Global spin alignment of vector mesons and Electromagnetic field effect in heavy-ion collisions at RHIC

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RHIC/AGS Users's Meeting

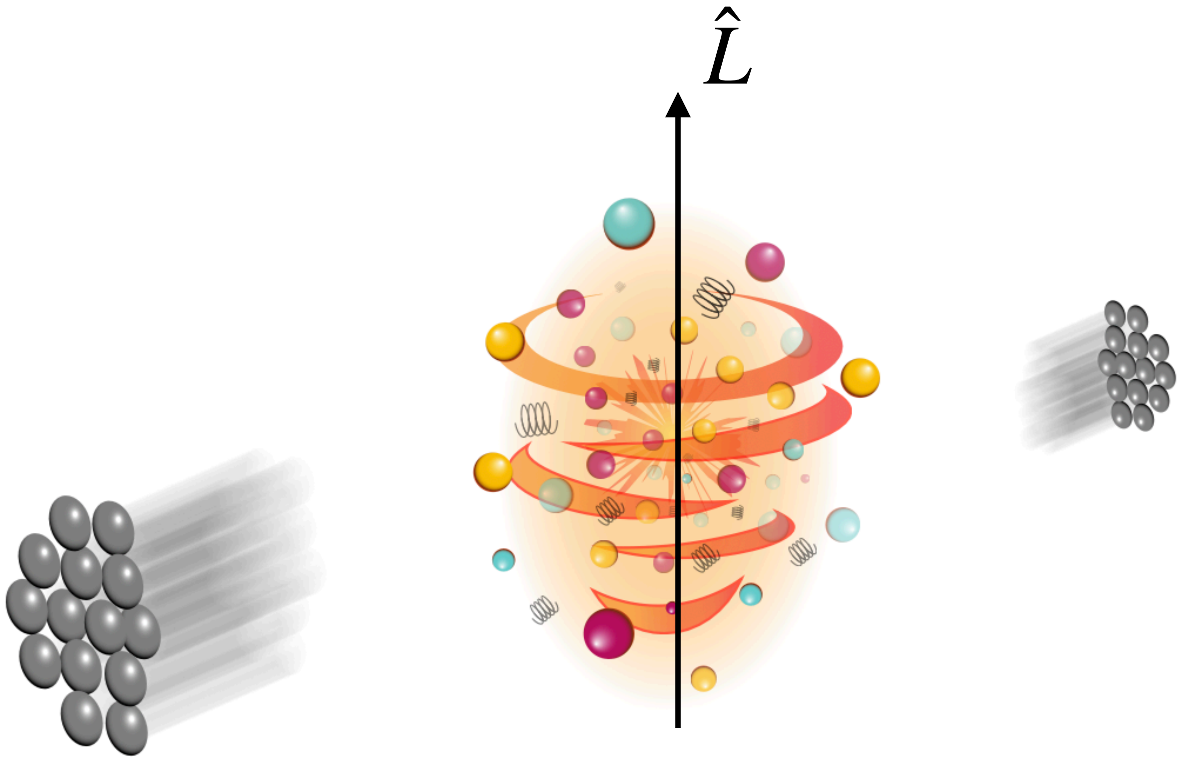
June 11, 2024

Global polarization in HIC

Liang, Wang Phys. Rev. Lett. **94**, 102301(2005); Phys. Lett. B **629**, 20 (2005)

$$d\Delta\sigma/d^2x_T \equiv d\sigma_+/d^2x_T - d\sigma_-/d^2x_T,$$

$$\frac{d\Delta\sigma}{d^2x_T} = -\mu\frac{\vec{p}\cdot(\hat{x}_T\times\vec{n}_b)}{E(E+m_q)}4C_T\alpha_s^2K_0(\mu x_T)K_1(\mu x_T),$$



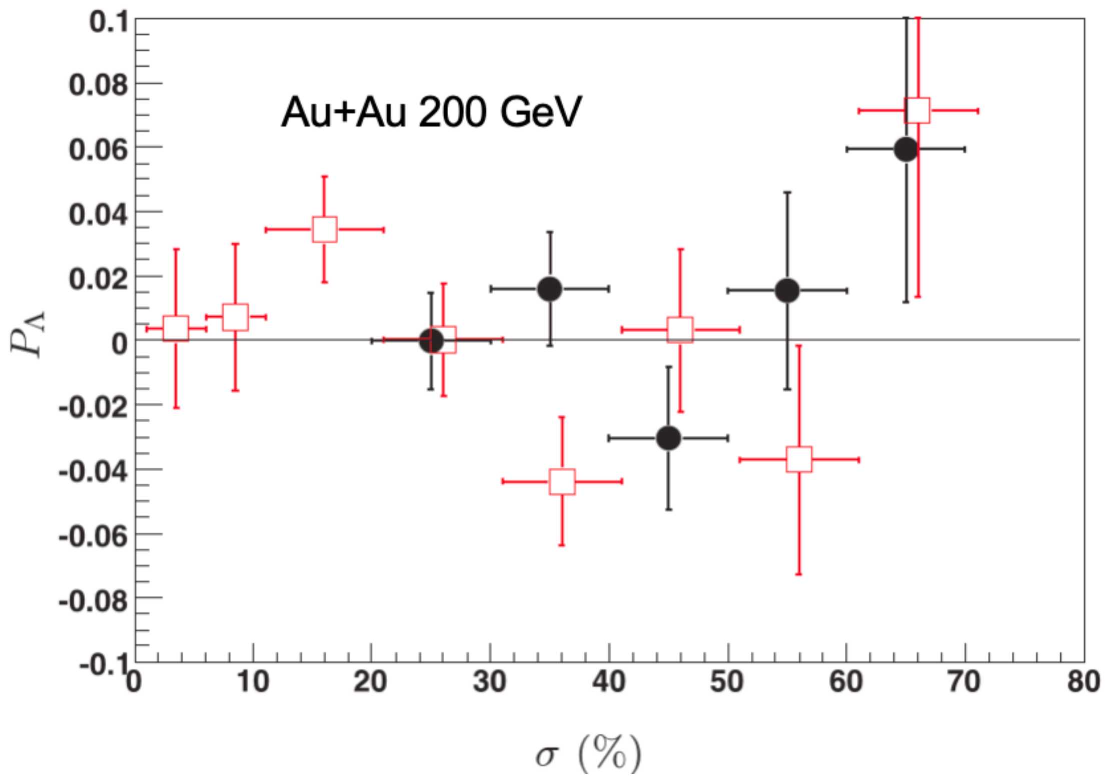
$\hat{x}_T$ Partons impact parameter

$\vec{n}_b$ Reaction plane

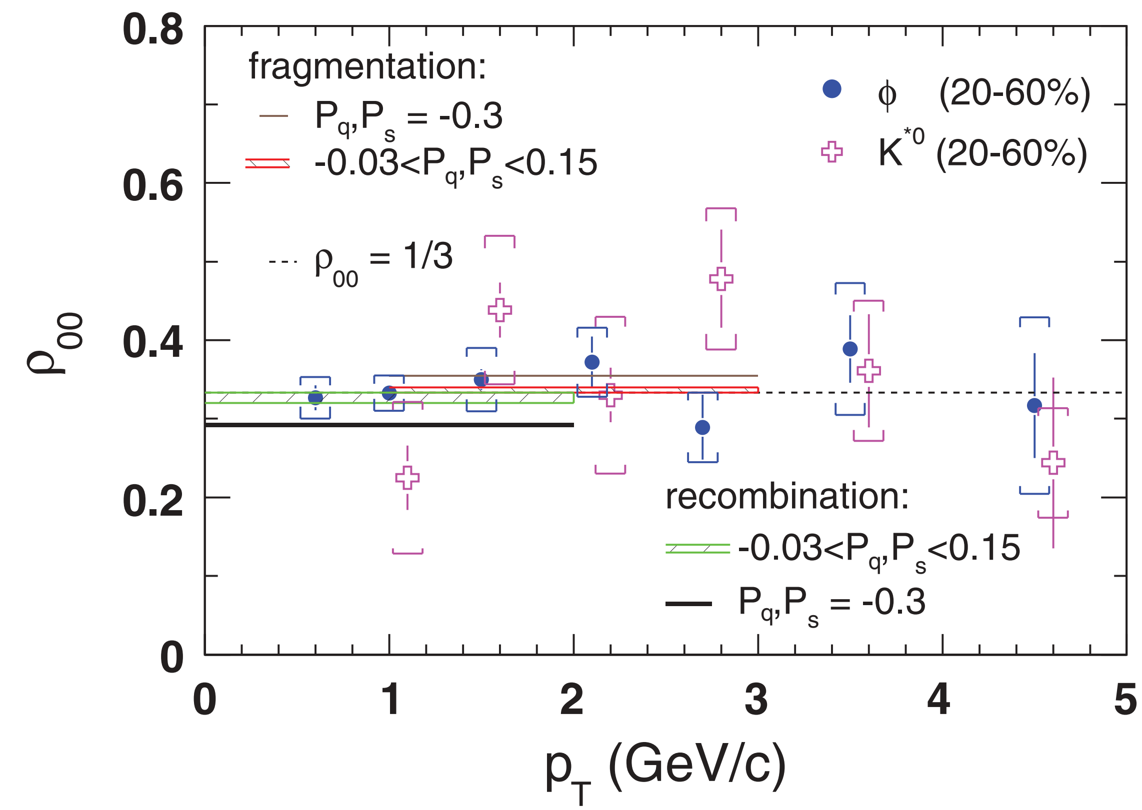
- The initial momentum gradient will result in a rotating QGP in non-central heavy-ion collisions.
- Quarks with spin 1/2 will be polarized due to spin-orbit coupling.
- Global polarization of hyperons and spin alignment of vector mesons.

Early measurements from the STAR

Two years later after the theory paper.. Liang, Wang PRL 94, 102301(2005);



STAR Col. Phys. Rev. C 76, 024915 (2007)

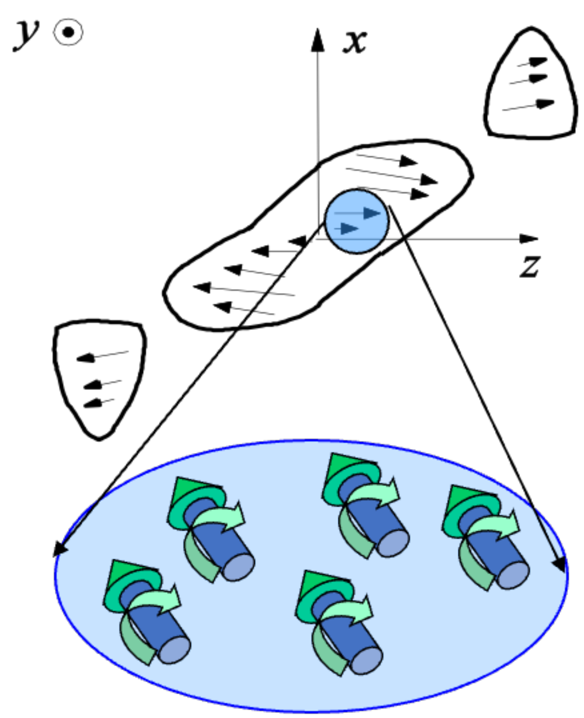


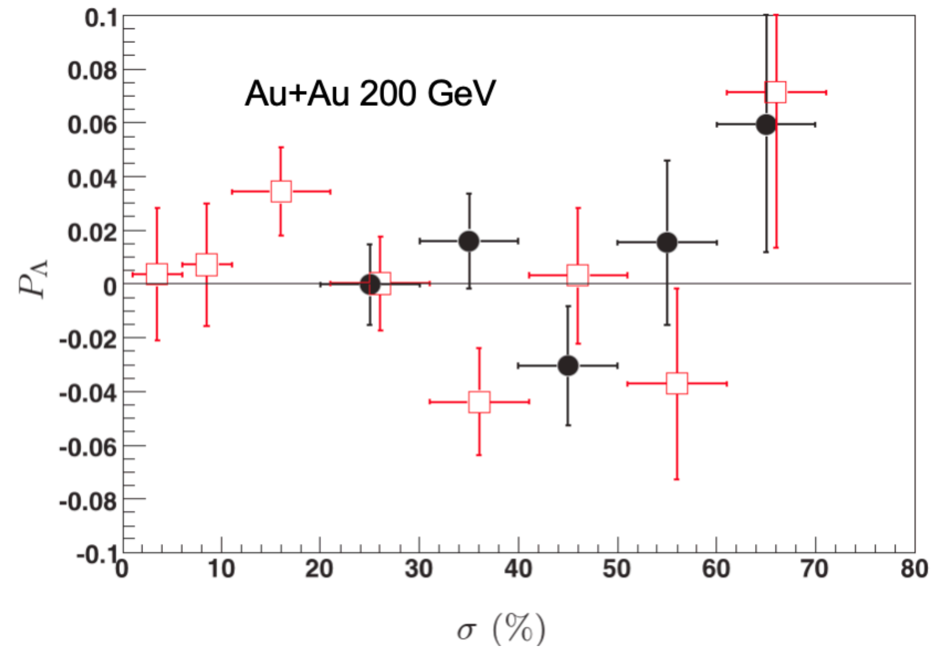
STAR Col. Phys. Rev. C 77, 061902 (2008)

- Early measurements of Λ polarization and vector meson spin alignment in the STAR collaboration have large uncertainties.

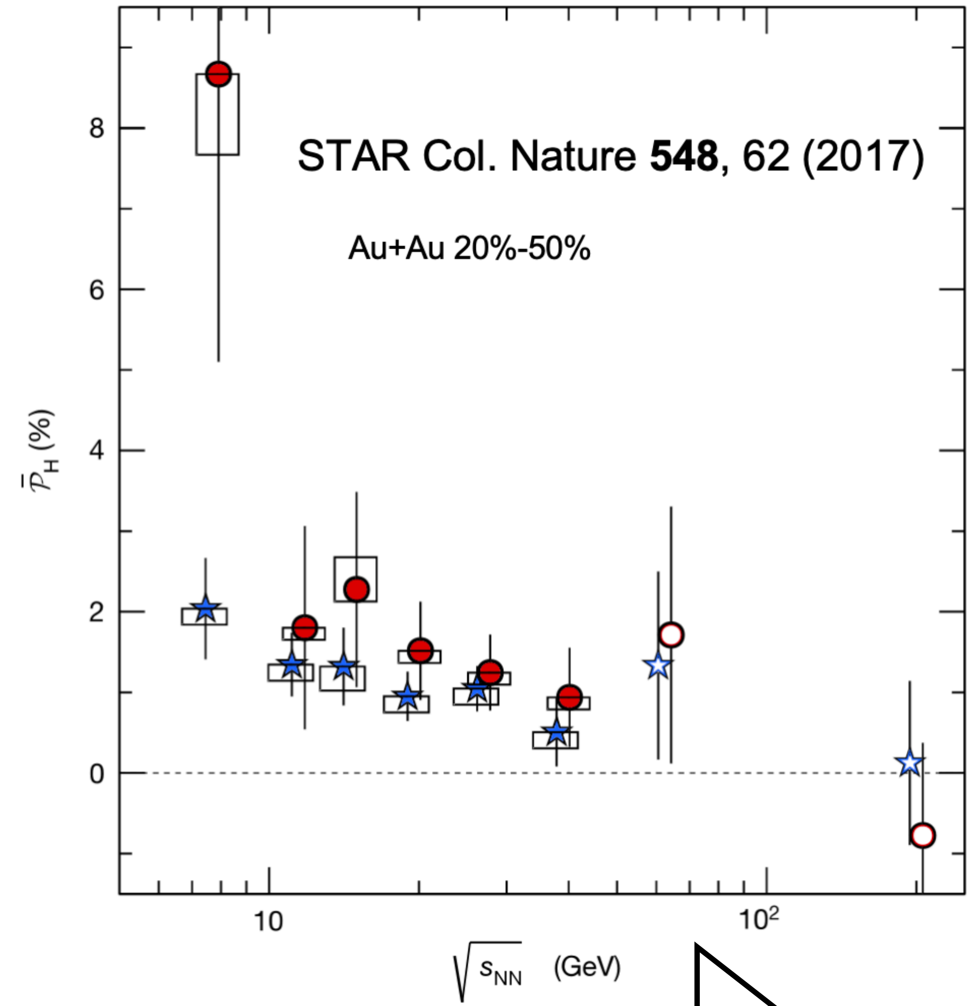
Global polarization of Λ

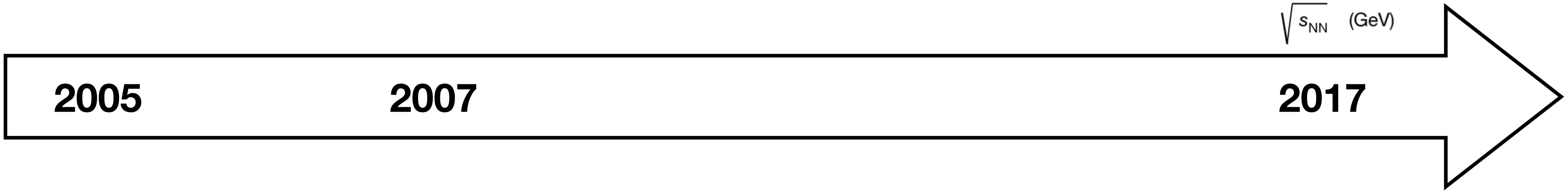
Liang, Wang Phys. Rev. Lett. **94**, 102301





STAR Col. Phys. Rev. C 76, 024915 (2007)

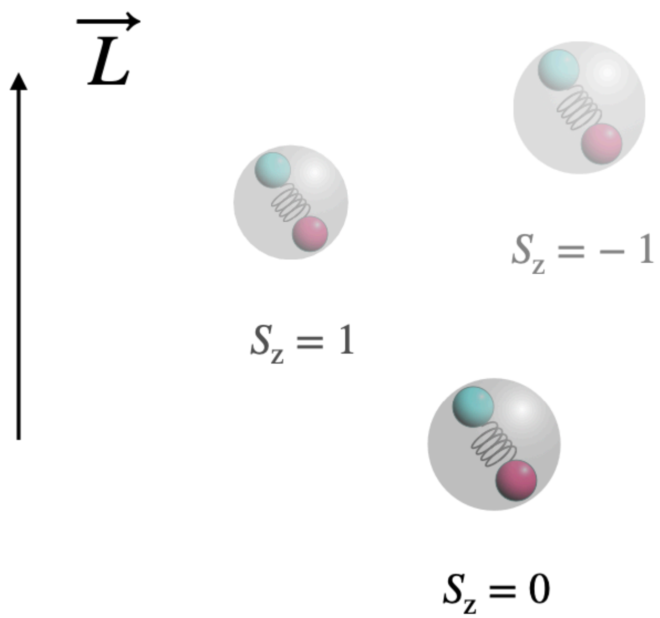




- The global polarization of Λ has been observed in STAR BES-I.
- Global spin alignment of vector mesons?

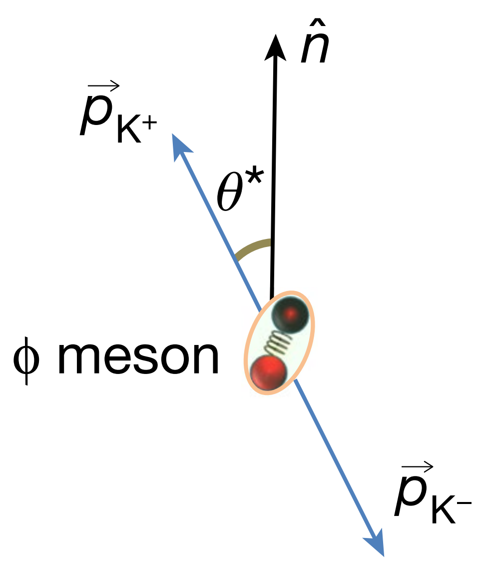
Vector meson spin alignment

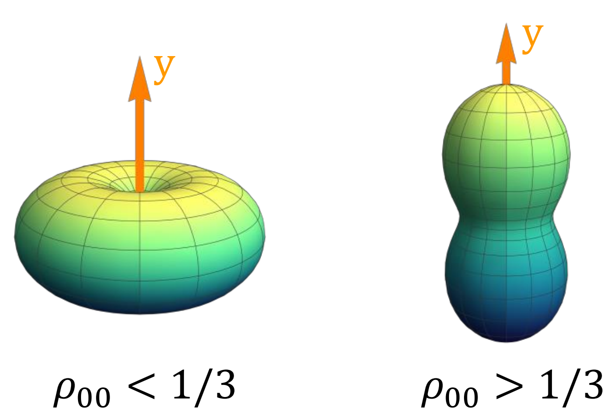
Z.T. Liang et al., Physics Letters B 629 (2005) 20–26



- Spin state of spin 1 particle along OAM.
- ρ_{00} can be determined by the momentum distribution of decay products.

$$\rho^V = \begin{pmatrix} \rho_{11} & \rho_{10} & \rho_{1-1} \\ \rho_{01} & \rho_{00} & \rho_{0-1} \\ \rho_{-11} & \rho_{-10} & \rho_{-1-1} \end{pmatrix}$$

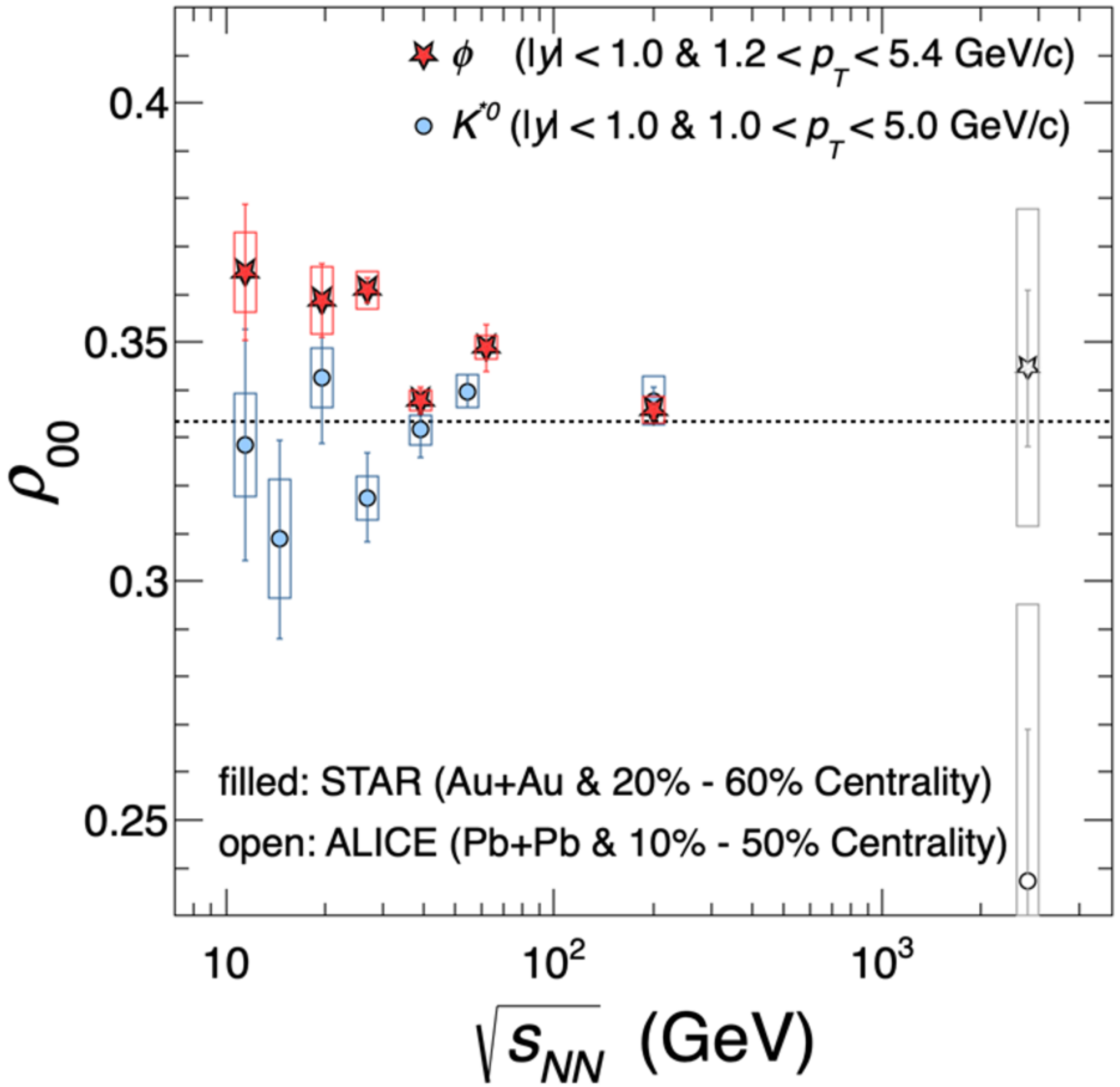




$$\frac{dN}{d(\cos\theta^*)} \propto (1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*$$

ϕ and K^{*0} spin alignment in BES-I

STAR, Nature 614, 244 (2023)



1)ϕ-meson is significantly above 1/3 below 62 GeV (the ρ_{00} was expected to be ρ_{00} - 1/3 ~ -10^{-4} from Λ results).

2)K* is almost consistent with 1/3

3)Averaged over 62 GeV and below:

•0.3541 ± 0.0017 (stat.) ± 0.0018 (sys.) for ϕ (~ 8 sigma from 1/3)
•0.3356 ± 0.0034 (stat.) ± 0.0043 (sys.) for K* (~ 1 sigma from 1/3)

Interpretations of the signal

Z. T. Liang, Chirality 2023

For $q_1^{\uparrow} + \bar{q}_2^{\uparrow} \to V$

$$\rho_{00}^{V} = \frac{1 - \langle P_{q_1} P_{\bar{q}_2} \rangle}{3 + \langle P_{q_1} P_{\bar{q}_2} \rangle} \overset{?}{=} \frac{1 - P_q^2}{3 + P_q^2}$$

For $q_1^{\uparrow} + q_2^{\uparrow} + q_3^{\uparrow} \to H$

$$P_H = \left\langle \left\langle c_1 P_{q_1} + c_2 P_{q_2} + c_3 P_{q_3} \right\rangle_H \right\rangle_S = \left\langle c_1 \langle P_{q_1} \rangle_H + c_2 \langle P_{q_2} \rangle_H + c_3 \langle P_{q_3} \rangle_H \right\rangle_S$$

$$= c_1 \left\langle \langle P_{q_1} \rangle_H \right\rangle_S + c_2 \left\langle \langle P_{q_2} \rangle_H \right\rangle_S + c_3 \left\langle \langle P_{q_3} \rangle_H \right\rangle_S = c_1 \langle P_{q_1} \rangle + c_2 \langle P_{q_1} \rangle + c_3 \langle P_{q_1} \rangle$$

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

One has to take fluctuations into account, so that: $\langle P_q P_{\bar{q}} \rangle \neq \langle P_q \rangle \langle P_{\bar{q}} \rangle$

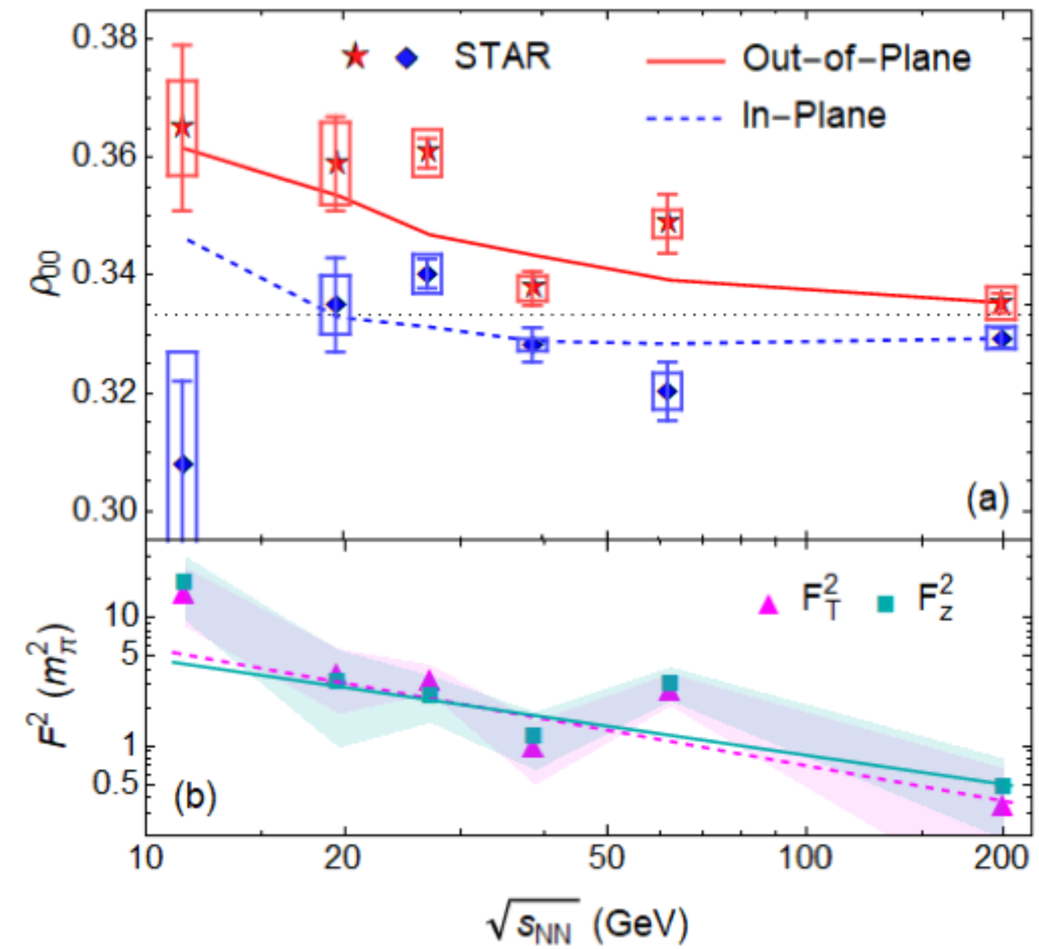
By studying P_H, we study the average of quark polarization P_q;
by studying ρ_{00}^{V}, we study the correlation between P_q and $P_{\bar{q}}$.

Interpretations of the signal

$$\rho_{00}^{\phi} \approx \frac{1}{3} + c_{\omega} + c_{\varepsilon} + c_{\mathrm{EM}} + c_{\phi} + c_{\mathrm{LV}} + c_{h} + c_{\mathrm{TC}} + c_{\mathrm{shear}}$$

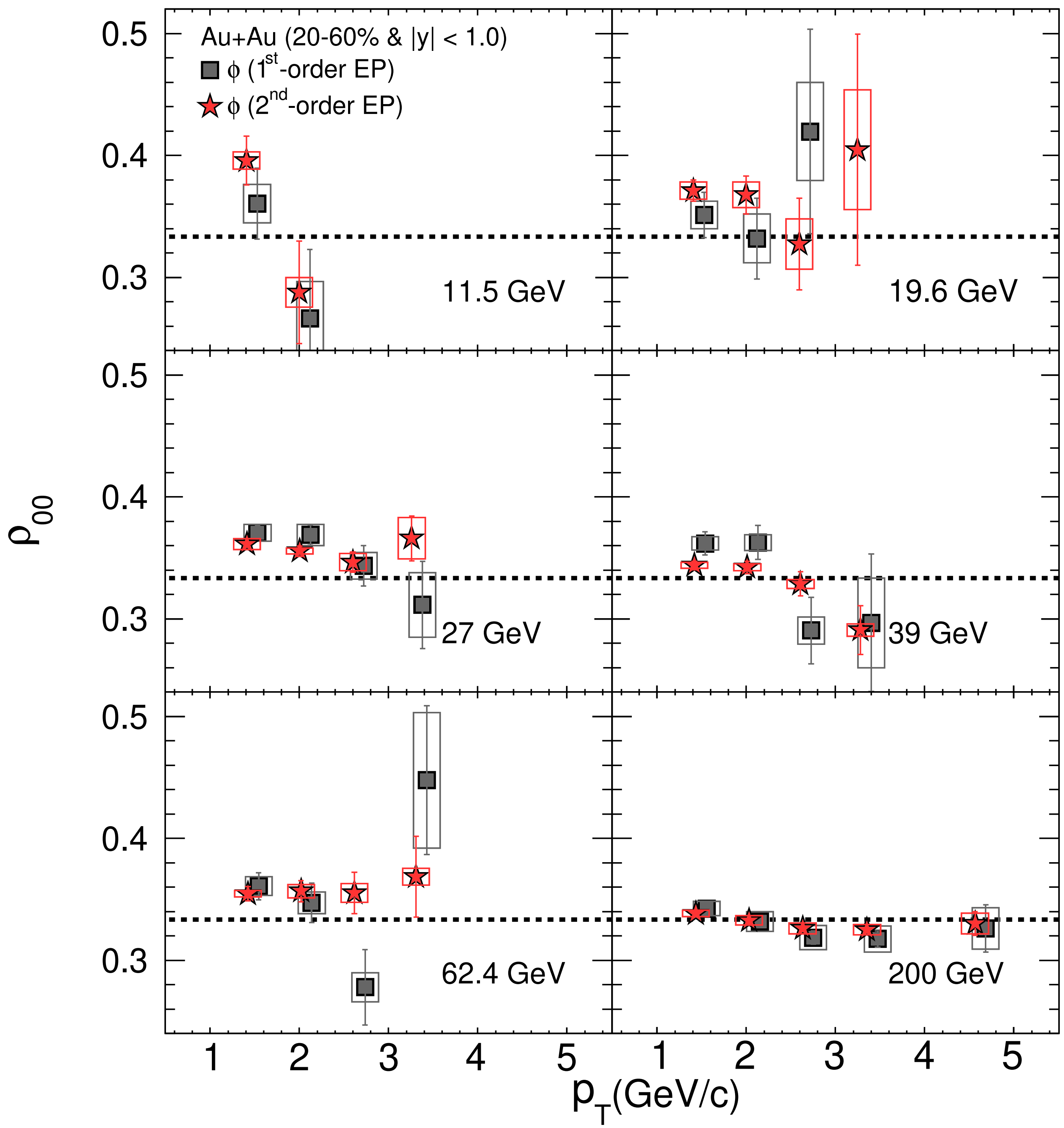
Physics Mechanisms	(ρ_{00})
c_Λ: Quark coalescence vorticity & magnetic field[1]	< 1/3 (Negative ~ 10^{-5})
c_ε: Vorticity tensor[1]	< 1/3 (Negative ~ 10^{-4})
c_E: Electric field[2]	> 1/3 (Positive ~ 10^{-5})
Fragmentation[3]	> or, < 1/3 (~ 10^{-5})
Local spin alignment and helicity[4]	< 1/3
Turbulent color field[5]	< 1/3
c_ϕ: Vector meson strong force field[6]	> 1/3

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)

Transverse momentum dependence

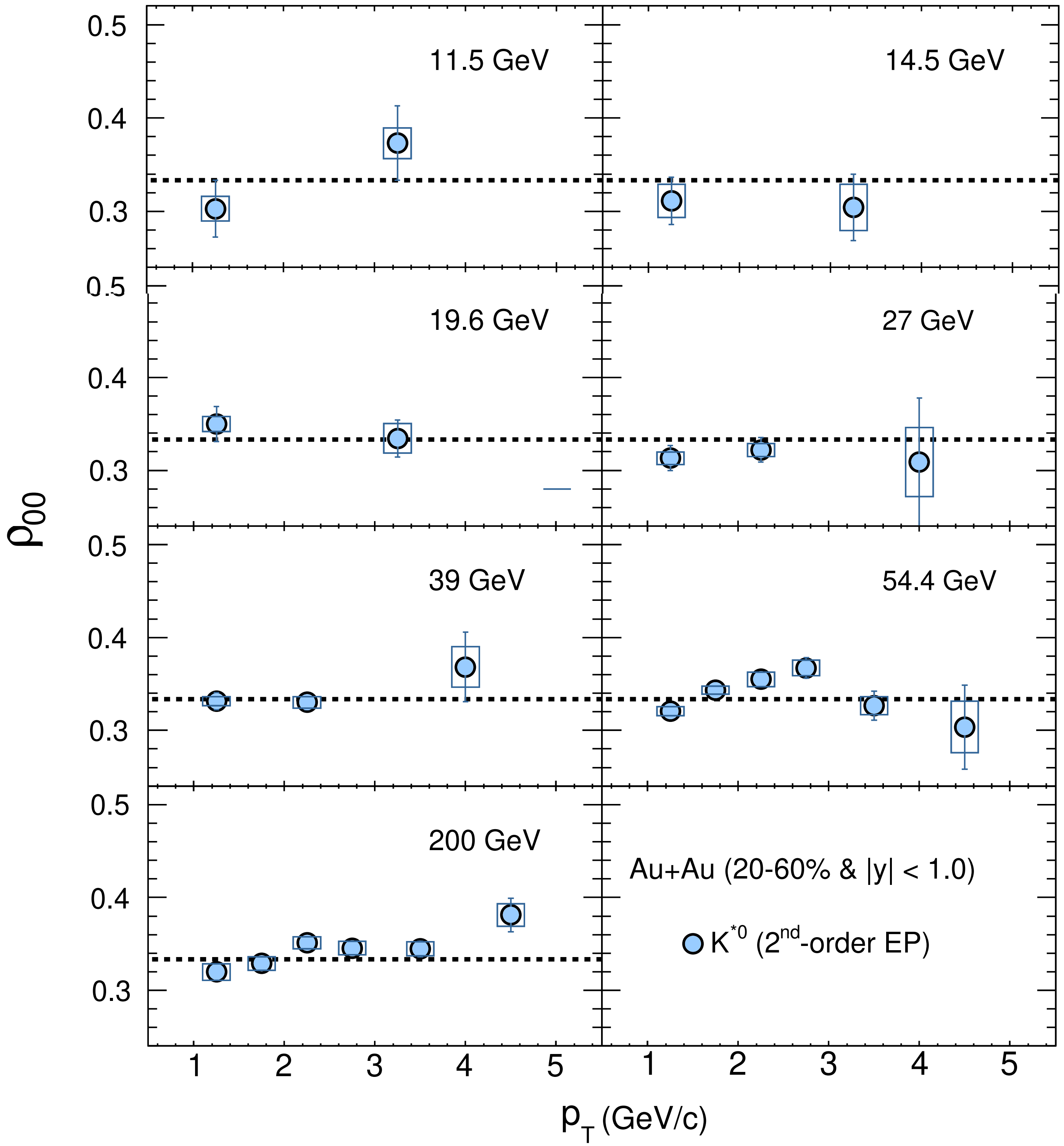


STAR Nature 614, 244 (2023)

- BES-I measurements extend the study to lower energies with high statistics.
- We see that the signal for the ϕ meson occurs mainly within ~1.0-2.4 GeV/c; at larger p_T the results can be regarded as being consistent with 1/3 within ~2σ or less.

* 1st order EP: ZDC or BBC
* 2nd order EP: TPC

Transverse momentum dependence



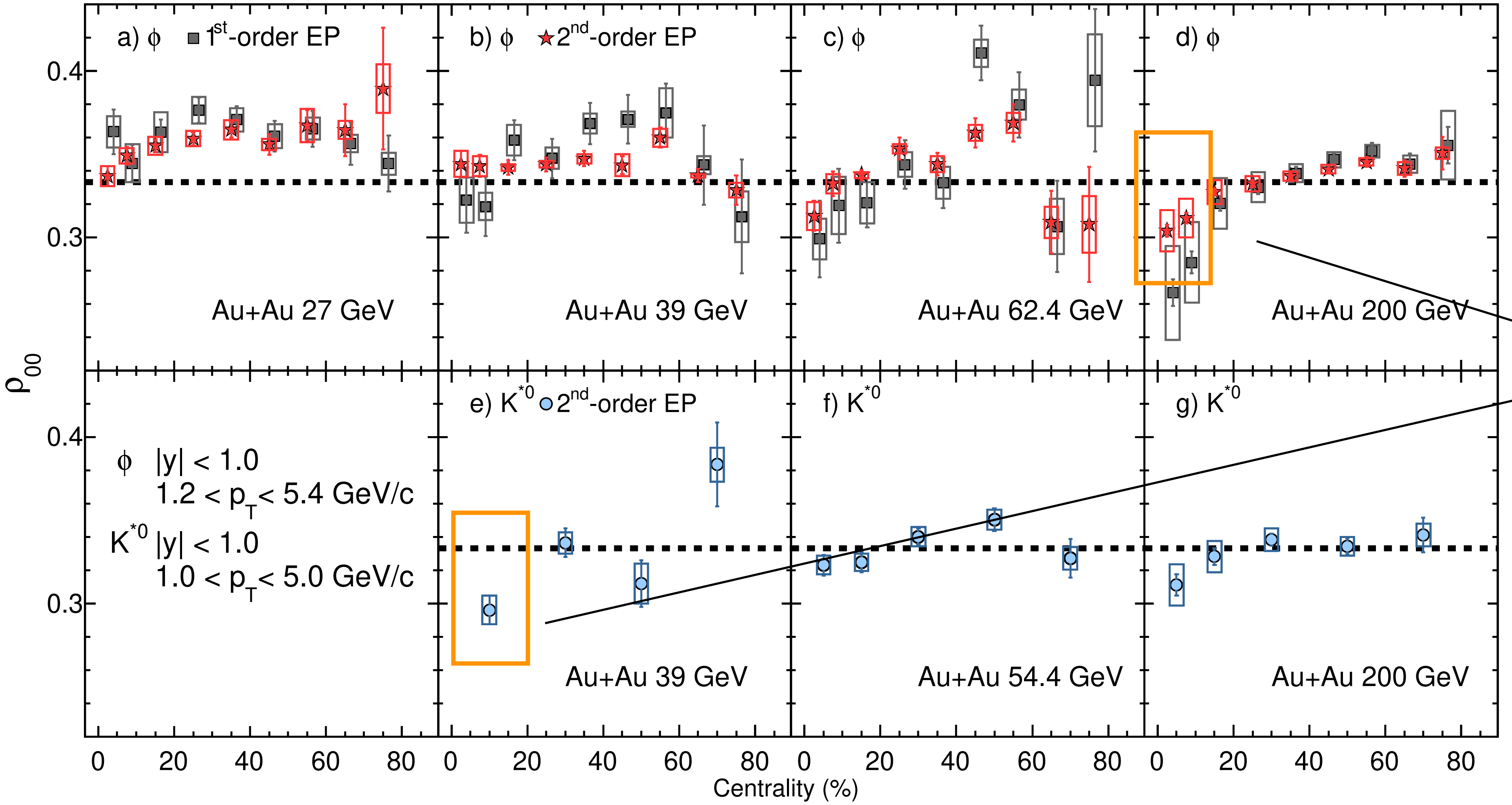
STAR, Nature 614, 244 (2023)

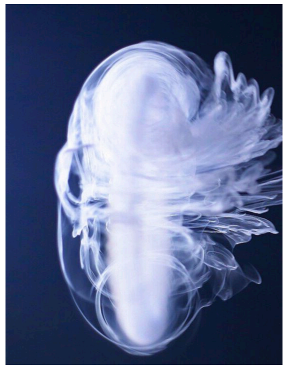
- K^{*0} is a combination of K^{*0} and anti-K^{*0}

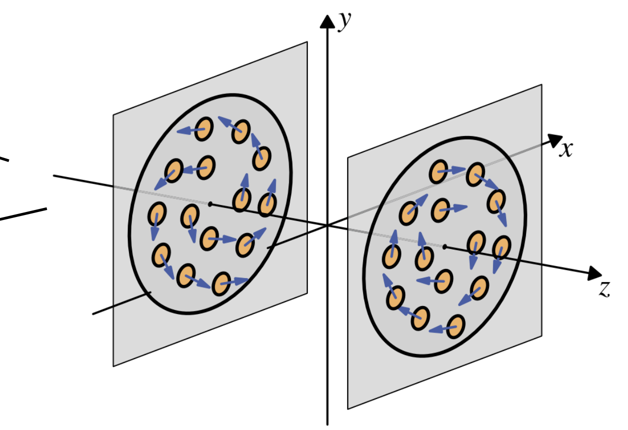
- Different from the ϕ meson data, the K^{*0} data is consistent with 1/3, within statistics and systematical uncertainties.

Centrality dependence

STAR, Nature 614, 244 (2023)







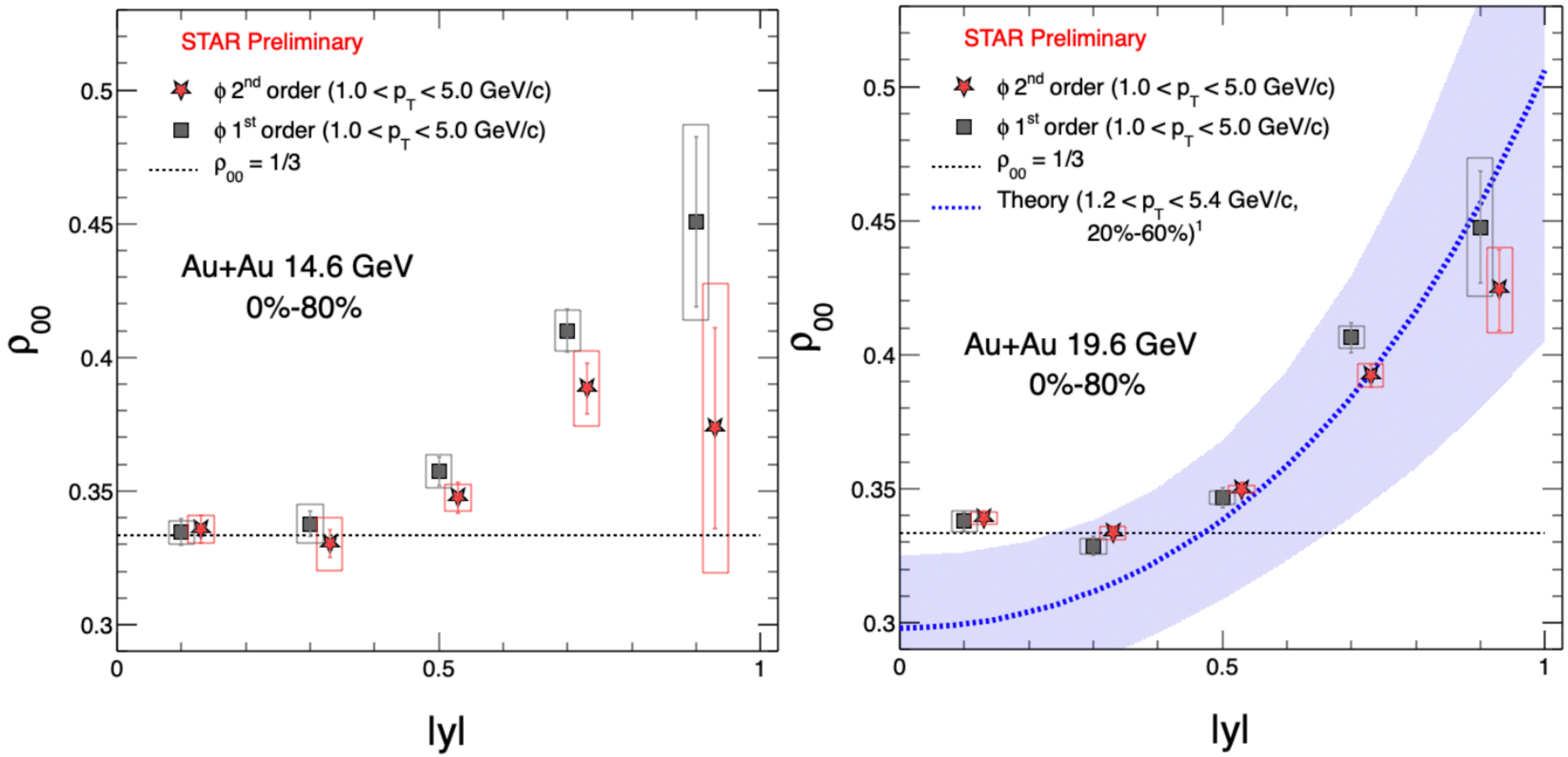
Xia et., al., Phys. Lett. B 817, 136325 (2021);

- Signs of ρ_{00}< 1/3 in central collisions, it might be an indication of transverse local spin alignment?
- Center of the collision has smaller velocity (larger stoping effect).

Ongoing analysis: BESII ϕ mesons

STAR, QM 2023

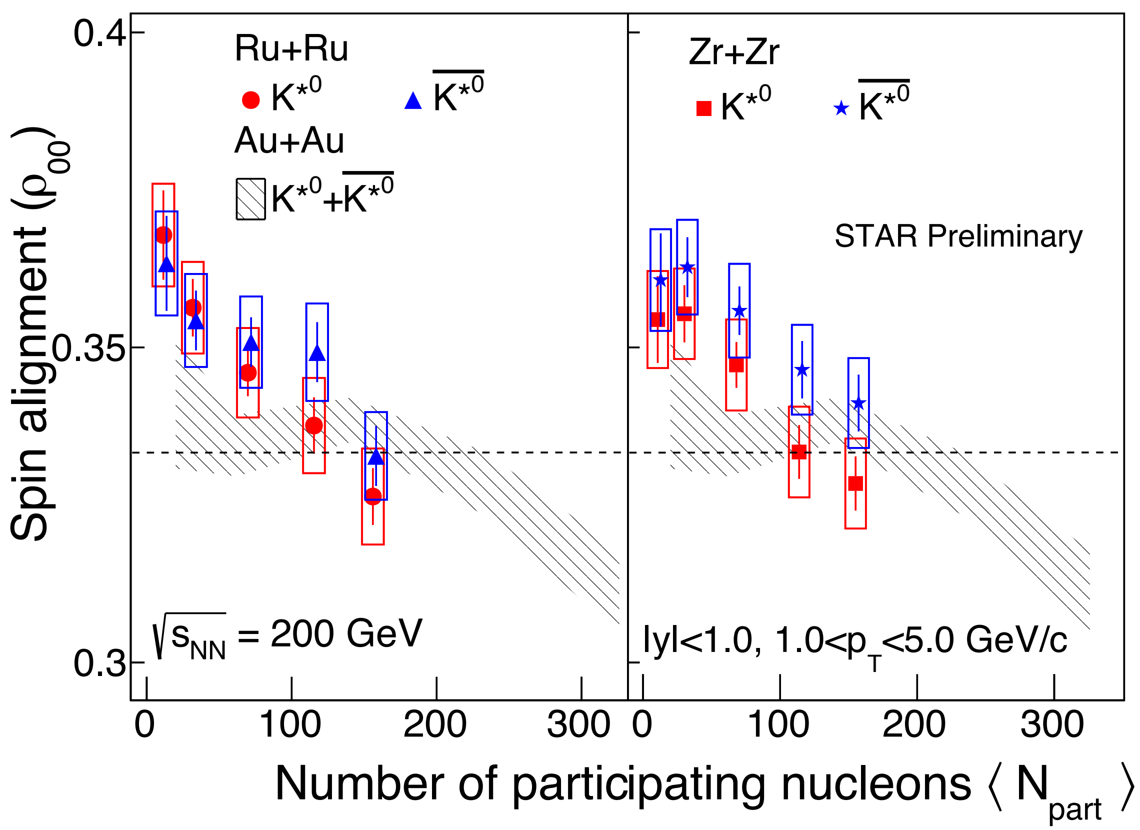
Theory curve: Sheng et al., *Phys.Rev.C* 108 (2023) 5, 054902

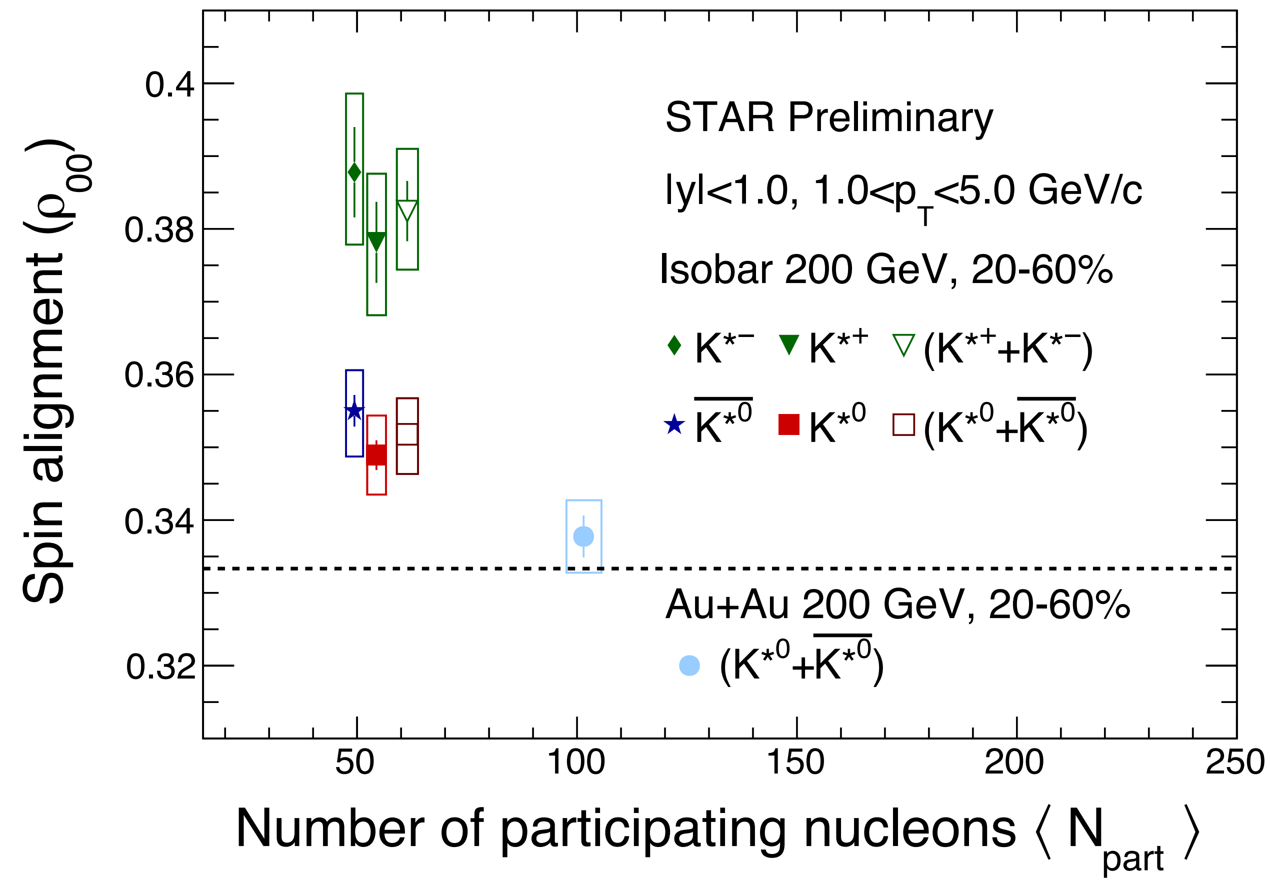


- Rapidity dependence is qualitatively consistent with theoretical calculations from ϕ field.
- Larger field fluctuations in the direction perpendicular to ϕ motion.

Ongoing analysis: $K^{*0}, K^{*\pm}$ mesons

STAR, QM 2022

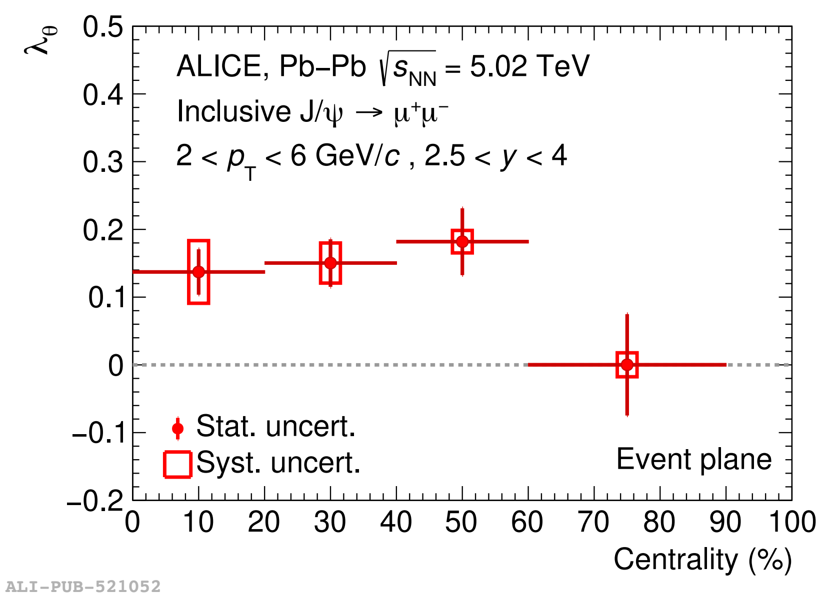


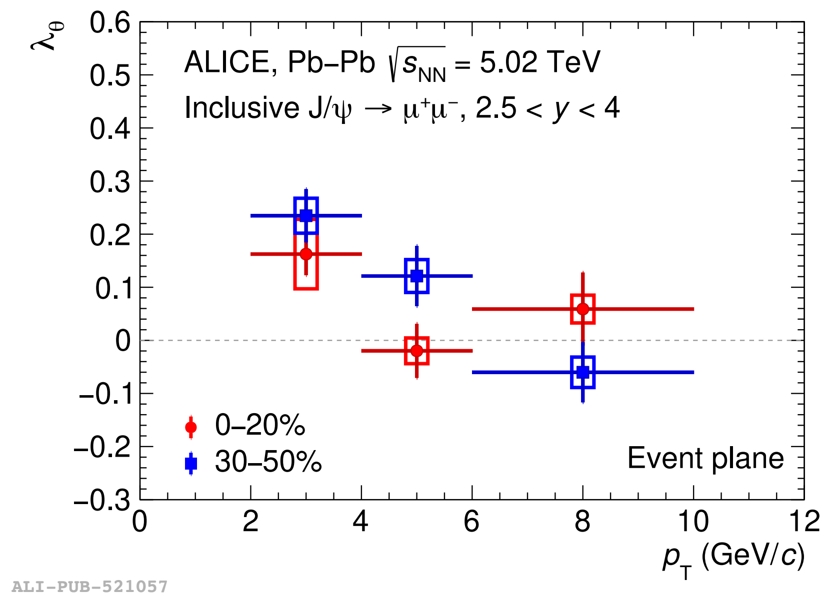


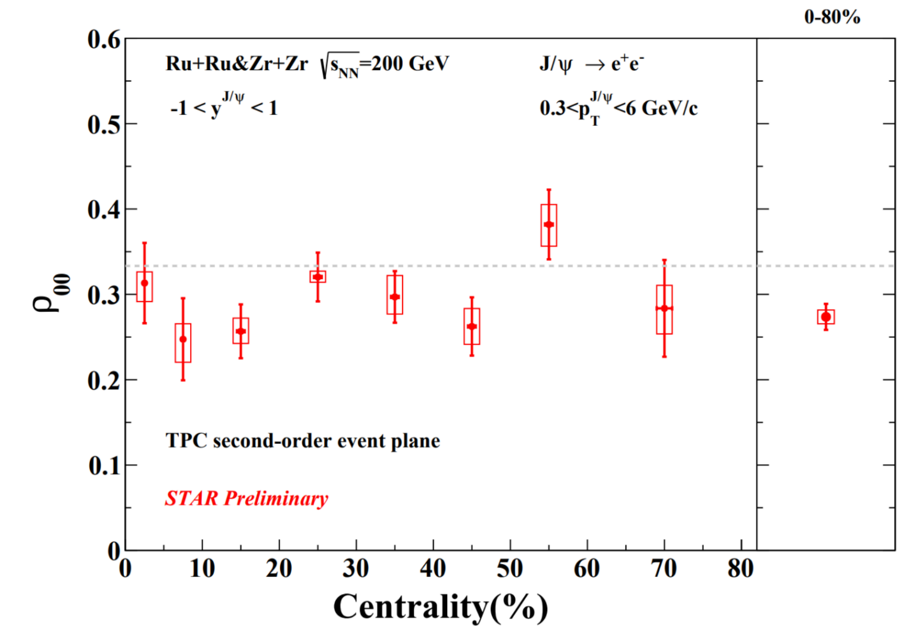
- K^{*0} is larger than 1/3 at smaller N_{part}, it is comparable to Au+Au at a similar N_{part}
- Charged K^* is larger than 1/3, it is larger than neutral K^* with 3.9σ.

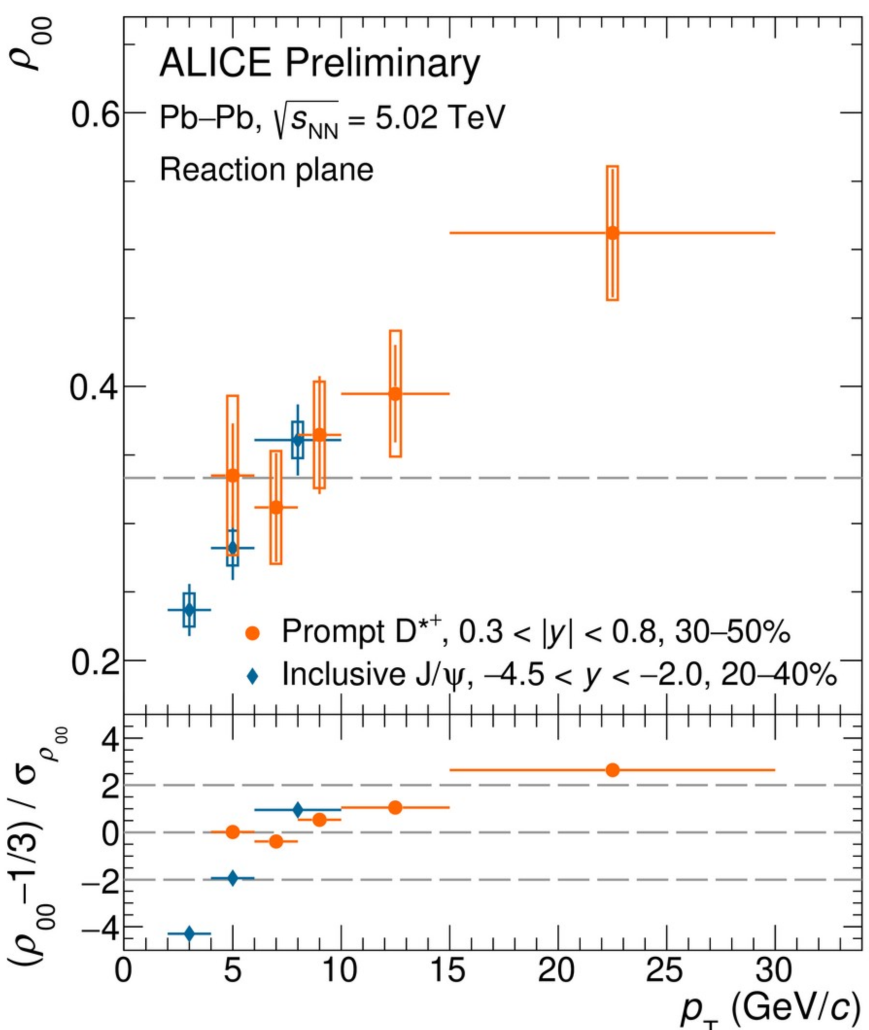
From ϕ to other mesons

ALICE, Phys. Rev. Lett. 131, 042303 (2023)







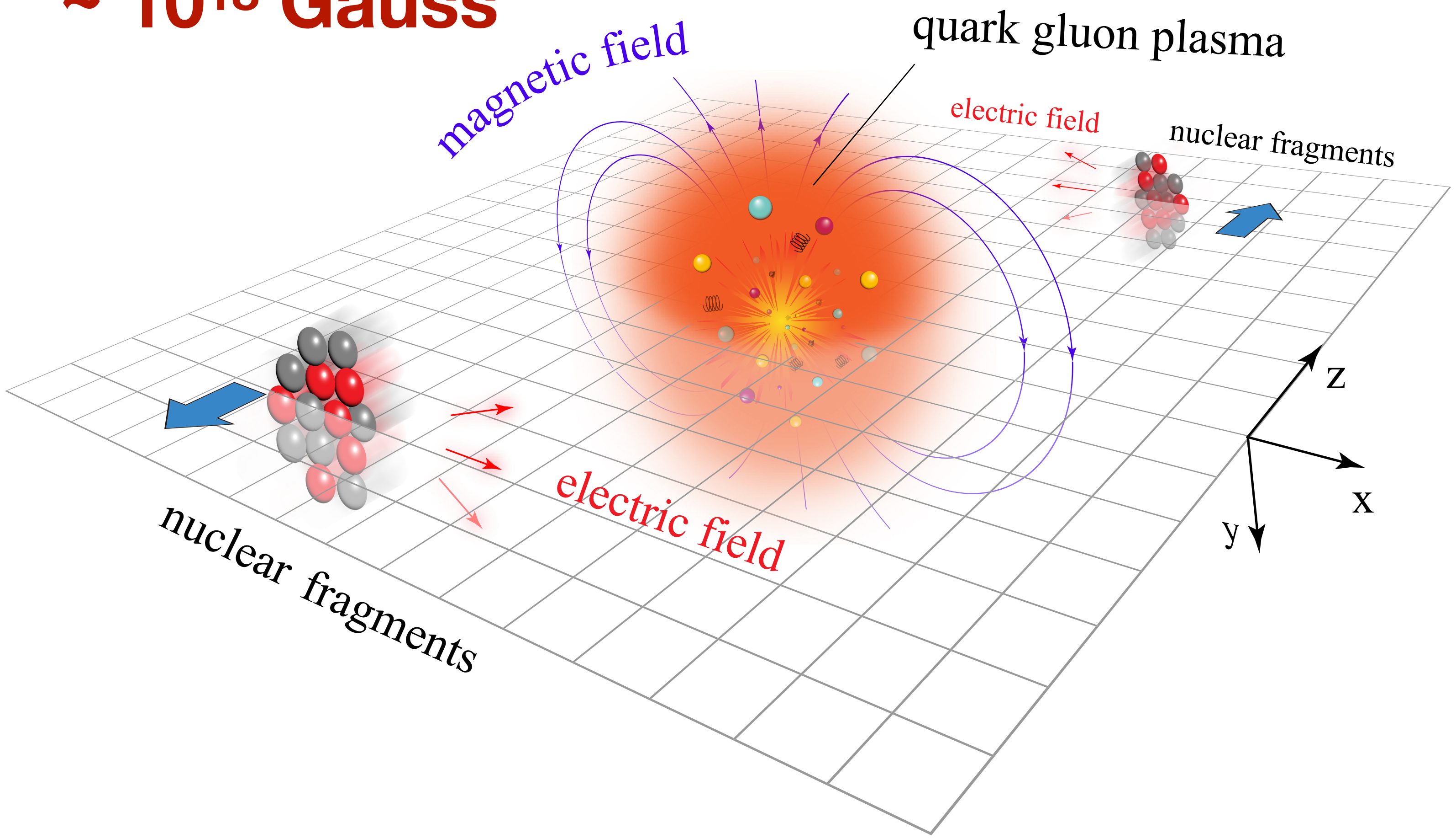


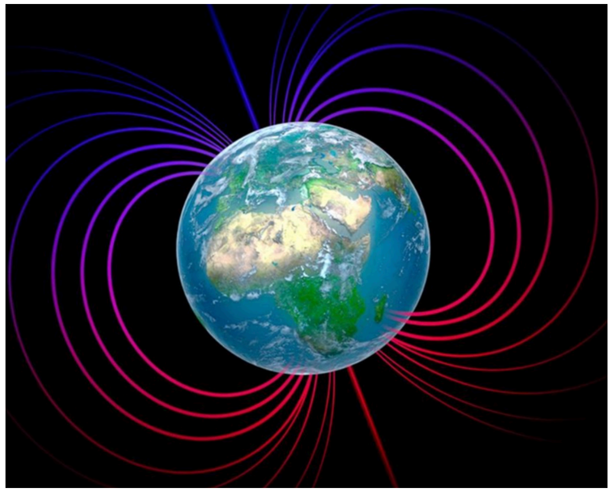
- Forward rapidity J/psi ρ_{00} < 1/3 (ρ_{00} = 0.25) at LHC.
- Preliminary shows midrapidity J/psi ρ_{00} < 1/3 at RHIC.
- D^{*+} ρ_{00} > 1/3 at high p_T.

$D^{*+}(c\bar{d}) \rightarrow D^0 + \pi^+$
↳ $K^- + \pi^+$

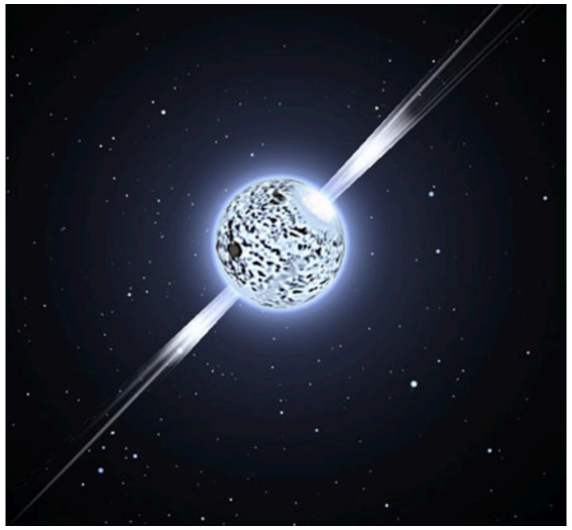
The EM-field in HIC: Generation

~ 10^{18} Gauss





Earth ~ 0.5 Gauss



Neutron Star: ~ 10^{14} Gauss

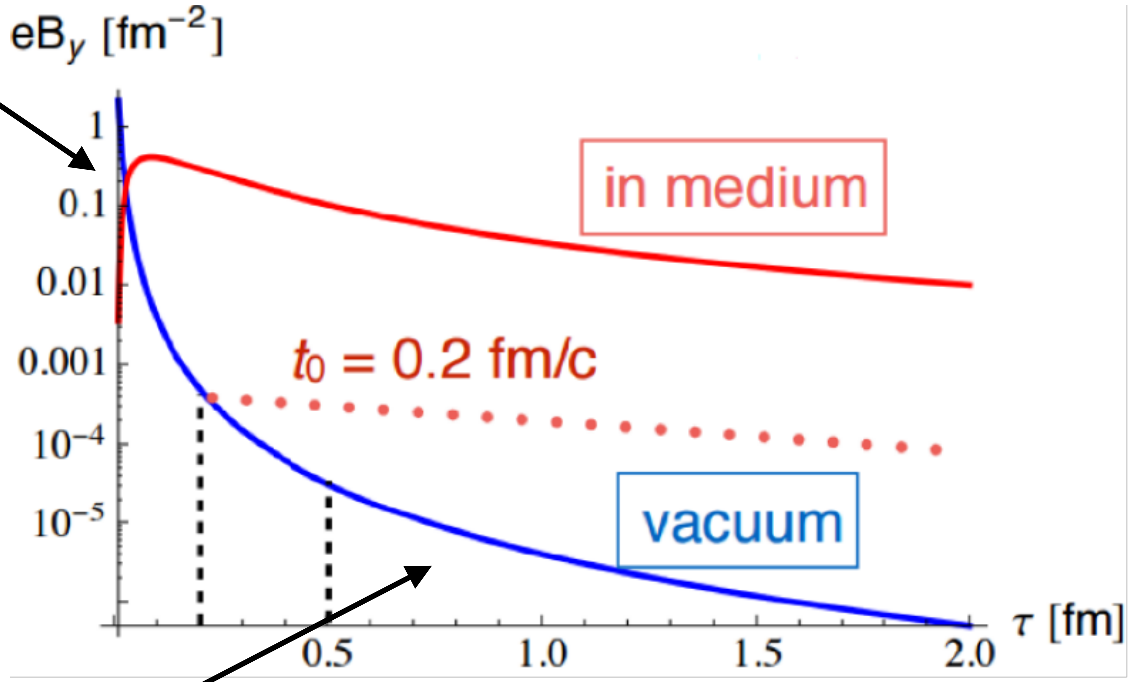
- An ultra-strong magnetic field along -y, on the order of 10^{18} Gauss, can be generated.

The EM-field in HIC: Evolution

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

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

The peak value of B field is accurate in QED



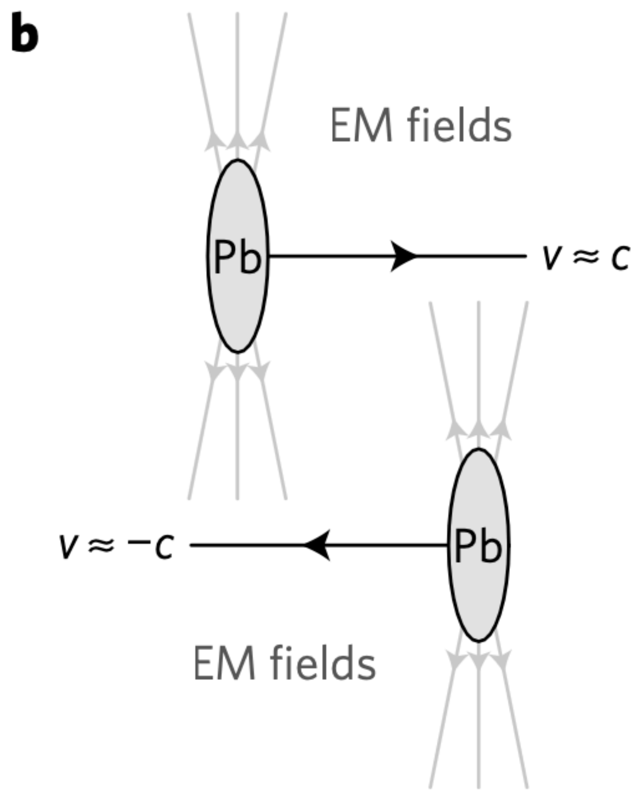
The evolution of B field is challenging in theory

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

L. Yan, et.al., PRD 107 094028 (2023)   Z. Wang, et.al., PRC 105 L041901 (2022)

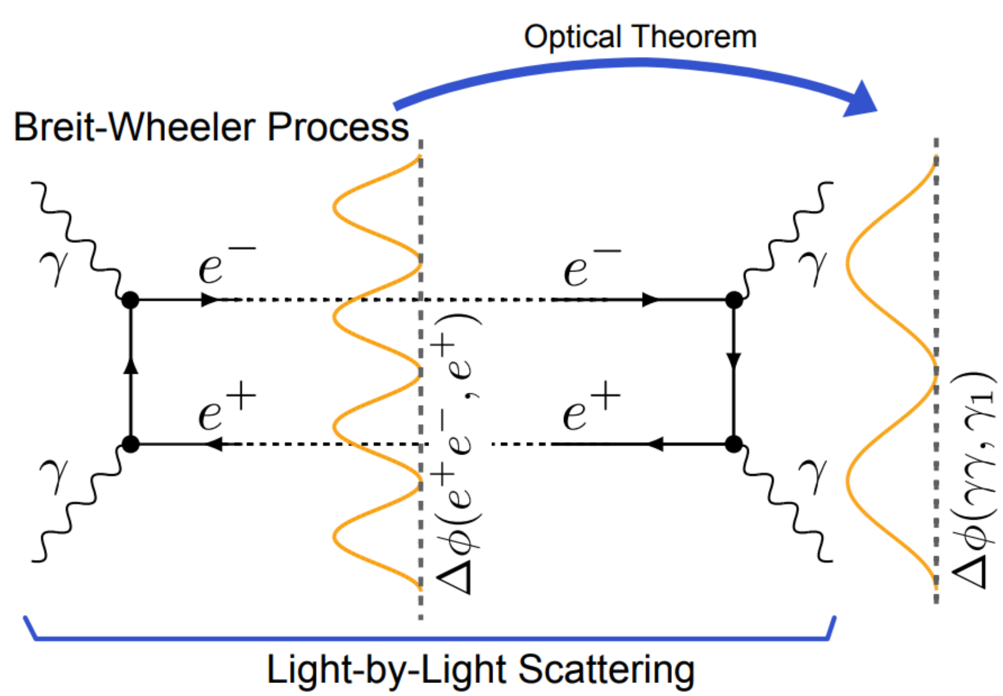
U. Gürsoy, et.al., PRC 89 054905 (2014)

The EM-field in UPC



ATLAS Collaboration, Nature Phys. 13 (2017) 9, 852-858

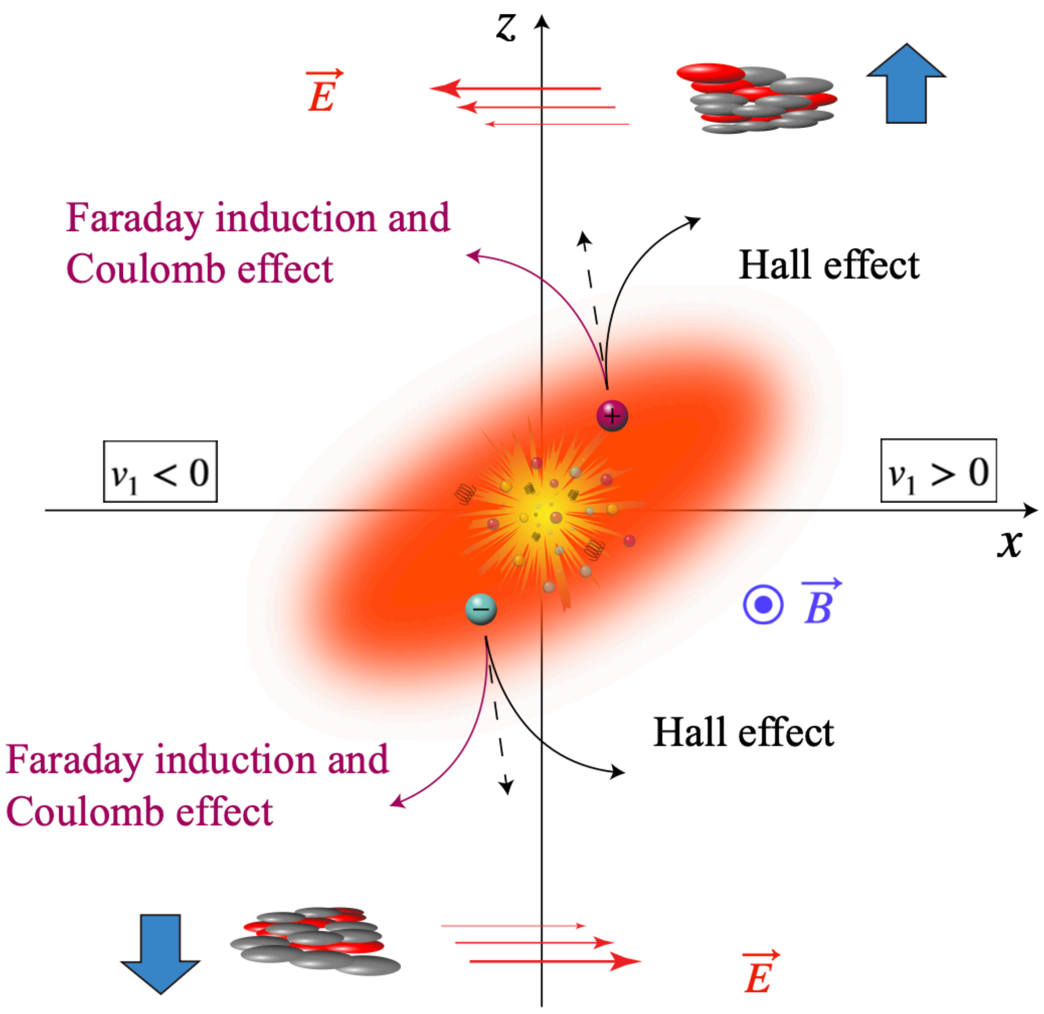
- γγ →γγ in UPC Pb-Pb collisions at 5.02 TeV



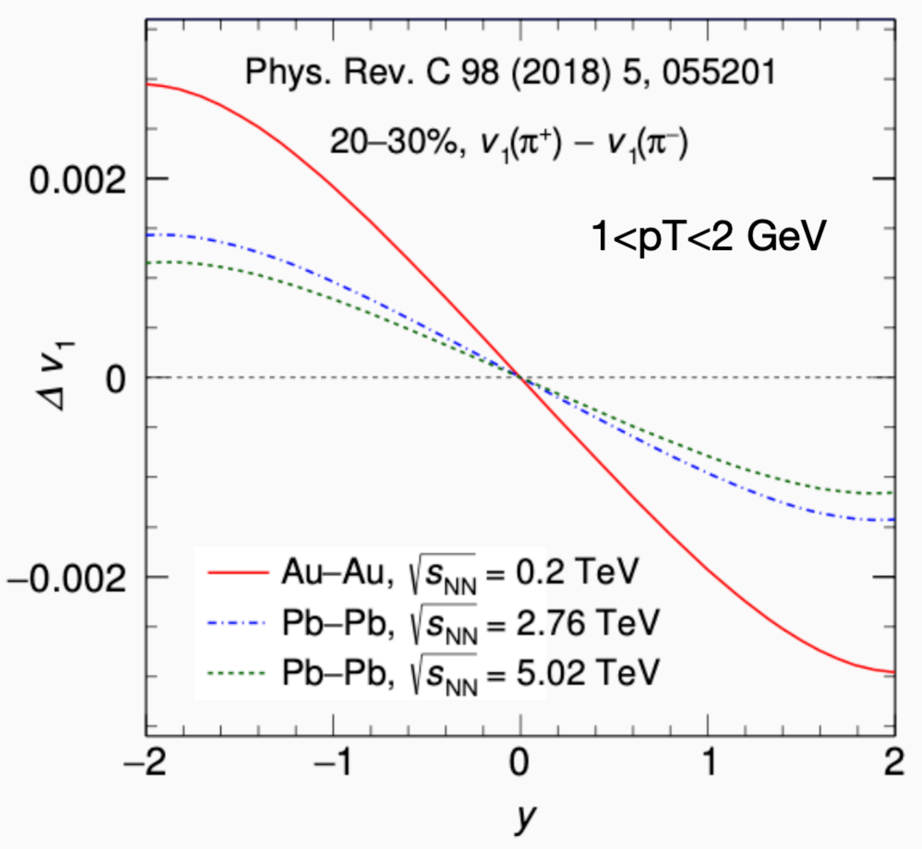
STAR Collaboration, Phys. Rev. Lett. 127, 052302 (2021)

- γγ → e^+e^- in UPC Au+Au collisions at 200 GeV.

EMF in QGP: Charge-dependent v1



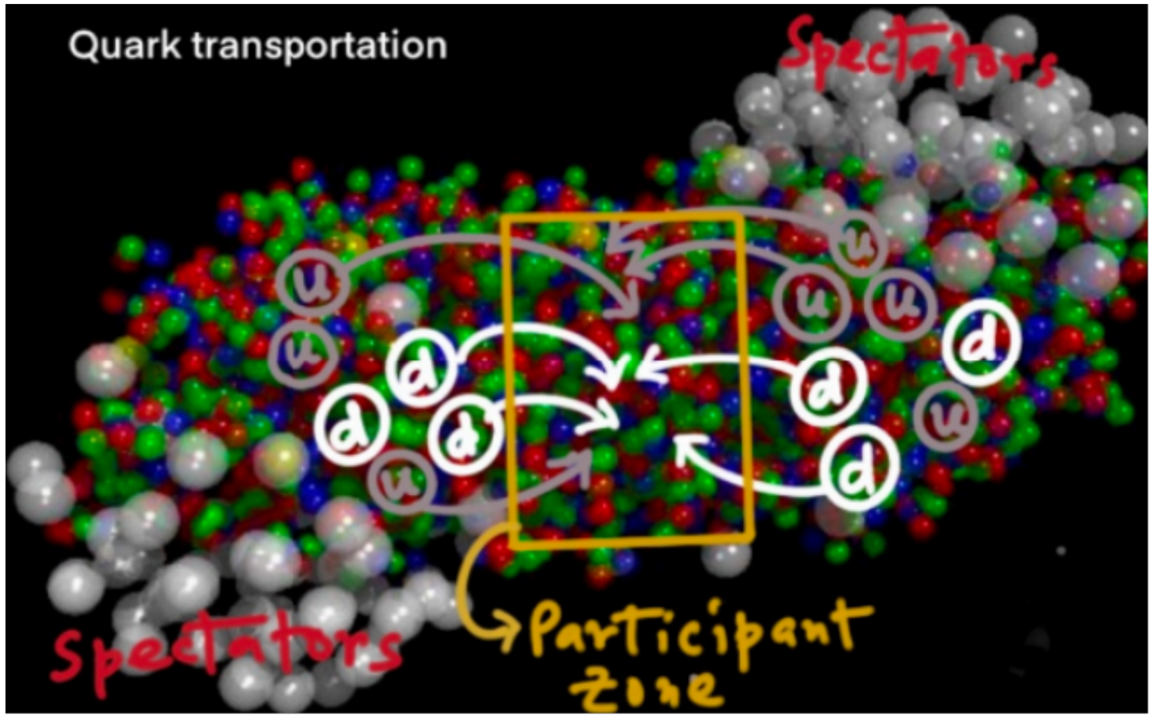
- Coulomb field from spectator
- Faraday induction, vortical electrical field
- Hall effect due to Lorentz force



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, PRC 107 034912 (2023);
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.

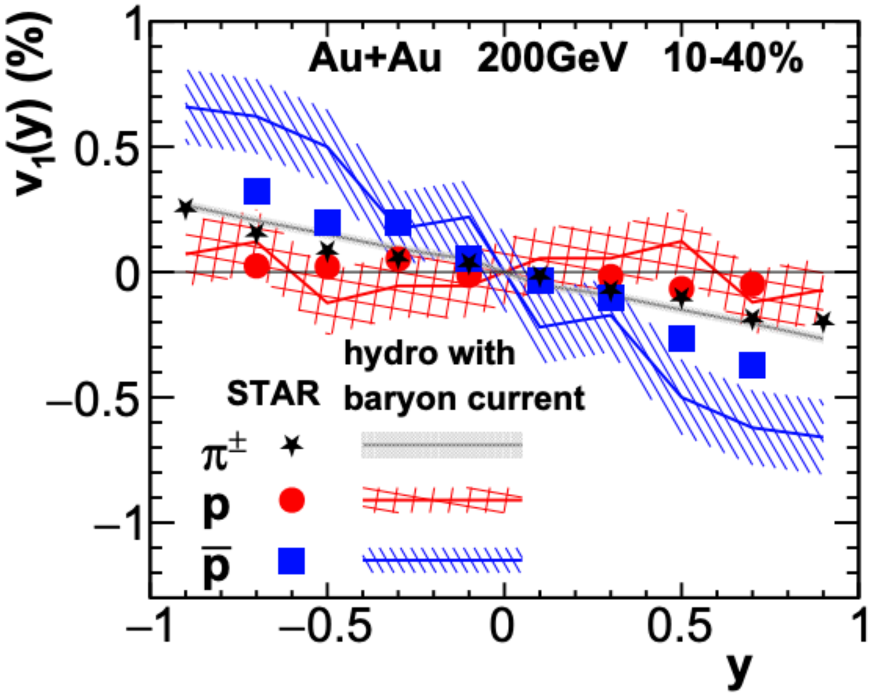
Transported quarks

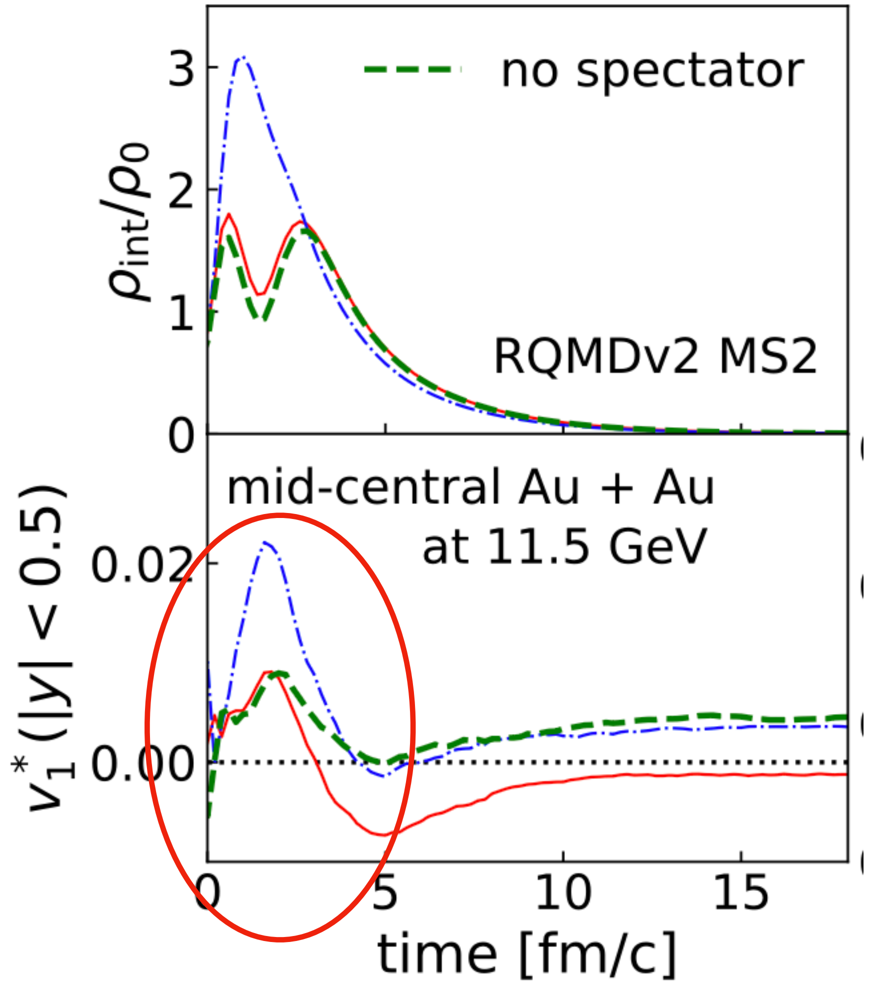


Features:

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

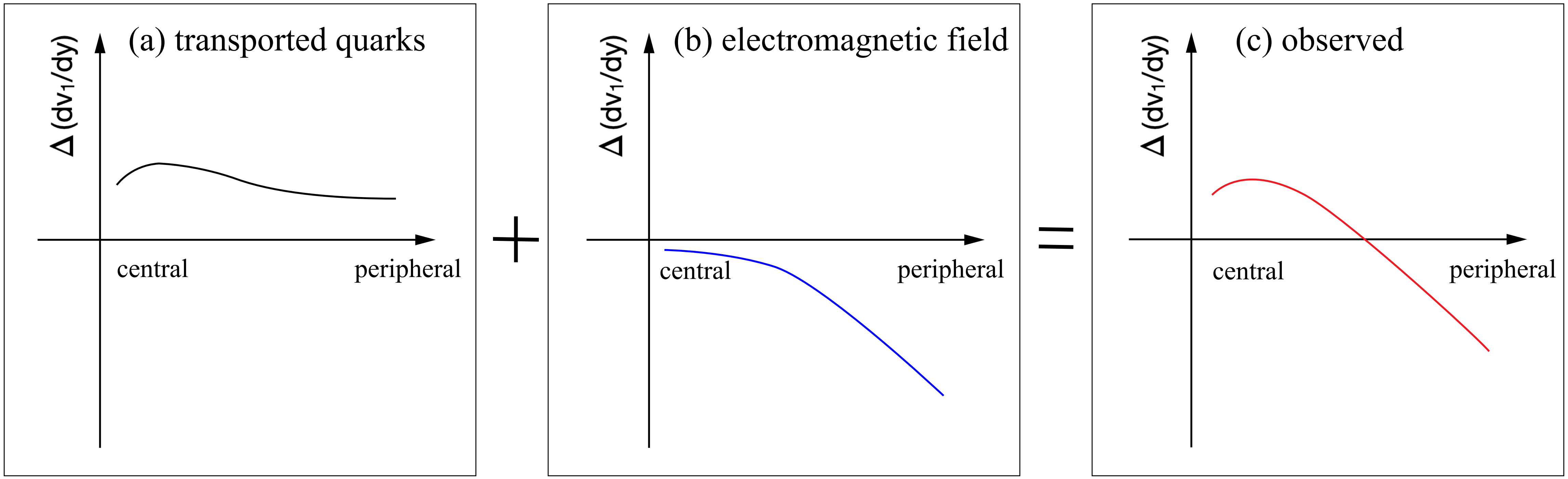
P. Bozek, PRC 106 L061901;





Yasushi Nara, PRC 105 014911 (2022)

Δv_1 of EM-field + transported quarks

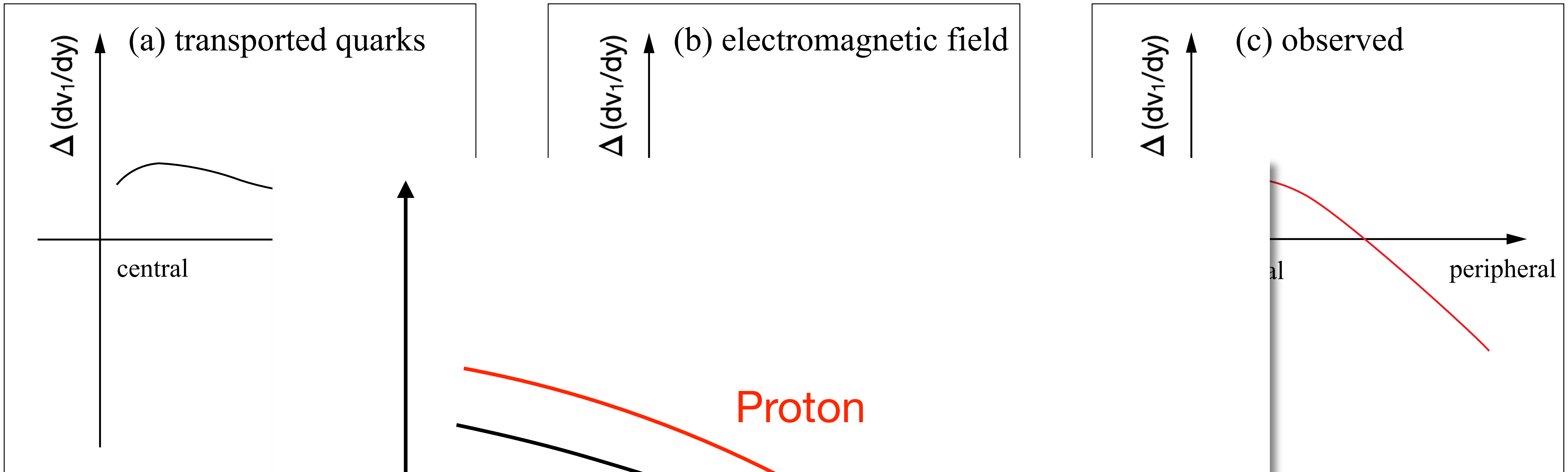


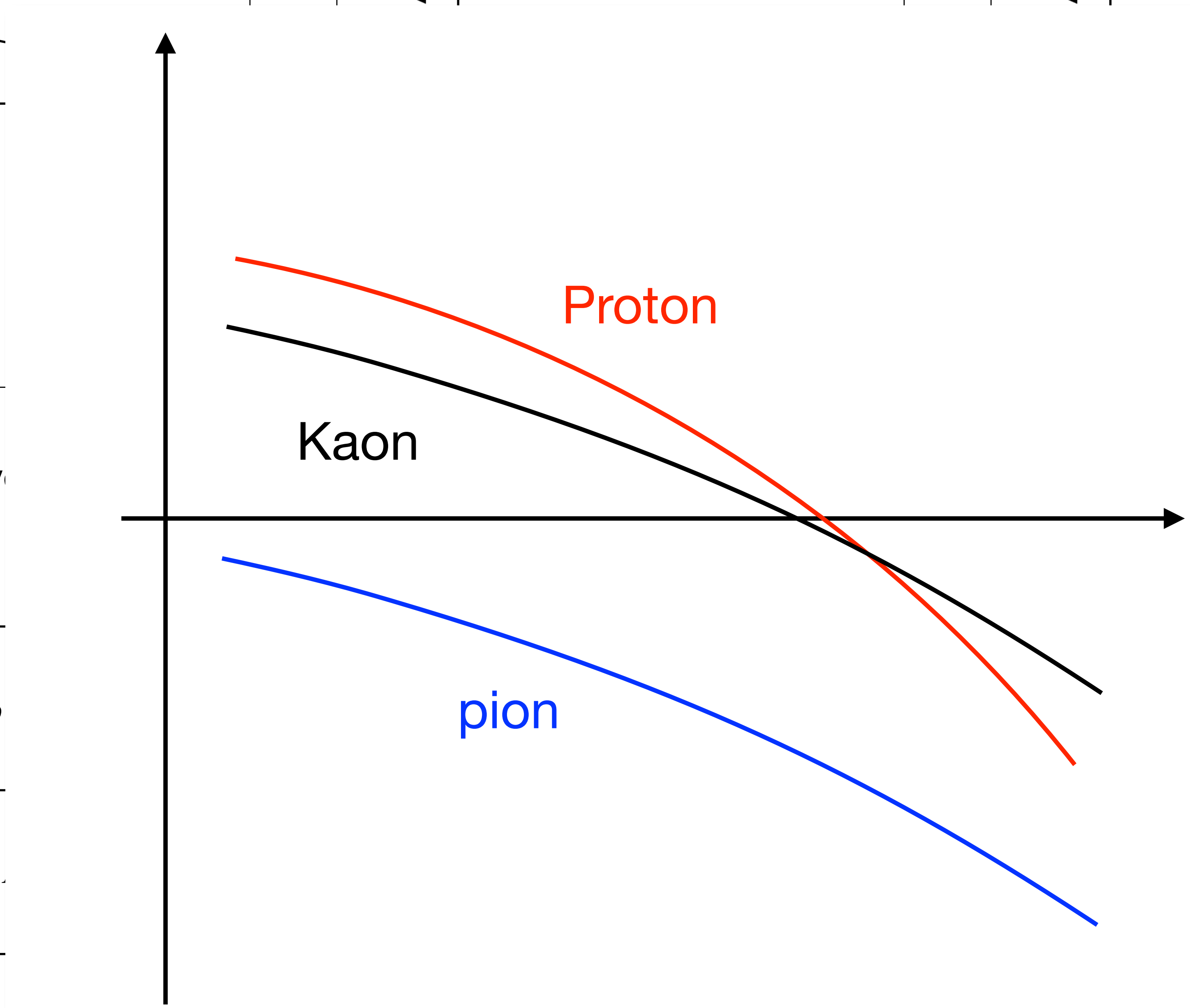
As transported quarks have positive dv_1/dy[1][2],

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

	dv_1/dy		dv_1/dy		$\Delta(dv_1/dy) = dv_1^+/dy - dv_1^-/dy$
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
π^+ : $u\bar{d}$ π^- : $\bar{u}d$	$\pi^+ < \pi^-$		$\pi^+ < \pi^-$		Negative

Δv_1 of EM-field + transported quarks



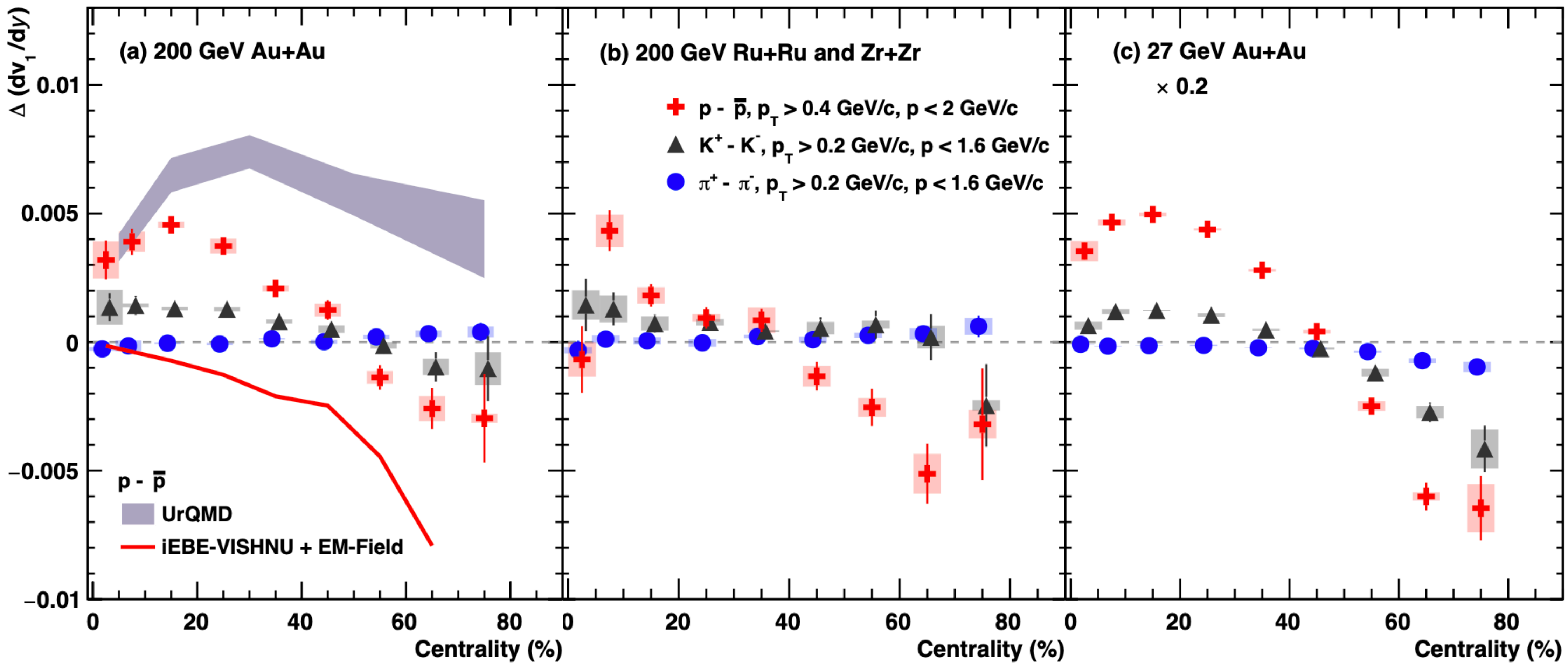


As transported quarks hav
dv_1/dy[1][2],

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

dv_1/dy		
p : uud $\bar{p}$: $\bar{u}\bar{u}\bar{d}$	$p > \bar{p}$	if transported quarks + Hall win ive if Faraday + Coulomb win
K^+ : $u\bar{s}$ K^- : $\bar{u}s$	$K^+ >$	if transported quarks + Hall win ive if Faraday + Coulomb win
π^+ : $u\bar{d}$ π^- : $\bar{u}d$	$\pi^+ < \pi$ $\pi^+ < \pi$	Negative

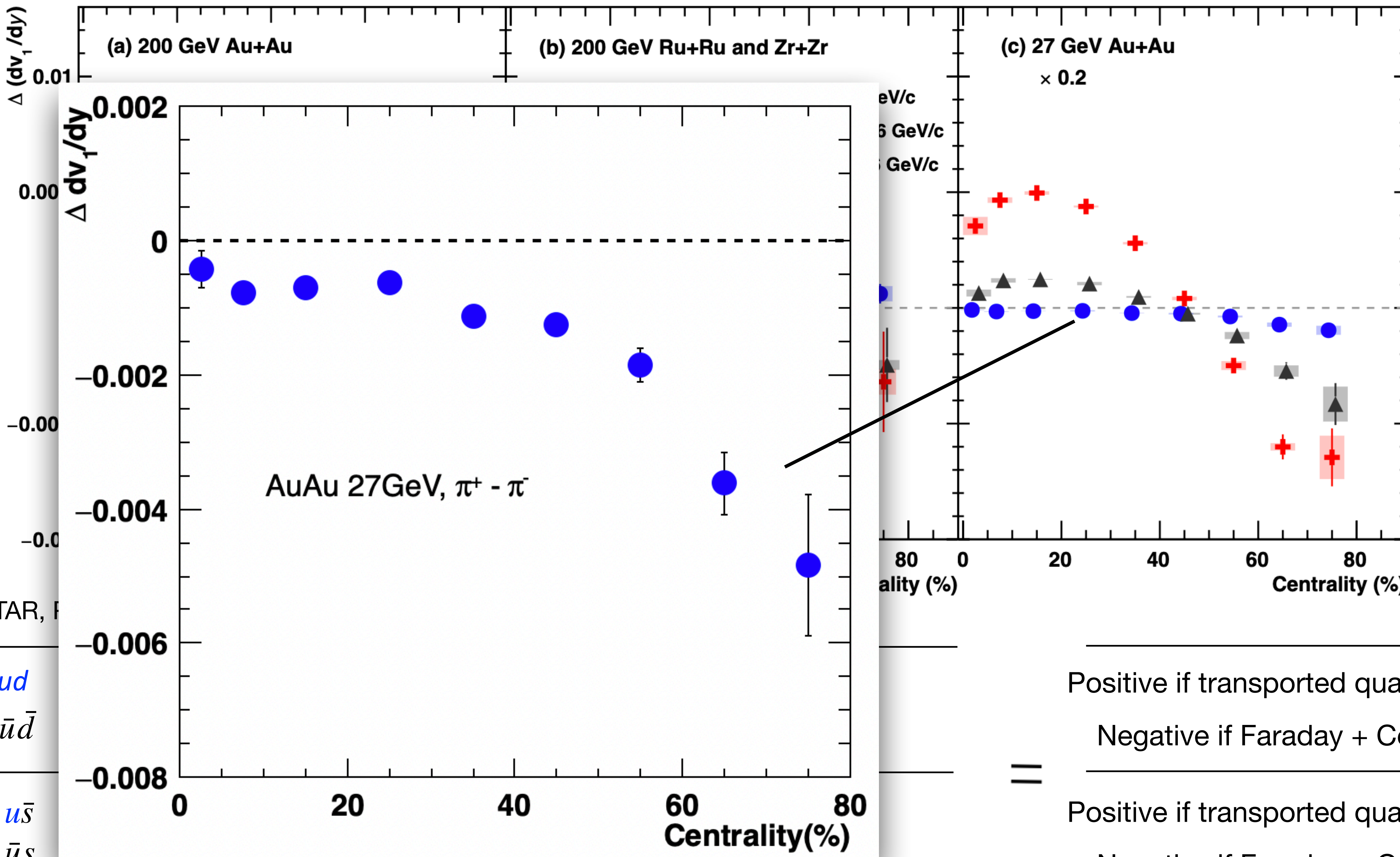
Sign change of $\Delta dv_1/dy$



STAR, Phys. Rev. X **14**, 011028

$p : uud$ $\bar{p} : \bar{u}\bar{u}\bar{d}$	$p > \bar{p}$		$p < \bar{p}$		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

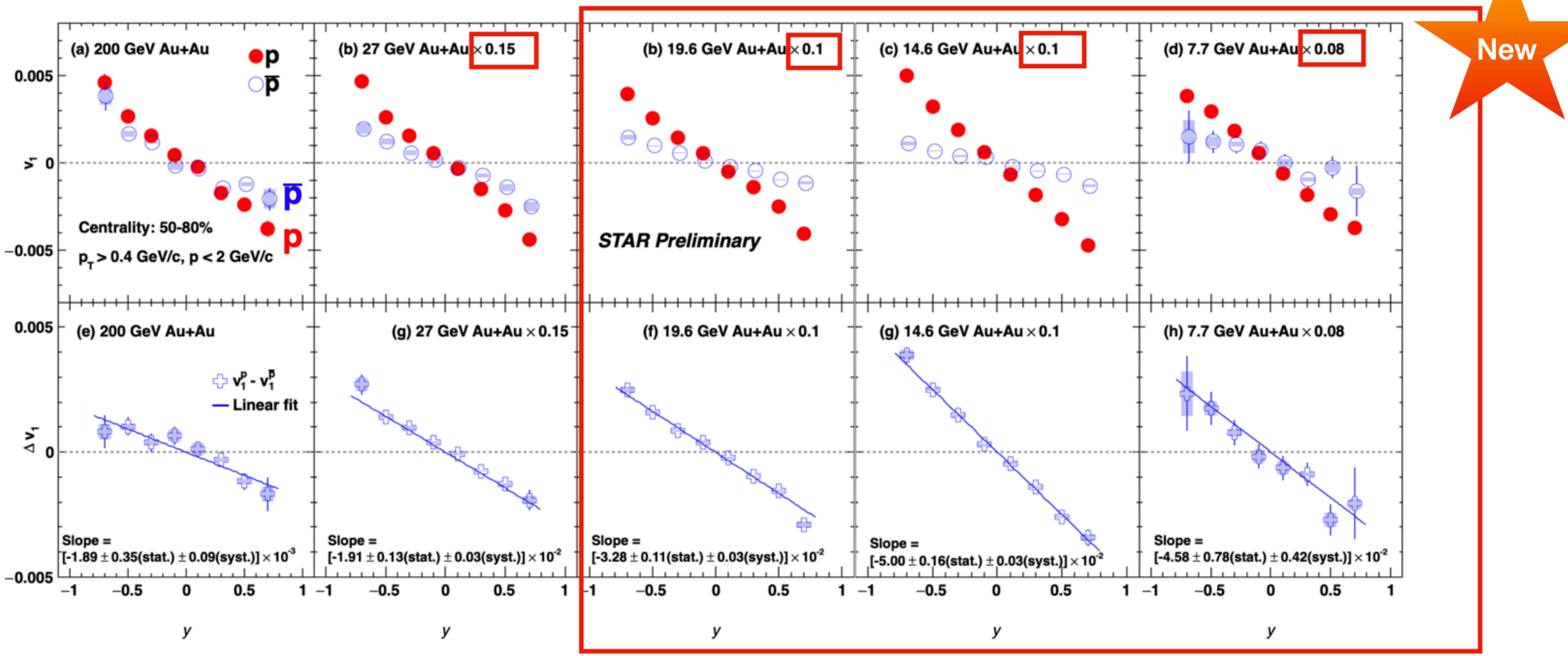
Sign change of $\Delta dv_1/dy$



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

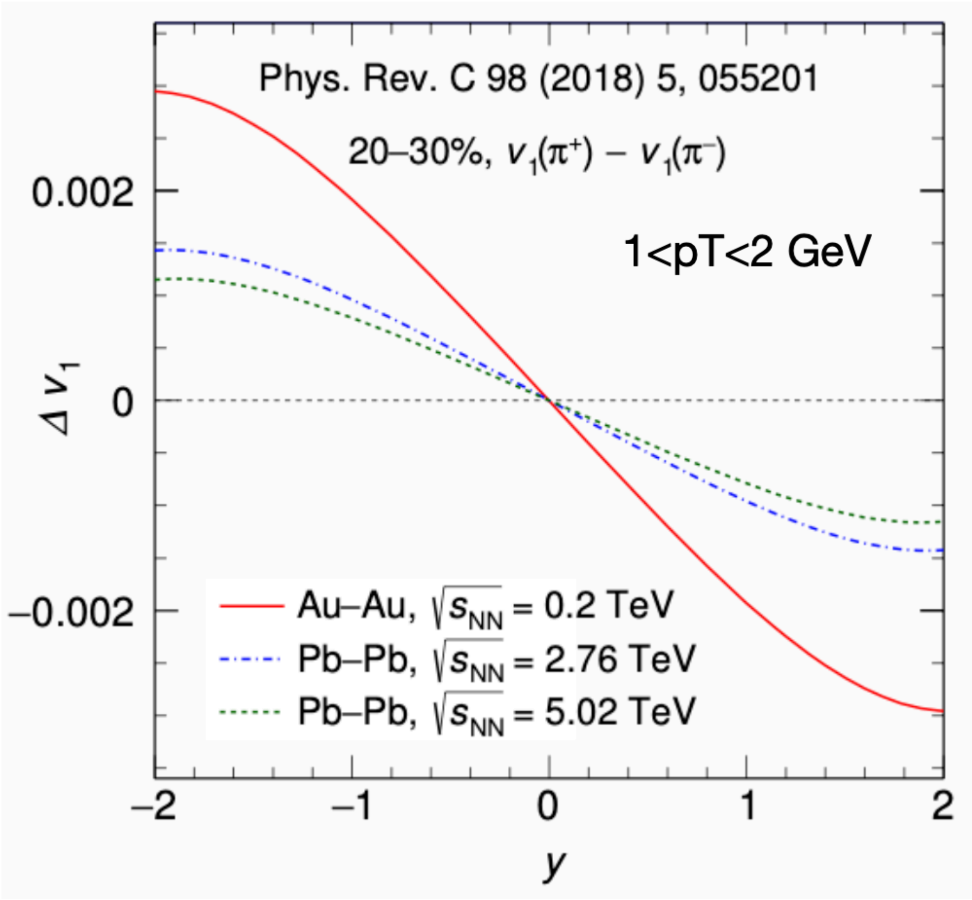
Beam energy dependency in 50-80% cent.

See Aditya's talk
BES session at 16:30 on June 12th

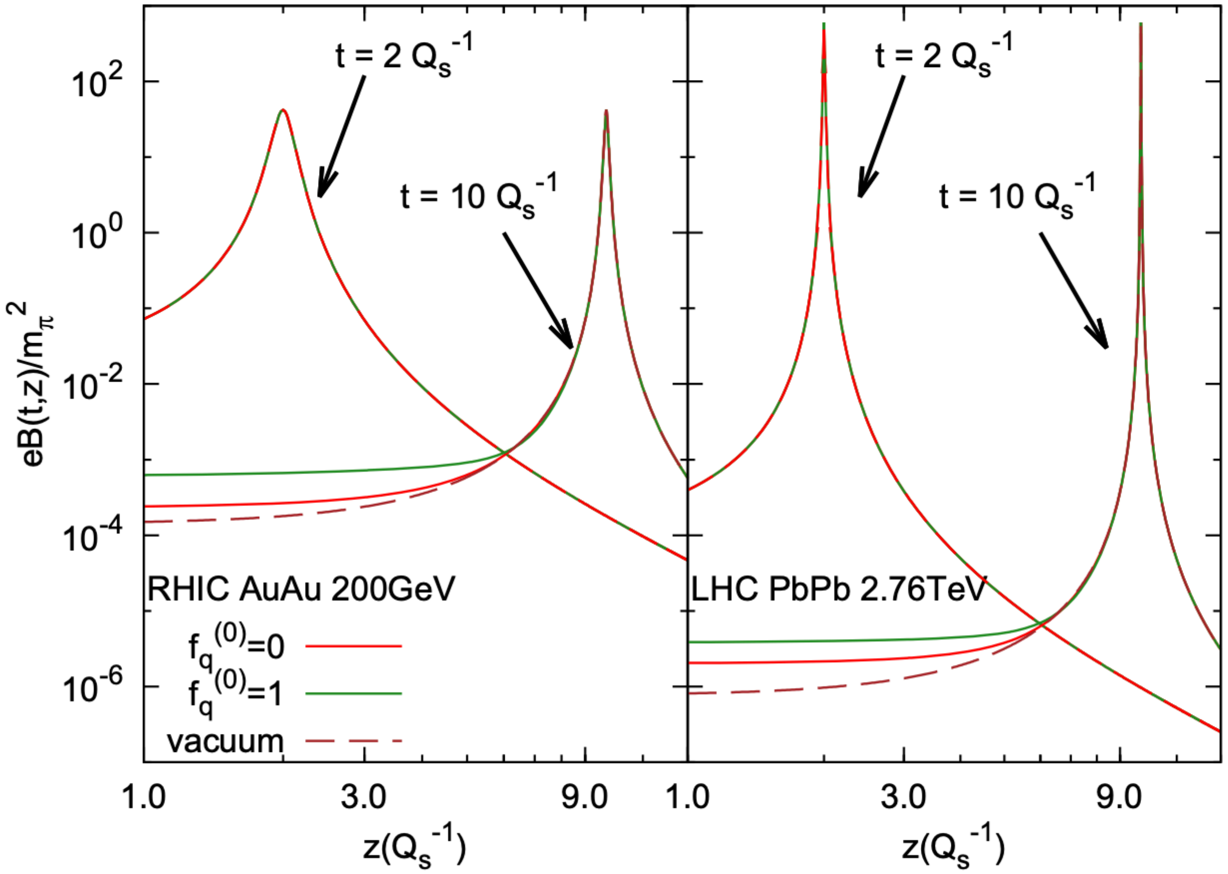


- More significant at low energy.

Lifetime effect?



Li Yan and Xu-Guang 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.

Summary

Spin alignment of vector mesons:

- Global spin alignment effect has been observed for several mesons in heavy-ion collisions.
- Surprisingly large pattern for ϕ mesons indicates a local fluctuation/correlation between s and $\bar{s}$ polarization.
- Fine measurements are on going using BESII data, rich physics to be explored.

Electromagnetic field effect in HIC:

- Charge-dependent collective motion provides first evidence of EM-field effect in QGP.
- Quantitative comparison with theory needs either subtracting transported quark contrition from experimental measurements or including transported quark in theoretical calculation.
- Efforts in experiment are ongoing in BESII analysis, call for theory inputs.