広島大学

Quark Physics Laboratory
Hiroshima University, Japan

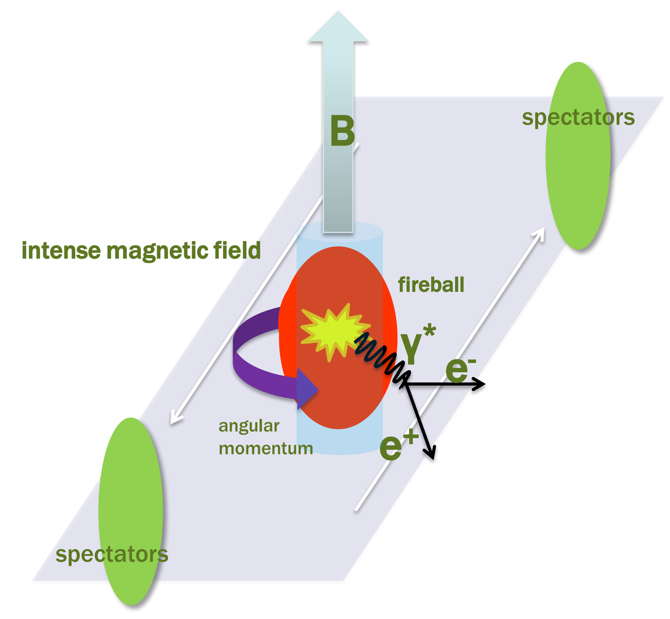
Hiroshima University Theoretical Particle Physics Group

Intense Magnetic Field Production in Non-Central Relativistic Nucleus-Nucleus Collisions

Kenta Shigaki, Ken-Ichi Ishikawa, and Asako Tsuji (Hiroshima University)

Physics Interests

A very intense magnetic field is expected in non-central nucleus-nucleus collisions, and to reach ~ 10^{14} T at the LHC energies. Not only being the strongest magnetic field in the Universe (*cf.* ~ 10^{11} T on the surface of magnetars), various consequences of physics interests are in discussion, including chiral magnetic effects (K.Fukushima, D.E.Kharzeev, H.J.Warringa, PRD78 (2008) 074033), synchrotron radiation, and non-linear behaviors of QED *e.g.* photon splitting and real photon decaying into di-leptons.



Unsung Experimental Topic

It should be noted that the field itself in nucleus-nucleus collisions is yet to be directly detected, along with the physics interests on the various consequent phenomena. Even though the field is generated by well-understood electro-magnetism and the component by the passing spectator nucleons is straightforward to calculate, the space-time evolution of the field is governed by that of the whole collision system. With a goal to directly detect and determine the field, we evaluate its expected intensity and lifetime based on cascade and static models, and its possible effects on real/virtual photon anisotropy and polarization based on QED calculations of polarization tensors. New approaches are then proposed and examined if feasible to detect the field via direct virtual photon (di-lepton) measurements at LHC-ALICE and RHIC-PHENIX experiments.

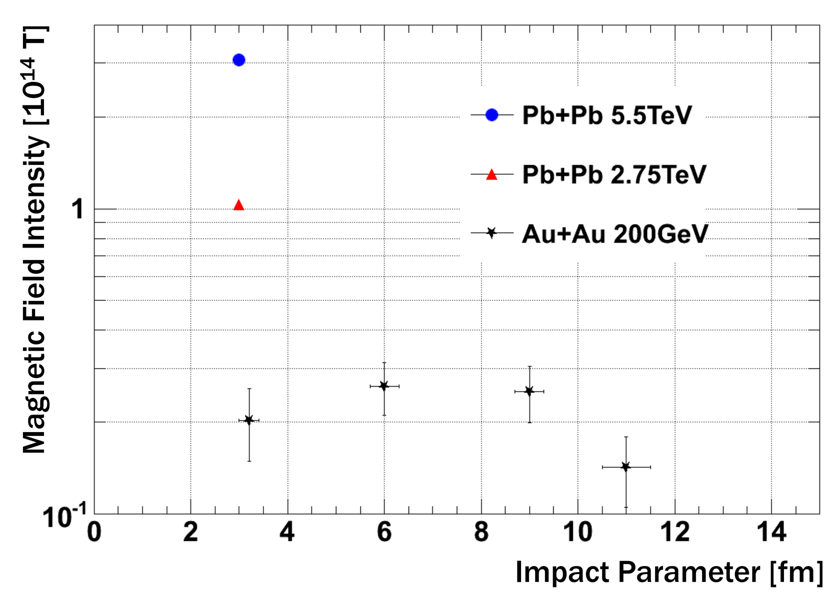
Field Intensity Estimations by Cascade Models

One of the standard approaches to estimate the magnetic field intensity in nucleus-nucleus collisions is to utilize cascade models, *e.g.* HIJING, JAM, *etc.*. A result showing the time evolution of the field is presented below. The cascade models predict the main component of the field is generated by the spectator nucleons, leading to the peripheral collisions to reach the maximum field intensity. The spectator component also grows with the beam energy in proportion to the $\beta\gamma$, while its lifetime gets inverse-proportionally shorter. Another component by the participant nucleons, or by the rotating fireballs after the collisions, is found to have much lower peak intensities, but with longer lifetimes. A hydro-dynamical model with local velocity distributions as an initial condition is desired for a better prediction of the potentially long-lived participant contribution, as the evolution of the component by the "perfect fluid" fireball may not be very properly handled in the present cascade models.

Data-Driven Estimation of Field Intensity in Fireball

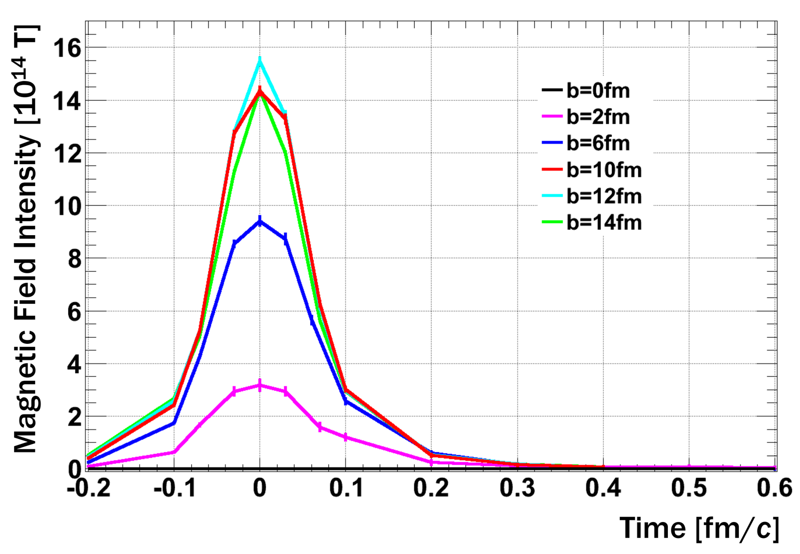
The fireball after a collision has an angular momentum in non-central cases as the finite stopping of the incoming nuclei leaves a fraction of the initial angular momentum of the system there. The field intensity due to the angular momentum of the positively charged fireball is evaluated by a Glauber calculation and the baryon stopping power based on real data and simulations. The results are shown in the plot on the right. It is found that the effect is most prominent in semi-central collisions, like the elliptic flow is.

Estimated Participant/Fireball Contribution



All the participant nucleons would contribute to the magnetic field at the center of the fireball if the complete nuclear stopping is achieved. The reality effect of finite stopping is evaluated from the net-proton (proton minus anti-proton) densities in the mid-rapidity region. The stopping power in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV is from BRAHMS data (BRAHMS Collaboration, PRC72 (2005) 014908). Those in Pb+Pb collisions at $\sqrt{s_{NN}}$ = 2.75 and 5.5 TeV are from simulations (Y.Mehtar-Tani, G.Wolschin, PLB688(2010)174).

Field Intensity Estimation with a Cascade Model JAM



A hadron cascade model JAM (Y.Nara, N.Otuka, A.Ohnishi, K.Niita, S.Chiba, PRC61 (2000) 024901) is used as a first step to estimate the magnetic field intensity in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. Such cascade models indicate that the spectator component is the dominant contribution, leading to the maximum field intensity reached in peripheral collisions, though with a relatively short lifetime. It should be however noted that the participant/fireball contribution may not be handled very properly in this type of models.

Experimental Approaches and Feasibilities

New approaches to detect the magnetic field via virtual photon (low mass di-lepton) measurements are proposed and their experimental feasibilities are under examination.

(1) anisotropy of direct virtual photons. The existence of an intense magnetic field allows virtual photons to decay into di-leptons only at the Landau levels, and hence affect the production rate of di-leptons. QED calculations of vacuum polarization tensors of photons indicate the effect is in the order of $o(10^{-2})$ with the field intensity expected at LHC and RHIC, which is within an experimental reach though challenged by other sources of anisotropy also known as the elliptic flow.

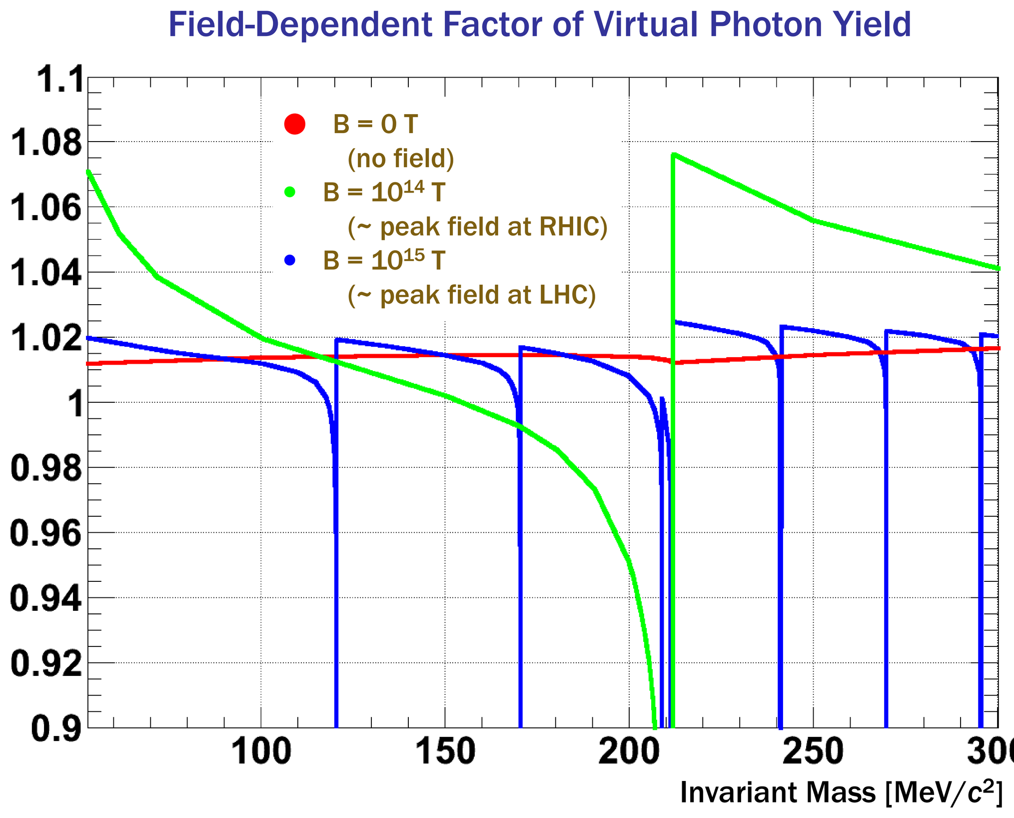
(2) polarization of direct real/virtual photons. Photons get polarized in magnetic field. That of virtual photons is an especially promising probe, while none of current heavy ion experiments at LHC or RHIC is capable of measuring that of real photons. The polarization should be in the similar order of magnitude to the anisotropy. In case virtual photons are polarized in the order of $o(10^{-2})$, both the LHC-ALICE and RHIC-PHENIX experiments should be marginally able to detect it assuming the statistics and signal-to-background ratios in the past data.

Predictions of Experimental Signals

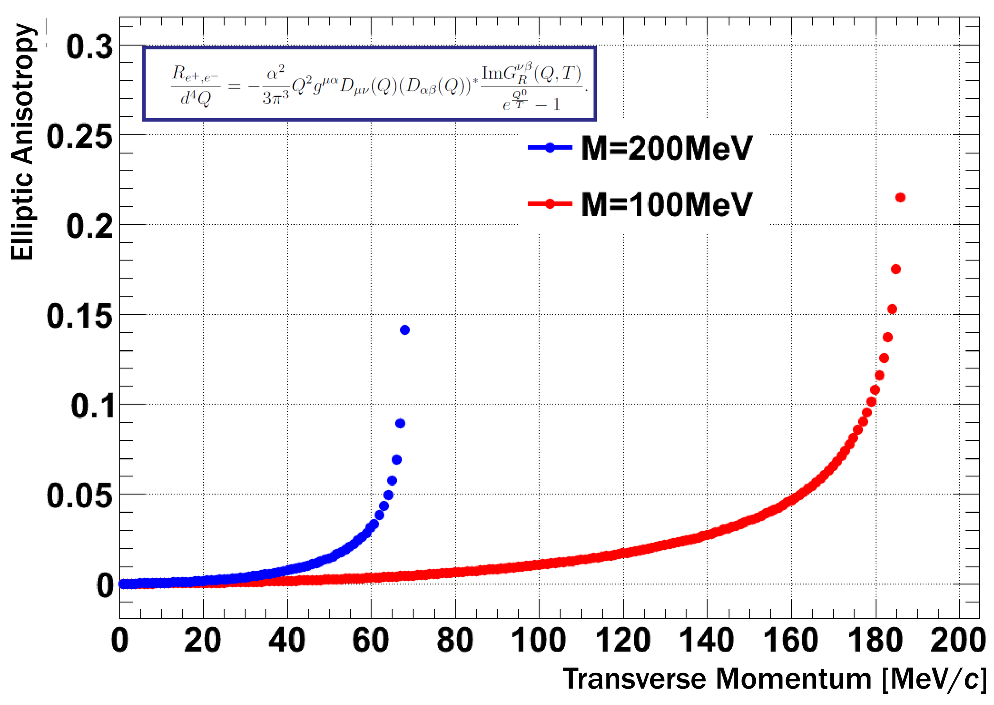
Effects of the intense magnetic field are quantitatively evaluated via QED calculations of vacuum polarization tensors of photons. As one of the first results, the expected anisotropy of virtual photons due to the field is shown in the plot below. At this moment, the calculable ranges are limited in low mass and/or low transverse momentum regions, without the di-muon channels to open. Polarization of virtual photons is also under calculation within the same framework. It can be naively expected that the polarization is in the similar order to the anisotropy, while more quantitative studies are still in progress.

The field-dependent factor of the yield of virtual photons in parallel to the magnetic field, as a function of the invariant mass, based on QED calculations of vacuum polarization tensors of photons.

Field-Dependent Factor of Virtual Photon Yield

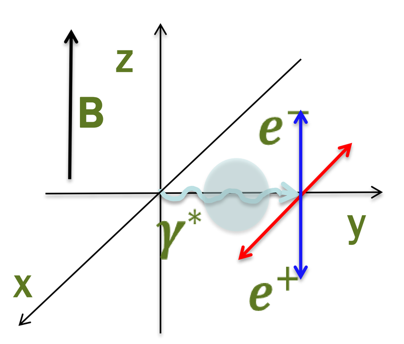


Virtual Photon Production Anisotropy

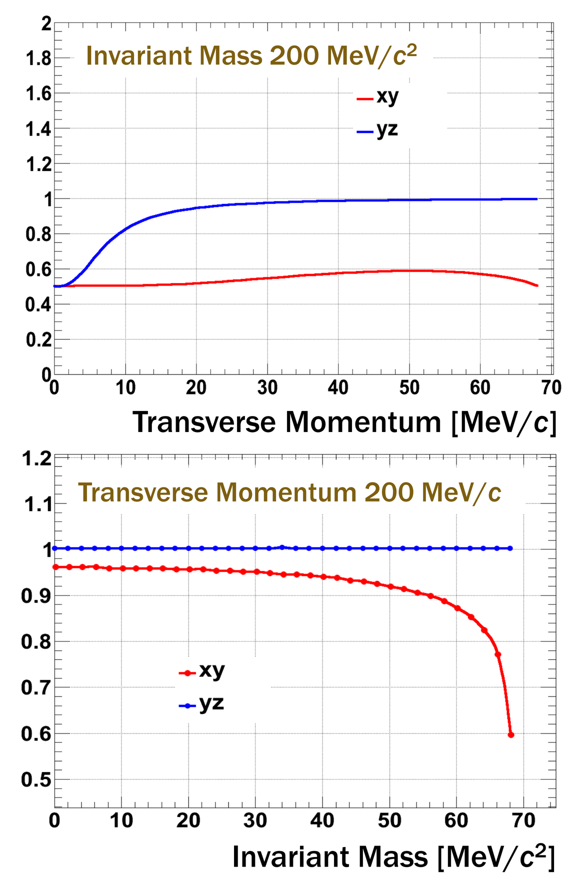


The anisotropy of virtual photon production due to the magnetic field, as a function of transverse momentum at two different invariant masses, based on QED calculations of vacuum polarization tensors of photons. B = 10^{14} T.

Virtual Photon Decay Anisotropy (Polarization)



The decay anisotropy, or the polarization, of virtual photons perpendicular to the magnetic field is calculated in low mass and/or transverse momentum regions without the di-muon channel to open.
(Top) Invariant mass = 200 MeV/c^2, B = 10^{14} T.
(Bottom) Transverse momentum = 200 MeV/c, B = 10^{14} T.



Experimental Prospects

LHC-ALICE and RHIC-PHENIX both have capabilities to measure electron pairs with respect to the reaction plane (or the vector) in nucleus-nucleus collisions. Polarization of direct virtual photons is an especially promising probe of the intense magnetic field, while the anisotropy of direct (virtual) photons due to the field may be overwhelmed by the elliptic flow and other effects. Subtraction of virtual photons from other sources, *e.g.* Dalitz decays of π^0, η, *etc.* will be a key issue. The experimental data analysis has started in parallel to theoretical predictions.

Theoretical Prospects

Calculations of virtual photon rates in higher mass and transverse momentum regions are required to match the experimentally accessible kinematic regions. An exact calculation is made in the case of photons parallel to the field even above the di-muon channel threshold. That for photons perpendicular to the field is in progress, while the lowest Landau level approximation is used for di-electron channels, to complete quantitative predictions of anisotropy and polarization of virtual photons due to the magnetic field.

presented by K.Shigaki, K.Ishikawa, and A.Tsuji (Hiroshima University) at the 23rd International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions (Quark Matter 2012) in Washington D.C., U.S.A., on August 13 - 18, 2012