ATHIC
Asian Triangle Heavy Ion Conference

The 4th Asian Triangle Heavy Ion Conference
in Pusan, South Korea on November 14-17, 2012

Perspectives of search for ultra-strong magnetic field via direct virtual photon measurement with ALICE at the LHC

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for the ALICE collaboration

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ALICE

広島大学

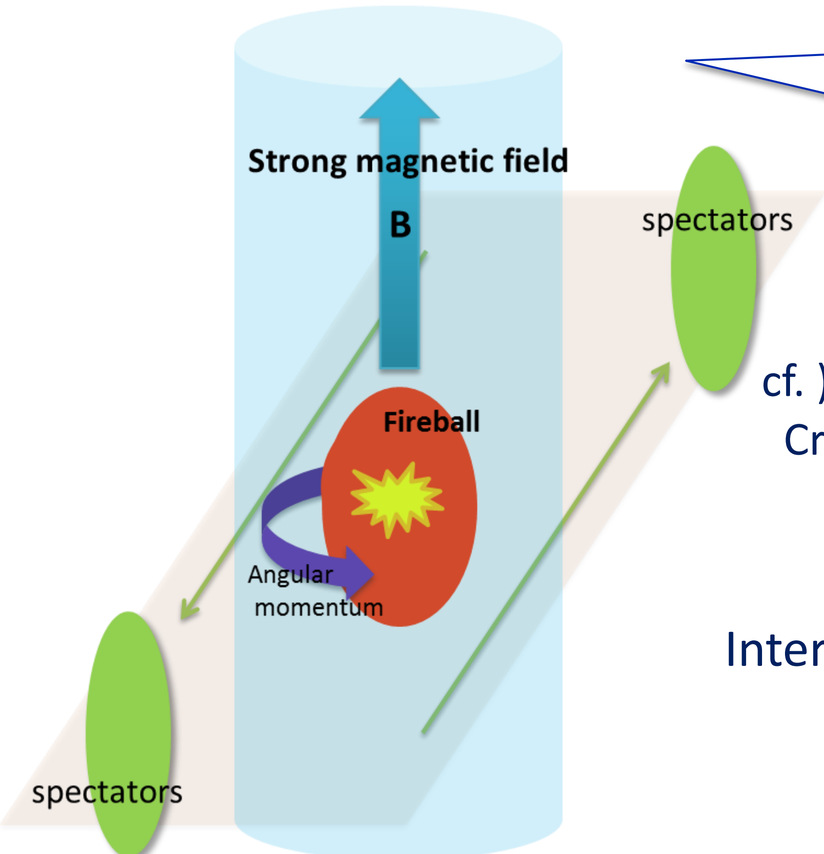
Quark Physics Laboratory
Hiroshima University, Japan

Outline

- **Physics Motivation**
  – Ultra-strong magnetic field in HIC
- **Theoretical study**
  – Calculation of vacuum polarization tensor
  – Virtual photon Anisotropy and Polarization estimations
- **Experimental approach**
  – e^+e^- measurement and E.P. determination at ALICE
  – Feasibility of the field detection
- **Ongoing efforts of real data analysis**
- **Summary & Conclusion**

Physics Motivation

Ultra-strong magnetic field created in HIC



B ~10^{15} Tesla @LHC
~10^{14} Tesla @RHIC

Very Strong!!

cf.) LHC superconducting magnets : 8.3 Tesla
Critical magnetic field of electrons B_c : 4×10^9 Tesla
Magnetars : ~10^{11} Tesla

Interesting phenomena : Chiral magnetic effect*
Synchrotron radiation
Non-linear QED effects

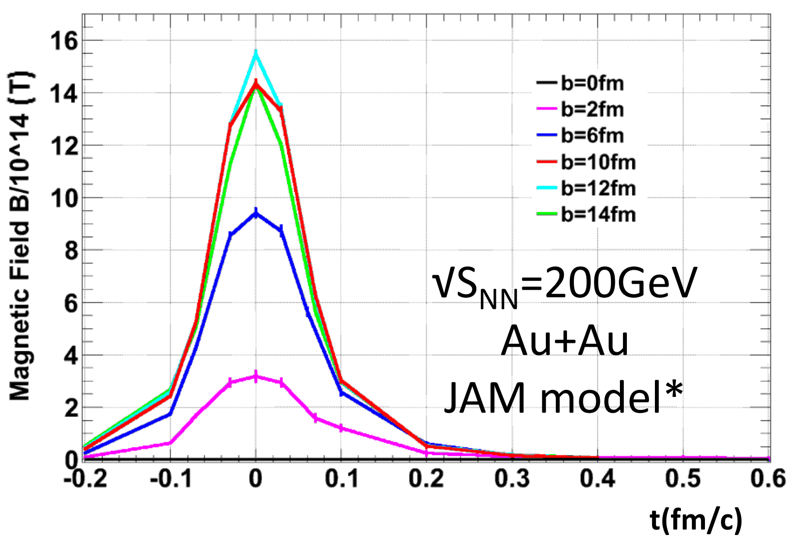
<u>The field is not yet directly detected!!</u>

*K.Fukushima, D.E.Kharzeev, H.J.Warringa, PRD78 (2008) 074033

The field estimation

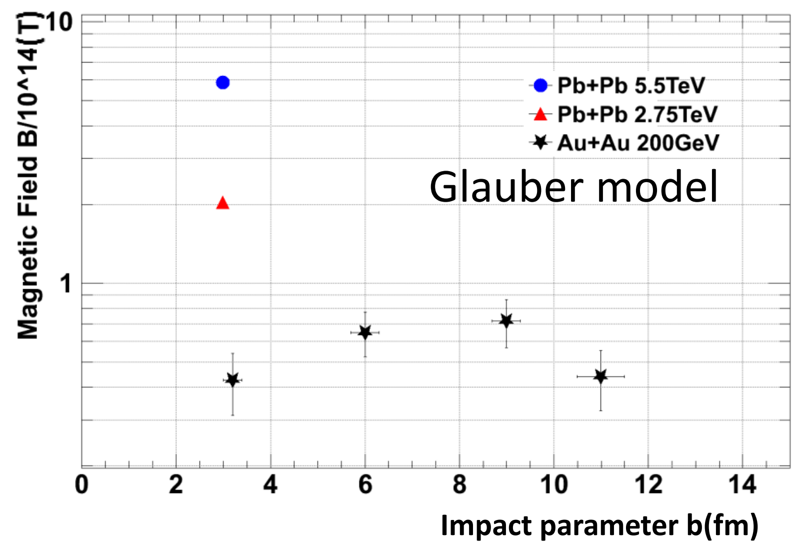
- **Impact parameter, energy, and time dependence**

Spectators and participants



Participants only

By A.Tsuji



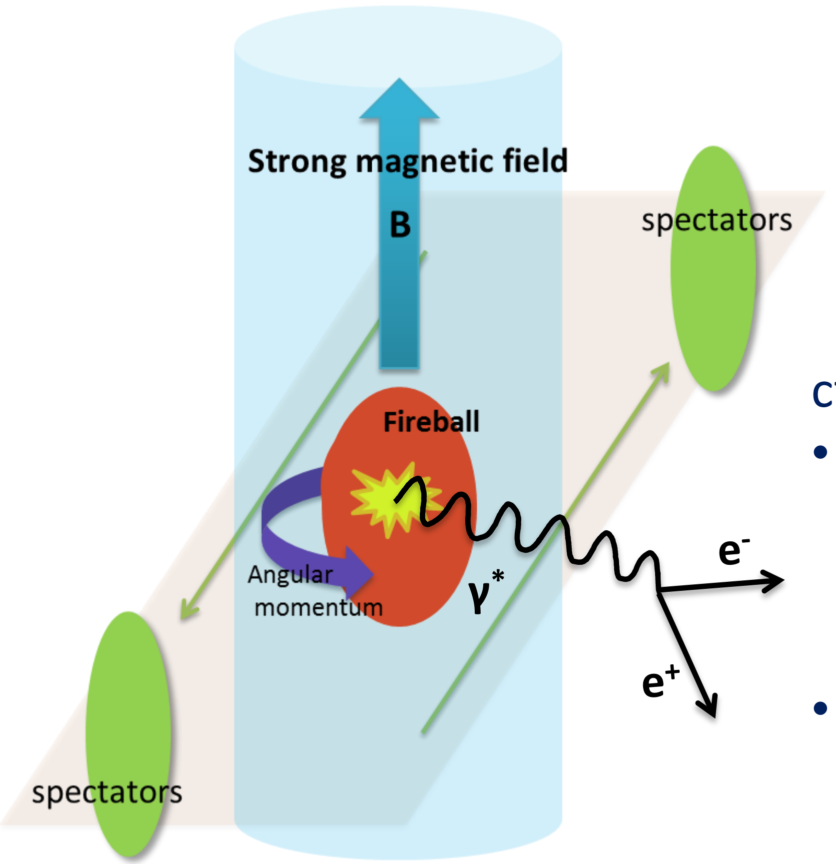
- The field intensity reaches maximum in peripheral collisions (B_{max}~10^{15}Tesla) and grows with the beam energy.
- The field rapidly damps, but is still above B_c for a few fm/c.

* JAM (Y.Nara, N.Otuka, A.Ohnishi, K.Niita, S.Chiba, PRC61 (2000) 024901)

ALICE

A new approach to detect the field

Via virtual photon (low mass e^+e^-) measurement



(1)Anisotropy (v_2)

(2)Polarization

cf.)

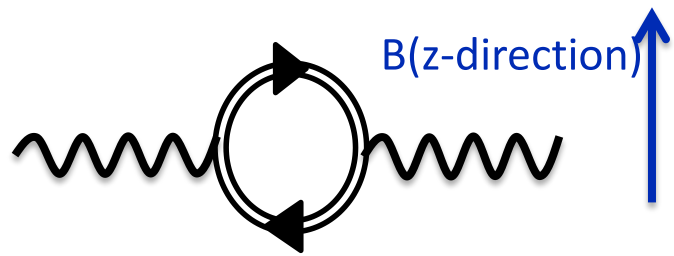
- Real photon measurement
  - challenging to subtract a large background from hadron decays.
  - no detector to measure polarization.
- Virtual photon (low mass e^+e^-) measurement
  - signal to background ratio is dramatically improved by selecting a mass region above π^0 mass.
  - achievable with present detectors.

Theoretical Study

Calculation of vacuum polarization tensor

- **In strong magnetic field**
  - Photon propagator

$$D_{\mu\nu}(q) = \frac{-i}{q^2}\left[g^{\mu\nu} - \frac{1}{q^2}\Pi^{\mu\nu}(q,B) \right]^{-1}$$



q : 4D momentum of virtual photon

  - Vacuum polarization tensor

$$\Pi^{\mu\nu}(q,B) = \left[\left(g^{\mu\nu}q^2 - q^\mu q^\nu \right) - \left(g_\parallel^{\mu\nu}q_\parallel^2 - q_\parallel^\mu q_\parallel^\nu \right) - \left(g_\perp^{\mu\nu}q_\perp^2 - q_\perp^\mu q_\perp^\nu \right) \right]\overline{N}_0 + \left(g_\parallel^{\mu\nu}q_\parallel^2 - q_\parallel^\mu q_\parallel^\nu \right)\overline{N}_1 + \left(g_\perp^{\mu\nu}q_\perp^2 - q_\perp^\mu q_\perp^\nu \right)\overline{N}_2$$

- When $q_\perp^2 = 0$, it is integrable for all $q_\parallel^2$ region.
  [in terms of DiGamma, Kerbstein et al.
  Intl.J.Mod.Phys.[arXiv:1111.5984[hep-ph]].
- For $q_\perp^2 \neq 0$ case, Hattori-Itakura has obtained Landau level summation form recently (Hattori,Itakura [arXiv:1209.2663]).
- One-loop calculation of electron and muon.
- In our calculation, $\overline{N}_2$ is not included yet.

Anisotropy of virtual photons

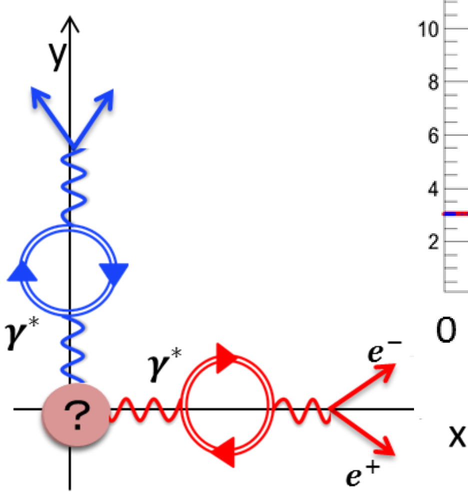
- **Di-electron production rate**

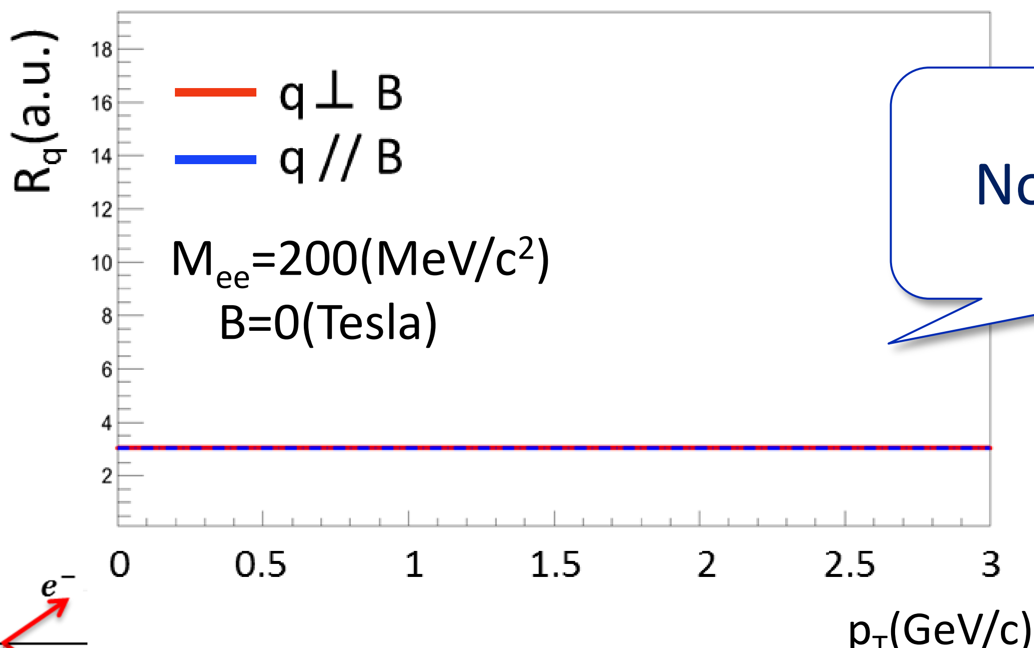
$$R_q \equiv \frac{R_{e^+e^-}}{d^4q} = -\frac{\alpha^2}{3\pi^3} q^2 g^{\mu\alpha} D_{\mu\nu}(q,eB) D_{\alpha\beta}(q,eB)^* \frac{\mathrm{Im}\, G_R^{\nu\beta}(q,T,eB)}{e^{q^0/T}-1}$$

q : 4D momentum of electron pair

G : source of virtual photons

  – Last factor is approximated as a constant term.
  – **When B=0, the rate is isotropic.**





No anisotropy.

by K.Ishikawa and A.Tsuji

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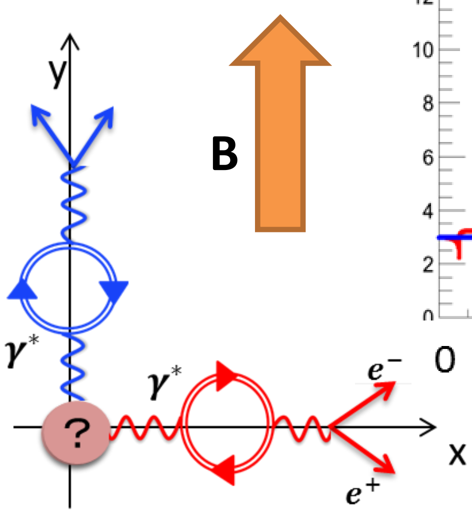
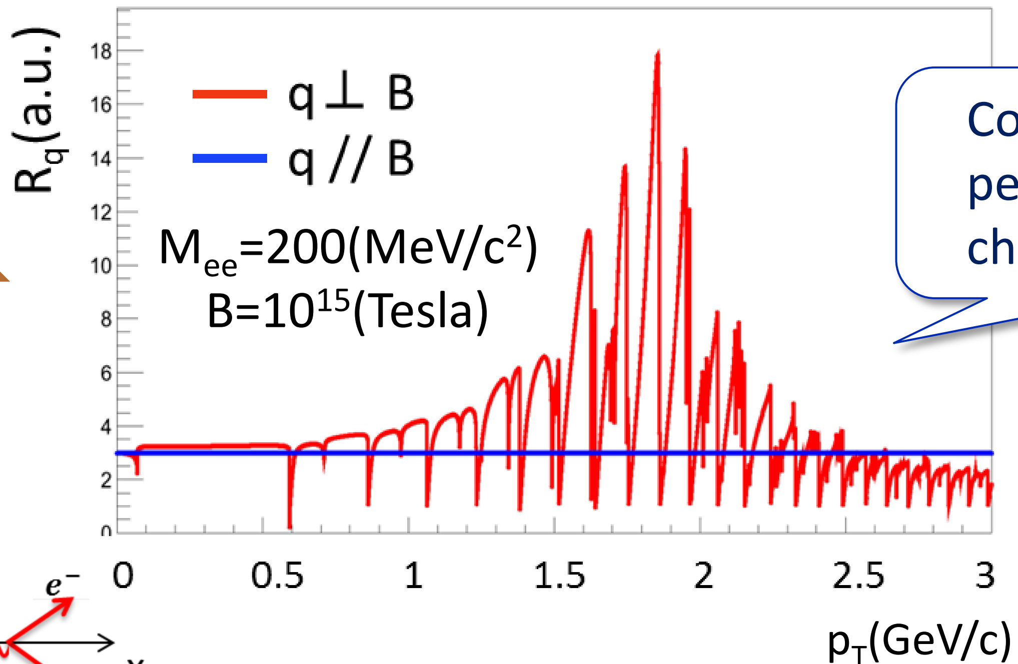




Component perpendicular to B changed!

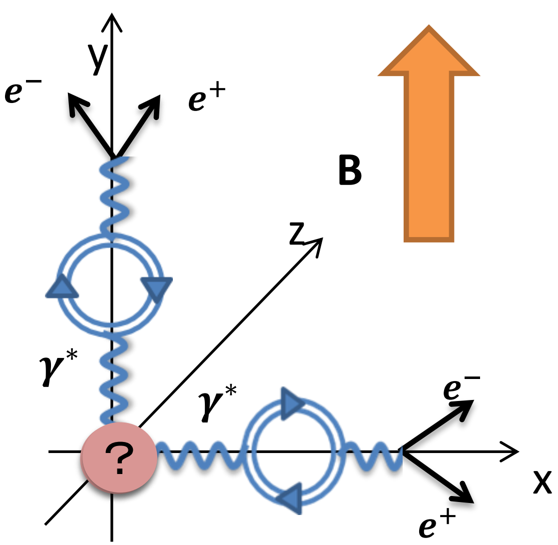
by K.Ishikawa and A.Tsuji

ALICE

Anisotropy of virtual photons

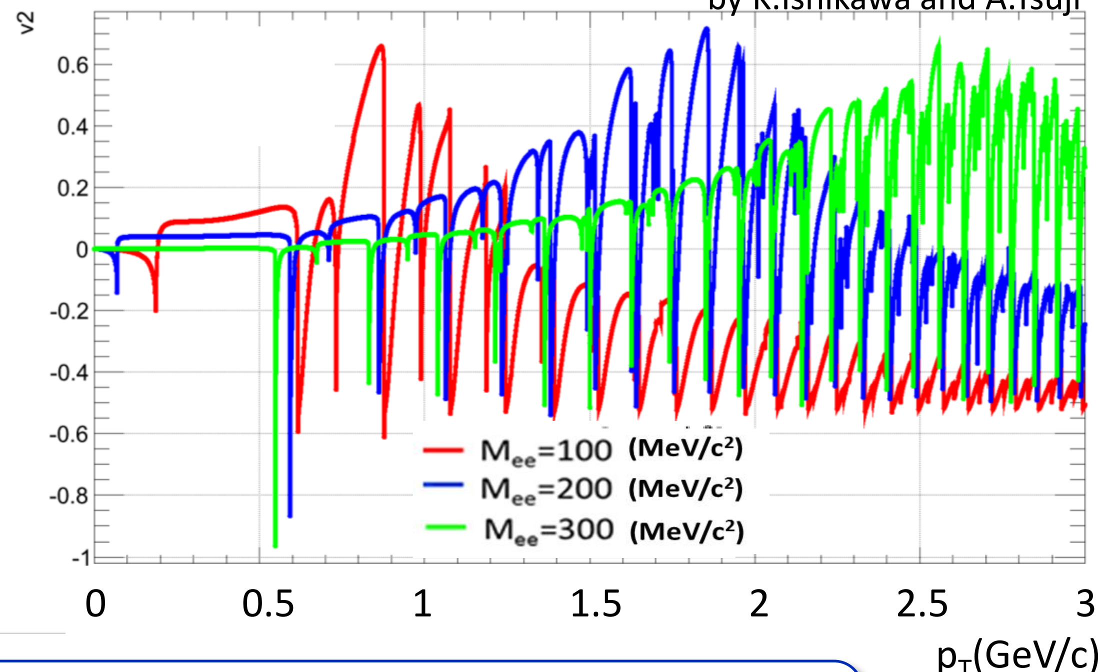
$$Anisotropy(v_2) = \frac{R_\perp - R_{//}}{R_\perp + R_{//}}$$

R:di-electron production rate



Anisotropy of Virtual photon (B=10^{15}Tesla)

by K.Ishikawa and A.Tsuji



The Anisotropy is in the order of 10^{-1}!!

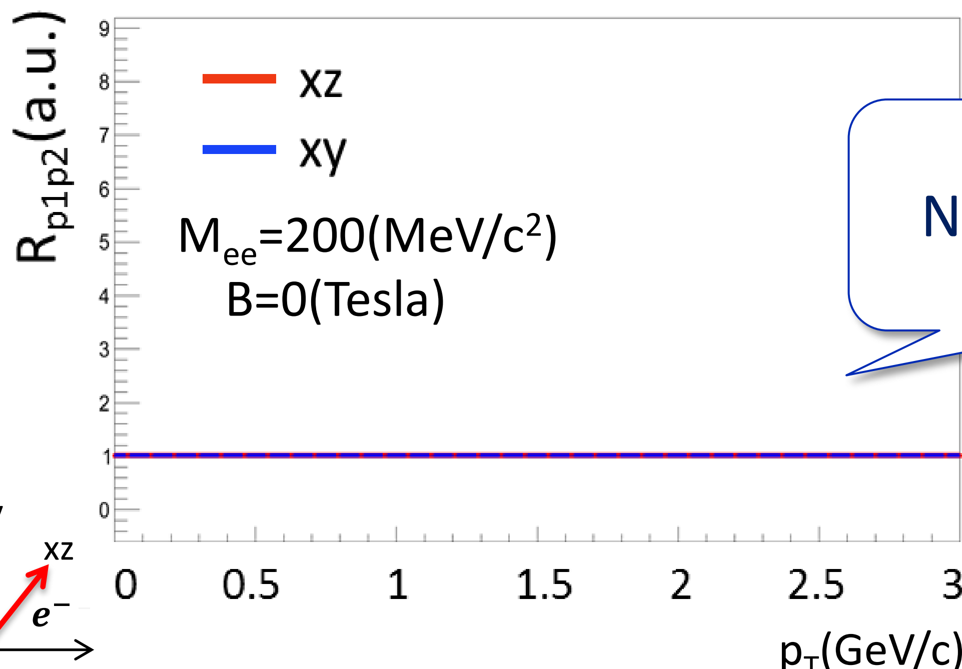
Polarization of virtual photons

- **Di-electron production rate**

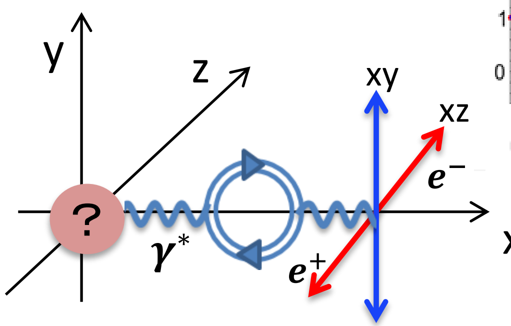
$$R_{p_1p_2} \equiv \frac{E_1E_2dN_{e^+e^-}}{d^3p_1d^3p_2d^4x} = \frac{\alpha^2}{2\pi^4} L^{\mu\nu}(p_1,p_2)D_{\mu\alpha}(q,eB)D_{\nu\beta}(q,eB)^* \frac{\mathrm{Im}\,G_R^{\alpha\beta}(q,T,eB)}{e^{q^0/T}-1}$$

  - Last factor is approximated as a constant term.
  - **When B=0, virtual photon decay is isotropic.**

$p_{1,2}$: 4D momentum of leg-electron
L : kinematics of electron pair



No polarization.



by K.Ishikawa and A.Tsuji

Polarization of virtual photons

- **Di-electron production rate**

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  - Last factor is approximated as a constant term.
  - **For B≠0 case, virtual photon decay is anisotropic.**

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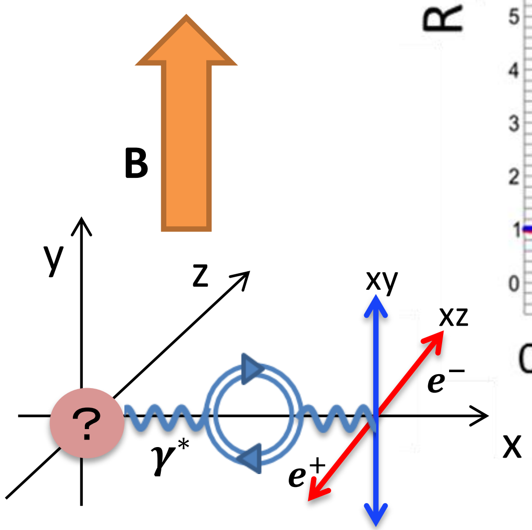
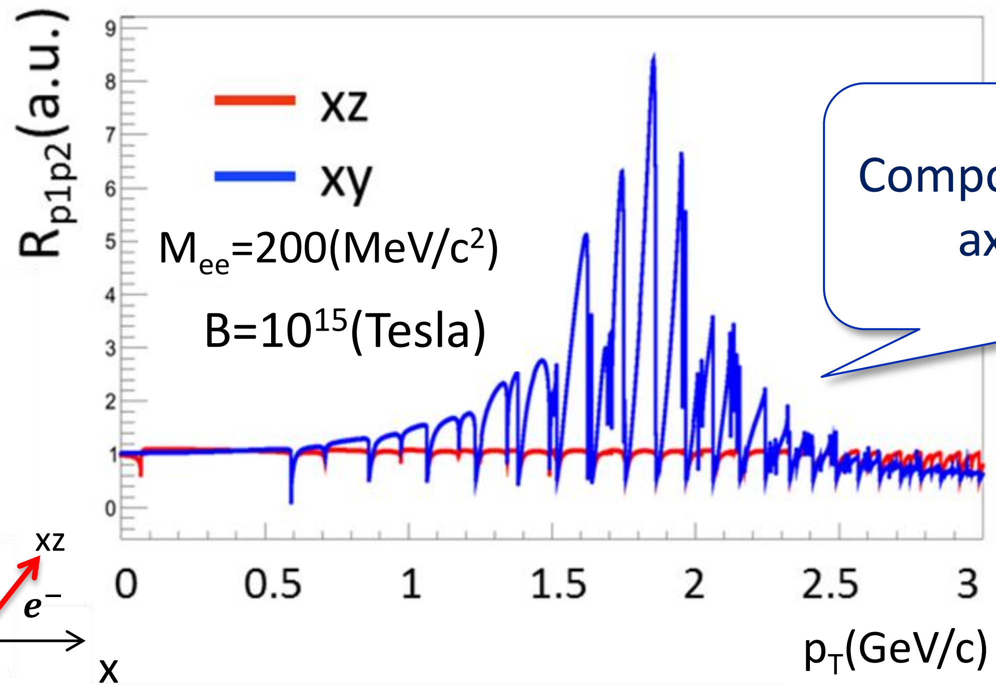




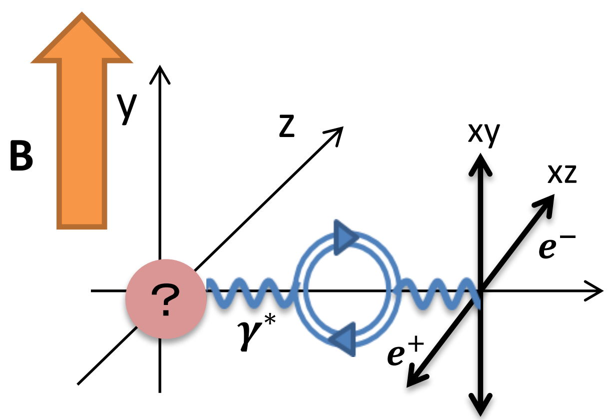
Component along the B axis increases!

by K.Ishikawa and A.Tsuji

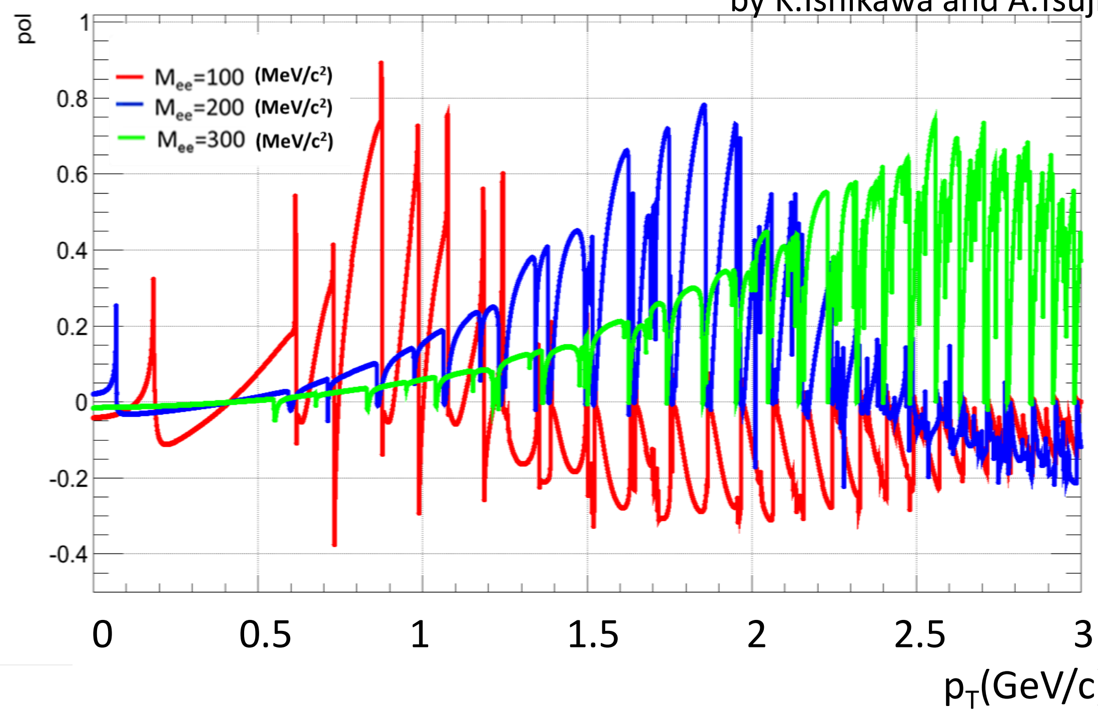
Polarization of virtual photons

$$polarization = \frac{R_{xz} - R_{xy}}{R_{xz} + R_{xy}}$$

R:di-electron production rate
including leg-electron information



Polarization of virtual photons (B=10^{15}Tesla)
by K.Ishikawa and A.Tsuji



Virtual photons are polarized in the order of 10^{-1}!!

Experimental approach

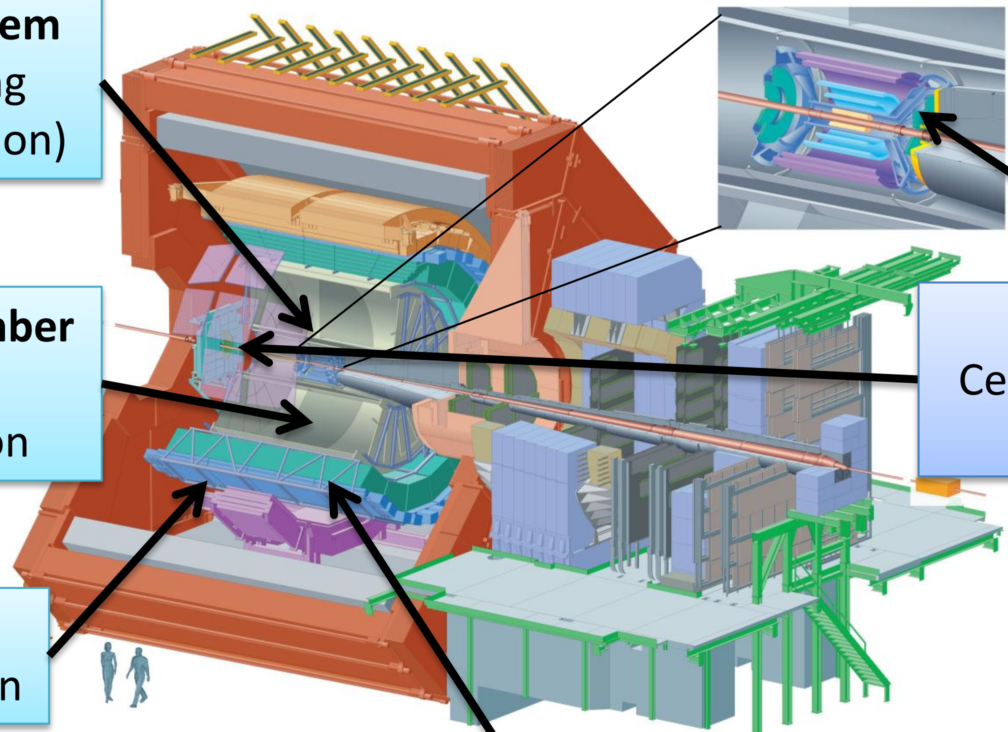
The ALICE Detector

Low mass di-electron analysis with event plane(E.P.)

Inner Tracking System
Tracking/Vertexing
(particle identification)

Time Projection Chamber
Tracking
particle identification

Time Of Flight
particle identification



VZERO A&C
Centrality/Event plane
determination

Transition Radiation Detector
High p_t electron identification

Feasibility of field detection @ ALICE

Example: 2011Pb-Pb $\sqrt{S_{NN}}$=2.76TeV 0-10% central

(Real analysis will utilize non-central collisions.)

$0.1\mathrm{GeV}/c^2 \le M_{ee} \le 0.3\mathrm{GeV}/c^2$, $1.0\mathrm{GeV}/c \le p_t^{pair} \le 2.0\mathrm{GeV}/c$

$$\text{statistical significance} = \frac{\text{signal}}{\sqrt{\text{signal} + \text{background}}}$$

$$\approx \frac{N_{e^+e^-}^{all} \times S/B_{cb} \times (1 - f_{hadronic}) \times R_{E.P.} \times A}{\sqrt{N_{e^+e^-}^{all}}}, \frac{N_{e^+e^-}^{all}/2 \times S/B_{cb} \times (1 - f_{hadronic}) \times R_{E.P.} \times P}{\sqrt{N_{e^+e^-}^{all}/2}}$$

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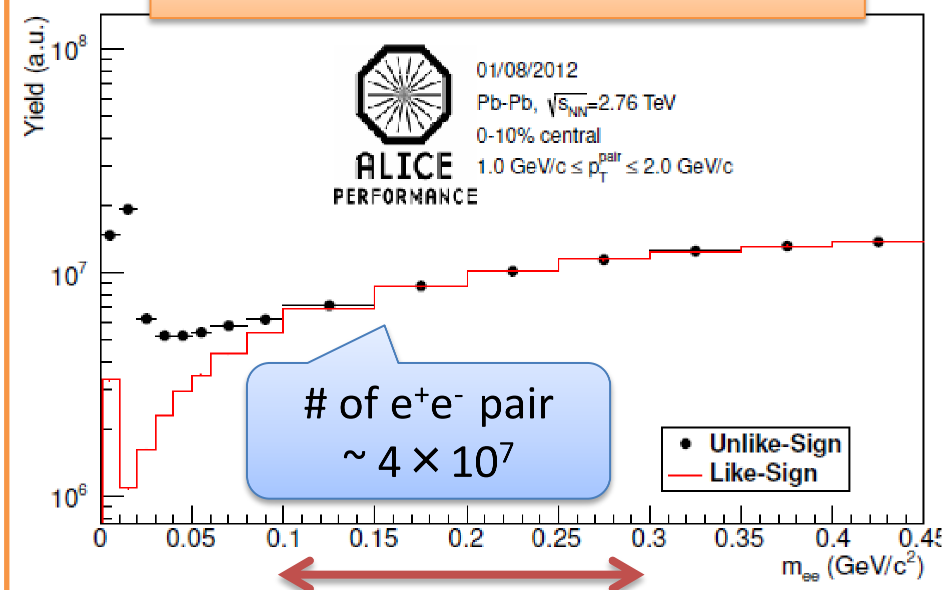
✓ # of all e$^+$e$^-$ pair ~4×10^7

ALICE statistics in 2011 Pb-Pb



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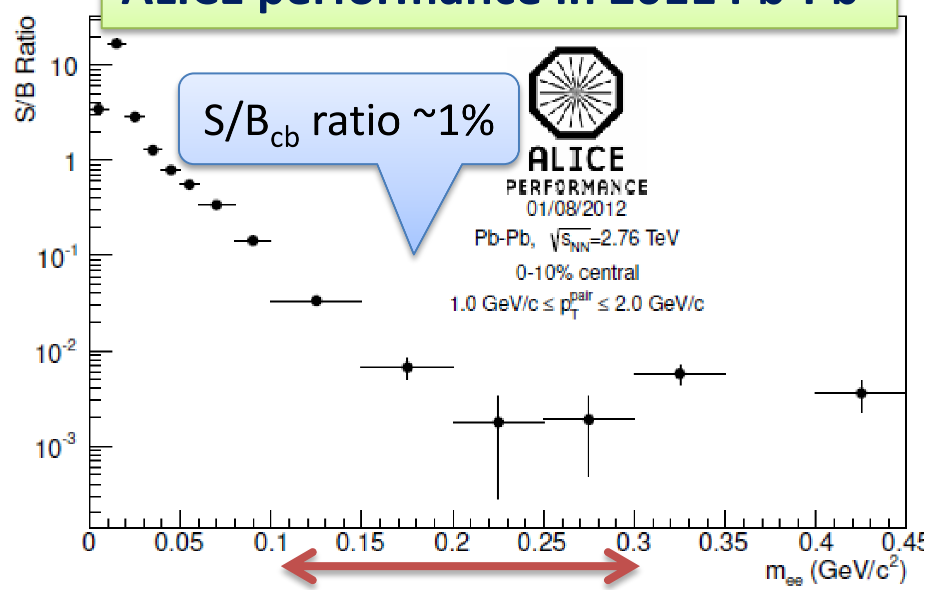
- ✓ # of all e^+e^- pair ~4×10^7
- ✓ S/B_{cb} ratio ~1%

ALICE performance in 2011 Pb-Pb



ALICE

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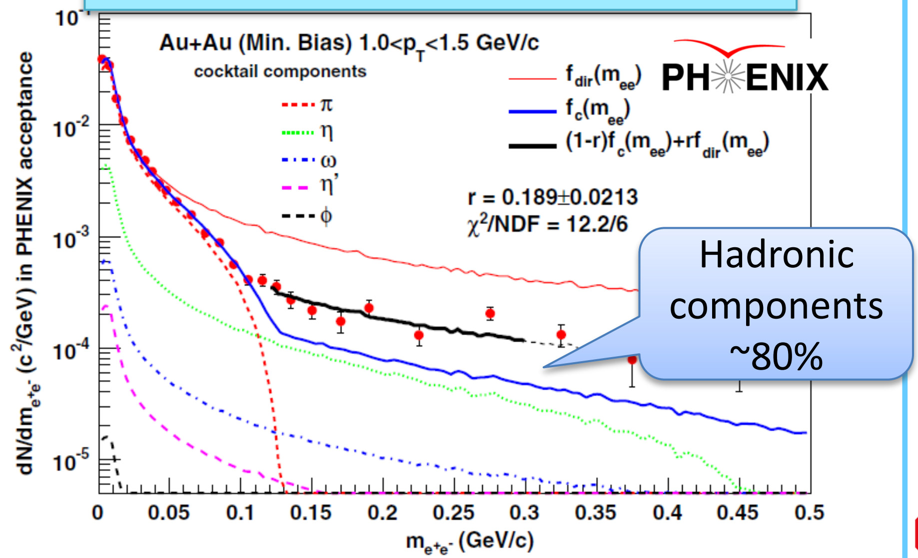
- ✓ # of e^+e^- pair ~4×10^7
- ✓ S/B_{cb} ratio ~1%
- ✓ Direct components ~20%

borrowed from PHENIX
(PRL 104, 132301 (2010))



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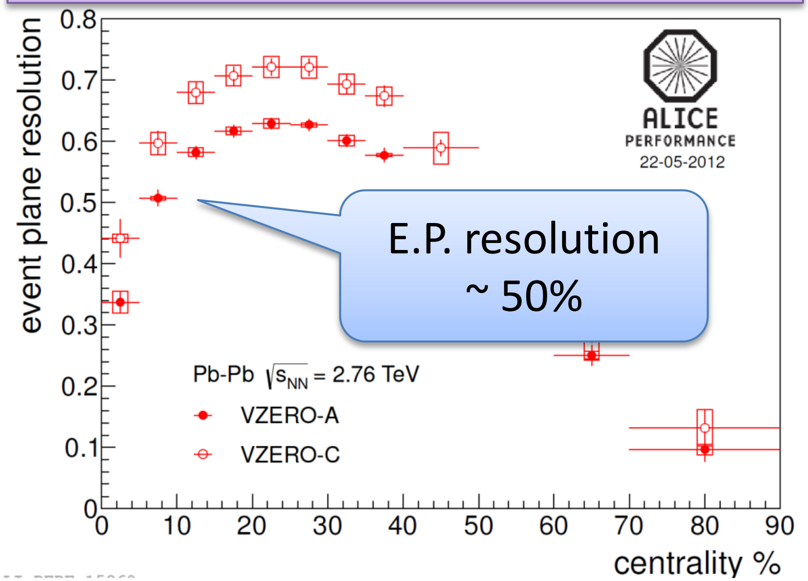
- ✓ # of all e^+e^- pair ~4×10^7
- ✓ S/B_{cb} ratio ~1%
- ✓ Direct components ~20%
- ✓ E.P. resolution ~ 50%

ALICE performance in 2011 Pb-Pb



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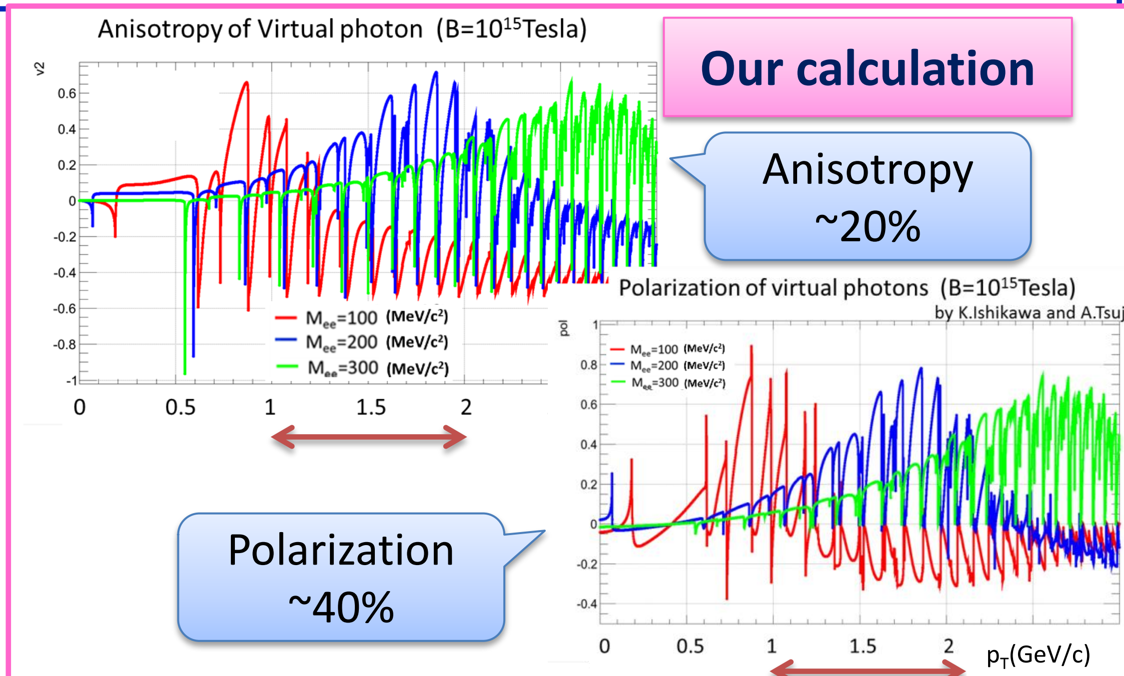
- ✓ Direct components ~20%
- ✓ E.P. resolution ~ 50%
- ✓ Anisotropy ~20%
- ✓ Polarization ~40%



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- ✓ S/B_{cb} ratio ~1%
- ✓ Direct components ~20%
- ✓ E.P. resolution ~ 50%
- ✓ Anisotropy ~20%
- ✓ Polarization ~40%

Expected statistical significances

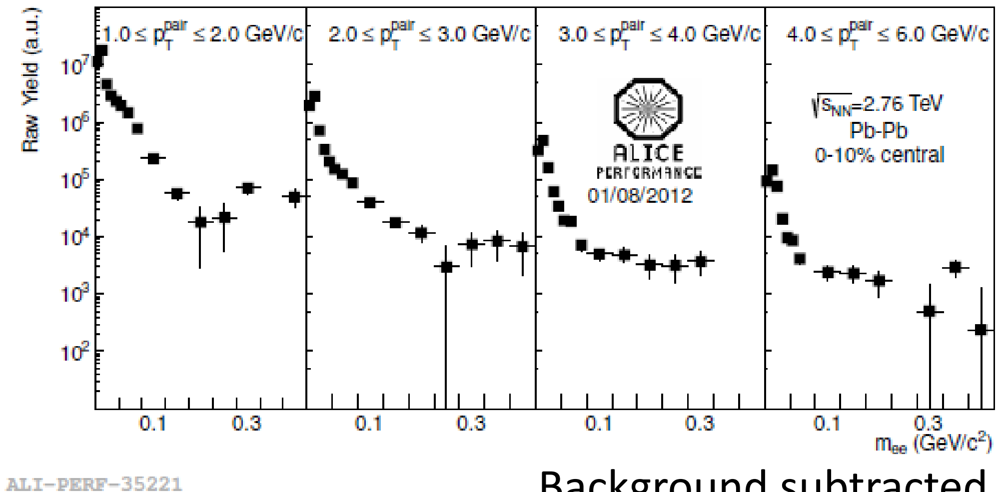
Anisotropy ~1σ

Polarization ~2σ

having possibility that we detect the field !!!

Ongoing efforts of real data analysis

- **ALICE low mass e^+e^- analysis framework already exists.**



Background subtracted di-electron signal

- **Under development**
  1. combine with event plane information
     - to see the magnetic field axis
  2. add leg-electron three dimensional momentum information
     - to see direction of decay angle with respect to E.P. (B field)

Summary & Conclusion

- **Ultra-strong magnetic field in HIC**
  - B~10^{15}Tesla @LHC, B~10^{14}Tesla@RHIC
  - The field is above B_c even after a few fm/c
  - Various interesting phenomena are under discussion
- **Studying to detect the field via virtual photon measurements at ALICE**
  - Estimation of effects of the field
    - Anisotropy of virtual photon : $o(10^{-1})$
    - Polarization of virtual photon : $o(10^{-1})$
  - Feasibility of detection of the field
    - Anisotropy of virtual photon : o(1σ)
    - Polarization of virtual photon : o(1σ)

I'm analyzing real data and shall show you results in the near future!!

Back up !!

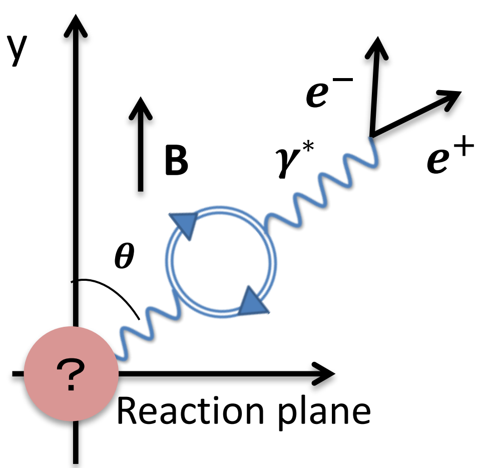
Di-electron production rate

$$R_q \equiv \frac{R_{e^+e^-}}{d^4q} = -\frac{\alpha^2}{3\pi^3} q^2 g^{\mu\alpha} D_{\mu\nu}(q,eB) D_{\alpha\beta}(q,eB)^* \frac{\operatorname{Im} G_R^{\nu\beta}(q,T,eB)}{e^{q^0/T}-1}$$

q : 4D momentum of electron pair

$$R_{p_1p_2} \equiv \frac{E_1E_2 dN_{e^+e^-}}{d^3p_1 d^3p_2 d^4x} = \frac{\alpha^2}{2\pi^4} L^{\mu\nu}(p_1,p_2) D_{\mu\alpha}(q,eB) D_{\nu\beta}(q,eB)^* \frac{\operatorname{Im} G_R^{\alpha\beta}(q,T,eB)}{e^{q^0/T}-1}$$

$p_{1,2}$: 4D momentum of leg-electron



$$\frac{\operatorname{Im} G_R^{\nu\beta}(q,T,eB)}{e^{q^0/T}-1} = (-g^{\alpha\beta}q^2 + q^\alpha q^\beta)C$$

$$D_{\mu\nu}(q) = \frac{-i}{q^2}\left(g^{\mu\nu} - \frac{1}{q^2}\Pi^{\mu\nu}(q)\right)^{-1}$$

$$L^{\mu\nu} = p_1^\mu p_2^\nu + p_1^\nu p_2^\mu - (p_1 \cdot p_2 + m_e^2) g^{\mu\nu}.$$

- *G* is the retarded Green function of electric current in the thermal and magnetic environment and source of the virtual photons.
- It is still difficult to argue for the detail of the virtual photon source in the heavy ion collision and here we do not consider them, for which we employ a simple constant form with current coservation projection;

$$\boxed{\frac{\mathrm{Im}\, G_R^{\nu\beta}(q,T,eB)}{e^{q^0/T}-1} = (-g^{\alpha\beta}q^2 + q^\alpha q^\beta)C}$$

Photon vacuum polarization tensor in strong B

$$\boxed{\begin{aligned}\Pi^{\mu\nu}(q,B) = &\left[\left(g^{\mu\nu}q^2 - q^\mu q^\nu\right) - \left(g_\parallel^{\mu\nu}q_\parallel^2 - q_\parallel^\mu q_\parallel^\nu\right) - \left(g_\perp^{\mu\nu}q_\perp^2 - q_\perp^\mu q_\perp^\nu\right)\right]\overline{N}_0 \\ &+ \left(g_\parallel^{\mu\nu}q_\parallel^2 - q_\parallel^\mu q_\parallel^\nu\right)\overline{N}_1 + \left(g_\perp^{\mu\nu}q_\perp^2 - q_\perp^\mu q_\perp^\nu\right)\overline{N}_2\end{aligned}}$$

$$\overline{N}_j = -\frac{\alpha}{4\pi}\int_{-1}^{1} dv \int_{0-i\varepsilon}^{\infty-i\varepsilon} \frac{dz}{z}\left[e^{-i\Phi}\frac{z}{\sin z}F_j(v,z) - [\text{c.t.}]\right]$$

$$F_0(v,z) = \cos(vz) - v\frac{\cos(z)\sin(vz)}{\sin z}, F_1(v,z) = (1-v^2)\cos z, F_2(v,z) = 2\frac{\cos(vz) - \cos z}{\sin^2 z}$$

$$[c.t.] = (1-v^2)e^{-i\frac{z}{\mu}},\ \Phi \equiv \frac{1-(1-v^2)r}{\mu}z - 2\frac{\cos(vz) - \cos z}{\sin z}\frac{q}{\mu},$$

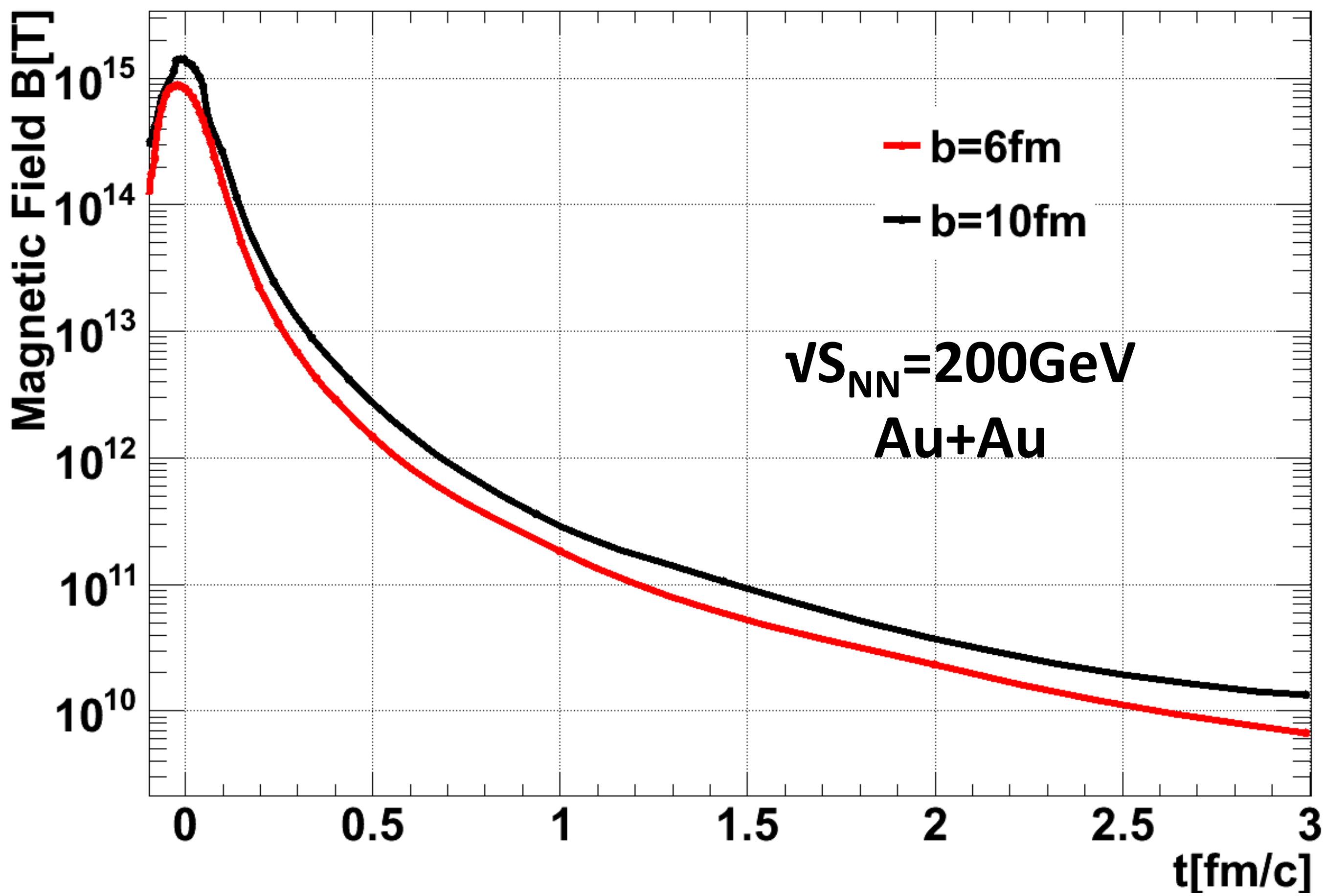
$$\mu \equiv \frac{m^2}{eB},\quad r \equiv \frac{q_\parallel^2}{4m^2},\quad q \equiv \frac{q_\perp^2}{4m^2},\quad q_\parallel^2 = (q_t)^2 - (q_z)^2,\ q_\perp^2 = -(q_x)^2 - (q_y)^2$$

Tsai,Phys.Rev.D10(1974); Baier,Katkov,Strankhovenko,Sov.Phys.JETP41(1975); Melrose,Stoneham,J.Phys.A.Math.Gen.10(1977)…..

ALICE

Time dependence

- **Impact parameter = 6,10fm, spectators only**



By using JAM model