Progress on measurements of EM-field effect and vector meson spin alignment in heavy-ion collisions

Jinhui Chen

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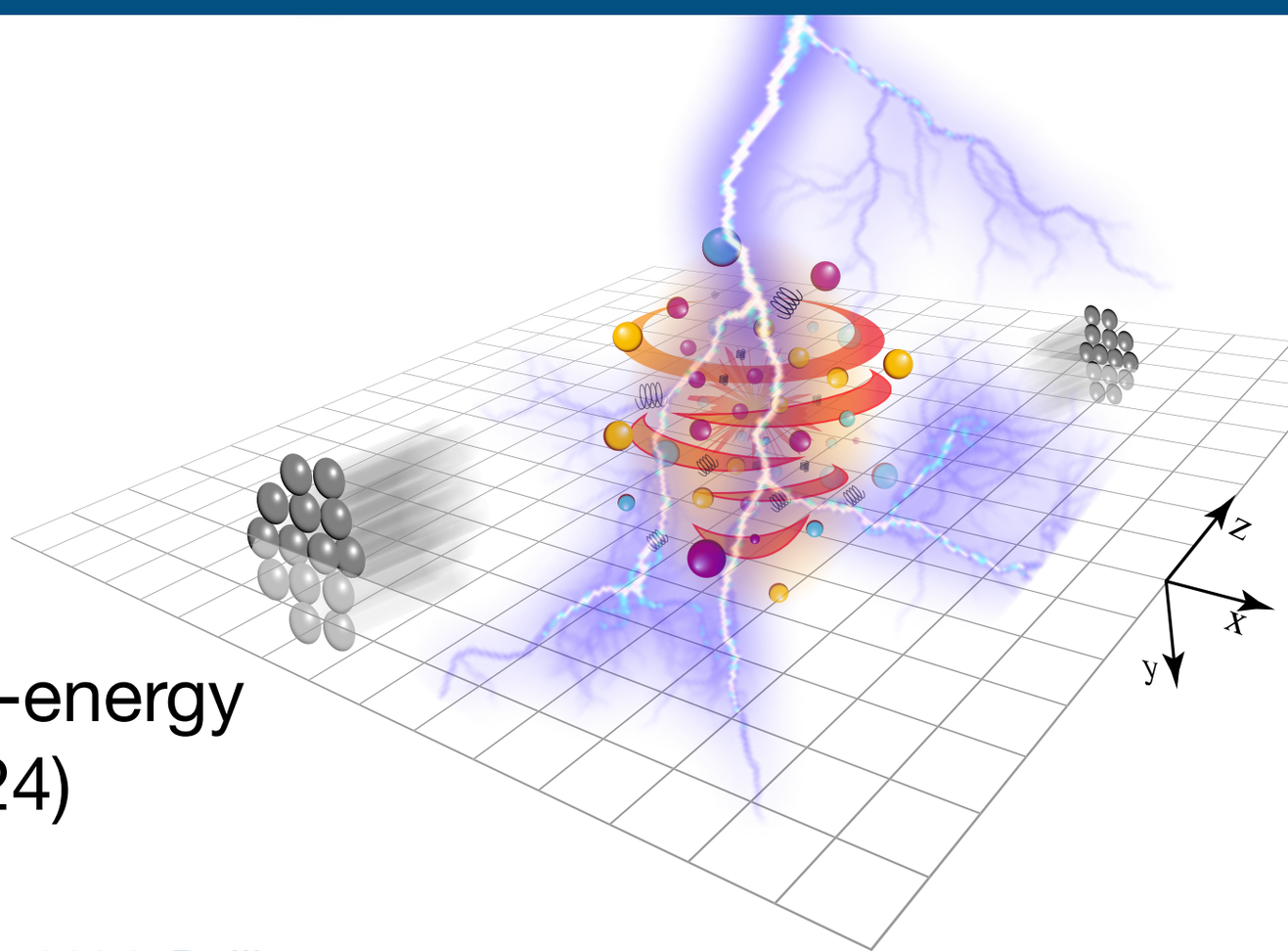
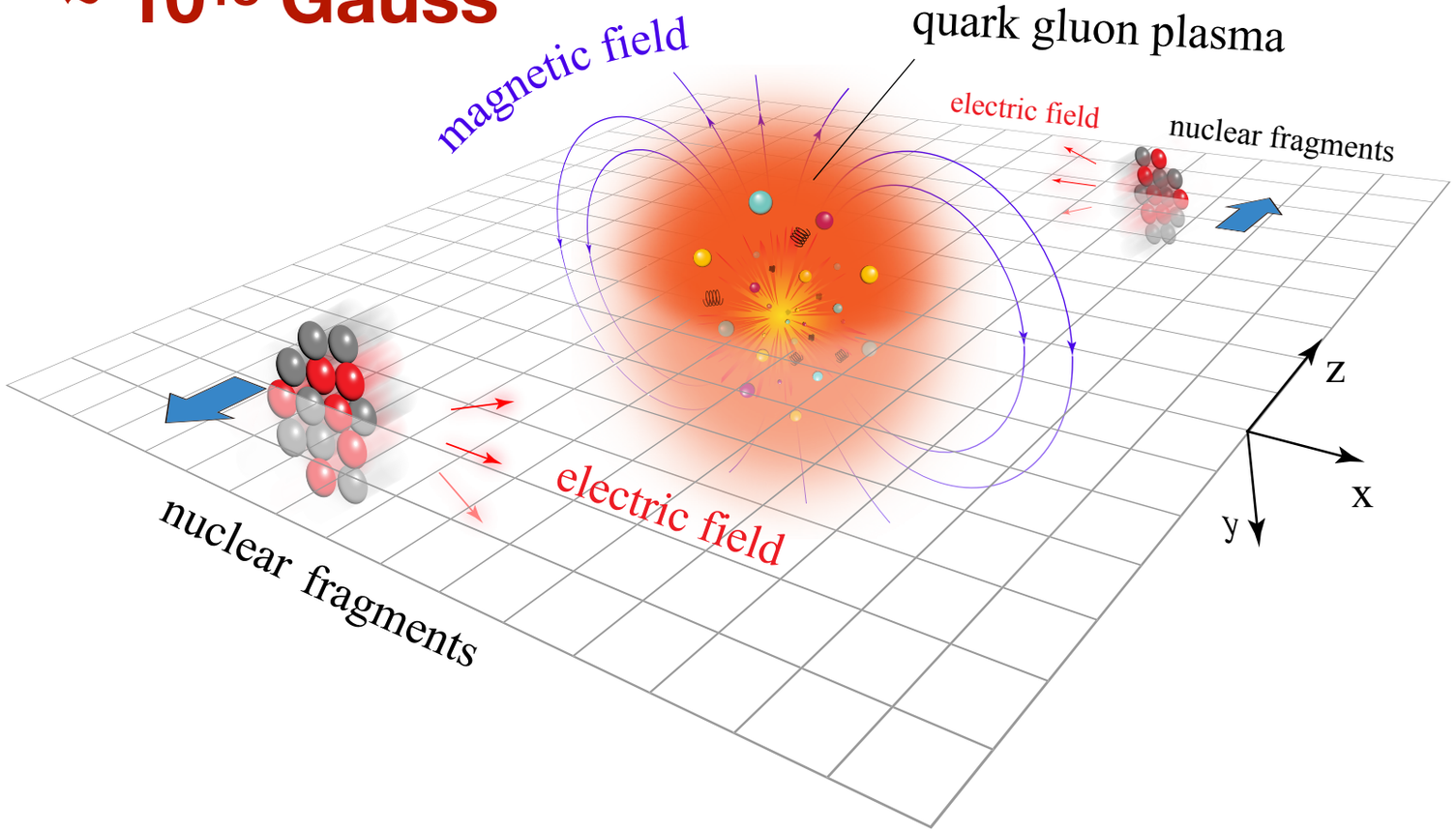
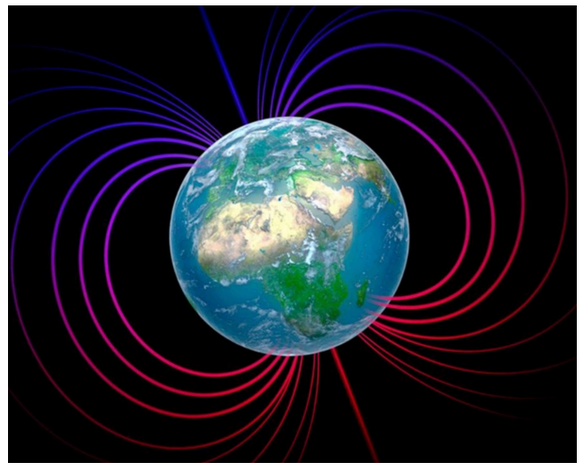


2nd Symposium on Intermediate-energy Heavy Ion Collisions (iHIC24)

The EM-field in HIC: its generation

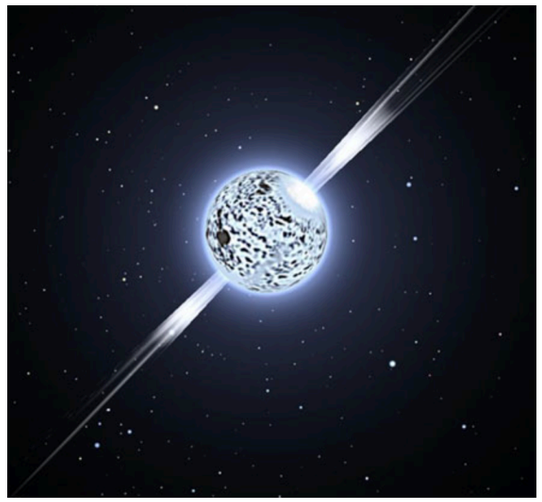
~ 10^{18} Gauss





Earth ~ 0.5 Gauss

- An ultra-strong magnetic field along -y, on the order of 10^{18} Gauss, can be generated.



Neutron Star: ~ 10^{15} Gauss

D. Price, S. Rosswog, Science 312, 719 (2006)

The EM-field in HIC: its generation and evolution

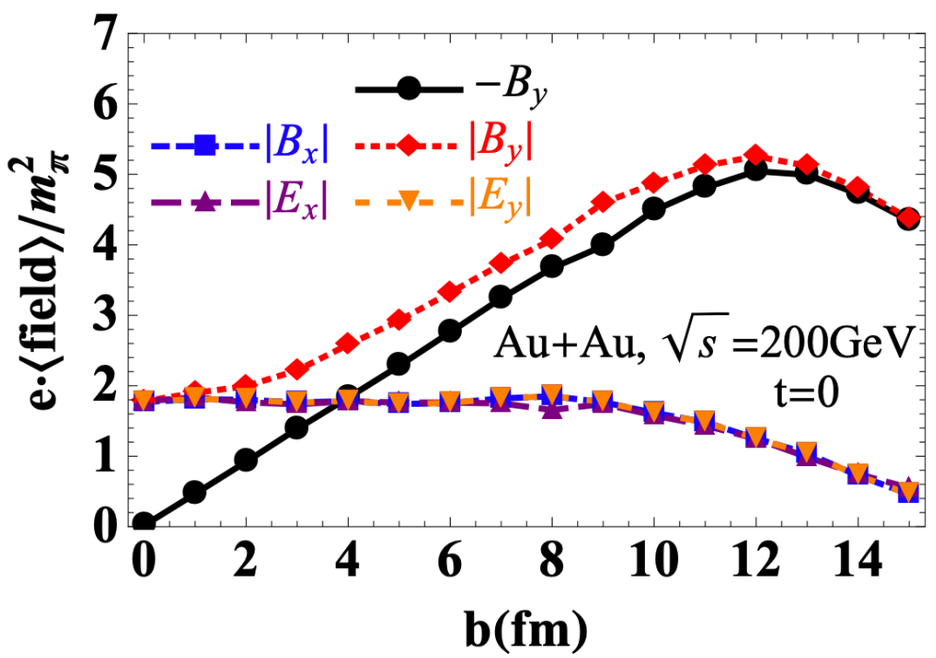
Liénard-Wiechert potentials

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

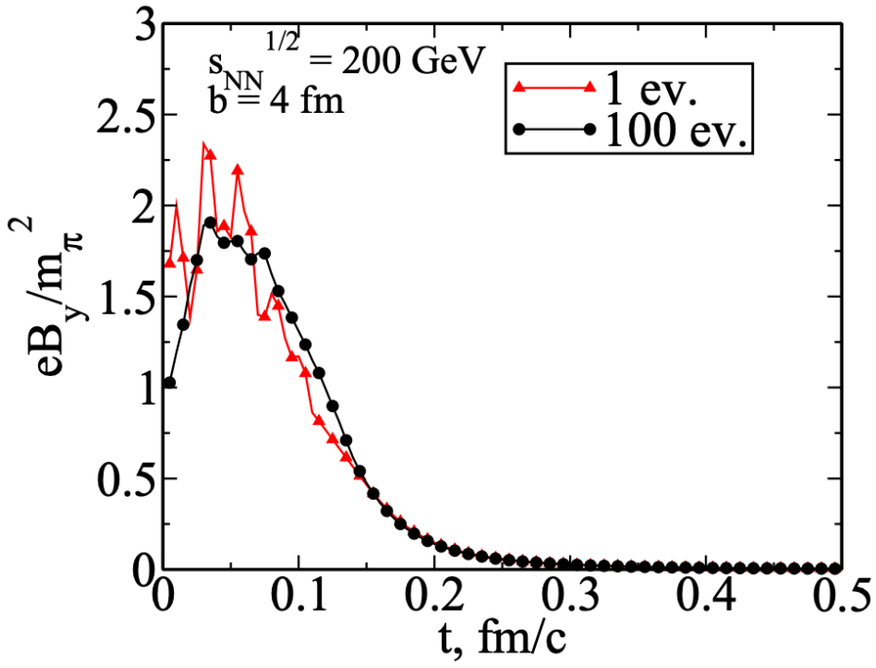
$$e\mathbf{B}(t,\mathbf{r}) = \frac{e^2}{4\pi}\sum_n Z_n \frac{\mathbf{v}_n \times \mathbf{R}_n}{(R_n - \mathbf{R}_n\cdot\mathbf{v}_n)^3}(1-v_n^2),$$

- Calculating the peak value of the B field is accurate.
- Describing its evolution is challenging.
  - Pre-equilibrium quark gluon plasma, formation time of quarks
  - Electrical conductivity of QGP

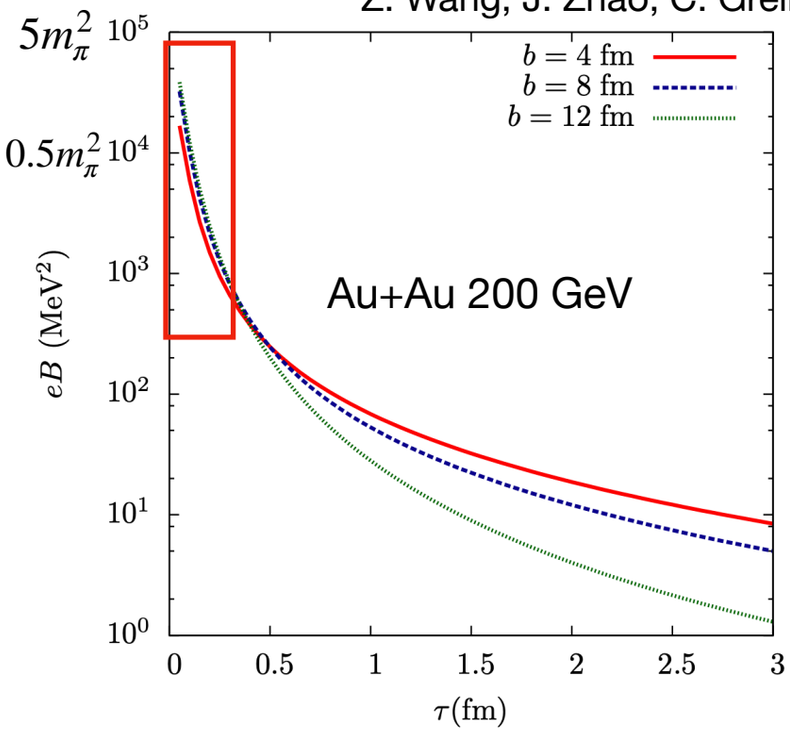
W.T. Deng and X.G. Huang, PRC 85, 044907 (2012)



V. Skokov, et al., *Int.J.Mod.Phys.A* 24, 5925 (2009)

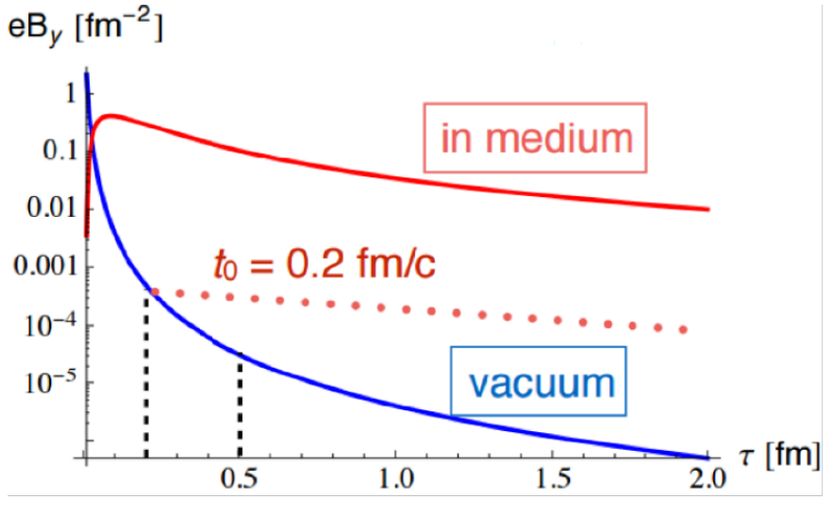


D. E. Kharzeev, et.al., NPA 803, 227 (2008)



L. Yan, X.-G. Huang, PRD 107, 094028 (2023)

Z. Wang, J. Zhao, C. Greiner, Z. Xu, P. Zhuang, PRC 105, L041901 (2022)



The EM-field in HIC: its impacts

- QCD phase diagram under strong EM-field.

PHYSICAL REVIEW D **78,** 025016 (2008)

Chiral transition in a strong magnetic background

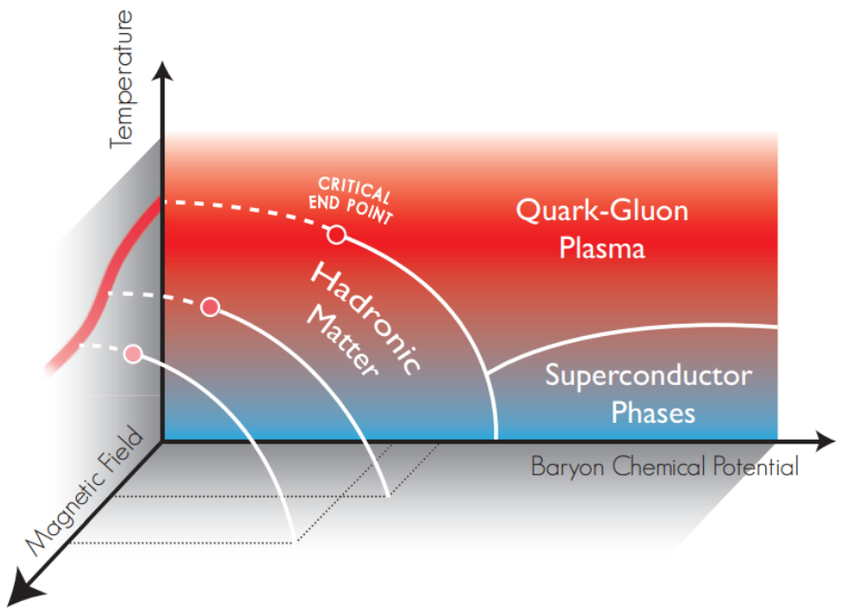
The presence of a strong magnetic background can modify the nature and the dynamics of the chiral phase transition at finite temperature. We compute the modified effective potential in the linear sigma

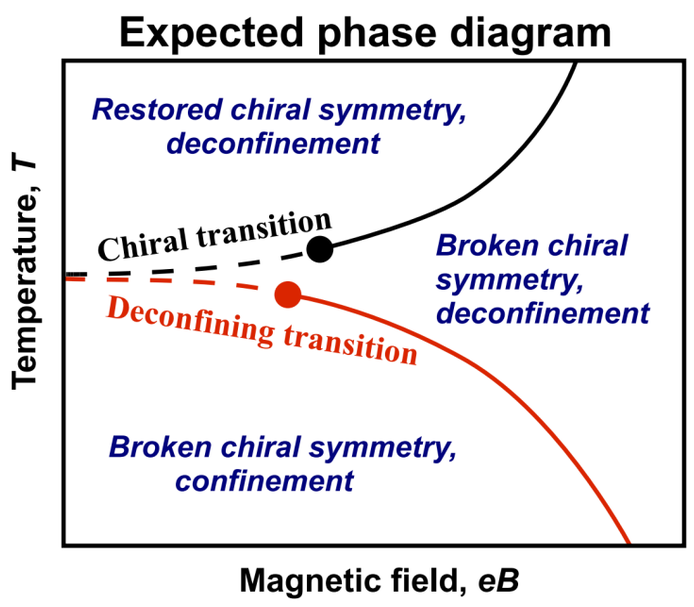
PHYSICAL REVIEW D **82,** 105016 (2010)

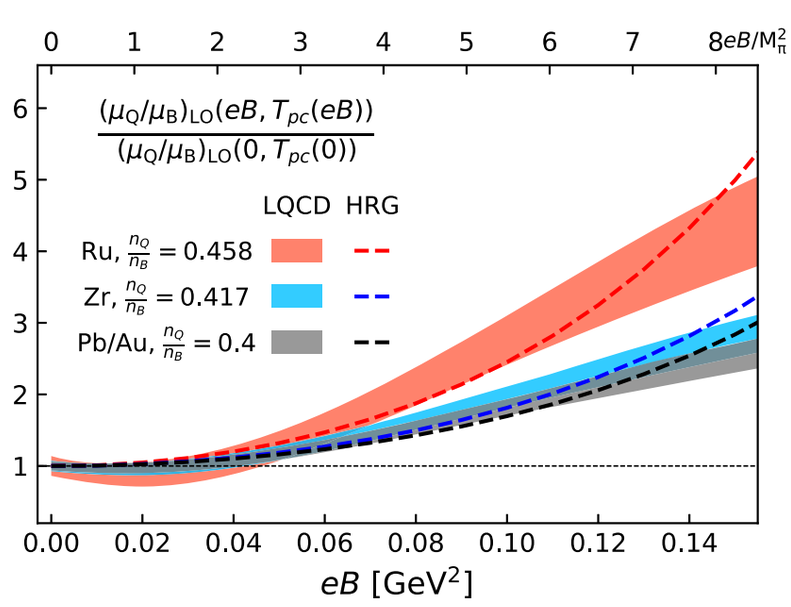
Phase diagram of hot QCD in an external magnetic field: Possible splitting of deconfinement and chiral transitions

PHYSICAL REVIEW LETTERS **132,** 201903 (2024)

Baryon Electric Charge Correlation as a Magnetometer of QCD







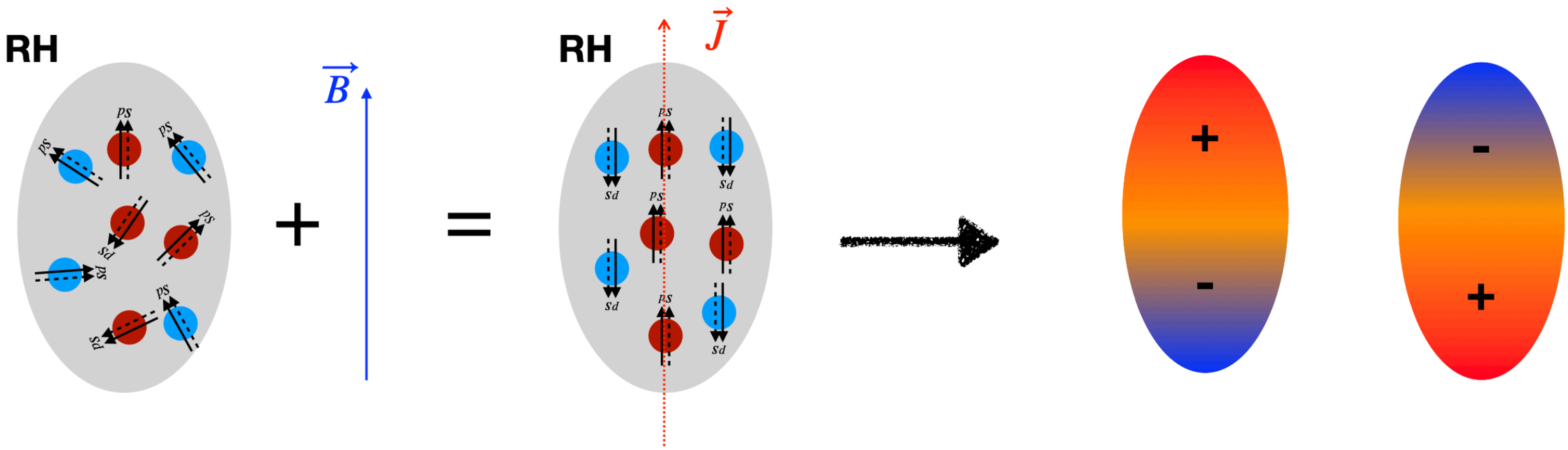
The EM-field in HIC: its impacts

- Measure the local CP violation in QCD, like CME, CMW…

K. Fukushima, D.E. Kharzeev, H.J. Warringa, PRD 78 074033 (2008)

D.E. Kharzeev, J.F. Liao, P. Tribedy, arXiv:2405.05427

Chirality imbalance + Magnetic field = Electric current



$$\boldsymbol{j} = \frac{e^2 \mu_5}{2\pi^2} \boldsymbol{B}.$$

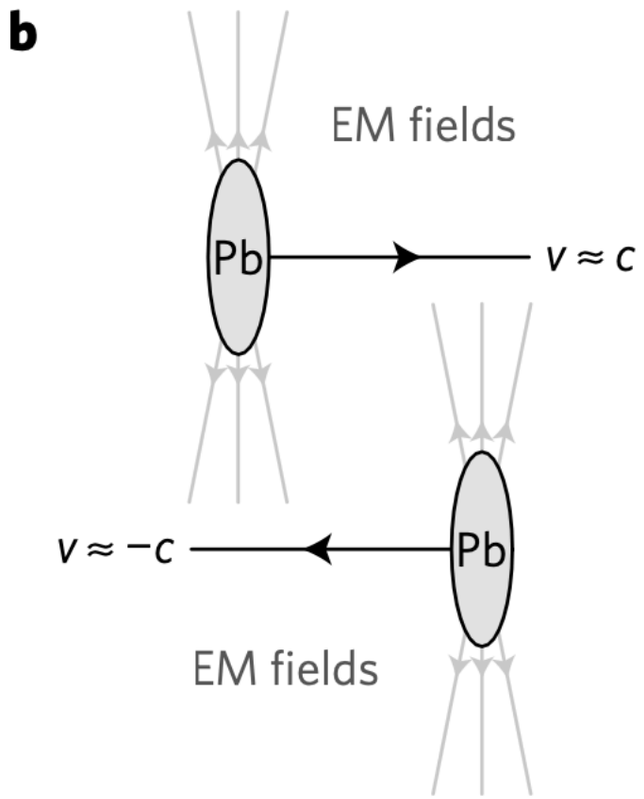
- Quarks with opposite charges will be polarized in opposite direction —> charge separation effect !

The EM-field in Experiments: UPC

ARTICLES
PUBLISHED ONLINE: 14 AUGUST 2017 | DOI: 10.1038/NPHYS4208
nature physics
OPEN

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

ATLAS Collaboration†

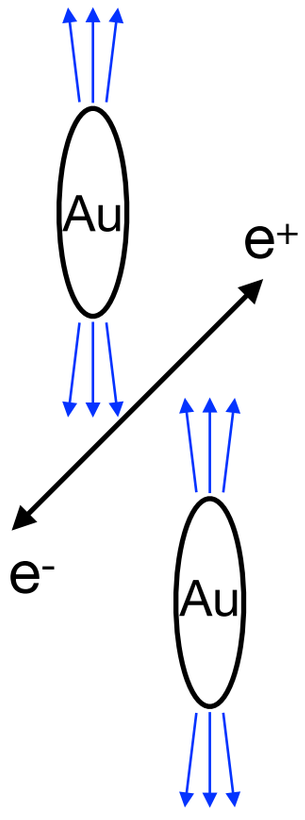


- $\gamma\gamma \rightarrow \gamma\gamma$ in ultra-peripheral Pb-Pb collisions at 5.02 TeV.
- No generation of QCD medium.

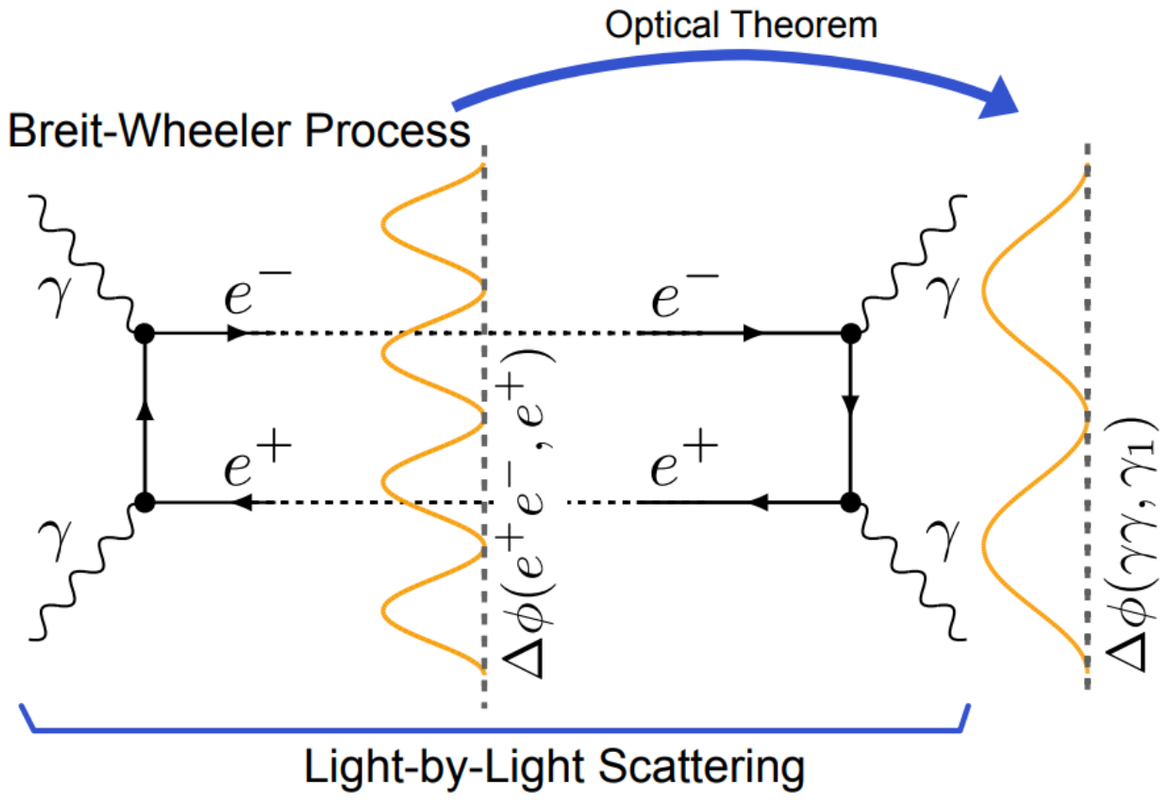
The EM-field in Experiments: UPC

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

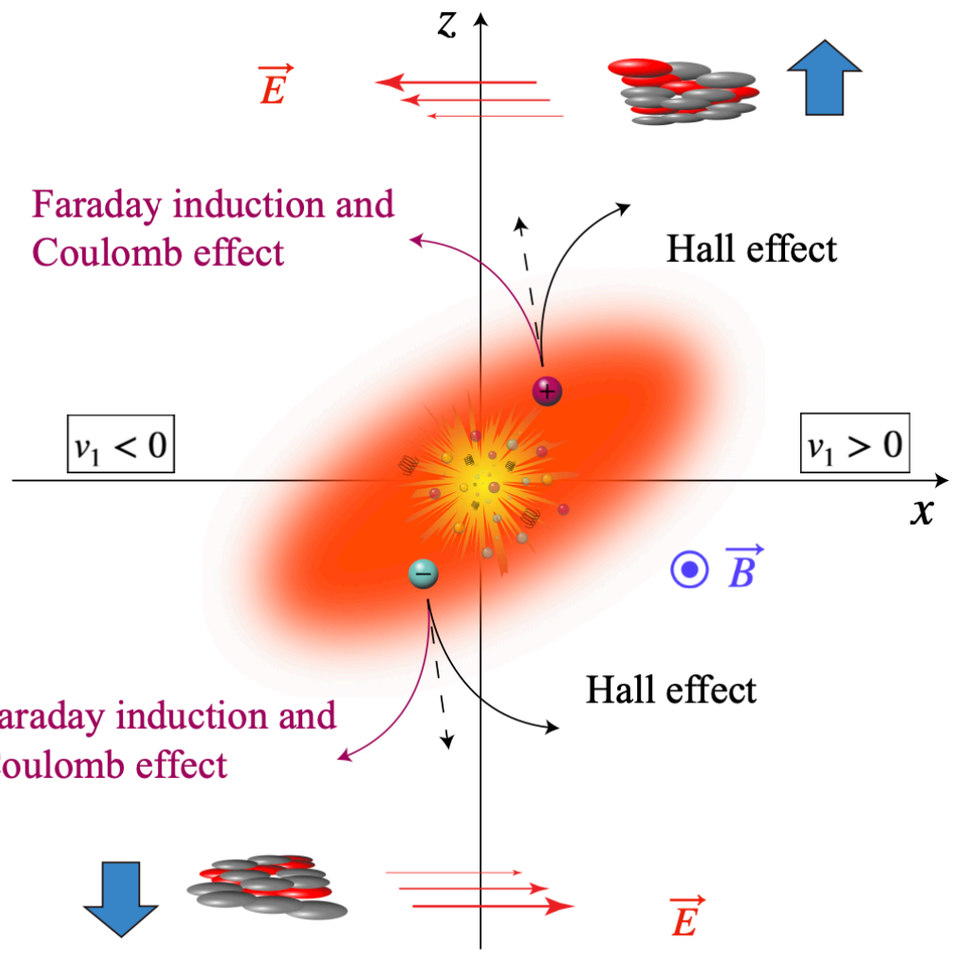
J. Adam *et al.* (STAR Collaboration)
Phys. Rev. Lett. **127**, 052302 – Published 27 July 2021



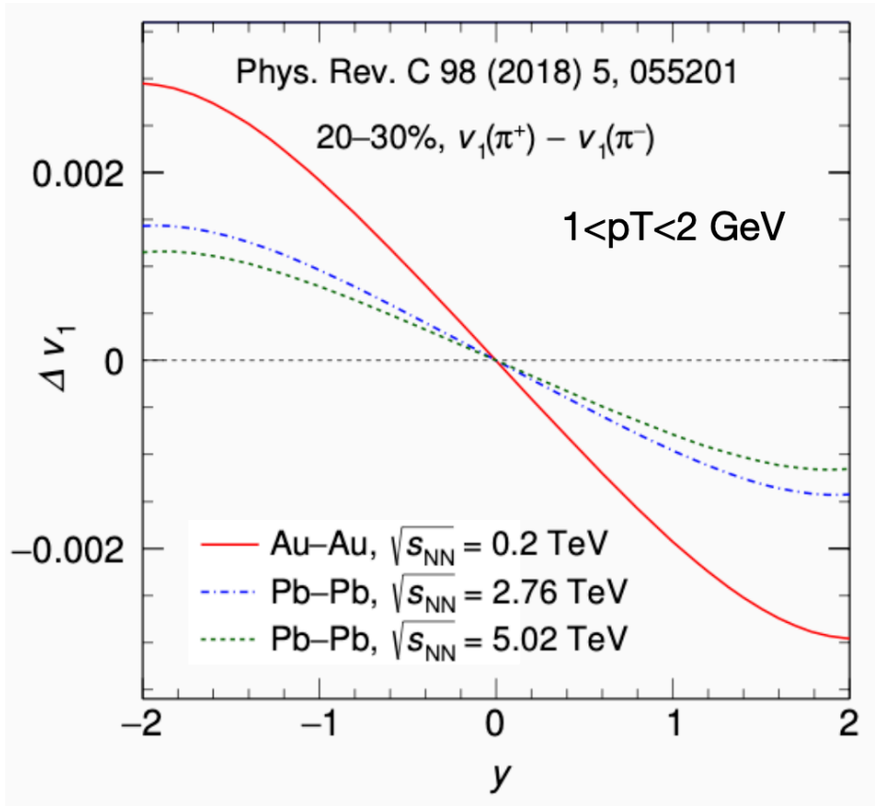
- $\gamma\gamma \rightarrow e^+e^-$ in ultra-peripheral Au+Au collisions at 200 GeV.
- No generation of QCD medium.



EM-field in medium: Charge-dependent v_1



- Coulomb field from spectator
- Faraday induction, vortical electrical field
- Hall effect due to Lorentz force

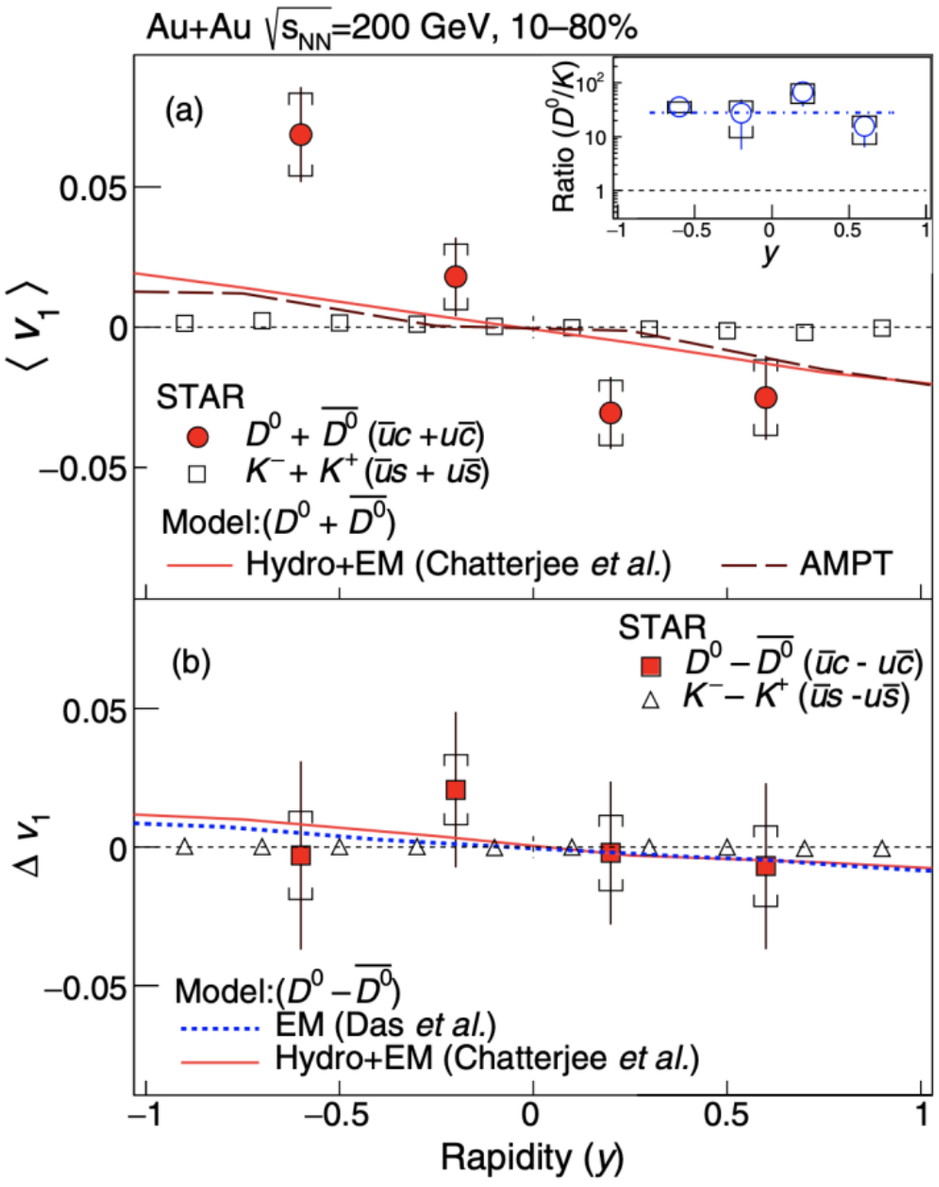


U. Gürsoy, et.al., PRC 98 055201 (2018); U. Gürsoy, et.al., PRC 89 054905 (2014)
S.K. Das et.al., PLB 768 260 (2017); K. Nakamura et.al, RPC 107 014901 (2023)
…

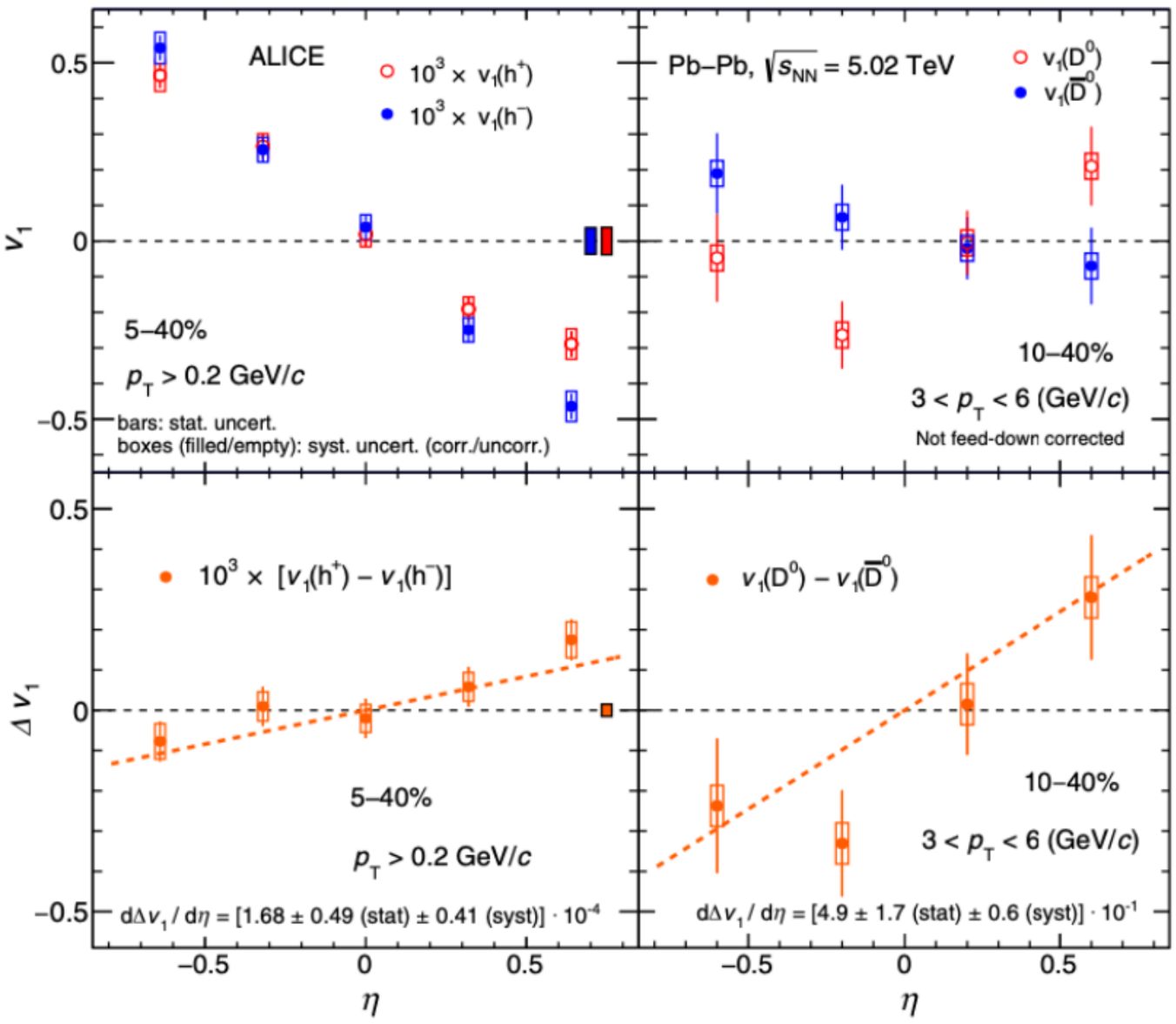
- Faraday induction + Coulomb effect dominate over Hall effect for light flavors (thermalized).
- Negative $\Delta dv_1/dy$ between positive and negative charges.
- More obvious at low energy.

Experimental observations: Δv_1 of D^0

STAR, PRL 123 162301 (2019)



ALICE, PRL 125 022301 (2020)

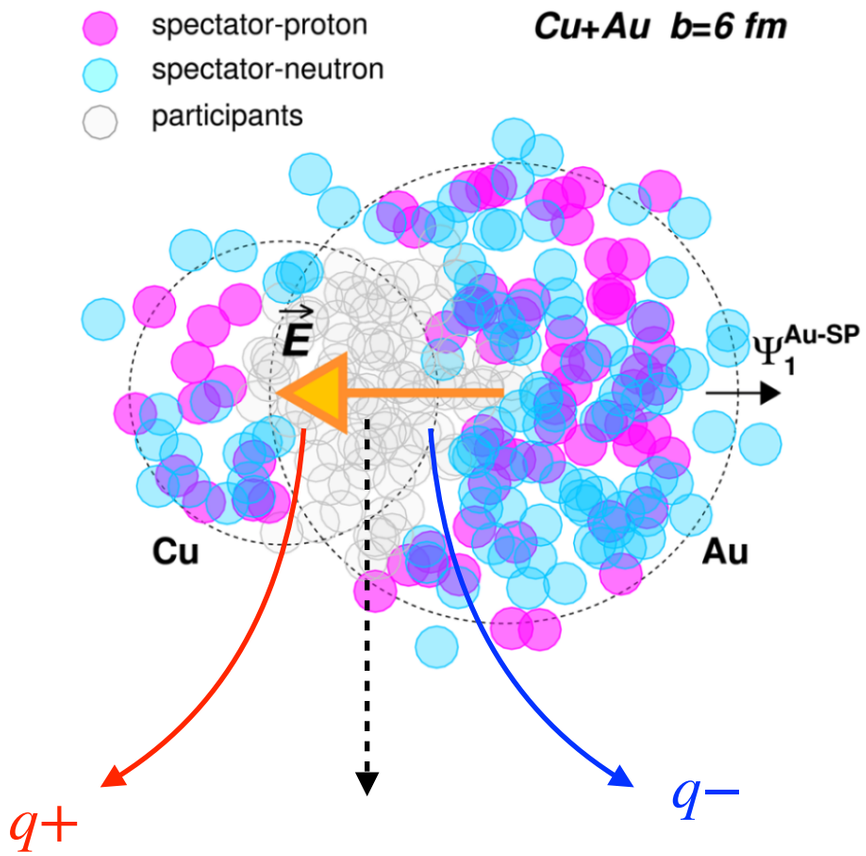


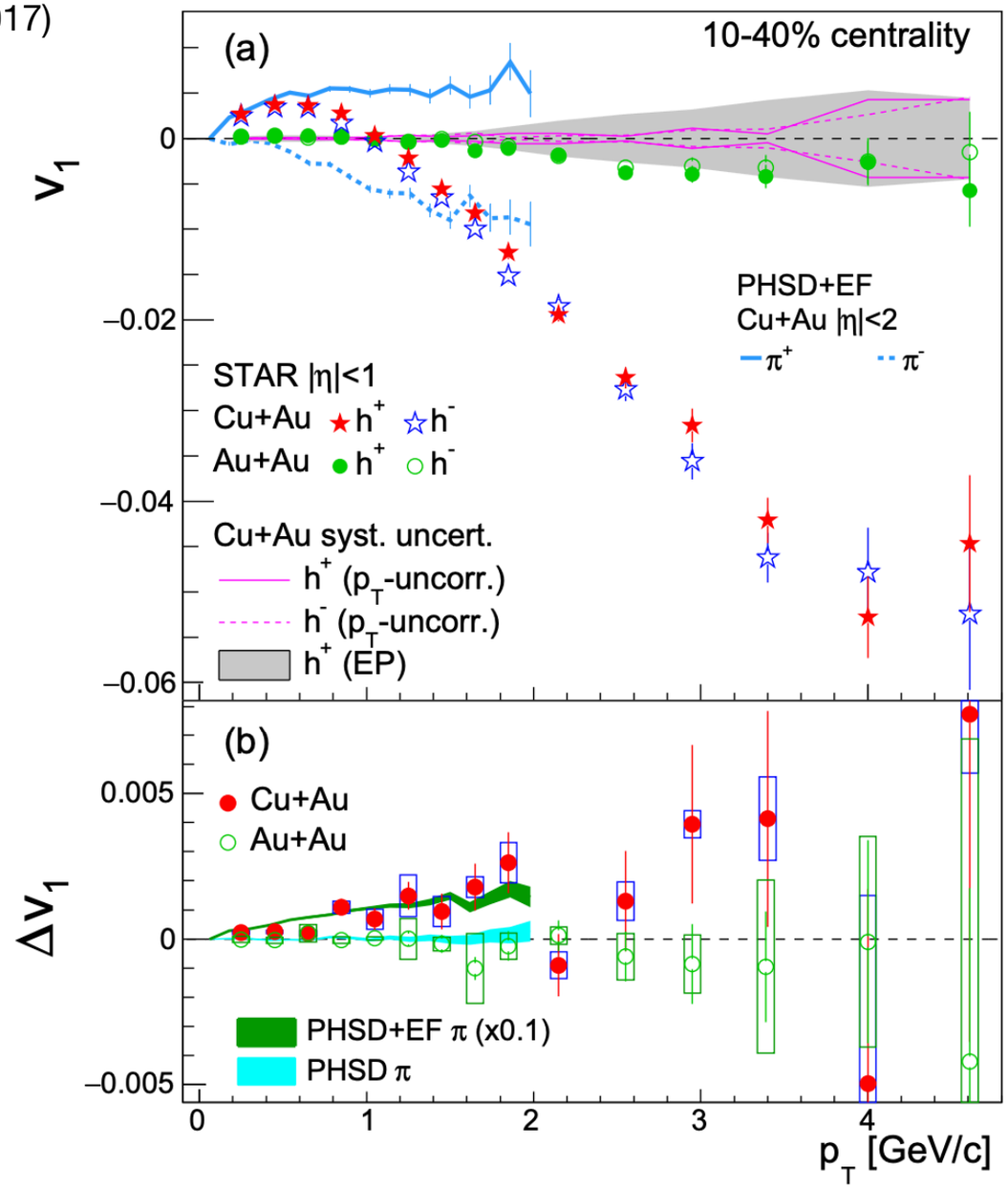
- Δv_1 between D^0 and $\bar{D}^0$ is sensitive to early stage B field.
- Data seem consistent with Hall effect dominating for heavy quarks.

S.K. Das et.al., PLB 768 260 (2017)

Experimental observations: Δv_1 in Cu+Au

STAR, PRL 118 012301 (2017)



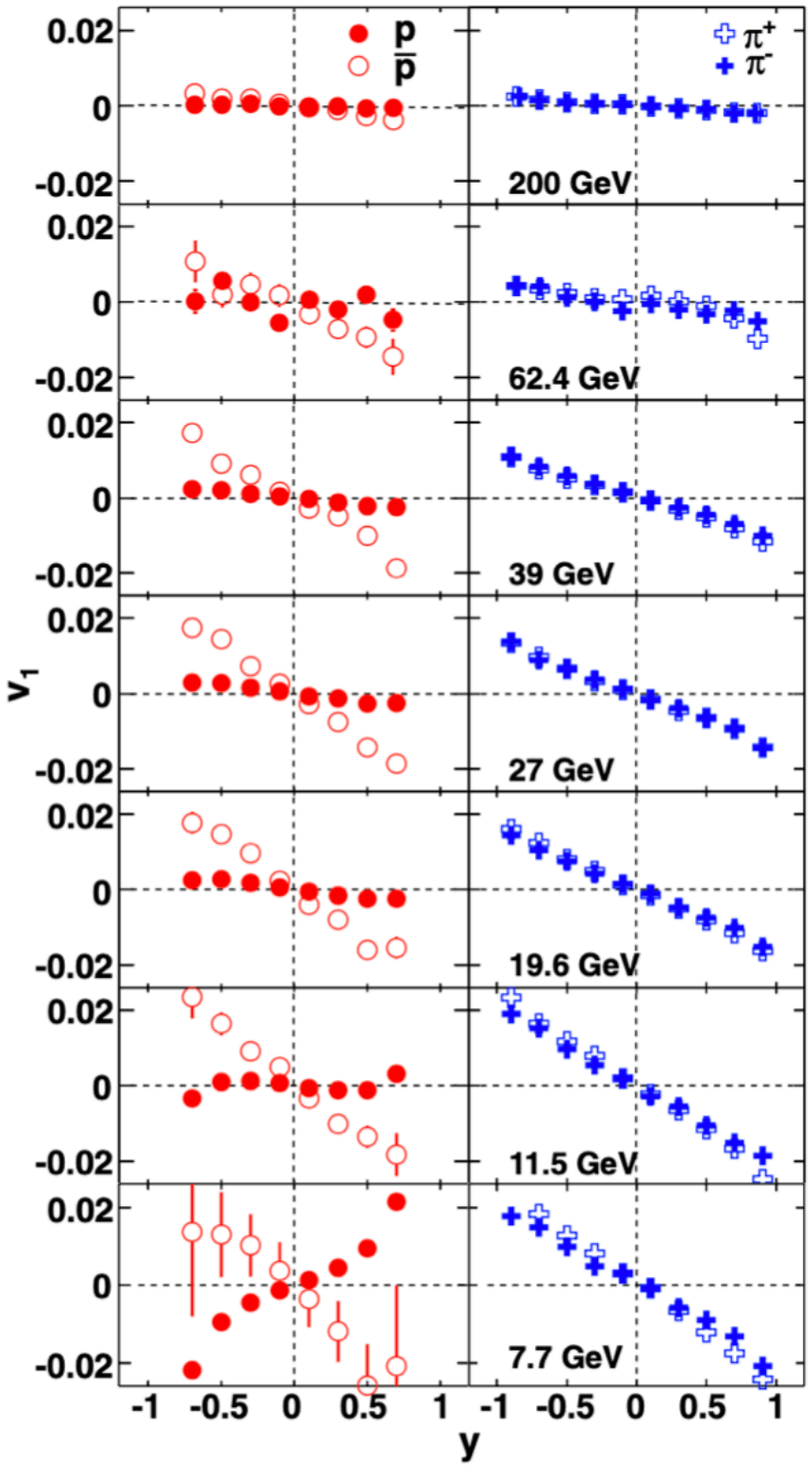


- Net electrical field in asymmetry Cu+Au collisions.
- Evidence of the interaction between the Coulomb field and QGP.

Experimental observations: Δv_1 in 10-40%

PRL 112, 162301 (2014)

Au+Au 10-40%

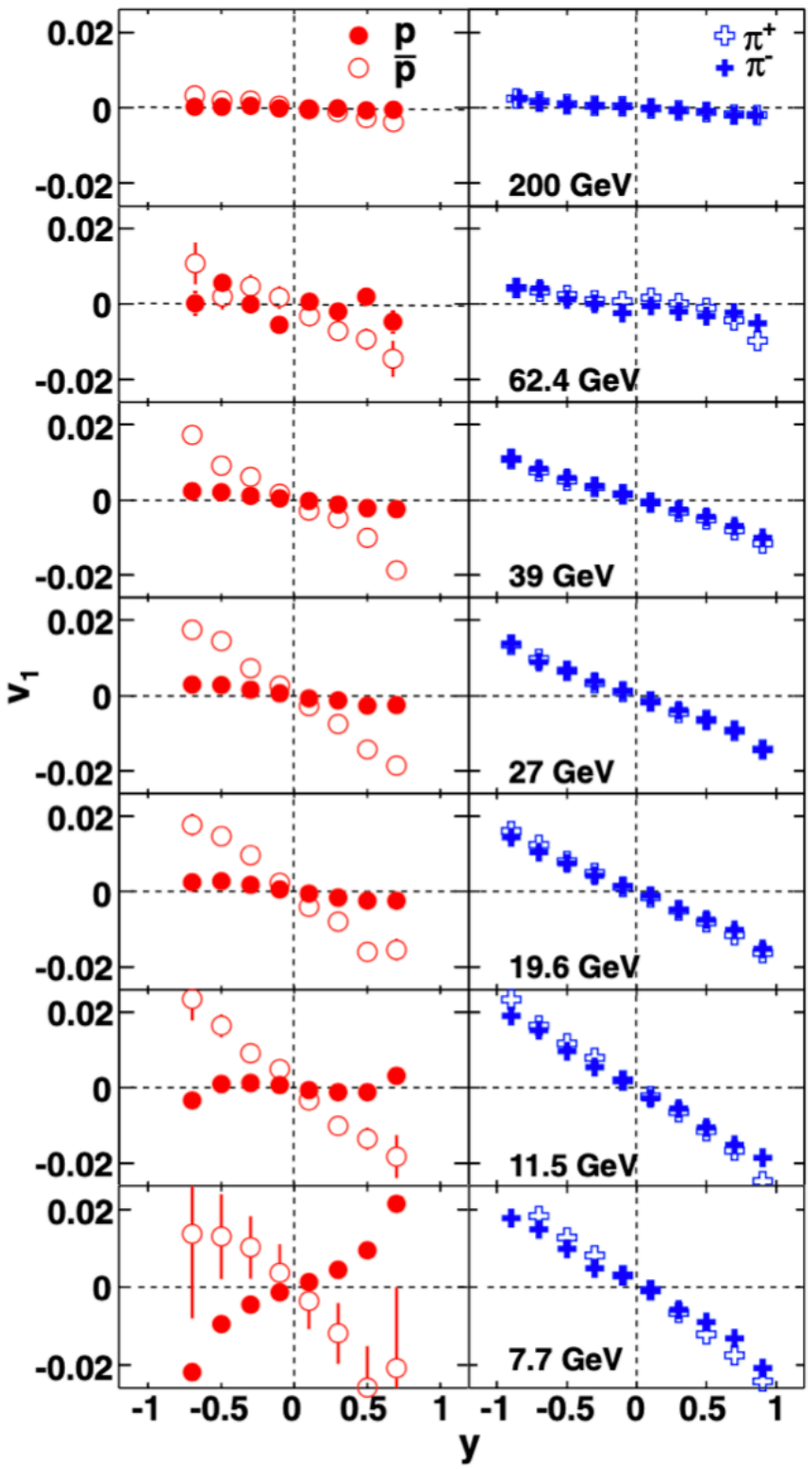


- Δv_1 between p and $\bar{p}$ is positive in 10-40% centrality, a feature different from Faraday + Coulomb expectation?

Transported quarks

PRL 112, 162301 (2014)

Au+Au 10-40%



Transport quark effect:

$p : uud$

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

$dv_1/dy : \ p > \bar{p}$

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

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

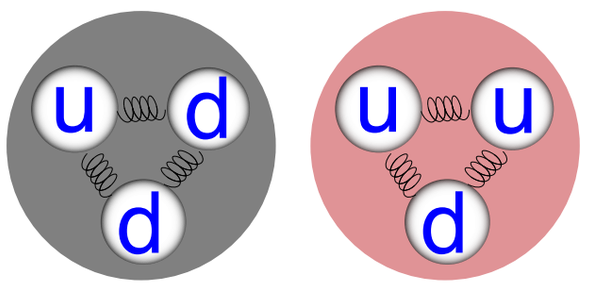
$dv_1/dy : \ K^+ > K^-$

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

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

$dv_1/dy : \ \pi^- > \pi^+$

(#d>#u, Au neutron rich)

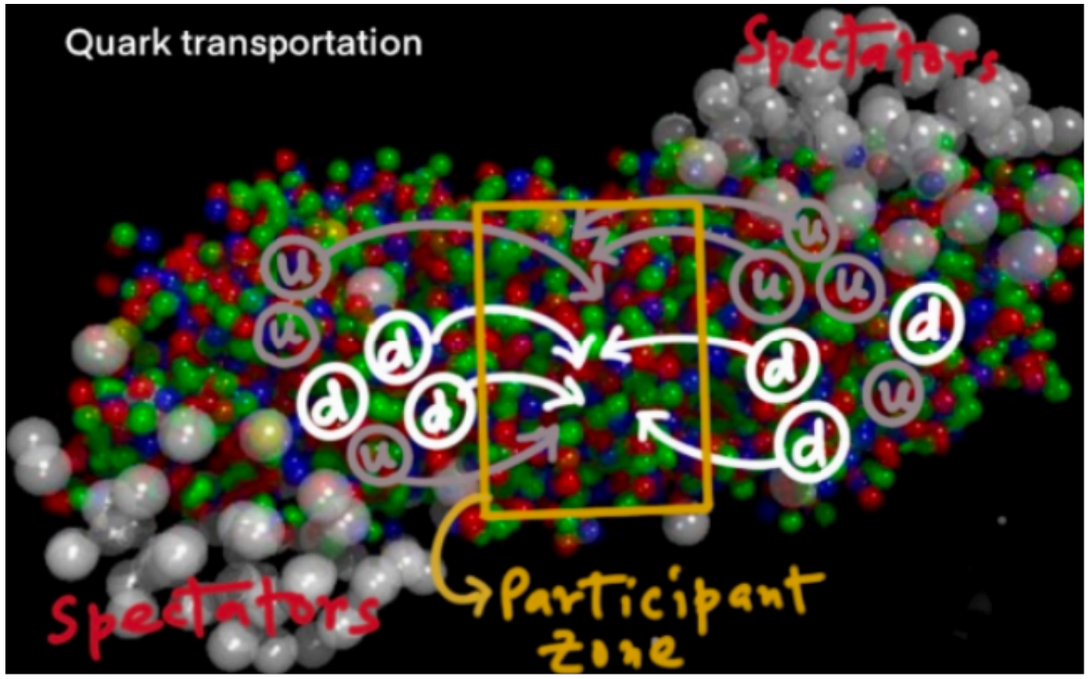


(#d>#u, Au neutron rich)

Neutron Proton

J. Dunlop, M. Lisa, P. Sorensen, PRC 84, 044914 (2011)
Y. Guo, F. Liu, A. Tang, PRC 86, 044901 (2012)
K. Nayak, S. Shi, N. Xu, Z. Lin, PRC 100, 054903 (2019)
P. Bozek, PRC 106, L061901 (2022)

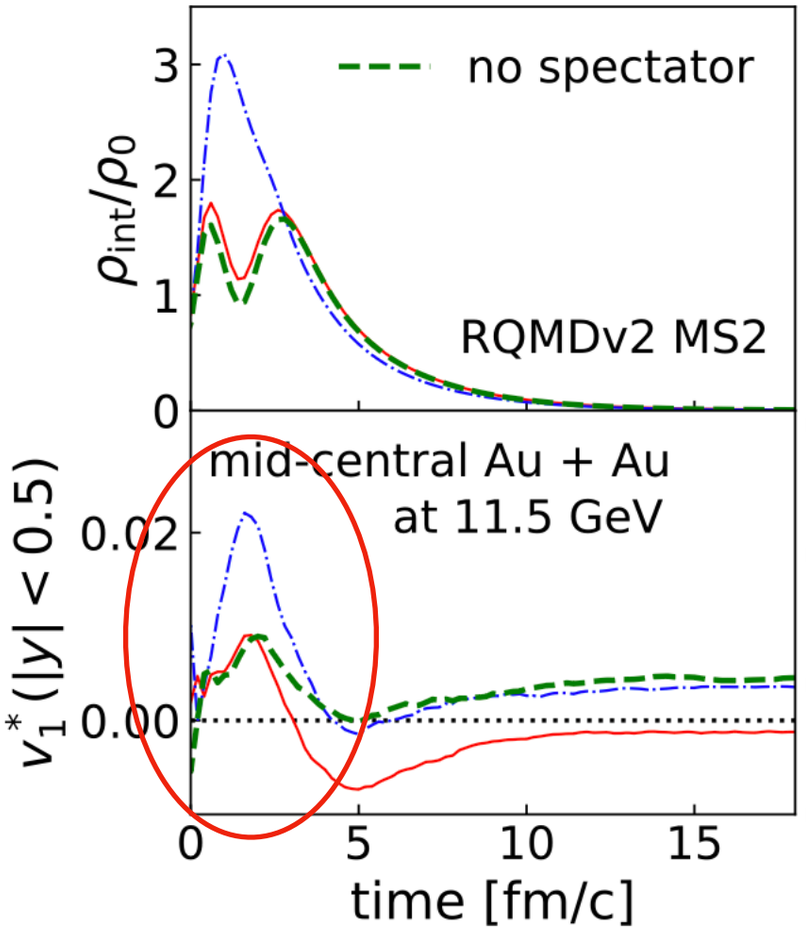
Transported quarks



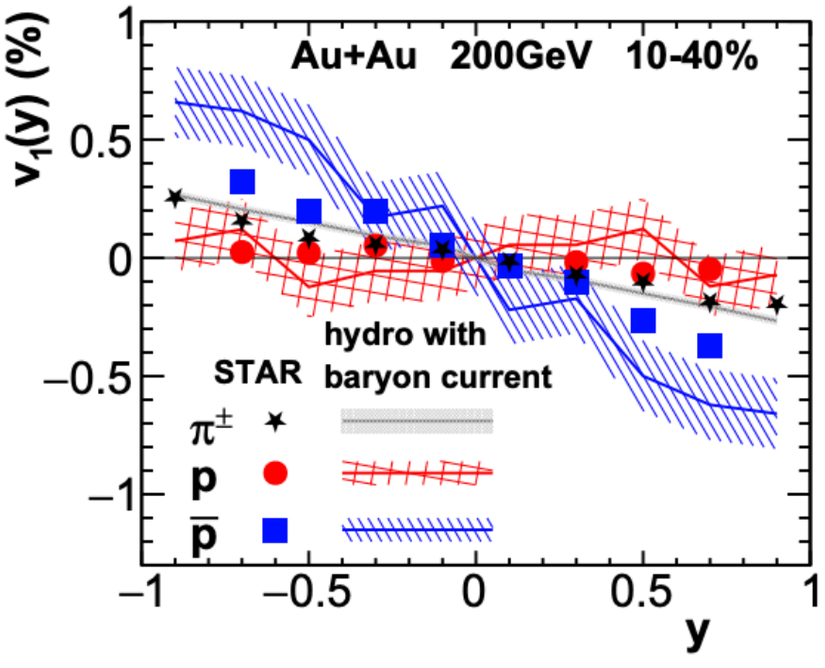
Features:

- Exist at the beginning of the collisions.
- Sensitive to early stage dynamics (compress, EoS, mean field potential).

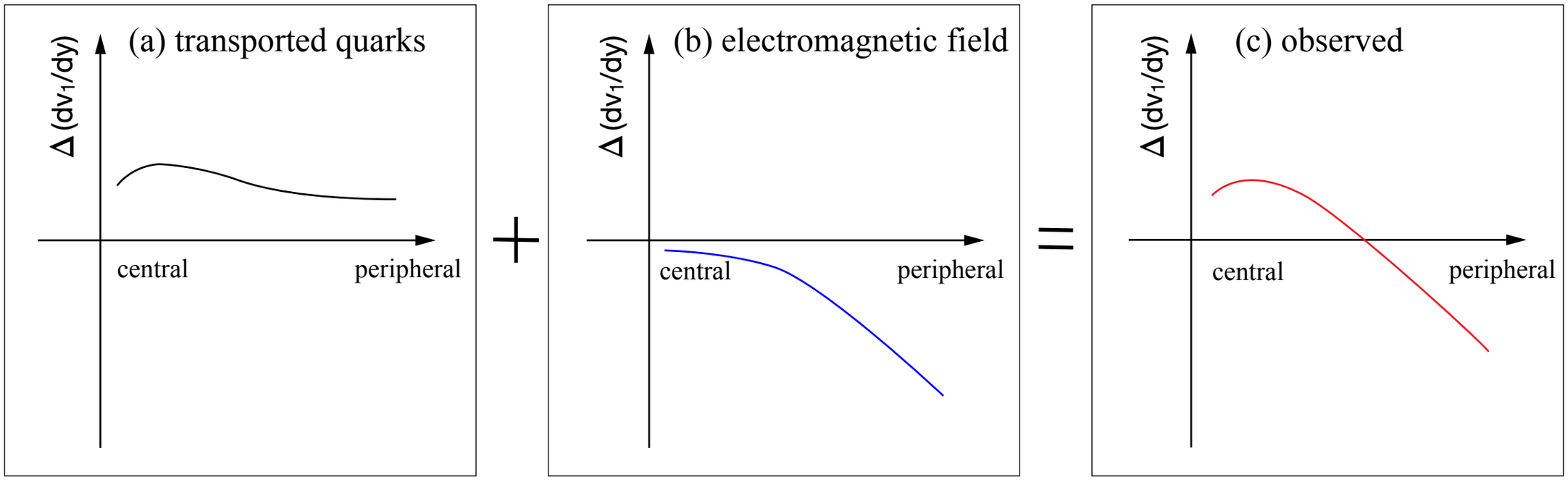
…momentum-dependent hadronic mean fields in a cascade model…
Y. Nara, A. Ohnishi, PRC 105, 014911 (2022)



…expansion of a baryon inhomogeneous fireball…
P. Bozek, PRC 106 L061901(2022)



Δv_1 of EM-field + transported quarks



As transported quarks have positive dv_1/dy[1][2],

dv_1/dy	
$p : uud$ $\bar{p} : \bar{u}\bar{u}\bar{d}$	$p > \bar{p}$
$K^+ : u\bar{s}$ $K^- : \bar{u}s$	$K^+ > K^-$
$\pi^+ : u\bar{d}$ $\pi^- : \bar{u}d$	$\pi^- > \pi^+$

+

Faraday effect/spectator Coulomb dominate over Hall effect[3][4],

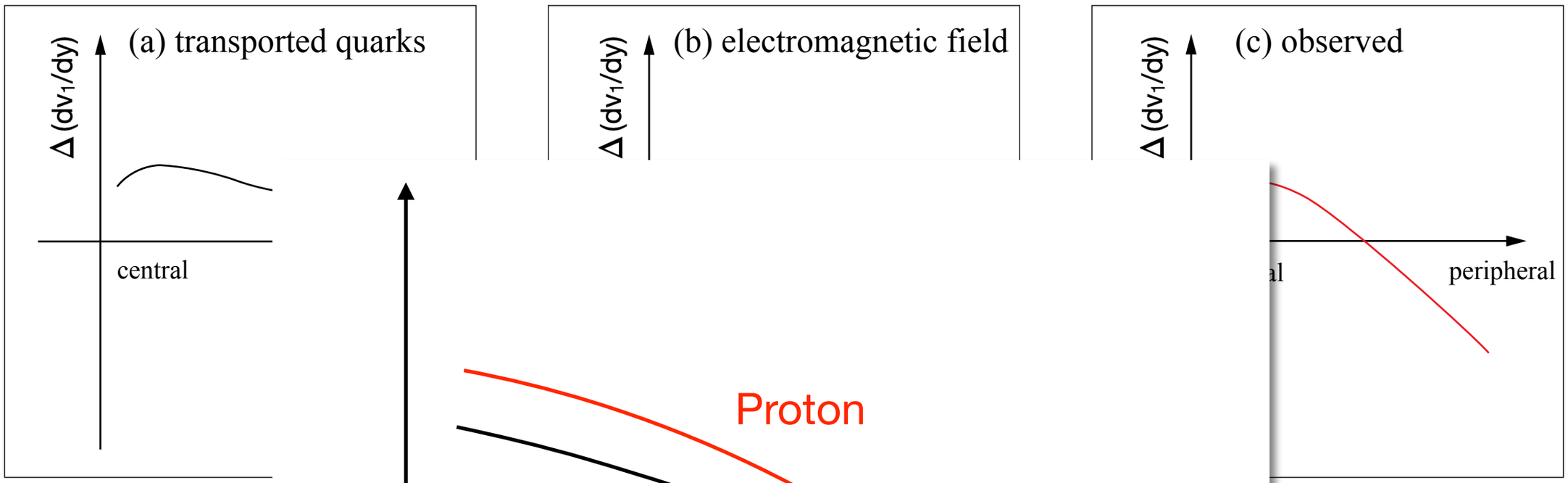
dv_1/dy
$p < \bar{p}$
$K^+ < K^-$
$\pi^- > \pi^+$

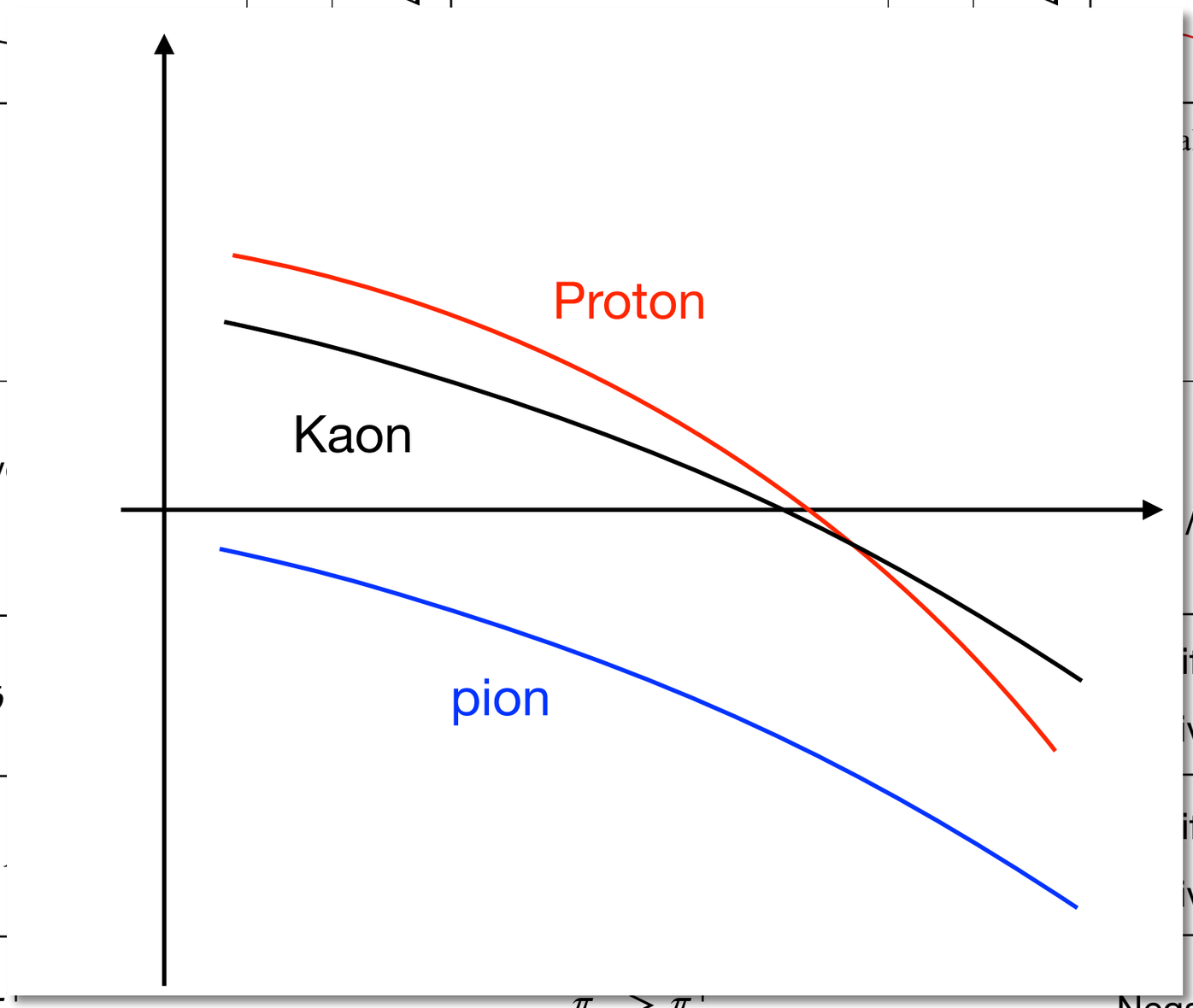
=

$$\Delta(dv_1/dy) = dv_1^+/dy - dv_1^-/dy$$

Positive if transported quarks + Hall win Negative if Faraday + Coulomb win
Positive if transported quarks + Hall win Negative if Faraday + Coulomb win
Negative

Δv_1 of EM-field + transported quarks





As transported quarks hav

dv_1/dy[1][2],

	dv_1/dy
$p : uud$ $\bar{p} : \bar{u}\bar{u}\bar{d}$	$p > \bar{p}$
$K^+ : u\bar{s}$ $K^- : \bar{u}s$	$K^+ >$
$\pi^+ : u\bar{d}$ $\pi^- : \bar{u}d$	$\pi^- > \pi$

$/dy) = dv_1^+/dy - dv_1^-/dy$

if transported quarks + Hall win

ve if Faraday + Coulomb win

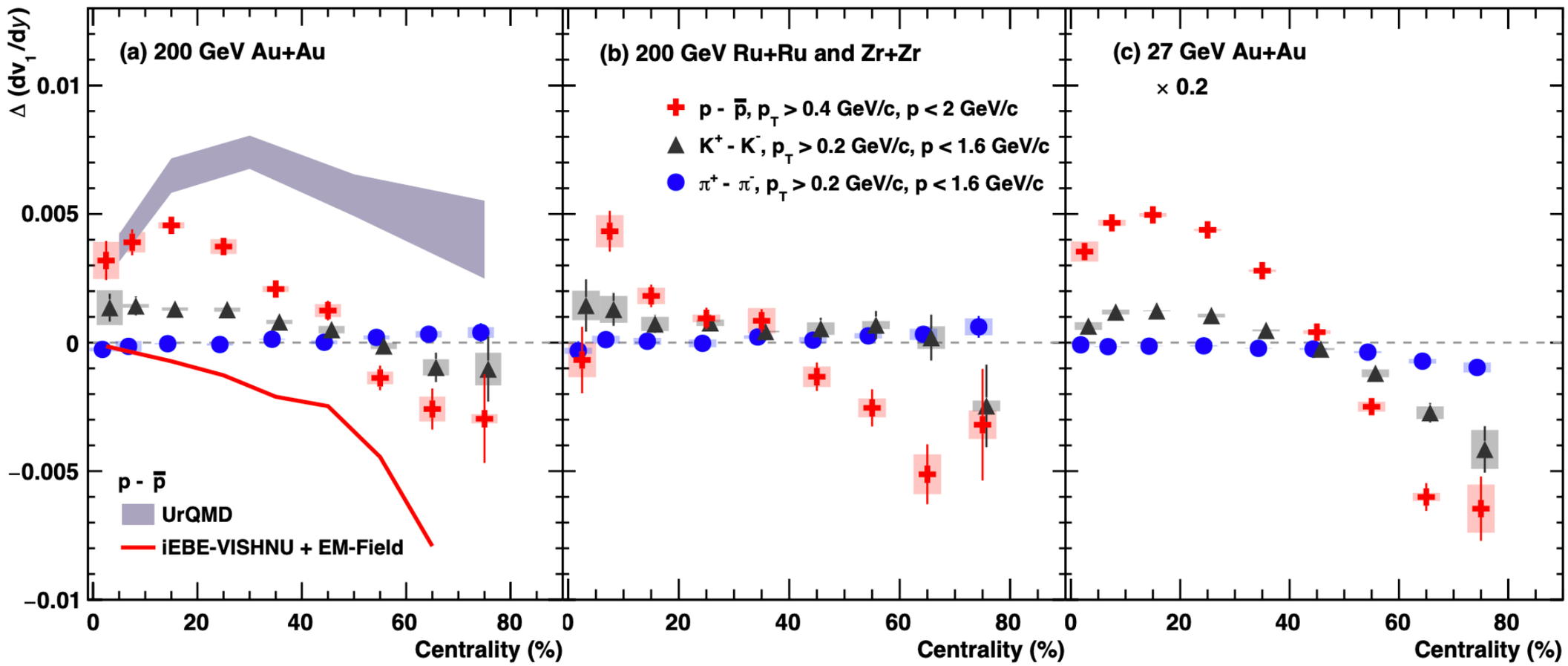
if transported quarks + Hall win

ve if Faraday + Coulomb win

$\pi^- > \pi^+$

Negative

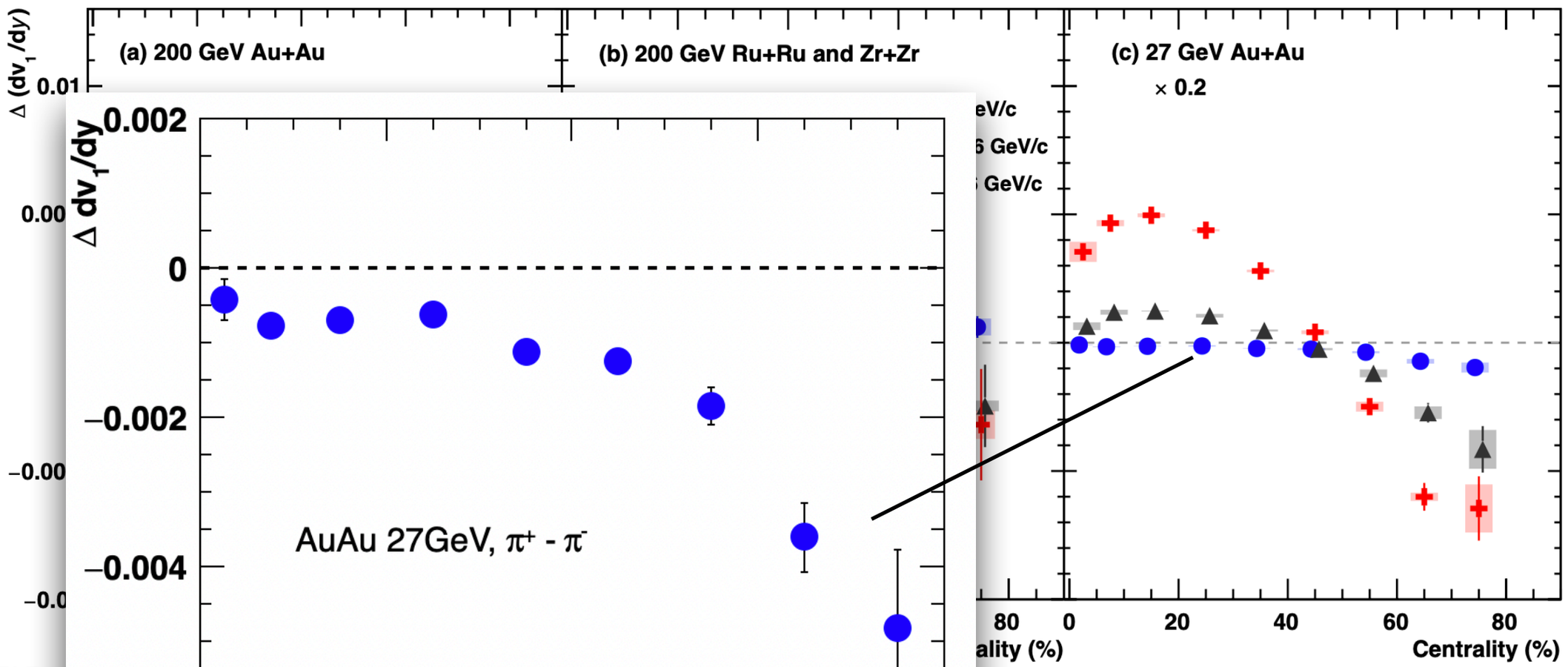
Sign change of $\Delta dv_1/dy$



STAR, Phys. Rev. X **14**, 011028 (2024)

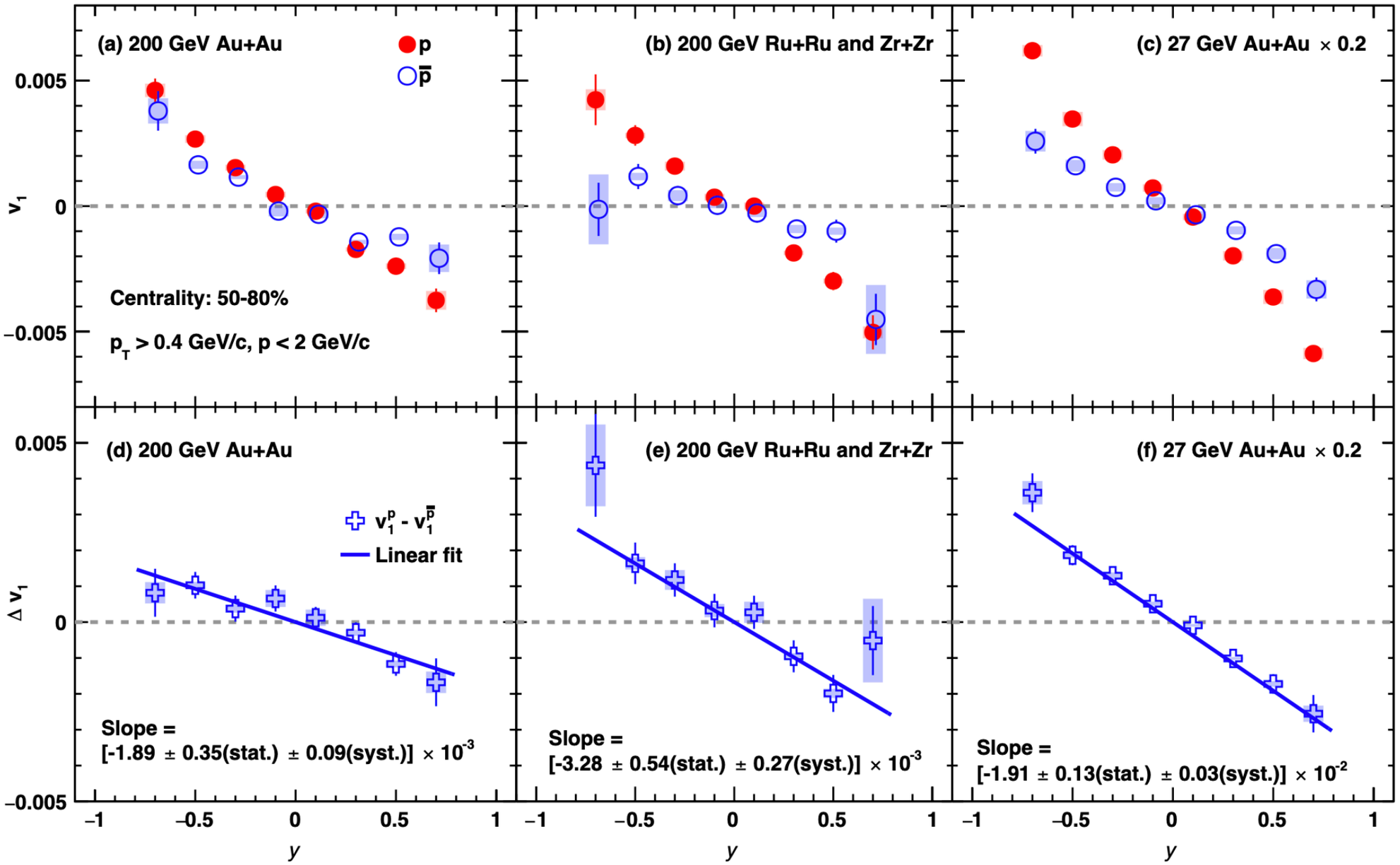
$p : uud$ $\bar{p} : \bar{u}\bar{u}\bar{d}$	$p > \bar{p}$	+	$p < \bar{p}$	= Positive if transported quarks + Hall win Negative if Faraday + Coulomb win
$K^+ : u\bar{s}$ $K^- : \bar{u}s$	$K^+ > K^-$		$K^+ < K^-$	Positive if transported quarks + Hall win Negative if Faraday + Coulomb win
$\pi^+ : u\bar{d}$ $\pi^- : \bar{u}d$	$\pi^- > \pi^+$		$\pi^- > \pi^+$	Negative

Sign change of $\Delta dv_1/dy$



$p : uud$ $\bar{p} : \bar{u}\bar{u}\bar{d}$			Positive if transported quarks + Hall win Negative if Faraday + Coulomb win
$K^+ : u\bar{s}$ $K^- : \bar{u}s$		=	Positive if transported quarks + Hall win Negative if Faraday + Coulomb win
$\pi^+ : u\bar{d}$ $\pi^- : \bar{u}d$	$\pi^- > \pi^+$	$\pi^- > \pi^+$	Negative

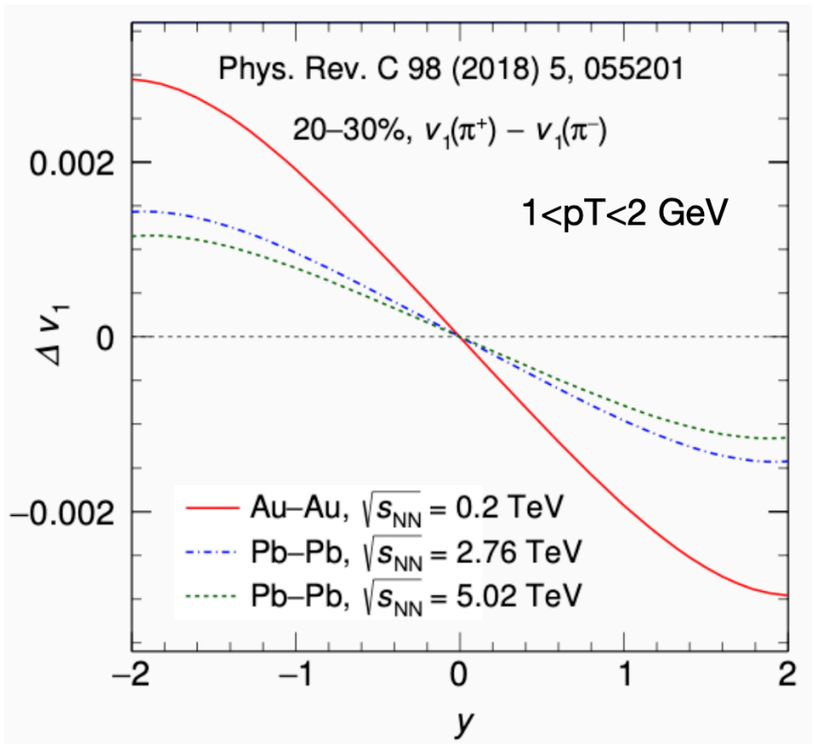
Proton Δv_1 in 50-80% centrality

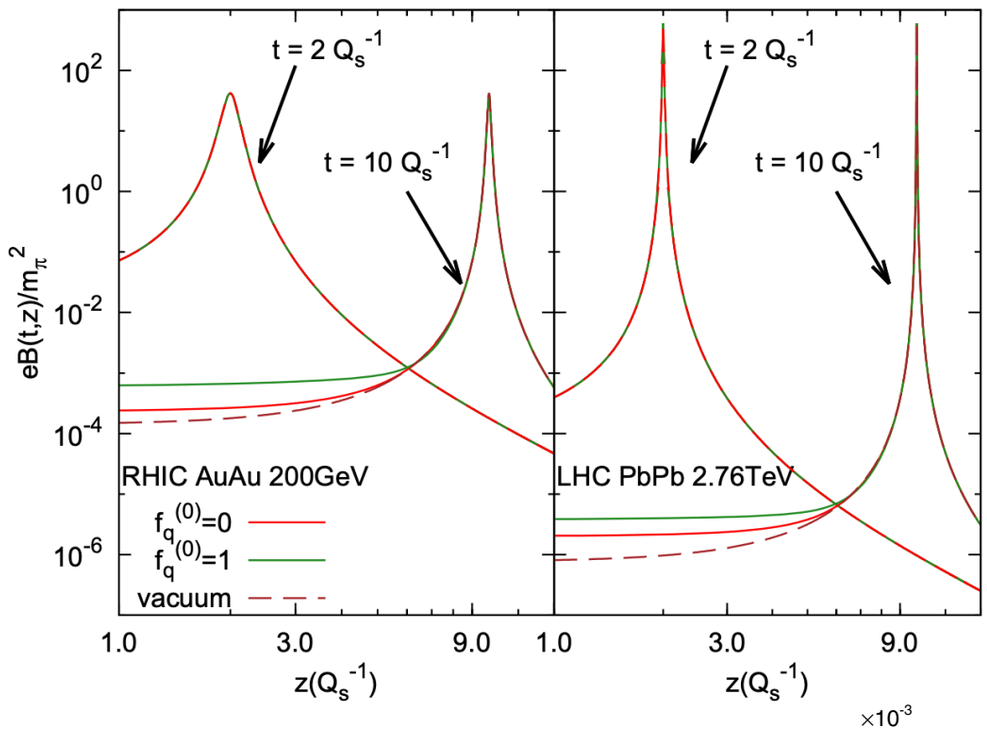


STAR, Phys. Rev. X **14**, 011028 (2024)

- Negative slope of Δv_1 as a function of y, significance more than 5σ.
- Consistent with Faraday + Coulomb effect.

Lifetime effect?

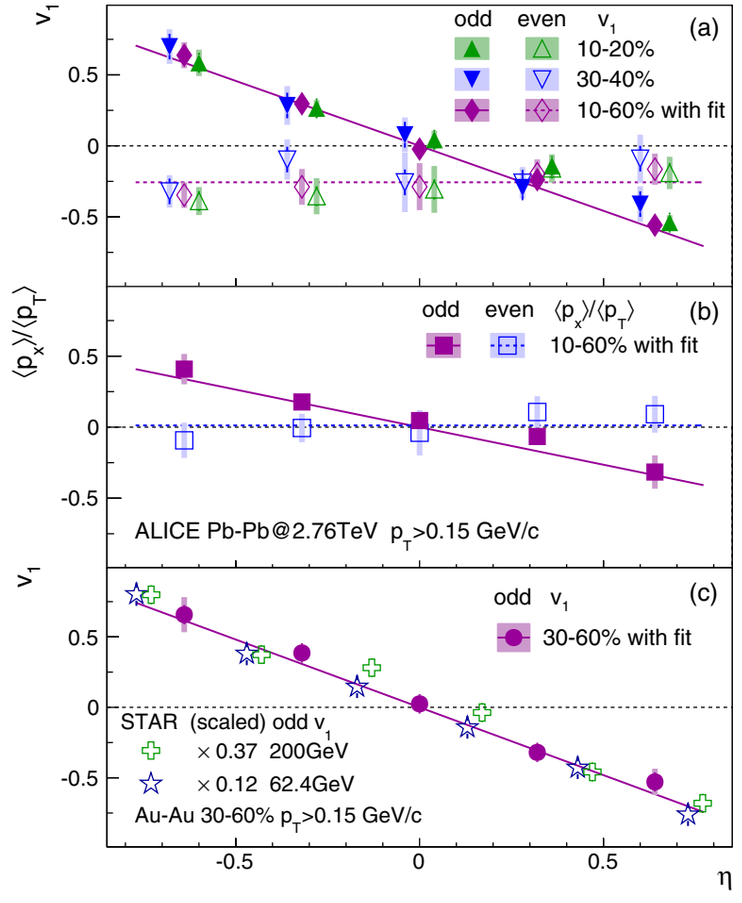




ALICE, PRL 111 232302 (2013)

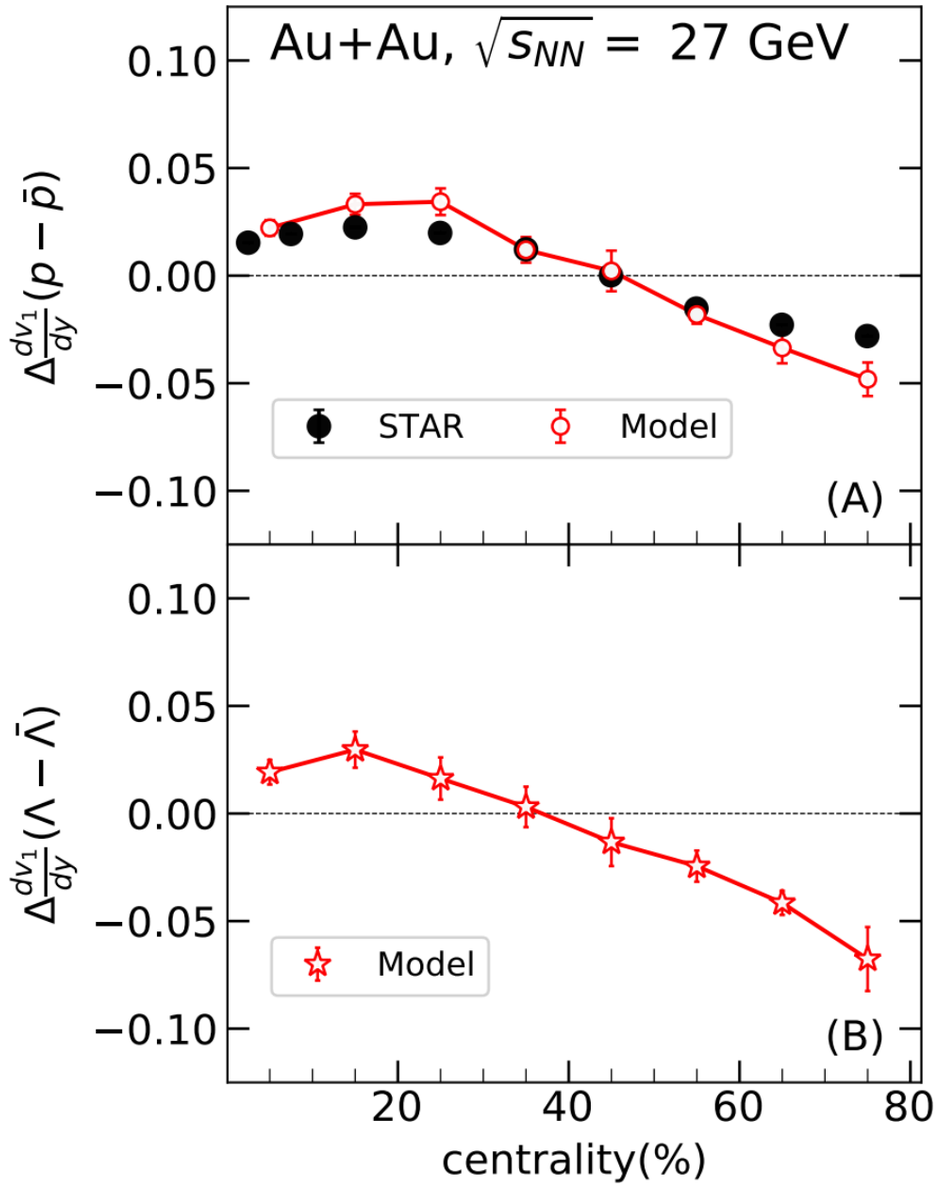
U. Gürsoy, et.al., PRC 98 055201 (2018)
L. Yan and X.-G. Huang, PRD 107 094028 (2023)

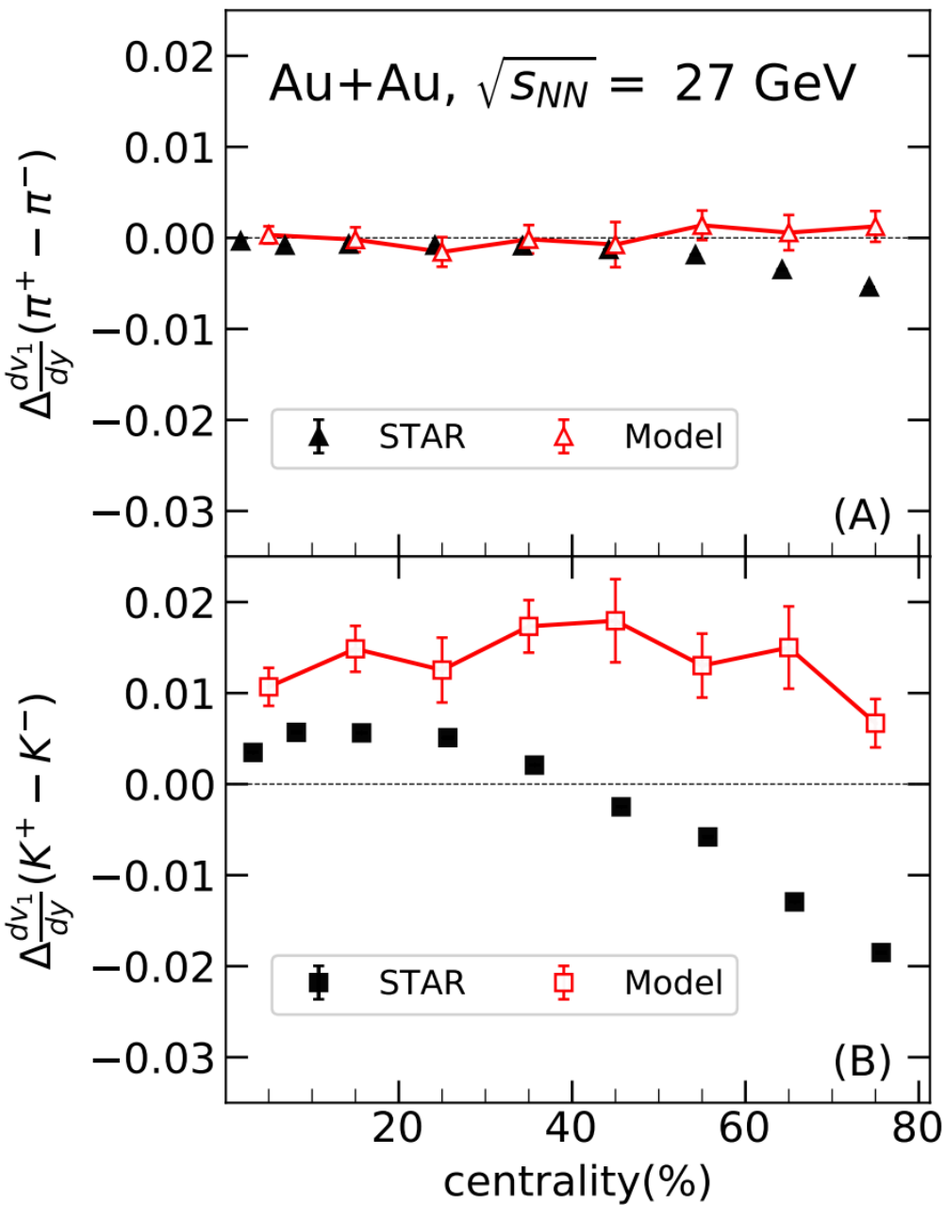
- Stronger signal at low energy?
- From high energy to low energy:
  - B field decays slower -> stronger B when medium is formed.
  - Shorter life time of QGP -> stronger B at freeze-out surface.
  - Longer time for Coulomb field to take an effect.



Baryon inhomogeneities effect

T. Parida et.al., arXiv:2305.08806

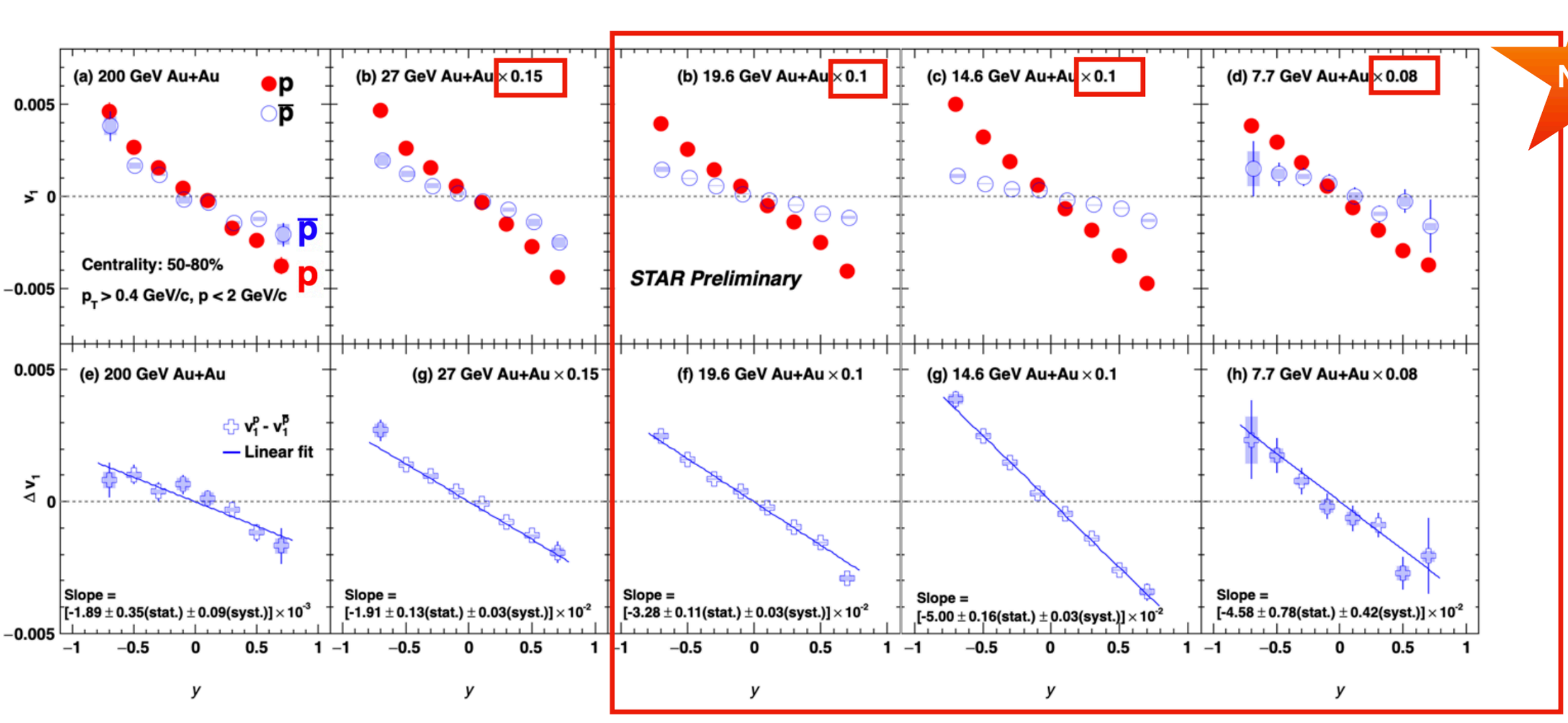




- Can reproduce the sign change of proton $\Delta dv_1/dy$.
- Challenging to describe mesons.

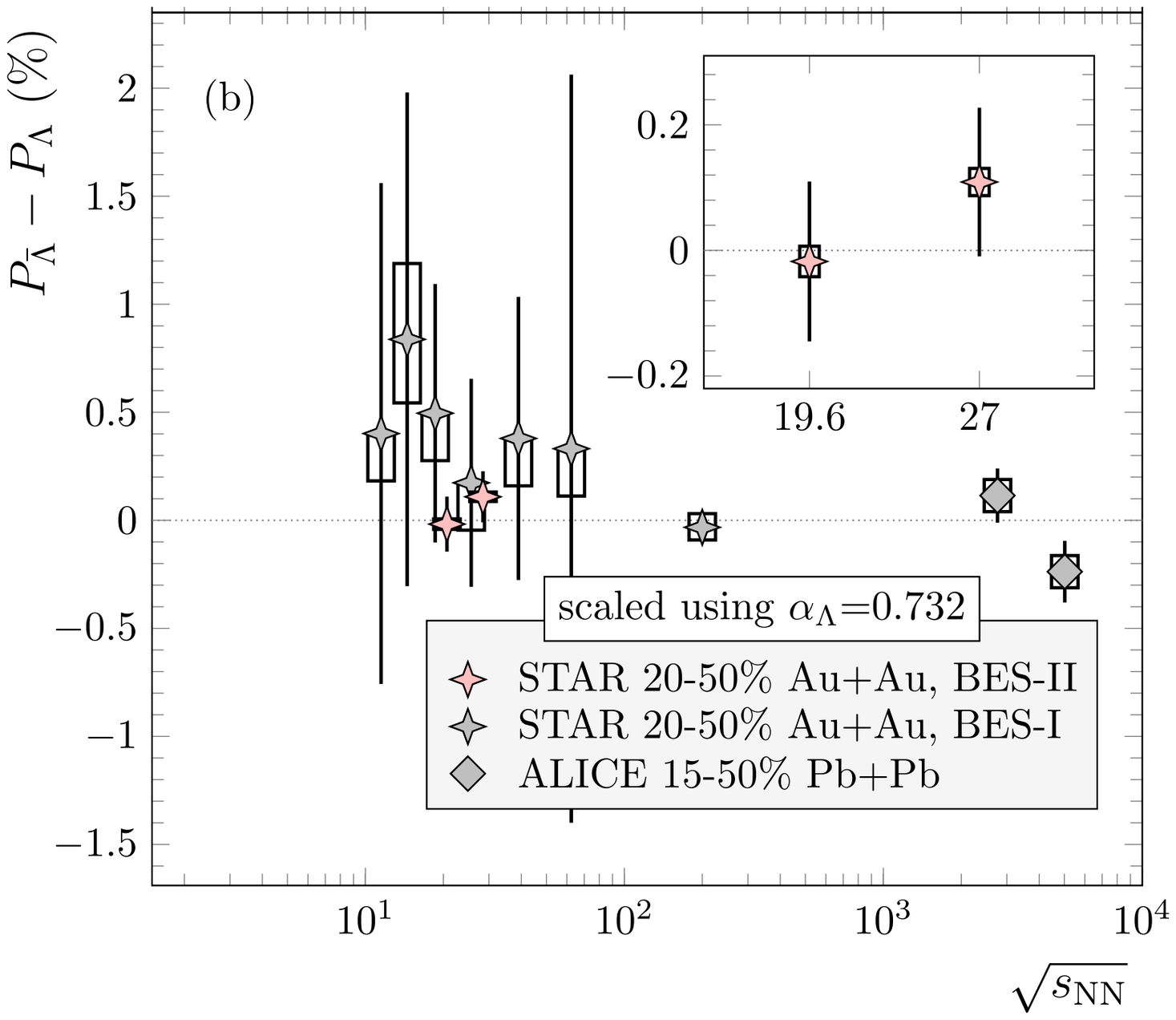
Baryon difference in BES-II data

STAR, Aditya, QM2023



- More significant at low energy.

Study the EM-field by Λ polarization



STAR, Phys. Rev. C **108**, 014910 (2023)

- Late-stage B field

$$|B| \approx \frac{T_s |P_{\bar{\Lambda}} - P_{\Lambda}|}{2|\mu_{\Lambda}|}$$

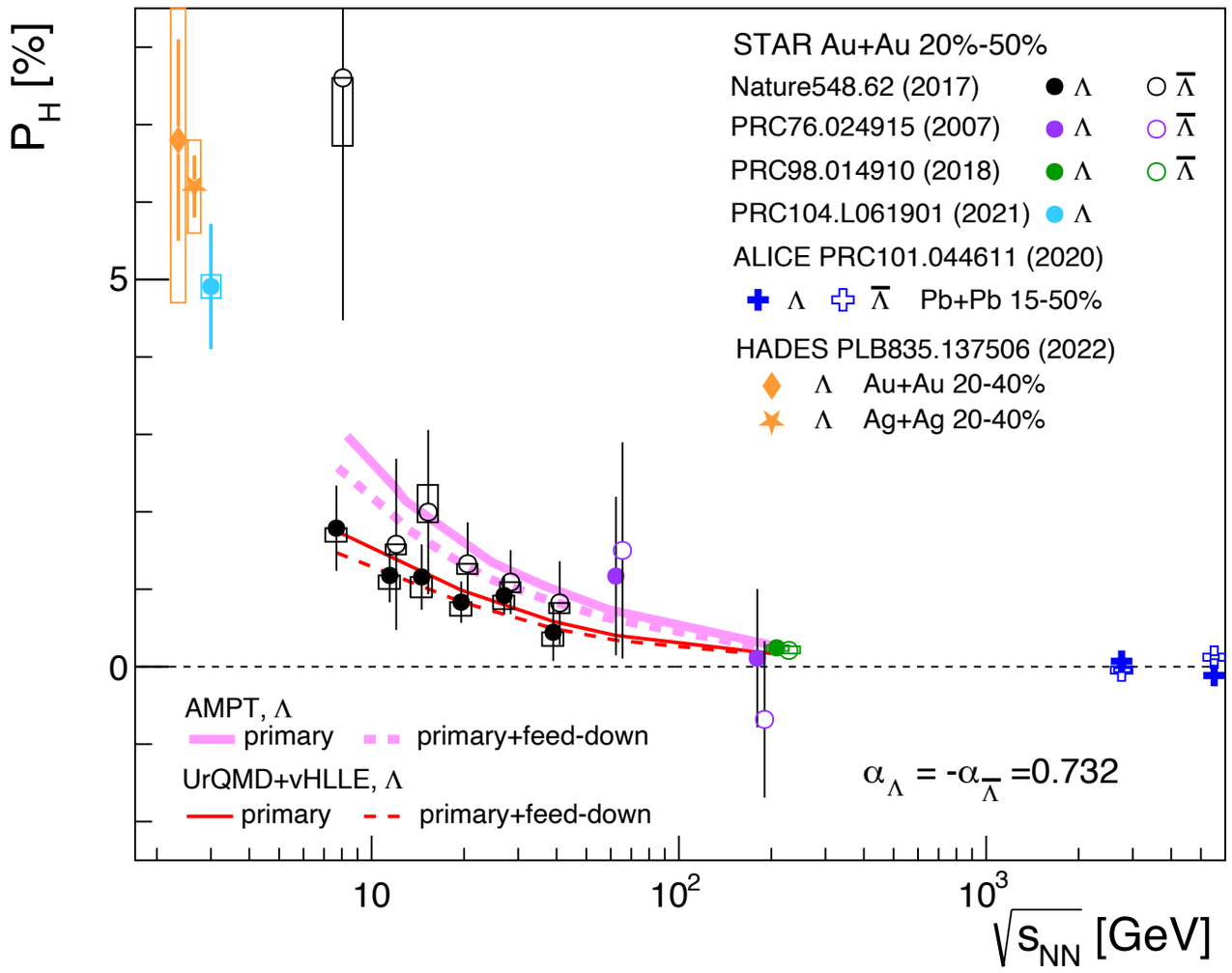
- High precision BES-II data (19.6 and 27 GeV)

-0.018 ± 0.127 (stat.) ± 0.024 (syst.)

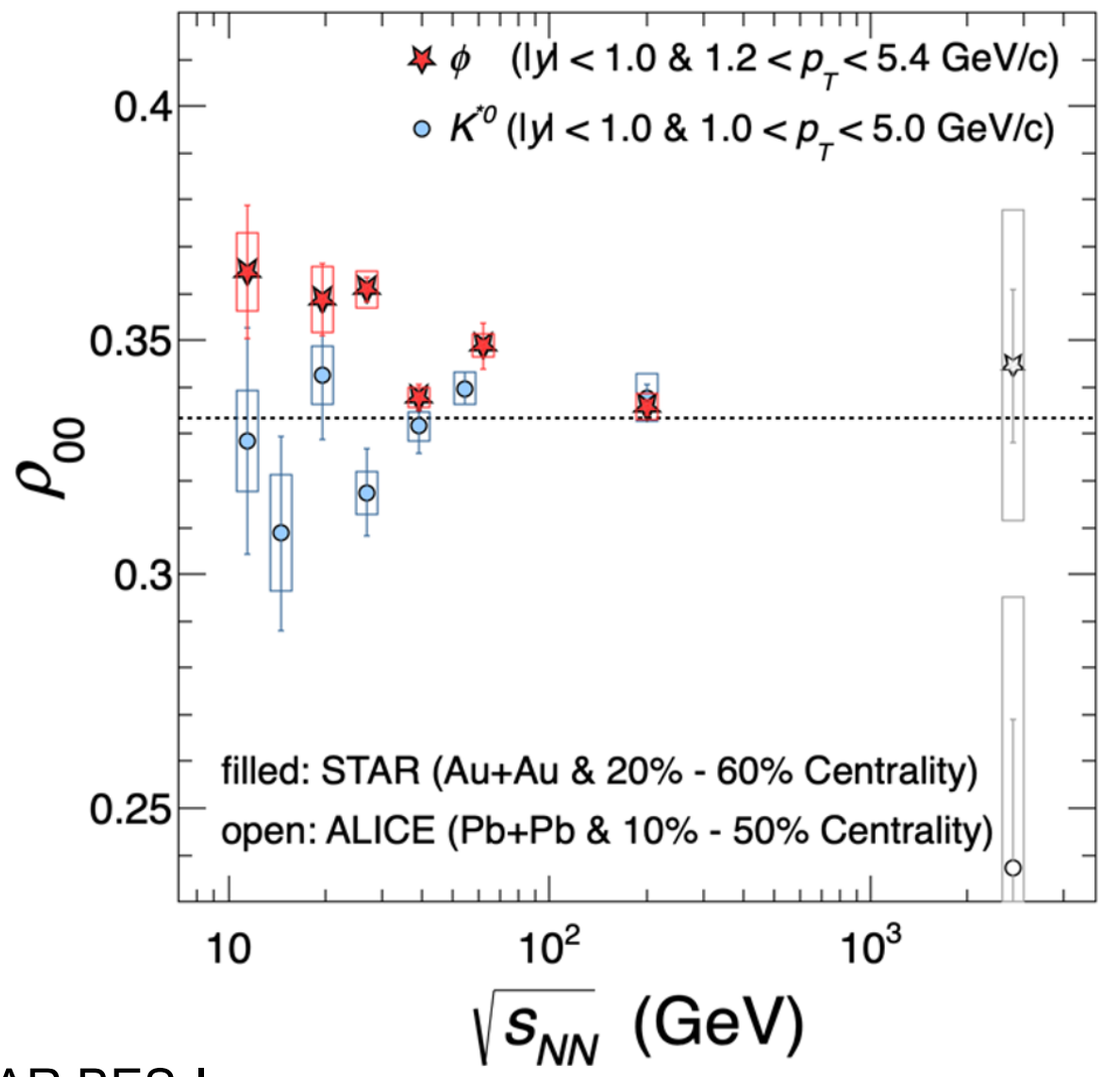
0.109 ± 0.118 (stat.) ± 0.022 (syst.)

$B < 9.4 \times 10^{12}$ T and $B < 1.4 \times 10^{13}$ T

The Λ polarization and vector meson spin alignment



see talk of Xu Sun



- The collision energy-average polarization data from STAR BES-I indicate a vorticity of **$(9\pm1)\times10^{21}$ s^{-1}**, experimental access to the vortical structure of the QGP
- The local correlation or fluctuation of φ fields is the dominant mechanism for the observed Φ-meson ρ_{00}

Sheng, et al., Phys. Rev. Lett. **131**, 042304 (2023)

STAR Phys. Rev. C **76**, 024915 (2007)
STAR Nature **548**, 62 (2017)
STAR Phys. Rev. C **77**, 061902® (2008)
ALICE Phys. Rev. Lett. **125**, 012301 (2020)
STAR Nature **614**, 244 (2023)
…

The ‘small’ Λ vs. ‘large’ ϕ-meson signal

Z. T. Liang, Chirality 2023, J. Lv, Z. Yu, Z.T. Liang, Q. Wang, X.-N. Wang, Phys. Rev. D 109, 114003 (2024)

$$\left|\rho_{00}^{V}-\frac{1}{3}\right| \gg P_{\Lambda}^{2} \sim P_{q}^{2}$$

$$\rho_{00}^{V}-\frac{1}{3} \sim \langle P_q P_{\bar{q}} \rangle$$

The STAR data show that: $\langle P_q P_{\bar{q}} \rangle \neq \langle P_q \rangle \langle P_{\bar{q}} \rangle$ $\quad \langle P_q P_{\bar{q}} \rangle \gg \langle P_q \rangle \langle P_{\bar{q}} \rangle$

By studying P_H, we study the average of quark polarization P_q;

by studying ρ_{00}^{V}, we study the correlation between P_q and $P_{\bar{q}}$.

How to separate long range or local correlations

$$C_{NN}^{H_i\bar{H}_j} \equiv \frac{N_{H_i\bar{H}_j}^{\uparrow\uparrow}+N_{H_i\bar{H}_j}^{\downarrow\downarrow}-N_{H_i\bar{H}_j}^{\uparrow\downarrow}-N_{H_i\bar{H}_j}^{\downarrow\uparrow}}{N_{H_i\bar{H}_j}^{\uparrow\uparrow}+N_{H_i\bar{H}_j}^{\downarrow\downarrow}+N_{H_i\bar{H}_j}^{\uparrow\downarrow}+N_{H_i\bar{H}_j}^{\downarrow\uparrow}}$$

sensitive to the long range correlation

$$\rho_{10}^{V}=\frac{P_{qz}(1+P_{\bar{q}y})+(1+P_{qy})P_{\bar{q}z}-iP_{qx}(1+P_{\bar{q}y})-i(1+P_{qy})P_{\bar{q}x}}{\sqrt{2}(3+\vec{P}_q\cdot\vec{P}_{\bar{q}})}$$

$$\rho_{0-1}^{V}=\frac{P_{qz}(1-P_{\bar{q}y})+(1-P_{qy})P_{\bar{q}z}-iP_{qx}(1-P_{\bar{q}y})-i(1-P_{qy})P_{\bar{q}x}}{\sqrt{2}(3+\vec{P}_q\cdot\vec{P}_{\bar{q}})}$$

$$\rho_{1-1}^{V}=\frac{P_{qz}P_{\bar{q}z}-P_{qx}P_{\bar{q}x}+i(P_{qx}P_{\bar{q}y}+P_{qy}P_{\bar{q}x})}{3+\vec{P}_q\cdot\vec{P}_{\bar{q}}}$$

They should be sensitive to the local correlations.

Summary

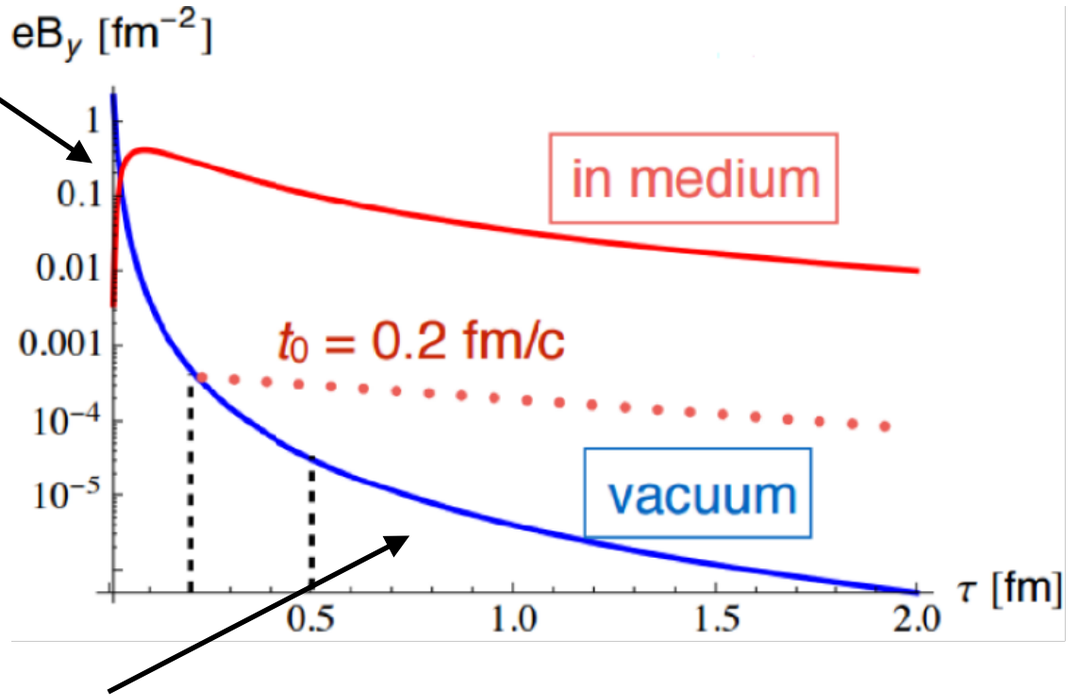
- **Experimental data of v_1 splitting between positive charge and negative charge is consistent with EM-field expectation in QGP**
- **Experimental data of vector meson spin alignment is larger than Λ polarization, it is consistent with calculation of meson-field fluctuation**
- **The study of strong EM-field in hot QCD and its impact is progressing well**

The EM-field in HIC: its evolution

The peak value of B field is accurate in QED

W.T. Deng and X.G. Huang, PRC 85, 044907 (2012)

D. E. Kharzeev, et.al., NPA 803, 227 (2008)



The evolution of B field is challenging in theory

- Pre-equilibrium quark gluon plasma, formation time of quarks
- Electrical conductivity of QGP

L. Yan, X.-G. Huang, PRD 107, 094028 (2023)

Z. Wang, J. Zhao, C. Greiner, Z. Xu, P. Zhuang, PRC 105, L041901 (2022)

U. Gürsoy, et.al., PRC 89 054905 (2014)

Light quarks vs. heavy quarks

“ With the evolution of the electromagnetic fields in hand, the next step is to compute the drift velocity $\vec{v}_{\text{drift}}$ that the electromagnetic field induces at each point on the freeze-out surface. ”

PHYSICAL REVIEW C **98**, 055201 (2018)

Why is freeze-out surface?

“ It is important to stress that a main feature of the CQs that turns out to favor the formation of a sizable directed flow is the relative large equilibration time w.r.t. light quarks. In fact, the relaxation time of CQs can be estimated as $\tau_c^{eq} \simeq 1/\Gamma \approx 5$–$8$ fm/c which is much larger than the light quark and gluon equilibration time, $\tau_{QGP}^{eq} \approx 0.5$–$1$ fm/c. ”

Physics Letters B 768 (2017) 260–264

Light quarks have short memory, they can’t remember what happened before!

$$m\frac{d\vec{v}_{\text{drift}}^{\,\text{lrf}}}{dt} = q\vec{v}_{\text{drift}}^{\,\text{, lrf}} \times \vec{B}^{\,\text{lrf}} + q\vec{E}^{\,\text{lrf}} - \mu m\vec{v}_{\text{drift}}^{\,\text{lrf}} = 0 \quad (9)$$

Equilibrium.

For light quarks in PHYSICAL REVIEW C 98, 055201 (2018)

Δv_1 for light quarks is determined by EMF on freeze-out surface => Faraday dominate over Hall

$$\mathbf{F}_{ext} = q\mathbf{E}' + \frac{q}{E_p}(\mathbf{p} \times \mathbf{B}') \quad (9)$$

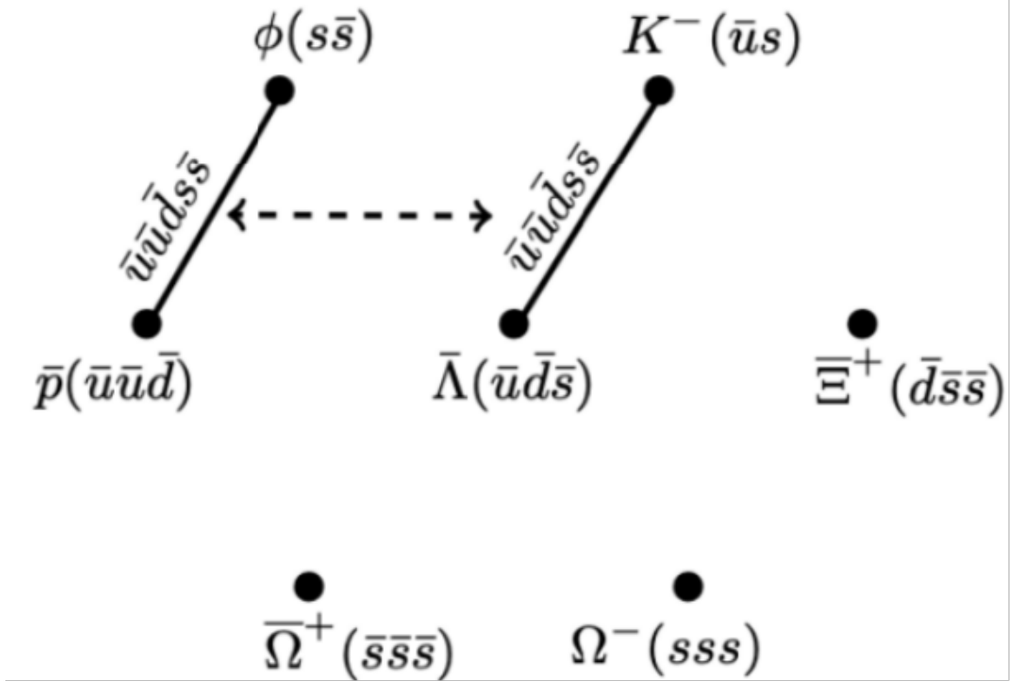
Out of equilibrium

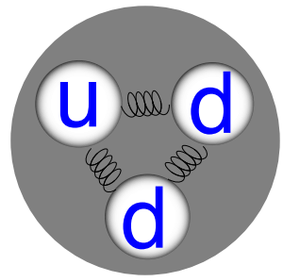
For charm quarks in Physics Letters B 768 (2017) 260–264

Δv_1 for charms is determined by early stage EMF => Hall dominate over Faraday

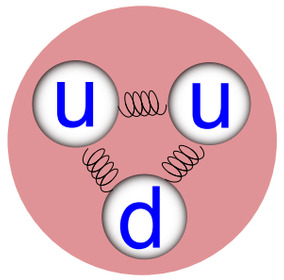
Using produced particles + NCQ

A. Ikbal, et.al., PRC 105 014912 (2022)





Neutron



Proton

(#d>#u, Au neutron rich)

NCQ scaling: $v_n^h = \sum v_n^{q_i}$

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

- Use particles which do not have u or d quark.

Using produced particles + NCQ

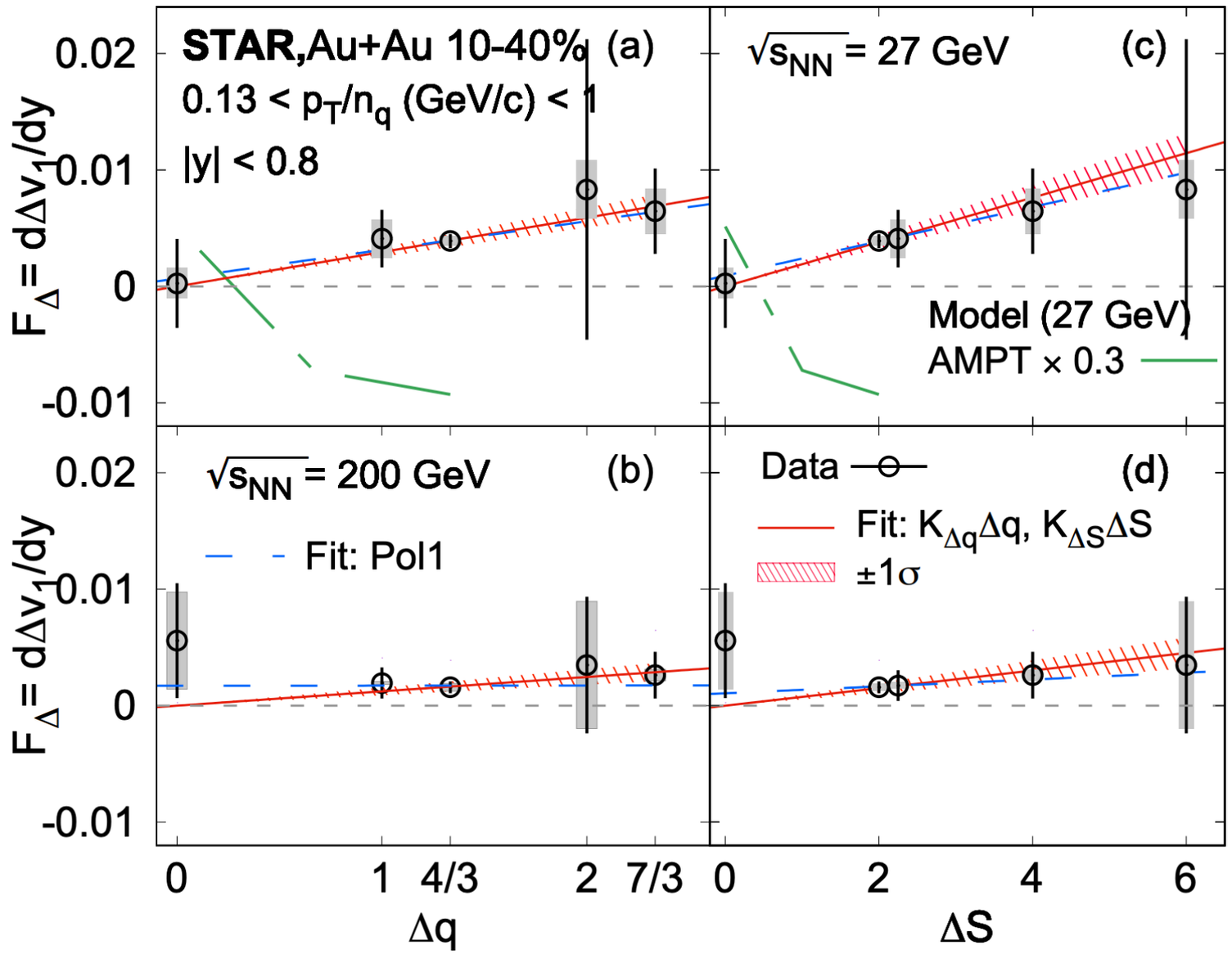
A. Ikbal, et.al., PRC 105 014912 (2022)

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

- Combinations of nearly same quark mass but different Δq and ΔS.
- Measure flow difference for difference Δq and ΔS.
- Δq and ΔS are correlated in those combinations.

Using produced particles + NCQ

STAR, arXiv:2304.02831 (2023)



- Splitting increases with Δq and ΔS.
- From the perspective of charge effect, it consistent with the Hall effect.
- EM-field effect may have centrality or flavor dependence.

Other possibilities?

Collectives (flow) = initial condition + system evolution (hydro/transport model)

What breaks the symmetry of charge distribution?



Other possibilities?

Collectives (flow) = initial condition + system evolution (hydro/transport model)

For system evolution, no matter what the mathematical approach is, it has to be from basic interactions

What breaks the symmetry of charge distribution?

Strong interactions ✗

Weak interactions ✗

Gravity ✗

Electromagnetic interactions

Other possibilities?

Collectives (flow) = initial condition + system evolution (hydro/transport model)

What breaks the symmetry of charge distribution?

Produced quarks (pair production) should share same initial distribution ✗

Transported quarks
- Explain 10-40% centrality, where pions are opposite to protons and kaons.
- Cannot explain peripheral collisions where both pions, kaons and protons are negative.