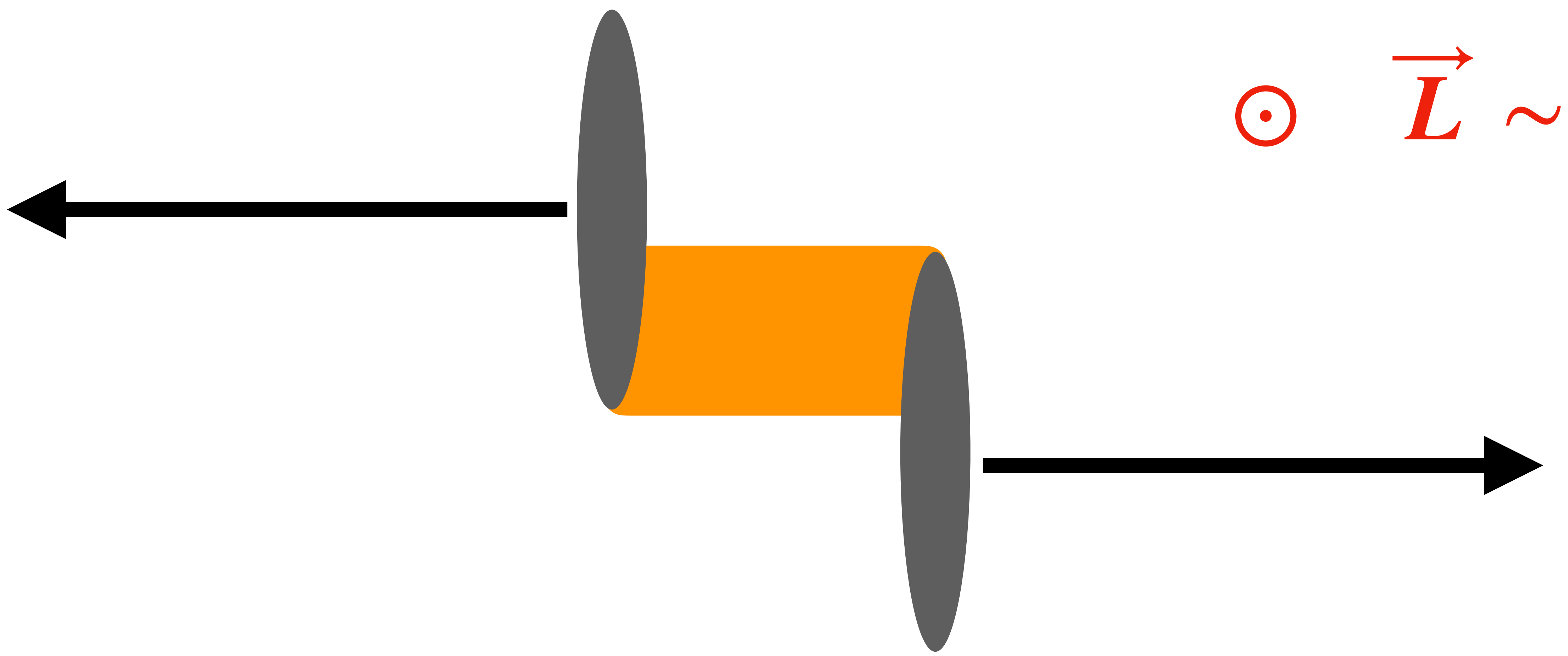
QPT2023, 珠海

Spin and Chirality Transport Theories

施舒哲(Shuzhe Shi)

清华大学(Tsinghua Univ.)

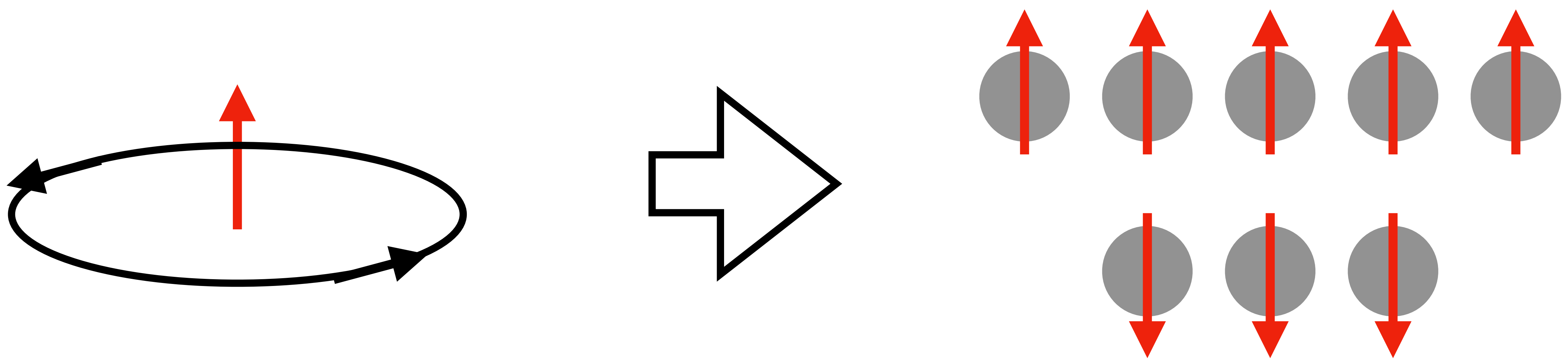
spin polarization



$\odot \quad \vec{L} \sim 10^{4-5}\hbar$

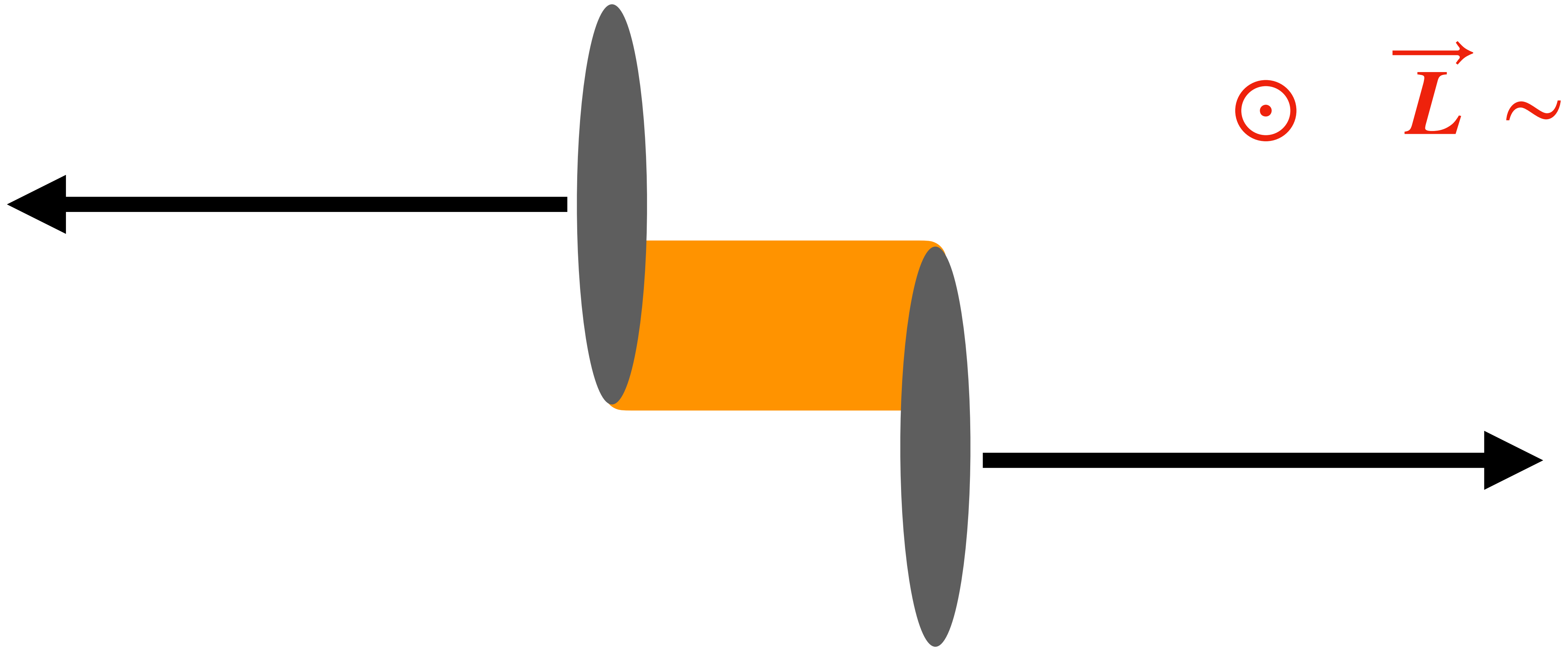
Angular Velocity: $\omega \sim 10^{21}$ Hz

rotation spin



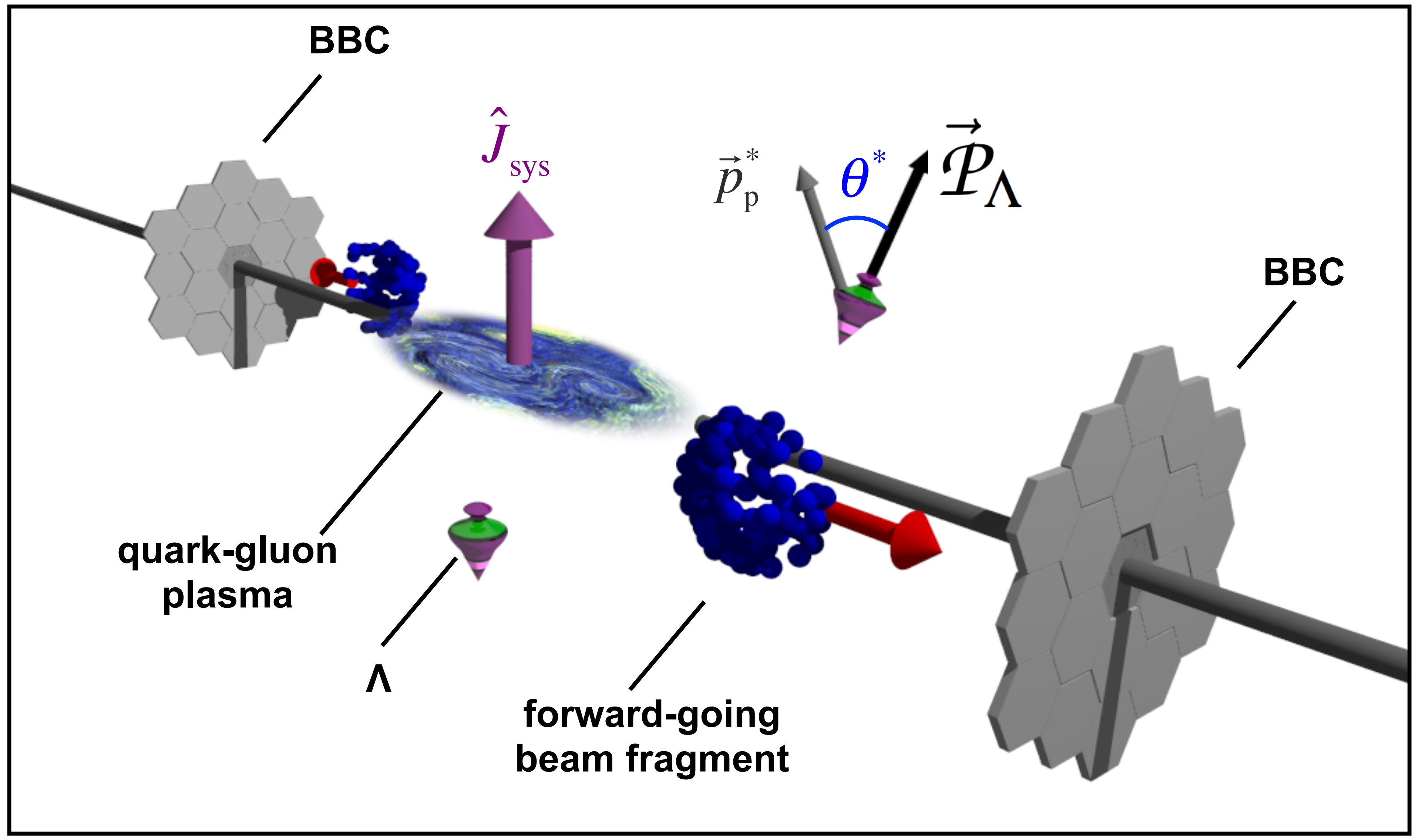
Zuo-Tang Liang, Xin-Nian Wang, PhysRevLett.94.102301

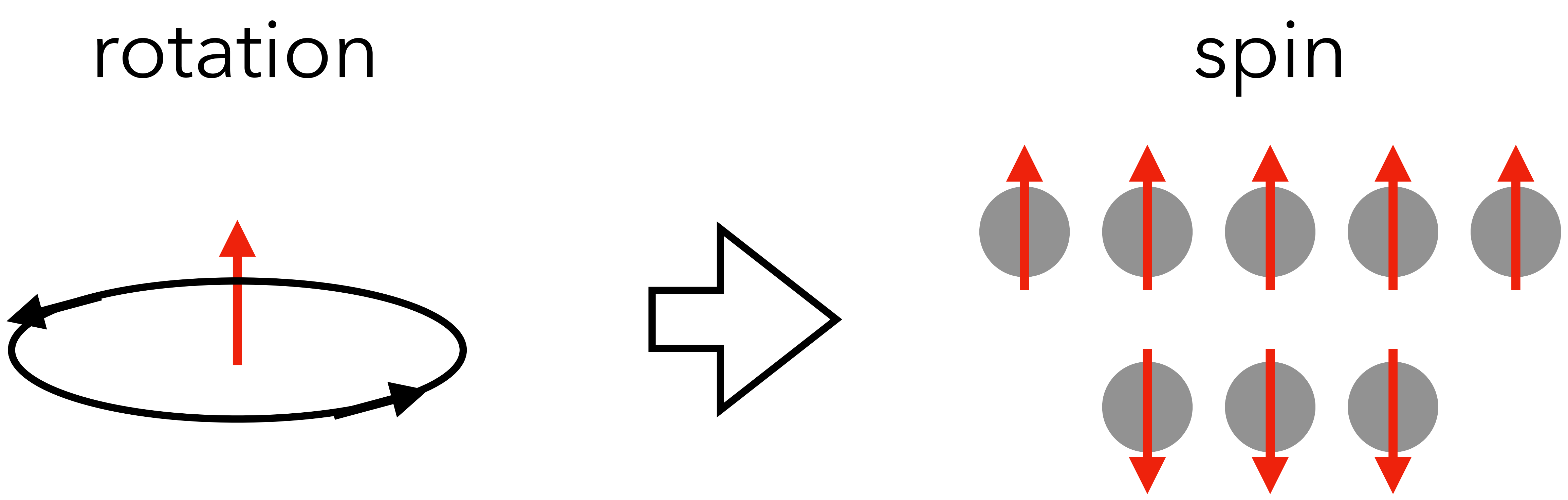
spin polarization



$\odot \quad \vec{L} \sim 10^{4-5}\hbar$

Angular Velocity: ω ~ 10^{21} Hz

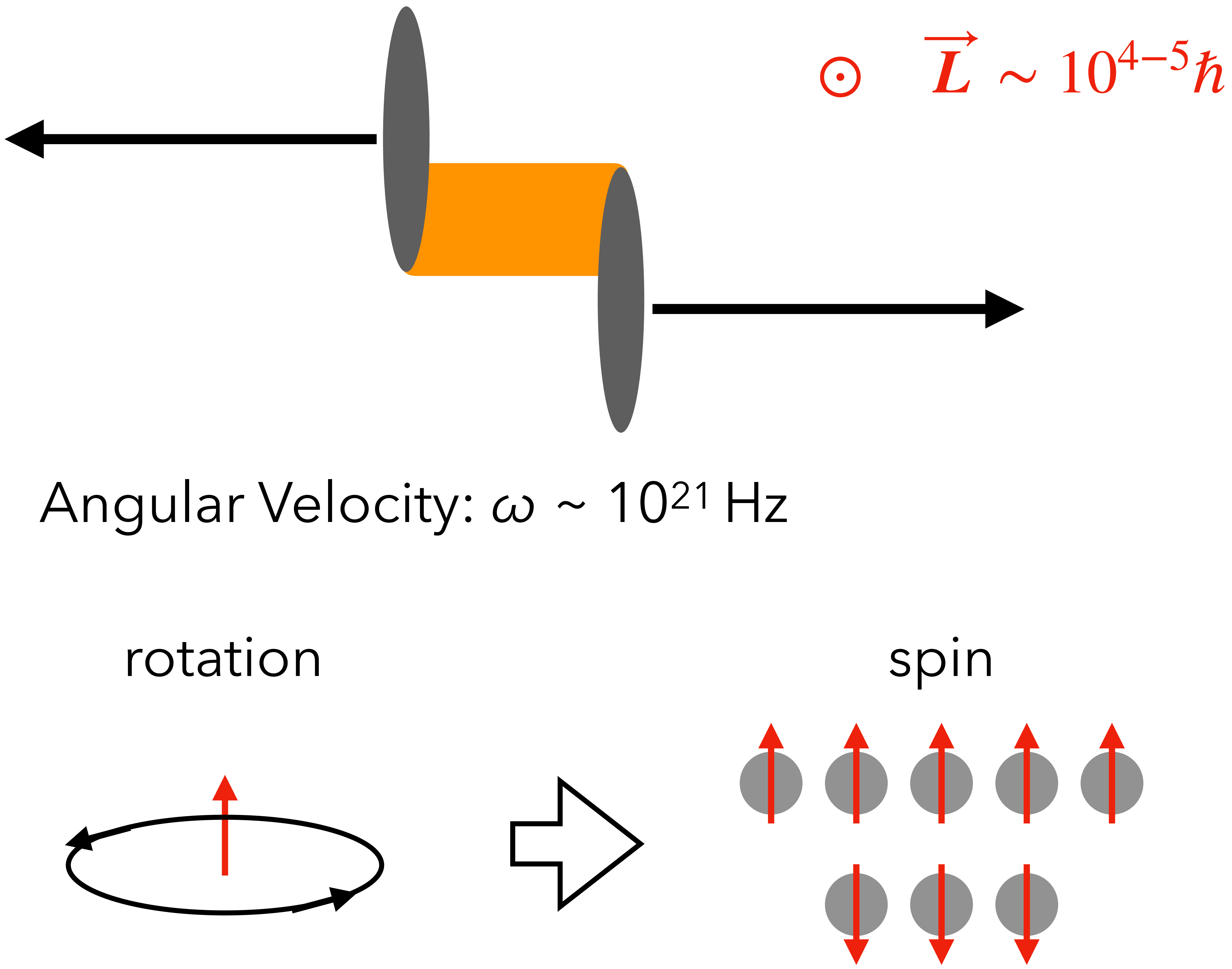


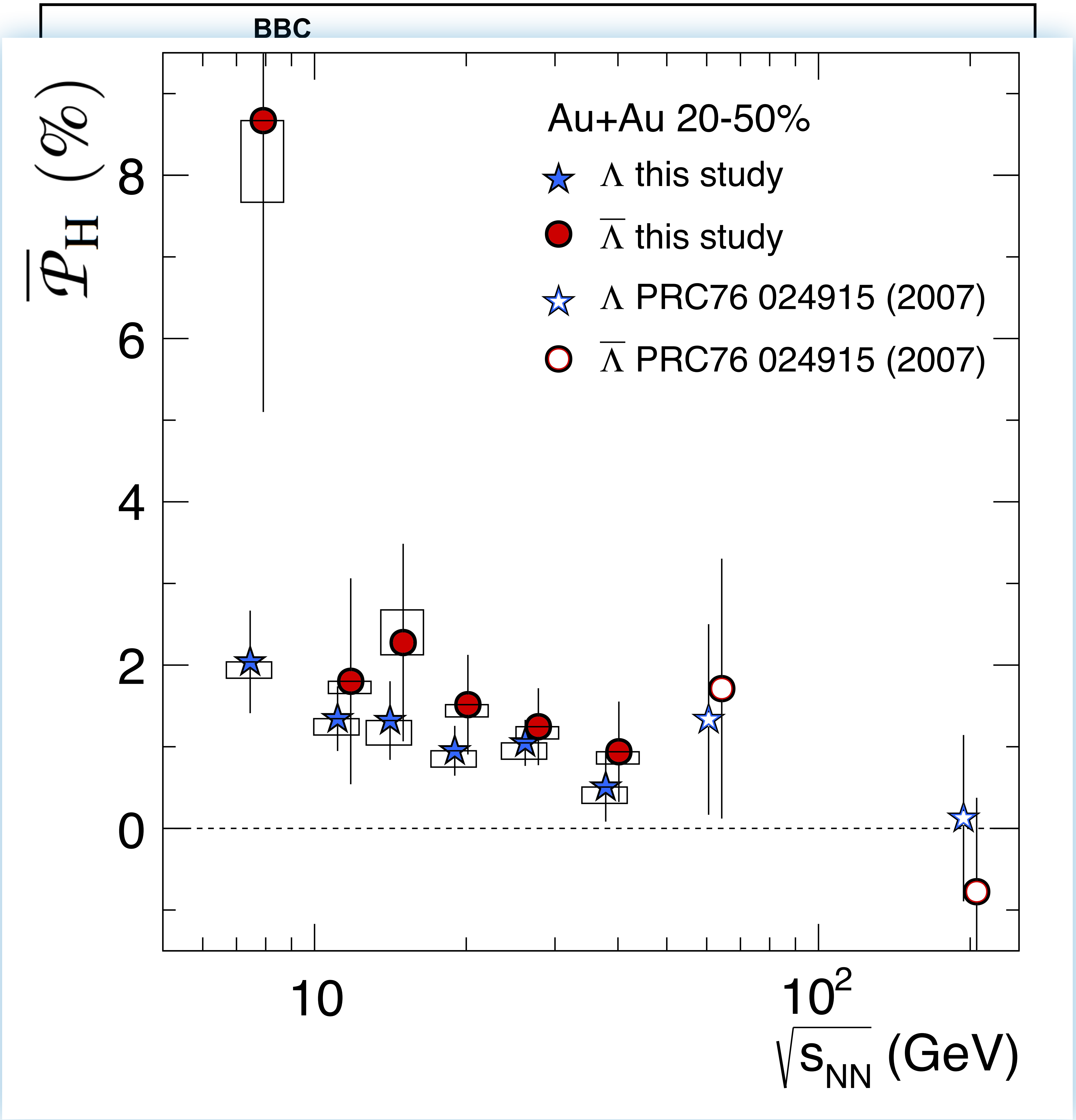


Zuo-Tang Liang, Xin-Nian Wang, PhysRevLett.94.102301

STAR, Nature 548 (2017) 62-65

spin polarization

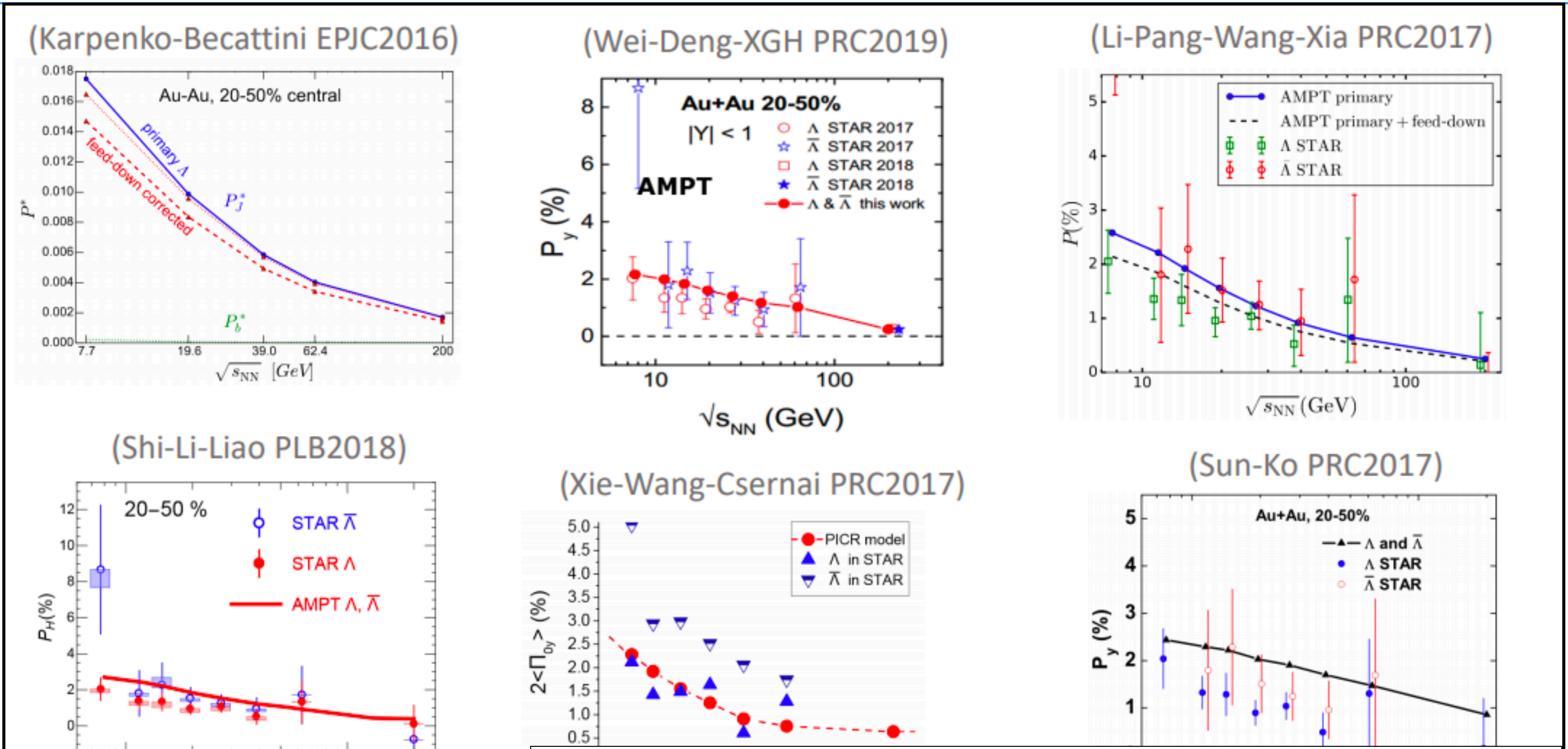




Zuo-Tang Liang, Xin-Nian Wang, PhysRevLett.94.102301

STAR, Nature 548 (2017) 62-65

polarization along out-of-plane direction



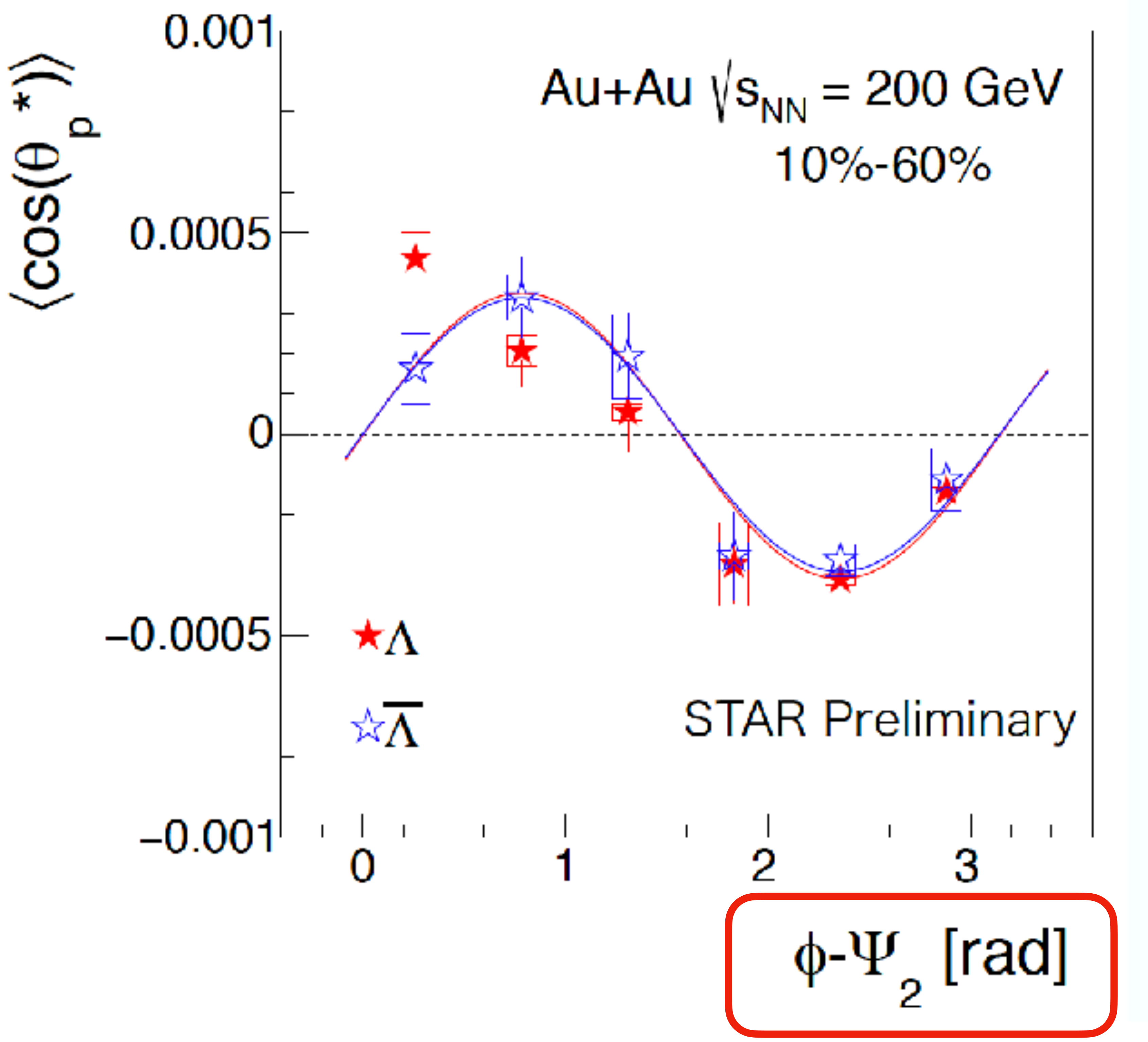
Slide from Xu Guang Huang's QM19 Plenary Talk

Assuming equilibrium of the spin degrees of freedom,
global polarization rate can be well understood by theo. models.

$$\varpi^{\mu\nu} \equiv \frac{1}{2}\left(\partial_\nu \frac{u_\mu}{T} - \partial_\mu \frac{u_\nu}{T}\right)$$

polarization along beam direction

Local longitudinal polarization due to collective flow



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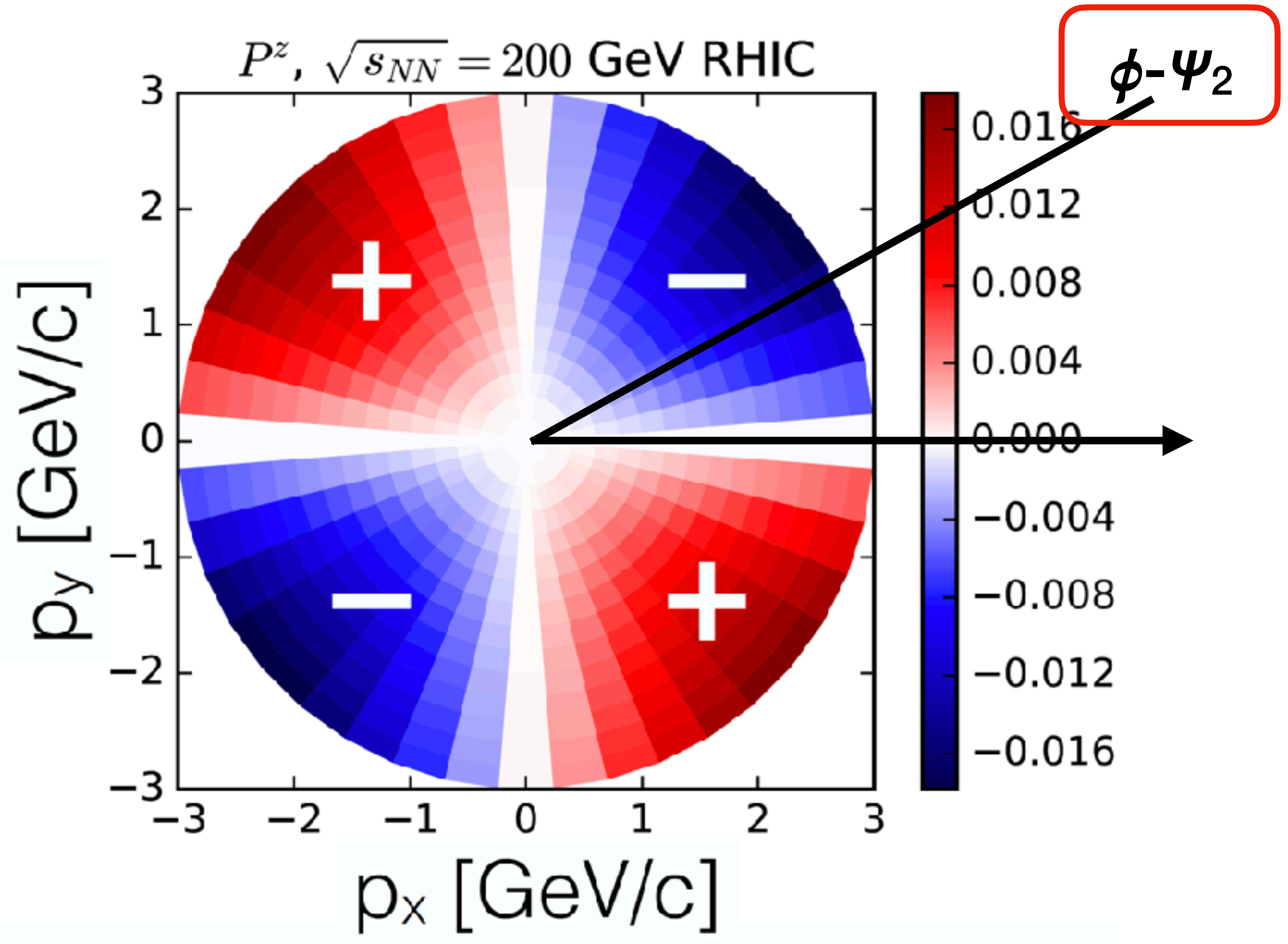

- (Hydro) F. Becattini & I. Karpenko, PRL 2018

Similarly in other models

Microscopic:

Macroscopic:

distribution function

$\int_p$

conserved (hydrodynamic) currents

$$W_{ab}(x,p) \equiv \left\langle \int \mathrm{d}^4y \, e^{i\frac{p\cdot y}{\hbar}} \bar{\psi}_b(x+\frac{y}{2})\psi_a(x-\frac{y}{2}) \right\rangle ,$$

$$J^\mu(x), \quad T^{\mu\nu}(x), \quad S^{\mu\nu\lambda}(x)$$

Vortical+Magnetic Effect

Non-Equilibrium Effect

transport of spin dof: microscopic

Wigner Function

$$W_{ab}(x,p) \equiv \left\langle \int \mathrm{d}^4 y \, e^{i\frac{p\cdot y}{\hbar}} \bar{\psi}_b(x+\frac{y}{2})\psi_a(x-\frac{y}{2}) \right\rangle ,$$

a 4×4 matrix, decomposed in Clifford basis

$$W = \frac{1}{4}\left(\mathscr{F} + i\mathscr{P}\gamma^5 + \mathscr{V}_\mu \gamma^\mu + \mathscr{A}_\mu \gamma^5 \gamma^\mu + \frac{1}{2}\mathscr{L}_{\mu\nu}\sigma^{\mu\nu} \right),$$

transport of spin dof: microscopic

Wigner Function

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- Boltzmann equation
- Lorentz force
- chiral vortical effect + spin polarization
- chiral magnetic effect

Dirac Equation

$$\gamma^\mu(i\hbar\partial_\mu - QA_\mu)\,\psi(x) = 0$$

⇨

$$\mathscr{J}^\mu_\pm \equiv \frac{\mathscr{V}^\mu \pm \mathscr{A}^\mu}{2} = \left[p^\mu\delta(p^2) \pm \hbar\delta(p^2)\frac{\epsilon^{\mu\nu\lambda\rho}p_\nu n_\lambda}{2p\cdot n}\nabla_\rho \pm \hbar Q\delta'(p^2)\widetilde{F}^{\mu\nu}p_\nu\right]f_\pm,$$

$$0 = \delta\left(p^2 \mp \hbar Q\frac{p\cdot B}{p\cdot n}\right)\left[p\cdot\partial - Qp^\mu F_{\mu\nu}\partial^\nu_p \pm \hbar\left(\partial_\mu\frac{\epsilon^{\mu\nu\lambda\rho}p_\nu n_\lambda}{2p\cdot n}\right)\nabla_\rho \mp \hbar Q\frac{\epsilon^{\mu\nu\lambda\rho}E_\mu n_\nu p_\lambda}{2(p\cdot n)^2}\nabla_\rho \pm \hbar\frac{Q}{2p\cdot n}p_\lambda\left(\partial_\sigma\widetilde{F}^{\lambda\nu}\right)n_\nu\partial^\sigma_p\right]f_\pm.$$

Huang, ***SS***, Jiang, Liao, and Zhuang, Phys.Rev.D(2018)

transport of spin dof: macroscopic

Wigner Function

$$W_{ab}(x,p) \equiv \left\langle \int \mathrm{d}^4 y \, e^{i\frac{p\cdot y}{\hbar}} \bar{\psi}_b(x+\frac{y}{2})\psi_a(x-\frac{y}{2}) \right\rangle ,$$

a 4×4 matrix, decomposed in Clifford basis

$$W = \frac{1}{4}\left(\mathscr{F} + i\mathscr{P}\gamma^5 + \mathscr{V}_\mu \gamma^\mu + \mathscr{A}_\mu \gamma^5 \gamma^\mu + \frac{1}{2}\mathscr{L}_{\mu\nu}\sigma^{\mu\nu} \right),$$

⇒

Hydrodynamic Quantities:

$$J^\mu \equiv \langle \bar{\psi}\gamma^\mu \psi \rangle = \int \frac{\mathrm{d}^4 p}{(2\pi)^4} \mathscr{V}^\mu ,$$

$$T^{\mu\nu} \equiv \langle \bar{\psi}(i\gamma^\mu \partial^\nu)\psi \rangle = \int \frac{\mathrm{d}^4 p}{(2\pi)^4} p^\mu \mathscr{V}^\nu ,$$

$$S^{\lambda\mu\nu} \equiv \frac{1}{4}\langle \bar{\psi}\{\gamma^\lambda, \sigma^{\mu\nu}\}\psi \rangle = \frac{\epsilon^{\lambda\mu\nu\sigma}}{2} \int \frac{\mathrm{d}^4 p}{(2\pi)^4} \mathscr{A}_\sigma ,$$

transport of spin dof: macroscopic

Wigner Function

$$W_{ab}(x,p) \equiv \left\langle \int d^4y\, e^{i\frac{p\cdot y}{\hbar}} \bar{\psi}_b(x+\frac{y}{2})\psi_a(x-\frac{y}{2}) \right\rangle,$$

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$$W = \frac{1}{4}\left(\mathscr{F} + i\mathscr{P}\gamma^5 + \mathscr{V}_\mu \gamma^\mu + \mathscr{A}_\mu \gamma^5\gamma^\mu + \frac{1}{2}\mathscr{L}_{\mu\nu}\sigma^{\mu\nu} \right),$$

Hydrodynamic Quantities:

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SHI, GALE, AND JEON

Substituting the distribution function in the definitions (13)–(15), we find the RH and LH particle currents and energy-momentum stress tensor,

$$\pm\frac{\hbar}{2}\epsilon^{\mu\rho\sigma\lambda}u_\rho\partial_\sigma\left(\frac{G^{(1),\pm}_{4,1}}{D^{\pm}_{3,1}}\nu_{\pm,\lambda}\right)$$

$$\pm\frac{\hbar J^{\pm}_{2,2}}{4J^{\pm}_{4,2}}(\epsilon^{\mu\rho\sigma\lambda}u_\rho\sigma_\sigma{}^\xi\pi_{\lambda\xi} - \pi^{\mu\lambda}\omega_\lambda)$$

$$\equiv n_\pm u^\mu + \nu^\mu_\pm + \hbar J^\mu_{\mathrm{quantum},\pm}, \qquad (67)$$

$$T^{\mu\nu} = \varepsilon u^\mu u^\nu - P\Delta^{\mu\nu} + \pi^{\mu\nu} + \frac{4\hbar}{5}\omega^\mu(\nu^\nu_+ - \nu^\nu_-)$$

$$+\frac{\hbar n_A}{4}(8\omega^\mu u^\nu + T\epsilon^{\mu\nu\sigma\lambda}\varpi_{\sigma\lambda})$$

$$\ldots \frac{J^-_{3,2}}{J^-_{4,2}}\Big)\pi_{\lambda\xi}\Big]$$

$$+\frac{\hbar}{2}\epsilon^{\mu\rho\sigma\lambda}u_\rho u^\nu\partial_\sigma(\nu^+_\lambda - \nu^-_\lambda)$$

$$-\frac{\hbar}{10}\epsilon^{\mu\nu\rho\sigma}u_\rho(\partial_\sigma u^\lambda)(\nu^+_\lambda - \nu^-_\lambda)$$

$$+\frac{2\hbar}{5}\epsilon^{\mu\lambda\rho\sigma}u_\rho(\partial_\sigma u^\nu)(\nu^+_\lambda - \nu^-_\lambda)$$

$$\equiv \varepsilon u^\mu u^\nu \ldots$$

Chiral-viscous hydrodynamic equations

SS, Gale, and Jeon, Phys.Rev.C(2021)

transport of spin dof: macroscopic

Wigner Function

$$W_{ab}(x,p) \equiv \left\langle \int d^4y\, e^{i\frac{p\cdot y}{\hbar}} \bar{\psi}_b(x+\frac{y}{2})\psi_a(x-\frac{y}{2}) \right\rangle ,$$

Hydrodynamic Quantities:

$$J^\mu \equiv \langle \bar{\psi}\gamma^\mu\psi \rangle = \int \frac{d^4p}{(2\pi)^4} \mathscr{V}^\mu ,$$

many other references:

SYSU, Fudan, USTC, Shandong Univ., Tsinghua, …

Cracow, Frankfurt, Florence, …

SHI, GALE, AND JEON

Substituting the distribution function in the definitions (13)–(15), we find the RH and LH particle currents and energy-momentum stress tensor,

Chiral-viscous hydrodynamic equations

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$$\pm\frac{\hbar J^\pm_{2,2}}{4J^\pm_{4,2}}(\epsilon^{\mu\rho\sigma\lambda}u_\rho\sigma_\sigma{}^\xi\pi_{\lambda\xi} - \pi^{\mu\lambda}\omega_\lambda)$$

$$\equiv n_\pm u^\mu + \nu^\mu_\pm + \hbar J^\mu_{\text{quantum},\pm}, \qquad (67)$$

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$$+\frac{\hbar n_A}{4}(8\omega^\mu u^\nu + T\epsilon^{\mu\nu\sigma\lambda}\varpi_{\sigma\lambda})$$

$$\ldots \pi_{\lambda\xi}\Big]$$

$$+\frac{\hbar}{2}\epsilon^{\mu\rho\sigma\lambda}u_\rho u^\nu\partial_\sigma(\nu^+_\lambda - \nu^-_\lambda)$$

$$-\frac{\hbar}{10}\epsilon^{\mu\nu\rho\sigma}u_\rho(\partial_\sigma u^\lambda)(\nu^+_\lambda - \nu^-_\lambda)$$

$$+\frac{2\hbar}{5}\epsilon^{\mu\lambda\rho\sigma}u_\rho(\partial_\sigma u^\nu)(\nu^+_\lambda - \nu^-_\lambda)$$

$$\equiv \varepsilon u^\mu u^\nu \ldots$$

SS, Gale, and Jeon, Phys.Rev.C(2021)

transport of spin dof: macroscopic

a different approach: conservation law + second law of thermodynamics

Fate of spin polarization in a relativistic fluid: An entropy-current analysis
Koichi Hattori, M.Hongo, Xu-Guang Huang, M.Matsuo, H.Taya, Phys.Lett.B 795 (2019) 100-106

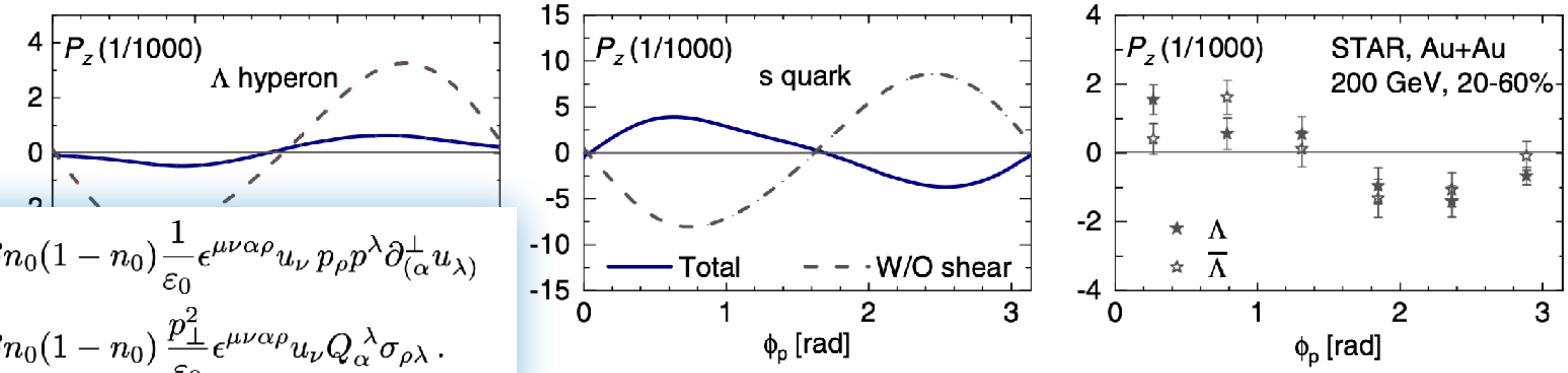
Spin hydrodynamics and symmetric energy-momentum tensors – A current induced by the spin vorticity
Kenji Fukushima, Shi Pu, Phys.Lett.B 817 (2021) 136346

Cross effects in spin hydrodynamics: Entropy analysis and statistical operator
Jin Hu, PhysRevC.107.024915

12.17 afternoon, II, 国兴厅

17:30-17:50	Spin hydrodynamics, entropy principle and fluctuations	Lixin Yang

a possible explanation: shear-induced polarization



$$\mathcal{A}^{\mu}_{\mathrm{SIP}} = -\beta n_0(1-n_0)\frac{1}{\varepsilon_0}\epsilon^{\mu\nu\alpha\rho}u_\nu\, p_\rho p^\lambda \partial^\perp_{(\alpha}u_{\lambda)}$$
$$= -\beta n_0(1-n_0)\frac{p_\perp^2}{\varepsilon_0}\epsilon^{\mu\nu\alpha\rho}u_\nu Q_\alpha^{\ \lambda}\sigma_{\rho\lambda}\,.$$

Spin polarization induced by the hydrodynamic gradients
Shuai Y.F. Liu, Yi Yin, JHEP 07 (2021) 188

Shear-Induced Spin Polarization in Heavy-Ion Collisions
Baochi Fu, Shuai Y.F. Liu, Long-Gang Pang, Huichao Song, Yi Yin, PhysRevLett.127.142301

Local Polarization and Isothermal Local Equilibrium in Relativistic Heavy Ion Collisions
F. Becattini, M. Buzzegoli, G. Inghirami, I. Karpenko, A. Palermo, PhysRevLett.127.272302

Spin-thermal shear coupling in a relativistic fluid
F. Becattini, M. Buzzegoli, A. Palermo, Phys.Lett.B 820 (2021) 136519

more @ QPT2023

Experiment

12.17 afternoon, II, 国兴厅

15:20-15:40	Measurements of Global and Local Polarization of Hyperons in Heavy Ion Collisions from STAR	Xingrui Gou

Theory

12.17 afternoon, II, 国兴厅

14:40-15:00	Spin Polarization, Anomalous Magnetic Moment and Transportation in the magnetized QCD background	Shengqin Feng
16:10-16:30	A topological realization of spin polarization through vortex formation in collisions of Bose-Einstein condensates	Jian Deng
16:30-16:50	Polarized hadron production in unpolarized high energy collisions	Shu-yi Wei

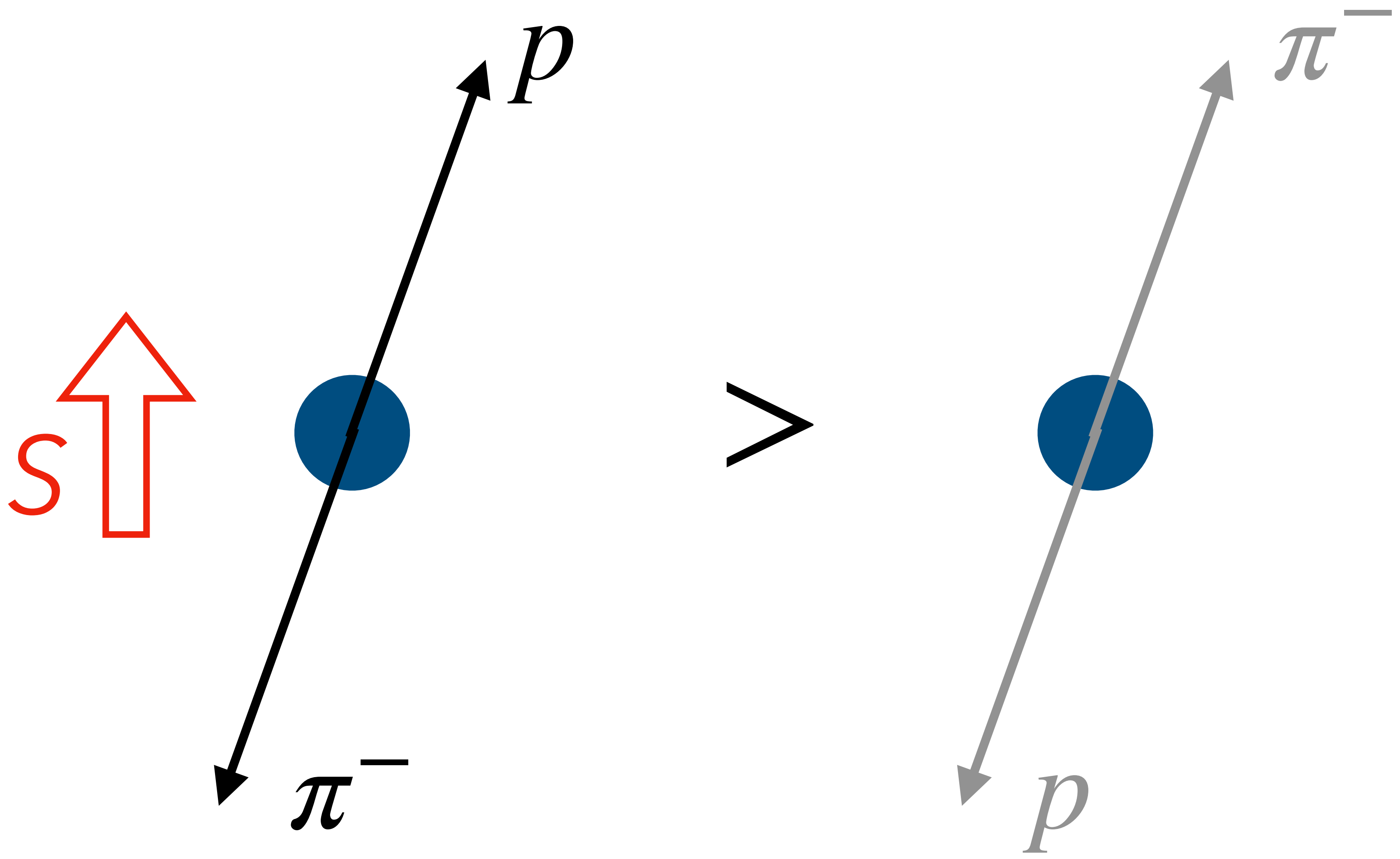
12.17 afternoon, III, 国旺厅

17:30-17:50	The relation of global polarization and directed flow in Au+Au collisions at RHIC	Ze-Fang Jiang

vector meson spin alignment

weak decay (Λ)

$\not{P}$

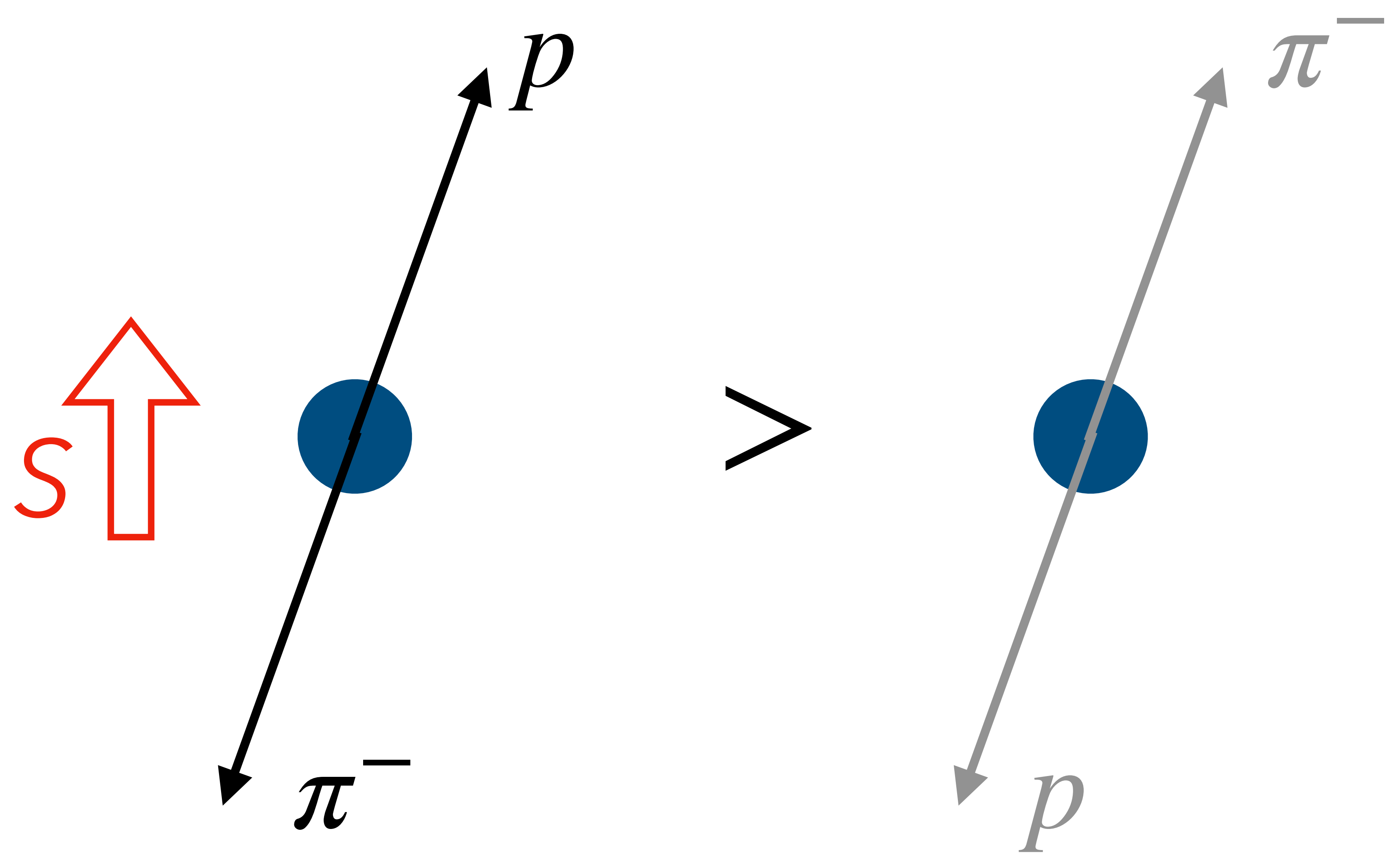


$$P \propto \frac{\omega}{T}$$

vector meson spin alignment

weak decay (Λ)

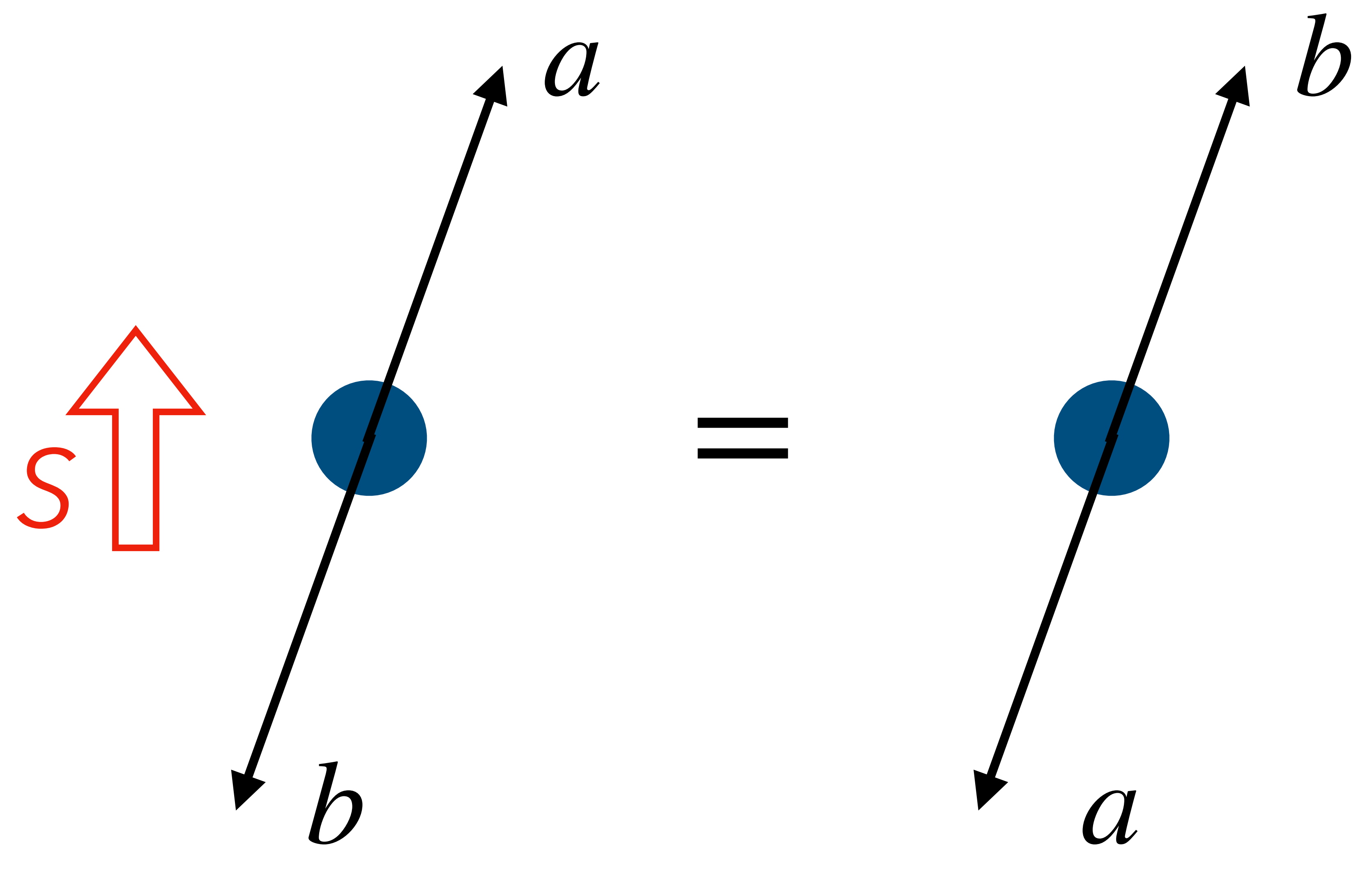
$\not{P}$



$$P \propto \frac{\omega}{T}$$

strong/EM decay $(\phi, \rho, K^*, J/\psi)$

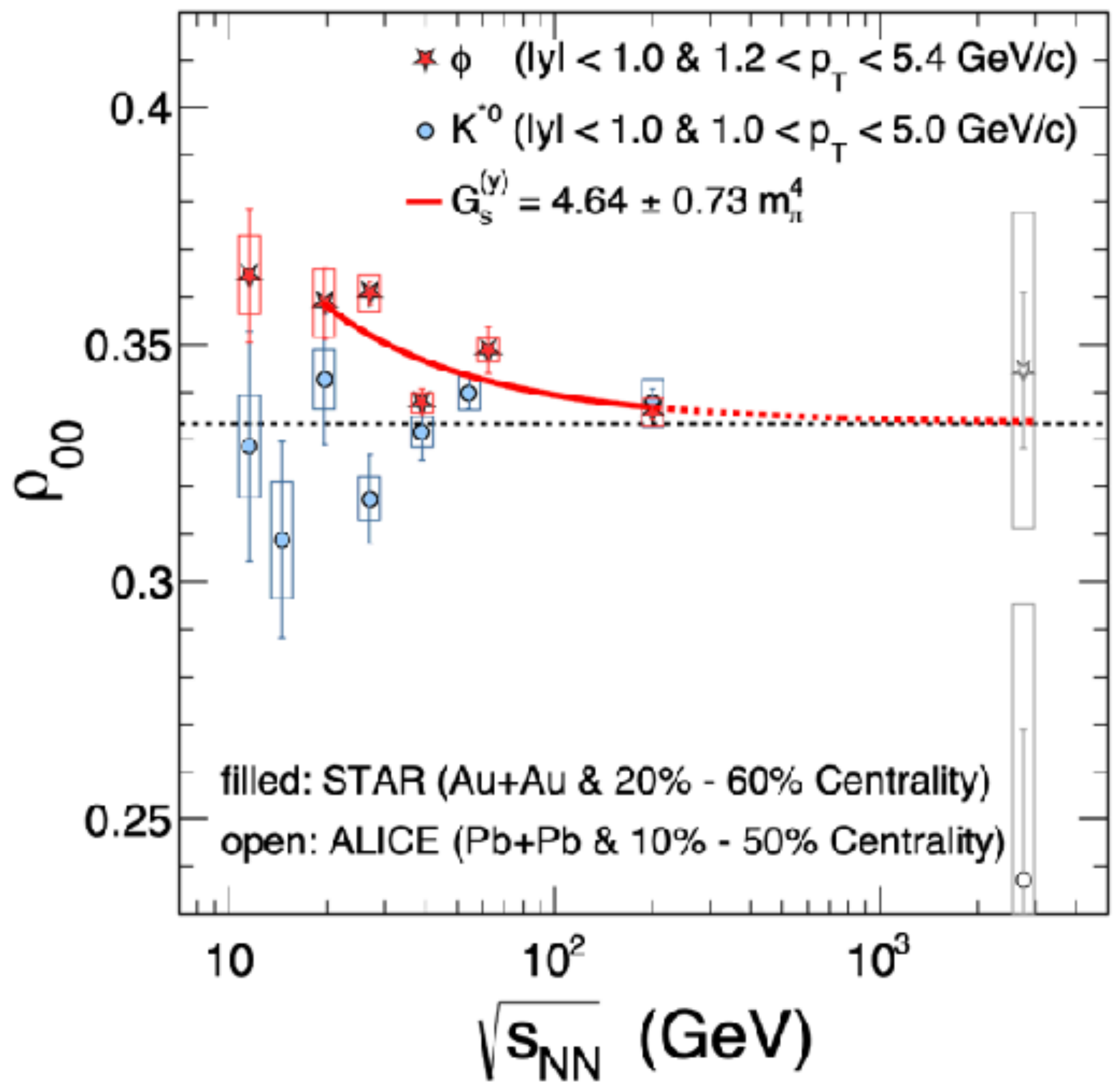
P



vector mesons

$$\Delta\rho_{00} \propto \left(\frac{\omega}{T}\right)^2$$

vector meson spin alignment/polarization: experimental measurement



STAR, Nature 614 (2023) 244

12.17 afternoon, II, 国兴厅

14:20-14:40	Vector meson polarization measurements in pp and Pb-Pb collisions with ALICE at the LHC	Xiaozhi Bai
15:00-15:20	Measurements of J/ψ polarization and global spin alignment in Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}} = 200$ GeV from the STAR experiment	Qian Yang

vector meson spin alignment/polarization: theory developments

meson field:

Spin Alignment of Vector Mesons in Heavy-Ion Collisions
Xin-Li Sheng, L. Oliva, Zuo-Tang Liang, Qun Wang, Xin-Nian Wang, PhysRevLett.131.042304

shear-induced modification of polarization tensor:

Tensor Polarization and Spectral Properties of Vector Meson in QCD Medium
Feng Li, Shuai Y.F. Liu, 2206.11890

12.17 afternoon, II, 国兴厅

14:00-14:20	Spin alignment for K mesons	Shi Pu

12.18 morning, II, 国兴厅

9:00-9:20	Magneto-birefringence and axial Ward identity at finite temperature and density	Koichi Hattori

influence of $\vec{\omega}$ and/or $\vec{B}$ in thermodynamics/PT

12.17 afternoon, I, 国会厅

14:40-15:00	Fluctuations of conserved charges in strong magnetic fields in (2+1)-flavor QCD	Jinbiao Gu

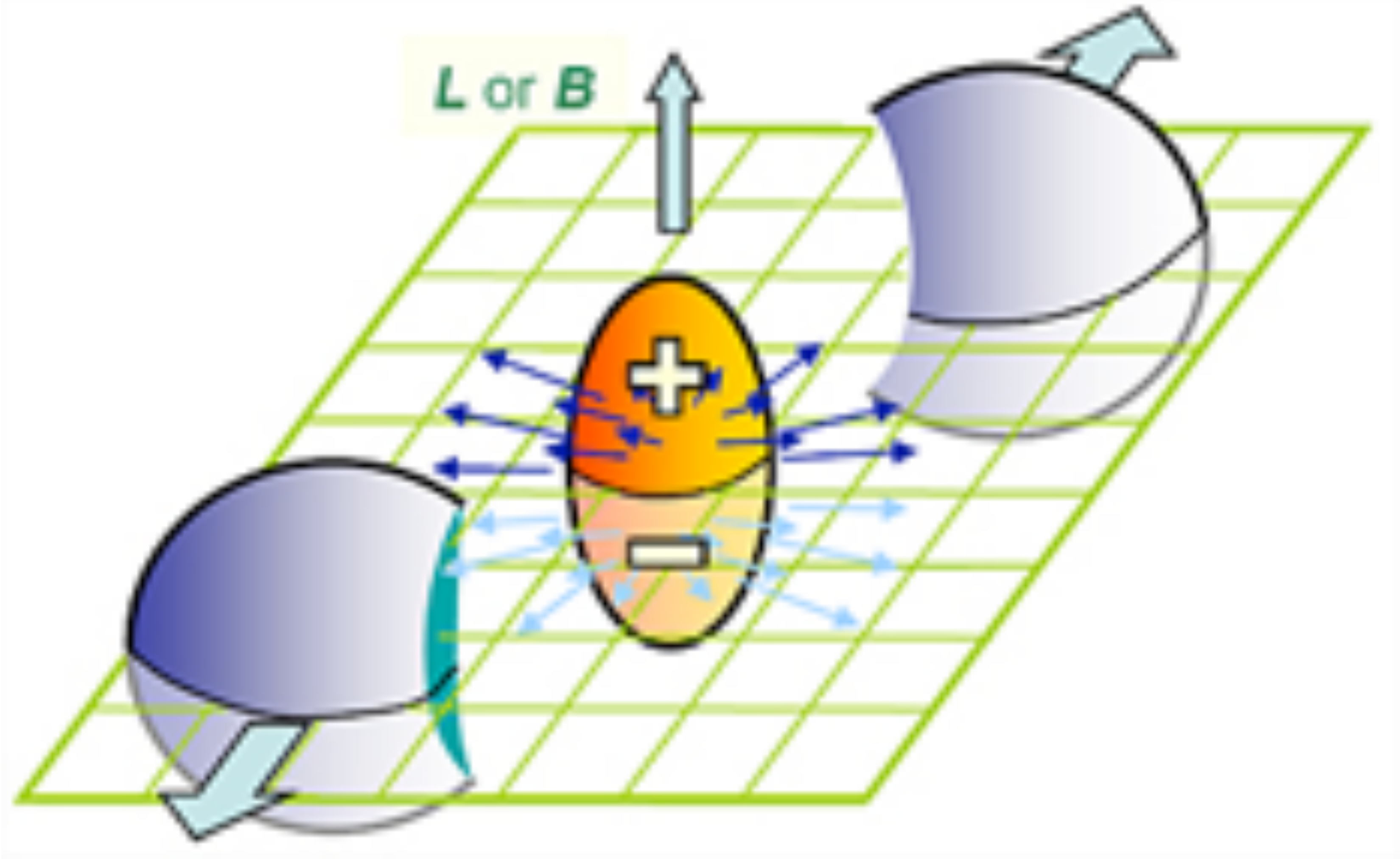
12.17 afternoon, II, 国兴厅

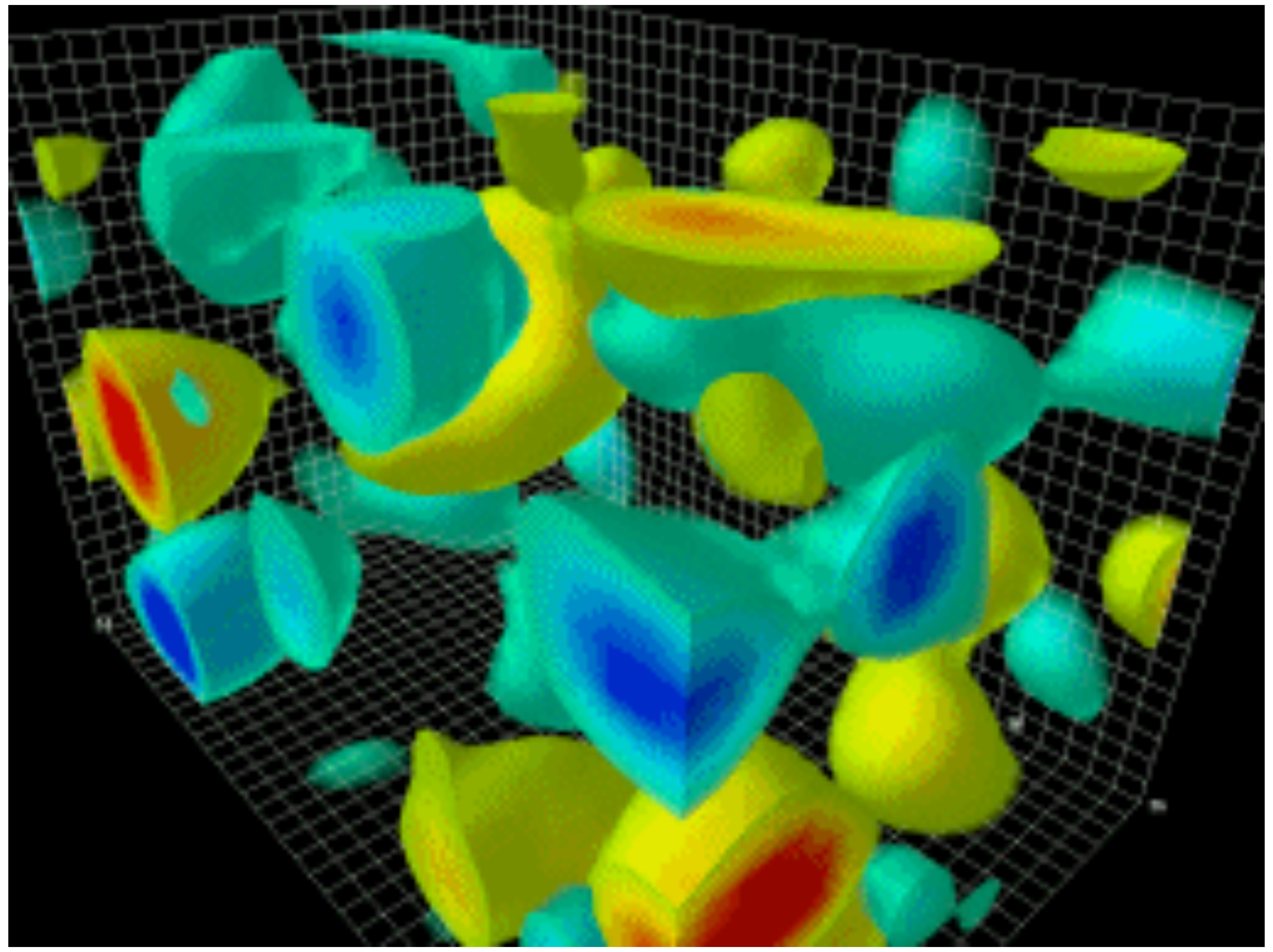
16:50-17:10	Thermodynamics for a Rotating Chiral Fermion System in the Uniform Magnetic Field	Ren-Hong Fang

12.18 morning, II, 国兴厅

9:20-9:40	Chiral vortical catalysis	Yin Jiang
10:00-10:20	The role of neutral and charged pions in (inverse) magnetic catalysis and diamagnetism	Jie Mei

Chiral Magnetic Effect





Magnetic Field

$B \sim \gamma Z Q b / R^3$

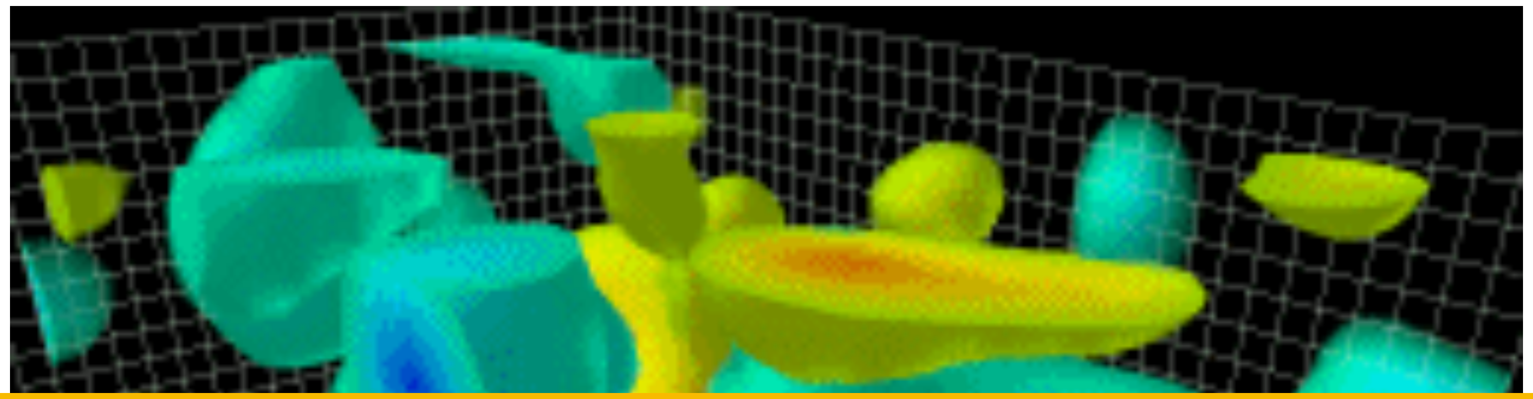
(10^{15} T @ 200 GeV Au-Au)

$\otimes$

Topology
$\otimes$ Chiral
$\otimes$ Anomaly

$$Q_W = \frac{g^2}{32\pi^2} \int d^4x \, F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a$$

Chiral Magnetic Effect



The Chiral Magnetic Effect

Kenji Fukushima, Dmitri Kharzeev, H.Warringa, PhysRevD.78.074033

a recent review:

Chiral magnetic effect reveals the topology of gauge fields in heavy-ion collisions

Dmitri Kharzeev, Jinfeng Liao, Nature Review Physics 3 (2021) 1, 55-63

Magnetic Field

B ~ γ Z Q b / R^3

(10^{15} T @ 200 GeV Au-Au)

$\otimes$

Topology

$\otimes$ **Chiral**

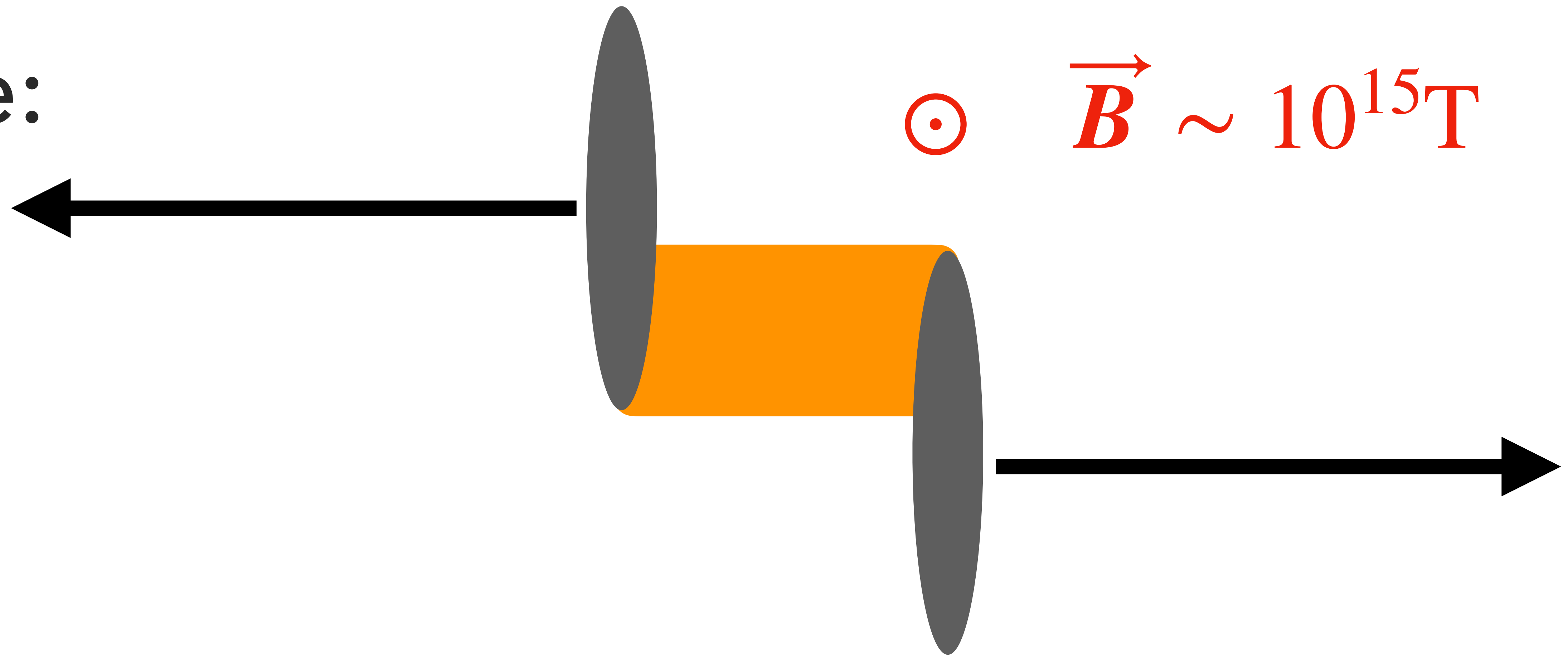
$\otimes$ **Anomaly**

$$Q_{\mathrm{w}} = \frac{g^2}{32\pi^2} \int \mathrm{d}^4 x\, F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a$$

Chiral Magnetic Effect

For right-handed particles w/ positive charge:

1. $\vec{p} \parallel \vec{S} \parallel \vec{\mu}$
2. $\text{Energy} = -\vec{\mu} \cdot \vec{B} \propto -\vec{p} \cdot \vec{B}$



⇒ lower energy if moving along B field direction

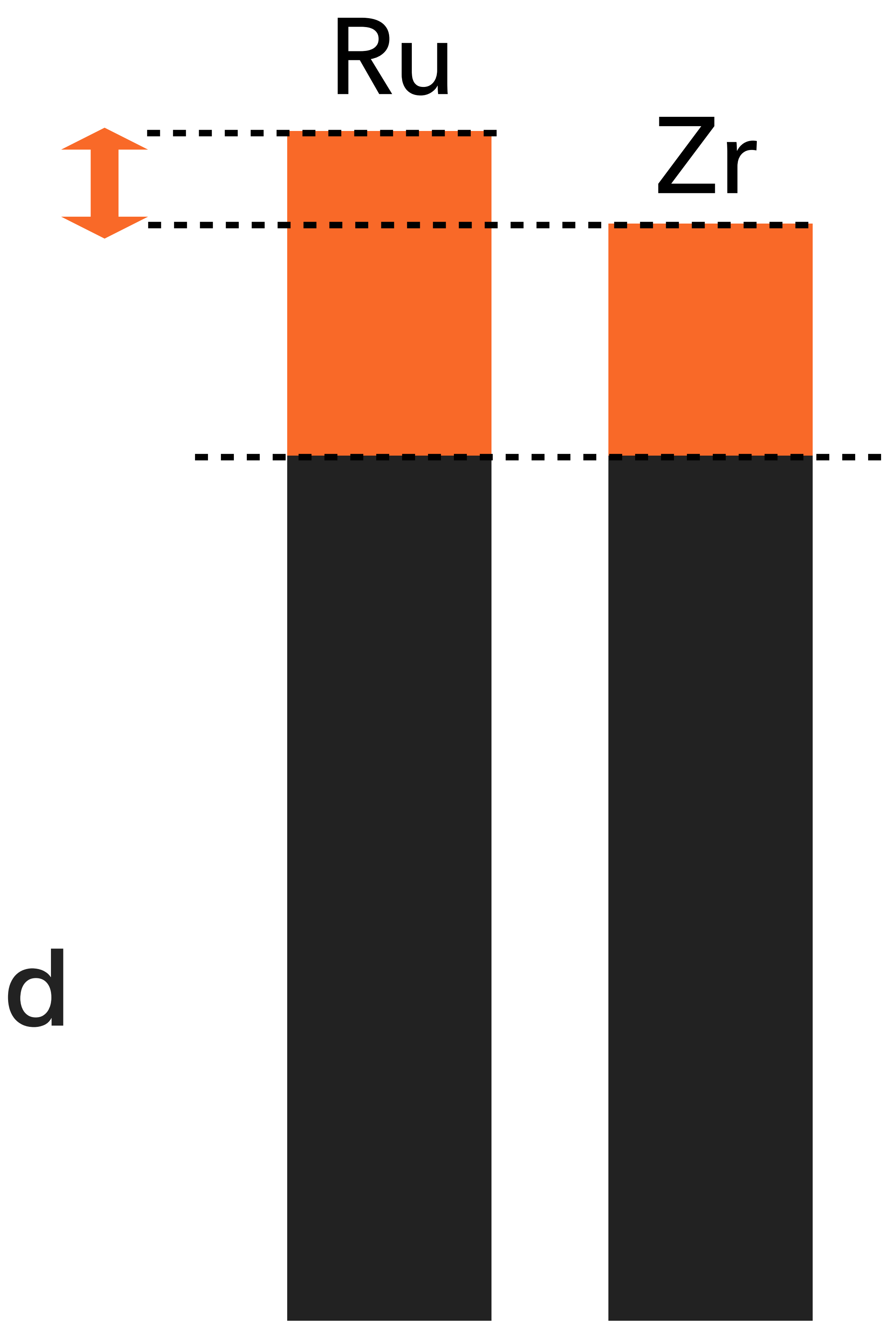
$$\vec{J} = \sigma_A \mu_A \vec{B}$$

measuring CME in isobar

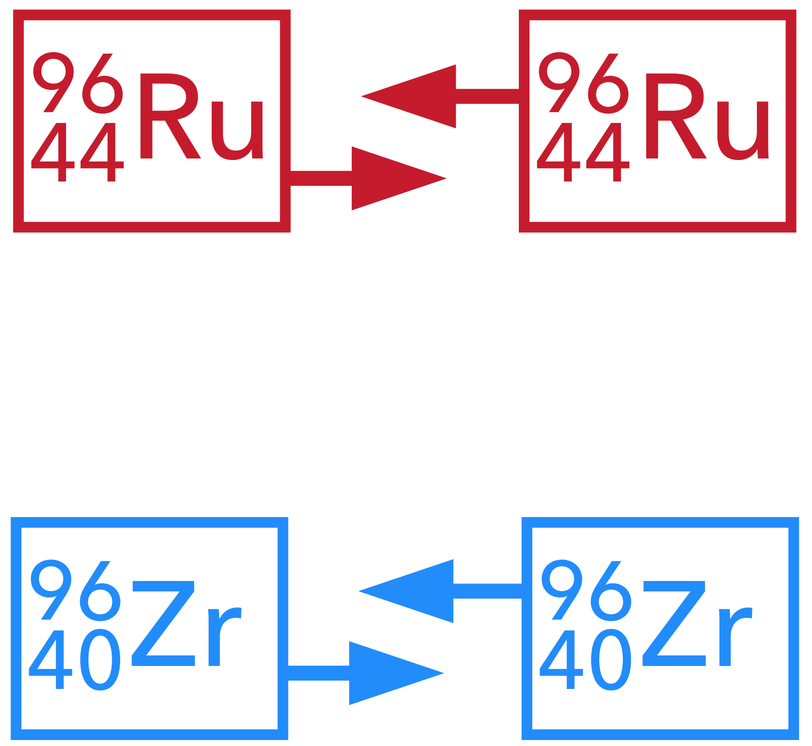
expectation before the isobar collisions:

Correlator[Ru] > *Correlator*[Zr] → **CME**

Correlator[Ru] = *Correlator*[Zr] → **no CME**



Different Proton # → **Different CME Signal**



Same Baryon # → **Same Background**

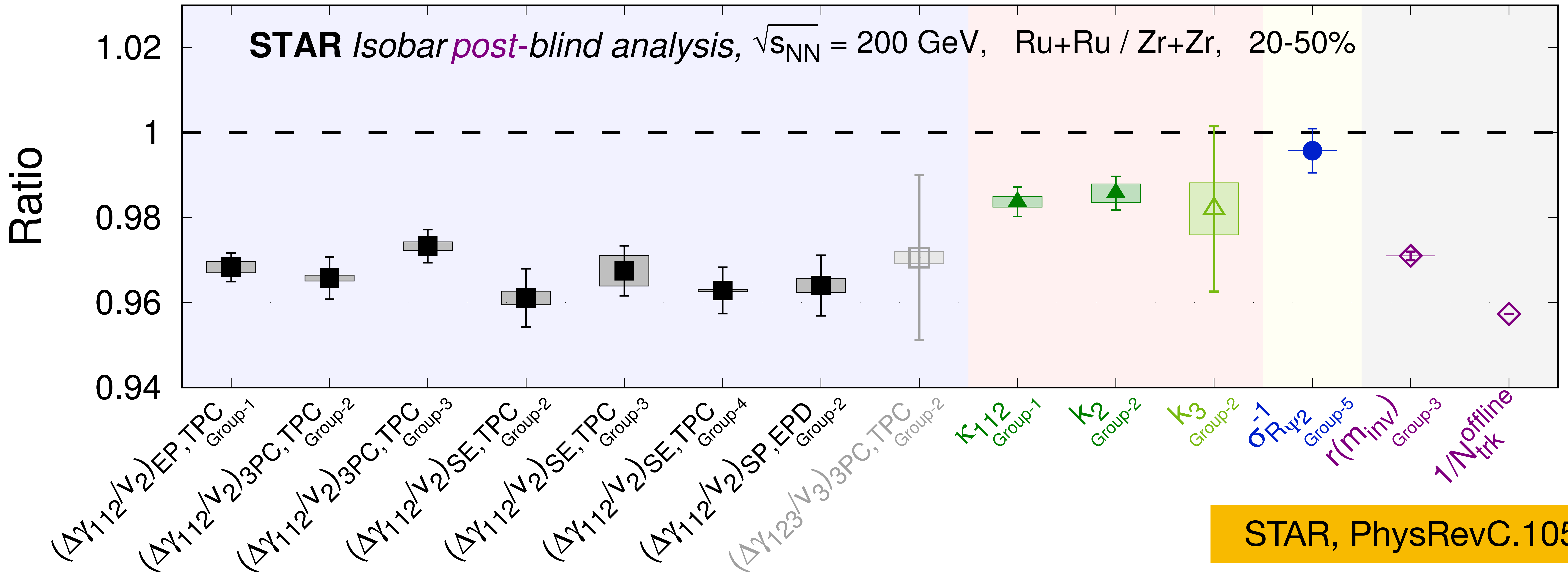
measuring CME in isobar

expectation before the isobar collisions:

Correlator[Ru] > *Correlator*[Zr] → **CME**

Correlator[Ru] = *Correlator*[Zr] → **no CME**

measurement: *Correlator*[Ru] < *Correlator*[Zr]



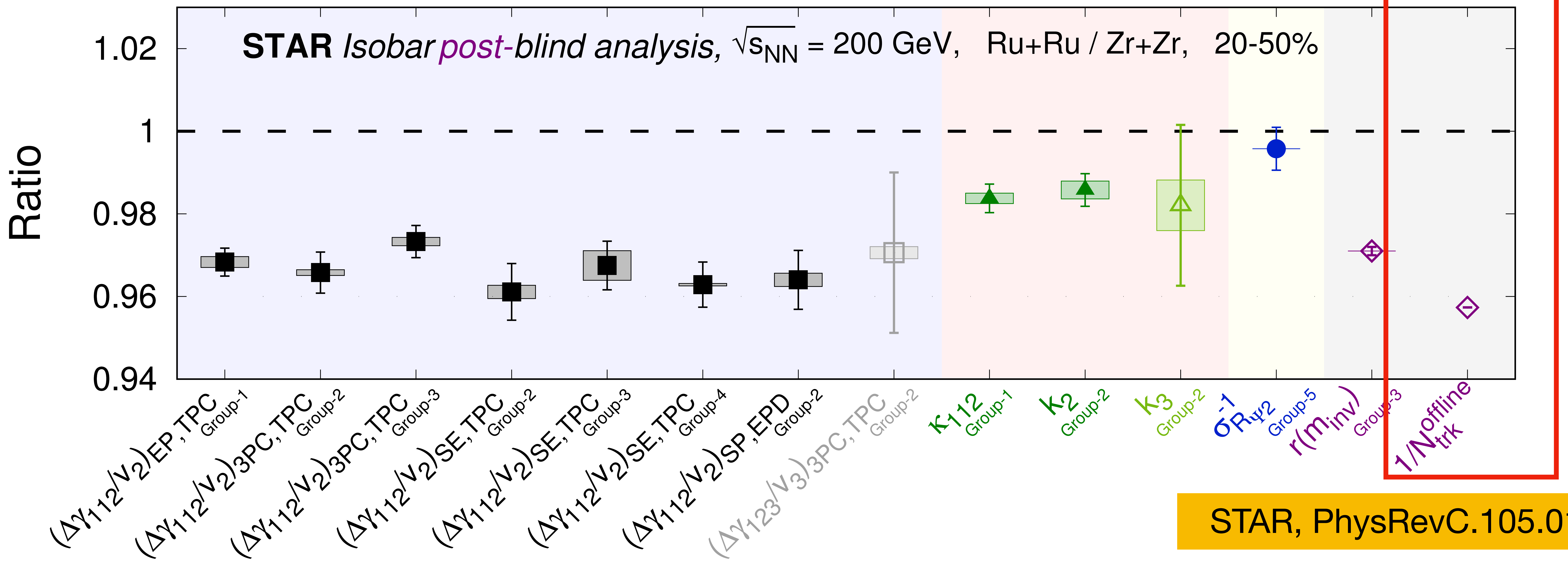
STAR, PhysRevC.105.014901

expectation before the isobar collisions:

Correlator[Ru] > *Correlator*[Zr] → **CME**

Correlator[Ru] = *Correlator*[Zr] → **no CME**

measurement: *Correlator*[Ru] < *Correlator*[Zr]



STAR, PhysRevC.105.014901

measuring CME in isobar

expectation before the isobar collisions:

Correlator[Ru] > *Correlator*[Zr] → **CME**

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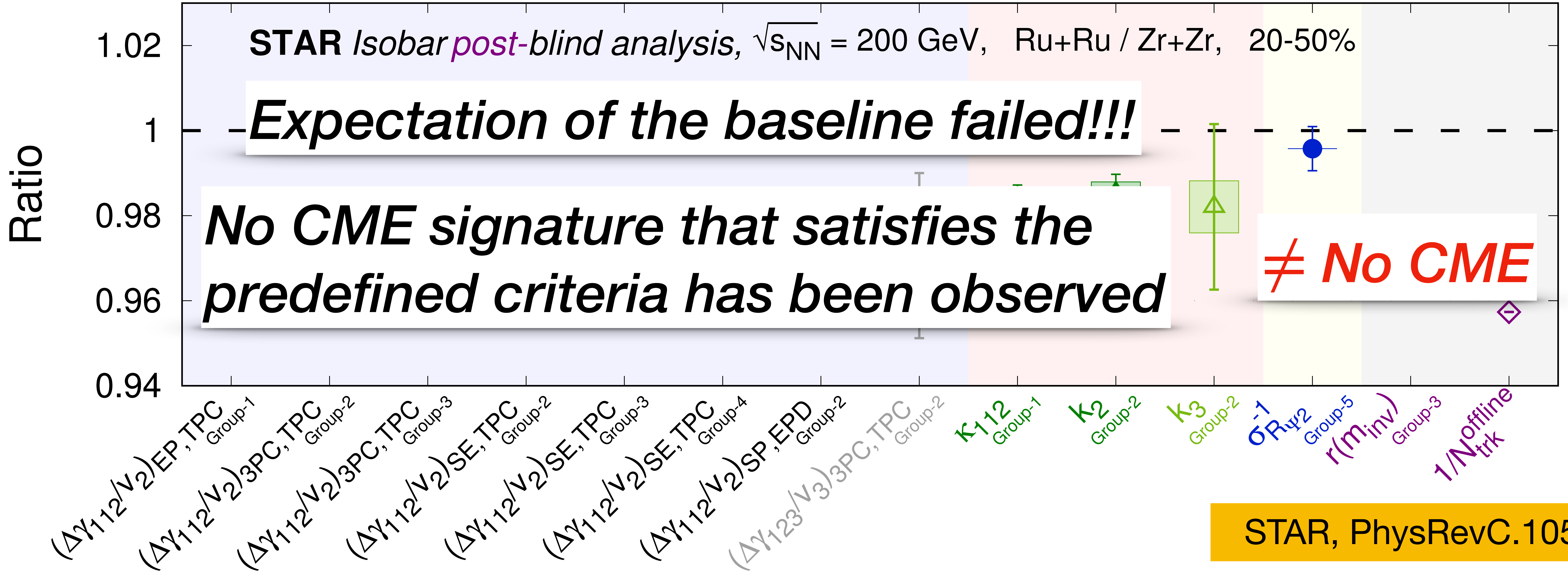
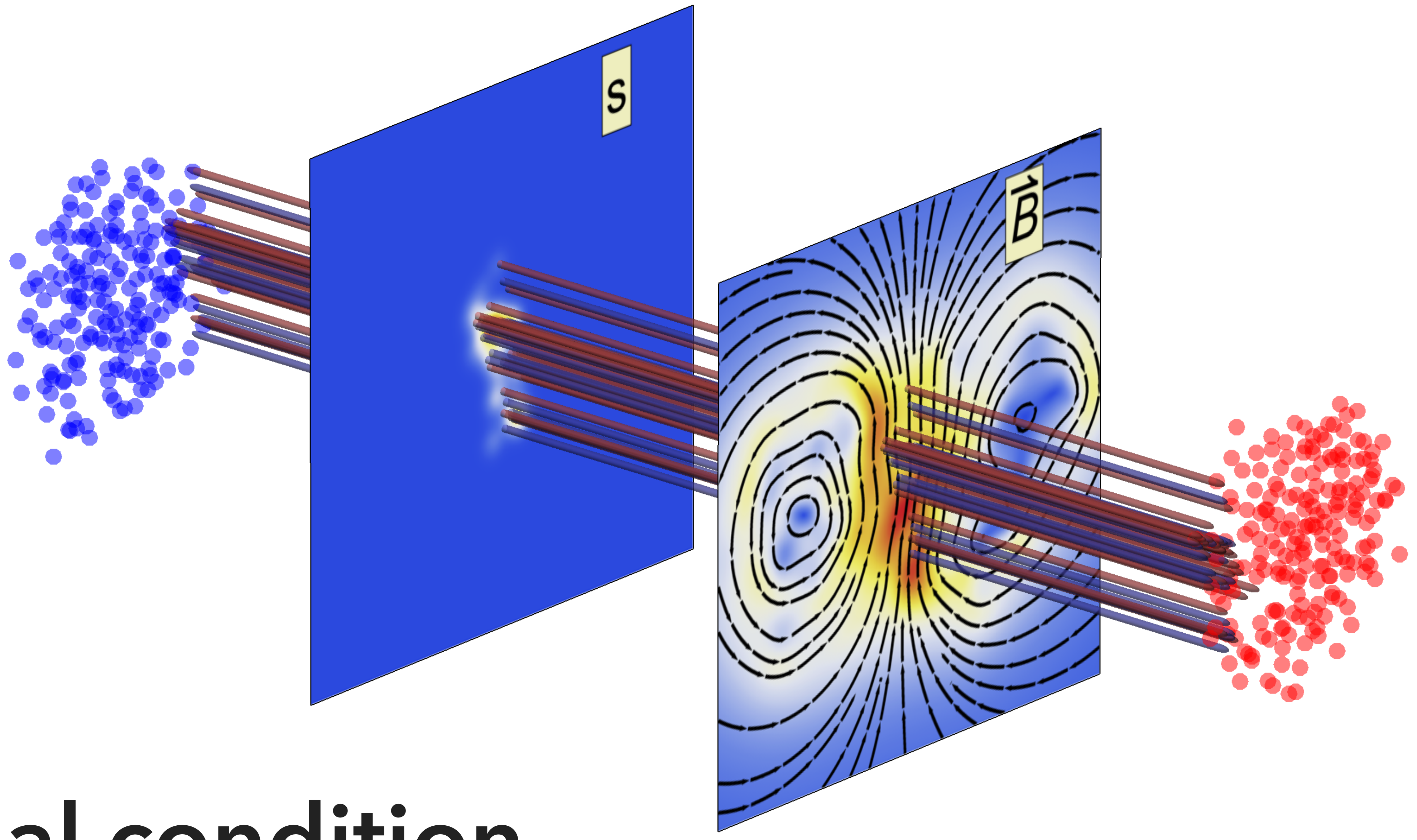


STAR, PhysRevC.105.014901

understanding CME signal and background in isobar

E-by-E IC of Bulk, n, n5, and B field



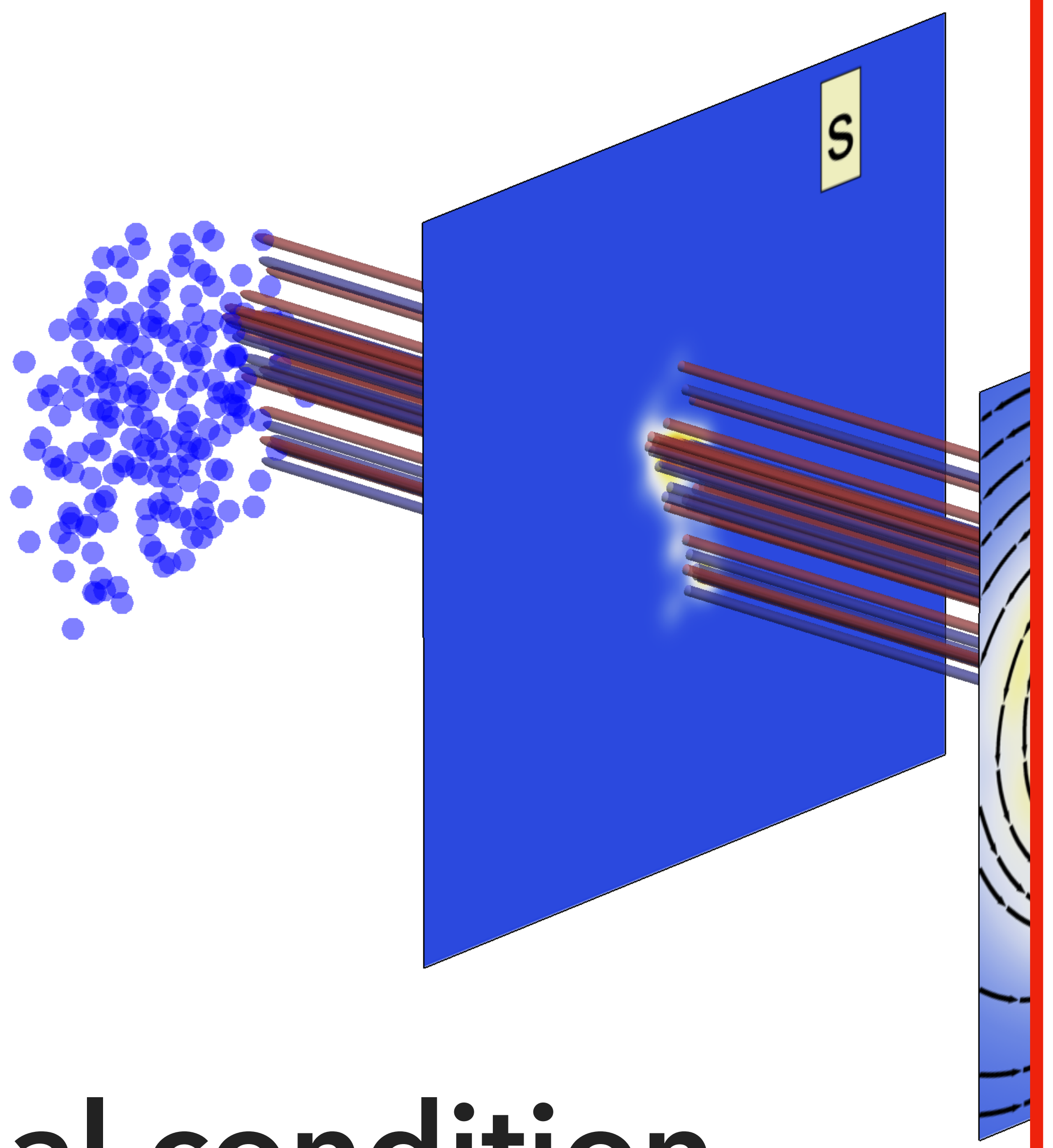
Initial condition

+ Driving force

SS, Zhang, Hou, and Liao, Phys.Rev.Lett.(2020)
SS, Jiang, Lilleskov, and Liao, Annals Phys(2018)
Jiang, ***SS***, Yin, and Liao, Chin.Phys.C(2018)

understanding CME signal and background in isobar

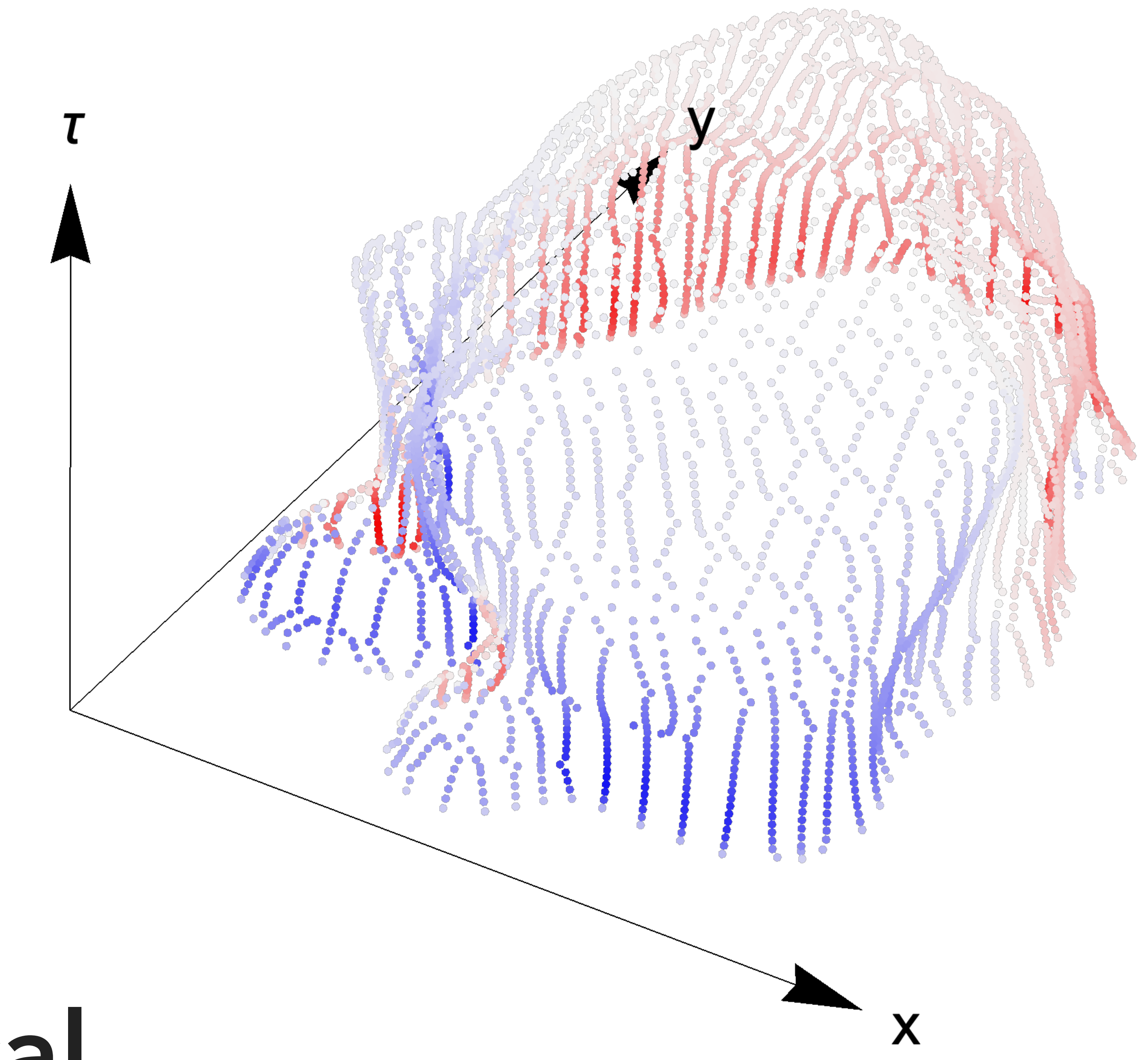
E-by-E IC of Bulk, n, n5, and B field



Initial condition

+ Driving force

Bulk => n, n5 evolution



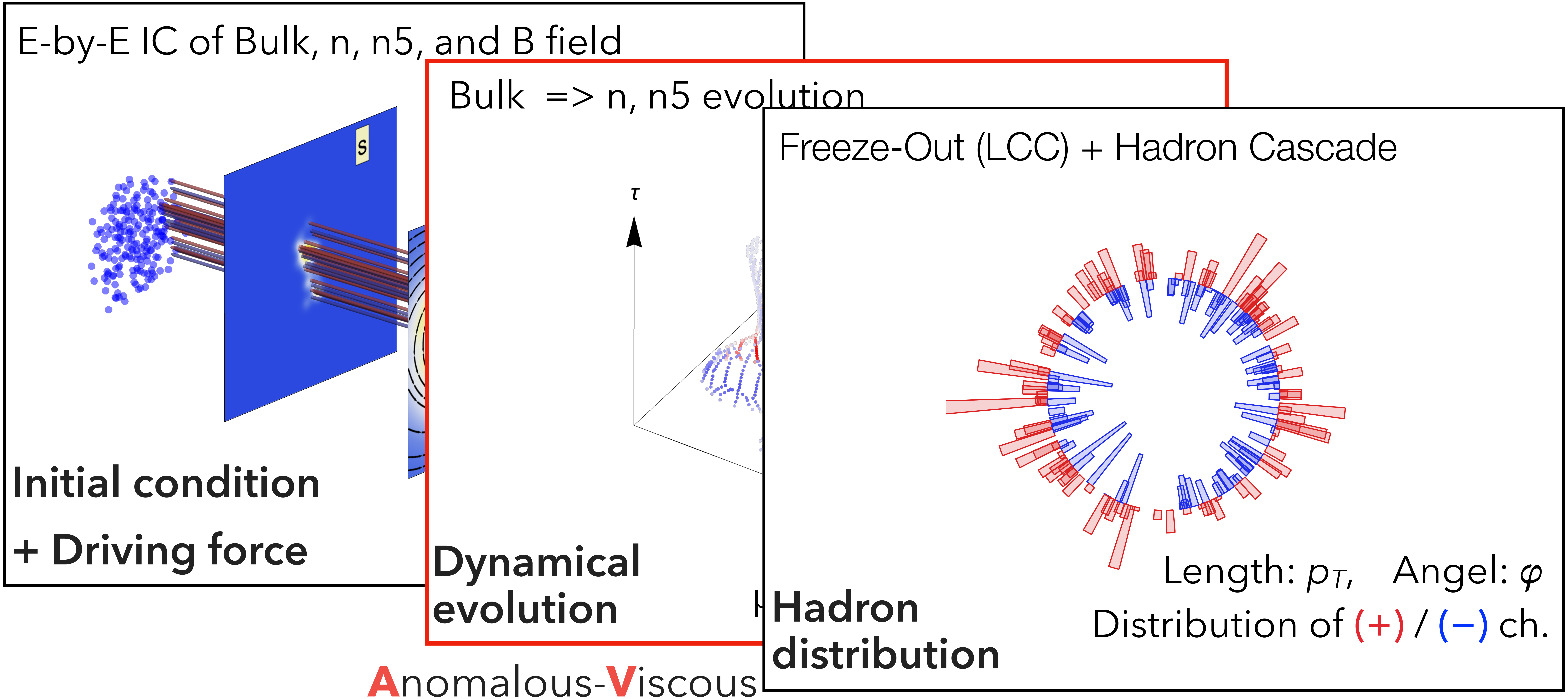
Dynamical evolution

μ_Q @ FO

Anomalous-**V**iscous **F**luid **D**ynamics

SS, Zhang, Hou, and Liao, Phys.Rev.Lett.(2020)
SS, Jiang, Lilleskov, and Liao, Annals Phys(2018)
Jiang, ***SS***, Yin, and Liao, Chin.Phys.C(2018)

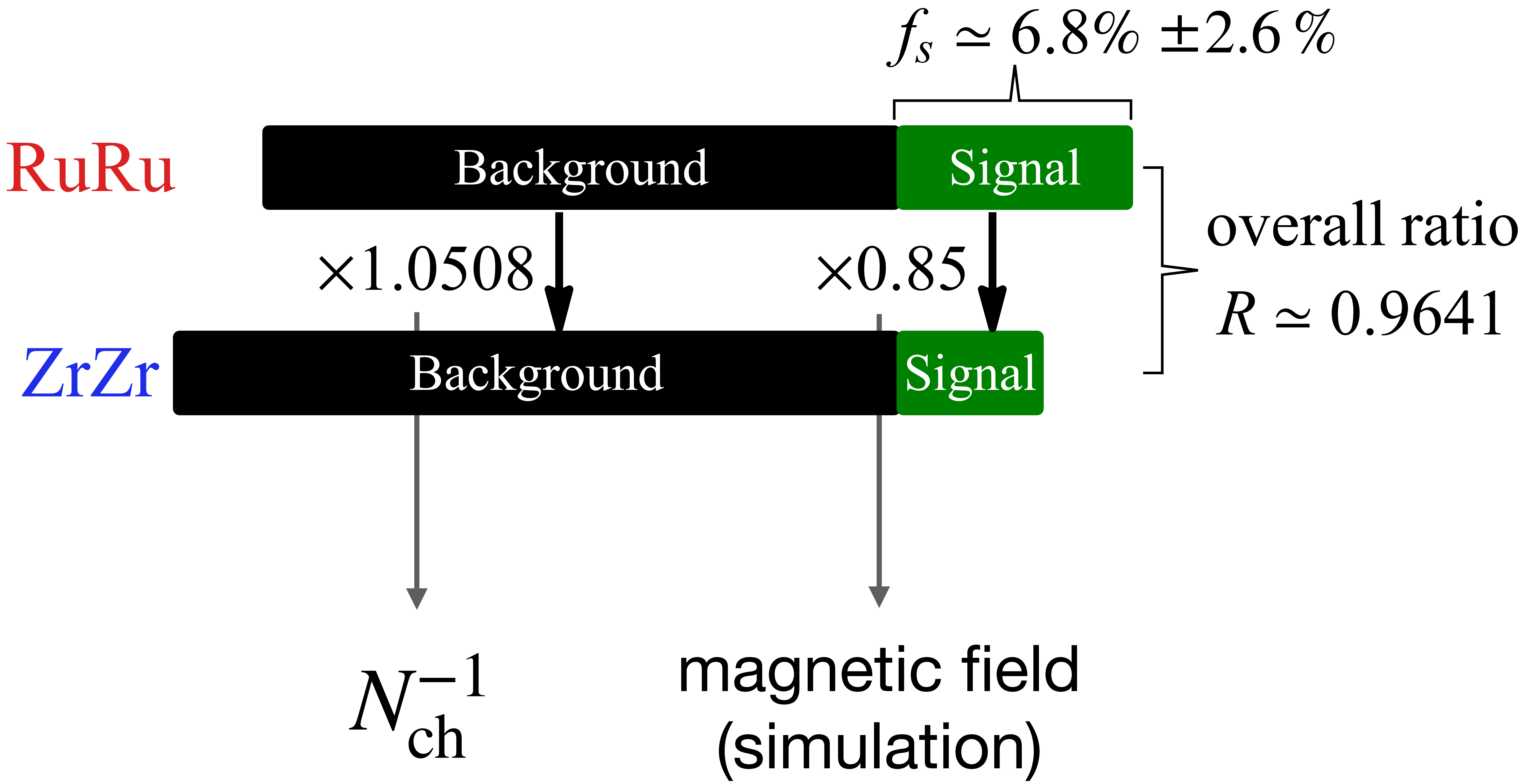
understanding CME signal and background in isobar



Anomalous-**V**iscous
Fluid **D**ynamics

SS, Zhang, Hou, and Liao, Phys.Rev.Lett.(2020)
SS, Jiang, Lilleskov, and Liao, Annals Phys(2018)
Jiang, ***SS***, Yin, and Liao, Chin.Phys.C(2018)

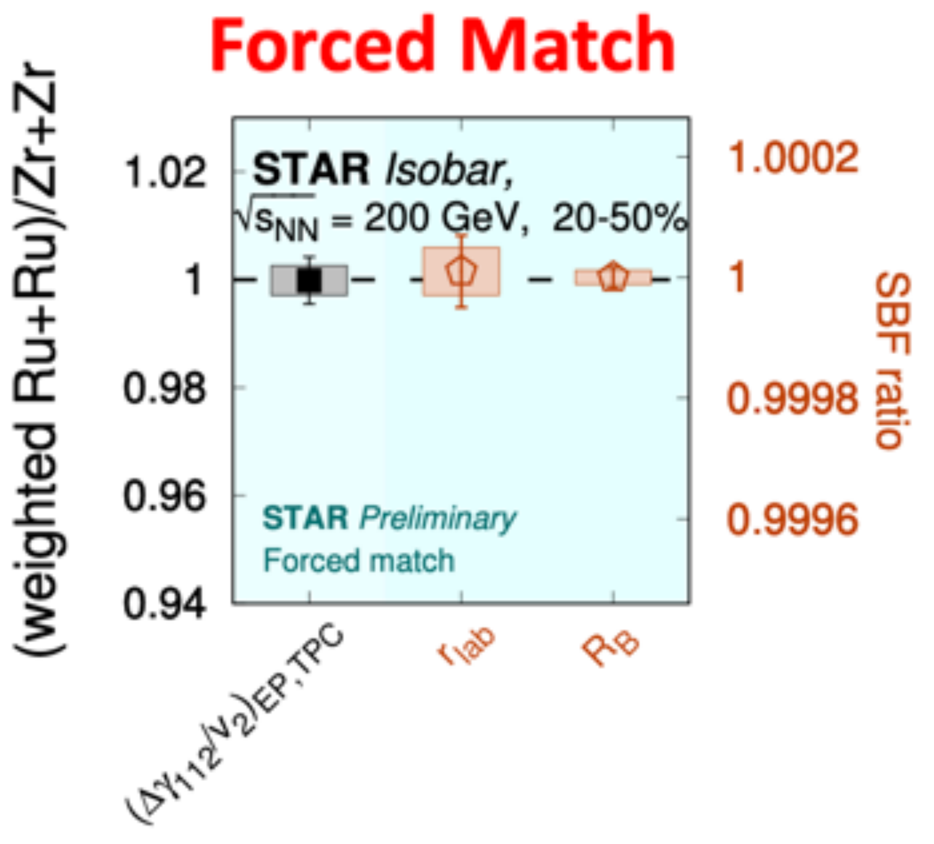
possible CME signal in isobar?



Dmitri Kharzeev, Jinfeng Liao, SS, PhyRevC.106.L051903

possible CME signal in isobar?

updates on experiment:



12.18 morning, II, 国兴厅

9:40-10:00	Search for the Chiral Magnetic Effect with Forced Match of Multiplicity and Elliptic Flow in Isobar Collisions at STAR	Yufu Lin

N_{ch}^{-1}

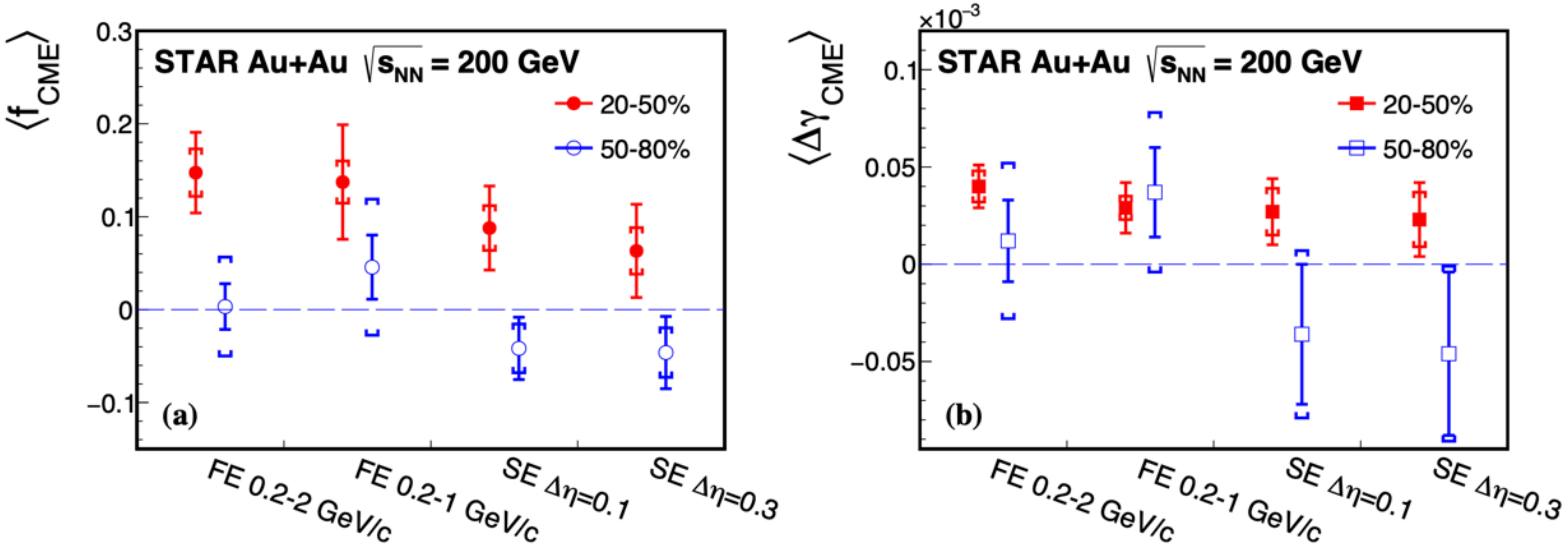
magnetic field (simulation)

Dmitri Kharzeev, Jinfeng Liao, SS, PhyRevC.106.L051903

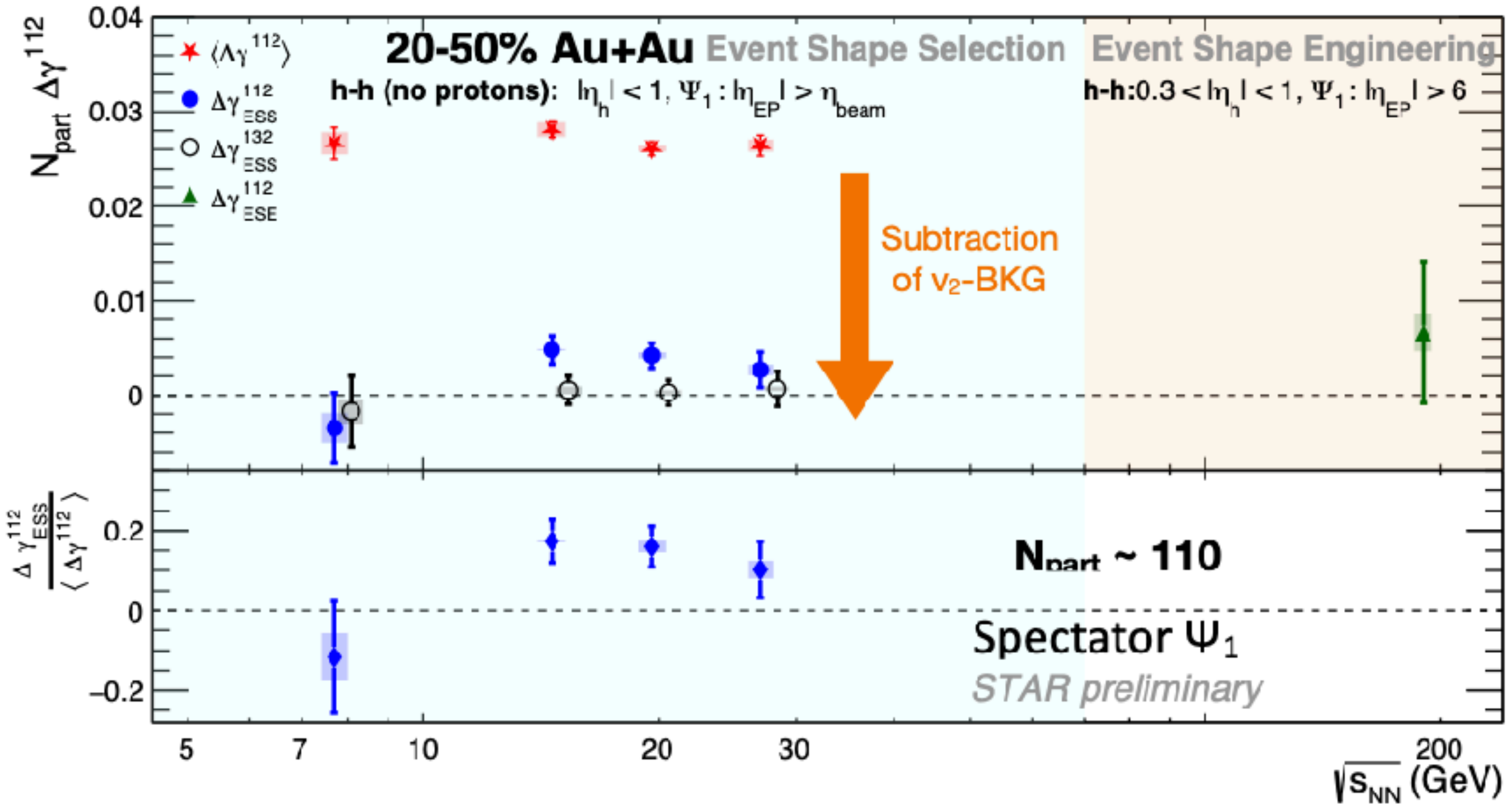
more opportunities for measuring CME

new method

STAR, PhysRevLett.128.092301



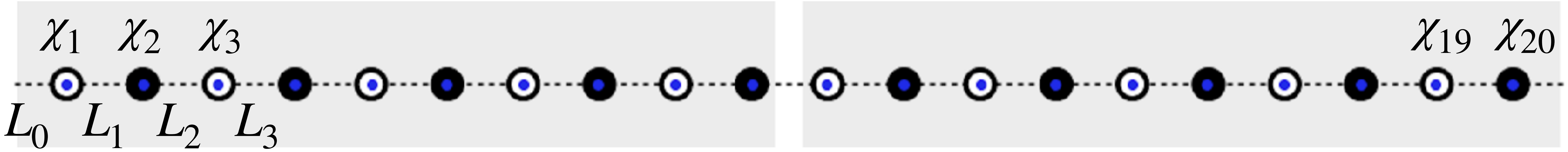
lower energy



1+1D massive Schwinger model

$$H = \int \left(\frac{E^2}{2} - \bar{\psi}(i\gamma^1 \partial_x - g\gamma^1 A - m)\psi \right) \mathrm{d}x \,.$$

discretize and matrix(gate) representation:



$$H = \frac{1}{4a} \sum_{n=1}^{N-1} (X_n X_{n+1} + Y_n Y_{n+1}) + \frac{m}{2} \sum_{n=1}^{N} (-1)^n Z_n + \frac{a\,g^2}{2} \sum_{n=1}^{N-1} L_n^2 \,.$$

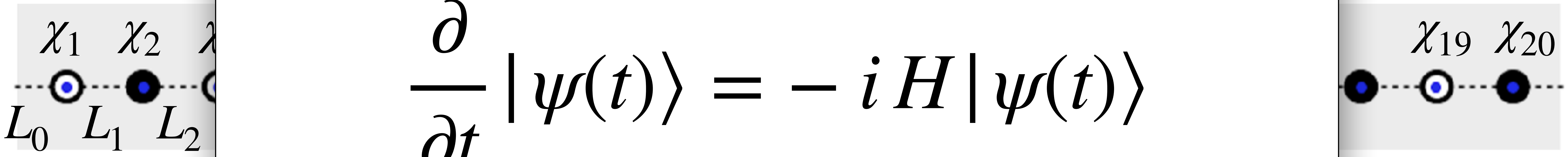
Pauli matrices: X, Y, Z

chirality transport using Quantum Simulation

1+1D massive Schwinger model

$$H = \int \left(\frac{E^2}{2} - \bar{\psi}(i\gamma^1 \partial_x - g\gamma^1 A - m)\psi \right) \mathrm{d}x \, .$$

discretize and m



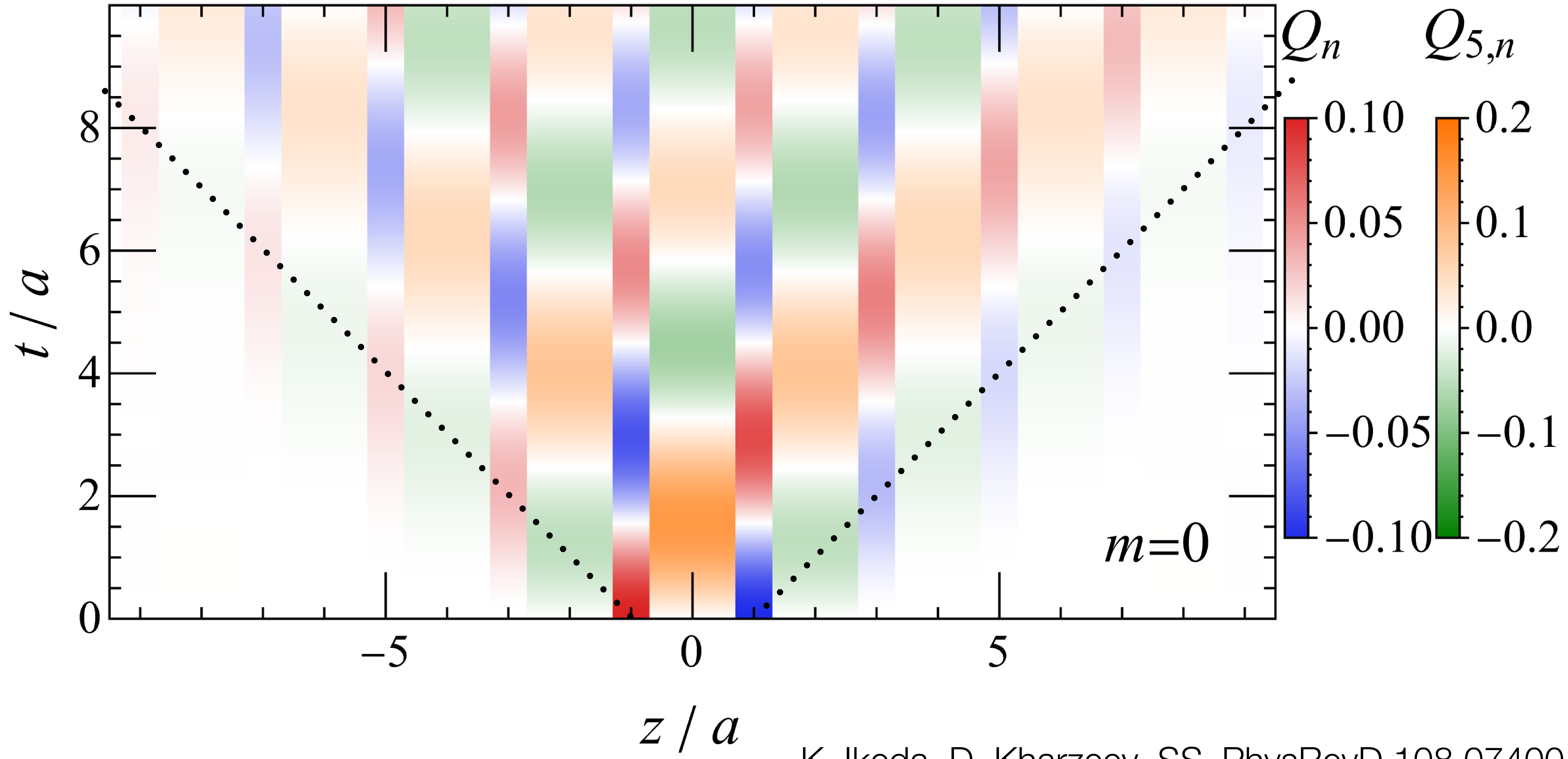
time-dependent Schroedinger equation:

$$\frac{\partial}{\partial t} | \psi(t) \rangle = - i \, H \, | \psi(t) \rangle$$

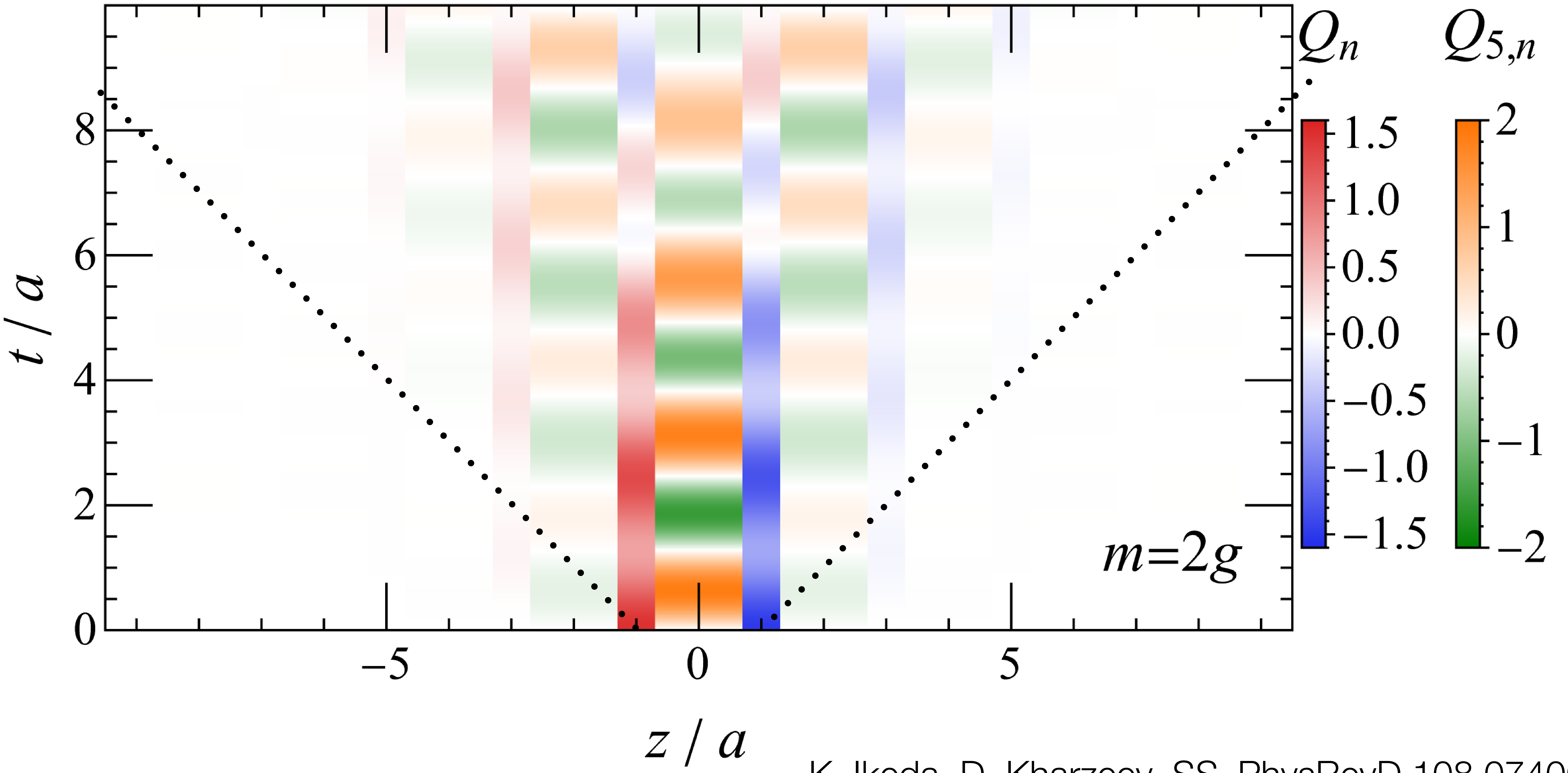
$$H = \frac{1}{4a} \sum_{n=1}^{N-1} (X_n X_{n+1} + Y_n Y_{n+1}) + \frac{m}{2} \sum_{n=1}^{N} (-1)^n Z_n + \frac{a\,g^2}{2} \sum_{n=1}^{N-1} L_n^2 \, .$$

Pauli matrices: X, Y, Z

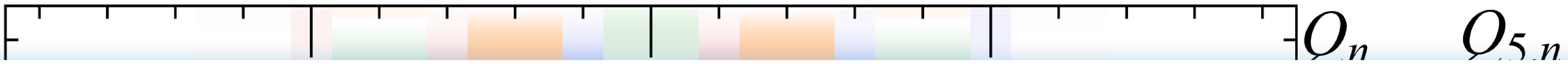
chirality transport using Quantum Simulation



K. Ikeda, D. Kharzeev, *SS*, PhysRevD.108.074001



K. Ikeda, D. Kharzeev, *SS*, PhysRevD.108.074001



More on quantum computation:

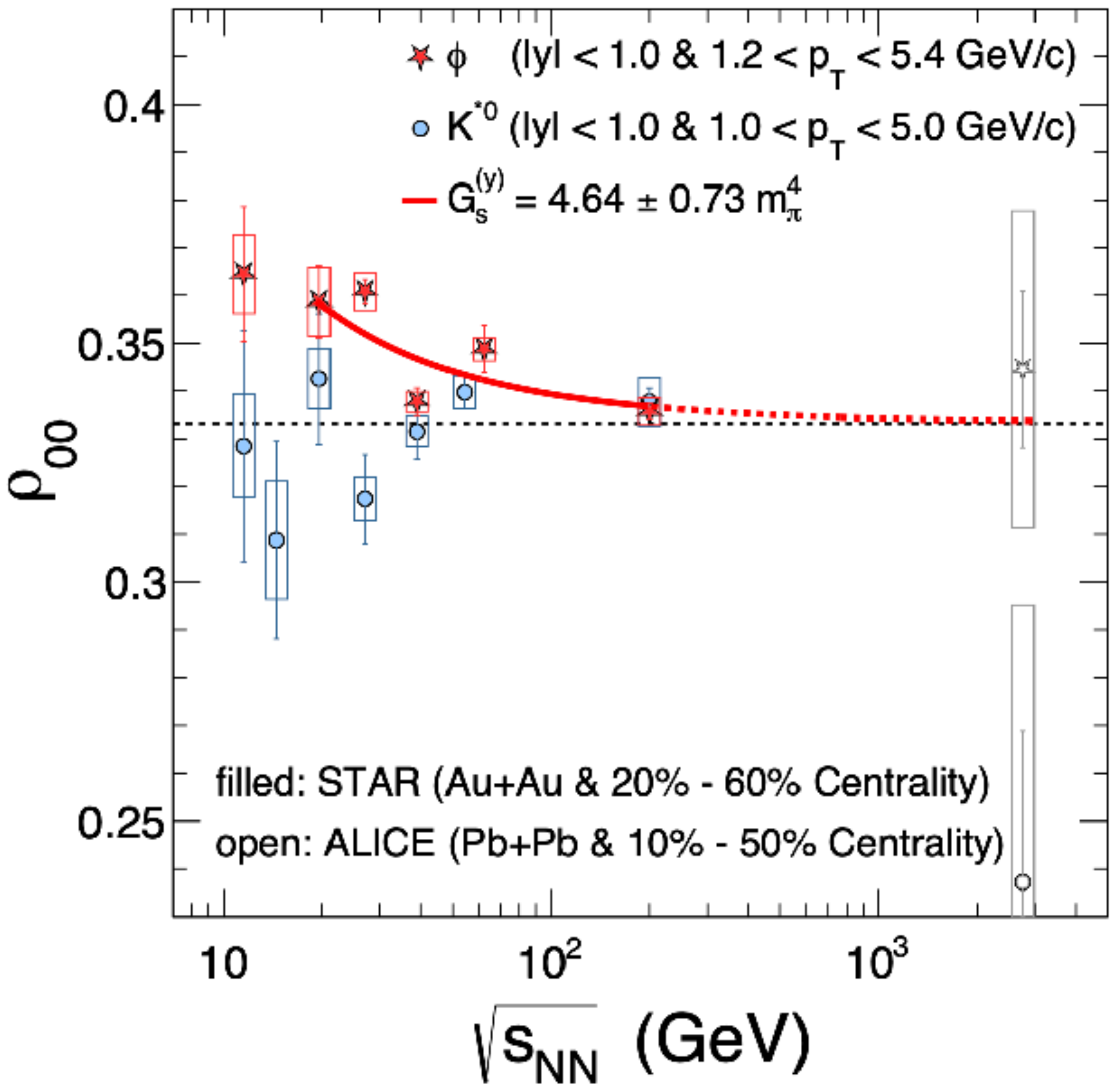
12.18 morning, II, 国兴厅		
11:50-12:10	Quantum computing for parton fragmentation functions	Tianyin Li

12.18 afternoon		
15:00-15:30	Quantum computing in QCD	郭星雨

$z\,/\,a$

K. Ikeda, D. Kharzeev, *SS*, PhysRevD.108.074001

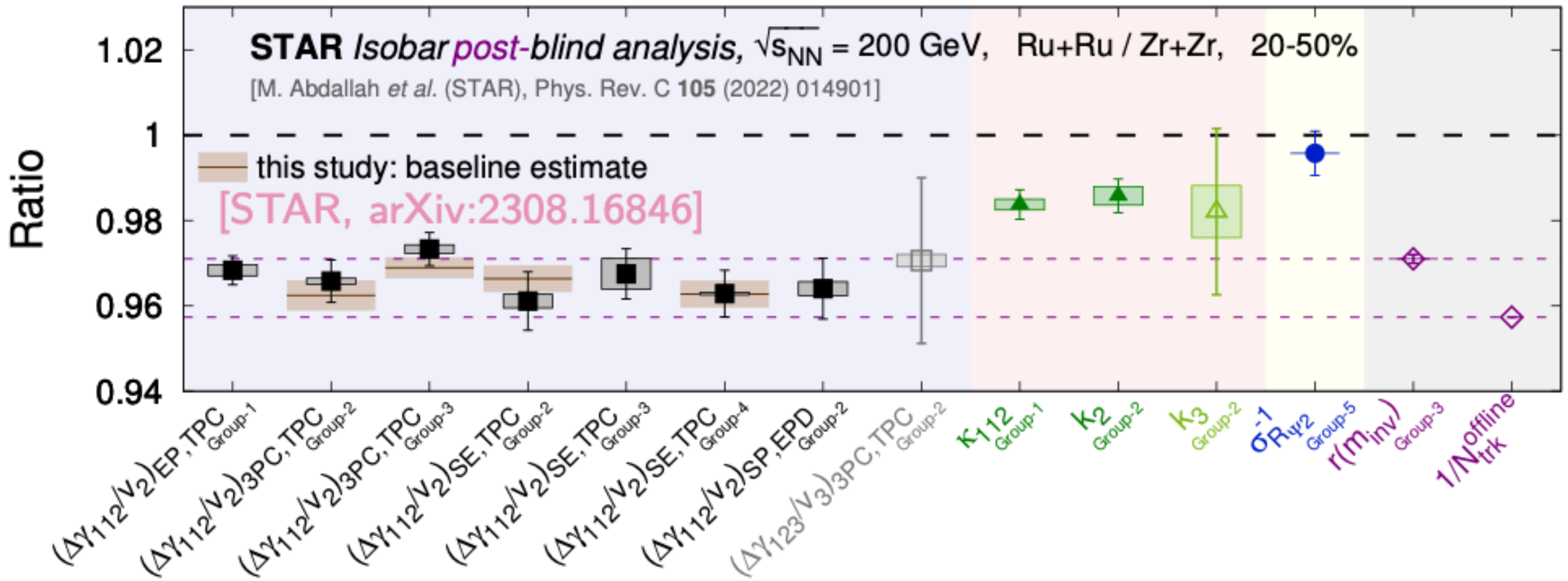
open questions



systematic understanding of

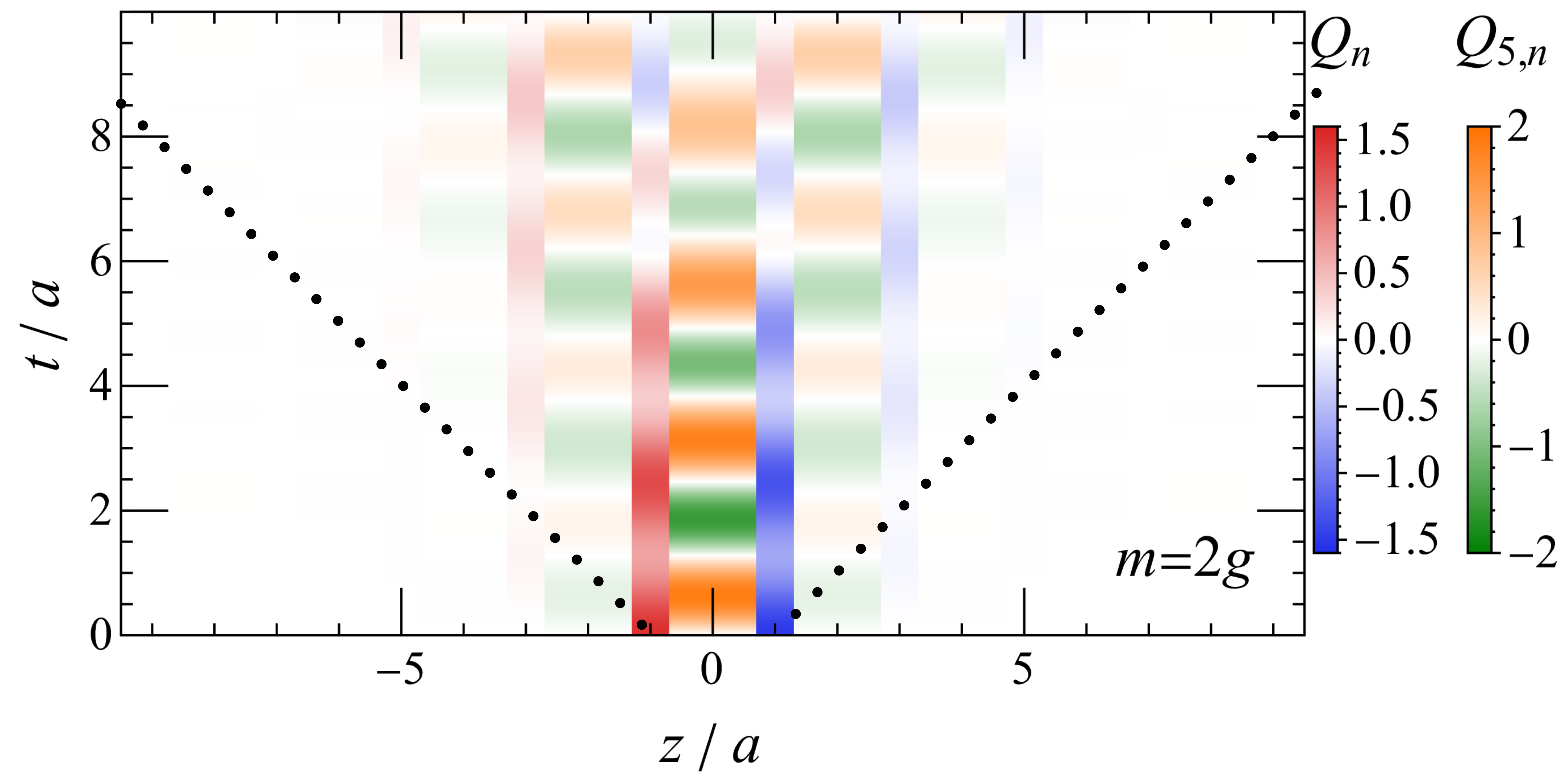
vector meson spin alignment

background of CME across beam energy



new opportunities using new computation techniques

quantum computation:



deep learning:

12.18 afternoon		
14:30-15:00	Machine learning in QCD	王凌霄