Directed flow splitting and EM field effects

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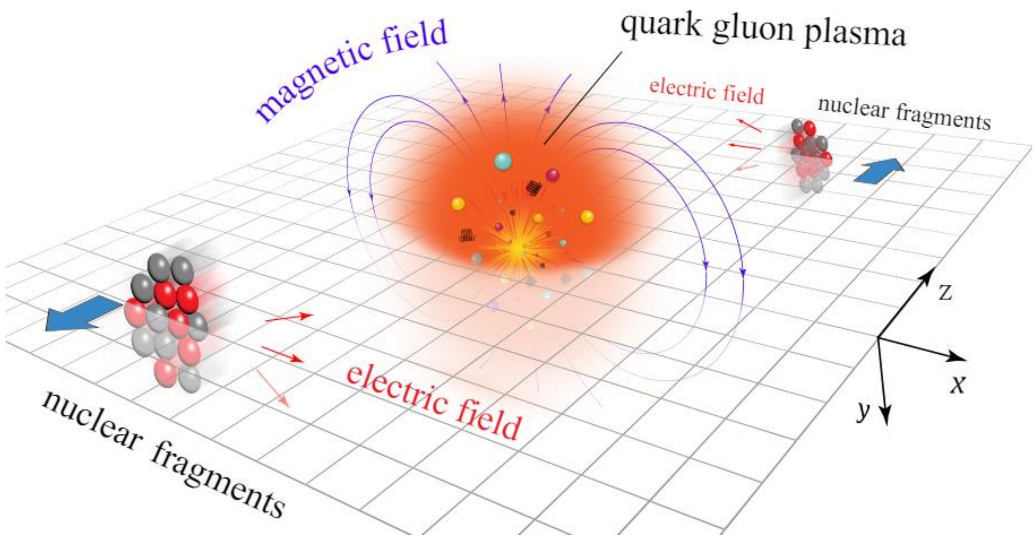
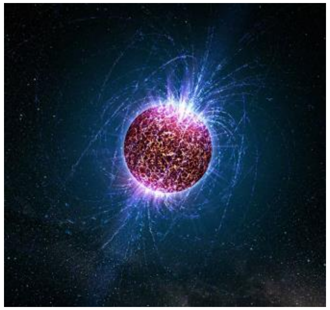
EM Field in Heavy-ion Collisions



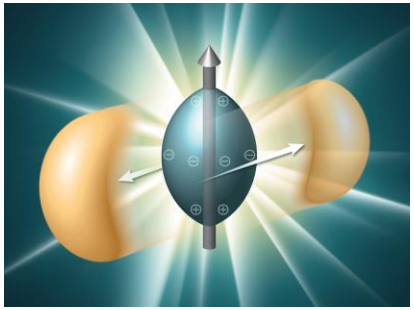
Strongest man-made magnetic field : peak value of eB ~ 10^{18} Gauss at top RHIC energy.

Earth
~ 0.5 Gauss

Lightning
~ 10^4 - 10^5 Gauss



Neutron Star (Magnetar)
~ 10^{14} Gauss



Heavy ion collisions
~ 10^{18} Gauss

EM Field in Heavy-ion Collisions

Kharzeev, McLerran and Warringa, Nucl. Phys. A 803 227 (2008)
Fukushima, Kharzeev and Warringa, PRD 78 074033 (2008)

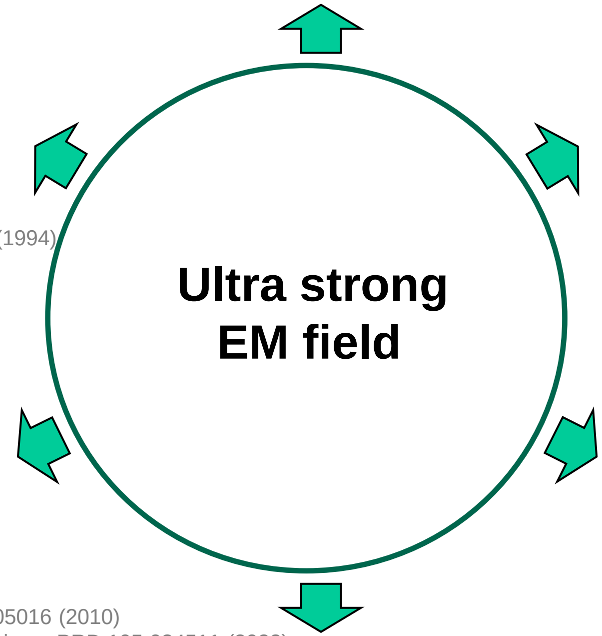
CME

Jet energy loss

Tuchin, PRC 82 034904 (2010)

Catalyst for chiral symmetry breaking

Gusynin, Miransky and Shovkovy, PRL 73 3499 (1994)



Photon and dilepton production

Tuchin PRC 87 (2) 024912 (2013)
Basar, Kharzeev and Shurayak, PRC 90 014905 (2014)

Fine structure on the phase diagram

Mizher, Chernodub and Fraga, PRD 82 105016 (2010)
M Elia, L. Maio, F. Sanfilippo and A. Stanzione, PRD 105 034511 (2022)
E. Fraga and A. Mizher, PRD 78 025016 (2008)

Elliptic and directed flow

Mohapatra, Saumia and Srivastava, PLA 26 2477 (2011)
Tuchin, JPG Nucl.Part.Phys. 39 025010 (2012)
Guo et al., PLB 751 215 (2015)
Fukushima et al., PRD 93 (7) 074028 (2016)
Fiazzo et al., PRD 94 054020 (2016)

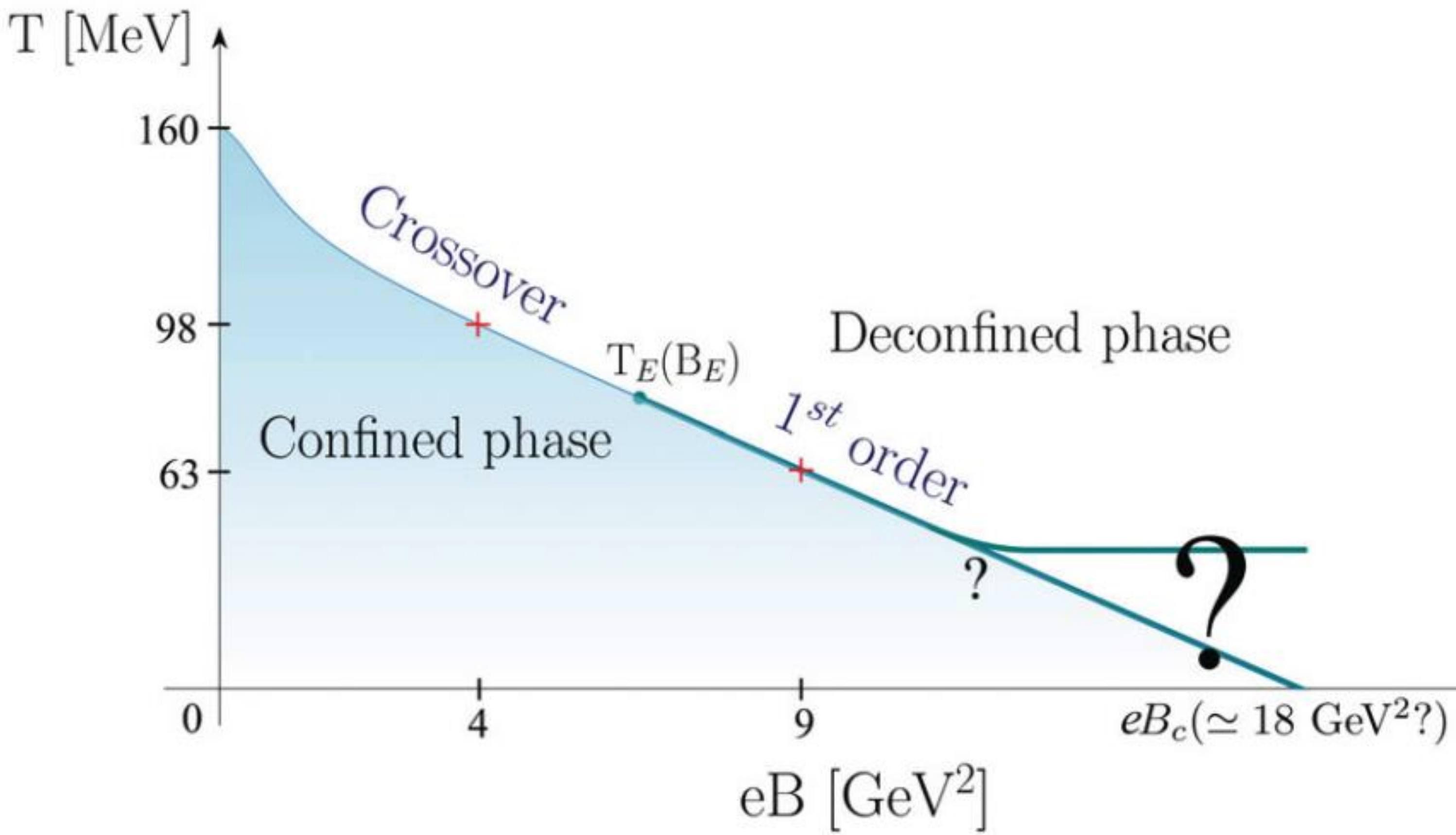
Gursoy, Kharzeev and Rajagopal, PRC 89 054905 (2014)
Das etal, PLB 768 260 (2017)
Gursoy et al., PRC 98 055201 (2018)

Breit-Wheeler process

STAR, PRL 127, 052302 (2021)

Multiple connections to rich physics !

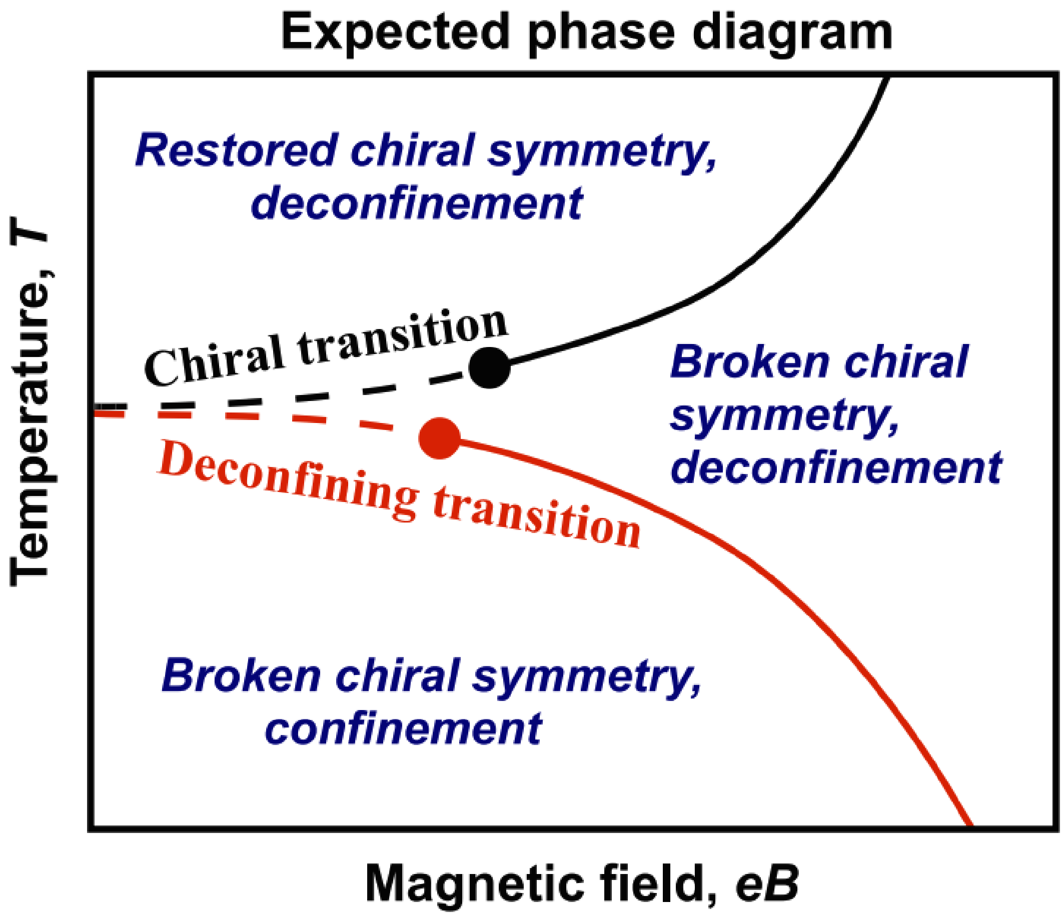
EM Field in Heavy-ion Collisions



M Elia, L. Maio, F. Sanfilippo and A. Stanzione, PRD 105 034511 (2022)

QCD phase diagram under strong EM field.

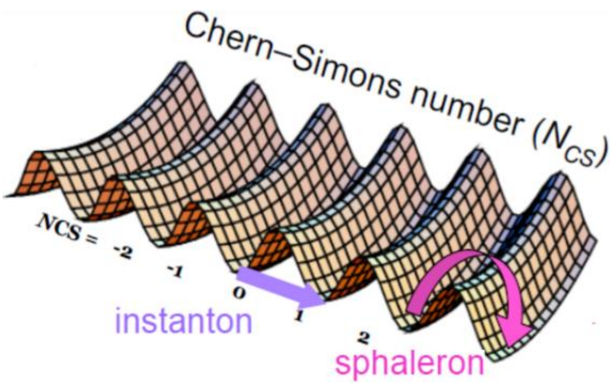
EM Field in Heavy-ion Collisions



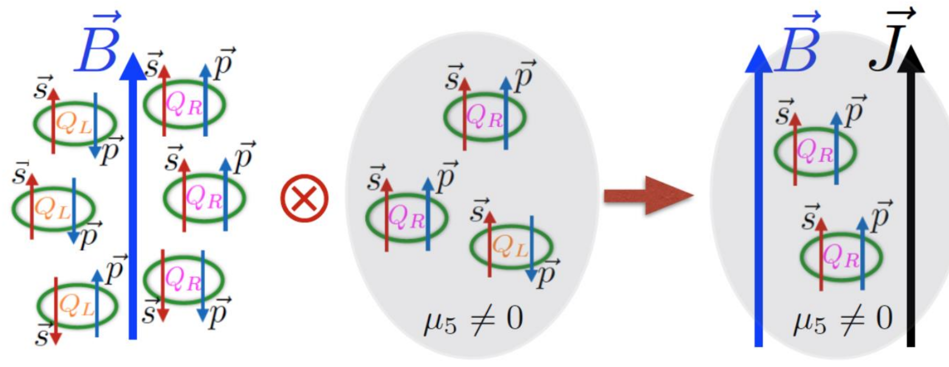
Mizher, Chernodub and Fraga, PRD 82 105016 (2010)
E. Fraga and A. Mizher, PRD 78 025016 (2008)

Rich structure of QCD phase diagram under strong EM field.

EM Field in Heavy-ion Collisions



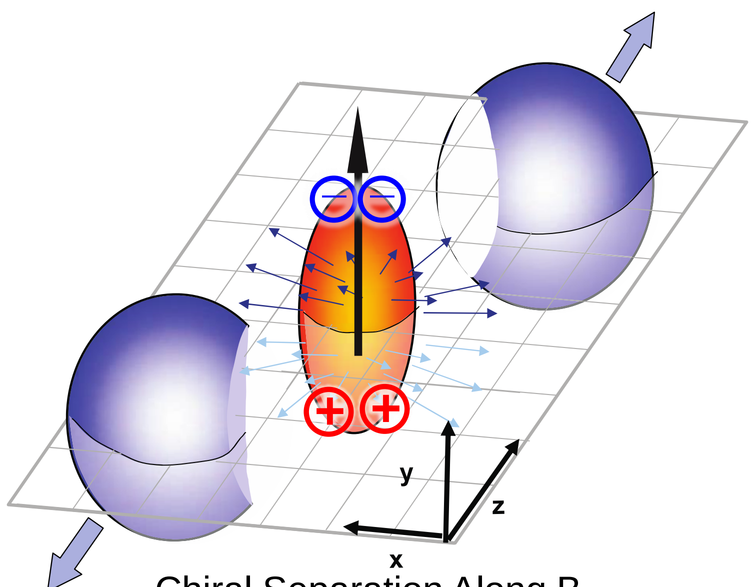
QCD vacuum topology (finite μ_5)



Chiral Magnetic Effect

Charge current

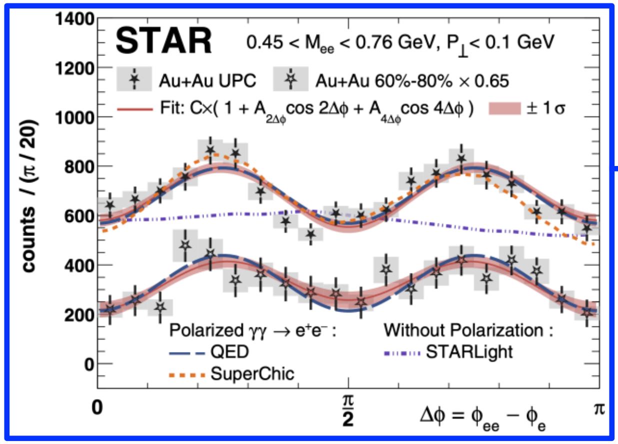
$$j_V = \frac{N_c e}{2\pi^2} \mu_A B$$



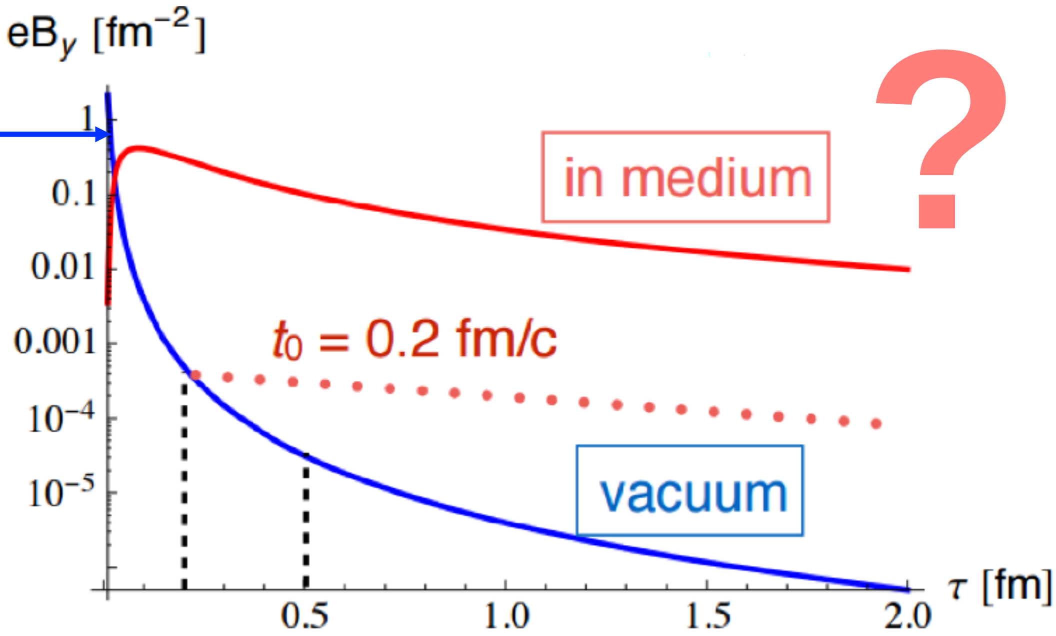
Chiral Separation Along B

Chiral Magnetic Effect with strong magnetic field.

EM Field in Heavy-ion Collisions



STAR, PRL 127, 052302 (2021)
STAR, Sci. Adv Vol 9 Issue 1 (2023)



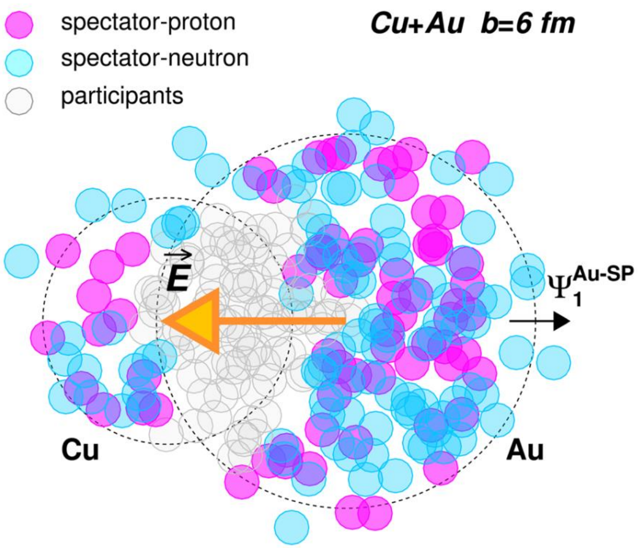
Ultra-peripheral Collisions
Vacuum + strong B

No QGP medium
No constraints on the evolution of B

Gürsoy, Kharzeev & Rajagopal, Phys. Rev. C 89, 054905 (2014) …

Despite wide expectation of its existence, its imprint in QGP has been elusive.

Probe E Field in Cu + Au Collisions



Asymmetric collisions (Cu+Au) create in-plane E fields.

Charge-dependence of v_1

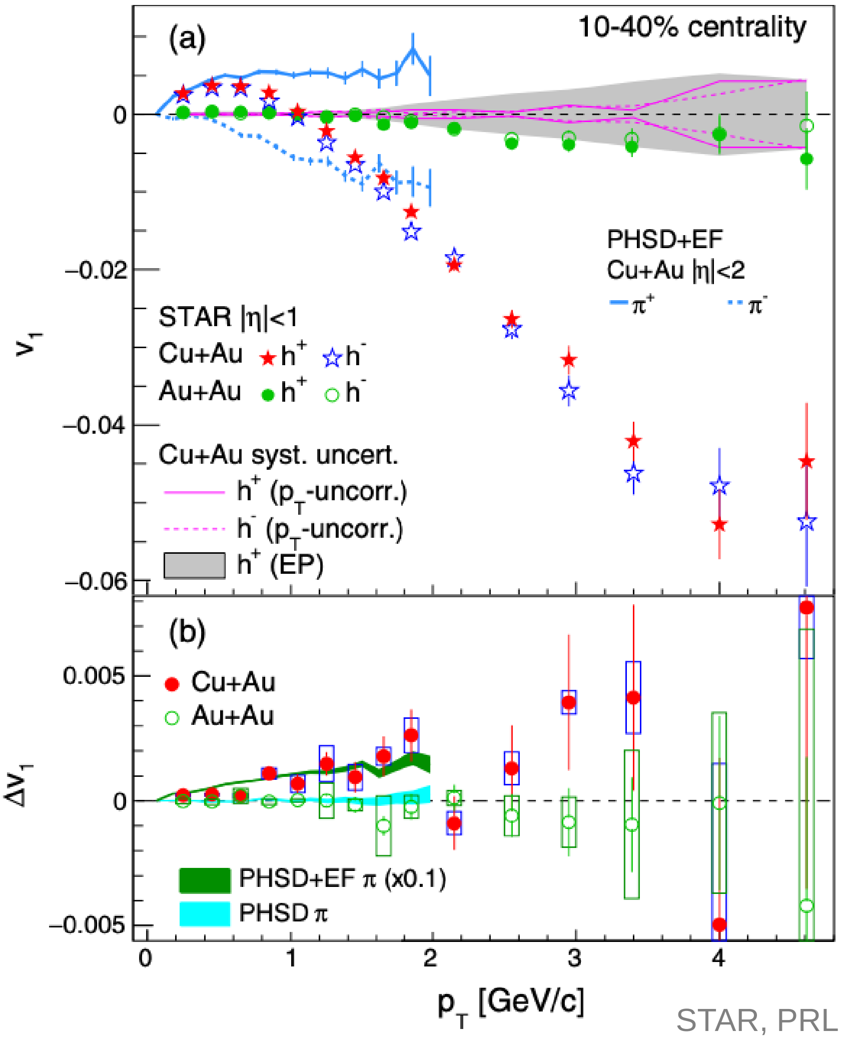
$$v_1^{\pm} = v_1 \pm Ad'_e$$

$$Ad'_e \sim -\frac{\pi \sigma \tau}{N_{\rm tot}|e|} \int_S \vec{E} \cdot d\vec{S}$$

Hirono, Hongo and Hirano, Phys. Rev. C 90, 021903 (2014)
…

Study electric conductivity of medium via Cu+Au collisions

Evidence of the Coulomb Field



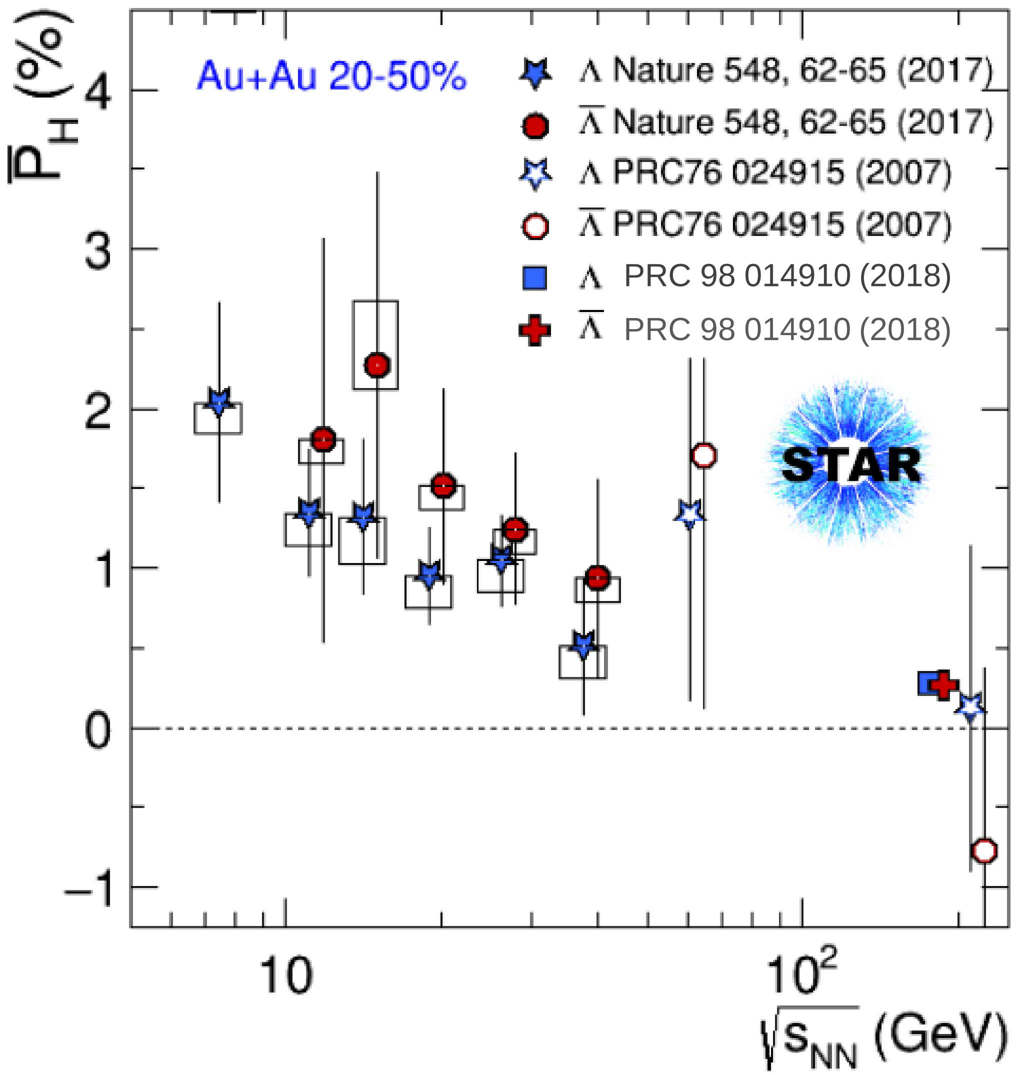
STAR, PRL 118 012301 (2017)

Qualitatively agrees with expectation from strong E field

10 times smaller than PHSD which uses a lower value of σ. Probably due to that (anti)quarks not all created when EF is strong (< 1 fm).

Study electric conductivity of medium via Cu+Au collisions

Λ and anti-Λ Polarization

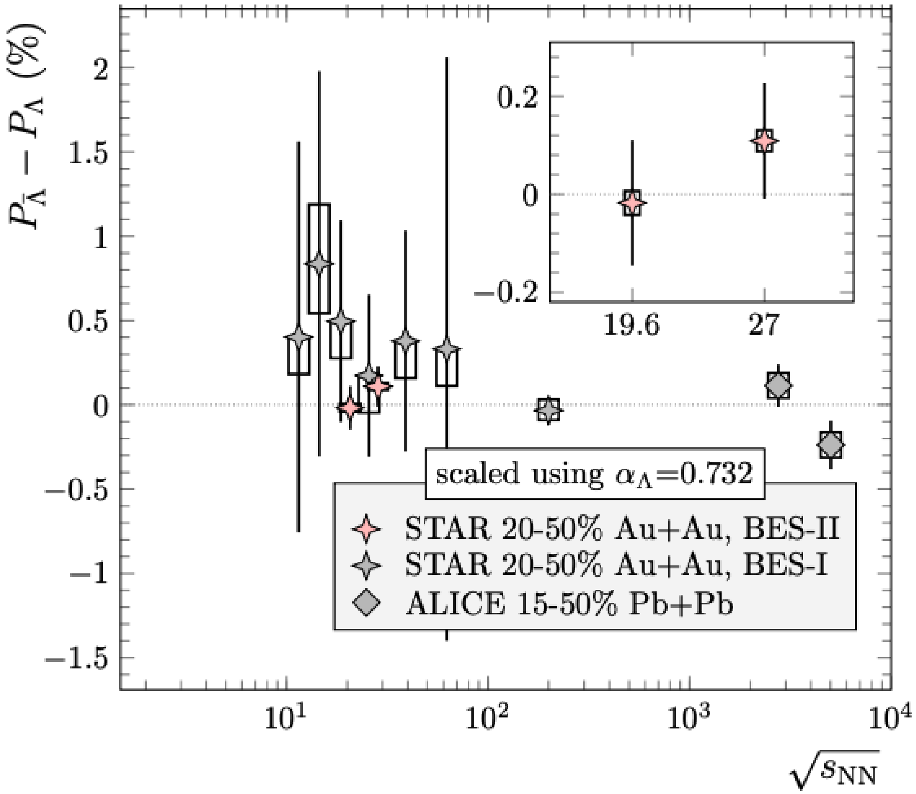


$$P_\Lambda \approx \frac{1}{2}\frac{\omega}{T} + \frac{\mu_\Lambda B}{T}$$

$$P_{\bar{\Lambda}} \approx \frac{1}{2}\frac{\omega}{T} - \frac{\mu_\Lambda B}{T}$$

Challenging to see the B effect at later stage

Λ and anti-Λ Polarization

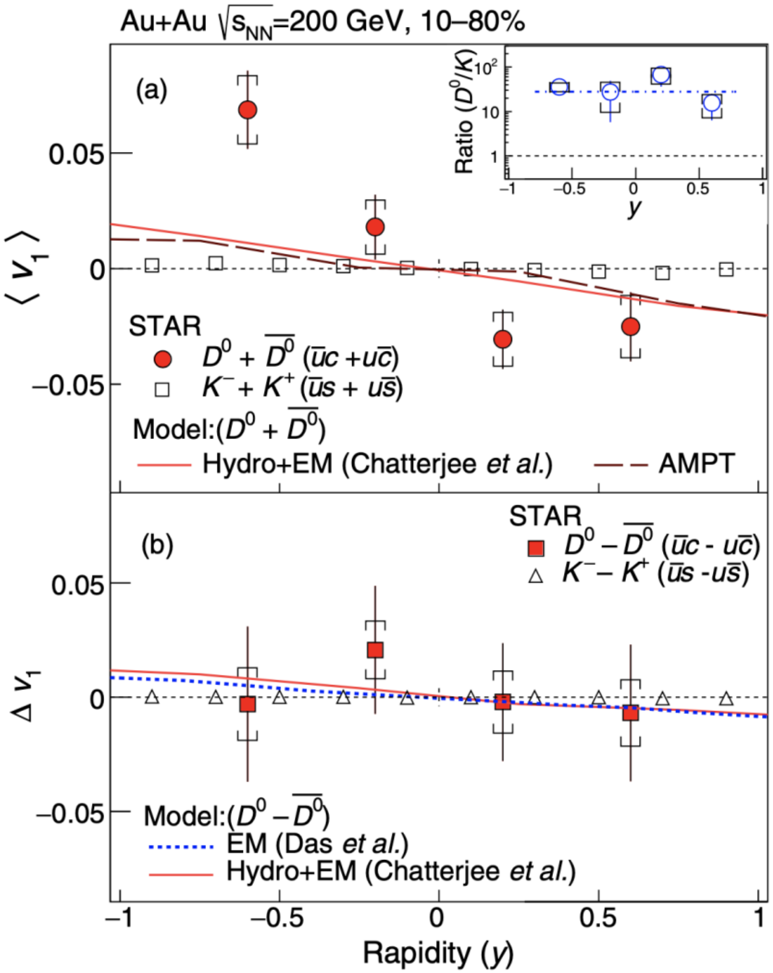


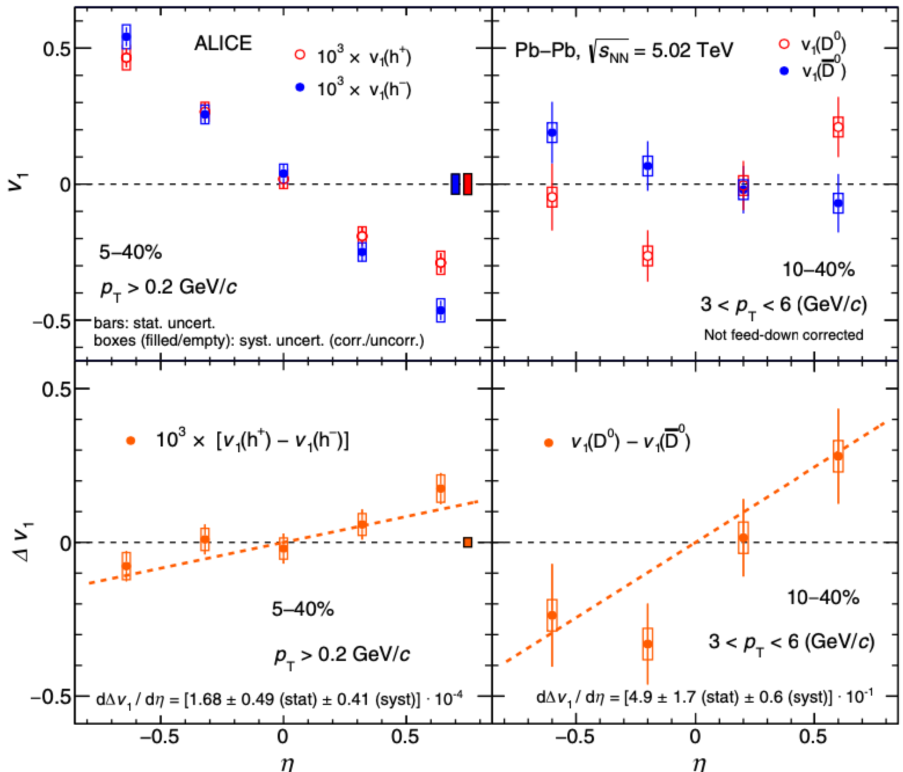
STAR, PRC 108 014910 (2023)

$$P_{\bar{\Lambda}} - P_{\Lambda} = -2\frac{\mu_\Lambda B}{T}$$

Challenging to see the B effect at later stage

v_1 Splitting of D Mesons





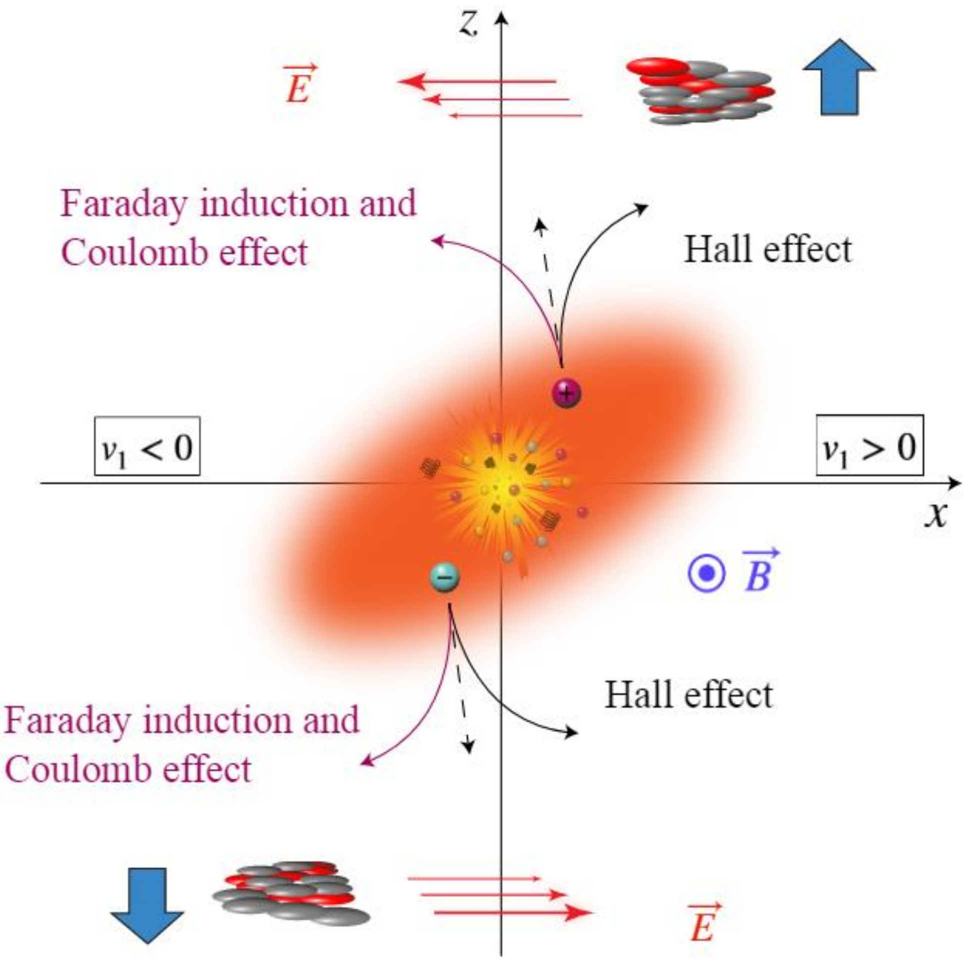
ALICE, PRL 125 022301 (2020)

Large v_1 and large v_1 splitting

STAR, PRL 123 162301 (2019)

Consistent with Hall effect dominating for heavy quarks.

Hall, Faraday and Coulomb Effect

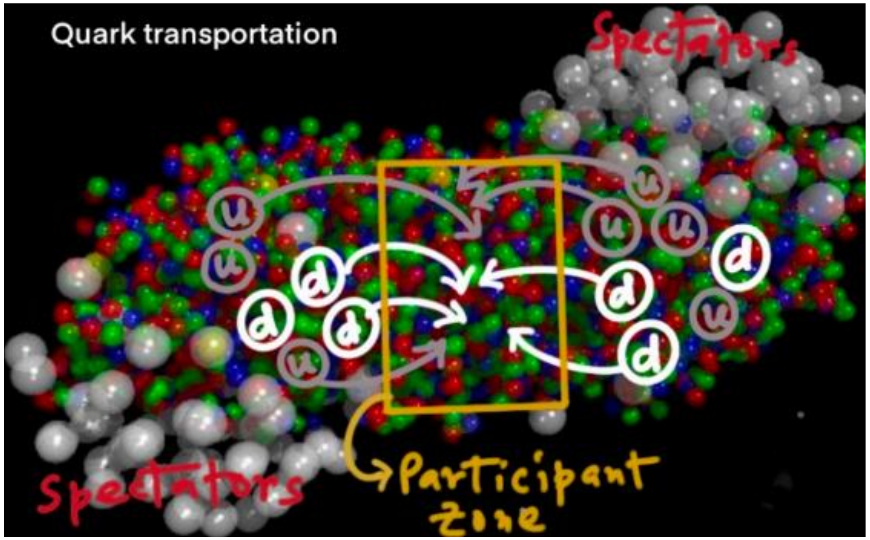


Hall effect (Lorentz force) and Faraday + Coulomb effect compete each other.

Calculations indicate Faraday + Coulomb effect dominate over Hall effect for light hadrons.

Gursoy, Kharzeev and Rajagopal, PRC 89 054905 (2014)
S.K. Das et al., PLB 768 260 (2017)
Umut Gursoy, et al., PRC 98 055201 (2018)
K. Nakamura et. al., PRC 107 034912 (2023)
K. Nakamura et. Al., PRC 107 014901 (2023)

Transported Quarks



$p : uud$

$\bar{p} : \bar{u}\bar{u}\bar{d}$

$v_1^p > v_1^{\bar{p}}$ at $\eta > 0$

$K^+ : u\bar{s}$

$K^- : \bar{u}s$

$v_1^{K^+} > v_1^{K^-}$ at $\eta > 0$

$\pi^+ : u\bar{d}$

$\pi^- : \bar{u}d$

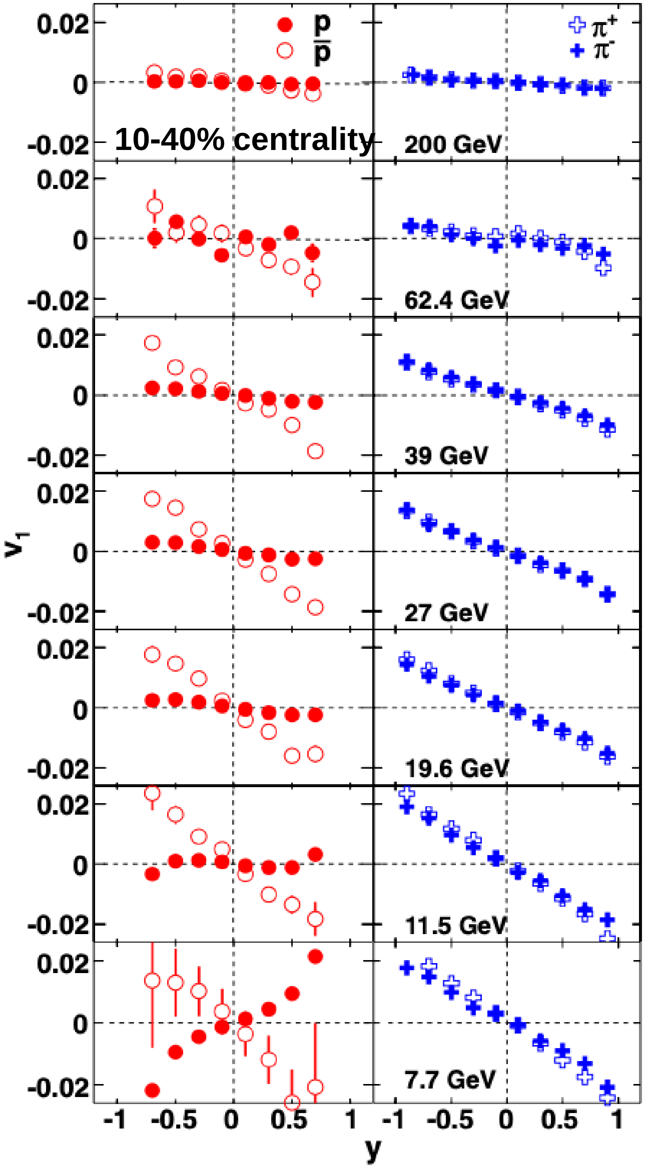
$v_1^{\pi^-} > v_1^{\pi^+}$ at $\eta > 0$

(#d>#u, Au neutron rich)

Dunlop, Lisa and Sorensen, PRC 84 044914 (2011)
Guo, Liu and Tang, PRC 86 044901 (2012)
Nayak, Shi, Xu and Lin, PRC 100 054903 (2019)
P. Bozek, PRC 106 L061901 (2022)

Transported quarks carry information from incident nucleons, causing v_1 splitting.

Transported Quarks



STAR, PRL 112 162301 (2014)

$p : uud$

$\bar{p} : \bar{u}\bar{u}\bar{d}$

$v_1^{p} > v_1^{\bar{p}}$ at $\eta > 0$

$K^+ : u\bar{s}$

$K^- : \bar{u}s$

$v_1^{K^+} > v_1^{K^-}$ at $\eta > 0$

$\pi^+ : u\bar{d}$

$\pi^- : \bar{u}d$

$v_1^{\pi^-} > v_1^{\pi^+}$ at $\eta > 0$

(#d>#u, Au neutron rich)

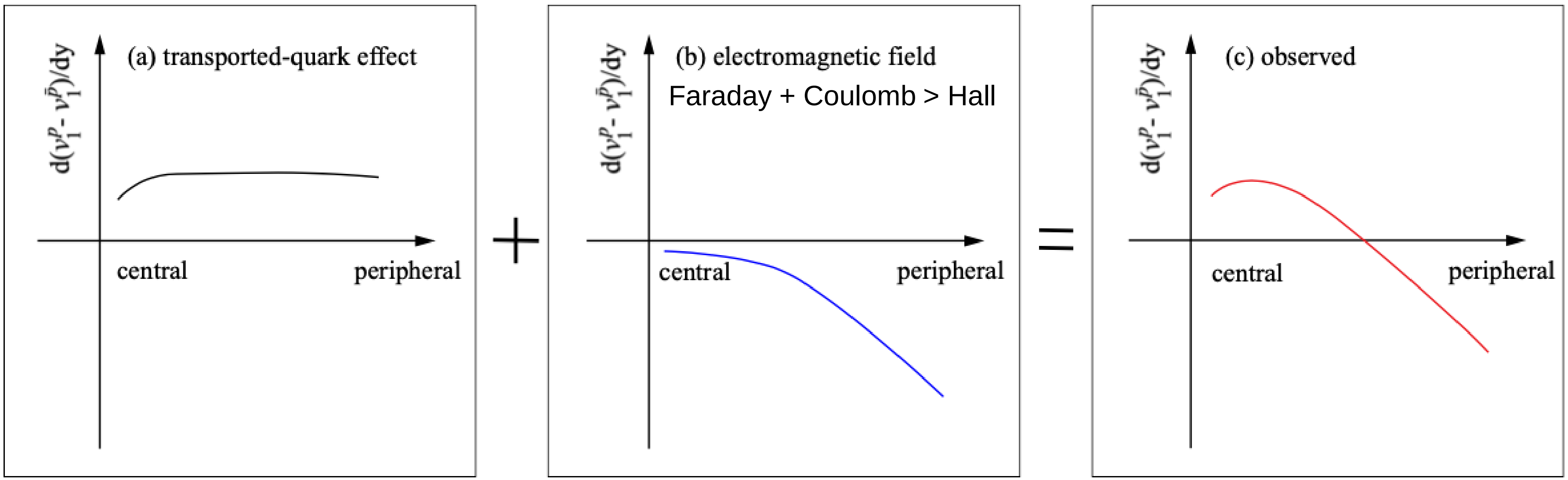
Transported quarks carry information from incident nucleons, causing v_1 splitting.

Interplay between Effects

proton $d(v_1^{+}-v_1^{-})/dy$: Hall ⇧ transported quark ⇧ Faraday ⇩ Coulomb ⇩

Happens early more relevant for heavy quarks

light quarks only



$p : uud$ $v_1^{p} > v_1^{\bar{p}}$ at $\eta > 0$

$\bar{p} : \bar{u}\bar{u}\bar{d}$

v_1 slope difference between protons and antiprotons.
Possible sign change as a function of centrality.

$K^{+} : u\bar{s}$ $v_1^{K^+} > v_1^{K^-}$ at $\eta > 0$

$K^{-} : \bar{u}s$

Similar pattern expected for kaons.

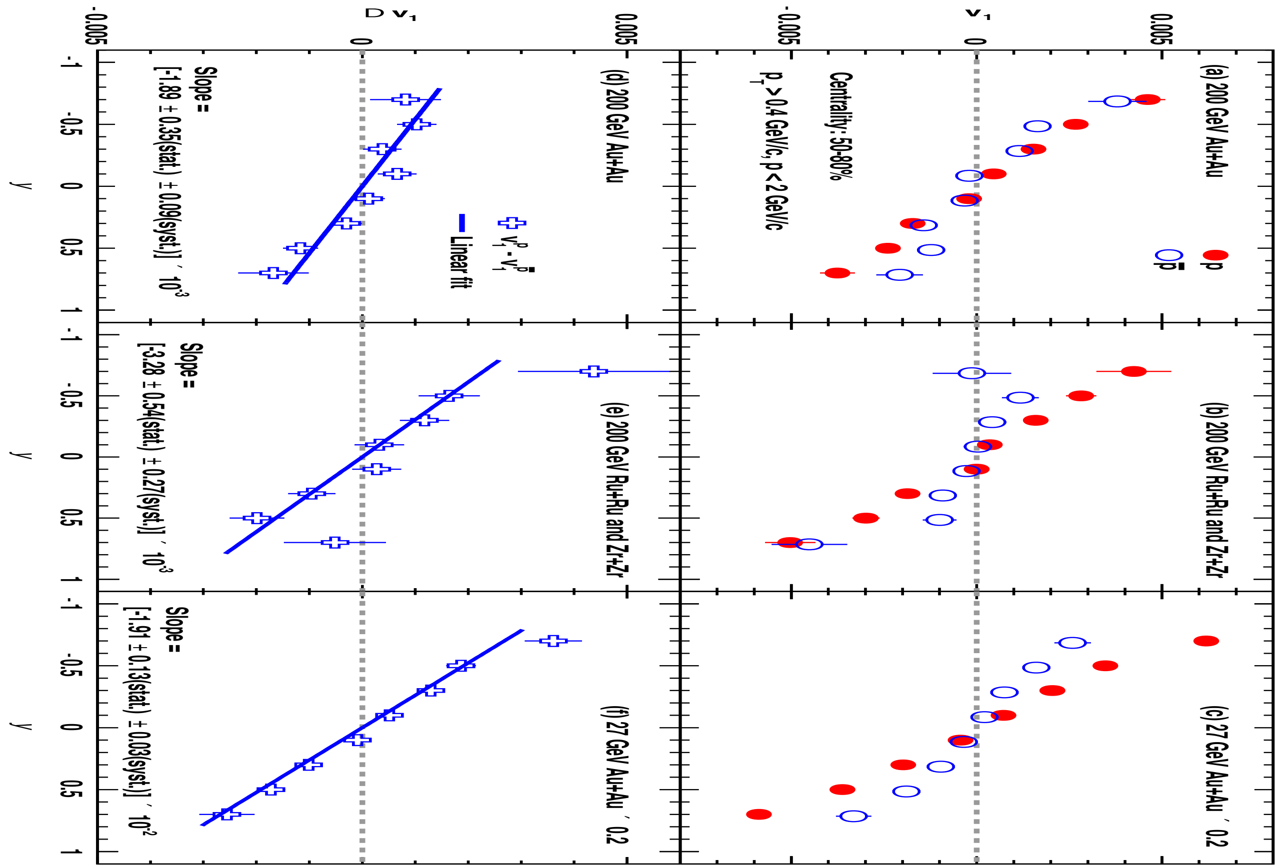
$\pi^{+} : u\bar{d}$ $v_1^{\pi^-} > v_1^{\pi^+}$ at $\eta > 0$

$\pi^{-} : \bar{u}d$ (#d>#u, Au neutron rich)

No sign change expected for pions.

Proton Splitting in 50-80% Centrality

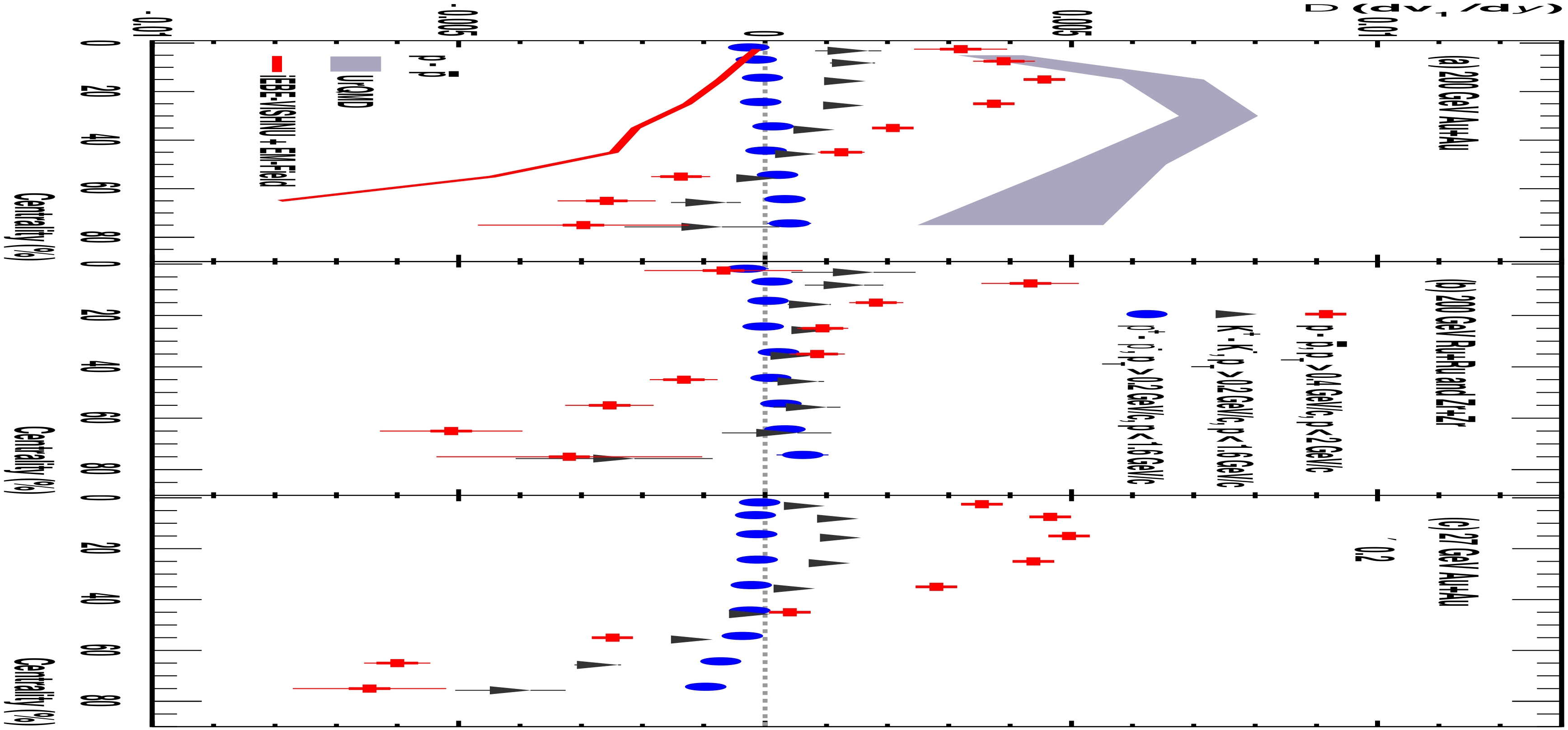
STAR, arXiv:2304.03430 (2023)
PRX in production



v_1 slope difference between protons and antiprotons is negative with > 5σ significance.
Cannot be explained by transported or Hall effect alone. Faraday + Coulomb is needed.

Strong evidence in favor of EM field at work in QGP

Sign Change of Δ(dv_1/dy)

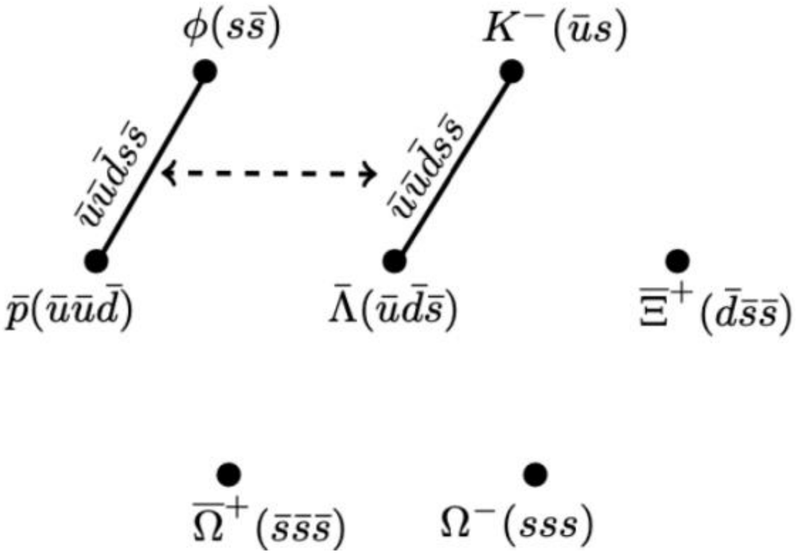


STAR, arXiv:2304.03430 (2023)
PRX in production.

Sign change in Δ(dv1/dy) occurs for both protons and kaons.
The magnitudes follow the expected ordering between protons and kaons.
Pion results are either consistent with zero or negative, as expected.
The electric conductivity of QGP used in iEBY-VISHNU+EM model lies within a plausible interval. (σ=0.023 fm^{-1})

Strong evidence in favor of EM field at work in QGP

Using Produced Particles Only



Use only produced particles.

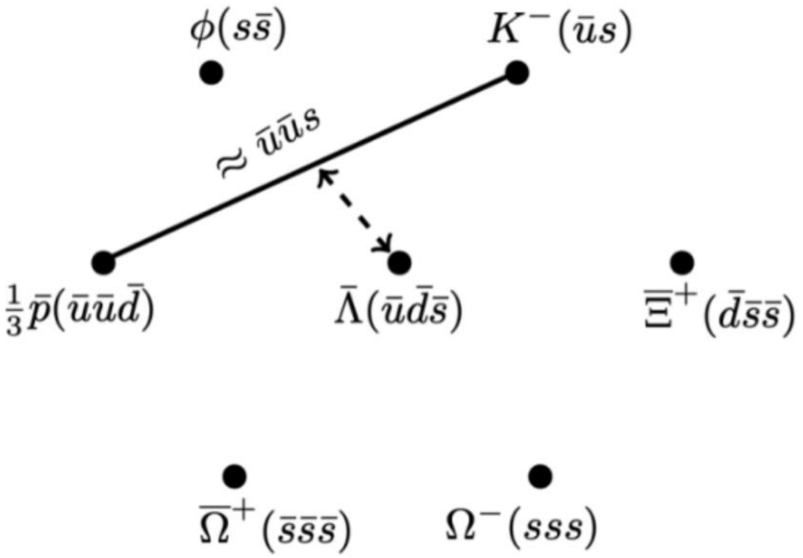
Coalescence sum rule.

$$v_1[K^-(\bar{u}s)] + v_1[\bar{\Lambda}(\bar{u}\bar{s}\bar{d})] = v_1[\bar{p}(\bar{u}\bar{u}\bar{d})] + v_1[\phi(s\bar{s})]$$

Baseline case : Δq = 0 and ΔS = 0

A. Ikbal, D. Keane and P. Tribedy, PRC 105 014912 (2022)

Using Produced Particles Only



Use only produced particles.

Coalescence sum rule.

$$v_1[\bar{\Lambda}(\bar{u}\bar{s}\bar{d})] \quad vs \quad v_1[K^-(\bar{u}s)] + \frac{1}{3}v_1[\bar{p}(\bar{u}\bar{u}\bar{d})]$$

Signal case : Δq = 4/3 and ΔS = 2

A. Ikbal, D. Keane and P. Tribedy, PRC 105 014912 (2022)

Using Produced Particles Only

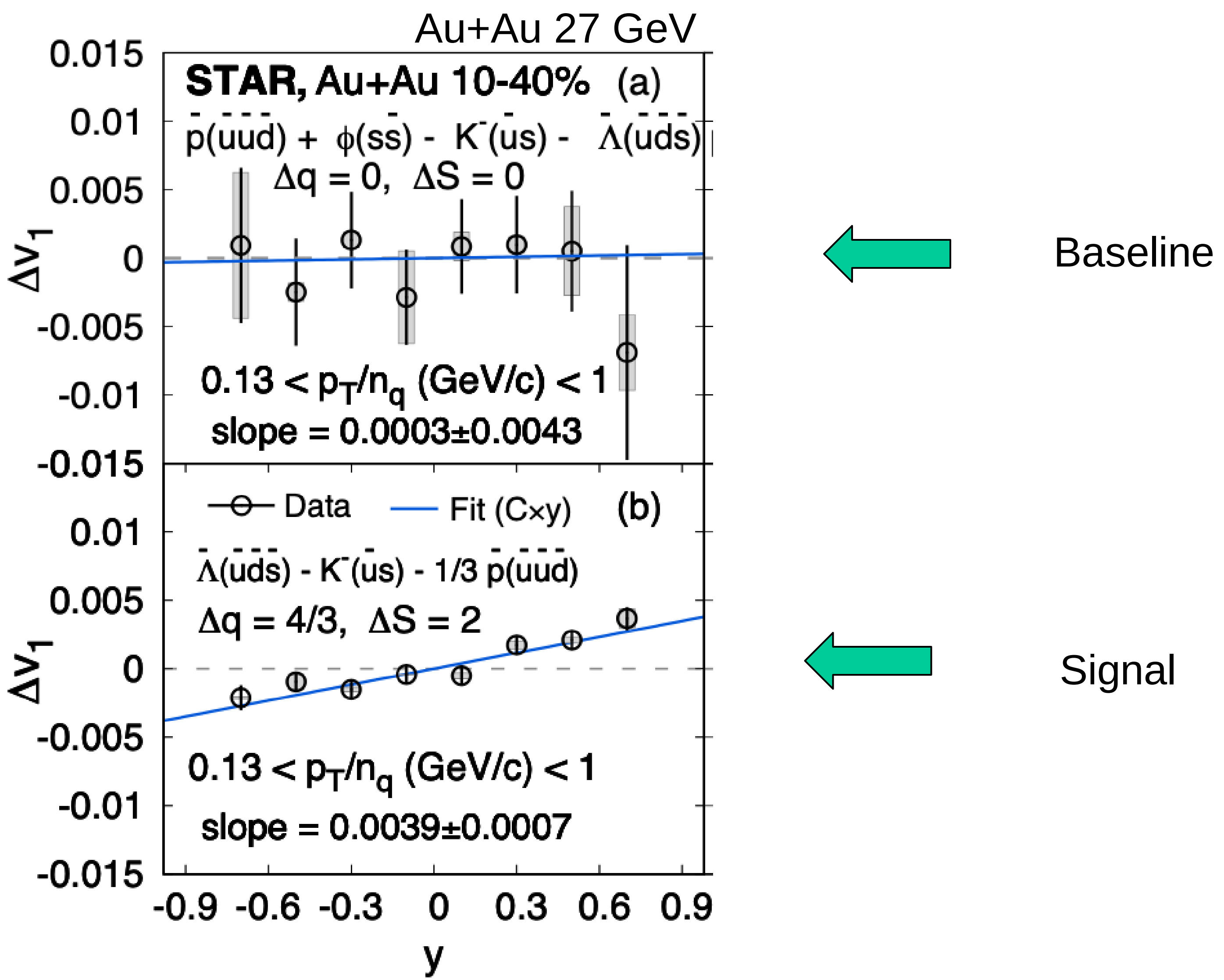
Index	Quark Mass	Charge	Strangeness	Expression
1	$\Delta m = 0$	$\Delta q = 0$	$\Delta S = 0$	$[\bar{p}(\bar{u}\bar{u}\bar{d}) + \phi(s\bar{s})] - [K^-(\bar{u}s) + \bar{\Lambda}(\bar{u}\bar{d}\bar{s})]$
2	$\Delta m \approx 0$	$\Delta q = 1$	$\Delta S = 2$	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [\frac{1}{3}\Omega^-(sss) + \frac{2}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$
3	$\Delta m \approx 0$	$\Delta q = \frac{4}{3}$	$\Delta S = 2$	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [K^-(\bar{u}s) + \frac{1}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$
4	$\Delta m = 0$	$\Delta q = 2$	$\Delta S = 6$	$[\overline{\Omega}^+(\bar{s}\bar{s}\bar{s})] - [\Omega^-(sss)]$
5	$\Delta m \approx 0$	$\Delta q = \frac{7}{3}$	$\Delta S = 4$	$[\overline{\Xi}^+(\bar{d}\bar{s}\bar{s})] - [K^-(\bar{u}s) + \frac{1}{3}\Omega^-(sss)]$

A. Ikbal, D. Keane and P. Tribedy, PRC 105 014912 (2022)

Combinations having same or nearly same quark mass but different Δq and ΔS.

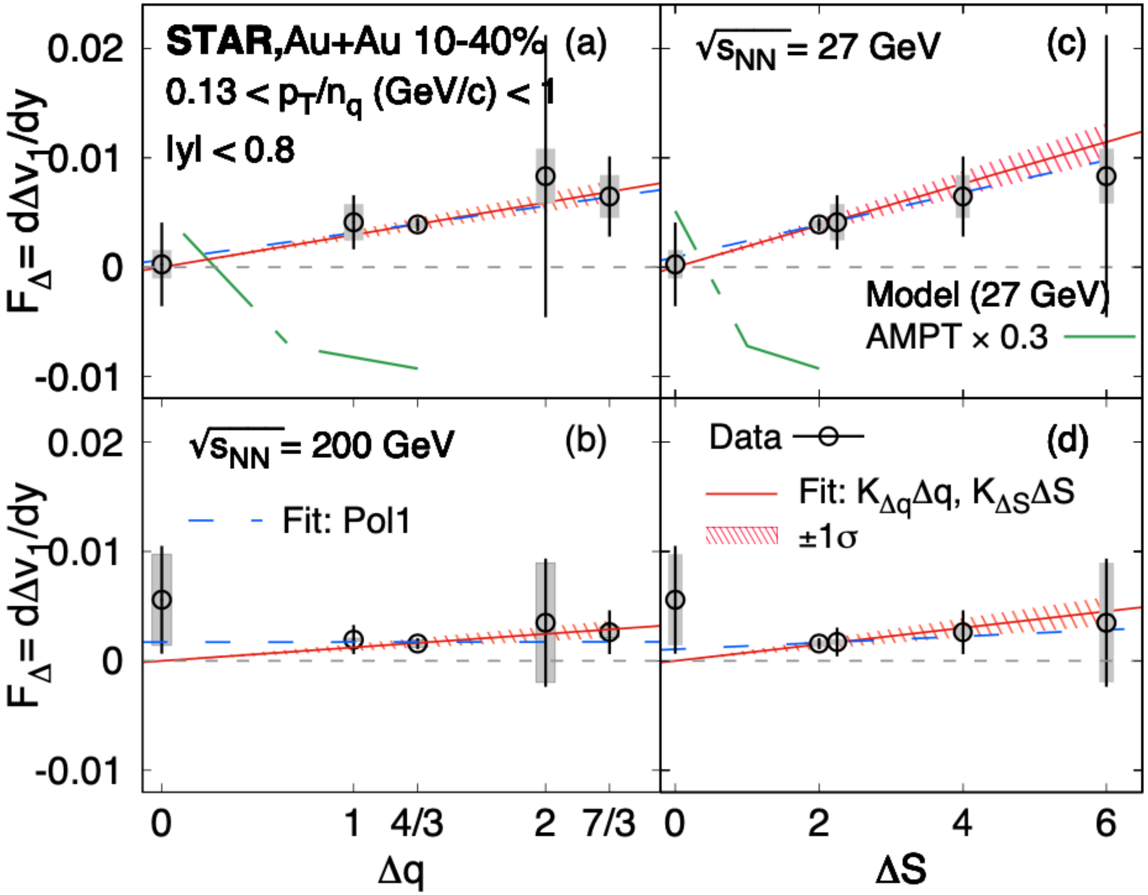
Measure splitting with Δq and ΔS, though they are correlated.

Using Produced Particles Only



STAR, arXiv:2304.02831 (2023)

Using Produced Particles Only

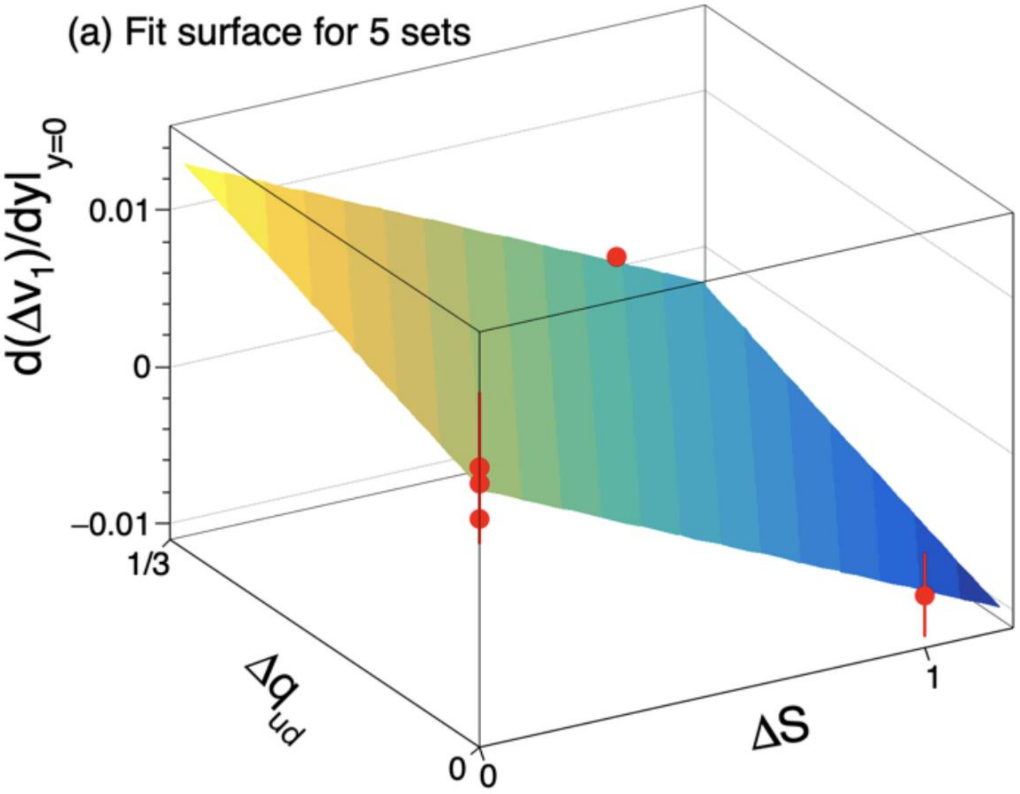


STAR, arXiv:2304.02831 (2023)

Positive splitting, increases with Δq and ΔS.

Consistent with Hall effect dominating over Coulumb + Faraday in mid-central collisions.

Using Produced Particles Only



K. Yayak, S. Shi and Z-W Lin, arXiv 2311.02307

2-D fitting proposed to decouple the correlation between Δq and ΔS.

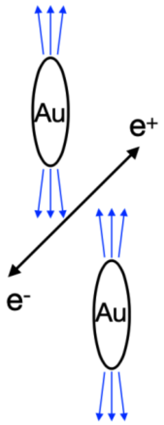
Summary

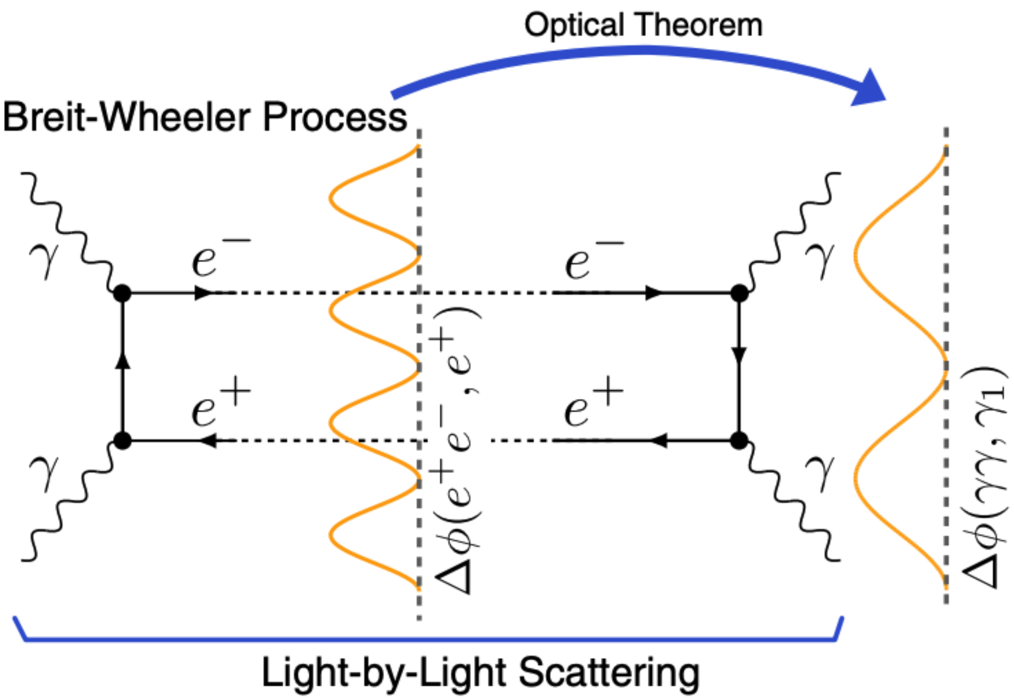
- Evidence of Coulomb effect in asymmetric collisions.
- Hall effect is more relevant for heavy quarks or at early stages.
- Evidence of Hall effect dominating in mid-central collisions, in particular for strange quarks.
- Faraday + Coulomb effects dominate the significant v_1 splitting of hadrons with light quarks.
- Qualitatively consistent with theoretical expectations. Guidance provided on the value of electric conductivity of QGP.

Strong evidence in favor of EM field at work in QGP

Backup Slides

EM-field in HIC





$\gamma\gamma \rightarrow e+e-$ linearly polarized photons from strong EM field

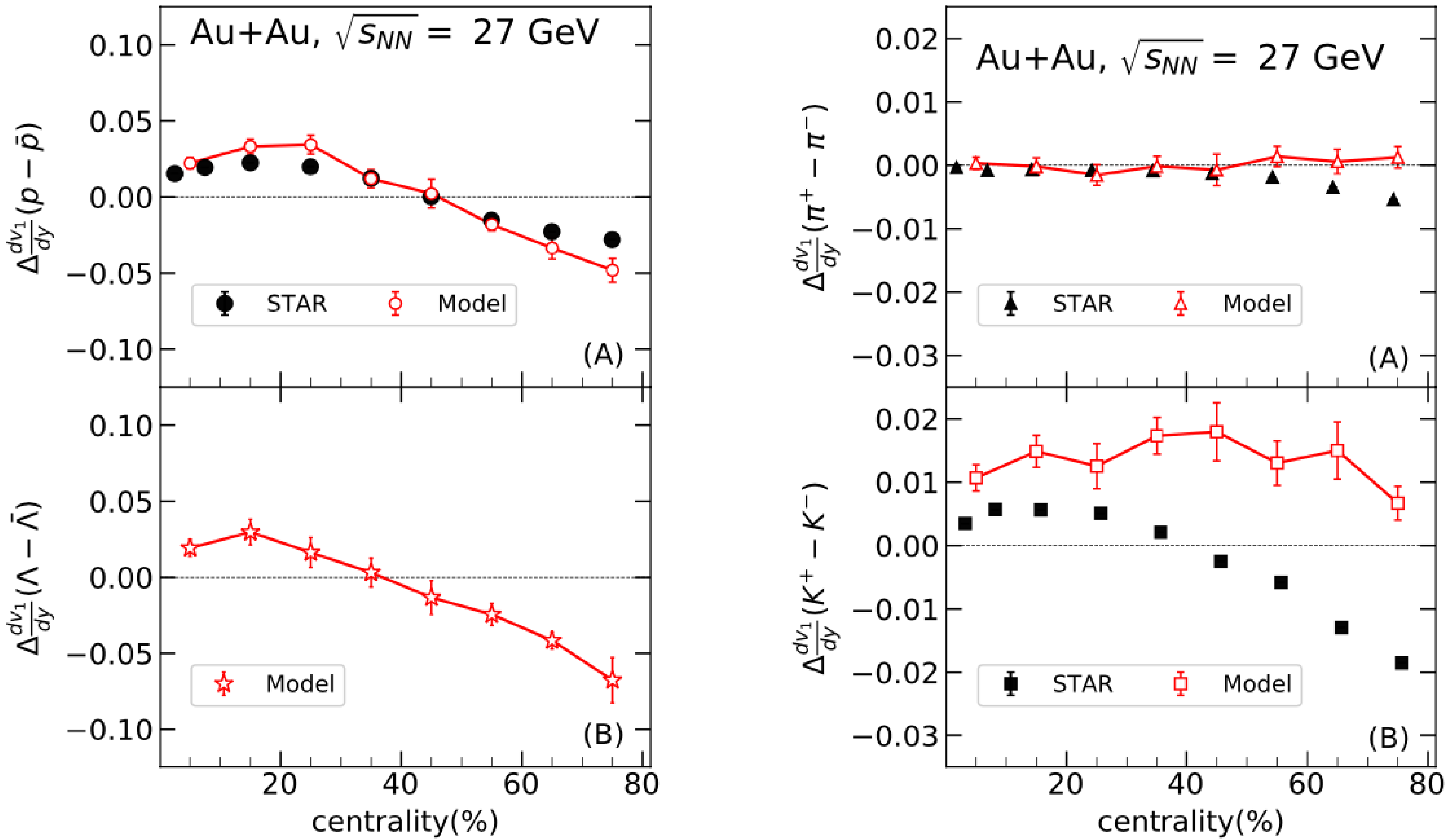
No generation of QCD medium

STAR PRL 127 052302 (2021)

No constraints on the evolution of B field

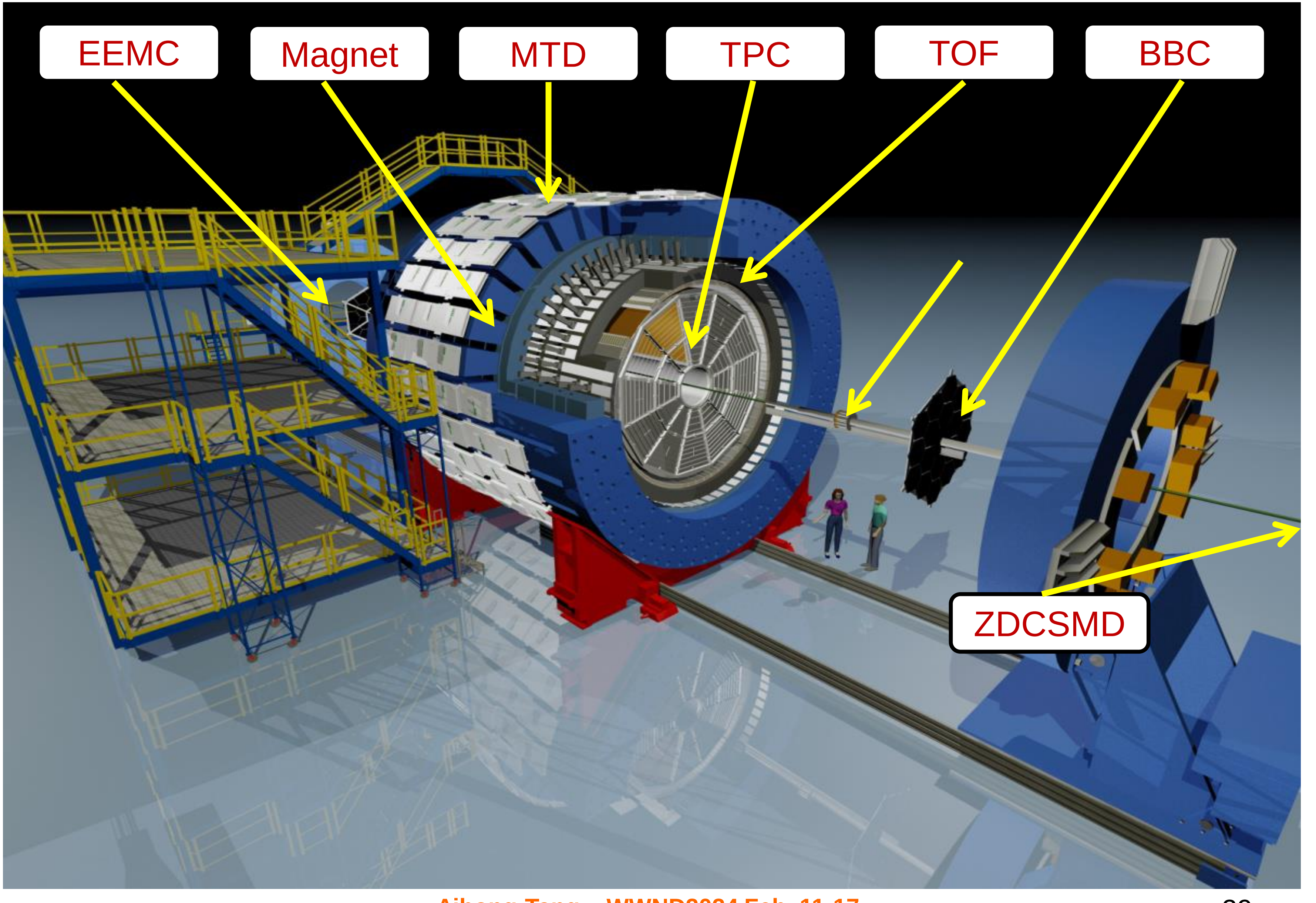
Study EM field in ultra-peripheral AuAu collisions

STAR : Uniform and Large Acceptance

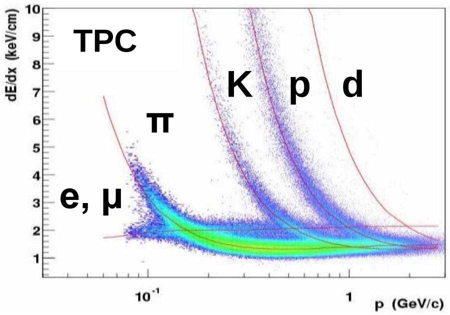


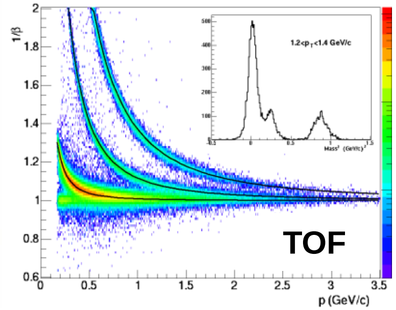
T. Parida and S. Chatterjee, arXiv:2305.08806 (2023)

STAR : Uniform and Large Acceptance

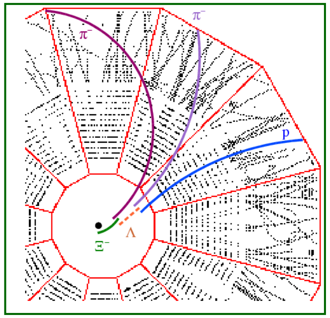


STAR : Excellent PID and Tracking

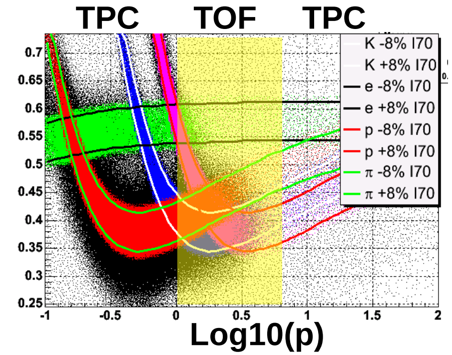


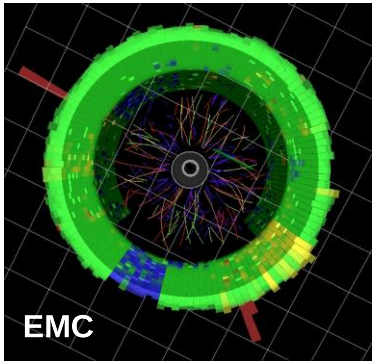


Charged hadrons

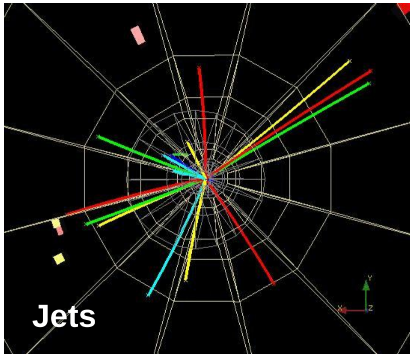


Hyperons & Hyper-nuclei

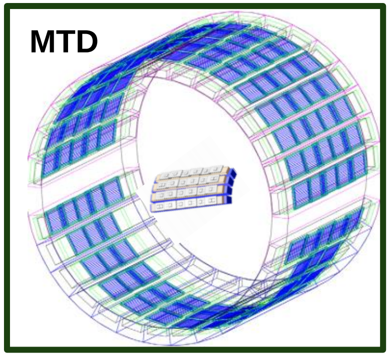




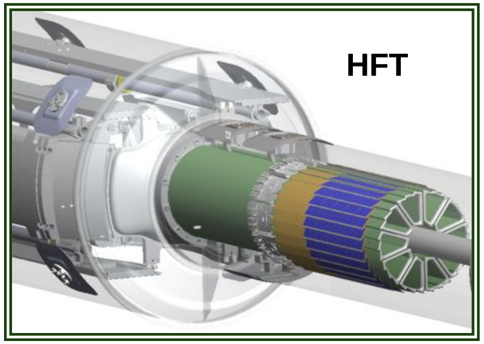
Neutral particles



Jets & Correlations

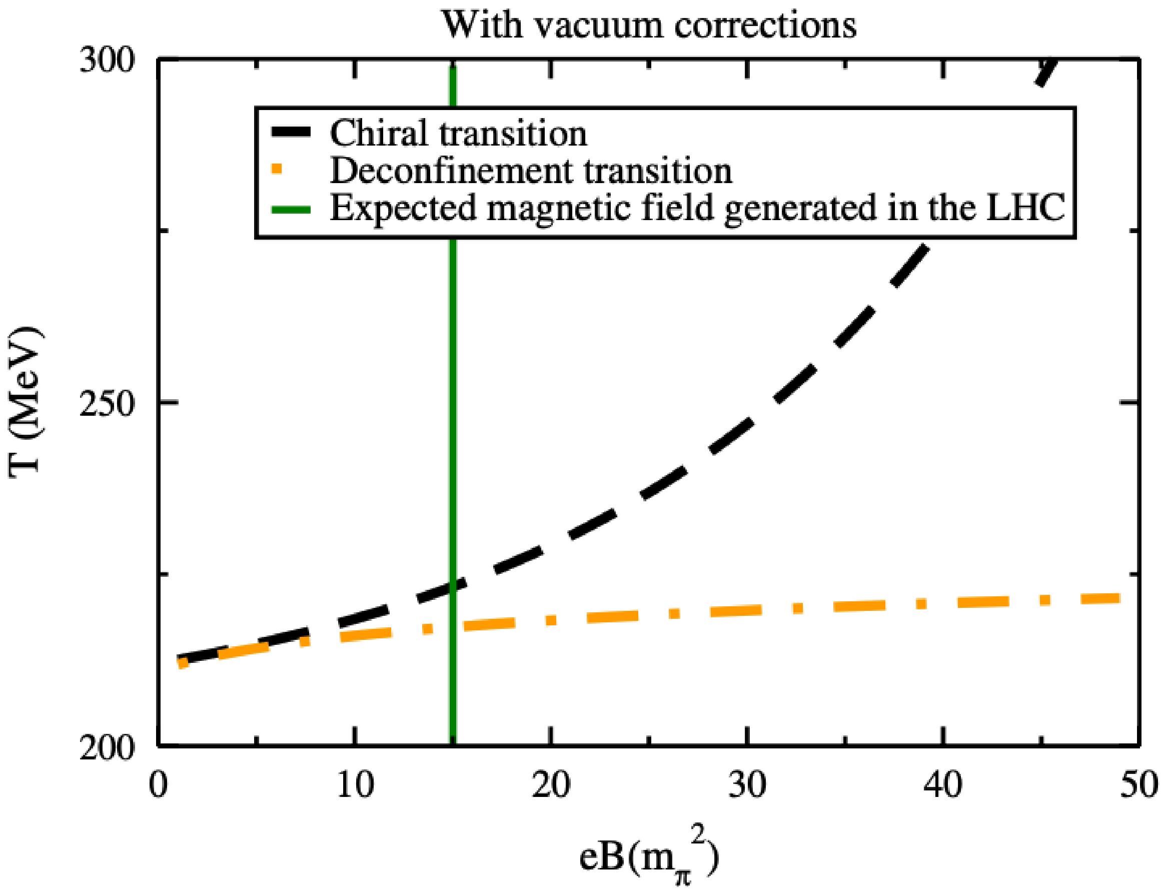


High pT muons



Heavy-flavor hadrons

EM Field in Heavy-ion Collisions



Mizher, Chernodub and Fraga, PRD 82 105016 (2010)
E. Fraga and A. Mizher, PRD 78 025016 (2008)

Rich structure of QCD phase diagram under strong EM field.