「偏極、CME、CVE」

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U.S. DEPARTMENT OF ENERGY | Office of Science

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2019年8月19-21日, 理化学研究所

Important features in non-central heavy-ion collisions

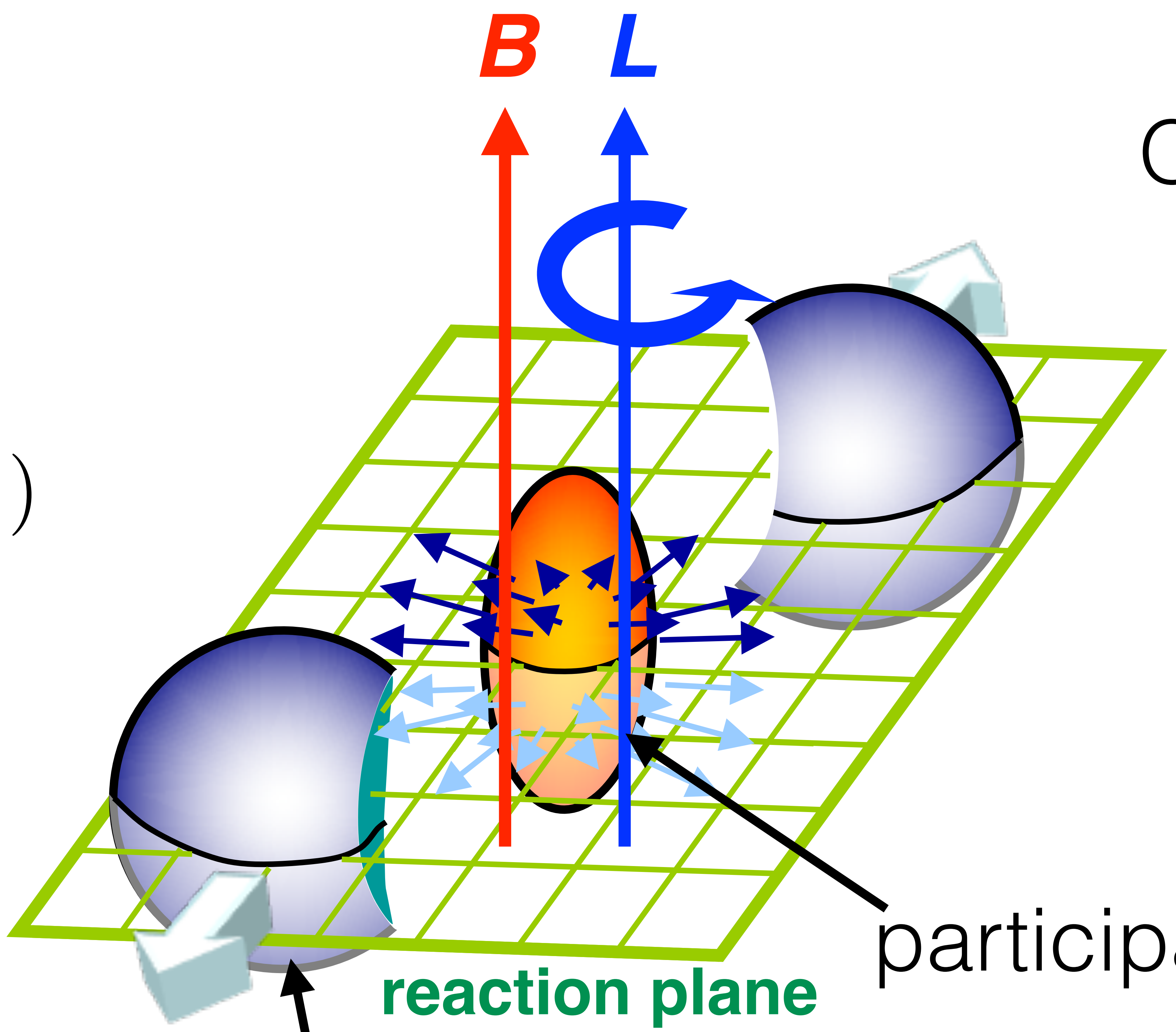
Strong magnetic field

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

$$(eB \sim \mathrm{MeV}^2\ (\tau = 0.2\ \mathrm{fm}))$$

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

→Chiral magnetic effect
Chiral magnetic wave
Particle polarization



participants

spectators

Orbital angular momentum

$$L \sim 10^5 \hbar$$

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

→Chiral vortical effect
Particle polarization

Chiral Magnetic Effect (CME)

詳細は山本さんの講演参照

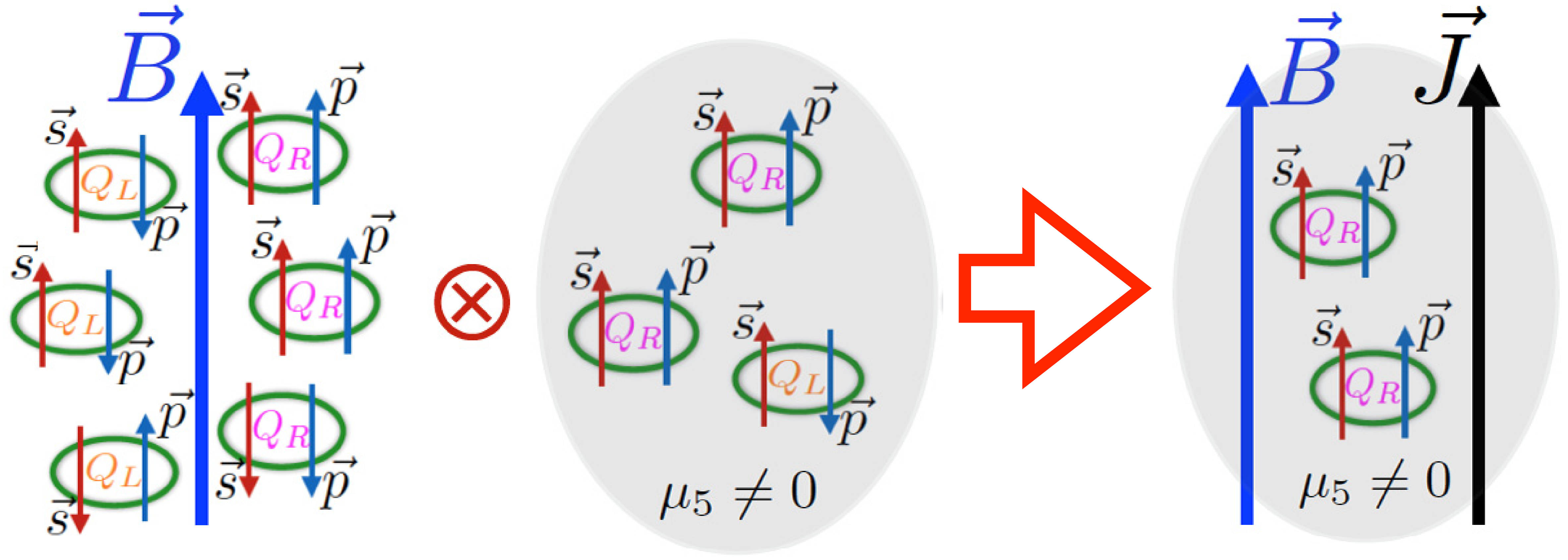
D. Kharzeev, R. Pisarski, M. Tytgat, PRL81, 512 (1998)
D. Kharzeev, PPNP75(2014)133-151

Magnetic field + massless quarks + chirality imbalance

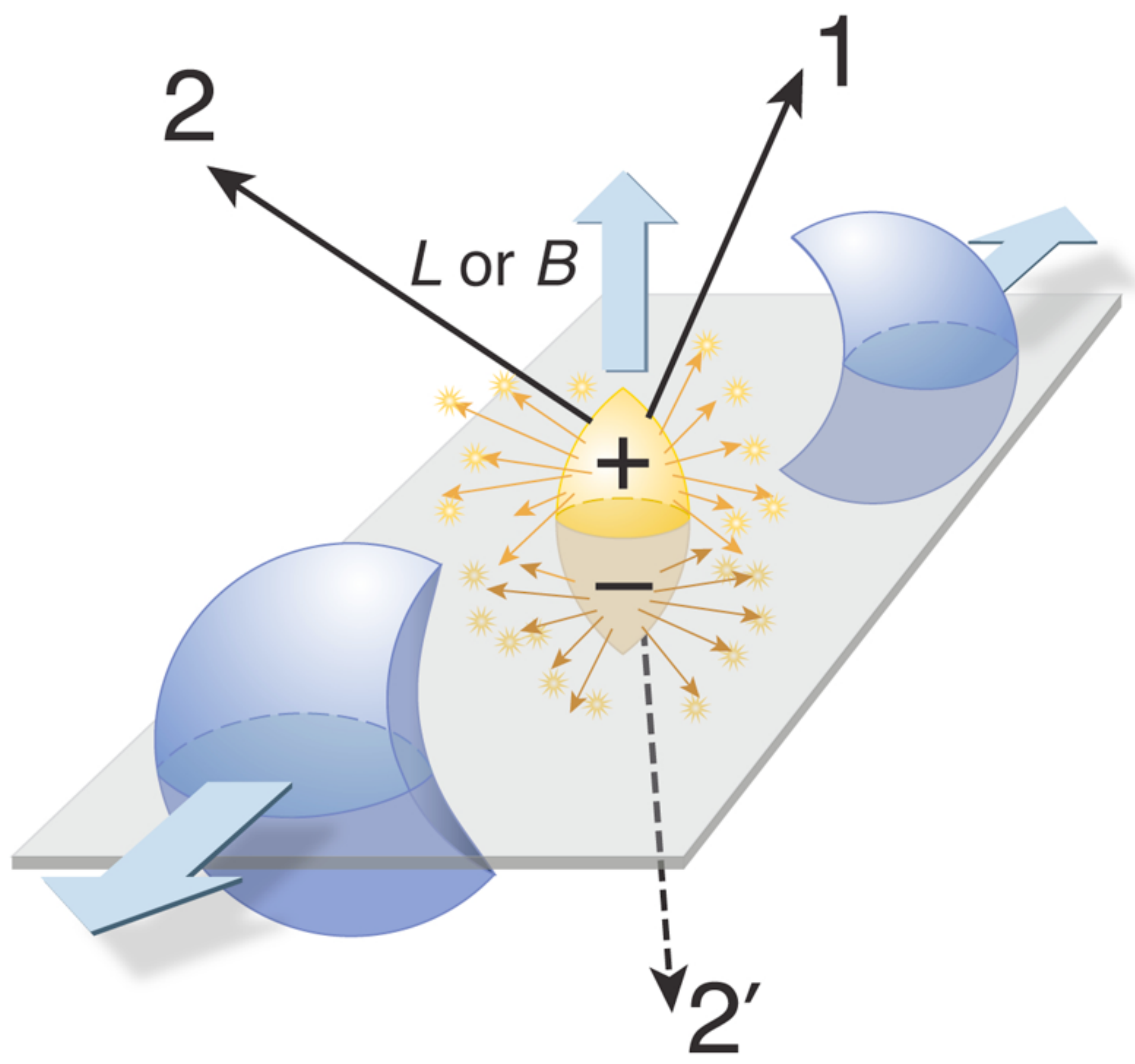
spin alignment (opposite direction for opposite sign)

spin and momentum in (anti-)parallel for right(left)-handed quarks

right-handed quarks ≠ left-handed quarks

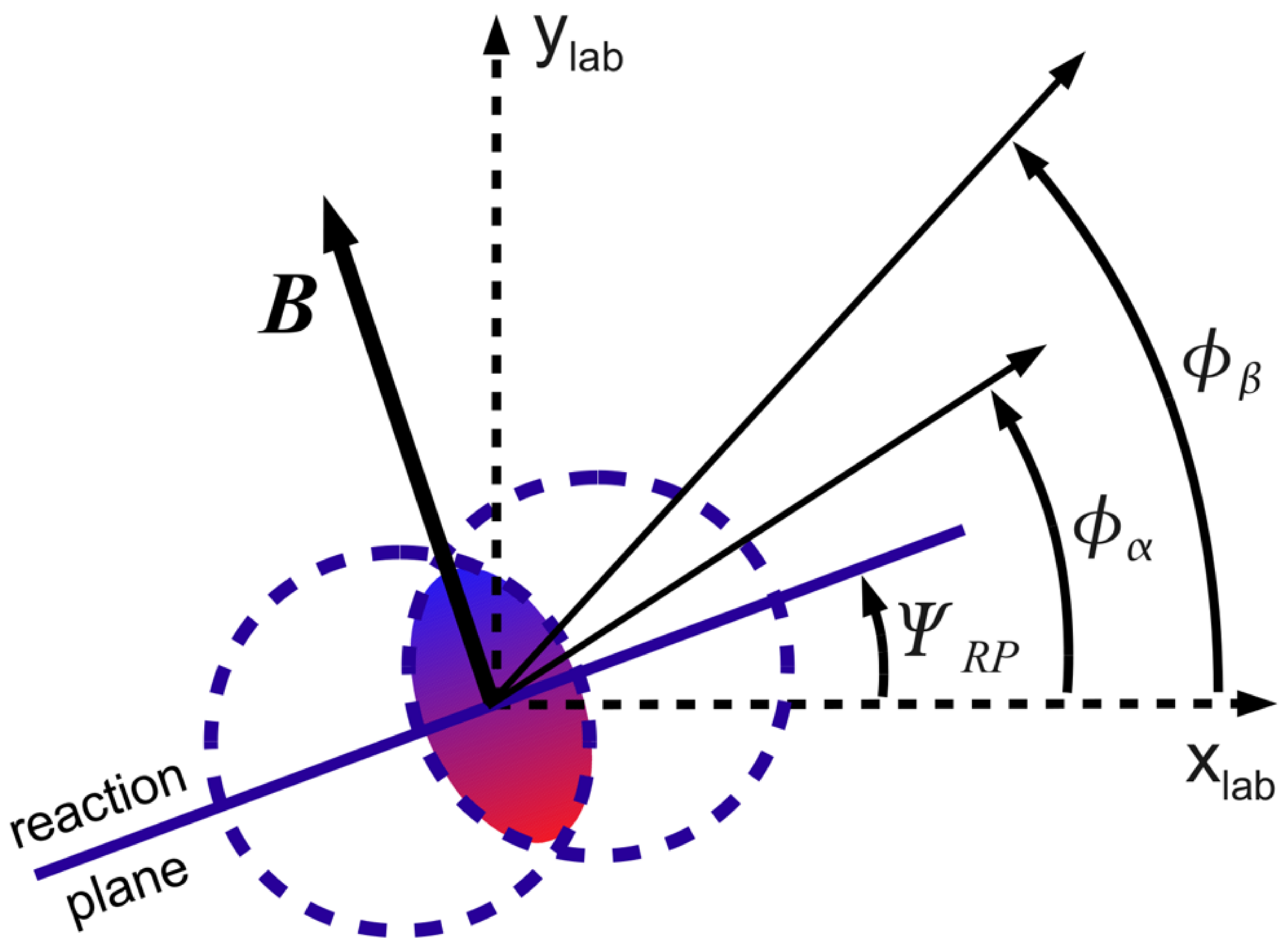


$$\vec{\mathbf{J}} \propto (Qe)\mu_5\vec{\mathbf{B}}$$



Induction of electric current along the magnetic field is called *Chiral Magnetic Effect (CME)*

Experimental observable of CME



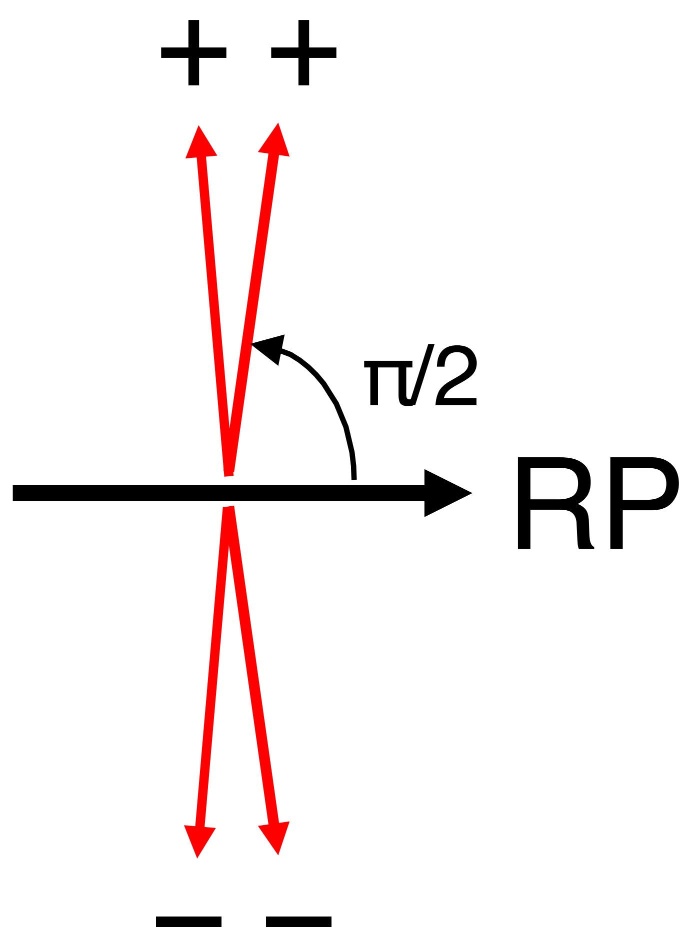
* Magnetic field direction is perpendicular to the reaction plane in heavy-ion collisions

"Gamma correlator" sensitive to the charge separation

S.Voloshin PRC70, 057901 (2004)

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

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



e.g. extreme case of charge separation

$$\gamma_{+-} = \langle \cos(\pi/2 - \pi/2) \rangle = 1$$

$$\gamma_{\pm\pm} = \langle \cos(\pi/2 + \pi/2) \rangle = -1$$

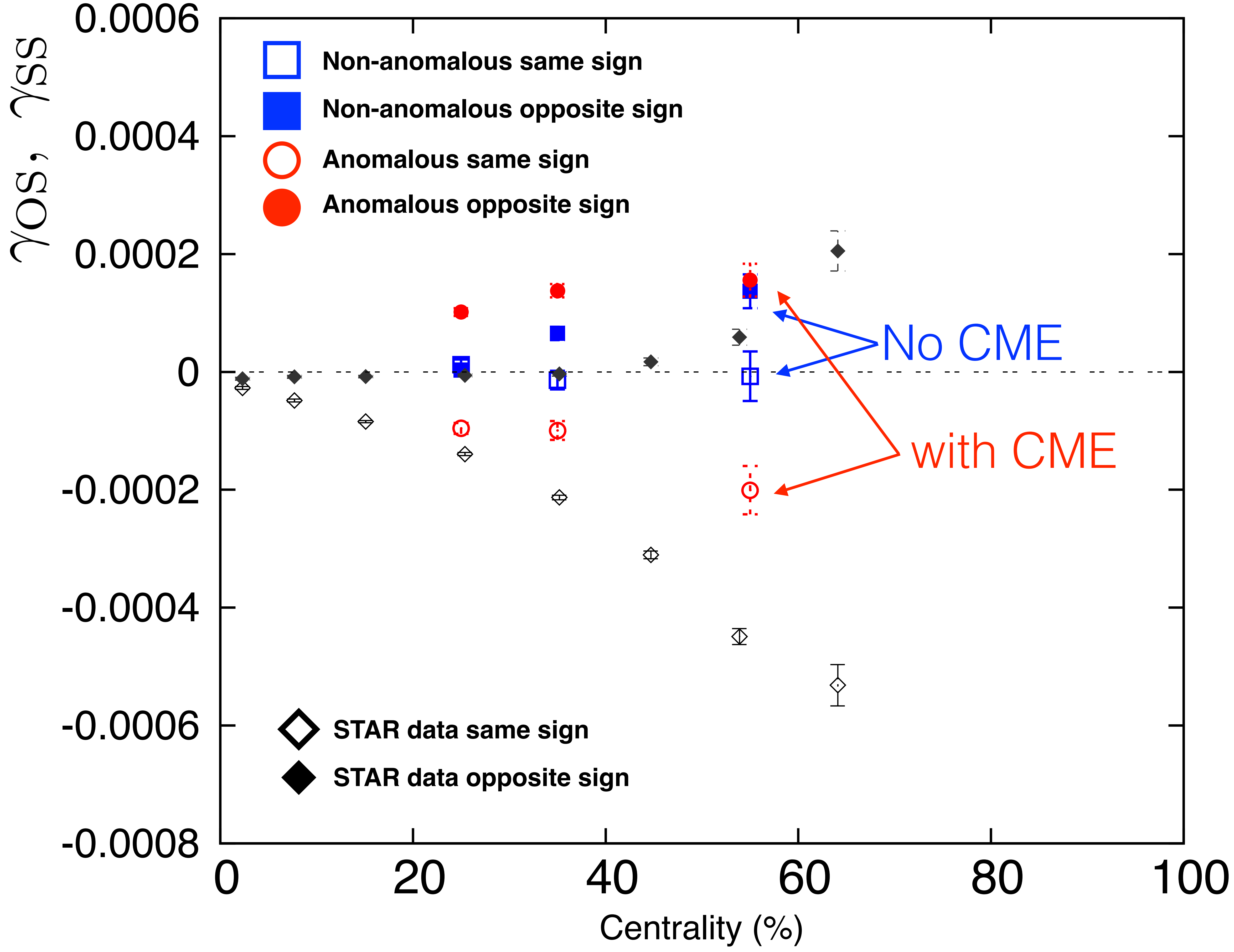
$$\Delta\gamma = 2$$

γ correlator in anomalous hydrodynamics

Y. Hirono, T. Hirano, and D. Kharzeev, arXiv:1412.0311

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

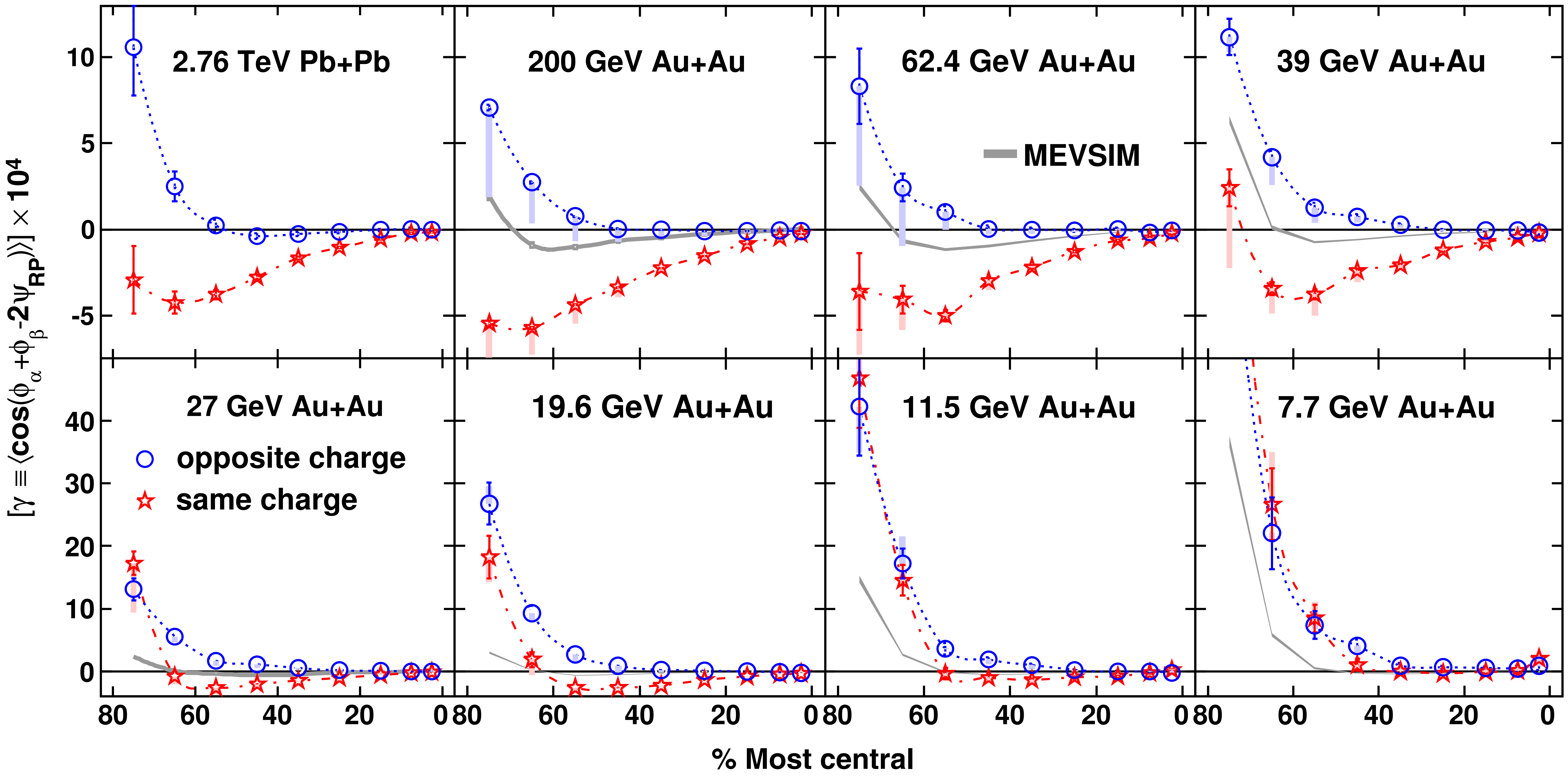
$$\Delta\gamma = \gamma_{+-} - \gamma_{\pm\pm}$$



γ correlator is indeed sensitive to CME!

γ-correlator at RHIC and the LHC

D. Kharzeev, J. Liao, S. Voloshin, and G. Wang, PPNP88(2016)1-28
STAR, PRL113, 052302 (2014)
ALICE, PRL110, 021301 (2013)



Charge separation was observed at RHIC and the LHC!
The difference between charge combinations (Δγ) decreases in lower energies.

Known background

S.Voloshin PRC70, 057901 (2004)
S. Schlichting and S. Pratt, PRC83, 014913 (2011)
A. Bzdak, V. Koch, and J. Liao, PRC83, 014905 (2011)

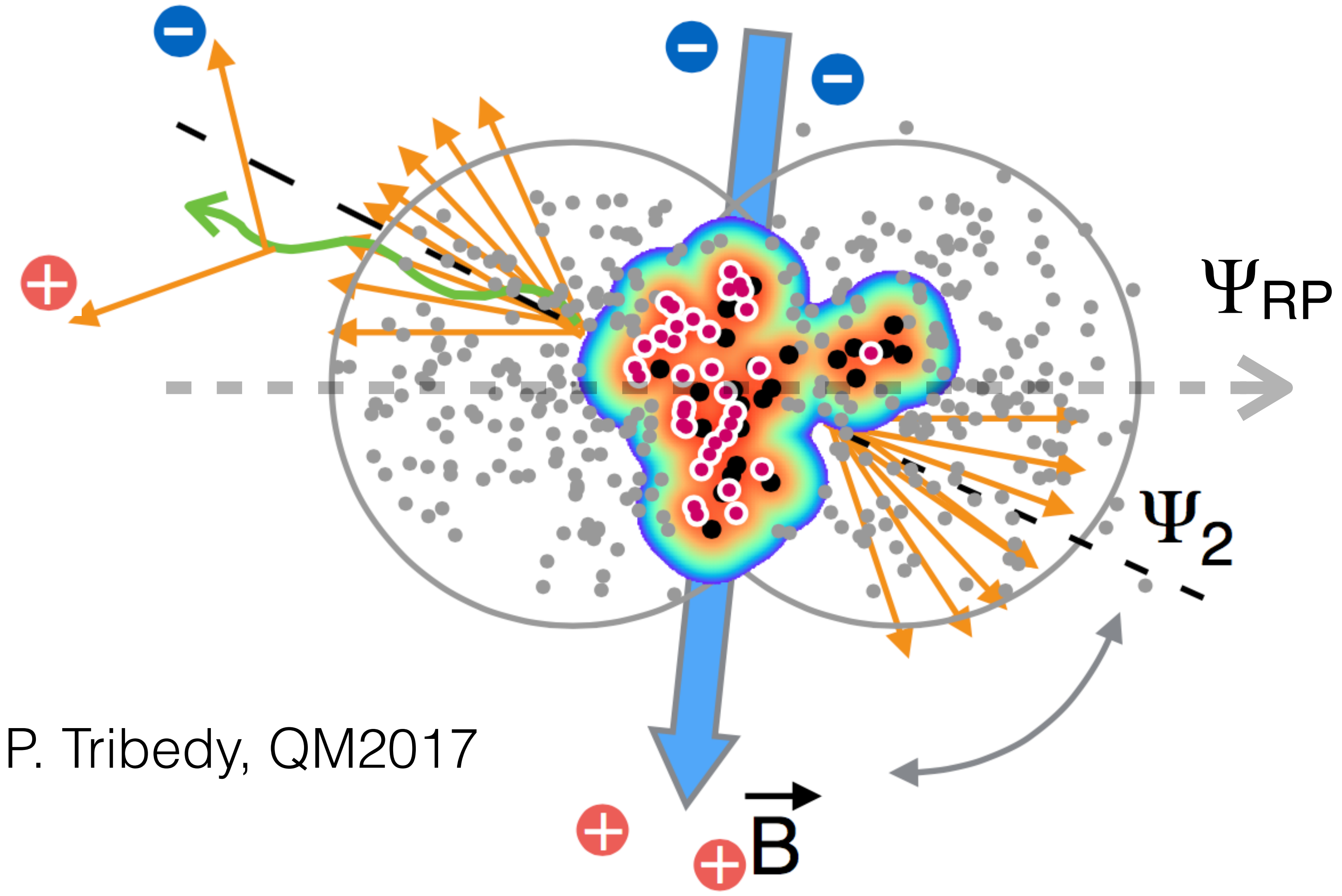
“Flowing clusters”
(Local charge conservation + v_2)

e.g. resonance contributes to Δγ, stronger collimation in in-plane

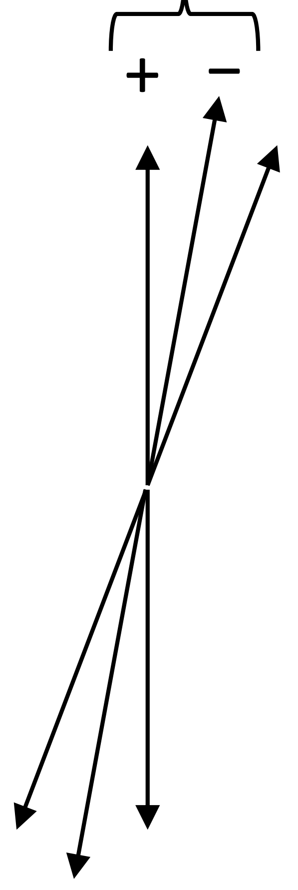
RP-independent background

e.g. back-to-back jets, important at low multiplicity, η gap wouldn’t help

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

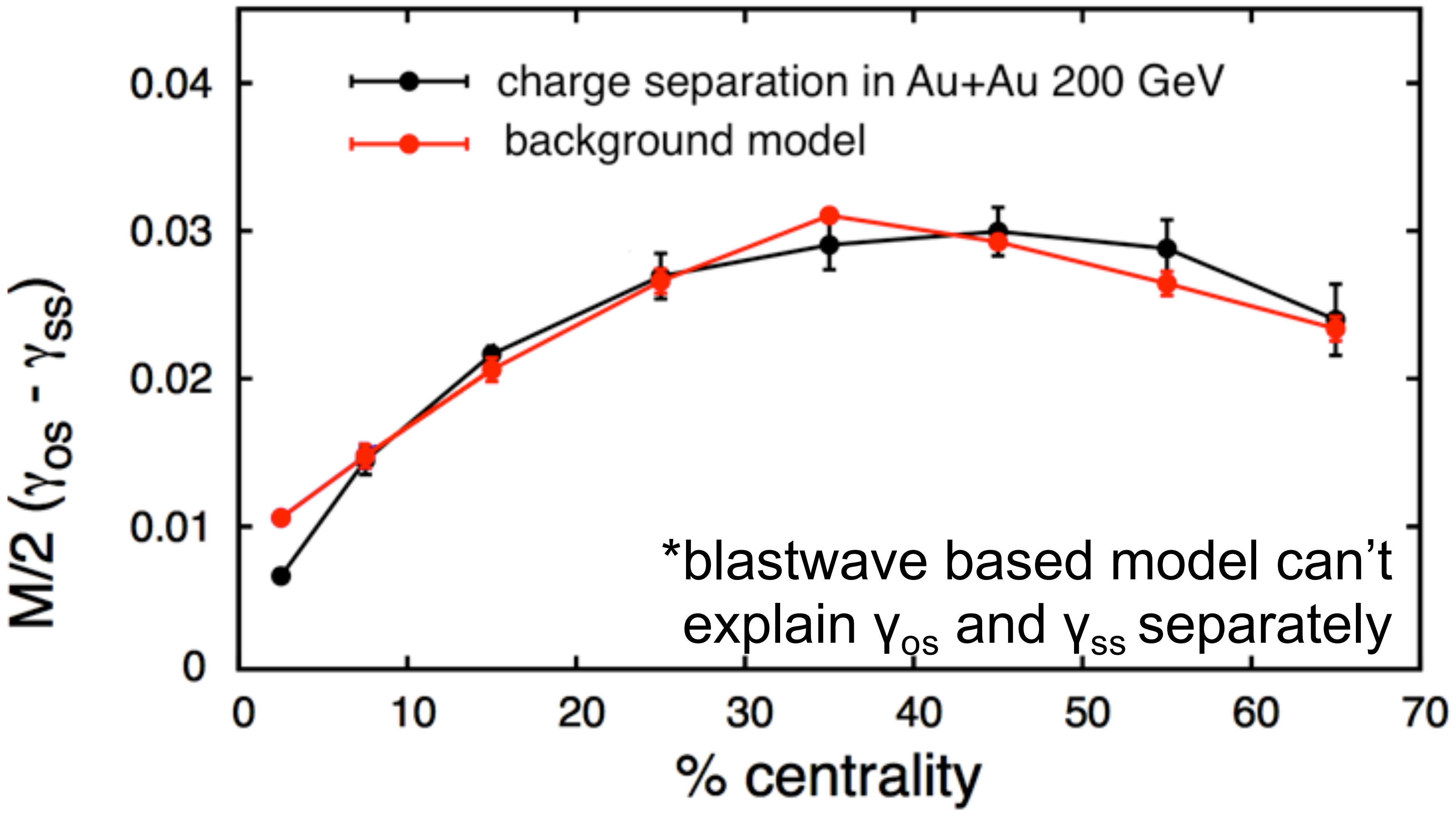


cartoon: P. Tribedy, QM2017



back-to-back jet

S. Schlichting and S. Pratt, Phys. Rev. C **83**, 014913 (2011)



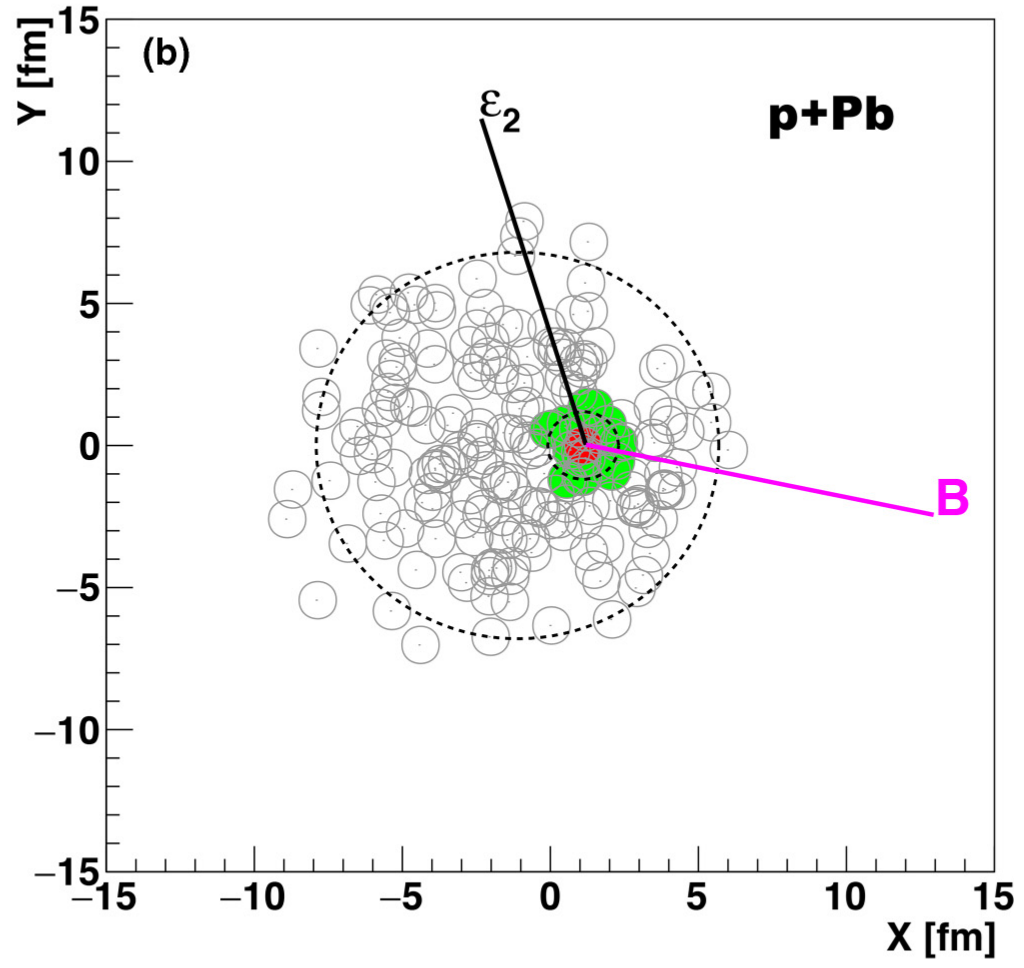
*blastwave based model can’t explain γ_{os} and γ_{ss} separately

At Small system

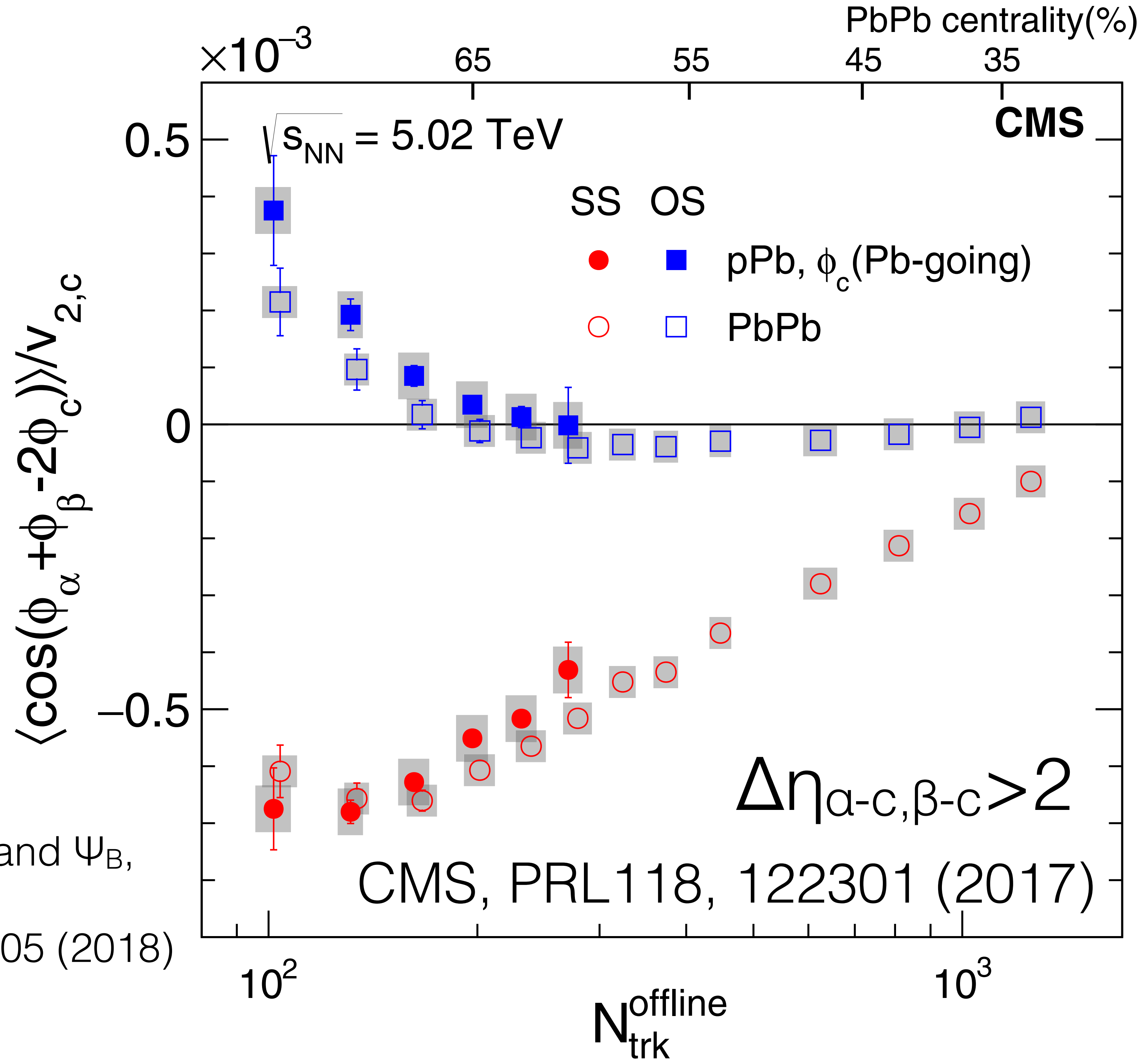
Idea: Event plane (Ψ_{EP}) and B-field (Ψ_B) orientations are uncorrelated
- R. Belmont and J. Nagle, PRC96, 024901 (2017)

η-gap

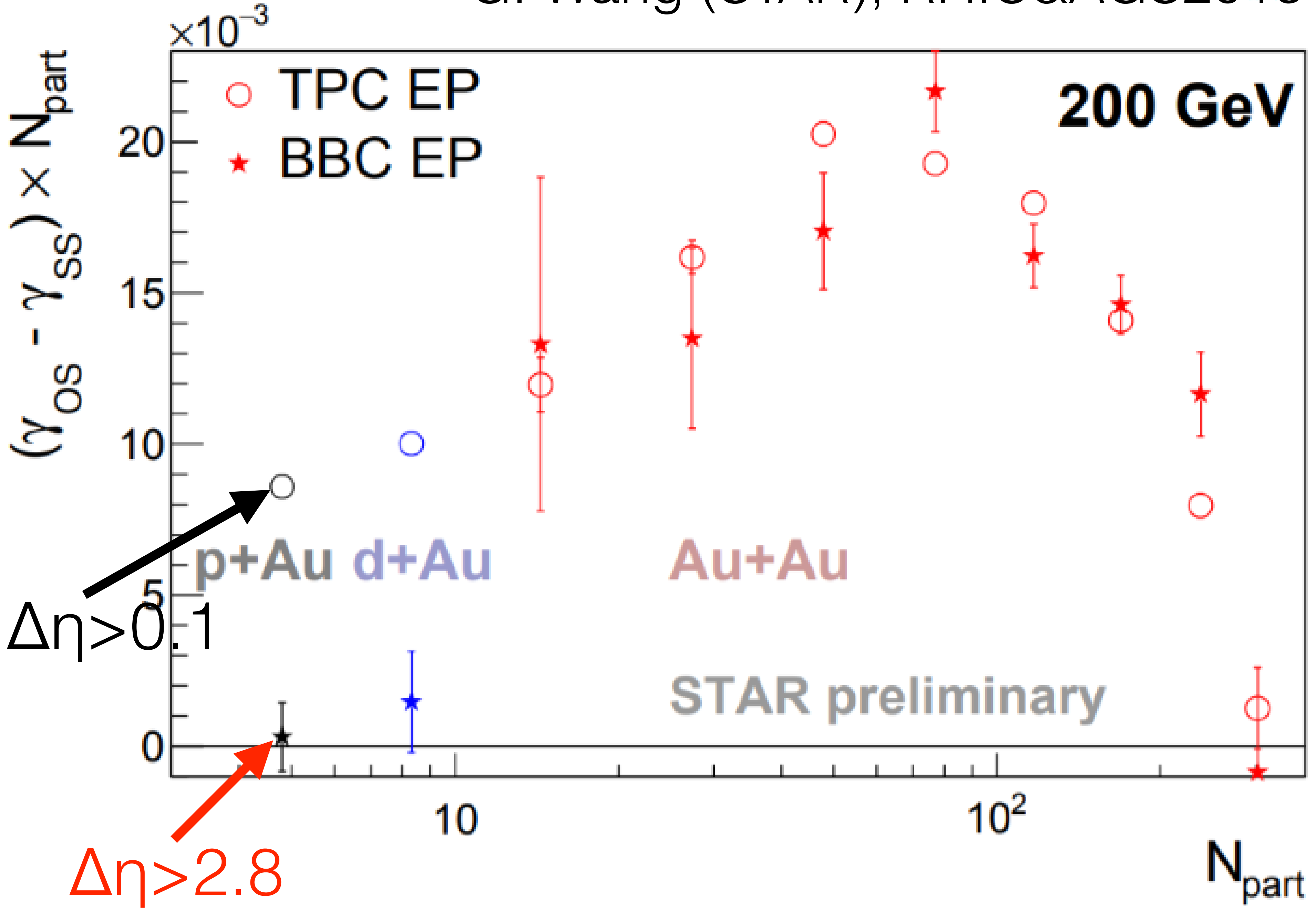
$$\gamma_{\alpha\beta} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$$
$$\Delta\gamma = \gamma_{+-} - \gamma_{\pm\pm}$$



proton size fluctuations gives finite correlation btw Ψ_{EP} and Ψ_B, but much smaller CME signal in p-Pb than in Pb-Pb
- D. Kharzeev, Z. Tu, A, Zhang, and W. Li, PRC97, 024905 (2018)



G. Wang (STAR), RHIC&AGS2018



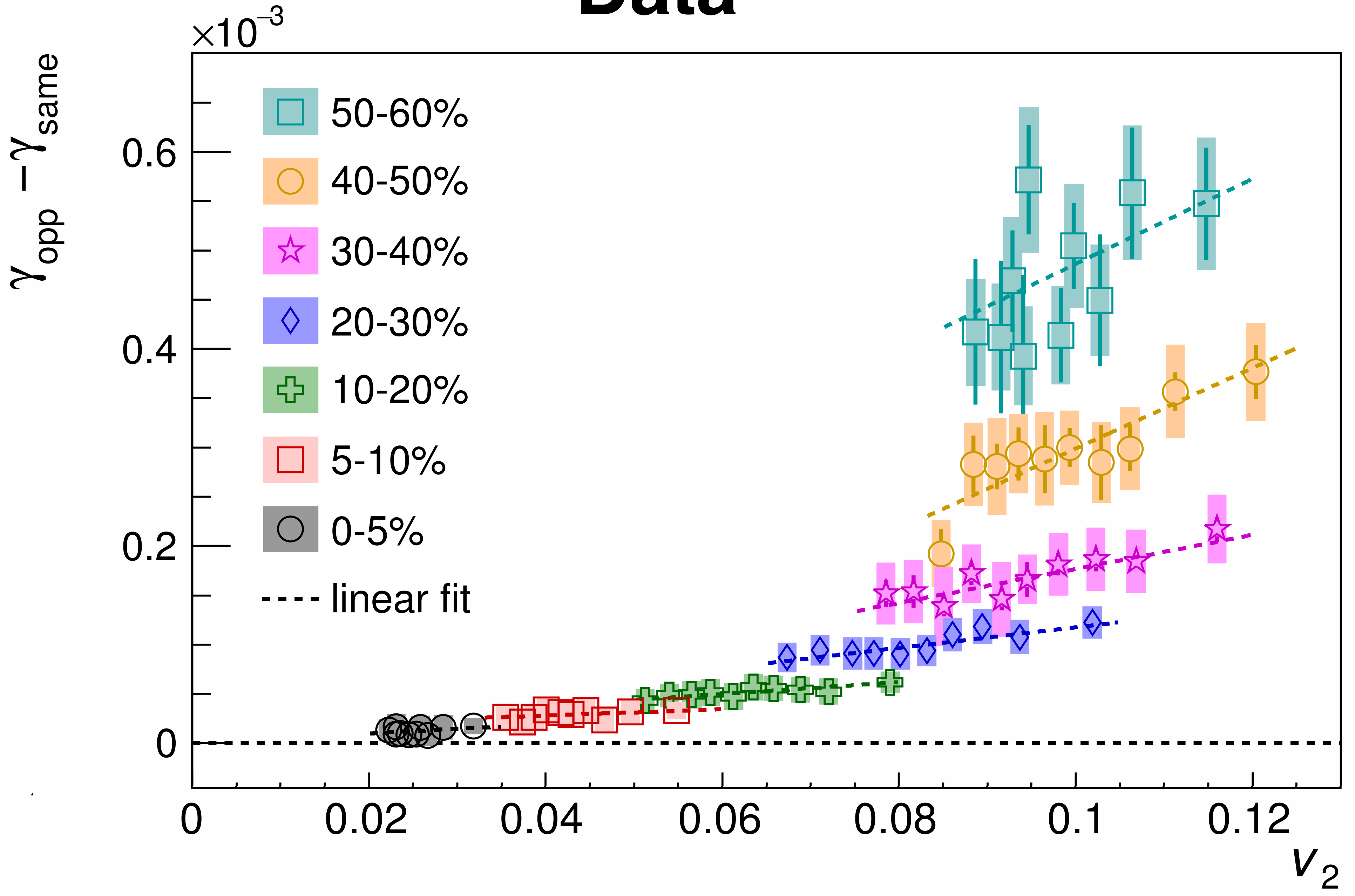
CME is not expected in p(d)+A collisions.
Background (back-to-back jets) would be dominant in low multiplicity events.

Using event shape engineering

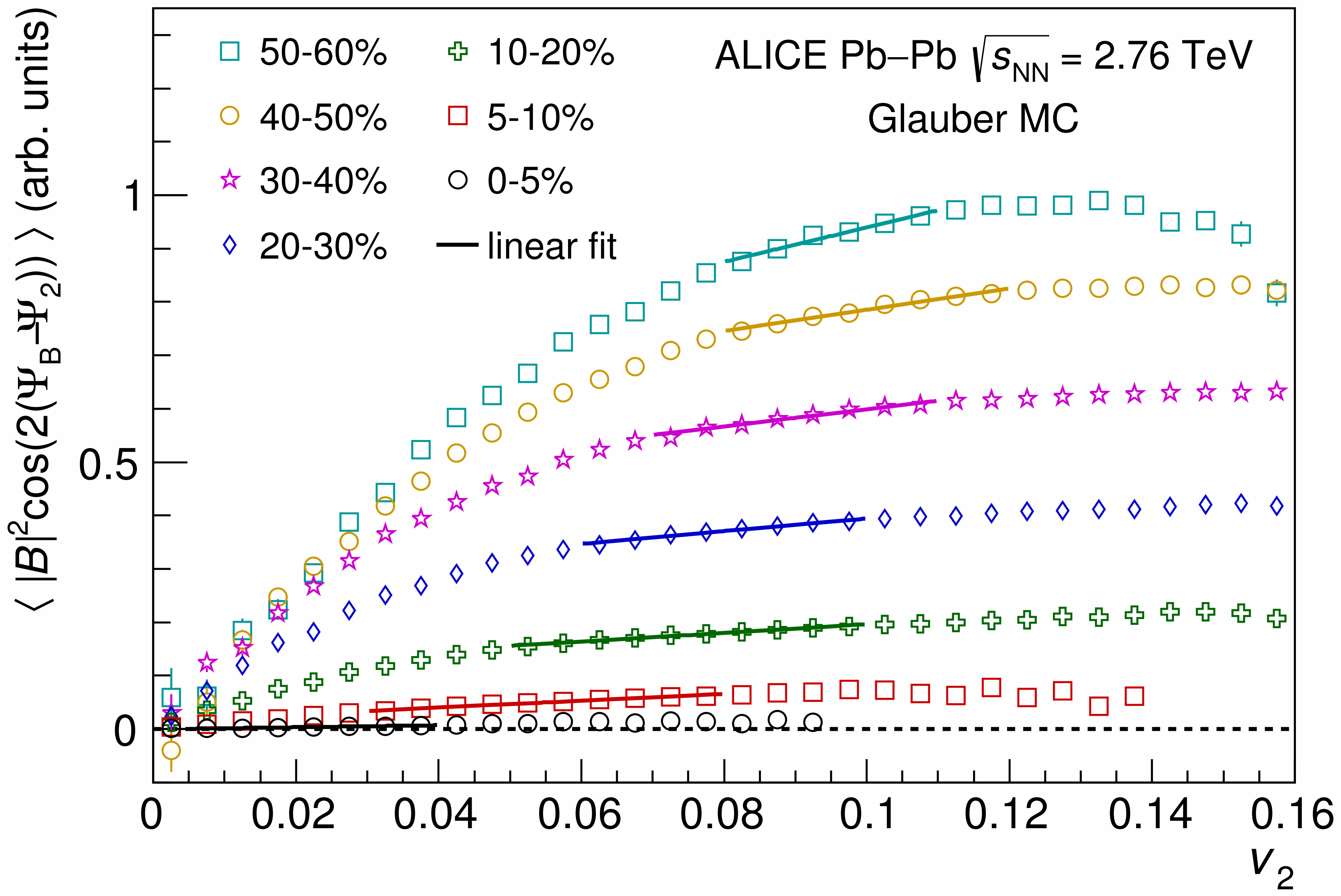
ALICE, PLB777(2018)151

Event shape engineering (ESE) J. Schukraft, A. Timmins, and S. Voloshin, PLB719 (2013) 394
Select larger/smaller v_2 events, likely selecting initial eccentricity

Data



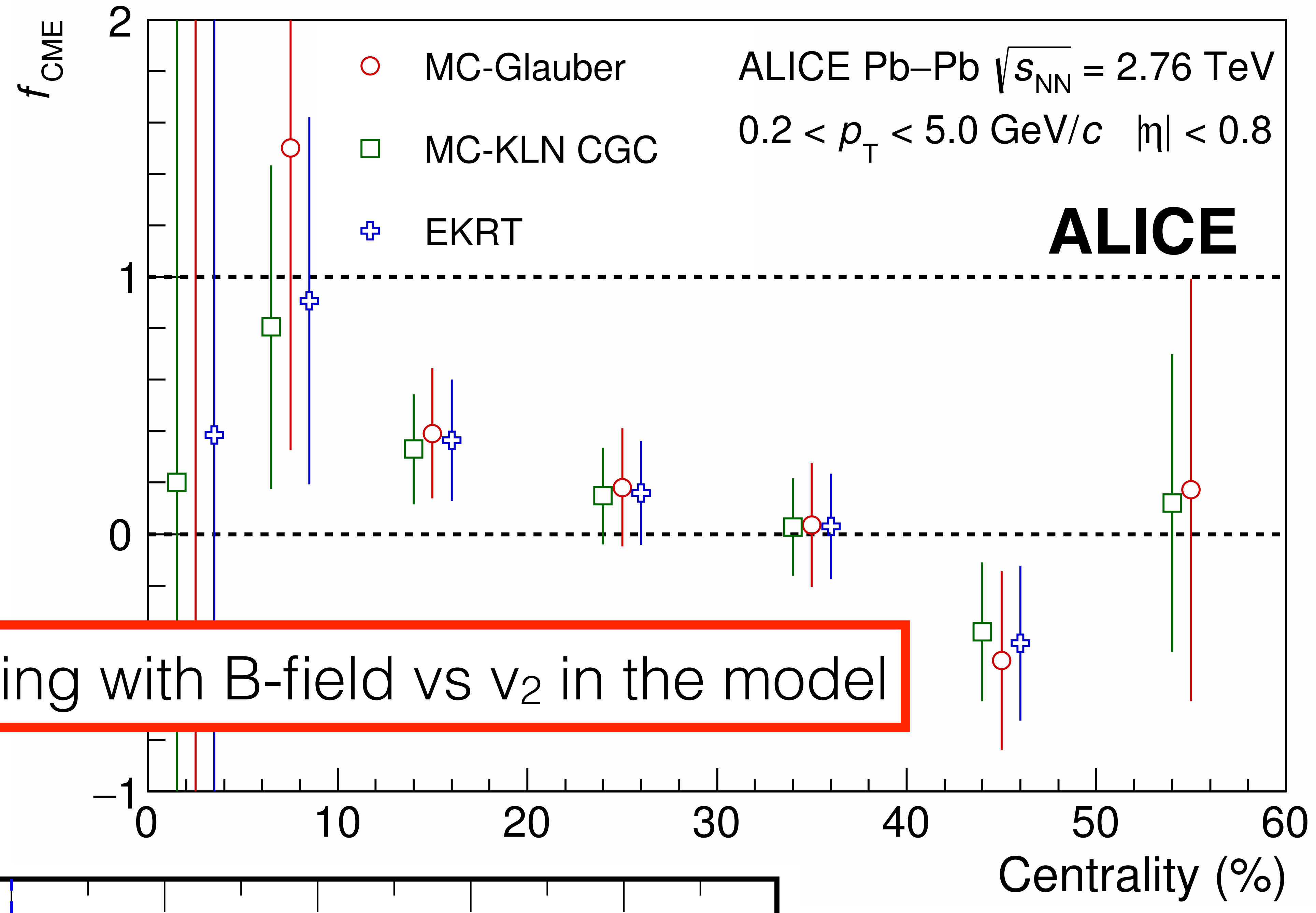
MC simulations $\Delta\gamma^{\rm CME} \propto \langle B^2 \cos(2\Psi_B - 2\Psi_2)\rangle$



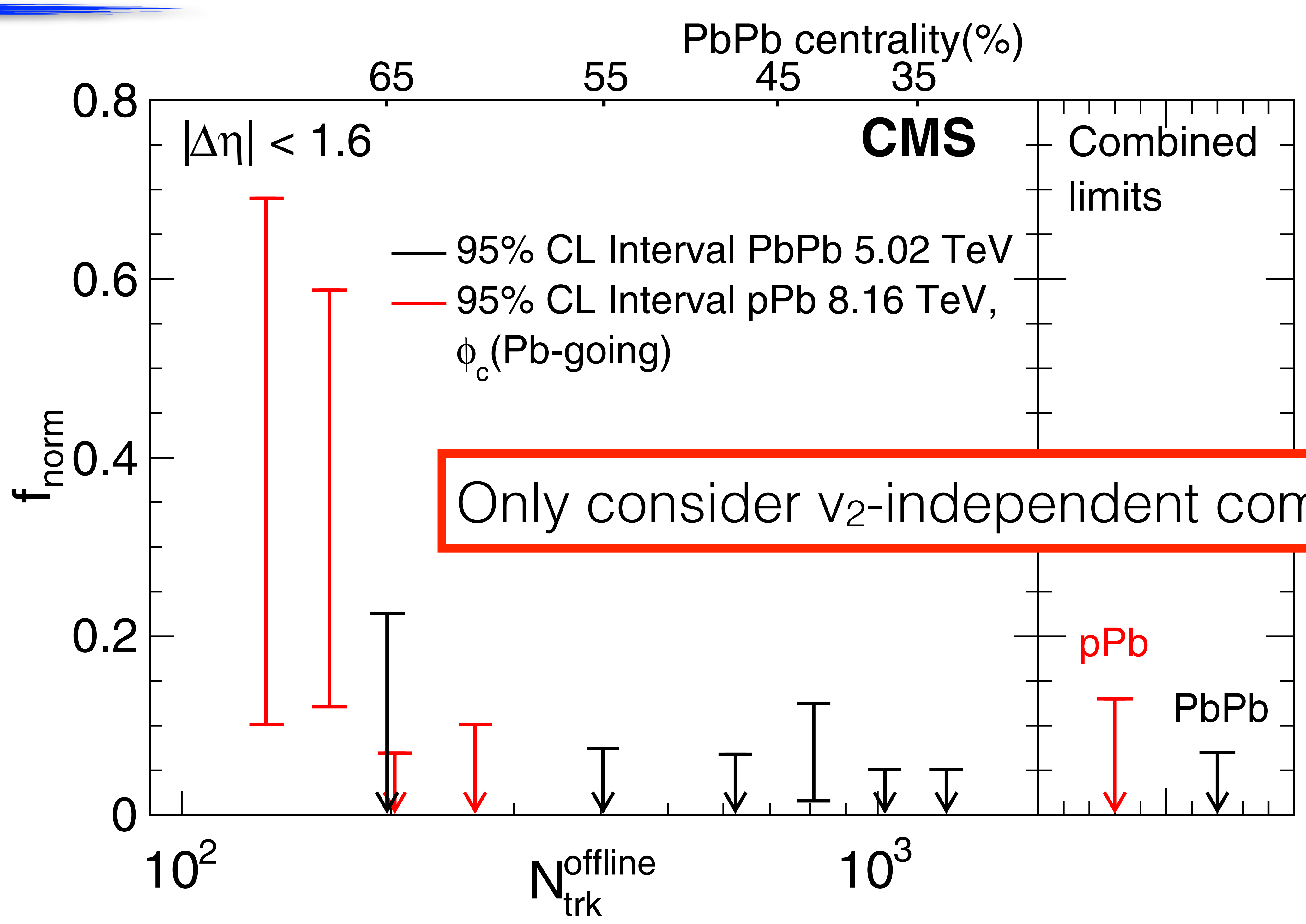
Estimate the CME contribution comparing the slopes with models
- assuming the background is linearly proportional to v_2
- model-dependent estimate of magnetic field at τ=0.2 fm/c

Possible CME contribution

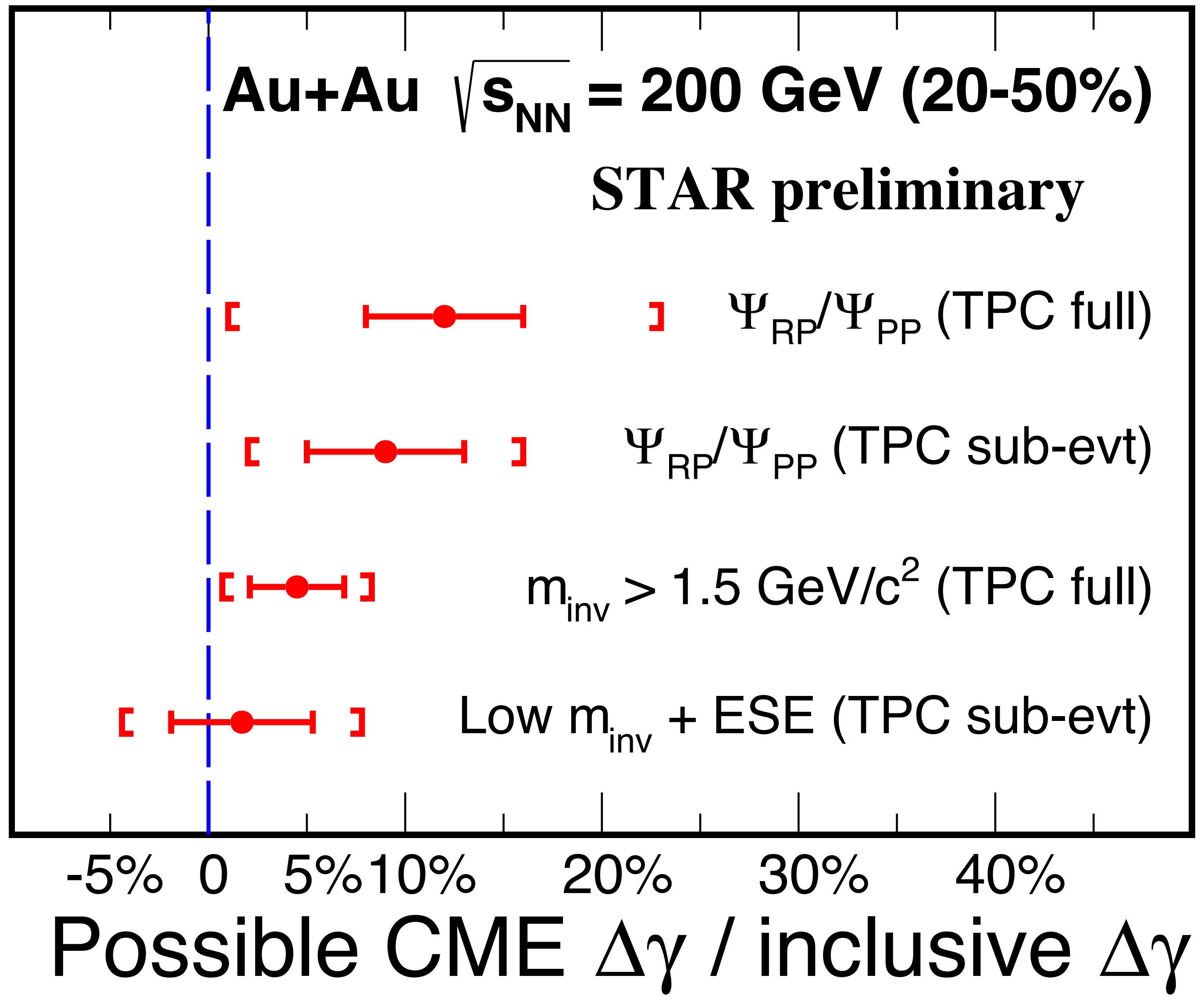
CMS, PRC97, 044912 (2018)
ALICE, PLB777(2018)151
STAR, QM2018



Comparing with B-field vs v_2 in the model



Only consider v_2-independent component



ALICE : <30% in Pb+Pb 2.76 TeV
CMS : <7% in Pb+Pb 5 TeV and <13% in p-Pb 8.16 TeV
STAR : <20% in Au+Au 200 GeV

Good progress to quantify possible CME contribution.
Need to be careful what assumptions are there.

Current observables at a glance

Slide from S. Voloshin @chirality workshop 2019

Observable	(Just a few) names	Problems/questions	My opinion
$\Delta\gamma$ ESE			
ESE “CMS”		Dependence of the signal on v2?	
“q2obs”ESE	F. Wang, G. Wang	“Play” on stat. fluctuations, Not-interpretable?	
small systems	CMS, F. Wang, others	Strong RP independent background, nothing/little to say about CME	
Mixed harmonics	Voloshin, CMS, many others	Requires detailed knowledge about the kinematic of the cluster decays (as e.g. pT)	
invariant mass	F. Wang, J. Zhao	Requires knowledge of the inv. mass spectrum of “sphaleron” decays	
Spectator /participant EP	F. Wang, J. Zhao; S. Voloshin	Promising with careful treatment of contributions to v2 and gamma	
$\Delta\gamma,\ \Delta\delta;\ H, F, \kappa$	J. Liao, G. Wang, et al	No strict justification => imprecise	
“Balance function”	A. Tang	“General” questions from previous page	?
ΔS	R. Lacey	“General” questions from previous page	

page 2 5-th Chirality workshop... Tsinghua U., April 9, 2019 S.A. Voloshin WAYNE STATE UNIVERSITY

- A lot of idea/observables but need to make their assumptions clear

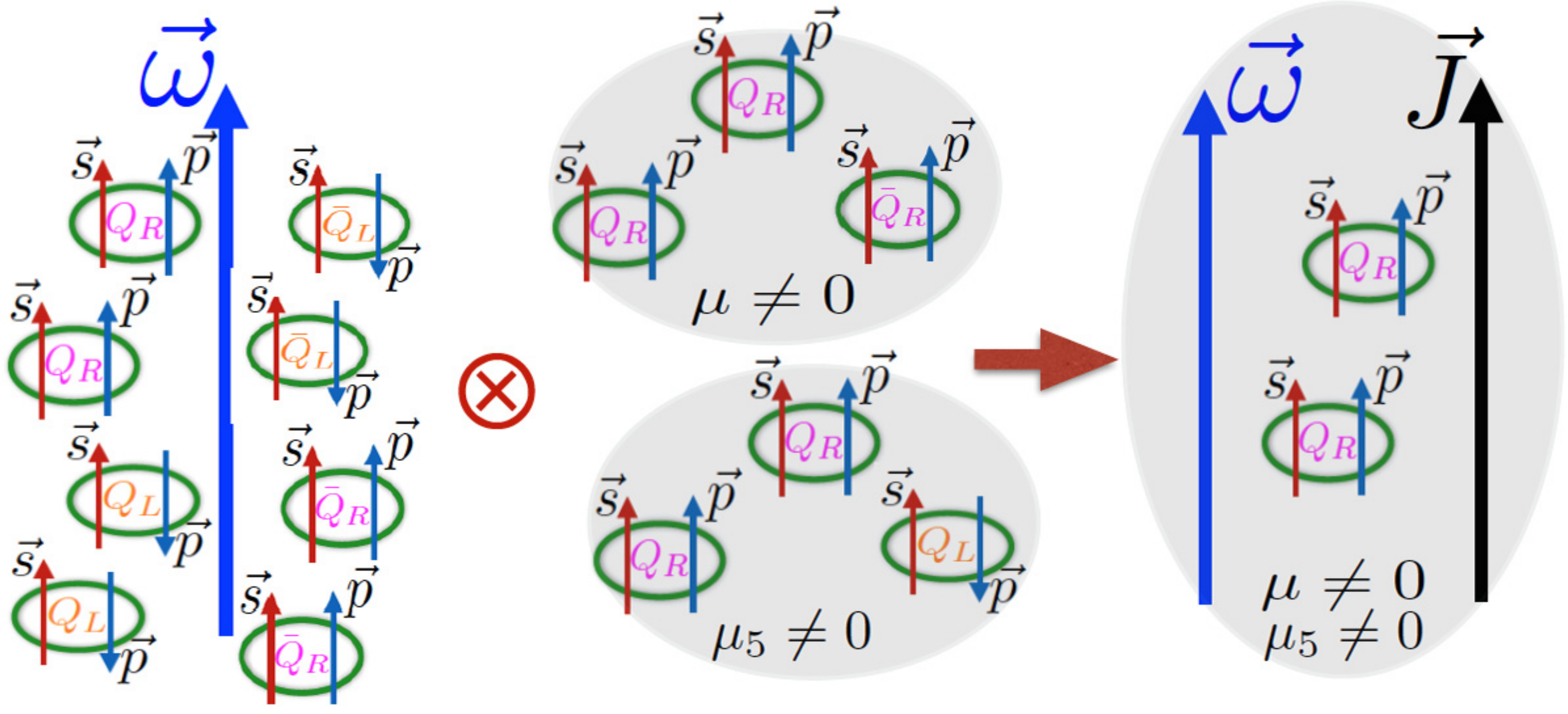
- Results of isobaric collisions will come soon (see outlook slide)

Chiral Vortical Effect (CVE)

詳細は山本さんの講演参照

Similar to CME,
system rotation leads to vector and axial current along ω

D. Kharzeev and D. Son, PRL106.062301 (2011)
D. Kharzeev et al., PPNP88(2016)1-28



$$J_E^{\mathrm{CME}} \sim \tfrac{2}{3}(N_f = 3) \quad \text{or} \quad \tfrac{5}{9}(N_f = 2)$$
$$J_B^{\mathrm{CME}} = 0(N_f = 3) \quad \text{or} \quad \sim \tfrac{1}{9}(N_f = 2).$$

$$J_E^{\mathrm{CVE}} = 0(N_f = 3) \quad \text{or} \quad \sim \tfrac{1}{3}(N_f = 2);$$
$$J_B^{\mathrm{CVE}} \sim 1(N_f = 3) \quad \text{or} \quad \sim \tfrac{2}{3}(N_f = 2).$$

Q(u, d, s)=(+2/3, -1/3, -1/3)
B(u, d, s)=(1/3, 1/3, 1/3)

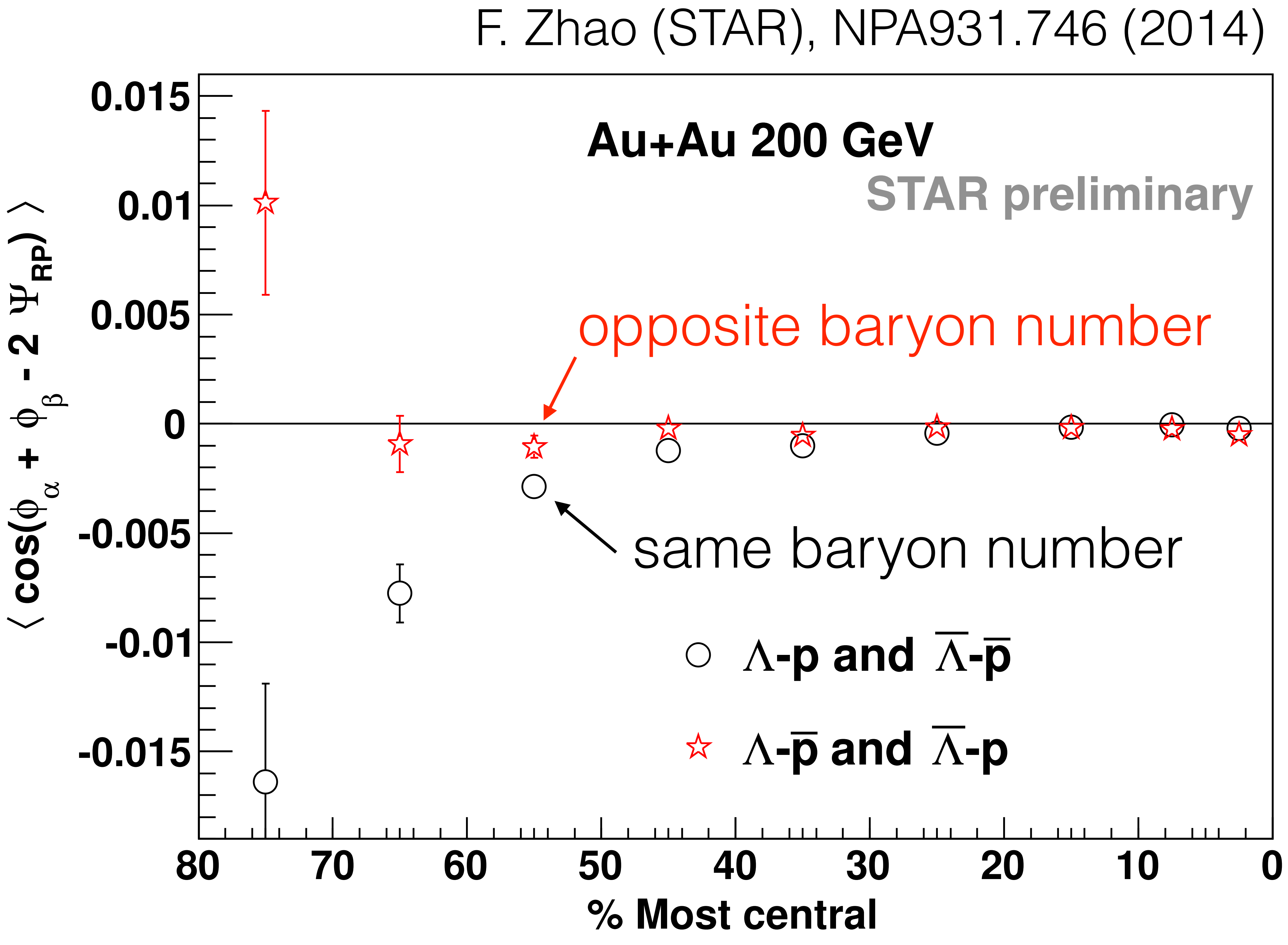
$$\vec{J}_{\mathrm{v}} = \frac{1}{\pi^2}\mu\mu_5\vec{\omega}$$

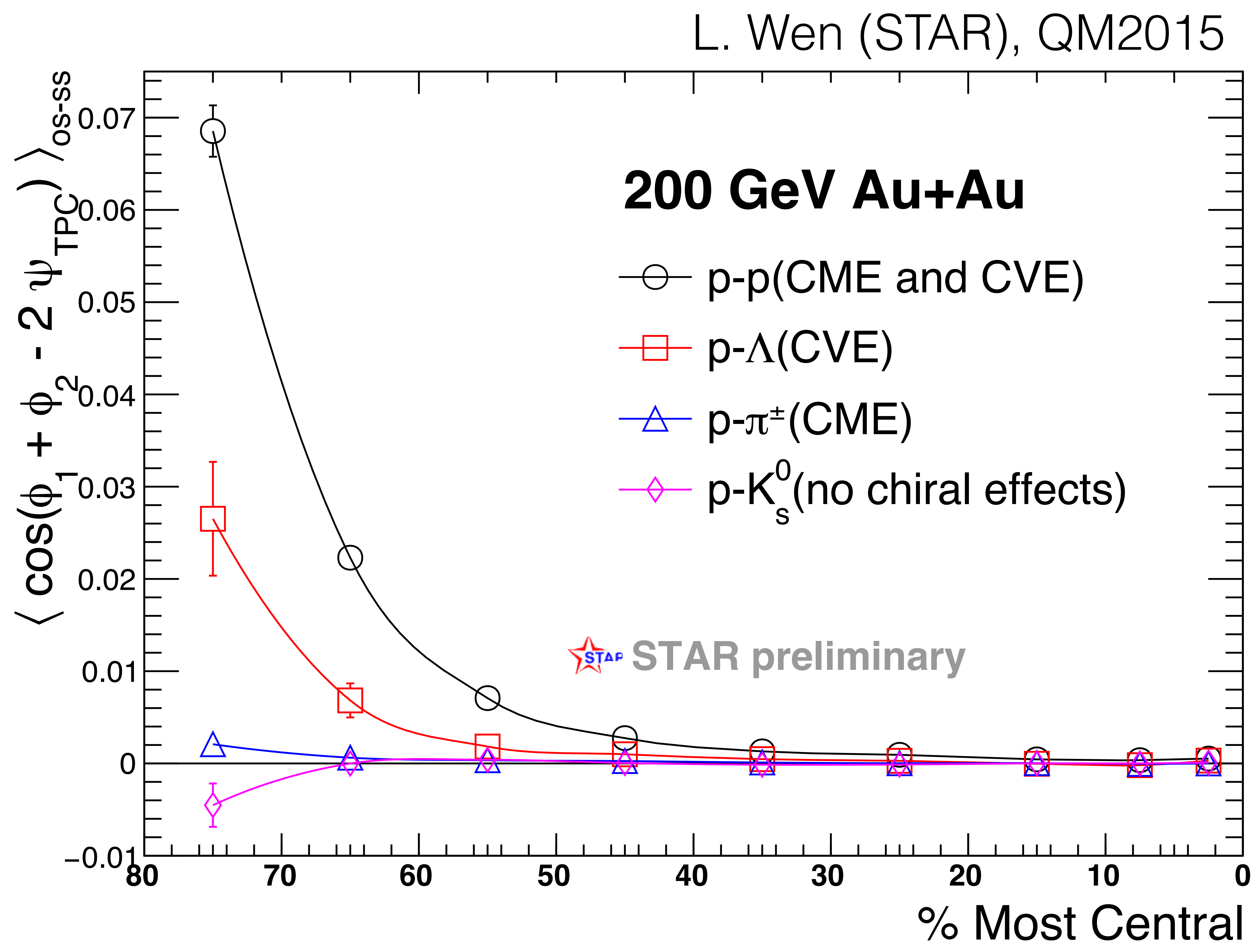
$$\vec{J}_5 = \left[\frac{1}{2\pi^2}(\mu^2 + \mu_5^2) + \frac{1}{6}T^2\right]\vec{\omega}$$

(analogous to CSE)

Spin polarization by vorticity is “charge-blind”.
CVE mostly contributes to baryon current.

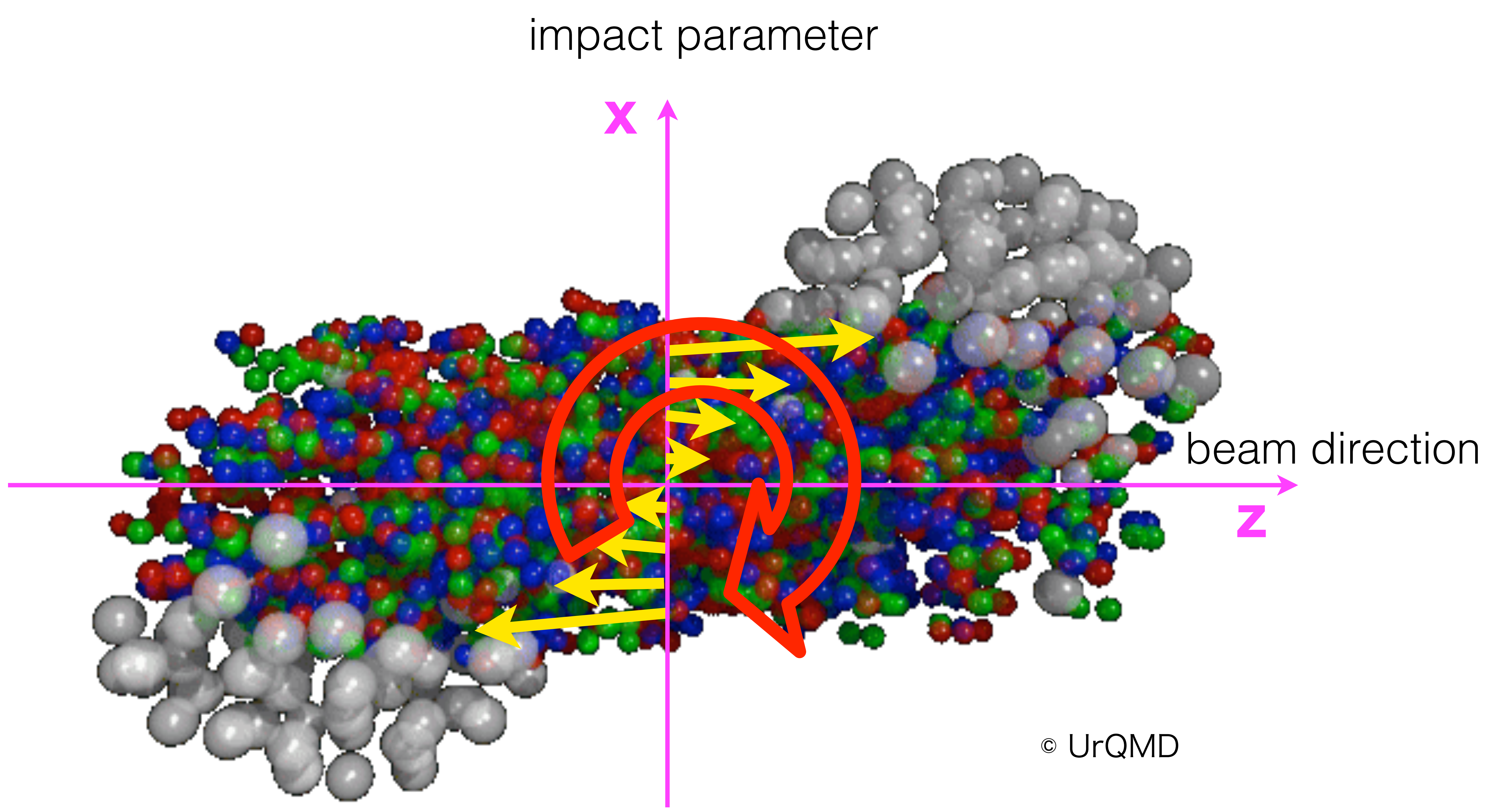
Baryon-baryon (hadron) correlations





$\gamma_{OS} > \gamma_{SS}$ and hierarchy of p-hadron γ correlator, consistent with CVE expectation, although there would be BG effects.

Vorticity in HIC

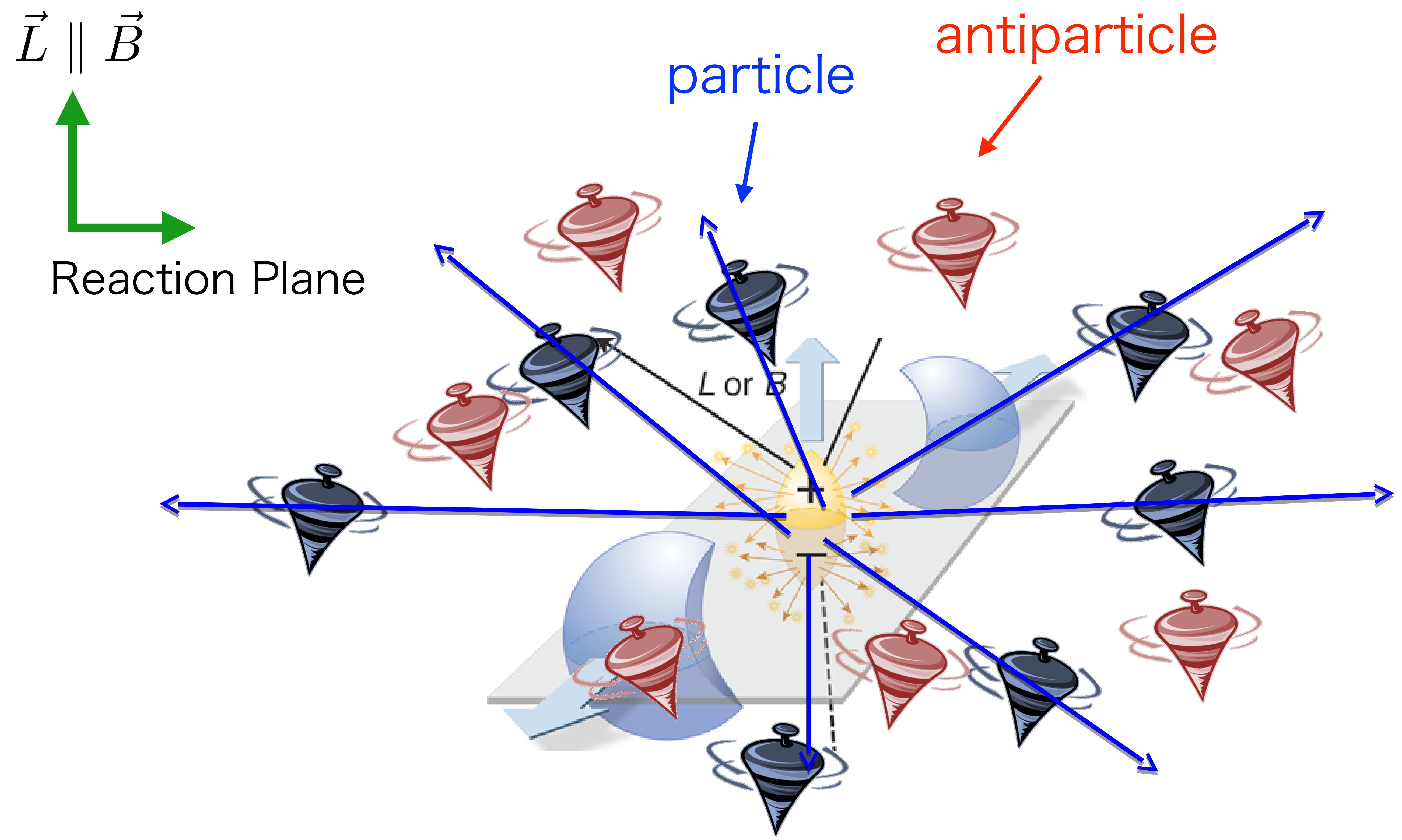


In non-central collisions,
the initial collective longitudinal flow velocity depends on x.

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

Global polarization

- Z.-T. Liang and X.-N. Wang, PRL94, 102301 (2005)
- S. Voloshin, nucl-th/0410089 (2004)



- Non-zero angular momentum transfers to the spin degrees of freedom
  - Particles' and anti-particles' spins are aligned with angular momentum, ***L***
- Magnetic field align particle's spin
  - Particles' and antiparticles' spins are aligned oppositely along ***B*** due to the opposite sign of magnetic moment

Rotation vs. Polarization

Barnett effect:

rotation→polarization

Magnetization of an uncharged body when spun on its axis

S. Barnett, Phys. Rev. 6, 239 (1915)

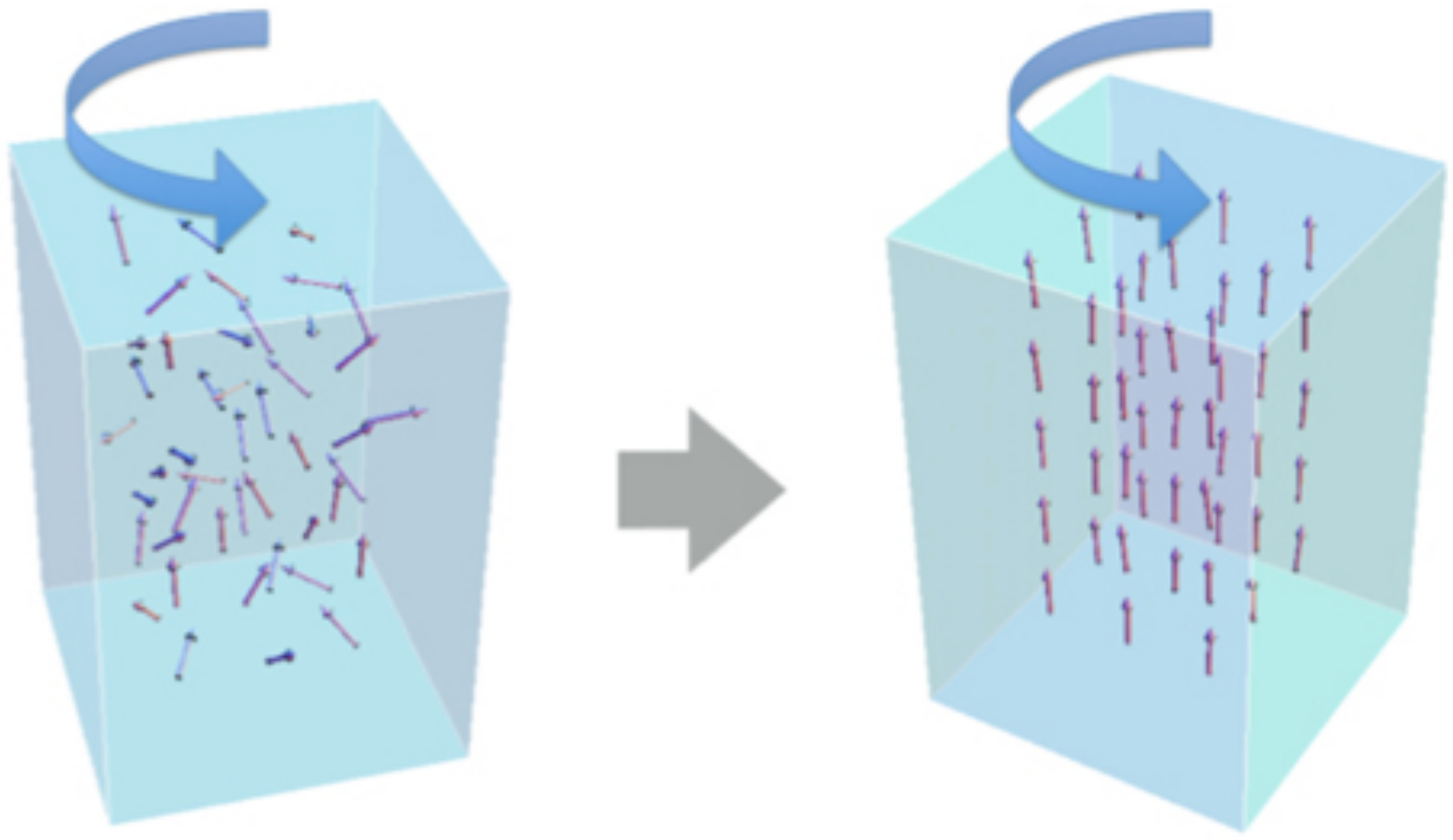


figure: M. Matsuo et al., Front. Phys., 30 (2015)

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

χ: magnetic susceptibility
γ: gyromagnetic ratio

Einstein-de-Haas effect:

polarization→rotation

"the only experiment by Einstein"

Rotation of a ferromagnet under change in the direction/strength of magnetic-field to conserve the total angular momentum.

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

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

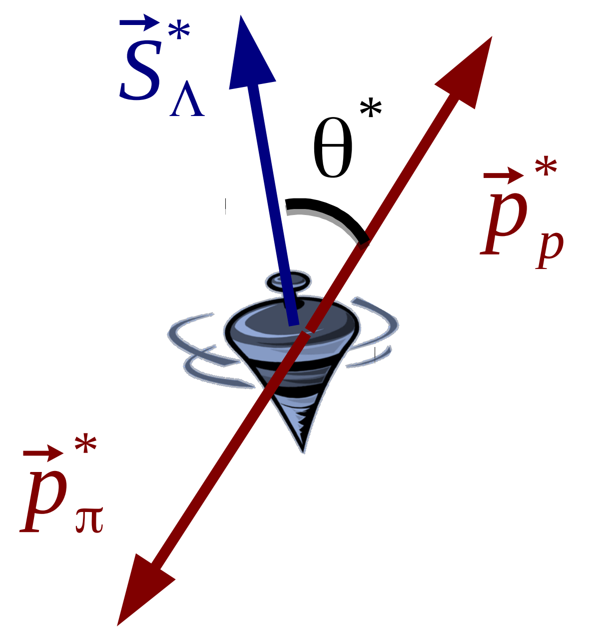
How to measure the global polarization?

Parity-violating decay of hyperons

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

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

P_H: Λ polarization
p_p^*: proton momentum in the Λ rest frame
α_H: Λ decay parameter
($\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.642 \pm 0.013$)



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

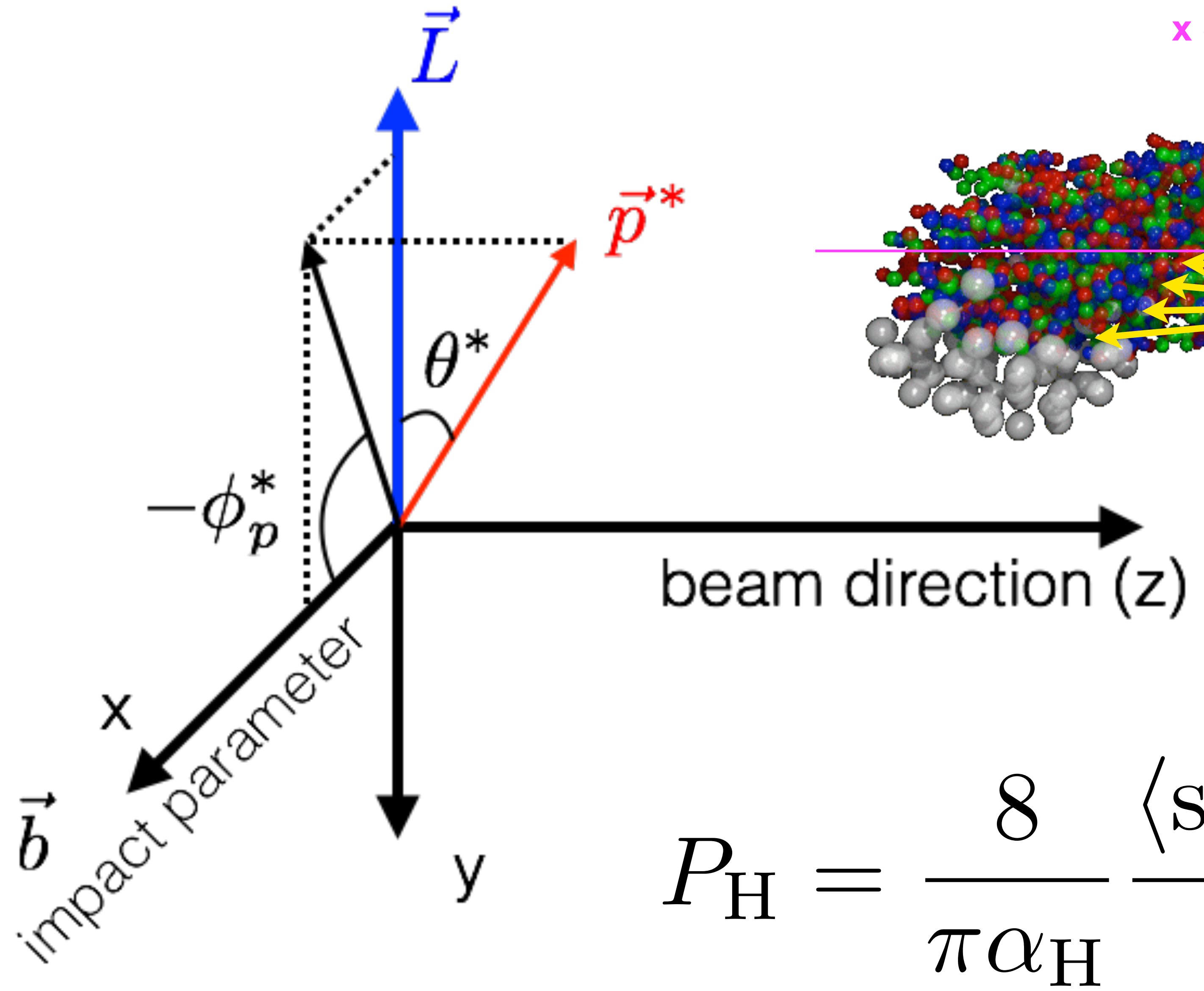
(BR: 63.9%, cτ ~7.9 cm)

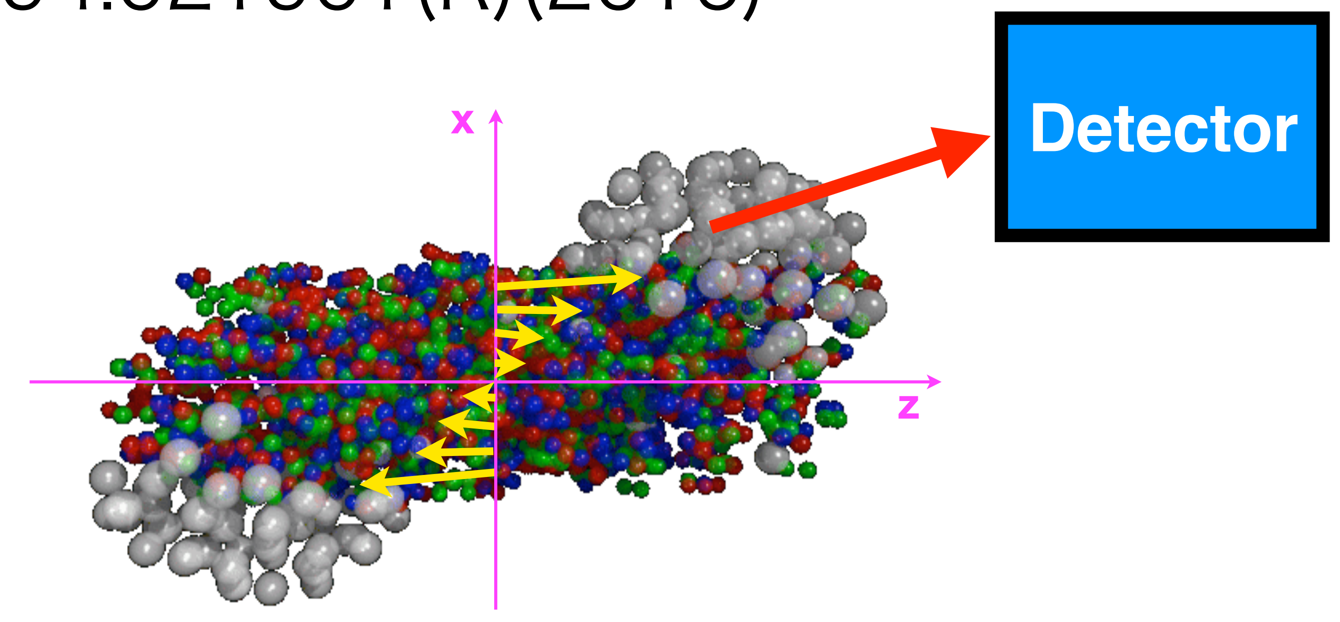
C. Patrignani et al. (PDG), Chin. Phys. C 40, 100001 (2016)

Projection onto the transverse plane

Angular momentum direction can be determined by spectator deflection (spectators deflect outwards)

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

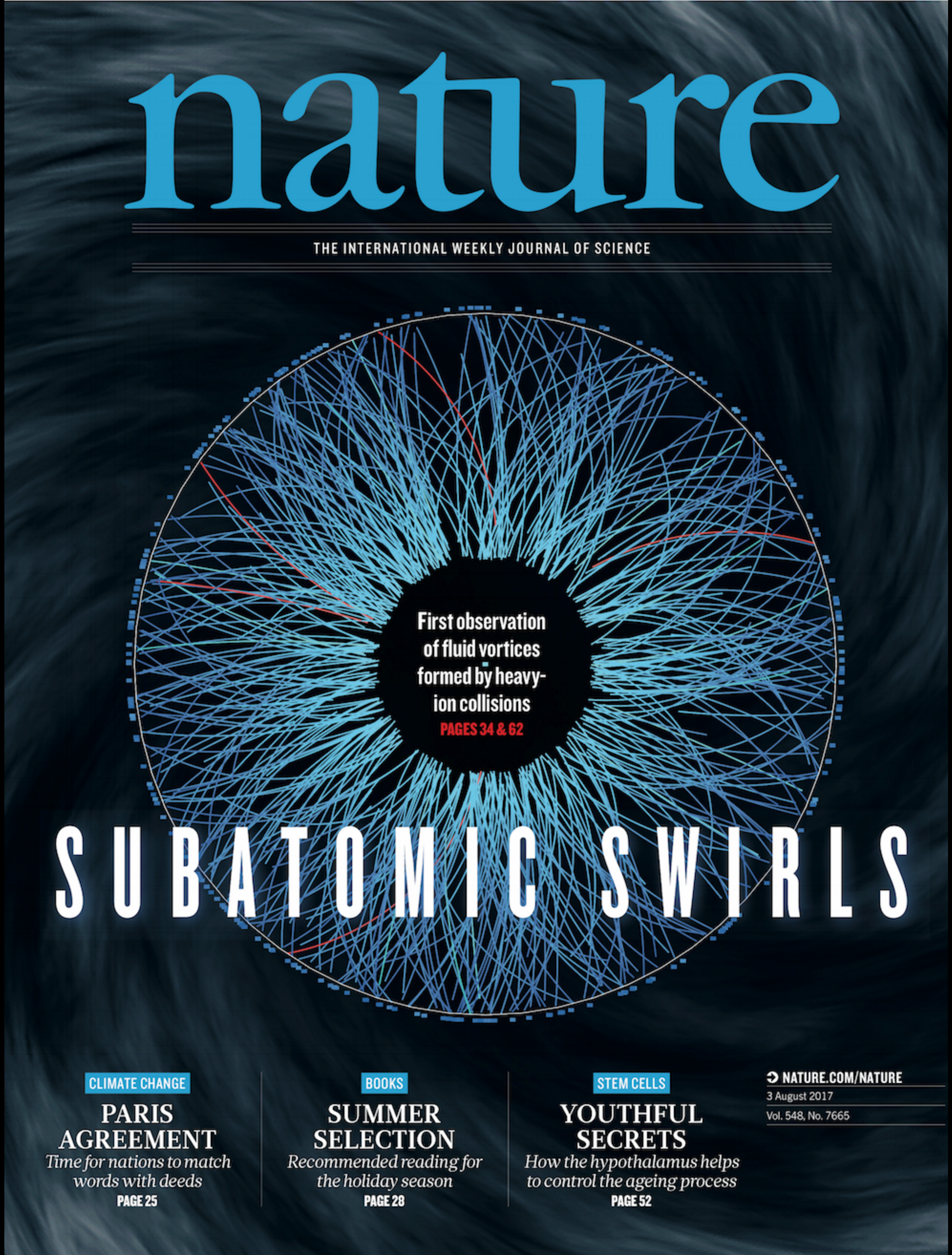




$$P_{\rm H} = \frac{8}{\pi\alpha_{\rm H}}\frac{\langle\sin(\Psi_1 - \phi^*_p)\rangle}{{\rm Res}(\Psi_1)}$$

Ψ_1: azimuthal angle of b
ϕ_p^*: ϕ of daughter proton in Λ rest frame

STAR, PRC76, 024915 (2007)

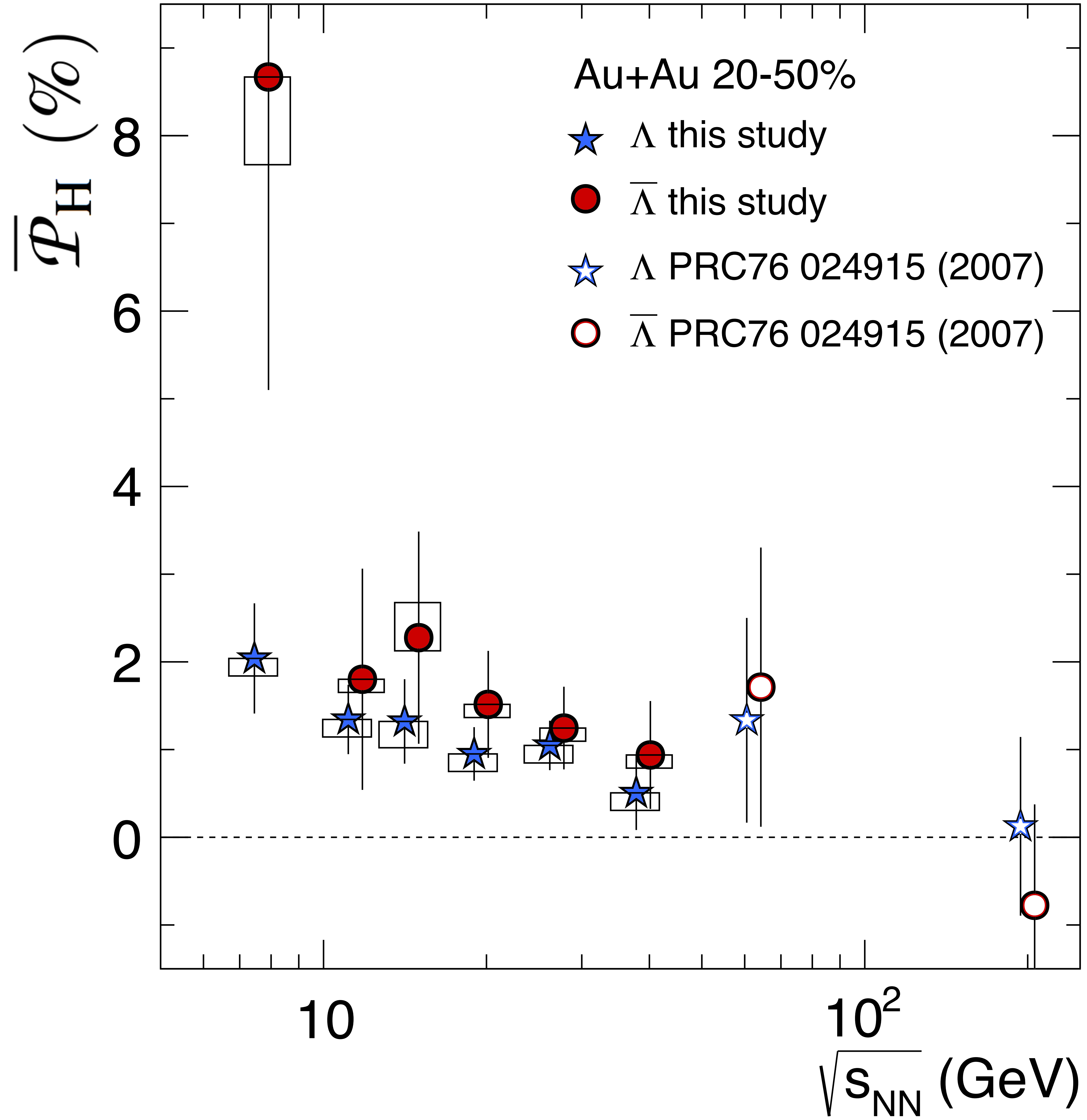


First observation of
fluid vortices formed by HIC

Discover Magazine, 2017

First observation of fluid vortices in HIC

STAR, Nature 548, 62 (2017)



Positive polarization signal at lower energies!

-- The most vortical fluid!

$$\omega = (P_\Lambda + P_{\bar{\Lambda}}) k_B T / \hbar$$
$$\sim 0.02\text{-}0.09 \ \mathrm{fm}^{-1}$$
$$\sim 0.6\text{-}2.7 \times 10^{22} \mathrm{s}^{-1}$$ (T=160 MeV)

μ_Λ: Λ magnetic moment
T: temperature at thermal equilibrium

- P_H looks to increase in lower energies

- Hint of the difference in P_H between Λ and anti-Λ
  -- Effect of the initial magnetic field? → BESII

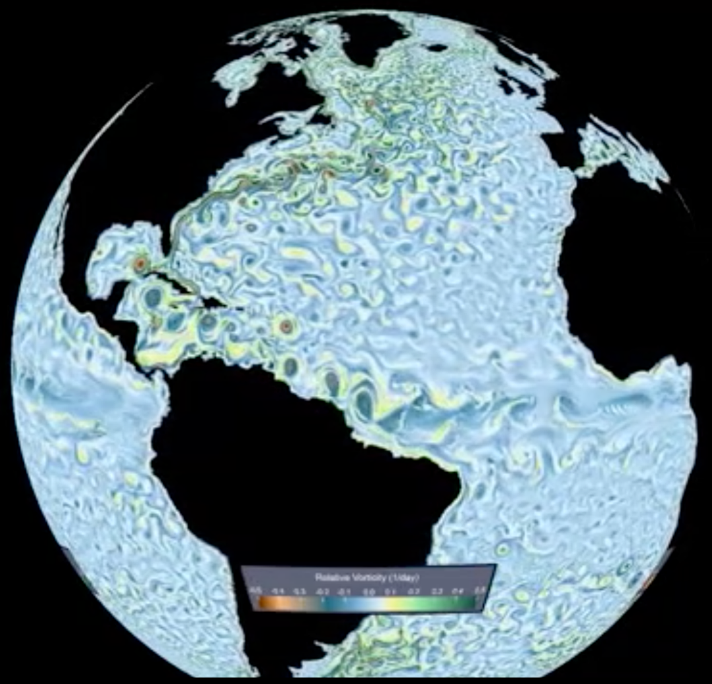
$$P_\Lambda \simeq \frac{1}{2}\frac{\omega}{T} + \frac{\mu_\Lambda B}{T}$$
$$P_{\bar{\Lambda}} \simeq \frac{1}{2}\frac{\omega}{T} - \frac{\mu_\Lambda B}{T}$$

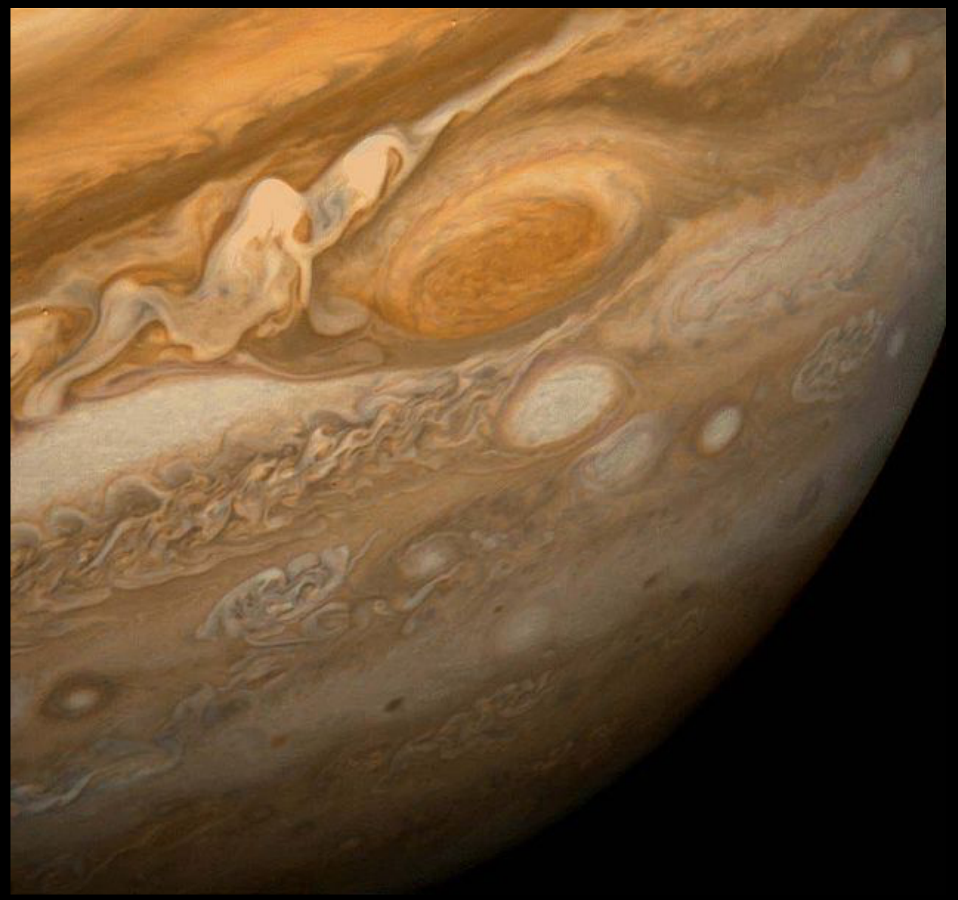
Becattini, Karpenko, Lisa, Upsal, and Voloshin, PRC95.054902 (2017)

Vorticity we know

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

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

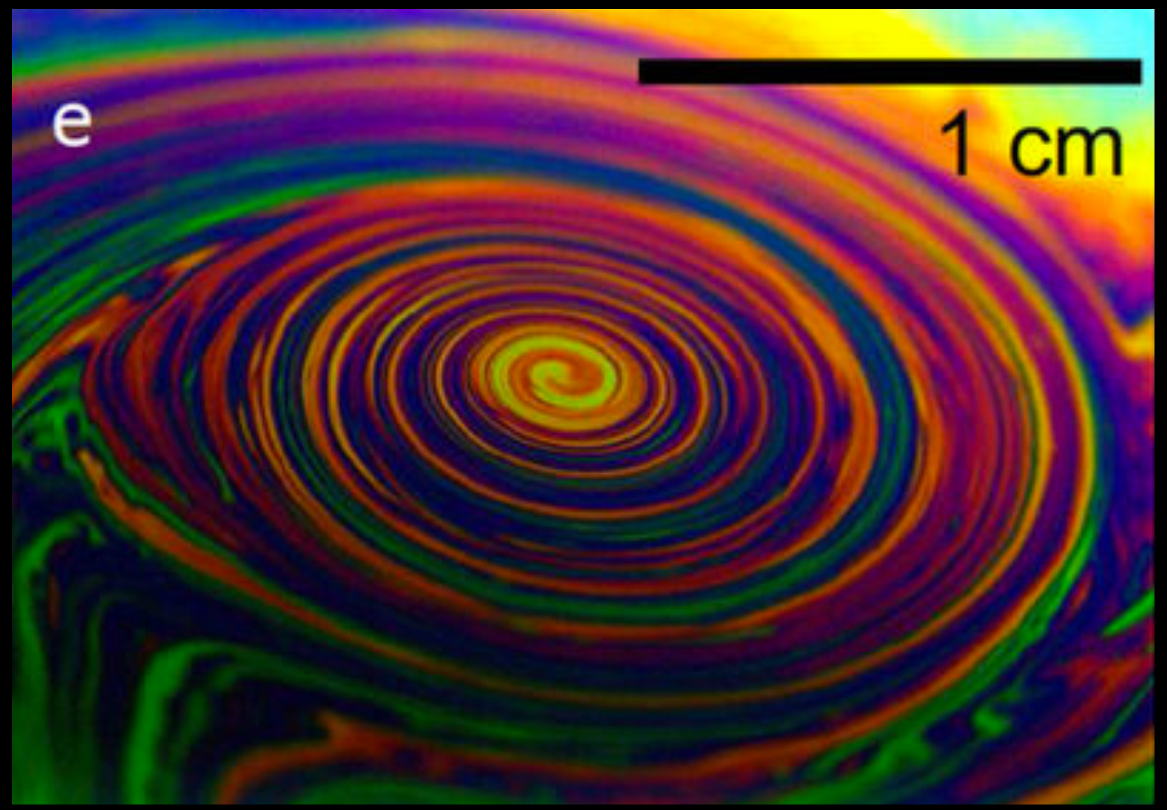


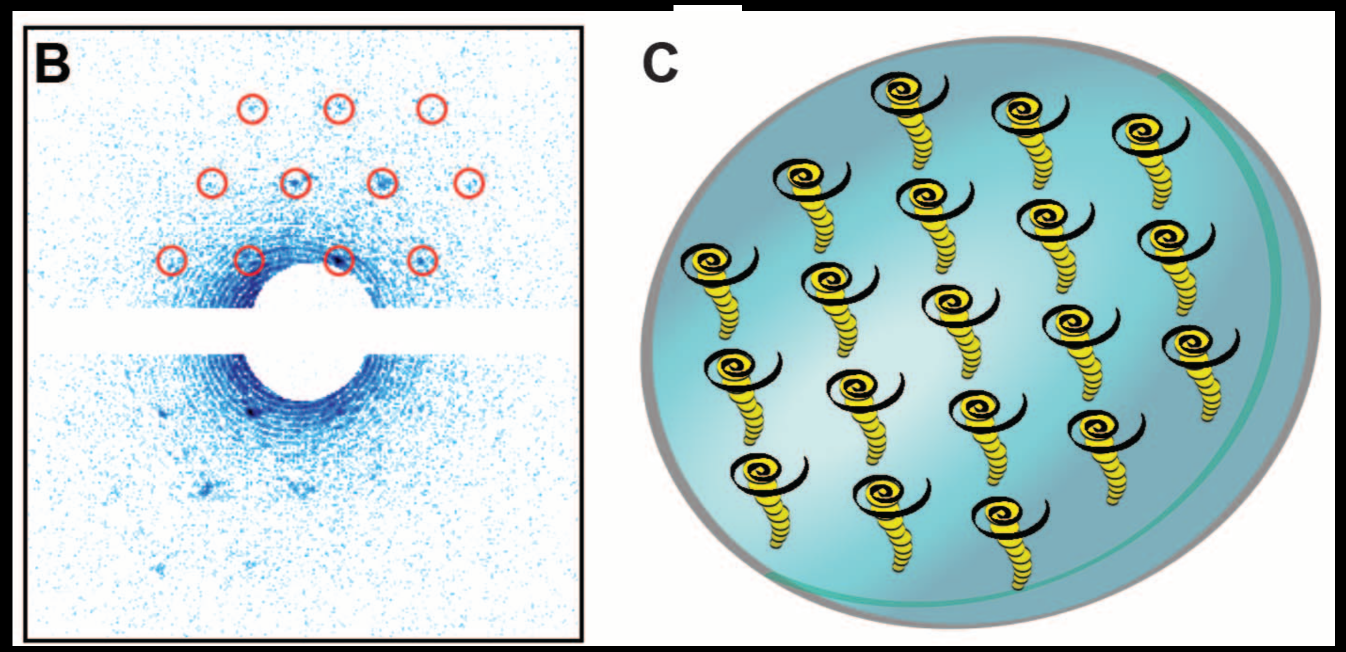


Great red spot of Jupiter
(from wikipedia)

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!

Ocean surface vorticity $\sim 10^{-5}\ s^{-1}$

Jupiter's great red spot $\sim 10^{-4}\ s^{-1}$

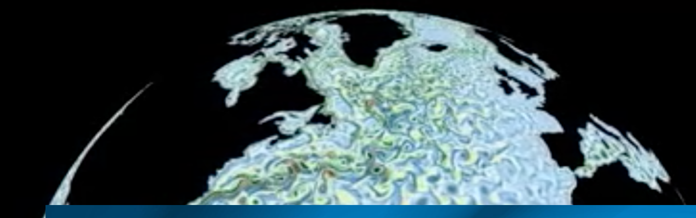
Core of supercell tornado $\sim 10^{-1}\ s^{-1}$

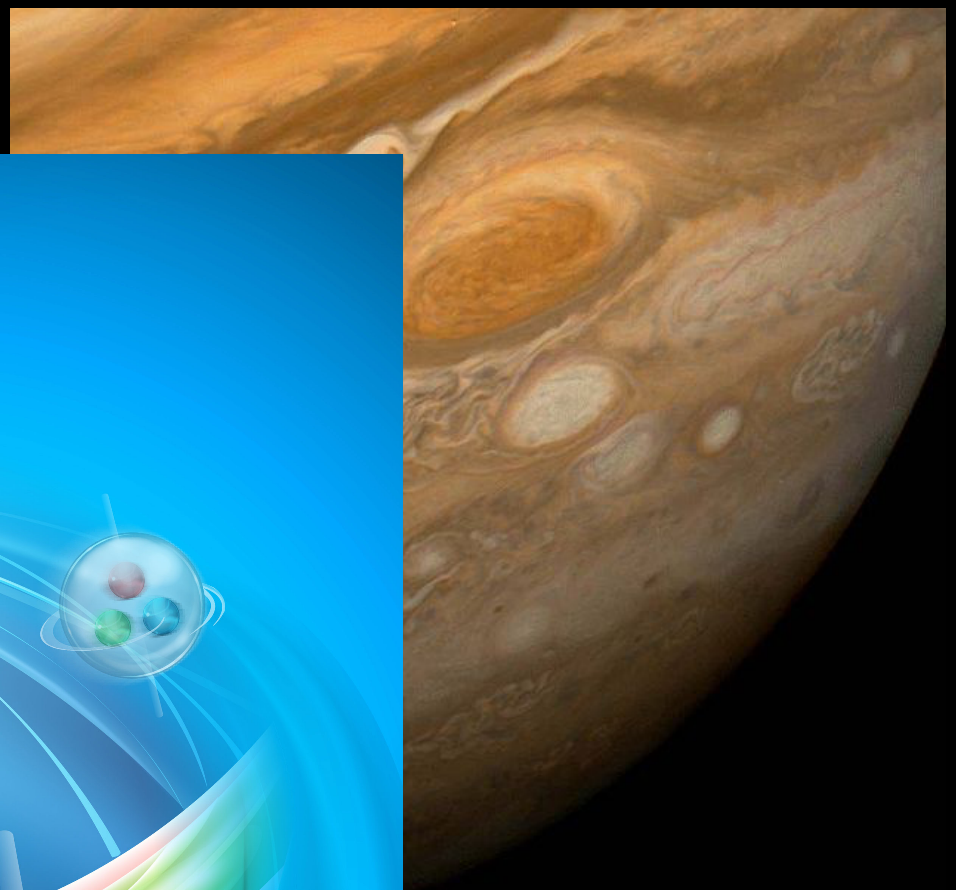
Rotating, heated soap bubbles $\sim 10^{2}\ s^{-1}$

Superfluid helium nano droplet $\sim 10^{6}\ s^{-1}$

Matter in heavy ion collisions $\sim 10^{22}\ s^{-1}$

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





t of Jupiter
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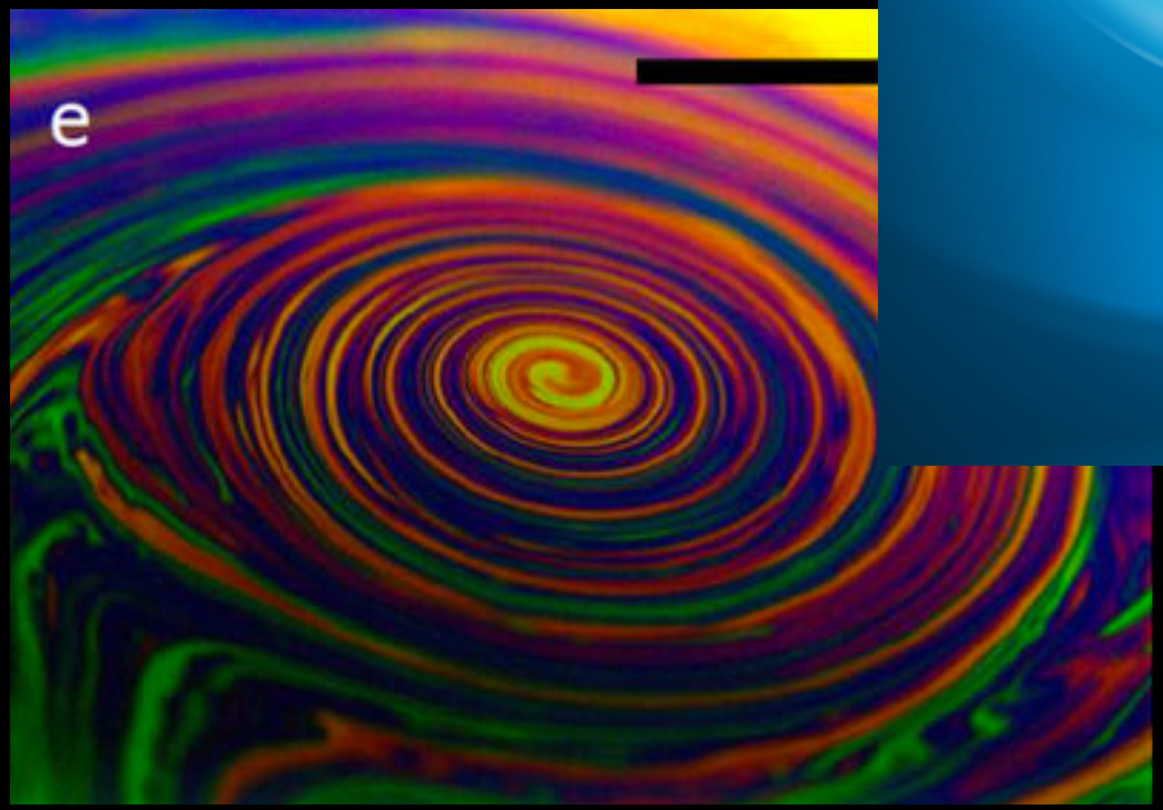
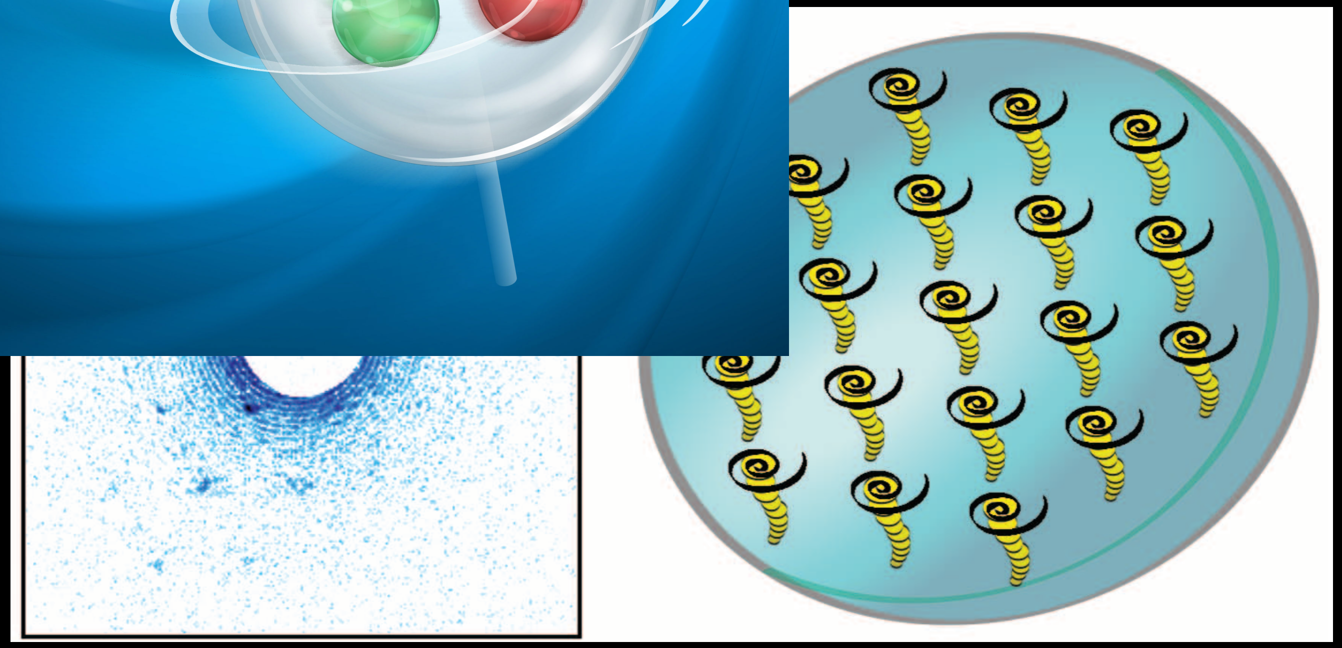
T. Muel et al., Scientific Report 3





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

Feed-down effect

- Only ~25% of measured Λ and anti-Λ are primary, while ~60% 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

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

$C_{\Lambda R}$: 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

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

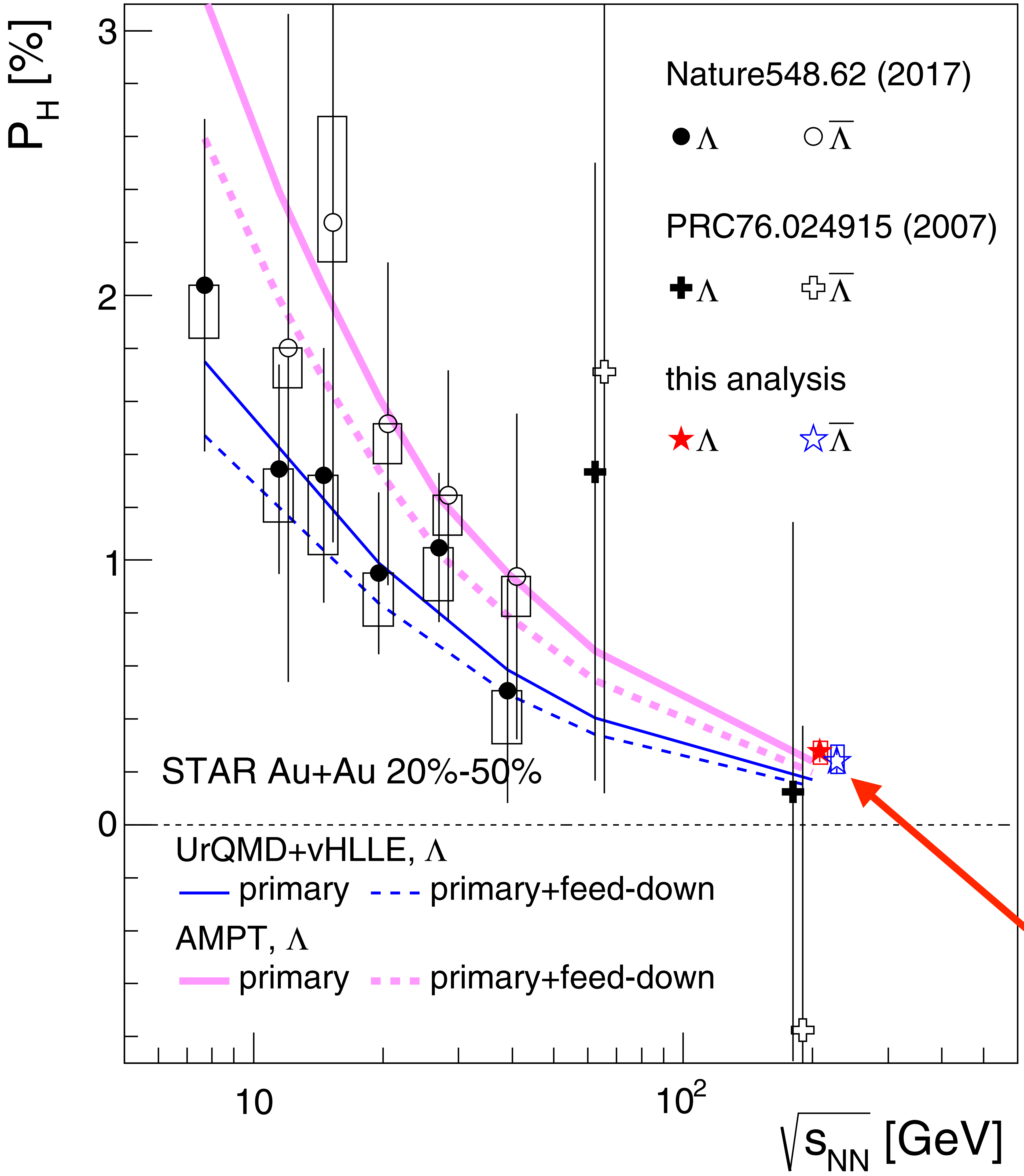
$$\begin{pmatrix} \varpi_c \\ B_c/T \end{pmatrix} = \begin{bmatrix} \frac{2}{3}\sum_R \left(f_{\Lambda R}\, C_{\Lambda R} - \frac{1}{3} f_{\Sigma^0 R}\, C_{\Sigma^0 R}\right)\; S_R(S_R+1) & \frac{2}{3}\sum_R \left(f_{\Lambda R}\, C_{\Lambda R} - \frac{1}{3} f_{\Sigma^0 R}\, C_{\Sigma^0 R}\right)\; (S_R+1)\,\mu_R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

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
$\Sigma^0 \to \Lambda + \gamma$	$-1/3$

15%-20% dilution of primary Λ polarization (model-dependent)

More precise measurement at $\sqrt{s_{NN}}$ = 200 GeV

STAR, PRC98, 014910 (2018)



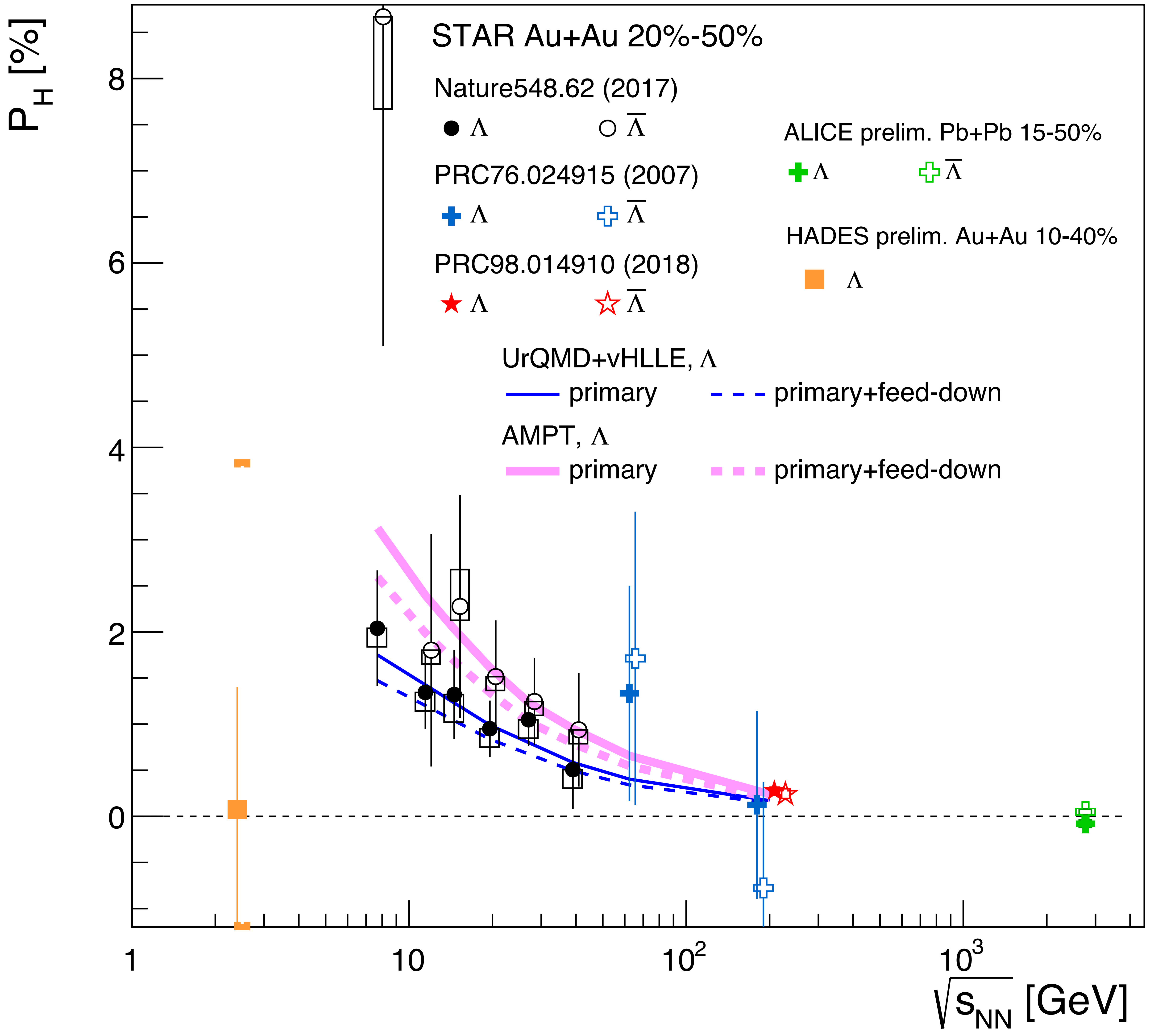
- Confirmed energy dependence of P_H with new results for 200 GeV
  - >5σ significance utilizing 1.5B events (2010+2011+2014)
  - partly due to stronger shear flow structure in lower $\sqrt{s_{NN}}$ because of baryon stopping

- Theoretical models can describe the data well

I. Karpenko and F. Becattini, EPJC(2017)77:213, UrQMD+vHLLE
H. Li et al., PRC96, 054908 (2017), AMPT
Y. Sun and C.-M. Ko, PRC96, 024906 (2017), CKE
Y. Xie et al., PRC95, 031901(R) (2017), PICR
D.-X. Wei et al., PRC99, 014905 (2019), AMPT

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

How about at higher/lower energy?



- **ALICE** preliminary Pb+Pb at $\sqrt{s_{NN}}$ = 2.76 TeV

$$P_H(\Lambda)[\%] = -0.08 \pm 0.10\ (\text{stat}) \pm 0.04\ (\text{syst})$$
$$P_H(\bar{\Lambda})[\%] = \quad 0.05 \pm 0.10\ (\text{stat}) \pm 0.03\ (\text{syst})$$

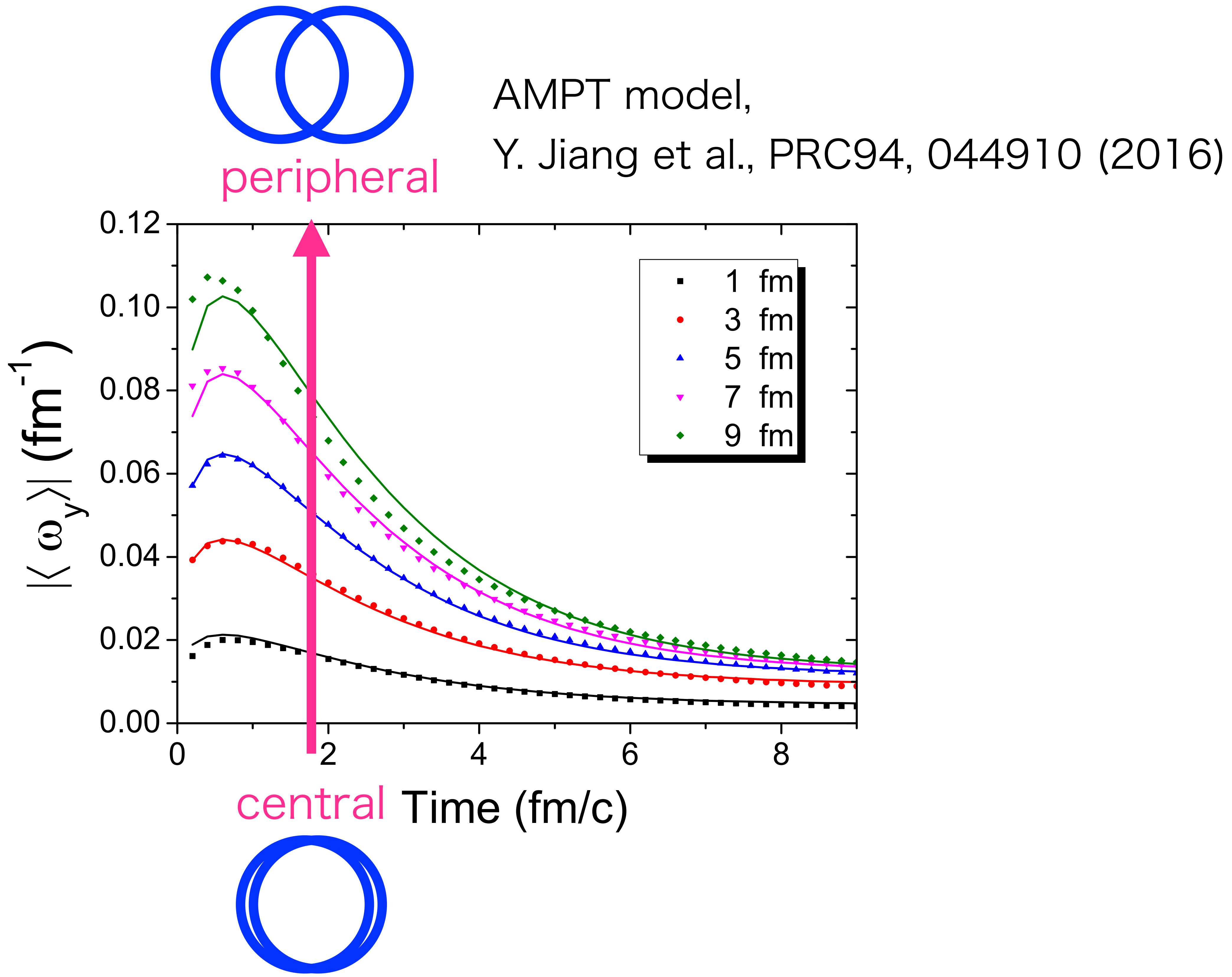
M. Konyushikhin, QCD Chirality Workshop 2017

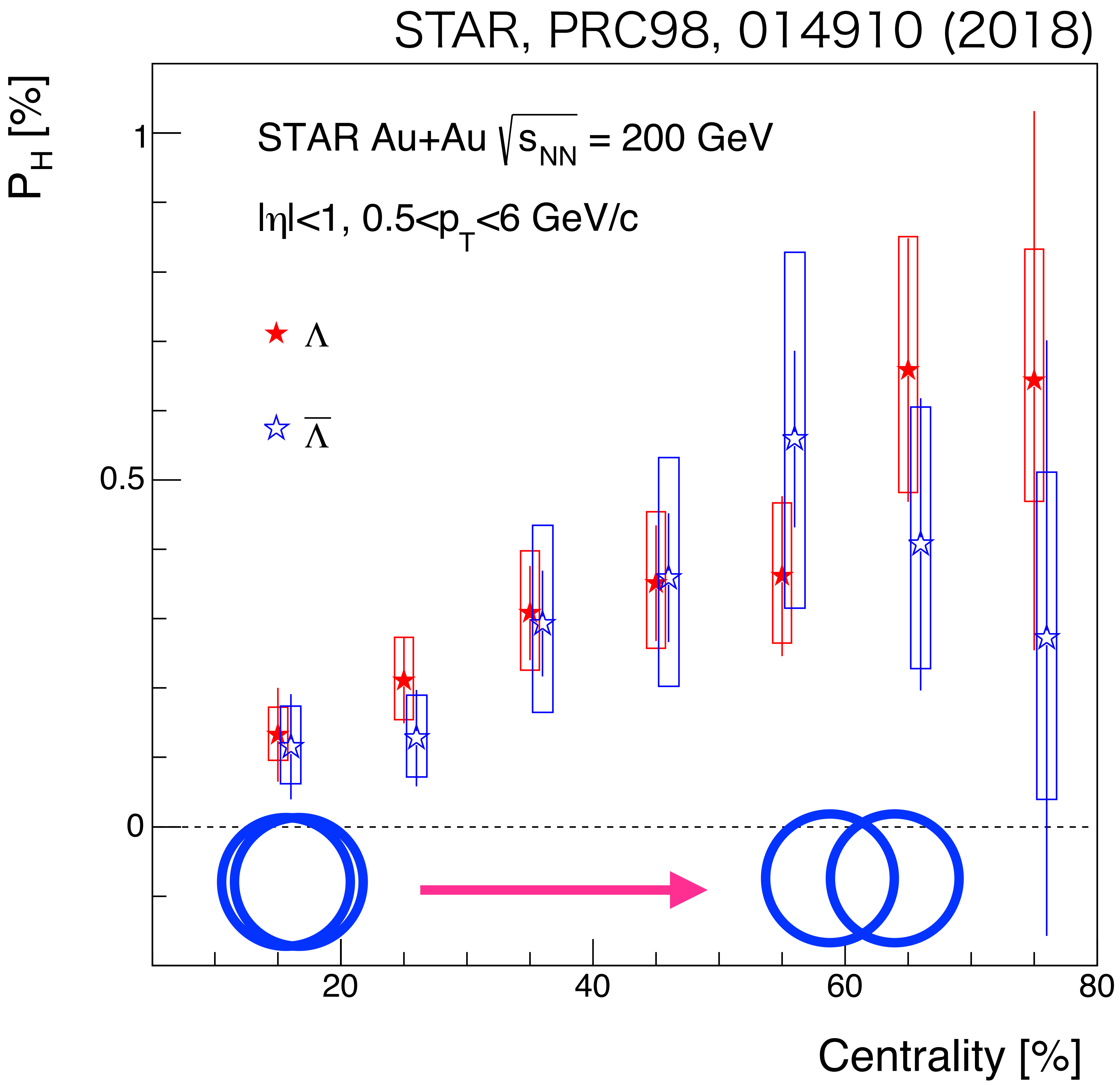
- **HADES** preliminary Au+Au at $\sqrt{s_{NN}}$ = 2.4 GeV

$$P_H(\Lambda)[\%] = 3.672 \pm 0.699\ (\text{stat.})$$
$$P_H^{\text{BG}}[\%] = 3.689 \pm 1.133\ (\text{stat.})$$

F. Kornas, SQM2019

Centrality dependence of P_H



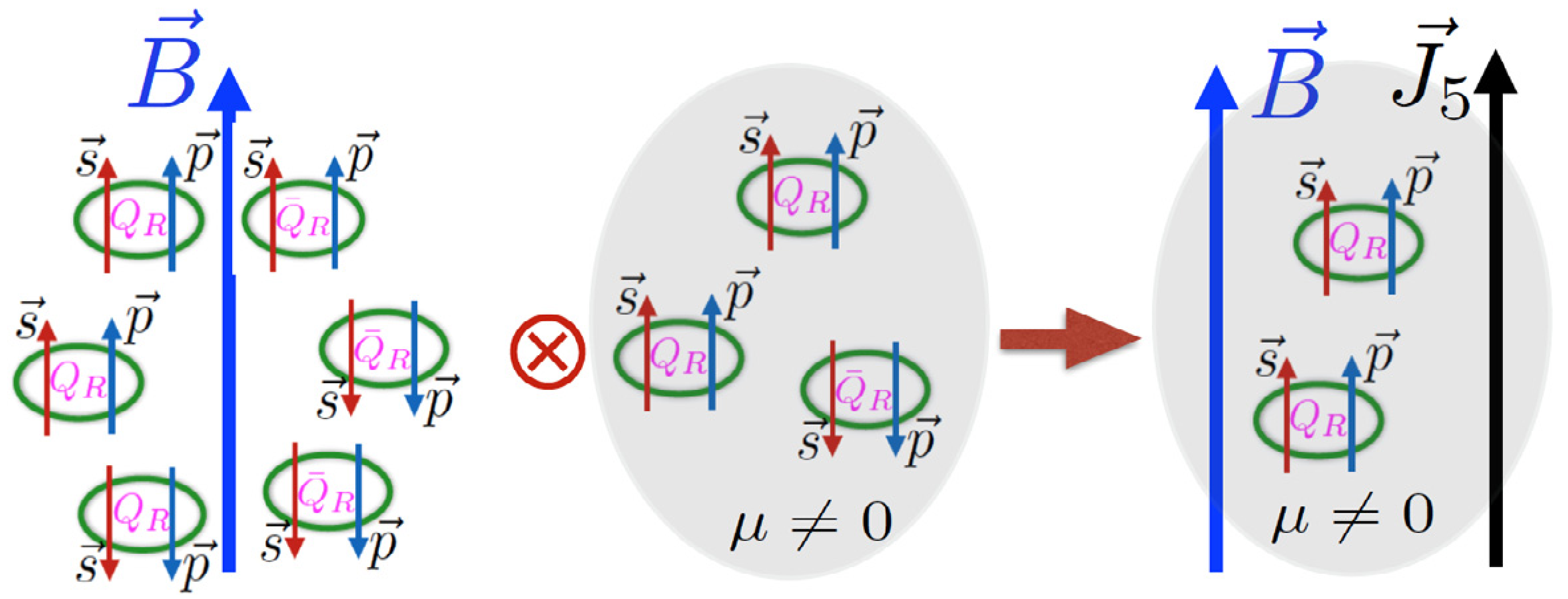


In most central collision → no initial angular momentum

As expected, the polarization decreases in more central collisions

Λ polarization vs. charge asymmetry

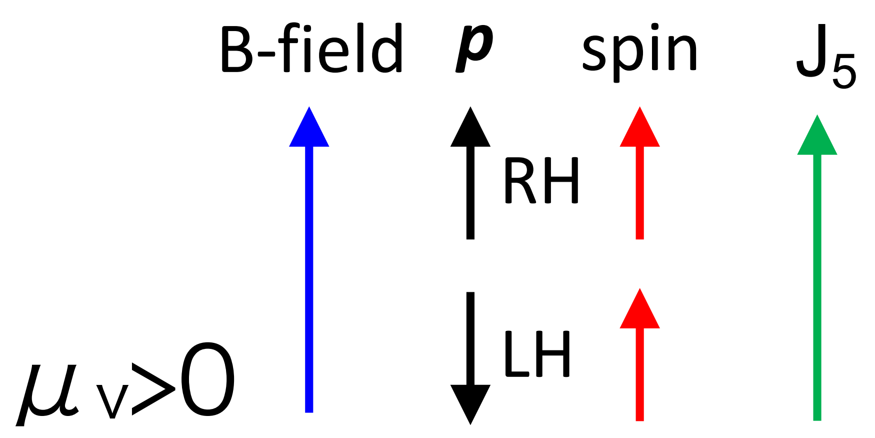
Chiral Separation Effect



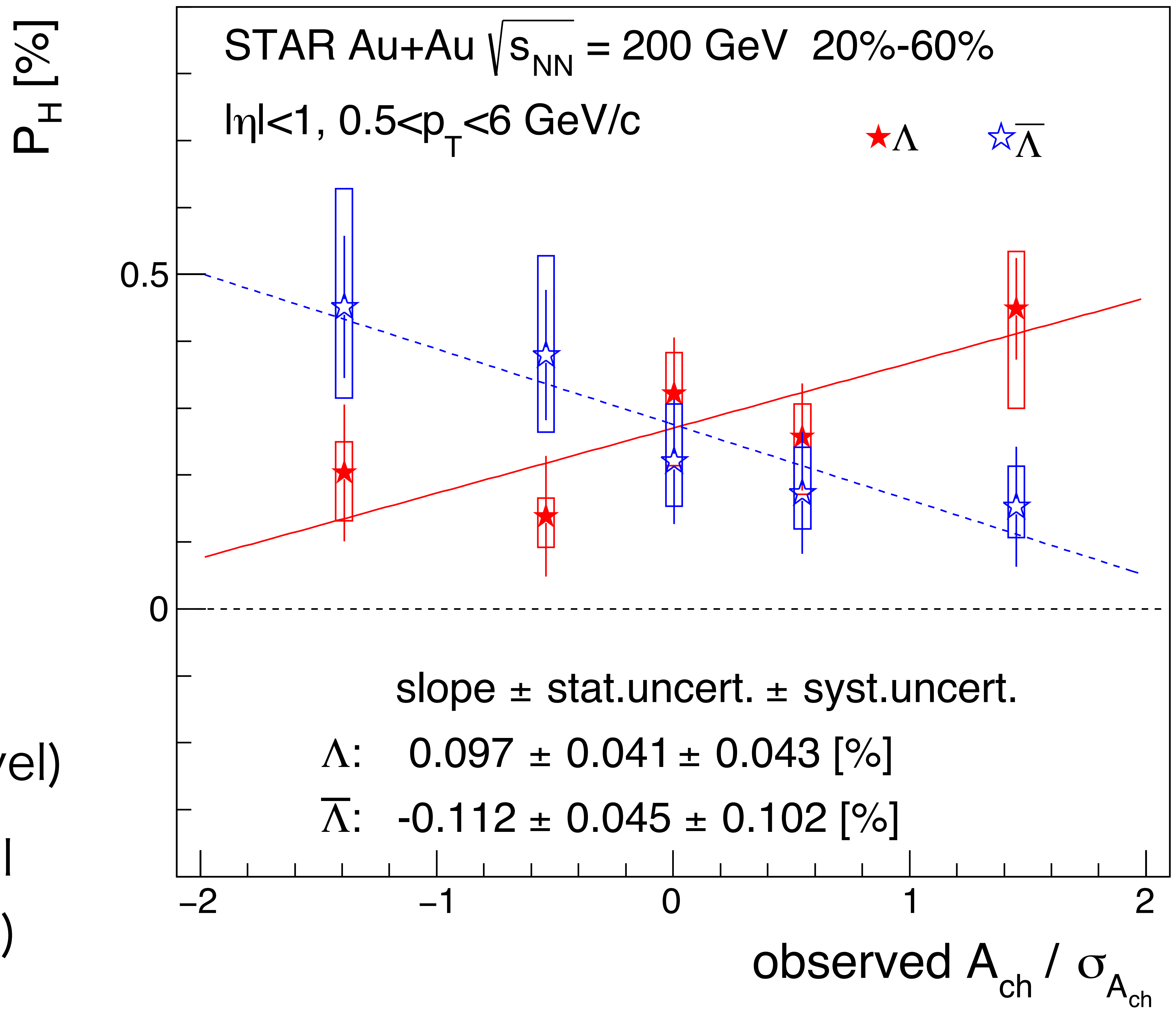
$$\mathbf{J}_5 \propto e\mu_\mathrm{v}\mathbf{B}$$

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

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



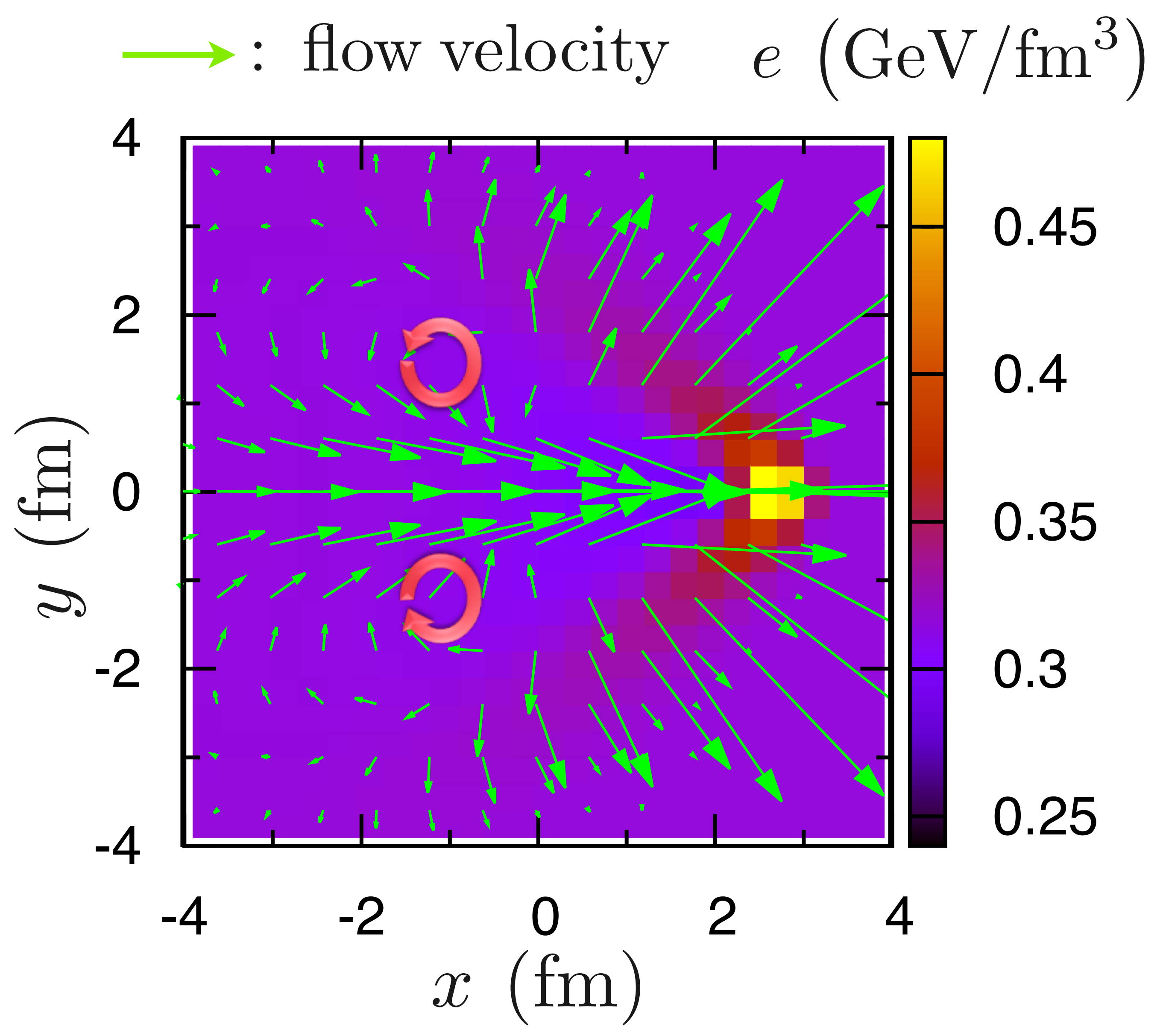
STAR, PRC98, 014910 (2018)



- Slopes of Λ and anti-Λ seem to be different (~2σ level)
- Possible contribution to the polarization from the axial current J_5 induced by B-field (Chiral Separation Effect)
  S. Shlichting and S. Voloshin

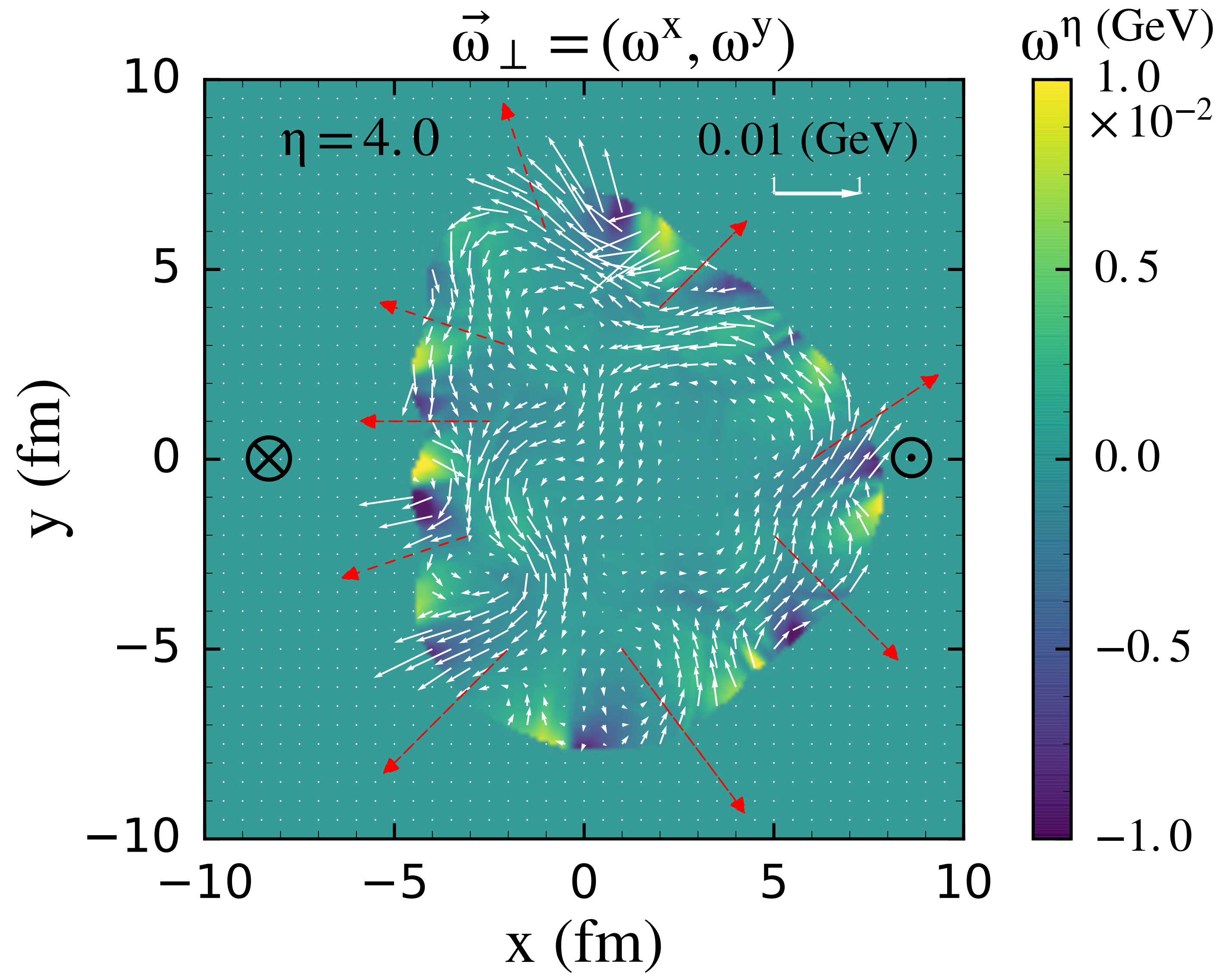
Local vorticity

vortex induced by jet



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

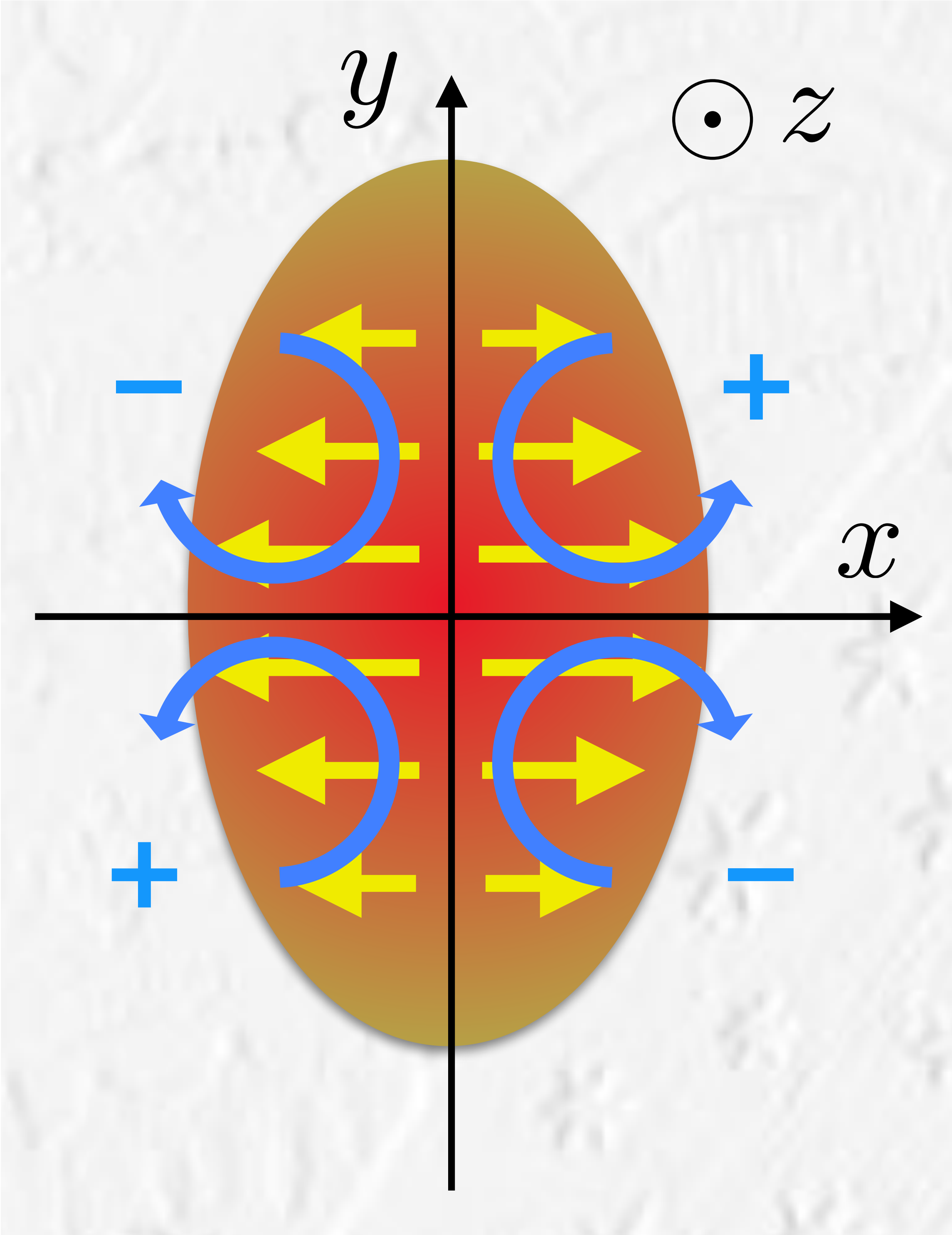
local vorticity induced by collective flow

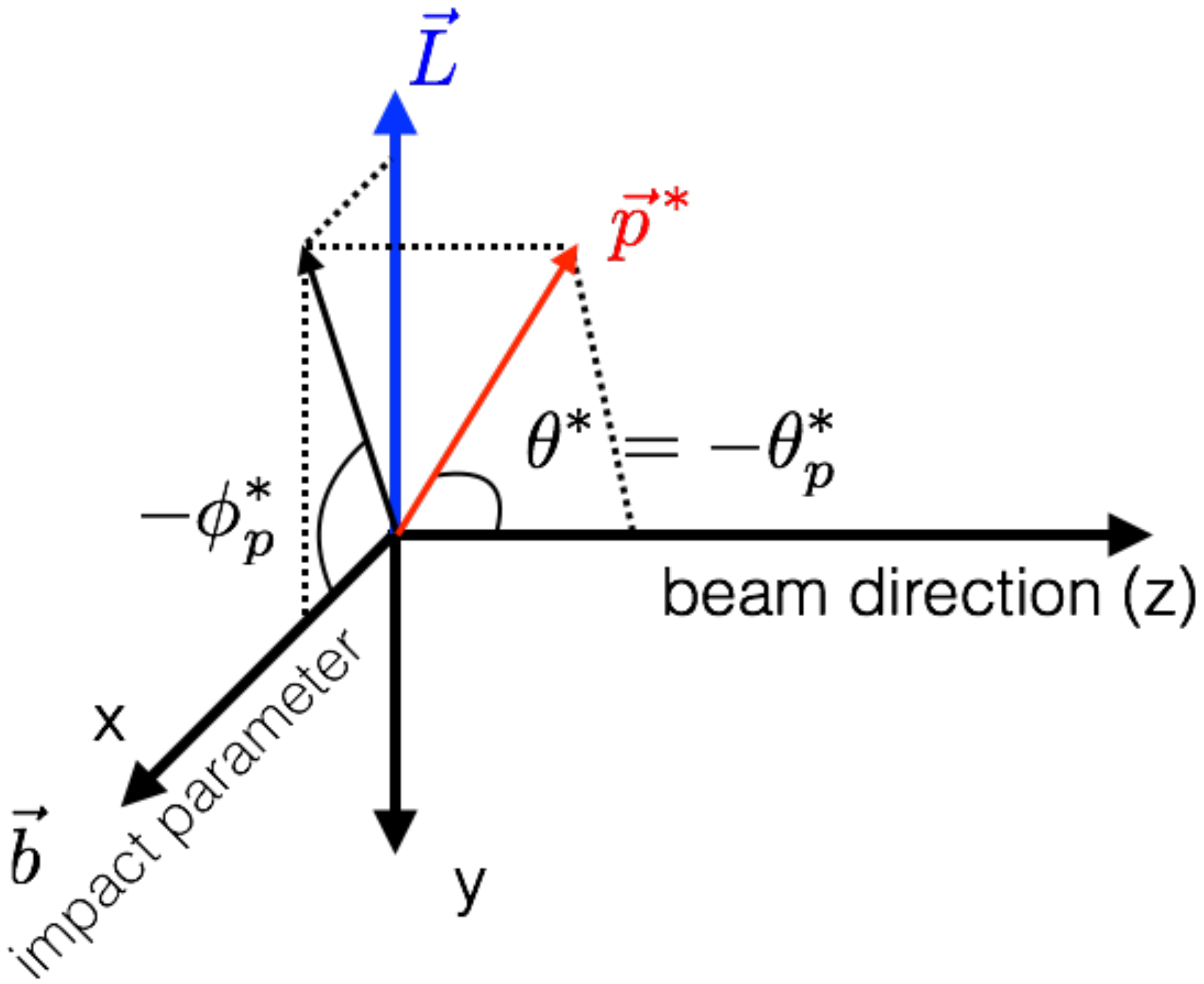


L.-G. Pang, H. Peterson, Q. Wang, and X.-N. Wang, PRL117, 192301 (2016)
F. Becattini and I. Karpenko, PRL120.012302 (2018)
S. Voloshin, EPJ Web Conf.171, 07002 (2018)

Polarization along the beam direction

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





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

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

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

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

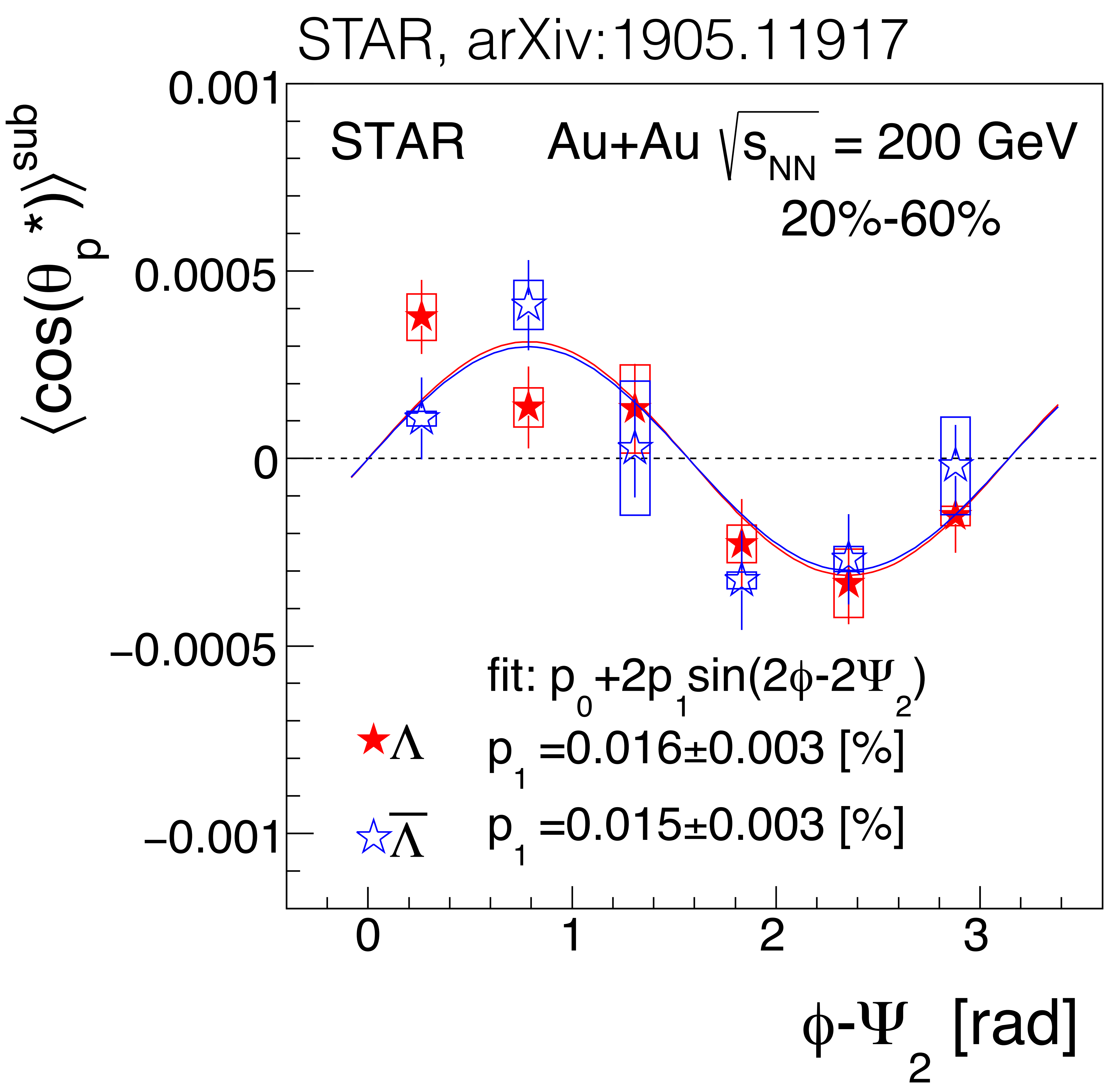
$$= \frac{3\langle\cos\theta^*_p\rangle}{\alpha_{\rm H}}$$ (if perfect detector)

$\alpha_{\rm H}$: hyperon decay parameter
θ_p^*: θ of daughter proton in Λ rest frame

Stronger flow in in-plane than in out-of-plane could make local polarization along beam axis!

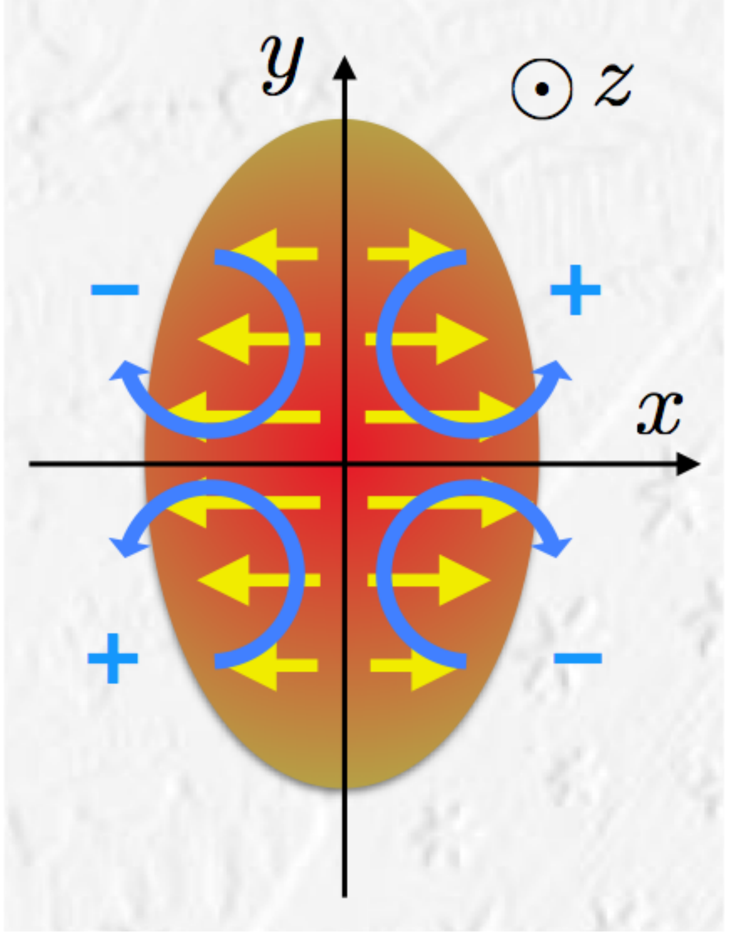
Longitudinal component, P_z, can be expressed with $\langle\cos\theta_p^*\rangle$.
$\langle(\cos\theta_p^*)^2\rangle$ accounts for an acceptance effect

Polarization along the beam direction

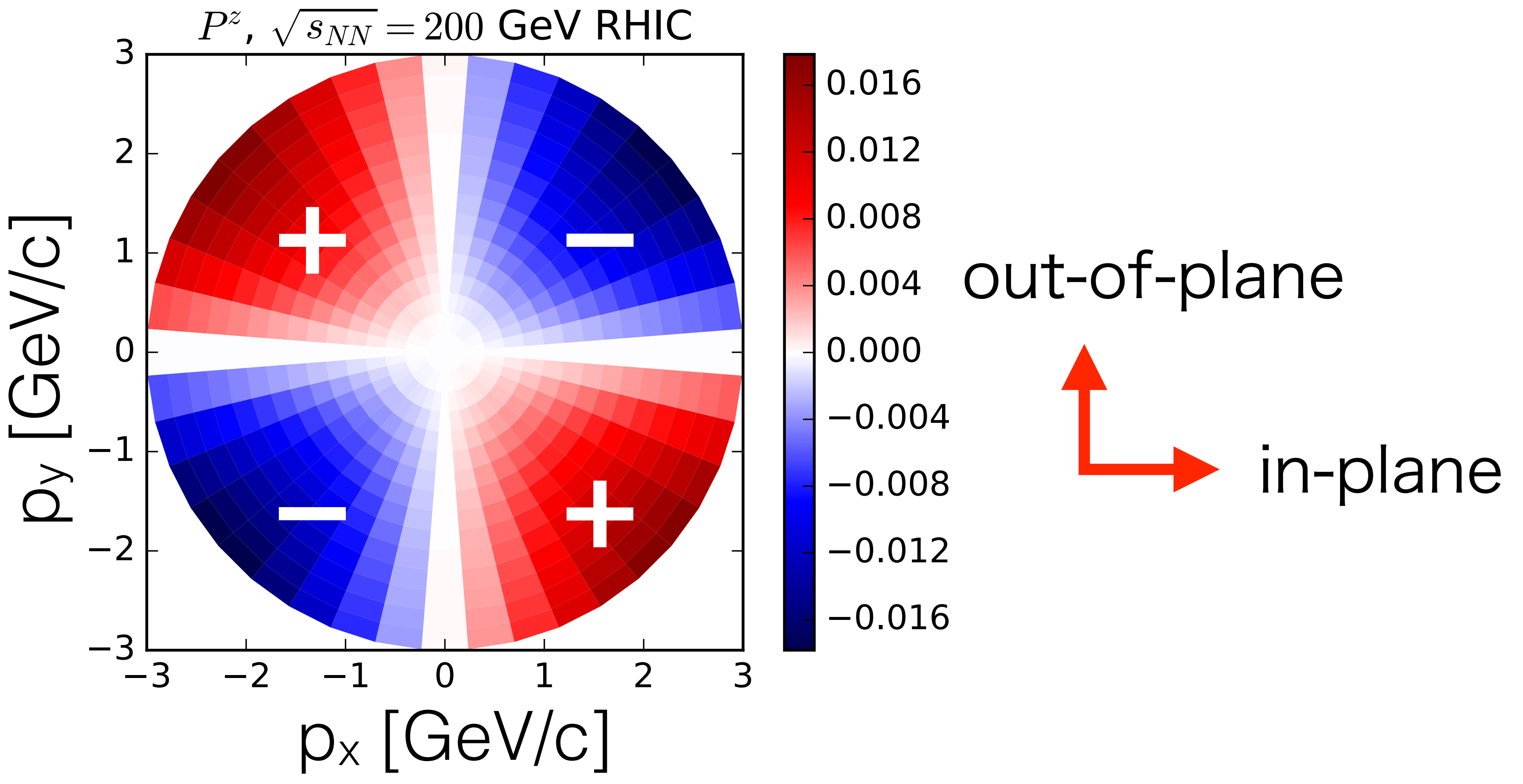


- Effect of Ψ_2 resolution is not corrected here

S. Voloshin, SQM2017



F. Becattini and I. Karpenko, PRL.120.012302 (2018)

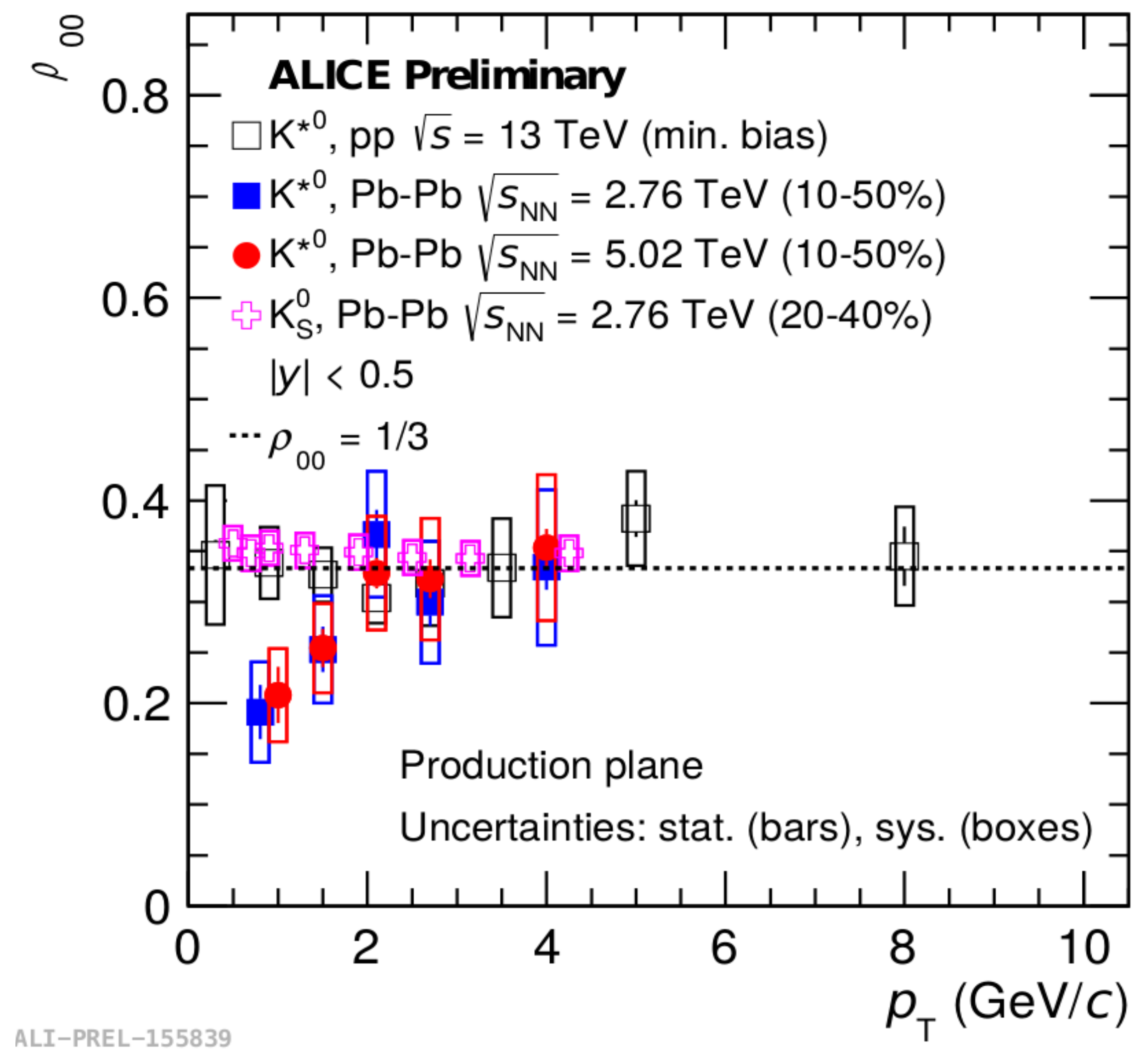


- Sine structure as expected from the elliptic flow!
- Opposite sign to the hydrodynamic model and transport model (AMPT)
  - F. Becattini and I. Karpenko, PRL.120.012302 (2018)
  - X. Xia, H. Li, Z. Tang, Q. Wang, PRC98.024905 (2018)
- Chiral kinetic and PICR models predict the same sign
  - Y. Sun and C.-M. Ko, PRC99, 011903(R) (2019)
  - Y. Xie, D. Wang, and L. P. Csernai, arXiv:1907.00773

Other related observables

Spin alignment of vector meson

ALICE, STAR, QM18



deviation from 1/3 indicates spin alignment

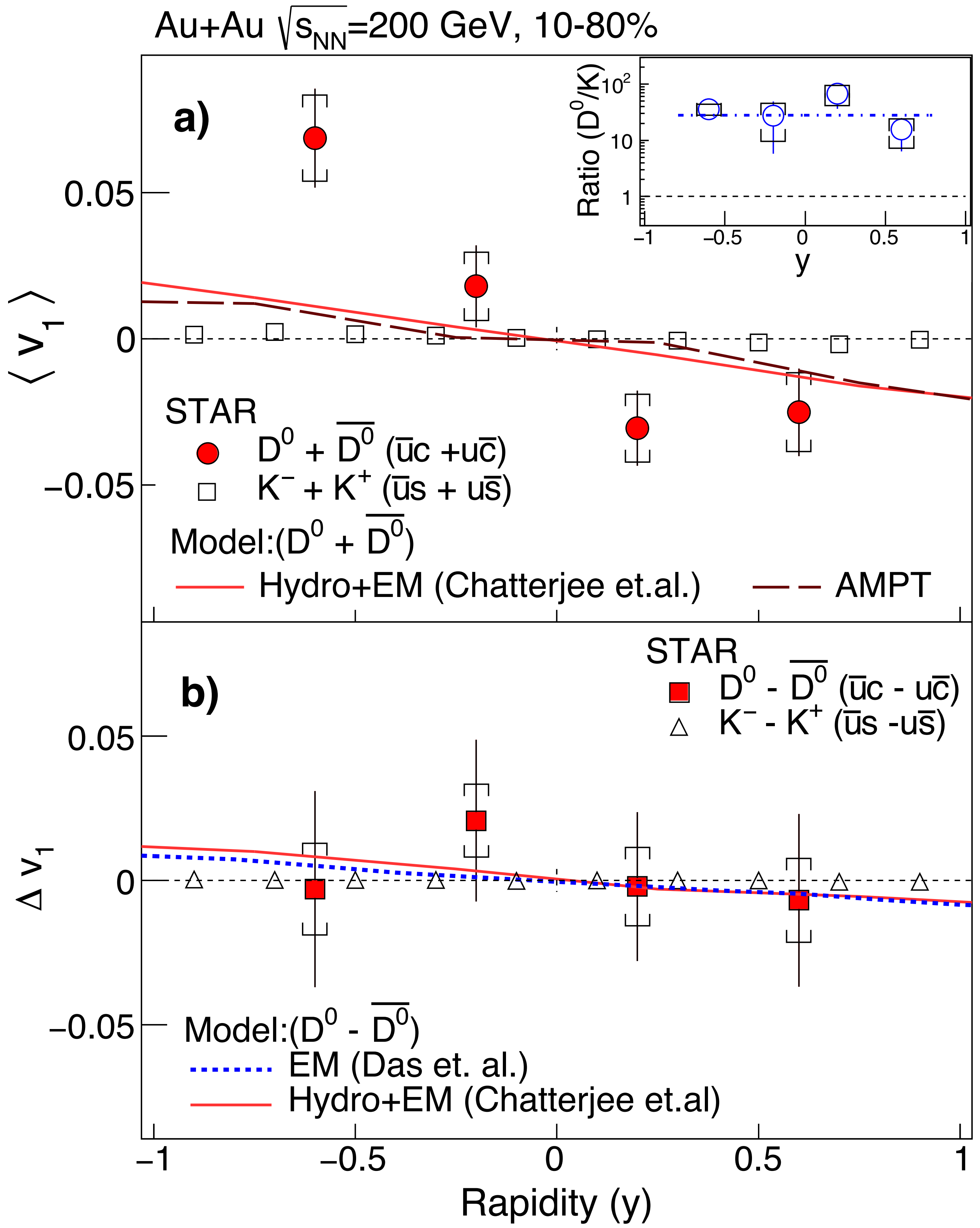
$$\rho_{00} = 1/[3 + (\omega/T)^2]$$

S. Voloshin, SQM18 proc.

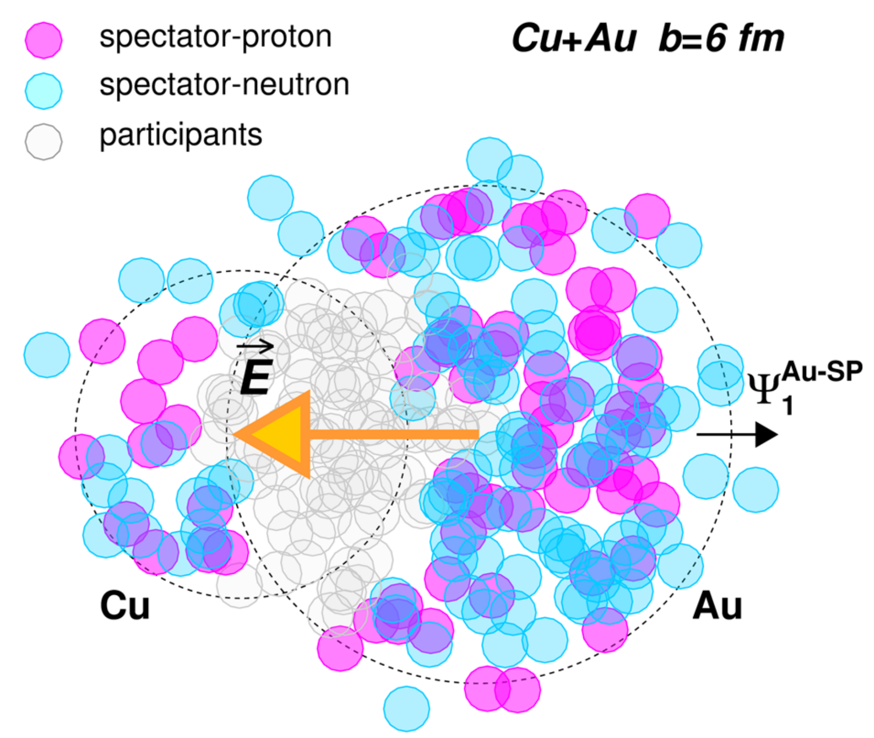
inconsistent with Λ polarization?

D_0 v_1, sensitive to the initial tilt and EM-field

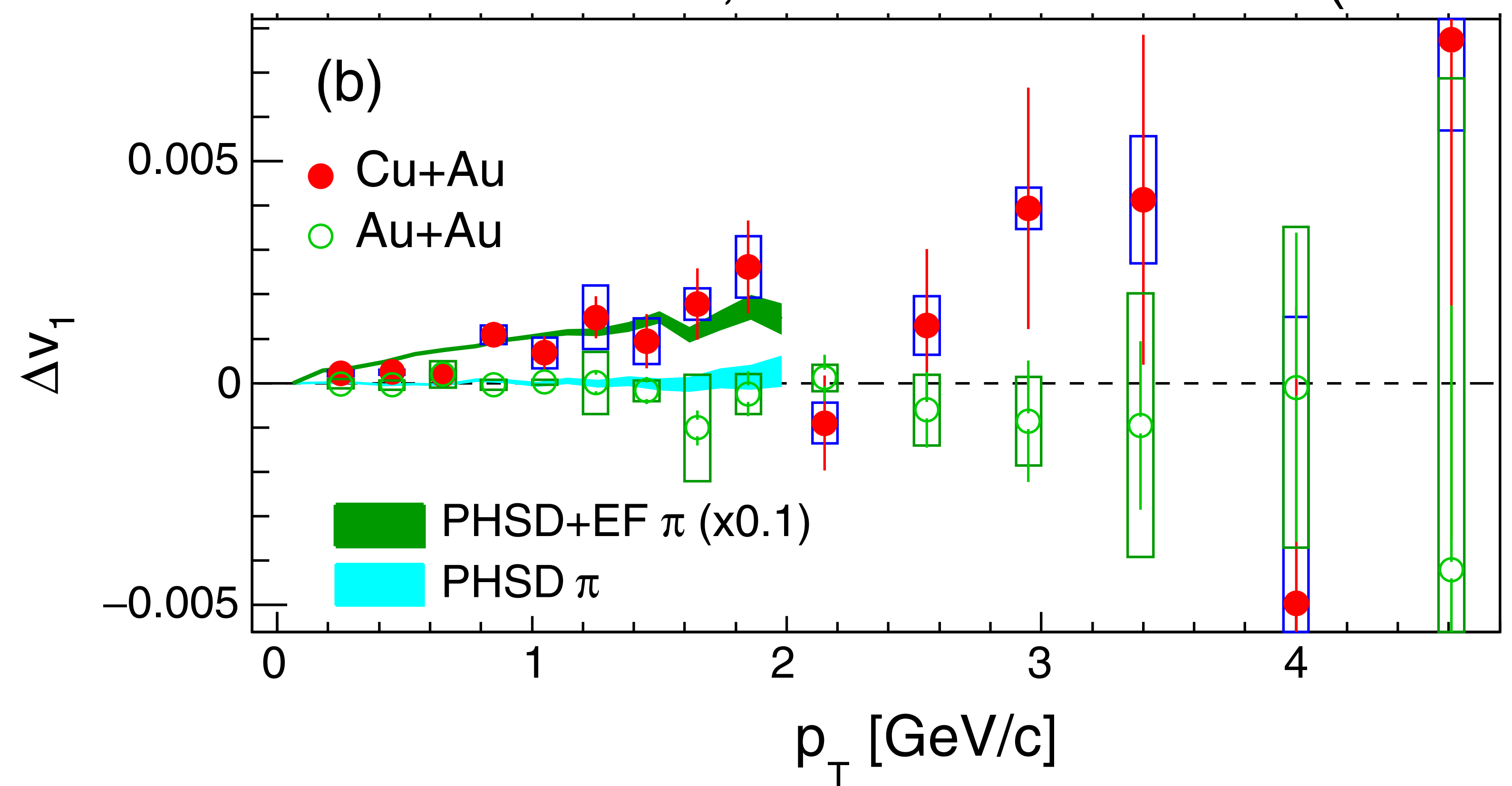
STAR, arXiv:1905.02052



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

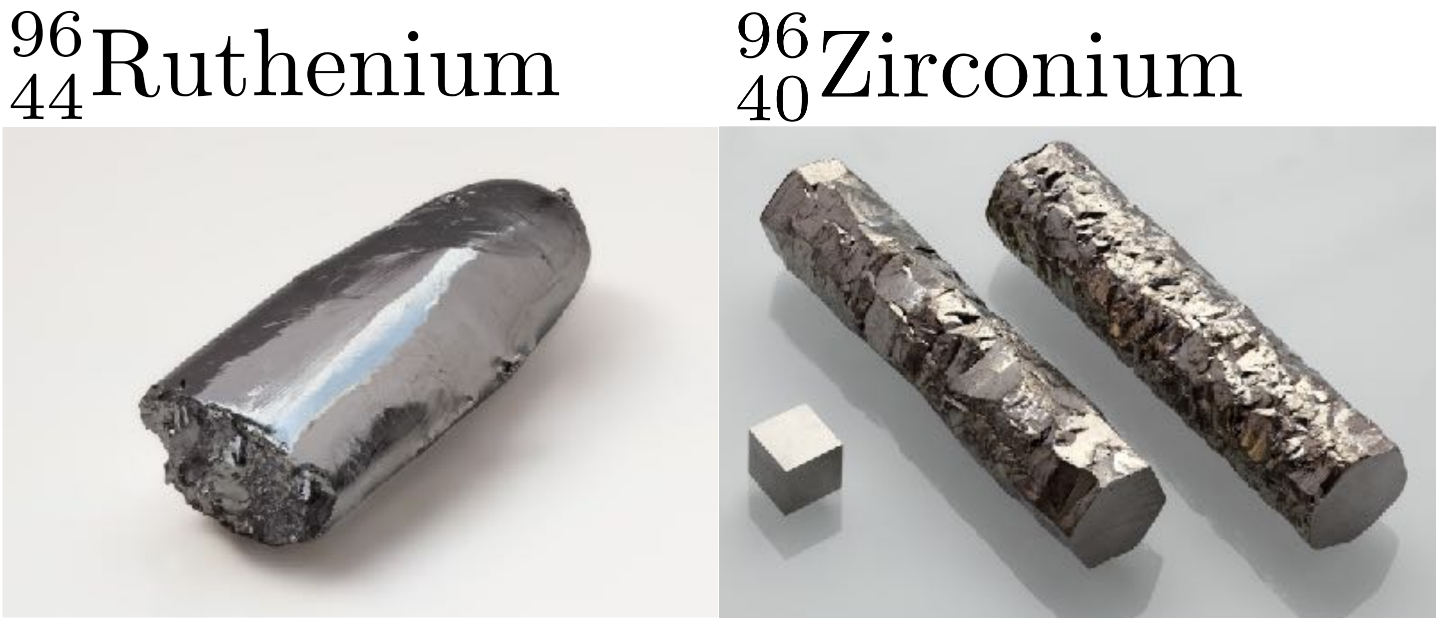


STAR, PRL118.012301 (2017)

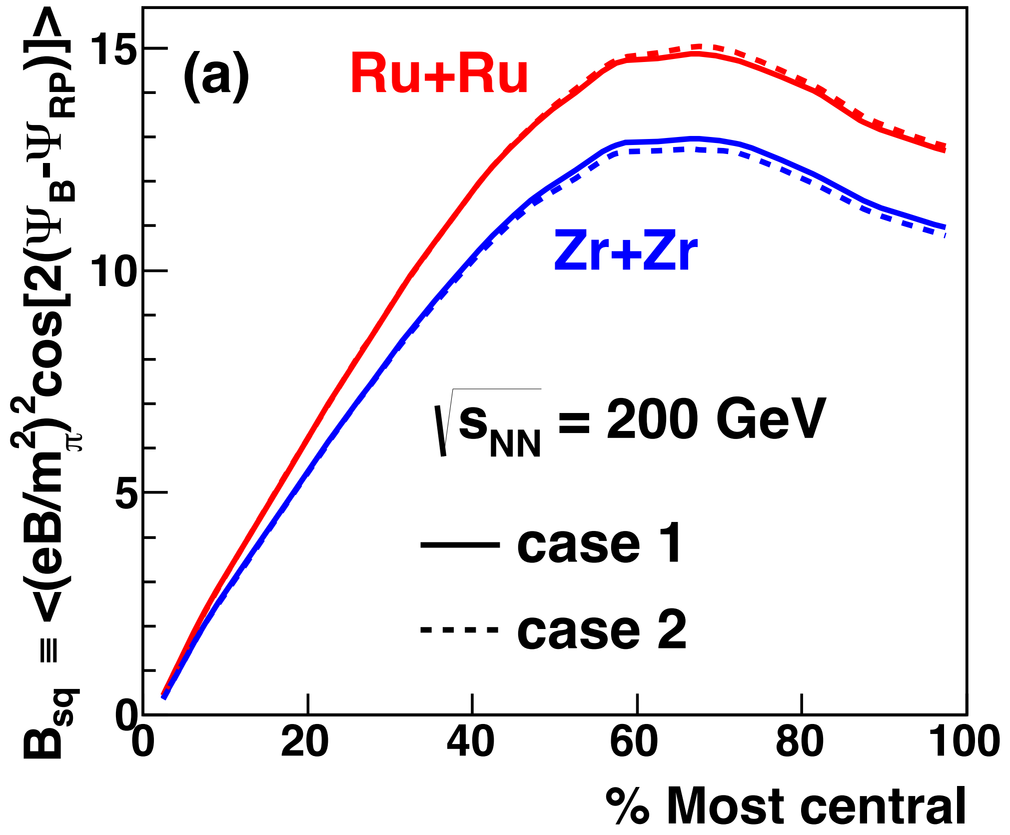


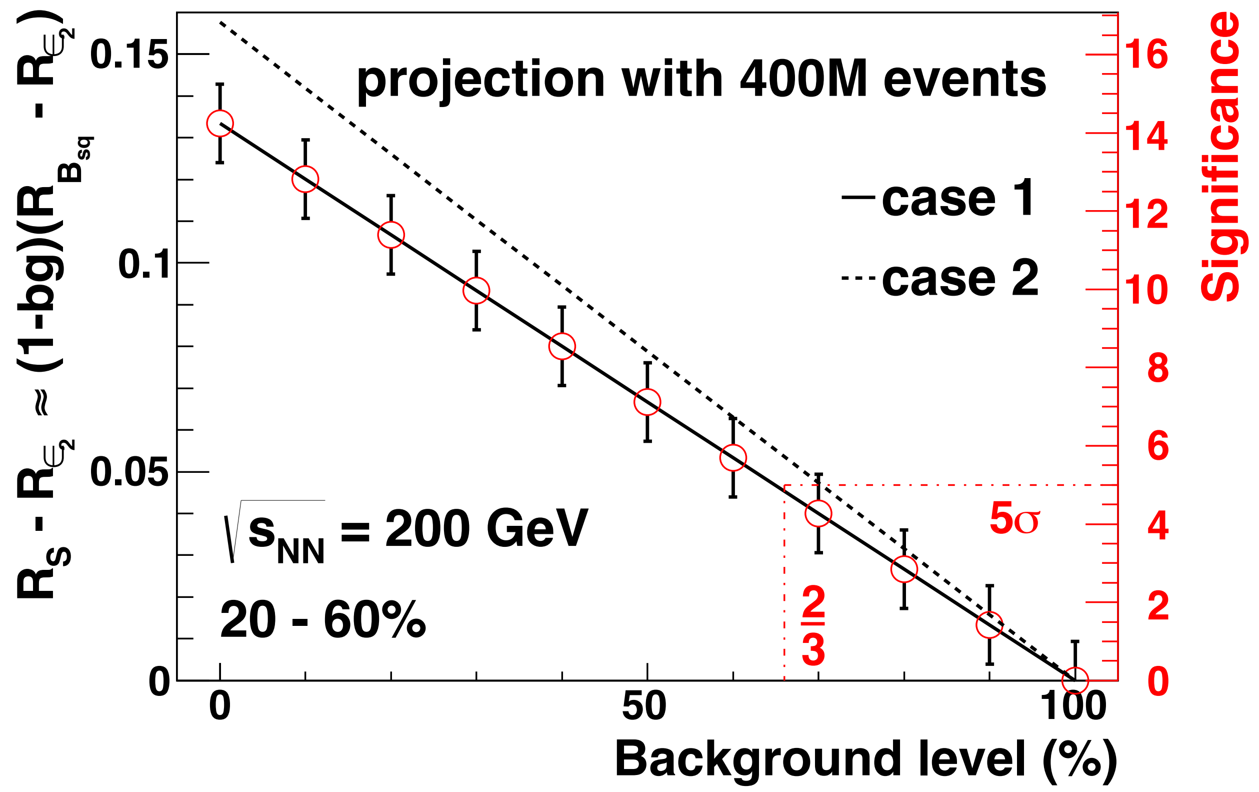
Outlook

- Isobaric collision data (Ru+Ru, Zr+Zr)
  - Same mass number but different number of protons
    →~10% difference in B-field
  - Test for CME as well as P_H splitting
- New data of 27 GeV and BESII for 7.7-19.6 GeV (collider) and 3-7.7 GeV (fixed target) with iTPC and EPD (x10 events, x1.5 better EP)
- Global polarization of multi-strangeness (Ξ and Ω)

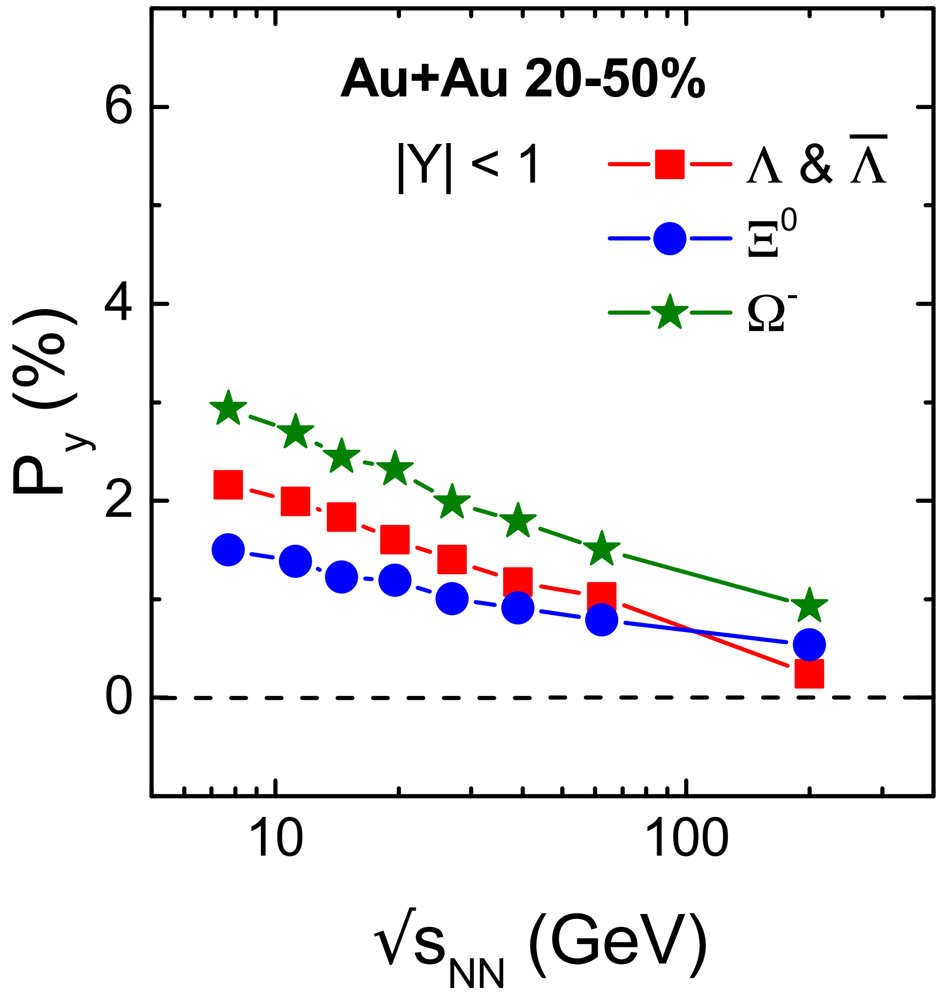


W.-T. Deng et al., PRC94.041901





D.-X. Wei *et al.*, PRC99.014905 (2019)



Summary

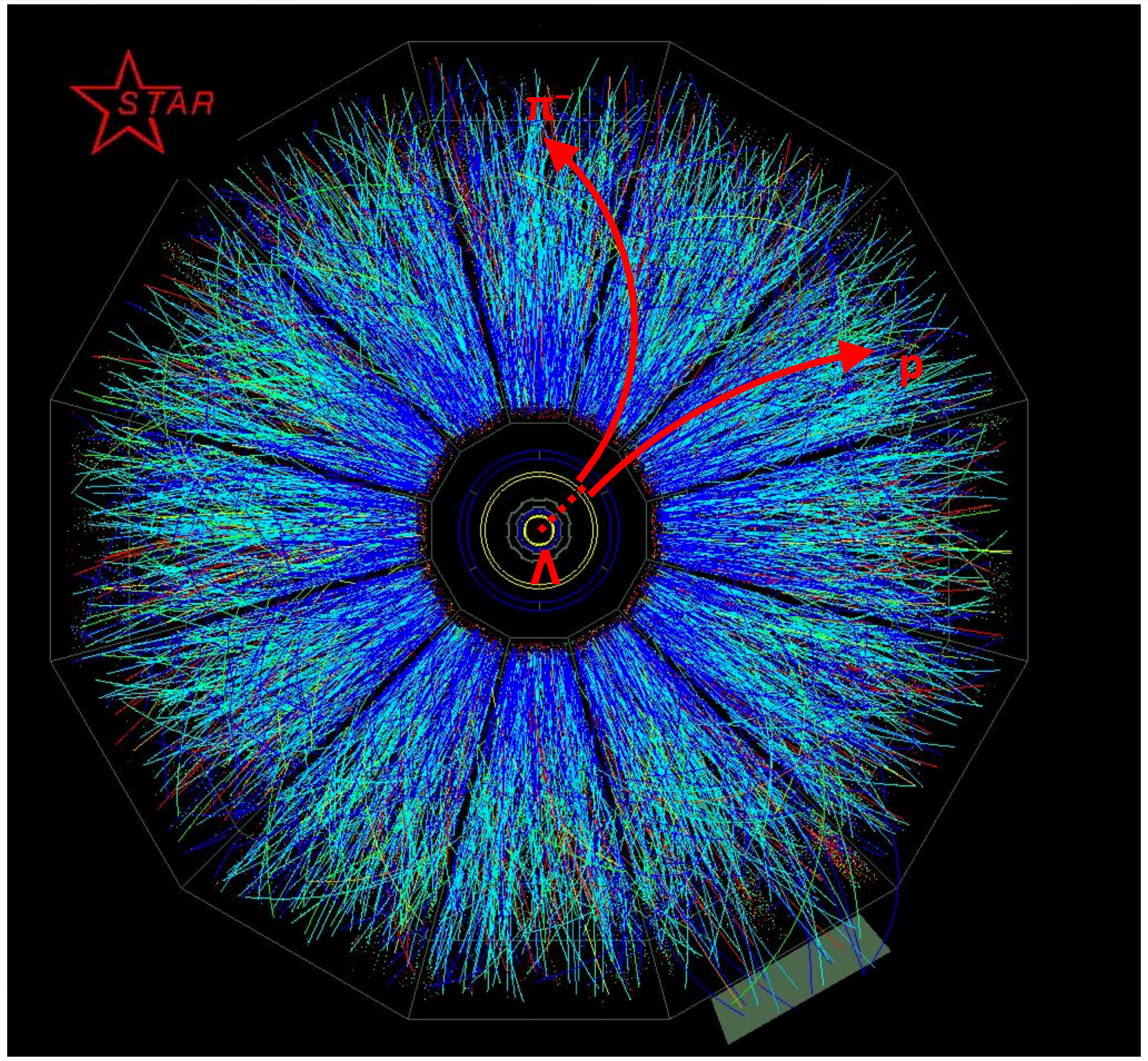
- CME/CVE
  - A lot of studies with various observables are ongoing but no definitive conclusion so far
  - Good progress to quantify possible CME contributions to the measurements
  - Stay tuned for isobaric data

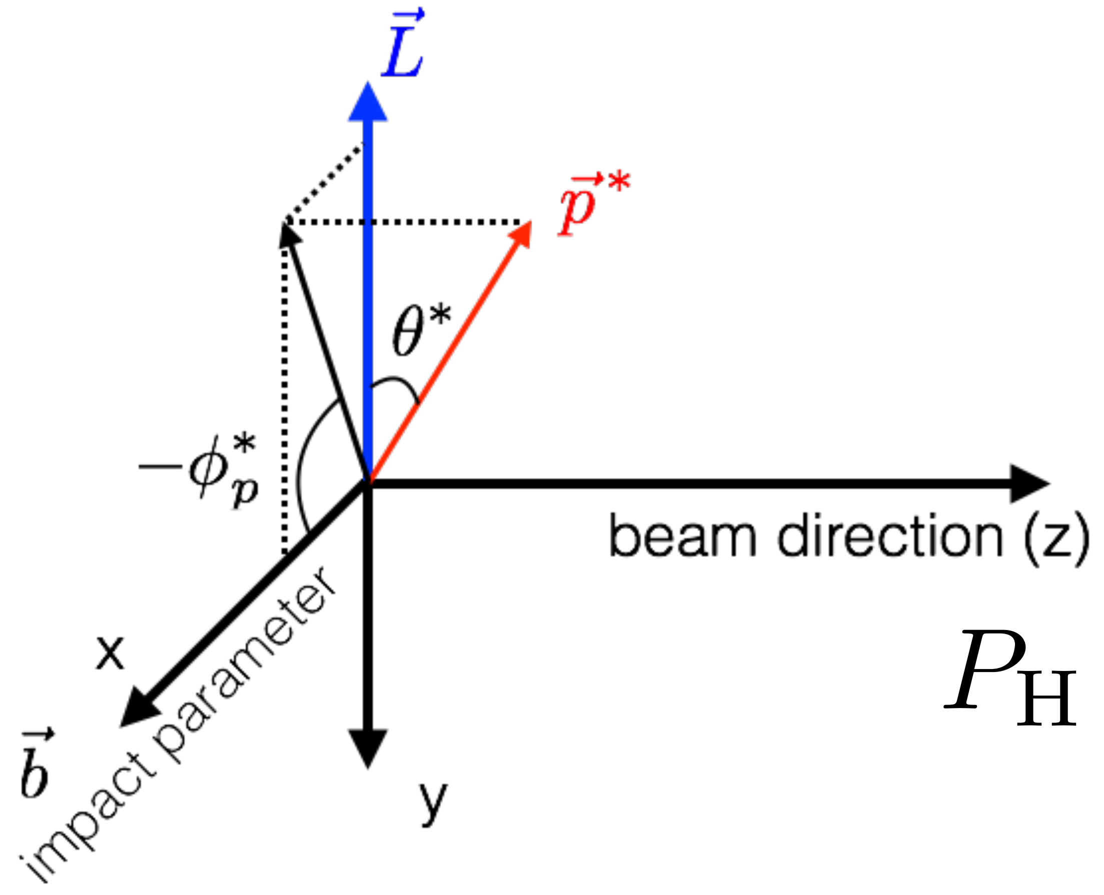
- Λ global polarization
  - Experimental evidence of the most vortical fluid
  - Polarization increases in lower energies within $\sqrt{s_{NN}}$ = 7.7-200 GeV, consistent with theoretical models
  - HADES result indicates the polarization decreases around $\sqrt{s_{NN}}$ = 2.4 - 7.7 GeV
    → BES II STAR-FXT $\sqrt{s_{NN}}$ = 3-7.7 GeV

- First study of Λ polarization along the beam direction at $\sqrt{s_{NN}}$ = 200 GeV
  - Quadrupole structure of the polarization relative to the 2nd-order event plane
    → consistent with a picture of the elliptic flow but agree/disagree among the data and theoretical calculations in the sign

Back up

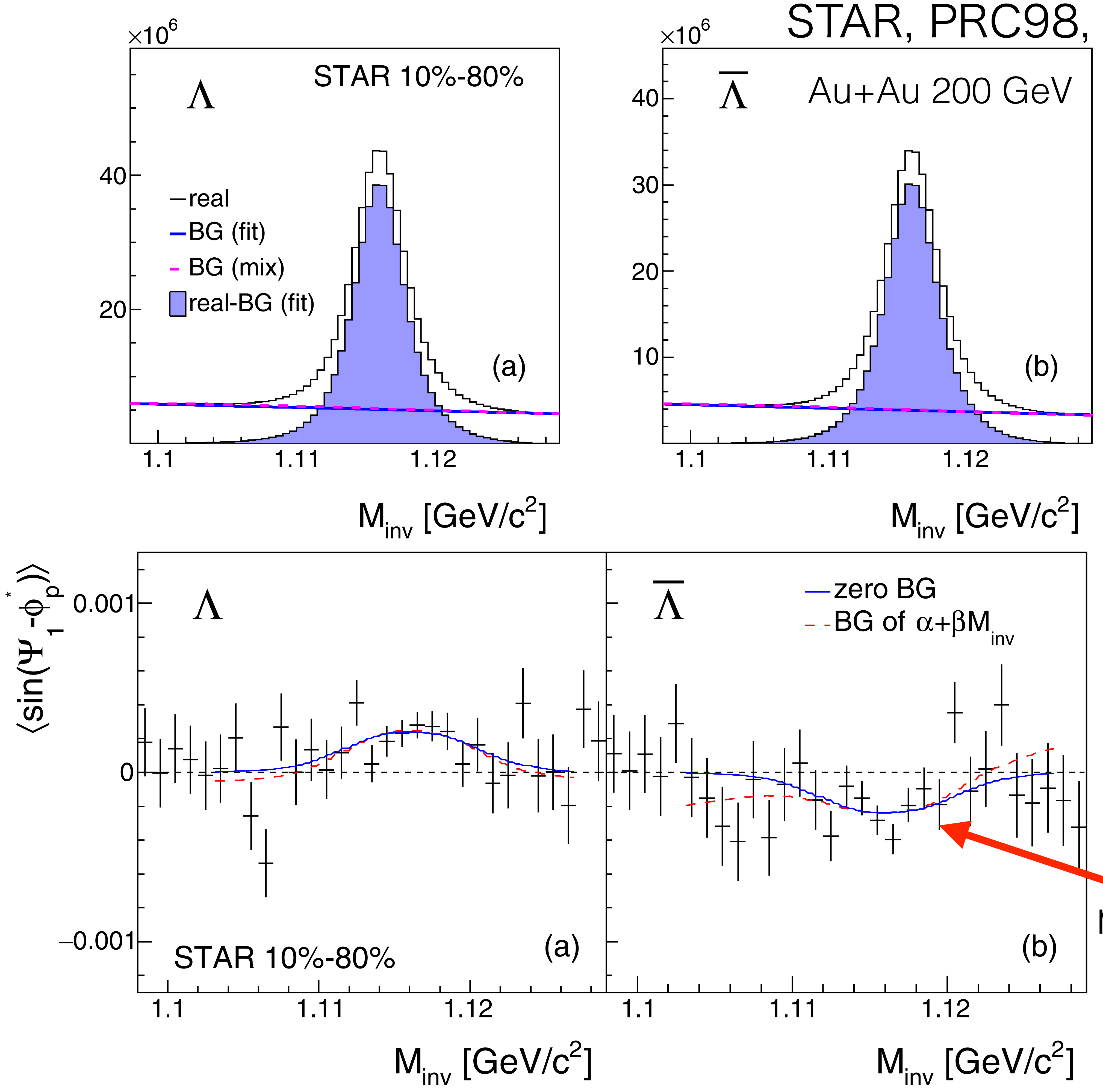
Signal extraction with Λ hyperons





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

STAR, PRC98, 014910 (2018)



negative for anti-Λ

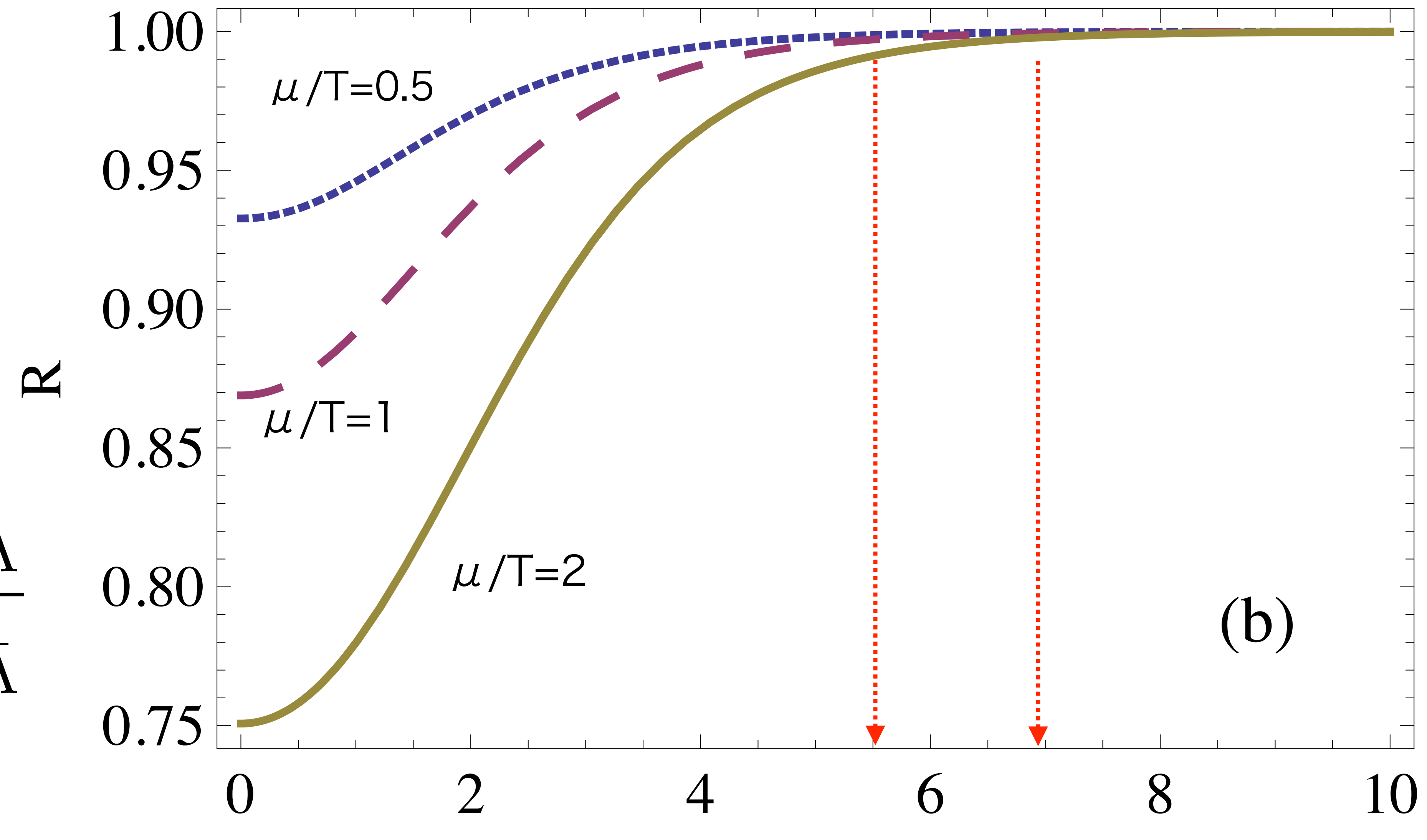
$$\alpha_H = -\alpha_{\bar{H}}$$

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

Effect of non-zero chemical potential

R. Fang, L. Pang, Q. Wang, and X. Wang, PRC94, 024904 (2016)

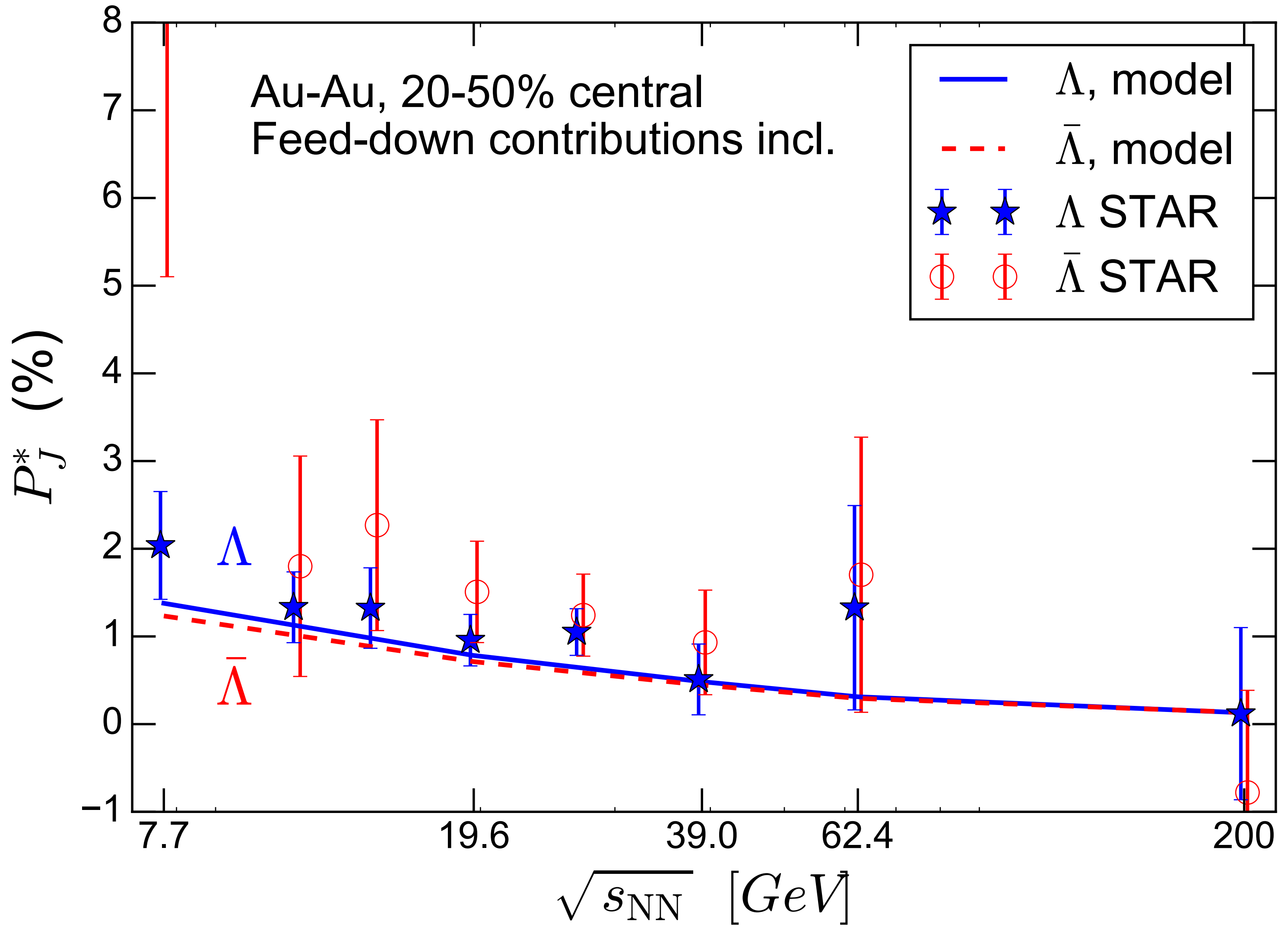
$$R = \frac{P_\Lambda}{P_{\bar{\Lambda}}}$$



βm = m/T
~ 1.1GeV/(160-200)MeV
~ 5.5-6.8

Y. Karpenko, sQM2017

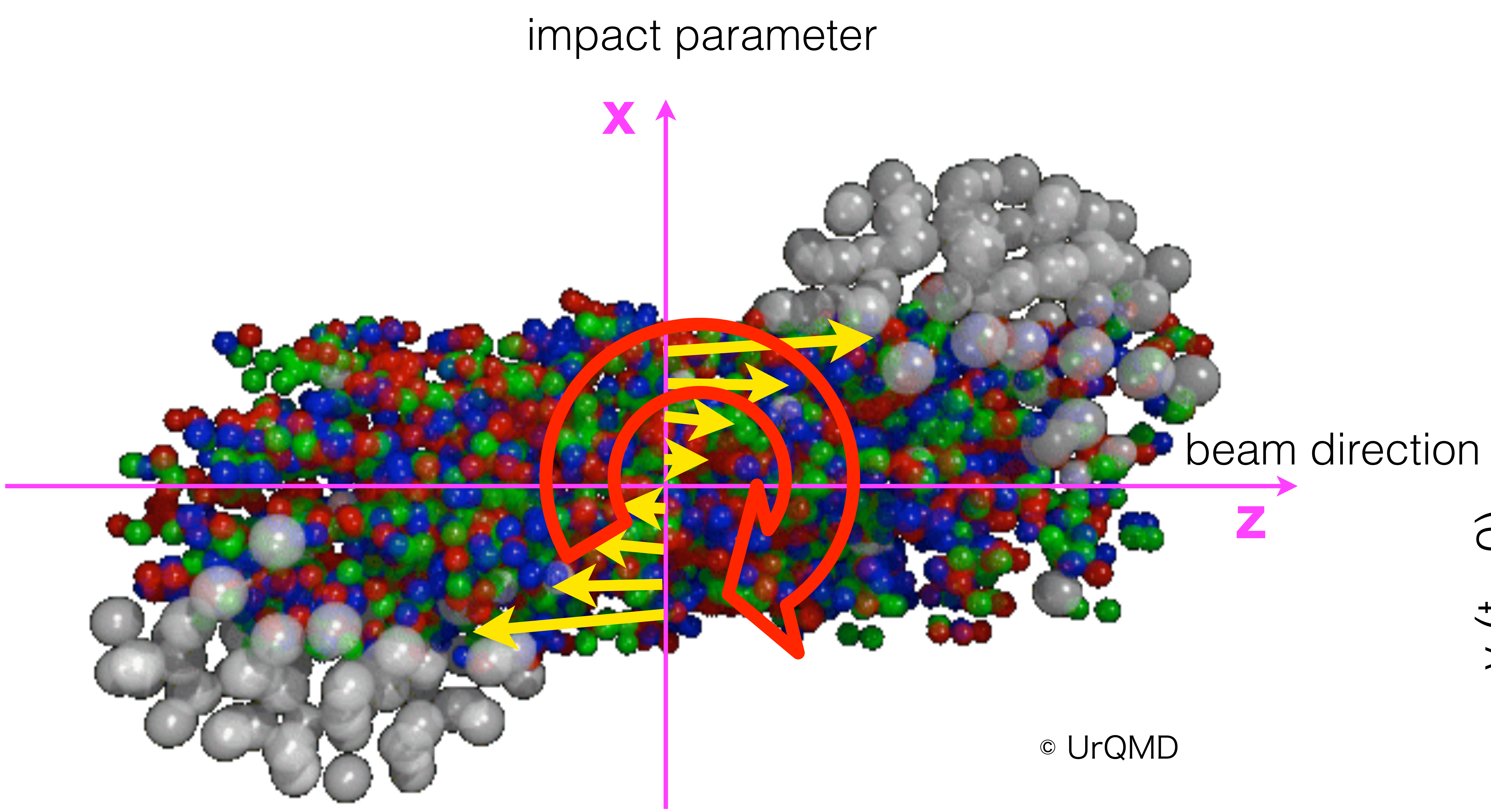
Λ and $\bar{\Lambda}$: UrQMD+vHLLE vs experiment



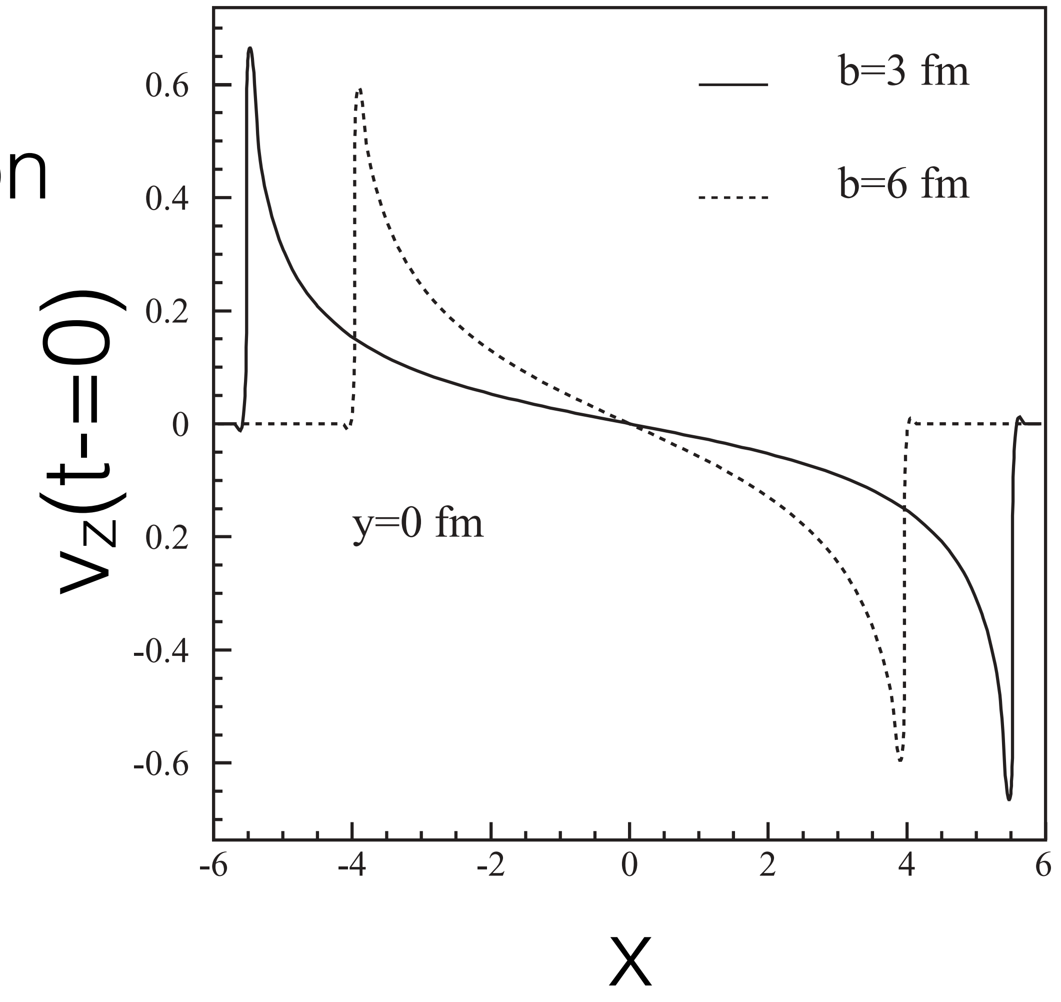
only μ_B effect in model

Non-zero chemical potential makes polarization splitting between Λ and anti-Λ, but the effect seems to be small.

Vorticity in HIC



Becattini et al.,
PRC77, 024906 (2008)

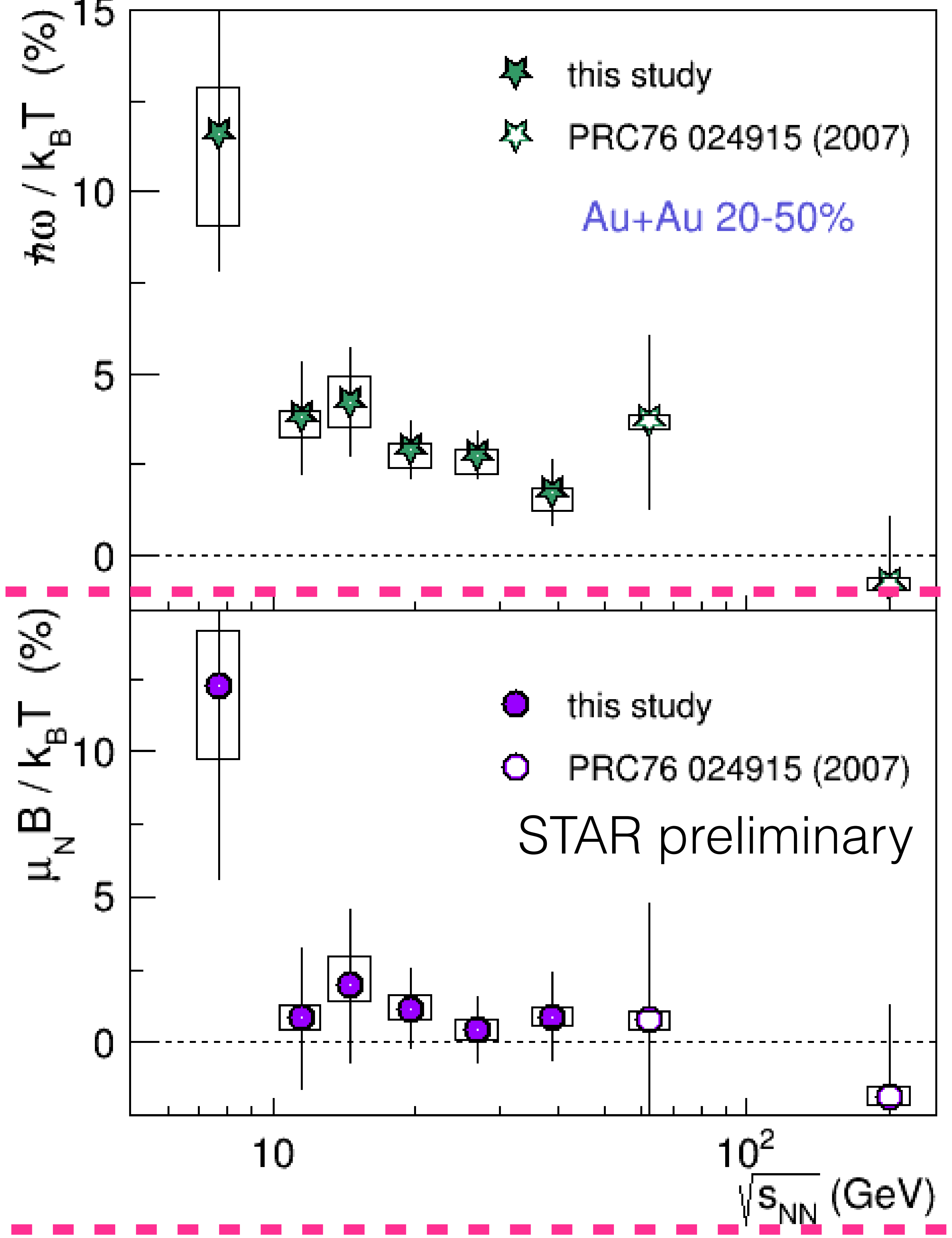


In non-central collisions,
the initial collective longitudinal flow velocity depends on x.

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

Possible probe of magnetic field

QM17, I. Upsal (STAR)



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

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

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

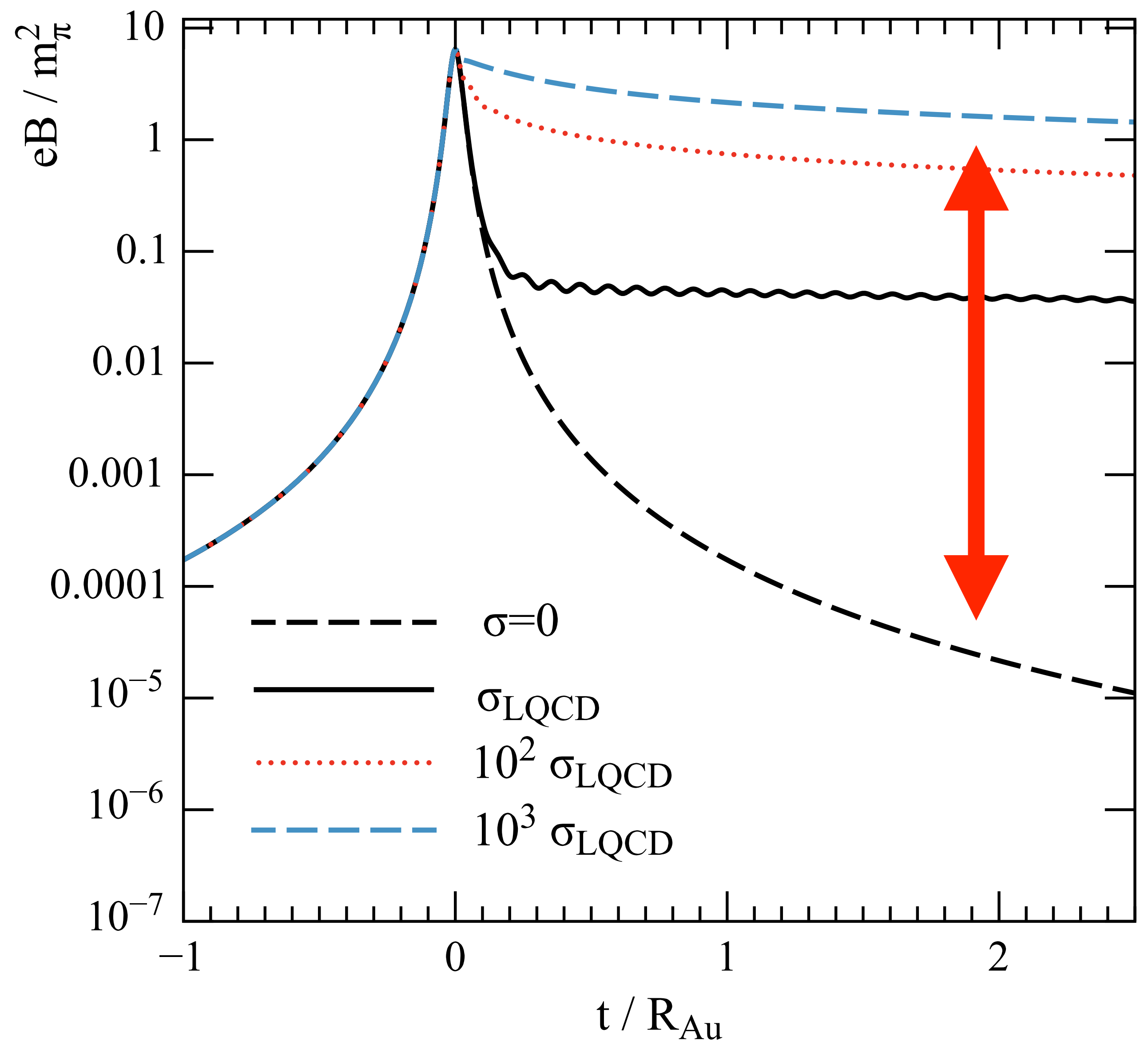
μ_Λ: Λ magnetic moment

$$B = (P_\Lambda - P_{\bar{\Lambda}})k_B T/\mu_N$$

$$\sim 5.0 \times 10^{13} \text{ [Tesla]}$$

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

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



conductivity increases lifetime (not magnitude)

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

$$(eB \sim \text{MeV}^2 \ (\tau = 0.2 \text{ fm}))$$

Extracted B-field is close to our expectation.
Need more data with better precision
→BES-II and Isobaric collisions

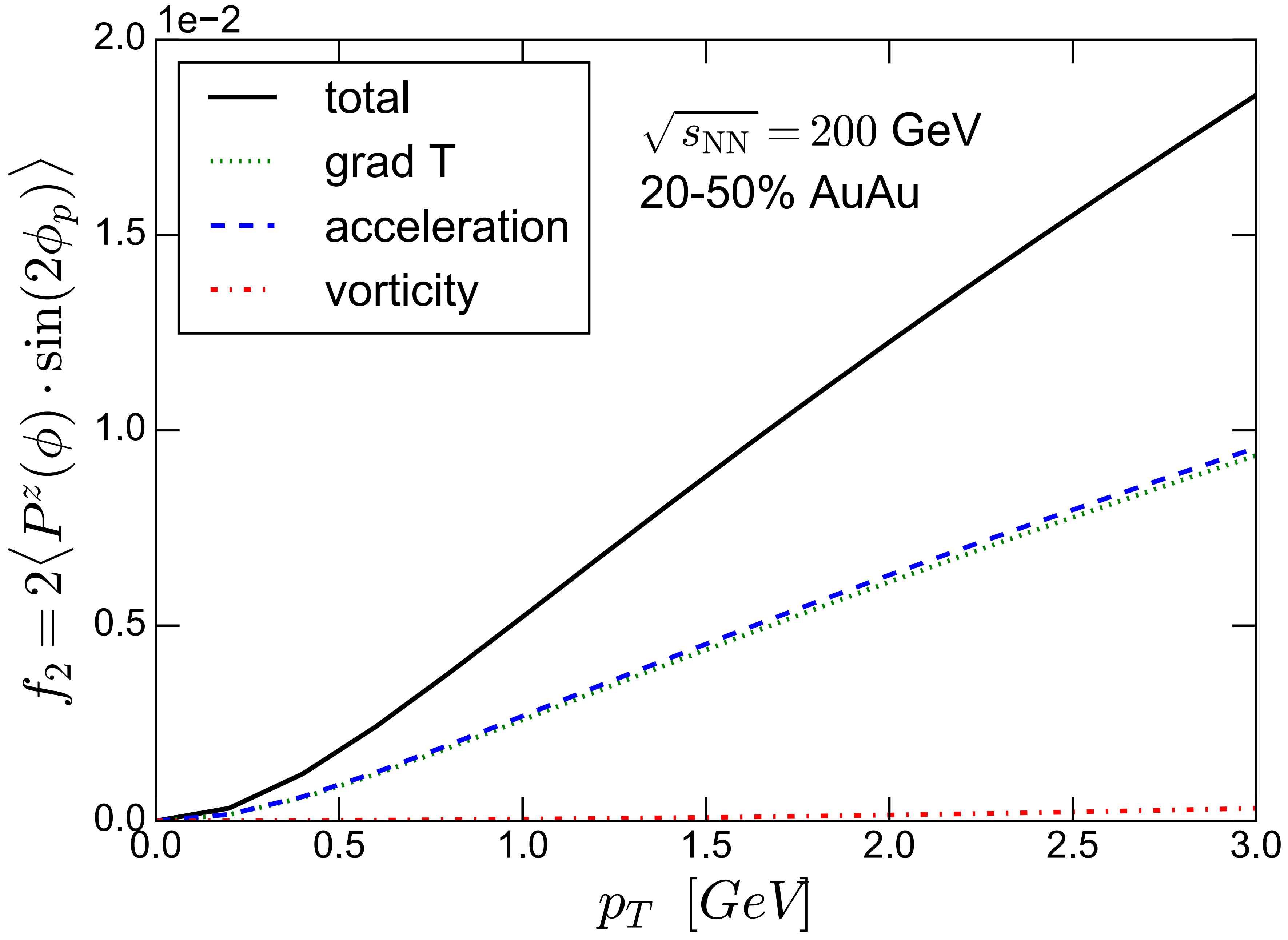
Contributions to P_z in hydro

I. Karpenko, QM2018

$$S^\mu \propto \varepsilon^{\mu\rho\sigma\tau}\varpi_{\rho\sigma}p_\tau = \varepsilon^{\mu\rho\sigma\tau}(\partial_\rho\beta_\sigma)p_\tau = \underbrace{\varepsilon^{\mu\rho\sigma\tau}p_\tau\partial_\rho\left(\frac{1}{T}\right)u_\sigma}_{\text{grad}T} + \underbrace{\frac{1}{T}2\left[\omega^\mu(u\cdot p) - u^\mu(\omega\cdot p)\right]}_{\text{“NR vorticity”}} + \underbrace{\varepsilon^{\mu\rho\sigma\tau}p_\tau A_\sigma u_\rho}_{\text{acceleration}}$$

temperature gradient **kinematic vorticity** **relativistic term**

Longitudinal quadrupole f_2:



P_z dominated by temperature gradient and relativistic term, but not by kinematic vorticity based on the hydro model.

Can we get such a small kinetic vorticity in the blast-wave model?

Variations of model parameters for P_H

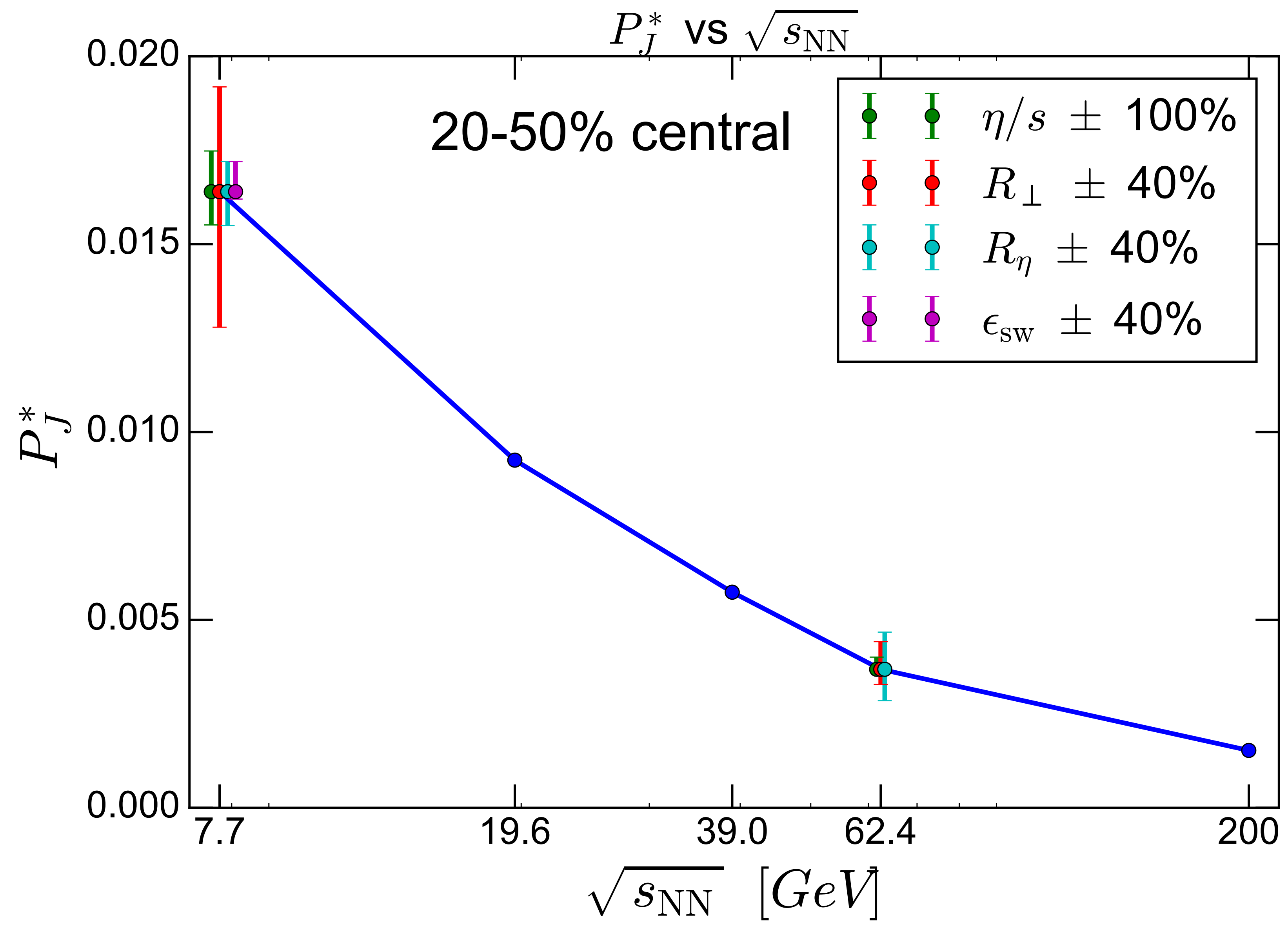
I. Karpenko, QM2017

Initial state:
$R_\perp$: transverse granularity
R_η: longitudinal granularity

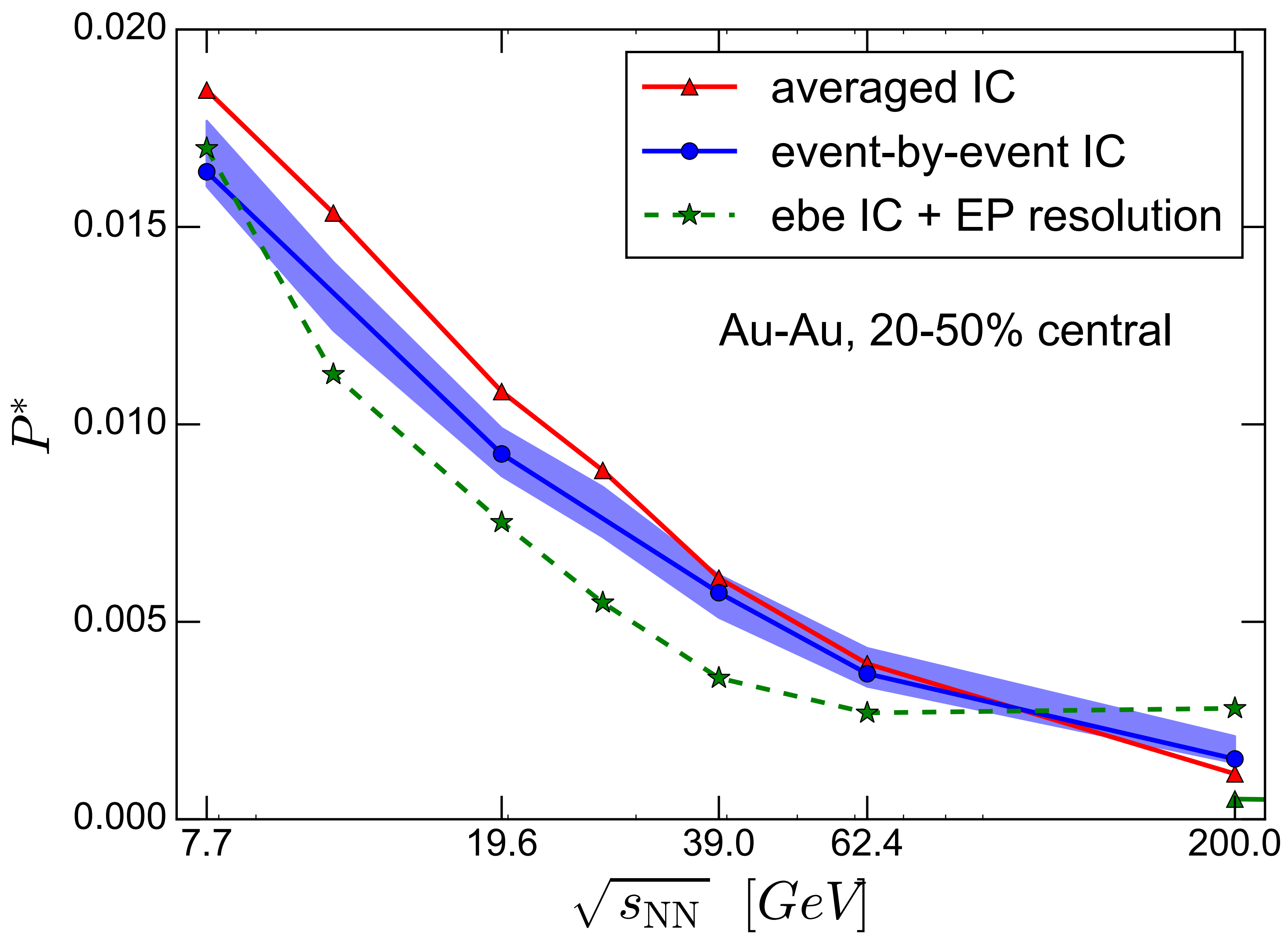
Fluid phase:
η/s: shear viscosity of fluid

Particlization criterion:
$\varepsilon_{sw} = 0.5$ GeV/fm^3

variation of model parameters

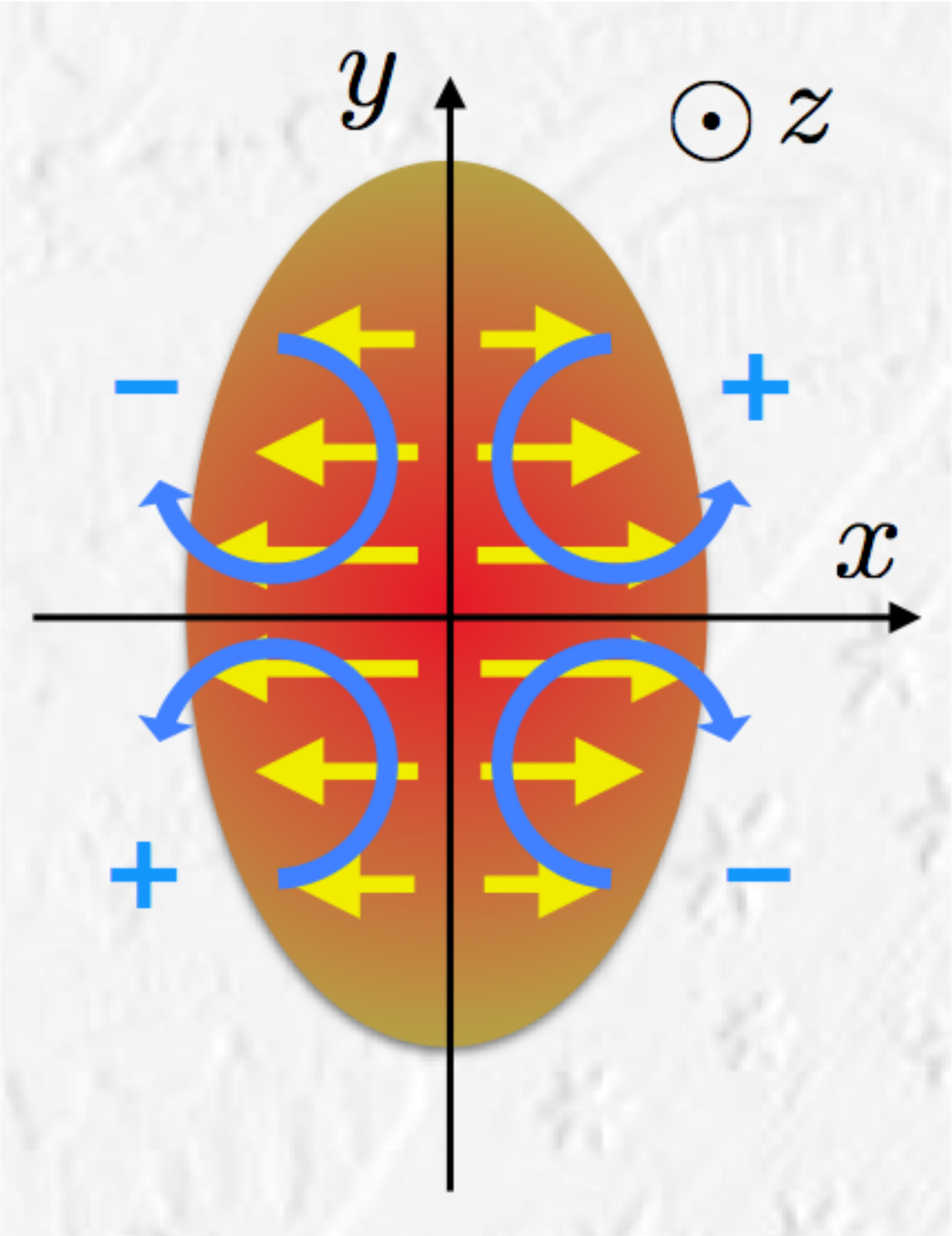


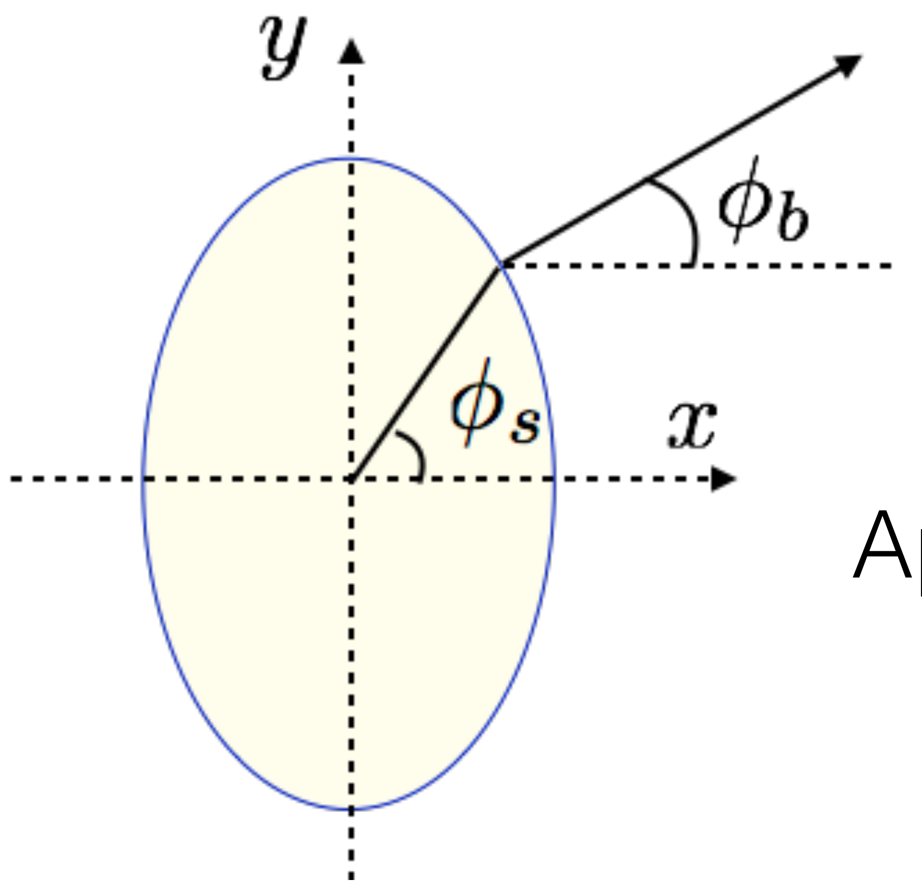
event-by-event vs. averaged



- Collision energy dependence is robust with respect to variation of the parameters of the model.
- There is no big difference between event-by-event and single shot hydrodynamic description.

Estimate kinematic vorticity with the blast-wave model





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

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

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

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

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

a_n: spatial anisotropy
b_n: flow anisotropy
R: reference source radius
ρ_t: transverse flow velocity

Sine modulation of ω_z is expected with the factor $[b_n - a_n]$.
The sign could be negative depending on the relation of flow and spatial anisotropy.

Blast-wave model parameterization

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

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

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

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

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

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

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

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

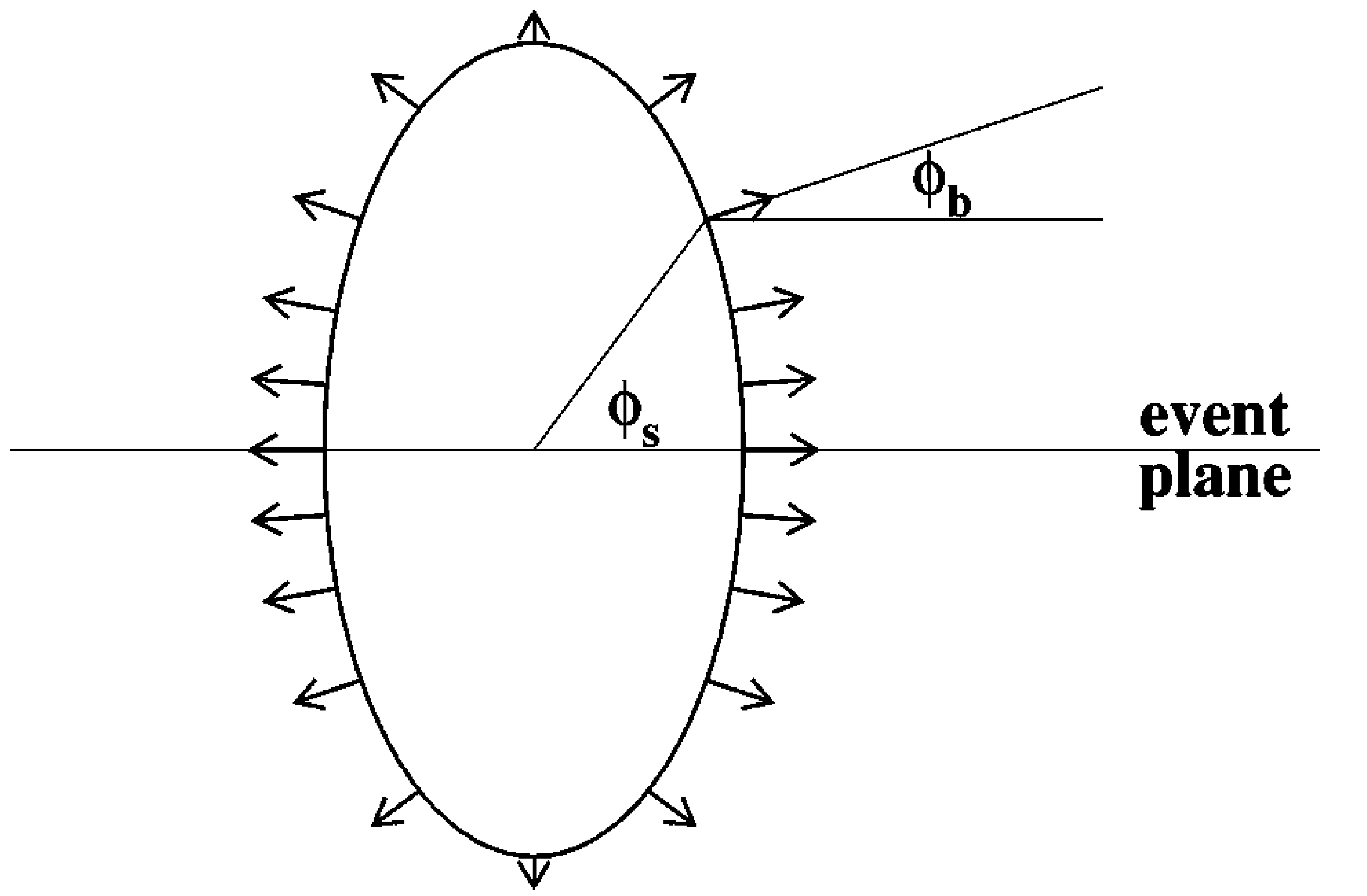


FIG. 2. Schematic illustration of an elliptical subshell of the source. Here, the source is extended out of the reaction plane ($R_y > R_x$). Arrows represent the direction and magnitude of the flow boost. In this example, $\rho_2 > 0$ [see Eq. (4)].

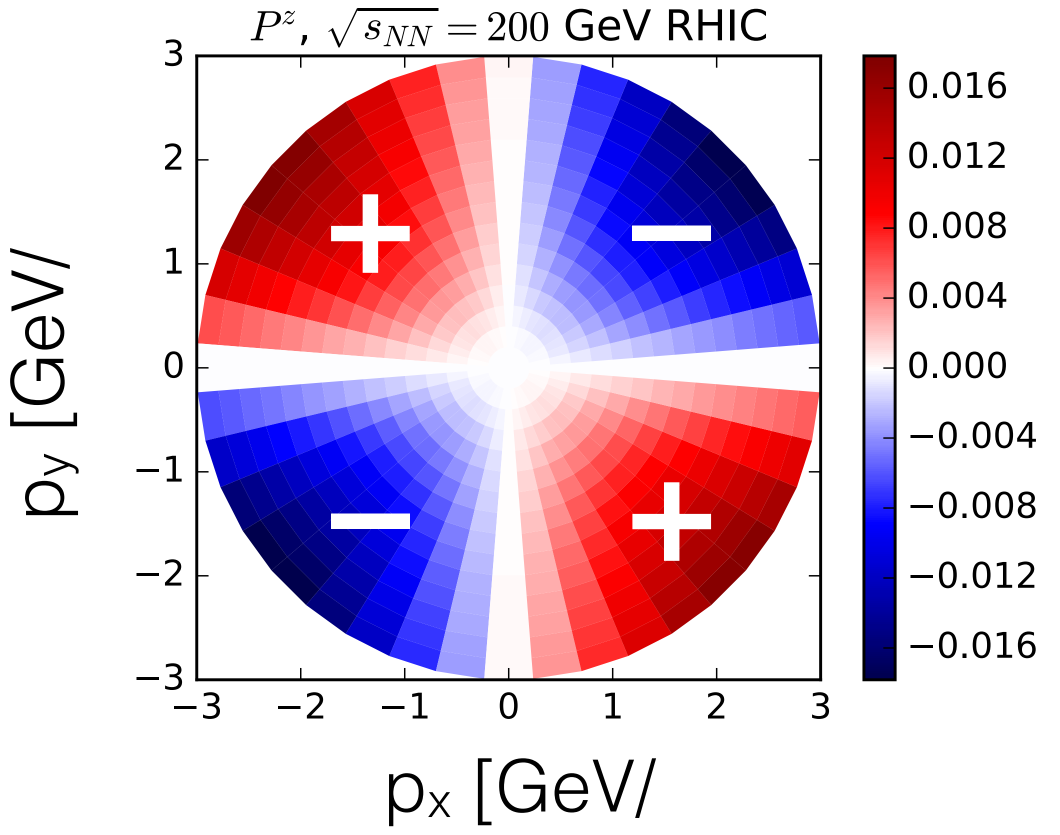
ϕ_s: azimuthal angle of the source element
ϕ_b: boost angle perpendicular to the elliptical subshell

Disagreement in P_z sign

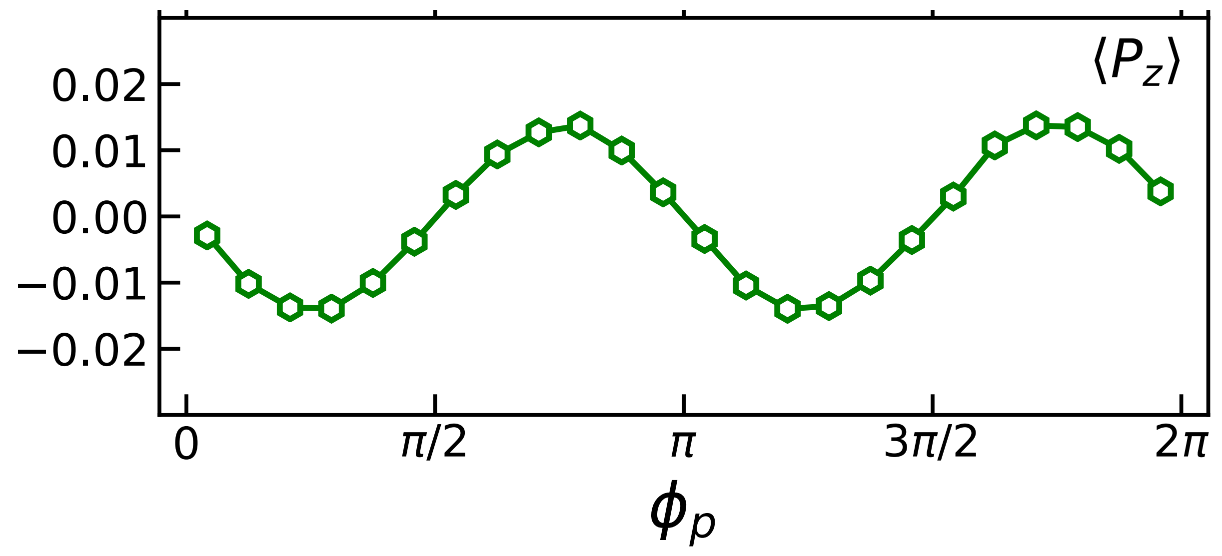
Opposite sign

- UrQMD (or Glauber) IC + hydrodynamic model
  F. Becattini and I. Karpenko, PRL.120.012302 (2018)
  -- Assuming a local thermal equilibrium
- AMPT
  X. Xia, H. Li, Z. Tang, Q. Wang, PRC98.024905 (2018)

Hydrodynamic model



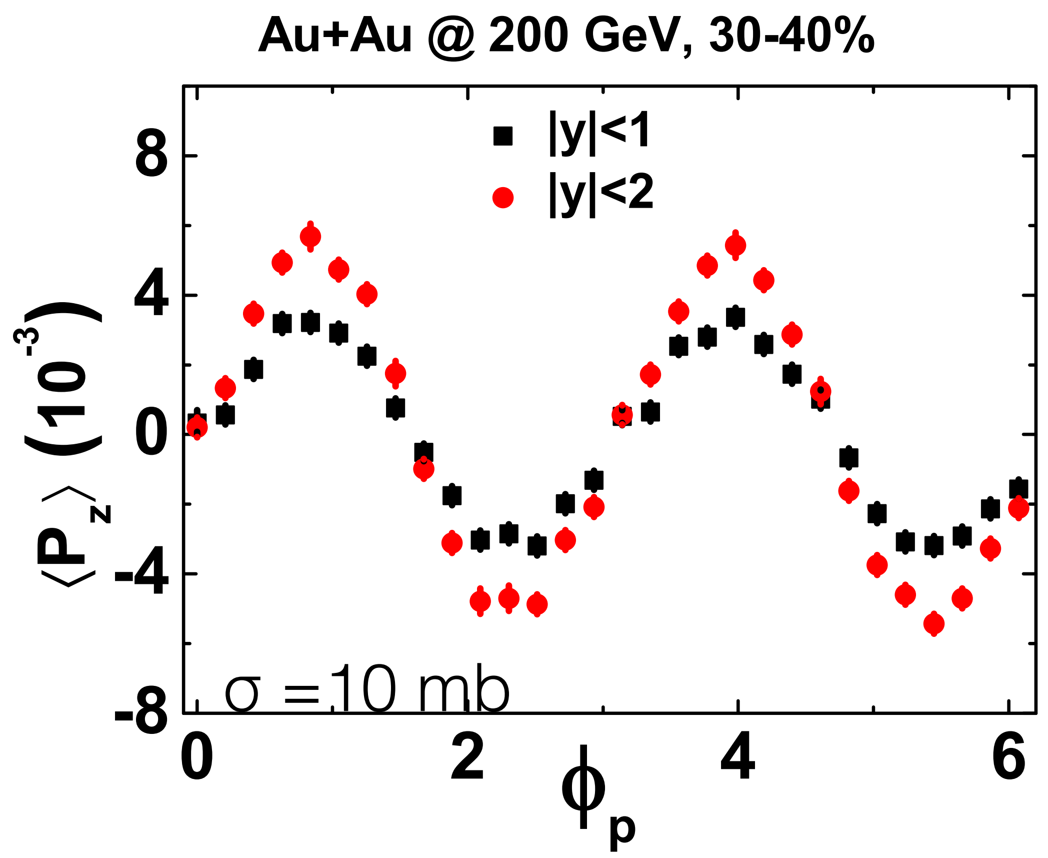
AMPT, Au+Au 200 GeV 20-50%



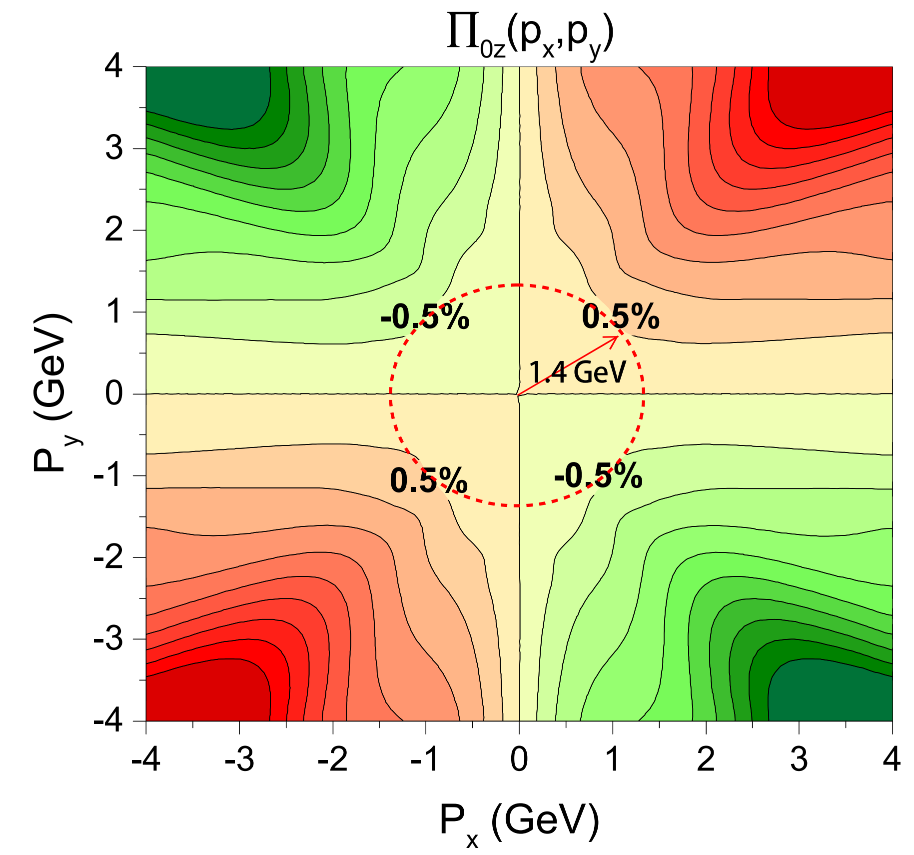
Same sign

- Chiral kinetic approach
  Y. Sun and C.-M. Ko, PRC99, 011903(R) (2019)
  -- Assuming non-equilibrium of spin degree of freedom
- PICR hydrodynamic model
  Y. Xie, D. Wang, and L. P. Csernai, arXiv:1907.00773
  -- Yang-Mills flux tube IC

Chiral kinetic approach



PICR model

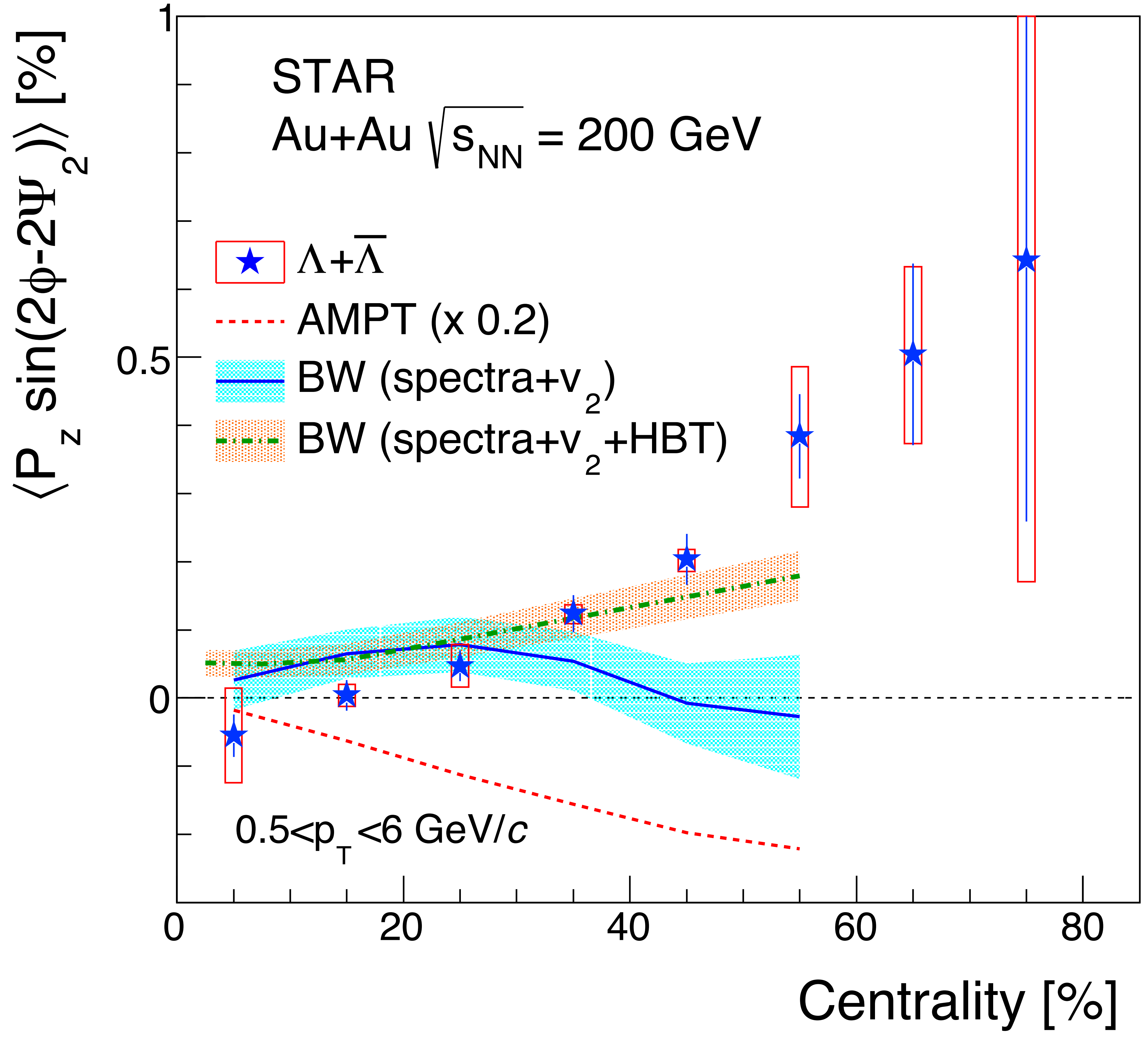


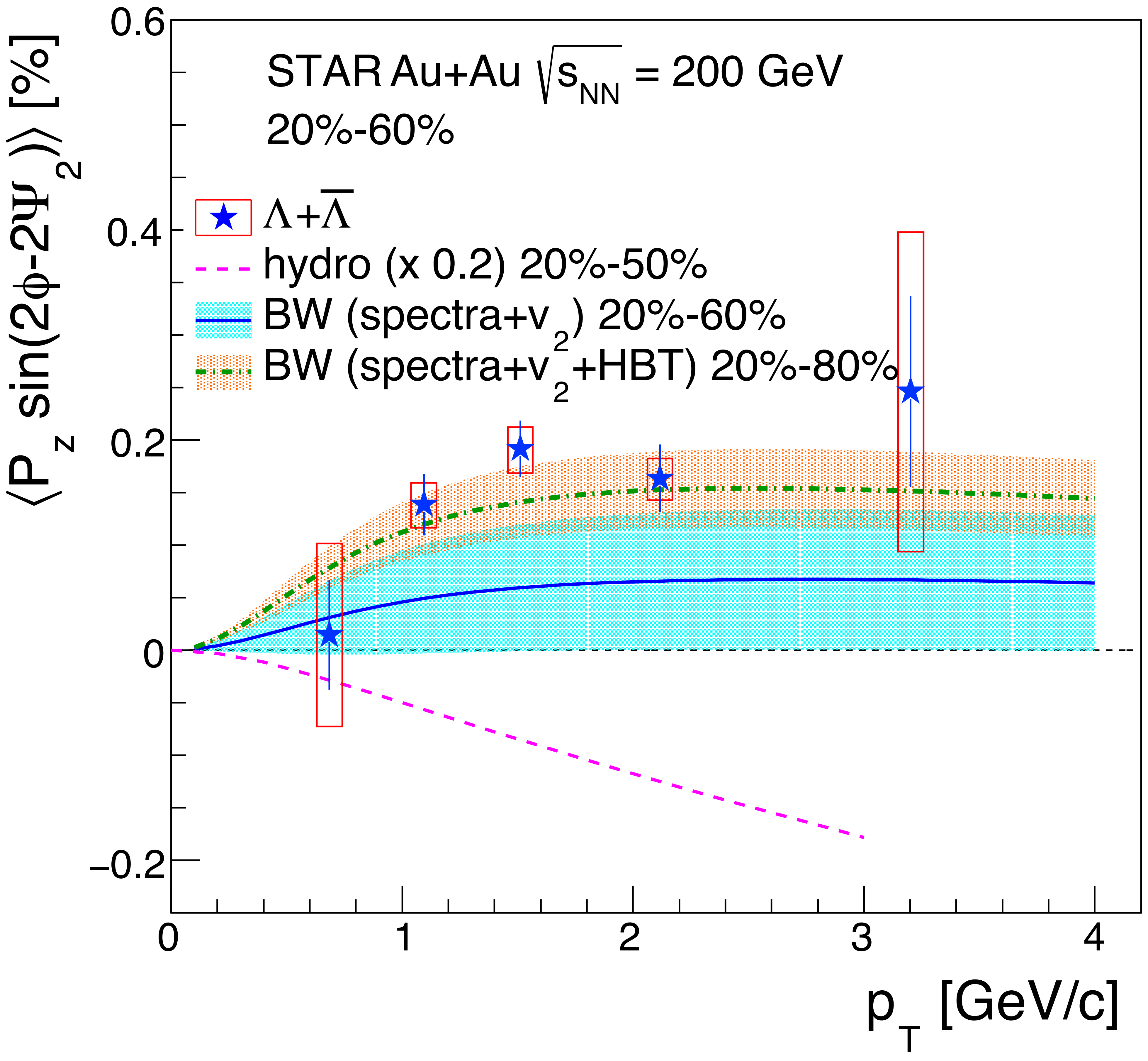
Incomplete thermal equilibrium of spin degree of freedom?
In hydrodynamic model, importance of relativistic contribution (from expansion and temporal term) in addition to kinematic vorticity.

P_z modulation from the BW model

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

STAR, arXiv:1905.11917





- Simple estimate for kinematic vorticity contribution with BW model
  - Similar magnitude to the data
  - Inclusion of HBT in the fit affects the sign in peripheral collisions

T. Niida, S. Voloshin, A. Dobrin, and R. Bertens, in preparation