The magnetic dissipative effect on quark-gluon plasma

direct photon production and hyperon local spin polarization

Chirality2024 @ Timisoara, România

arxiv:2302.07696
Phys.Rev.C 109 (2024) 3, 034917
arxiv:2401.07458

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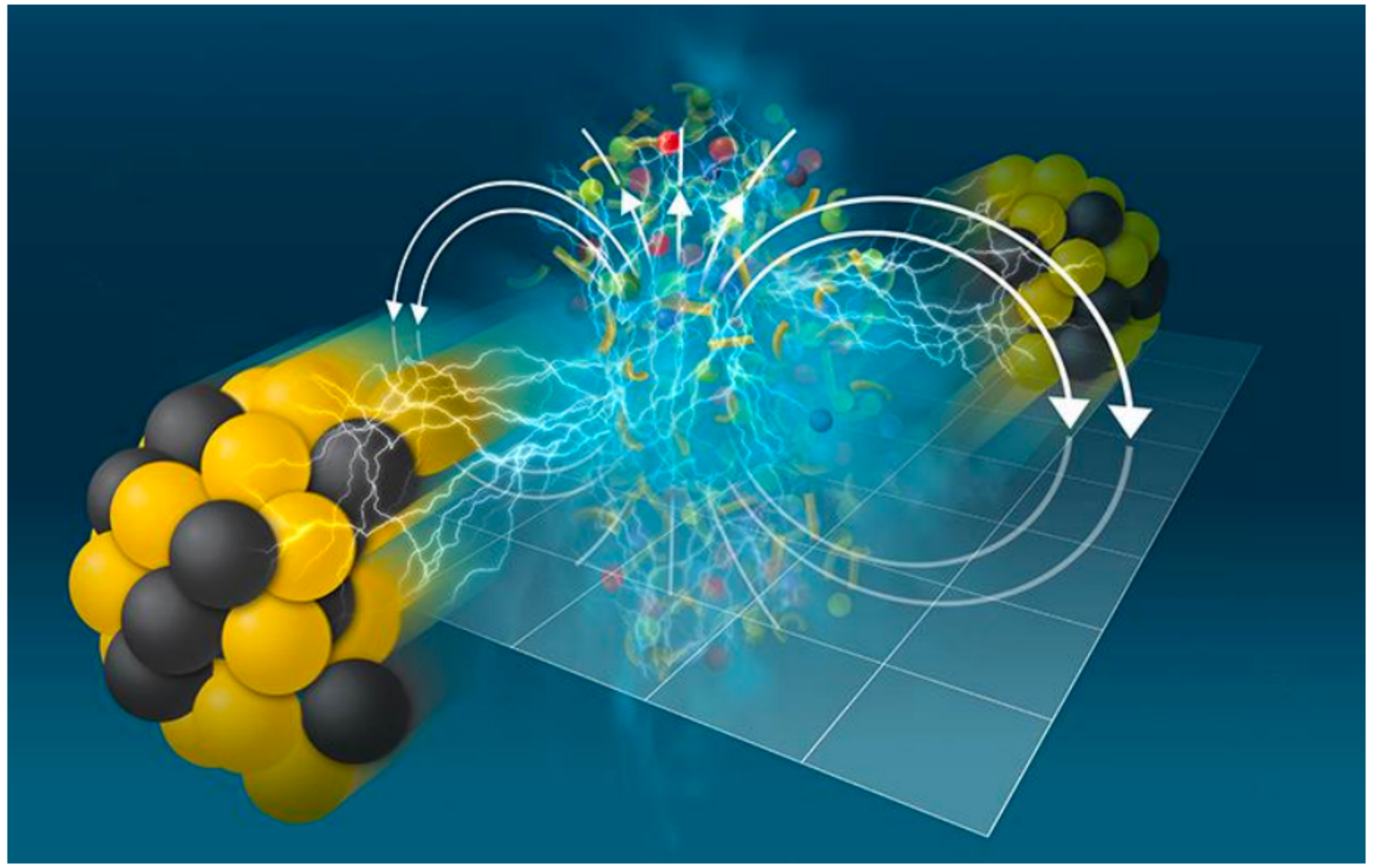
2024.07.23

with Li Yan

Outline

○ The magnetic field in HIC and weak magnetic effect in QGP
○ The direct photon v_2 and the weak magnetic emission
○ The spin polarization and the weak magnetic polarization
○ Summary and outlook

The magnetic field in the heavy-ion collisions

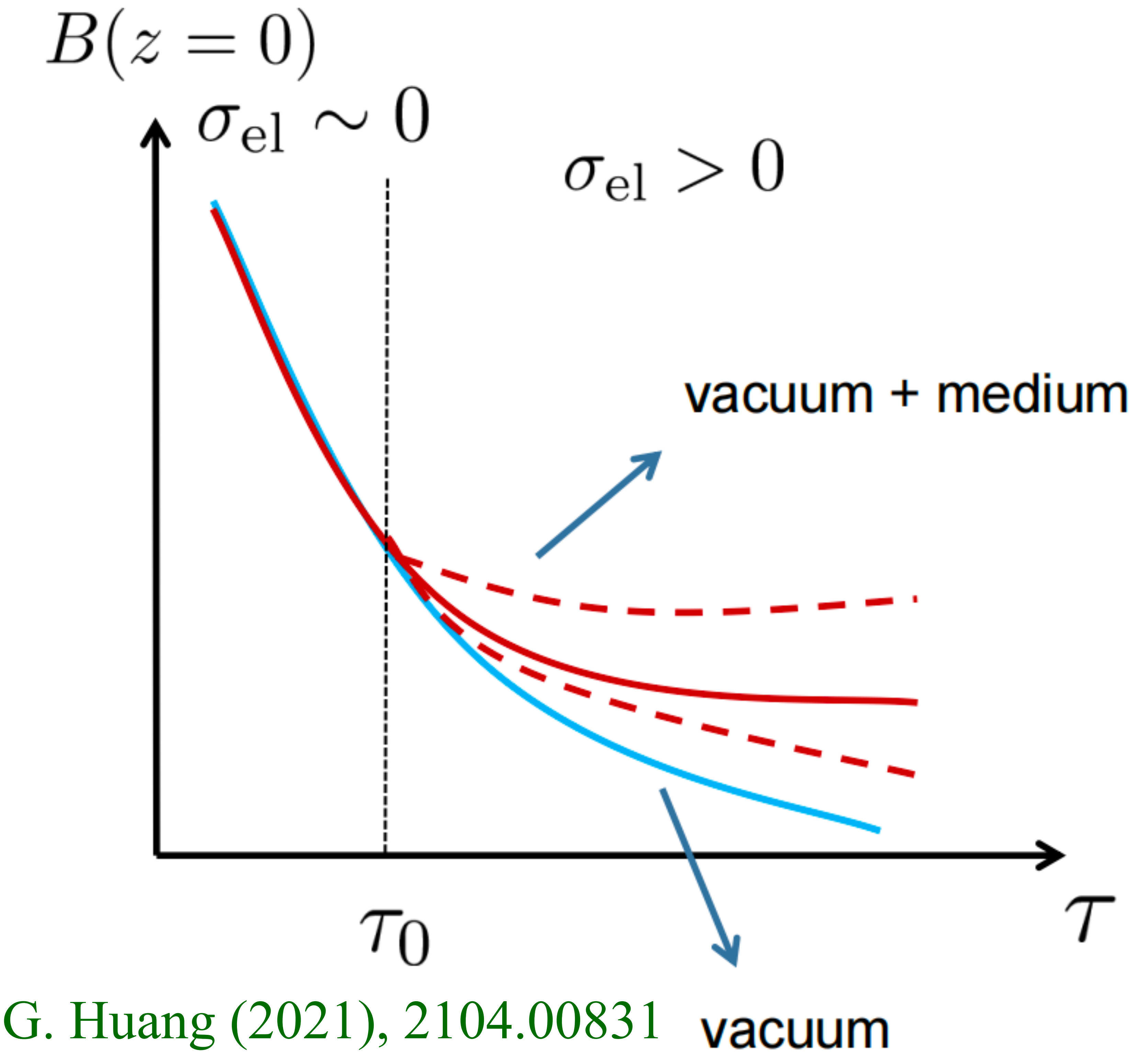


T. Bowman and J. Abramowitz/Brookhaven National Laboratory

- There must be a B field generated.
- orientated out of plane
- Extremely strong initially.

$$eB/m_\pi^2 \sim \begin{cases} O(1) & \text{RHIC} \\ O(10) & \text{LHC} \end{cases}$$

$m_\pi^2 \approx 10^{17}$ Gauss



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

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

- The B field decays dramatically
- B field during the QGP expansion is weak.

$$|B(\tau_0)| \sim 10^{-3}|B(0)| \ll m_\pi^2$$

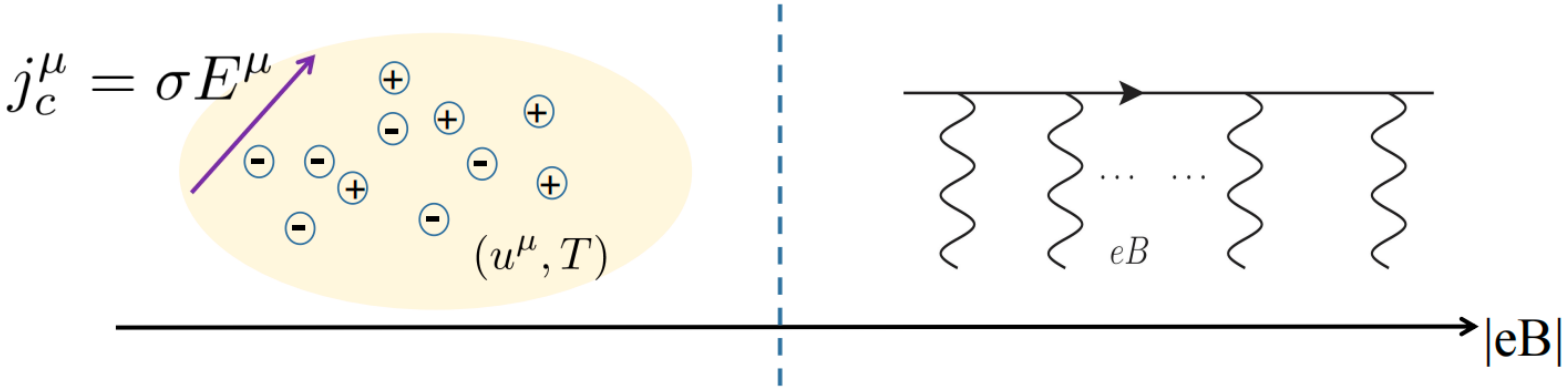
A. Huang et.al (2022),2212.08579.

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

The magnetic effect in QGP: weak vs strong

A slightly redistribution of the
charged components in a fluid cell.

Landau Level



$|eB| \sim T\nabla \ll \epsilon^{1/2}$ $\quad O(m_\pi^2)$ $\quad |eB| \gg g^2T^2$

A weak B field:

- The QCD matter dynamics is merely affected: **scattering process, transport coefficients…**

The magnetic field can be safely viewed as the perturbations of hydro background

Huang, Zhao and Zhuang, 2208.01407

The dissipation due to EM field: w/o spin

- The dissipative correction from the Chapman-Enskog expansion:

$$|eB| \ll T^2$$

$$p^\mu \partial_\mu f + \underbrace{qF^{\mu\nu} p_\mu \frac{\partial}{\partial p^\nu}}_{\text{Vlasov term}} f = C[f] \sim \frac{f - n_{\rm eq}}{\tau_R}$$

at the leading order of $\dfrac{|eB|}{T^2}$

$$\delta f_{\rm EM} \sim \tau_R q F^{\mu\nu} p_\mu \frac{\partial}{\partial p^\nu} n_{\rm eq}$$

- Landau matching: dissipative correction in conserved current

$$J_{a,\mu} = eQ_a n_a u^\mu + eQ_a N_{a,\mu} \qquad N_{a,\mu} = \int \frac{d^3p}{(2\pi)^3 E_p} p^\mu \delta f_{a,EM}$$

$$J_\mu = \sum_a J_{a,\mu} = \sigma_{el} F_{\mu\nu} u^\nu \equiv \sigma_{el} E_\mu$$

The dissipation due to EM field: with spin

F. Becattini et al., Annals of Physics 338 (2013) 32–49

Effects of dissipation
S. Bhadury's talk on Friday

- The Chapman-Enskog expansion with spin d.o.f:

$$p^\mu \partial_\mu \mathscr{F} + QF^{\mu\nu} p_\mu \frac{\partial \mathscr{F}}{\partial p^\nu} = -\mathscr{C}[\mathscr{F}] = -(p \cdot u) \frac{\mathscr{F} - \mathscr{F}_{\rm eq}}{\tau_R}$$

$$\mathscr{F}_{\rm eq} = \frac{1}{2m} \overline{U}(p) X(x,p) U(p)$$

$$\boxed{\delta \mathscr{F}_{\rm EM} = -\frac{\bar{\tau}}{T} QF^{\mu\nu} p_\mu \frac{\partial}{\partial p^\nu} \mathscr{F}_{\rm eq} = \frac{1}{2m} \overline{U}(p) Y(x,p) U(x,p)}$$

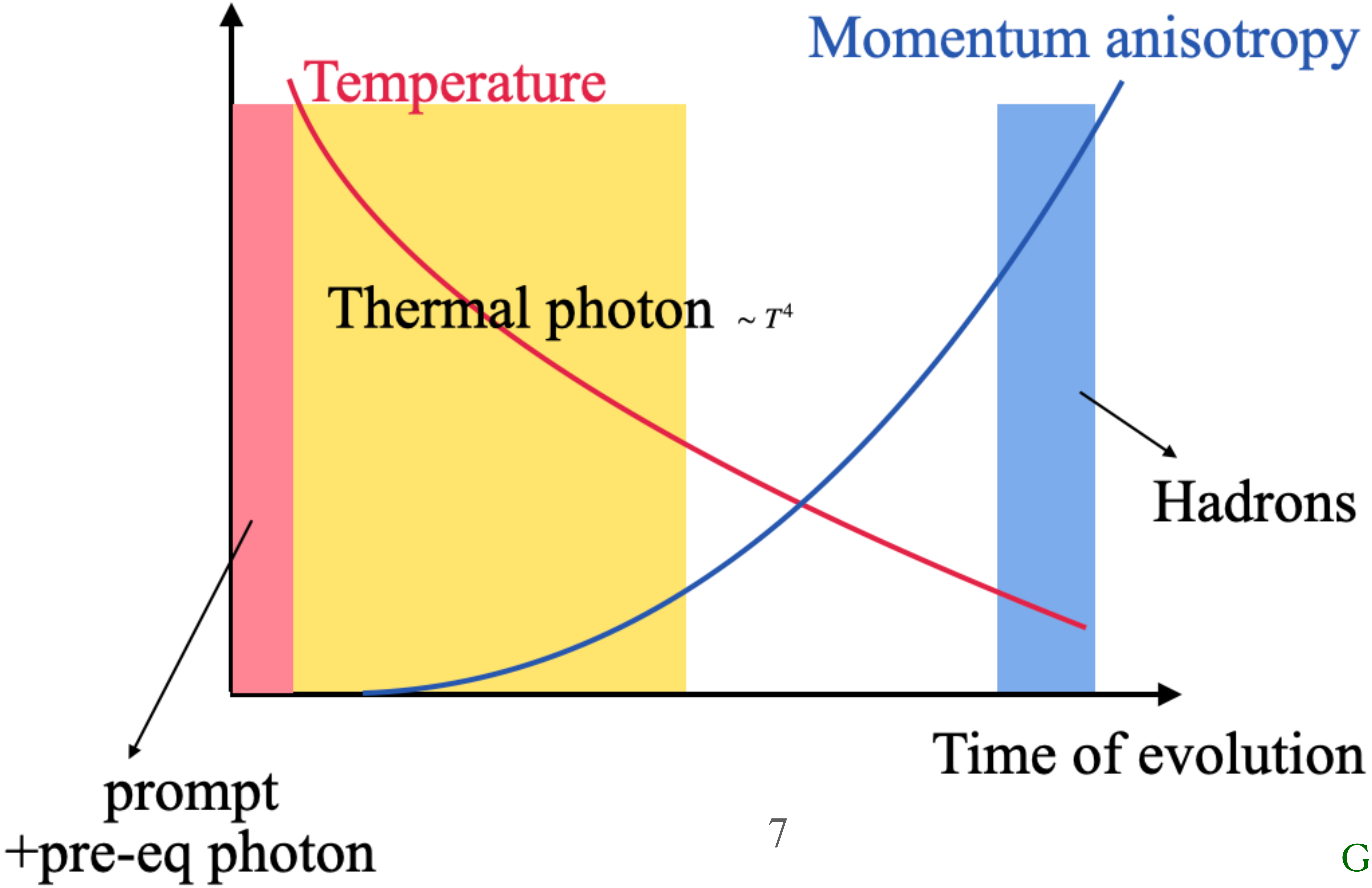
$$Y(x,p) \equiv -\frac{\bar{\tau}}{T} QF^{\mu\nu} p_\mu \frac{\partial X}{\partial p^\nu} = \frac{\bar{\tau}}{T} QF^{\mu\nu} p_\mu \beta_\nu e^{\beta \cdot p} X^2 \exp\left(-\frac{1}{2}\omega_{\alpha\beta}\Sigma^{\alpha\beta}\right) .$$

- The spin averaged quark distribution function reduces to

$$\frac{1}{2}\mathrm{tr}_2 \mathscr{F}_{\rm eq} = n_{\rm eq} \qquad \frac{1}{2}\mathrm{tr}_2 \delta\mathscr{F}_{\rm EM} = \delta f_{\rm EM}$$

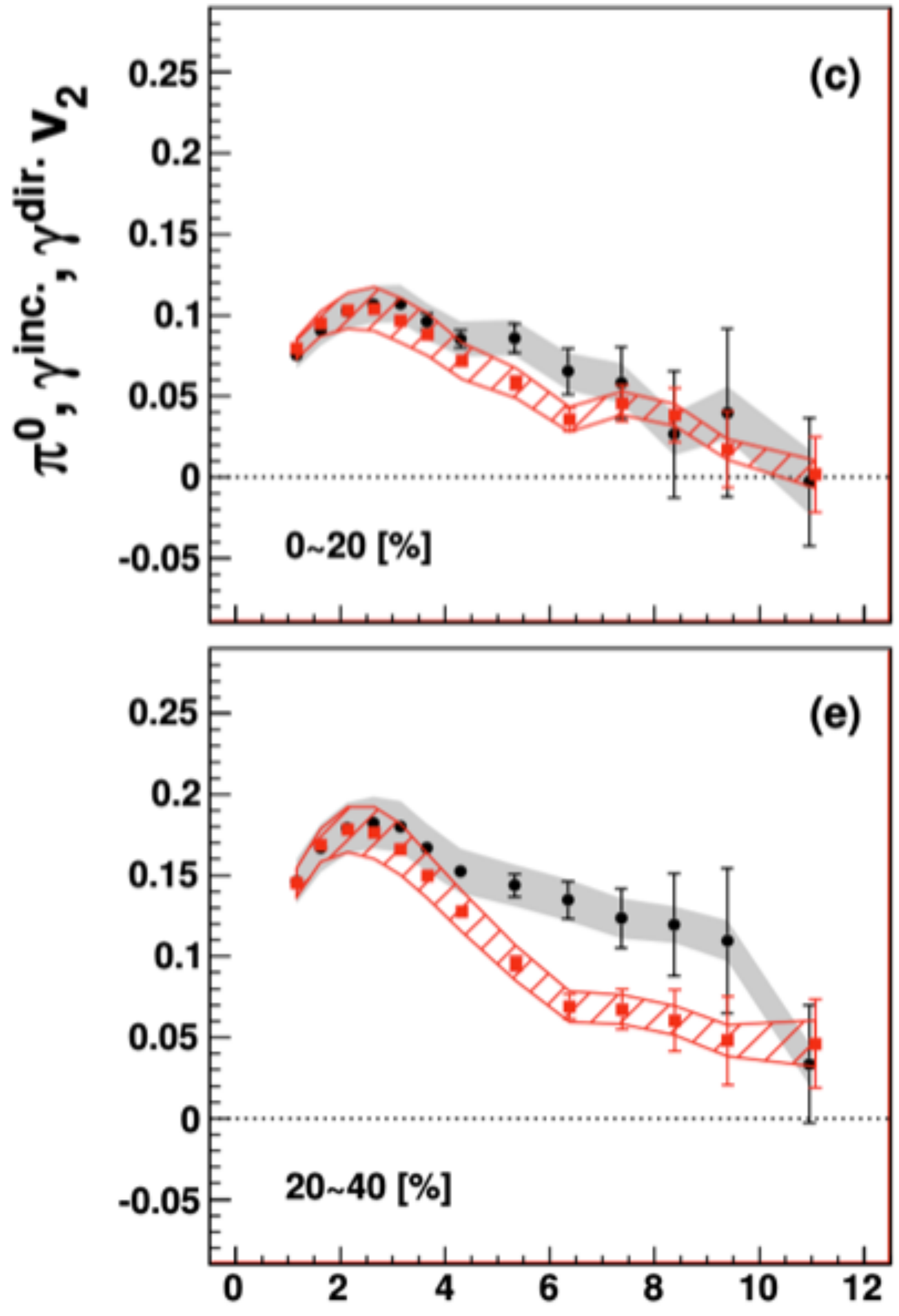
Direct photon v_2: theoretical expectation

- **Direct photons: all sources except hadron decay.**
- Theory expects smaller v_2 of direct photons than hadrons

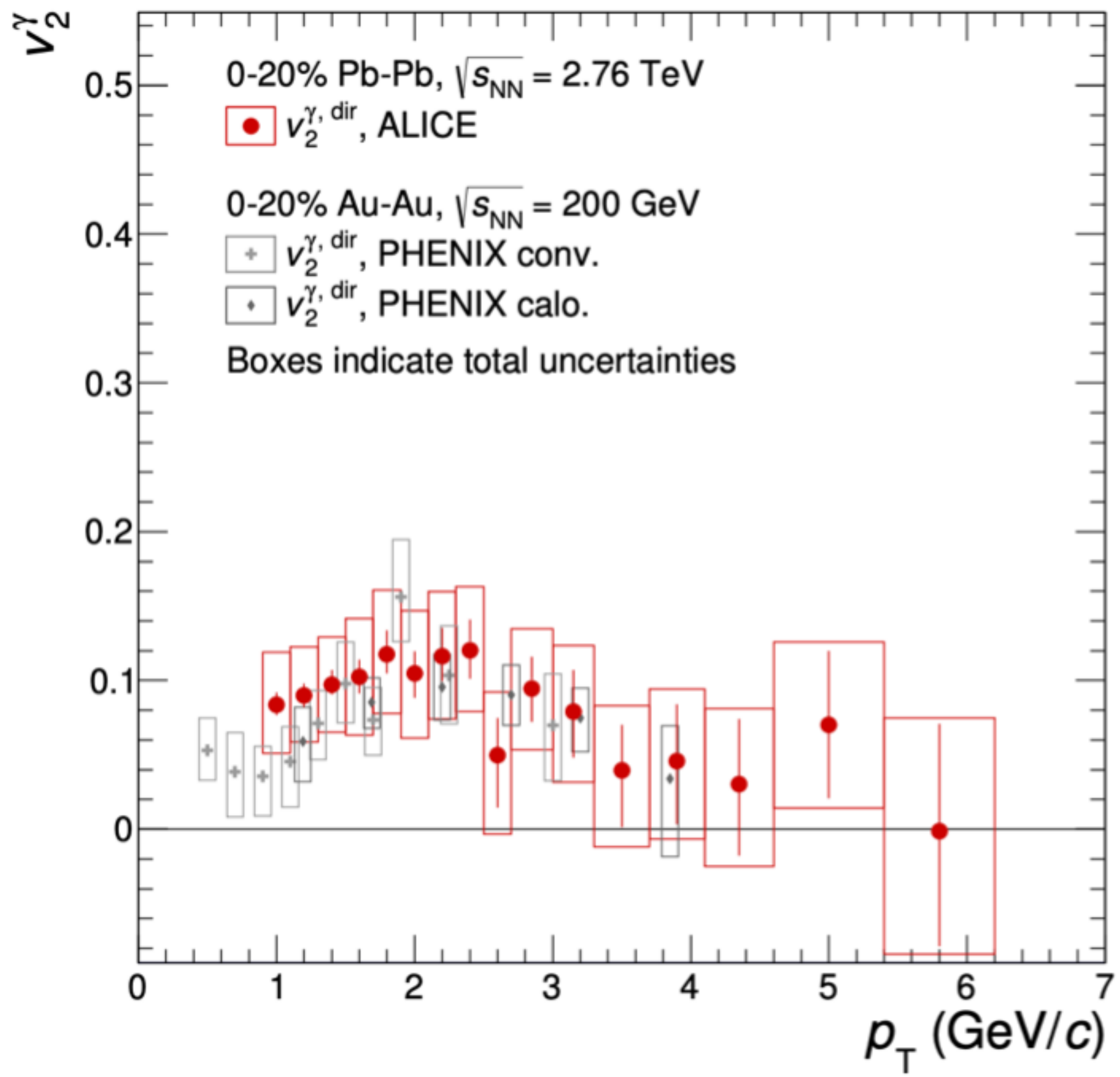


Gabor David, arXiv:1907.08893v2

Direct photon v_2: Experimental results



PHENIX, PRL (2012)



ALICE PLB (2019)

Theory

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

↑

Puzzle!

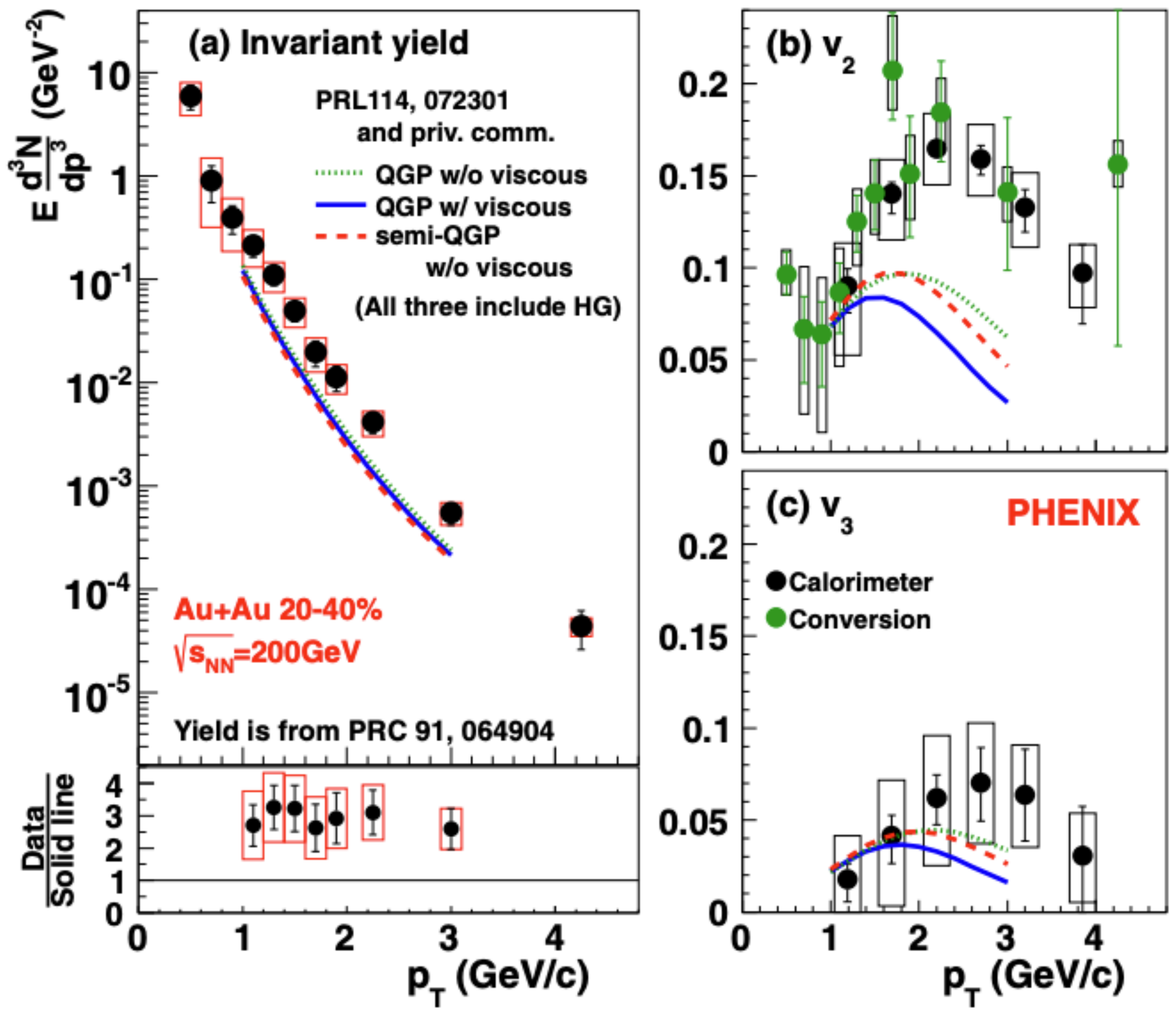
↓

Experiment

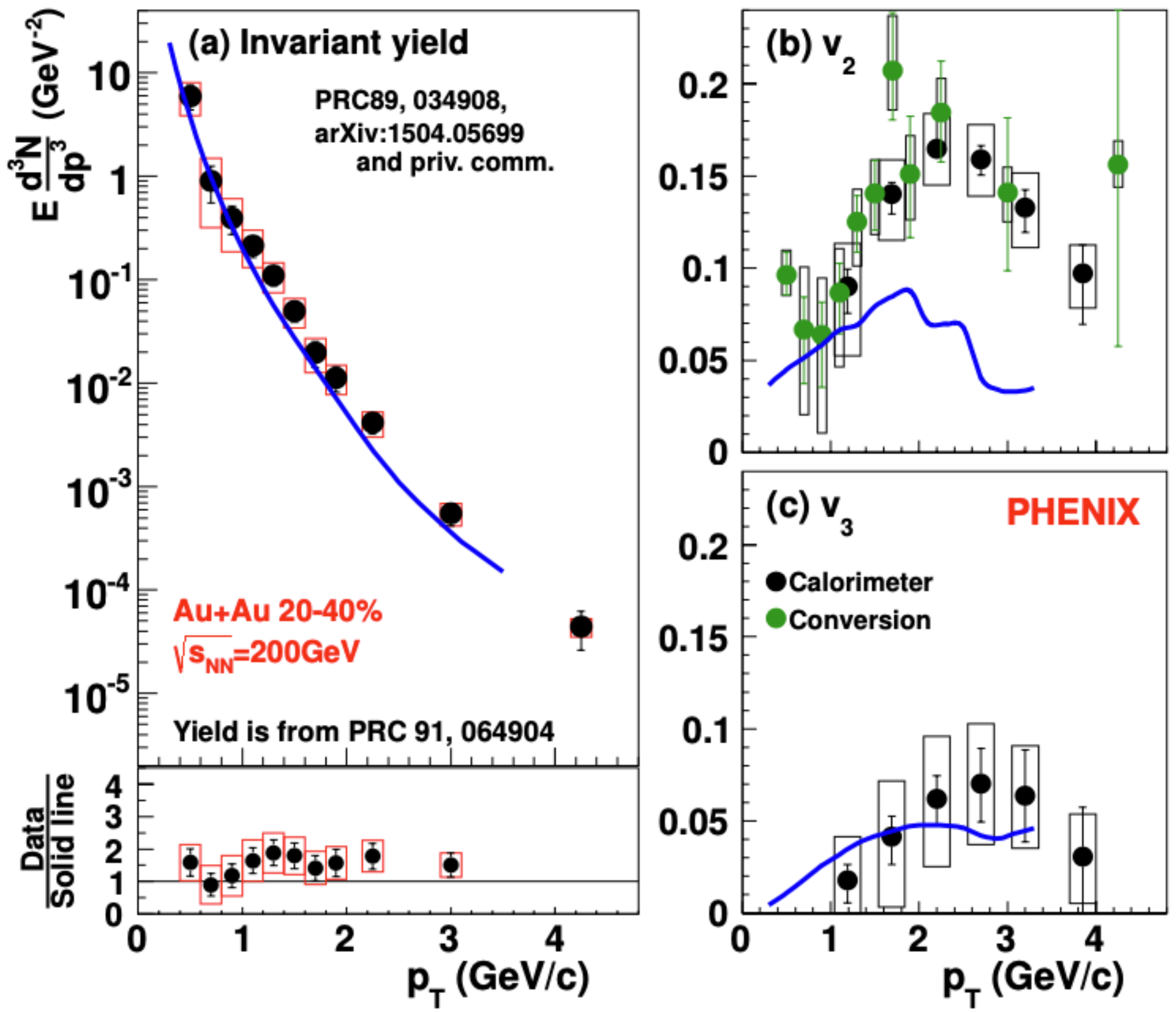
$v_2^\gamma \approx v_2^{\text{hadron}}$

Experiments vs theory

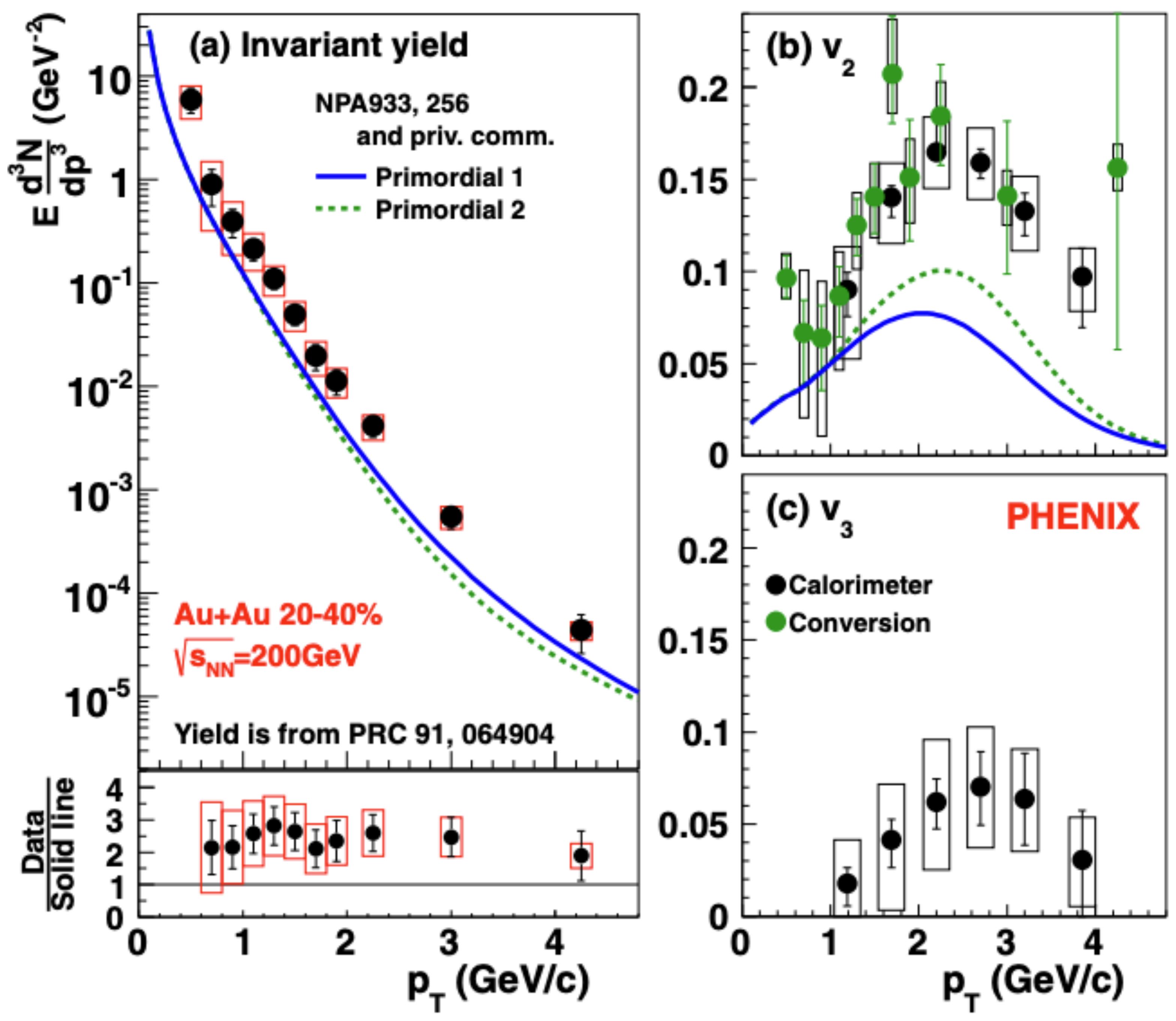
Hydrodynamical models



Transport calculations



Fireball model



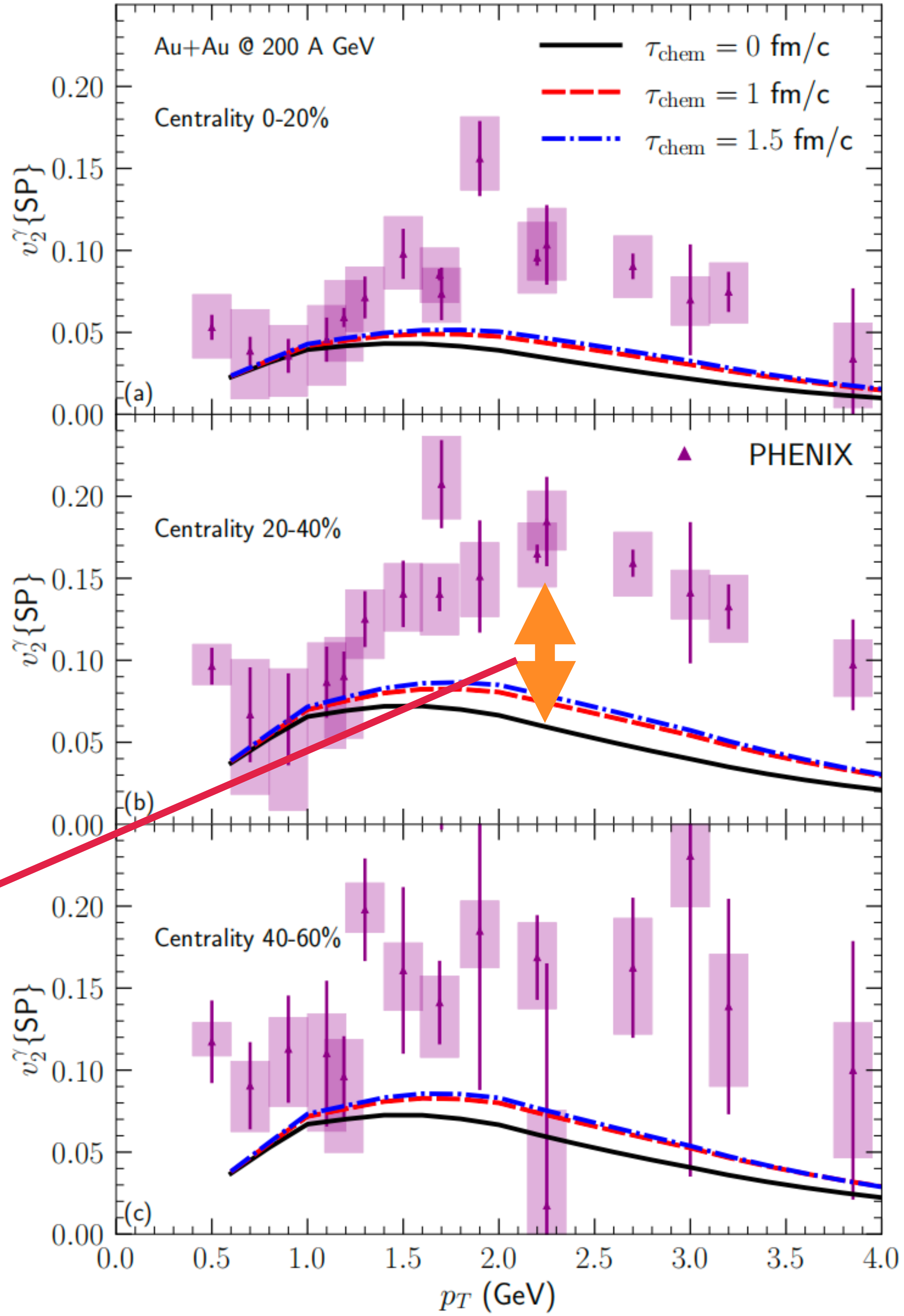
- **"Not too much of a puzzle left for yields."** [K. Reygers, Quark Matter 2022 plenary talk]
- The present models are being challenged. A. Adare et al. (PHENIX),Phys. Rev. C94, 064901 (2016)

Direct photon v_2: the most updated calculations

- Pre-equilibrium dynamics (KoMPost)
- Chemical equilibration in QGP
- NNLO pQCD for prompt photons
- **Dissipation corrections from shear and bulk**

………

$$f_q = n_q + \delta f$$



The v_2 of direct photon is still **under-predicted.**

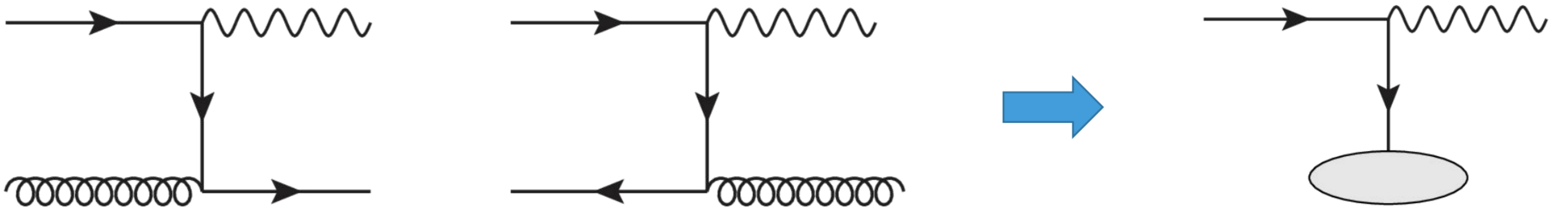
The gap $\sim 0.05 - 0.10$

J-F Paquet, et,al Phys. Rev. C93, 044906 (2016)

C. Gale, J.-F. Paquet, B. Schenke, and C. Shen, Phys.Rev. C 105, 014909(2022)

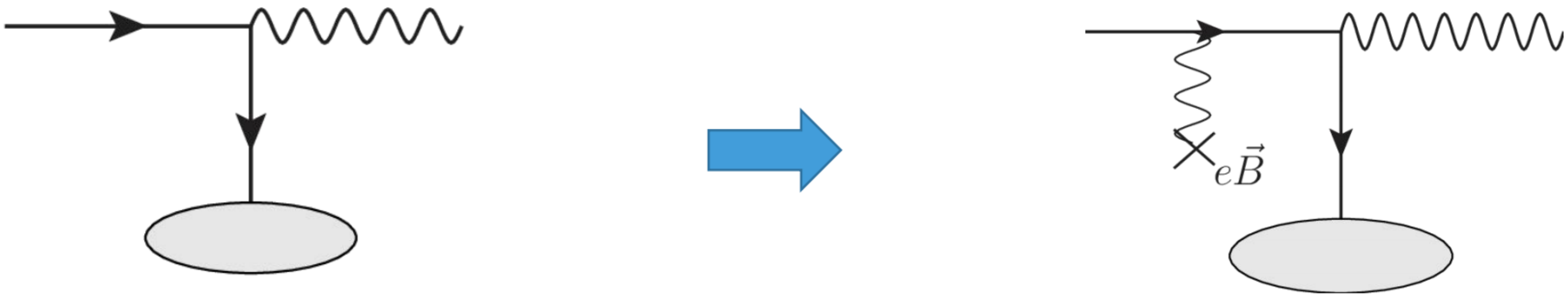
The weak magnetic photon emission

- Small angle approximation



The blobs represent the effect of QGP medium

- Include also dissipative correction due to EM field



$$R^\gamma \propto \quad f_q = n_q + \delta f + \delta f_{EM}$$

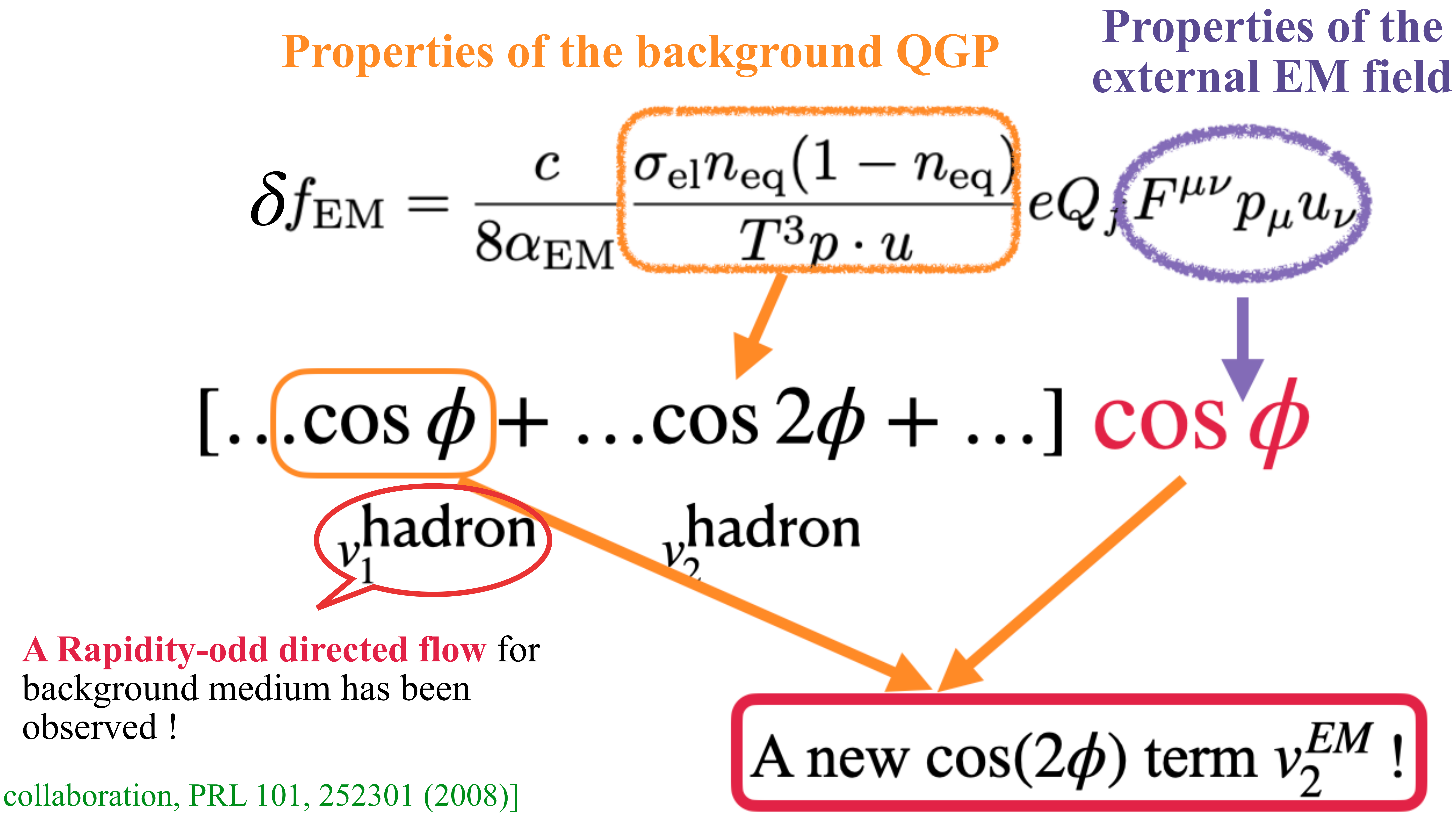
Spin not involved

- **No significant difference beyond the small angle approximation**

J.Sun et.al, in progress

The source of momentum anisotropy

- The **coupling** effect between the **weak magnetic field** and the **longitudinal dynamics of the fireball**



Properties of the background QGP

Properties of the external EM field

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

$$[\ldots\boxed{\cos\phi} + \ldots\cos 2\phi + \ldots]\cos\phi$$

v_1^{hadron} v_2^{hadron}

A Rapidity-odd directed flow for background medium has been observed !

A new cos(2ϕ) term v_2^{EM} !

Bjorken analysis

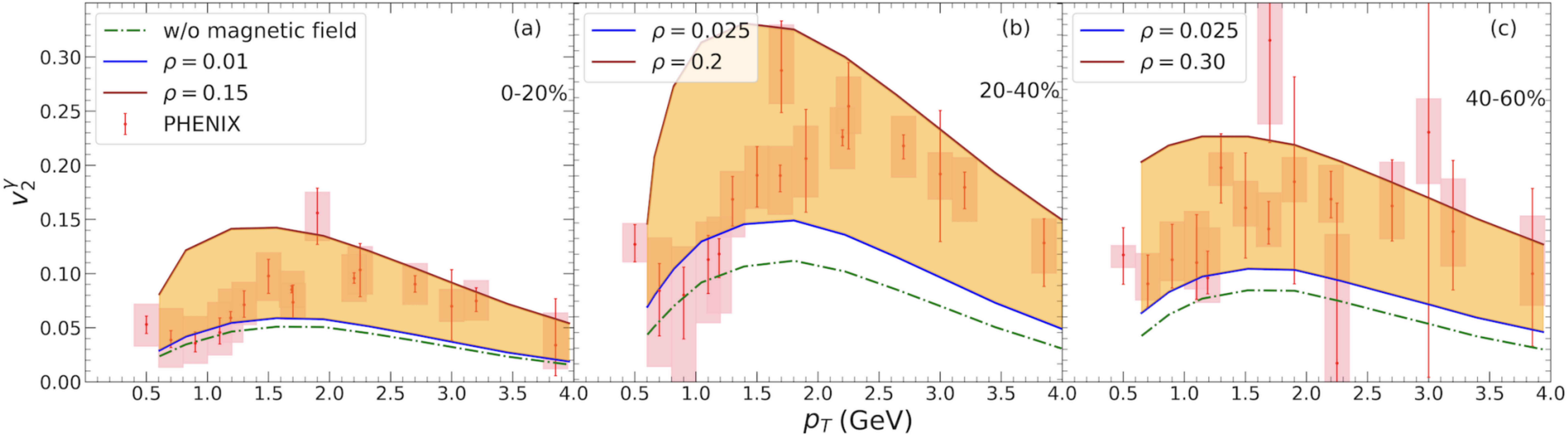
$$v_2^{EM} \sim 0.5$$

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

Gursoy, Dima Kharzeev and Rajagopal, PRC (2014)

EBE hydro v_2: RHIC

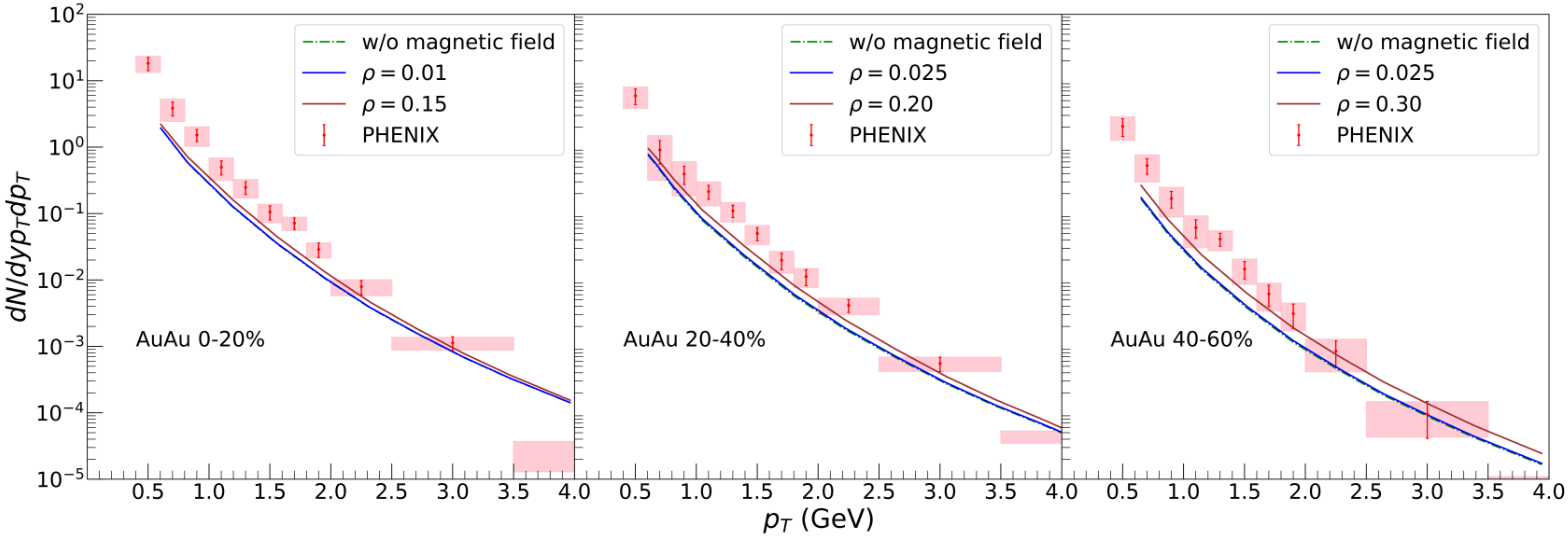
AuAu@200GeV



- A realistic simulation: Trento3D + MUSIC (1,000 events each centrality)
- "All" source of direct γ + weak magnetic emissions
- A dimensionless parameter ρ tuned to cover the data
- The **photon elliptic flow** can be enhanced significantly and confront the experiment data with the weak magnetic emission .

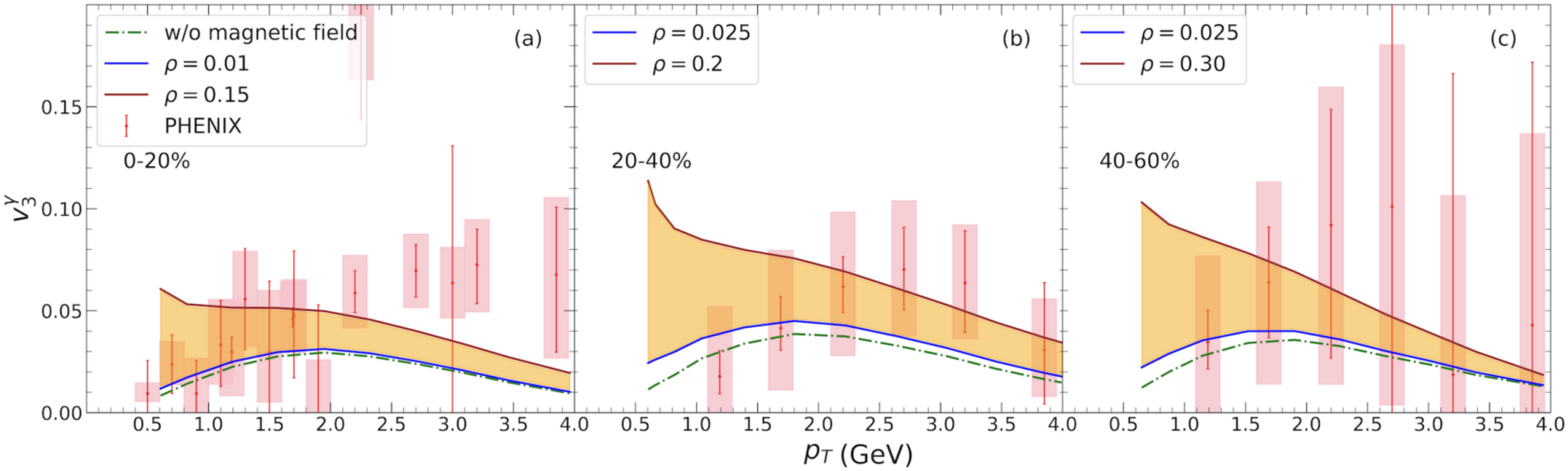
$$\rho \equiv \frac{\sigma_{\text{el}}}{T} \overline{\frac{eB_y}{m_\pi^2}}$$

EBE hydro yield: RHIC



- The tuned ρ for v_2^γ is used to calculate the photon yields.
- The increased yields $\sim$ **10%-20%,** small and acceptable.

EBE hydro v_3: RHIC

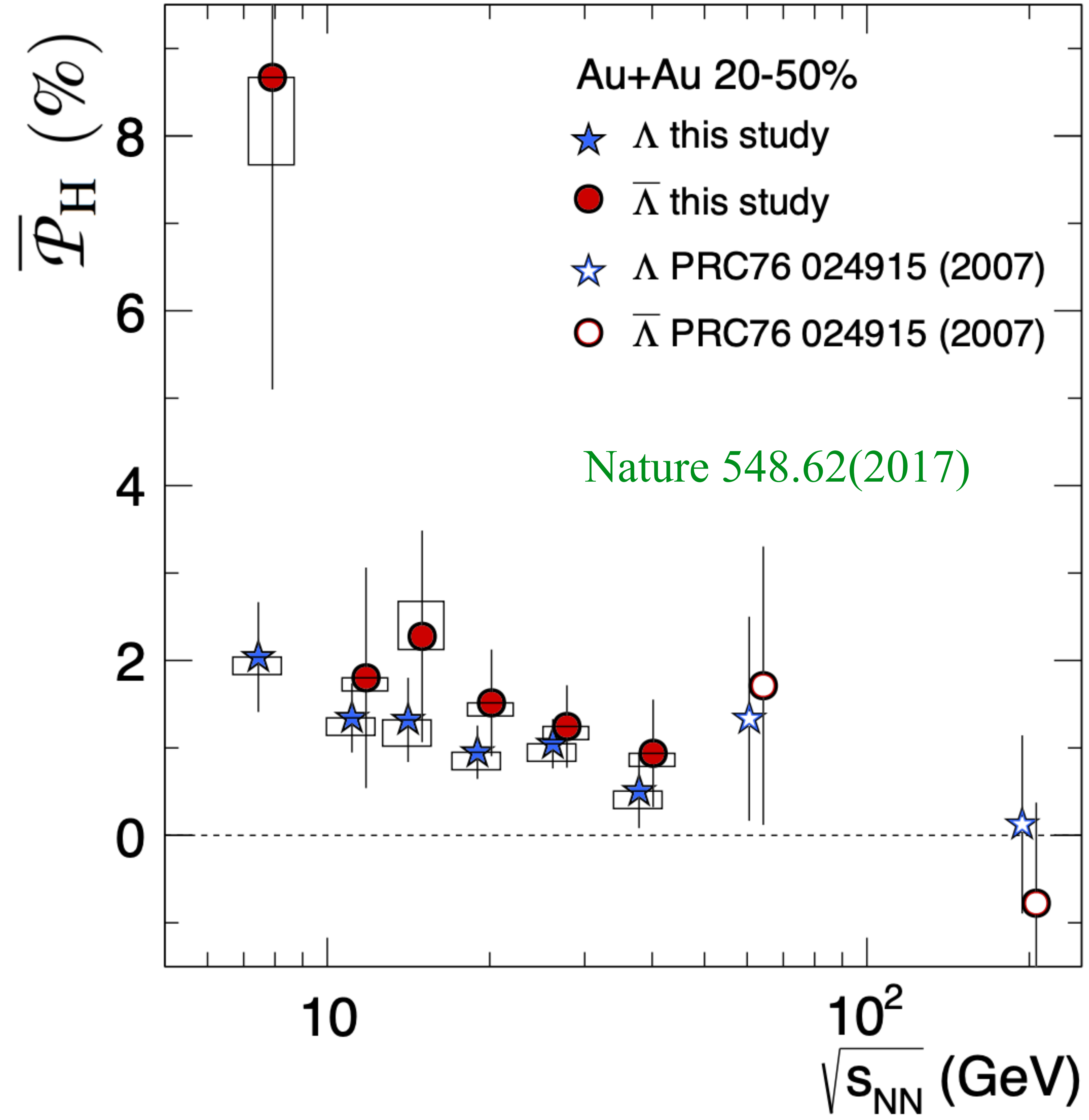


- The significant **triangle flow increment** demonstrates the non-trivial weak magnetic effect furthermore.

The Global spin polarization

- the most vortical system

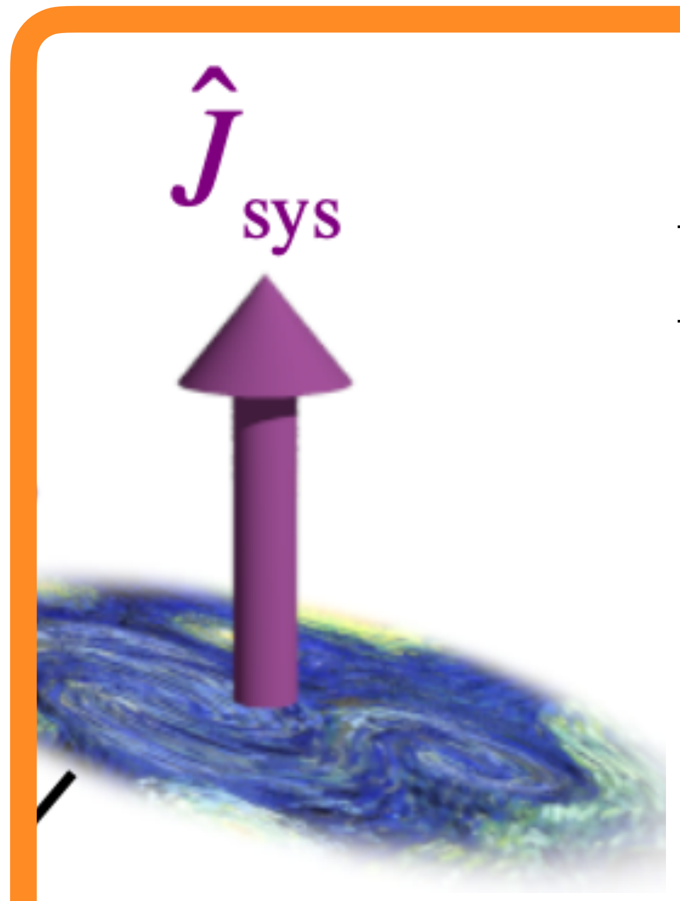
$$\omega = (9 \pm 1) \times 10^{21} s^{-1}$$



Nature 548.62(2017)

- Consistent with the hydrodynamic prediction

- How the orbit angler momentum is converted to the spin of particles



Rotated QGP

↓ *Global equilibrium*

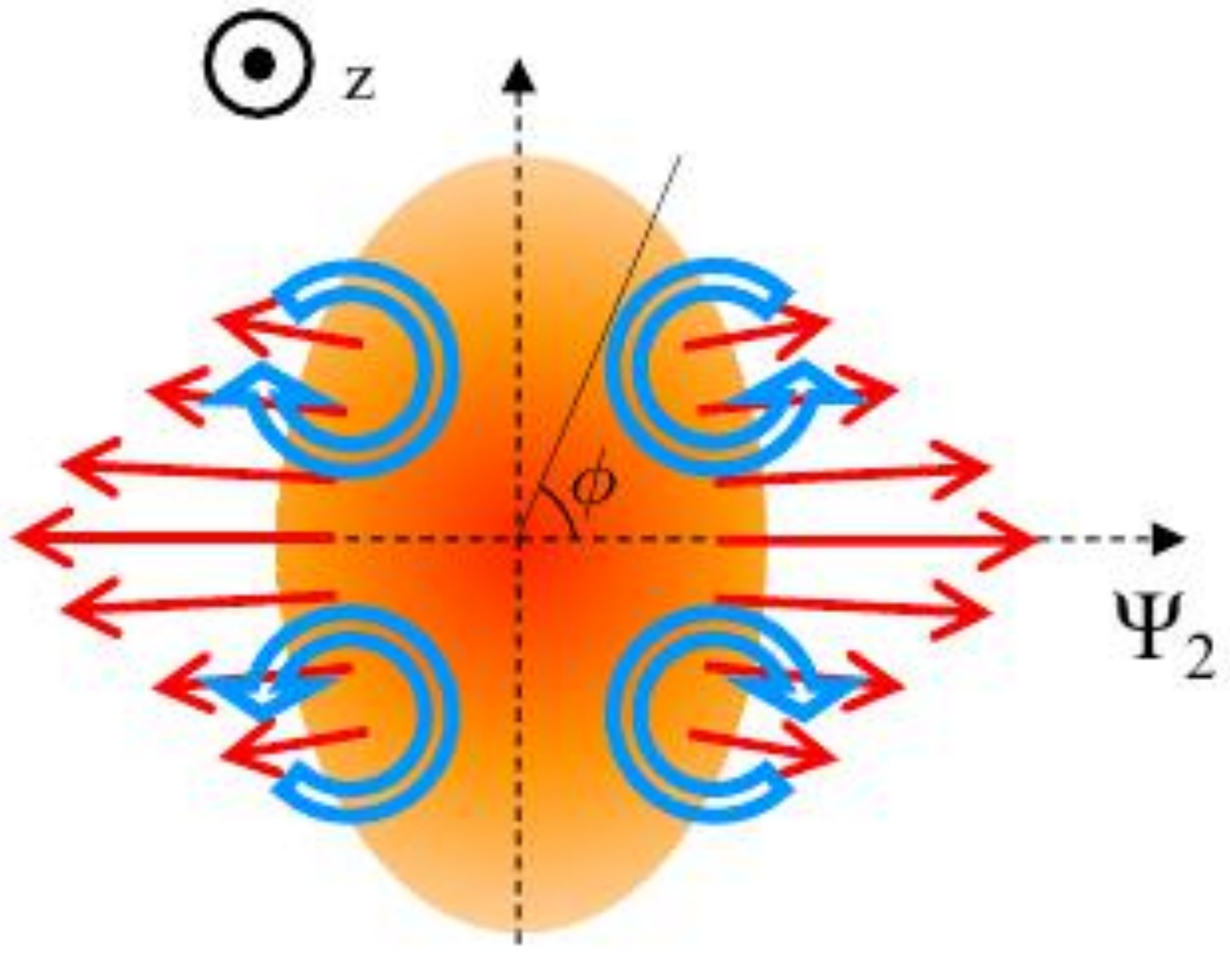
Thermal vorticity $\varpi_{\mu\nu} = -\frac{1}{2}(\partial_\mu\beta_\nu - \partial_\nu\beta_\mu)$

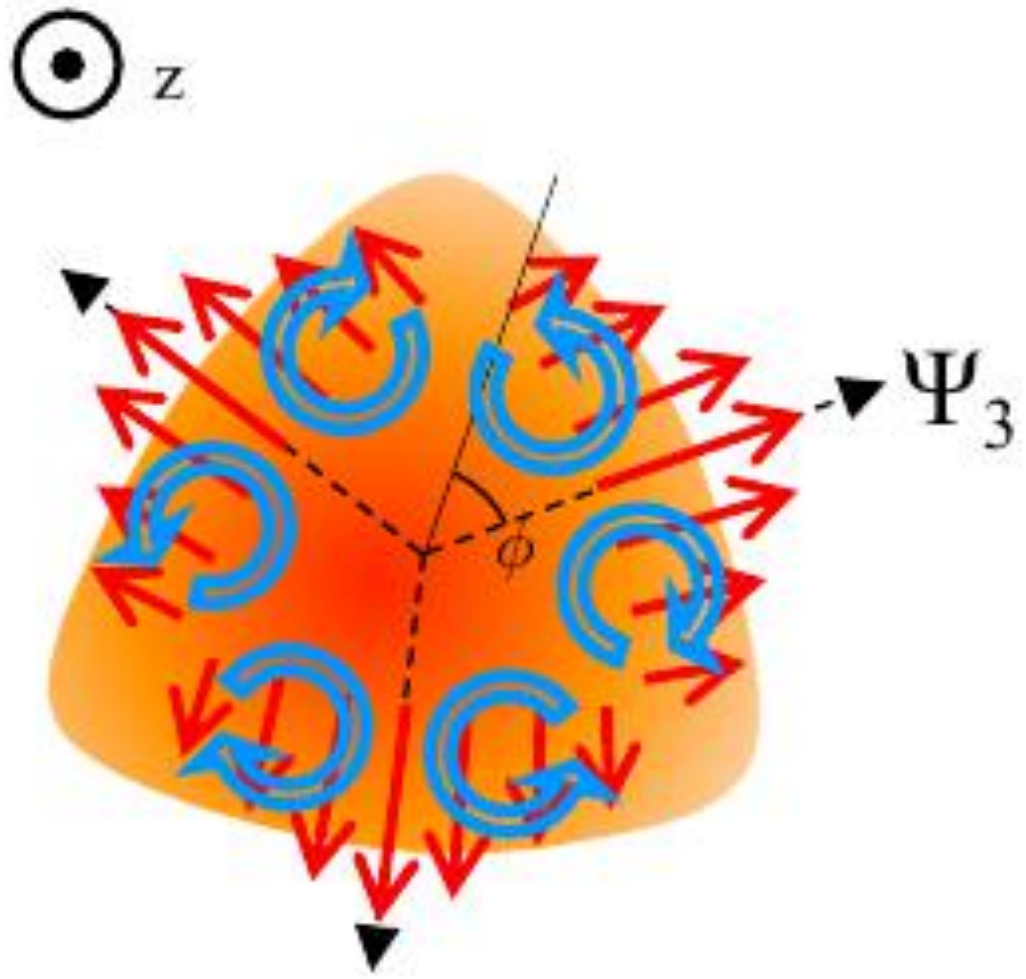
↓ *spin-orbit coupling*

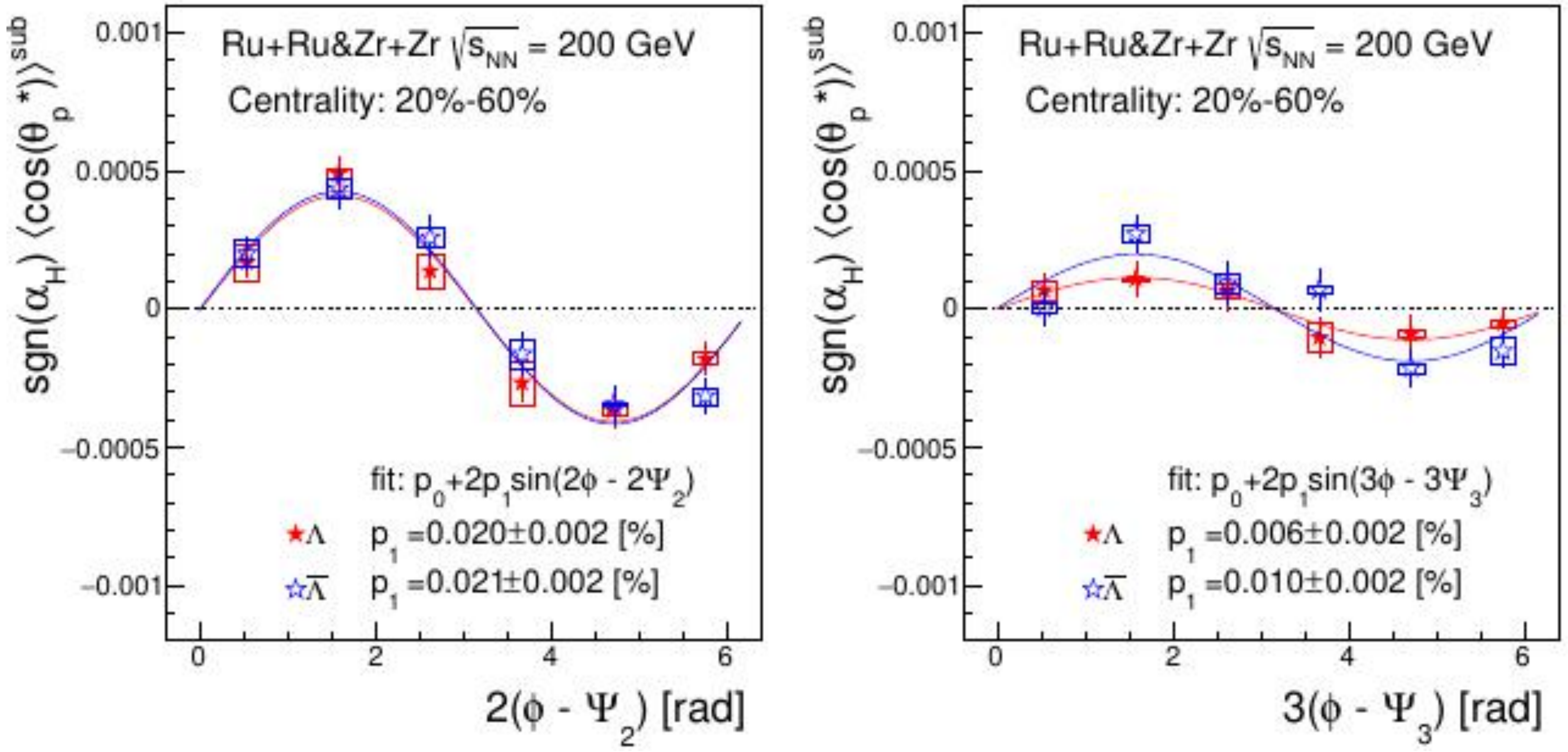
Global spin polarization

The local spin polarization

Along the beam direction







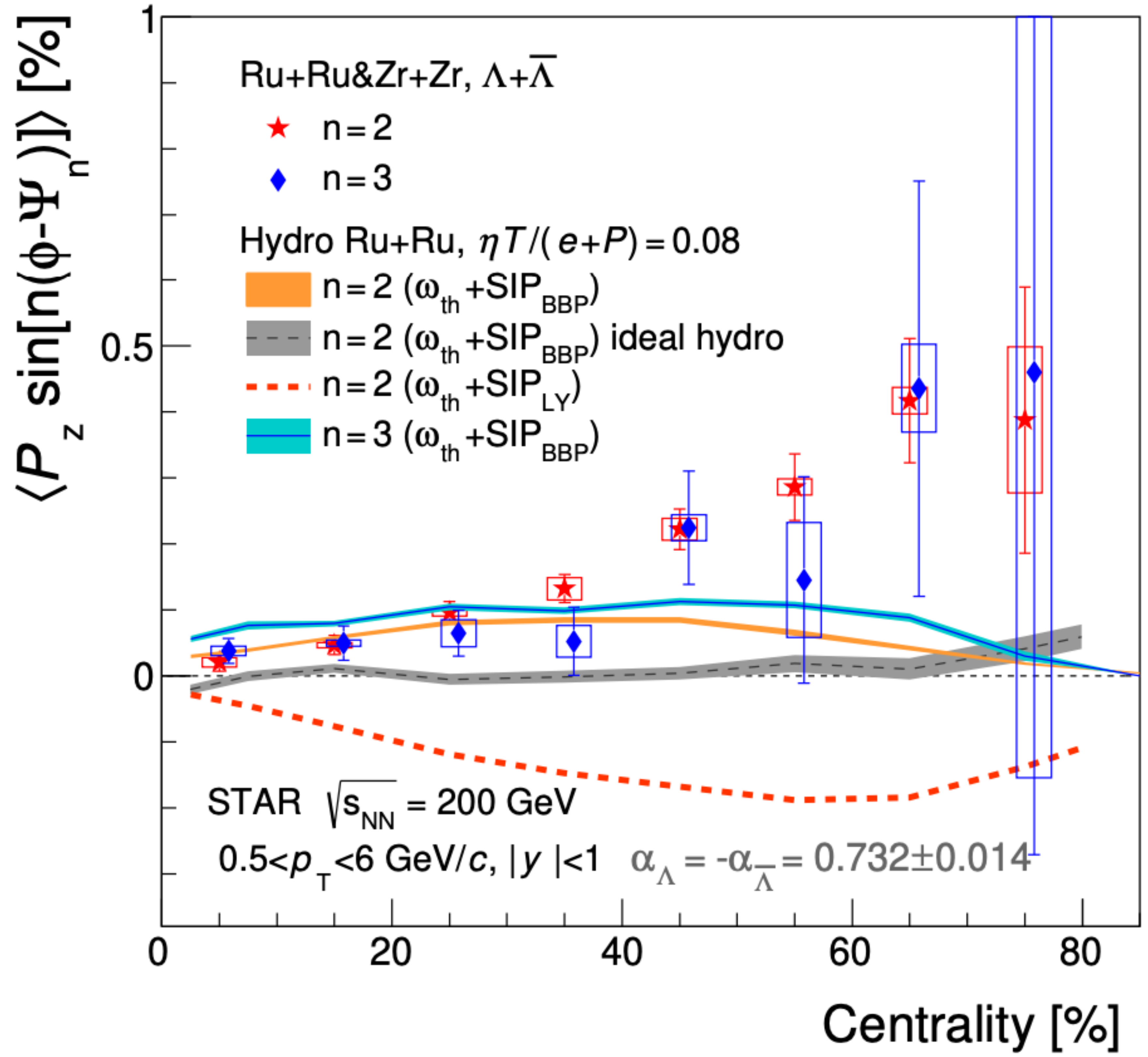
STAR 2023 PhysRevLett.131.202301

Alzhrani S, Ryu S, Shen C. Physical Review C, 2022, 106(1): 014905.

- In thermal equilibrium: thermal vorticity driven by initial geometry, leading to spin polarization.
- **Sign observed against** naive hydro expectation using thermal vorticity.

Beyond global equilibrium: thermal shear coupling

$$\bar{\omega}^{\rho\sigma} \to \bar{\omega}^{\rho\sigma} + \mathrm{SIP}$$

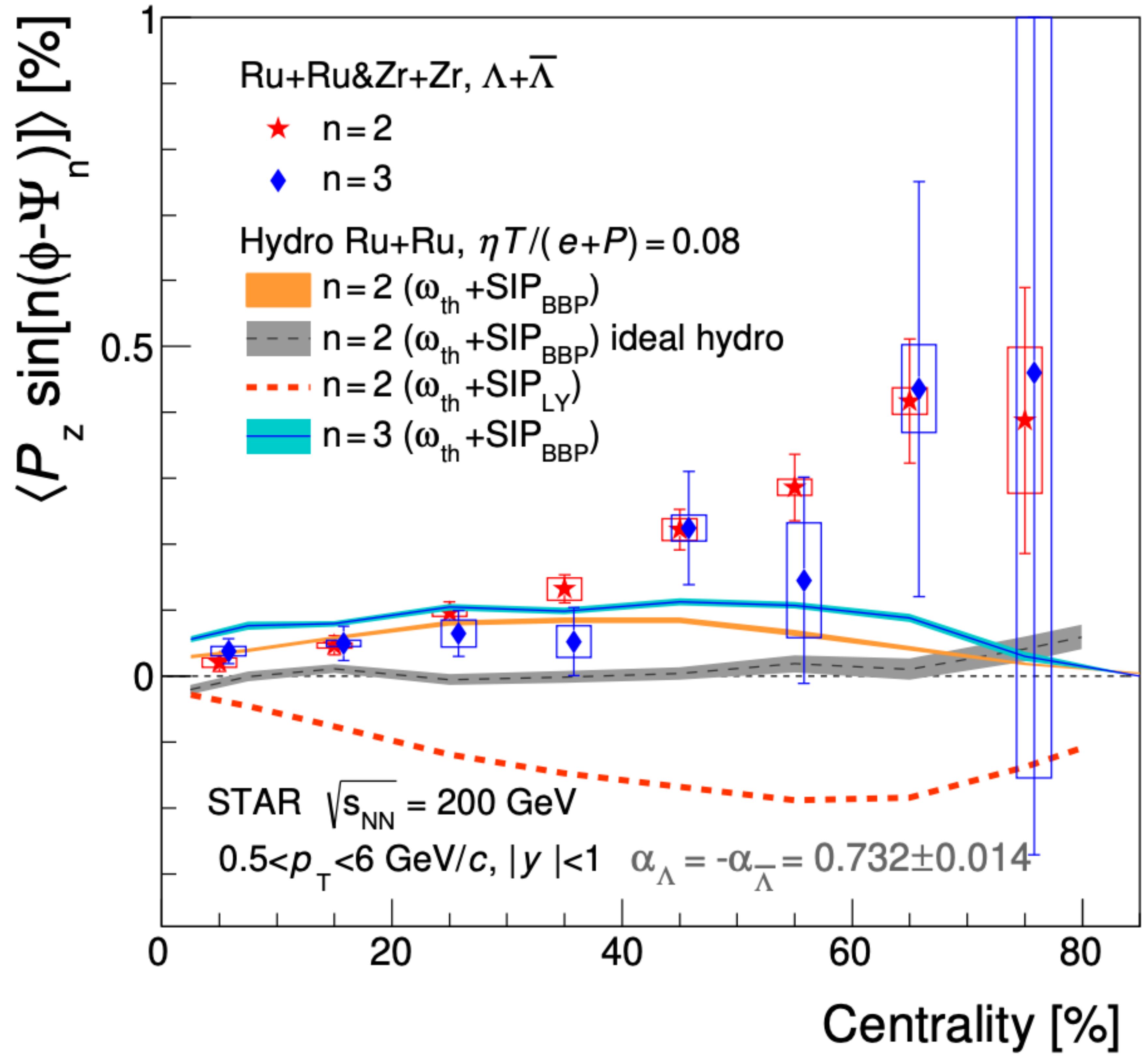


- The sign can be flipped by the SIP(BBP).
- With SIP, the third-order modulation is greater than the second-order one.
- The centrality dependence can not be reproduced with SIP.

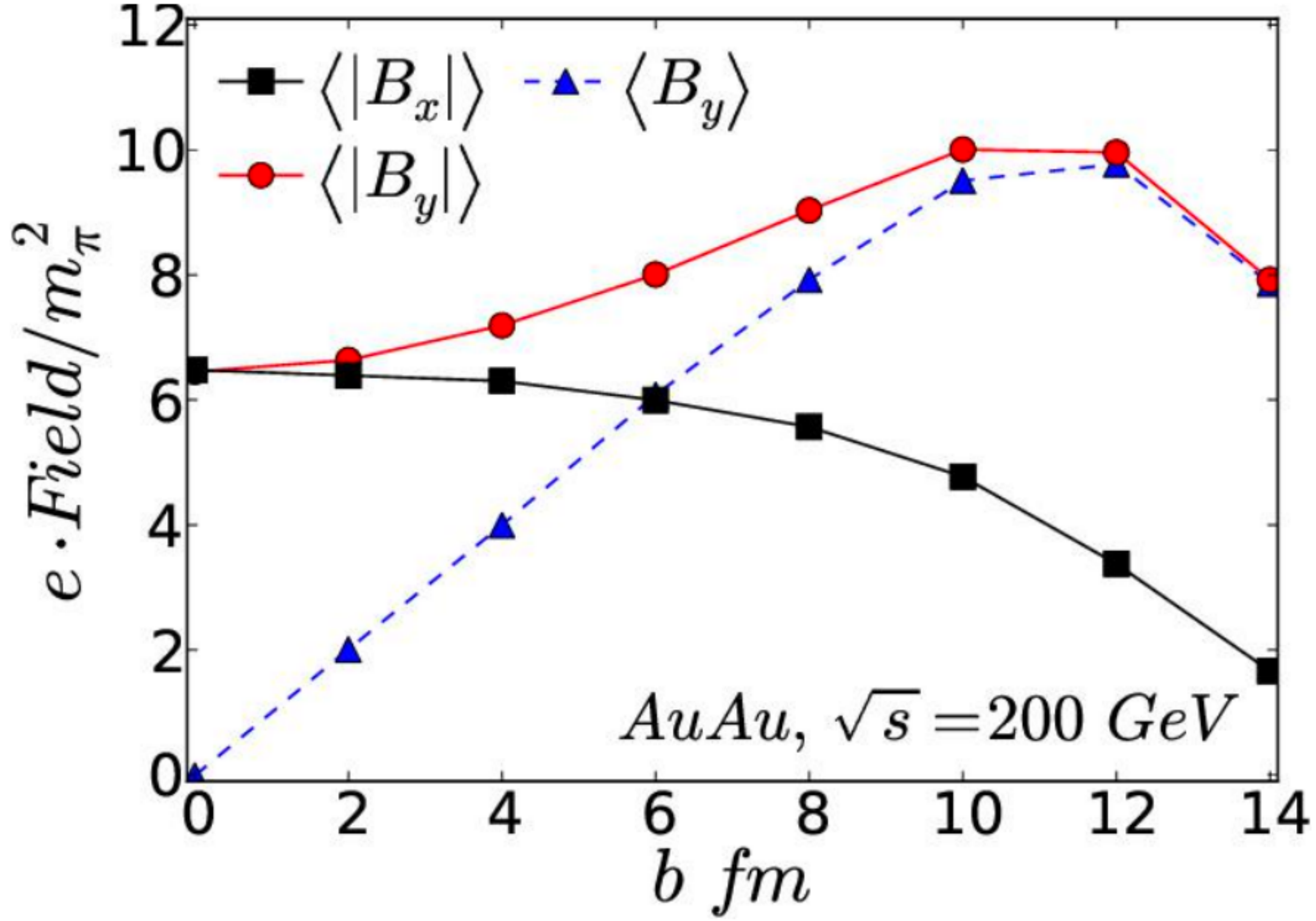
S. Y. F. Liu and Y. Yin, JHEP 07, 188 (2021)
F. Becattini, M. Buzzegoli, and A. Palermo, Phys. Lett. B 820, 136519 (2021), arXiv:2103.10917

Beyond global equilibrium: thermal shear coupling

$$\bar{\omega}^{\rho\sigma} \to \bar{\omega}^{\rho\sigma} + \mathrm{SIP}$$



A. Bzdak, V. Skokov, 1111.1949



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The weak magnetic polarization

Dissipative terms introduced by the weak B

F. Becattini et al., Annals of Physics 338 (2013) 32–49

$$\mathscr{F} = \mathscr{F}_{\rm eq} + \delta\mathscr{F}_{\rm EM} = \frac{1}{2m}\bar{U}(p)(X+Y)U(p)$$

- Spin tensor:

$$s^{\lambda,\rho\sigma}(x) = \frac{1}{2}\int \frac{d^3\boldsymbol{p}}{2p^0}{\rm tr}_2\left(\mathscr{F}\overline{U}(p)\{\gamma^\lambda,\Sigma^{\rho\sigma}\}U(p)\right) = \int \frac{d^3\boldsymbol{p}}{2p^0}\left[p^\lambda\Theta^{\rho\sigma} + p^\rho\Theta^{\sigma\lambda} + p^\sigma\Theta^{\lambda\rho}\right]$$

$$\boxed{\Theta^{\mu\nu}(x) \equiv {\rm tr}_2\left[(X+Y)\Sigma^{\mu\nu}\right] = \left[n_F(1-n_F) + (1-2n_F)\delta f_{\rm EM}\right]\omega^{\mu\nu}}$$

- Polarization vector

$$P_\mu(x,p) = -\frac{1}{2{\rm tr}_2 f}\epsilon_{\mu\rho\sigma\tau}\frac{ds^{0,\rho\tau}}{d^3p}\frac{p^\tau}{m} = -\frac{1}{2{\rm tr}X}\epsilon_{\mu\rho\sigma\tau}\Theta^{\rho\sigma}\frac{p^\tau}{m}$$

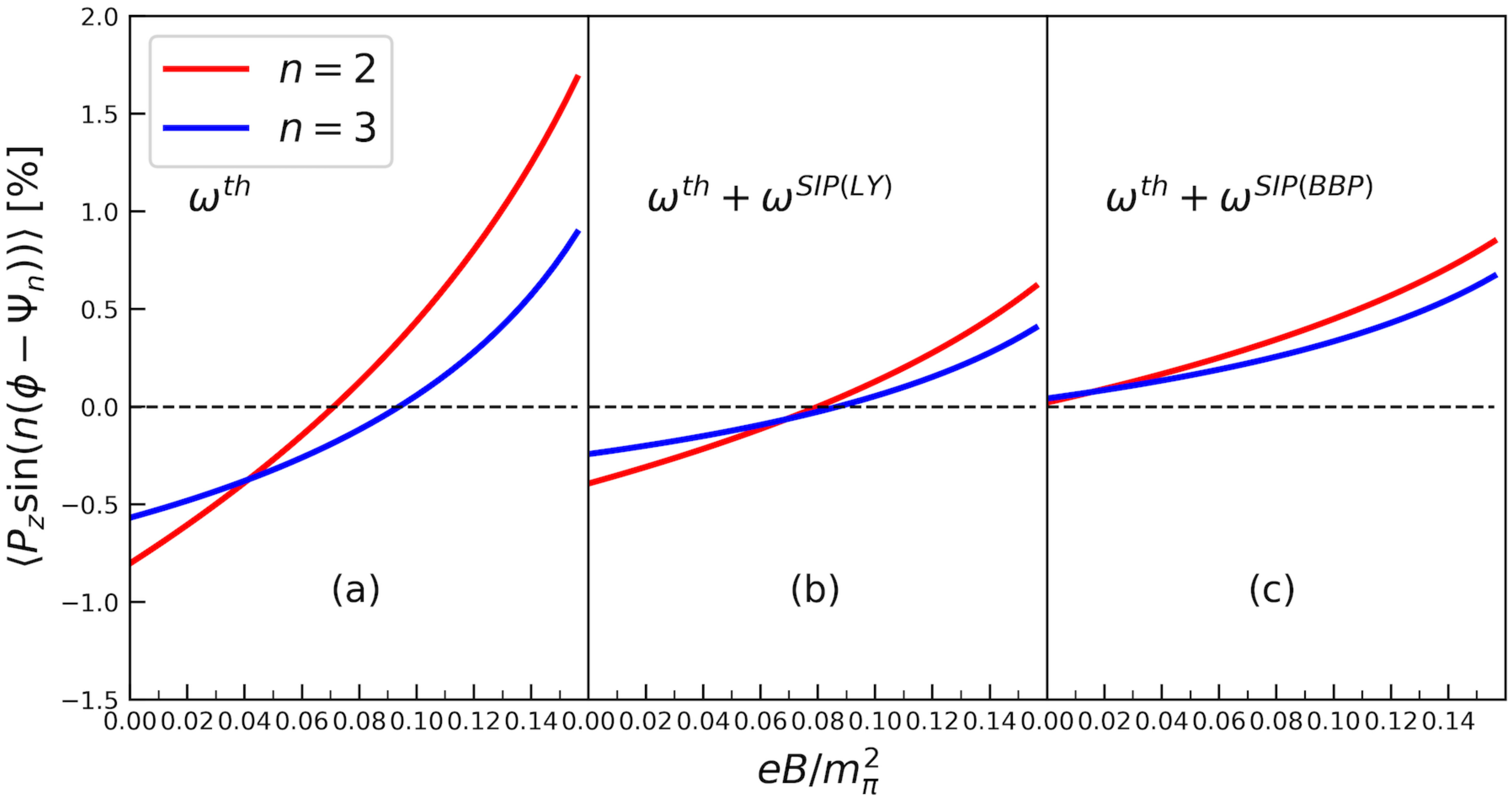
$$\boxed{\begin{aligned}\langle P_\mu\rangle &= -\frac{1}{4}\frac{p^\tau}{m}\epsilon_{\mu\rho\sigma\tau}\frac{\int d\Sigma\cdot p\; n_F(1-n_F)\bar{\omega}^{\rho\sigma} + (1-2n_F)\delta f_{\rm EM}\bar{\omega}^{\rho\sigma}}{\int d\Sigma\cdot p\;{\rm tr}f}\\ &\approx -\frac{1}{8}\frac{p^\tau}{m}\epsilon_{\mu\rho\sigma\tau}\frac{\int d\Sigma\cdot p\;(n_F+\delta f_{\rm EM})\bar{\omega}^{\rho\sigma}}{\int d\Sigma\cdot p\;(n_F+\delta f_{\rm EM})}\end{aligned}}$$

The extracted sin modulation: eB dependence

$$\frac{\sigma_{el}}{T} = 1$$

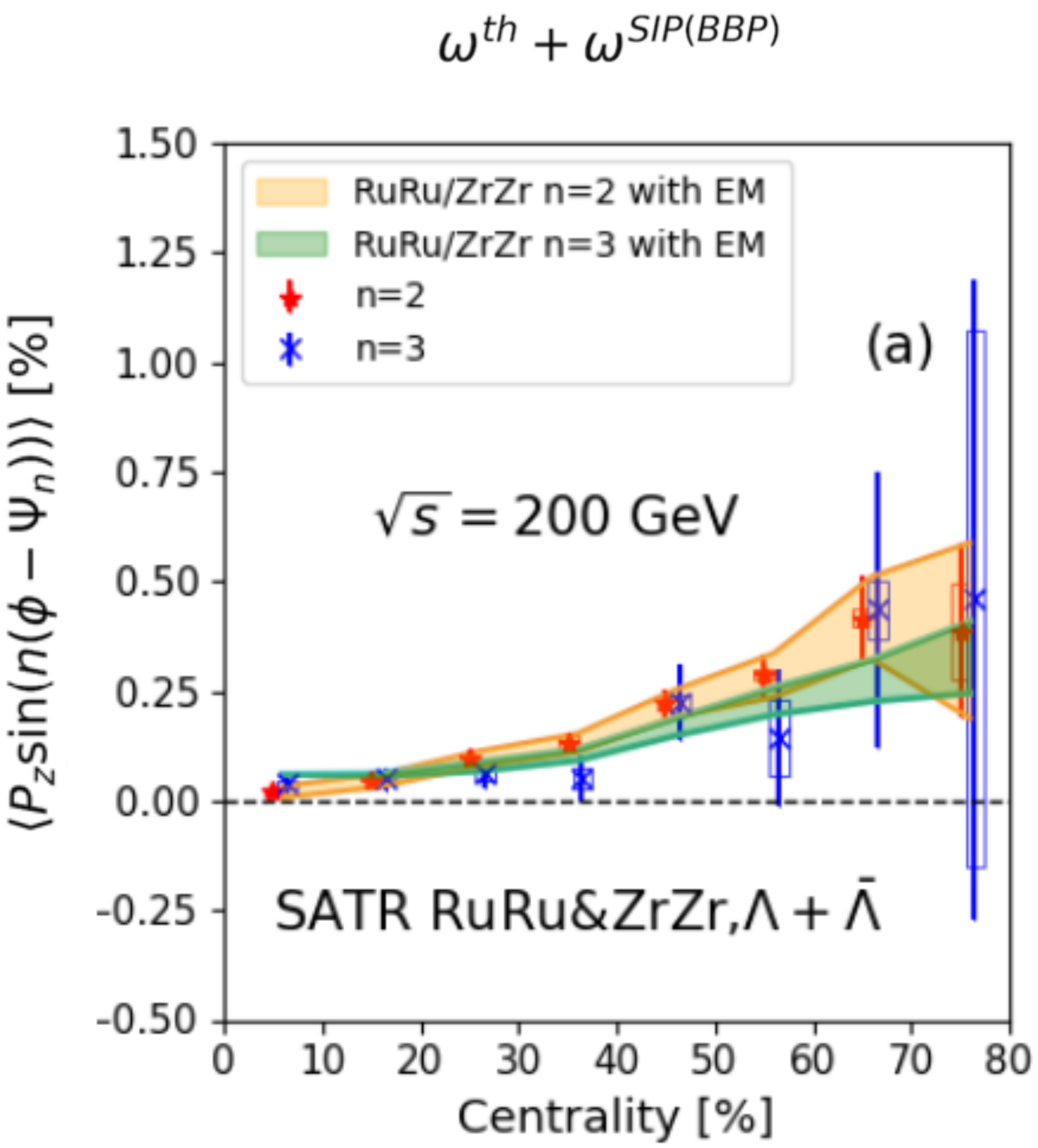
$$b = 7\ \mathrm{fm}$$
$$m_s = 0.3\ \mathrm{GeV}$$

RuRu@200GeV



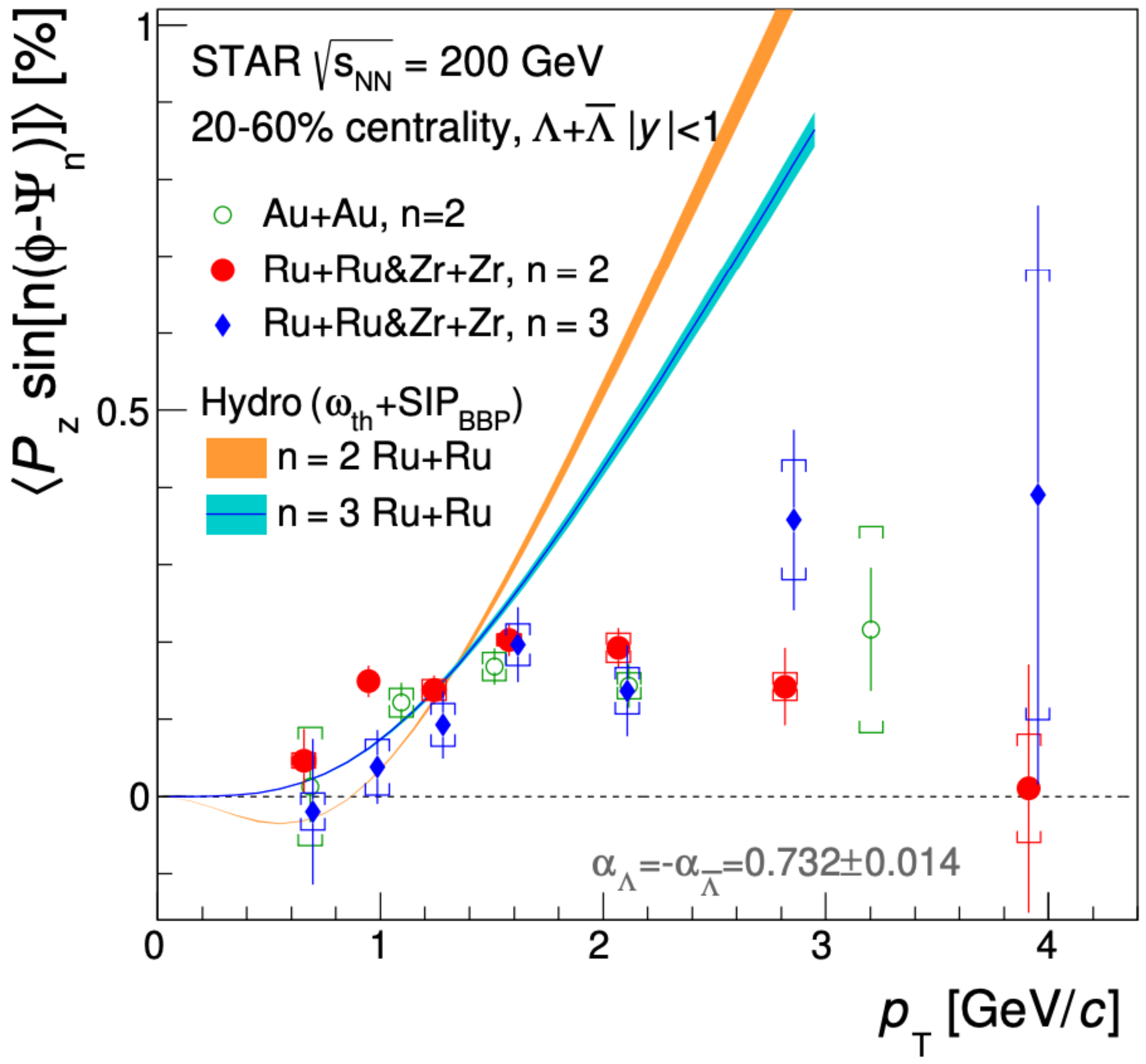
- Both modulations **get increased monotonically** with the B field introduced
- The ordering that the 2nd modulation > 3rd one, is found with the magnetic field.

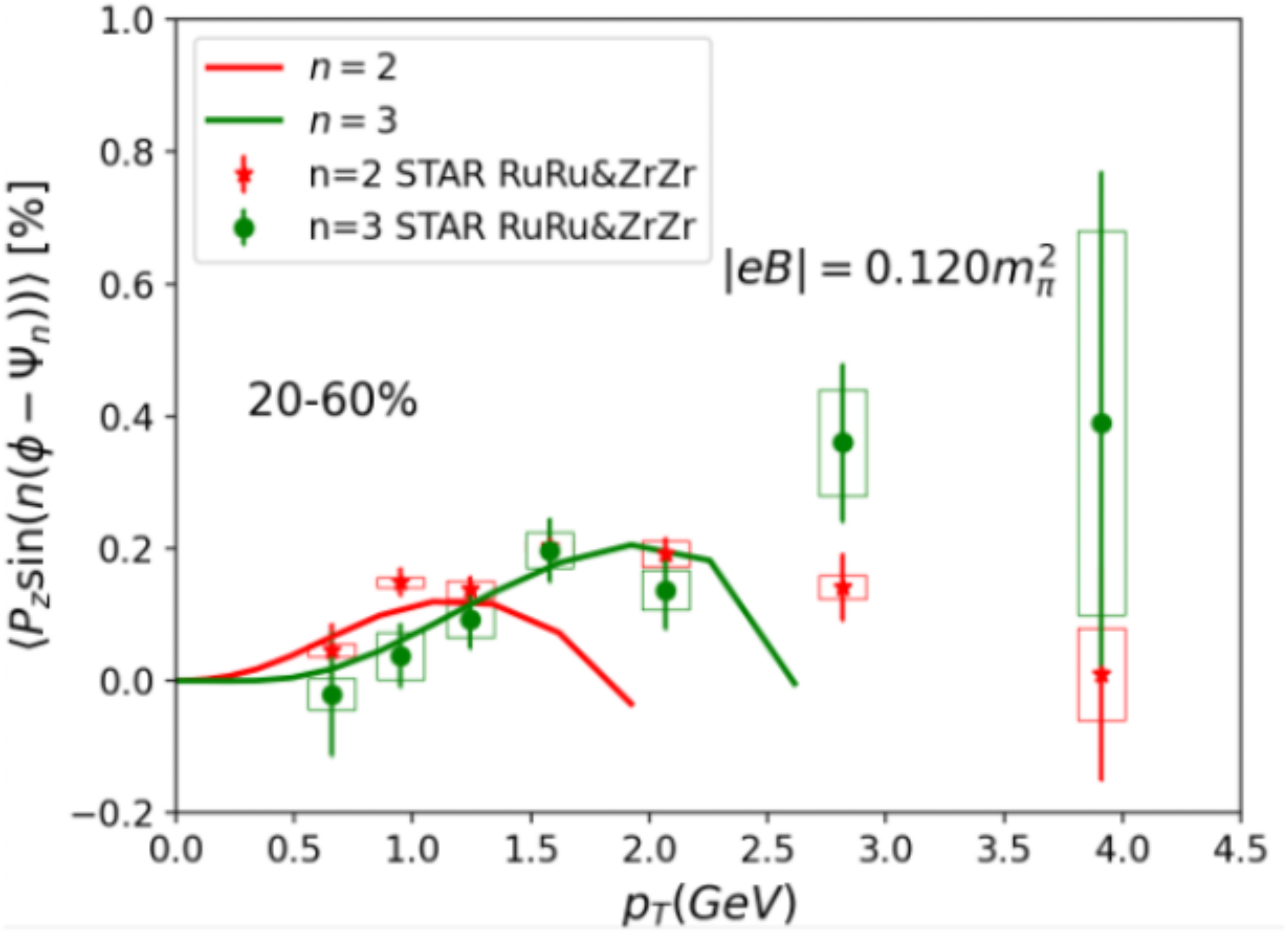
The centrality dependence



- The 2nd harmonics experimental data is used to extract the B field.
- The extracted B field is applied to calculate the 3rd harmonics.
- The 2nd and 3rd harmonics centrality trend can be well reproduced.

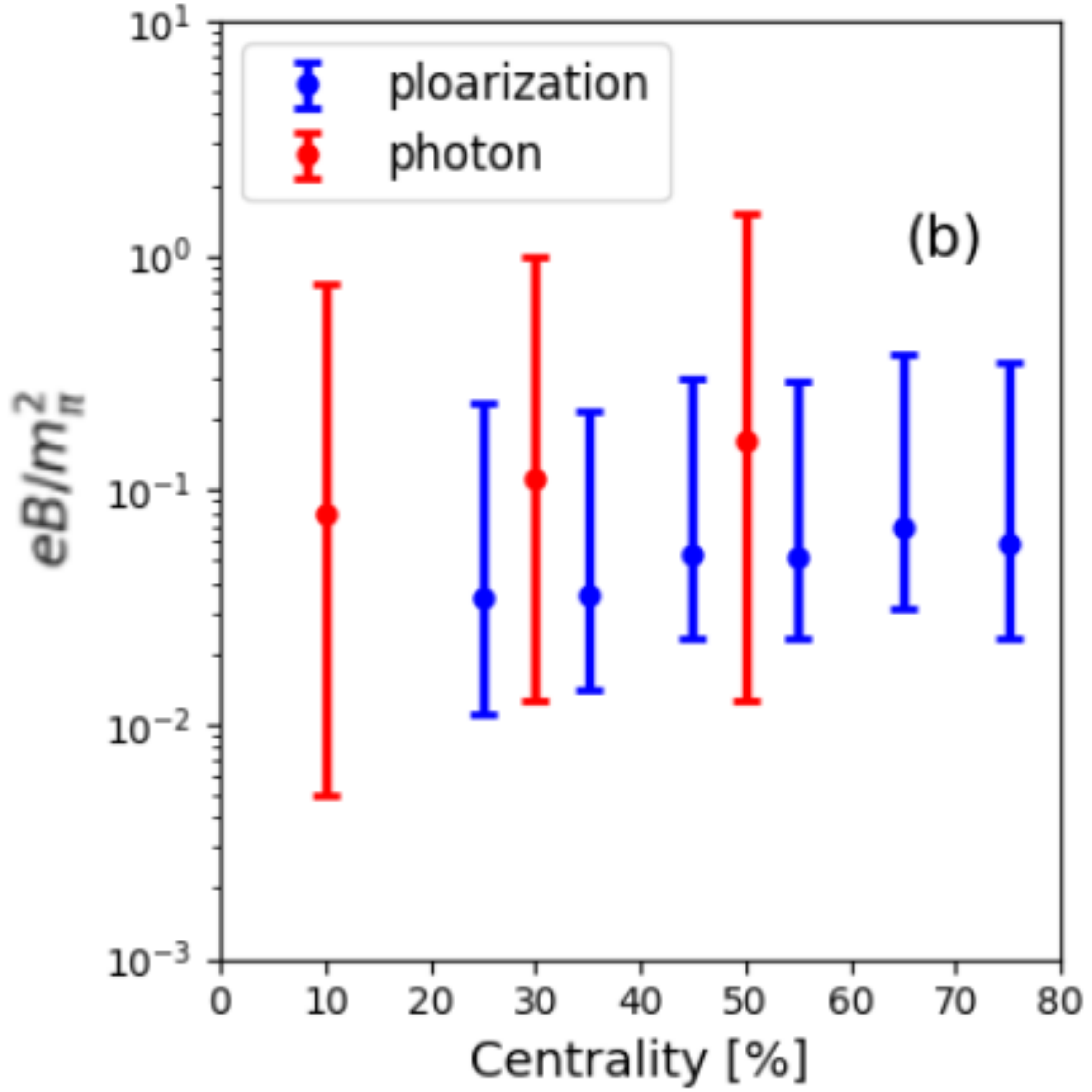
The momentum dependence





- Our theoretical calculation gives consistent description of the p_T dependence.
- At low p_T region, 2nd>3rd, **this ordering indicates the presence of a weak magnetic field**.
- The deviations at large p_T, where hydrodynamics becomes invalid, shouldn't be a surprise.

The time averaged B strength



$$\frac{\sigma}{T} \in [0.2,2]$$

$$\sim 0.1 m_\pi^2$$

- Weak B field in QGP
- The extracted field strength grows as centrality increases.
- It is too weak to induce the splitting between Λ and $\bar{\Lambda}$ global polarization, as well, the photon yields.

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 $P_{\Lambda}^{z}(\phi)$ is flipped and the centrality dependence are reproduced.

As a benchmark, if there is **no rapidity-odd v_1** , the **v_2^{γ} and $P_z(\phi)$ remains unchanged** whatever the B field strength is.

- Possible observables witnessing the novel effect:

The **polarization of di-leptons**? The **v_1 splitting** of mesons and baryons?
The spin polarization in pA system?

Arxiv:2406.10041

Thank you for your attention!

Back up

$$E_p \frac{d^3 \bar{N}}{d^3\mathbf{p}} = \int_V \bar{\mathcal{R}}^{\gamma}(P,X) = \bar{v}_0(1 + 2\bar{v}_2 \cos 2\phi_p) \qquad E_p \frac{d^3 N_{\mathrm{EM}}}{d^3\mathbf{p}} = \int_V \mathcal{R}^{\gamma}_{\mathrm{EM}}(P,X) = v_0^{\mathrm{EM}}(1 + 2v_2^{\mathrm{EM}} \cos 2\phi_p$$

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

- Bjorken analysis for illustration

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

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

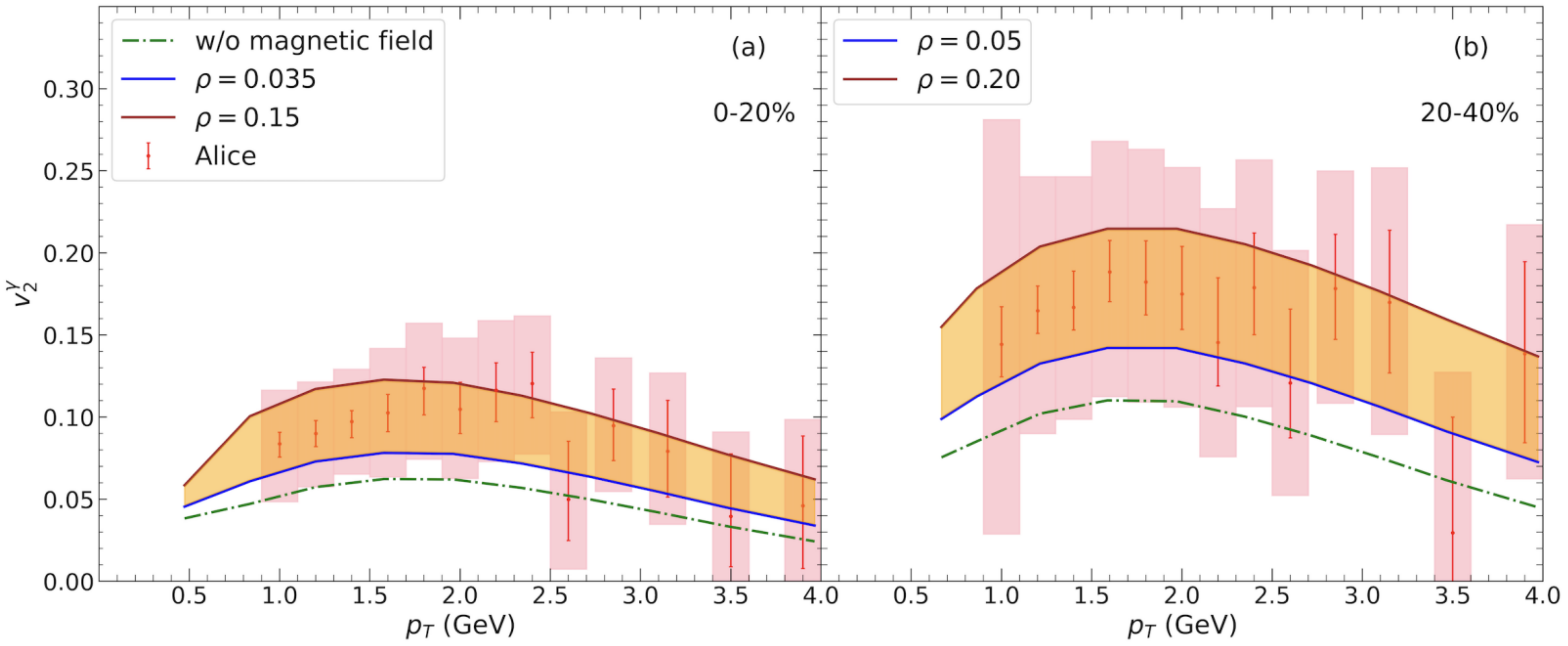
$$= QB_y \frac{\tau_R}{T}\frac{\sinh\eta_s}{\cosh(y-\eta_s)}\left[\frac{A_1}{2} + A_0\cos\phi + \frac{A_1}{2}\cos 2\phi\right]$$

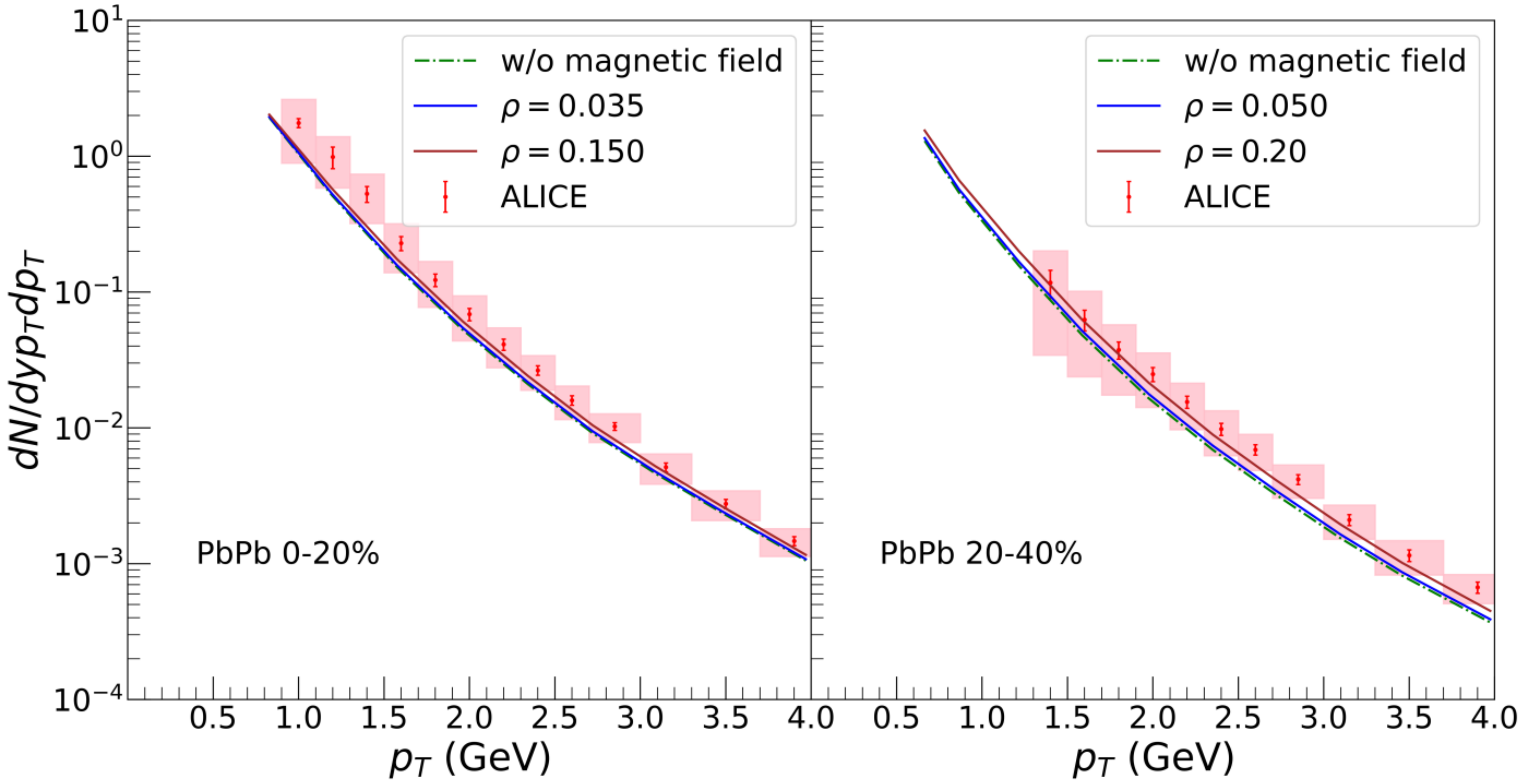
This cos ϕ is from weak magnetic field.

Rapidity-odd!

Must be Rapidity-odd

Back up


w/o magnetic field
$\rho = 0.035$
$\rho = 0.15$
Alice
(a)
0-20%
$\rho = 0.05$
$\rho = 0.20$
(b)
20-40%
v_2^γ
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
p_T (GeV)
p_T (GeV)


w/o magnetic field
$\rho = 0.035$
$\rho = 0.150$
ALICE
w/o magnetic field
$\rho = 0.050$
$\rho = 0.20$
ALICE
PbPb 0-20%
PbPb 20-40%
dN/dyp_Tdp_T
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
p_T (GeV)
p_T (GeV)

The sum of quark and anti-quark contribution

$$f_{EM} + \bar{f}_{EM}$$

$$[\ldots\boxed{\cos\phi} + \ldots\cos 2\phi + \ldots]\ \cos\phi$$

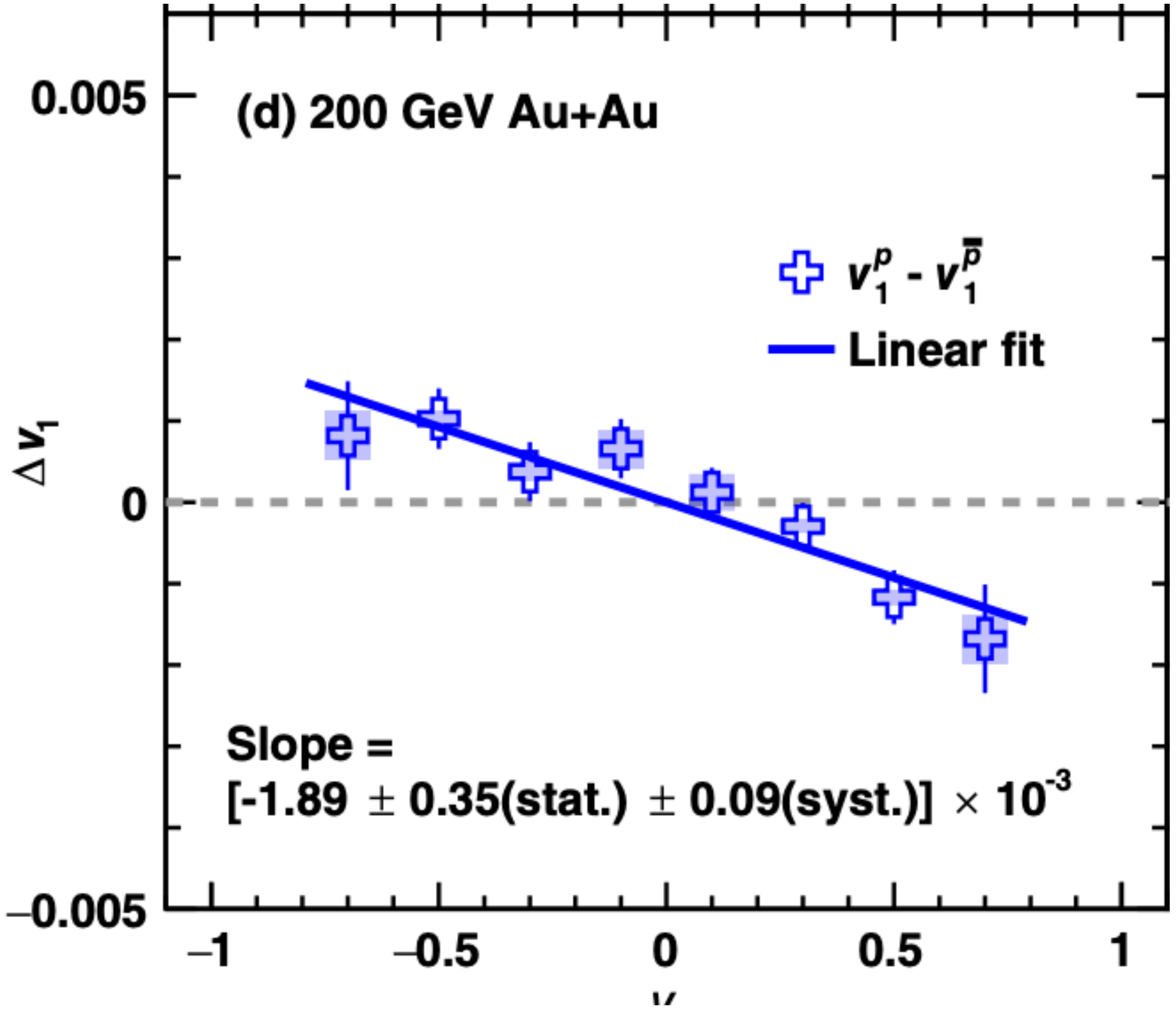
$\Delta v_1^{\text{hadron}}$

A Rapidity-odd v_1 splitting has been experimentally measured!

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

STAR QM2023

STAR arxiv2304.03430



The magnetic field profile

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

- 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.

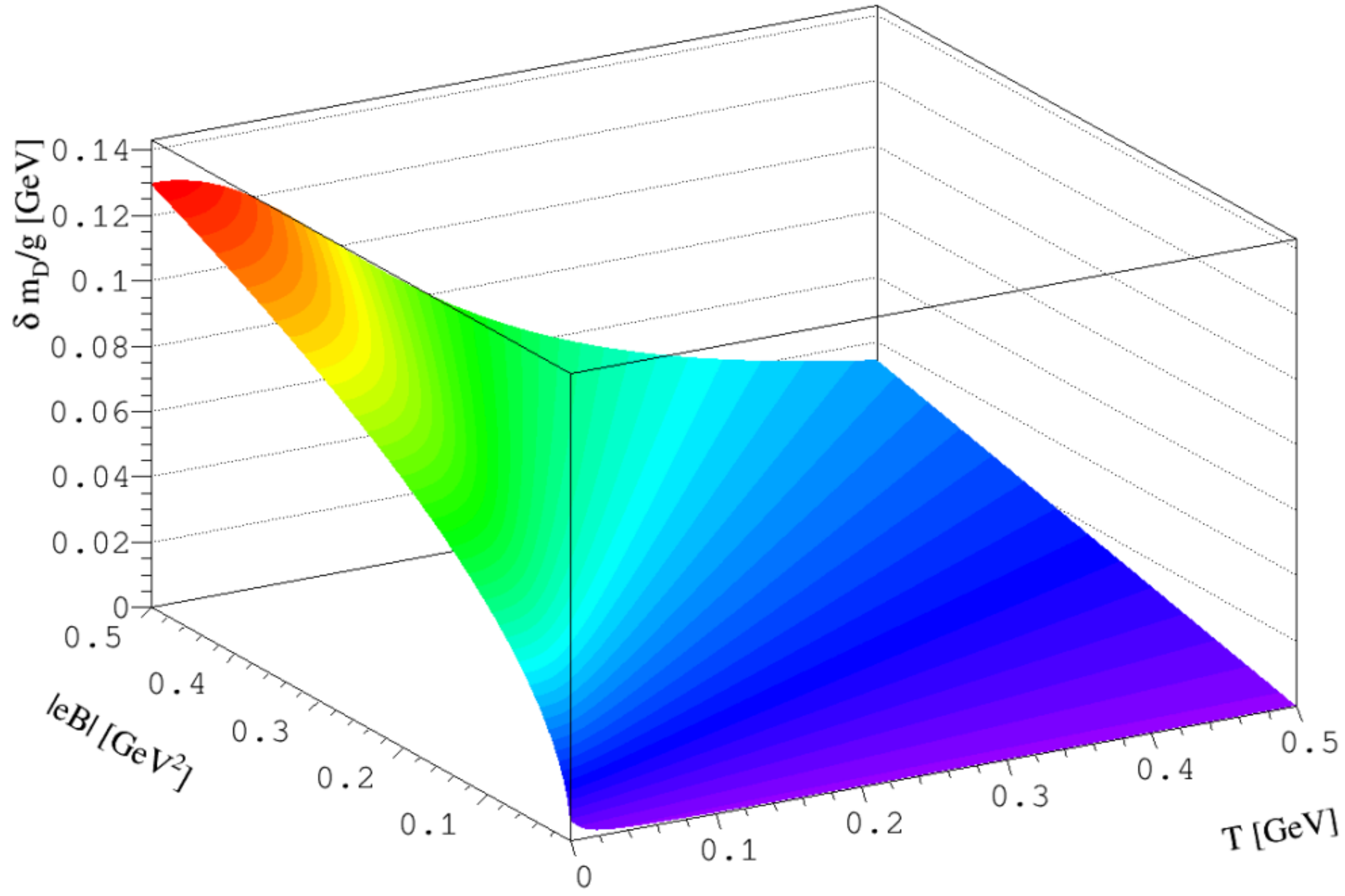
$$\Gamma(\eta) = \frac{1}{(b^2/4 + \gamma^2\tau_0^2(\sinh\eta_s + v\cosh\eta_s)^2)^{3/2}} + \frac{1}{(b^2/4 + \gamma^2\tau_0^2(\sinh\eta_s - v\cosh\eta_s)^2)^{3/2}}$$

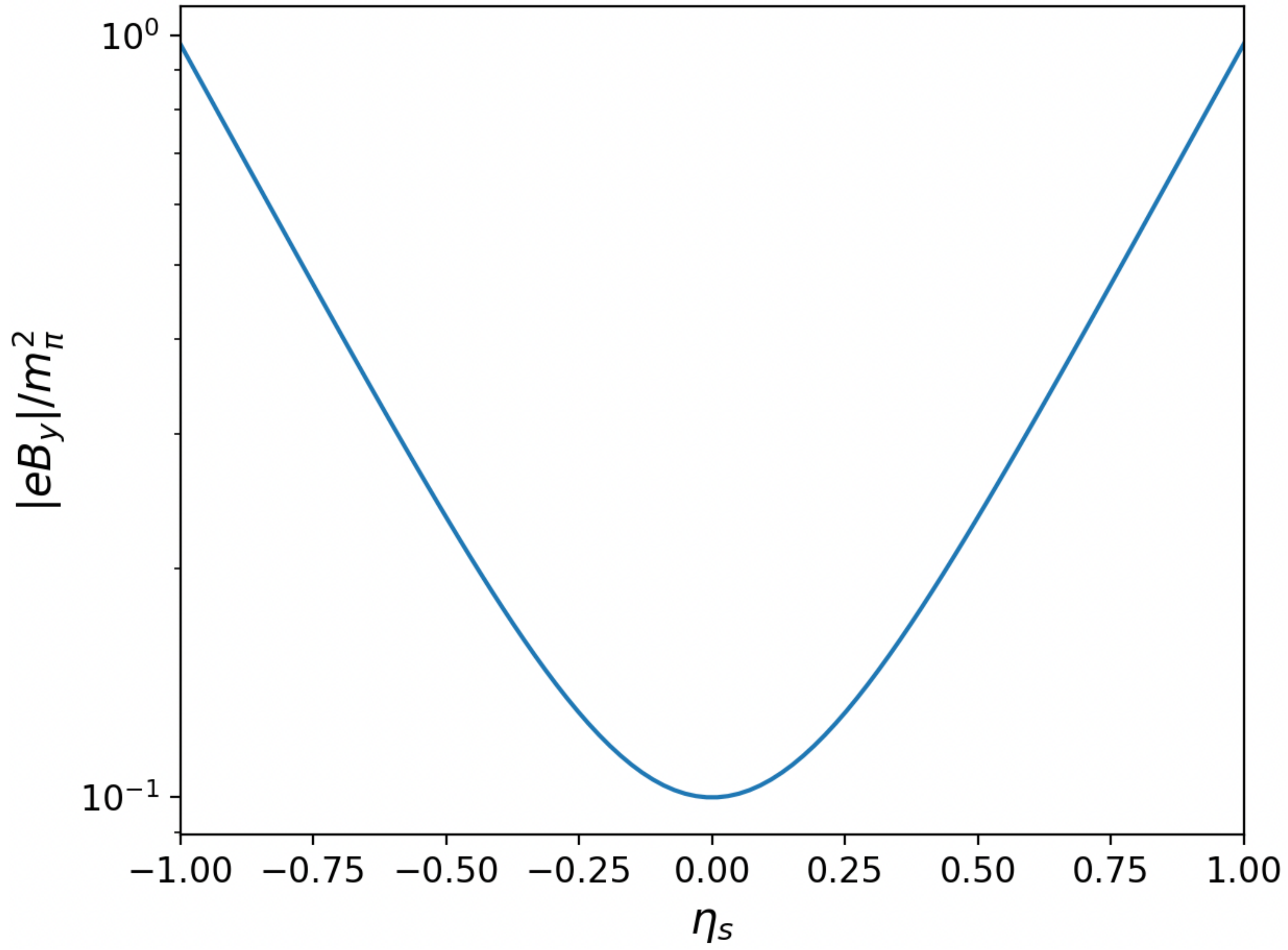
$$|eB_y| = \overline{eB_y}\frac{\Gamma(\eta)}{\Gamma(0)}$$

PRC 92 011901, PRC 96 044912.

K. Hattori and X. Huang, 1609.00747

JETSCAPE framework, arxiv 1903.07706


δ m_D/g [GeV]
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
|eB| [GeV^2]
0.5
0.4
0.3
0.2
0.1
0
T [GeV]
0.1
0.2
0.3
0.4
0.5



$\overline{eB_y} = 0.1 m_\pi^2$

$\tau_0 = 0.4$ fm

SIP(BBP): $\varepsilon^{\mu\rho\sigma\tau}\frac{1}{E}\hat{t}_\rho \xi_{\sigma\lambda} p^\lambda p_\tau$

SIP(LY): $\varepsilon^{\mu\rho\sigma\tau}\frac{1}{E}u_\rho \xi_{\sigma\lambda} p_\perp^\lambda p_\tau$ $\quad p_\perp^\lambda = p^\lambda - (u\cdot p)u^\lambda$

$$\xi^{\mu\nu} \equiv \frac{1}{2}\left[\partial^\mu\left(\frac{u^\nu}{T}\right) + \partial^\nu\left(\frac{u^\mu}{T}\right)\right]$$