Chirality and Magnetic Field

Jinfeng Liao
Plan of This Talk

- Chromodynamics & Chirality
- Magnetic Fields
- Novel Effects
Exciting Progress: See Recent Reviews

Mapping the Phases of Quantum Chromodynamics with Beam Energy Scan

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Chromodynamics: Gluon Topology

Twisting chromo-fields around spacetime boundary

Mobius strip

Gluon topological structures play key role in confinement and chiral symmetry breaking.

Topo-component in QGP [talk by M. Gyulassy]

How to observe their effects experimentally?

\[ Q_w = \frac{1}{32\pi^2} \int d^4x \ (gG_{\mu\nu}^a) \cdot (g\tilde{G}_{\mu\nu}^a) \]
P & CP “Violation” in Big Bang & Little Bang

Rapidly expanding primordial non-Abelian plasma &
Topological transitions of non-Abelian gauge fields
→
Frozen P and CP odd domains

Quoting D. Kharzeev:
Unique/last opportunity in the next couple of years to probe such phenomenon in laboratories and help understand “why are we here”
Spin & Chirality

Dirac fermion in massless limit: chirality well defined

\[ \mathcal{L} \rightarrow \bar{\Psi}_L \gamma^\mu \partial_\mu \Psi_L + \bar{\Psi}_R \gamma^\mu \partial_\mu \Psi_R \]

Axial symmetry

\( \rightarrow \) classical conserved axial current

Specific correlation between spin and momentum!!

A (large) mass term spoils all that:

\[ m\bar{\Psi}\Psi = m \left( \bar{\Psi}_L \Psi_R + \bar{\Psi}_R \Psi_L \right) \]

\[ \partial_\mu J_5^\mu = 2im \bar{\Psi} \gamma^5 \Psi \]

In QCD:

\[ M = m - 2G \langle \bar{\psi}\psi \rangle \]

(Nearly) chiral quarks only upon chiral restoration
Chiral Anomaly

Chiral anomaly is a fundamental aspect of QFT with chiral fermions.

Classical axial symmetry broken at QM level:

$$\partial_\mu J^\mu_5 = C_A \vec{E} \cdot \vec{B}$$

$$dQ_5/dt = \int_x C_A \vec{E} \cdot \vec{B}$$

* $C_A$ is universal anomaly coefficient
* Anomaly is intrinsically QUANTUM effect

Illustration based on LLL

Illustration of chirality generation based Schwinger mechanism

[talk by Shi Pu]
From Gluon Topology to Quark Chirality

QCD anomaly: gluon topology $\leftrightarrow$ chirality imbalance

$$Q_w = \frac{1}{32\pi^2} \int d^4x \left( g G_{\mu \nu}^a \right) \cdot \left( g \tilde{G}_{\mu \nu}^a \right)$$

$$N_5(t \rightarrow +\infty) - N_5(t \rightarrow -\infty) = \frac{g^2}{16\pi^2} \int dt d^3r \ G_{\mu \nu}^a \tilde{G}_{\mu \nu}^a$$

QCD anomaly: gluon topology $\leftrightarrow$ chirality imbalance

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

Net chirality $\leftrightarrow$ topo fluctuations & chiral restoration
A Deep Mathematical Connection

Atiyah-Singer Index Theorem

**Theorem** (M.F. Atiyah and I.M. Singer): Let $P(f) = 0$ be a system of differential equations. Then

$$\text{analytical index}(P) = \text{topological index}(P).$$

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

Net chirality $\leftrightarrow$ topo fluctuations & chiral restoration

Probing topology & chirality is of fundamental interest!
A nearly perfect quantum fluid (in terms of energy-momentum transport)

A quantum spin fluid!
What happens to spin DoF?

Emerging sub-field with many interesting developments!
Playing with Spin: Chirality, Vorticity, M-Field

Interesting interplay —> highly nontrivial phenomena!
QCD Matter under New Extreme Conditions

QCD matter under extreme conditions of chirality, vorticity and magnetic field!
— phase structure & thermal properties
— novel transport processes
Extreme Vorticity & Magnetic Field

\[ L_y = \frac{Ab\sqrt{s}}{2} \sim 10^4 \sim 5 \hbar \]

\[ eB \sim \gamma \frac{Z\alpha_{EM}}{R_A^2} \sim \text{few m}^2/\pi \]

\[ P_z = -\frac{A\sqrt{s_{NN}}}{2} \]

\[ P_z = +\frac{A\sqrt{s_{NN}}}{2} \]

Extremely strong B field

Approximately out-of-plane, but…

Azimuthally Fluctuating Magnetic Field


Two very important points in this paper:
* azimuthal correlation/de-correlation between B field and geometry
* finite size of proton must be taken into account

B field has different angular (de-)correlation with RP and with EP, and is NOT correlated with triangular-EP — a valuable feature for validating B-field signal !!
Time Evolution of B-Field

It is highly uncertain at this point...
It is strongly dependent on medium feedback effect(s)

Compilation from arXiv:1703.08856 [see more refs therein]
Time Evolution of B-Field

Magneto-hydro type of simulations with varied approximations/limitations were done and are progressing well

[talk by D. Kharzeev]

ECHO-QGP


Takeaway Message: B-field lifetime on the order ~ 0.5fm/c at RHIC energy is conceivable!
Time Evolution of B-Field

Theoretical development of magneto-hydro dynamic framework

Second-order equations of motion for dissipative currents

\[ \tau_{\Pi} \dot{\Pi} + \Pi = -\zeta_{\Pi} \theta - \ell_{\Pi\nu} \nabla_{\mu} V_{f}^{\mu} - \tau_{\Pi\nu} V_{f}^{\mu} \dot{u}_{\mu} - \delta_{\Pi\nu} \Pi \theta - \lambda_{\Pi\nu} V_{f}^{\mu} \nabla_{\mu} \alpha_{0} + \lambda_{\Pi\pi} \pi^{\mu\nu} \sigma_{\mu\nu} - \delta_{\Pi\nu} q E_{\mu} V_{f}^{\mu} \]

where

\[ \dot{u}_{\mu} = \frac{1}{\varepsilon_{0} + P_{0}} \left[ \nabla_{\mu} P_{0} - \Delta_{\nu}^{\mu} \partial_{\pi} \pi^{\kappa\nu} - \Pi \dot{u}_{\mu} + \nabla_{\mu} \Pi + \Pi_{\nu} q E_{\nu}^\mu + \epsilon_{\mu\nu\alpha\beta} u_{\alpha} q B_{\beta} V_{f,\nu} \right] \]

Particle diffusion current

\[ \tau_{\nu} \dot{V}_{f}^{(\mu)} + V_{f}^{\mu} = \kappa \nabla_{\mu} \alpha_{0} - \tau_{\nu} V_{f,\nu} \omega_{\mu}^\nu - \delta_{\nu\mu} V_{f}^{\mu} \theta - \ell_{\nu\mu} \nabla_{\nu} \Pi_{\mu} + \ell_{\nu\pi} \Delta_{\nu}^{\mu
u} \nabla_{\lambda} \pi_{\nu}^\lambda + \tau_{\nu\Pi} \nabla_{\mu} \Pi_{\nu} - \tau_{\nu\pi} \pi^{\mu\nu} \Pi_{\nu} - \lambda_{\nu\Pi} \Pi_{\mu} \nabla_{\nu} \alpha_{0} + \lambda_{\nu\pi} \Pi \nabla_{\nu} \alpha_{0} - \lambda_{\nu\pi} \pi^{\mu\nu} \nabla_{\nu} \alpha_{0} + \delta_{\nu\Pi} q E_{\mu}^\nu + \delta_{\nu\pi\nu} q E_{\mu}^\nu \Pi + \delta_{\nu\pi\nu} q E_{\mu}^\nu \Pi + \delta_{\nu\Pi} \epsilon_{\mu\nu\alpha\beta} u_{\alpha} q B_{\beta} V_{f,\nu} \]

Shear-stress tensor

\[ \tau_{\pi\pi}^{(\mu\nu)} + \pi^{\mu\nu} = 2\eta \sigma_{\mu\nu} + \tau_{\pi\pi} \pi_{\lambda}^{(\mu} \omega_{\nu)}^\lambda - \delta_{\pi\nu} \pi^{\mu\nu} \theta - \tau_{\pi\pi} \pi^{\lambda(\mu} \sigma_{\nu)}^\lambda + \lambda_{\Pi\pi} \nabla_{\mu} \alpha_{0} \]

\[ - \tau_{\pi\nu} V_{f}^{(\mu} \dot{V}_{f}^{\nu)} + \ell_{\pi\nu} \nabla_{(\mu} V_{f}^{\nu)} + \lambda_{\pi\nu} V_{f}^{(\mu} \nabla_{\nu)} \alpha_{0} + \delta_{\pi\nu} q E_{(\mu} V_{f}^{\nu)} + \delta_{\pi\nu} \epsilon_{\alpha\beta\rho\sigma} u_{\rho} q B_{\sigma} \Delta_{\alpha\beta}^{\mu \nu} \pi_{\nu}^\kappa \]

Rischke, et al, arXiv:1804.05210;1902.01699; [see more refs therein]
**Time Evolution of B-Field**

*Use phenomenology to constrain B-field lifetime:*

\[ t_B \approx 0.5\text{ to } 1 \text{ fm/c at RHIC} \]

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**STAR talk**

by J. Adams

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**Mueller & Schaefer, arXiv:1806.10907**

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\[ t_B = t_s \left( \frac{B_0}{B(t_s)} \right)^{-1} \approx 1 \text{ fm/c}, \quad (23) \]

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\[ \tilde{t}_B = \frac{A}{\sqrt{s_{NN}}} \quad \text{with} \quad A = 115 \pm 16 \text{ GeV} \cdot \text{fm/c} \]
New Mechanism of B-Field in Charged Swirl

\[ e\vec{B} = \frac{e^2}{4\pi} nA\vec{\omega} \]

Important at low beam energy!

B-Field Induced Effects

Many observable effects could be induced by strong B-field:

- Direct production from strong nuclear fields of vector particles & di-leptons
- Charge-dependent flow

Talk by Zhangbu Xu

Related measurements by STAR, ALICE, ATLAS

Inghirami, et al., arXiv:1908.07605

Talk by D. Kharzeev;
Exp talks by STAR, ALICE
The Chiral Magnetic Effect (CME)

\[ \mathbf{J} = \frac{Q^2}{2\pi^2} \mu_5 \mathbf{B} \]

Electric Current \hspace{5cm} Magnetic Field

Q.M. Transport

Chirality & Anomaly & Topology

The starting point:

Further laying the foundation:

Intuitive Picture of CME

Intuitive understanding of CME:

Magnetic polarization \( \rightarrow \) correlation between micro. SPIN & EXTERNAL FORCE

Chiral imbalance \( \rightarrow \) correlation between directions of SPIN & MOMENTUM

Transport current along magnetic field

\[ \vec{J} = \frac{Q^2}{2\pi^2} \mu_5 \vec{B} \]

Chiral restoration is needed!
From Micro. Laws To Macro. Phenomena

Micro. Laws:
- Symmetry;
- Lagrangian;
- Conservation laws;
- ...

Macro. Phenomena:
- Thermodynamics;
- Transport;
- Fluid Dynamics;
- ...

WHAT ABOU the “SEMI”-SYMMETRY???
i..e ANOMALY?!

Micro quantum anomaly

→ Macro anomalous chiral transport effects!
CME in Other Areas of Physics

CME has provoked significant interests in multiple branches of physics!

Weyl semimetal
(non-degenerated bands)

Dirac semimetal
(doubly degenerated bands)

Chiral qubit based on CME

Kharzeev, Li, arXiv: 1903.07133
Theoretical Framework Developments

Quantum transport including spin-DoF:
- Massless — chiral kinetic theory;
- Finite mass — spin / axial components


- Wigner function formalism
- Worldline formalism
- High density effective theory
- Massive case
- CKT in different dim., in curved space
- Lorentz invariance “issue”
- Kinetic theory on Landau level basis

Beautiful theoretical results that will remain part of our knowledge about many-body theory

Talks by: Jian-hua Gao; Qun Wang; Ziyue Wang; Nora Weickgenannt; Shiyong Li [see also X. Huang’s talk]
Theoretical Framework Developments

From transport to fluid dynamics:
Massless — anomalous fluid dynamics
Finite mass — spin hydrodynamics

**Talks by F. Becattini; W. Florkowski; Shuzhe Shi**

**Anomalous Hydrodynamics**

\[ \partial_\mu J^\mu = C_A E^\mu B_\mu \]  
\[ J^\nu = n u^\mu + \nu^\mu + \nu_\alpha^\mu \]

- **Viscous-Current**
- **Anomalous Current**

\[ \nu^\mu = \frac{\sigma T}{2} \Delta^{\mu \nu} \partial_\nu \left( \frac{\mu}{T} \right) \]  
\[ + \frac{\sigma}{2} E^\mu \]  
\[ \nu^\mu_\alpha = \xi B B^\mu \]  
\[ + \xi \omega^\mu \]

- **Diffusion**
- **Conduction**

**Chiral Kinetic Theory \( \oplus (14+6) \) moment expansion \Rightarrow**

**Viscous-Spin Hydrodynamics (for Massless Fermions)**

\[ J^{\mu}_{\text{eq.}} = \frac{n \pm \nu^\mu}{6} \left( T^2 + \frac{\mu^2}{\pi^2} \right) u^\mu \pm \frac{h}{2} \left( \frac{T^2}{6} + \frac{\mu^2}{2\pi^2} \right) \omega^\mu \]

- **chiral-vortical current**

\[ T^{\mu \nu}_{\text{eq}} = \left( \frac{7\pi^2 T^4}{45} + \frac{2T^2(\mu_3^2 + \mu_4^2)}{3} + \frac{4\mu_3^4 + 6\mu_3^2 \mu_4^2 + \mu_4^4}{3\pi^2} \right) (\omega^{\mu} u^{\nu} - g^{\mu \nu}/4) \]

\[ + \frac{h}{12} \mu_A \left( T^2 + \frac{3\mu_3^2 + \mu_4^2}{\pi^2} \right) (8 \omega^{\mu} u^{\nu} + T \epsilon^{\mu \nu \lambda \sigma} \omega_{\sigma \lambda}) \]

- **feedback to the medium**

**Spin-Hydro with Non-Equilibrium Correction:**

\[ J^\mu_\pm = n u^\mu + \nu^\mu \pm h \left( \frac{3 J_{1,1}^\pm}{2T} - \frac{3 \Pi^2}{2m^2} \right) \omega^\mu \pm \frac{h}{2} \epsilon^{\mu \rho \sigma \lambda} u_\rho \partial_\sigma \left( \frac{G^{(1),\pm}_{4,1}}{D_{5,1}} u_{\pm,\lambda} \right) \]

\[ \pm \frac{h}{2} \epsilon^{\mu \rho \sigma \lambda} u_\rho \sigma_\sigma \xi \left( \frac{J_{2,2}^\pm}{2J_{4,2}^\pm} \pi_\lambda \right) \pm \frac{h}{2} \omega_\lambda \left( \frac{J_{2,2}^\pm}{2J_{4,2}^\pm} \pi^\lambda \right) \]

Son, Surowka; ……

**From talk by Shuzhe Shi**
Chiral Magnetic Effect: Exp. Status

Charged balance function: supportive for nonzero signal!

Extraction based on different angle correlation between B and EP/RP
the combined result is $(8 \pm 4 \pm 8)\%$

[R-correlator results support nonzero signal by R. Lacey et al (shown at QM2018)]

Talks by M. Lisa; Z. Xu; J. Zhao; Y. Lin
My take on latest RHIC & LHC measurements:
— improving methods for background removal/suppression
— crucial to understand/reconcile different observables
— current RHIC results are hard to explain as pure background
— RHIC vs LHC important test for theoretical interpretations
— system scan would be useful too
— putting upper limit with confidence level would be very useful
Modeling CME: Integration into Bulk Evolution

* Approach based on fluid dynamics (AVFD)
  — our focus here

* Approach based on transport models.
  — AMPT based  
    (Guoliang Ma, Yugang Ma, and collaborators)
  — Chiral kinetic transport based  
    (Che-ming Ko and collaborators)
Transport Modeling Results

Posters by G.L. Ma (CH-15); L. Huang (QA-5); Y. Chen (CH-8)

Isobar expectations

Study of observable sensitivity

Ref:
Beam Energy Scan Theory (BEST) Collaboration

CME Working Group

- Initial conditions
- Dynamical magnetic fields
- Non-equilibrium anomalous transport coefficient
- Fluid dynamics framework with anomalous current
- Quantification of both signal and backgrounds
In the glasma framework:
* Computed topological Chern-Simons number evolution
* Extracted significant non-equilibrium sphaleron rate
* Anomalous transport during the pre-thermal stage

Mace, Schtliting, Venugopalan, PRD2016; Muller, Schtliting, Sharma, PRL2016; Mace, Muller, Schtliting, Sharma, PRD2017 & arXiv:1910.01654
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!

The Charge Separation from AVFD

Chirality imbalance $\rightarrow$ R/L asymmetry $\rightarrow$ charge asymmetry

$B$ field $\otimes \mu_5 \Rightarrow$ current $\Rightarrow$ dipole (charge separation)

$$\frac{dN_{\pm}}{d\phi} \propto 1 + 2a_{1\pm} \sin(\phi - \psi_{RP}) + \ldots$$

$$H_{SS} - H_{OS} \leftrightarrow 2(a_1)^2$$
CME is quantitatively viable for describing relevant experimental observable.

Axial Charge Dynamics within AVFD

Topo-fluctuations “along the way” cause dissipation of axial charge

Iatrakis, Lin, Yin, PRL2015; JHEP2015; Hou, Lin, PRD2018

We recently implemented this into AVFD.

\[
\begin{align*}
\partial_t n_5 + \nabla \cdot j_5 &= -2q, \\
j_5 &= -D \nabla n_5 + \xi, \quad \text{thermal fluctuation} \\
q &= \frac{n_5}{2\tau_{CS}} + \xi_q, \quad \text{topological fluctuation}
\end{align*}
\]

dissipation

\[
\partial_t N_5 = -\frac{N_5}{\tau_{CS}}
\]

\[
\langle \xi_q(t, x)\xi_q(t', x') \rangle = \Gamma_{CS} \delta(t - t') \delta^3(x - x'),
\]

\[
\langle \xi_i(t, x)\xi_j(t', x') \rangle = 2\sigma T \delta_{ij} \delta(t - t') \delta^3(x - x'),
\]

\[
\langle \xi_i(t, x)\xi_q(t', x') \rangle = 0.
\]

Einstein relations

\[
\sigma = \chi D, \quad \tau_{CS} = \frac{\chi T}{2\Gamma_{CS}}
\]

1st attempt to quantitatively characterize topological charge in HIC!
Include EBE fluctuations:

- Initial Conditions
- Statistic @ Freeze-out
- Hadron Cascade (~ half of all bkg.)

Important for better understanding:
* Interplay between signal and BKG;
* Experimental analysis methods

Young AVFD warriors: Shuzhe Shi, Hui Zhang, Anping Hui
EBE-AVFD-LCC

— EBE-AVFD-LCC is the latest version for quantitative study of CME signal and backgrounds together.
— LCC implementation based on Schenke, Shen, Tribedy, PRC2019
— It has now been widely used for studying observables.
— A package has been shared for STAR and now widely used for understanding features of observables.

CME (0->weak->strong)
LCC (0->weak->strong)
Hadron cascade (on/off)

— A public version (as BEST effort) will be available in the future.
— Calibration with AuAu data: LCC ~ hadron cascades
— Near Future: use particlization as the best way to quantify LCC

Koch, Oliinychenko, PRL2019
A Decisive Experiment: Isobaric Collisions

New opportunity of potential discovery: Isobaric Collision @ RHIC

Key idea: contrasting two systems with identical bulk, varied magnetic fields.

After complete removal of backgrounds with isobar subtraction: Expect all unique features of a PURE CME signal!!

Signatures of Chiral Magnetic Effect in the Collisions of Isobars

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(Dated: October 31, 2019)

Quantum anomaly is a fundamental feature of chiral fermions. In chiral materials the microscopic anomaly leads to nontrivial macroscopic transport processes such as the Chiral Magnetic Effect (CME), which has been in the spotlight lately across several branches of physics. The quark-gluon plasma (QGP) created in relativistic nuclear collisions provides the unique example of a chiral material consisting of intrinsically relativistic chiral fermions. Potential discovery of CME in QGP is of utmost significance and extensive experimental searches have been carried out over the past decade. A decisive new collider experiment, dedicated for possibly detecting CME in the collisions of isobars, has been performed in 2018 with analysis underway. In this paper, we develop the necessary and state-of-the-art theoretical tool for describing CME phenomenon in these collisions and propose an appropriate isobar subtraction strategy for the best background removal. Based on that, we make quantitative predictions for signatures of CME in the collisions of isobars.

EBE-AVFD; Isobar Subtraction Strategy; Predictions for various observables

arXiv: 1910.14010
CME: Understanding Backgrounds

Key for success: identical bulk between RuRu & ZrZr. There may be worries owing to uncertainty in nuclear geometry.


Strategies to overcome the issue:
— apply joint multiplicity—ellipticity cut for event samples
— stay at the relatively peripheral region

arXiv: 1910.14010
Use gamma and delta together to remove uncertainty! [unique feature of pure signal!]

This ratio is independent of initial axial charge! [unique feature of pure signal!]

\[ \langle \cos (2\Psi_B - 2\Psi_{EP}) \rangle \simeq -0.46 \]
AVFD Predictions for Isobars


\[ \gamma_{\text{Ru-Zr}} \bigg|_{RP} \approx (1.94 \pm 0.72) \times 10^{-3} \times \left( \frac{n_5}{s} \right)^2 \]

\[ \delta_{\text{Ru-Zr}} \bigg|_{RP} \approx -(2.17 \pm 0.72) \times 10^{-3} \times \left( \frac{n_5}{s} \right)^2 \]

Use gamma and delta together to remove uncertainty!
[unique feature of pure signal!]

This ratio is independent of initial axial charge!
[unique feature of pure signal!]

\[ \zeta_{\text{isobar}} = \frac{\gamma_{\text{Ru-Zr}}}{\delta_{\text{Ru-Zr}}} \bigg|_{RP} \approx -(0.90 \pm 0.45) \]

\[ \langle \cos(2\Psi_B - 2\Psi_{RP}) \rangle \approx -0.95 \]
AVFD Predictions for Isobars

Unique feature of pure signal: independent of event shape [except mild complication of EP resolution]

AVFD Predictions for Isobars


Look for absolute difference between isobars (after joint-cut)!
Look for R-correlator shape!
Summary/Outlook

Fundamentally important physics with exciting progress on many fronts!

Axial-topo-dynamics; Non-eq CME

Chromodynamics & Chirality

Magnetic Fields

Dynamical B-field Evolution; CMHD

BEST Modeling; Observables/BKG

Exciting time(~2020):
Let us cross our fingers and wait for the isobars!
Backup Slides
AVFD Framework

Note: bulk properties fully data-validated

[arXiv:1611.04586; arXiv:1711.02496]
AVFD provides the tool to quantify various features of CME signals.

One Example: Flavor Dependence

Kaons are sensitive to anomalous transport of s-quarks. Theory analysis (S. Lin, D. Hou, …): $u, d \sim s$
Implementing Local Charge Conservation (LCC)

To quantify background correlations in state-of-art hydro framework

[Schenke, Shen, Tribedy, PRC2019]

New development of particlization: the best way to quantify LCC

[Koch, Oliinychenko, PRL2019]
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!!!
Exp. Search for CME

New observables

Lacey, Magdy, et al

A. Tang
Demonstrating the AVFD

Upper: NO magnetic field
Lower: with B field (along y+ direction)
Demonstrating the AVFD

Upper: Left-Handed (LH), with B field (along y+ direction)
Lower: Right-Handed (RH), with B field (along y+ direction)
Isobars: Subtraction Strategy

Insight from initial conditions: joint cut on Multiplicity-Eccentricity

Conventional centrality selection:
Risk of inadequate background removal;
Depending on signal/bkg ratio.
Joint multiplicity-geometry cut:
Vanishing difference in bulk properties,
Sizable difference in magnetic fields!!!
AVFD Predictions for Isobars

10 million events for each system
40 $\sim$ 50% centrality range

$65 \leq N_{ch}^{|y|<1} \leq 96$ and $0.05 < v_2 < 0.25$

After selection: about 44% events are left.

Post check: isobars having identical multiplicity & $v_2$

$$\langle N_{ch} \rangle = 80.4 \pm 8.5 \quad \langle v_2 \rangle = 0.1132 \pm 0.046$$

Look for absolute difference between isobars (after joint-cut)!
Look for consistency across multiple observables!
Look for unique features that are only true for a PURE SIGNAL!