Searches for EM Fields & CME in Heavy-Ion Collisions with the CMS Detector

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Outlook

Describe studies performed in

- Search for EM fields using elliptic flow of $D^0$ mesons

- Studies of CME using charge-dependent correlations in pPb and PbPb
QGP & Azimuthal Correlations

Fluctuating initial geometry + pressure

Two-particle correlations

Back-to-back jets
Jet fragmentation

Projecting in $\Delta \phi$ the long-range correlations

In Hydrodynamic models: $v_2$ (elliptic flow) and $v_3$ (triangular flow)

Related to medium response to initial collision geometry and its fluctuations
Electromagnetic (EM) Fields in AA Collisions

Strong and short lived EM fields expected to be created

- Contributions from spectators and participants
  - Produce significant charge-odd contributions to flow coefficients

Measurements would help to constraint medium parameters

- Drag coefficient
- Electrical conductivity

Collision impact parameter in x direction

Effect in Flow Coefficients Measurements

QGP can increase lifetime of EM fields

EM fields can introduce

- Rapidity odd (even) contributions to $v_n$, with $n$ odd (even)

$\Delta \equiv (\pi^+ - \pi^-)$


Studies using $D^0$ mesons

Why use $D^0$ ($\bar{u}c$) mesons?

- Heavy-flavor quarks mostly produced in primordial stages of collision (~0.1 fm/c)
  - $M_{c/b} \gg$ typical medium temperatures
    - Low probability of annihilation

- EM fields expected to vanish relatively fast
  - Peak magnitude at around 0.1 - 0.2 fm/c

Illustration of few $c\bar{c}$ pair trajectories in the expanding medium after 10 fm/c
Effect on $\Delta v_1$ between $D^0(\bar{u}c)$ and $\bar{D}^0(u\bar{c})$

Non-zero $\Delta v_1$ mainly due to magnetic field from spectators

$\Delta \equiv (\pi^+ - \pi^-)$

![Graphs showing effect on $\Delta v_1$](image)

Larger effect on $D^0$ mesons


Effect on $\Delta v_2$ of $D^0$ Mesons

Mostly produced by Electric field from collision participants

- Coulomb interaction

\[ \Delta \equiv (\pi^+ - \pi^-) \]

Bigger effect on $D^0$ meson $\Delta v_2$?

The CMS Detector

**CMS DETECTOR**
- Total weight: 14,000 tonnes
- Overall diameter: 15.0 m
- Overall length: 28.7 m
- Magnetic field: 3.8 T

**ECAL/HCAL**
- Hadron Forward (HF) calorimeters

**STEEL RETURN YOKE**
- 12,500 tonnes

**SILICON TRACKERS**
- Pixel (100x150 μm) ~ 16m² ~66M channels
- Microstrips (80x180 μm) ~200m² ~9.6M channels

**SUPERCONDUCTING SOLENOID**
- Niobium titanium coil carrying ~18,000 A

**MUON CHAMBERS**
- Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
- Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

**PRESHOWER**
- Silicon strips ~16m² ~137,000 channels

**FORWARD CALORIMETER**
- Steel + Quarta fibres ~2,000 Channels

**CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)**
- ~76,000 scintillating PbWO₄ crystals

**HADRON CALORIMETER (HCAL)**
- Brass + Plastic scintillator ~7,000 channels
D⁰ Reconstruction & Selection

Minimum Bias events from PbPb collisions at 5.02 TeV

D⁰(̅u̅c) → Kπ , BR = 3.88 ± 0.05 %, cτ(D⁰) = 122.9 µm

D⁰ Reconstruction
- Pairing oppositely charged tracks (no PID)
- Secondary vertex reconstruction

Prompt D⁰ candidate selection
- MVA Boosted Decision Tree (BDT)
  - D⁰ variables
    - d₀/σ(d₀), α, SV probability
  - Tracks (Kπ)
    - Distance of closest approach significance, error on p_T, number of hits

Nonprompt D⁰ (from B hadron decay) contamination (as systematic uncertainty)
- Estimate contribution using DCA variable (nonprompt D⁰ enriched region for DCA > 0.012 cm)
Flow Measurement: Scalar Product Method

\( v_2, v_3, \Delta v_2 (D^0 - \bar{D}^0) \) as functions of centrality, rapidity and \( p_T \)

- \( Q_{nA} \)
- \( Q_{n} \)
- \( Q_{nB} \)
- \( Q_{nC}, |\eta| < 0.75 \)

- \( Q_n = \sum_j w_j e^{i \phi_j} \) (\( w_j = \) tower \( E_T \) for HF, \( w_j = \) track \( p_T \) for tracker, \( w_j = 1 \) for \( D^0, \bar{D}^0 \))

- \( v_n\{\text{SP}\} = \frac{\langle Q_n^D / D^0 Q_{nA}^* \rangle}{\sqrt{\langle Q_n A Q_{nB}^* Q_{nC}^* \rangle / \langle Q_n A Q_{nB} Q_{nC}^* \rangle}} \)

- \( \Delta v_n\{\text{SP}\} = \frac{\langle Q_n^D Q_{nA}^* \rangle - \langle Q_n^D \bar{D}^0 Q_{nA}^* \rangle}{\sqrt{\langle Q_n A Q_{nB}^* Q_{nC}^* \rangle / \langle Q_n B Q_{nC}^* \rangle}} \)

Average over all events
Signal Extraction: Simultaneous Fit on Mass

Simultaneous fit on mass distribution and $v_n (\Delta v_n)$ versus mass

- Mass fit: background (3rd order polynomial), signal (double Gaussian), swap (single Gaussian)
- $v_n$ background (linear function), $\Delta v_n$ (background is canceled)
Flow Coefficients \((v_2 & v_3)\) as Functions of \(p_T\)

Mid-rapidity Region (\(|y|<1\)) & forward region (1<\(|y|<2\))

\(v_2\) : considerable dependence on centrality

\(v_3\) : small dependence on centrality
$\Delta v_2(D^0 - \bar{D}^0)$ as Function of Rapidity

Electric field can generate non-zero $\Delta v_2$

- Currently, no theoretical predictions for $D^0$ mesons
  - Predictions for charged hadrons at LHC energies: $\Delta v_2 \sim -0.001$ [Phys. Rev. C 98, 055201 (2018)]
  - Expected bigger values for $D^0$ [Phys. Rev. C 98, 055201 (2018)]

Average value extracted with a fit to data

- $\Delta v_2^{\text{Fit}} = 0.001 \pm 0.001 \text{ (stat)} \pm 0.003 \text{ (syst)}$

Comparable to the values for charged hadrons

- Constrain medium properties: electric conductivity

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 CMS

Prompt $D^0 - \bar{D}^0$

- 20-70%, $2.0 < p_T < 8.0 \text{ GeV/c}$

- Average value

Constrain medium properties: electric conductivity

Charged hadrons

$\Delta v_2^{\text{Avg}} = 0.001 \pm 0.001 \text{ (stat)} \pm 0.003 \text{ (syst)}$
What can we try next in the CMS experiment?

Need to improve precision of the measurements
- Statistical uncertainties: more data collected in the next LHC runs
- Systematics uncertainties: improving methods to measure heavy-flavor $v_n$

Reaction Plane Detector (RPD) in future runs $\rightarrow$ Spectator plane
- Directed flow of
  - Charged particles, $V^0$ particles & $D^0$ mesons
  - Leptons from $Z^0$ boson decay \cite{Phys. Lett. B 816, 136271 (2021)}

More ideas???
Chiral Magnetic Effect (CME) Studies

USING UNIDENTIFIED CHARGED PARTICLES
Chiral Magnetic Effect in AA Collisions

In peripheral ultrarelativistic nucleus-nucleus collisions

- Possible domains of chirality imbalance + strong magnetic field
  - Expected to lead to an electric current perpendicular to the reaction plane
    - Final-state charge separation phenomenon: chiral magnetic effect (CME)
      - A signature
        - Back-to-back emissions of opposite-sign (OS) charged hadrons
        - Collimated emissions of same-sign (SS) charged hadrons
Searches for CME in AA Collisions

3-particle correlators (contain P-odd term)

\[ \gamma \equiv \frac{\langle \cos(\phi_{A} + \phi_{B} - 2\phi_{C}) \rangle}{v_{2,c}} = \frac{\langle Q_{112}Q_{2,\text{HF}+}^{*} \rangle}{\sqrt{\langle Q_{2,\text{HF}+Q_{2,\text{HF}+}} \rangle \langle Q_{2,\text{HF}+Q_{2,\text{trk}}} \rangle}} \]


\[ Q_{112} \equiv \frac{\left( \sum_{j=1}^{w} w_{j} e^{i\phi_{j}} \right)^{2} - \sum_{j=1}^{w} w_{j}^{2} e^{i2\phi_{j}}}{\left( \sum_{j=1}^{w} w_{j} \right)^{2} - \sum_{j=1}^{w} w_{j}^{2}} \]

Experiments observed CME-like charge dependent correlations

- But background expected to be of same order of \( \Delta \gamma (\text{OS} - \text{SS}) \) [mainly charge-dependent ones \( \propto 1/N \) (N event multiplicity)]
CME Studies in the CMS Experiment

Strategy

- The CME effect is expected to be negligible in pPb collisions
  - Angle between the direction of $\vec{B}$ and the event plane expected to be randomly distributed

Comparison of pPb & PbPb for $\Delta \gamma$ (OS - SS)

Compatible within uncertainties

Why background is identical in pPb and PbPb?

- What is the origin of background in $\Delta \gamma$?

Observables & Strategy (I)

To minimize $\Psi_2$-independent background (non-flow)

- Use rapidity gap of 2 units
  - Particles $\alpha$ e $\beta$ in the Tracker ($|\eta| < 2.4$)
  - Particles $c$ in the HF detector ($4.4 < |\eta| < 5$)

The $\Psi_2$-dependent background is modeled using
(from local charge conservation coupled to elliptic flow)

- $\Delta \gamma^{BKG} = \kappa_2 \cdot \nu_2 \cdot \Delta \delta$  
  - $\delta \equiv \langle \cos(\phi_\alpha - \phi_\beta) \rangle$ is the two-particle correlator
  - $\kappa$ is a constant independent of $\nu_2$ (undetermined)

How much of the observed charge-dependent correlations come from this source?
Observables & Strategy (II)

Weak correlation between $\Psi_2$ and $\Psi_3 \Rightarrow$ negligible charge separation effect w.r.t. $\Psi_3$

- CME signal free 3$\text{rd}$-order harmonic charge-dependent correlator
  - $\gamma_{123} \equiv \langle \cos(\phi_\alpha + 2\phi_\beta - 3\Psi_3) \rangle$
  - Similar to $\Delta \gamma^{BKG}$: $\Delta \gamma_{123} = \kappa_3 \cdot v_3 \cdot \Delta \delta$

Assumption to check

- If charge dependence of the 3-particle correlators is dominated by the effect of local charge conservation coupled with the anisotropic flow (defining $\gamma \equiv \gamma_{112}$)
  - Expected to have: $\frac{\Delta \gamma_{112}}{v_2 \Delta \delta} \approx \frac{\Delta \gamma_{123}}{v_3 \Delta \delta}$
Results

\[
\left( \Delta \delta_{p\Pb} > \Delta \delta_{\Pb\Pb} \& \nu_{2}^{p\Pb} < \nu_{2}^{\Pb\Pb} \right) \Rightarrow \Delta \gamma_{p\Pb} \approx \Delta \gamma_{\Pb\Pb}
\]

- Also observed compatibility in $|\Delta \eta|$, $|\Delta p_T|$ and $\vec{p}_T$

Event-Shape Engineering Method

Tentative to establish linearity $\Delta \gamma^{\text{BKG}} \sim v_2$

- Trying to quantify the amount of CME signal

In a narrow centrality or event multiplicity range

- Events are further classified in terms of event ellipticity

$$q_2 = \left| \frac{\sum j w_j e^{2i\phi_j}}{\sum_j w_j} \right|$$

Figure: Number of events as a function of $q_2$ for PbPb 5.02 TeV and CMS PbPb 5.02 TeV, pPb 8.16 TeV. Events classified into ESE classes: 1, 95 - 100%; 2, 80 - 95%; 3, 60 - 80%; 4, 50 - 60%; 5, 40 - 50%; 6, 30 - 40%; 7, 20 - 30%; 8, 10 - 20%; 9, 5 - 10%; 10, 1 - 5%; 11, 0 - 1%.

Nonzero intercept value of the $\gamma$ correlators $\rightarrow$ strength of the CME PbPb in centrality bins

Linear, intercepting close to zero

$\Delta \delta$ not really independent of $q_2/v_2$

Results (II)

PbPb in centrality bins

- Use the ratio

\[ \Delta \gamma \over \Delta \delta = \kappa v_2 + \Delta \gamma^{CME} \over \Delta \delta \]

What is the effect from non-flow???

Upper Limits @ 95% C.L. in PbPb Collisions

Suppose a non-negative CME signal

\[ f_{\text{norm}} = \frac{\Delta \gamma^{\text{CME}}}{\Delta \gamma} \]

<table>
<thead>
<tr>
<th>PbPb centrality(%)</th>
<th>Combined limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>65</td>
<td>PbPb 5.02 TeV</td>
</tr>
<tr>
<td>55</td>
<td>pPb 8.16 TeV,</td>
</tr>
<tr>
<td>45</td>
<td>( \phi_c )(Pb-going)</td>
</tr>
<tr>
<td>35</td>
<td>95% CL limit on ( f_{\text{norm}} )</td>
</tr>
<tr>
<td>25</td>
<td>0.1</td>
</tr>
<tr>
<td>35</td>
<td>0.2</td>
</tr>
<tr>
<td>45</td>
<td>0.3</td>
</tr>
</tbody>
</table>

\( N_{\text{trk}}^{\text{offline}} \)

\( \Delta \gamma^{\text{CME}} / \Delta \gamma < 7\% \)

What can we try next in the CMS experiment?

Some methods have been tried in the RHIC and LHC experiments

- **1) Event-shape engineering**
  

- **2) Isobar collisions** [Phys. Rev. C 105, 014901 (2022)]

- **3) Measurements w.r.t. spectator and participant plane** [Phys. Rev. Lett. 128 (2022) 092301]

Method “3)” showed a hint of possible CME in AuAu collisions

- ~2σ significance

Reaction Plane Detector (RPD) in future runs → Spectator plane

- Can try also method “3)”?

More ideas???
Thank You!

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BACKUP
$\Psi_{EP}$-independent BKG

$$\langle \cos 2(\phi_\alpha - \Psi_{EP}) \rangle \approx \frac{\langle \cos 2(\phi_\alpha - \phi_c) \rangle}{v_{2,c}}$$

Negligible with (1) large $|\Delta \eta|$ and (2) high multiplicities
Origin of background in $\Delta \gamma$?

$$\gamma = \left< \cos(\phi_\alpha + \phi_\beta - 2 \Psi_{EP}) \right> \overset{!}{=} \frac{\left< \cos(\phi_\alpha + \phi_\beta - 2 \phi_c) \right>}{v_{2,c}}$$

- $\Psi_{EP}$-independent
  - between $\alpha$ ($\beta$) and $c$
  - short-range correlations (jets, clusters etc.)
  - "Nonflow"

- $\Psi_{EP}$-dependent
  - between $\alpha$ and $\beta$
  - (jet, clusters etc.)
  - $\times$
  - both correlate to $\Psi_{EP}$
  - (elliptic flow)

Charge-dep. due to charge conservation, ordering etc.