THE SEARCH FOR QCD SPHALERONS AND THE CHIRAL MAGNETIC EFFECT IN HEAVY-ION COLLISIONS WITH ALICE
OUTLINE

- Introduction
- Chiral Magnetic Effect (CME)
- CME with Event-Shape Engineering
- Charge-dependent directed flow
- Outlook

what are we talking about?
how do we measure it?
constraining signal/background
constraining the magnetic field
what’s next?
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SPHALERONS AND INSTANTONS

- non-Abelian YM theory $\rightarrow$ several vacua with different topology ($N_{cs}$)
- transitions are allowed: sphalerons and instantons
  - strictly non-perturbative phenomenon
  - predicted by SM, not yet observed
  - associated to quantum anomalies
    $\rightarrow$ non-conservation of quantum numbers

G. ’t Hooft, PRL 37, 8 (1976)
L. McLerran et al., PRD 42, 171 (1990)
...
for a given energy barrier $E_{\text{sph}} \sim 1/\alpha$

- $E < E_{\text{sph}}$: instantons (tunneling) \quad \sigma \propto \exp(-2\pi E_{\text{sph}}) \\
- $E > E_{\text{sph}}$: sphalerons (thermal) \quad \sigma \propto \exp(-E_{\text{sph}}/kT)$
## QCD VS EW

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<tr>
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- hard to estimate, potentially accessible
- estimates exist, hard to access

heavy-ion collisions: QCD system with $kT > \Lambda_{QCD}$
HEAVY-ION PHYSICS

Heavy-Ion Physics: exploring QCD at high temperatures and/or densities

Quark-Gluon Plasma: \( T > 150 \) MeV, \( \varepsilon > 0.2 \) GeV/fm\(^3\)

arXiv:1510.04200
HEAVY-ION COLLISIONS

Different stages in a Heavy-Ion collision
MAGNETIC FIELD

fast-moving non-colliding protons  \[ \text{strong (} \sim 10^{15} \text{T)} \text{ magnetic field} \]
CHIRAL MAGNETIC EFFECT

QCD sphalerons → chiral imbalance: $\mu_5 = n_L - n_R \neq 0$

strong magnetic field + chiral imbalance → charge separation along B

D. Kharzeev, PLB 633, 260 (2006)
D. Kharzeev et al, NPA 797, 67 (2007)
D. Kharzeev et al, NPA 803, 227 (2008)
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UNKOWNES

- Evolution of the magnetic field
  
  *How long does it last?*
  
  *What is the conductivity of the system?*

- Competing sources of chiral imbalance
  
  *Local axial currents (e.g. due to CSE)?*

- Pre-equilibrium dynamics
  
  *Sphalerons in vacuum, Glasma or QGP?*

- Collective dynamics and hadronization
  
  *Electric charge conservation (local in phase-space)?*
  
  *Effects of the anisotropic expansion of the medium?*

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U. Gursoy et al., PRC 89, 054905 (2014)
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M. Mace et al., PRD 93, 074036 (2016)
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C. Shen, iEBE-VISHNU

QGP, hadrons
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CHIRAL MAGNETIC EFFECT

the experimental observable: charge separation across the reaction plane
OBSERVABLES

CME: charge-dependent out-of-plane directed flow

\[ \frac{dN_{\pm}}{d\phi} \propto 1 + 2a_{\pm} \sin(\phi_{\pm} - \Psi_{\text{RP}}) \]

It can be measured with charge-dependent 2- and 3-particle correlators:

\[ \delta_{+, -} = \langle \cos(\phi_{+} - \phi_{-}) \rangle \sim \langle a_{+}a_{-} \rangle \]
\[ \gamma_{+, -} = \langle \cos(\phi_{+} + \phi_{-} - \Psi_{\text{RP}}) \rangle \sim -\langle a_{+}a_{-} \rangle \]

S. Voloshin, PRC 70 (2004) 057901

the sign of \( a_{\pm} \) changes event-by-event, but is always opposite for opposite charges

\[ \gamma_{a,b} < 0 \text{ for same charges } (\pm, \pm) \text{ and } \gamma_{a,b} > 0 \text{ for opposite charges } (\pm, \mp) \]

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- for \(\delta_{ab}\) is the opposite
CME CORRELATORS

- significant difference in $\gamma_{a,b}$ same vs opp.
- sign of the difference correct, but the average is not 0
  background largely present!

ALICE, PRL 110 (2013) 012301
BACKGROUND

Main sources:

- transverse momentum conservation (TMC)
- flow fluctuations
- local charge conservation (LCC)
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Main sources:

- transverse momentum conservation (TMC)
- flow fluctuations
- local charge conservation (LCC)

charge-independent: cancel in opp.- vs same-charge difference:

\[
\Delta \delta_{a,b} \equiv \frac{1}{2} (\delta_{\pm,\mp} - \delta_{\pm,\pm})
\]

\[
\Delta \gamma_{a,b} \equiv \frac{1}{2} (\gamma_{\pm,\mp} - \gamma_{\pm,\pm})
\]
BACKGROUND

Main sources:

- transverse momentum conservation (TMC)
- flow fluctuations
- local charge conservation (LCC)

To be understood!
Not correctly reproduced by existing MC (Pythia, AMPT, HIJING…)

E.g. Balance Functions:

\[
c_{(+,-)} = \frac{1}{N_{\text{trig},+}} \frac{d^2N_{\text{assoc},-}}{d\Delta\eta d\Delta\varphi}
\]

\[
B(\Delta\eta, \Delta\varphi) = \frac{1}{2} \left[ c_{(+,-)} + c_{(-,+)} - c_{(+,+)} - c_{(-,-)} \right]
\]

ALICE, EPJ C 76 (2016) 86
CMS compared Pb-Pb and p-Pb:

- expected in p-Pb collisions: small magnetic field, uncorrelated with $\psi_{RP}$
- at comparable system size ($\sim$charged track multiplicity), results are consistent: no CME?

CMS, PRL 118, 122301 (2017)
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EVENT SHAPE ENGINEERING

Event Shape Engineering (ESE) (J. Schukraft et al., arXiv:1208.4563):

classify events according to the strength of elliptic flow ($v_2$)

$$Q_2 = \sum_{j=1}^{M} e^{2i\varphi_j} \quad \rightarrow \quad q_2 = \frac{|Q_2|}{\sqrt{M}}$$

- large $q_2$
  - 90-100%
  - $v_2 > \langle v_2 \rangle$

- small $q_2$
  - 0-10%
  - $v_2 < \langle v_2 \rangle$
CME CORRELATORS

- Reaction plane angle \((\psi_{RP})\) not accessible experimentally
- Main axis along which \(v_2\) develops \((\psi_2)\) is used instead

\[
Q_2 = \sum_{j=1}^{M} e^{2i\phi_j}
\]

\[
\Psi_2 = \frac{1}{2} \text{atan2}(\text{Im} \, Q_2, \text{Re} \, Q_2)
\]

\[
\gamma_{a,b} = \langle \cos(\phi_a + \phi_b - 2\Psi_2) \rangle
\]

adapted from S. Voloshin et al., PLB 659 537-541 (2008)
why studying CME correlators with ESE?

LCC background is modulated by $v_2$:

- charge-independent:
  stronger $v_2$ $\rightarrow$ stronger boost $\rightarrow$
  stronger correlation in phase-space

- charge-dependent:
  balancing charge more likely in-plane ($\psi_2$)

Simple expectation: background in $\Delta\gamma_{a,b}$ scales linearly with $v_2$
CME CORRELATORS WITH ESE

Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV
CME correlators ($\delta$, $\gamma$) vs $v_2$

Observations:

- $\Delta \gamma_{ab}$ depends linearly on $v_2$
- $\Delta \gamma_{ab}$ scaled by multiplicity ($dN/d\eta$) falls on a common line

Higher mult. dilutes LCC?

Qualitatively consistent with background-only hypothesis!

ALICE, arXiv:1709.04723
CMS reported similar observations in Pb-Pb $\sqrt{s_{NN}} = 5.02$ TeV

- Assumption: CME is $v_2$-independent, background is not

- Upper limit extracted from intercept $p_0$ in the fit

$$\frac{\Delta \gamma_{a,b}}{\Delta \delta_{a,b}} = p_1 v_2 - p_0$$

CME signal 3.8% of $\Delta \gamma_{ab}$ at 95% C.L. in centrality 30-70%
alignment between B and $\psi_2$
depends linearly on $v_2$ around $\langle v_2 \rangle$

signal in $\Delta \gamma_{ab} \propto |B|^2 \cos^2(\psi_B-\psi_2) \propto v_2$
Possible to extract a slope $p_1$ from a fit $F(v_2) = p_0 \left( 1 + p_1 \frac{v_2 - \langle v_2 \rangle}{v_2} \right)$.

Both for measured $\Delta \gamma_{ab} (p_1^{\text{data}})$ and simulated $|B|^2 \cos 2(\psi_B - \psi_2) (p_1^{\text{MC}})$.

Some differences observed between different initial-state models.
UPPER LIMIT (2)

CME signal fraction $S/(S+B)$ computed as

$$f_{\text{CME}} \times p_{1}^{\text{MC}} + (1 - f_{\text{CME}}) \times 1 = p_{1}^{\text{data}}$$

CME signal 26-33% of $\Delta \gamma_{ab}$ at 95% C.L. in centrality 10-50%

assumptions on signal and background scaling with $v_{2}$:

- signal slope as $|B|^2 \cos^2(\psi_B - \psi_2)$
- background slope is unity
CONCLUSIONS

- First measurements on CME correlators with Event-Shape-Engineering in Pb-Pb collisions at the LHC by ALICE and CMS
- Results are compatible with background-only hypothesis
- Upper limits (3.8% CMS, 26-33% ALICE) strongly depend on assumptions on signal and background: more studies are needed!
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MAGNETIC-INDUCED CHARGED CURRENTS

The proposal (U. Gursoy et al., PRC 89, 054905 (2014)):

- measure a simpler observable (not related to chiral imbalance), use it to calibrate the strength and lifetime of the magnetic field

Where does it come from?

- electric field induced by decreasing $B$ (Faraday effect)
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ELLIPITIC VS DIRECTED FLOW

elliptic flow: in-plane vs out-of-plane

directed flow: same or opposite direction w.r.t. the impact parameter
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\[
\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}
\]
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\[ \mathbf{F} = q \mathbf{v} \times \mathbf{B} \]
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**competing effects!**

adapted from U. Gursoy et al., PRC 89, 054905 (2014)
CHARGE-DEPENDENT DIRECTED FLOW

• the signal: $\Delta v_1^{\text{odd}} = v_1^{\text{odd}(+)} - v_1^{\text{odd}(-)}$

• predictions for Pb-Pb @ 2.76 TeV: $10^{-5}$ or less

U. Gursoy et al., PRC 89, 054905 (2014)
DIRECTED FLOW W.R.T. SPECTATORS

How do we measure directed flow?

- as a proxy for reaction plane, we use the direction of the spectator neutrons "spectator plane"

- N.B. the convention is to choose $v_1 > 0$ for spectators at $\eta > 0$
SPECTATOR PLANE RECONSTRUCTION

Zero-Degree Calorimeters (ZDC), energy of spectator neutrons

- located at beam rapidity: $|\eta| > 8.8$
- hadronic “spaghetti” calorimeters: tungsten + quartz fibres
- fibres divided into 4 segments going to 4 PMTs (+ 1 common)

Spectator plane from

$$\vec{Q}_{A,C} = \sum_{i=1}^{4} \vec{x}_i / \sum_{i=1}^{4}$$

$$\Psi_{A,C} = \text{atan2}(Q_y, Q_x)$$

$x_i$ coordinates of the tower centres (cm),

$\alpha = 0.395$, ZDC-A
SPECTATOR PLANE RECONSTRUCTION

Zero-Degree Calorimeters (ZDC), energy of spectator neutrons

• located at beam rapidity: $|\eta| > 8.8$
• hadronic "spaghetti" calorimeters: tungsten + quartz fibres
• fibres divided into 4 segments going to 4 PMTs (+ 1 common)

Spectator plane from the signal ($E_i$) into the 4 ZDC segments:

$$\vec{Q}_{A,C} = \sum_{i=1}^{4} \vec{x}_i \frac{E_i^\alpha}{\sum_{i=1}^{4} E_i^\alpha}$$

$$\Psi_{A,C} = \text{atan2}(Q_{A,Cy}, Q_{A,Cx})$$

$x_i$ coordinates of tower centre positions (cm),
$\alpha = 0.395$, ZDC-A: $\eta > 8.8$, ZDC-C: $\eta < -8.8$
MEASURING DIRECTED FLOW

Directed flow measured with the scalar product method:

\[ v_1\{\Psi_{A,C}\} = \frac{\langle \vec{u} \cdot \vec{Q}_{A,C} \rangle}{\sqrt{\langle \vec{Q}_A \cdot \vec{Q}_C \rangle}} \]

\[ \vec{u} = \left( \frac{\sum_{i=1}^{N_{\text{trk}}} w_i \cos \varphi}{\sum_{i=1}^{N_{\text{trk}}} w_i}, \frac{\sum_{i=1}^{N_{\text{trk}}} w_i \sin \varphi}{\sum_{i=1}^{N_{\text{trk}}} w_i} \right) \]

Track weights \( w_i(\varphi, \eta, p_T) \) for non-uniform acceptance and reconstruction efficiency

then separate rapidity-odd component:

\[ v_1^{\text{odd}} = \frac{1}{2} \left( v_1\{\Psi_A\} - v_1\{\Psi_C\} \right) \]

separately for pos. and neg. charged tracks: \( v_1^{\text{odd}}(\pm) \)
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separately for pos. and neg. charged tracks:

\[ v_{1}^{\text{odd}}(\pm) \]
RESULTS

hint of a charge difference: $\Delta v_1^{\text{odd}} = v_1^{\text{odd}(+)} - v_1^{\text{odd}(-)} \neq 0$

ALICE Preliminary

Pb-Pb $\sqrt{s_{NN}} = 5.02$ TeV 5-40% 2.8 $\mu$b$^{-1}$

$p_T > 0.2$ GeV/c

bars: stat. err.
boxes (filled/empty): syst. err. (corr./uncorr.)
RESULTS

2.6σ significance of a non-zero slope in $\Delta v_1^{oom}$

Compared to predictions at 2.76 TeV and similar $<p_T>$:

- 1-2 orders of magnitude bigger: long-lived magnetic field? early thermalisation?
- opposite sign: dominance of Hall effect?
RESULTS

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fit with a function: $v_1 = k \cdot \eta$

$k = 1.68 \pm 0.49 \text{ (stat)} \pm 0.41 \text{ (syst)} \cdot 10^{-4}$
CONCLUSIONS

• Rapidity-odd directed flow ($v_1^{\text{odd}}$) with respect to the spectator plane measured for the first time in Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV

• Hint of a charge-dependent difference $\Delta v_1^{\text{odd}}$ of $O(10^{-4})$
  • can be caused by early-time magnetic field

• results at 5.02 TeV compared to predictions for 2.76 TeV: 1-2 orders of magnitude bigger, opposite sign → challenge predictions

• More statistics needed to confirm or disprove it
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OUTLOOK: WHAT’S NEXT?

• Understand the background: tune and/or improve existing MC generators to match data on charge-dependent angular correlations
  • balance functions
  • higher harmonic correlators (background-only)

\[ \langle \cos(m\phi_1 + n\phi_2 - (m + n)\phi_3) \rangle \]

• Understand the signal
  • dynamics of chiral charges in the medium: magneto-hydrodynamics
  • constrain the magnetic field: charge-dep. \( v_1 \), global lambda polarisation

• Try different experimental approaches
  • isobaric collisions at RHIC: dedicated run in 2018
  • searches for new phenomena: Chiral Magnetic Wave, ecc.
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J. Mlynarz, QM’12
OUTLOOK: WHAT'S NEXT?

- Understand the background: tune and/or improve existing MC generators to match data on charge-dependent angular correlations
- balance functions
- higher harmonic correlators (without CME contribution)
- Understand the signal
  - chirality in the medium: anomalous-magneto-hydrodynamics
  - constrain the magnetic field: charge-dep. $v_1$, global lambda polarisation
- Try different experimental approaches
  - isobaric collisions at RHIC: dedicated run in 2018
  - searches for new phenomena: Chiral Magnetic Wave, ecc.

Y. Jiang et al., arXiv:1611.04586

\[ \langle \cos(m\phi_1 + n\phi_2 - (m + n)\phi_3) \rangle \]

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  - constrain the magnetic field: charge-dep. $v_1$, global lambda polarisation.
- Try different experimental approaches:
  - searches for new phenomena: Chiral Magnetic Wave, ecc.

V. Skokov et al., arXiv:1608.00982

$96_{40}^{40}Zr + 96_{40}^{40}Zr \text{ vs. } 96_{44}^{44}Ru + 96_{44}^{44}Ru$

Projection with 1.2B events:
- case 1
- case 2

Rel. diff. in $\Delta y (RuRu-ZZ)$ w.r.t. $e^2$

$S_{NN} = 200 \text{ GeV}$

Background level (%) vs. Significance

20 - 60%
thank you!
Blast-Wave models incorporating LCC show that in a background-only scenario $\Delta \gamma_{a,b}$ scales linearly with $v_2$
DIRECTED FLOW

directed flow ($v_1$) usually decomposed into a rapidity-odd and rapidity-even component:

- $v_1^{\text{odd}}$: compressibility $\rightarrow$ initial tilt / rotation of the system
- $v_1^{\text{even}}$: initial state fluctuations (dipole-like)
DIRECTED FLOW

directed flow \((v_1)\) usually decomposed into a rapidity-odd and rapidity-even component:

- \(v_1^{\text{odd}}\): compressibility \(\rightarrow\) initial tilt / rotation of the system
- \(v_1^{\text{even}}\): initial state fluctuations (dipole-like)

P. Bosek et al., PRC 81 054902 (2010)
directed flow \((v_1)\) usually decomposed into a rapidity-odd and rapidity-even component:

- \(v_1^{\text{odd}}\): compressibility \(\rightarrow\) initial tilt / rotation of the system
- \(v_1^{\text{even}}\): initial state fluctuations (dipole-like)

\[
\rho \frac{d\vec{v}}{dt} = -\vec{\nabla} P
\]
Blast-Wave models incorporating LCC are able to explain the entire difference in $\Delta \delta_{ab}$ → consistent with NO CME signal …

Y. Hori et al., arXiv:1208.0603
... but fail to reproduce all correlators simultaneously!  
background remains largely unconstrained
ENERGY DEPENDENCE

STAR, PRL 113, 052302 (2014)

- RHIC Beam Energy Scan (Au+Au from 200 to 7.7 GeV)
  - $\Delta\gamma_{ab}$ decreases with energy: qualitative consistent with signal expectations
  - not clear how the background depends on collision energy
Several other phenomena predicted from the interplay of chiral imbalance + magnetic fields and/or angular momentum of the system

- Chiral Separation Effect (CSE)
- Chiral Electric Separation Effect (CESE)
- Chiral Vortical Effect (CVE)
- Chiral Magnetic Wave (CMW)
- Chiral Vortical Wave (CVW)

D. E. Kharzeev, Prog. Part. Nucl. Phys. 75, 133 (2014)
J. Liao, Pramana 84, no. 5, 901 (2015)
X. G. Huang, arXiv:1509.04073

D.E. Kharzeev et al., arXiv:1511.04050
theory uncertainties: QGP conductivity

- QGP conductivity $\sigma = 0.023$ fm$^{-1}$ taken from lattice calculations
- small effect on $dv_1/dY$ at mid-rapidity ($|Y|<1$)

from E. Marcus, "Magnetohydrodynamics at Heavy Ion Collisions", Bachelor thesis (Utrecht University)
theory uncertainties: drag coeff.

- drag coefficient $\mu m$ taken from heavy quarks in $N = 4$ SYM
- $\nu_1$ extremely sensitive around $\langle \mu m \rangle$

from E. Marcus, “Magnetohydrodynamics at Heavy Ion Collisions”, Bachelor thesis (Utrecht University)
predictions at LHC: protons

FIG. 6: $v_1$ for protons (solid curves) and antiprotons (dashed curves) in our calculation with the same parameters as in Fig. 4, namely parameters chosen with 20-30% centrality heavy ion collisions at the LHC in mind. We plot $v_1$ as a function of momentum space rapidity $Y$ at $p_T = 0.5$ (blue), 1 (red) and 2 GeV (black).

arXiv:1401.3805
predictions at RHIC

FIG. 7: $v_1$ for positively (solid curves) and negatively (dashed curves) charged pions with parameters chosen as for a 20-30% centrality heavy ion collision at RHIC. We plot $v_1$ as a function of momentum space rapidity $Y$ at $p_T = 0.25$ (green), 0.5 (blue) 1 (red) and 2 GeV (black). Antiprotons are not displayed in this figure for visual clarity.

FIG. 8: $v_1$ for protons with parameters chosen as in Fig. 7, so as to yield estimates for RHIC. We plot $v_1$ as a function of $Y$ at $p_T = 0.5$ (blue), 1 (red) and 2 GeV (black). Anti-protons are not displayed in this figure for visual clarity.

arXiv:1401.3805
$v_1^{\text{odd}}$ from BES I (STAR)
$\Delta v_1^{\text{odd}}$ in Cu-Au @ 200 GeV (STAR)

STAR, PRL 118 (2017) 012301
detectors and data samples

- Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV, $55 \cdot 10^6$ minimum bias events
- Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV, $14 \cdot 10^6$ minimum bias events
- track selection: $|\eta| < 0.8$, $p_T > 0.2$ GeV/c

- Time-Projection Chamber tracking, vertexing
- Inner Tracking System tracking vertexing
- V0 trigger, centrality
- Zero Degree Calorimeters spectator plane
CHIRAL MAGNETIC WAVE

Electric charge separation (CME) is coupled to chiral charge separation (CSE); the two, combined, give rise to what is called Chiral Magnetic Wave (CMW)
CHIRAL MAGNETIC WAVE

the experimental observable: charge-dependent elliptic flow
CMW MEASUREMENTS

Measured with the 3-particle correlator:

\[ \langle \cos[n(\phi_1 - \Psi_n)]c_3 \rangle - \langle \cos[n(\phi_1 - \Psi_n)] \rangle \langle c_3 \rangle \]

S. Voloshin, R. Belmont
arXiv:1408.0714

allows more differential studies \(\rightarrow\) more discriminating power