Feasibility study of ultra-intense magnetic field detection via virtual photon derived dimuon polarization in ALICE Run 3

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Motivation

We propose virtual photon polarization as a detection method for undetected ultra-intense magnetic fields. The polarization is measured by quantifying and measuring the anisotropy of the muon pair decay plane through the virtual photon. **In this study, I evaluate the detectability of virtual photon polarization in ALICE Run 3 Pb-Pb collision.**

Introduction

- **Ultra-intense magnetic effect**
  Non-central heavy Ion collision generate ultra-intense magnetic field. Because the charged particles move at relativistic speeds, the generated magnetic field becomes very strong.

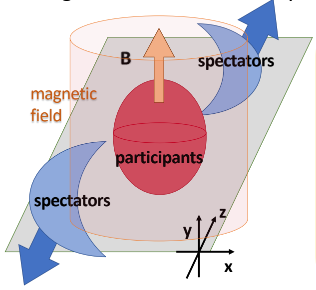

Figure1: Strong magnetic field generation in nuclear collisions

Maximum magnetic field strength: 10^{15} T
Strongest magnetic field in the universe
Lifetime : 0.1 fm/c

- **Chiral magnetic effect**
- **Synchrotron radiation of quarks**
- **Effects of nonlinear QED**
  (Includes virtual photon polarization)
  ...etc.,

ultra-intense magnetic fields causing unusual phenomena.

- **Chiral magnetic effect**

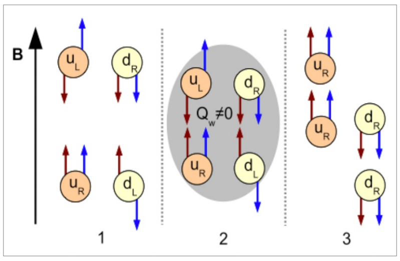

Figure2: Chiral magnetic effect[1]

- Spin directions are aligned when a strong magnetic field is applied to a mixture of right-handed and left-handed quarks.
- If P symmetry is broken, momentum directions are aligned.
- As a result, the direction of quark motion is aligned, and electric current is produced
- Powerful tool in the search for P and CP asymmetries in QCD.

(The red arrows denote the direction of momentum, the blue arrows denote the spin of the quarks.)

<u>・・・However, strong magnetic fields are not yet detected</u>

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<u>**We believe that if virtual photon polarization could be measured, it would provide direct evidence of strong magnetic field generation.**</u>

Measurement

- **Measurement of virtual photon polarization**
  Polarized virtual photons appear anisotropic in the decay plane when they decay into lepton pairs.

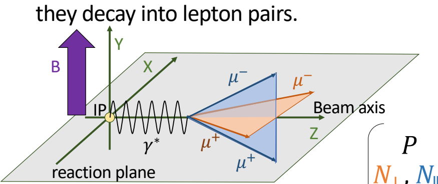

Figure3: Virtual Photons and Their decay plane

Definition of Polarization

$$P \equiv \frac{N_\perp - N_\parallel}{N_\perp + N_\parallel}$$

P : polarizability
$N_\perp, N_\parallel$: Number of decays perpendicular and parallel to the magnetic field

Anisotropy was quantified by calculating the angles between the decay plane and the magnetic field and classifying them as shown in the following figure.

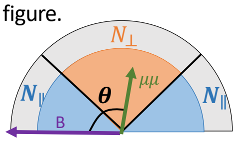

Figure4: Angle of the decay plane to magnetic field

$45° < \theta < 135° \rightarrow N_\perp$
$0° < \theta < 45°$,
$135° < \theta < 180° \rightarrow N_\parallel$

$N_\perp \neq N_\parallel$
↓
polarize

- **Prompt photon**
  Since the lifetime of a strong magnetic field is short, prompt photons, which are produced early, are mainly affected by the strong magnetic field and polarized. Among direct photons, immediate photons are dominant for $p_T > 4$ GeV/c.

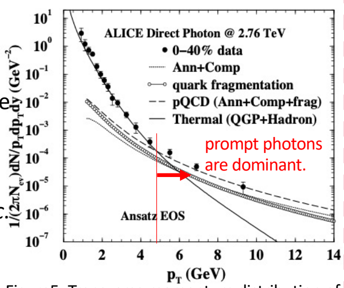

Figure5: Transverse momentum distribution of direct photons[2]

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Measure Dimuons with pT > 4 GeV

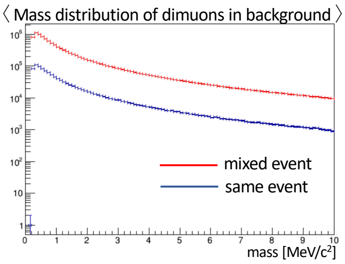
Data set of simulation

<u>Simulation of Pb-Pb collisions in ALICE Run 3 (2022-2025)</u>,
<u>polarized virtual photon-derived dimuons are assumed to be produced</u>.
I generated background and signal, respectively, and measured the polarization of the embedded data.

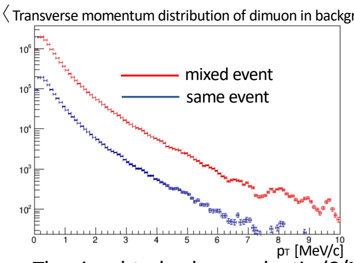
- **Background**: Pb-Pb collision $\sqrt{s_{NN}} = 5.52$ TeV, minimum bias, 10000event
- **Signal** : Selected dimuon from pp collision($\sqrt{s} = 5.5$ TeV) and deflected angle
  Polarization is set to P=0, 0.12, 1.0, (Each 1000event)

To increase the background statistics, a method called event mixing was used. Event mixing is a method of analysis using information from multiple collisions. This method increased the BG statistics by a factor of 100.

〈Mass distribution of dimuons in background〉



〈Transverse momentum distribution of dimuon in background〉



Periods	Cuts	N_s	N_B
Run 3	All dimuons	$\sim 10^6$	$\sim 10^{11}$
	$p_T > 4\mathrm{GeV}/c$	$\sim 10^5$	$\sim 10^7$
This study(All dimuons)		10^3	10^8

Table1: Statistics of dimuon estimated in Run 3 [3] and dimuon of this study

The signal-to-background ratio (S/N) is matched to this simulation and the estimated statistics of Pb-Pb collisions in Run 3.

<u>Current status : $S/N = \sim 10^{-5}$</u>
(signal indicates a virtual photon-derived Dimuons polarized by a magnetic field)

Results and consideration

Dimuons in the background

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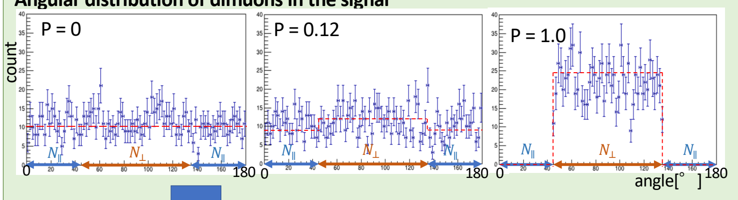
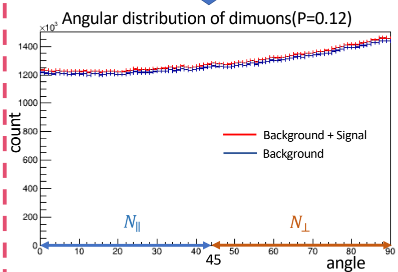
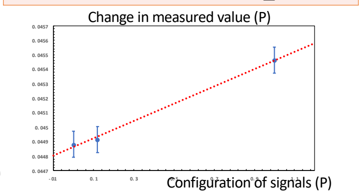
Angular distribution of dimuons in the signal





signals	Results (P)
Data set as P=0	0.04488 ± 0.00009
Data set as P=0.12	0.04491 ± 0.00009
Data set as P=1	0.04546 ± 0.00009



When the polarization P of the signal is changed from 0 to 1, the value of the measurement result also changes, indicating that <u>**polarization is significantly measured**</u>.

For more accurate polarization measurements・・・

- Increasing the signal statistics and making the S/B as high as the estimate in Run 3 is expected to make the polarization of the signal easier to detect
- Increase the purity of μ-particle pair detection among μ-particle pairs derived from direct virtual photons by accounting for detector effects
- By narrowing the transverse momentum of μ-particle pairs to $p_T > 4$ GeV/c (Figure 5), we can detect μ-particle pairs originating from prompt photons among direct photons.

Conclusion

- **Polarization can be significantly measured.**
- **Will improve the accuracy of virtual photon polarization measurements by increasing simulation statistics, refining the transverse momentum of μ-particle pairs, and accounting for detector effects.**

<u>references</u>

[1] D. E. Kharzeev, L. D. McLerran, and H. J. Warringa. The effects of topological charge change in heavy ion collisions:“ event by event p and cp violation ”. *Nuclear Physics A*, 803(3-4):227–253, 2008.
[2] Karel Safarik (for ALICE collabora- tion), Quark Matter-2012; M. Wilde et al., ALICE collaboration, arxiv:1210.5958 (2012).
[3] Kento Kimura, M.S. Thesis, Hiroshima University, 2022. “Detection feasibility of ultra-intense magnetic field generated in non-central Pb-Pb collisions with dimuon measurement at ALICE “
[4] K.-I. Ishikawa, D. Kimura, K. Shigaki, and A. Tsuji, J. Mod. Phys. A28 (2013) 1350100.
[5]Asako Tsuji, M.S. Thesis, Hiroshima University, 2013. “Evaluation and Measurement of Virtual Photon Polarization due to Strong Magnetic Field Generation in 2.76 TeV per Nucleon Pair Lead + Lead Nucleus Collisions"