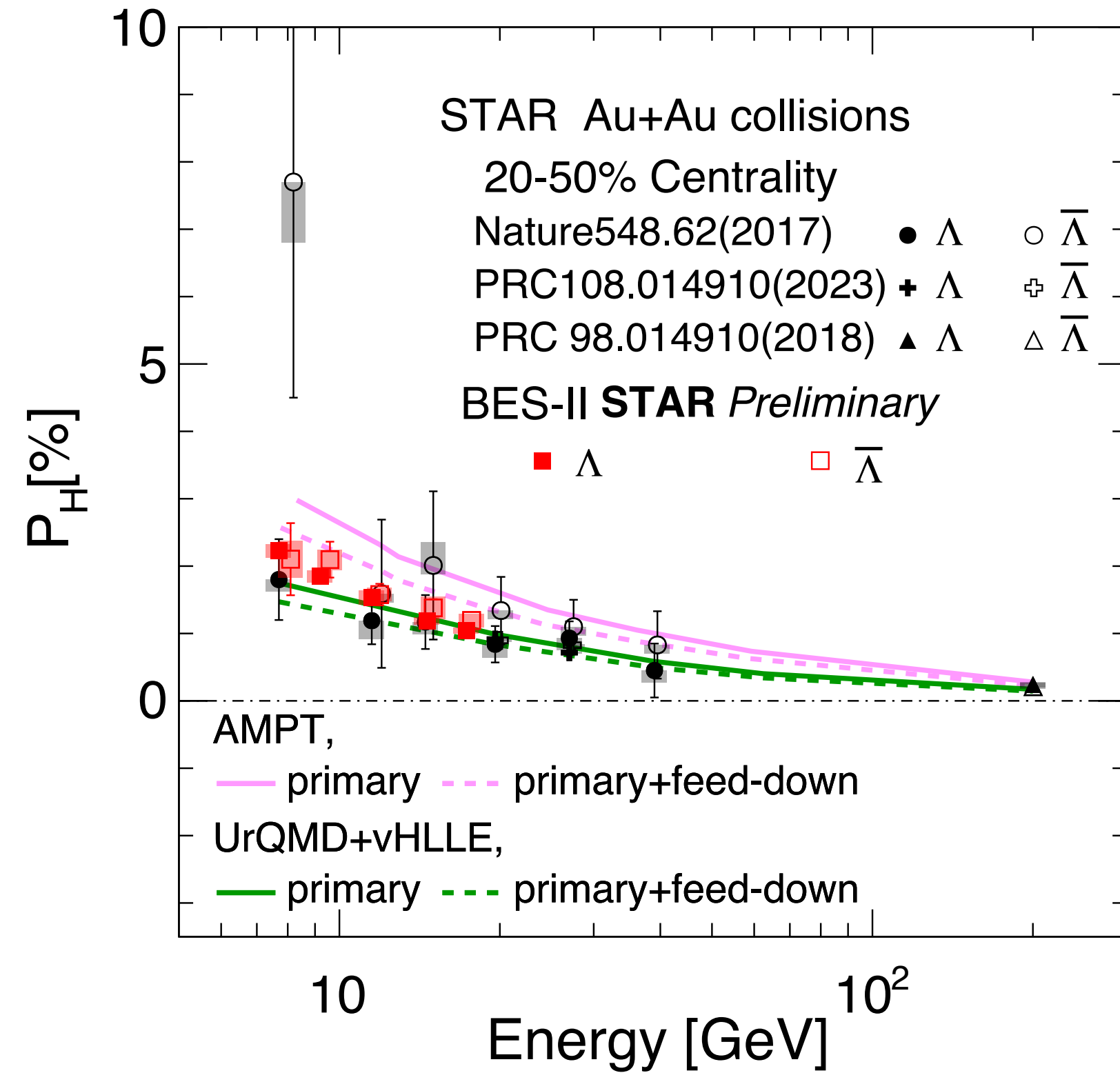


- Better description of v_1 with the tilted source
which accounts for vorticity.

- v_1 slope seems to follow the trend of P_H
-> expect $P_H(\text{LHC}) \sim P_H(\text{RHIC-top})/2$

Λ global polarization at RHIC

Tong Fu (STAR), QM2025



14.6 GeV

$$P_H(\%) = 1.17 \pm 0.40(\text{stat}) \pm 0.27(\text{syst}) \text{ [BES-I]}$$

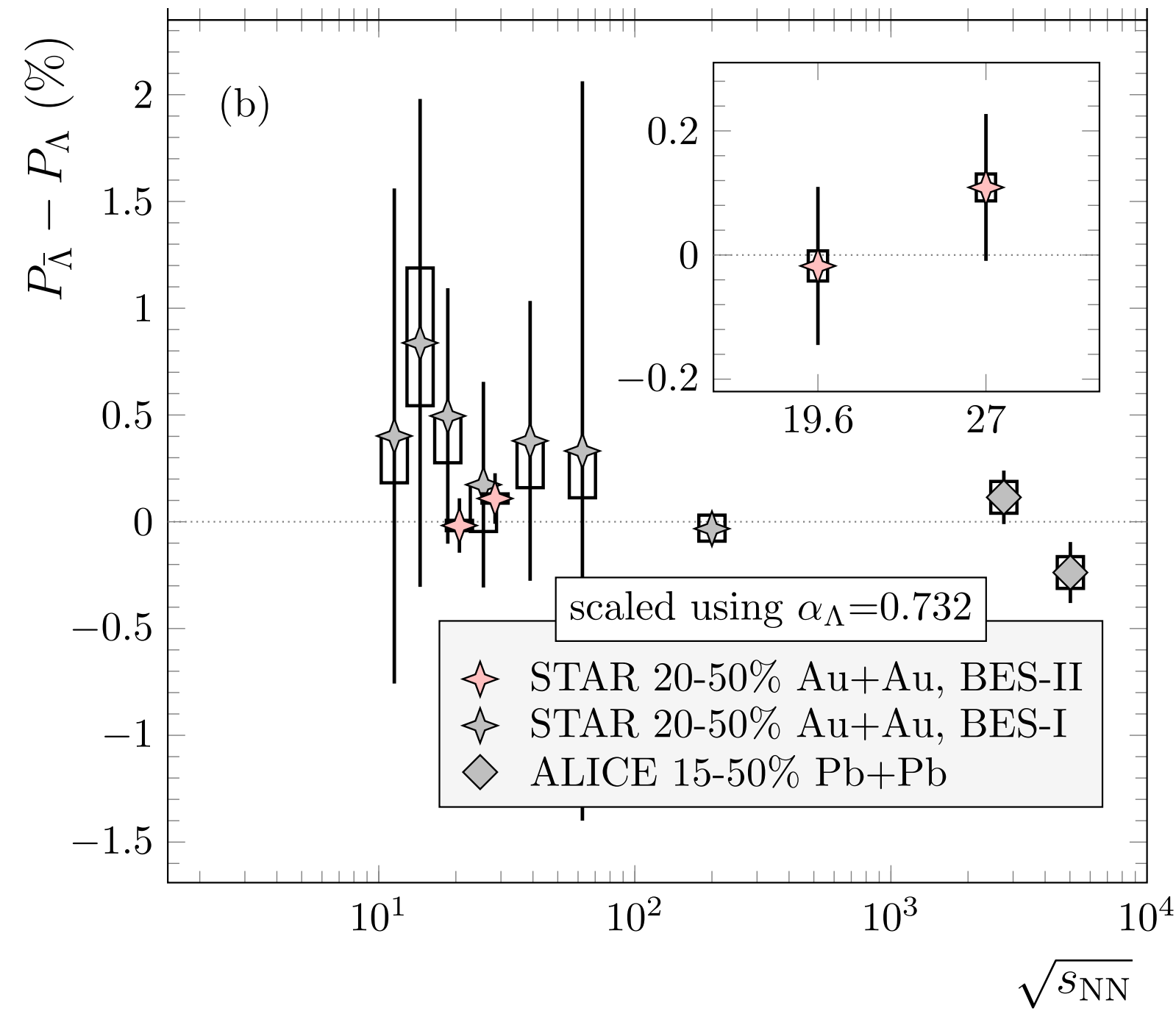
$$P_H(\%) = 1.19 \pm 0.04(\text{stat}) \pm 0.05(\text{syst}) \text{ [BES-II]}$$

- Much improvement with the STAR BES-II data
- No significant difference between Λ and $\bar{\Lambda}$

Upper limit on the late-stage magnetic field



STAR, PRC108, 014910 (2023)



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

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

μ_{Λ} : Λ magnetic moment

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

$$\approx 30 \Delta P_{\Lambda} \times 10^{14} [T]$$

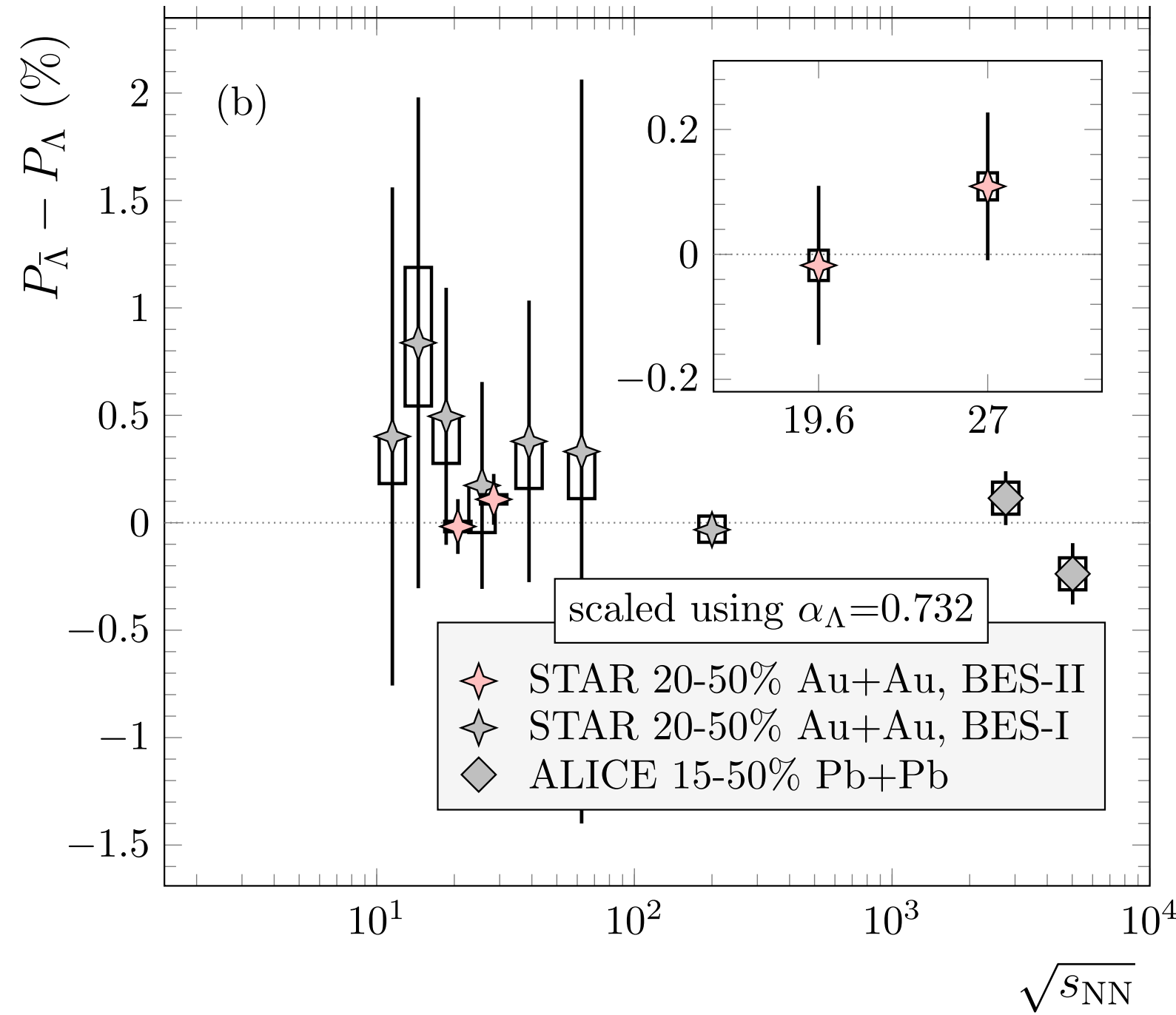
$$eB/m_{\pi}^2 \sim 10 \Delta P_{\Lambda} \quad (T=120 \text{ MeV})$$

B. Muller and A. Schafer, STAR, PRF98, 071902(R) (2018)

Upper limit on the late-stage magnetic field



STAR, PRC108, 014910 (2023)



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

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

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

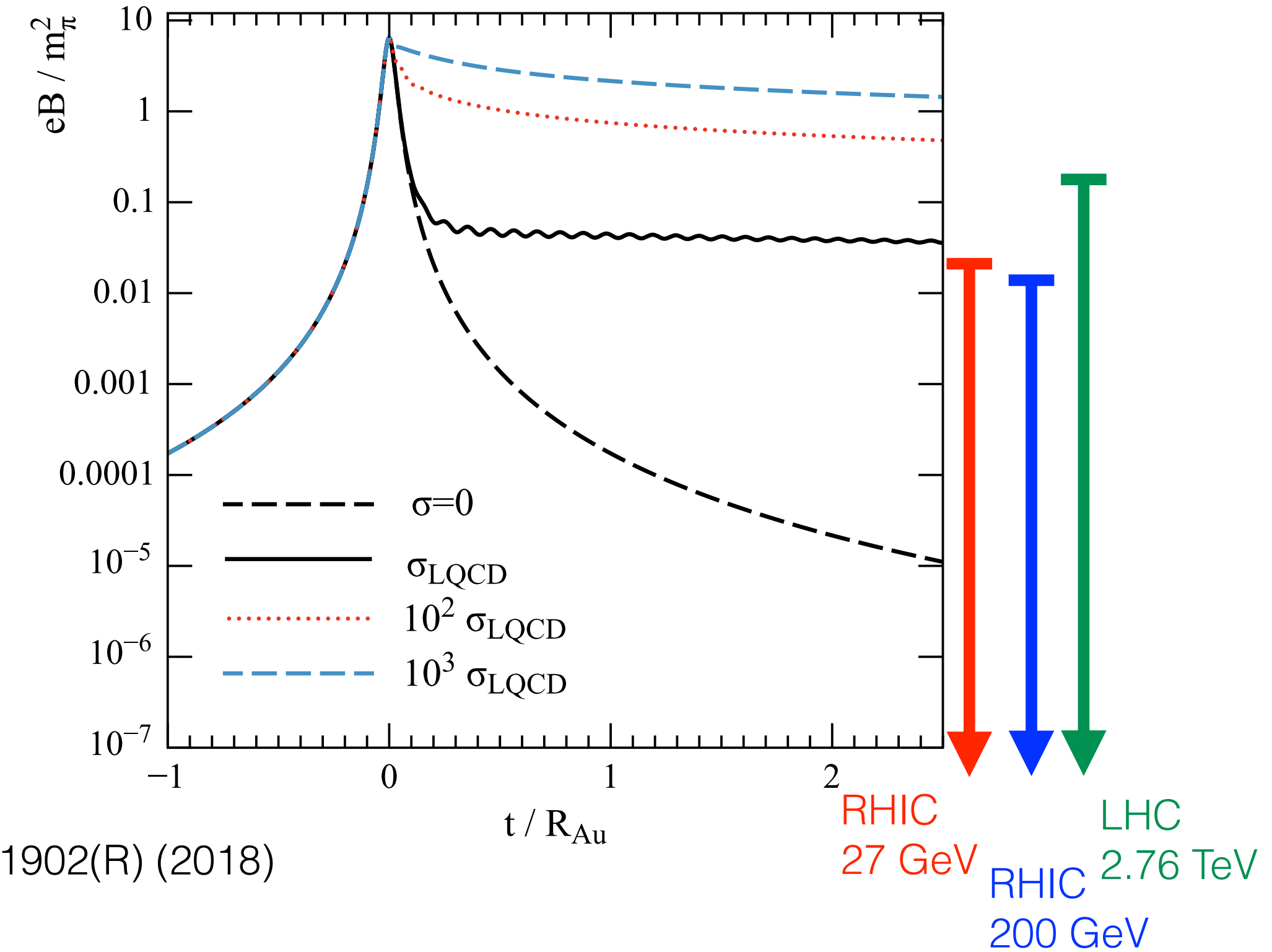
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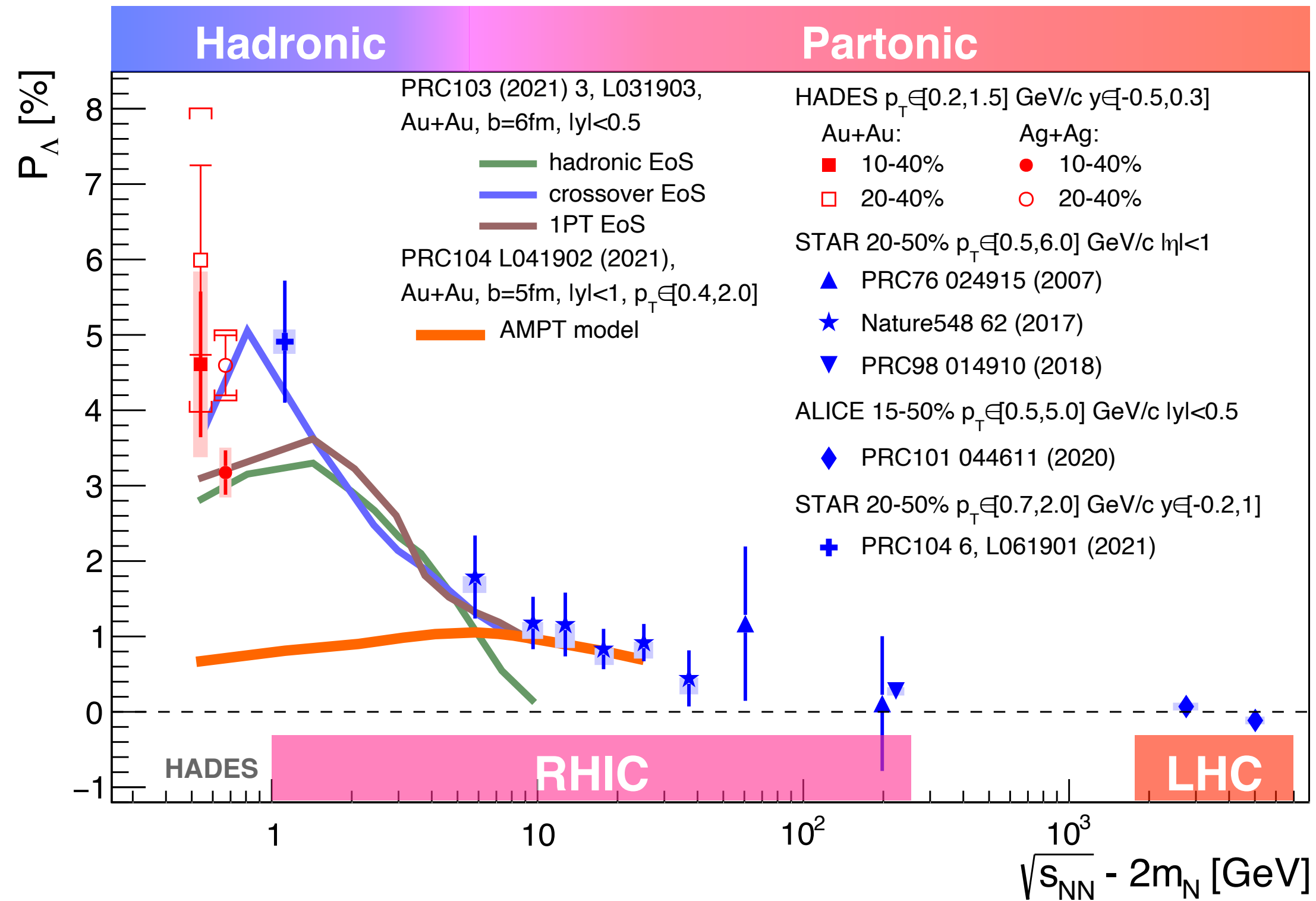
B. Muller and A. Schafer, STAR, PRF98, 071902(R) (2018)



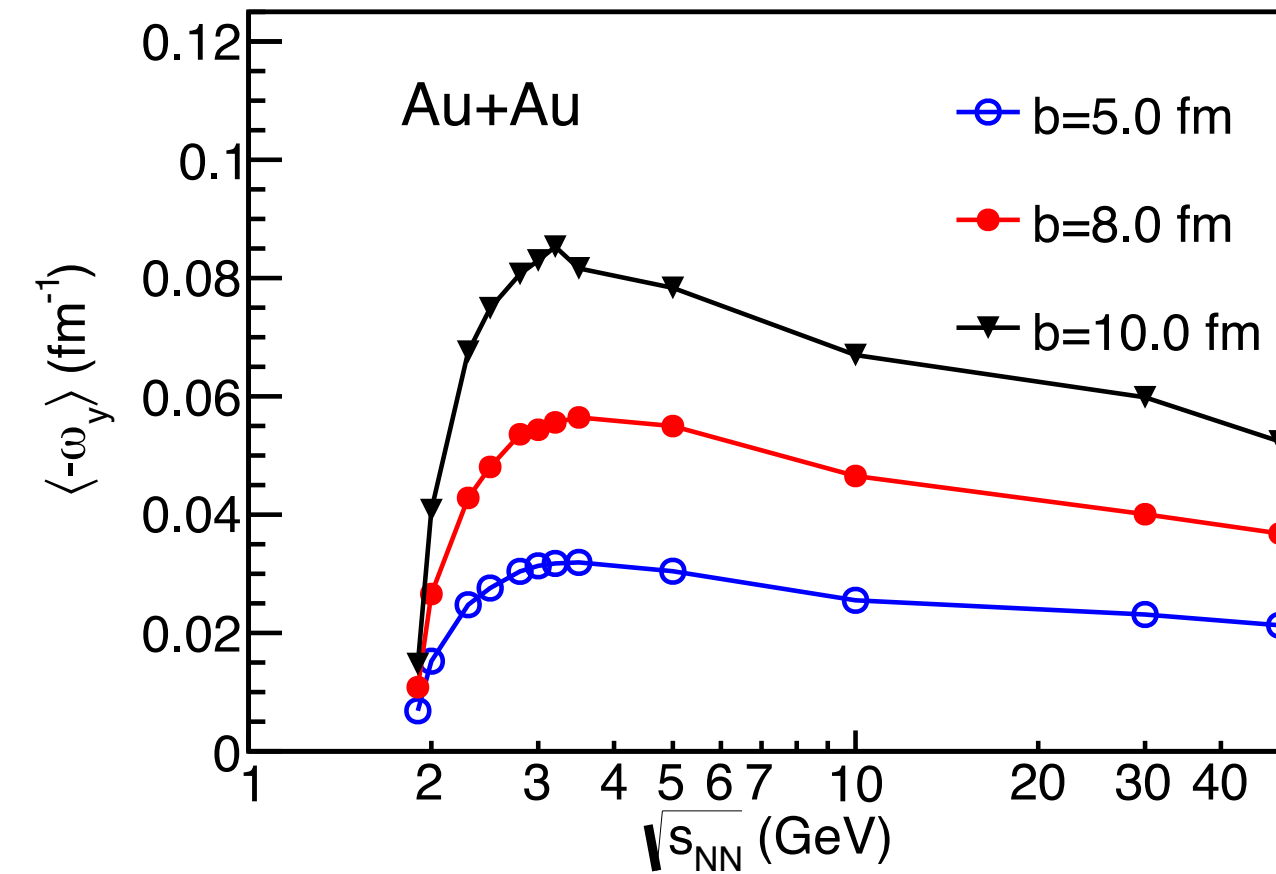
- Taking $\Delta P_{\Lambda} \sim 0.3\%$ (2σ), the upper limit of the late-stage B-field would be $< 10^{13}$ T
- Note: The splitting could be other effects, e.g. finite μ_B and different freeze-out in space-time

Λ global polarization at a few GeV

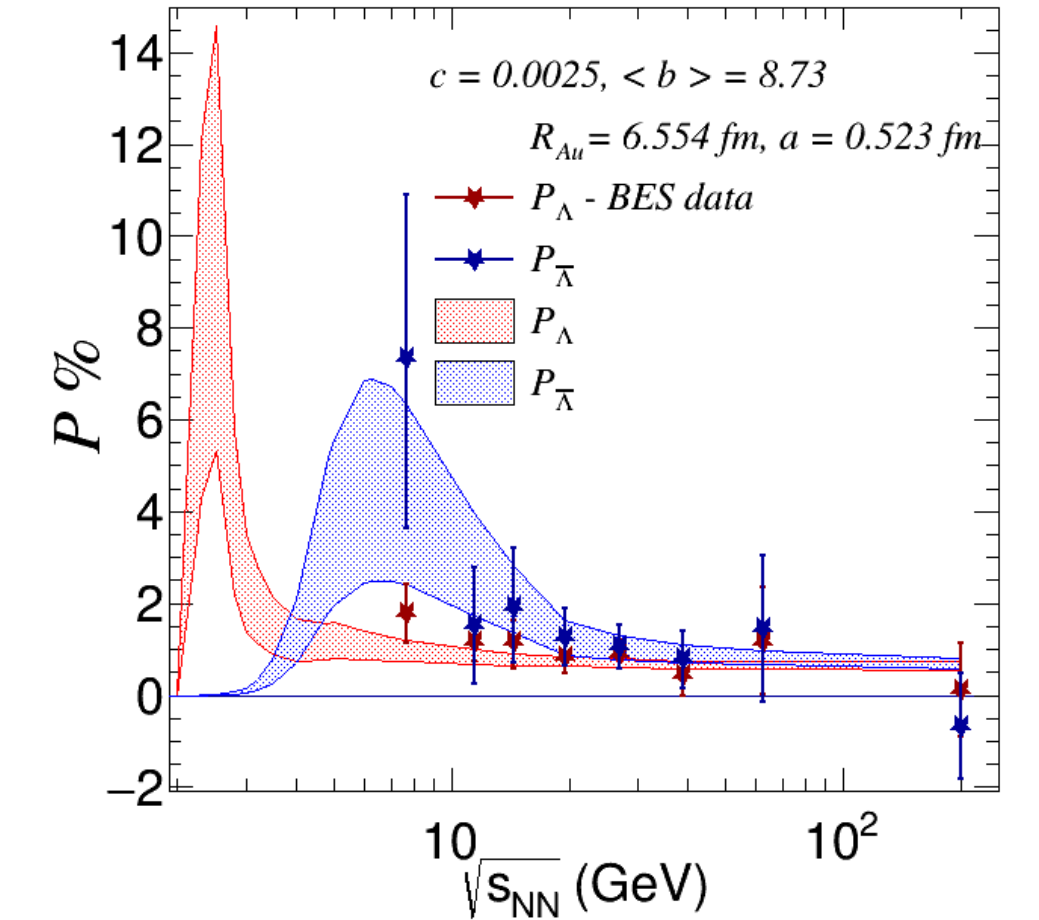
STAR, PRC104, L061901 (2021)
HADES, PLB835(2022)137506



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



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



- Data from STAR/HADES at lower energies
- Continuous increase down to $\sqrt{s_{NN}} \sim 2.5$ GeV
 - Predicted to have the maximum around $\sqrt{s_{NN}} = 3$ GeV
 - Initial L & “stopping” to “transparency” at midrapidity
- To be investigated in future experiments (CBM, H-NS, NICA...)

Feed-down effect

- Only ~25% of measured Λ and anti- Λ are primary, while ~60% are feed-down from $\Sigma^* \rightarrow \Lambda\pi$, $\Sigma^0 \rightarrow \Lambda\gamma$, $\Xi \rightarrow \Lambda\pi$
- Polarization of parent particle R is transferred to its daughter Λ

$$\mathbf{S}_\Lambda^* = C \mathbf{S}_R^*$$

$$\mathbf{S}_\Lambda^{*,\text{meas}} = \sum_R \left[f_{\Lambda R} C_{\Lambda R} - \frac{1}{3} f_{\Sigma^0 R} C_{\Sigma^0 R} \right] \mathbf{S}_R^*.$$

$C_{\Lambda R}$: Spin transfer coefficient in $R \rightarrow \Lambda$ decay

$\mathbf{S}_R$: Parent particle R's spin

$f_{\Lambda R}$: Fraction of Λ originating from parent R

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

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

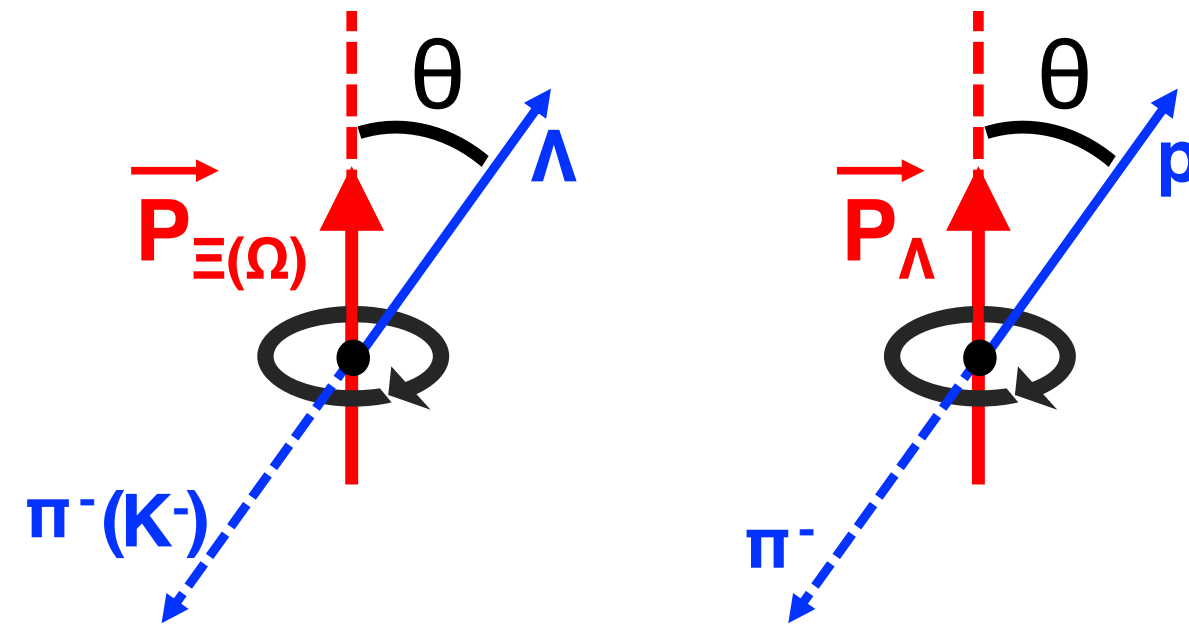
- 15%-20% dilution of primary Λ polarization (model-dependent)
- Polarization of daughter particles can be used to study their parent's polarization! e.g. Ξ and Ω

TABLE I. Polarization transfer factors C (see eq. (36)) for important decays $X \rightarrow \Lambda(\Sigma)\pi$

Multistrange hyperons: Ξ and Ω

- ▶ One can extend measurements to Ξ and Ω hyperons
- ▶ Challenging due to smaller $|\alpha_H|$ and low production rate...

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

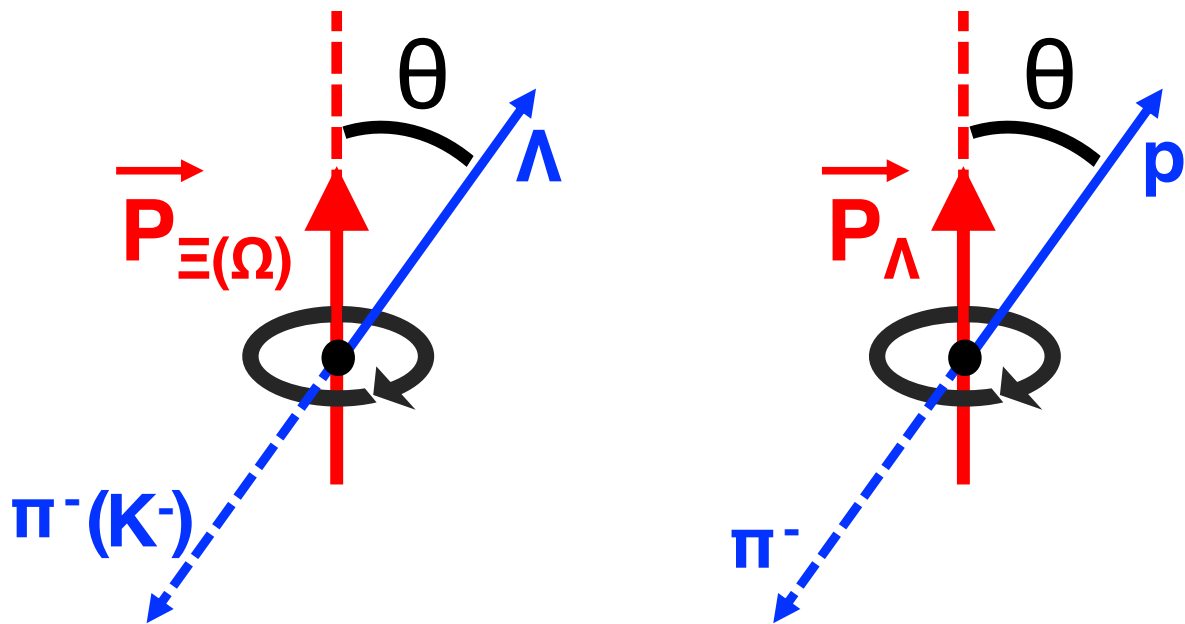


hyperon	decay mode	α_H	magnetic moment μ_H	spin
Λ (uds)	$\Lambda \rightarrow p\pi^-$ (BR: 63.9%)	0.732	-0.613	1/2
Ξ^- (dss)	$\Xi^- \rightarrow \Lambda\pi^-$ (BR: 99.9%)	-0.401	-0.6507	1/2
Ω^- (sss)	$\Omega^- \rightarrow \Lambda K^-$ (BR: 67.8%)	0.0157	-2.02	3/2

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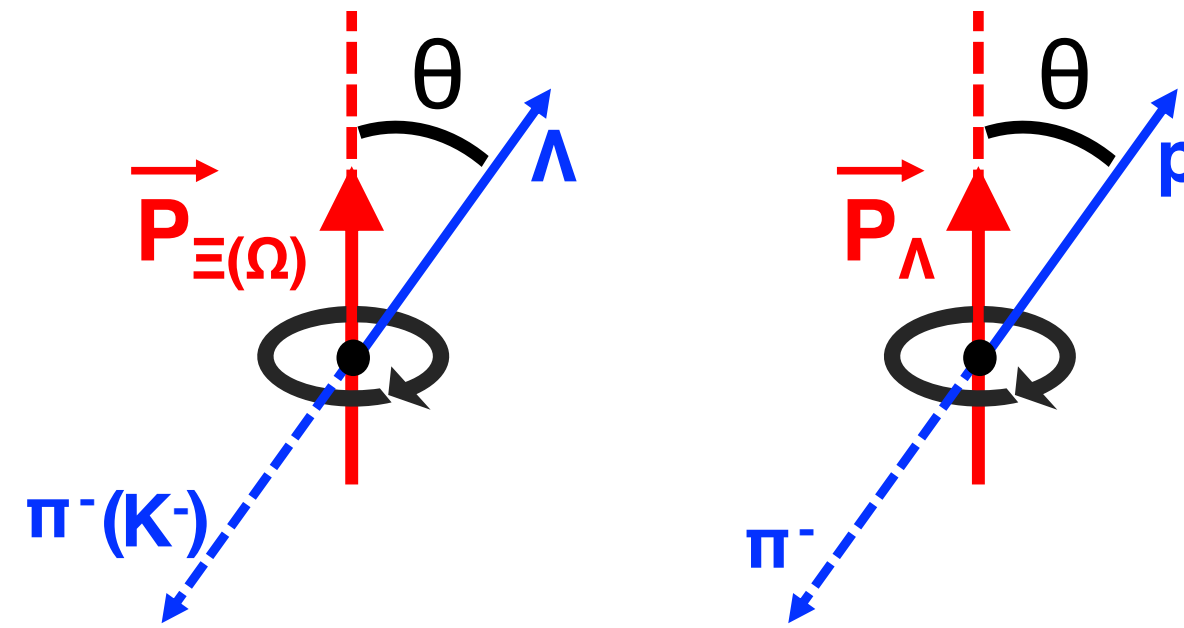


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- Polarization of daughter Λ in Ξ ($s=1/2$) $\rightarrow \Lambda$ decay

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

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

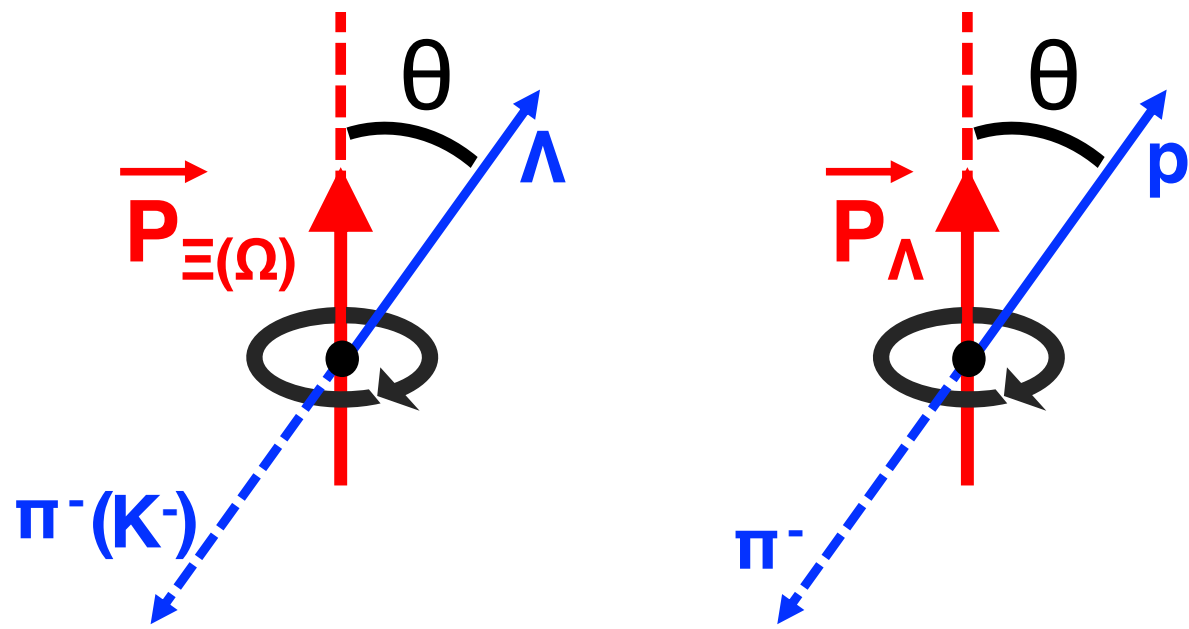
$$\mathbf{P}_\Lambda^* = C_{\Xi-\Lambda} \mathbf{P}_\Xi^* = \frac{1}{3} (1 + 2\gamma_\Xi) \mathbf{P}_\Xi^*. \quad \alpha^2 + \beta^2 + \gamma^2 = 1$$

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

Multistrange hyperons: Ξ and Ω

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

- Similarly, daughter Λ polarization from Ω ($s=3/2$)

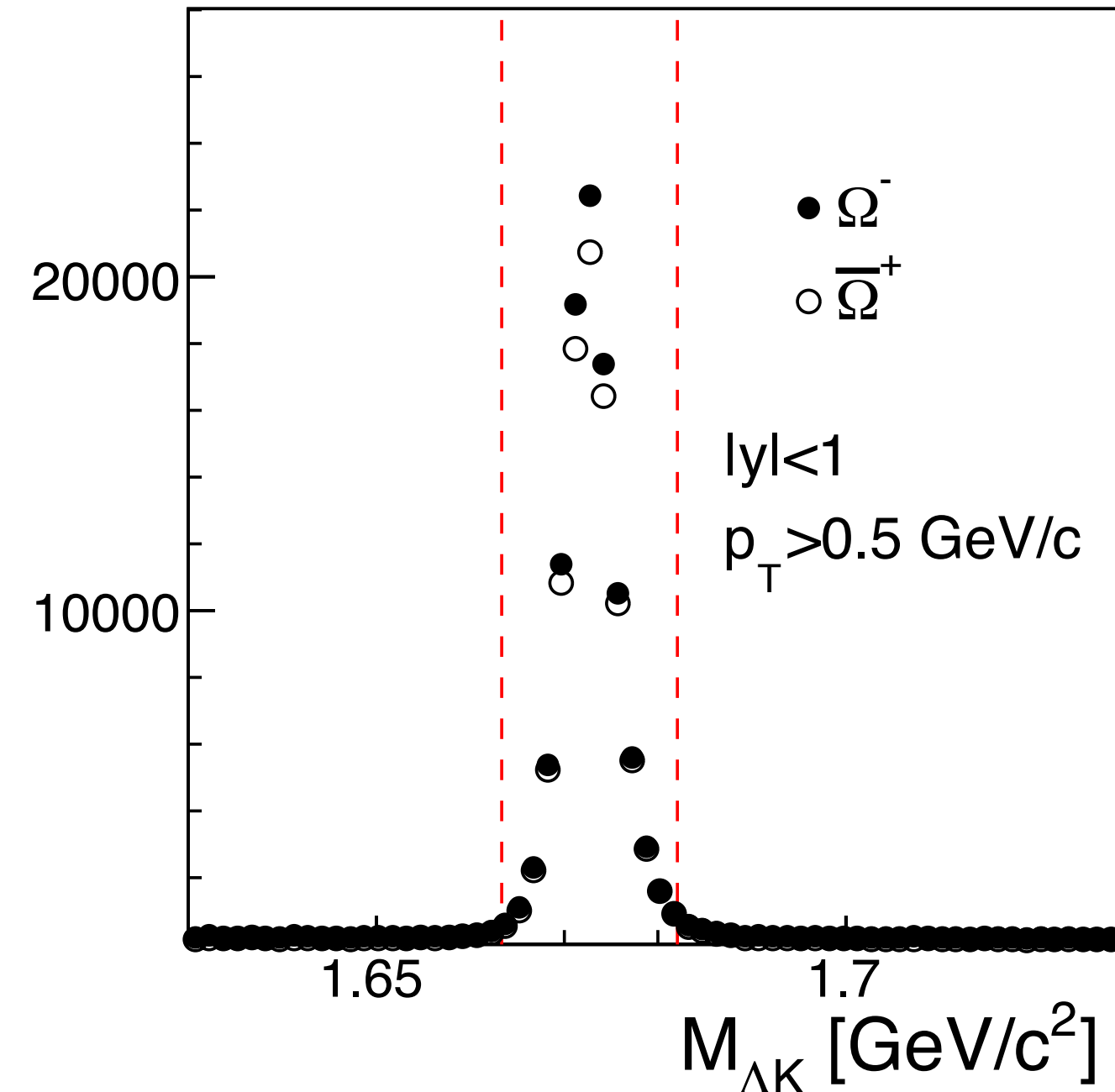
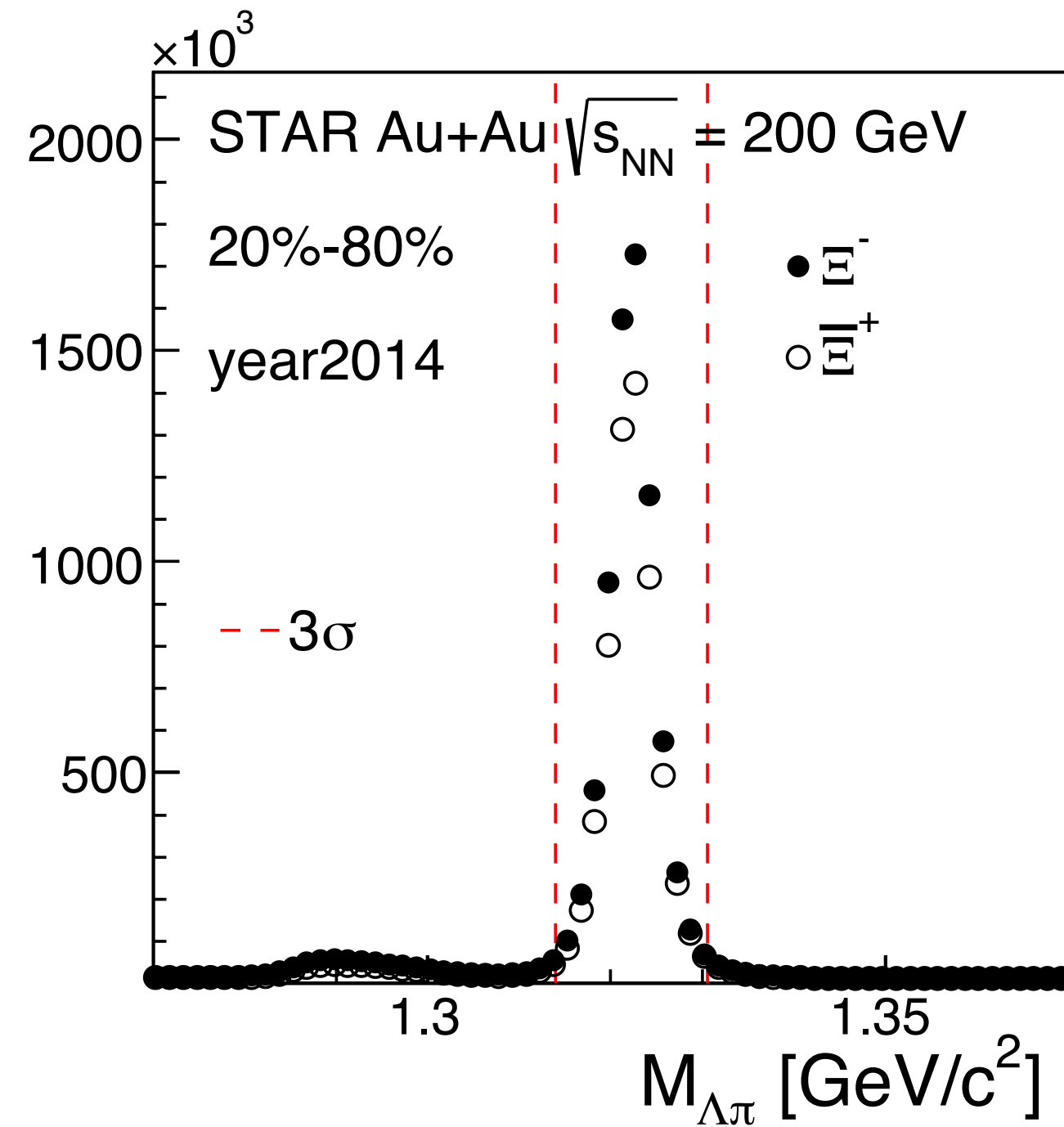
$$\mathbf{P}_\Lambda^* = C_{\Omega-\Lambda} \mathbf{P}_\Omega^* = \frac{1}{5} (1 + 4\gamma_\Omega) \mathbf{P}_\Omega^*.$$

Here γ_Ω is unknown.

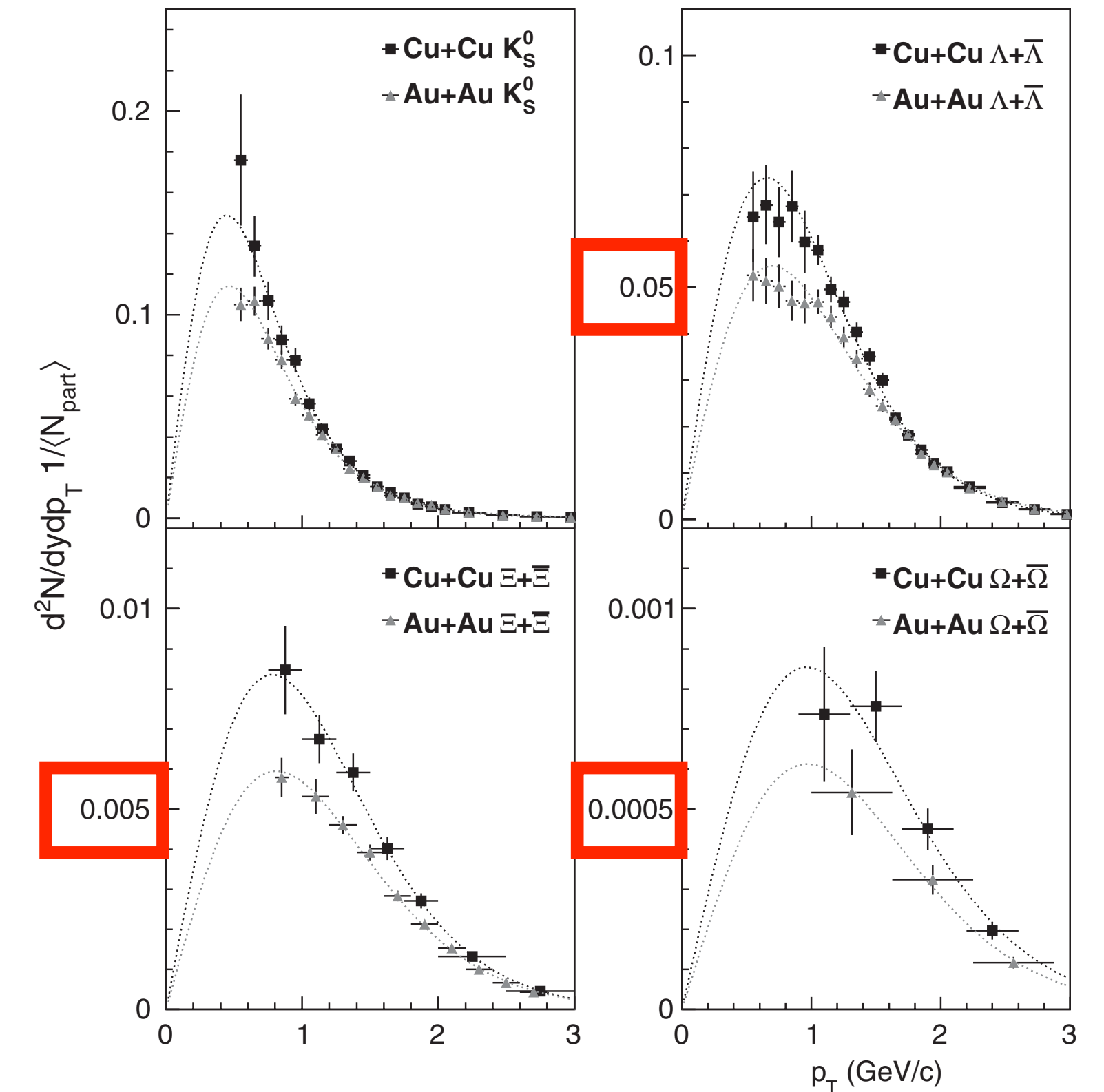
Considering $\alpha_\Omega, \beta_\Omega \ll 1, \gamma_\Omega \sim \pm 1$, the polarization transfer $C_{\Omega\Lambda}$ leads to: $C_{\Omega\Lambda} \approx +1$ or -0.6

Identification of Ξ and Ω hyperons

STAR, PRL126, 162301 (2021)



STAR, PRL108.072301(2012)



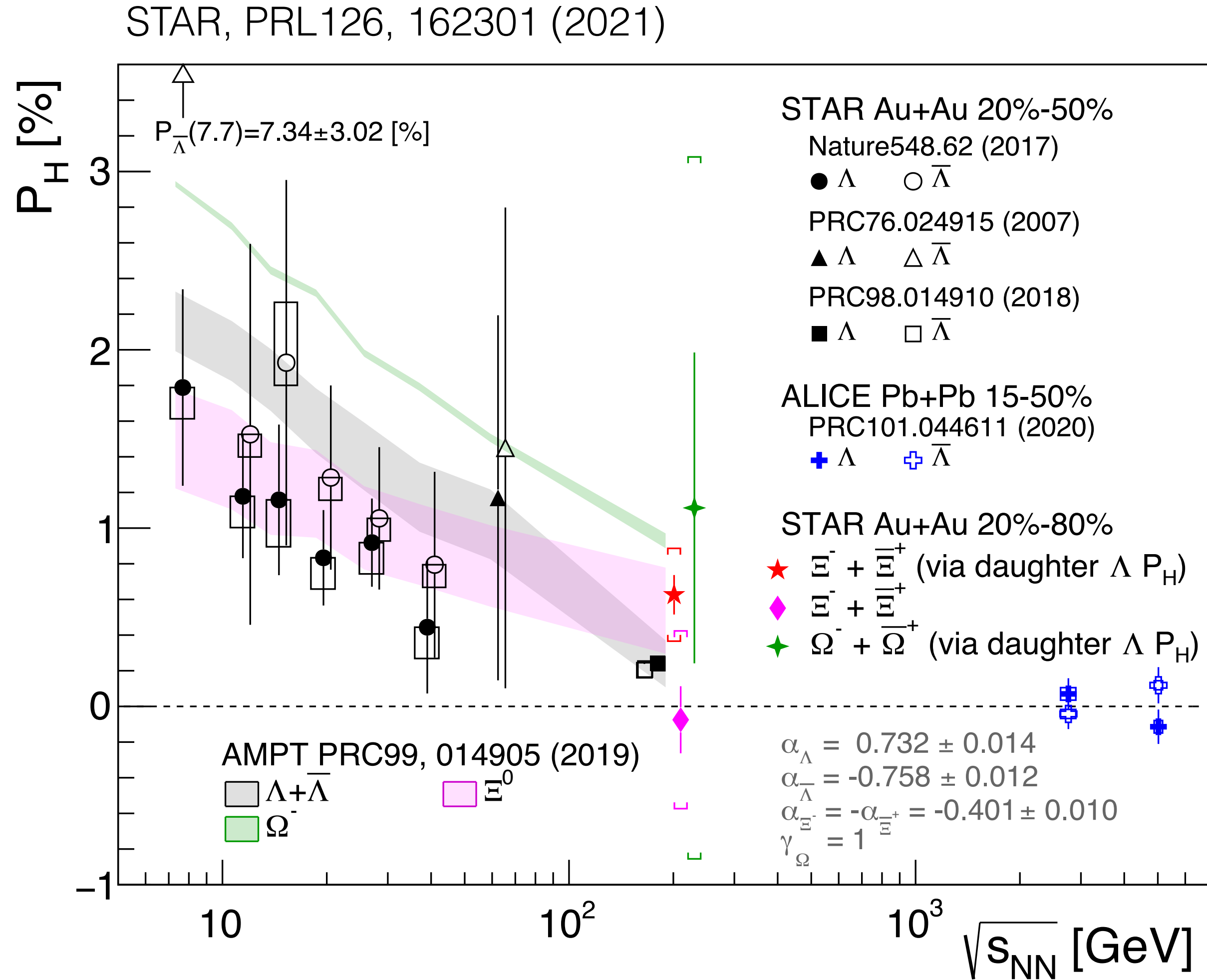
KF Particle:

I. Kisel, JPCS1070.012015 (2018)

S. Gorbunov, M. Zyzak, Ph.D. theses

Very good purity and significance of Ξ and Ω hyperons with KF Particle Finder package.
But still statistically very challenging, i.e. Ξ (Ω) yield $\sim 1/10$ ($1/100$) of Λ yield

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



► Hint of hierarchy in P_H : $P_{\Lambda} < P_{\Xi} < P_{\Omega}$

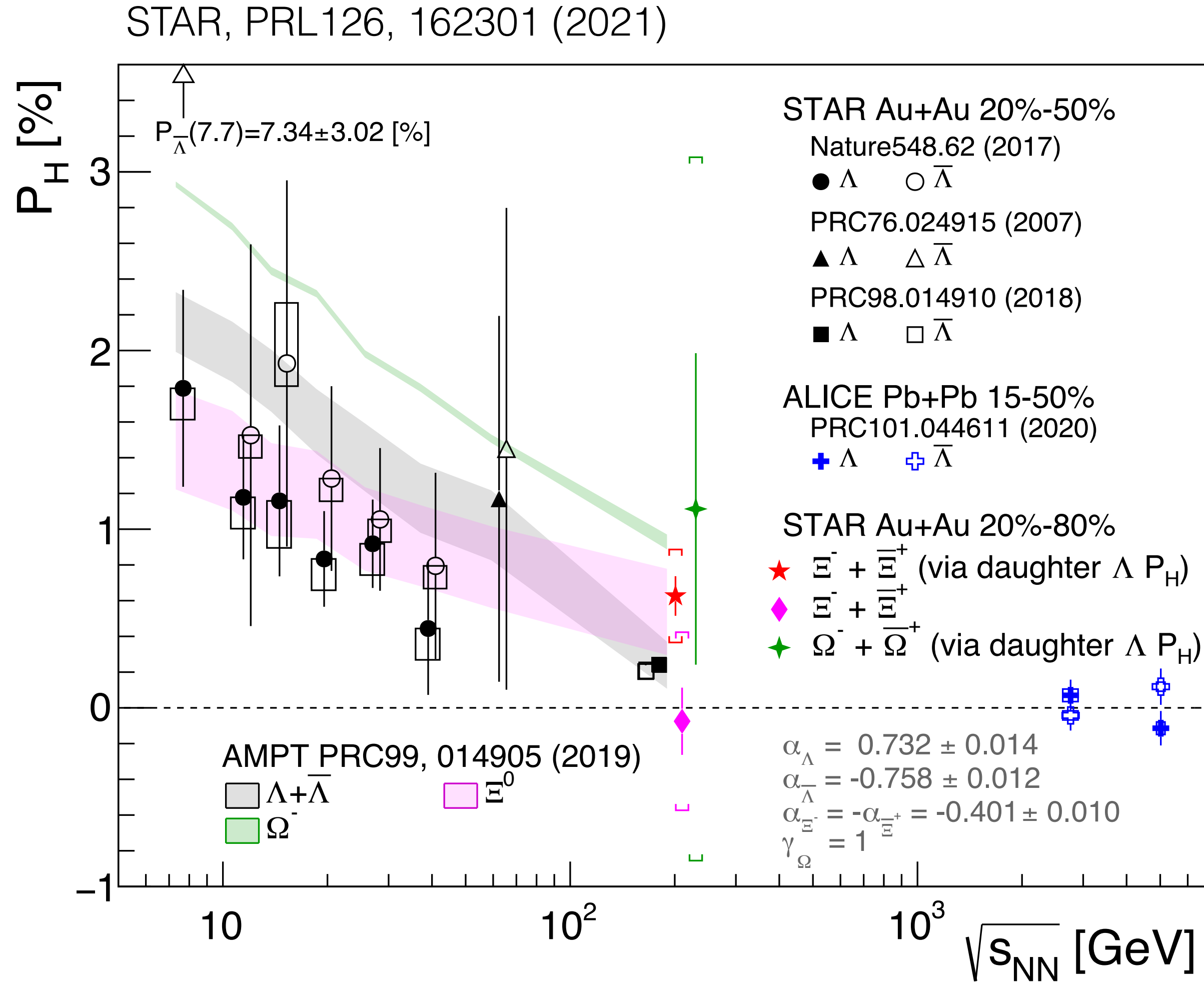
$$\langle P_{\Lambda} \rangle = 0.24 \pm 0.03 \text{ (stat)} \pm 0.03 \text{ (syst)} \%$$

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

$$\langle P_{\Omega} \rangle = 1.11 \pm 0.87 \text{ (stat)} \pm 1.97 \text{ (syst)} \%$$

* combined Ξ P_H from the two methods

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$$\langle P_{\Omega} \rangle = 1.11 \pm 0.87 \text{ (stat)} \pm 1.97 \text{ (syst)} \%$$

* combined Ξ P_H from the two methods

- Thermal model predicts: $P_{\Xi} = P_{\Lambda}$, $P_{\Omega} = \frac{5}{3} P_{\Lambda}$

$$\mathbf{P} = \frac{\langle \mathbf{s} \rangle}{s} \approx \frac{(s+1)}{3} \frac{\omega}{T} \quad \text{F. Becattini et al., PRC95.054902 (2017)}$$

- Earlier freeze-out leads to larger P_H

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

- Models including feed-down capture the trend

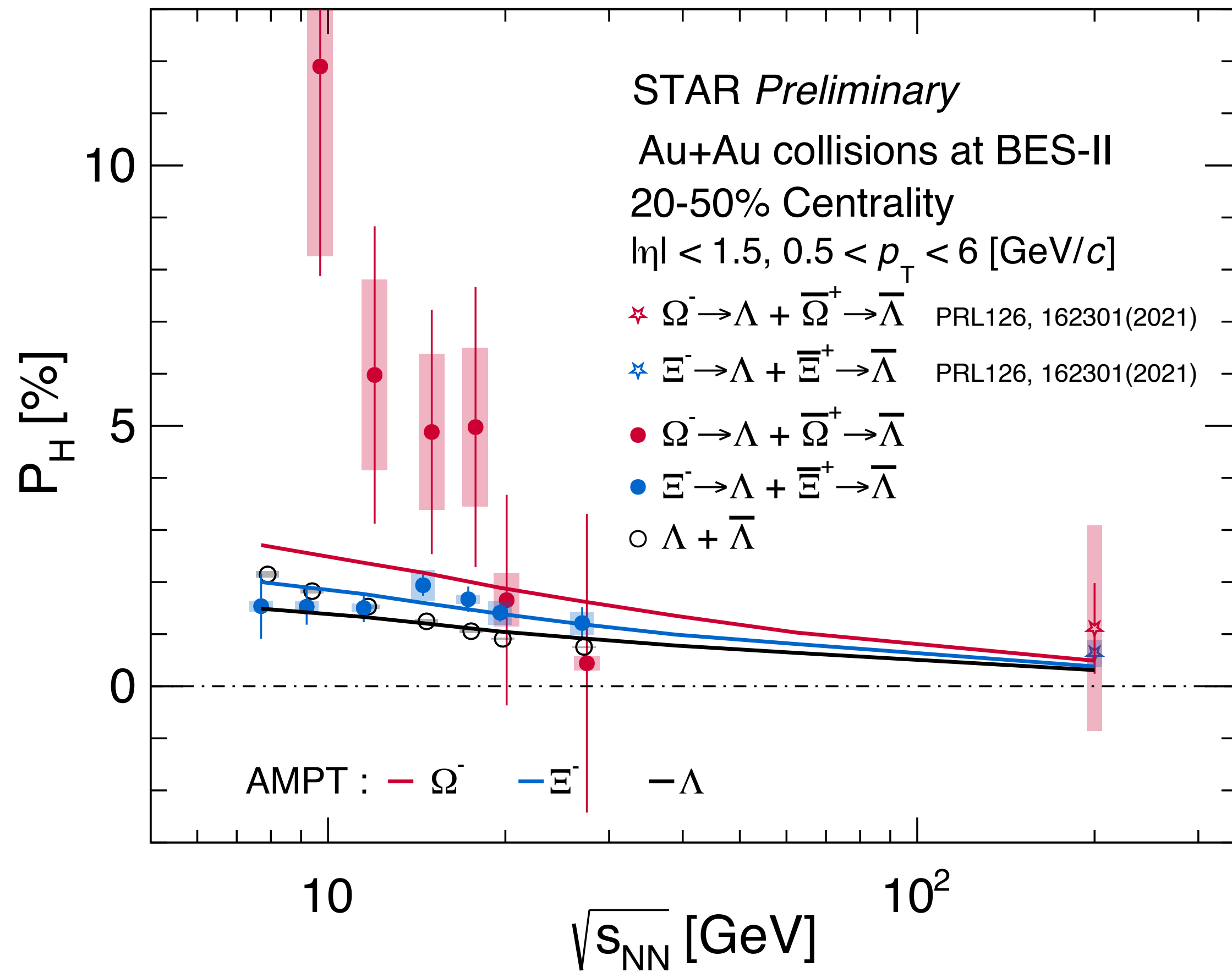
D.-X. Wei, W.-T. Deng, and X.-G. Huang, PRC99.014905 (2019)

B. Fu et al., PRC103.024903 (2021)

H. Li et al., PLB827(2022)136971

Ξ and Ω global polarizations from BES-II

X. Gou (STAR), QM2025



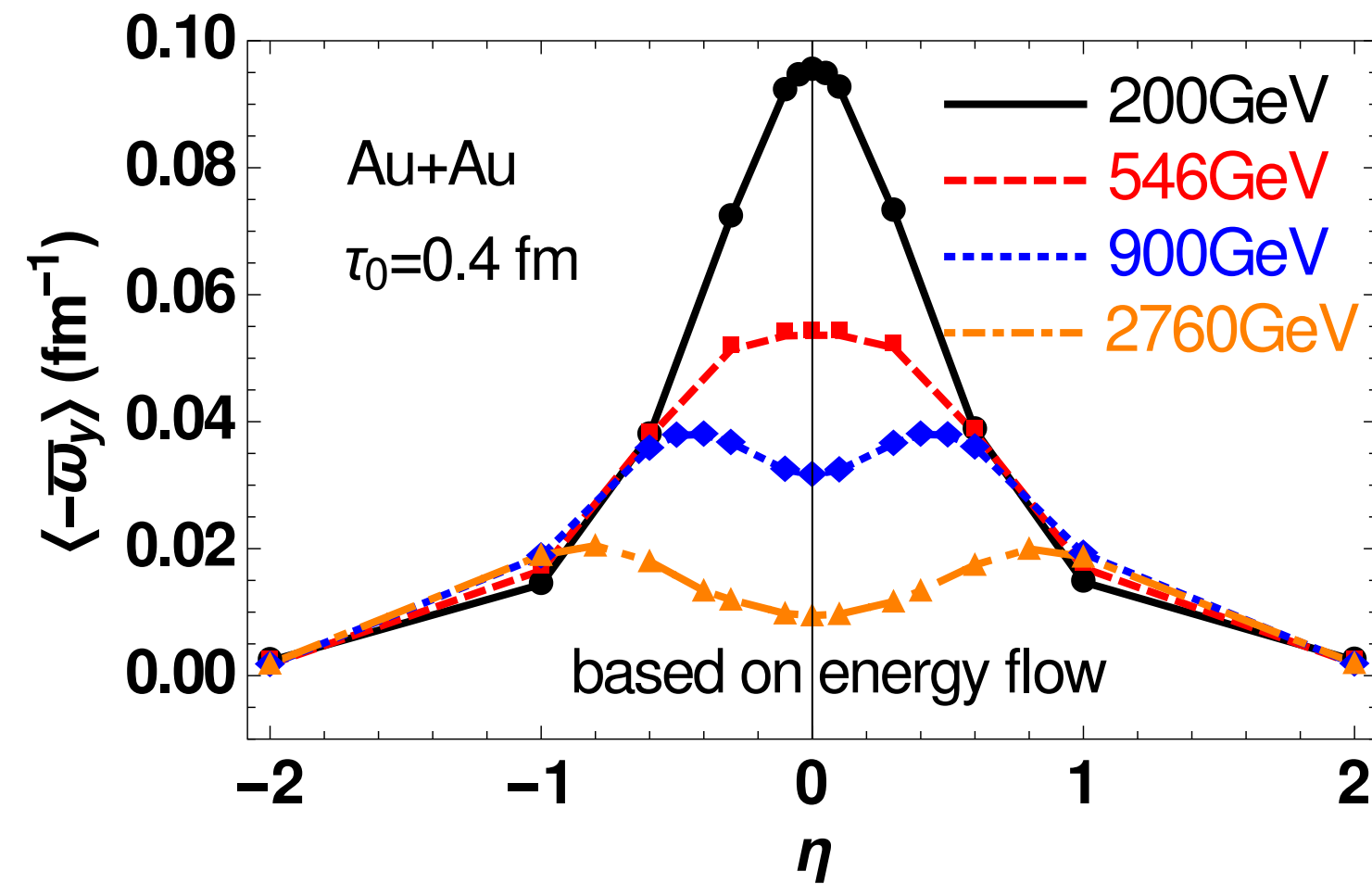
- ▶ Better significance of P_Ξ ($\sim 5\sigma$) from STAR BES-II
- ▶ Positive P_Ω with a hint of larger value than Λ & Ξ

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

- ▶ Based on the global vorticity picture, the unmeasured γ_Ω ($\gamma_\Omega = +1$ or -1) can be constrained
 $\gamma_\Omega = +1$ or $-1 \rightarrow C_{\Omega\Lambda} = 1$ or -0.6

Rapidity dependence?

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



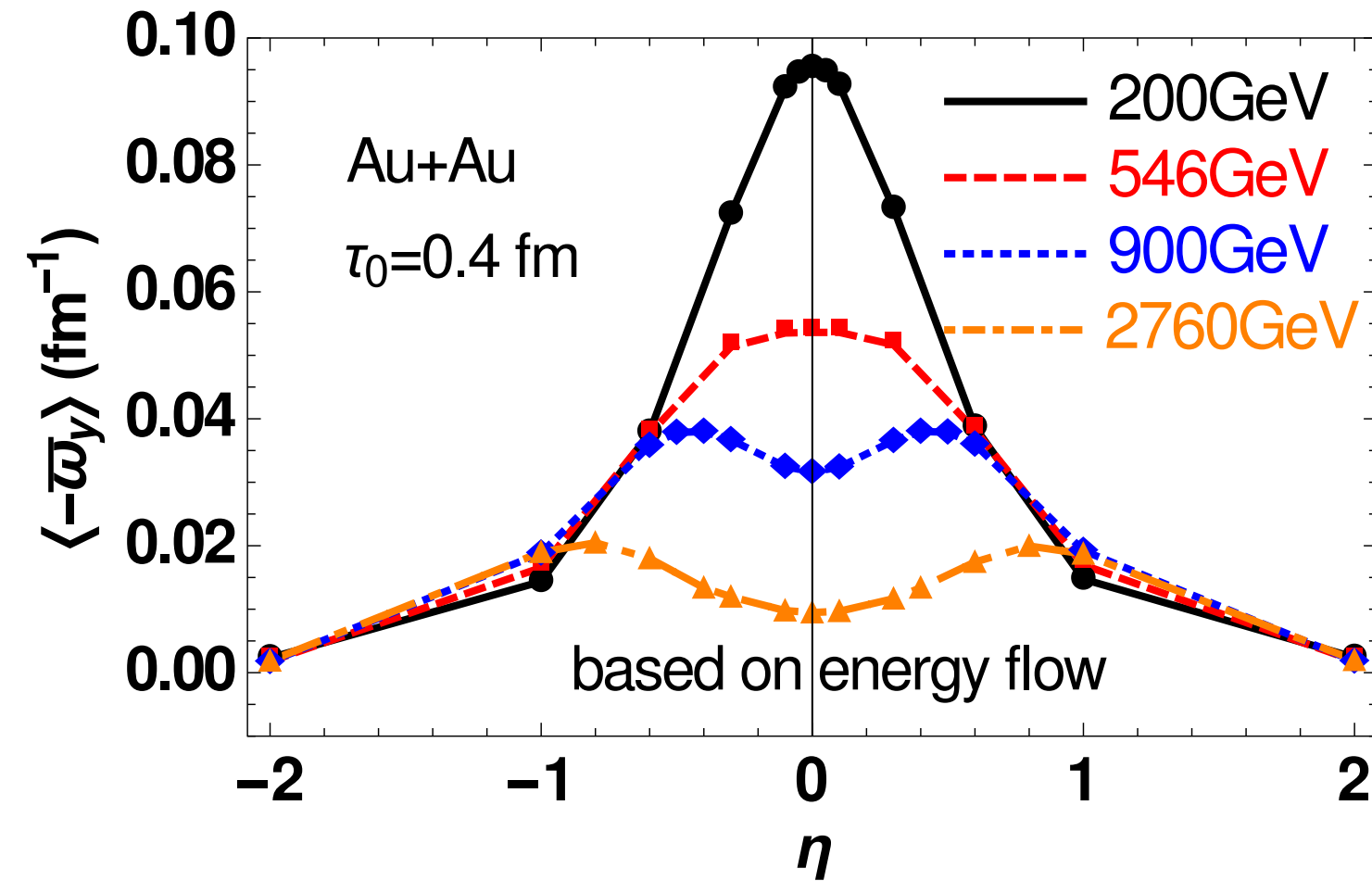
Energy dependence of vorticity vs. rapidity

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

But the predicted polarization trend differs among models

Rapidity dependence?

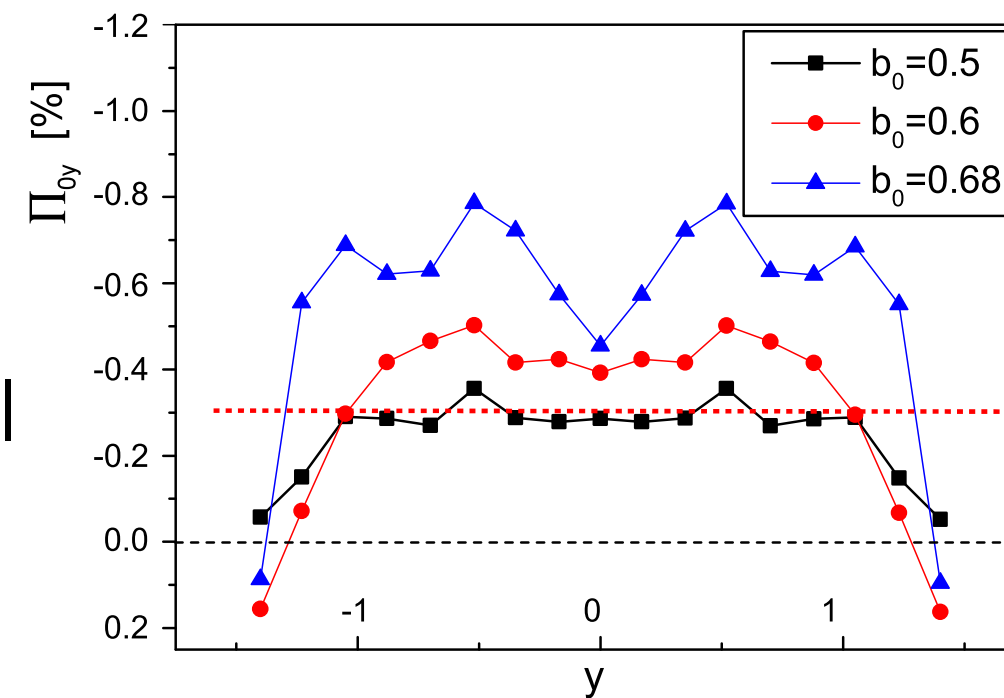
W.T.Feng and X.G.Huang, PRC93.064907 (2016)



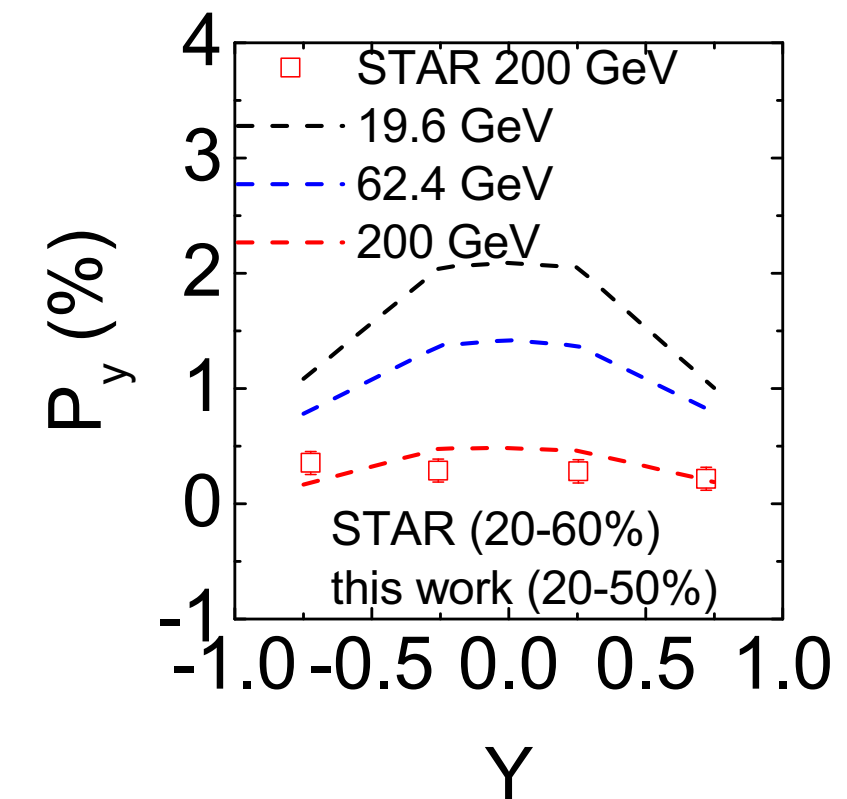
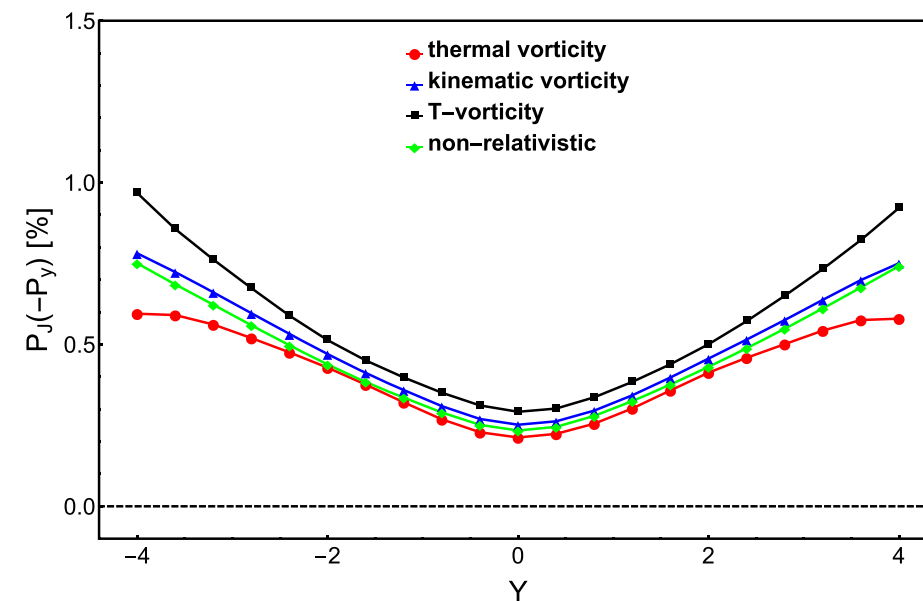
PICR model

Energy dependence of vorticity vs. rapidity
- Baryon stopping and velocity profile in the initial state at given acceptance

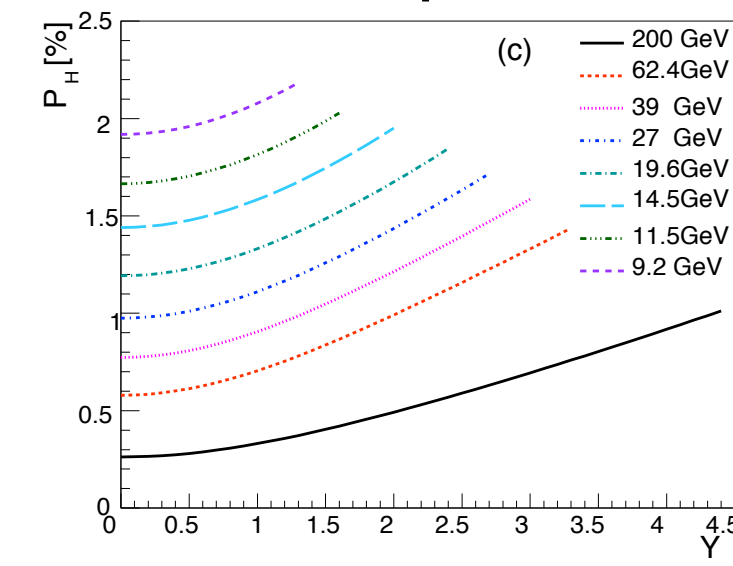
But the predicted polarization trend differs among models



CLVisc



AMPT



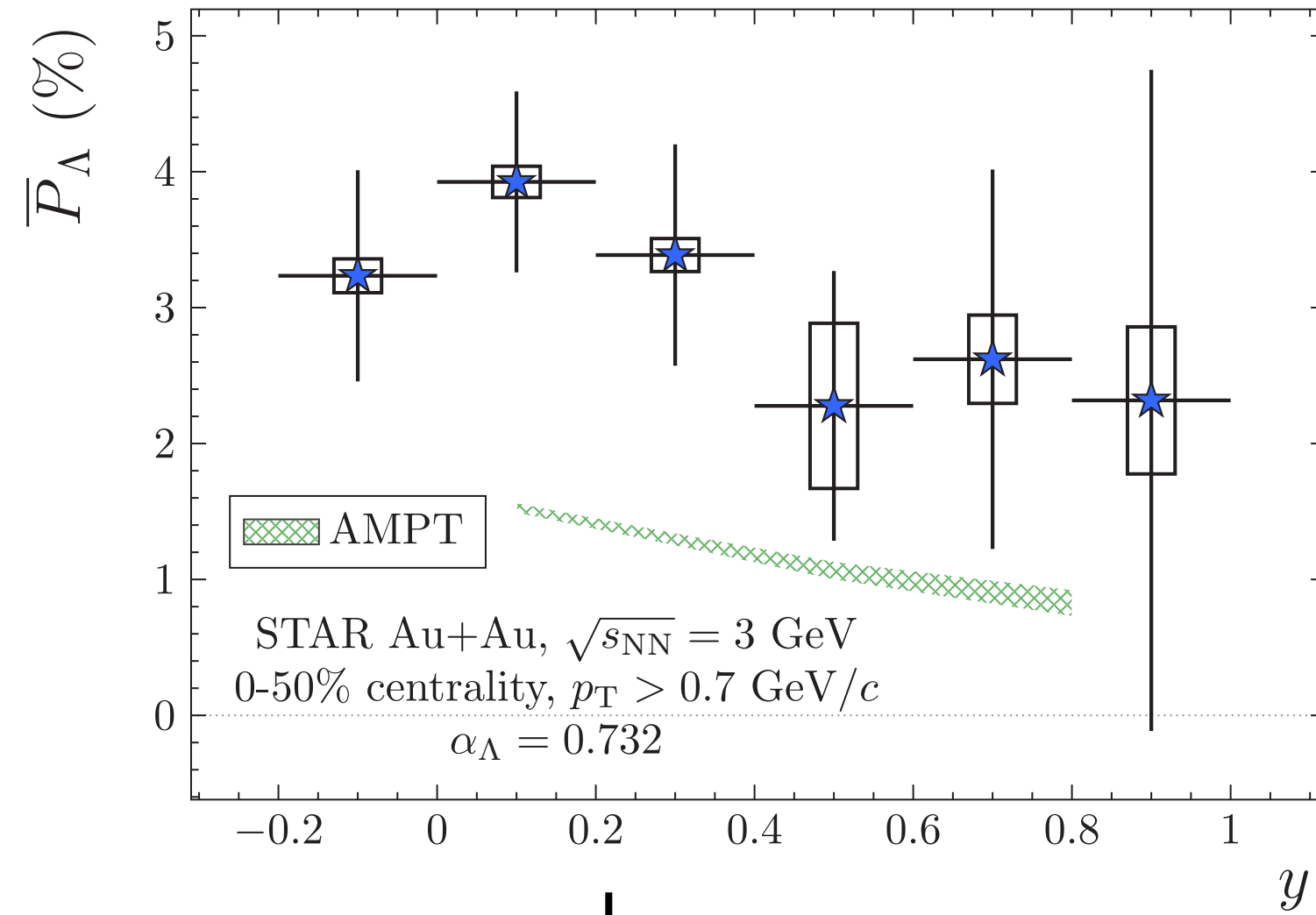
Geometrical model

Y.Xie, D.Wang, and L.P.Csernai, RPJ(2020)80:39
H.Z.Wu et al, PRRResearch1.033058(2019)

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

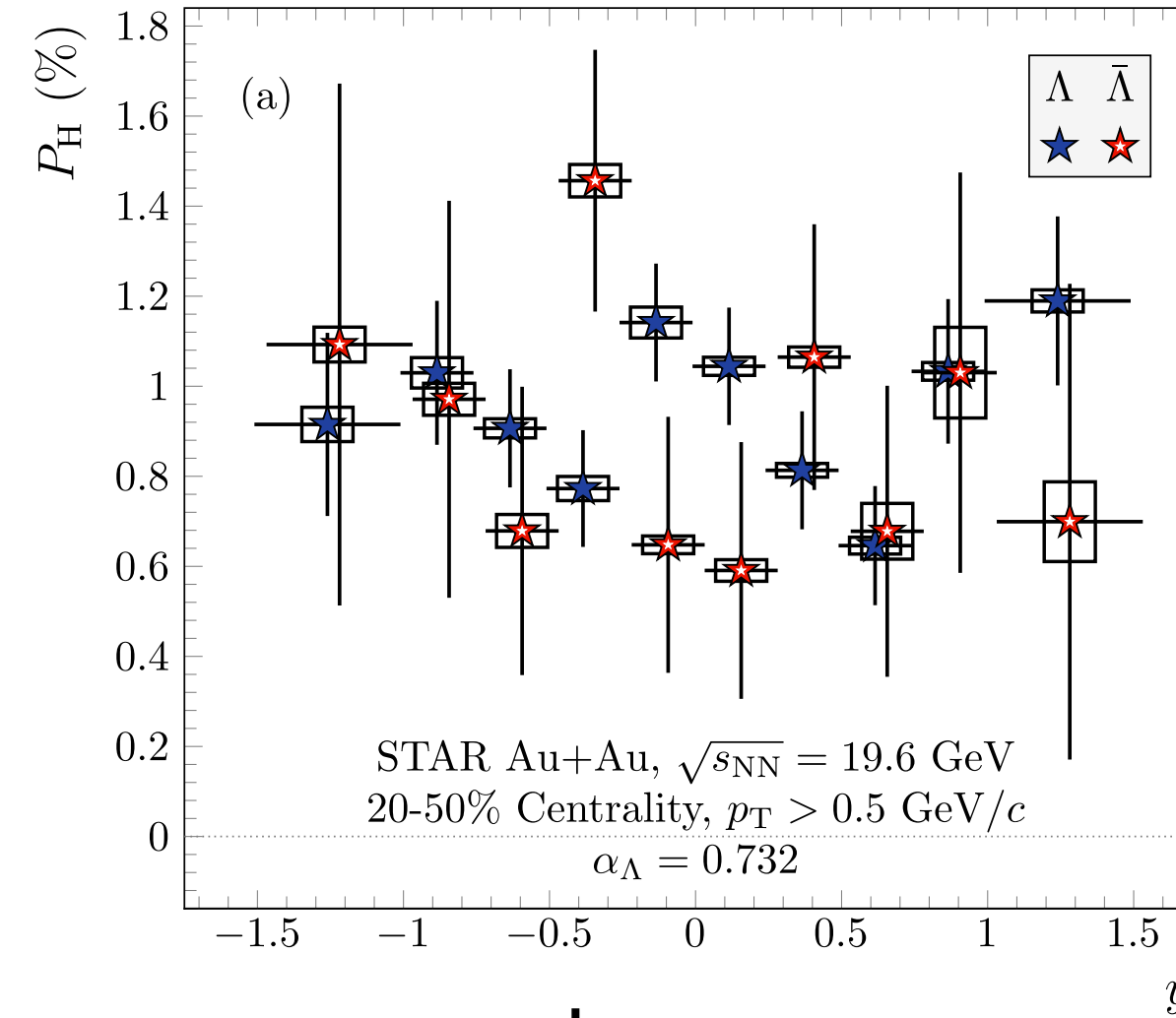
Rapidity dependence of P_J

STAR, PRC104, L061901 (2021)



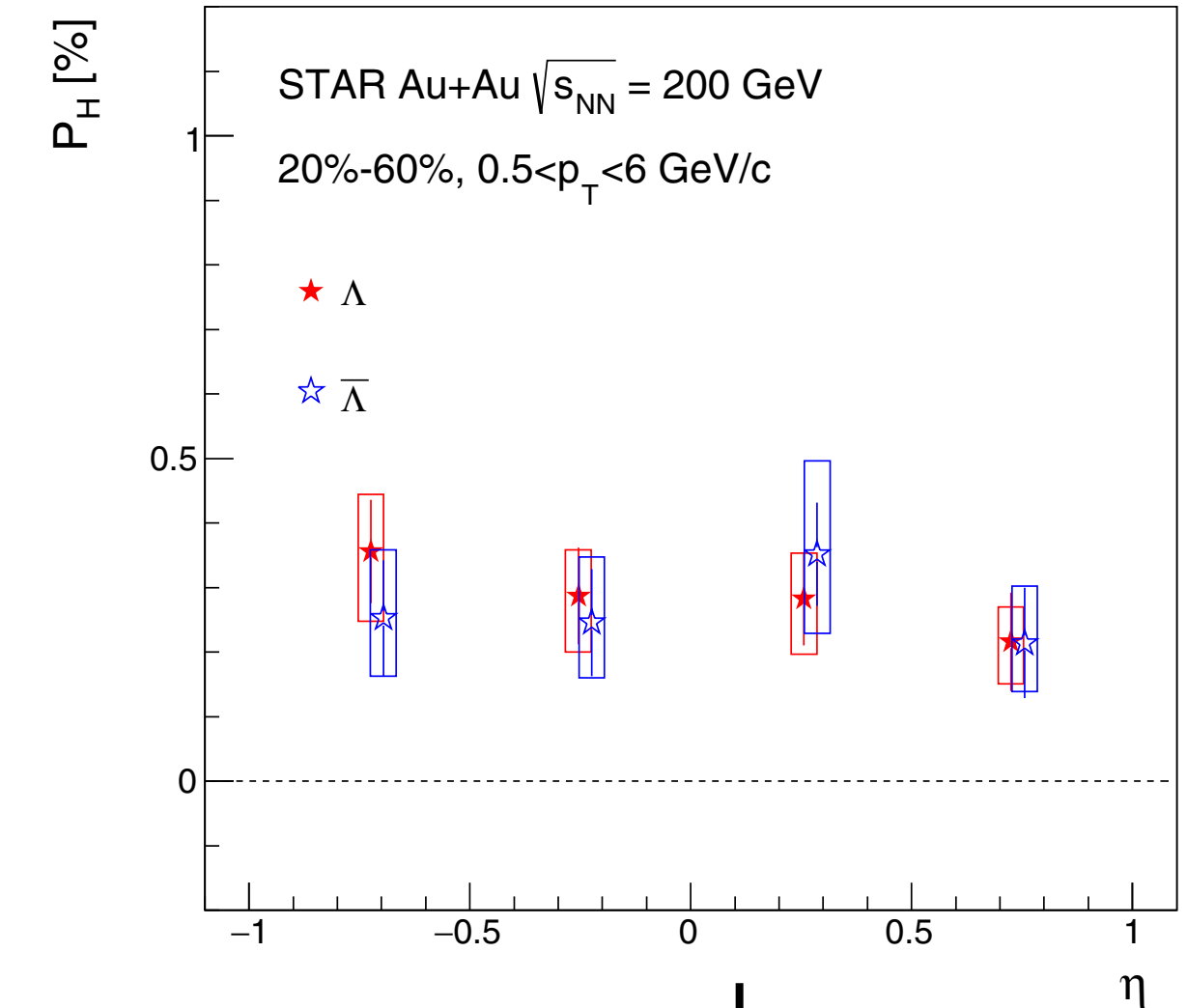
3 GeV
 $y_{\text{beam}} \approx 1.0$

STAR, PRC108, 014910 (2023)

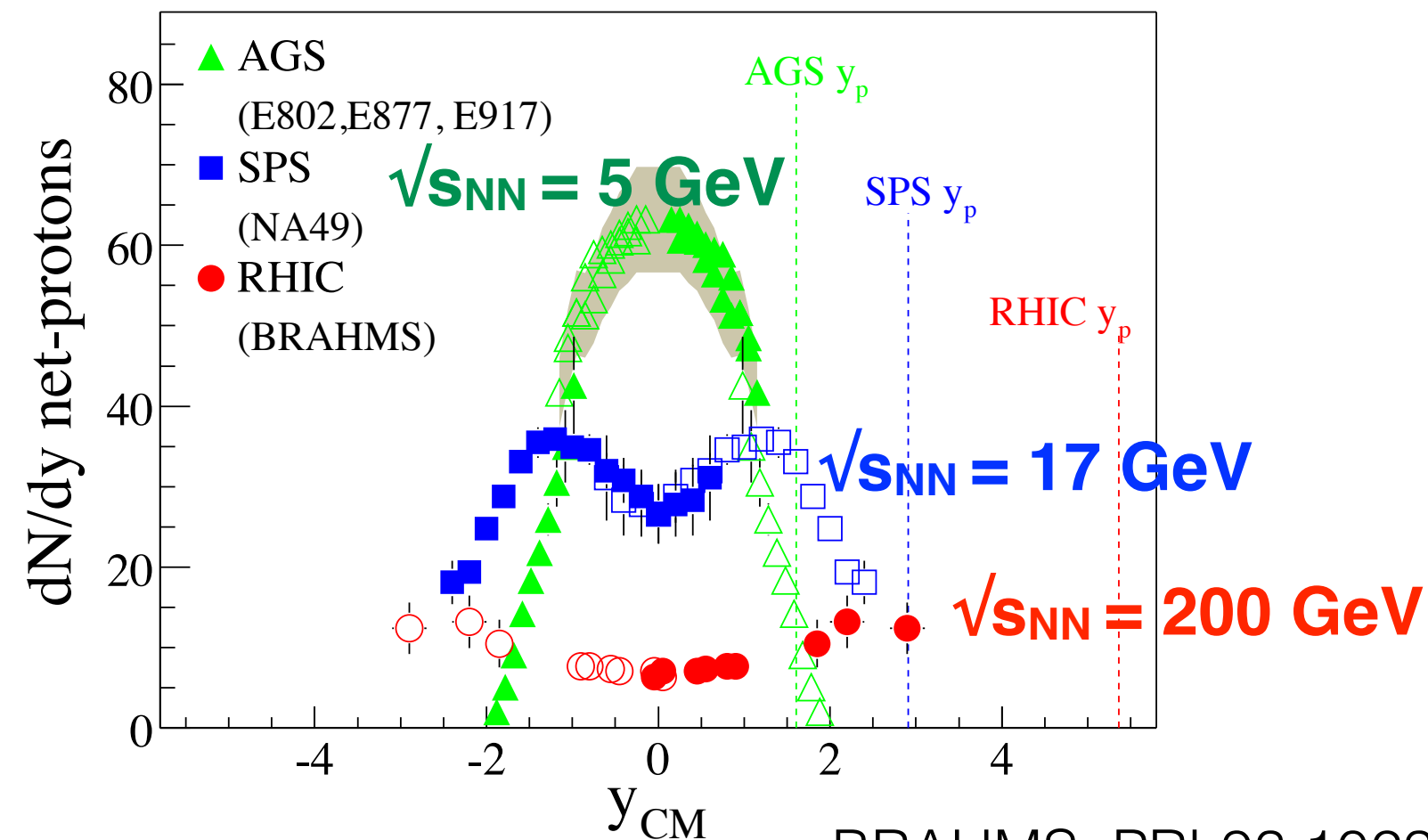


19.6 GeV
 $y_{\text{beam}} \approx 3.0$

STAR, PRC90, 014910 (2018)



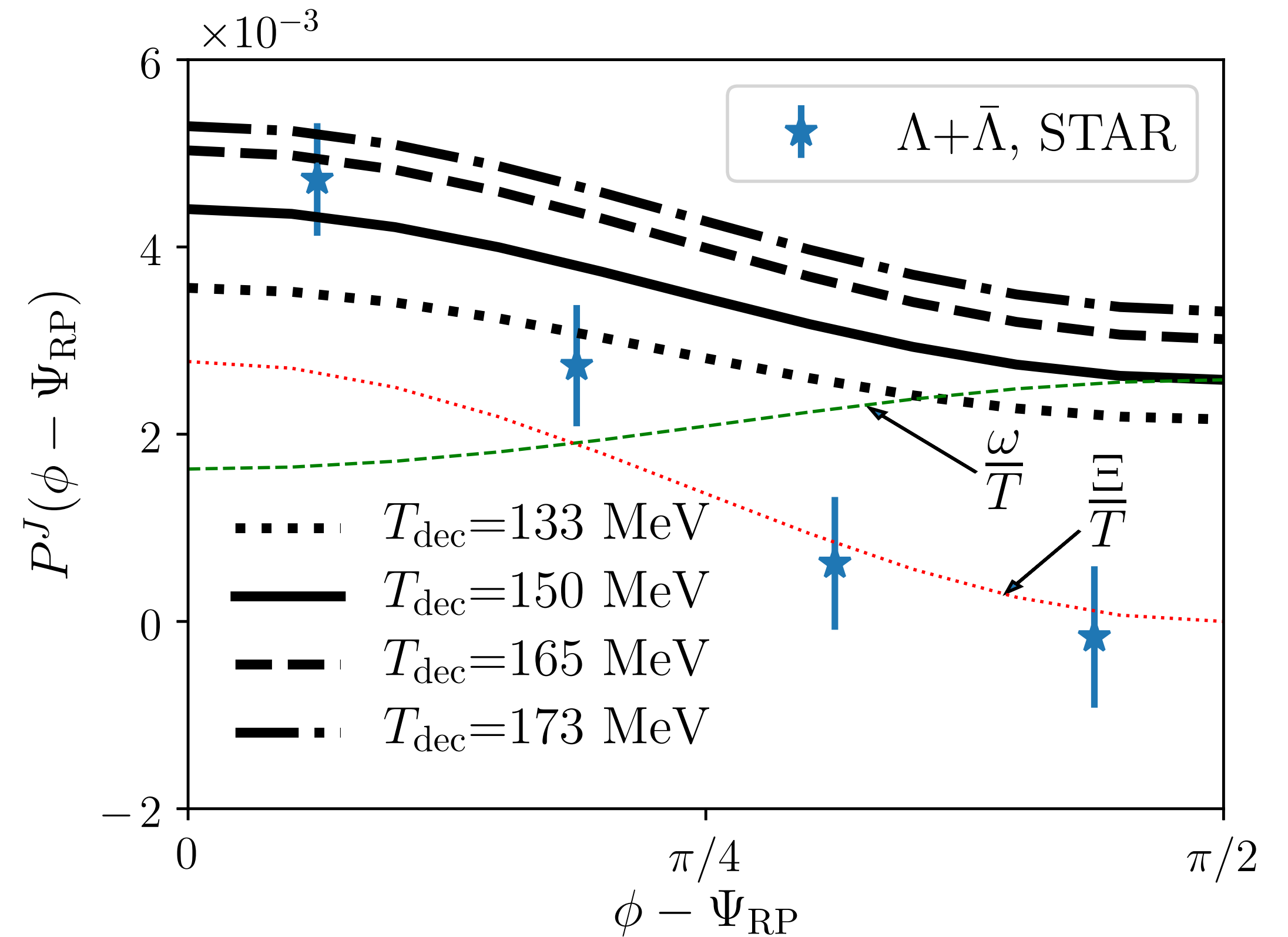
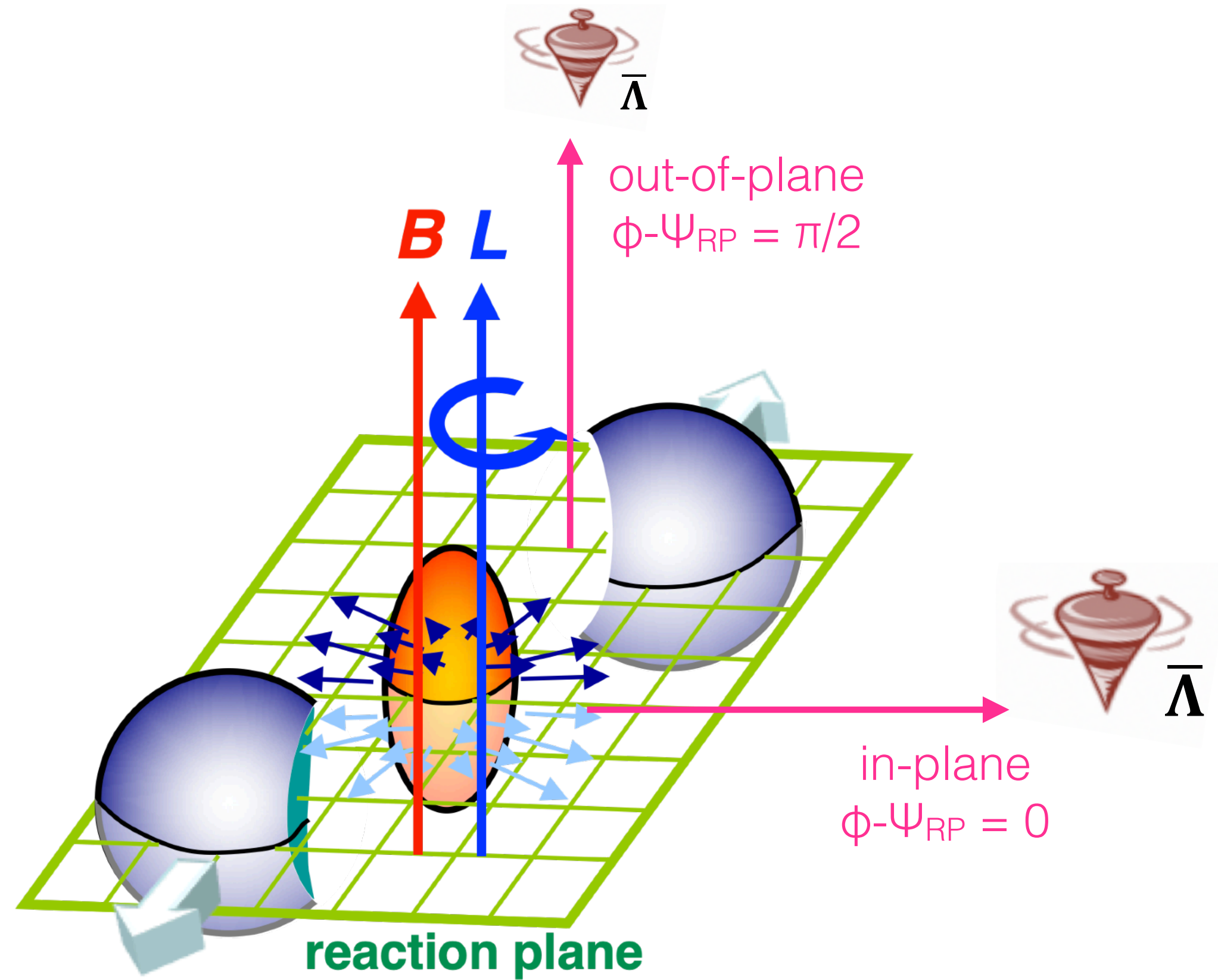
200 GeV
 $y_{\text{beam}} \approx 5.4$



BRAHMS, PRL93,102301(2004)

- At 3 GeV (FXT), the measurement almost reaches y_{beam} , but no clear rapidity dependence observed
- Uncertainties need to be reduced for a firm conclusion

Azimuthal angle dependence



- ▶ Larger polarization in in-plane than out-of-plane
- ▶ The data cannot be explained by thermal vorticity ω/T alone
 - “Spin puzzle” with the local polarization (discussed later)
- ▶ Including shear-induced polarization Ξ/T can reproduce the observed sign

Cosine modulation of P_y

STAR, PLB870 (2025) 139891

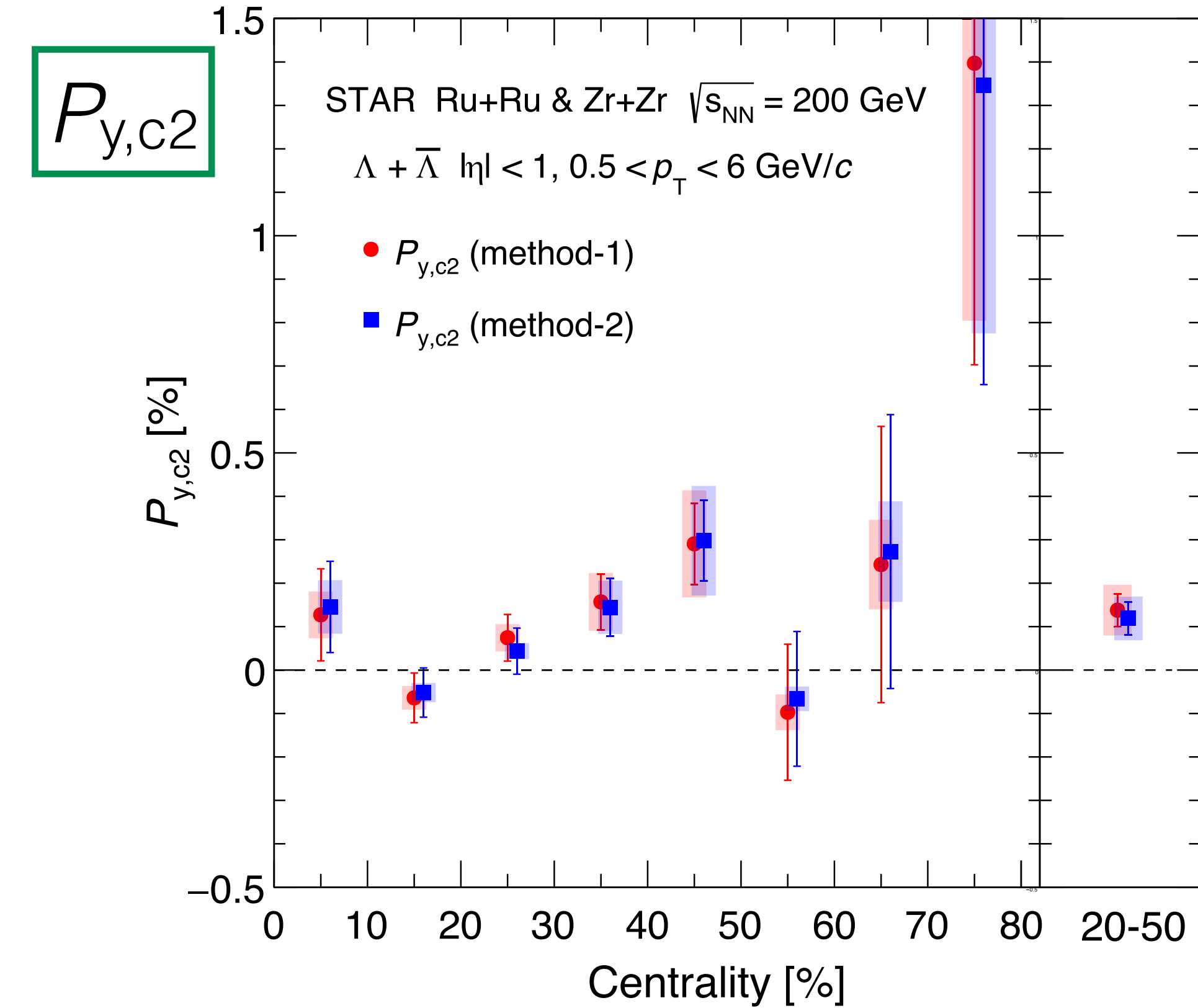
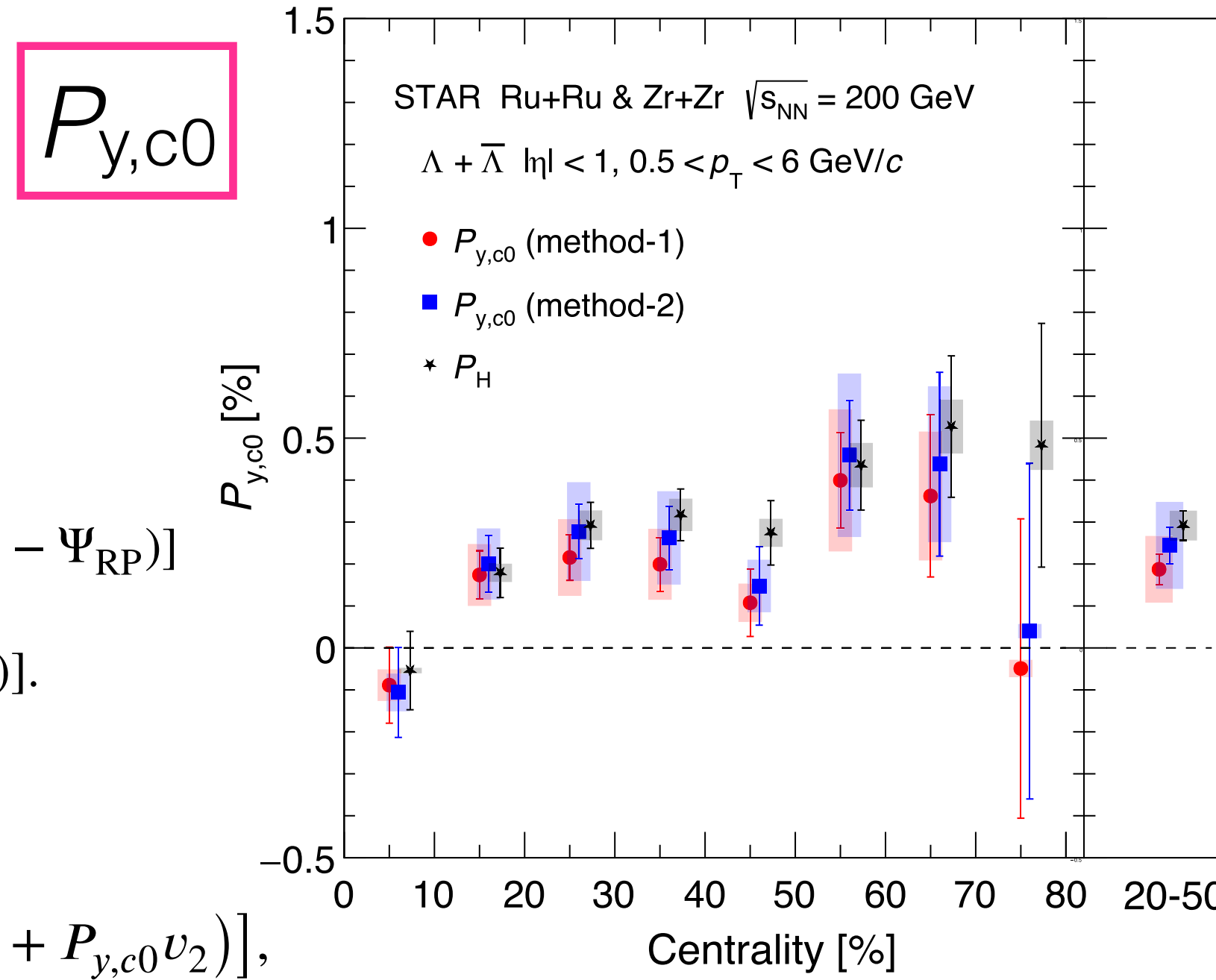
$$P_H(\phi_H - \Psi_{RP}) = P_{y,c0} + 2 \sum_{n=1}^{\infty} P_{y,c(2n)} \cos[2n(\phi_H - \Psi_{RP})]$$

$$\approx \underbrace{P_{y,c0}}_{\text{pink}} + 2 \underbrace{P_{y,c2}}_{\text{green}} \cos[2(\phi_H - \Psi_{RP})].$$

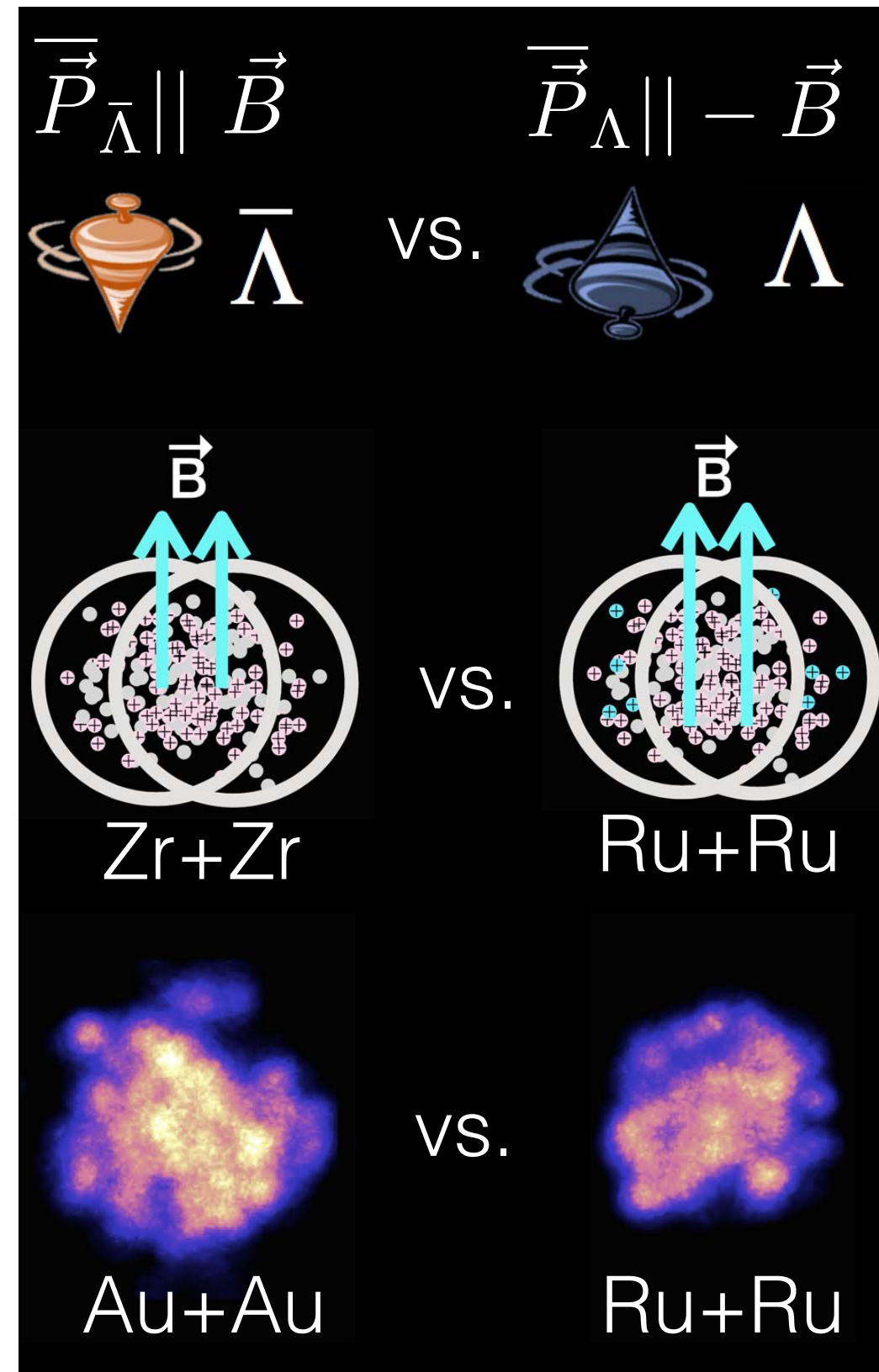
$$\langle \sin(\Psi_1 - \phi_B^*) \rangle = \frac{\alpha_H \pi}{8} [A_0(P_{y,c0} + 2P_{y,c2}v_2) - A_2(P_{y,c2} + P_{y,c0}v_2)],$$

$$\langle \sin(\Psi_1 - \phi_B^*) \cos[2(\phi_H - \Psi_{RP})] \rangle = \frac{\alpha_H \pi}{8} \left[A_0(P_{y,c2} + P_{y,c0}v_2) - \frac{1}{2} A_2(P_{y,c0} + 3P_{y,c2}v_2) \right],$$

- ▶ In Ru+Ru & Zr+Zr collisions, similar trend, i.e. larger P_y in in-plane, was observed after decoupling the effect of elliptic flow
 - Solving $P_{y,cn}$ convoluted with elliptic flow v_2
 - Accounting for the detector effect (A_0 , A_2)



System size dependence?

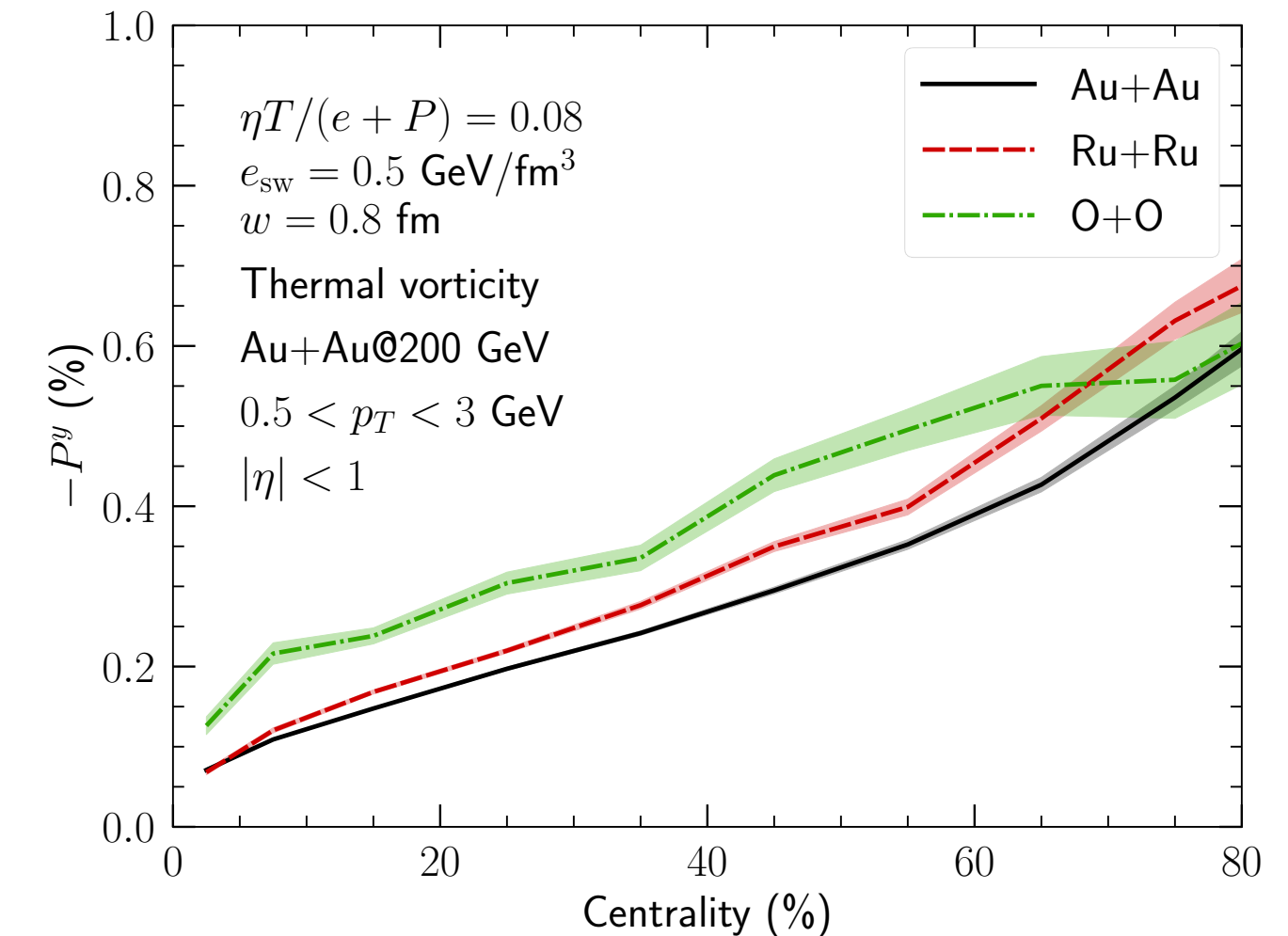
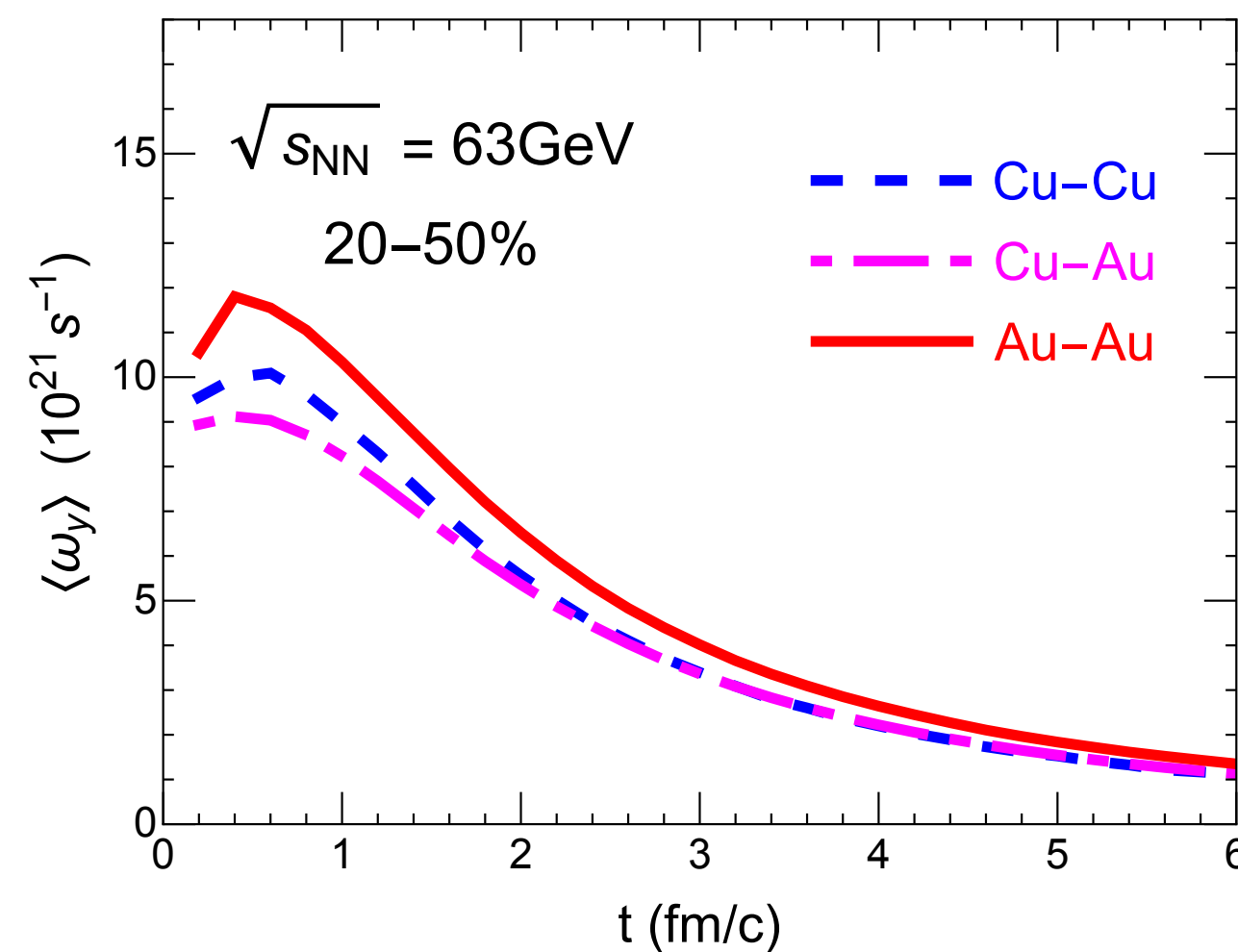


picture from P. Tribedy (QM22)

- System size dependence predicted (for a given centrality)
- Longer system lifetime dilutes the vorticity/polarization
- Initial B-field ($|B|^2$) difference is 10-15% between Ru+Ru and Zr+Zr

$$^{197}\text{Au} > ^{96}_{44}\text{Ru}, ^{96}_{40}\text{Zr} > ^{63}\text{Cu} > ^{16}\text{O}$$

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

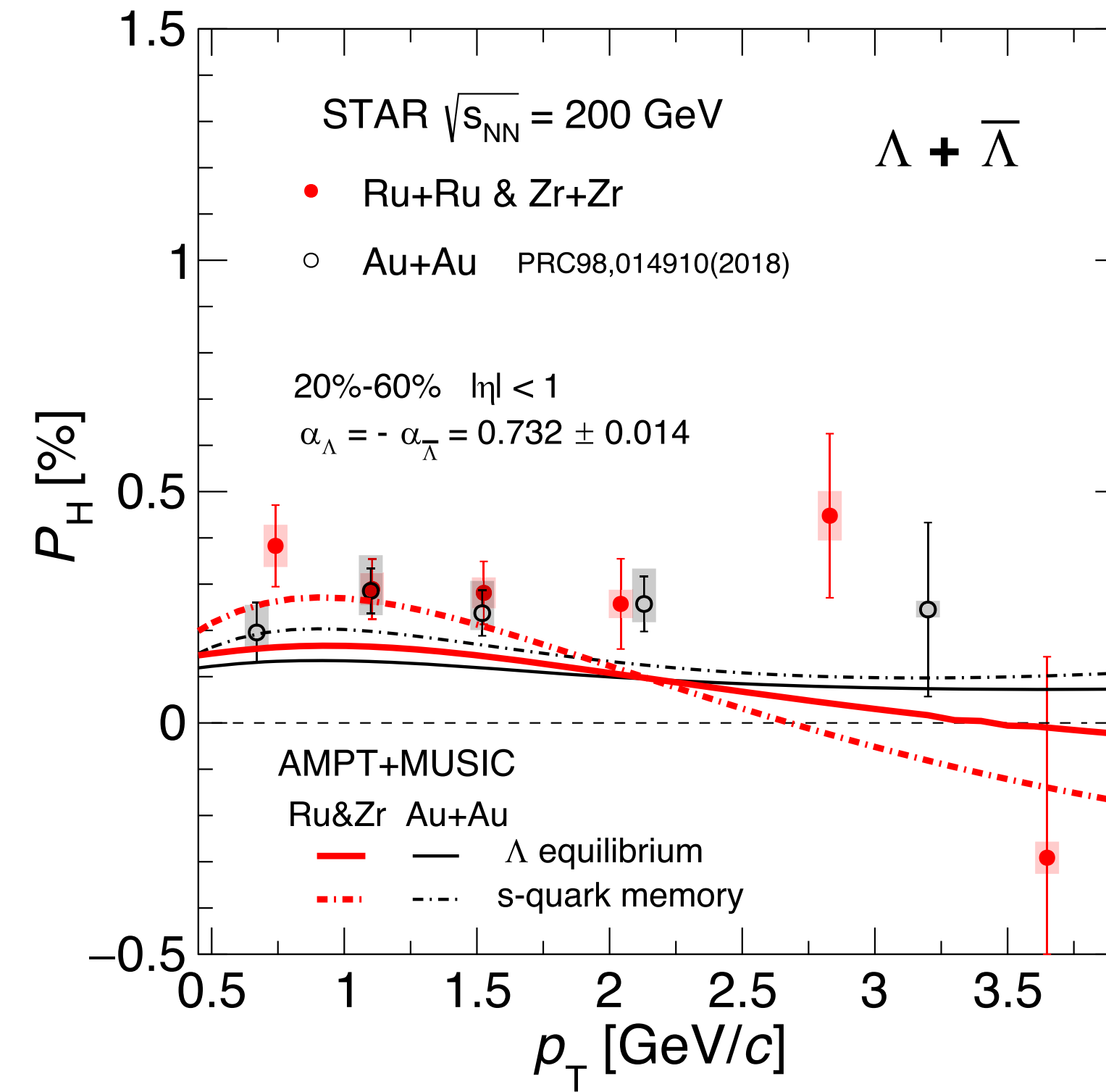
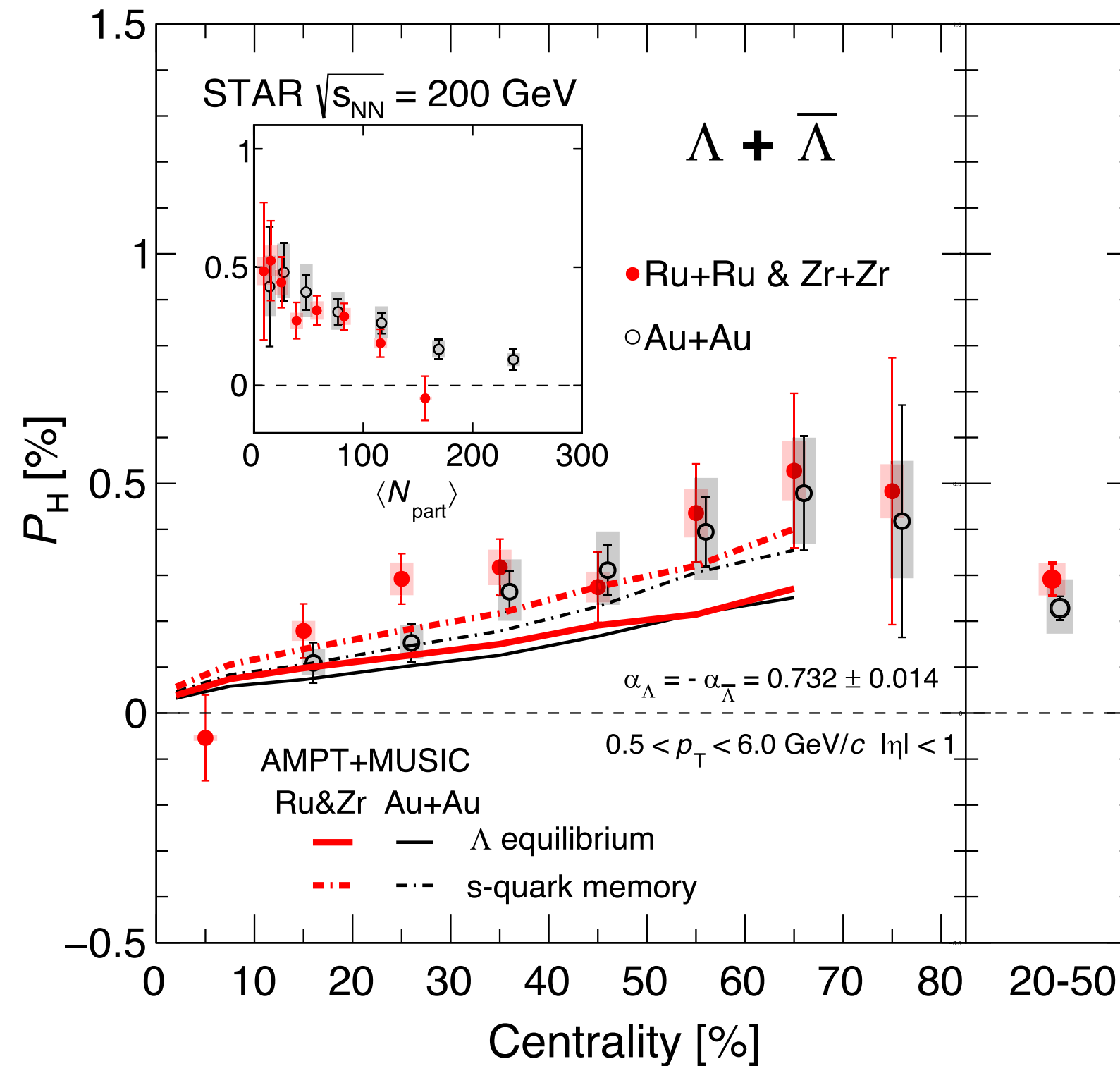


S. She et al., PLB788(2019)409

A. Alzhrani, S. Ryu, C. Shen, arXiv:2203.15718 46

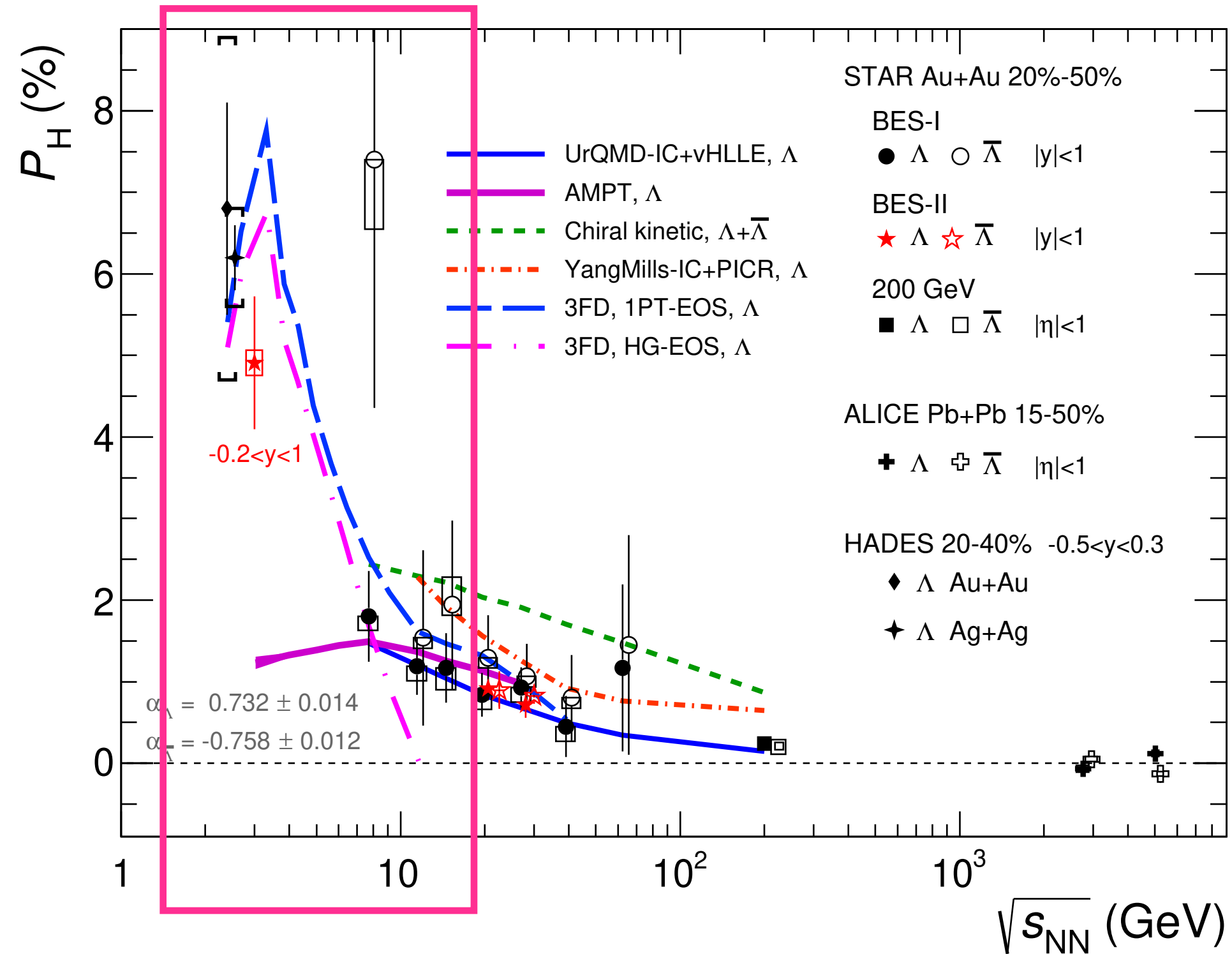
Global polarization in isobar collisions

STAR, PLB870 (2025) 139891



- Within current uncertainties, no difference between Au+Au and isobar systems
- No significant difference between Λ and anti- Λ in isobar collisions

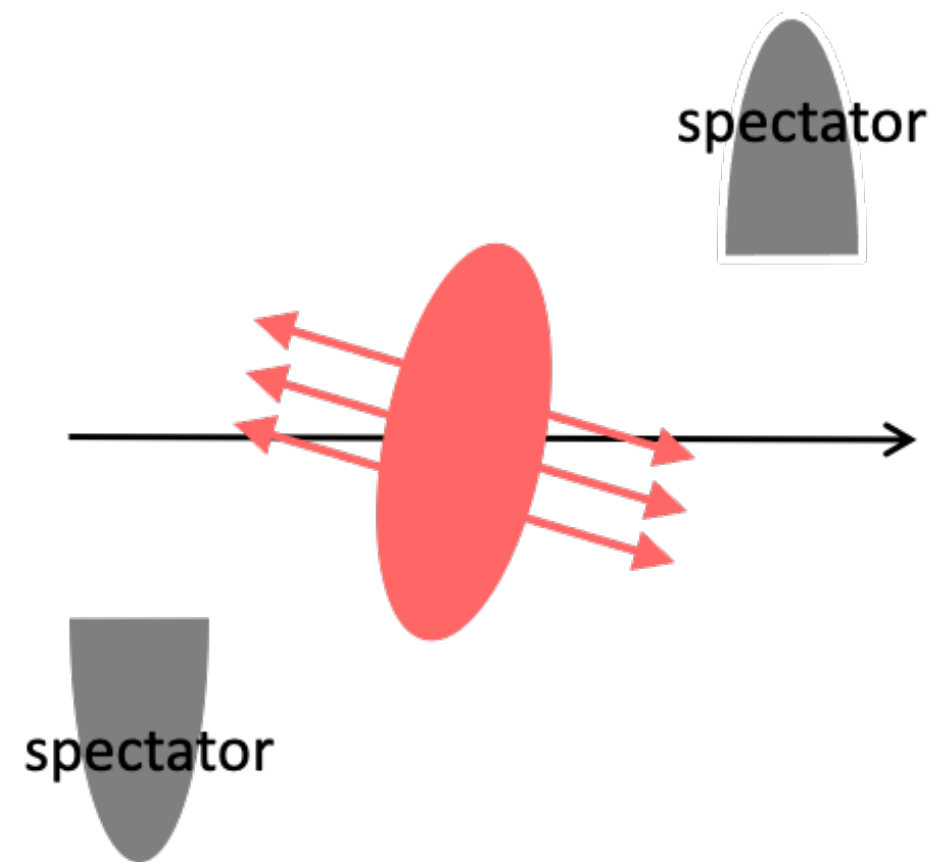
Effect of transverse polarization?



- Transverse polarization wrt production plane could contribute to the measured global polarization at low $\sqrt{s_{NN}}$, through coupling with directed flow

F. Liu and Z. Tu, PRD113, 114051 (2026)

Effect of transverse polarization?



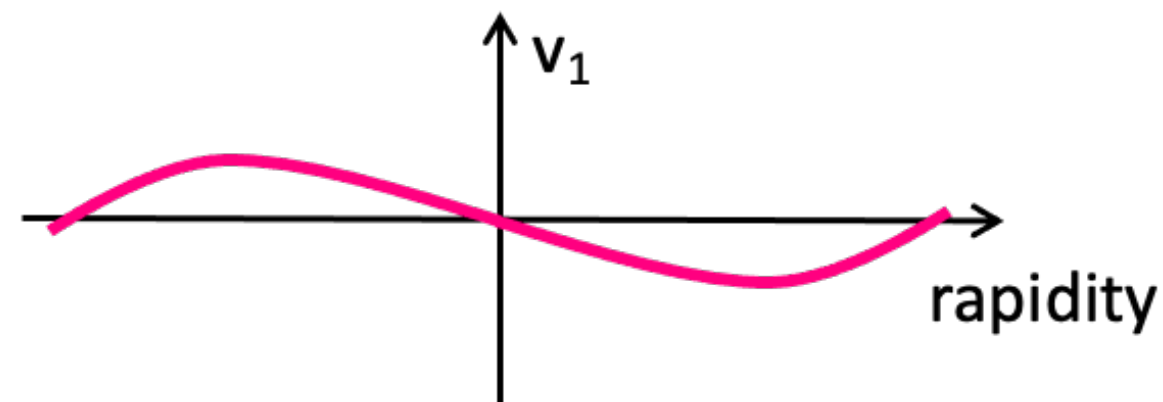
- Transverse polarization wrt production plane could be related to the measured global polarization at low $\sqrt{s_{NN}}$, through coupling with the directed flow

F. Liu and Z. Tu, PRD113, 114051 (2026)

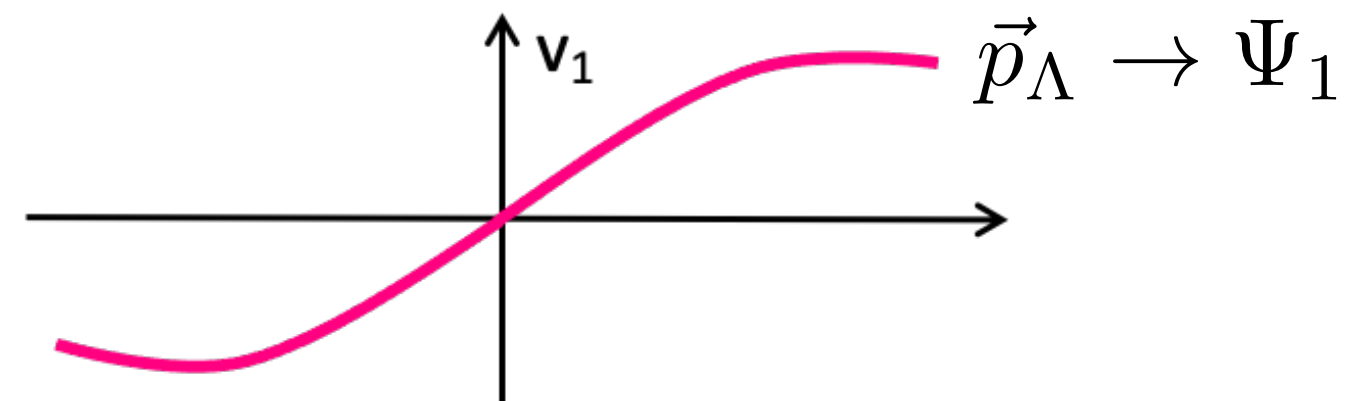
Production plane: $\vec{p}_{\text{beam}} \times \vec{p}_{\Lambda}$

Reaction plane: $\vec{p}_{\text{beam}} \times \vec{b}$

High $\sqrt{s_{NN}}$
(small $|v_1|$)

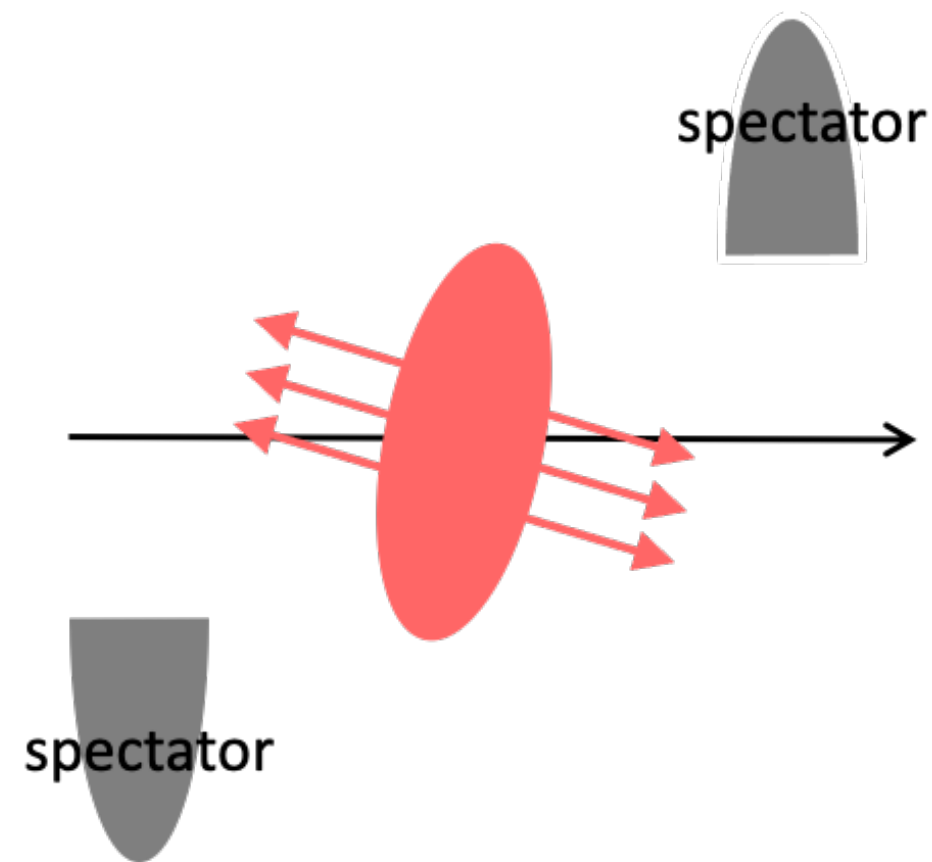


Low $\sqrt{s_{NN}}$
(large $|v_1|$)



$$v_1 = \langle \cos(\phi - \Psi_1) \rangle$$

Effect of transverse polarization?



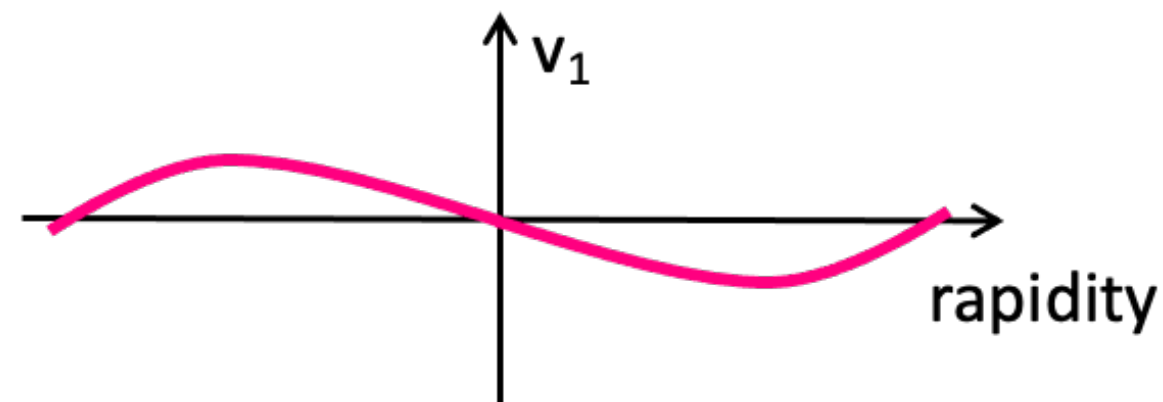
- Transverse polarization wrt production plane could be related to the measured global polarization at low $\sqrt{s_{NN}}$, through coupling with the directed flow

F. Liu and Z. Tu, PRD113, 114051 (2026)

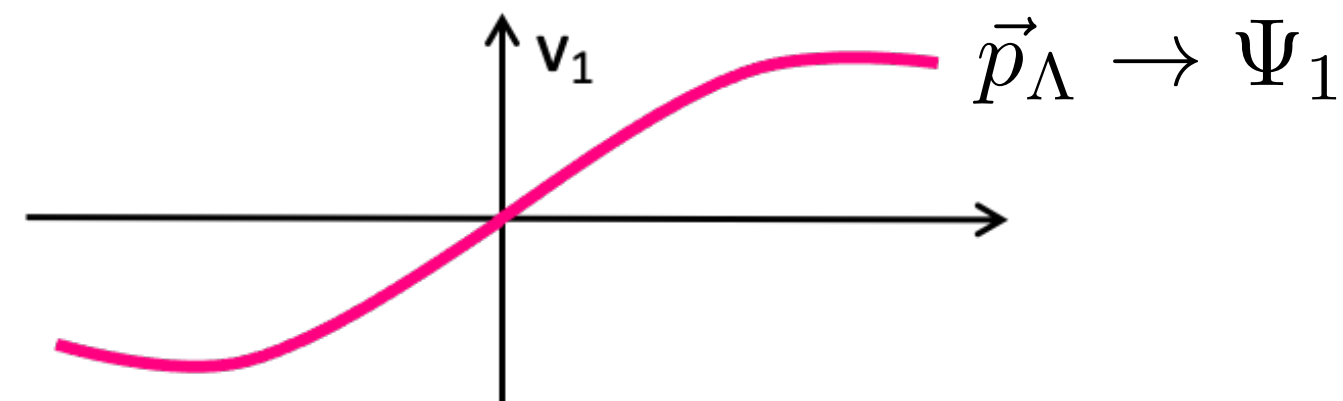
Production plane: $\vec{p}_{\text{beam}} \times \vec{p}_{\Lambda}$

Reaction plane: $\vec{p}_{\text{beam}} \times \vec{b}$

High $\sqrt{s_{NN}}$
(small $|v_1|$)

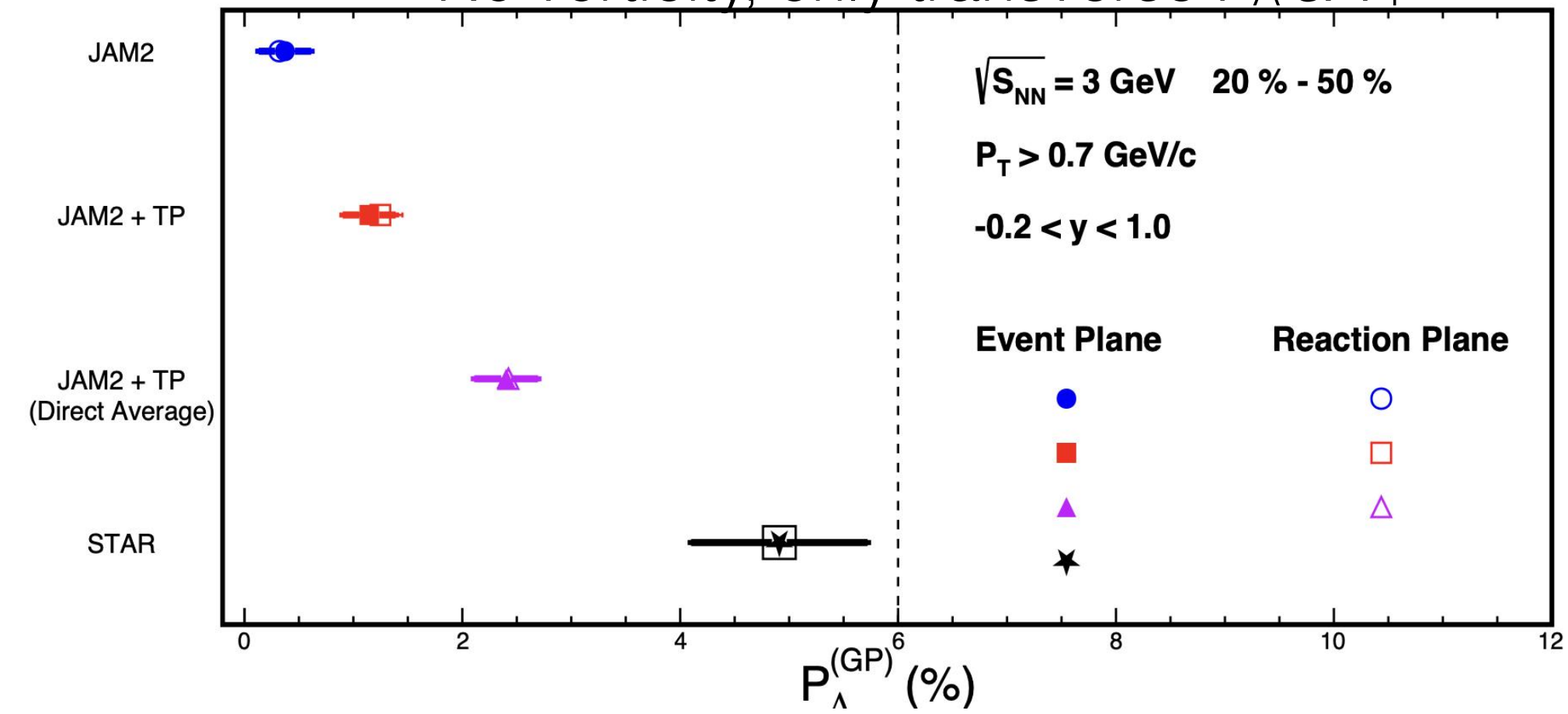


Low $\sqrt{s_{NN}}$
(large $|v_1|$)



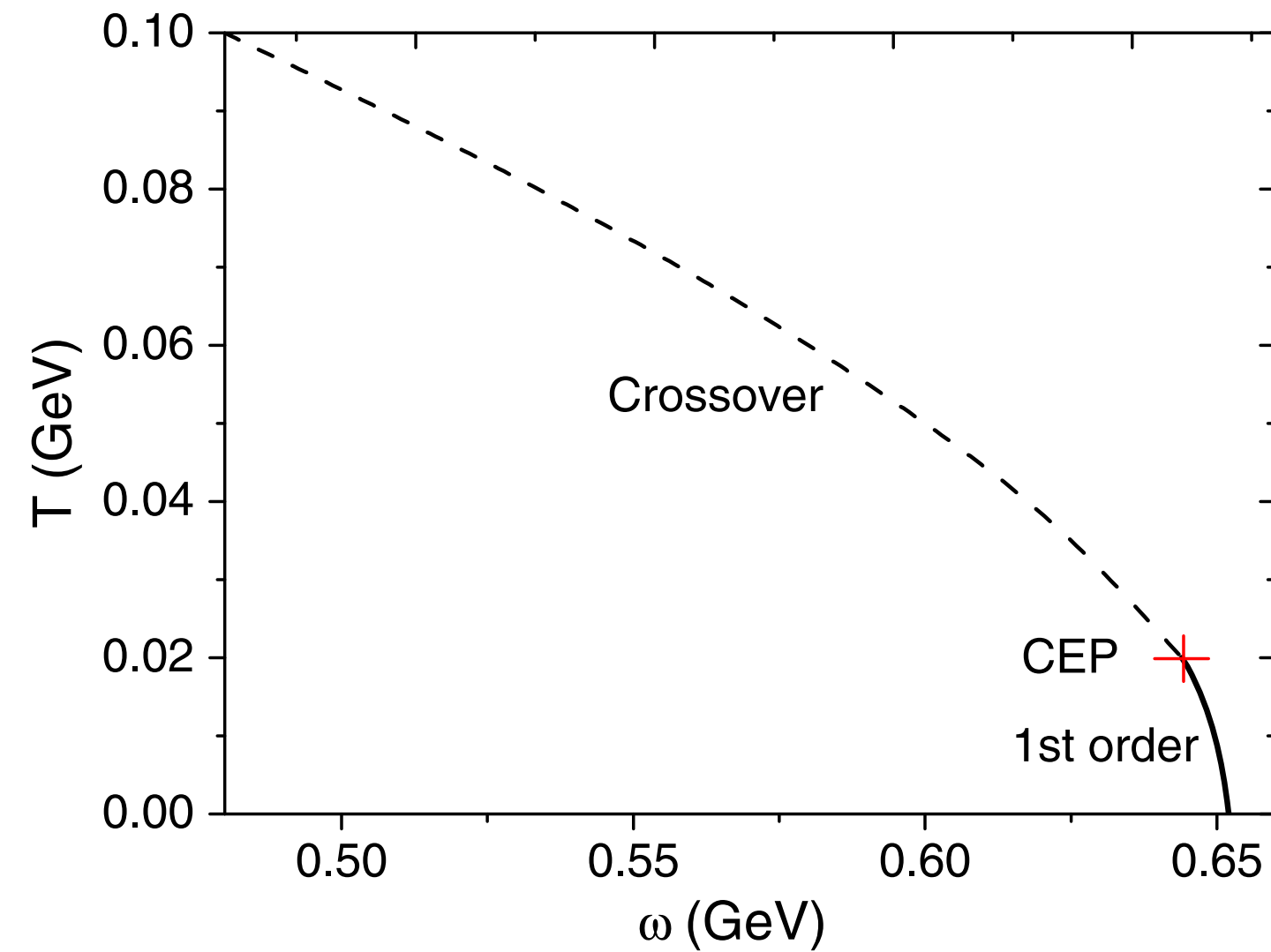
$$v_1 = \langle \cos(\phi - \Psi_1) \rangle$$

No vorticity, only transverse P_{Λ} & v_1

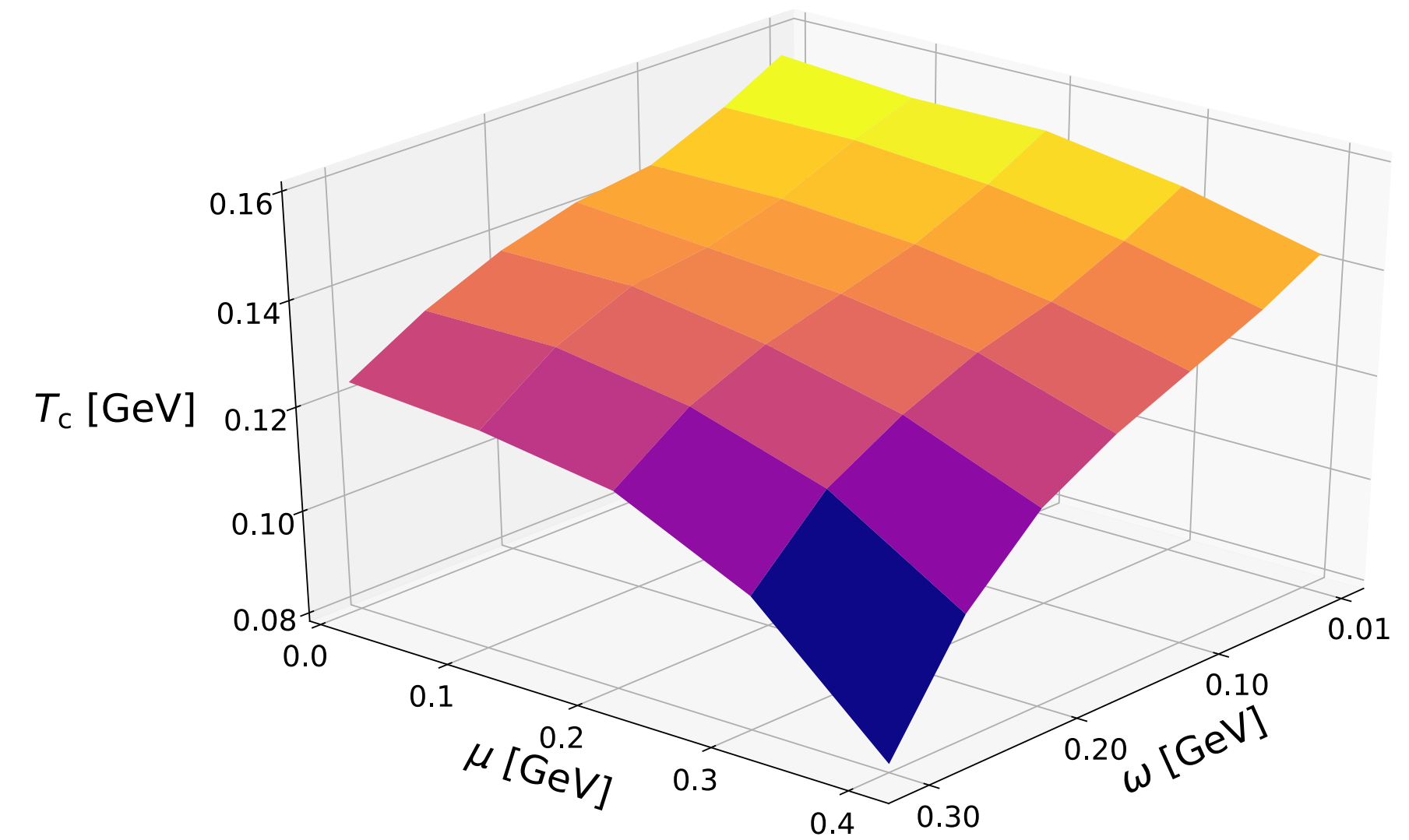


~20% of P_H could come from transverse Λ polarization based on a rough estimate,
Under investigation experimentally...

Connection to QCD phase diagram



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



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

- Vorticity ω can play a role similar to baryon chemical potential μ_B
- Deconfinement transition temperature becomes lower if the system is rotating
 - Opposite trend is found in LQCD

V.V. Braguta et al., PRD103, 094515 (2021)

Summary of day-3

- ▶ Hyperon global polarization was observed in relativistic heavy-ion collisions
 - ❑ Average global polarization can be explained by various models, supporting the global (thermal) vorticity picture
 - ❑ The estimated vorticity ω is of the order of $\omega \sim 10^{21} \text{ s}^{-1}$; the most vortical fluid ever observed
 - ❑ No significant magnetic-field-induced splitting was observed;
Upper limit of the late-stage magnetic-field: $B < 10^{13} \text{ T}$
 - ❑ Some open questions
 - Rapidity dependence, Polarization mechanism at low- $\sqrt{s_{NN}}$, Spin dependence of the polarization needs to be confirmed (Ω hyperons)