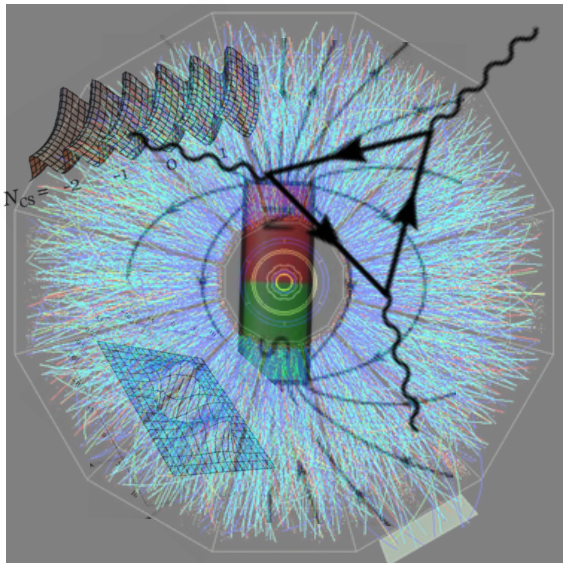
Status, Prospect, and the Path Forward



Jinfeng Liao

INDIANA UNIVERSITY

NSF

BEST COLLABORATION

Outline & Disclaimer

- *Brief Introduction*
- *Theoretical foundation*
- *Experimental status*
- *Phenomenological modeling*
- *Outlook*

Disclaimer: This is NOT a summary talk!

Thank everyone here for five days of exciting physics, via presentations and discussions

Thanks to Pengfei !

INT Program 2020

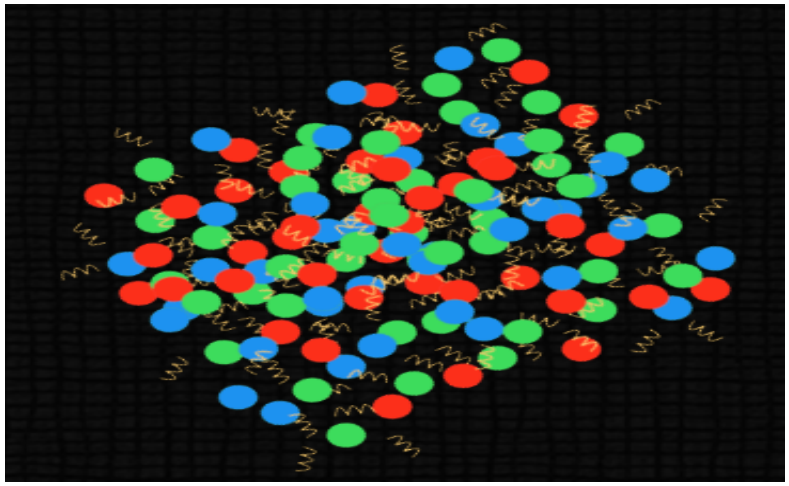
Chirality and Criticality:
Novel Phenomena in Heavy Ion Collisions

May 11 — June 5, 2020

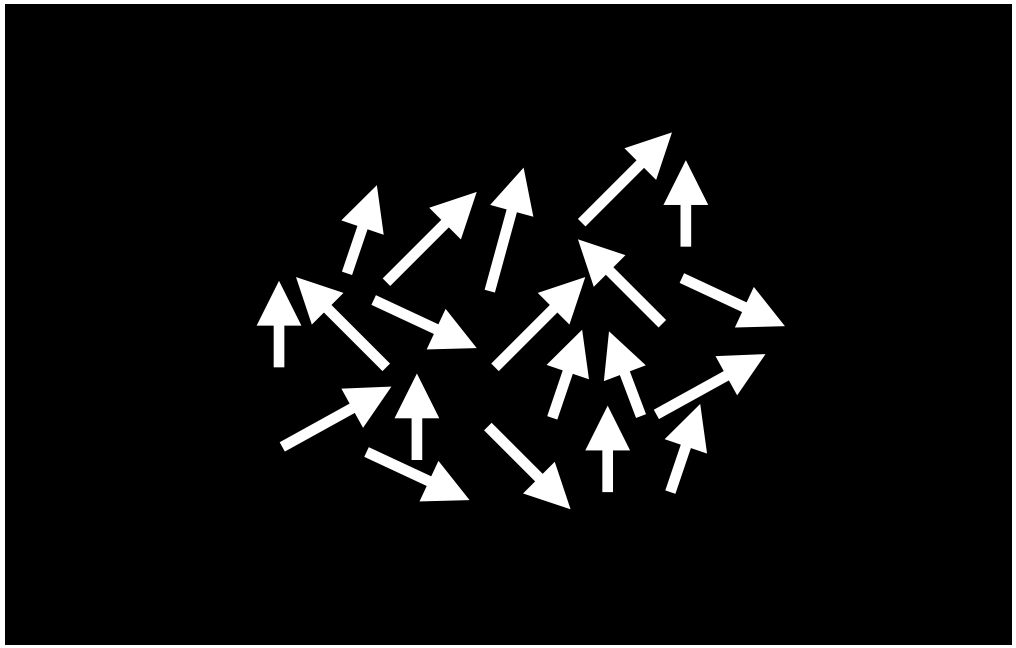
Organizers: J. Liao, M. Stephanov, H.-U. Yee, Z. Xu

A Fluid of Spin

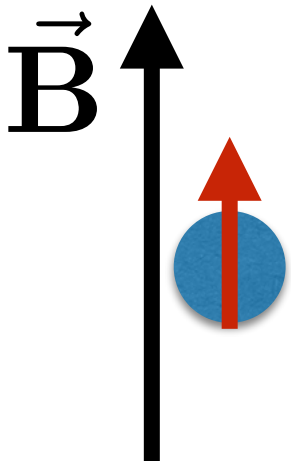
A nearly perfect fluid

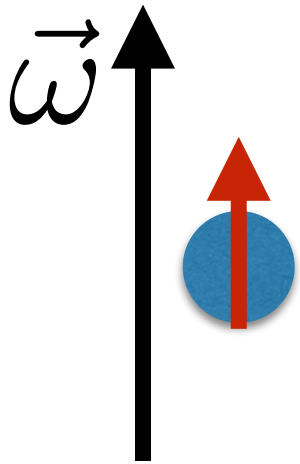


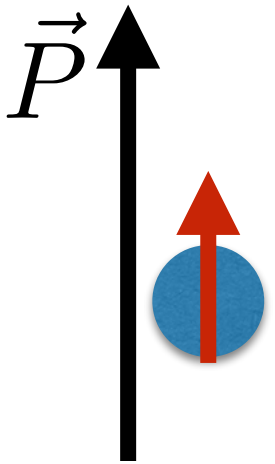
What happens to the spin DoF in the fluid???



Manipulating the Spin







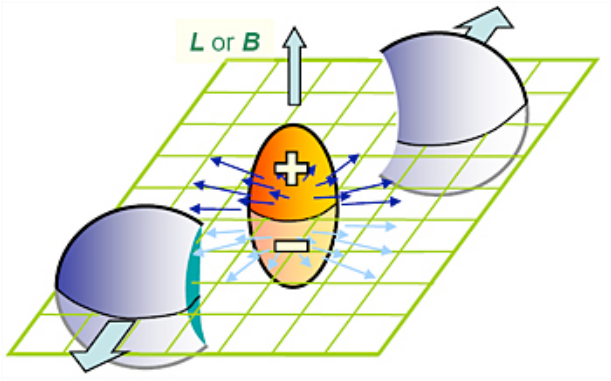
Magnetic Polarization

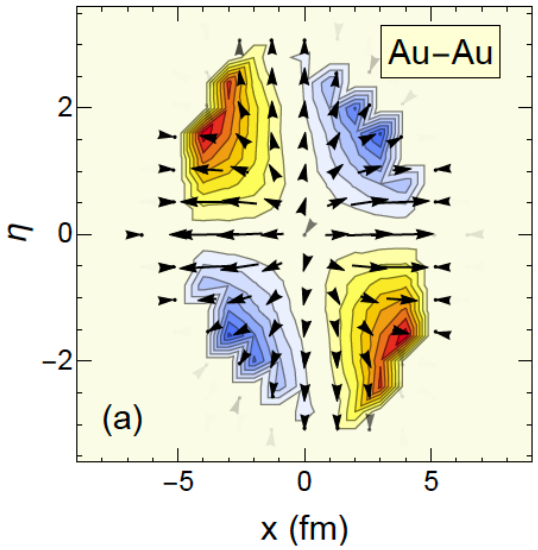
Rotational Polarization

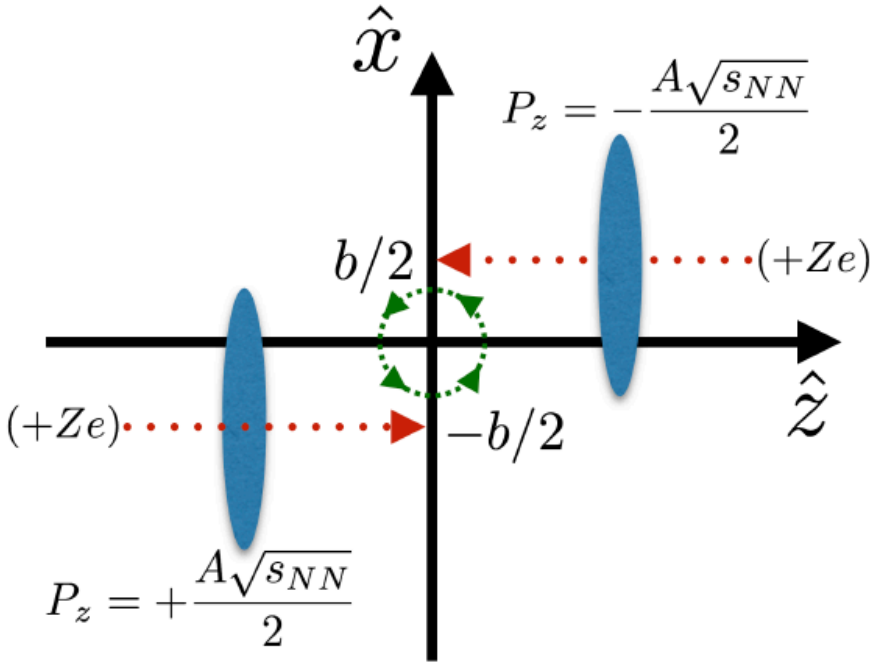
Chirality Polarization

Interesting interplay —> highly nontrivial phenomena!

Extreme Vorticity & EM Fields



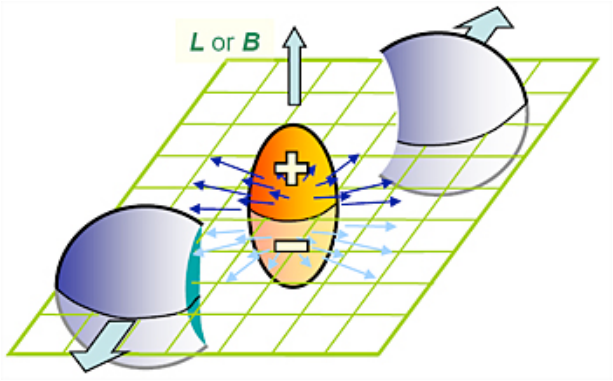


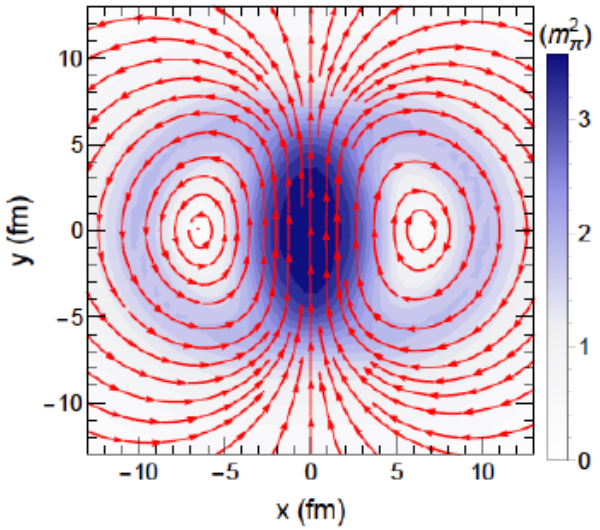


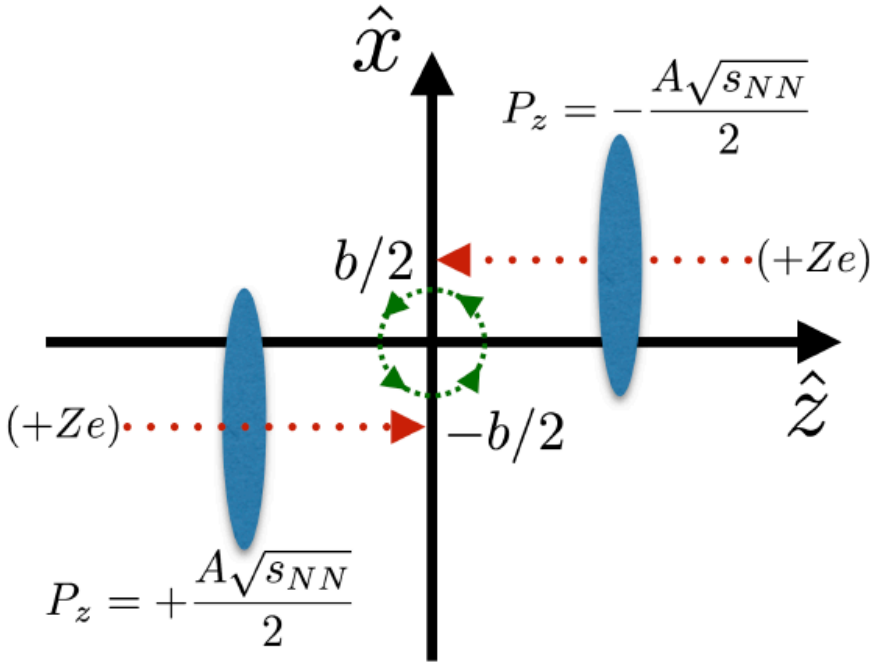
$$L_y = \frac{Ab\sqrt{s}}{2} \sim 10^{4\sim5}\hbar$$

Large angular momentum —> the most vortical fluid

Extreme Vorticity & EM Fields





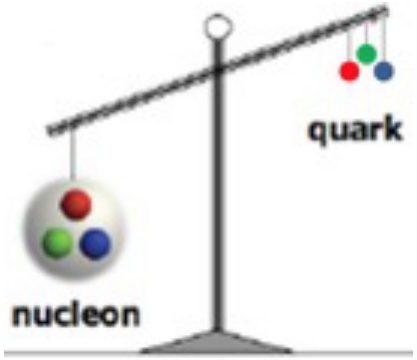


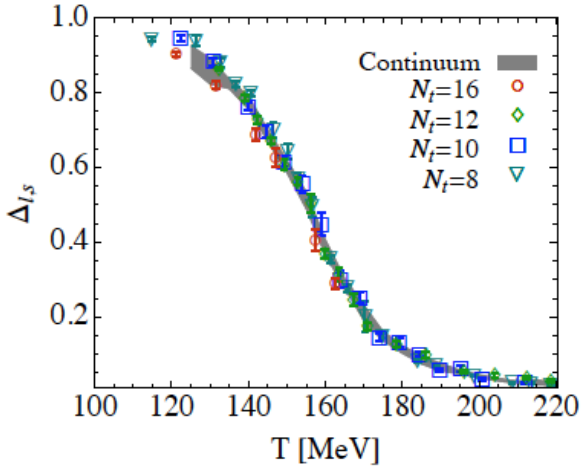
$$E, B \sim \gamma \frac{Z\alpha_{EM}}{R_A^2} \sim 3m_\pi^2$$

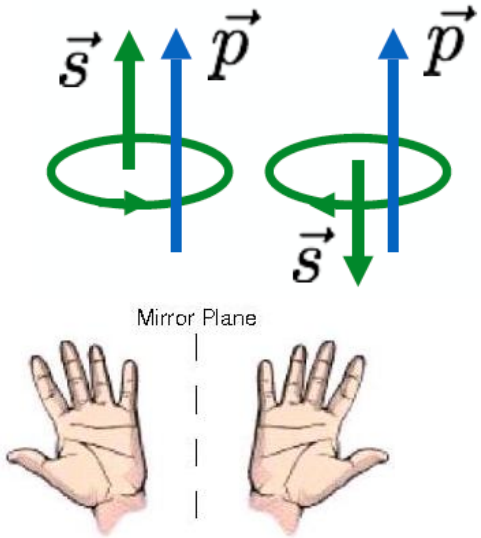
The angular momentum together with large (+Ze) nuclear charge —> the strongest magnetic field!

Chiral Symmetry Restoration

**** Spontaneously broken chiral symmetry in the vacuum is a fundamental property of QCD.***



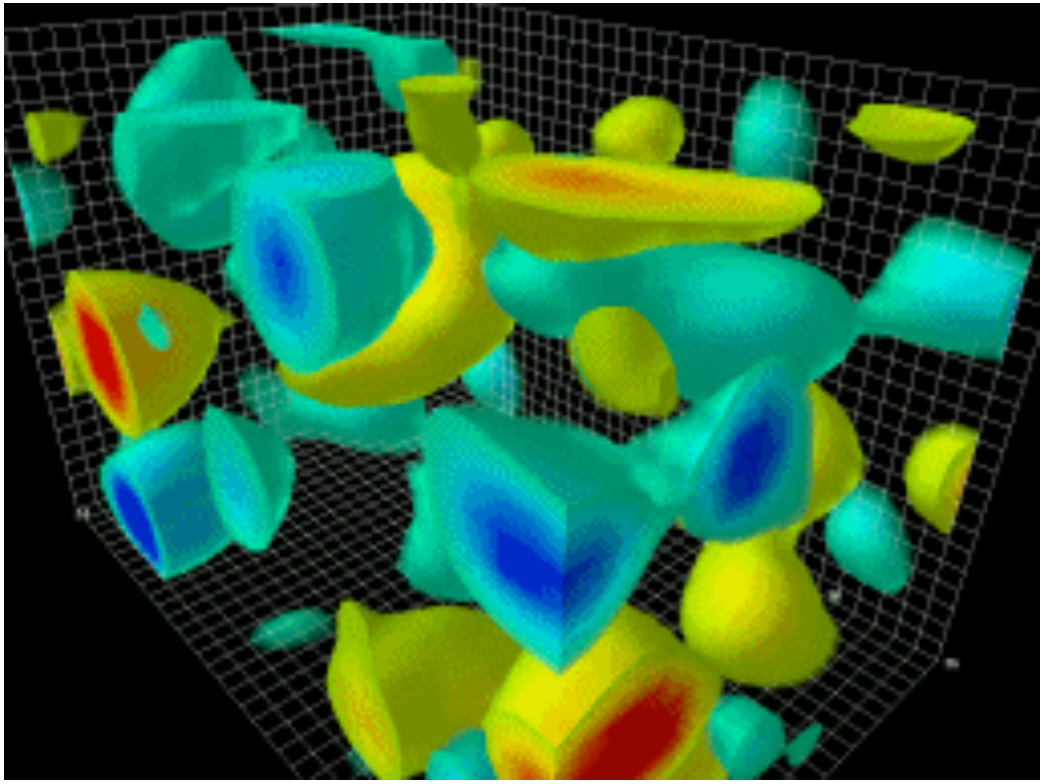




**** A chirally symmetric quark-gluon plasma at high temperature is an equally fundamental property of QCD!***

Could we see direct experimental evidence for that?

From Gluon Topology to Quark Chirality



$$Q_w = \frac{1}{32\pi^2}\int d^4x\,(gG_a^{\mu\nu})\cdot(g\tilde{G}^a_{\mu\nu})$$

$$N_5(t\to+\infty) - N_5(t\to-\infty) = \frac{g^2}{16\pi^2}\int dt d^3\mathbf{r}\, G_a^{\mu\nu}\tilde{G}^a_{\mu\nu}$$

QCD anomaly: gluon topology —> chirality imbalance

$$N_R - N_L = N_5 = 2Q_w$$

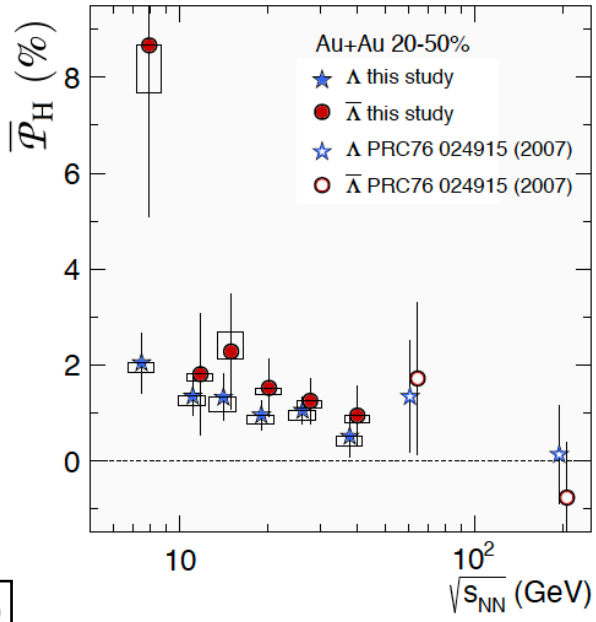
Novel Phenomena in the Subatomic Swirls

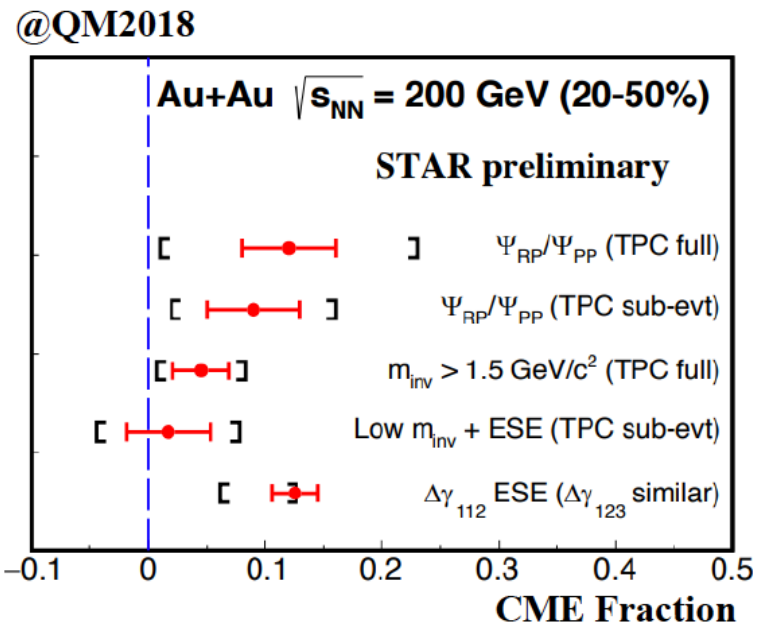
CME <—>

macroscopic chiral anomaly

$$\vec{J} = \frac{Q^2}{2\pi^2}\,\mu_5\,\vec{B}$$

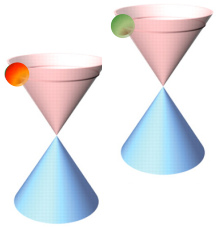
Rotational Spin Polarization





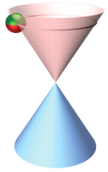
Interdisciplinary Interests

Weyl semimetal
(non-degenerated bands)

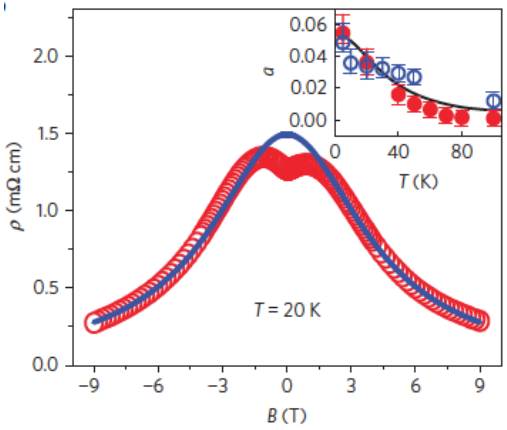


TaAs
NbAs
NbP
TaP

Dirac semimetal
(doubly degenerated bands)



$ZrTe_5$
Na_3Bi,
Cd_3As_2



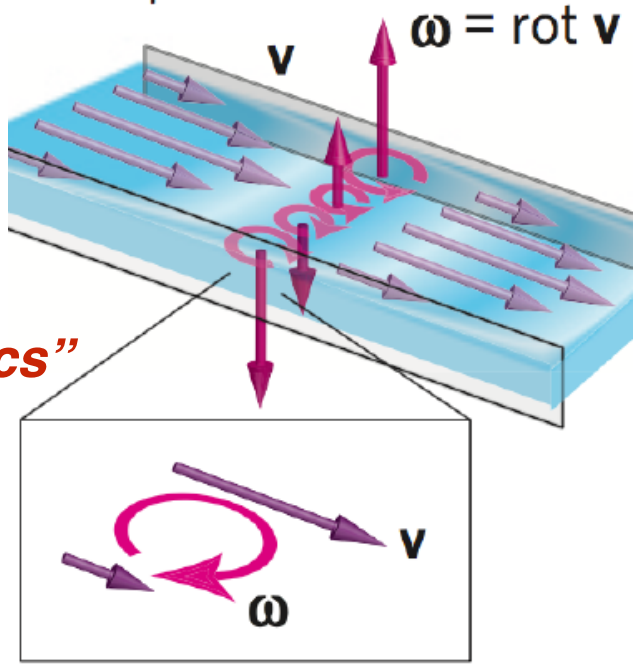
nature physics
LETTERS
PUBLISHED ONLINE: 8 FEBRUARY 2016 | DOI: 10.1038/NPHYS3648

Chiral magnetic effect in $ZrTe_5$

Qiang Li[1]*, Dmitri E. Kharzeev[2,3]*, Cheng Zhang[1], Yuan Huang[4], I. Pletikosić[1,5], A. V. Fedorov[6], R. D. Zhong[1], J. A. Schneeloch[1], G. D. Gu[1] and T. Valla[1]*

"Spin hydrodynamic generation"
Takahashi, *et al*. Nat. Phys. (2016)

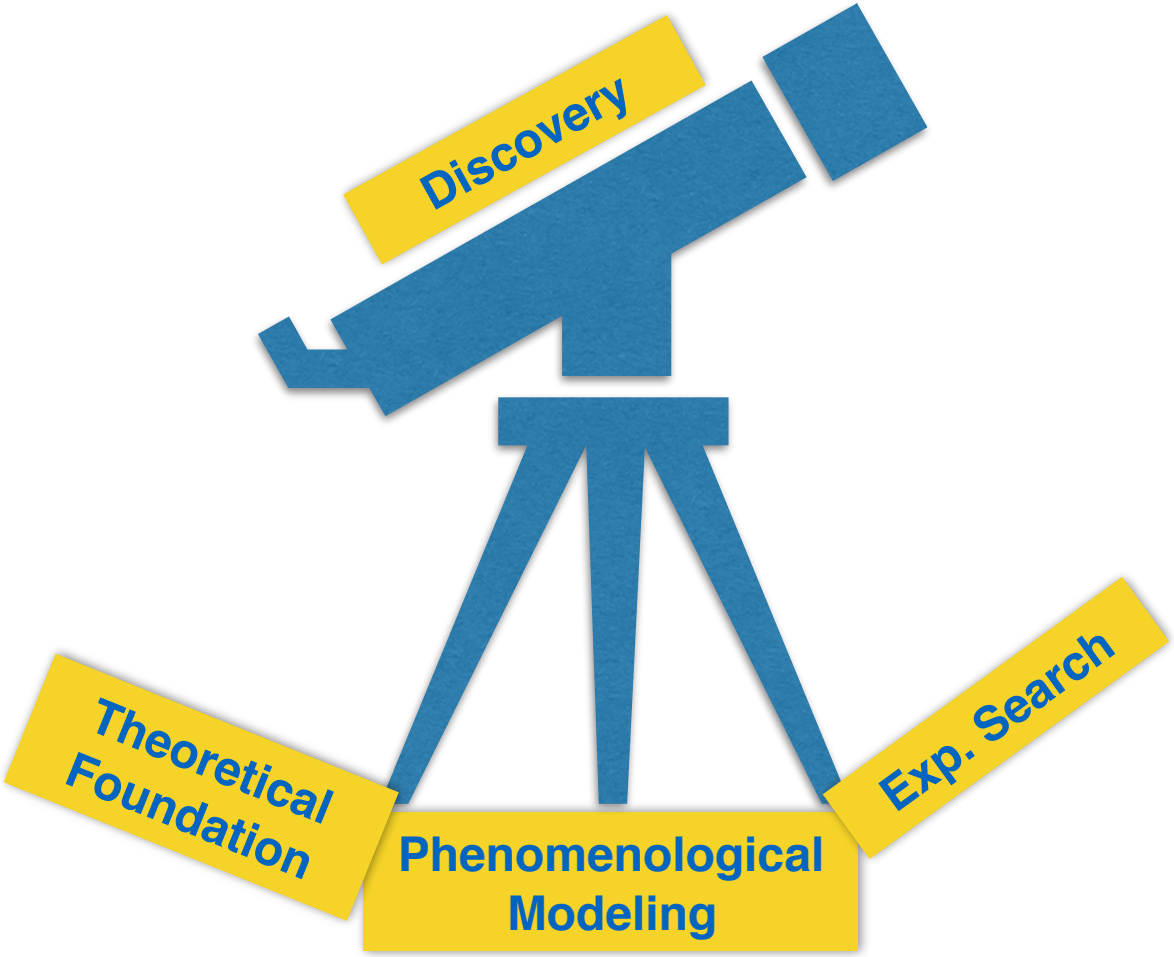
Liquid flow



"Fluid Spintronics"

Condensed matter, cold atomic gases, neutron stars, cosmology, plasma physics, etc

The "Three Legs"



Chiral/Spin Transport Theory

- *Wigner function formalism*
- *Worldline formalism*
- *High density effective theory*
- *Massive case*
- *CKT in different dim., in curved space*
- *Lorentz invariance "issue"*
- *…*

Talks by: X.G. Huang, J. Gao, N. Muller, A. Huang, …

Hydrodynamics with Spin

✓ **Constitutive relation for $T^{\mu\nu}$ up to 1st order with spin**

$$T^{\mu\nu}_{(0)} = eu^\mu u^\nu + p(g^{\mu\nu} + u^\mu u^\nu)$$

heat current shear viscous effect bulk viscous effect

$$T^{\mu\nu}_{(1)} = -2\kappa\left(Du^{(\mu} + \beta\partial_\perp^{(\mu}\beta^{-1}\right)u^{\nu)} - 2\eta\partial_\perp^{<\mu}u^{\nu>} - \zeta\left(\partial_\mu u^\mu\right)\Delta^{\mu\nu}$$

$$-2\lambda\left(-Du^{[\mu} + \beta\partial_\perp^{[\mu}\beta^{-1} + 4u_\rho\omega^{\rho[\mu}\right)u^{\nu]} - 2\gamma\left(\partial_\perp^{[\mu}u^{\nu]} - 2\Delta^\mu_\rho\Delta^\nu_\lambda\omega^{\rho\lambda}\right)$$

"boost heat current" *"rotational (spinning) viscous effect"*

NEW !

e.g. Eringen (1998); Lukaszewicz (1999)

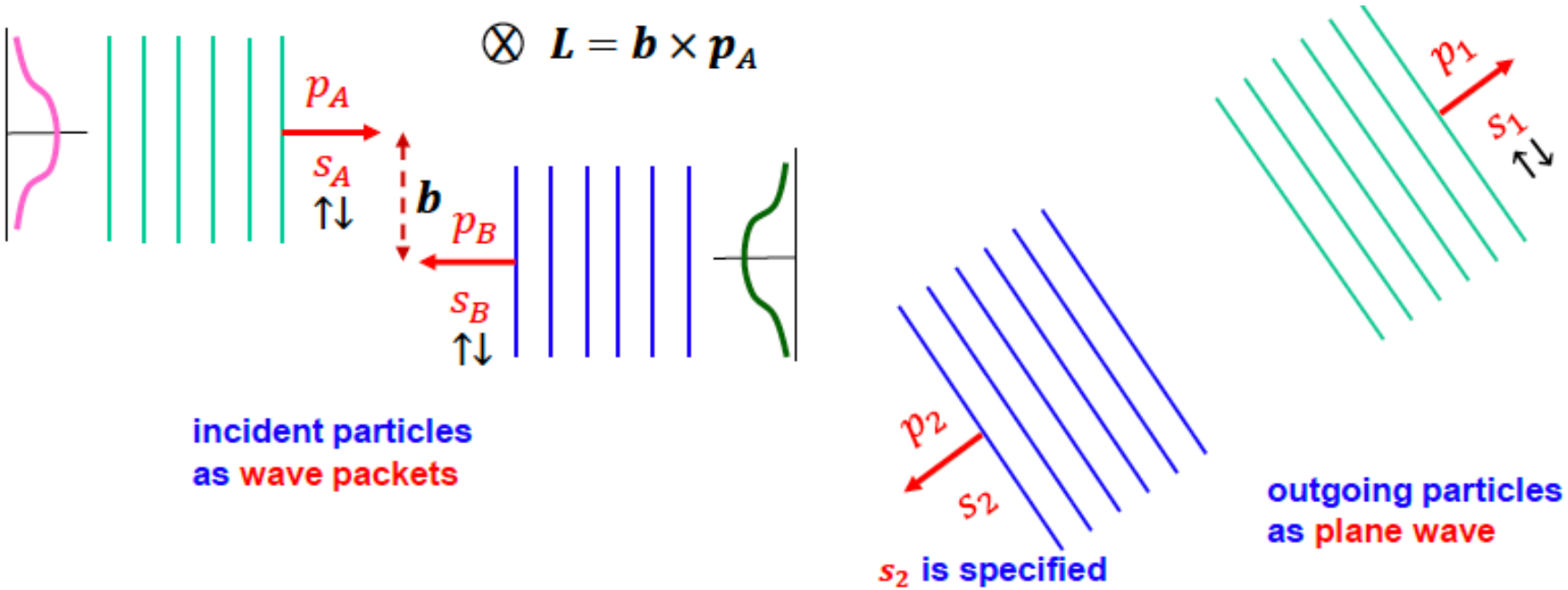
- ✓ Relativistic generalization of a non-relativistic micropolar fluid
- ✓ "boost heat current" is a relativistic effect

✓ **Hydrodynamics equation up to 1st order with spin**

$$0 = \partial_\mu(T^{\mu\nu}_{(0)} + T^{\mu\nu}_{(1)} + O(\partial^2)) \qquad \partial_\mu(u^\mu\sigma^{\alpha\beta}) = T^{\alpha\beta}_{(1)} - T^{\beta\alpha}_{(1)} + O(\partial^2)$$

Talks by: R. Ryblewski, H. Taya, E. Speranza, A. Kumar, Gallegos Pazos, …

Microscopic Dynamics for Polarization



Particle collisions as wave packets: there is a transverse distance between two wave packets (impact parameter) giving non-vanishing OAM and then the polarization of one final particle

$$\boldsymbol{L} = \boldsymbol{b} \times \boldsymbol{p}_A \Longrightarrow \left(\frac{d\sigma}{d\Omega}\right)_{s_2=\uparrow} \neq \left(\frac{d\sigma}{d\Omega}\right)_{s_2=\downarrow}$$

Talks by: Q. Wang, …

Magneto-Hydrodynamics

Second-order equations of motion for dissipative currents

Bulk viscous pressure

$$\tau_\Pi \dot{\Pi} + \Pi = -\zeta\theta - \ell_{\Pi V}\nabla_\mu V_{\rm f}^\mu - \tau_{\Pi V} V_{\rm f}^\mu \dot{u}_\mu - \delta_{\Pi\Pi}\Pi\theta - \lambda_{\Pi V} V_{\rm f}^\mu \nabla_\mu \alpha_0 + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu} - \delta_{\Pi V E}\, \mathrm{q} E_\mu V_{\rm f}^\mu$$

where

$$\dot{u}^\mu = \frac{1}{\varepsilon_0 + P_0}\left[\nabla^\mu P_0 - \Delta^\mu_\nu \partial_\kappa \pi^{\kappa\nu} - \Pi\dot{u}^\mu + \nabla^\mu\Pi + n_{\rm f0}\,\mathrm{q}E^\mu + \epsilon^{\mu\nu\alpha\beta}u_\alpha \mathrm{q}B_\beta V_{{\rm f},\nu}\right]$$

Particle diffusion current

$$\begin{aligned}\tau_V \dot{V}_{\rm f}^{\langle\mu\rangle} + V_{\rm f}^\mu &= \kappa\nabla^\mu\alpha_0 - \tau_V V_{{\rm f},\nu}\omega^{\nu\mu} - \delta_{VV} V_{\rm f}^\mu\theta - \ell_{V\Pi}\nabla^\mu\Pi + \ell_{V\pi}\Delta^{\mu\nu}\nabla_\lambda\pi^\lambda_\nu \\ &+ \tau_{V\Pi}\Pi\dot{u}^\mu - \tau_{V\pi}\pi^{\mu\nu}\dot{u}_\nu - \lambda_{VV} V_{{\rm f},\nu}\sigma^{\mu\nu} + \lambda_{V\Pi}\Pi\nabla^\mu\alpha_0 - \lambda_{V\pi}\pi^{\mu\nu}\nabla_\nu\alpha_0 \\ &+ \delta_{VE}\,\mathrm{q}E^\mu + \delta_{V\Pi E}\,\mathrm{q}E^\mu\Pi + \delta_{V\pi E}\,\mathrm{q}E_\nu\pi^{\mu\nu} + \delta_{VB}\,\epsilon^{\mu\nu\alpha\beta}u_\alpha\mathrm{q}B_\beta V_{{\rm f},\nu}\end{aligned}$$

Shear-stress tensor

$$\begin{aligned}\tau_\pi\dot{\pi}^{\langle\mu\nu\rangle} + \pi^{\mu\nu} &= 2\eta\sigma^{\mu\nu} + 2\tau_\pi\pi_\lambda^{\langle\mu}\omega^{\nu\rangle\lambda} - \delta_{\pi\pi}\pi^{\mu\nu}\theta - \tau_{\pi\pi}\pi^{\lambda\langle\mu}\sigma_\lambda^{\nu\rangle} + \lambda_{\pi\Pi}\Pi\sigma^{\mu\nu} \\ &- \tau_{\pi V} V_{\rm f}^{\langle\mu}\dot{u}^{\nu\rangle} + \ell_{\pi V}\nabla^{\langle\mu}V_{\rm f}^{\nu\rangle} + \lambda_{\pi V} V_{\rm f}^{\langle\mu}\nabla^{\nu\rangle}\alpha_0 \\ &+ \delta_{\pi V E}\,\mathrm{q}E^{\langle\mu}V_{\rm f}^{\nu\rangle} + \delta_{\pi B}\,\epsilon^{\alpha\beta\rho\sigma}u_\rho\mathrm{q}B_\sigma\Delta^{\mu\nu}_{\alpha\kappa}\pi^\kappa_\beta\end{aligned}$$

Talks by: D. Rischke, L. Yan, …

Anomalous Transport

Anomalous-Viscous Fluid Dynamics

$$D_\mu J_R^\mu = +\frac{N_c q^2}{4\pi^2} E_\mu B^\mu \qquad D_\mu J_L^\mu = -\frac{N_c q^2}{4\pi^2} E_\mu B^\mu$$

$$J_R^\mu = n_R\, u^\mu + \nu_R^\mu + \frac{N_c q}{4\pi^2}\,\mu_R\, B^\mu$$

$$J_L^\mu = n_L\, u^\mu + \nu_L^\mu - \frac{N_c q}{4\pi^2}\,\mu_L\, B^\mu$$

CME

Viscous Effect

$$\Delta^\mu{}_\nu\, \mathrm{d}\, \nu_{R,L}{}^\nu = -\frac{1}{\tau_{rlx}}(\nu_{R,L}{}^\mu - \nu_{NS}{}^\mu)$$

$$\nu_{NS}{}^\mu = \frac{\sigma}{2} T \Delta^{\mu\nu}\partial_\nu \frac{\mu}{T} + \frac{\sigma}{2} q\, E^\mu$$

$$\begin{cases} \partial_t n_5 + \nabla\cdot \mathbf{j}_5 = -2q, \\ \mathbf{j}_5 = -D\nabla n_5 + \xi, & \text{thermal fluctuation} \\ q = \dfrac{n_5}{2\tau_{CS}} + \xi_q; & \text{topological fluctuation} \end{cases}$$

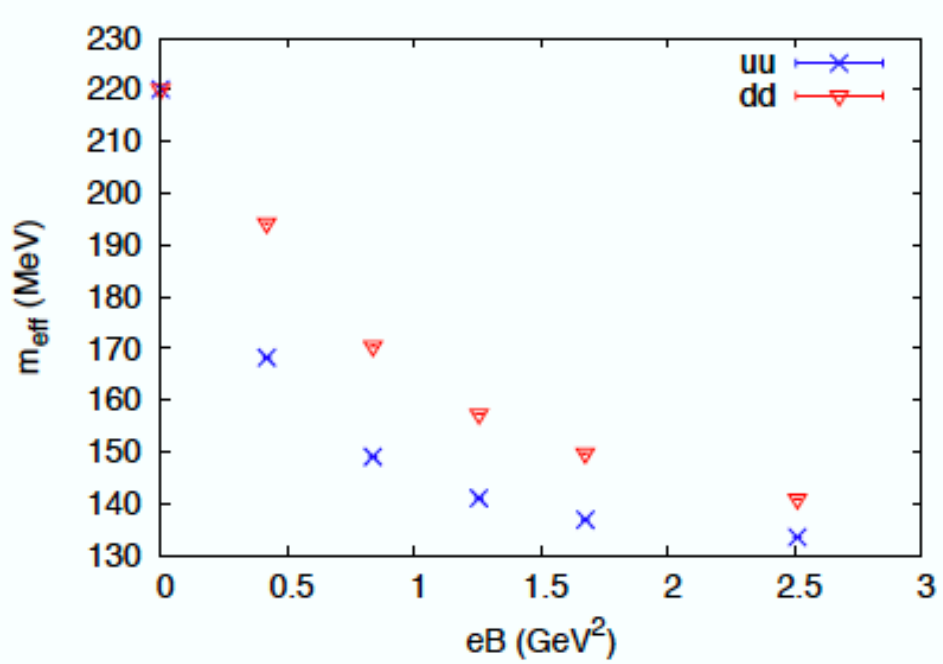
dissipation

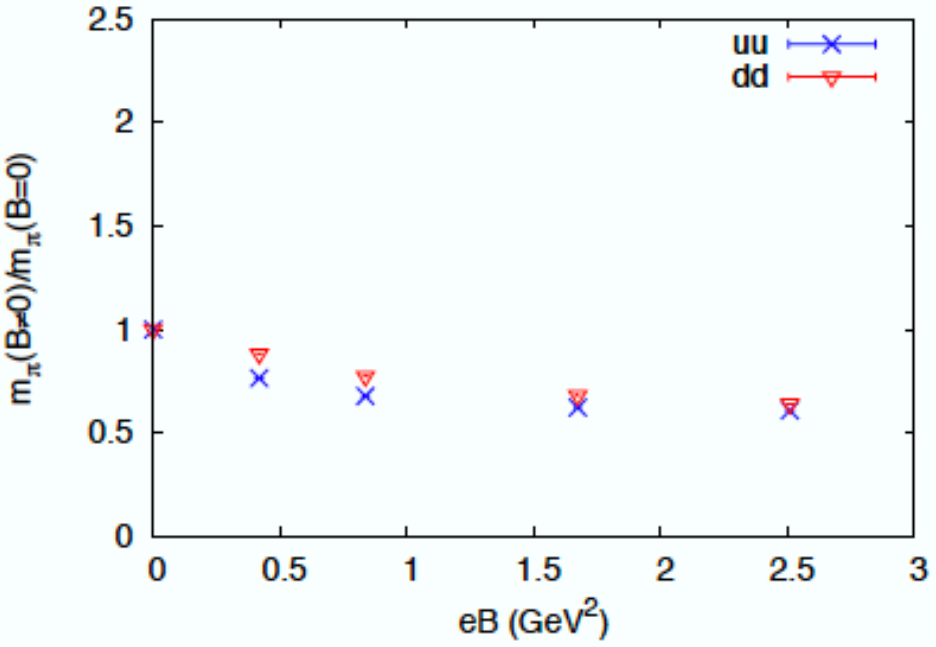
$$\partial_t N_5 = -\frac{N_5}{\tau_{cs}}$$

Corrections to "standard" CME: non-static case; higher order

Talks by: S. Lin, S. Shi, S. Pu, H. Liu, M. Horvath…

QCD Properties under Extreme Fields

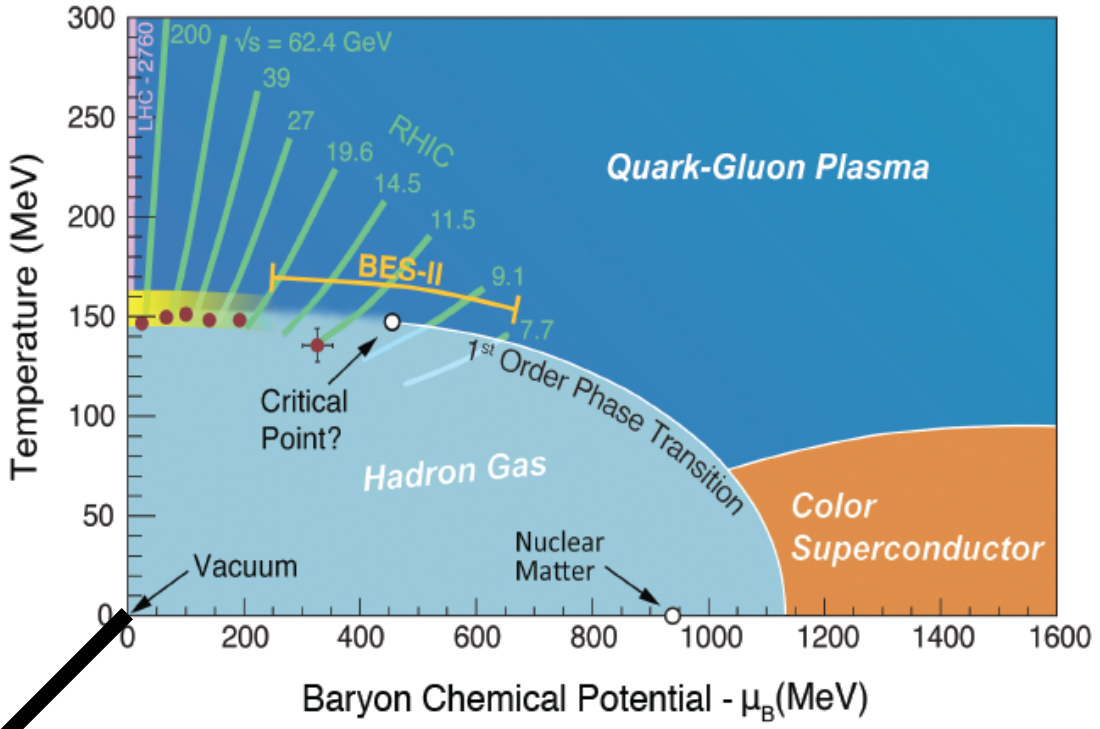


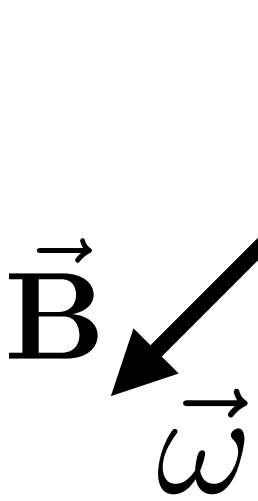


HTD, A. Tomiya, S. Mukherjee, Xiao-Dan Wang (汪晓丹) et al., work in progress

Talks by: H. Ding, M. Huang, K. Xun, …

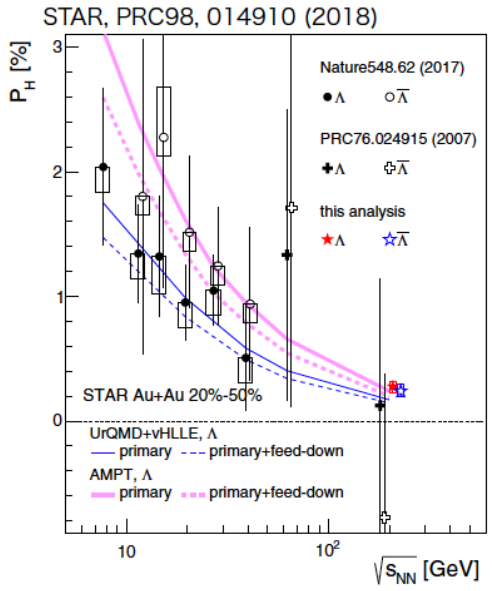
QCD Phase Structures under Extreme Fields

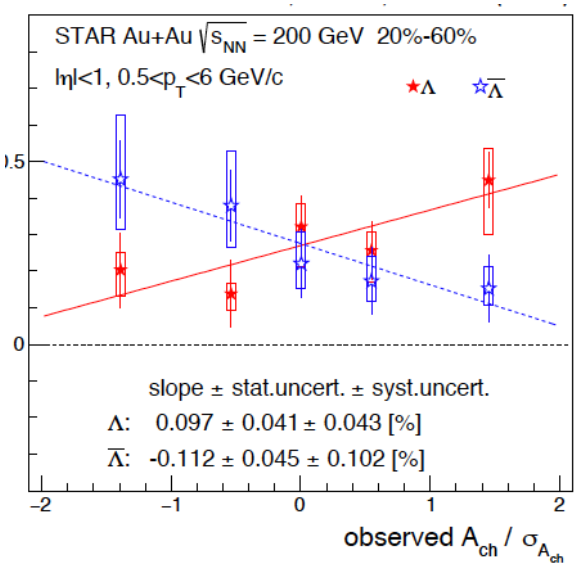


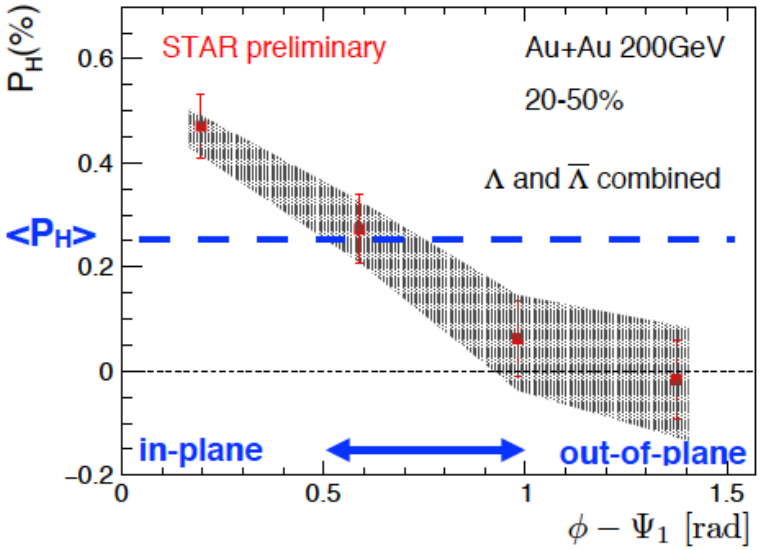


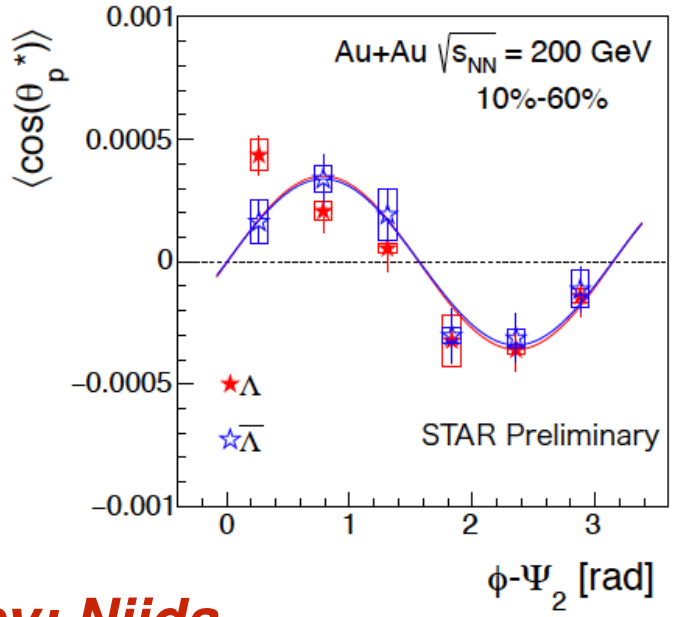
Talks by: M. Huang, D. Hou, L. He, Y. Jiang, …

Exp. Measurements of Spin Polarization: RHIC



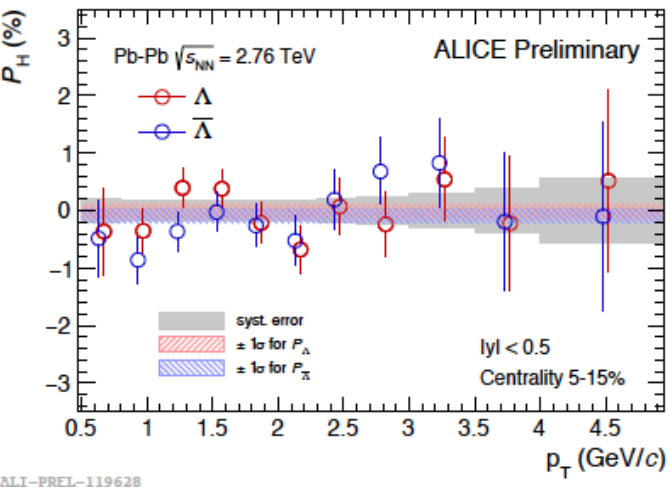


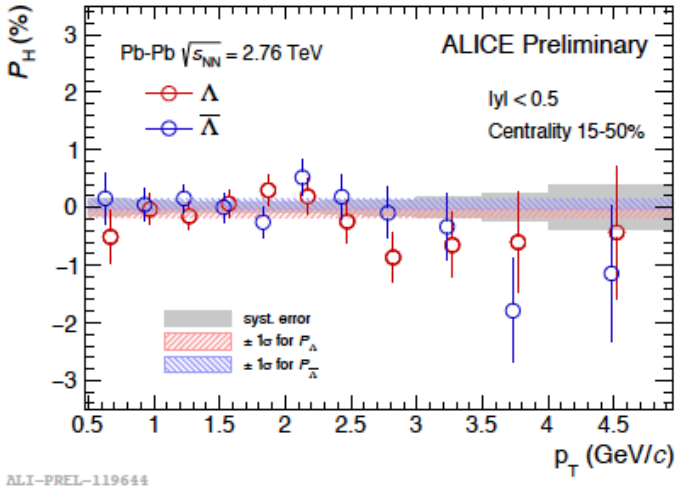




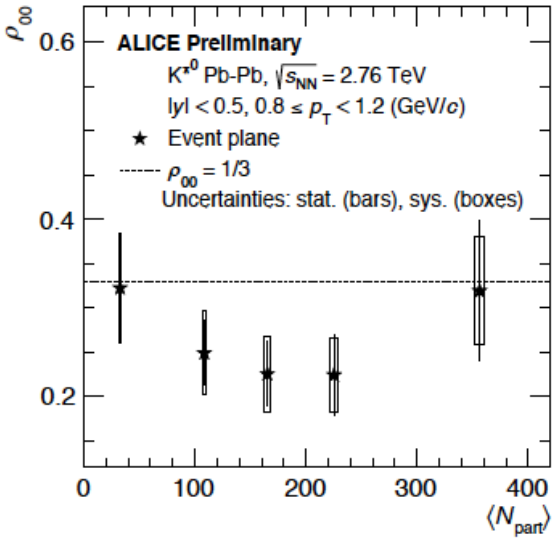
Talk by: Niida

Exp. Measurements of Spin Polarization: LHC

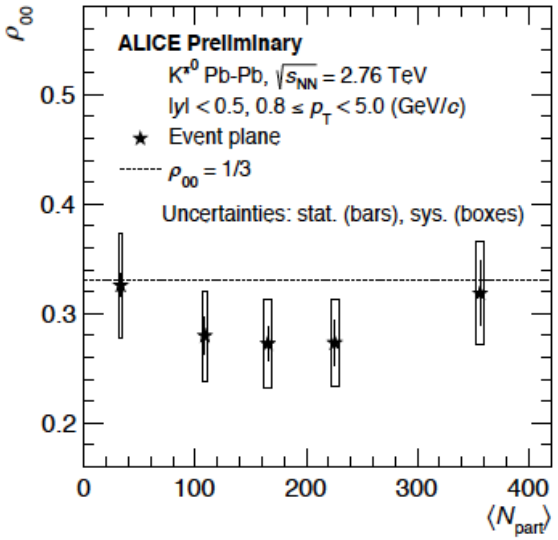




First p_T bin



Integrated p_T



Talk by: Singh

Phenomenology of Polarization

- ***AMPT***
- ***Chiral kinetic transport***
- ***Hydrodynamics***

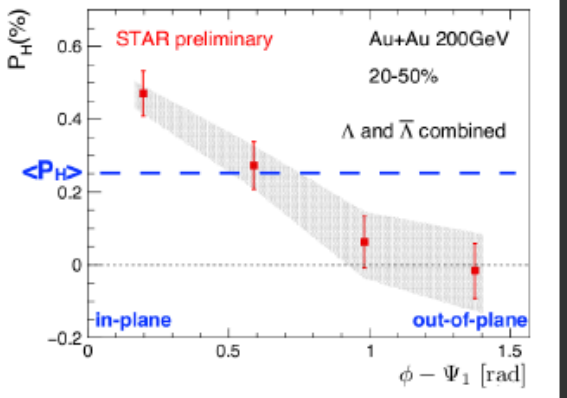
Consistent picture of vorticity structures;
Describing the average global polarization well.

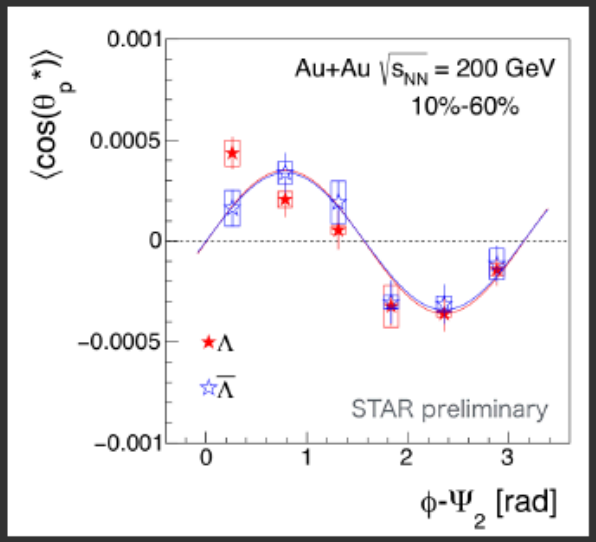
Talks by: C. Ko, F. Becattini, H. Li, X. Xia, G. Ma, J. Xu, …

Puzzles in Spin Polarization

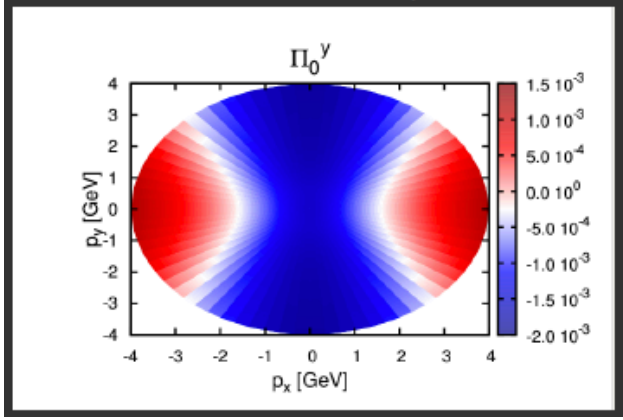
Disagreement between hydro and data

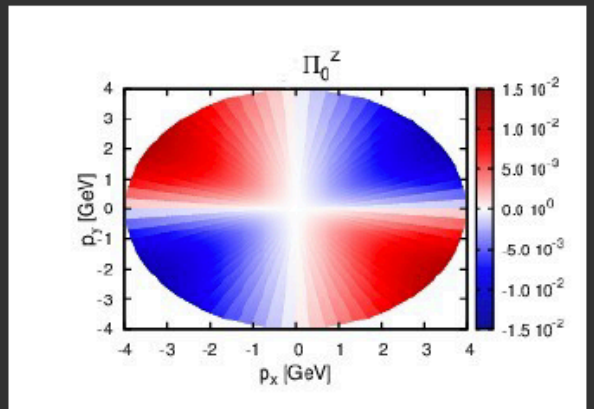
T. Niida, talk given at Quark Matter 2018
Nucl.Phys. A982 (2019) 511-514





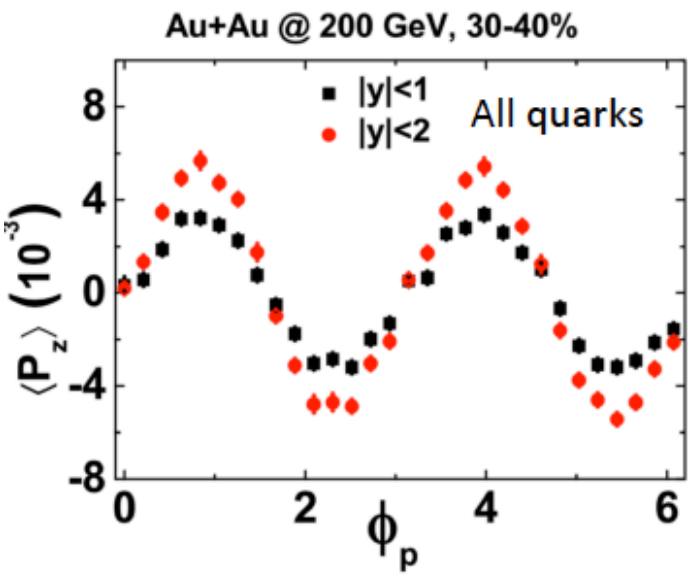
F. B., G. Inghirami et al., Eur. Phys. J C 75 (2015) 406

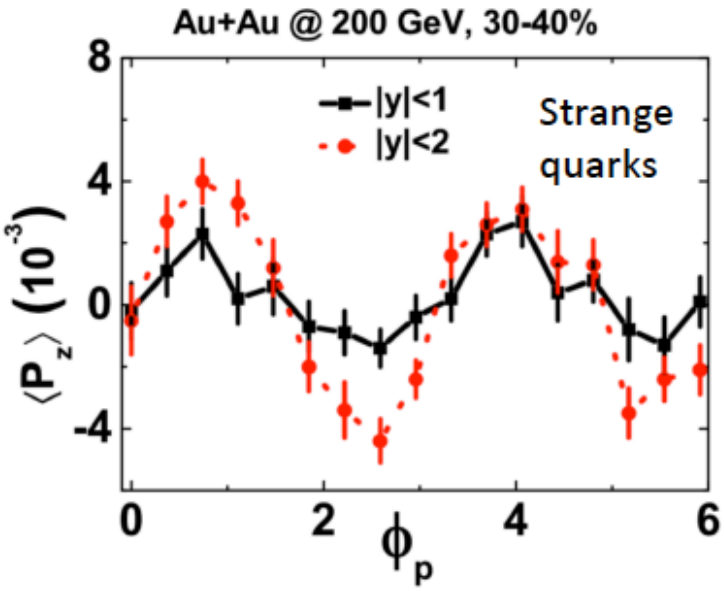


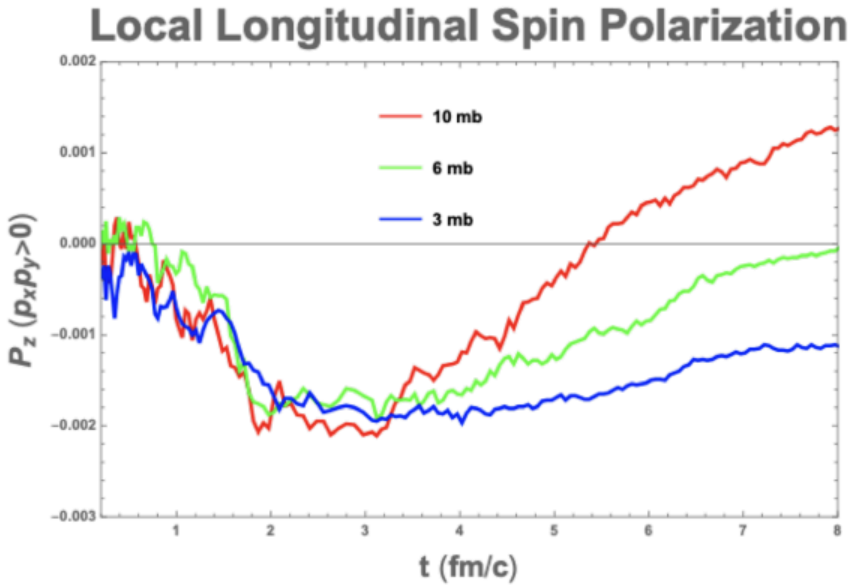


Talks by: Becattini, Niida, Ko, …

Puzzles in Spin Polarization







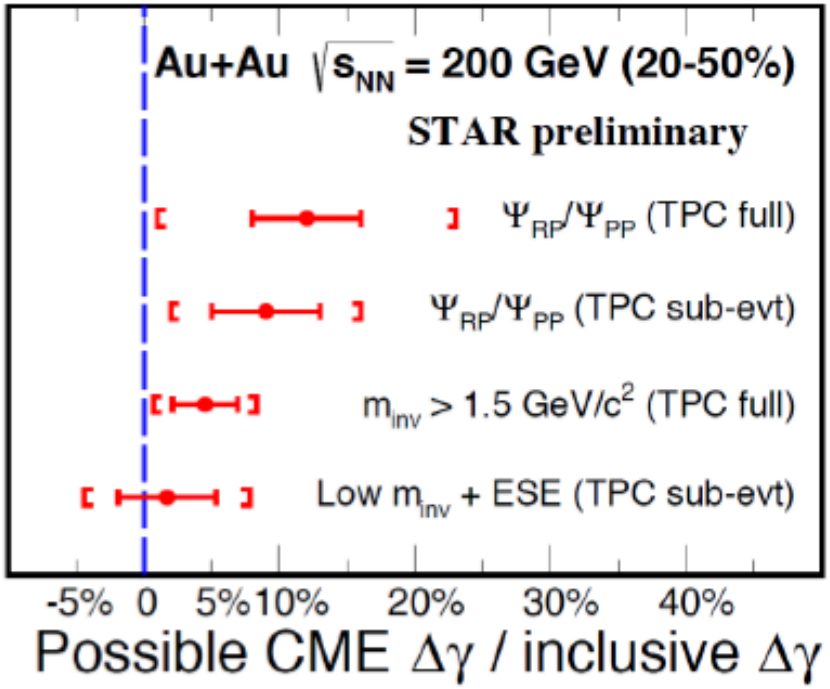
Talk by: Ko

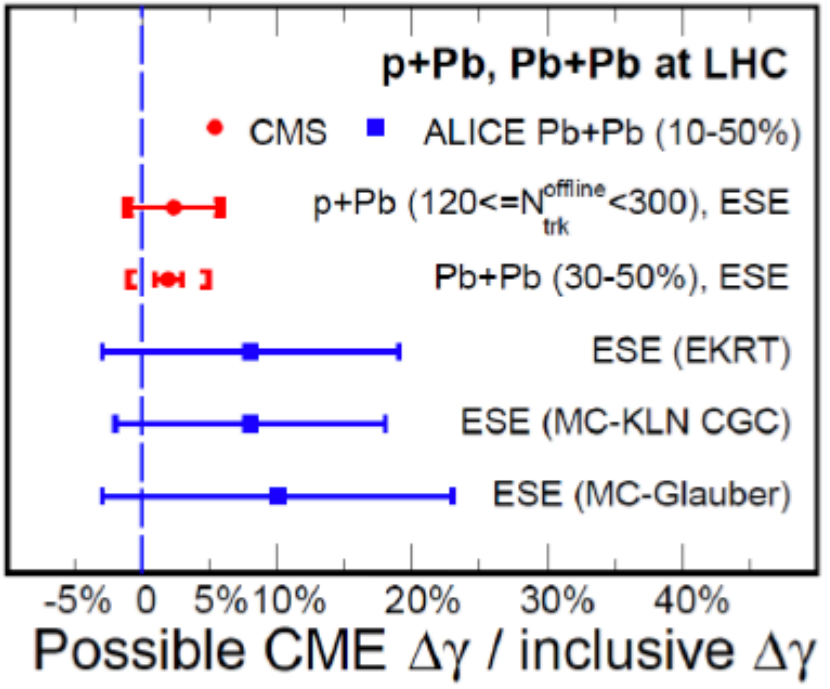
Path Forward

- ***Carefully check bulk modeling (initial conditions)***
- ***Using directed flow to help constrain bulk modeling***
- ***Better theory for mapping vorticity to polarization!!***
- ***Forward rapidity polarization measurements?***
- ***Consistent understanding of hyperons and mesons?***

Exp. Search for CME

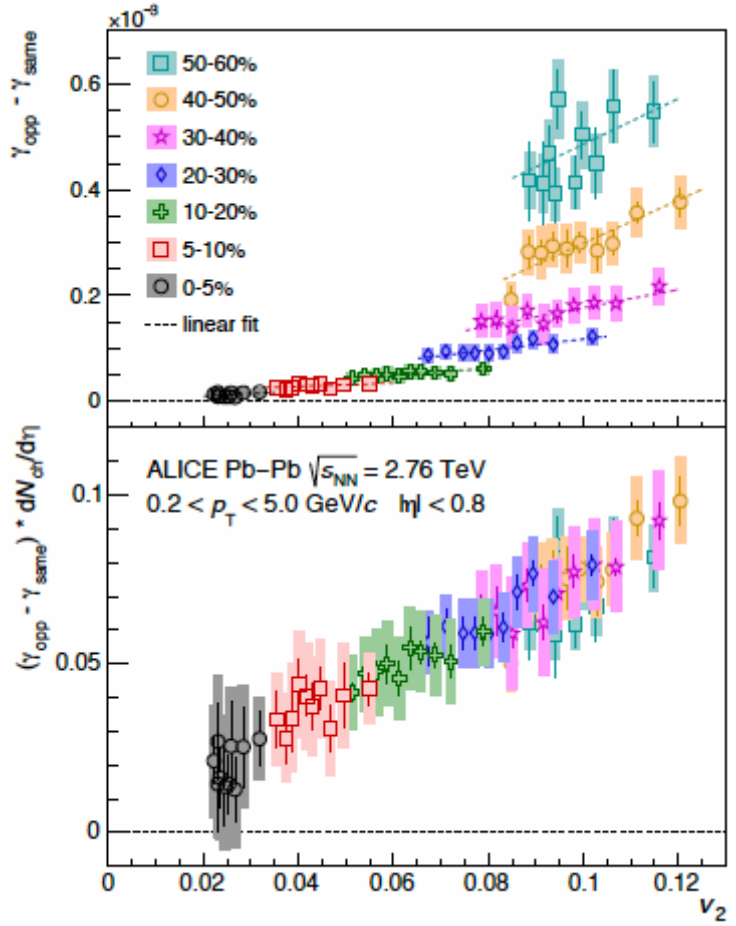
Most measurements based on:
gamma correlator + certain procedure to fight backgrounds



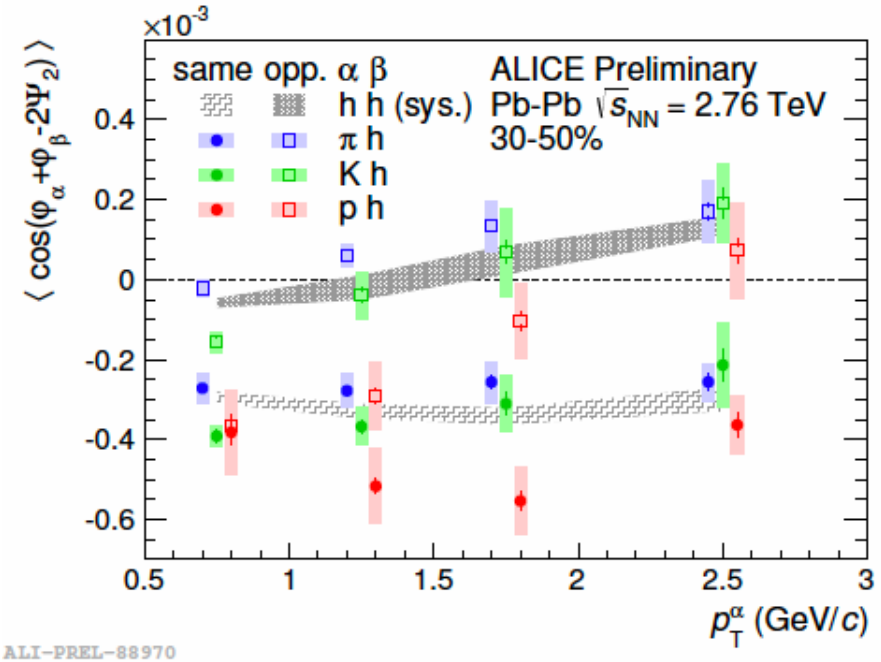


Talks by: H. Huang, F. Wang, R. Lacey, A. Tang,
G. Wang, J. Zhao, Q. Shou

Exp. Search for CME

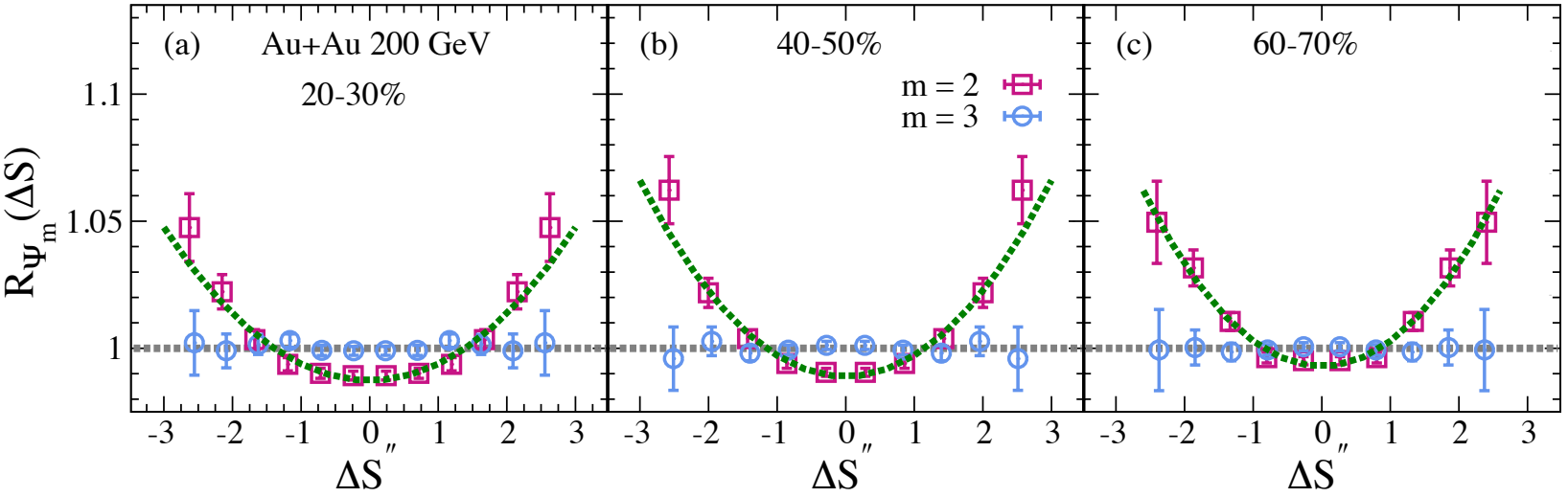


Flavor dependence is very interesting!



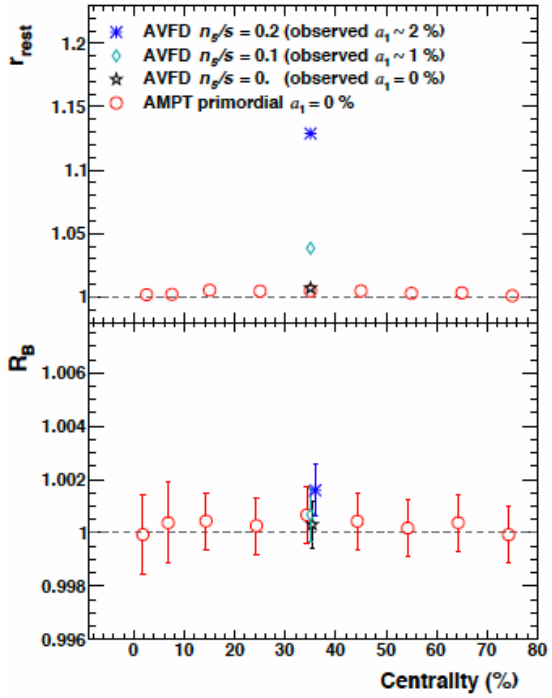
Talks by: H. Huang, F. Wang, R. Lacey, A. Tang, G. Wang, J. Zhao, Q. Shou

Exp. Search for CME



New observables

Talks by: H. Huang, F. Wang, R. Lacey, A. Tang, G. Wang, J. Zhao, Q. Shou



Challenges & Path Forward

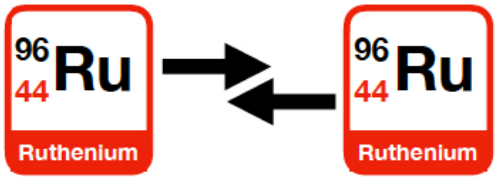
Observable	(Just a few) names	Problems/questions
$\Delta\gamma$ ESE		
ESE "CMS"		Dependence of the signal on v2?
"q2obs"ESE	F. Wang, G. Wang	"Play" on stat. fluctuations, Not-interpretable?
small systems	CMS, F. Wang, others	Strong RP independent background, nothing/little to say about CME
Mixed harmonics	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

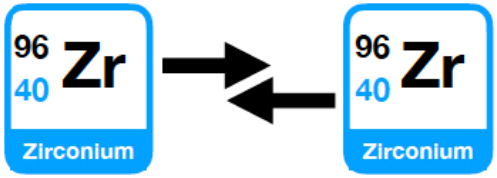
from: Voloshin

- ***Great to have many observables: consistency?***
- ***Very important: understanding observables & their relations!!***
- ***Use sophisticated modeling tools (signal+bkg.) to help***

Path Forward: Isobaric Collisions

New opportunity of potential discovery: Isobaric Collision @ RHIC

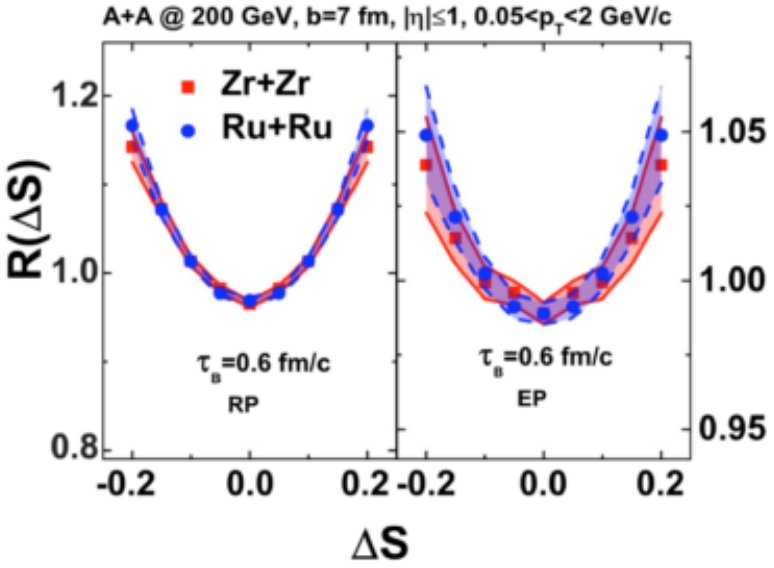


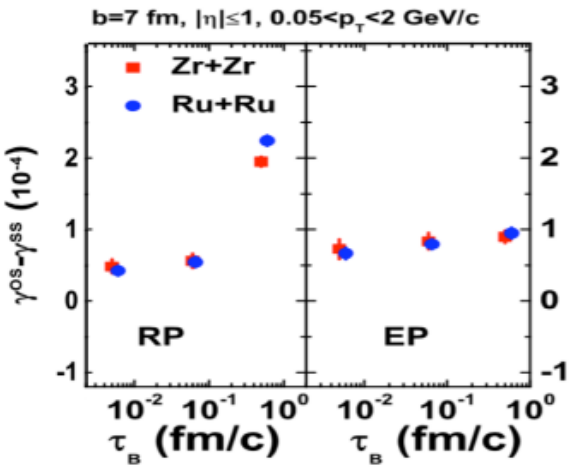


Charge Asymmetry Correlation Measurement

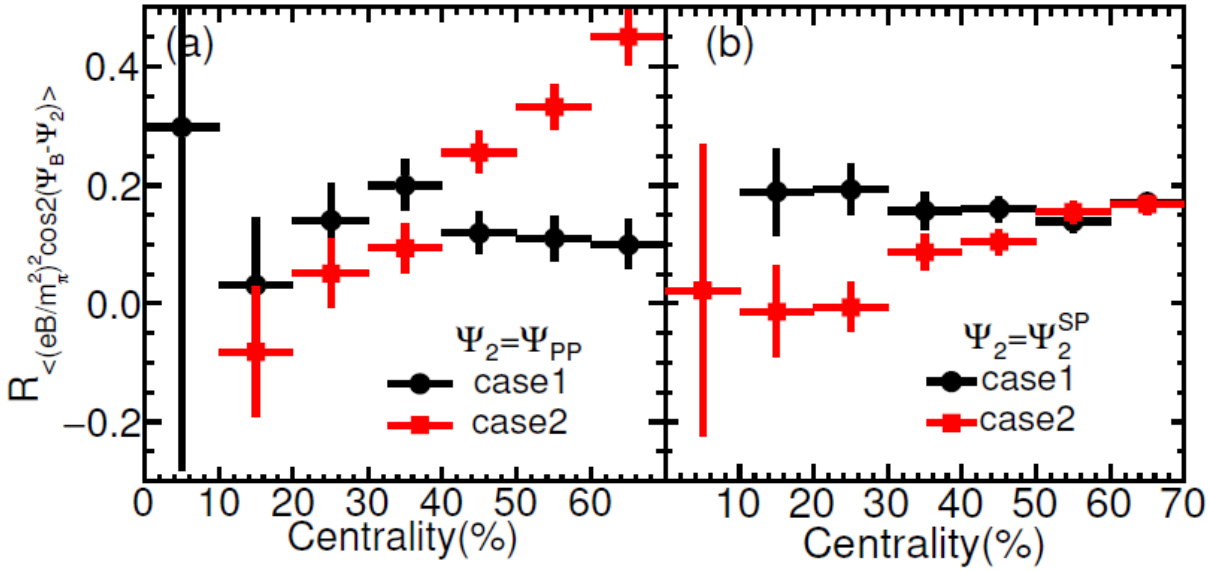
~2 billion data collected successfully in RHIC 2018 run; processing and analysis underway!

Phenomenology of CME





Transport modes:
Chiral kinetic transport;
AMPT.

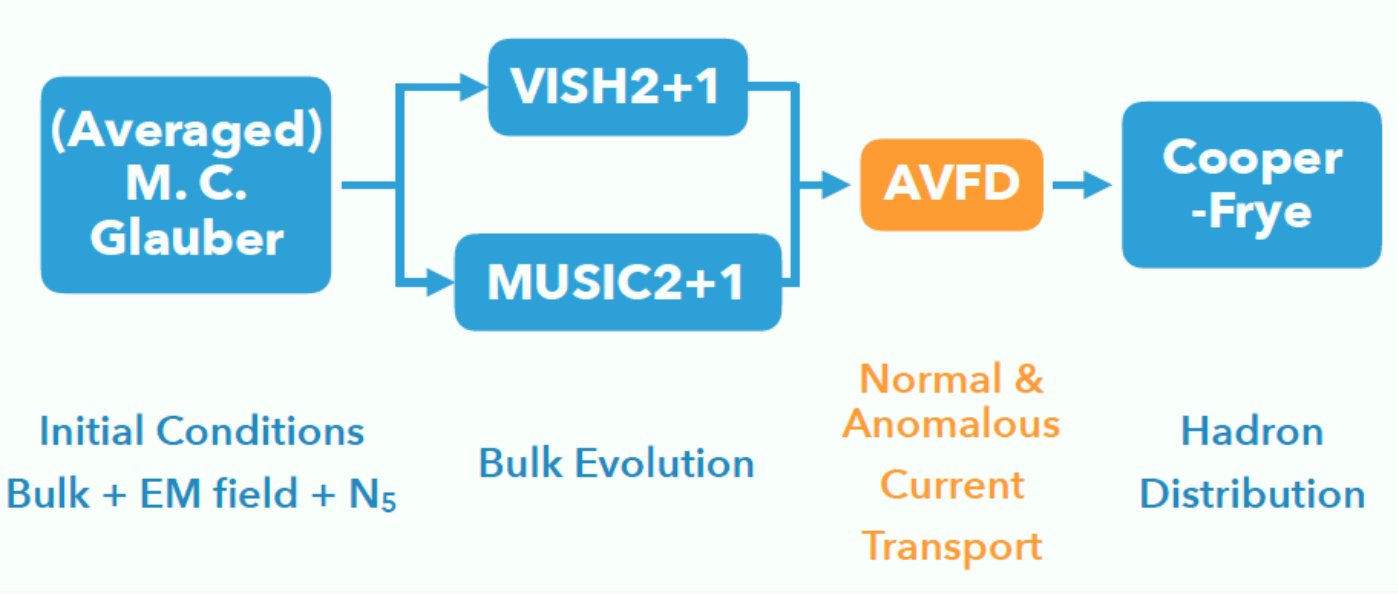


Talks by: C. Ko, J. Xu, G. Ma, …

Phenomenology of CME

Establishment of Anomalous-Viscous Fluid Dynamics (AVFD): Hydrodynamical realization of CME in HIC.

[newest developments: EBE-AVFD; AVFD+axial dynamics; AVFD+LCC]

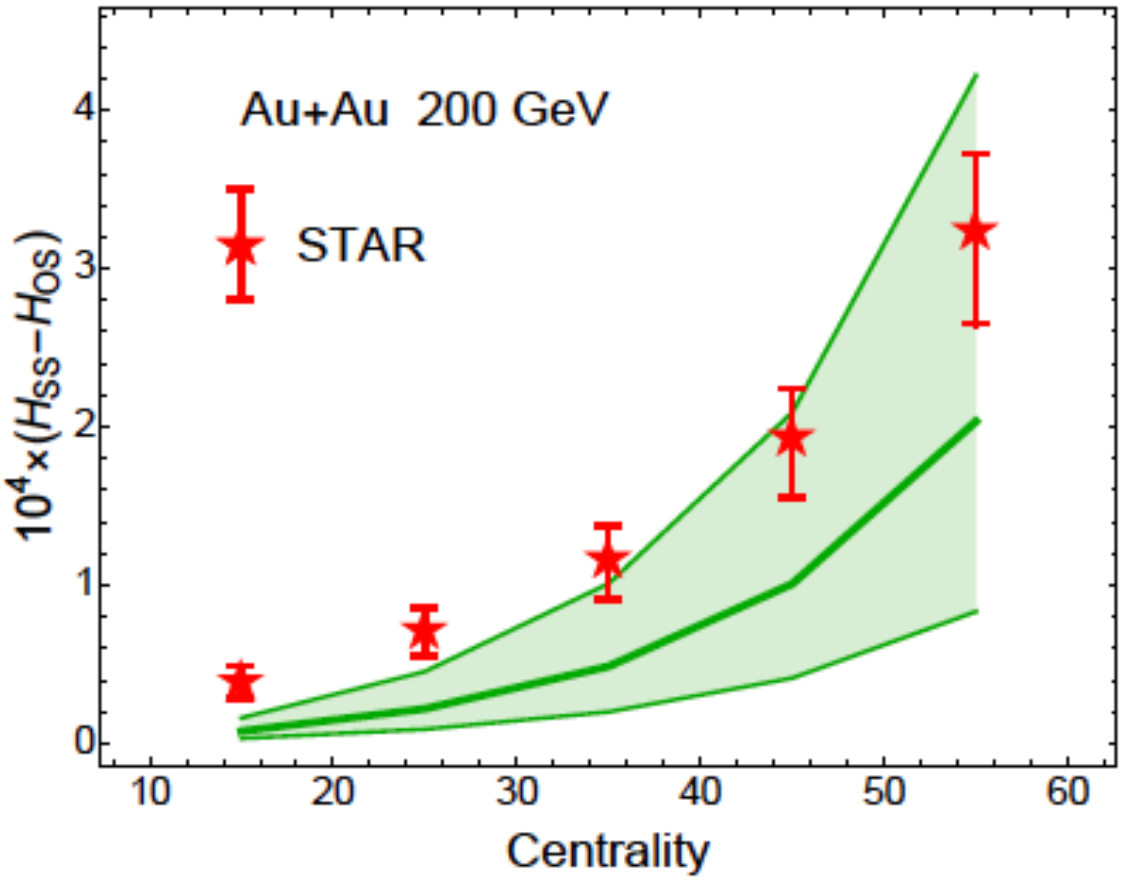


We now have a versatile tool to quantitatively understand and answer many important questions about CME in heavy ion collisions!

[Shi, Yin, JL, …, CPC2018, Annals of Physics 2018]

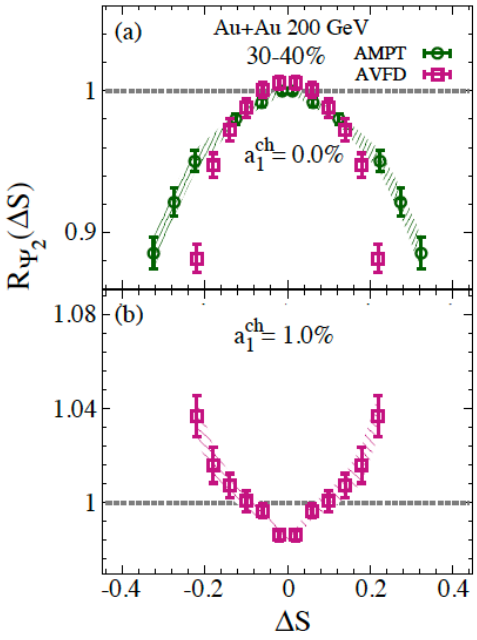
Talk by: S. Shi

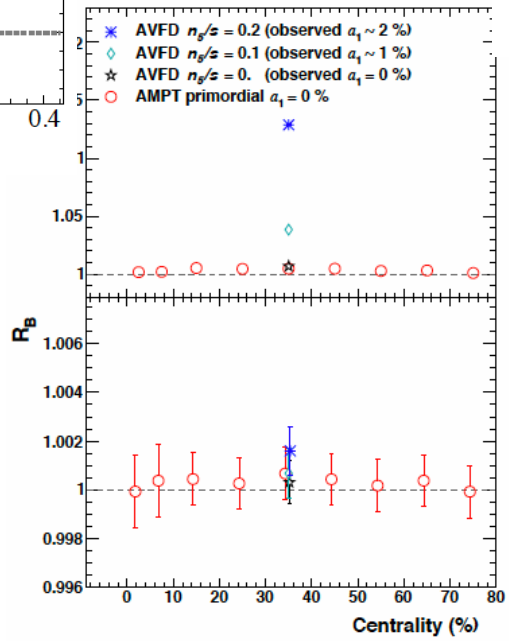
Phenomenology of CME

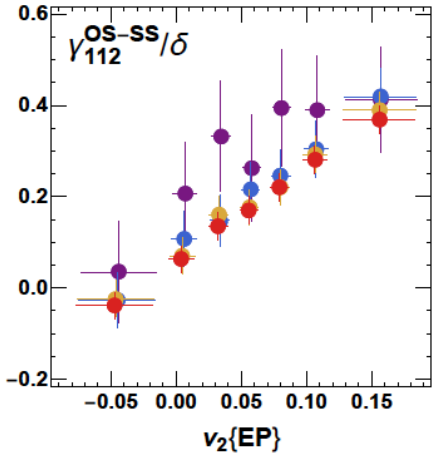


CME is quantitatively viable for describing relevant experimental observable.

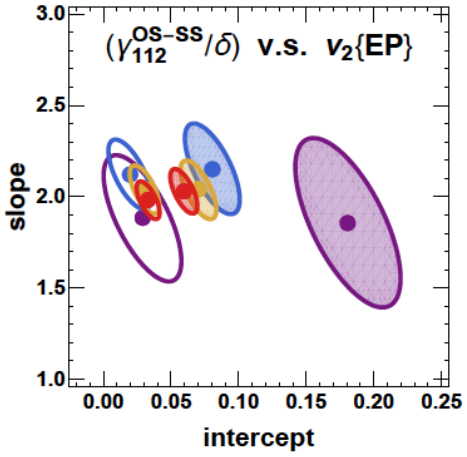
EBE-AVFD for Testing Observables





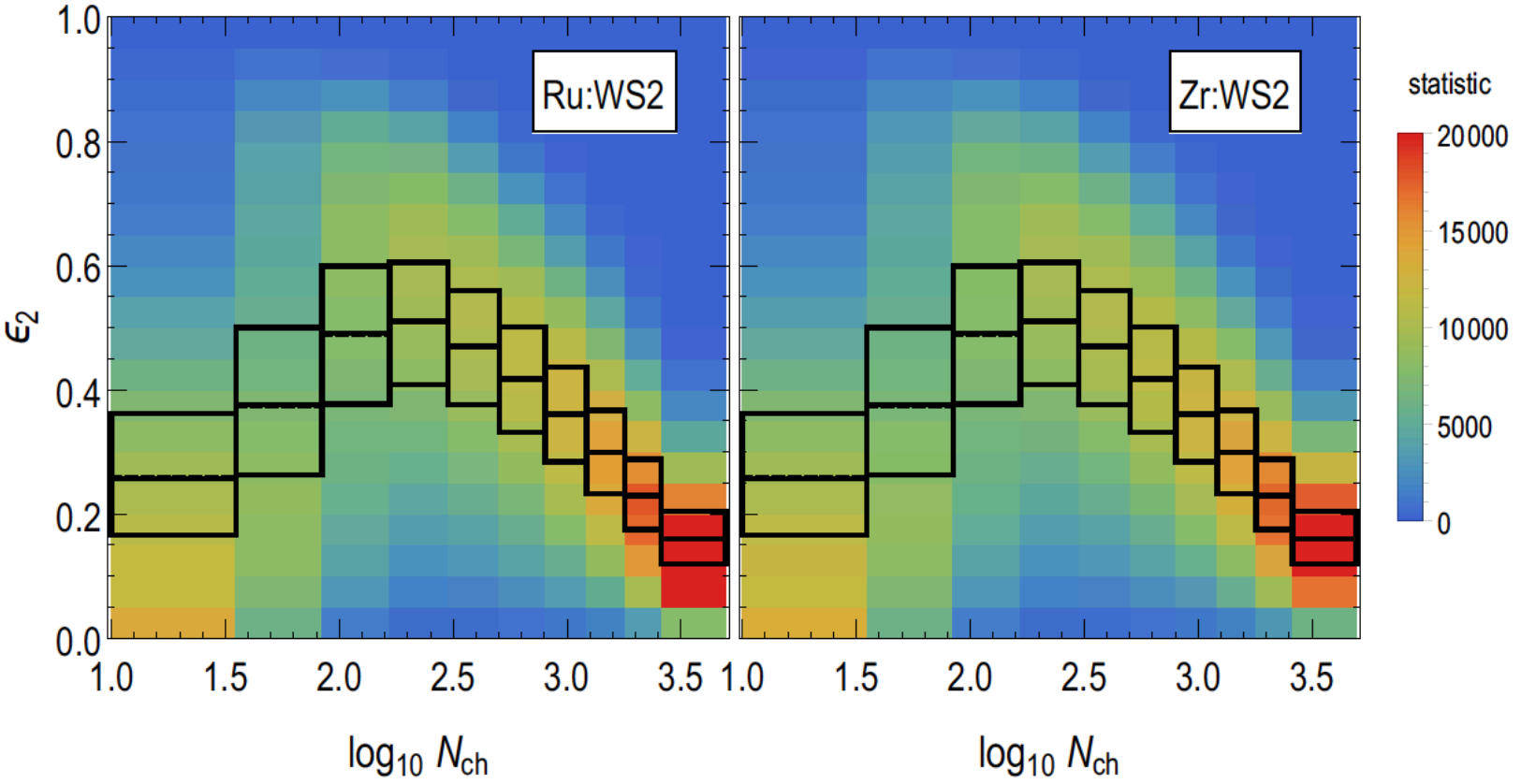


P_{LCC} = 0.00, 0.33, 0.67, 1.00



A useful tool for understanding different observables' sensitivity

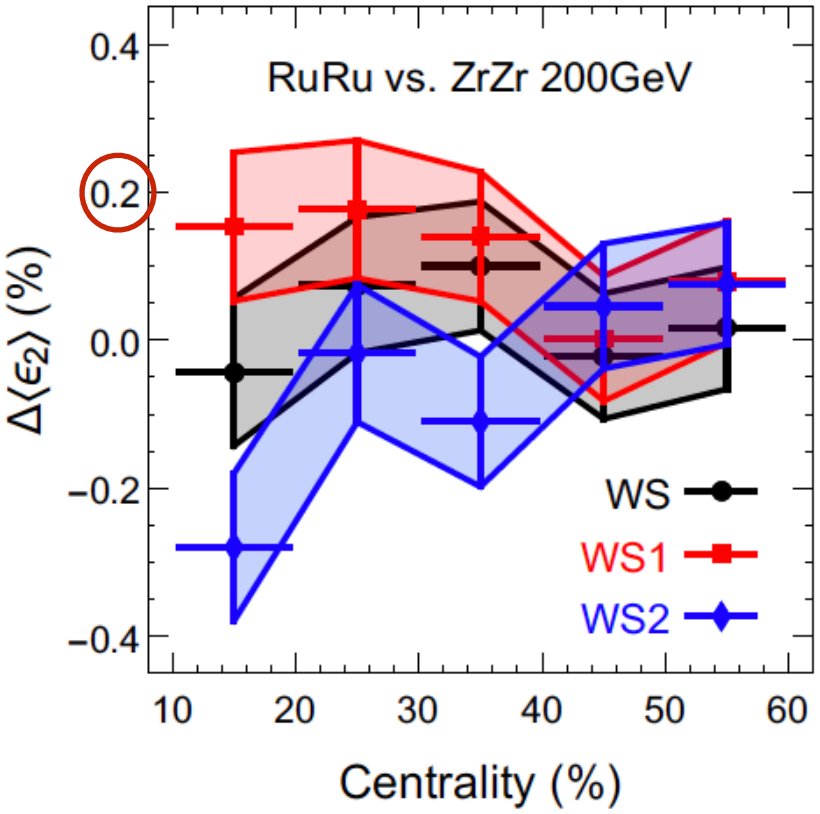
Isobars: How to Choose Identical Systems?



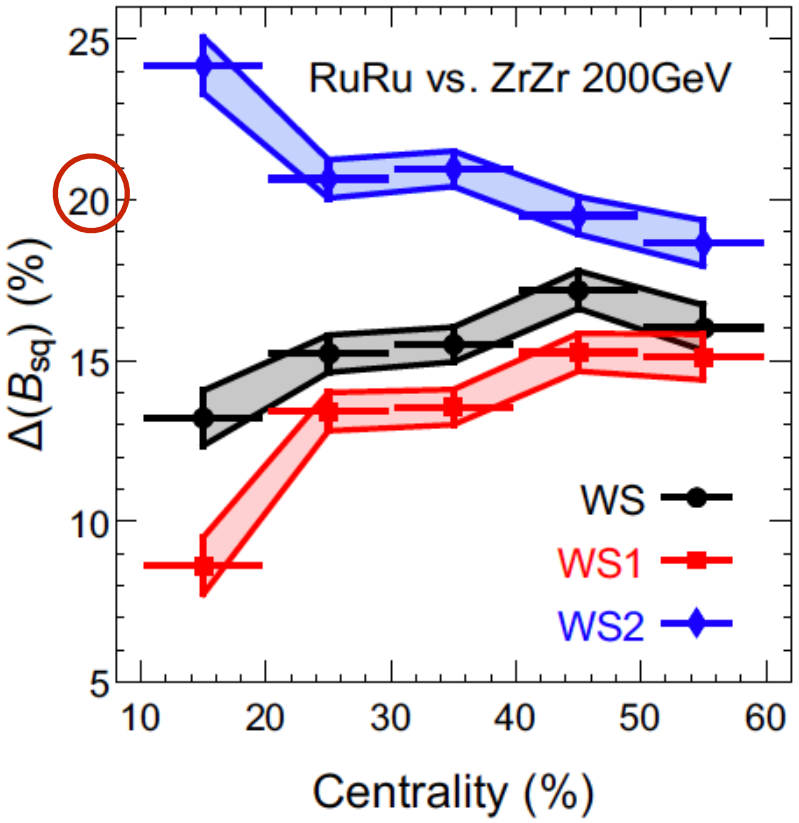
Insight from initial conditions:
joint cut on Multiplicity-Eccentricity

Isobars: How to Choose Identical Systems?

Eccentricity is guaranteed the same!



B field differs by 12~20% !



Joint multiplicity-geometry cut:
Vanishing difference in bulk properties,
Sizable difference in magnetic fields!!!

AVFD for Isobars

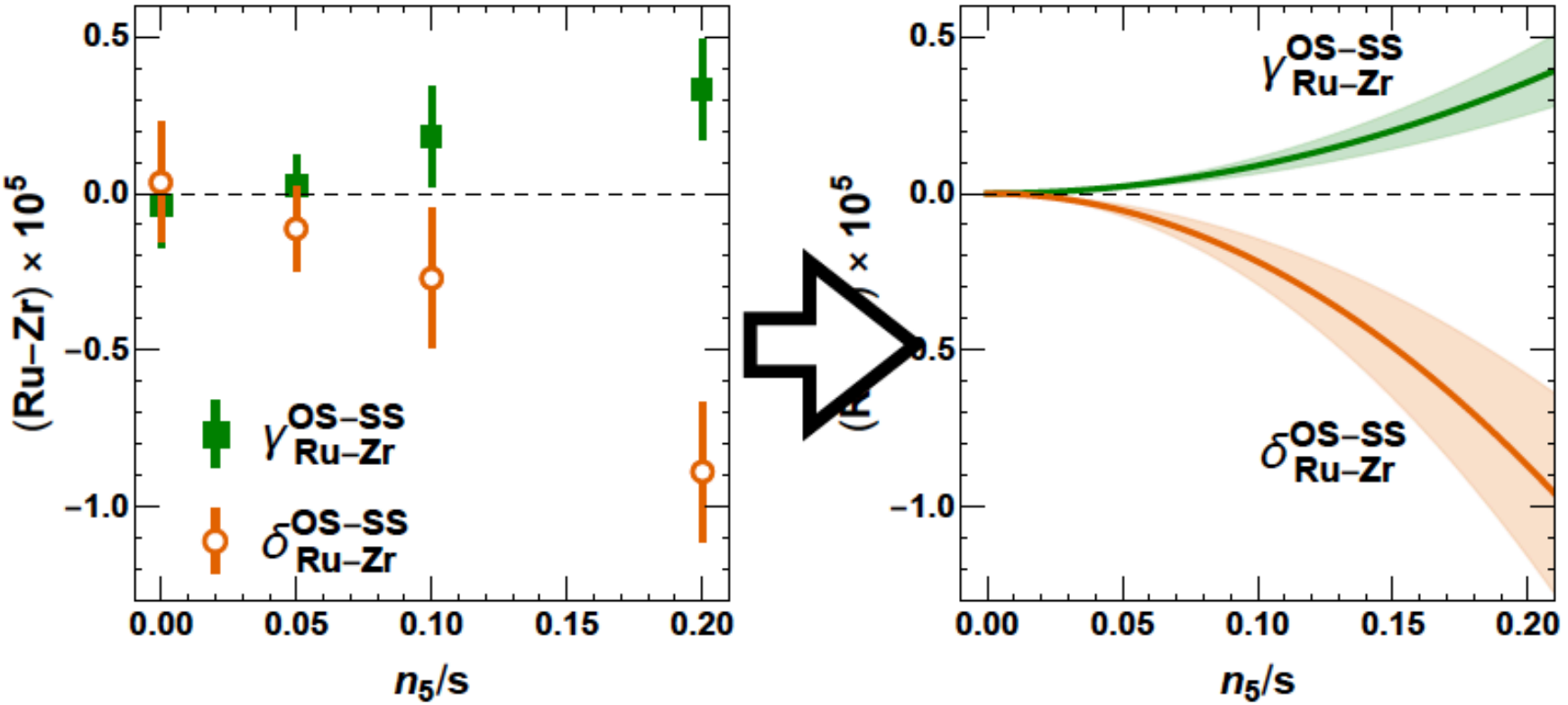
$-1 < \eta < 1$

$64 < N_{ch} < 96$

$0.05 < v_2^{ref} < 0.25$

Statistics: 10^7 events in AVFD simulation

~ 3×10^8 events in experiment

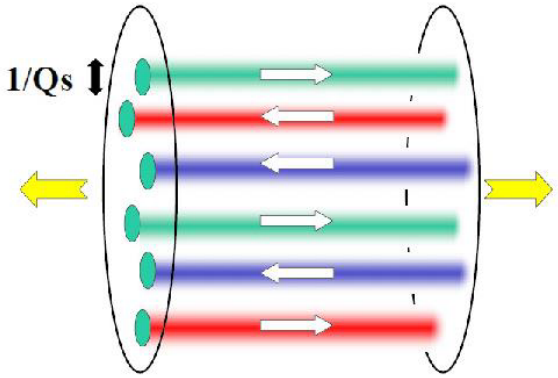


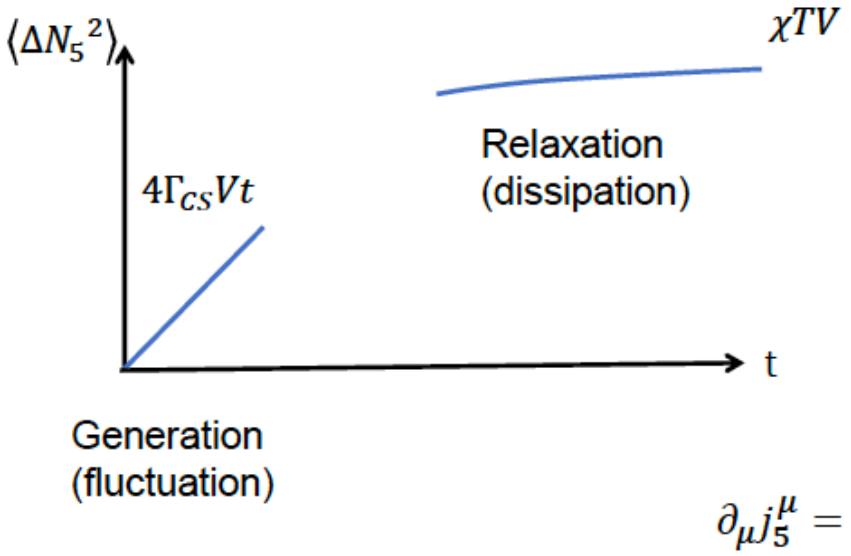
Look for absolute difference between isobars (after joint-cut)!

Look for consistency between delta- and gamma-correlators!

Challenges & Path Forward

- ***Axial charges [initial conditions v.s. thermal fluc.??]***
- ***Dynamical magnetic fields***
- ***Quantifying background correlations***

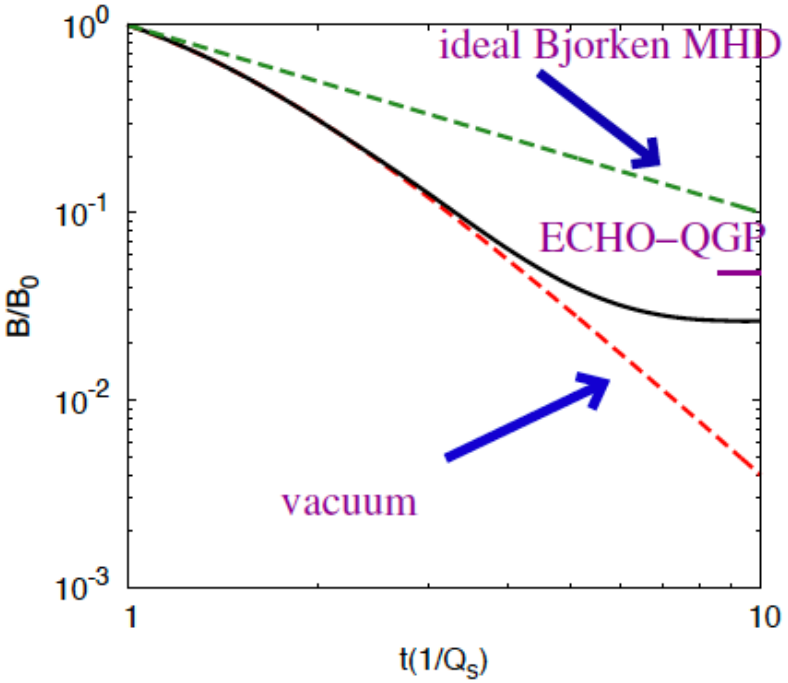




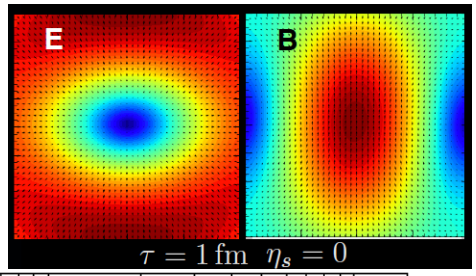
Talk by: S. Lin

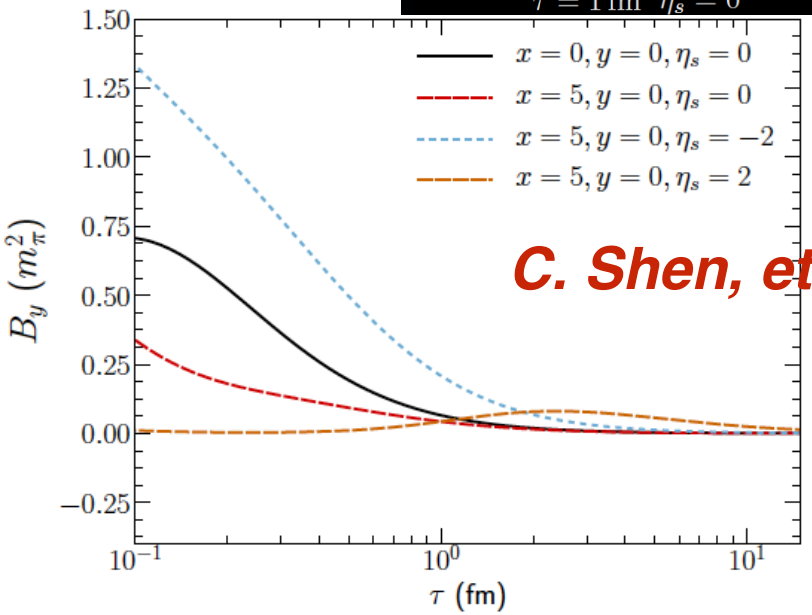
Challenges & Path Forward

- ***Axial charges [initial conditions v.s. thermal fluc.??]***
- ***Dynamical magnetic fields***
- ***Quantifying background correlations***



Talk by: L. Yan



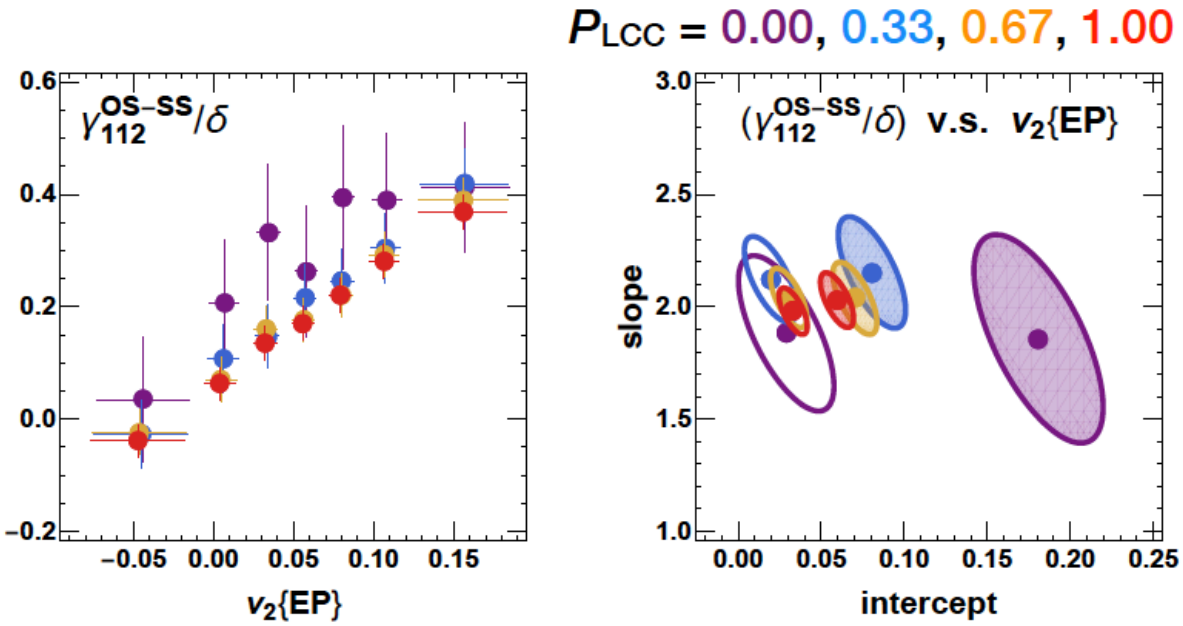


C. Shen, et al

Possible late B field effects: X. Guo; K. Xu

Challenges & Path Forward

- ***Axial charges [initial conditions v.s. thermal fluc.??]***
- ***Dynamical magnetic fields***
- ***Quantifying background correlations***



Talk by: S. Shi

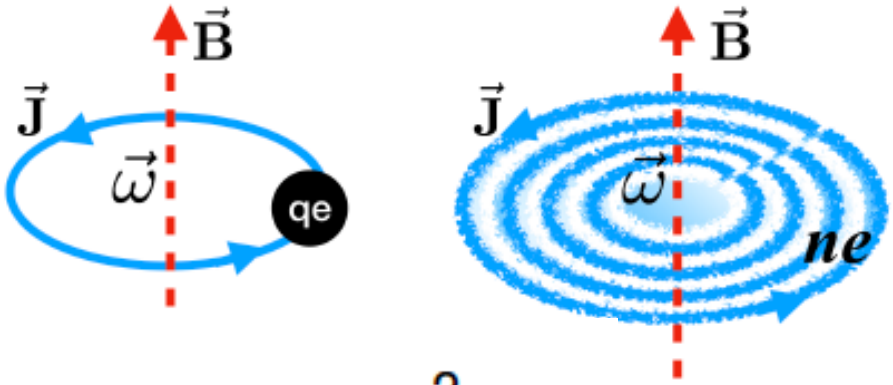
Challenges & Path Forward

- ***Axial charges [initial conditions v.s. thermal fluc.??]***
- ***Dynamical magnetic fields***
- ***Quantifying background correlations***

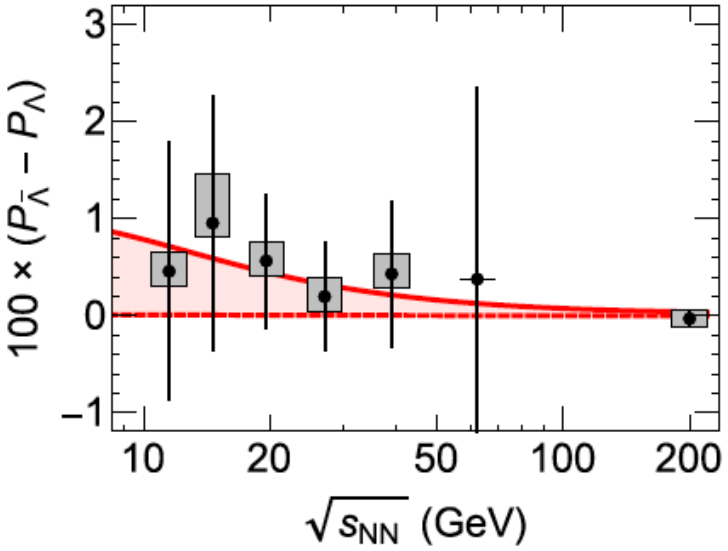
Path forward: build a fully dynamical tool for quantitative investigation of these issues!

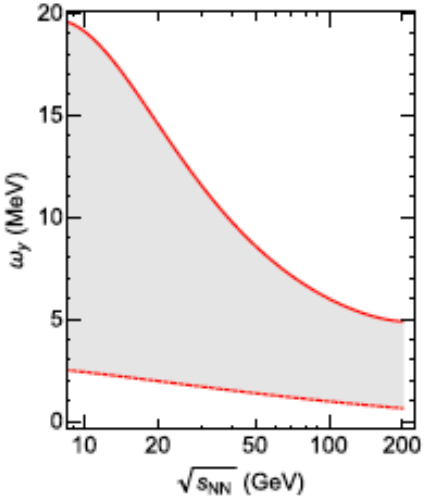
BEST Collaboration: EBE-AVFD-B-LCC

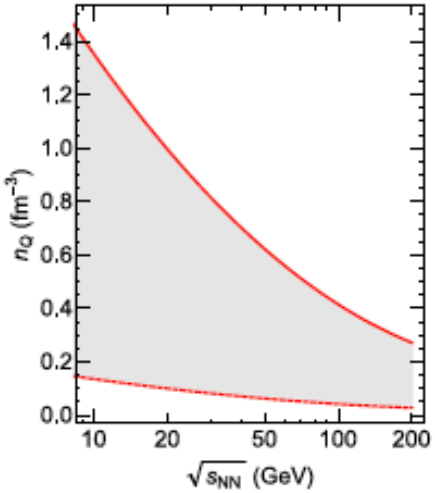
Toward Synergy of B and Rotation

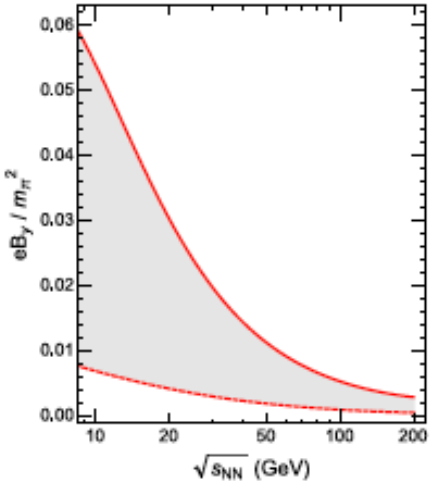


$$e\bar{\mathbf{B}} = \frac{e^2}{4\pi} nA\bar{\omega}$$



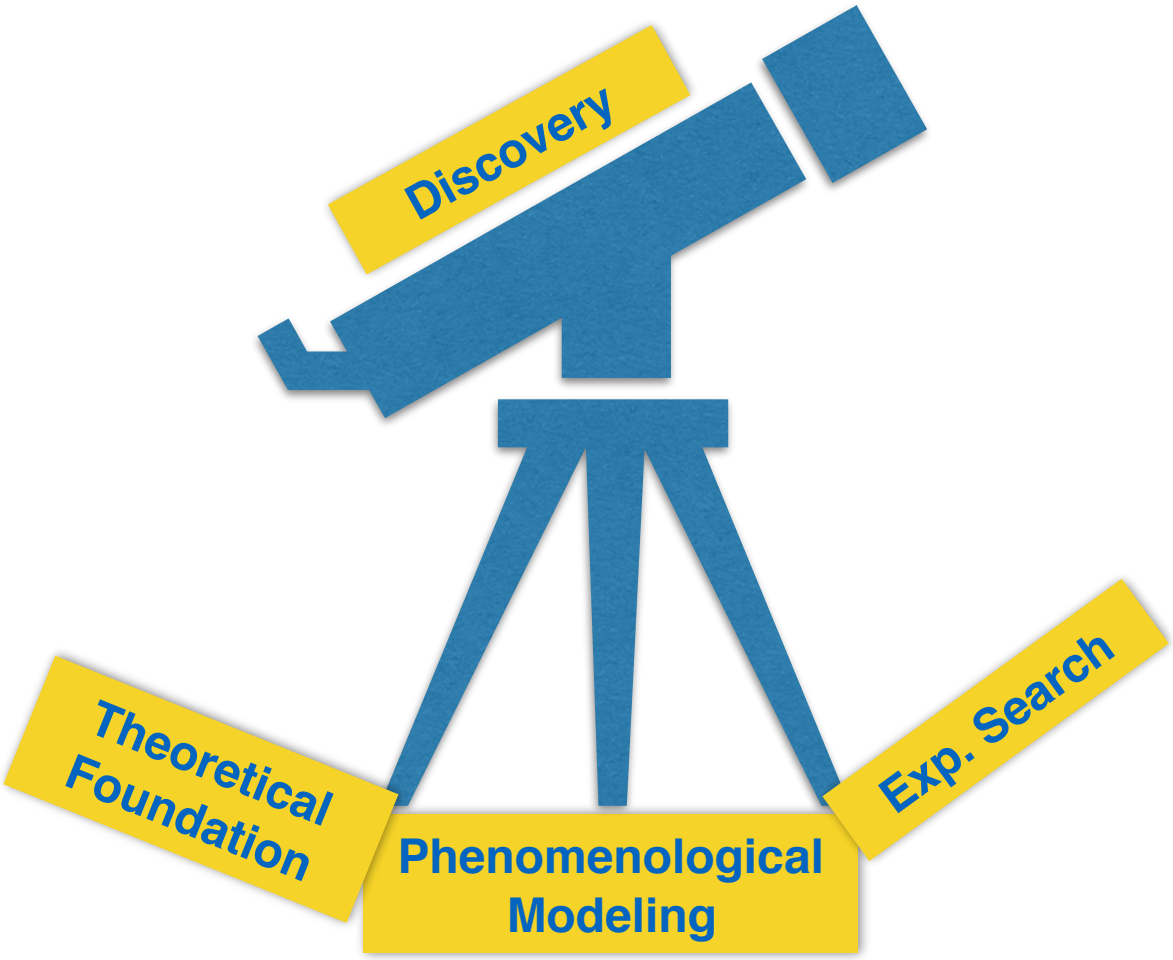






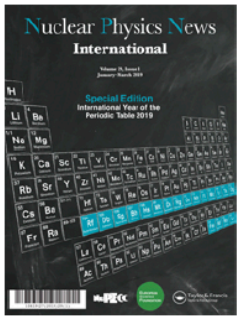
Talk by: X. Guo [arXiv:1904.04704]

The "Three Legs"



- *We already built a great chirality community*
- *The field develops with a healthy mix of three legs*
- *Pressing issues with both challenges & opportunities*

Real Near-Term Opportunity: Isobaric Collisions



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feature article

Isobar Collisions at RHIC to Test Local Parity Violation in Strong Interactions

D. E. KHARZEEV[1,2] AND J. LIAO[3]

versus the background level (horizontal axis). One expects that a 5 σ observation of the local parity violation will be possible if the background contributes less than two thirds of the measured correlation.

This decisive experiment for the search of CME had just begun in the spring 2018 RHIC run. If a conclusive observation of CME is achieved, it would amount to the experimental discovery of the restoration of chiral symmetry in hot QCD matter and to the first direct experimental observation of the topological fluctuations in QCD. We will be holding our breath awaiting the outcome of this groundbreaking experiment.

D. E. KHARZEEV

J. LIAO