高エネルギー原子核偏芯衝突における
高強度磁場生成の直接探索

志垣 賢太（ 広島大学 ）

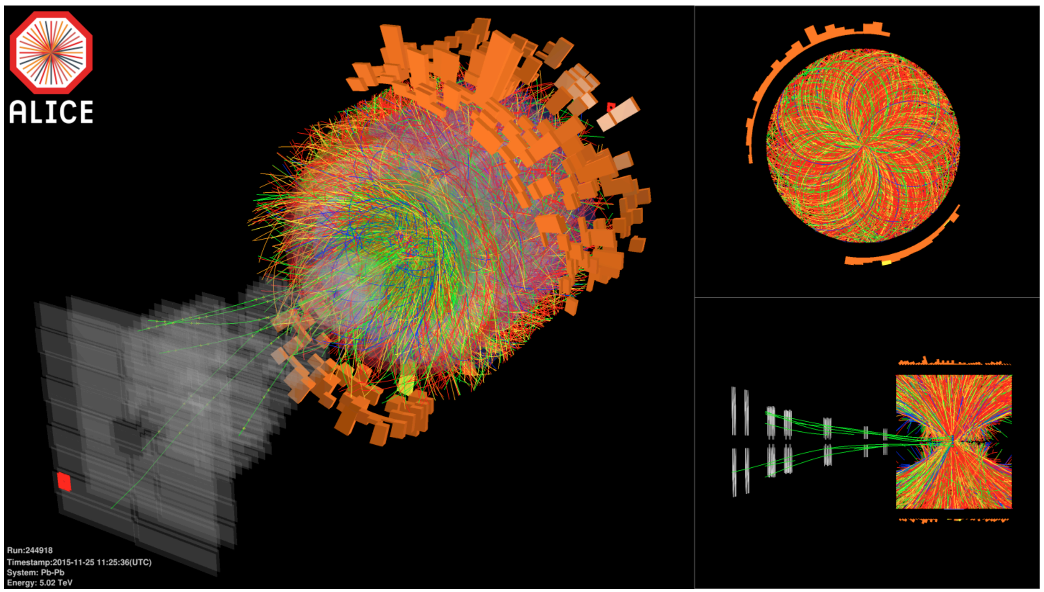
第 28 回 Heavy Ion Pub 研究会
2019 年 1 月 10 日 奈良女子大学

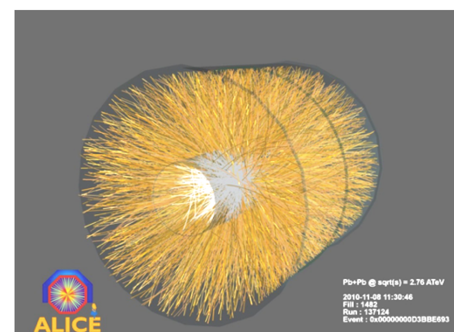
Presentation Outline

- heavy ion collisions at LHC
- physics under ultra-intense magnetic field
- field intensity and time structure
  - implication of long-lived source via vorticity
- experimental approaches
  - past attempts and key issues
- near-future prospects
  - electron and muon reunion at LHC
  - muon measurement at LHC/ALICE from 2021
- summary and concluding remarks

Pb-Pb at Highest Ever Energy

- $\sqrt{s_{NN}}$ = 5.02 TeV in 2015, 2018
  - 25 times higher than at RHIC
  - design energy at 5.5 TeV

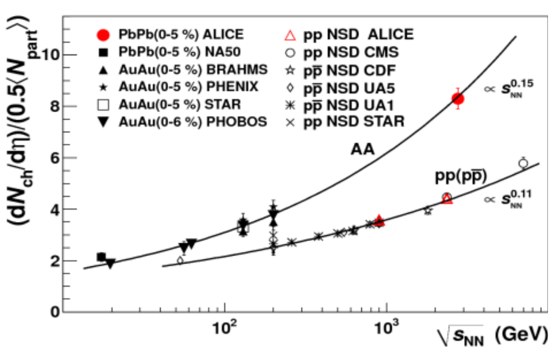


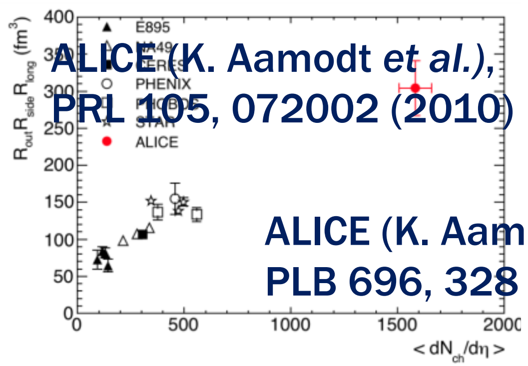


- 2.76 TeV in 2010 and 2011

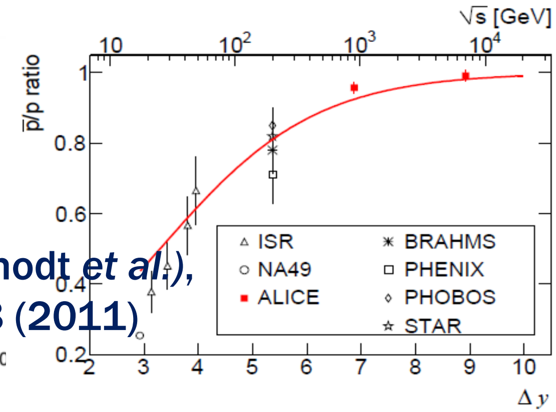
Hotter, Larger, Longer-Lived, and Purer

- fireball compared to that at RHIC
  - energy density × ~3, volume × ~2, life × 1.2–1.3
    - ~ 16 GeV/fm^3 (thermalization time ~ 1 fm/*c*)
    - ~ 300 fm^3, ~ 10 fm/*c*





ALICE (K. Aamodt *et al.*), PRL 105, 072002 (2010)



ALICE (K. Aamodt *et al.*), PLB 696, 328 (2011)

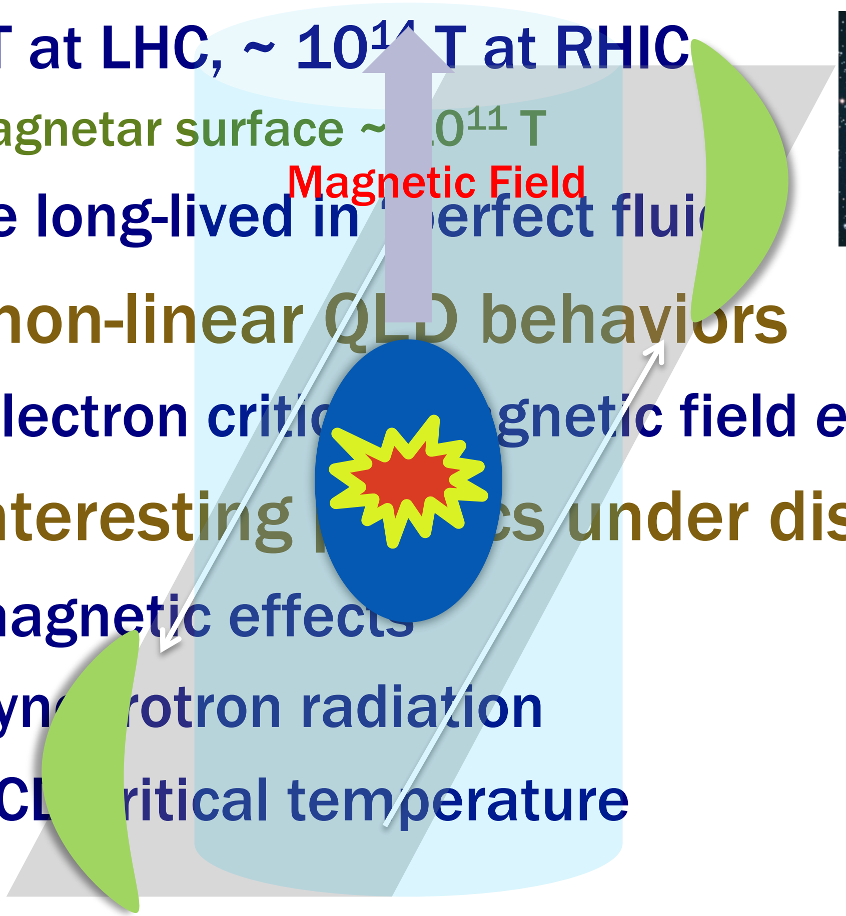
- net quark (baryon) density ~ 0
  - anti-proton/proton at mid-rapidity
    - *p*+*p* 900 GeV : 0.957 ± 0.006 (stat) ± 0.014 (sys)
    - *p*+*p* 7 TeV : 0.990 ± 0.006 (stat) ± 0.014 (sys)

Playground with Extreme Conditions

- deconfined quark/gluon phase now in hand
- quark behavior in strong QCD field
  - energy loss and redistribution
- quarks interaction in strong QCD field
  - color Debye screening to melt quarkonia
- chiral symmetry restoration
  - hadron mass modification
- more exotics
  - physics under ultra-intense magnetic field
  - ...

Ultra-Intense Magnetic Field

- U(1) magnetic field
  - naturally expected with moving charged sources (nuclei)
  - ~ 10^{15} T at LHC, ~ 10^{14} T at RHIC
    - *cf.* magnetar surface ~ 10^{11} T
  - could be long-lived in "perfect fluid"
- possible non-linear QED behaviors
  - above electron critical magnetic field $em_e^2 = 4\times10^9$ T
- various interesting physics under discussion
  - chiral magnetic effects
  - quark synchrotron radiation
  - lower QCD critical temperature

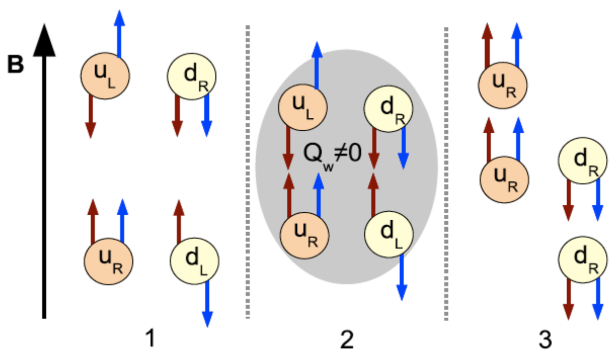


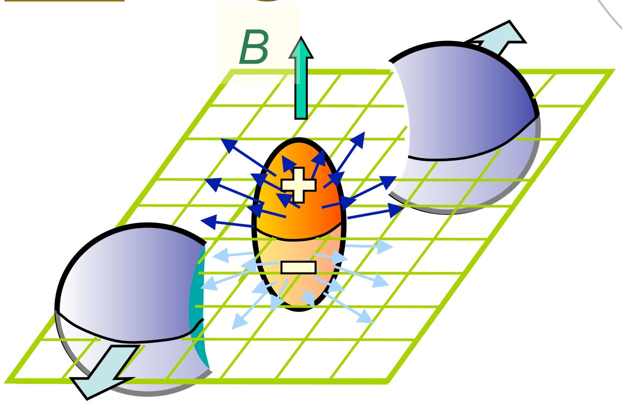
Critical Magnetic Field

- critical electric/magnetic field of electron
  - energy within Compton radius ≈ own rest mass
  - $eE_c h/m_e c = m_e c^2$; $E_c = m_e^2 c^3/eh \sim 10^{17}$ V/m
  - $eB_c h/m_e c = m_e c$; $B_c = m_e^2 c^2/eh \sim 10^9$ T
- Schwinger mechanism in case of electric field
  - e^+e^- pair production
  - no sense to consider $E > E_c$
- non-linear QED effects in case of magnetic field
  - *e.g.* $\gamma \rightarrow \gamma\,\gamma$, $\gamma \rightarrow e^+e^-$, birefringence, ...

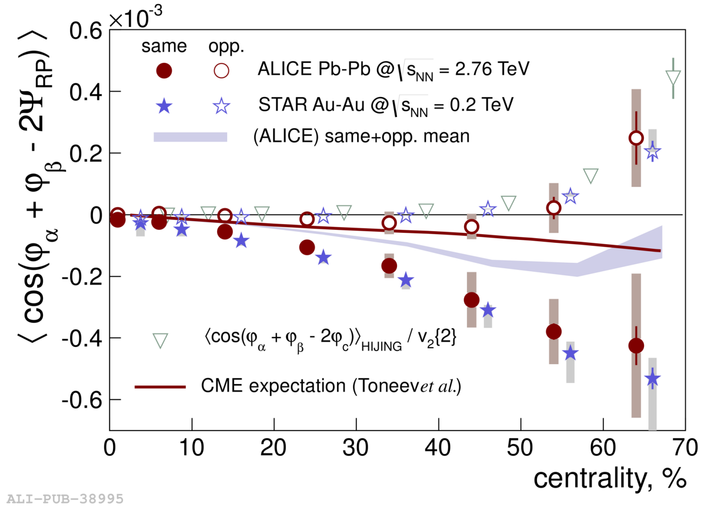
Chiral Magnetic Effects

- if strong parity violation *and* magnetic field





- charge separation, observed at RHIC and LHC



correlation between particles with different charges

correlation between particles with same charges

LPV Domain Size and Observables

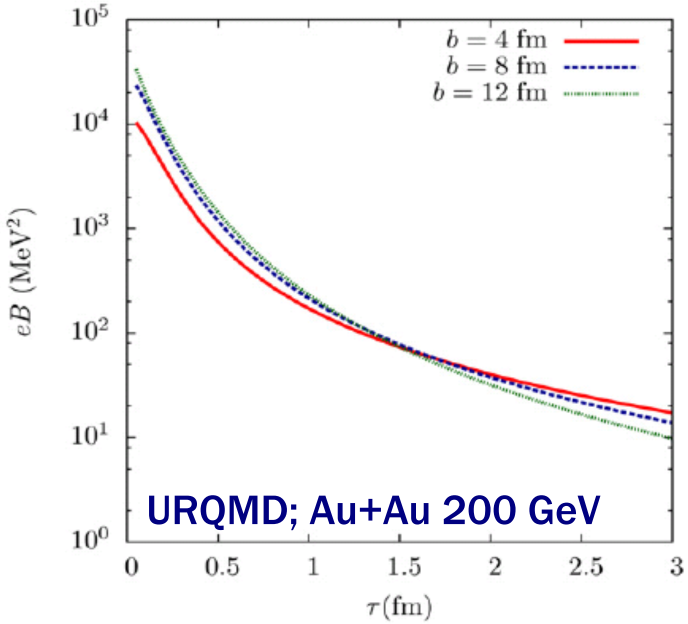
- assuming perfect alignment and distribution

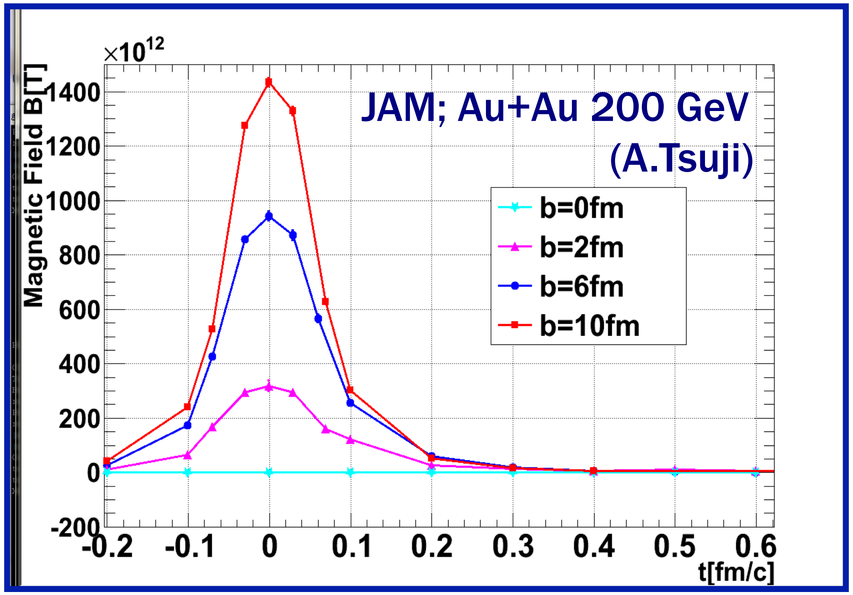
- if 1 domain, $[(n_+^{\uparrow} - n_+^{\downarrow})/(n_+^{\uparrow} + n_+^{\downarrow})]^2$ is ***always*** 1
- if 2, it is 1 (50%) or 0 (50%), *i.e.* average at 1/2
- if 3, it is 1 (25%) or 0.11 (75%), *i.e.* average at 1/3
- # domains $\leftrightarrow$ width of $[(n_+^{\uparrow} - n_+^{\downarrow})/n_+]^2$ distribution
- large N limit ≈ independent N particle production

- $[(n_+^{\uparrow} - n_-^{\downarrow})/(n_+^{\uparrow} + n_-^{\downarrow})]^2$ is ***always*** 0
  - note this ***does*** mean correlation
- large N limit ≠ independent N particle production

Field Intensity and Time Evolution

- cascade models: common approach
  - spectator contribution dominant but short lived
    - 10^{14} – 10^{15} T at LHC
    - life time < 1 fm/c due to Lorentz contraction
    - though still above m_e^2/e after several fm/c

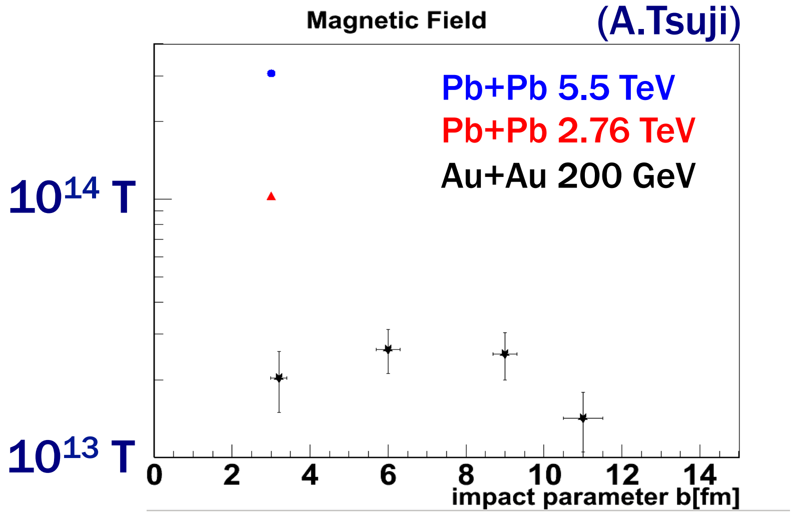




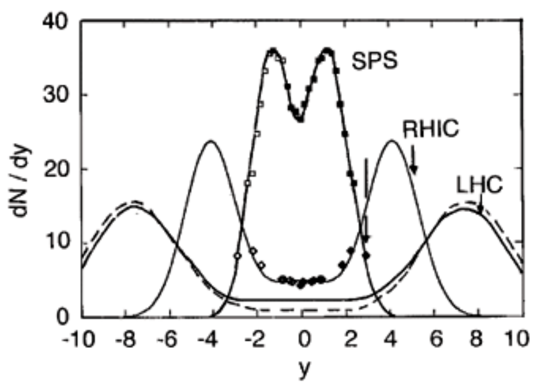
Field Sustainability Unknown

- participant contribution in "perfect fluid"?
  - "static field" approximation w/ Glauber model
    - finite baryon stopping taken into account
    - 10^{13} – 10^{14} T at LHC

(A.Tsuji)



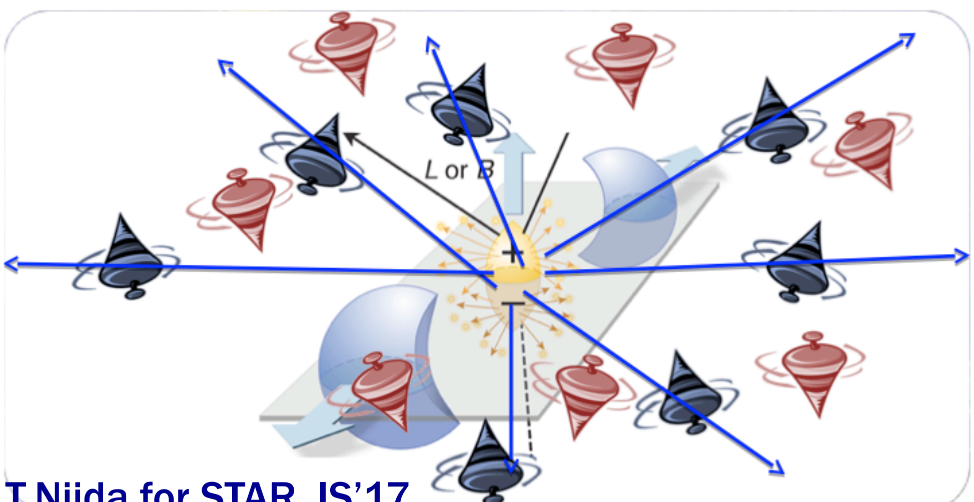
baryon stopping power
from net baryon distribution



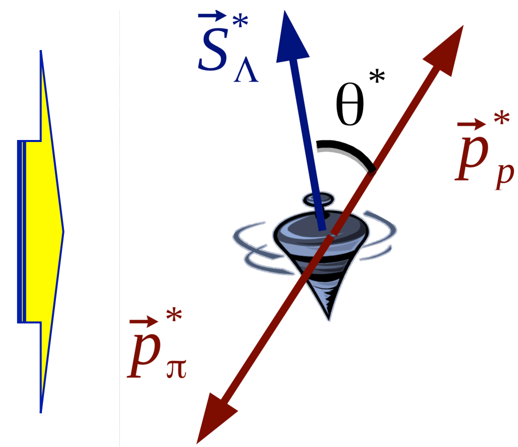
- hydro model with local charge nearly available (!)

Vorticity (and/or Magnetic Field)

- angular momentum transfer to Λ polarization
  - spin - orbit coupling
- magnetic field also possible Λ polarization source
  - opposite alignment of Λ and $\overline{\Lambda}$



T.Niida for STAR, IS'17

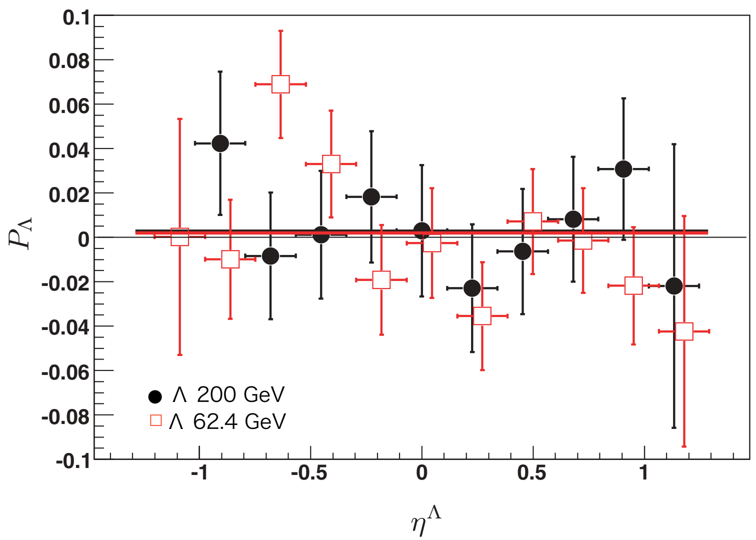


- detectable via parity violating Λ decay

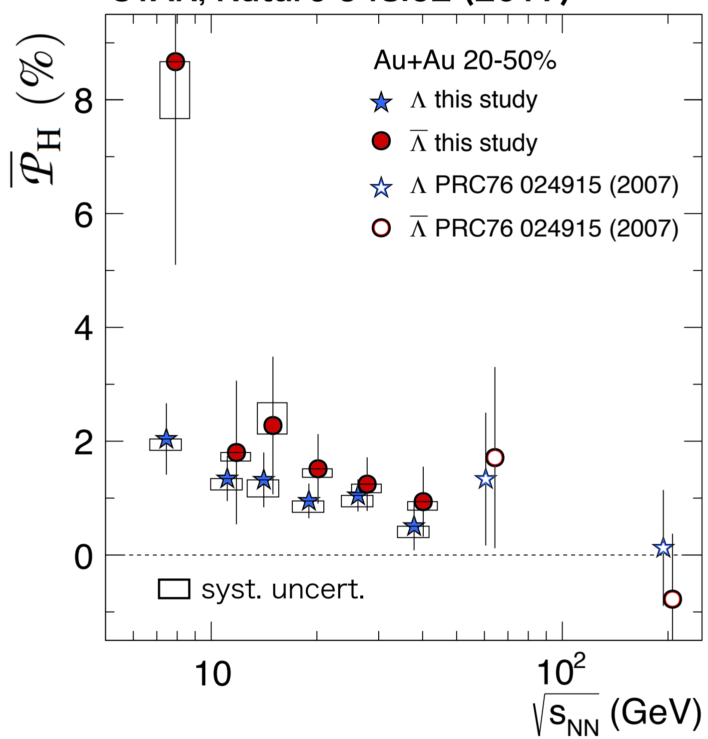
Λ Polarization Measurements

- successful example of precision improvement
  - zero consistent with upper limit at 0.2% in 2007
  - $\sqrt{s_{NN}}$ dependent polarization found by 2017

STAR, PRC76, 024915 (2007)



STAR, Nature 548.62 (2017)



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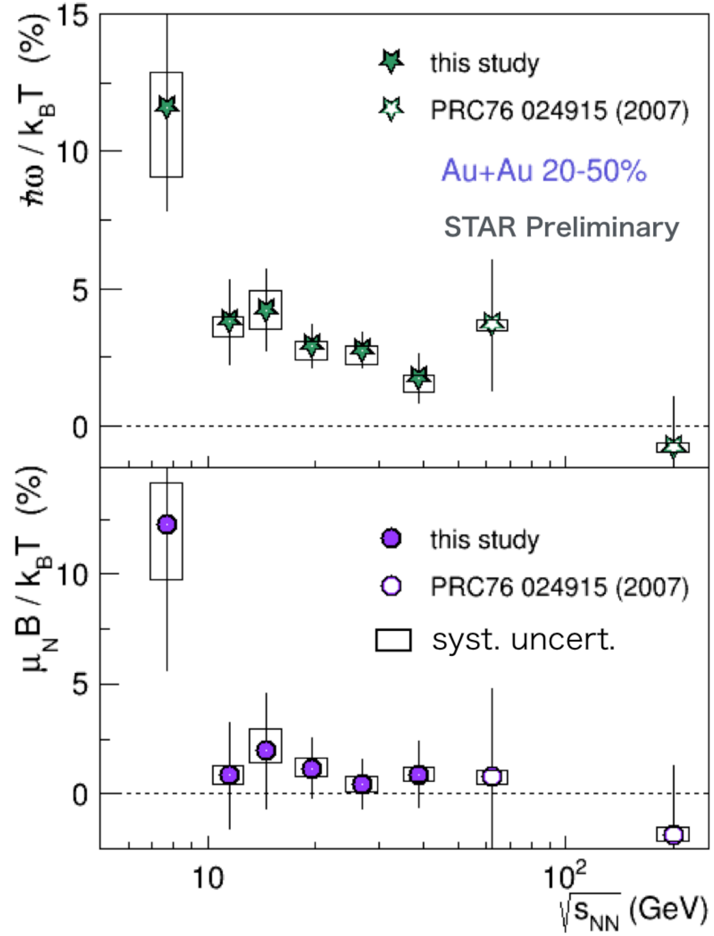
Non-Zero (and Large) Vorticity Found

- $\omega = (9 \pm 1) \times 10^{21}\ s^{-1}$
  - $\sqrt{s_{NN}}$ averaged
  - assuming T = 160 MeV
- magnetic field?
  - implied by Λ and $\bar{\Lambda}$ difference
  - though still zero consistent



T.Niida for STAR, IS'17

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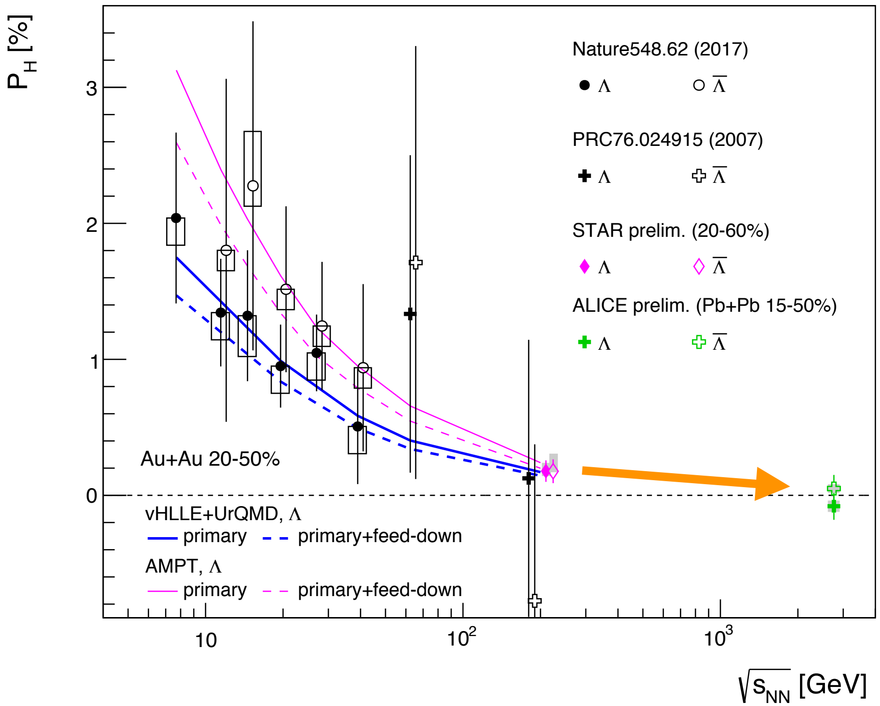
Implications for Magnetic Field Search

- magnetic field not yet caught
- long-lived medium rotation; very promising source

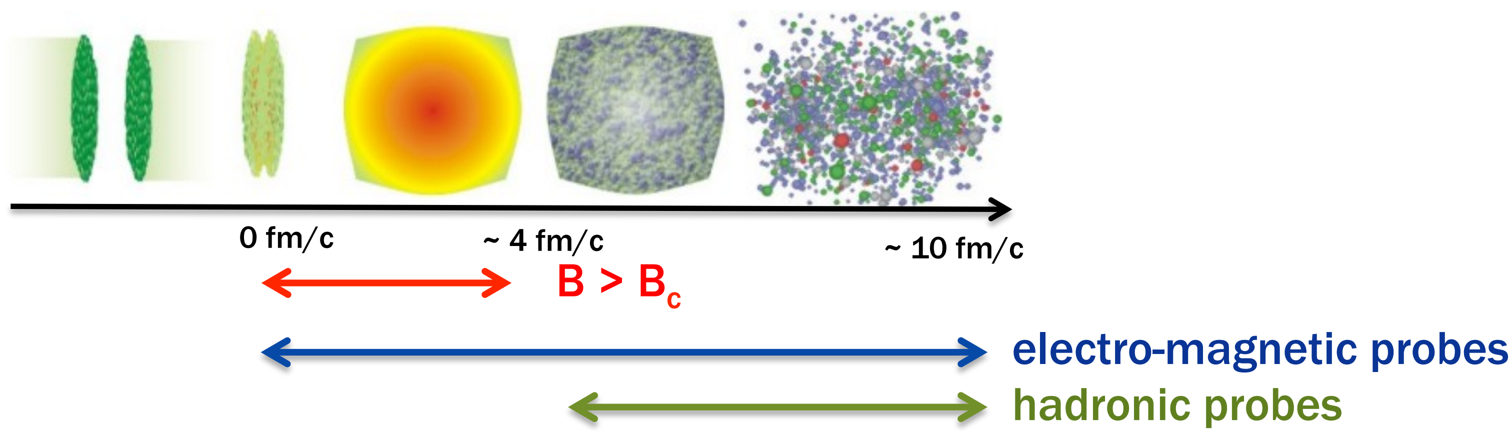


T.Niida for STAR, IS'17

- higher statistics required (and planned) at LHC

Direct Probes of Intense Field

- must originate from initial stages
  - field life time ~ 0.1 fm/c
- must be electro-magnetic

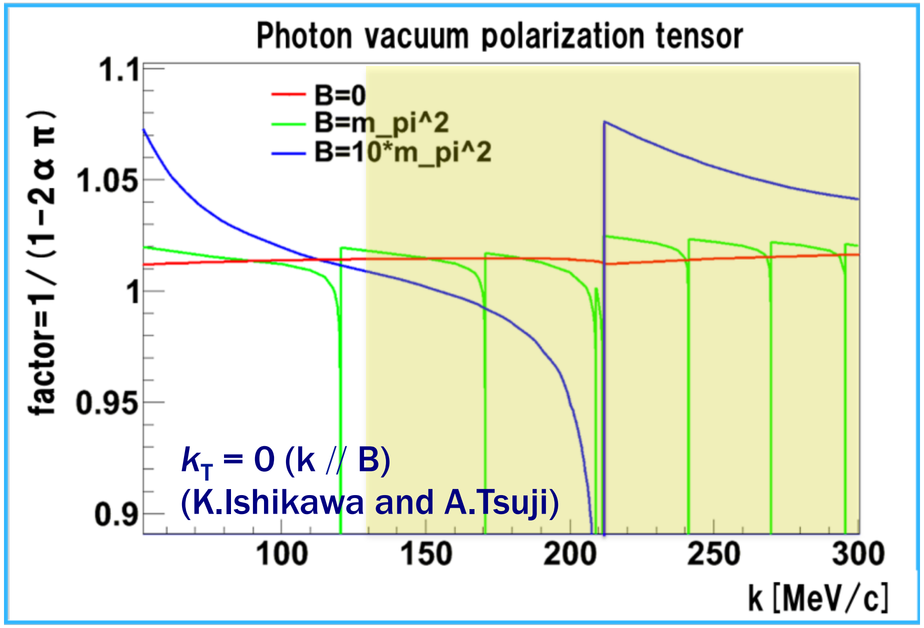


- ideal probe: direct γ/γ^* from pQCD processes
- good reference: γ/γ^* from later stages
  - e.g. π^0 decay γ/γ^* (Dalitz di-electron)

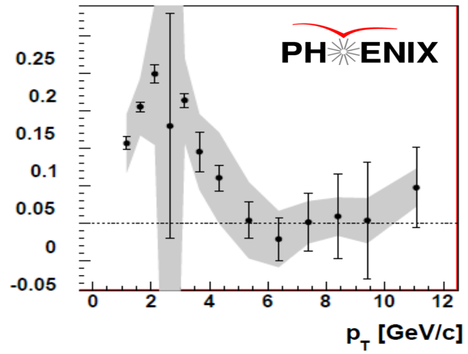
Proposal 1. Direct Photon Anisotropy

- **polarization tensor in magnetic field**
  - modification factor to $\frac{E_1 E_2 dN_{l+l-}}{d^3p_1 d^3p_2 d^4x} = \frac{\alpha^2}{2\pi^4 q^4} \frac{p_1^\mu p_2^\nu + p_2^\mu p_1^\nu - \frac{q^2}{2} g^{\mu\nu}}{\exp(q^0/T) - 1} \mathrm{Im} G_R^{\mu\nu}(q;T)$
  - seemingly $v_2 \sim o(10^{-2})$

Y.Akamatsu, H.Hamagaki, T.Hatsuda, T.Hirano
Phys. Rev. C 85, 054903 (2012)



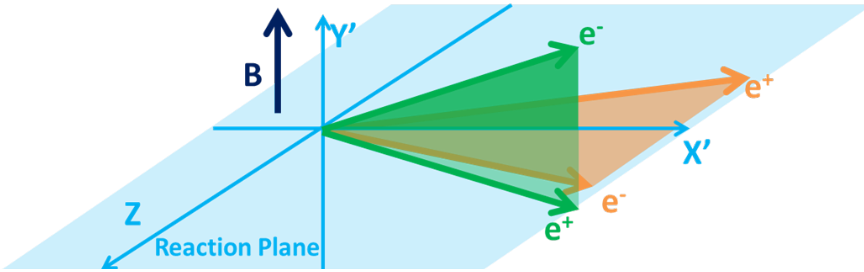
Au+Au 200 GeV (PHENIX)
20–40% centrality direct γ v_2

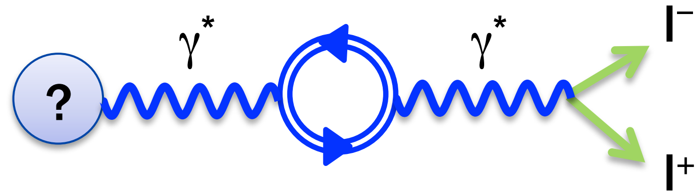


- **obvious existence of other contributions to v_2**

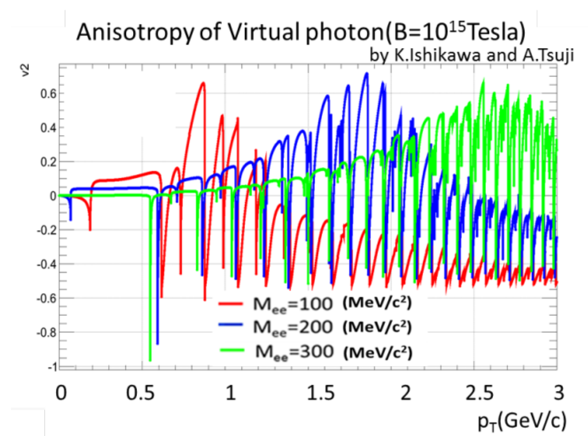
Proposal 2. Direct Photon Polarization

- anisotropic decay w.r.t. magnetic field





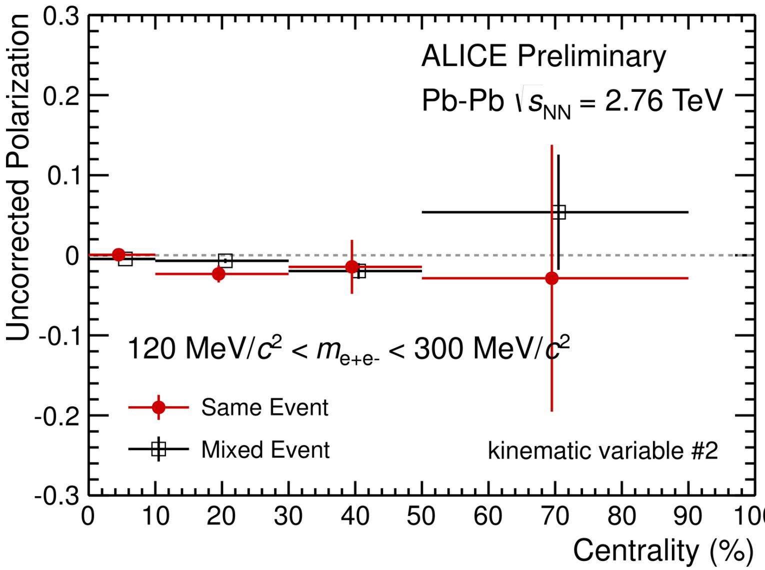
- feasibility study based on QED calculations
  - vacuum polarization tensors under magnetic field
    - summation for infinite Landau levels
    - photon momentum up to ~ GeV
    - *ref.* K.-I. Ishikawa, K. Shigaki, *et al.*, Int. J. Mod. Phys. A28, 1350100 (2013)



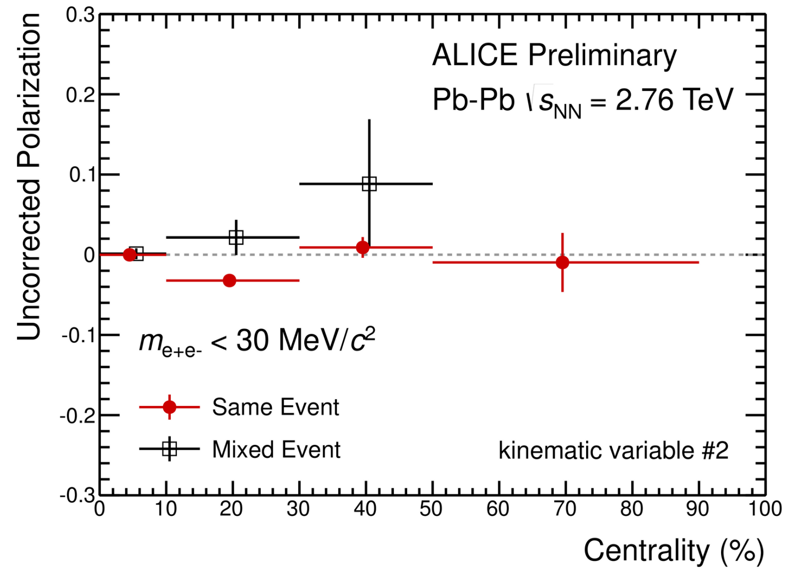
- anisotropy ~ $o(10^{-1})$

Preliminary Analysis in ALICE Run 1

- intermediate mass region containing direct γ*
  - though combinatorial dominant
- low mass region as reference
  - Dalitz decay dominant



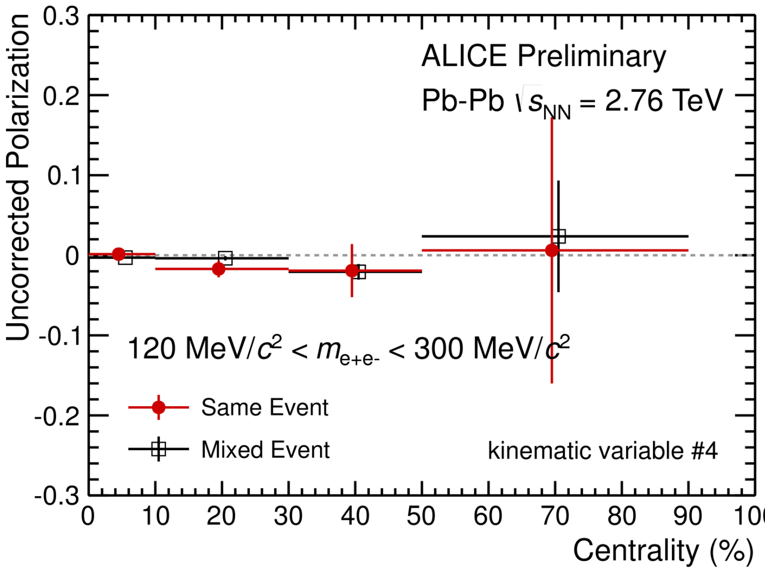
ALI-PREL-69180



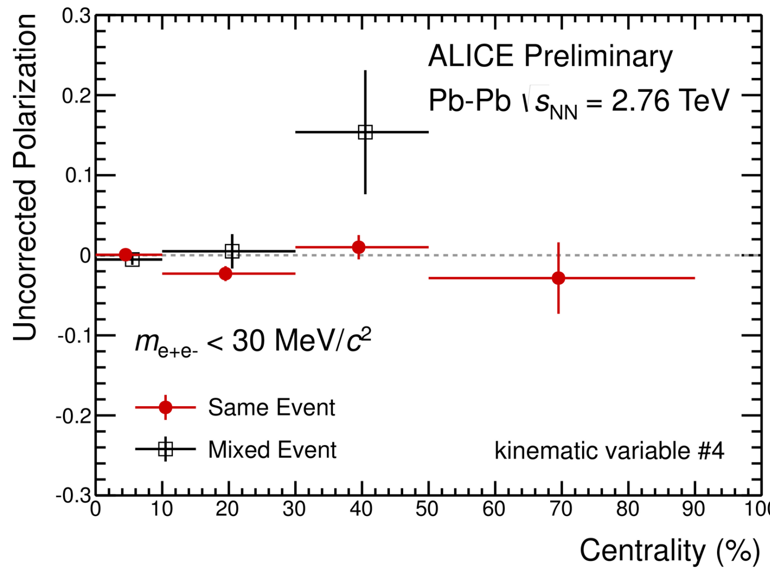
ALI-PREL-69172

Preliminary Analysis in ALICE Run 1

- intermediate mass region containing direct γ*
  - though combinatorial dominant
- low mass region as reference
  - Dalitz decay dominant



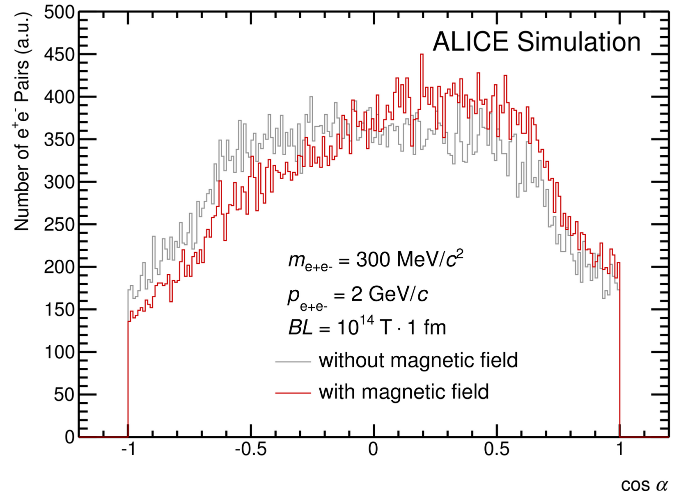
ALI-PREL-69184



ALI-PREL-69176

Proposal 3. Femto-Spectrometer

- bending power *Bdl* ~ 10^{14} T×10^{-15} m
- → bending angle ~ $3\times10^{-2}/p$ [rad/(GeV/*c*)]
- detectable as opening angle offset
  - e^+/e^- bent in opposite way around magnetic field axis
    - reaction axis from directional flow (v_1) in forward/backward
  - *o*(1) degree for *o*(1) GeV/*c* particles!



ALI-SIMUL-69193

Not Even Preliminary

- intermediate mass region containing direct γ*
  - though combinatorial dominant
- low mass region as reference
  - Dalitz decay dominant

Not Even Preliminary

- intermediate mass region containing direct γ*
  - though combinatorial dominant
- stronger deflection expected at low p_T

- R. Tanizaki, master's thesis, Hiroshima U., 2015

Key Issue: Significance, *i.e.* Statistics

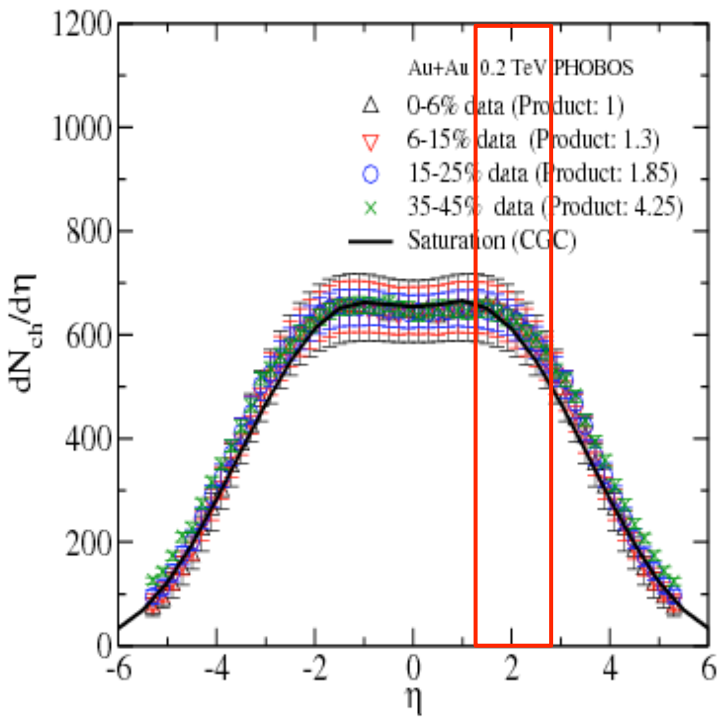
- marginal at best, in 2012–2016
  - 4 M.Sc. theses in 2013–2016
    - T.Hoshino, A.Tsuji, R.Tanizaki, Y.Ueda
  - 5 B.Sc. theses in 2012–2015
    - A.Tsuji, R.Tanizaki, Y.Ueda, A.Nobuhiro, K.Yamakawa
- higher statistics data available/coming in
  - 1 B.Sc. thesis in 2018
    - T.Osako; continuing, *e.g.* ATHIC 2018
- ALICE run 3 (2021–2023) even more promising
  - ×10 (di-)muons
  - ×100 minimum bias (di-)electrons

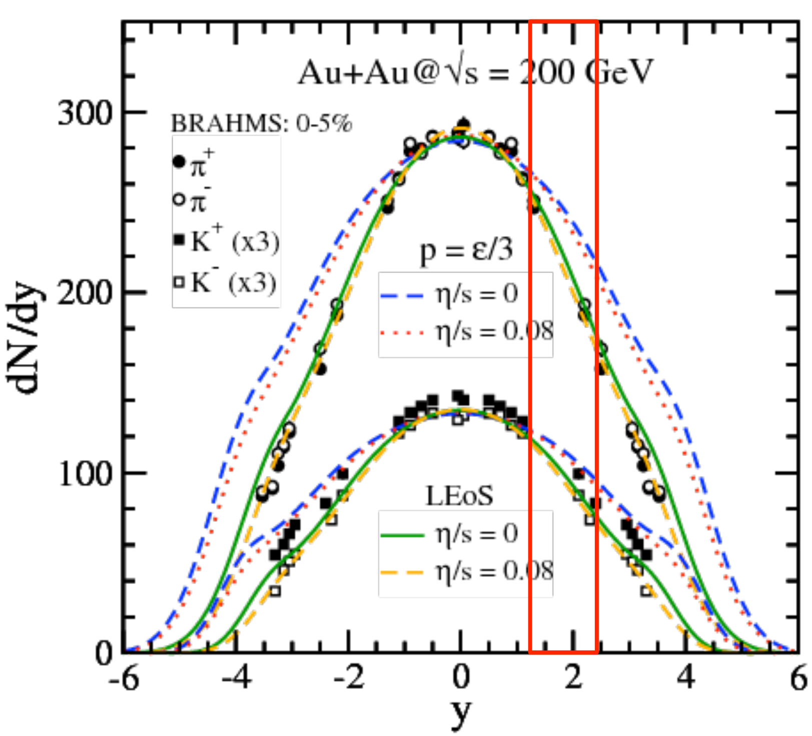
e and μ Reunion at LHC Energy

- parallel approaches to same physics up to SPS
  - muons at central (CMS) rapidity in fixed target exp.
    - *e.g.* NA38/50/51/60 dimuon spectrometer
- physics emphasis (and people) separated at RHIC
  - broad QGP physics with electrons in central barrel
  - focused topics, *e.g.* high mass/p_T and spin, with muons
    - *e.g.* PHENIX "forward" arms
    - low momentum μ ID technically challenging
- reunion at LHC
  - low p_T muons within prolonged central Bjorken plateau
  - parallel and complementary approaches (again)

Muon Measurement at PHENIX

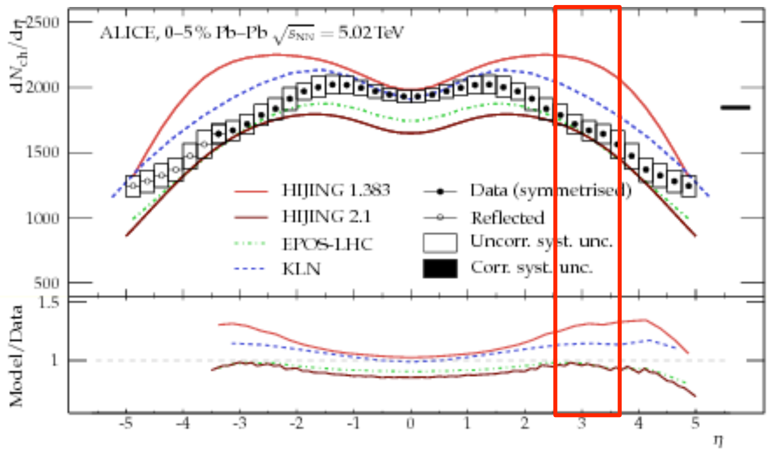
- muon arms: $1.2 < |\eta| < 2.4$
- minimum $p_T \sim 1.0 - 1.5$ GeV/c

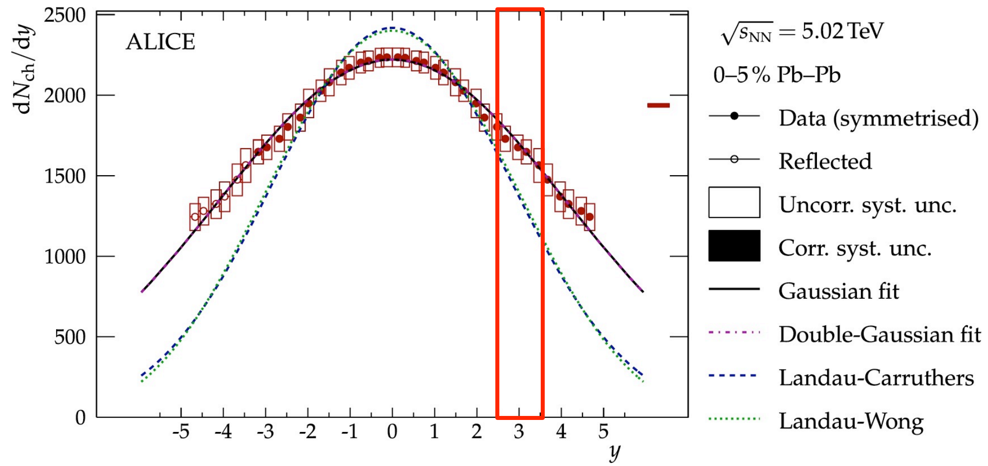




Muon Measurement at ALICE

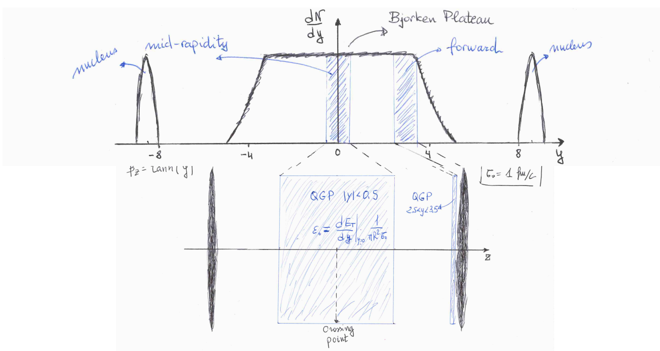
- muon arm: 2.5 < |η| < 4.0
- MFT: 2.5 < |η| < 3.6
- minimum p_T ~ 0.5 GeV/*c*

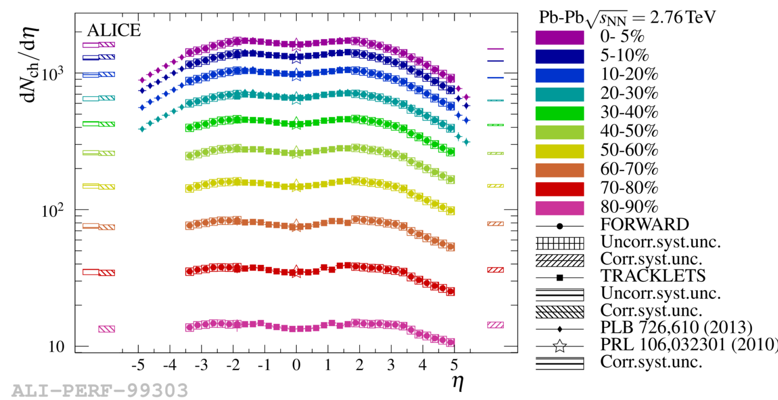




New Relation between e and μ at LHC

- two interesting regimes of quark-gluon phase
  - exploration on QCD phase diagram

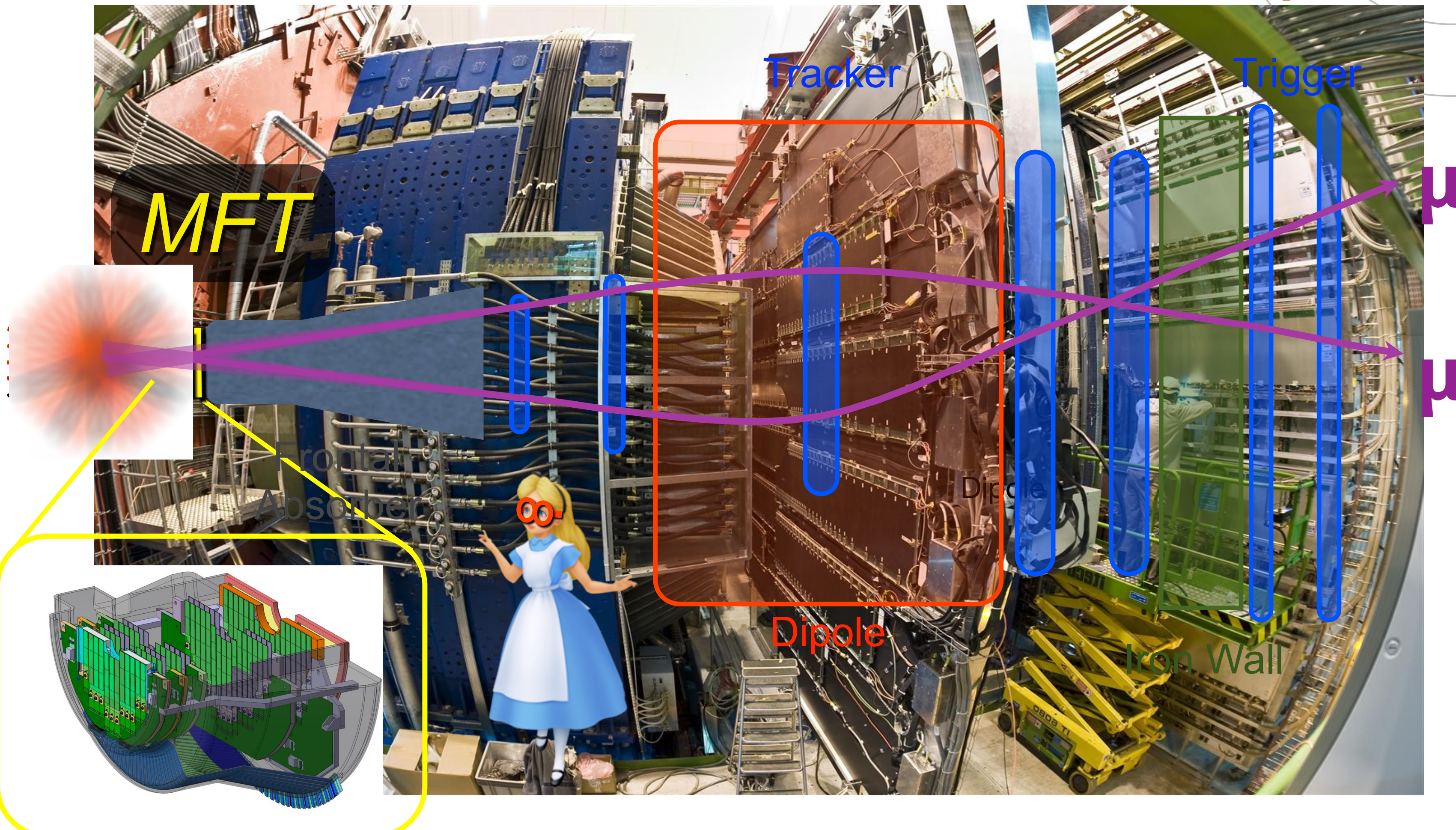




- new opportunity only at LHC energy (and above)
  - *forward enough* for (low p_T) muon measurement
    - e.g. |y| above ~ 3.4 for p_T < 0.25 GeV/c, p > 4 GeV/c
  - *not too forward* for “central” physics
    - |y| up to ~ 4 at LHC (~ 2 at RHIC)

Muon Forward Tracker (2021–)

- vertex and invariant mass resolutions to improve

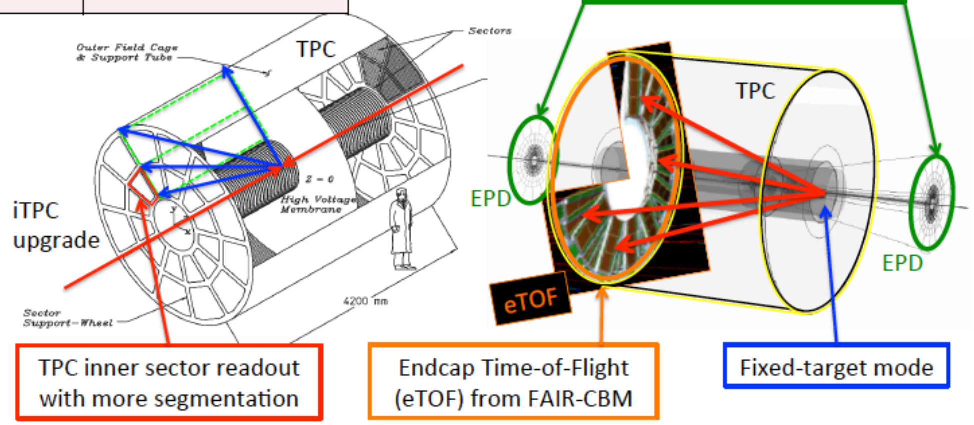


Another Obvious Stage: RHIC BES-II

- **2019–2021, STAR only**
- **$\sqrt{s_{NN}}$ = 7.7–19.6 GeV, 3.0–7.7 GeV (fixed target)**

RUN17	500 GeV p+p 54 GeV Au+Au
RUN18	200 GeV Zr+Zr, Ru+Ru 27 GeV Au+Au Fixed-target test run
RUN19 RUN20 RUN21	14.5 - 20 GeV Au+Au 7 - 11 GeV Au+Au Fixed-target runs

STAR detector upgrade for BES-II



- **STAR starting to look into deflection**

Summary, Conclusions, and Remarks

- wide range of interests; not only LPV/CME(/CVE)
- field time structure: key for physical significance
  - longer-lived participant component in “perfect fluid”?
- proposals of experimental detection approaches
  - seemingly feasible, statistics permitting
  - simulations and real data analysis
    - direct photon polarization
    - femto-spectrometer
- high prospects in near-future high statistics data
  - both muons and electrons in ALICE run 3 (2021–2023)
  - RHIC BES-II (2019–2021) at STAR