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Importance of nuclear density distribution in the isobaric collisions

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4 November, 2018

with
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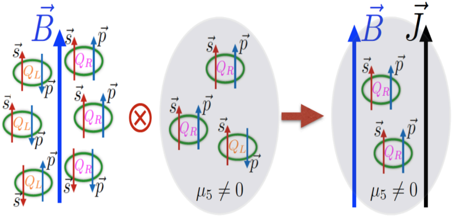
(arXiv:1710.03086, arXiv:1710.07265, arXiv:1808.06711)

The 7th Asian Triangle Heavy-Ion Conference
(ATHIC2018), Hefei, 3-6 Nov. 2018

Chiral magnetic effect

D. Kharzeev, PLB 633, 260 (2006)
D. Kharzeev et al, NPA 797, 67 (2007)
D. Kharzeev et al, NPA 803, 227 (2008)
K. Fukushima et al, PRD 78, 074033 (2008)
D. Kharzeev et al, PPNP 88, 1 (2016)



$$\mathbf{J_{cme}} = \sigma_5 \mathbf{B} = \left(\frac{(Qe)^2}{2\pi^2} \mu_5 \right) \mathbf{B}, \quad (1)$$

Relativistic Heavy Ion Collisions

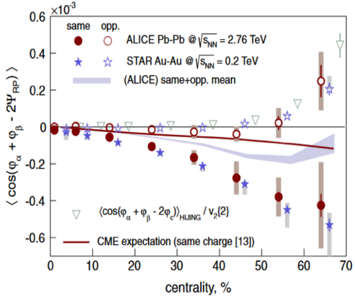
- Very strong magnetic field
- Chiral symmetry restoration
- Nontrivial topological structure of QCD vacuum

Observable: Event by event charge separation in heavy ion collisions

charge separation: the γ correlator

S. Voloshin, PRC 70, 057901 (2004)
STAR collaboration, PRL 113, 052302 (2014)

ALICE collaboration, PRL 110, 012301 (2013)



For example:
$\alpha = \pi/2, \beta = 3\pi/2 \rightarrow$
$\gamma = 1$

$\alpha = \pi/2, \beta = \pi/2 \rightarrow$
$\gamma = -1$

$$\gamma \equiv \langle \cos\left(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP}\right)\rangle \quad (2)$$

same: $\alpha = \beta$, opp.: $\alpha \neq \beta$, $\Delta\gamma = \gamma_{\text{opp}} - \gamma_{\text{same}}$

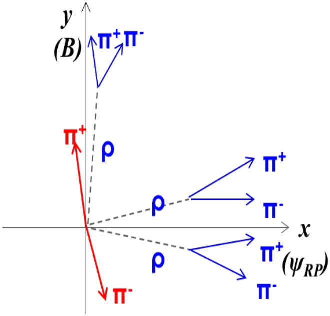
Event by event charge-dependent separation is observed in heavy ion collisions
Unnecessarily charge separation because of background contamination.

v_2-induced background

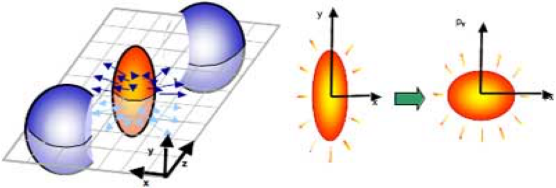
S. Schlichting, S. Pratt, PRC 83, 014913 (2011)
A. Bzdak et al, PRC 81, 031901 (2010)
F. Wang, PRC 81, 064902 (2010)

Cluster decay + elliptic flow(v_2)

$$\begin{aligned} & \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle \\ \propto \quad & \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_\rho + 2\phi_\rho - 2\Psi_{RP}) \rangle \\ \simeq \quad & \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_\rho) \rangle \langle 2(\phi_\rho - \Psi_{RP}) \rangle \\ = \quad & \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_\rho) \rangle v_2^\rho \end{aligned} \quad (3)$$



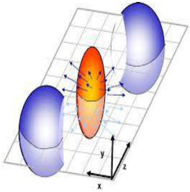
Elliptic flow (v_2) ⇐ initial geometry eccentritity (ϵ_2)

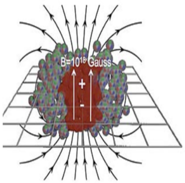


isobaric collisions

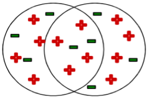
ϵ_2 determined by participant nucleons.

B dominated by spectator protons.

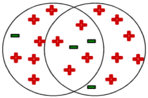




Isobaric collisions[S. Voloshin, PRL 105, 172301,(2010), W. Deng et al, PRC 94, 041901 (2016)]



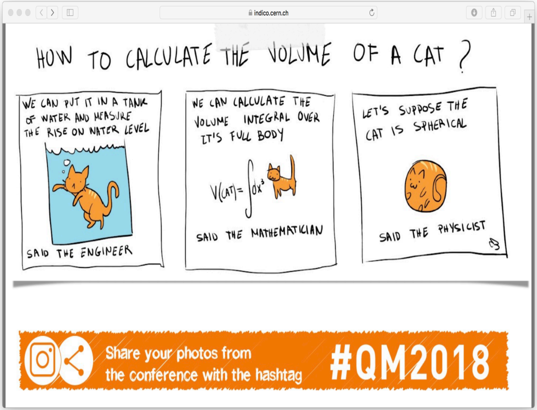
Vs

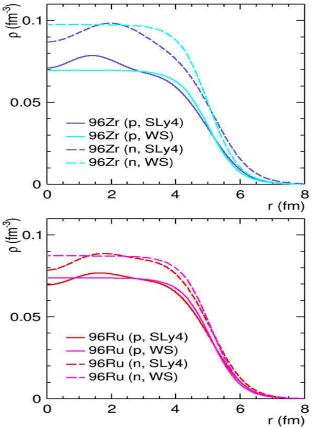


$_{40}Zr^{96} + _{40}Zr^{96}$ $_{44}Ru^{96} + _{44}Ru^{96}$

Same v_2-induced background while the magnetic field differ by 10% (Woods-Saxon density distributions)

Uncertainties





The assumption used in traditional study – the nuclear density for Zr and Ru are both Woods-Saxon distribution

$$\rho_{\rm WS}(r,\theta) = \frac{\rho_0}{1+\exp\left[r - r_0(1+\beta_2 Y_2^0(\theta))/a\right]} \qquad ??? \tag{4}$$

Density functional Theory

Walter Kohn, The Nobel Prize in Chemistry 1998

Many body system

$$H\Psi = [T + V + U]\Psi = \left[\sum_i^N -\frac{\nabla_i^2}{2m} + \sum_i^N V(\mathbf{r}) + \sum_{i<j} U(\mathbf{r_i}, \mathbf{r_j})\right]\Psi = E\Psi \qquad (5)$$

Hohenberg-Kohn theorems

- The ground state properties are uniquely determined by an electron density.

$$n(r) = \int \Psi(r, r_1, ..., r_N)^* \Psi(r, r_1, ..., r_N) d^3r_1 ... d^3r_N \qquad (6)$$

- The correct ground state electron density minimizes the energy functional.

$$E[n] = T[n] + U[n] + V[n] \qquad (7)$$

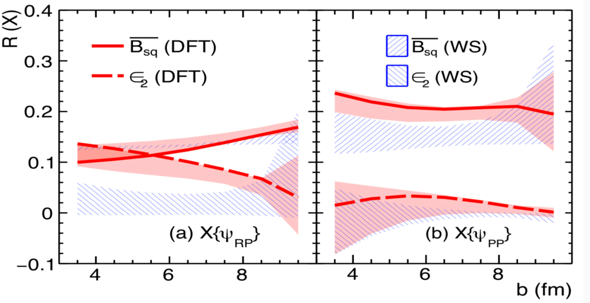
Our calculation is based on the Skyrme-like energy density functional (SLy4-HFB). See X. Wang et al, PRC 94, 034314 (2016) for more details.

Theoretical uncertainties are estimated by using different sets of density functionals (SLy5, Skm*, w/wo HFB), and found to be small

Monte Carlo Glauber model

HJX et al, PRL 121, 022301(2018)

$$R(X) \equiv 2\frac{X_{RuRu} - X_{ZrZr}}{X_{RuRu} + X_{ZrZr}} \quad (8)$$



$$\epsilon_2\{\psi\} = \langle\langle \cos 2(\phi - \psi)\rangle\rangle \quad (9)$$

$$\overline{B_{sq}}\{\psi\} = \langle \int N_{part}^2(\mathbf{r})(eB(r,0)/m_\pi^2)^2 \cos 2(\psi_B - \psi) d\mathbf{r} / \int N_{part}^2(\mathbf{r}) d\mathbf{r}\rangle \quad (10)$$

Reference planes: reaction plane $\psi = \psi_{RP}$ and participant plane $\psi = \psi_{PP}$.

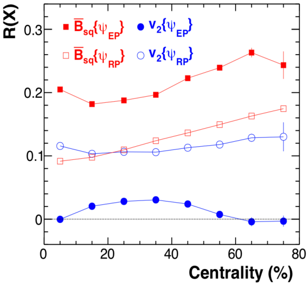
AMPT model

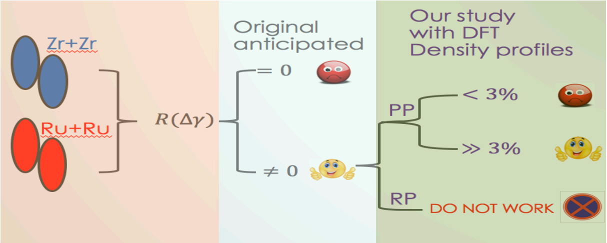
With AMPT simulations,

- $\epsilon_2 \Rightarrow v_2$
- $\psi_{PP} \Rightarrow \psi_{EP}$

general trends similar to MCG results

- Sizeable v_2/ϵ_2 differences, $3\%/4\%$.
- With respect to ψ_{RP}, the premise of isobaric collisions to help identify the CME does NOT HOLD.



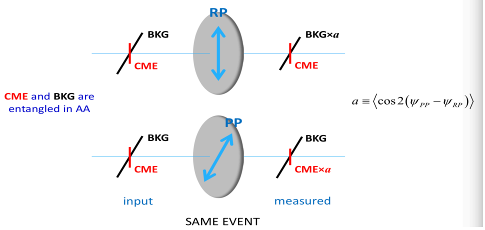


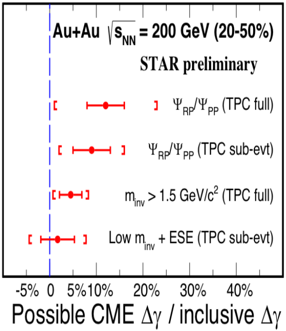
HJX et al, PRL 121, 022301 (2018)

CME- v_2 Filter

We propose a new observable [HJX et al, CPC 42, 084103 (2018)]

$$R^{PP}(X) \equiv 2\frac{X\{\psi_{RP}\} - X\{\psi_{PP}\}}{X\{\psi_{RP}\} + X\{\psi_{PP}\}} \qquad (11)$$





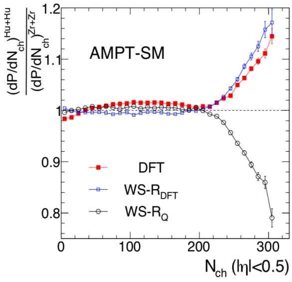
- Opposite behavior for CME and BKG in the same collision event.
- Eliminates large theoretical and experimental uncertainties.

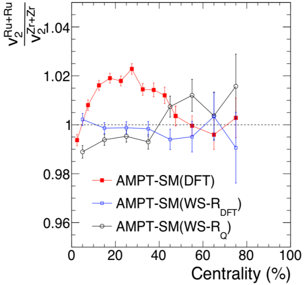
Apply to data (J. Zhao, arXiv:1807.09925, QM2018)

Flow observables

The AMPT prediction for isobaric collision with the parameter[H. Li, et.al, arXiv:1808.06711]

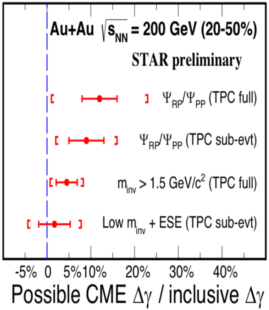
		$^{96}_{44}$Ru charge	$^{96}_{44}$Ru mass	$^{96}_{40}$Zr charge	$^{96}_{40}$Zr mass
WS-R_Q	R_0	5.085 [5]		5.020 [5]	
	$\sqrt{\langle r^2 \rangle}$	4.294		4.248	
DFT	$\sqrt{\langle r^2 \rangle}$	4.327	4.343	4.271	4.366
	$R_0 \equiv 1.183\sqrt{\langle r^2 \rangle}$	5.119	5.138	5.053	5.165





The centrality dependence of the v2 ratio in Ru+Ru to Zr+Zr collisions can decisively determine whether DFT density is more realistic than WS or not. [Hanlin Li's talk]

Summary



Apply to data (J. Zhao, QM2018)

- The isobar (nucleon/charge) density distributions are crucial for the CME search. With the DFT density profiles, we found
  - Sizeable v_2/ϵ_2 differences, reducing the premise of isobar collisions.
  - With respect to ψ_{RP}, isobars do not work.
- We proposed a new method to eliminates the corresponding uncertainties, based on the opposite behavior for CME and BKG in the same collision event,
- The flow observables are able to decisively determine the initial conditions of the isobaric collisions.

Based on:

- HJX, et.al PRL 121, 022301.arXiv:1710.03086.
- HJX, et.al CPC 42, 084103.arXiv:1710.07265.
- H. Li, et.al, arXiv:1808.06711.