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Exploring electromagnetic field effects using Beam Energy Scan

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RHIC AGS Annual Users Meeting
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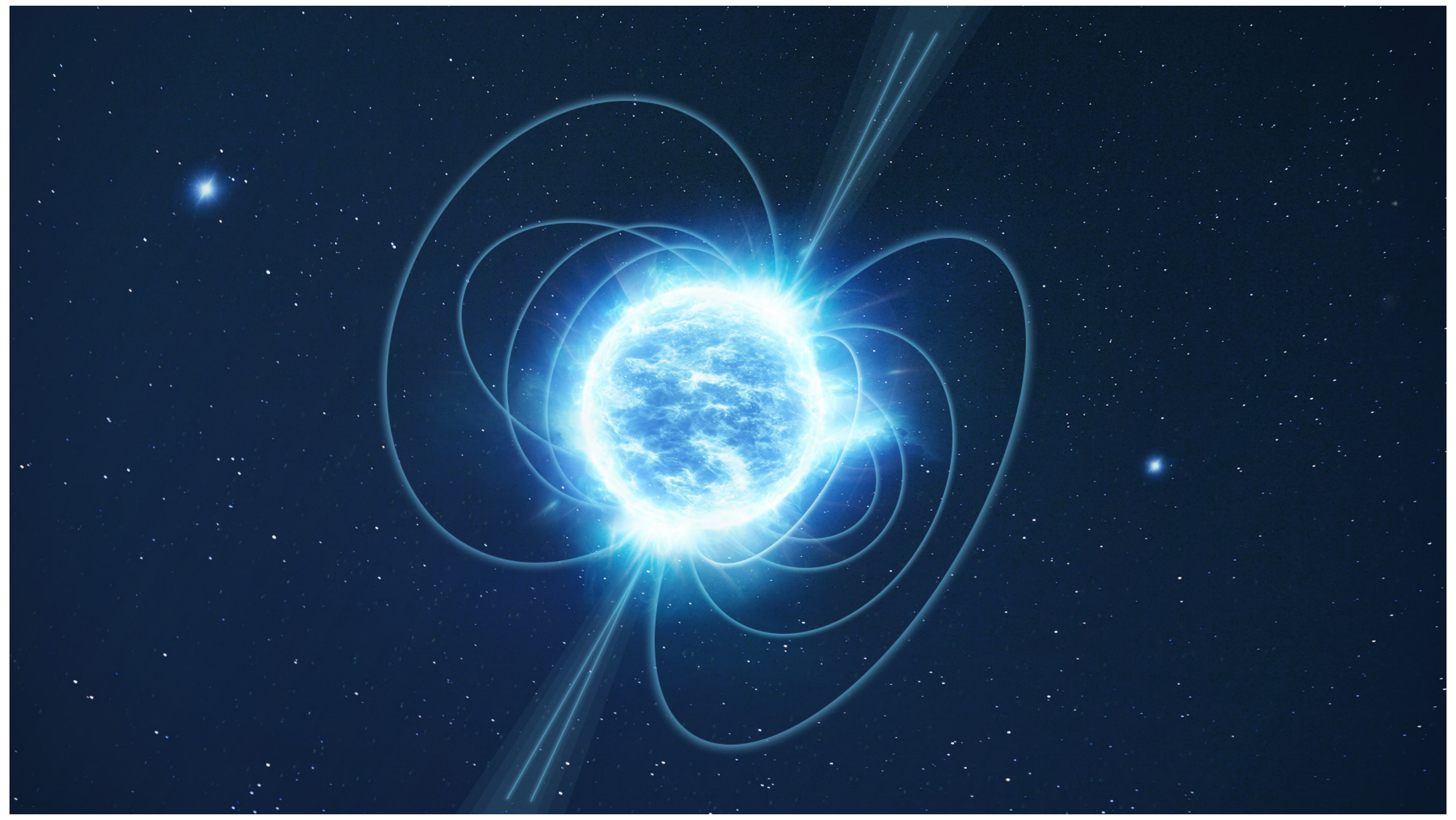
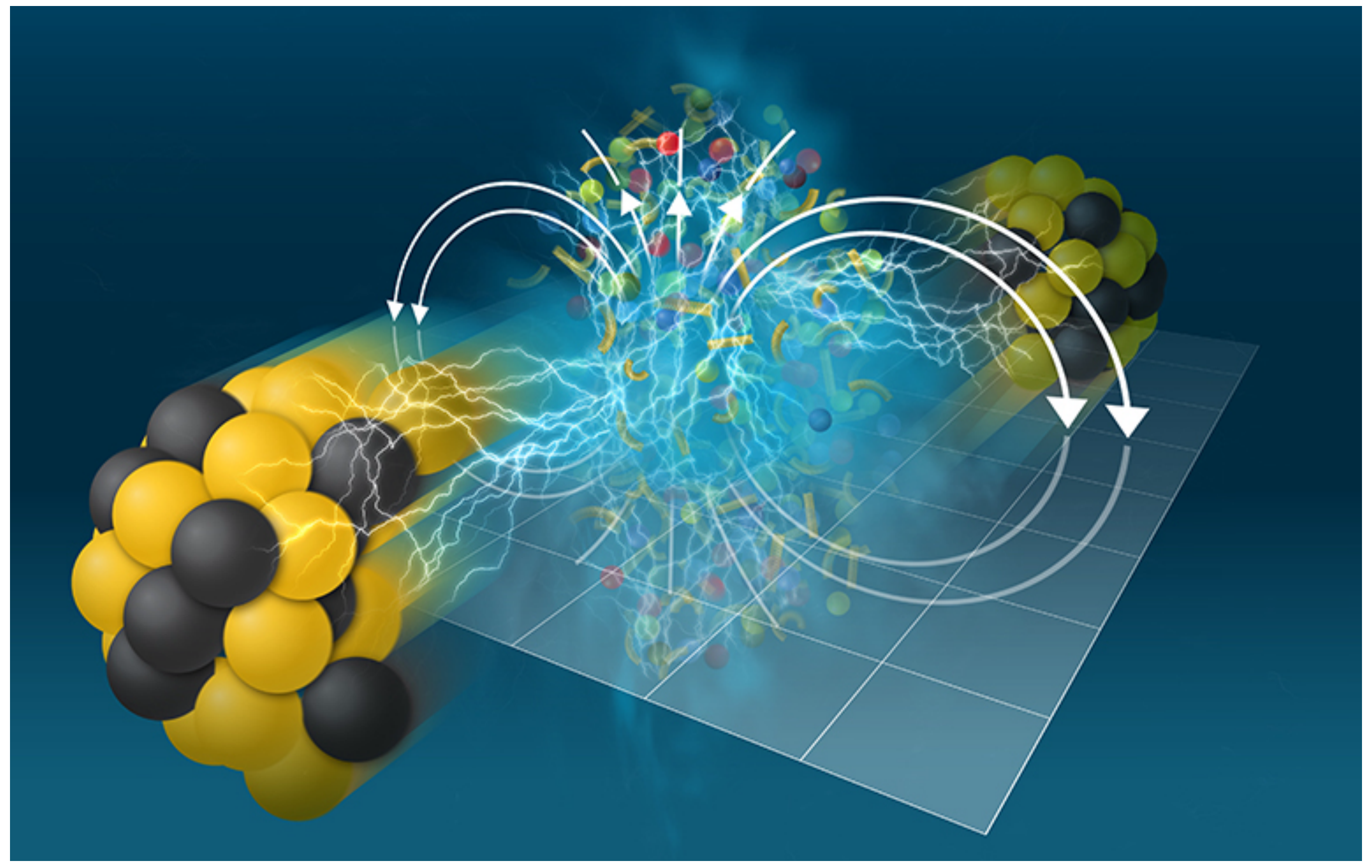
Motivation

- Ultra strong magnetic fields ~ 10^{18} G are expected in heavy ion collisions
- Greater than anywhere else observed in the universe
- What is its strength and how does it evolve?

Earth' surface ~ 0.5 G



Neutron Star ~ 10^{14} G



Heavy Ion Collisions ~ 10^{18} G

Image Credits: NASA, ESA, T. Bowman and J. Abramowitz/Brookhaven National Laboratory

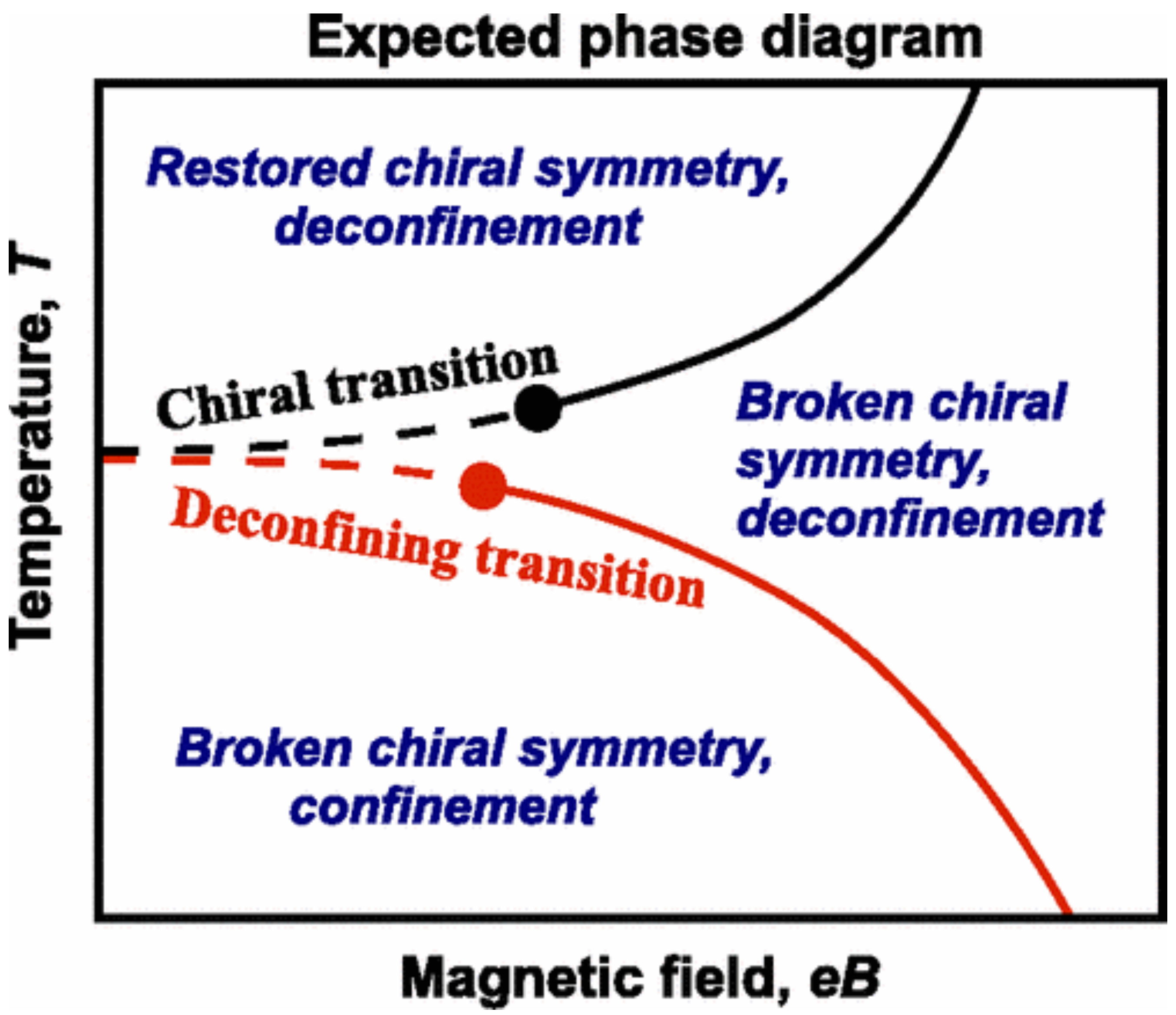
Impact of the electromagnetic field

QCD Phase Diagram

- Deconfinement and chiral transitions may split in the presence of magnetic fields
- QCD crossover may turn to a first order transition in the presence of magnetic fields

Phase diagram of hot QCD in an external magnetic field: Possible splitting of deconfinement and chiral transitions

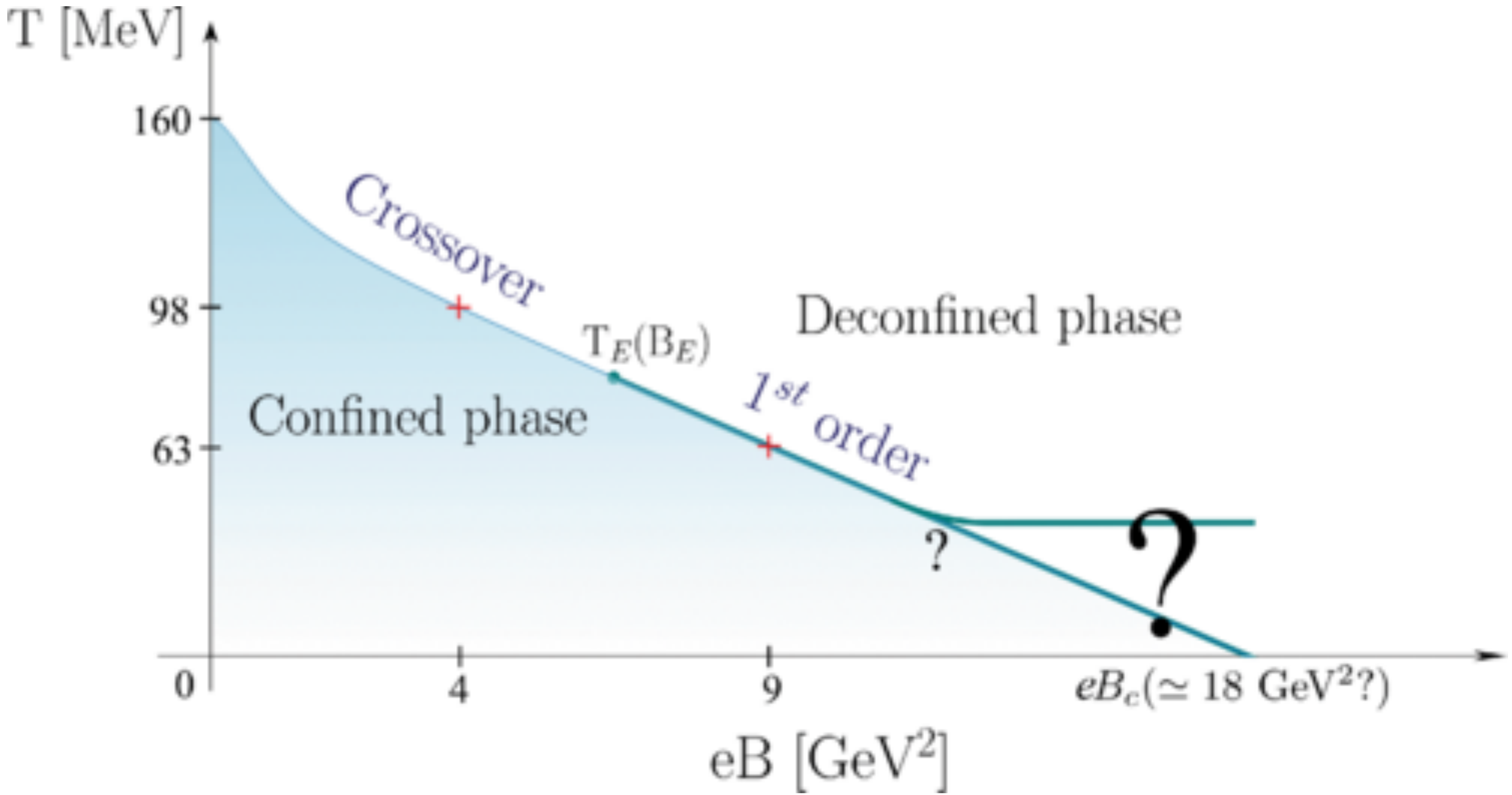
Ana Júlia Mizher, M. N. Chernodub, and Eduardo S. Fraga
Phys. Rev. D **82**, 105016 – Published 16 November 2010



PRD 82 105016

Phase diagram of QCD in a magnetic background

Massimo D'Elia, Lorenzo Maio, Francesco Sanfilippo, and Alfredo Stanzione
Phys. Rev. D **105**, 034511 – Published 23 February 2022



PRD 105, 034511

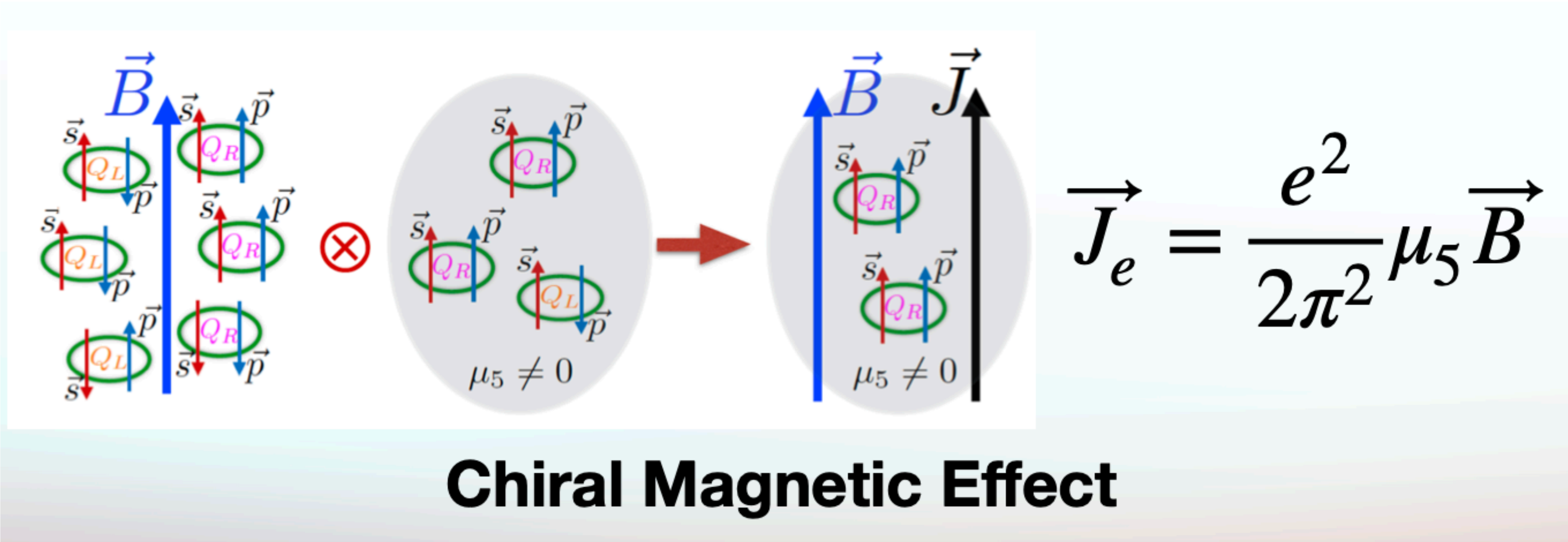
Impact of the electromagnetic field

Chiral Magnetic Effect

QCD topological vacuum transitions

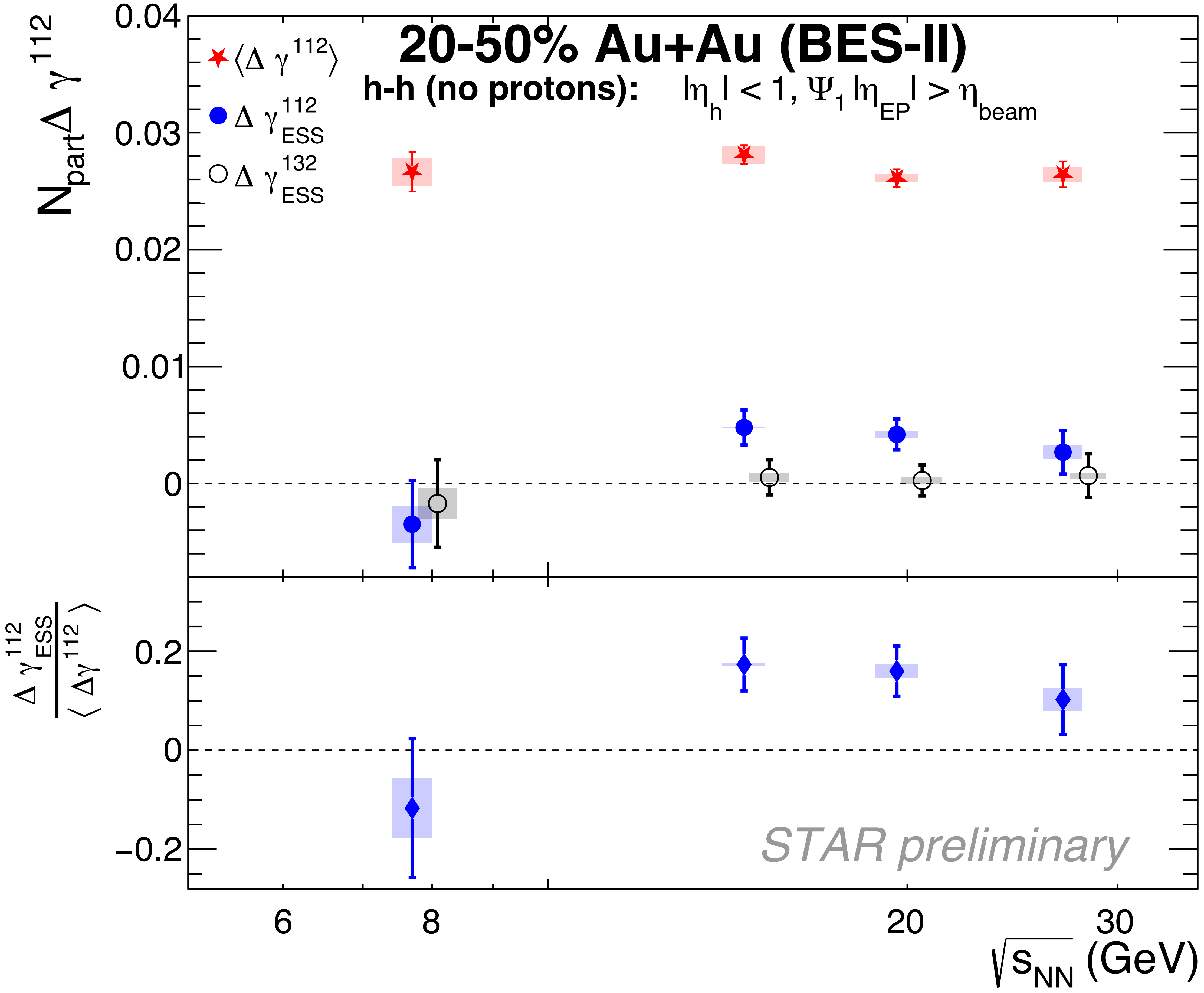
↓

Chirality Imbalance+ Strong magnetic field → Charge separation



$$\vec{J_e} = \frac{e^2}{2\pi^2}\mu_5 \vec{B}$$

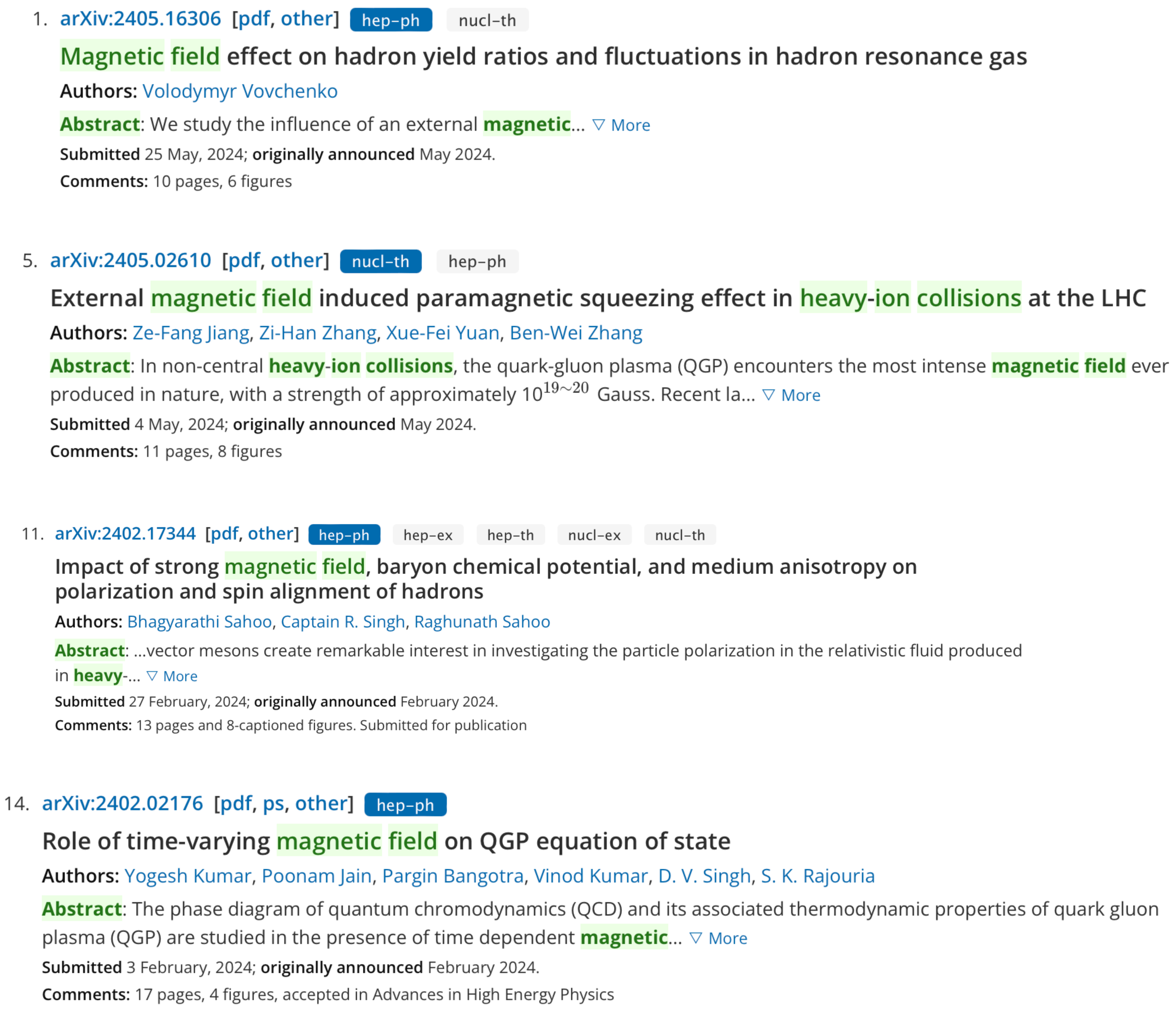
Chiral Magnetic Effect



Kharjeev et al., PRL 81(1998(512), S.A. Voloshin, PRC, 70, 057901 (2004), arXiv 2401.00317 , Z. Xu Quark Matter 2023

Under intense investigation

Some recent articles on arXiv



1. arXiv:2405.16306 [pdf, other] hep-ph nucl-th

Magnetic field effect on hadron yield ratios and fluctuations in hadron resonance gas

Authors: Volodymyr Vovchenko

Abstract: We study the influence of an external **magnetic**… ▽ More

Submitted 25 May, 2024; **originally announced** May 2024.

Comments: 10 pages, 6 figures

5. arXiv:2405.02610 [pdf, other] nucl-th hep-ph

External magnetic field induced paramagnetic squeezing effect in heavy-ion collisions at the LHC

Authors: Ze-Fang Jiang, Zi-Han Zhang, Xue-Fei Yuan, Ben-Wei Zhang

Abstract: In non-central **heavy-ion collisions**, the quark-gluon plasma (QGP) encounters the most intense **magnetic field** ever produced in nature, with a strength of approximately $10^{19\sim20}$ Gauss. Recent la… ▽ More

Submitted 4 May, 2024; **originally announced** May 2024.

Comments: 11 pages, 8 figures

11. arXiv:2402.17344 [pdf, other] hep-ph hep-ex hep-th nucl-ex nucl-th

Impact of strong magnetic field, baryon chemical potential, and medium anisotropy on polarization and spin alignment of hadrons

Authors: Bhagyarathi Sahoo, Captain R. Singh, Raghunath Sahoo

Abstract: …vector mesons create remarkable interest in investigating the particle polarization in the relativistic fluid produced in **heavy**-… ▽ More

Submitted 27 February, 2024; **originally announced** February 2024.

Comments: 13 pages and 8-captioned figures. Submitted for publication

14. arXiv:2402.02176 [pdf, ps, other] hep-ph

Role of time-varying magnetic field on QGP equation of state

Authors: Yogesh Kumar, Poonam Jain, Pargin Bangotra, Vinod Kumar, D. V. Singh, S. K. Rajouria

Abstract: The phase diagram of quantum chromodynamics (QCD) and its associated thermodynamic properties of quark gluon plasma (QGP) are studied in the presence of time dependent **magnetic**… ▽ More

Submitted 3 February, 2024; **originally announced** February 2024.

Comments: 17 pages, 4 figures, accepted in Advances in High Energy Physics

Citation counts of previous articles form Inspire HEP

Estimate of the magnetic field strength in heavy-ion collisions

V. Skokov (Darmstadt, GSI and Frankfurt U., FIAS and Dubna, JINR), A.Yu. Illarionov (Trento U.), V. Toneev (Darmstadt, GSI and Dubna, JINR)
Jul, 2009

8 pages
Published in: *Int.J.Mod.Phys.A* 24 (2009) 5925-5932
e-Print: 0907.1396 [nucl-th]
DOI: 10.1142/S0217751X09047570
View in: ADS Abstract Service

Magnetohydrodynamics, charged currents and directed flow in heavy ion collisions

Umut Gursoy (Utrecht U.), Dmitri Kharzeev (Brookhaven and SUNY, Stony Brook), Krishna Rajagopal (MIT, Cambridge, CTP)
Jan 15, 2014

12 pages
Published in: *Phys.Rev.C* 89 (2014) 5, 054905
Published: May 13, 2014
e-Print: 1401.3805 [hep-ph]
DOI: 10.1103/PhysRevC.89.054905
View in: OSTI Information Bridge Server, Nuclear Science References, ADS Abstract Service

Generation of the electromagnetic field

Colliding nuclei are positively charged and generate strong EM fields

Initial EM fields can be calculated using Lienard-Wiechert potentials

$$e\mathbf{E}(t,\mathbf{r}) = \frac{e^2}{4\pi}\sum_n Z_n \frac{\mathbf{R}_n - R_n\mathbf{v}_n}{(R_n - \mathbf{R}_n\cdot\mathbf{v}_n)^3}(1-v_n^2)$$

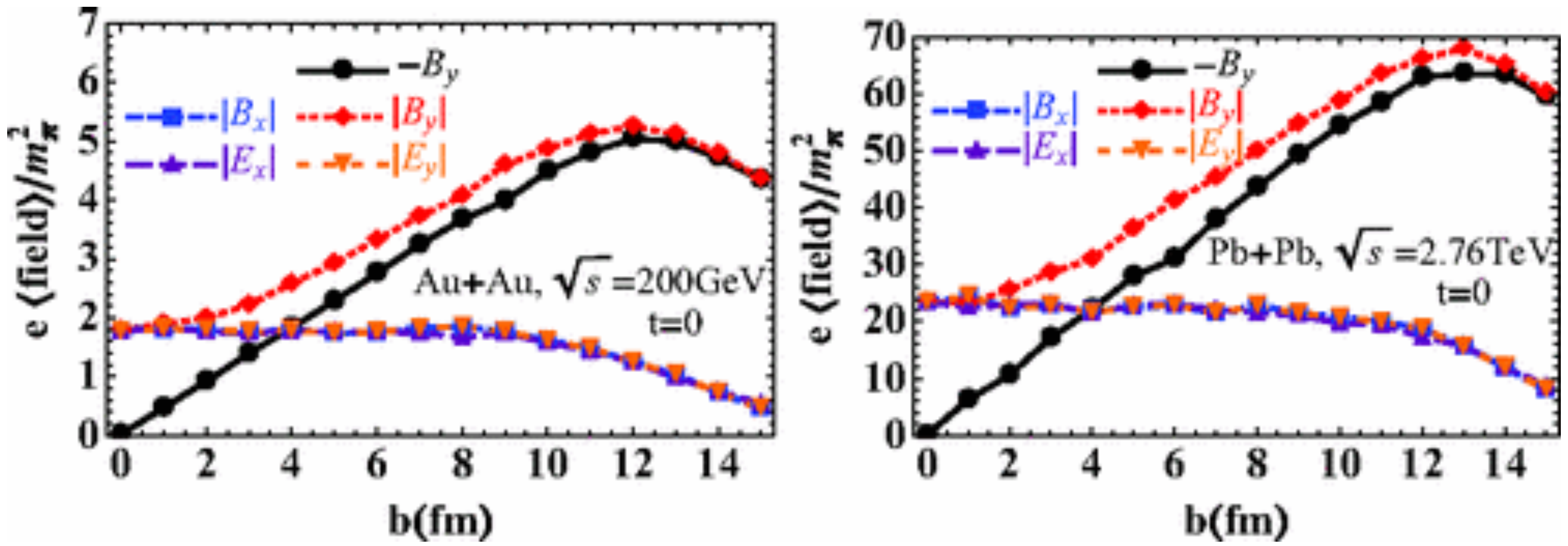
$$e\mathbf{B}(t,\mathbf{r}) = \frac{e^2}{4\pi}\sum_n Z_n \frac{\mathbf{v}_n\times\mathbf{R}_n}{(R_n - \mathbf{R}_n\cdot\mathbf{v}_n)^3}(1-v_n^2)$$

As magnetic field is generated by spectators and participants with $v_n = v_z = \sqrt{1-(2m_N/\sqrt{s})^2} \approx 1$,

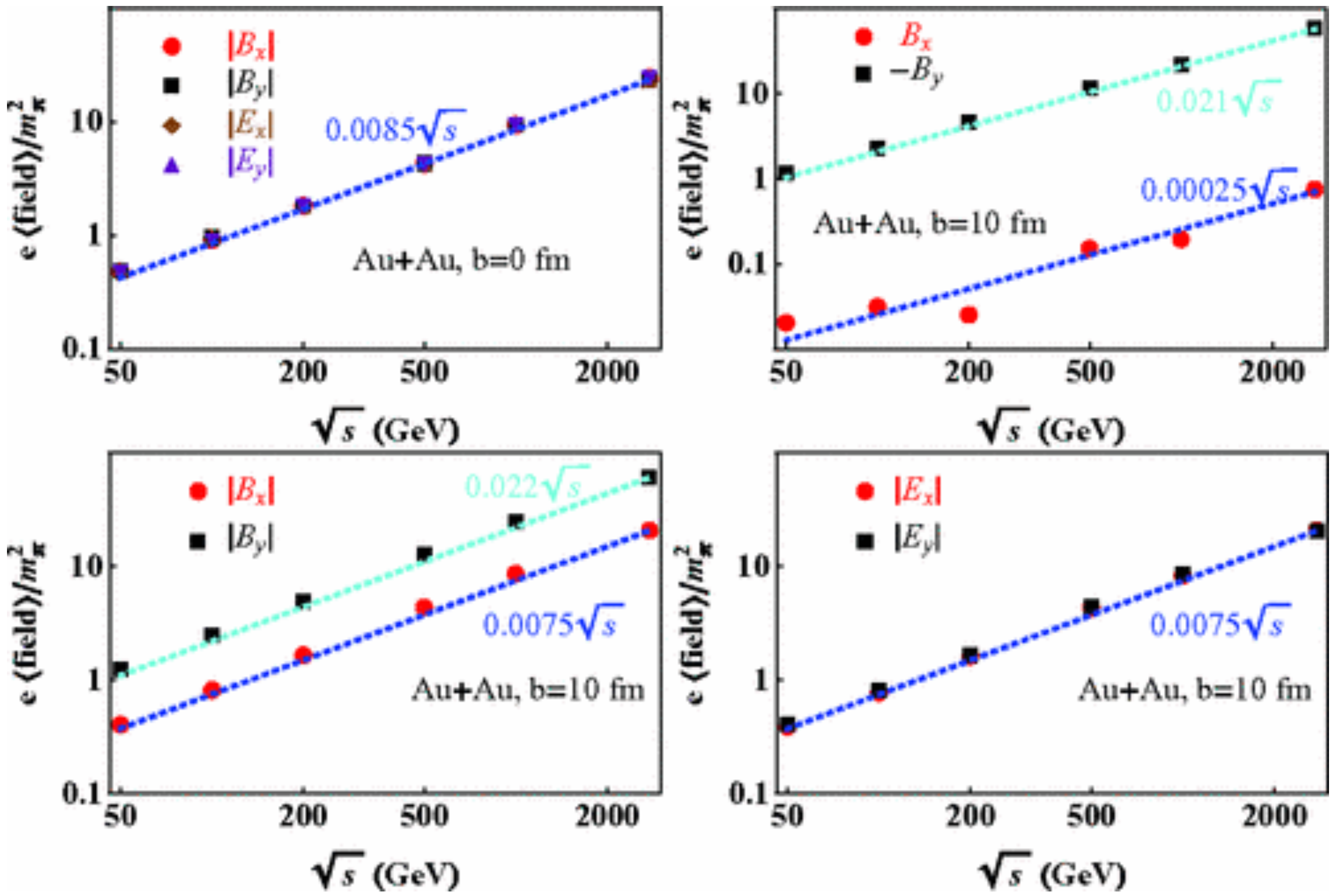
$$e\mathbf{E}_\perp(0,\mathbf{r}) \approx \frac{e^2}{4\pi}\frac{\sqrt{s}}{2m_N}\sum_n \frac{\mathbf{R}_{n\perp}}{R_{n\perp}^3},$$

$$e\mathbf{B}_\perp(0,\mathbf{r}) \approx \frac{e^2}{4\pi}\frac{\sqrt{s}}{2m_N}\sum_n \frac{\mathbf{e}_{nz}\times\mathbf{R}_{n\perp}}{R_{n\perp}^3},$$

Impact parameter dependence



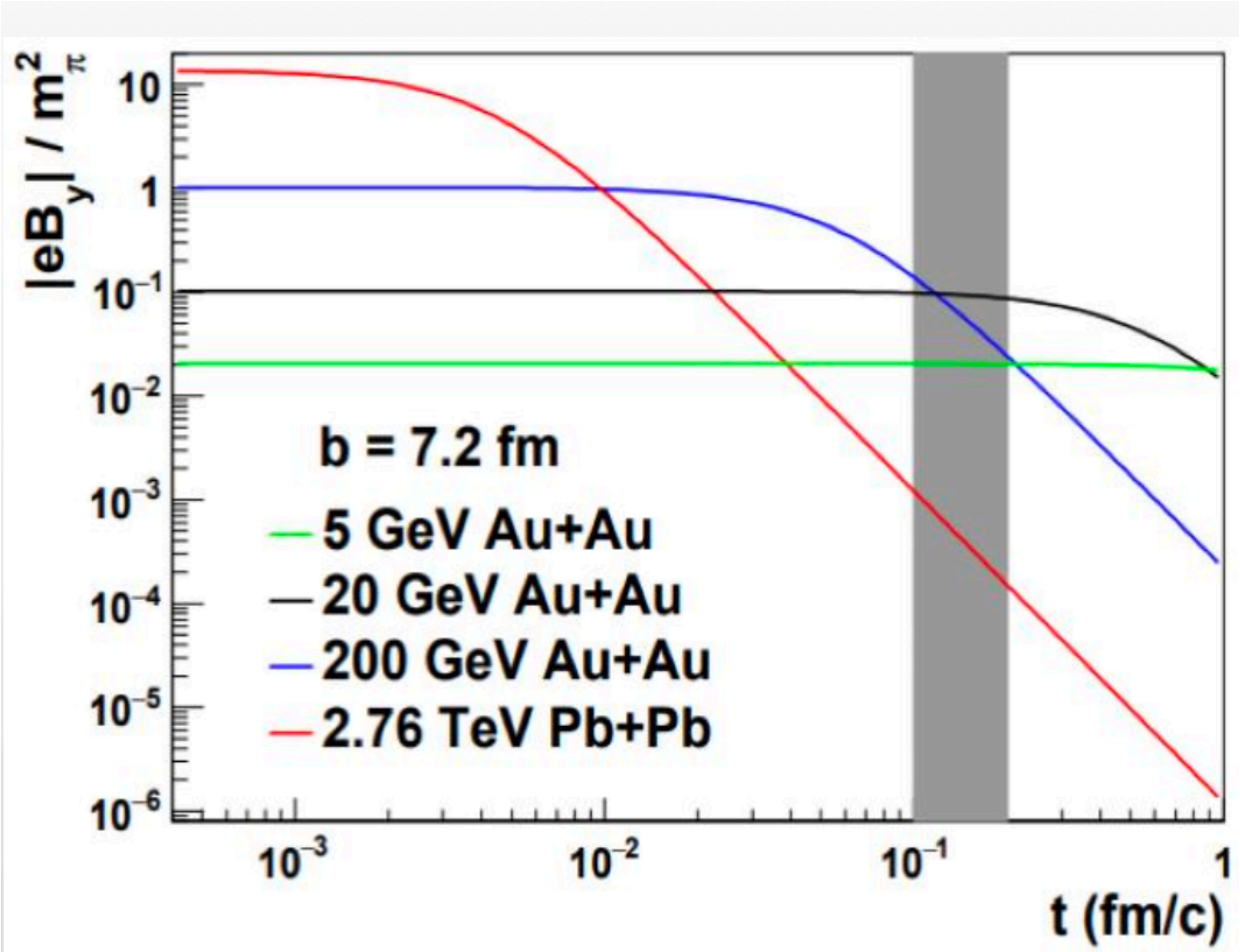
Beam Energy Dependence



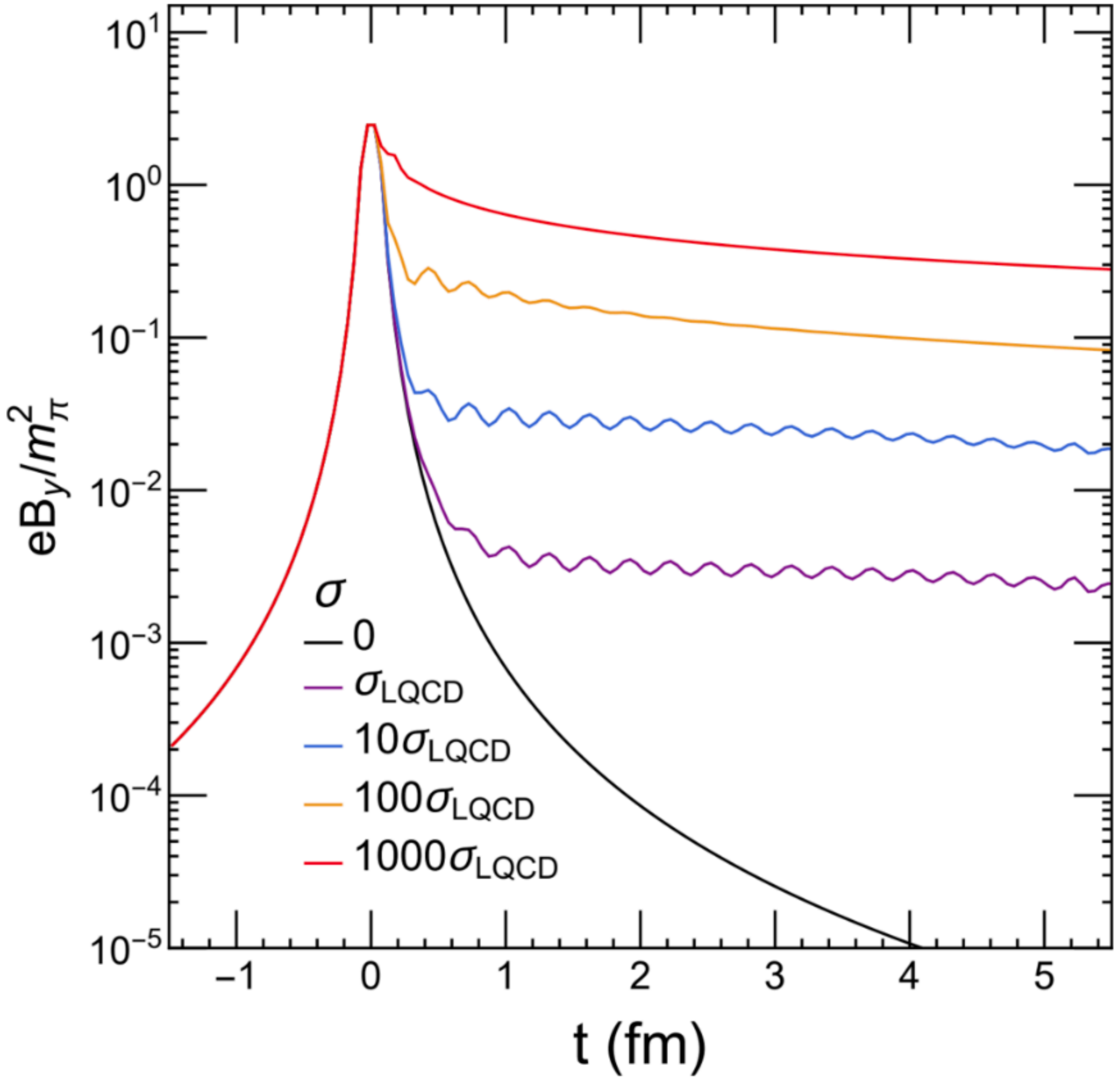
W. Deng et al. Phys. Rev. C 85, 044907 (2012)

Evolution of EM field

- Initial Stage- Gluon dominated -> Pre-equilibrium stage of rapid expansion in which quarks form -> Hydrodynamic stage with conductivity
- Field decays very fast in vacuum ~ formation time of quarks
- Conducting medium can sustain the field
- The field drops faster at higher beam energy



G. Wang Chirality Vorticity and Magnetic Field in Heavy Ion Collisions, UCLA 2022



A. Huang et al. PRC 107, 034901 (2023)

Experimental Signatures

EM fields in ultra Peripheral Collisions

Collisions with impact parameter larger than twice the radius of the nuclei
No QGP expected
Evidence of interaction between EM fields

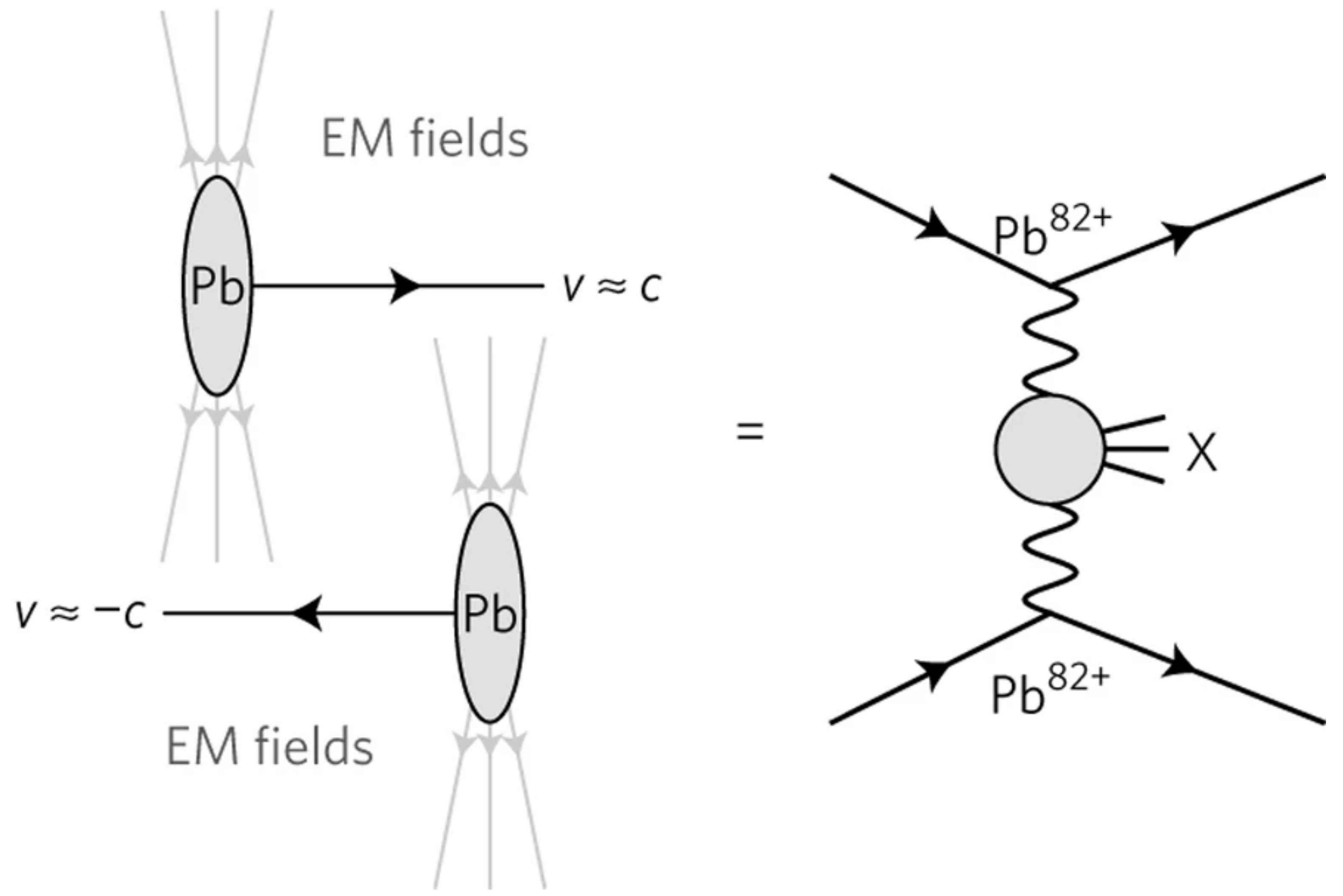
Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC

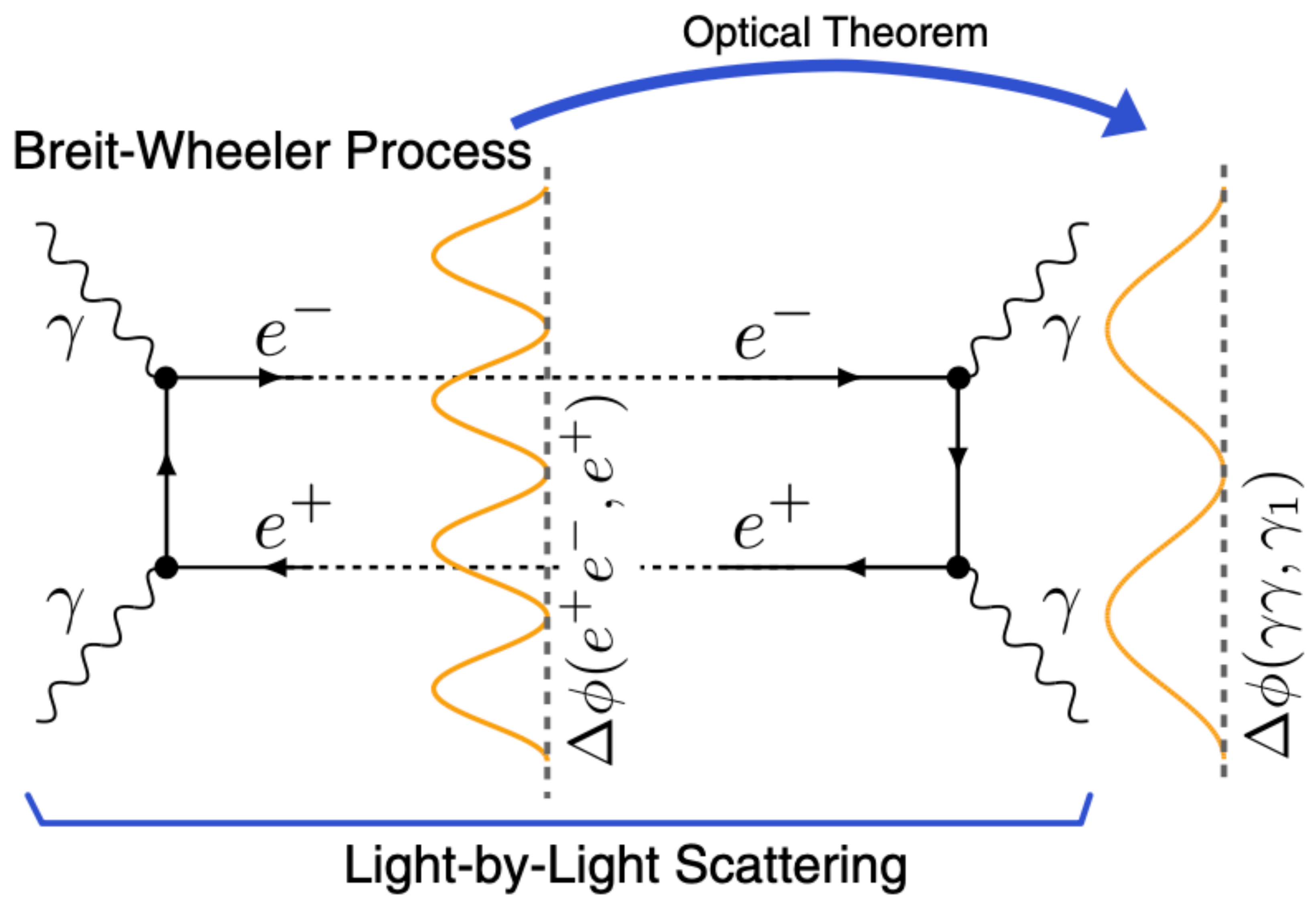
ATLAS Collaboration

Nature Physics **13**, 852–858 (2017) | Cite this article

Measurement of e^+e^- Momentum and Angular Distributions from Linearly Polarized Photon Collisions

J. Adam *et al.* (STAR Collaboration)
Phys. Rev. Lett. **127**, 052302 – Published 27 July 2021





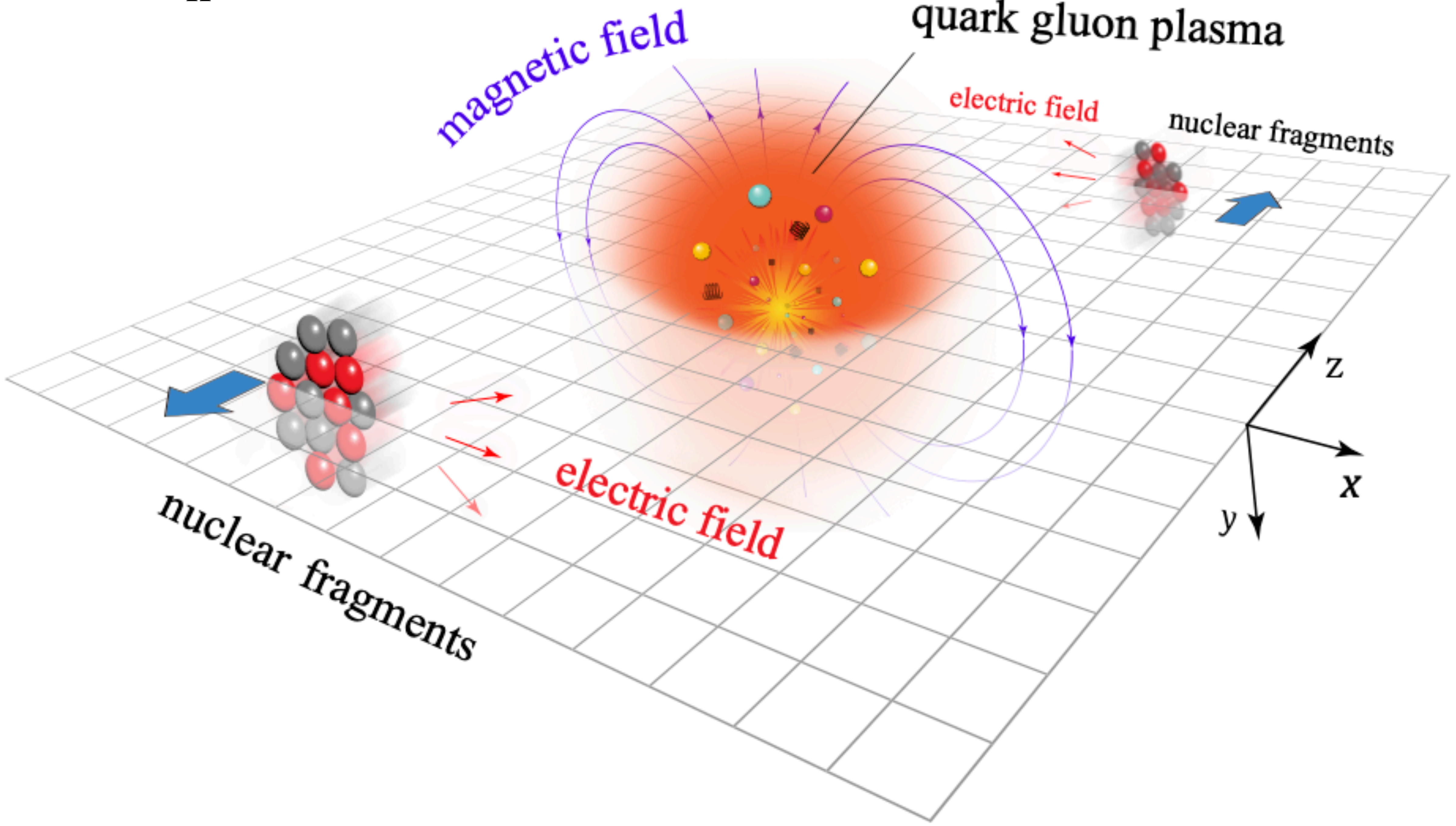
EM fields in Heavy Ion Collisions

EM forces affect azimuthal distribution of particles

Can be characterized by the Fourier expansion coefficients (v_n)

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos n(\phi - \Psi)\right)$$

[PRC 58 1671]



STAR, Phys. Rev. X 14, 011028

v_1 is called directed flow
Reflects asymmetric emission preference along the x axis
Can be measured by

$$v_1 = \langle \cos(\phi - \Psi_{\mathrm{EP}}) \rangle / R\{\Psi_{\mathrm{EP}}\}$$

ϕ=azimuthal angle of particle momentum
Ψ_{EP}= event plane (containing impact parameter and beam direction) azimuthal angle
R{Ψ_{EP}}= Event plane resolution

Electromagnetic field effects on directed flow

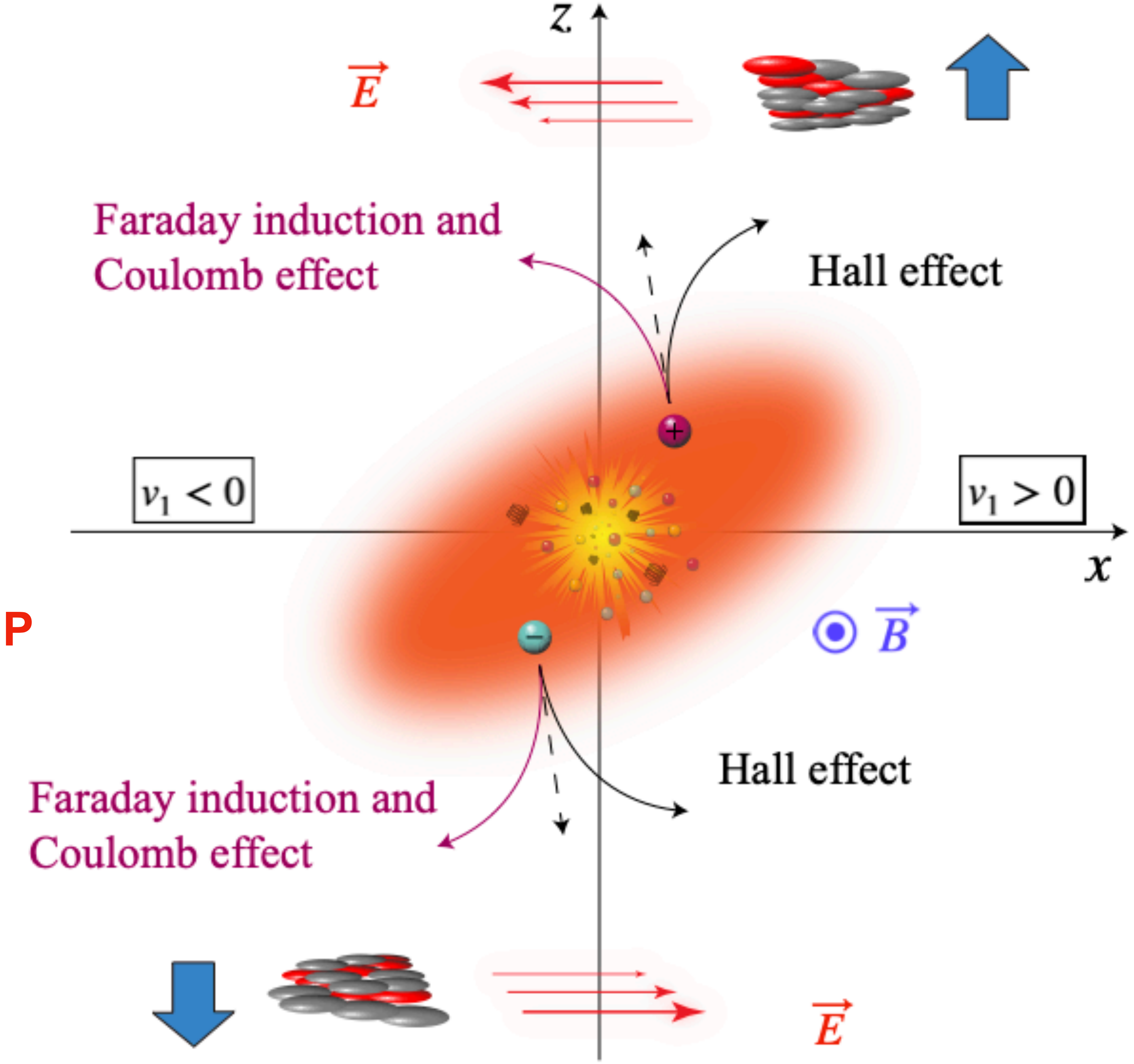
Different EM forces acting on QGP constituents

1. **Hall Effect**: **F**= q(**v**×**B**)
2. **Coulomb Effect**: **E** generated by spectators
3. **Faraday Induction**: Generated by decreasing magnetic field as spectators fly away

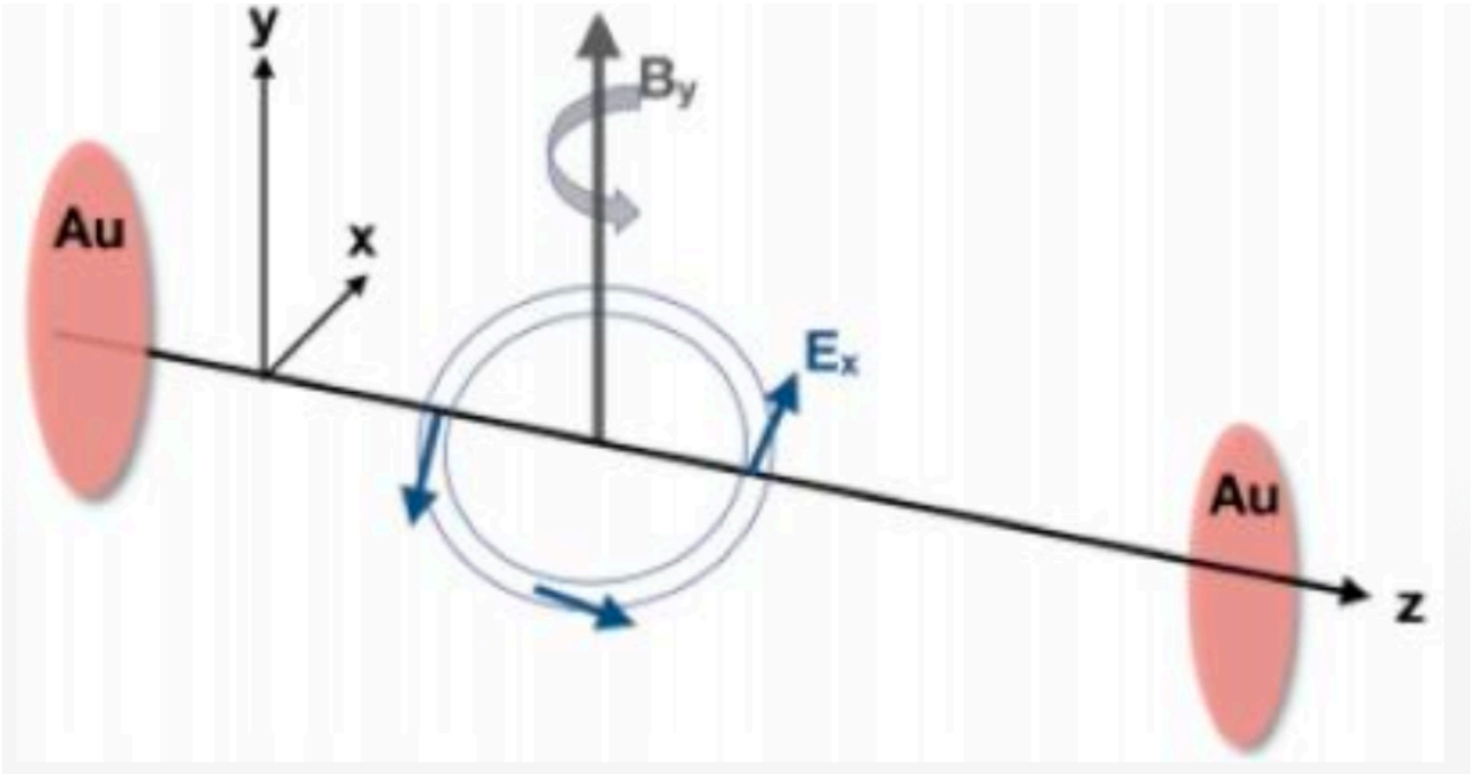
[PRC 98,055201, PRC 89 054905]

These EM forces give opposite v_1 to positively and negatively charged particles

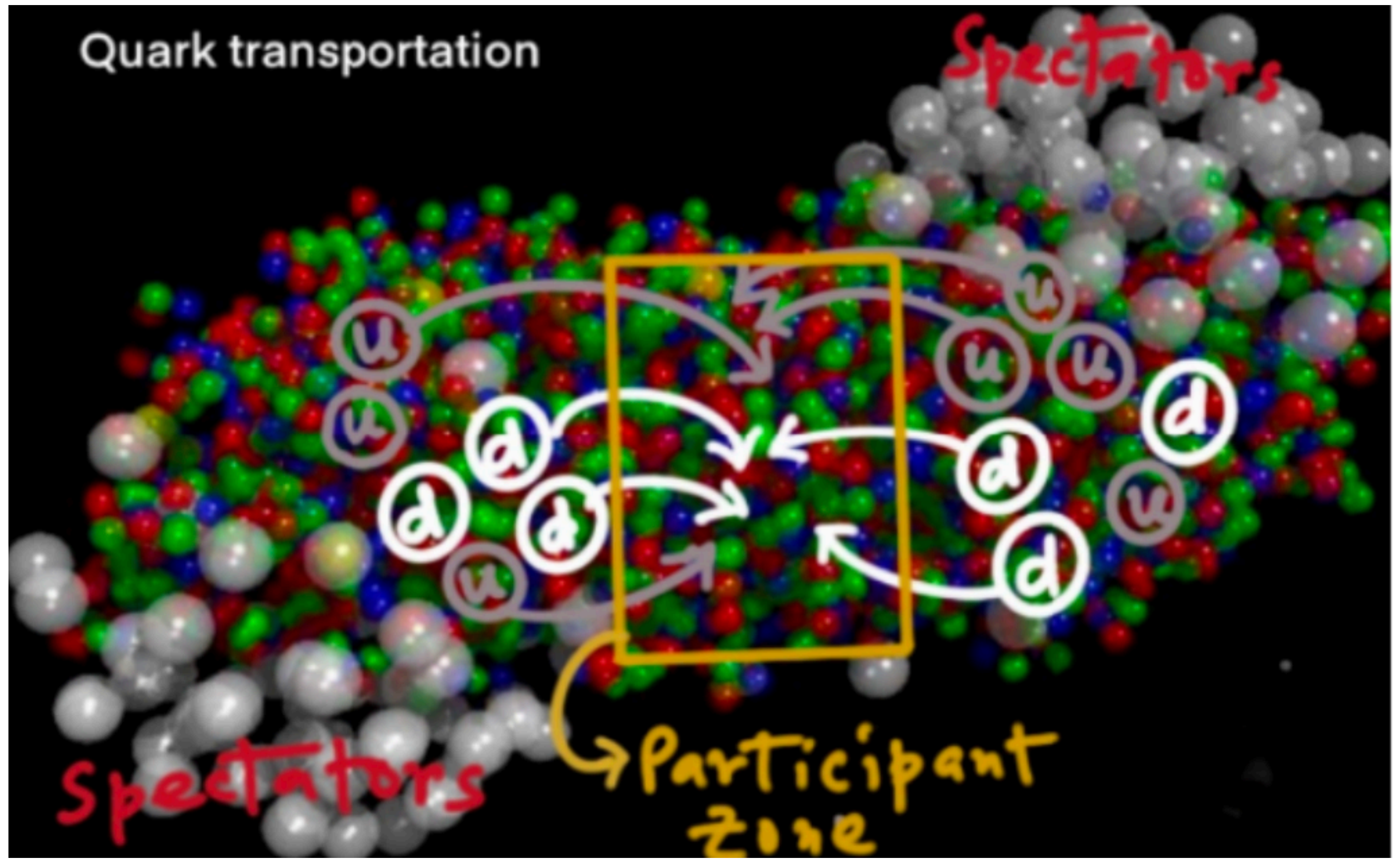
$\Delta dv_1/dy = dv_1(h^+)/dy - dv_1(h^-)/dy$ could reveal electromagnetic effects in QGP



STAR, Phys. Rev. X 14, 011028



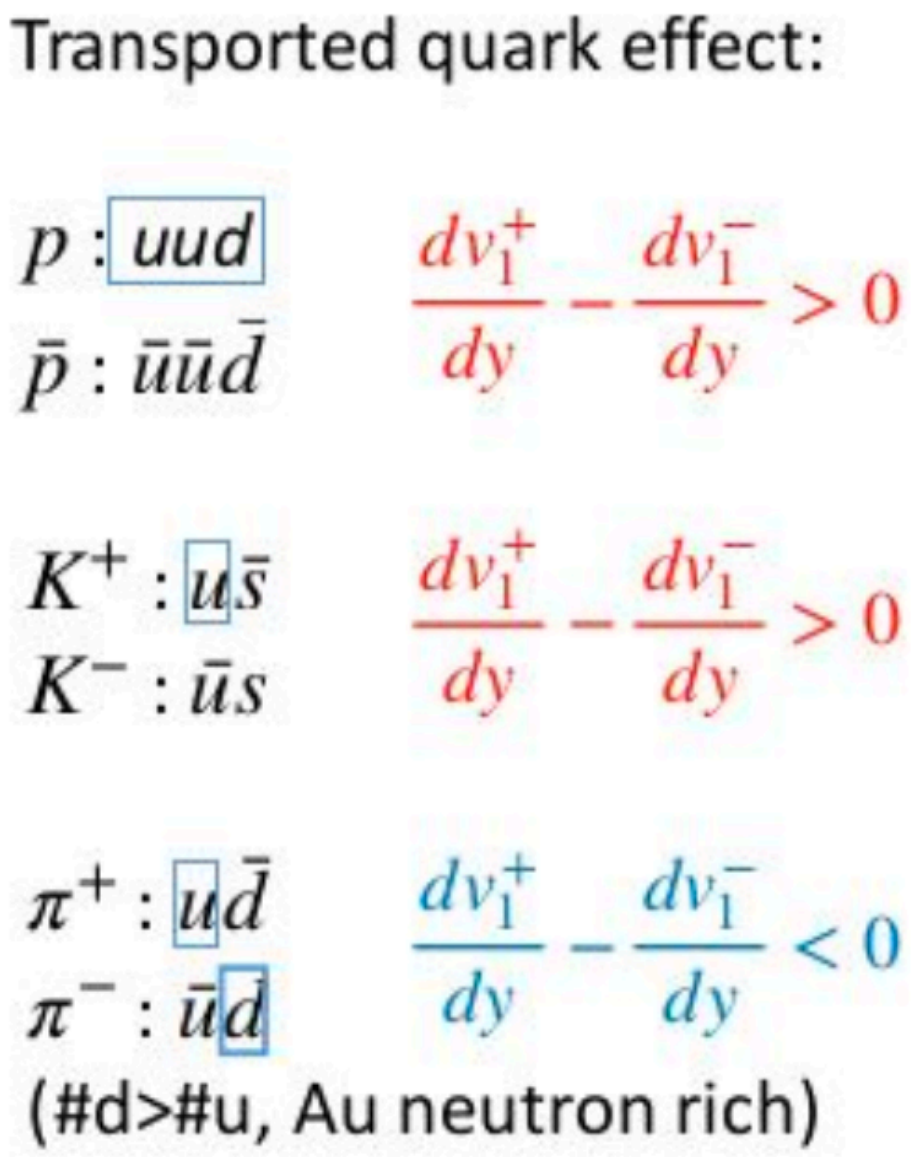
Transported quark effect



Transported quark effect: u and d quarks from incoming nuclei can have different v_1 than that of quarks produced in the interaction region due to initial stage effects

It can affect hadrons having u and d quarks.

Model studies show transported quarks have positive dv_1/dy



Transported quark effect:

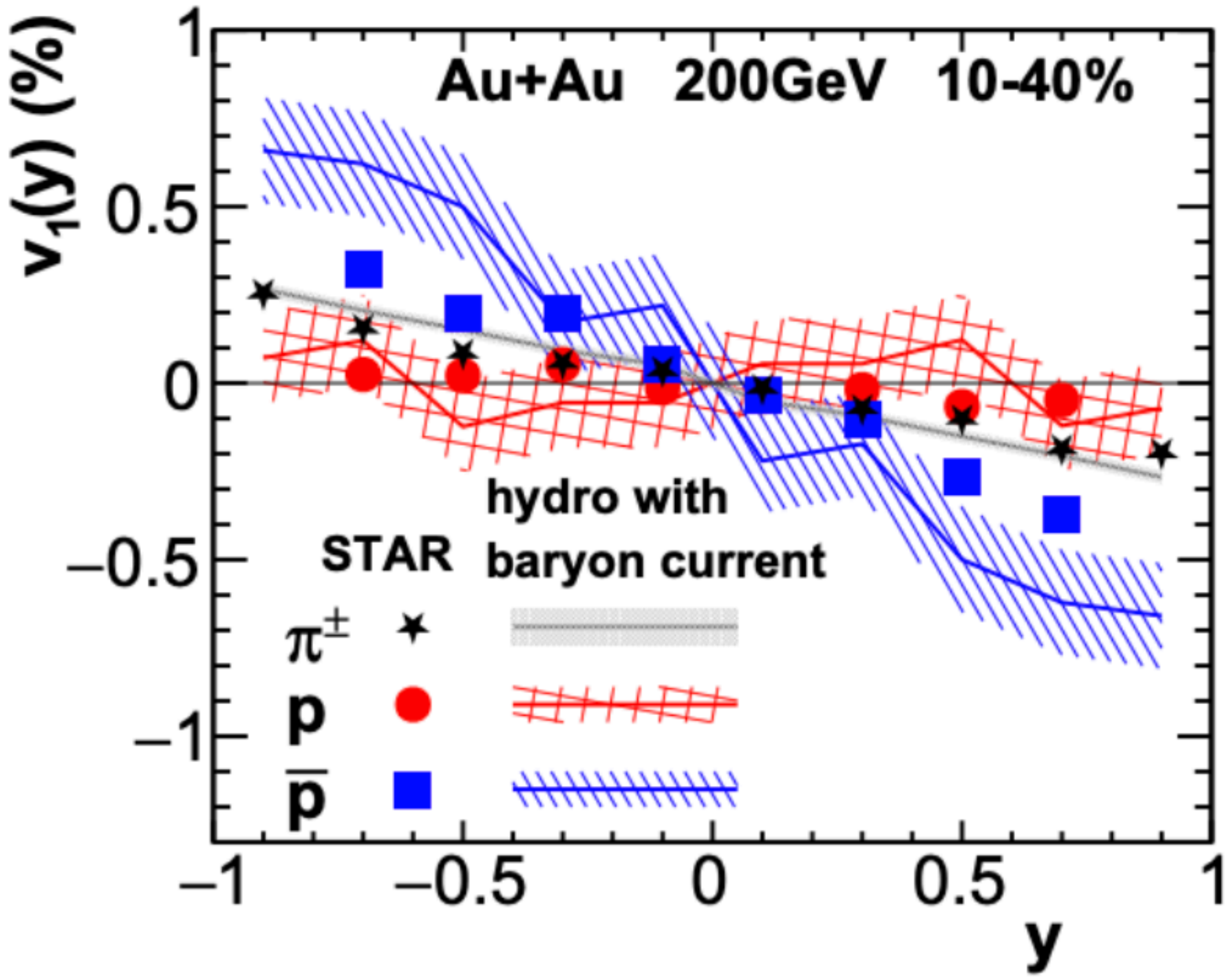
$p : \boxed{uud}$
$\bar{p} : \bar{u}\bar{u}\bar{d}$
$\frac{dv_1^+}{dy} - \frac{dv_1^-}{dy} > 0$

$K^+ : \boxed{u}\bar{s}$
$K^- : \bar{u}s$
$\frac{dv_1^+}{dy} - \frac{dv_1^-}{dy} > 0$

$\pi^+ : \boxed{u}\bar{d}$
$\pi^- : \bar{u}\boxed{d}$
$\frac{dv_1^+}{dy} - \frac{dv_1^-}{dy} < 0$

(#d>#u, Au neutron rich)

P. Bozek, PRC 106 L061901;

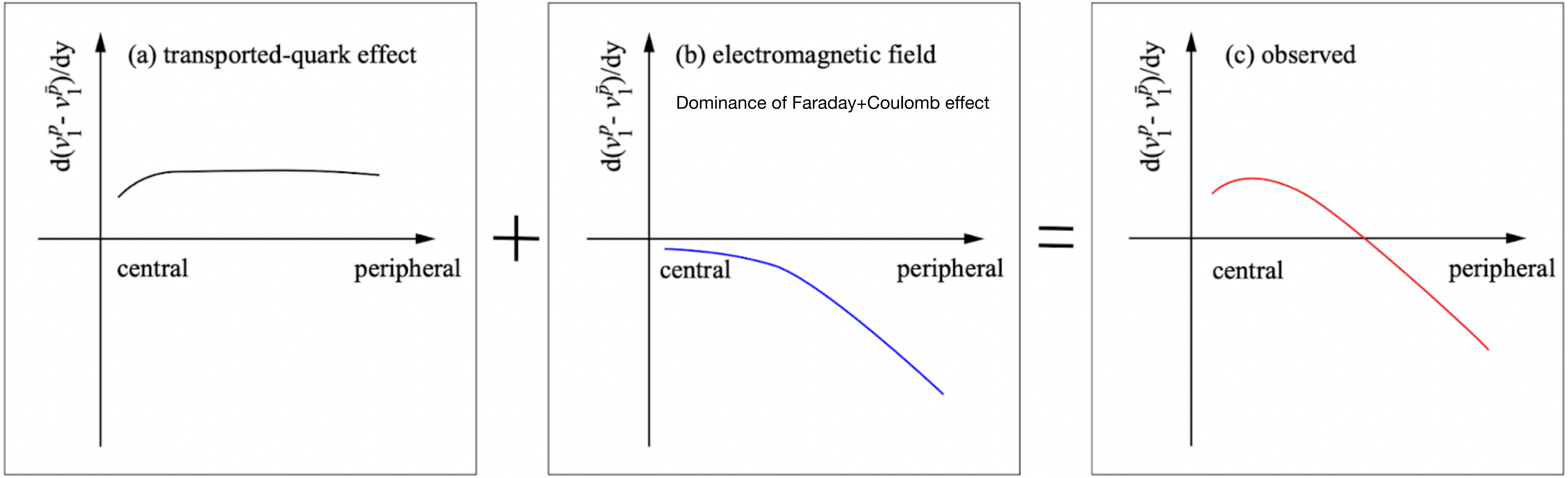


Transported quark effects on pions should give opposite $\Delta dv/dy_1$ compared to protons and kaons assuming quark coalescence.

J.C. Dunlop et.al, PRC 84 044914, K. Nayak et al PRC **100**, 054903, P. Bozeck PRC **106**, L061901, Image Credits: D. Shen

EM field effects + Transported quark effects expectation

Expectation for protons



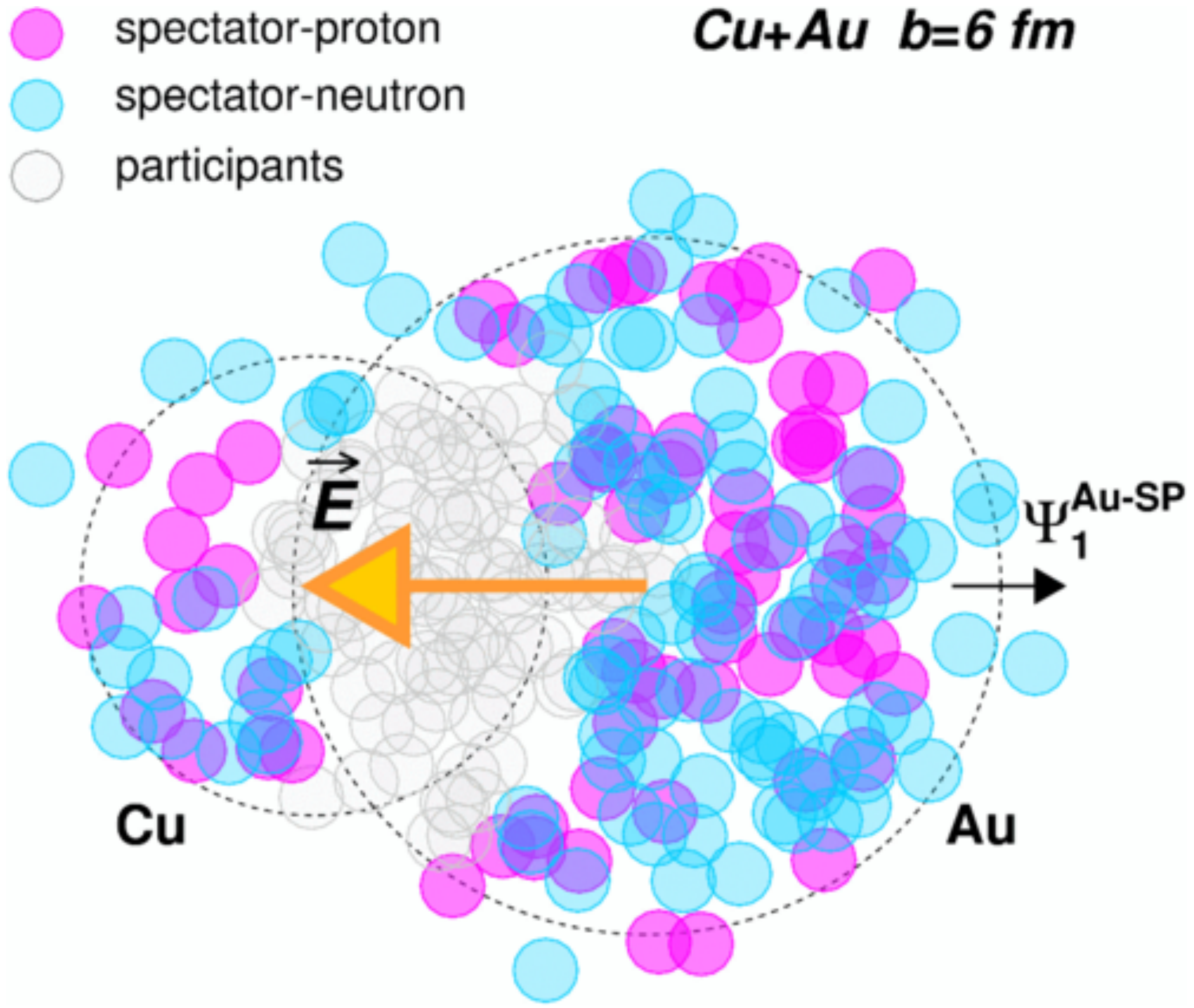
STAR, Phys. Rev. X 14, 011028

v_1~ linear function of rapidity. Faraday + Coulomb effect is expected to dominate among the electromagnetic forces [1]

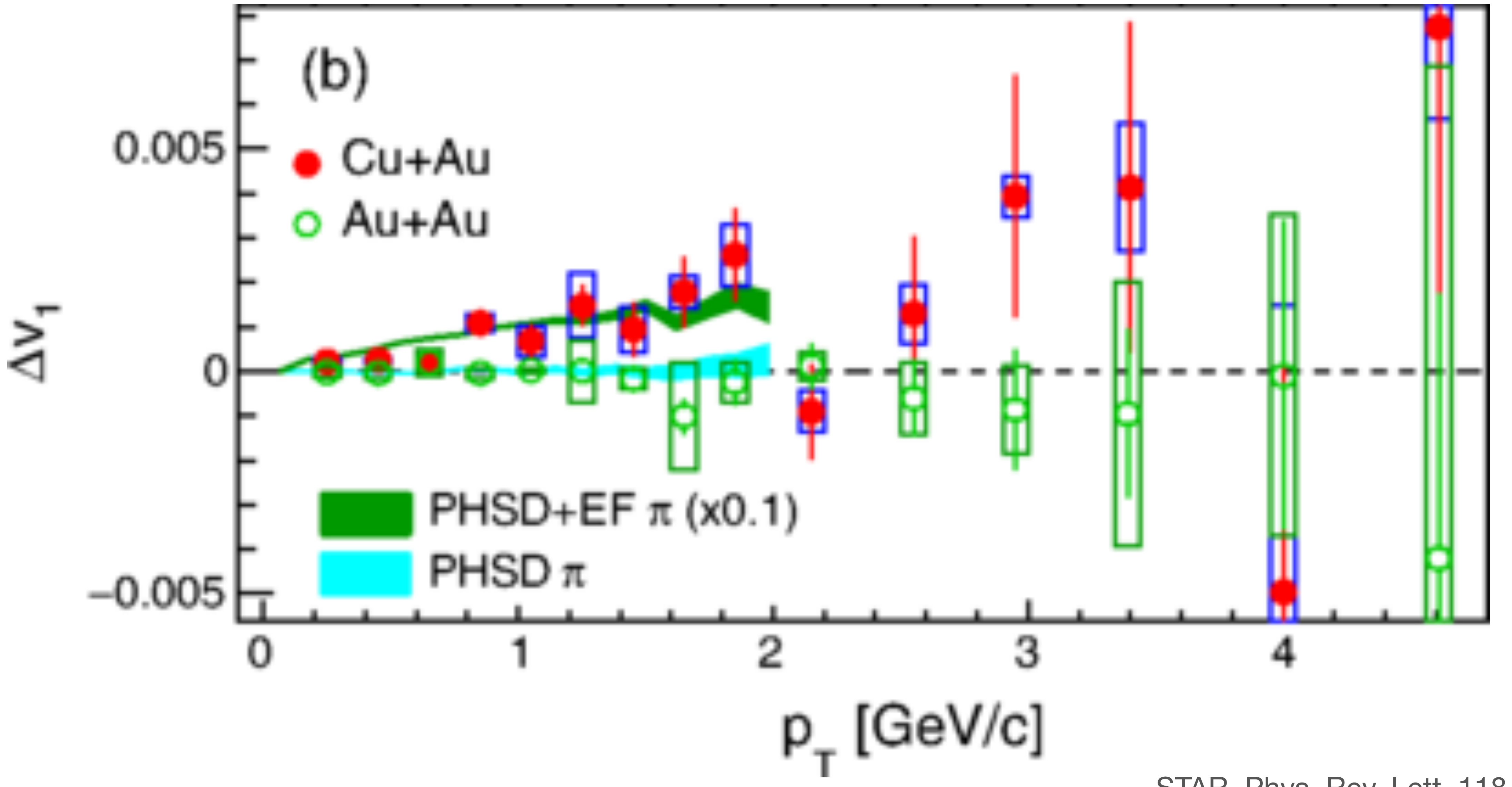
$\Delta dv_1/dy = dv_1(h^+)/dy - dv_1(h^-)/dy$ could reveal a sign change due to electromagnetic effects in QGP

[1] PRC 98,055201, PRC 89 054905, A.P. Dash Quark Matter 2023,

Δv_1 in Cu+Au Collisions



STAR, Phys. Rev. Lett. 118, 012301



STAR, Phys. Rev. Lett. 118, 012301

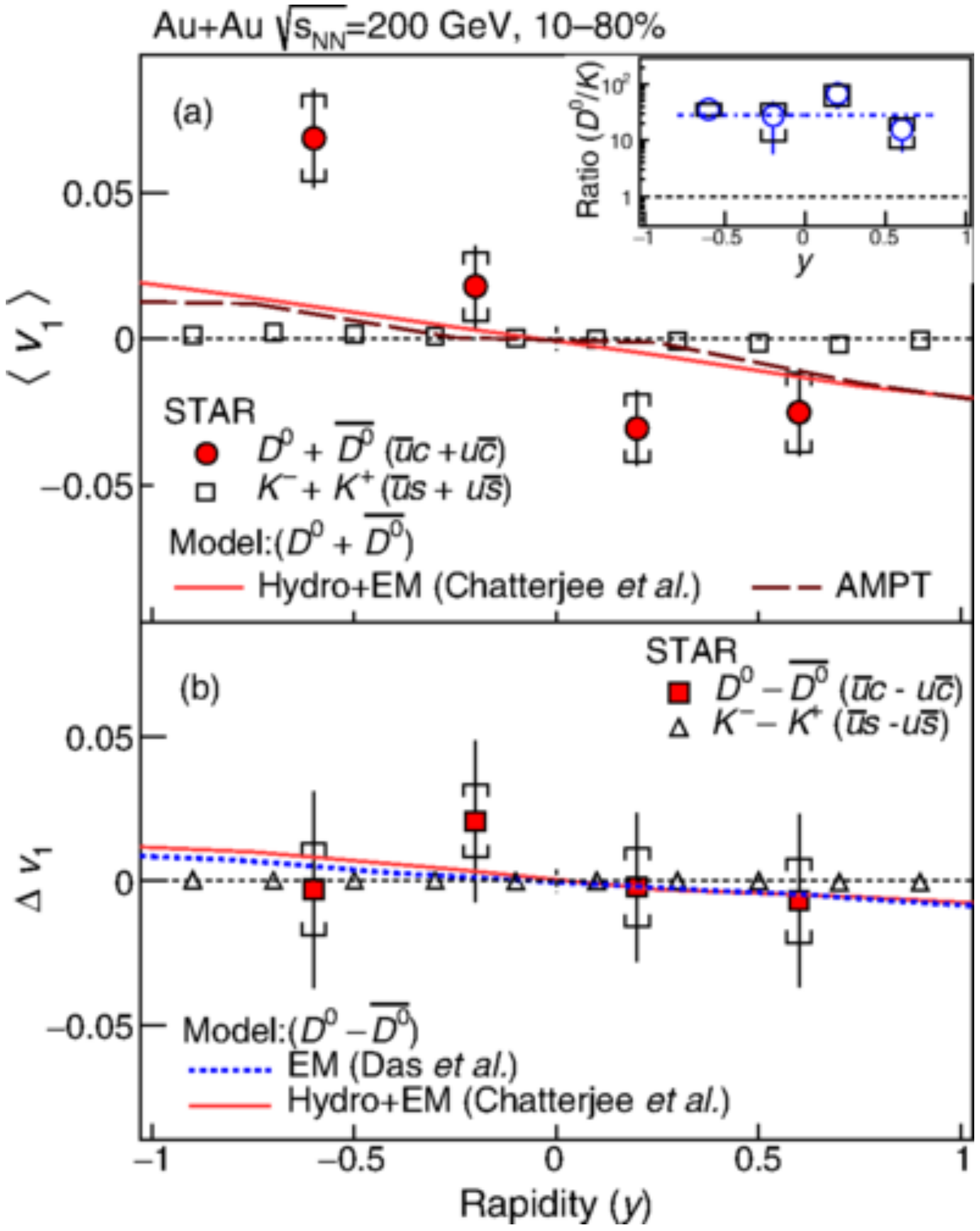
- Au has more charge and thus there should be a net electric field towards Cu
- Non-zero Δv_1 observed consistent with the Coulomb field

Δv_1 for charm quarks

- Charm quarks expected to form early
- Should feel stronger effect of the initial electromagnetic field

STAR results

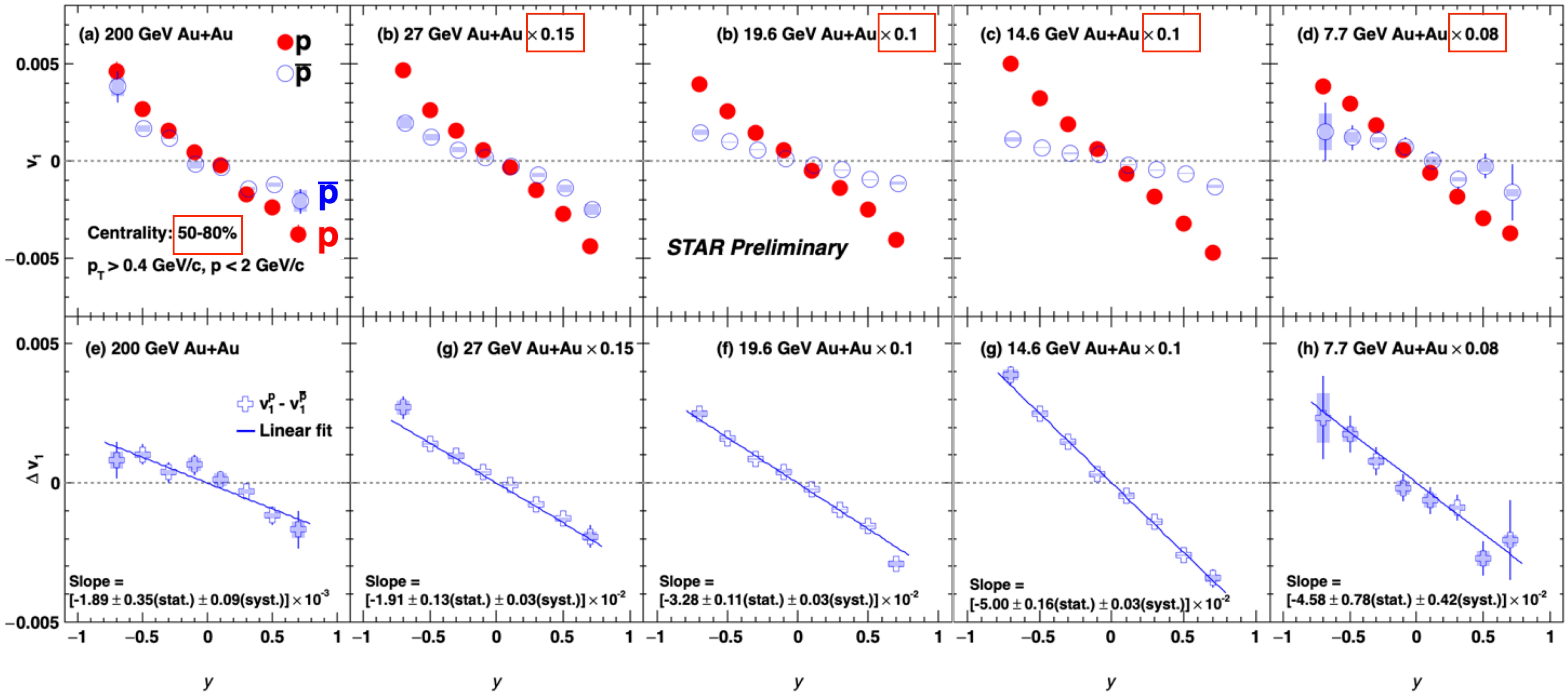
- v_1 slope (dv_1/dy) of D mesons ~ 25 times larger than that for charged kaons with 3.4σ significance
- Δv_1 slope ~ –0.011 ± 0.034 (stat) ± 0.020 (syst)
- Too large uncertainties to conclude Δv_1 splitting for D^0 and $\bar{D}^0$



STAR, Phys. Rev. Lett. 123, 162301

Similar study by ALICE Phys. Rev. Lett. 125, 022301 (2020), other magnetic field related searches: STAR, PRC 76 024915 (2007), STAR, Nature 548 (2017) 62, PRC 109, 034917 (2024)

$v_1(y)$ for $\pi^{\pm}, K^{\pm}, p(\bar{p})$ in peripheral collisions



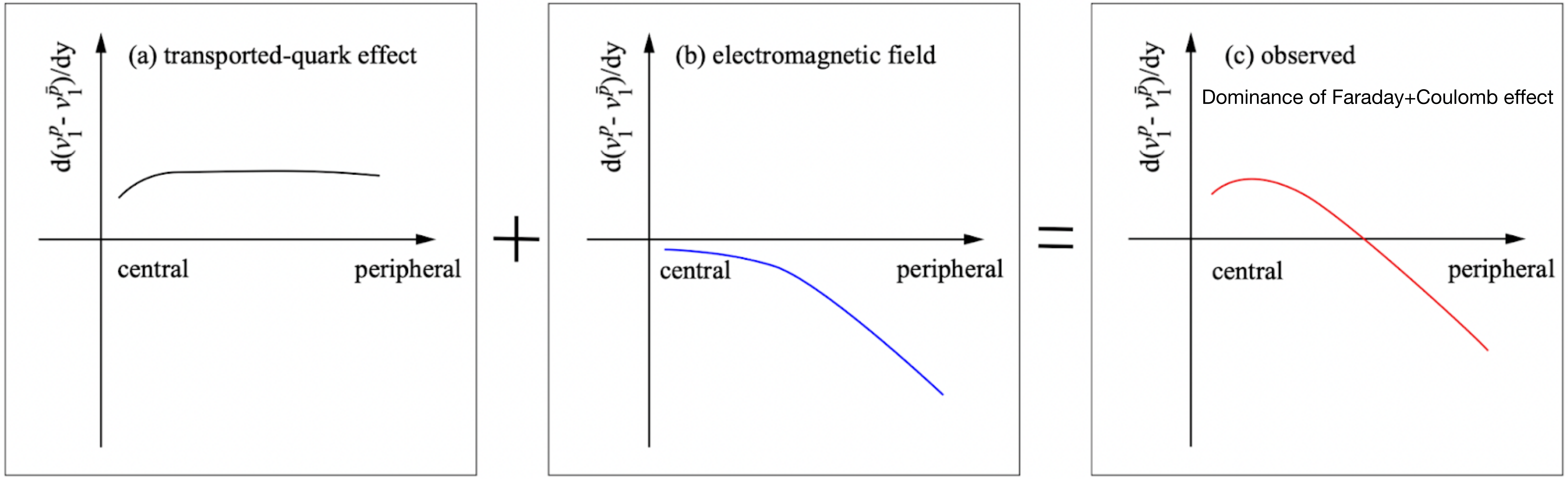
- **In peripheral collisions (50-80% centrality), proton $d\Delta v_1/dy$ is negative**
- Significantly negative slopes (from linear fit) in all considered energies

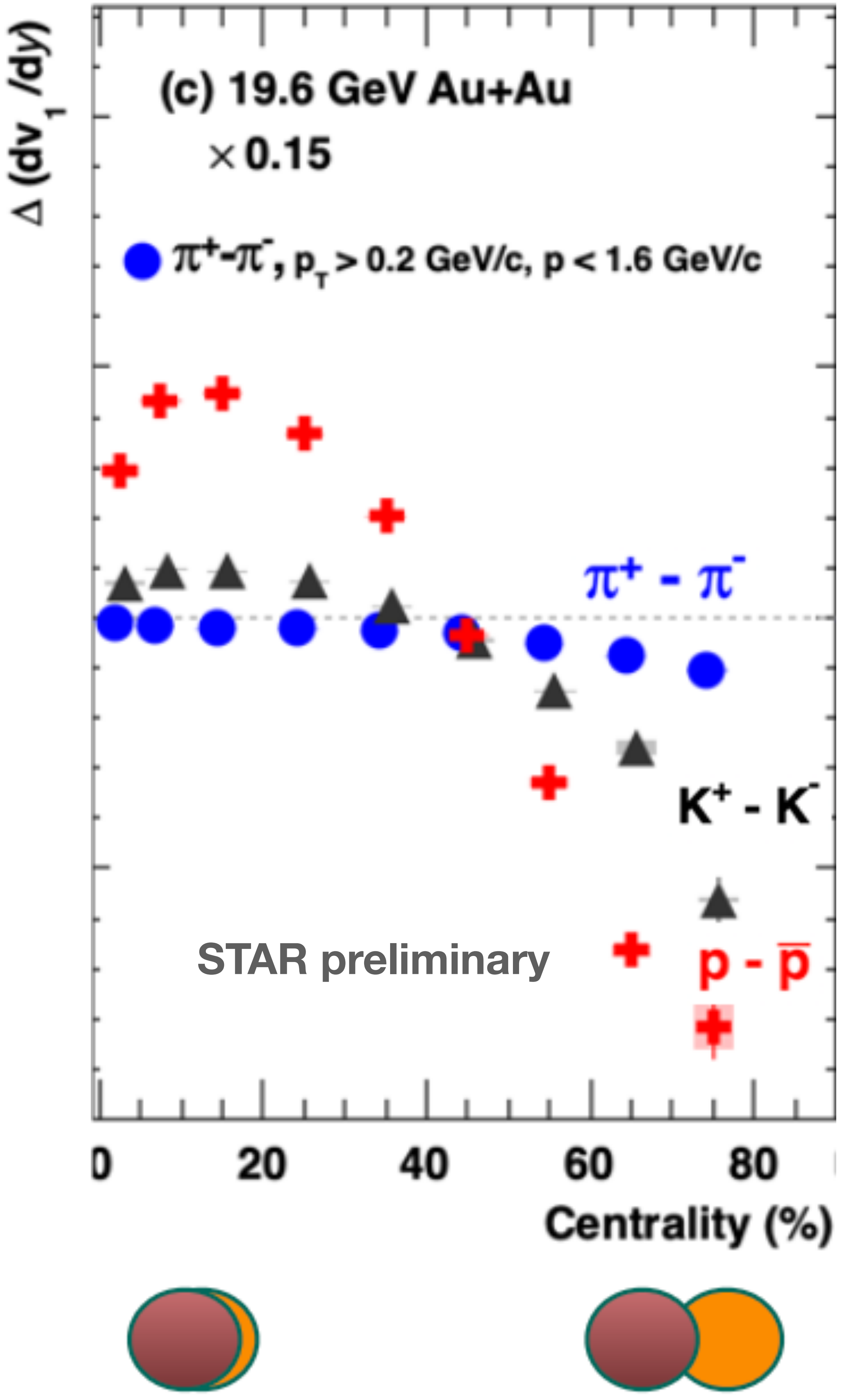
STAR, Phys. Rev. X 14, 011028, A.P. Dash Quark Matter 2023, arXiv:2401.04838

$v_1(y)$ vs centrality for $\pi^{\pm}, K^{\pm}, p(\bar{p})$ at 19.6 GeV

- Pattern consistent with expectations
- $\Delta(dv_1/dy)$ is positive in mid central collisions for protons and kaons
- $\Delta(dv_1/dy)$ turns negative in peripheral collisions as expected from dominance of Faraday+Coulomb effect

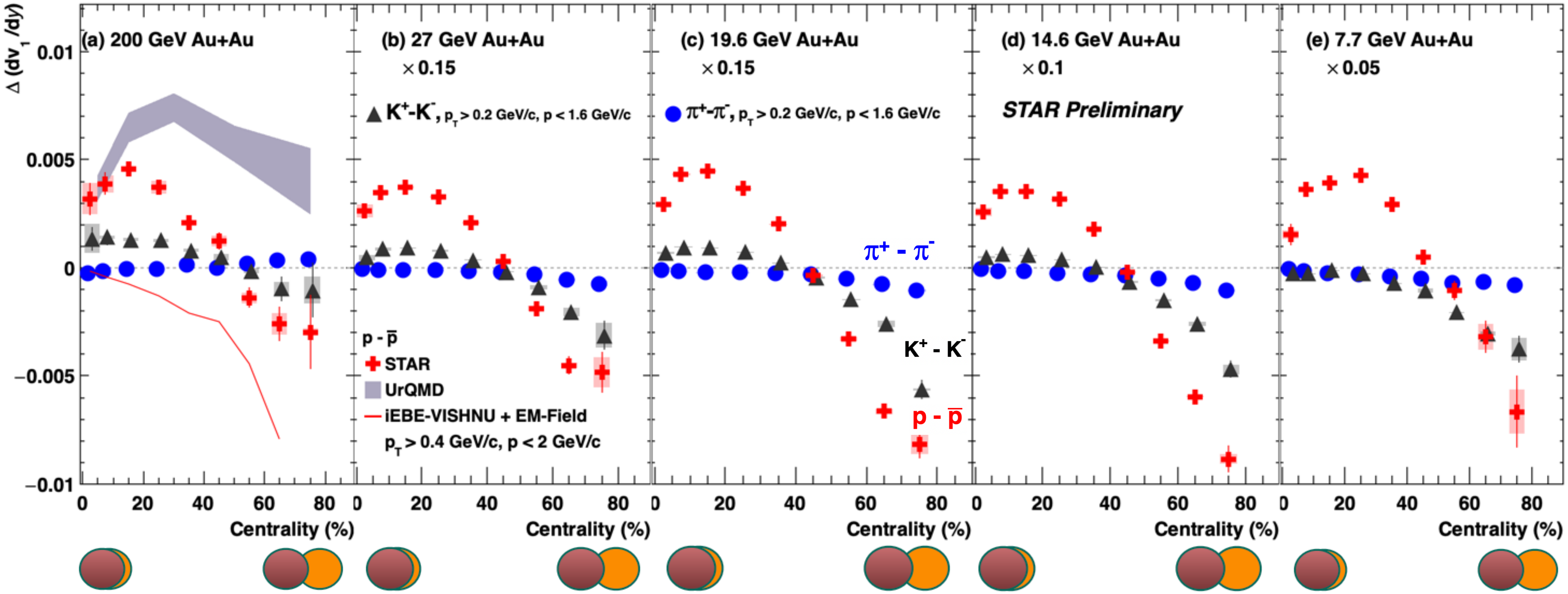
Expectation for protons





STAR, Phys. Rev. X 14, 011028, A. P. Dash QM 2023, arXiv:2401.04838

Particle species dependence at different collision energies

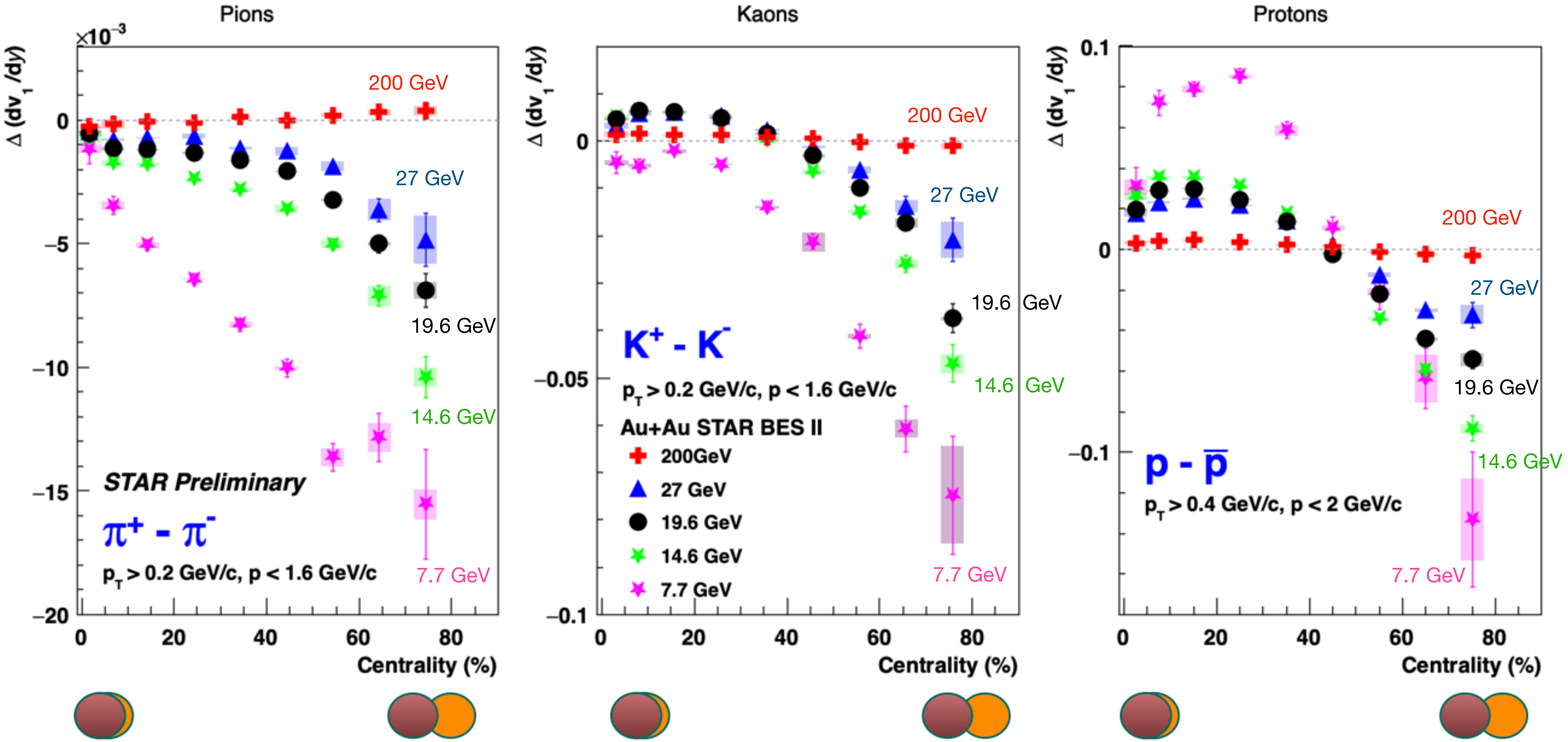


- **BES-II results of negative d(Δv1)/dy in peripheral collisions as expected from electromagnetic effects**
- Suggests dominance of Faraday+Coulomb effect in peripheral collisions
- Comparison to IEBE-VISHNU+EM field calculations indicates that the used **conductivity σ = 0.023 fm^{-1} falls within a reasonable range**

[PRC 98,055201, PRC 89 054905]

STAR, Phys. Rev. X 14, 011028, A. P. Dash QM 2023, arXiv:2401.04838

Beam energy dependence for a given particle

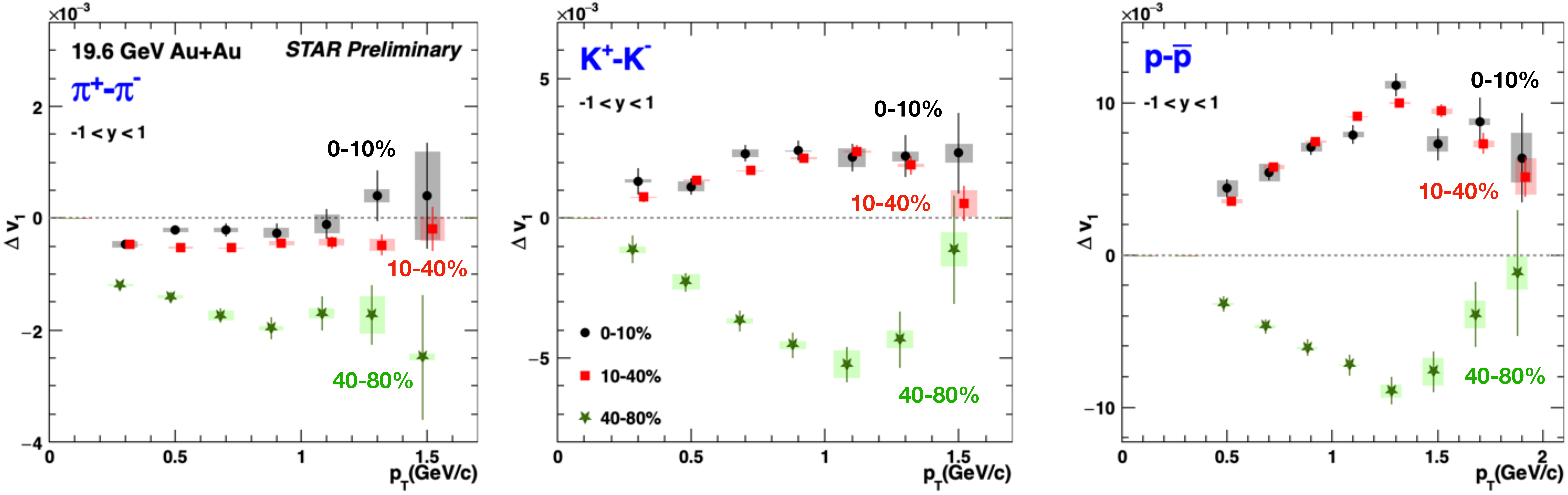


- ➢ **d(Δv₁)/dy in peripheral collisions is more negative at lower collision energies for each species**
- ➢ The passage time (2R/γ) is larger, and hence the lifetime of the electromagnetic field should be longer.
- ➢ The lifetime of the fireball is shorter at lower energies.

[PRC 98,055201, PRC 89 054905]

STAR, Phys. Rev. X 14, 011028, A. P. Dash QM 2023, arXiv:2401.04838

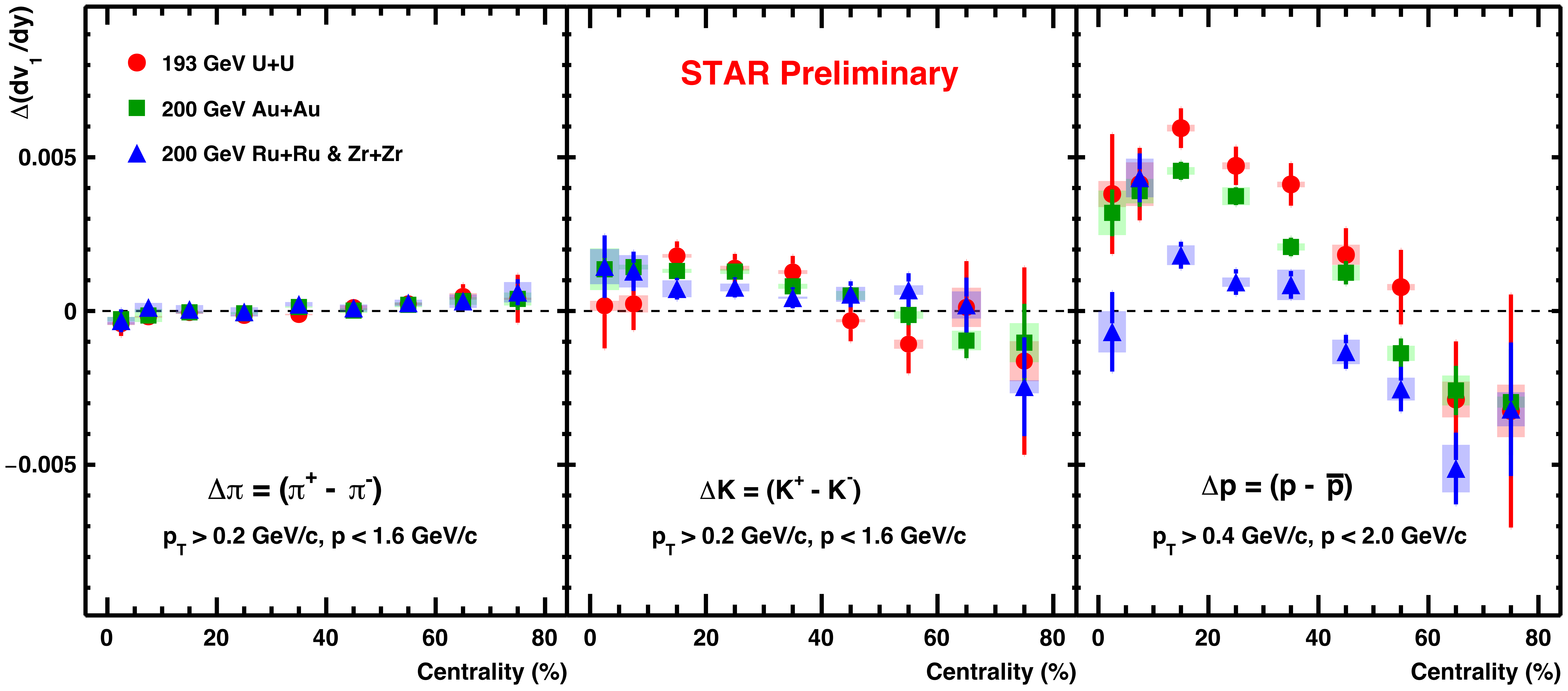
Δv_1 as a function of p_T



- ➢ Negative Δv_1 for p_T ranges considered in this analysis in peripheral collisions
- ➢ **Indication of larger splitting at higher p_T as expected from theory** [PRC 98,055201]
- ➢ Could arise from a decrease in the Hall effect at higher p_T (or smaller p_z)

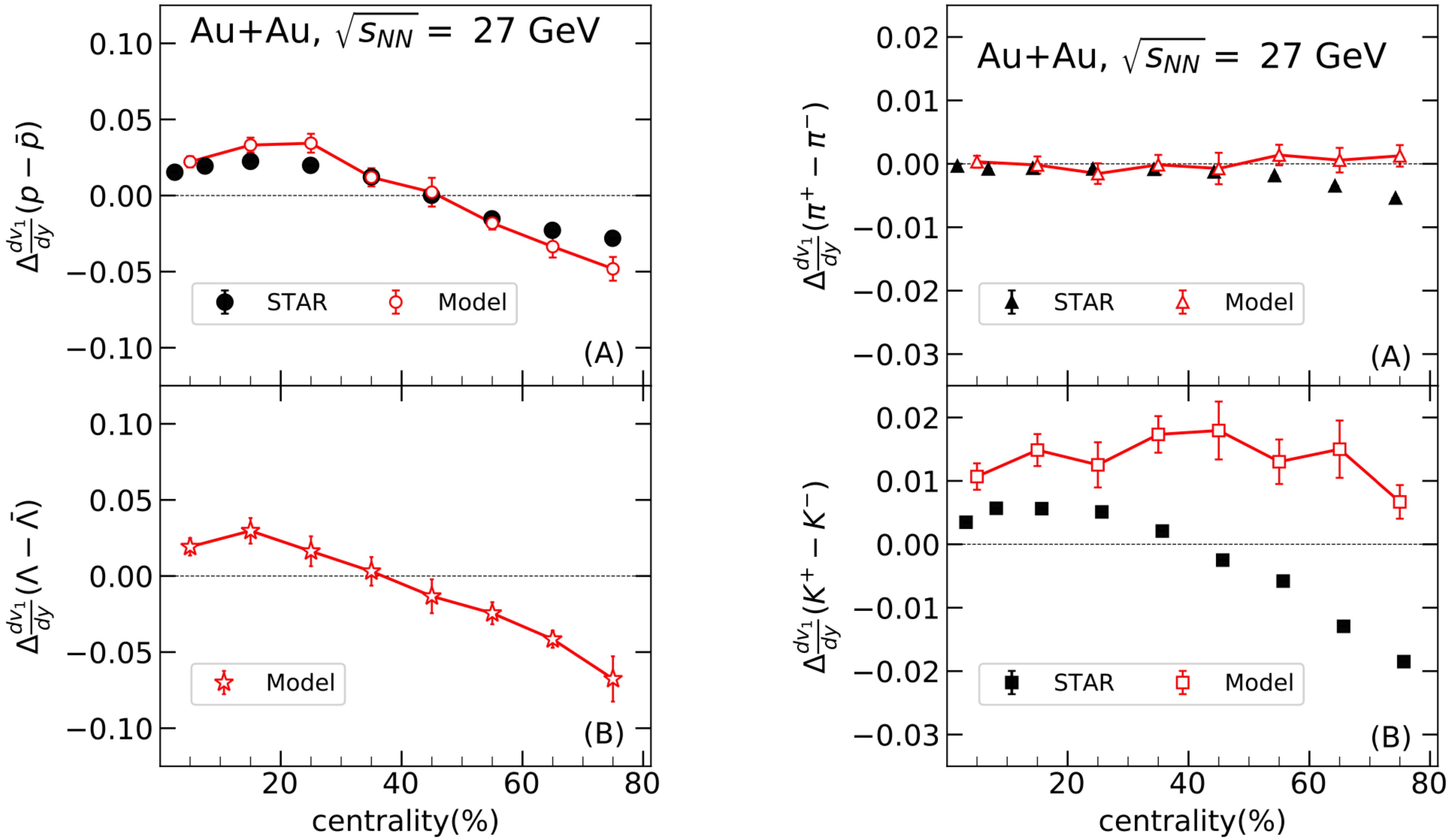
arXiv:2401.04838, A. P. Dash QM 2023

System Size Dependence



- Clear system size dependence for protons in mid central collisions
- Δv_1 for protons shows sign change in peripheral collisions
- Theoretical modeling needed to understand these results

Other possibilities?

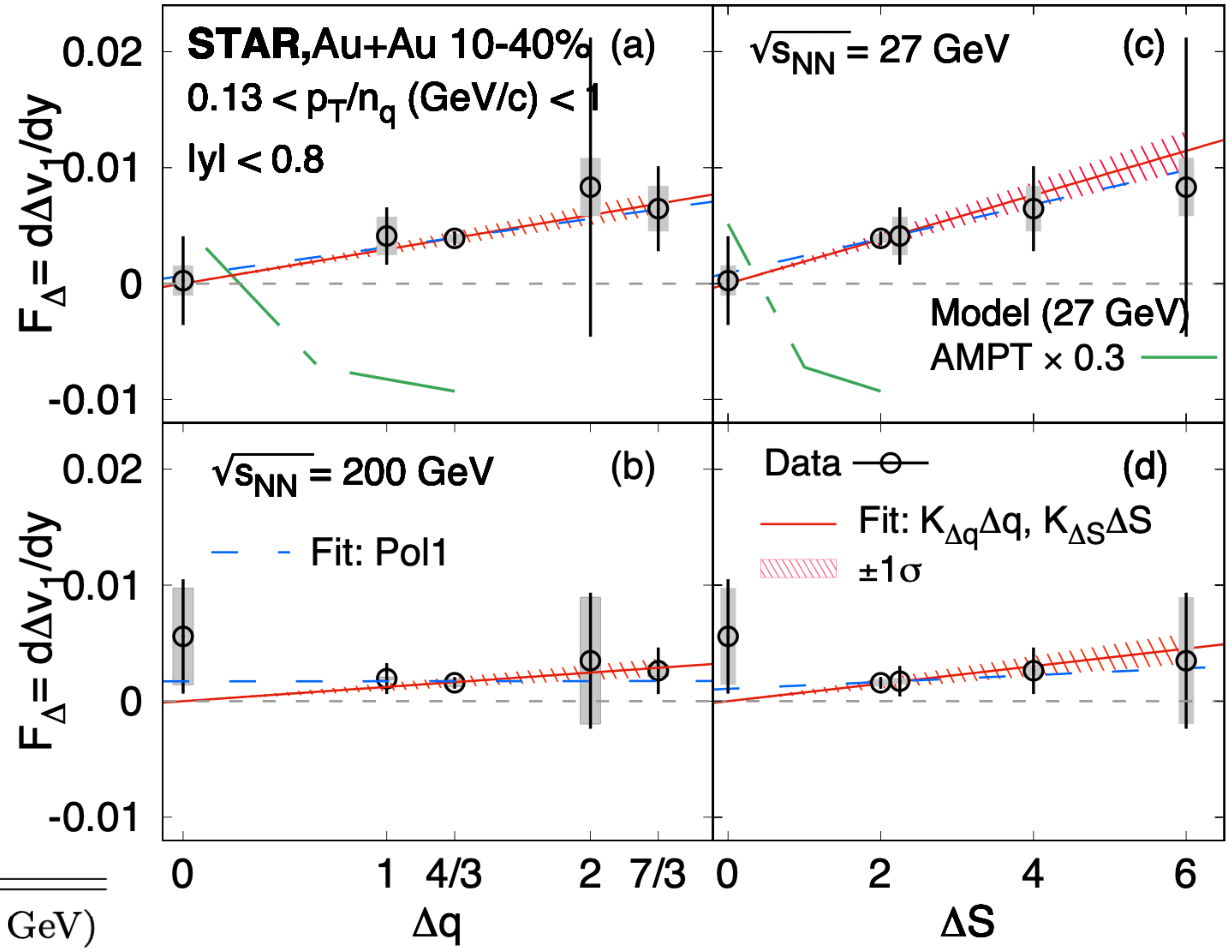


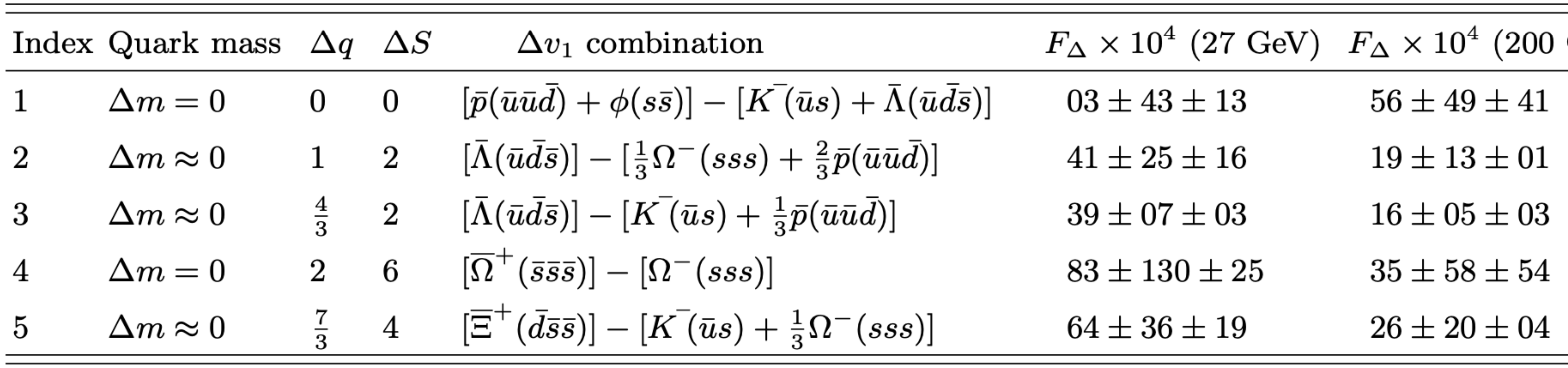
T. Parida et.al., arXiv:2305.08806

- Initial baryon distribution could be anisotropic which would produce asymmetry between particles and antiparticles
- Similar to transported quark effect and thus should give opposite contribution to pions compared to protons and kaons
- Cannot explain negative $\Delta(dv_1/dy)$ in peripheral collisions for $\pi^{\pm}, K^{\pm}, p(\bar{p})$
- Active research in other mechanisms for generating Δv_1

Δv_1 using produced quarks

- ➢ v_1 difference of particles with pair-produced quarks eg. $\bar{p}(\bar{u}\bar{u}\bar{d})$ and $K^-(\bar{u}s)$ are measured
- ➢ The $d\Delta v_1/dy$ combinations (fit constrained to origin) shows positive slope which increases with Δq and ΔS
- ➢ Hall effect could be dominant in mid central collisions





Index	Quark mass	Δq	ΔS	Δv_1 combination	$F_\Delta \times 10^4$ (27 GeV)	$F_\Delta \times 10^4$ (200 GeV)
1	$\Delta m = 0$	0	0	$[\bar{p}(\bar{u}\bar{u}\bar{d}) + \phi(s\bar{s})] - [K^-(\bar{u}s) + \bar{\Lambda}(\bar{u}\bar{d}\bar{s})]$	$03 \pm 43 \pm 13$	$56 \pm 49 \pm 41$
2	$\Delta m \approx 0$	1	2	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [\frac{1}{3}\Omega^-(sss) + \frac{2}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$	$41 \pm 25 \pm 16$	$19 \pm 13 \pm 01$
3	$\Delta m \approx 0$	$\frac{4}{3}$	2	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [K^-(\bar{u}s) + \frac{1}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$	$39 \pm 07 \pm 03$	$16 \pm 05 \pm 03$
4	$\Delta m = 0$	2	6	$[\overline{\Omega}^+(\bar{s}\bar{s}\bar{s})] - [\Omega^-(sss)]$	$83 \pm 130 \pm 25$	$35 \pm 58 \pm 54$
5	$\Delta m \approx 0$	$\frac{7}{3}$	4	$[\overline{\Xi}^+(\bar{d}\bar{s}\bar{s})] - [K^-(\bar{u}s) + \frac{1}{3}\Omega^-(sss)]$	$64 \pm 36 \pm 19$	$26 \pm 20 \pm 04$

[STAR,arXiv:2304.02831]

Summary

❖Ultra strong electromagnetic fields are expected in heavy ion collisions

❖Δv_1 ⟶ probe to ultra strong electromagnetic fields, can help constrain EM properties of QGP

❖$d(\Delta v_1(y))/dy$ in peripheral collisions

✓ Turns negative ⟶ expected from dominance of Faraday+Coulomb effect

✓More negative for lower collision energies ⟶ expected from longer lifetime of the electromagnetic field and shorter lifetime of the fireball at lower collision energies

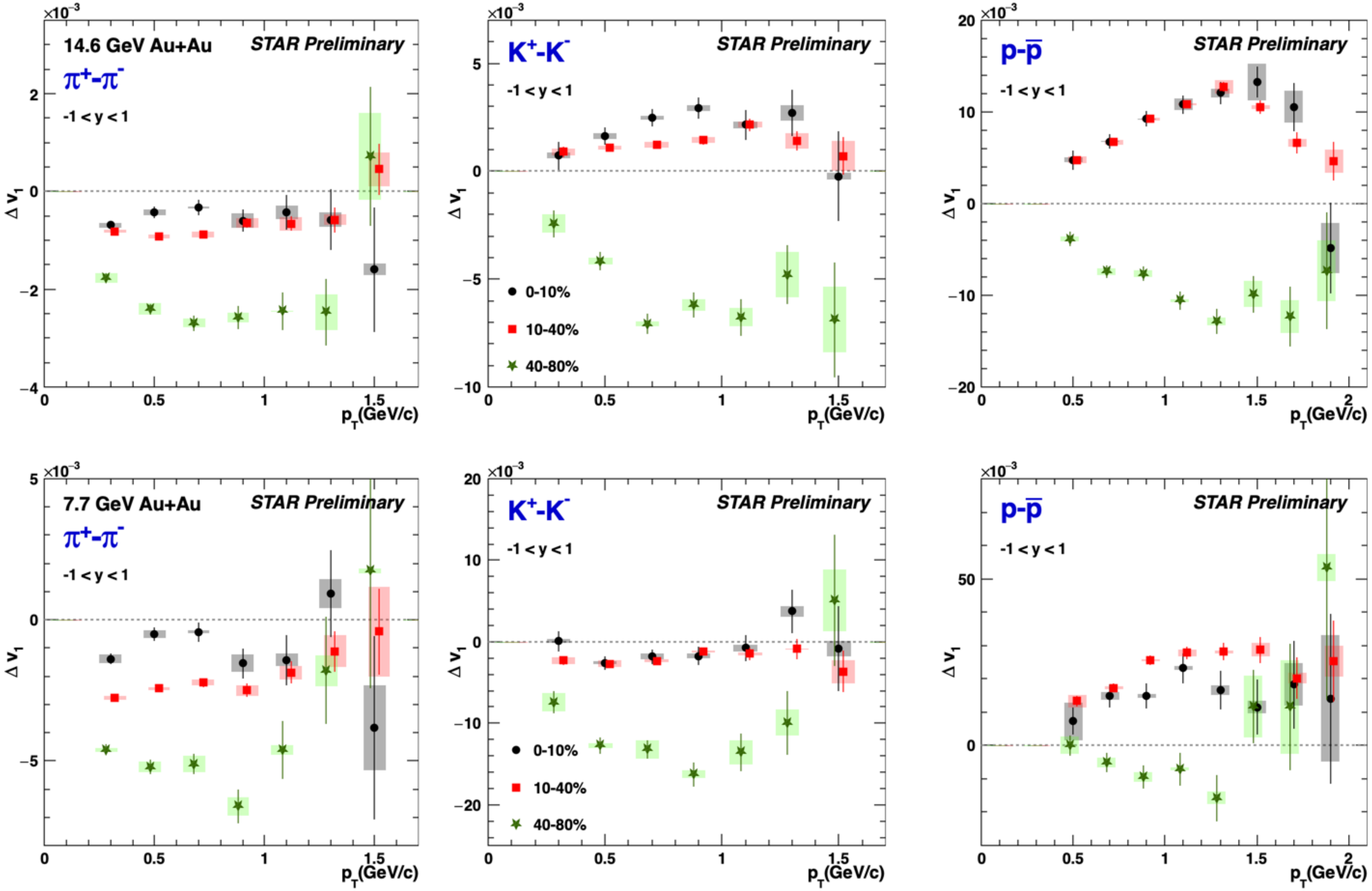
✓ Shows system size dependence

❖$|\Delta v_1(p_T)|$ in peripheral collisions ⟶ signs of increase with p_T expected from EM fields

❖Theoretical modeling needed for understanding the evolution of electromagnetic fields

Backup

$\Delta v_1(p_T)$ at 14.6GeV and 7.7GeV



- Similar p_T dependence trend at 19.6, 14.6 GeV and 7.7 GeV
- **Indication of larger splitting at higher p_T as expected from theory**
- Could arise from a decrease in the Hall effect at higher p_T (or smaller p_z)

[PRC 98, 055201, A.P. Dash Quark Matter 2023]

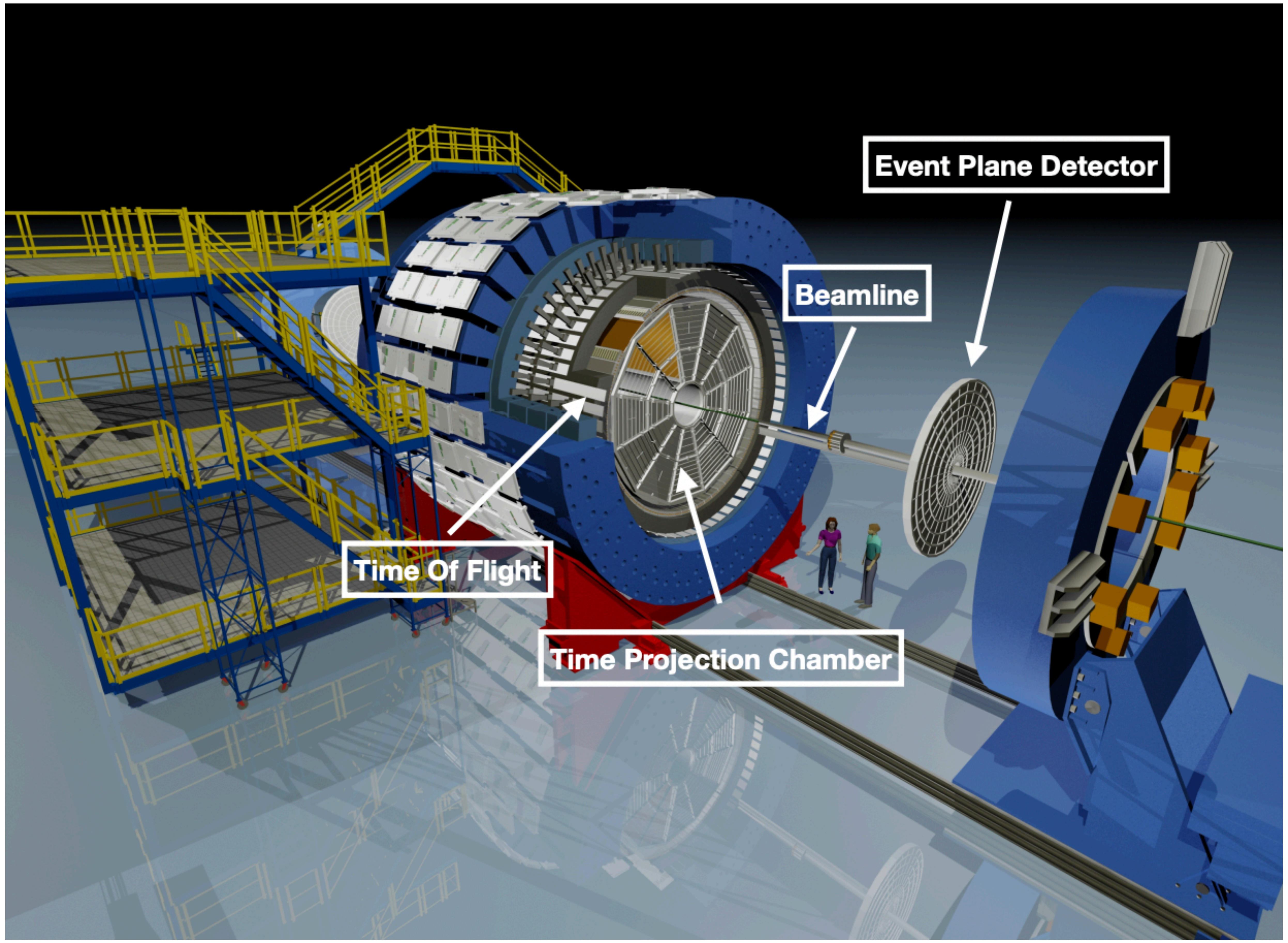
STAR experiment

Collision System: Au+Au
Beam Energies: 200, 54.4,19.6, 14.6 and 7.7 GeV in BES-II

Time Projection Chamber
Tracking of charged particles with $|\eta|<1$ and full azimuthal coverage

Time of Flight
Extends particle identification to higher momenta, $|\eta|<0.9$ and full azimuthal coverage

Event Plane Detector and Zero Degree Calorimeter
Used for event plane reconstruction, EPD($2.1<|\eta|<5.1$), ZDC-SMD($|\eta|>6.3$)



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