Significance estimation for virtual photon polarization measurement with dimuons at ALICE

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4 – 10 Apr 2022
Quark Matter 2022

Ultra-intense magnetic field in heavy-ion collisions

Outline

- Virtual photon polarization measurement
- Estimation of polarization significance
  - ✓ Numerical QED calculation of polarization
  - ✓ Yield estimation of signals ($\gamma^* \to \mu^+\mu^-$) and combinatorial background
- The ultra-intense magnetic field is possibly detectable at Run 3

$$\boldsymbol{B} = \boldsymbol{B}_{\mathbf{s}} + \boldsymbol{B}_{\mathbf{p}}$$

$\boldsymbol{B}_{\mathbf{s}}$: magnetic field generated by spectator

$\boldsymbol{B}_{\mathbf{p}}$: magnetic field generated by participant

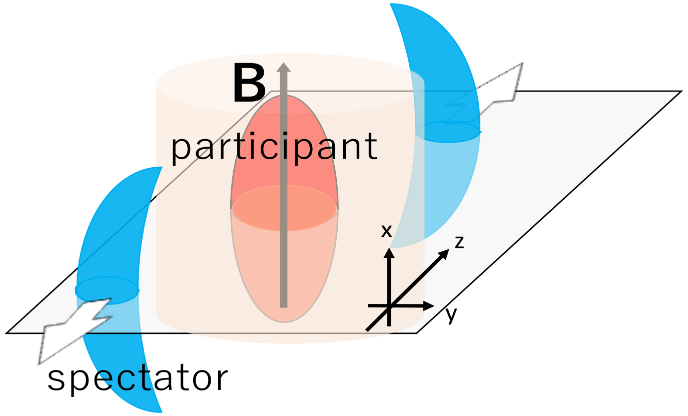
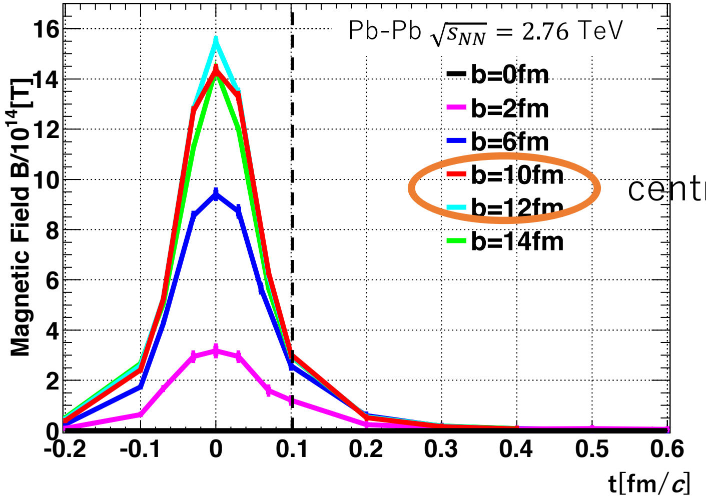


Fig. 1 Illustration of generated ultra-intense magnetic field

- **Maximum intensity**
  $\sim 10^{15}$ T @LHC in Pb-Pb at centrality 40 - 60%
  - Non-linear QED effect
    ex. vacuum birefringence, photon splitting
  - Chiral magnetic effect

- **Lifetime** $\sim 0.1\ \mathrm{fm}/c$
  - Possibly longer lifetime of B_{p} by QGP rotation
  - Vorticity Observed by STAR



centrality 40 - 60%

Fig. 2 centrality and time dependence[1]

[1] A.Tsuji master thesis Hiroshima Univ. (2014)

How to detect ultra-intense magnetic field

Virtual photon polarization

- Effect due to ultra-intense magnetic field
- Anisotropic decay plane of $\gamma^* \to \mu^+\mu^-$

$$[\langle N_\perp \rangle \neq \langle N_\parallel \rangle] \equiv \textbf{Polarization}$$

$\langle N_\perp \rangle$: perpendicular to B

$\langle N_\parallel \rangle$: parallel to B

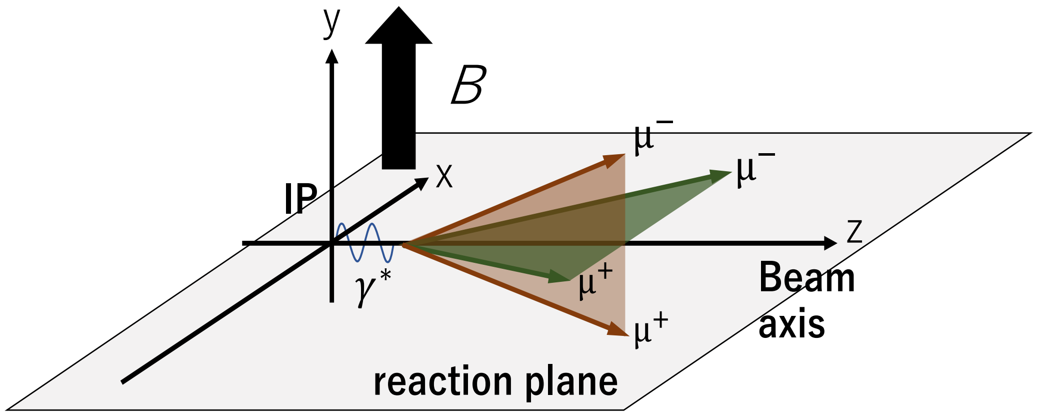


Fig. 3 Illustration of virtual photon polarization

Polarization measurement with dimuon

- Direct γ/γ^* from initial stage at high p_T

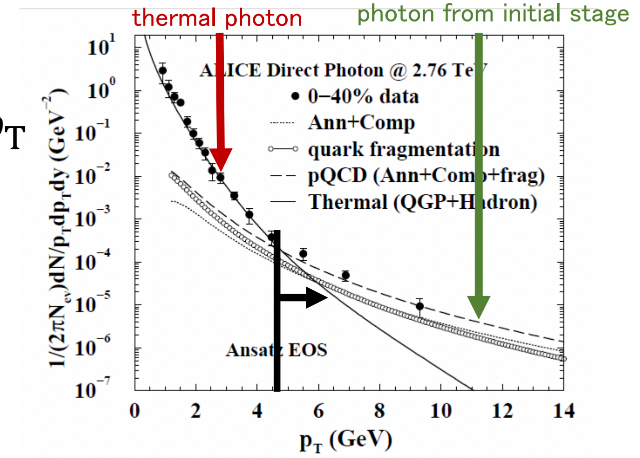


Fig. 4 Contribution from different source in Direct photon[2] and data from Pb-Pb at $\sqrt{s_{NN}}$=2.76 TeV [3]

- rejection of heavy quark decay muons
  - ➢ Muon Forward Tracker (MFT)

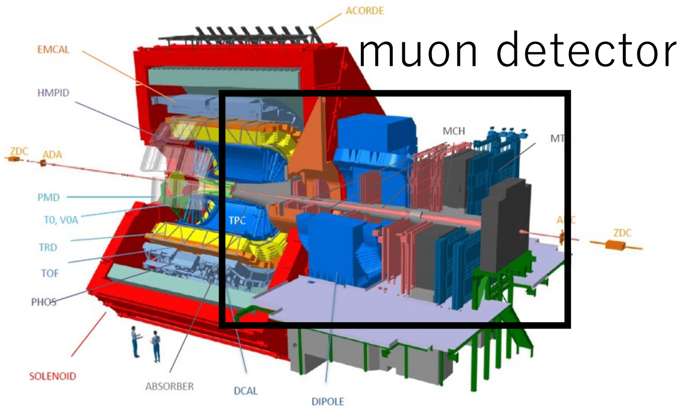


Fig. 5 ALICE detector

[2] Jajati K. Nayak. *DAE Symp. Nucl. Phys.*, 58:730–731, 2013.
[3] M. Wilde, ALICE collaboration, Nucl. Phys. A 904–905 (2013) 573c–576c

Numerical calculation of virtual photon polarization

Calculation formulae

- Dimuon production rate

$$R_{\mu^+\mu^-} = \frac{\alpha^2}{2\pi^4}\{(-g^{\alpha\beta}q^2 + q^\alpha q^\beta)\mathrm{C}\}D_{\mu\alpha}(q,eB)D^*_{\nu\beta}(q,eB)\ L^{\mu\nu}(p_1,p_2)$$

Photon source　　photon propagator　　Lepton tensor

- Vacuum polarization tensor in propagator [4]
  - Full landau level sum

from factor

$$\mathrm{N}_i = -\frac{\alpha}{4\pi}\sum_{n=0}^{\infty}\mathrm{C}_n\sum_{l=0}^{\infty}\Omega^n_{i,l}(r,\eta,\mu) - \frac{\alpha}{4\pi}\int_{-1}^{1}dv\int_0^{\infty}dz\,[(\bar{\mathrm{N}}_i(z,v)e^{i\psi(z,v)\eta} - \frac{1-v^2}{z})e^{-i\frac{z}{\mu}}]$$

n,l: landau level

- Extrapolation to infinity
  - ➢ Replaced to $n_{\max}^{-1}$ and $n_{\max}^{-1/2}$

    $n_{\max}$: upper limit of landau level n
  - ➢ Fit with 1st - 4th polynomial
- Systematic error
  - ➢ Extrapolation variability

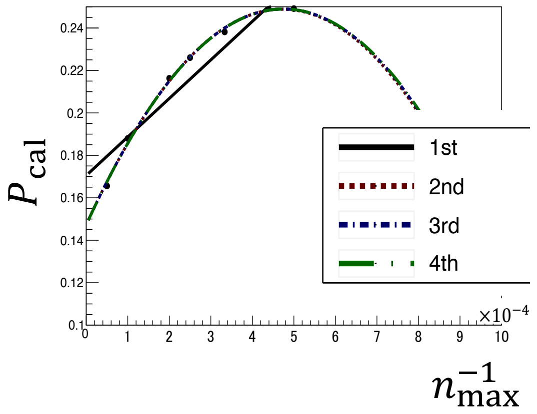


Fig. 6 Extrapolation at $p_{\mu\mu} = 35\ \mathrm{GeV}/c$ with $n_{\max}^{-1}$

Calculation results

Polarization $\quad P_{\mathrm{cal}} \equiv \frac{R_\perp - R_\parallel}{R_\perp + R_\parallel}$

$R_\perp$: perpendicular to B
$R_\parallel$: parallel to B

- Larger P_{cal} in higher $p_{\mu\mu}$
- $P_{\mathrm{cal}} = 0.12 \pm 0.03$ at $p_{\mathrm{T}} \cong 3.5\ \mathrm{GeV}/c$
- Expected larger P_{cal} for $p_{\mathrm{T}} > 4\ \mathrm{GeV}/c$

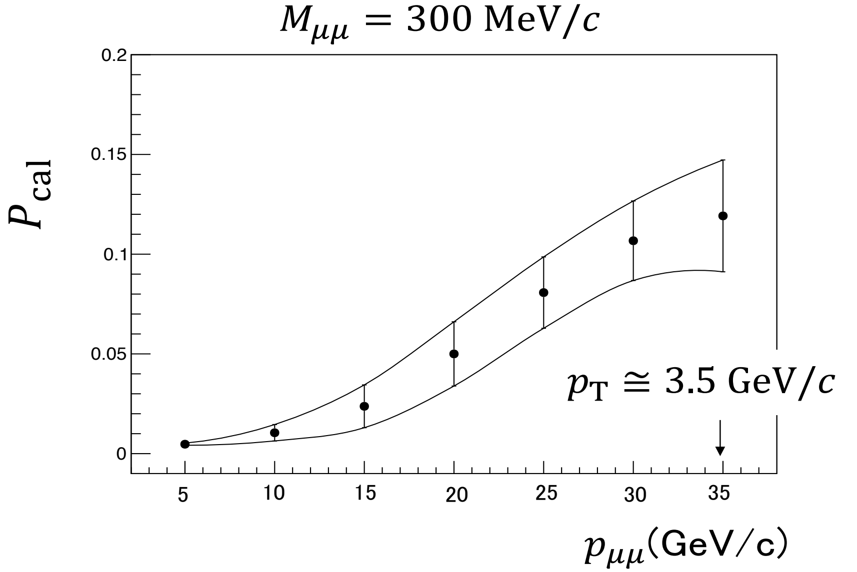


Fig. 7 Calculated polarization at $M_{\mu\mu} = 300\ \mathrm{MeV}/c$

[4]K.-I.Ishikawa *et al.*, Int. J. Mod. Phys. A 28, 1350100 (2013)

Yield estimation of signal and background $\mu^+\mu^-$

Assumption: no detector effect, purity and tracking efficiency 100%

Number of signals N_S

- $N_{\gamma^* \to \mu\mu}$ in pp 10^8 events with PYTHIA (tune: monash 2013) [5]
- η acceptance: -4.0 < η < -2.5
- Photon from parton scattering decay dimuons
- Scaling to stat. at Run 2 or 3 in Pb-Pb with centrality 40-60%

$$\text{Scaling factor} = N_{\text{coll}} \times \frac{\text{Run 2 or 3 stat.}}{\text{PYTHIA minimum bias events}} \times \frac{20[\%]}{100[\%]}$$

Number of combinatorial background N_B

- Selected centrality 40 -60 % in Pb-Pb 10^6 events with PYTHIA Angantyr [5]
- η acceptance: -4.0 < η < -2.5
- Selected decay muons (orange range in Fig.8)
- Scaling to stat. at Run 2 or 3 in Pb-Pb with centrality 40-60%

$$\text{Scaling factor} = \frac{\text{Run 2 or 3 stat.}}{\text{PYTHIA minimum bias events}}$$

		N_S	N_B
Run 2 (2015-2018)	All dimuons	$\sim 10^5$	$\sim 10^{10}$
	$p_T > 4$ GeV/c	$\sim 10^4$	$\sim 10^6$
Run 3 (2022-2025)	All dimuons	$\sim 10^6$	$\sim 10^{11}$
	$p_T > 4$ GeV/c	$\sim 10^5$	$\sim 10^7$

Minimum Bias Events

Run 2 $\sim 10^9$

Run 3 $\sim 10^{10}$

	N_s/events	N_B/events
All dimuons	$\sim 10^{-4}$	~ 10
$p_T > 4$ GeV/c	$\sim 10^{-5}$	$\sim 10^{-3}$

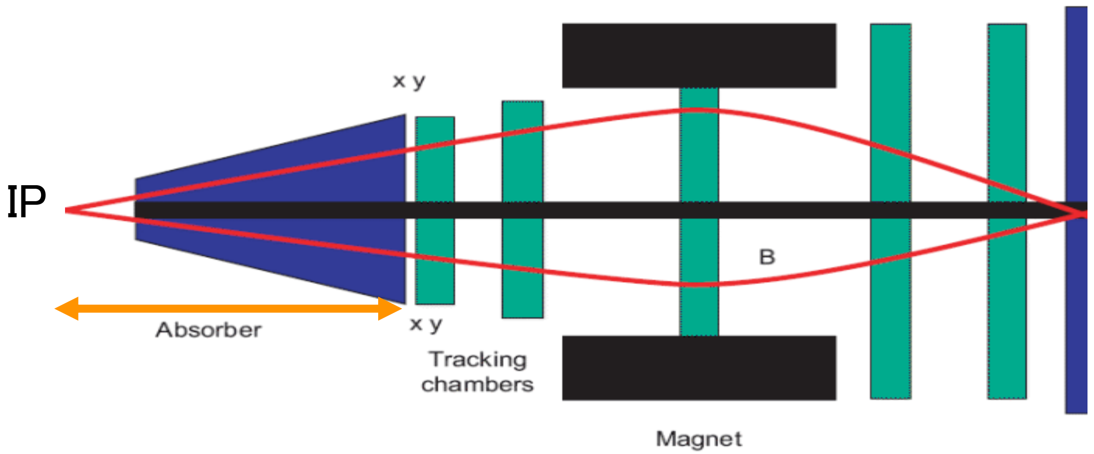


Fig. 8 Range of hadrons decaying as background

[5]T. Sjöstrand et al, Comput. Phys.Commun. 191 (2015) 159

Estimation of polarization significance

Assumption: no detector effect, purity and tracking efficiency 100%

Estimated polarization significance

$$P_{\mathrm{meas}} = \frac{\langle N_{\perp} \rangle - \langle N_{\parallel} \rangle}{\langle N_{\perp} \rangle + \langle N_{\parallel} \rangle}$$

$$\langle N_{\perp} \rangle = \frac{1}{2} N_{\mathrm{B}} + \frac{1 + P_{\mathrm{cal}}}{2} N_{\mathrm{S}}$$

$$\langle N_{\parallel} \rangle = \frac{1}{2} N_{\mathrm{B}} + \frac{1 - P_{\mathrm{cal}}}{2} N_{\mathrm{S}}$$

fixed $P_{\mathrm{cal}} = 0.12$

- Improving about 4.3 σ with Run 3 stat. and dimuons for $p_{\mathrm{T}} > 4\ \mathrm{GeV}/c$
  - ➢ Pb-Pb with centrality 40 – 60%

Polarization with all dimuons | Polarization with dimuons for $p_T > 4\ \mathrm{GeV}/c$

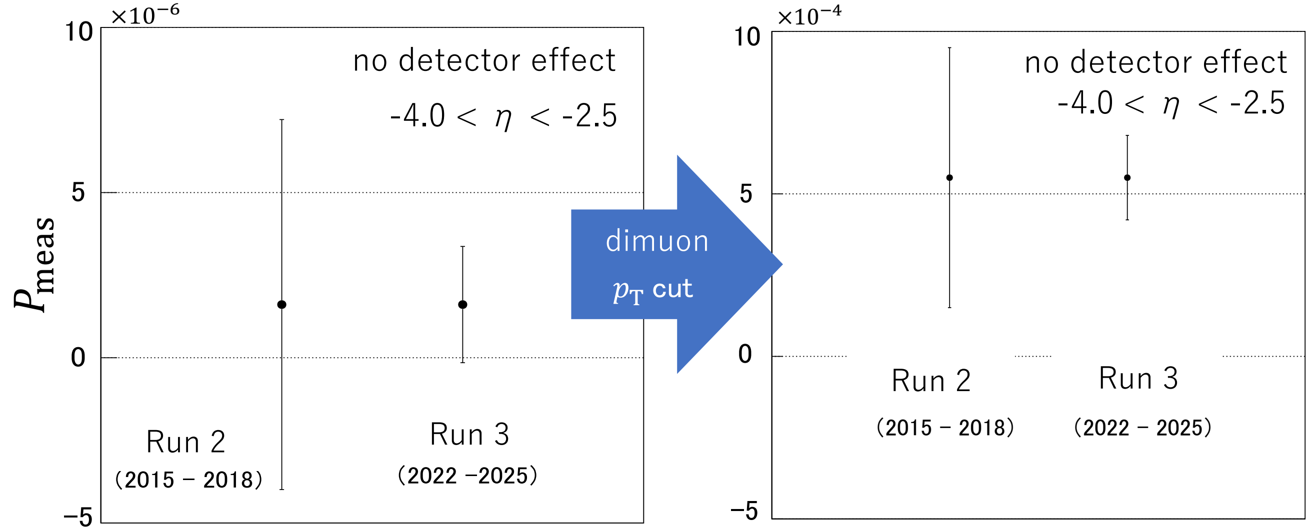


Fig. 9 Estimated polarization significance at Runs 2 and 3

Conclusion

Possible detection of ultra-intense magnetic field at Run 3

Prospects

- Optimization of dimuon p_{T} cut
- Decay dimuons rejection by MFT
- Analysis data at Run 3 (2022-)