Measurements of Chiral Magnetic Effect in Pb-Pb collisions with ALICE

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Introduction: Chiral Magnetic Effect (CME) in heavy-ion collisions

- Charged spectators create a strong (but short lived) magnetic field ($\vec{B}$), $\sim 10^{18}$ Gauss.
- The spins (momentum) of the right- and left-handed quarks are aligned along the $\vec{B}$ direction.
- In the presence of $\vec{B}$, net current in the hot and dense medium created in a heavy-ion collision becomes non-zero.

→ Charge separation in the QGP medium.

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Introduction: Observable for CME

Azimuthal distribution of produced particles can be described by a Fourier series,
\[ \frac{dN}{d\phi} \sim 1 + 2\Sigma (v_n \cos[n(\phi - \Psi_n)] + a_n \sin[n(\phi - \Psi_n)]) \]
where CME contribution is quantified by the sine terms with coefficients \( a_n \). \(^2\)

The leading term (i.e. \( a_1 \)) quantifies the magnitude of the separation w.r.t the symmetry plane. Higher harmonics (i.e. \( a_n \), with \( n > 1 \)) quantify the shape in azimuth.

CME Observables:

- \( \delta_{11} = \cos(\phi_\alpha - \phi_\beta) \sim \langle BG_{RP} + BG_{RPindependent} + a_1 a_1 \rangle \)
- \( \gamma_{112} = \cos(\phi_\alpha + \phi_\beta - 2\Psi_2) \sim \langle \delta BG_{RP} - a_1 a_1 \rangle , \)
  (where, \( \delta BG_{RP} = BG_{in,plane} - BG_{out,plane} \) and \( \alpha, \beta = \pm \))

The observable \( \delta_{11} \) is sensitive to correlations independent of symmetry plane (such as non-flow, resonances, jets).

\( \gamma_{112} \) is free from correlations independent of symmetry plane, however is sensitive to symmetry plane dependent backgrounds (such as \( v_1^2 \) fluctuations, flowing clusters, \( v_2 \)).

The same-sign (same) and opposite-sign (opp.) pairs show charge dependence.

Magnitude of $\gamma_{112}$ is of the same order at RHIC and LHC.

Caveat: $\delta_{11}$ contains background not related to CME, such as Local Charge Conservation (LCC) $\Rightarrow$ can be studied with the Balance Function

* See Balance Function talk by Jinjin Pan[4].

Recent results from CMS: smaller system, bigger challenge

- **Expectations:**
  - p-Pb system has very different magnetic field profile and size of the matter produce in the overlap zone.
  - Smaller systems such as pp and p–Pb can help to constrain background contributions, such as from LCC.

- **CMS Observation:**
  - $\gamma_{112}$ has similar magnitude in p-Pb and Pb-Pb$^5$.
  - No CME signal or the background overwhelms the signal?

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Motivation for further CME analysis in ALICE

- Particle species dependence:
  - 3-particle correlator $\gamma_{112}$, is measured at RHIC and LHC for inclusive charged pairs.
  - 3-particle correlator with one or two Identified particles $\Rightarrow$ flavour and mass dependence of CME.
  - How does the background to $\gamma_{112}$ in Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV compare to the same at $\sqrt{s_{NN}} = 2.76$ TeV?

- Constrain the background:
  - ALICE recently studied Event Shape Engineering method to constrain the background which scales with flow (e.g. $v_2$).
  - The mixed and higher harmonic 3-particle correlators ($\gamma_{132}$, $\gamma_{123}$, $\gamma_{224}$) are sensitive to the shape of the CME and help to constrain the background.
  - By tuning the CME background to reproduce mixed and higher harmonic 3-particle correlators, we can predict background in $\gamma_{112} \Rightarrow$ proper baseline of the background.
  - Background studies are done by measuring $\gamma_{112}$ in collisions simulated with event generator such as HIJING or models like LCC.
The ALICE experiment

- **Inner Tracking System (ITS):** used for tracking, triggering and vertex reconstruction.
- **Time Projection Chamber (TPC):** used for tracking and vertex reconstruction.
- **Tracks used:** $0.2 < p_T < 5.0 \text{ GeV}/c$, within $|\eta| < 0.8$
- **36.6 Million minimum bias events in Pb-Pb at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$.**
Recent CME results from ALICE: Event Shape Engineering

The $Q_2$ vector for 2\textsuperscript{nd} harmonic is defined as, $Q_2 = \sqrt{Q_x^2 + Q_y^2}$, where

$Q_x = \sum_{n=1}^{M} w_i \cos(2\phi_i)$

$Q_y = \sum_{n=1}^{M} w_i \sin(2\phi_i)$

($M = \text{Multiplicity}$).

The event shape selection is performed based on the magnitude of the second-order reduced flow vector $q_2$, where, $q_2 = \frac{|Q|}{M}$.

The ESE method allows to select events with smaller/larger average $v_2$ as illustrated in the figure.

Assumption: background in $\gamma_{112}$ scales linearly with $v_2$.

Use MC models to estimate $v_2$ scaling of the background.

ALICE puts an upper limit for the CME fraction in $\gamma_{112}$ correlator for 10–50% centrality of 26% to 33% (depending on the initial–state model) at a confidence level of 95%.

\( \gamma_{112} \) in Pb-Pb at \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \) (new)

### Expectations:
- The increase in \( v_2 \) from Pb-Pb at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \) to 5.02 TeV is small \( \sim 2-5\% \) (see Jacopo Margutti’s talk\(^7\)).
- However, there is an increase of radial flow in Pb-Pb at \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \) compared to 2.76 TeV\(^8\).
- Expect CME background contribution in \( \gamma_{112} \) correlator to slightly increase at \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \).

### Observation:
- \( \gamma_{112} \) in Pb-Pb at \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \) is similar within stat.+syst. errors to that at 2.76 TeV.

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\(^7\) Jacopo Margutti (for ALICE Collaboration), [https://indico.cern.ch/event/656452/contributions/2869803/](https://indico.cern.ch/event/656452/contributions/2869803/)

\(^8\) ALICE Collaboration, arXiv:1805.04390

\(^4\) Jinjin Pan (for ALICE Collaboration), [https://indico.cern.ch/event/656452/contributions/2869863/](https://indico.cern.ch/event/656452/contributions/2869863/)
\( \gamma_{132} \) in Pb-Pb \( \sqrt{s_{NN}} = 5.02 \) TeV (new)

- \( \gamma_{132} \) expected to have different CME and background contributions compared to \( \gamma_{112} \).
- We use a simple Blast Wave model which incorporates LCC\(^6\) effects. It is based on parameterization of \( \nu_n \) (\( n = 2, 3, 4 \)) in Pb-Pb \( \sqrt{s_{NN}} = 5.02 \) TeV and tuned to reproduce only the charge dependent part of the correlations, not the charge independent baseline.
- (Work-in-progress) tune the LCC model to reproduce the difference of opp. and same sign in \( \gamma_{132} \) and see what it will predict as a background contribution in \( \gamma_{112} \).

\( \gamma_{112} \) with one identified hadron in Pb-Pb at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)

- \( \gamma_{112} \) with one identified pion at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \) is found to be similar to that for inclusive charge particles, while results for protons indicate a particle type dependence for these correlations.

- \( \gamma_{112} \) measurement with two identified hadrons for Pb-Pb at \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \) is ongoing.

* Increased statistics expected for LHC RUN-3 will allow to significantly reduce statistical/systematic uncertainty for \( \gamma_{112} \) correlations with one and two identified hardons.
Projection for the CME fraction for LHC RUN-3 data

From RUN-3 we expect more than $10 \times$ statistics compared to RUN-2 [9], which allows the CME fraction to be investigated with a precision of $\sim 0.5\%$.

Summary:

- ALICE puts an upper limit for the CME fraction in $\gamma_{112}$ correlator for 10–50% centrality of 26% to 33% (depending on the initial-state model) at 95% confidence level.
- Projections for RUN3 statistics indicates that ALICE will be able to probe the CME fraction with precision of $\sim 0.5\%$.
- Comparison of the results for $\gamma_{112}$ at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV shows no significant energy dependence.
- $\gamma_{112}$ measured with one identified charged $\pi/K/p$ at $\sqrt{s_{NN}} = 2.76$ TeV indicates mass dependence of the correlator.

Outlook:

- A measurement of $\gamma_{112}$ with one and two identified hadrons at $\sqrt{s_{NN}} = 5.02$ TeV is in the pipeline.
- Fine tune the models to reproduce higher/mixed harmonic 3-particle correlator.
- Study of 3-particle correlator in smaller system (p-p and p-Pb).
- Stay tuned for new exciting results from ALICE.
Thank You...