The weak magnetic effect: direct photon v_2 and $\Lambda/\bar{\Lambda}$ local polarization

arXiv: 2302.07696

Jing-An Sun; Li Yan
Fudan University
jasun22@m.fudan.edu.cn

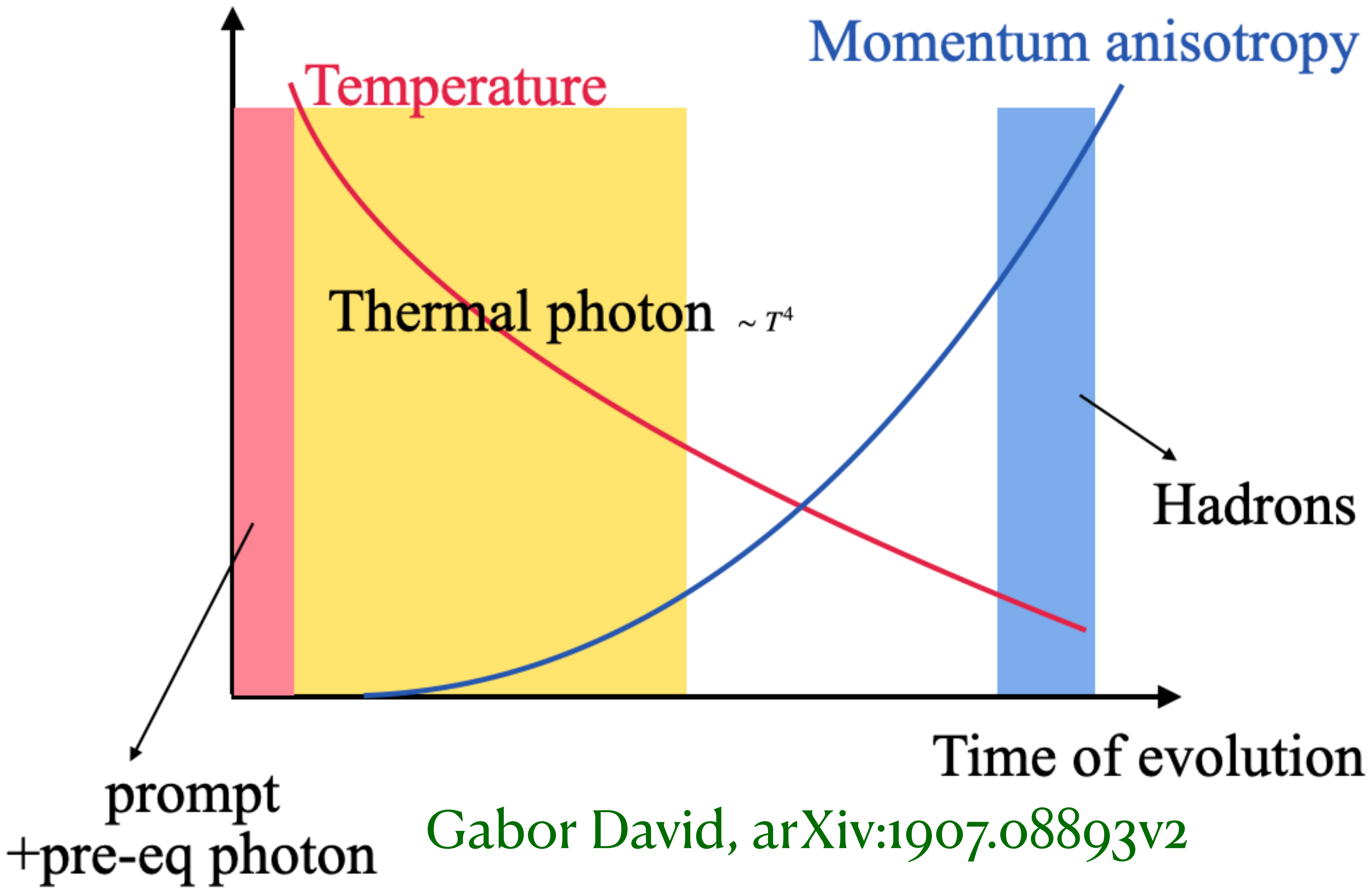
The 7th International Conference on Chirality, Vorticity and Magnetic Field in Heavy Ion Collisions

- The large v_2 of the direct photon
- The weak magnetic emission
- The local spin polarization: sign and centrality dependence
- $P^z(\phi)$ under a weak magnetic field

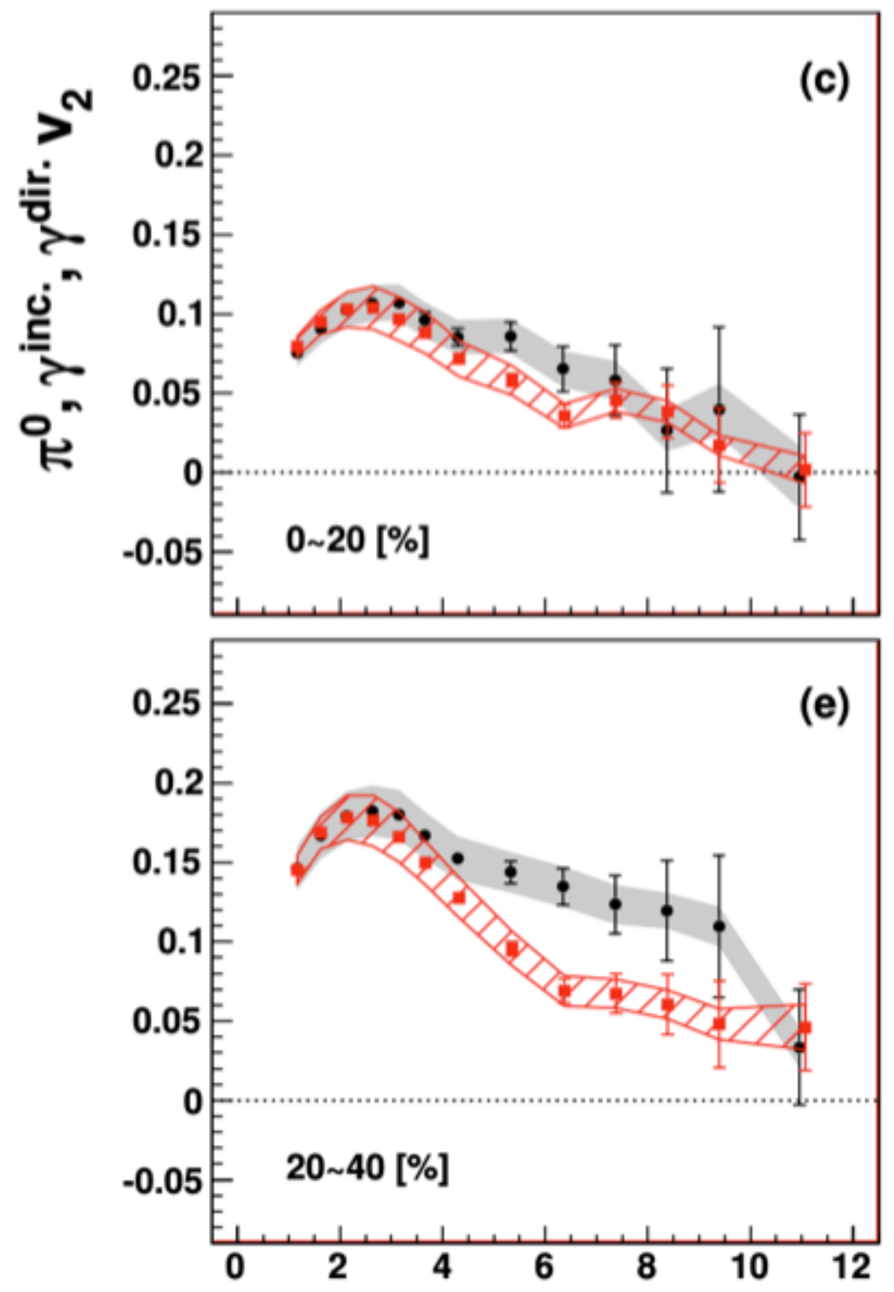
復旦大學

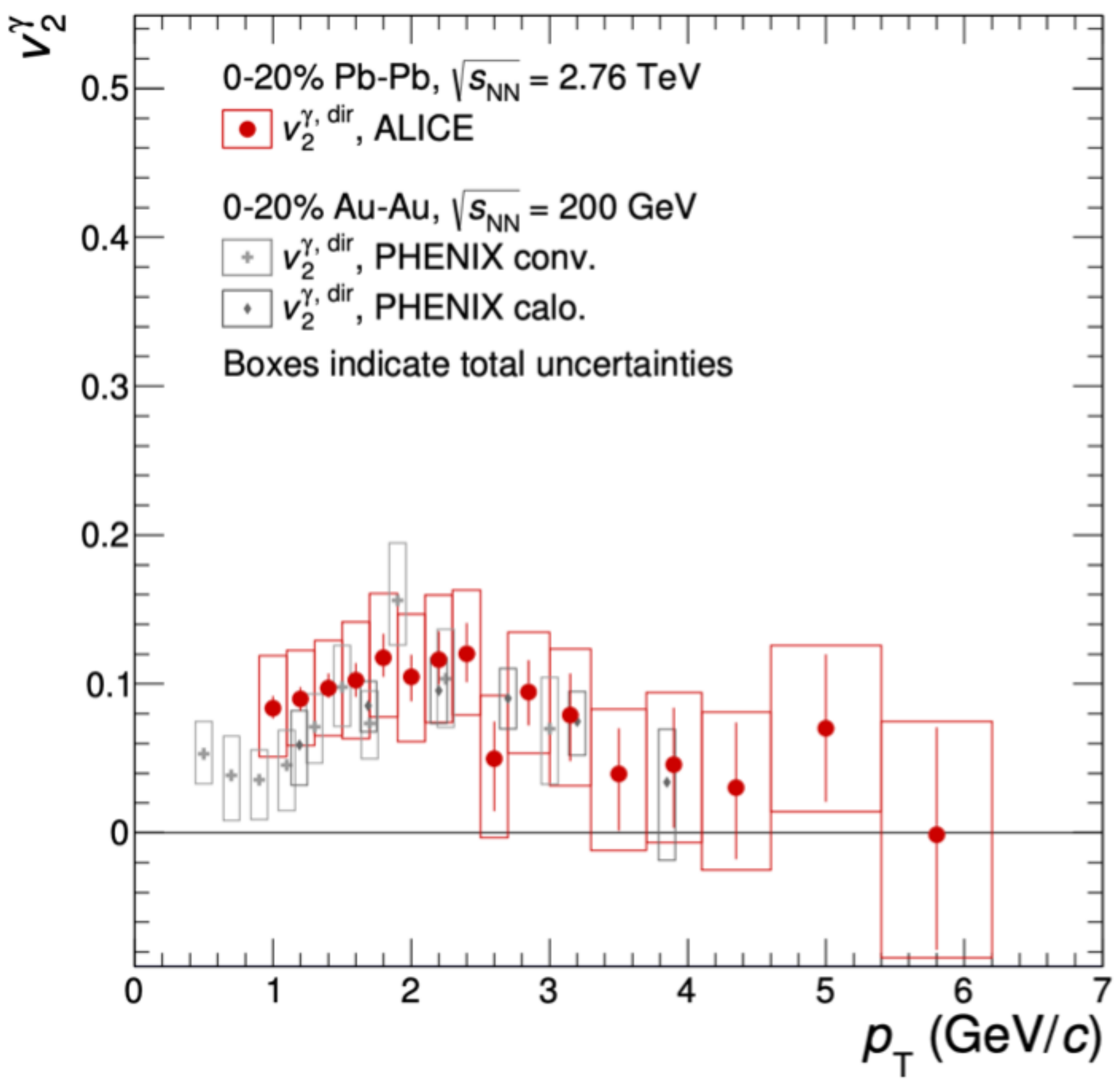
direct photon puzzle

No theory predict the observation of **large yields** and **large v_2** for direct photons!



Gabor David, arXiv:1907.08893v2





Theory

$v_2^\gamma \ll v_2^{hadron}$

Puzzle!

Experiment

$v_2^\gamma \approx v_2^{hadron}$

PHENIX, PRL (2012)

ALICE PLB (2019)

Weak magnetic field

Scales of magnetic field

Ayala et al, 1704.02433,
X. Wang, Meihuang et al, 2006.16254

K. Tuchin, PRC 91,1406.5097

G. Basar, et.al, PRL, 1206.1334.

$eB \gg g^2T^2$ The quantization of Landau level.

$T^2 \gg eB \gg T\nabla$ Magnetohydrodynamics (MHD).

$eB \ll T\nabla \sim m_\pi^2$ **Weak magnetic non-equilibrium correction.**

$$f_q = n_q + \delta f + f_{EM}$$

$$f_{\rm EM} = \frac{c}{8\alpha_{\rm EM}} \frac{\sigma_{\rm el} n_{\rm eq}(1 - n_{\rm eq})}{T^3 p \cdot u} eQ_f F^{\mu\nu} p_\mu u_\nu$$

Weak magnetic field

Scales of magnetic field

Ayala et al, 1704.02433,
X. Wang, Meihuang et al, 2006.16254

$eB \gg g^2T^2$ The quantization of Landau level.

K. Tuchin, PRC 91,1406.5097

$T^2 \gg eB \gg T\nabla$ Magnetohydrodynamics (MHD).

G. Basar, et.al, PRL, 1206.1334.

$eB \ll T\nabla \sim m_\pi^2$ **Weak magnetic non-equilibrium correction.**

$$f_q = n_q + \delta f + f_{EM}$$

$$f_{\mathrm{EM}} = \frac{c}{8\alpha_{\mathrm{EM}}} \frac{\sigma_{\mathrm{el}} n_{\mathrm{eq}}(1-n_{\mathrm{eq}})}{T^3 p\cdot u} eQ_f F^{\mu\nu} p_\mu u_\nu$$

$$[\ldots\cos\phi + \ldots\cos 2\phi + \ldots]$$

v_1^{hadron} v_2^{hadron}

Weak magnetic field

Scales of magnetic field

Ayala et al, 1704.02433,
X. Wang, Meihuang et al, 2006.16254

K. Tuchin, PRC 91,1406.5097

G. Basar, et.al, PRL, 1206.1334.

$eB \gg g^2 T^2$ The quantization of Landau level.

$T^2 \gg eB \gg T\nabla$ Magnetohydrodynamics (MHD).

$eB \ll T\nabla \sim m_\pi^2$ **Weak magnetic non-equilibrium correction.**

$$f_q = n_q + \delta f + f_{EM}$$

$$f_{\rm EM} = \frac{c}{8\alpha_{\rm EM}} \frac{\sigma_{\rm el} n_{\rm eq}(1-n_{\rm eq})}{T^3 p\cdot u} eQ_f F^{\mu\nu} p_\mu u_\nu$$

$$[\ldots\cos\phi + \ldots\cos 2\phi + \ldots] \cos\phi$$

$v_1^{\rm hadron}$ $v_2^{\rm hadron}$

Weak magnetic field

Scales of magnetic field

Ayala et al, 1704.02433,
X. Wang, Meihuang et al, 2006.16254

K. Tuchin, PRC 91,1406.5097

G. Basar, et.al, PRL, 1206.1334.

$eB \gg g^2T^2$ The quantization of Landau level.

$T^2 \gg eB \gg T\nabla$ Magnetohydrodynamics (MHD).

$eB \ll T\nabla \sim m_\pi^2$ **Weak magnetic non-equilibrium correction.**

$$f_q = n_q + \delta f + f_{EM}$$

$$f_{\mathrm{EM}} = \frac{c}{8\alpha_{\mathrm{EM}}} \frac{\sigma_{\mathrm{el}} n_{\mathrm{eq}}(1-n_{\mathrm{eq}})}{T^3 p\cdot u} eQ_f F^{\mu\nu} p_\mu u_\nu$$

$$[\ldots\cos\phi + \ldots\cos 2\phi + \ldots]\ \cos\phi$$

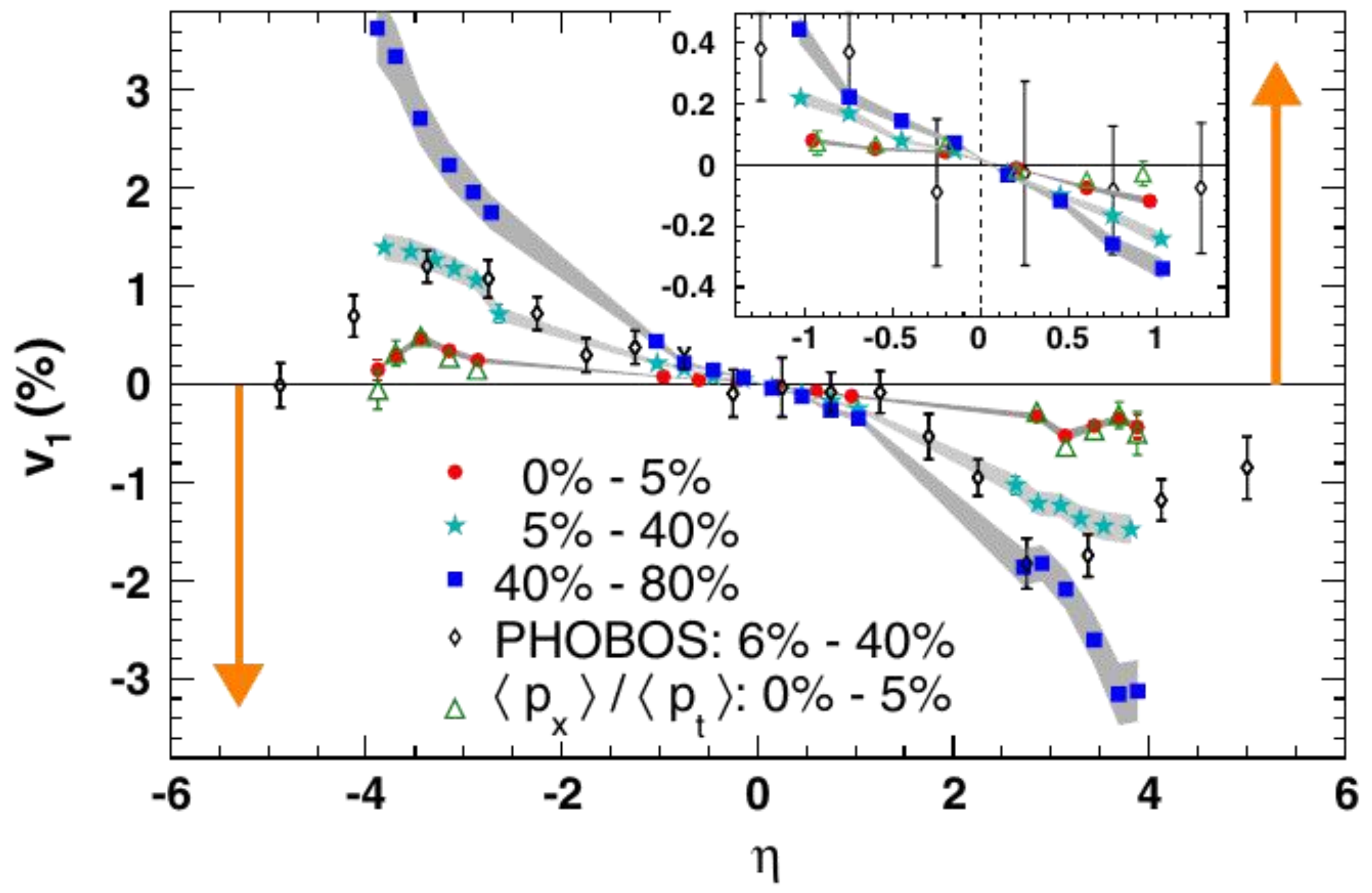
v_1^{hadron} v_2^{hadron}

A new $\cos(2\phi)$ term v_2^{EM} !

$v_2^{EM} \sim 0.5$

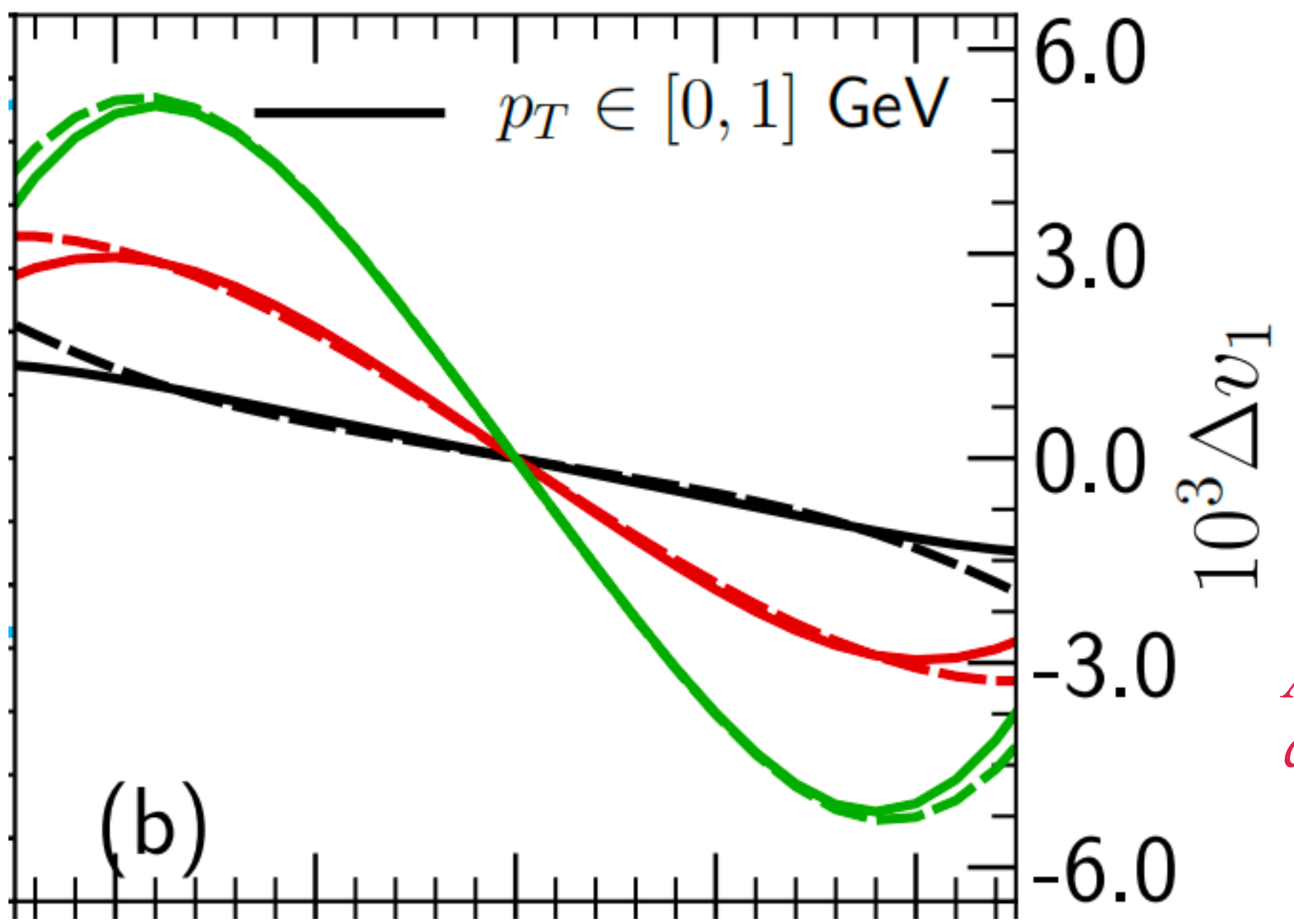
The weak magnetic effect: photon v_2

A Rapidity-odd directed flow for background medium is required !



[STAR collaboration, PRL 101, 252301 (2008)]

Negative v_1 slope for positive charges,
Positive v_1 slope for negative charges.



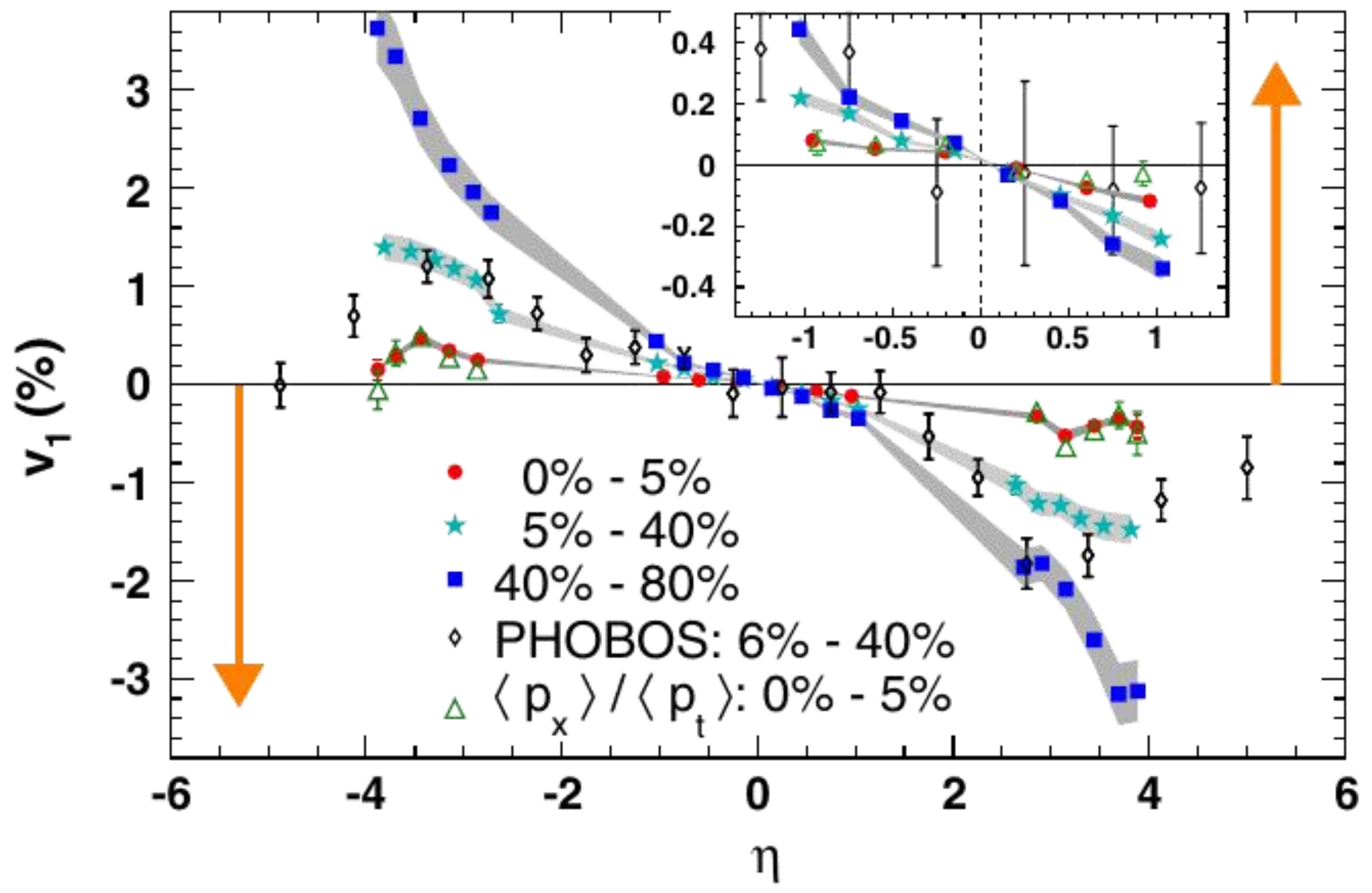
Gursoy, Dima Kharzeev and Rajagopal, PRC (2014)

Why quark/anti-quark contributions are not canceled!

Aihong Tang. Directed flow splitting and EM field effects. 7.16 8.30am

The weak magnetic effect: photon v_2

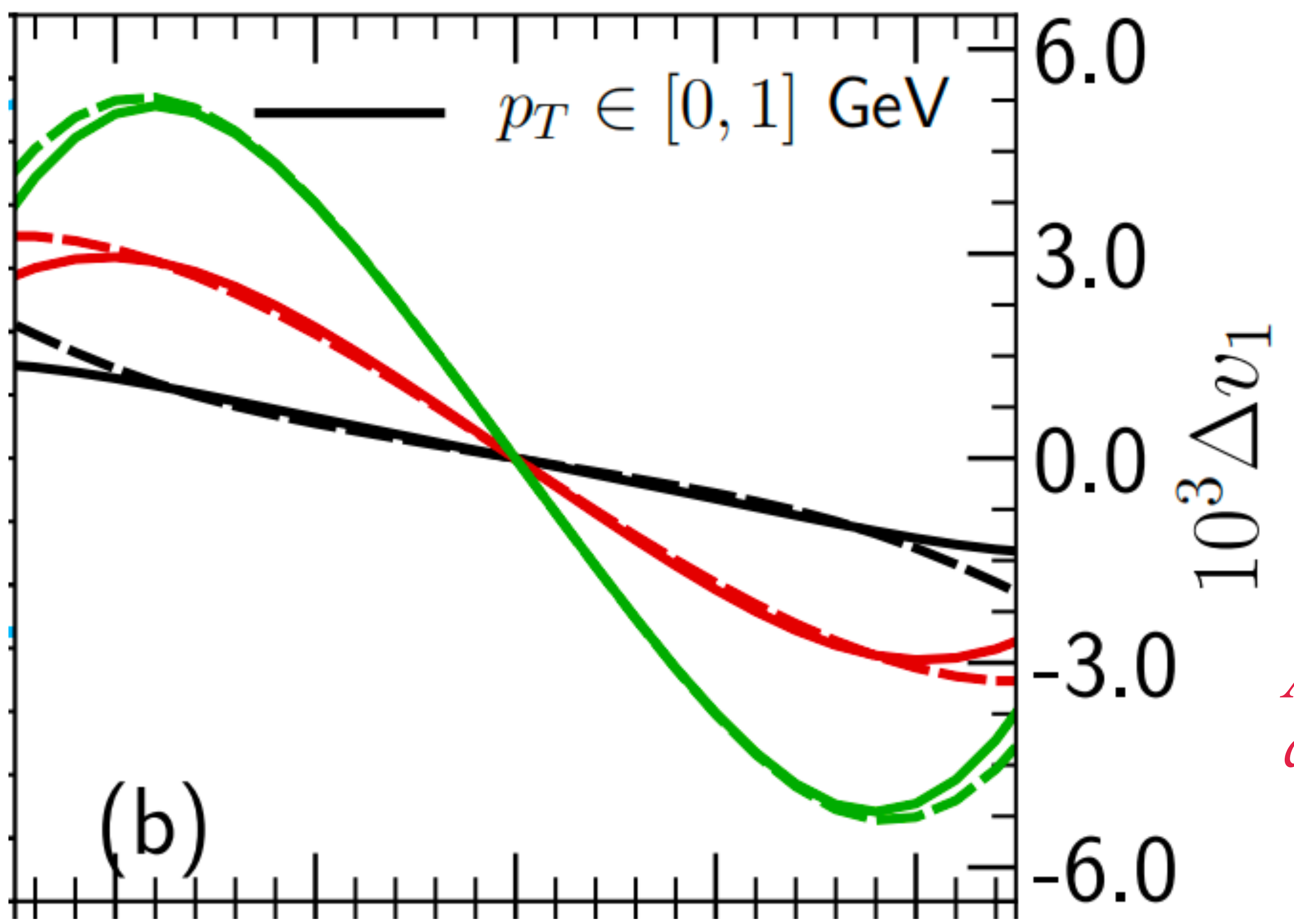
A Rapidity-odd directed flow for background medium is required !



[STAR collaboration, PRL 101, 252301 (2008)]

Negative v_1 slope for positive charges, Positive v_1 slope for negative charges.

Gursoy, Dima Kharzeev and Rajagopal, PRC (2014)



Why quark/anti-quark contributions are not canceled!

Aihong Tang. Directed flow splitting and EM field effects. 7.16 8.30am

Hydrodynamic simulation

- Trento3D + MUSIC : event-by-event simulation

Magnetic field profile

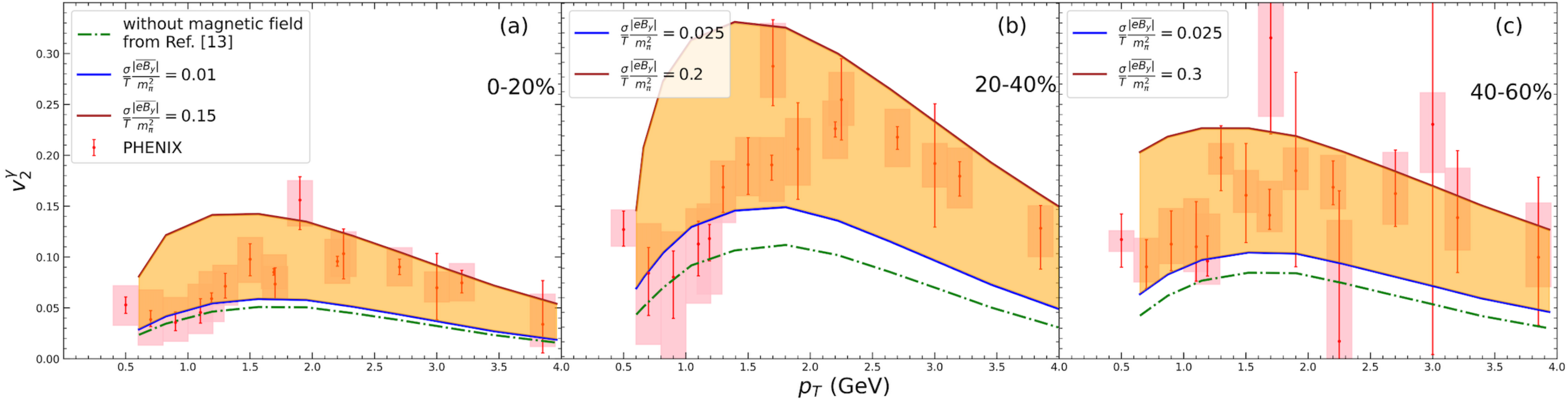
PRC 92 011901, PRC 96 044912.

JETSCAPE framework, arxiv 1903.07706

- Electrical conductivity: LO pQCD evaluation (AMY).
- η_s dependence is retained as in vacuum and the time averaged B field $e\bar{B}$ is extracted.

K. Hattori and X. Huang, 1609.00747

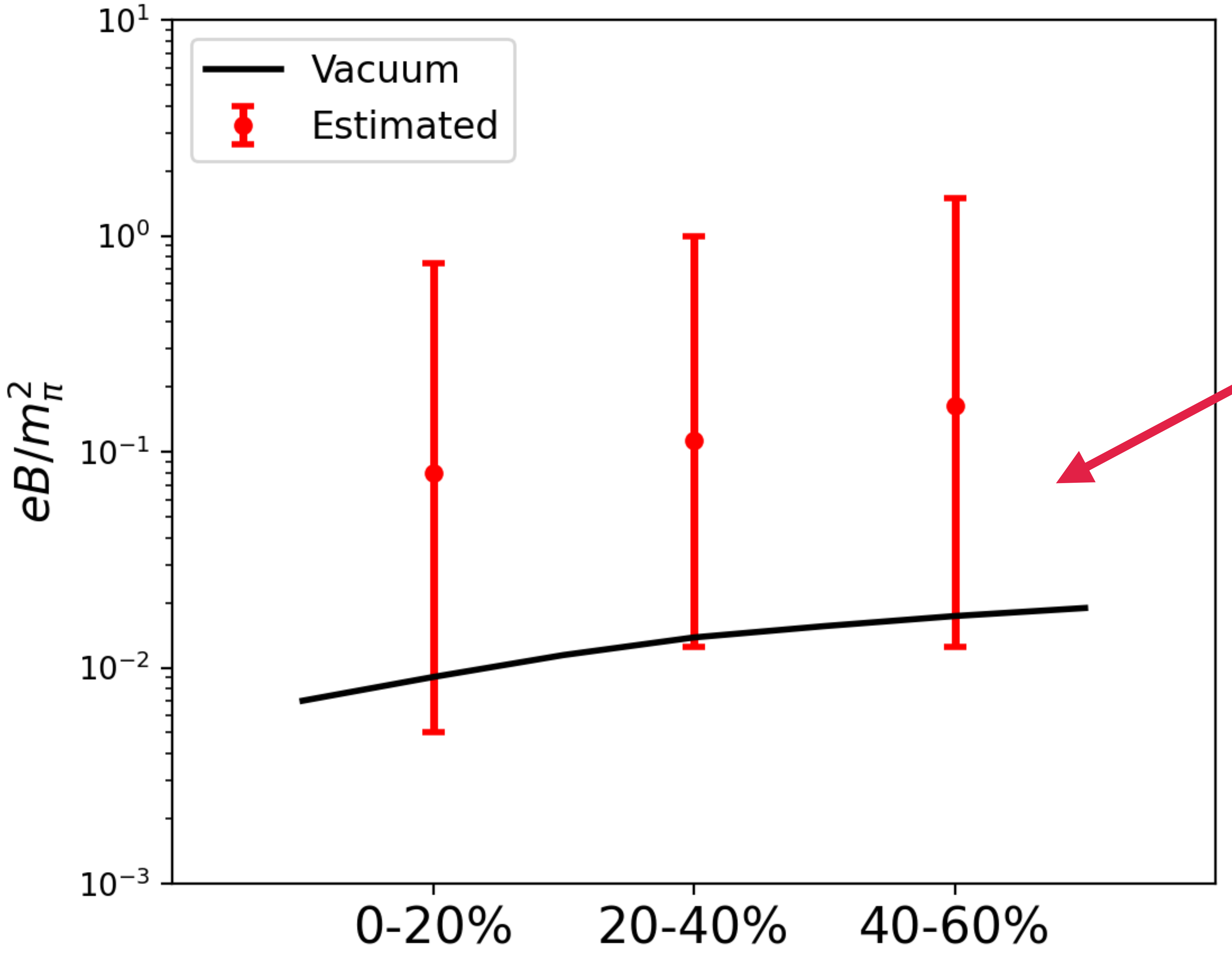
Results: photon v_2 with B

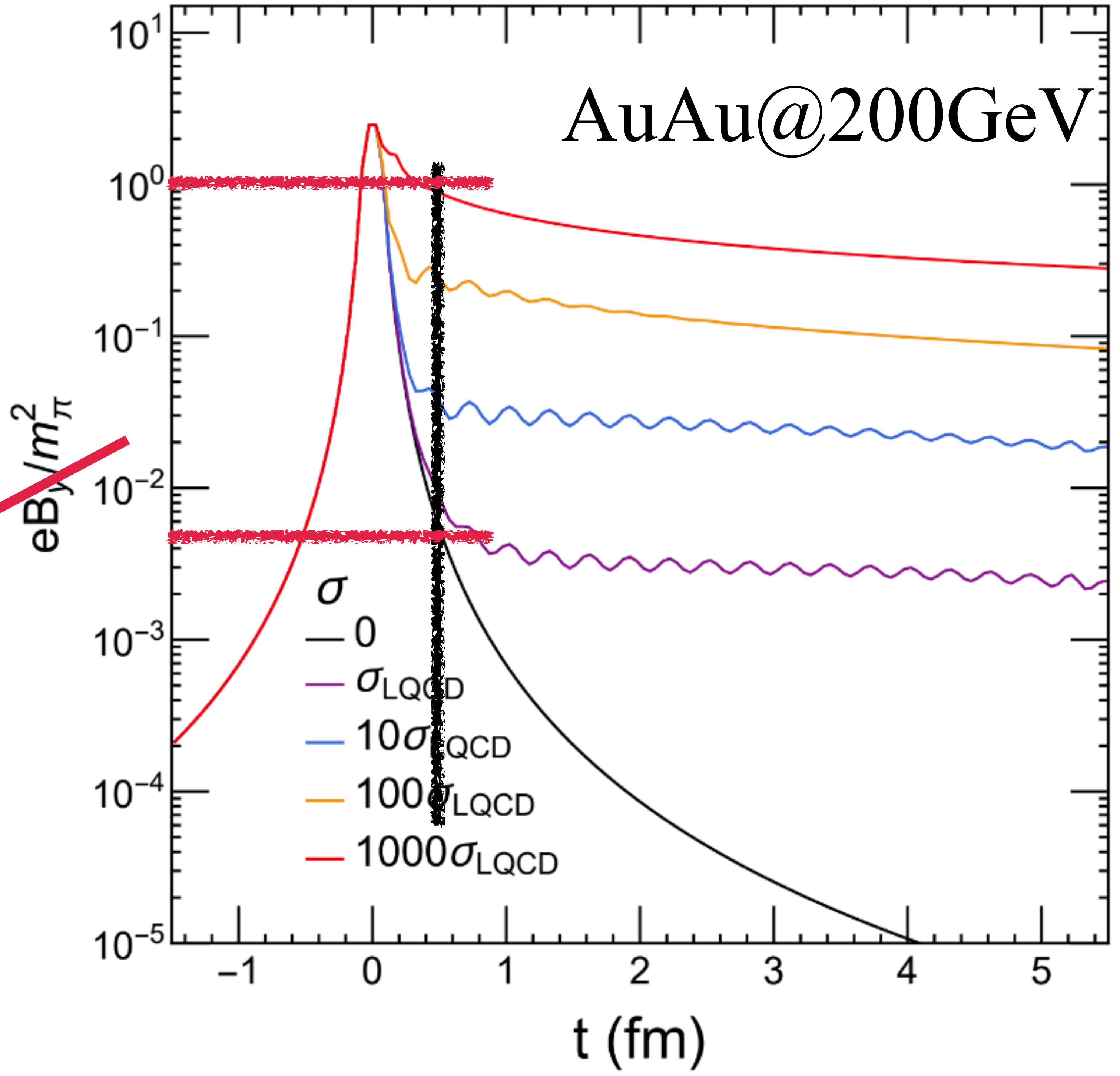


AuAu@200GeV

- The **experimental data are reproduced** excellently for all centralities.
- The used time averaged field strength is **under weak magnetic assumption.**
- The B field magnitude grows as centrality increases: **correct trend.**

Estimated time-averaged B field at $\eta = 0$ based on event-by-event simulations





A. Huang et.al (2022),2212.08579.

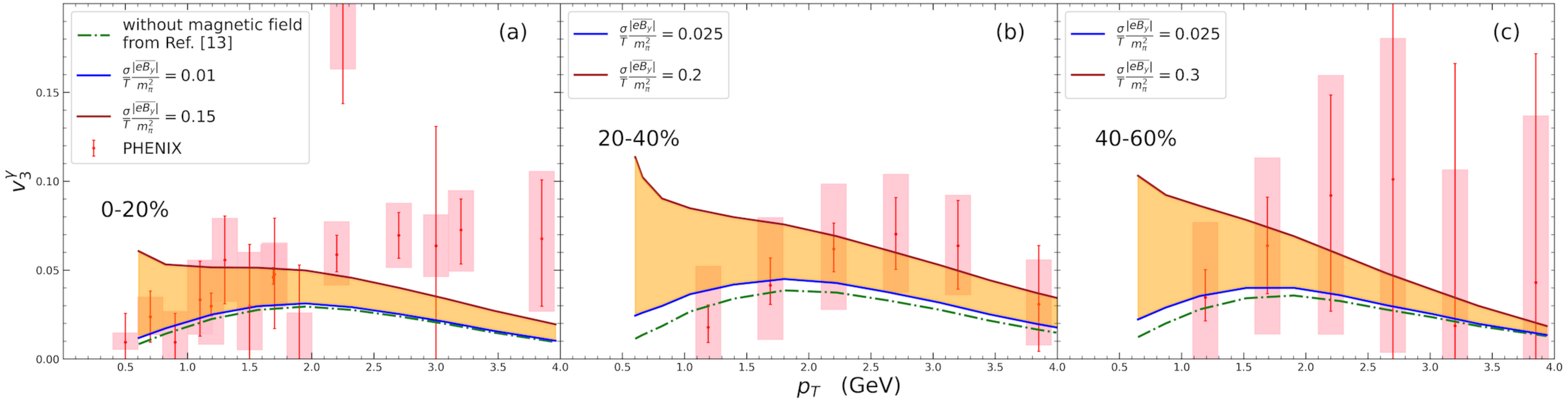
J.-J. Zhang, et.al , Phys. Rev. Res. **4**, 033138 (2022)

- The error-bar contains: theoretical + experimental

F.Stefan arxiv: 2112.12497 $\frac{\sigma}{T} \in [0.2,2]$ Cover the experimental elliptic flow data

Results: photon v_3 with B

AuAu@200GeV



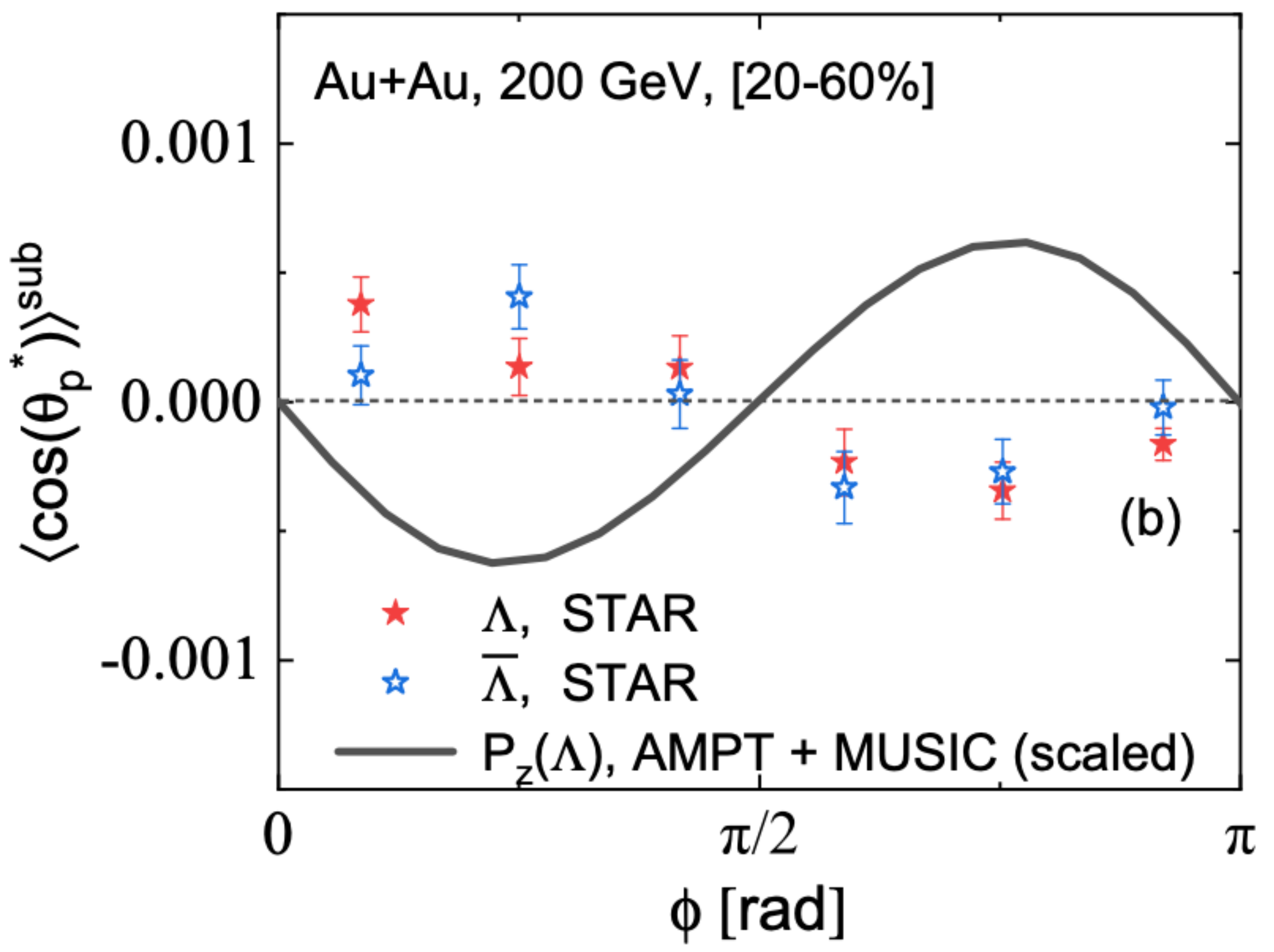
- The weak magnetic photon emission also has significant effect on the triangle flow.

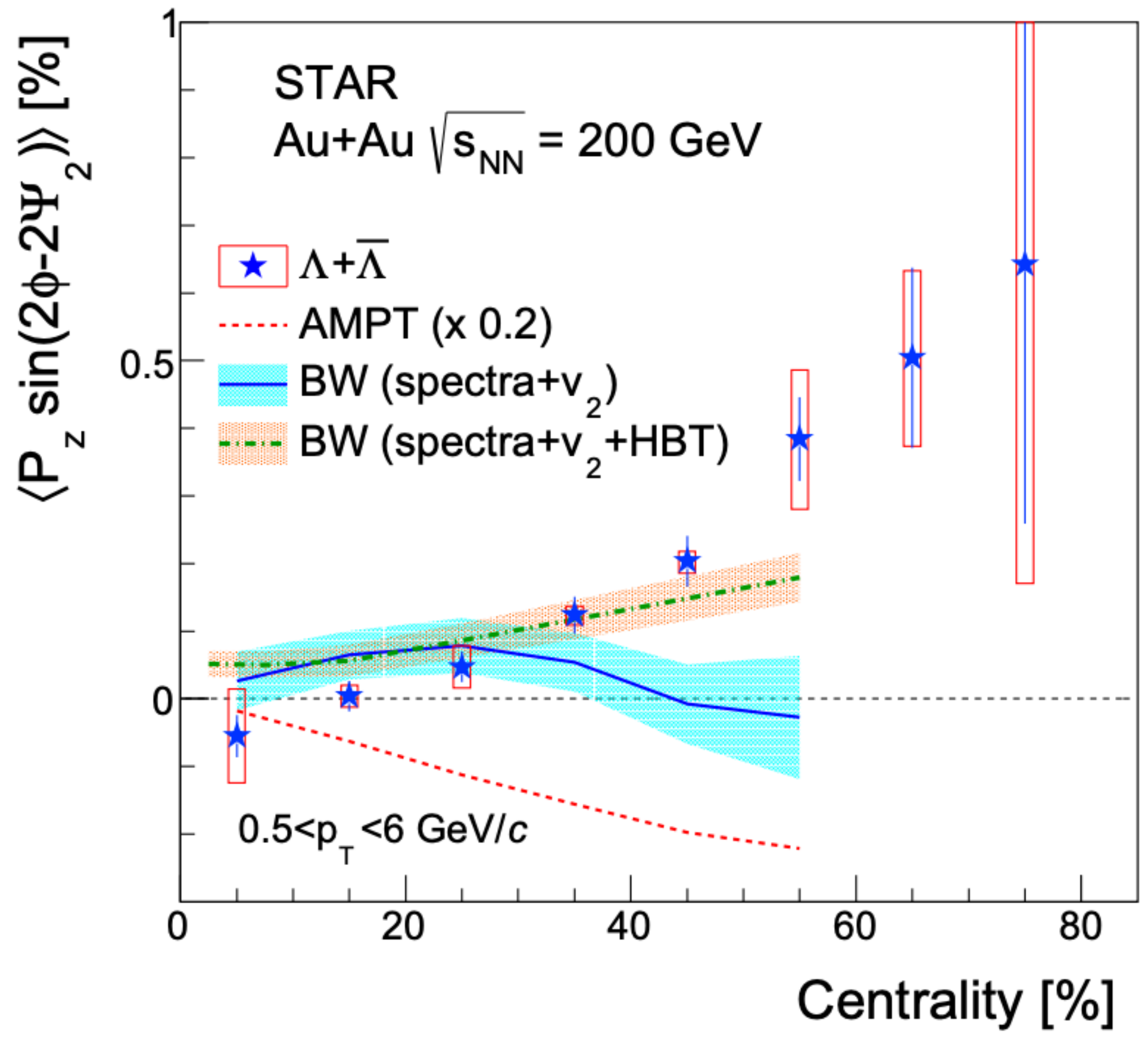
Non-trivial coupling effect: **weak magnetic field** + **longitudinal dynamics!**

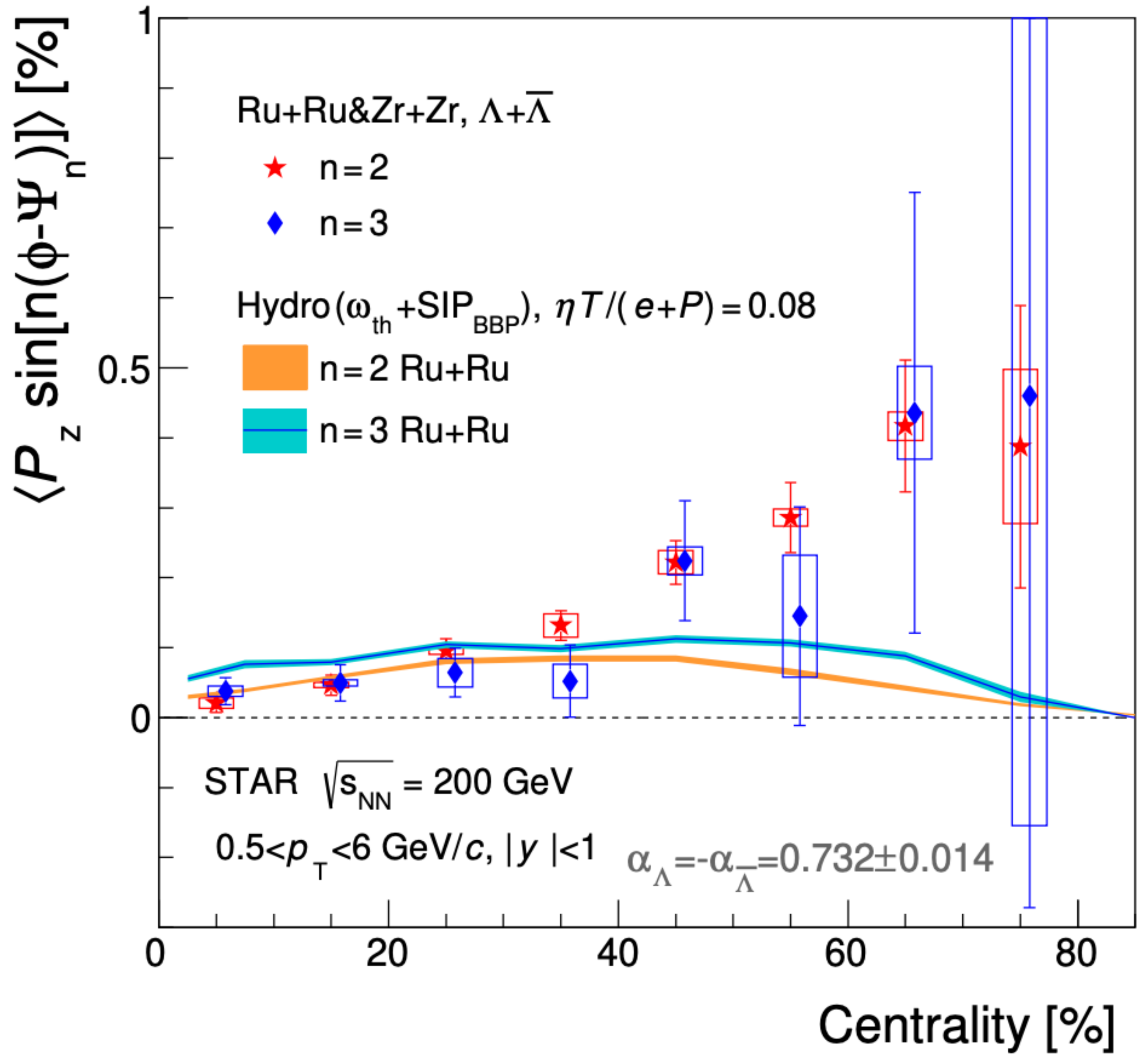
Hyperon Local polarization: sign puzzle

$$P_z = \frac{\langle \cos\theta_p^* \rangle}{\alpha_H \langle \cos^2\theta_p^* \rangle}$$

F Becattini. Spin polarization and thermal shear effect. 7.15 2:00pm
Baochi Fu Local Spin polarization. 7.15 2:30pm







- Opposite **sign** of the $P^z(\phi)$
- Opposite trend on the **centrality dependence**
- With SIP term, the sign can be flipped but the magnitude is almost centrality-independent.

STAR arxiv: 2303.09074
STAR arxiv: 1905.11917
Becattini, Karpenko, PRL 120 (2018) 012302
Karpenko, Becattini, EPJC 77 (2017) 4, 213
Baochi Fu et al PRC 103 (2021) 2
Baochi Fu et al PRL 127(2021) 14

The weak magnetic effect: $P^z(\phi)$

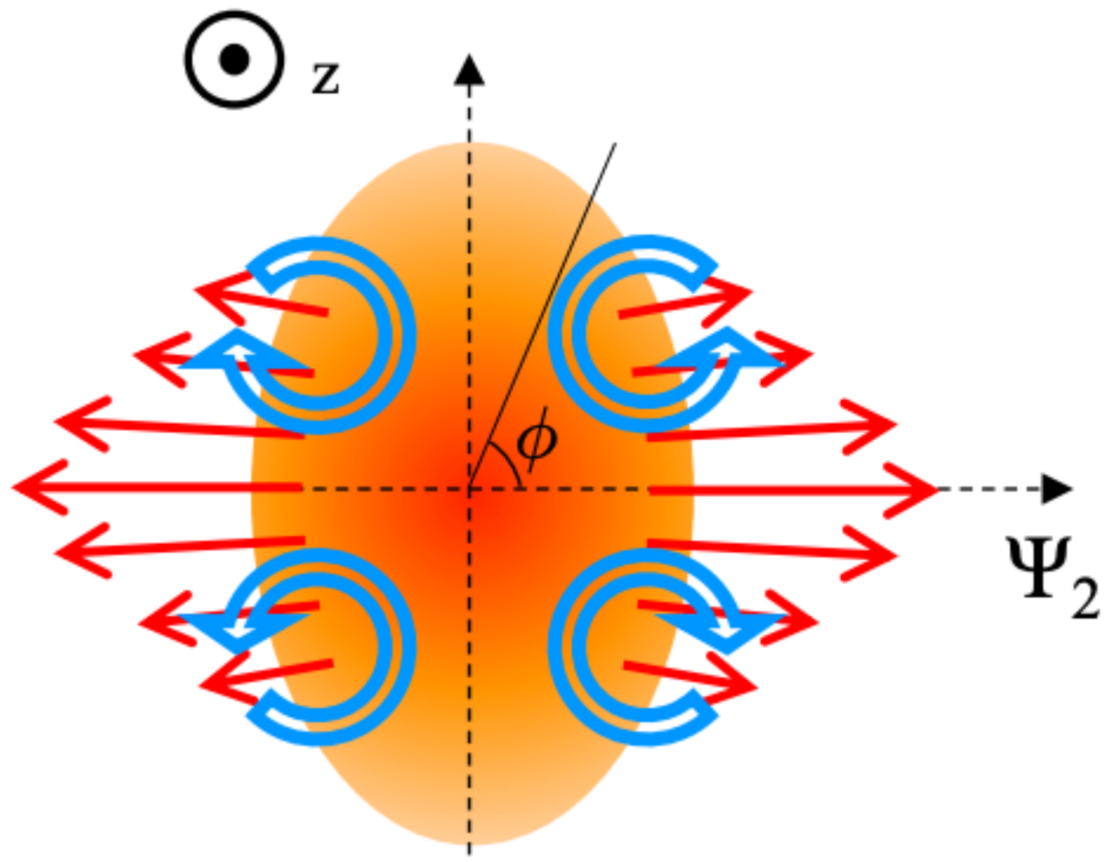
- Drag to non-eq on the hyper-surface.

More careful analysis is needed!

$$n_{\text{eq}}(\text{with spin}) \xrightarrow{\text{Boltzmann-Vlasov}} (n_{\text{eq}} + f_{EM}) \otimes \text{spin}$$

Only thermal vorticity!

- Trento3D is used to generate the smooth initial conditions:
  Rapidity-odd $v_1(\eta)$
- S-quark memory: $P^z_\Lambda = P^z_s$
- Constant eB

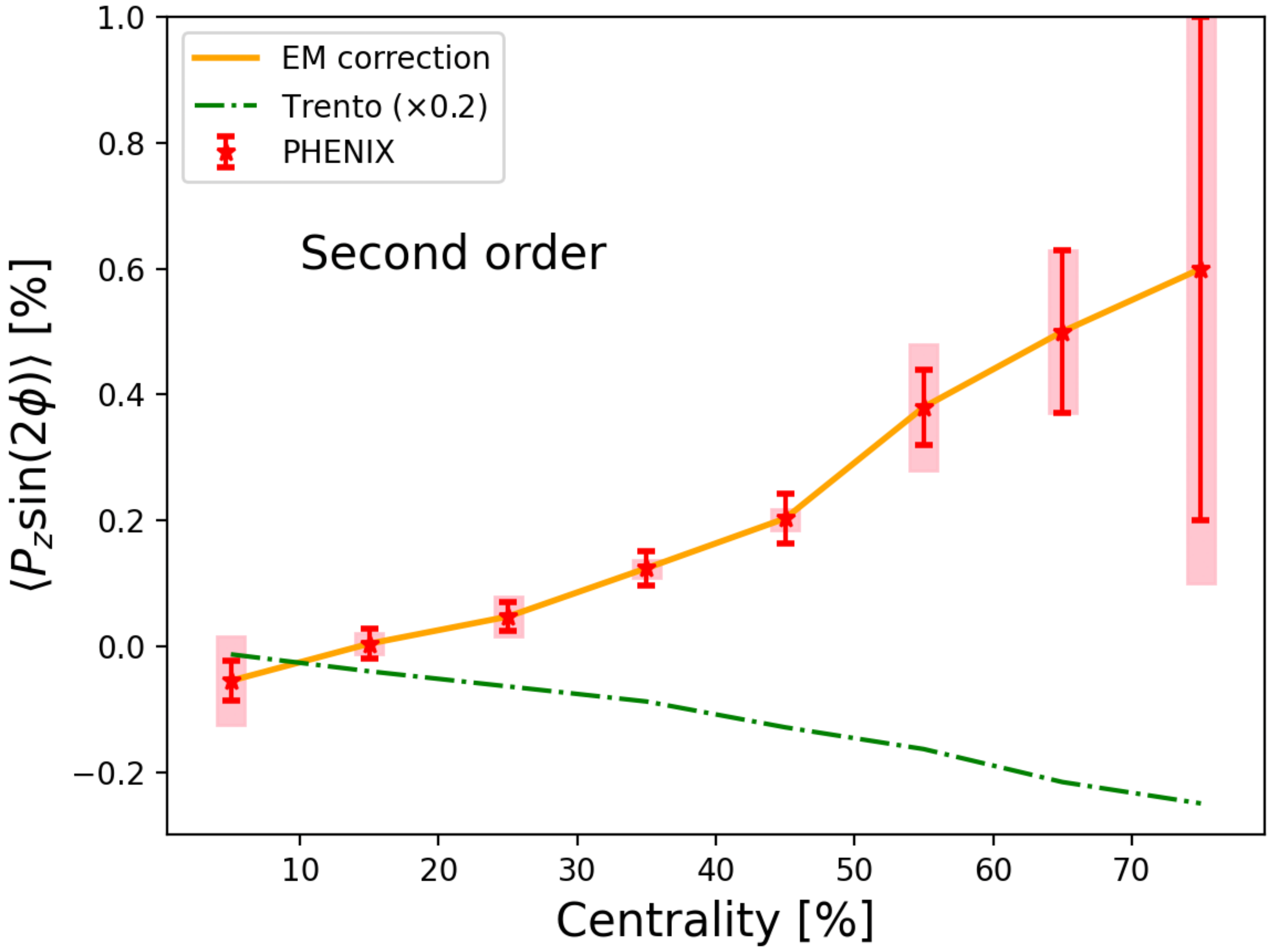


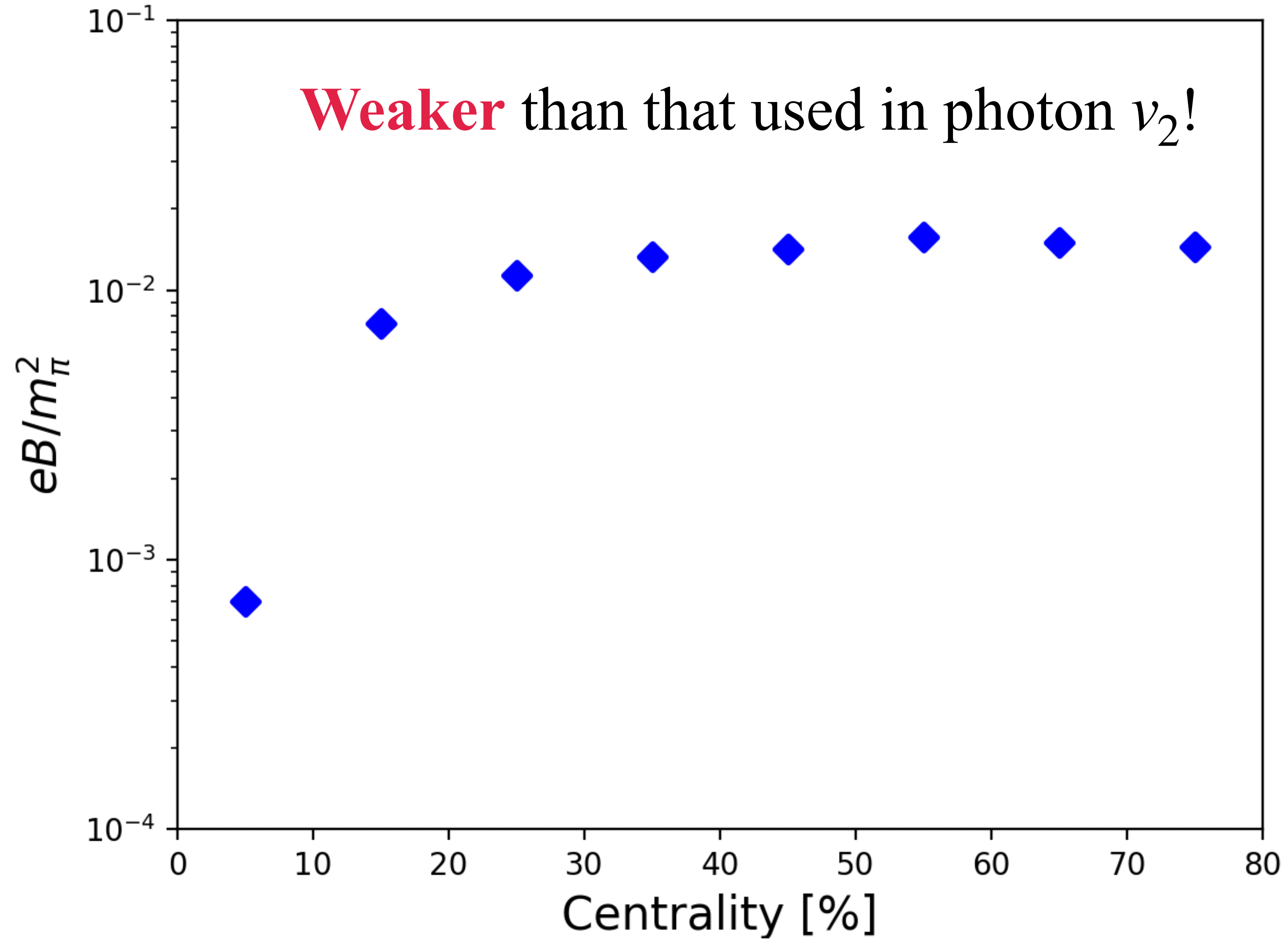
Baochi Fu et al PRL 127(2021) 14

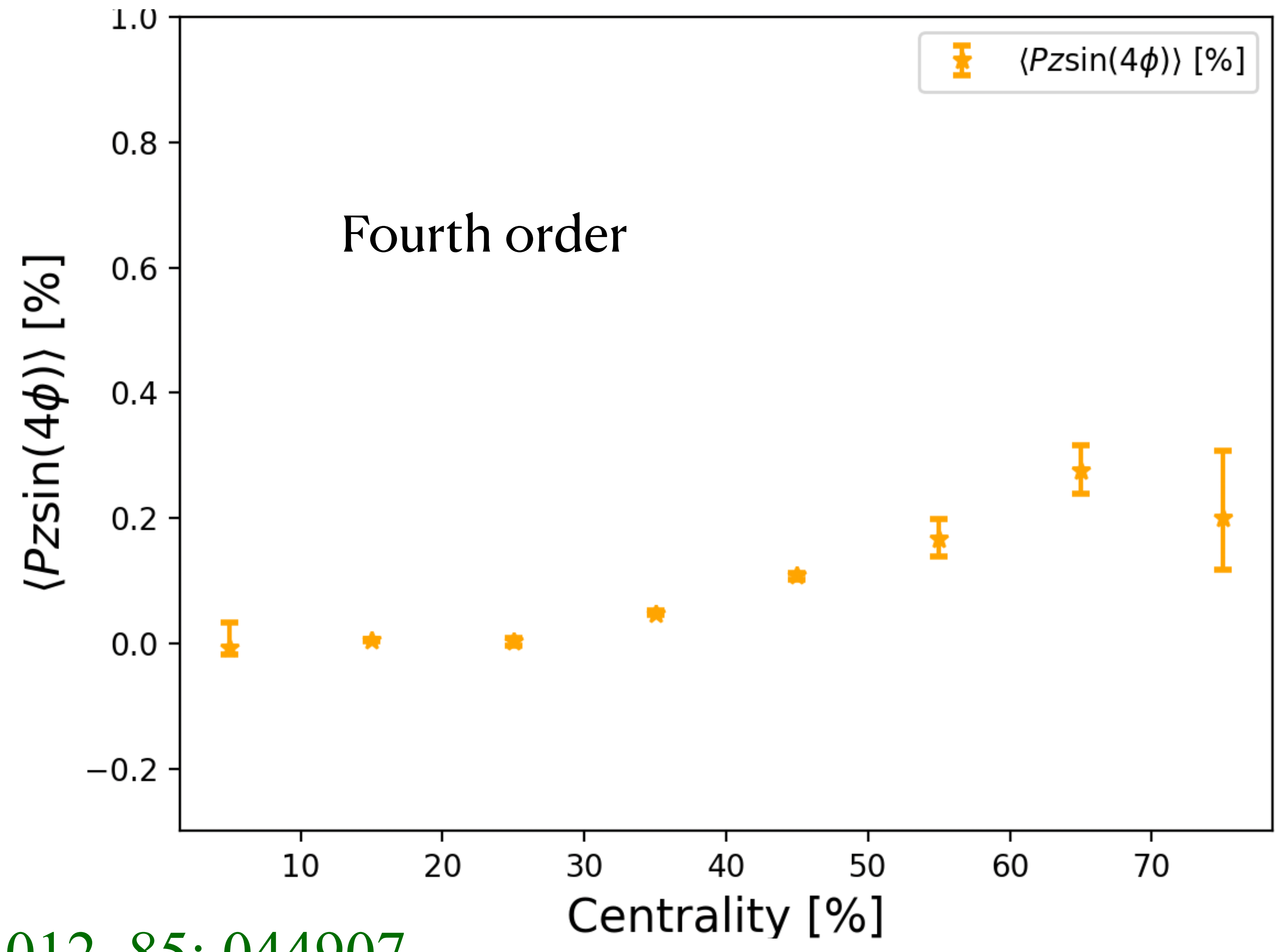
Results: $P^z(\phi)$ with B

Preliminary

Only thermal vorticity!







Deng W T, Huang X G. Phys. Rev. C, 2012, 85: 044907.

L. Yan and X.-G. Huang (2021), 2104.00831

- B field **flips the $P^z(\phi)$ sign** successfully and the **centrality dependence** is reproduced.
- The B field used to fit the experimental data is still weak and follows the centrality trend.
- The **sin(4ϕ) structure** in $P^z(\phi)$ is expected.

In preparation

Summary and Outlook

Non-trivial coupling effect between the **weak magnetic field** and the **longitudinal dynamics of the fireball!**

- The **elliptic and triangle flow of direct photon** both get significant increments, which confronts the experimental data.
- The sign of $P^z_\Lambda(\phi)$ is flipped and the centrality dependence are reproduced.
- The $\sin(4\phi)$ **structure** in $P^z(\phi)$ is expected.
- The event-by-event simulations for $P^z(\phi)$ is undergoing.

- Possible observables witnessing the novel effect:

The **polarization of di-leptons**? The v_1 **splitting** of mesons and baryons?………

Back up

$$v_0^\gamma = \bar{v}_0 + v_0^{\mathrm{EM}}\,, \qquad v_2^\gamma = \frac{\bar{v}_2\bar{v}_0 + v_2^{\mathrm{EM}} v_0^{\mathrm{EM}}}{\bar{v}_0 + v_0^{\mathrm{EM}}}$$

Bjorken analysis for illustration

For background medium: $n_{\mathrm{eq}} = A_0(\tau, \eta_s, p_T, Y) + A_1(\tau, \eta_s, p_T, Y)\cos\phi_p$

$$\begin{aligned} f_{\mathrm{EM}} &\propto QB_y \frac{\tau_R}{T}\frac{\sinh\eta_s}{\cosh(y-\eta_s)}(A_0 + A_1\cos\phi_p)\cos\phi_p \\ &= QB_y \frac{\tau_R}{T}\frac{\sinh\eta_s}{\cosh(y-\eta_s)}\left[\frac{A_1}{2} + A_0\cos\phi + \frac{A_1}{2}\cos 2\phi\right] \end{aligned}$$

Back up

$$v_0^\gamma = \bar{v}_0 + v_0^{\rm EM}\,, \quad v_2^\gamma = \frac{\bar{v}_2\bar{v}_0 + v_2^{\rm EM} v_0^{\rm EM}}{\bar{v}_0 + v_0^{\rm EM}}$$

Bjorken analysis for illustration

For background medium: $n_{\rm eq} = A_0(\tau,\eta_s,p_T,Y) + A_1(\tau,\eta_s,p_T,Y)\cos\phi_p$

$$f_{\rm EM} \propto QB_y \frac{\tau_R}{T}\frac{\sinh\eta_s}{\cosh(y-\eta_s)}(A_0 + A_1\cos\phi_p)\cos\phi_p$$

$$= QB_y \frac{\tau_R}{T}\frac{\sinh\eta_s}{\cosh(y-\eta_s)}\left[\frac{A_1}{2} + A_0\cos\phi + \frac{A_1}{2}\cos 2\phi\right]$$

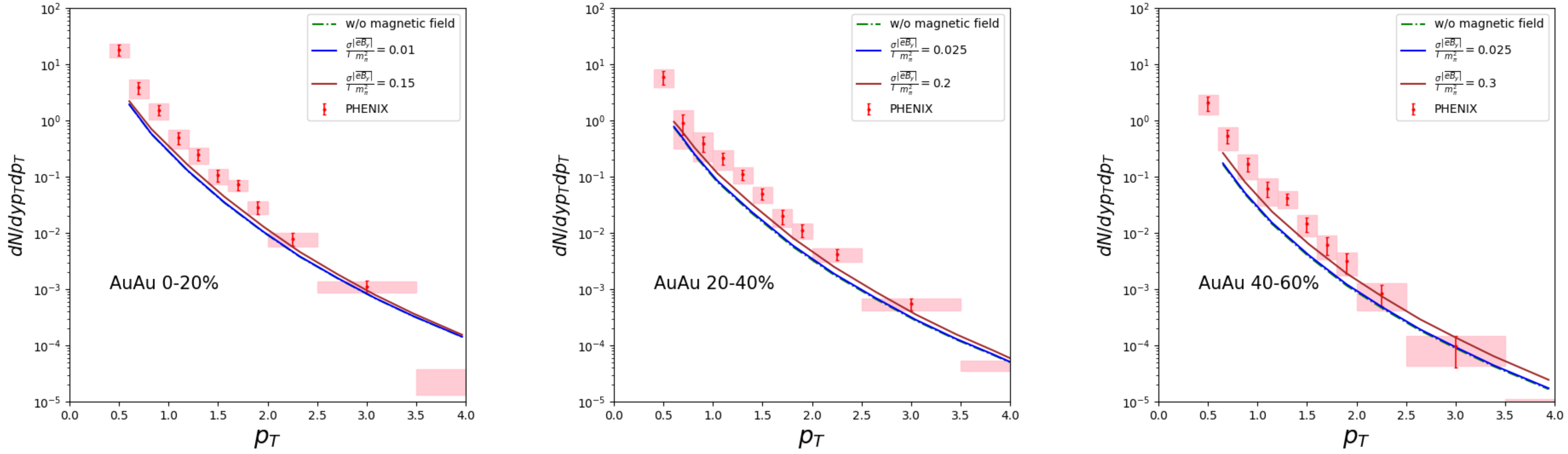
This $\cos\phi$ is from weak magnetic field.

$\rightarrow$ $v_2^{EM} \sim 0.5$

Rapidity-odd!

Must be Rapidity-odd

Back up

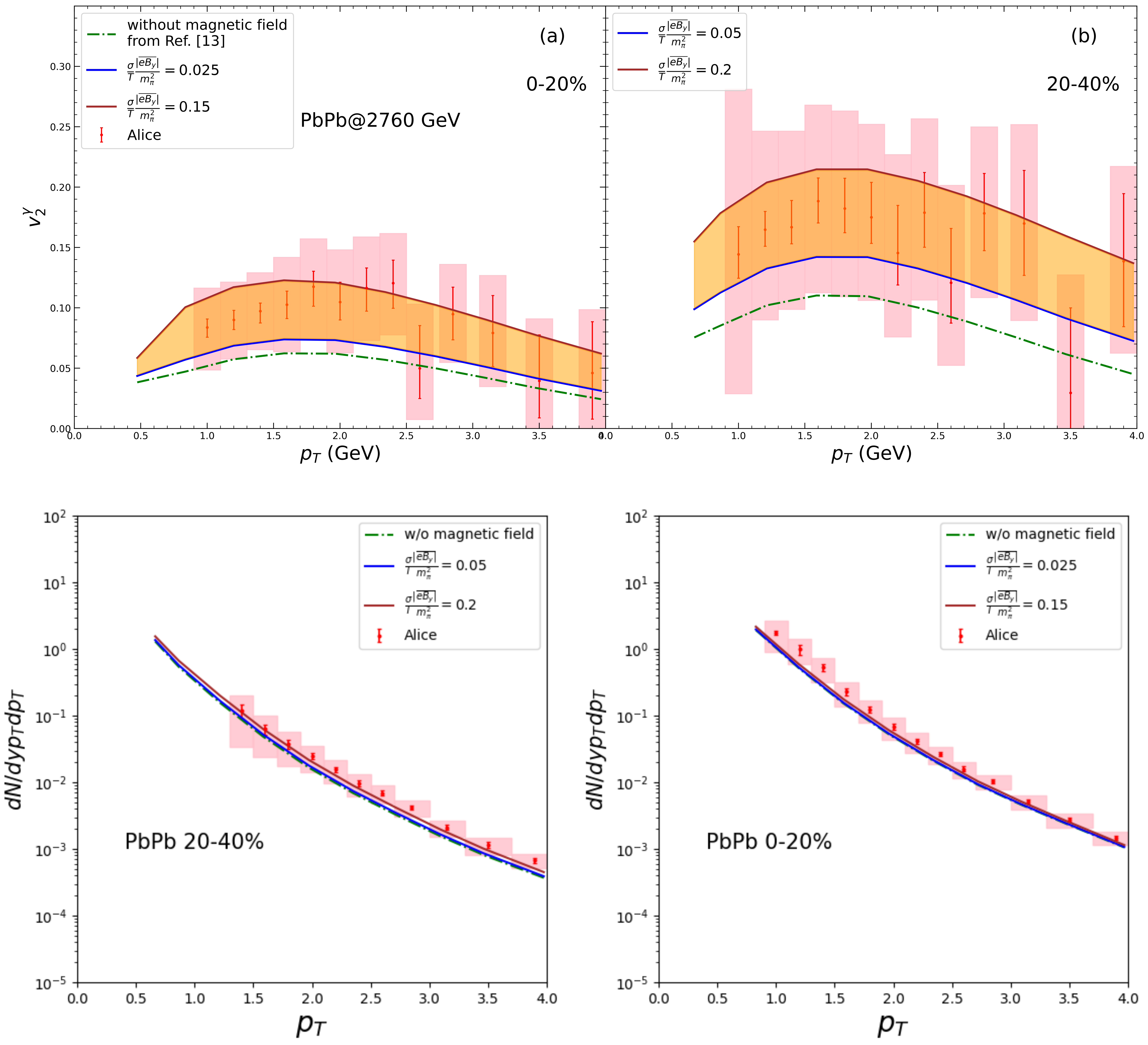


- v_2 increments are large at **low p_T region** because **the yield increments are large at low p_T region**

Average increment ~10 %

$v_2^{EM} \sim 0.5$

PbPb@2760GeV

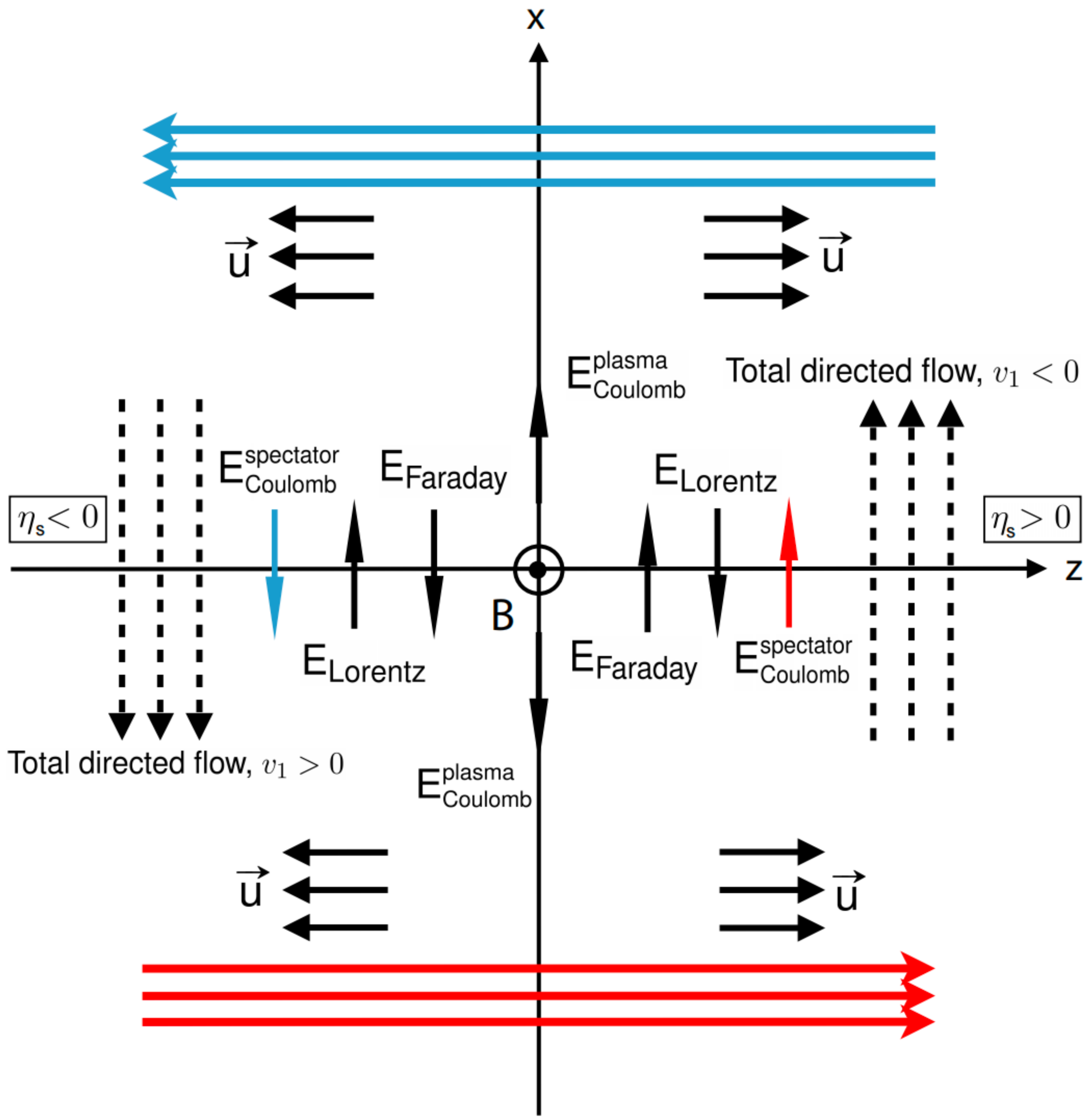


Back up

Aihong Tang. Directed flow splitting and EM field effects. 7.16 8.30am

Gursoy, Kharzeev and Rajagopal, PRC 89 054905 (2014)

v_1 of the quark



Negative v_1 slope for positive charges, and Positive v_1 slope for negative charges.

Back up

$$(A_0 + A_1 \cos\phi + A_2 \cos 2\phi)(w_0 + w_1 \sin\phi + w_2 \sin 2\phi)$$
$$\sim \frac{1}{2}\left(2A_0 w_0 + 2A_2 w_0 \cos 2\phi + (A_1 w_1 + 2A_0 w_2)\sin 2\phi + A_2 w_2 \sin 4\phi\right)$$

$$B\cos\phi(A_0 + A_1 \cos\phi + A_2 \cos 2\phi)(w_0 + w_1 \sin\phi + w_2 \sin 2\phi)$$
$$\sim \frac{1}{4}\left(2A_1 w_0 B + 2A_1 B w_0 \cos 2\phi + (2A_0 B w_1 + 2A_1 B w_2)\sin 2\phi + (A_2 B w_1 + A_1 B w_2)\sin 4\phi\right)$$

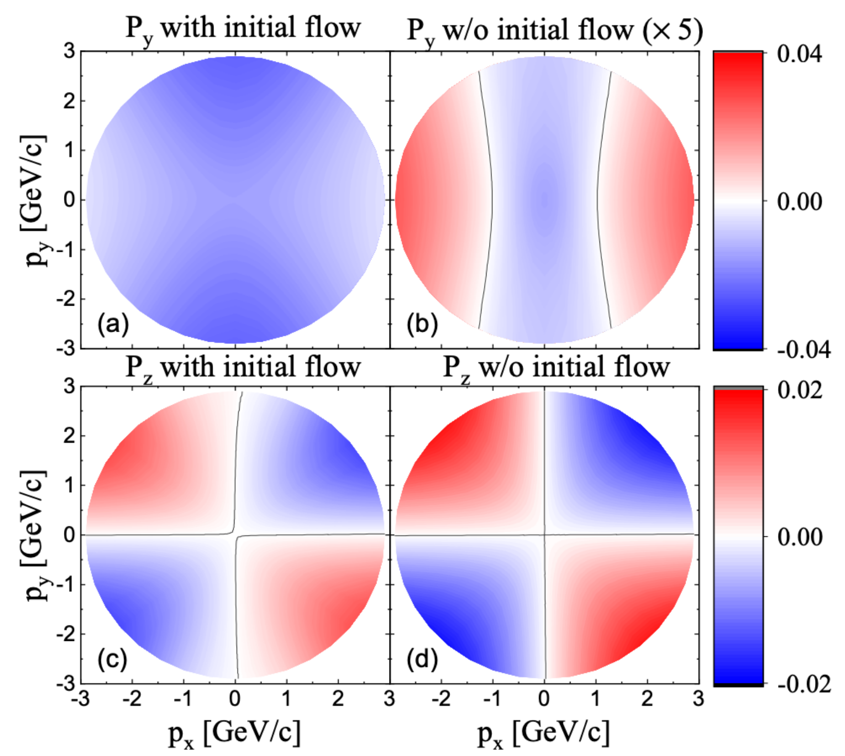


FIG. 7. The distribution of P_y and P_z at mid-rapidity in transverse p_x -p_y plane in 19.6 A GeV Au + Au collisions, calculated from AMPT+MUSIC with and without initial flow.

It is generally believed that the longitudinal polarization P_z is directly associated with the anisotropic transverse expansion of the systems but insensitive to the initial angular momentum [26]. This is confirmed by our AMPT+MUSIC calculations with and without initial flow, which demonstrate that P_z has similar structure in these two comparison runs, as shown by the lower panels of Fig. 7. This also means that the longitudinal vorticity P_z mainly probes the vortical structure developed during the hydrodynamic evolution.

arxiv:2011.03740

Back up

$$P_z^{\rm EM} = \frac{\int d\Sigma dy p_T dp_T f^{EM} \omega^{\rm th}}{\int d\Sigma dy p_T dp_T f^{EM}}$$

$$P_z^{\rm bare} = \frac{\int d\Sigma dy p_T dp_T f \omega^{\rm th}}{\int d\Sigma dy p_T dp_T f}$$

$$P_z^{\rm tot.} = \frac{\int d\Sigma dy p_T dp_T (f + f^{EM}) \omega^{\rm th}}{\int d\Sigma dy p_T dp_T (f + f^{EM})} = \frac{P_z^{\rm bare} + A P_z^{EM}}{1 + A}$$

$$A = \frac{\int d\Sigma dy p_T dp_T f^{EM}}{\int d\Sigma dy p_T dp_T f}$$

$$f \sim A_0 + A_1 \cos\phi + A_2 \cos 2\phi$$

$$\omega^{\rm th} \sim w_0 + w_1 \sin\phi + w_2 \sin 2\phi$$

$$\langle P_z^{\rm bare} \sin 2\phi \rangle \sim \frac{1}{4}\frac{A_1}{A_0}\frac{w_1}{w_0} + \frac{1}{2}\frac{w_2}{w_0}.$$

$$\langle P_z^{\rm EM} \sin 2\phi \rangle \sim \frac{1}{4}\frac{A_0}{A_1}\frac{w_1}{w_0} + \frac{1}{4}\frac{w_2}{w_0}$$

$$\langle P_z^{\rm tot} \sin 2\phi \rangle \sim \frac{1}{4}\frac{w_1}{w_0}\left(\frac{A_1}{A_0} + A\frac{A_0}{A_1}\right) + \frac{1}{2}\frac{w_2}{w_0}\left(1 + \frac{1}{2}A\right)$$