The direct photon puzzle and the weak magnetic photon emission from QGP

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arXiv: 2302.07696

Outline

Introduction:

- direct photon puzzle
- the magnetic field in heavy-ion collisions.

Methodology:

- an external weak magnetic field +
- a “tilted” fireball configuration.

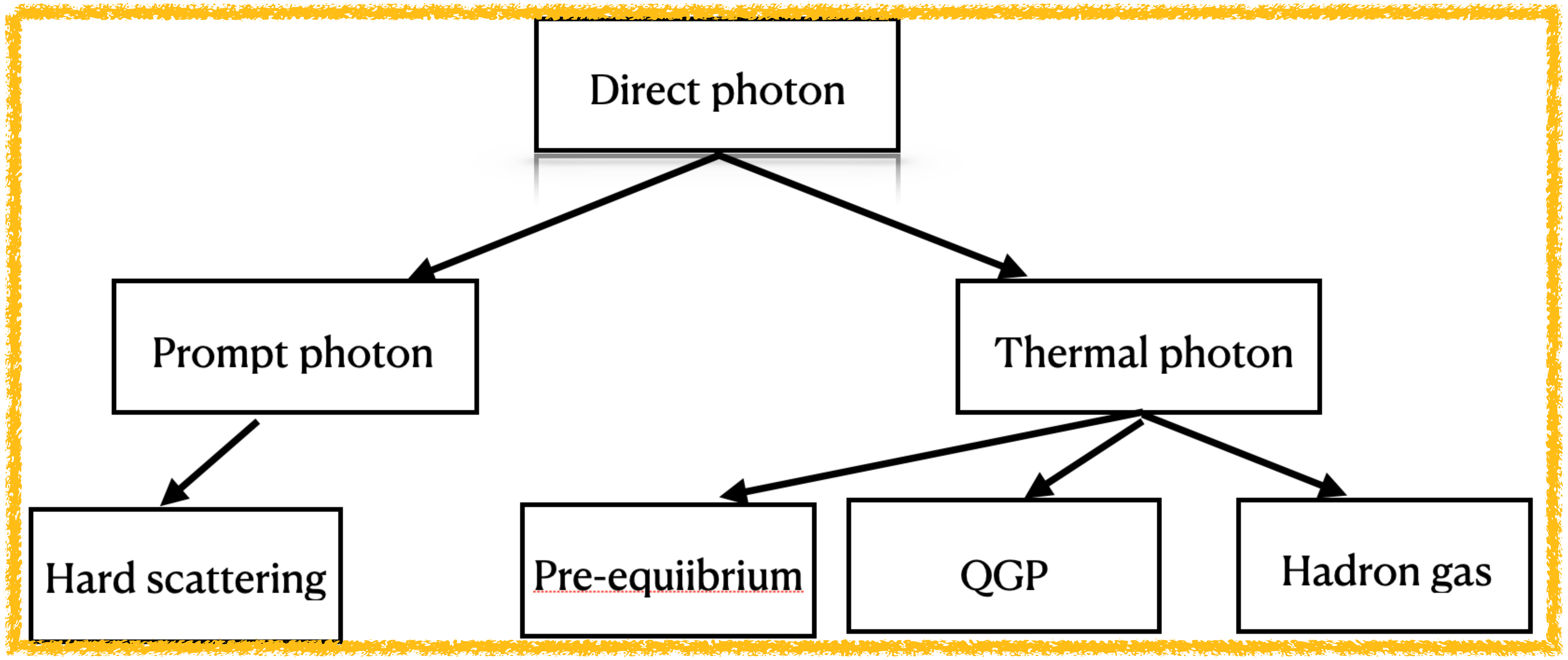
Results:

- the elliptic flow of direct photon
- the magnetic field at early stages.

Summary and Outlook

Direct photon

- **Direct photons**
  - **directly from a particle collision**



- **Large mean free path.**
- A perfect **“historian”**.
- A **“clean”** probe.

Gabor David, arXiv:1907.08893v2 [nucl-ex]

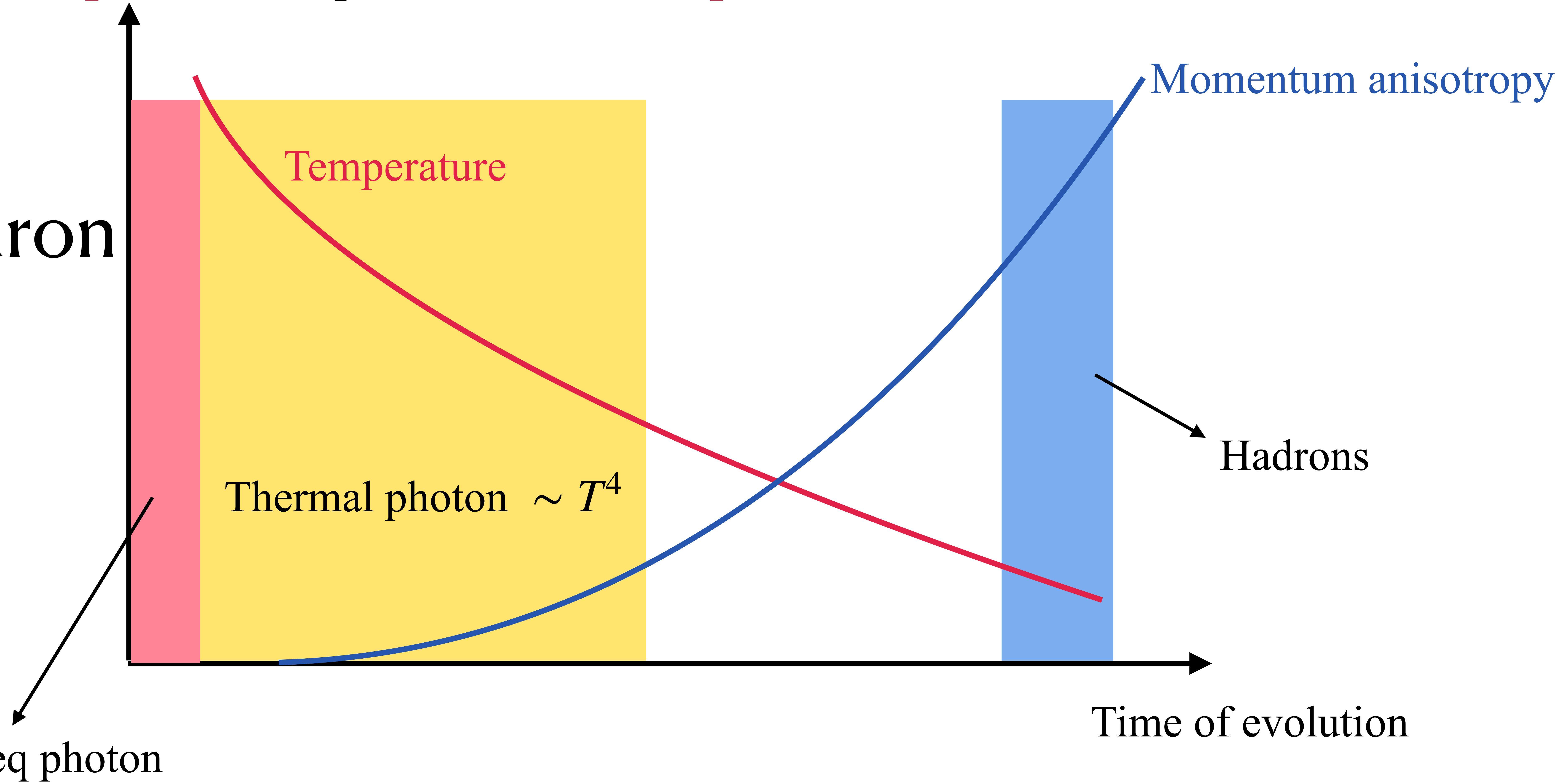
Chapline G F, Kerman A K. 1978.
Chin S A. Phys. Lett. B, 1978, 78: 552-555.
Anishetty R, Koehler P, McLerran L. Physical Review D, 1980,22(11): 2793
Escobar C. Nuclear Physics B, 1975, 98(1): 173-188.
Feinberg E L. Nuovo Cim. A, 1976, 34: 391.

Direct photon puzzle

Theoretical expectations

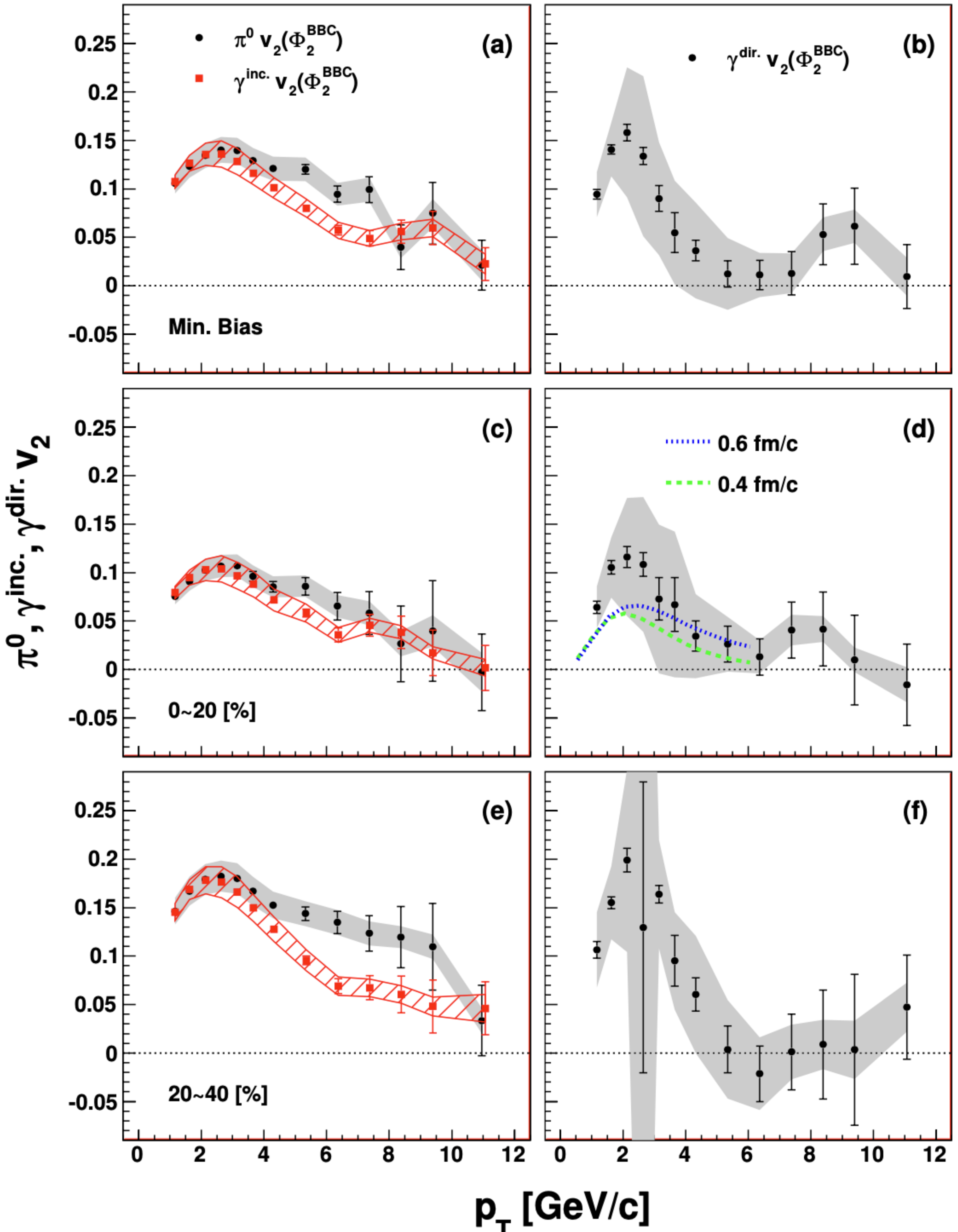
- **Hadrons** inherit the anisotropy of QGP, leading to **large v_2 naturally.**
- The **photons** are dominantly thermal photons, where **momentum anisotropy has not been fully developed**. It is expected to be **isotropic**.

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



Direct photon puzzle

Experimental observation



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

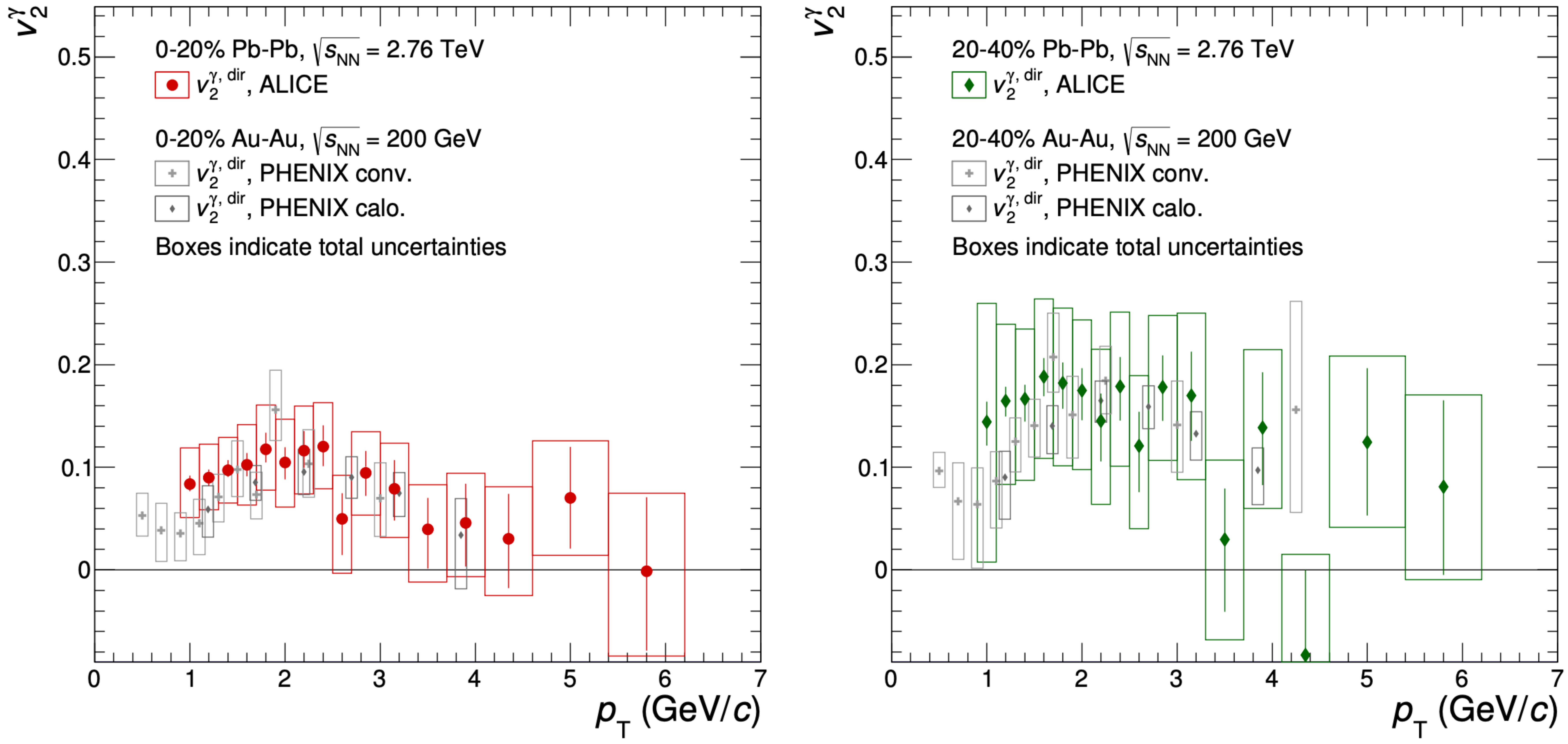
Puzzle!

No theory predict or could readily accommodate the simultaneous observation of **large yields** and **large v_2 for "thermal" photons**

A. Adare et al. (PHENIX), Phys. Rev. Lett. 109, 122302 (2012)

Direct photon puzzle

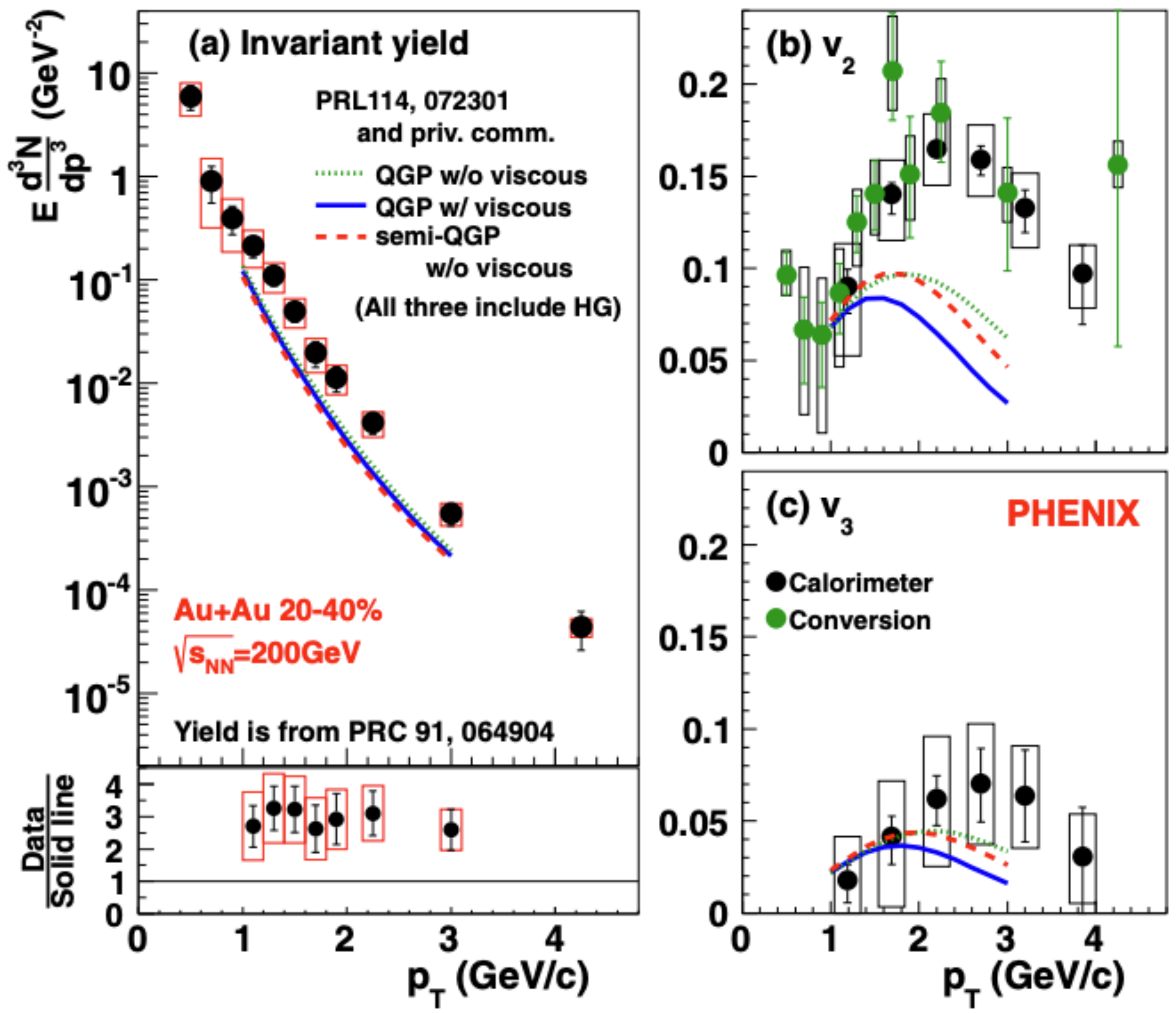
Experimental observation



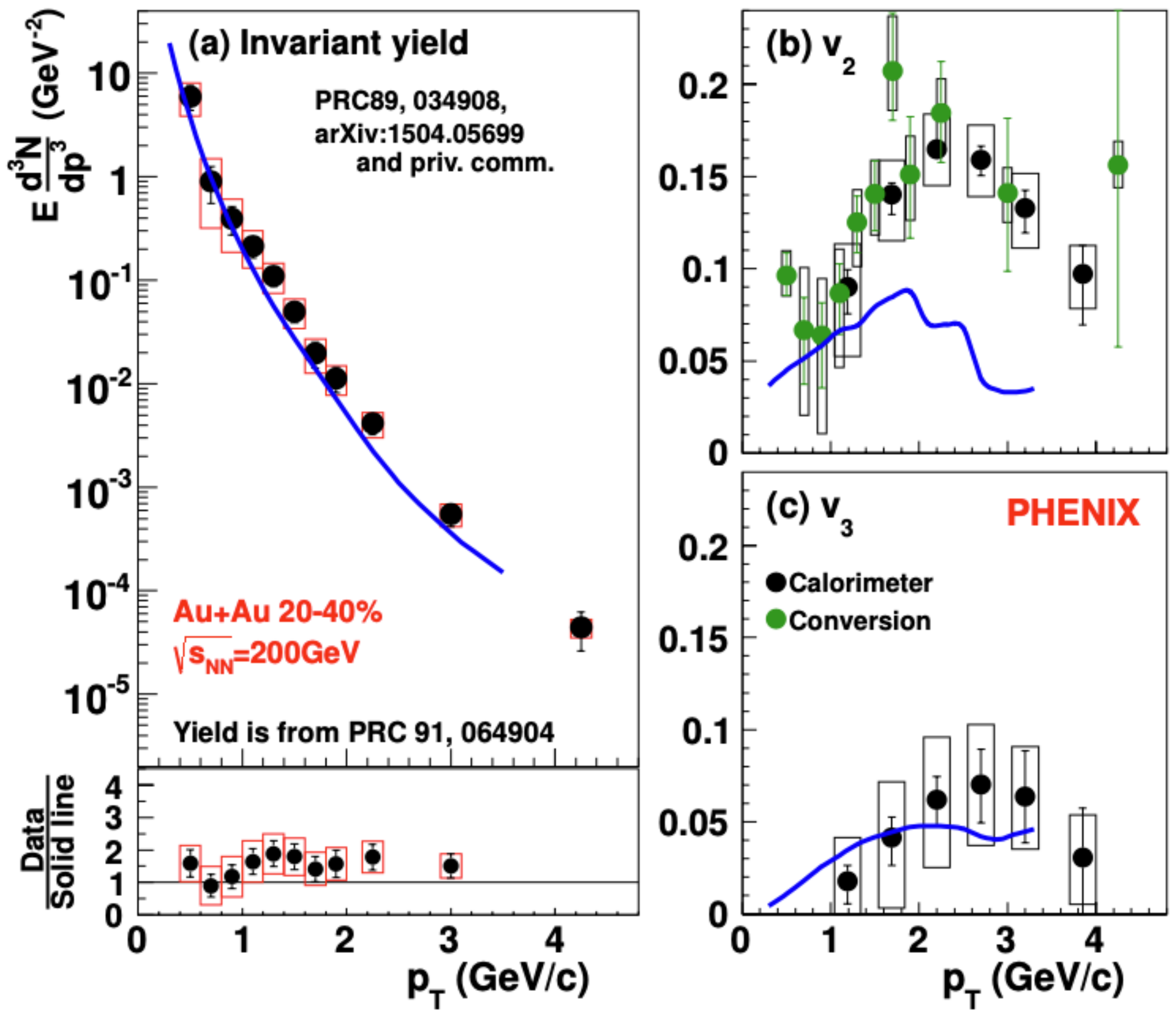
ALICE collaboration Physics Letters B 789 (2019): 308-322.

Experiment vs theories

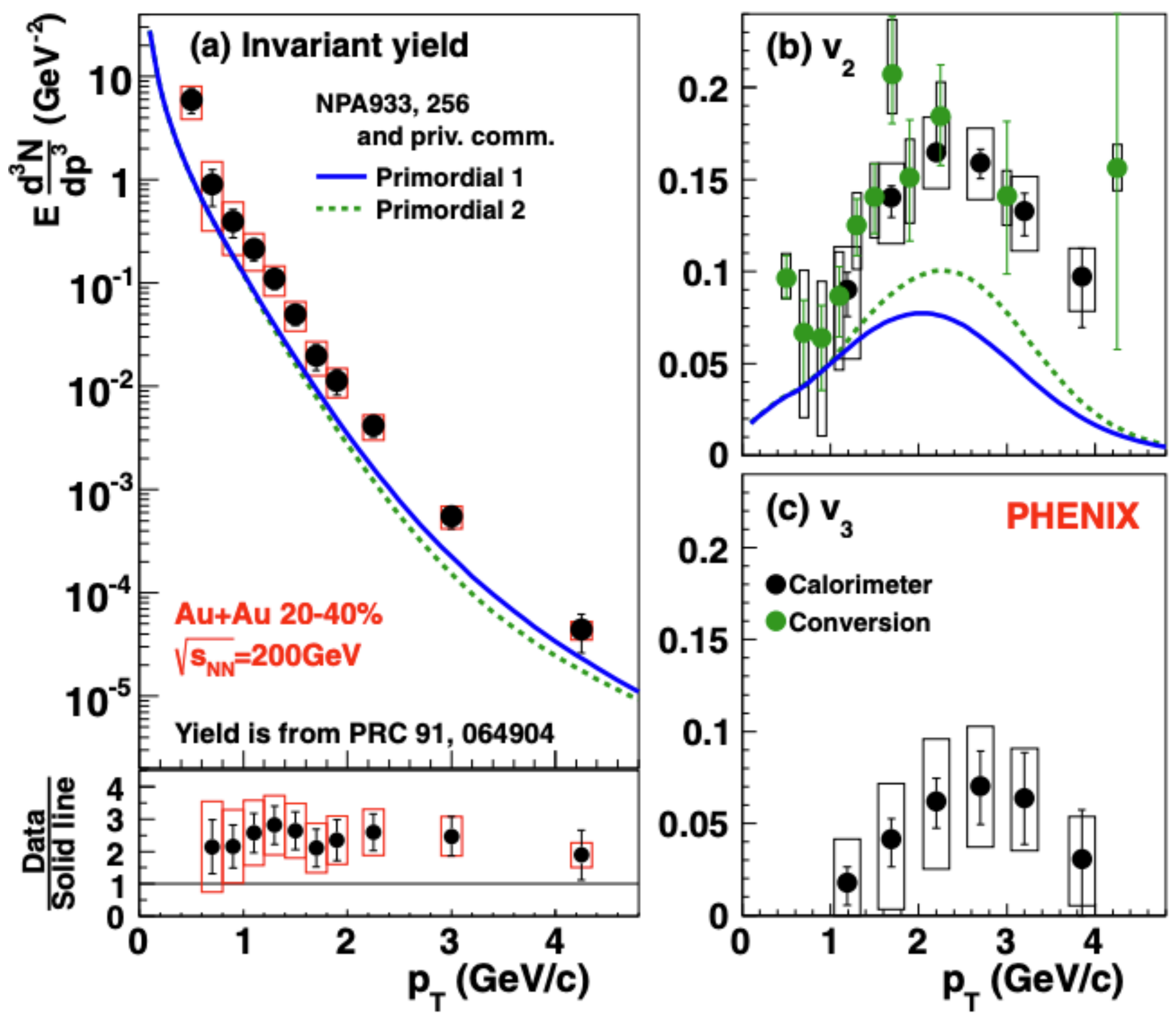
Hydrodynamical models



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)

The most updated calculation

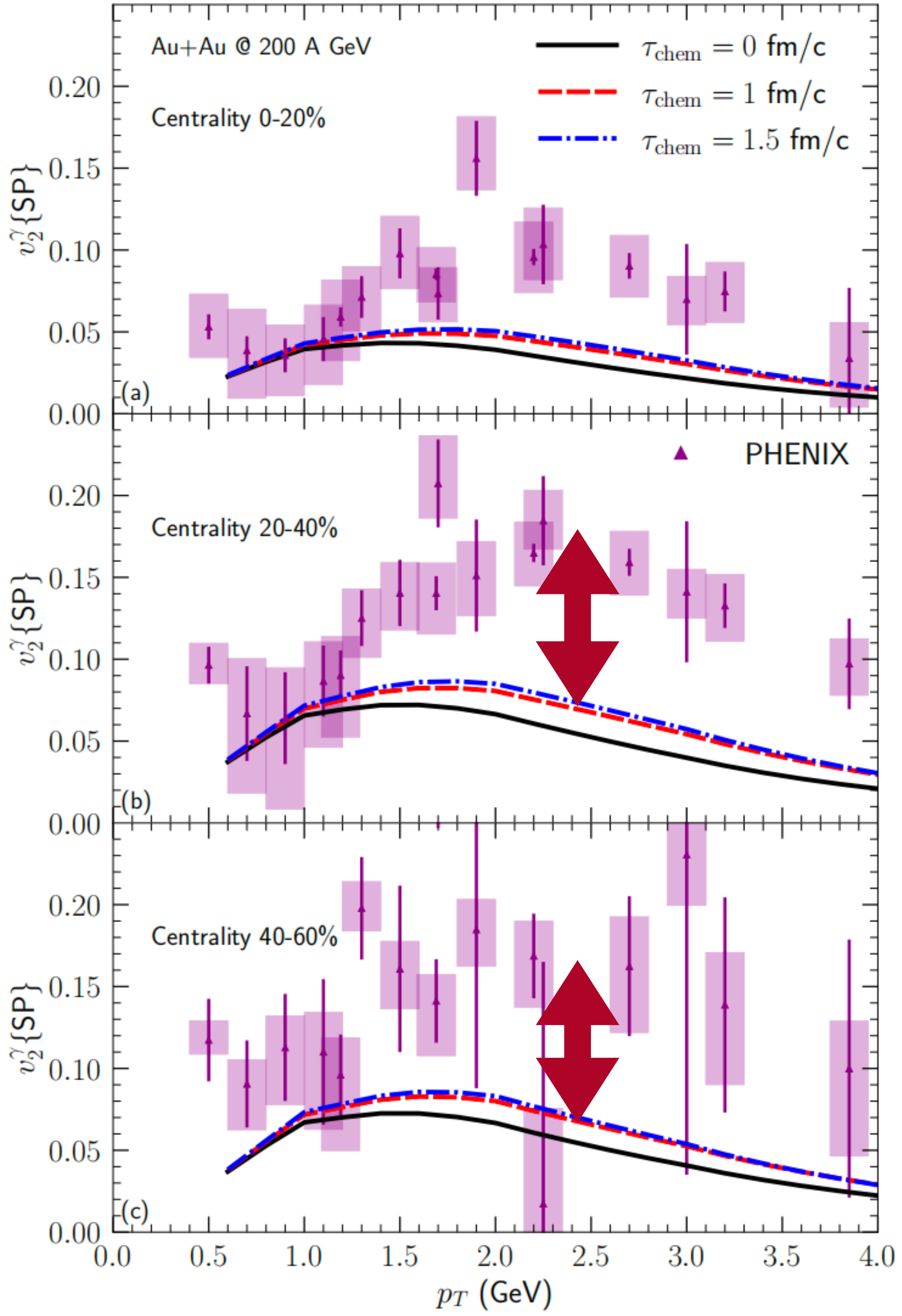
J-F Paquet, et,al Phys. Rev. C93, 044906 (2016)

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

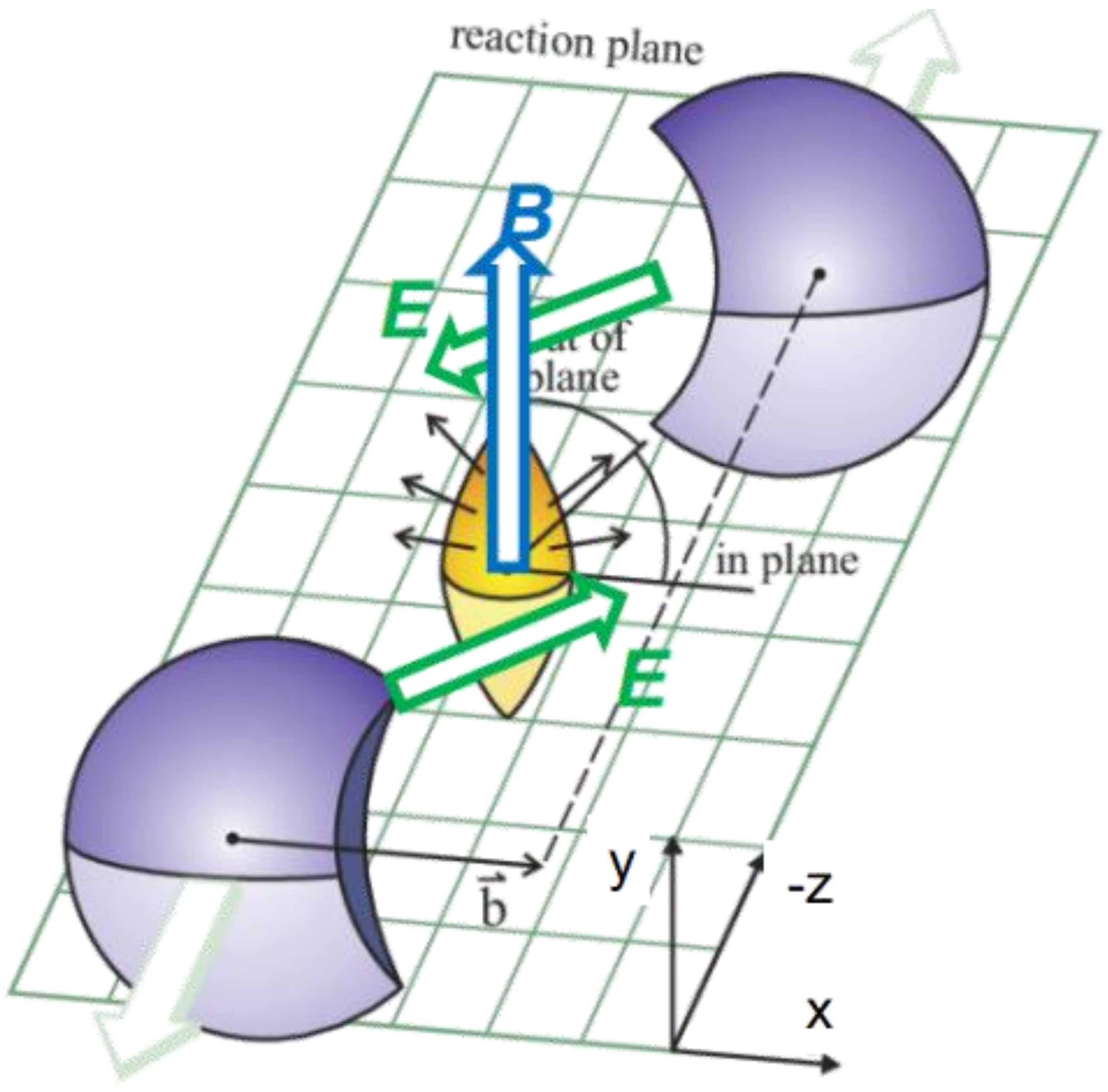
- Pre-equilibrium dynamics (KoMPost)
- Chemical equilibration in QGP
- NNLO pQCD for prompt photons
- Shear and bulk viscous correction.

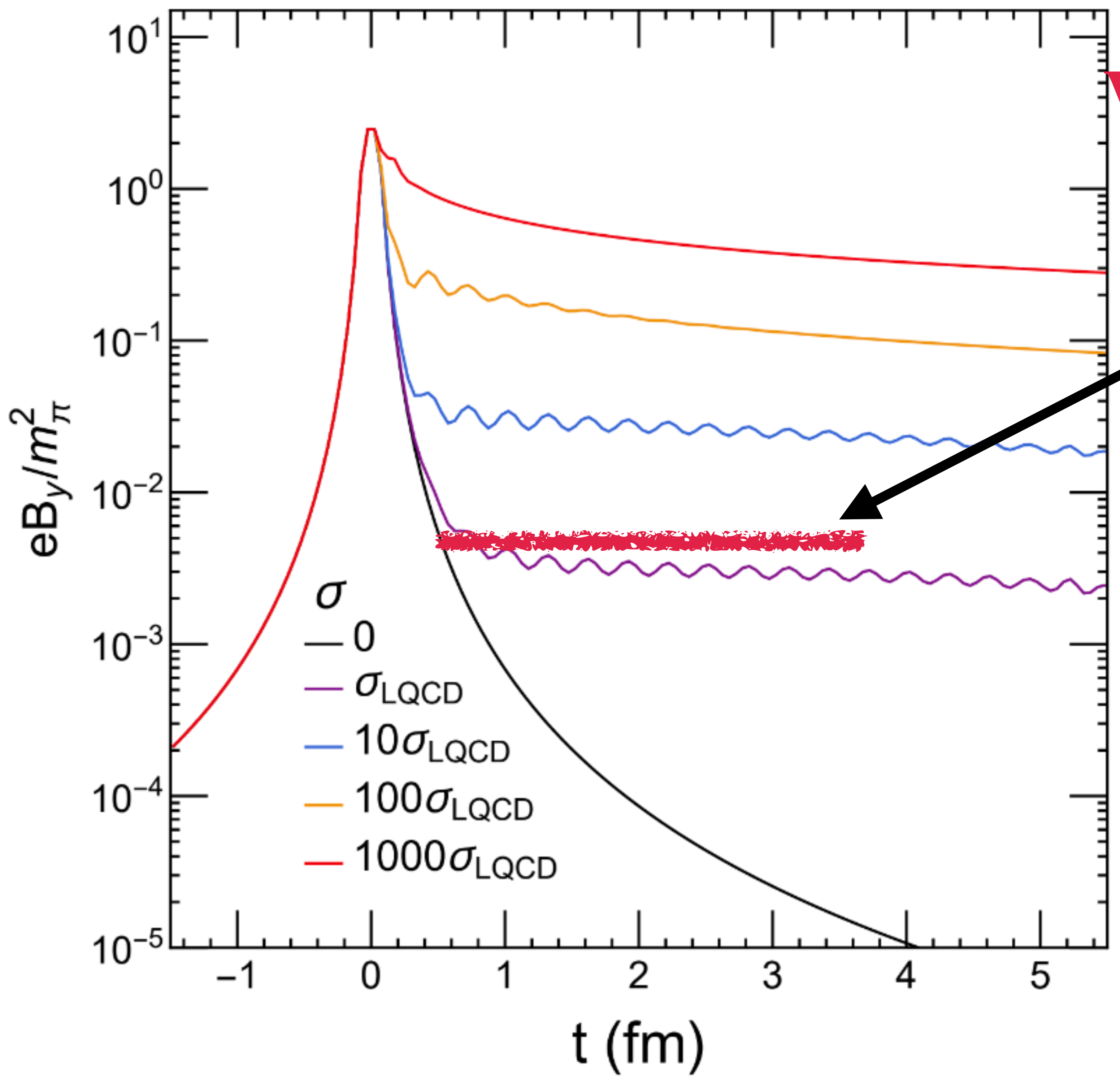
$$f_q = n_q + \delta f$$

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



Magnetic Field in RHIC





Weak at hydro-evolution

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

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

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

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

- B field is dominated out of plane, $\vec{B}\,||\,\hat{y}$.
- Strong initial magnetic field, $\propto \sqrt{s}$.
- **The lifetime of B** is determined by **the electrical conductivity** of medium, **but unknown.**

Magnetic field may be responsible for the "direct photon puzzle"?

- Magnetic field is **large and highly anisotropic.** → Maybe a natural source of the photons' anisotropy.
- **Be maximal at the early stage** of a collision. → Large yield of thermal photon.

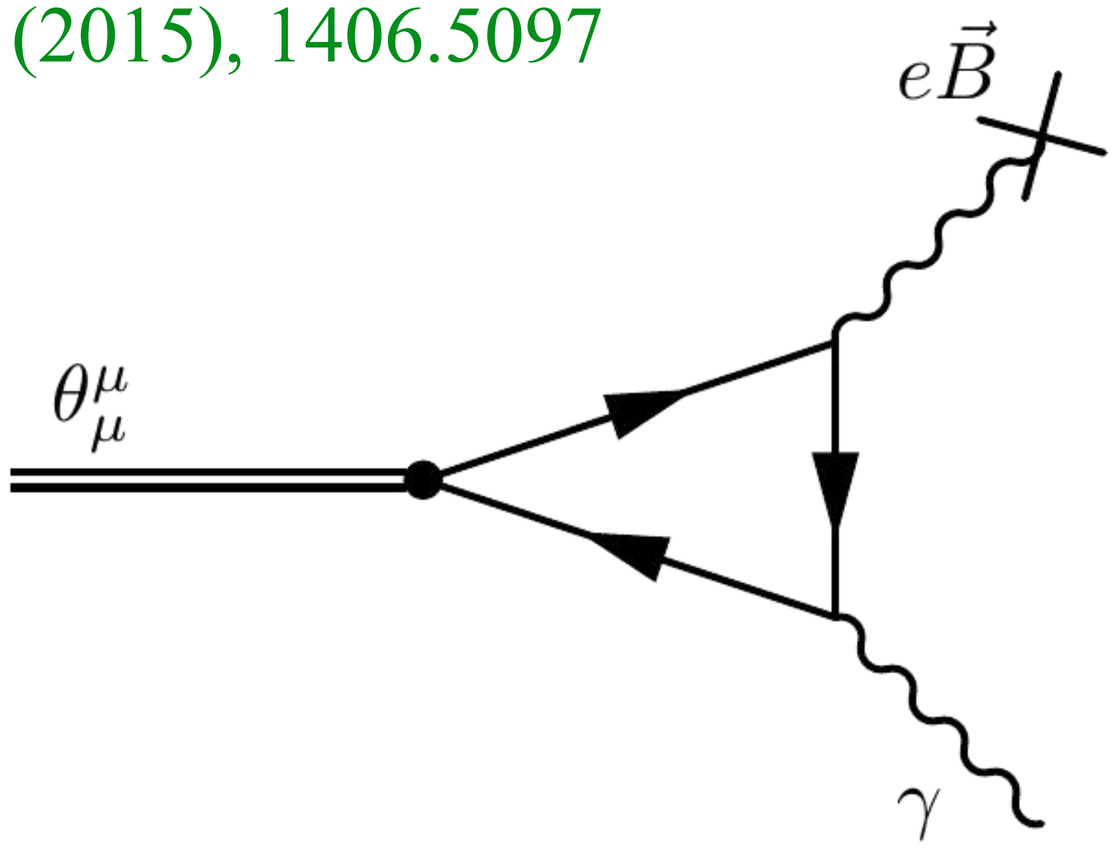
A. Bzdak et.al, Phys. Rev. Lett. 110, 192301(2013), 1208.5502.

Strong magnetic field and direct photon v_2

- Synchrotron radiation

K. Tuchin, Phys. Rev. C 91, 014902 (2015), 1406.5097

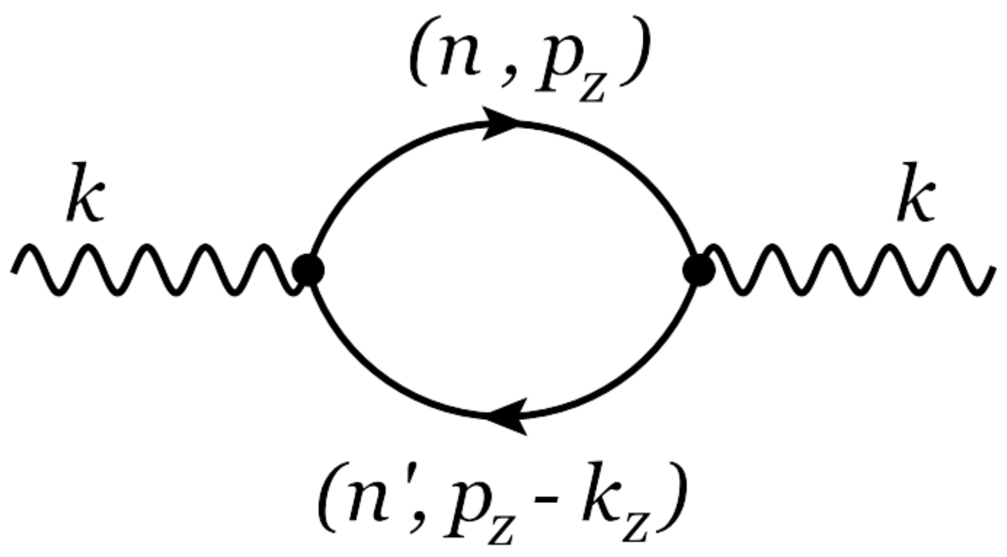
- Conformal anomaly

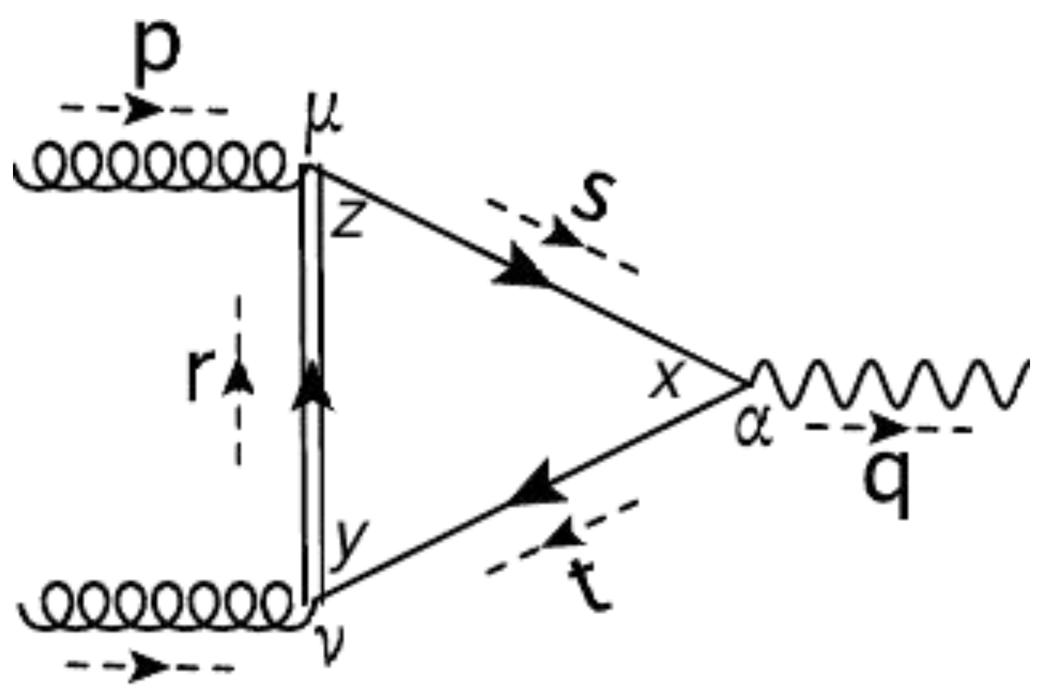


G. Basar, et.al, Phys. Rev. Lett. 109, 202303 (2012), 1206.1334.

- Quark with Landau level excitations

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





Weak magnetic field

Scales of magnetic field

$eB \gg g^2T^2$ 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.** $f_q = n_q + \delta f + f_{EM}$

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

An additional $\cos\phi$ term !

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

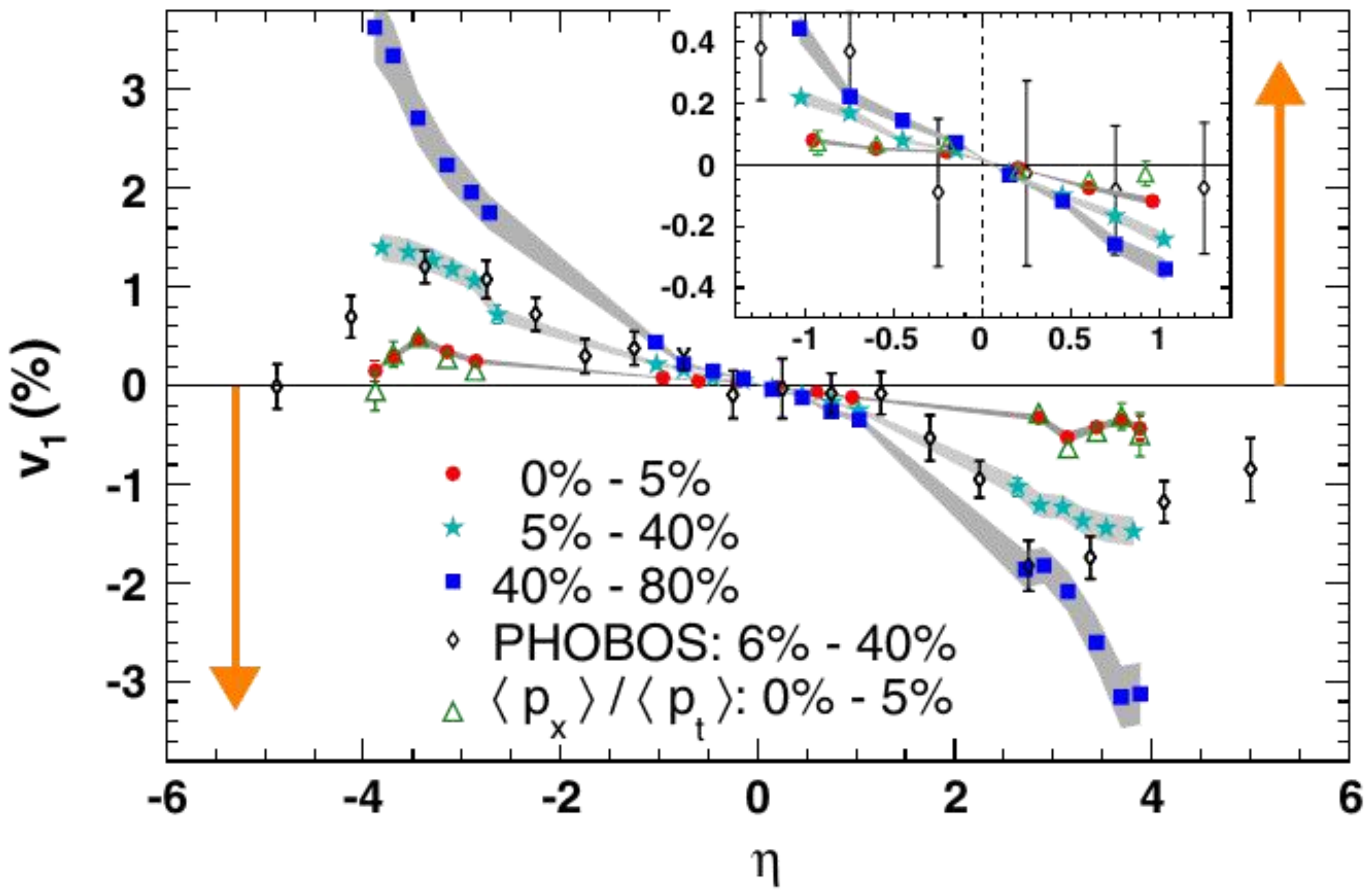
v_1^{hadron} v_2^{hadron}

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

$v_1^{\mathbf{odd}}(\eta)$ of hadrons

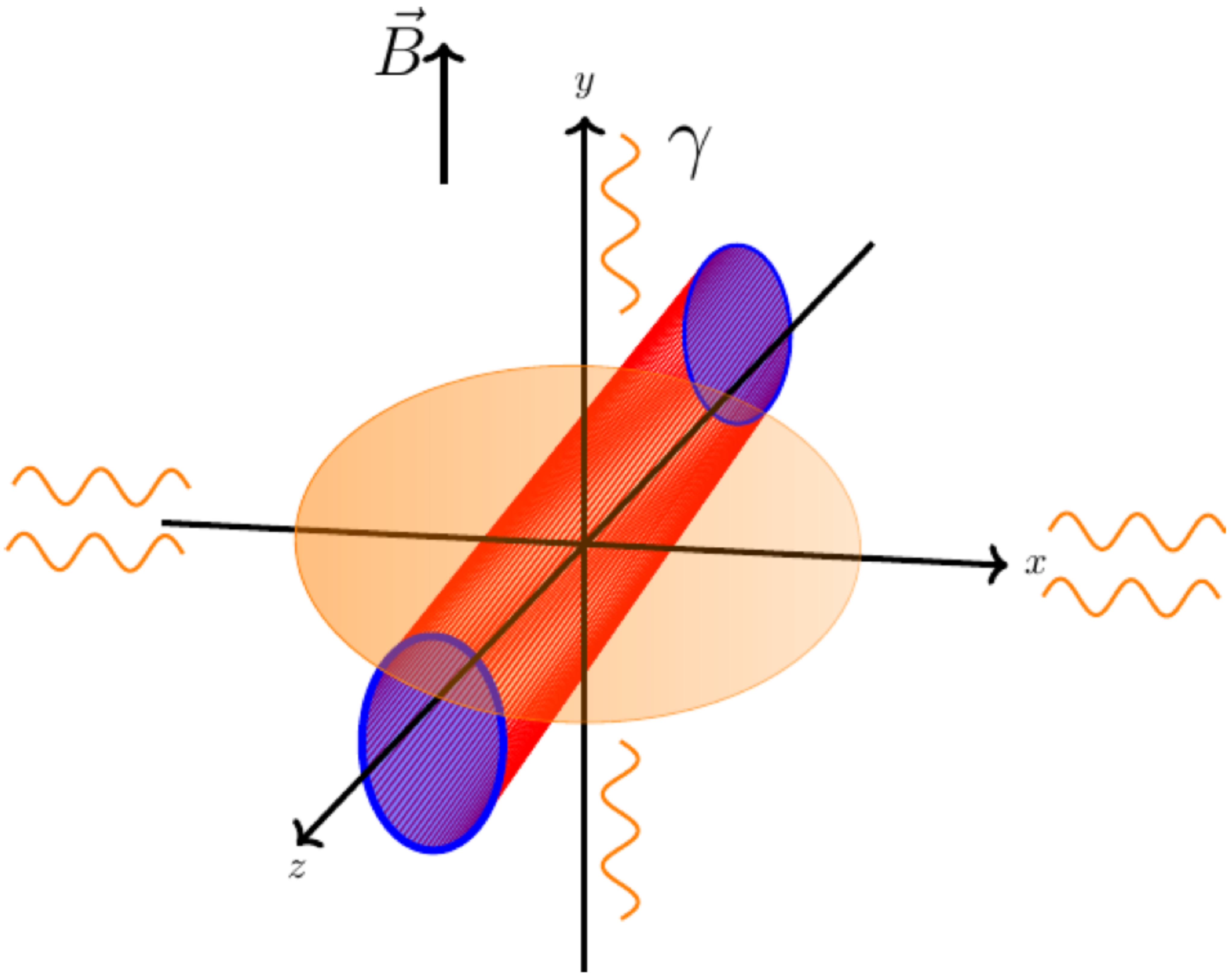
Rapidity-odd directed flow

The **rapidity-odd directed flow** of charge hadrons is **experimentally observed!**



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

Weak magnetic photon emission:



An external magnetic field
+ a “tilted” fireball

For rapidity-odd v_1^{hadron}

Elliptic flow of photons

Hydrodynamic simulation

- A “tilted” fireball : single-shot simulation

S. Chatterjee and P. Boz˙ek, Phys. Rev. Lett. 120, 192301 (2018)

Use a tilted fireball configuration to capture the rapidity-odd v_1 of charged hadrons

- Trento3D initial condition : event-by-event simulation

PRC 92 011901, PRC 96 044912.

Realistic conditions !

JETSCAPE framework, arxiv 1903.07706

Magnetic field profile

- LO pQCD evaluation (AMY) is used for Electrical conductivity, to be consistent with background photon results.
- Space-time dependence of external B field as in vacuum: “worst-case”

$$eB_y(\tau, \eta_s) = eB_y^0 \Gamma(\tau, \eta_s)$$

K. Hattori and X. Huang, 1609.00747

here eB_y^0 is the initial field strength when QGP evolves hydrodynamically

Single shot for RHIC

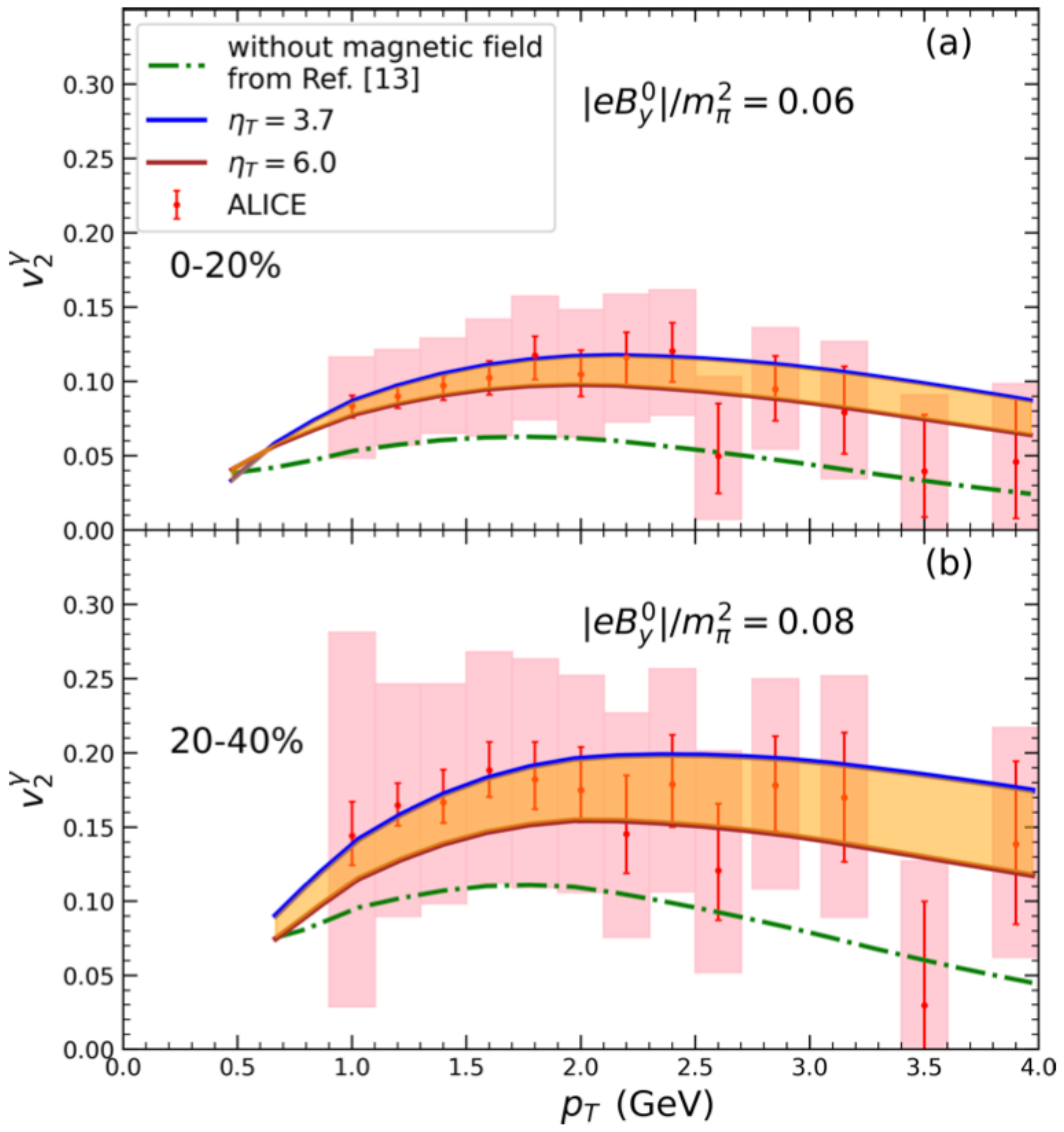
Confronts experiment at RHIC AuAu@200 GeV

- The **experimental data are reproduced** excellently for all centralities.
- Initial field strength is extracted and is **under weak magnetic assumption.**
- More "tilted", weaker magnetic field.
- The B field magnitude grows as centrality increases: **correct trend**!

Single-shot for LHC

Confronts experiment at LHC PbPb@2760 GeV

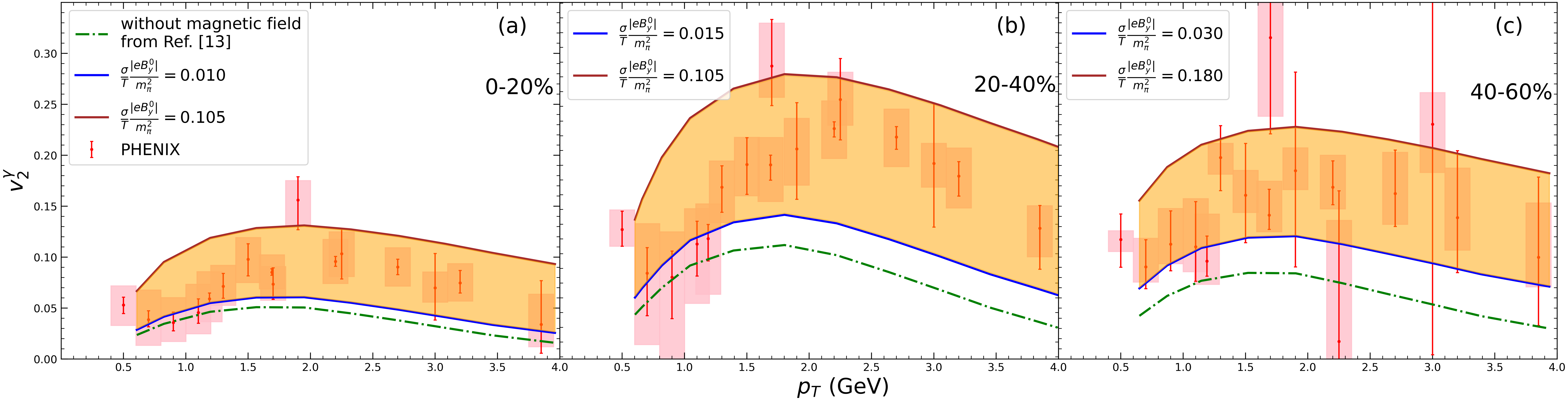
- The **experimental data are reproduced** excellently for all centralities.
- Initial field strength is extracted and is **under weak magnetic assumption.**
- More "tilted", weaker magnetic field.
- The B field magnitude grows as centrality increases: **correct trend**!



Extracting B field — ebe simulations

v_2 of direct photon

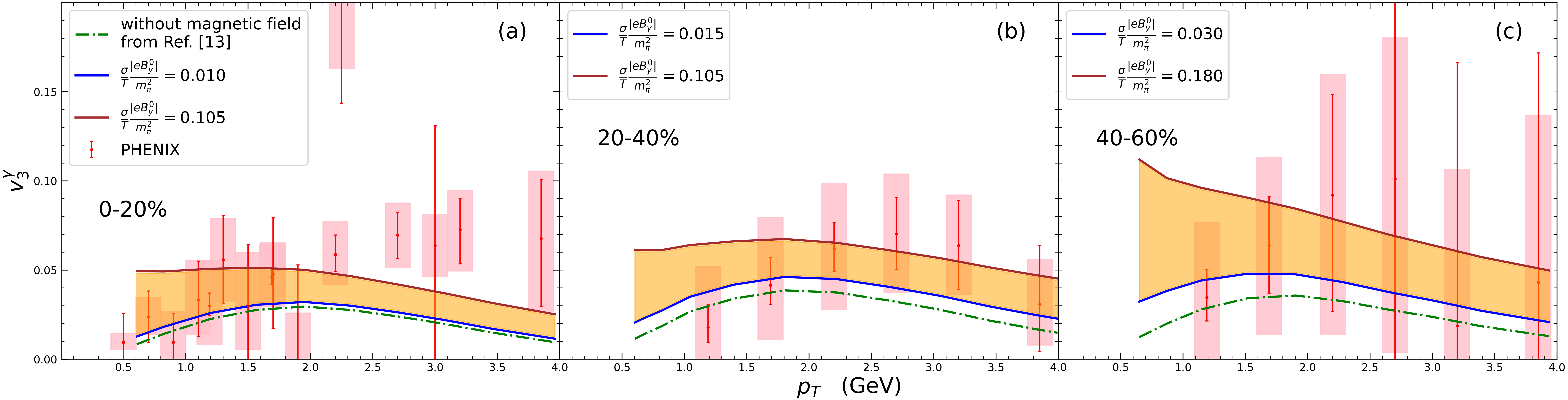
AuAu@200GeV



- Use the experimental measured elliptic flow to constrain the strength of B field.
- $eB^{\text{ebe}} \ll eB^{\text{Single}}$

v_3 of direct photon

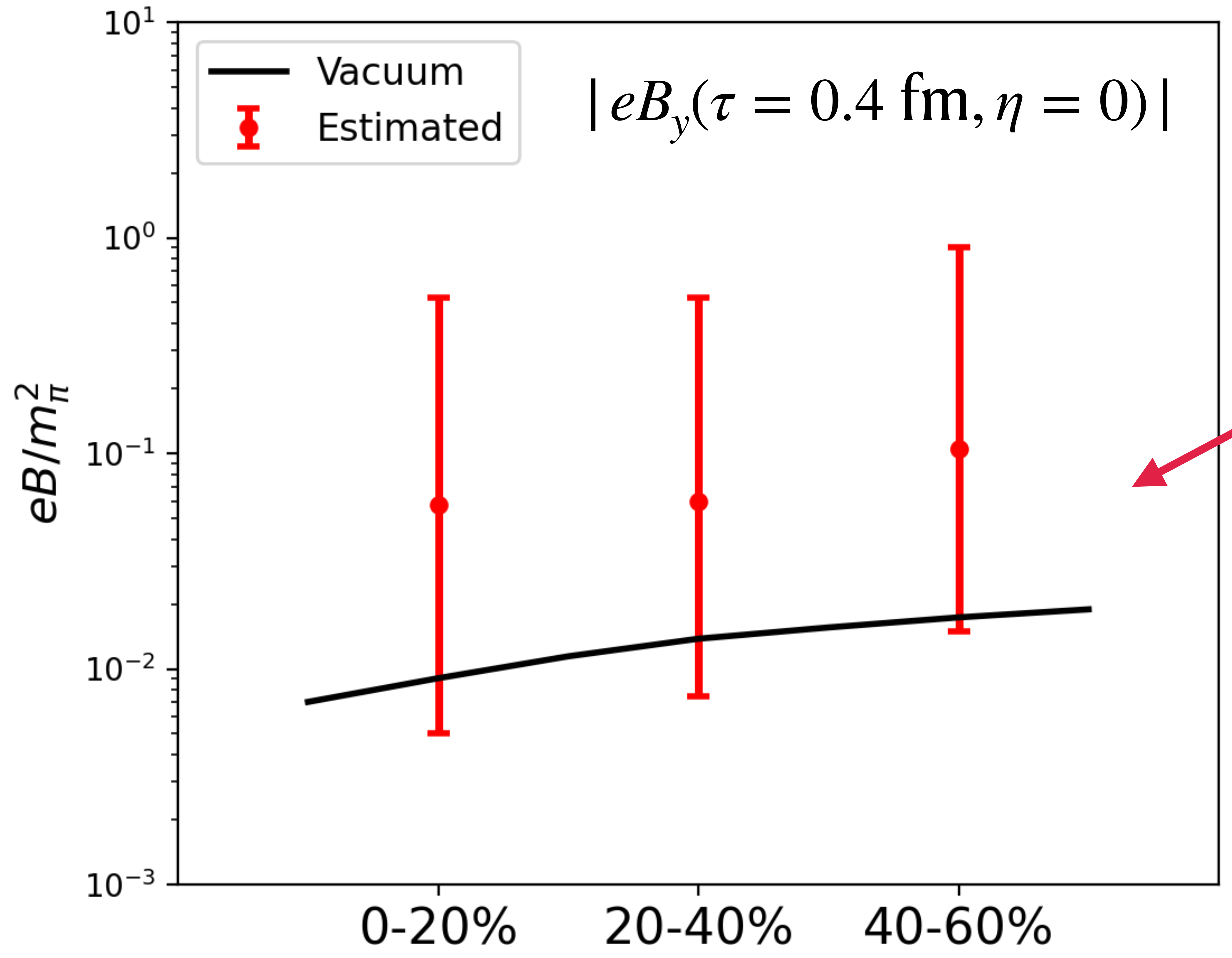
AuAu@200GeV

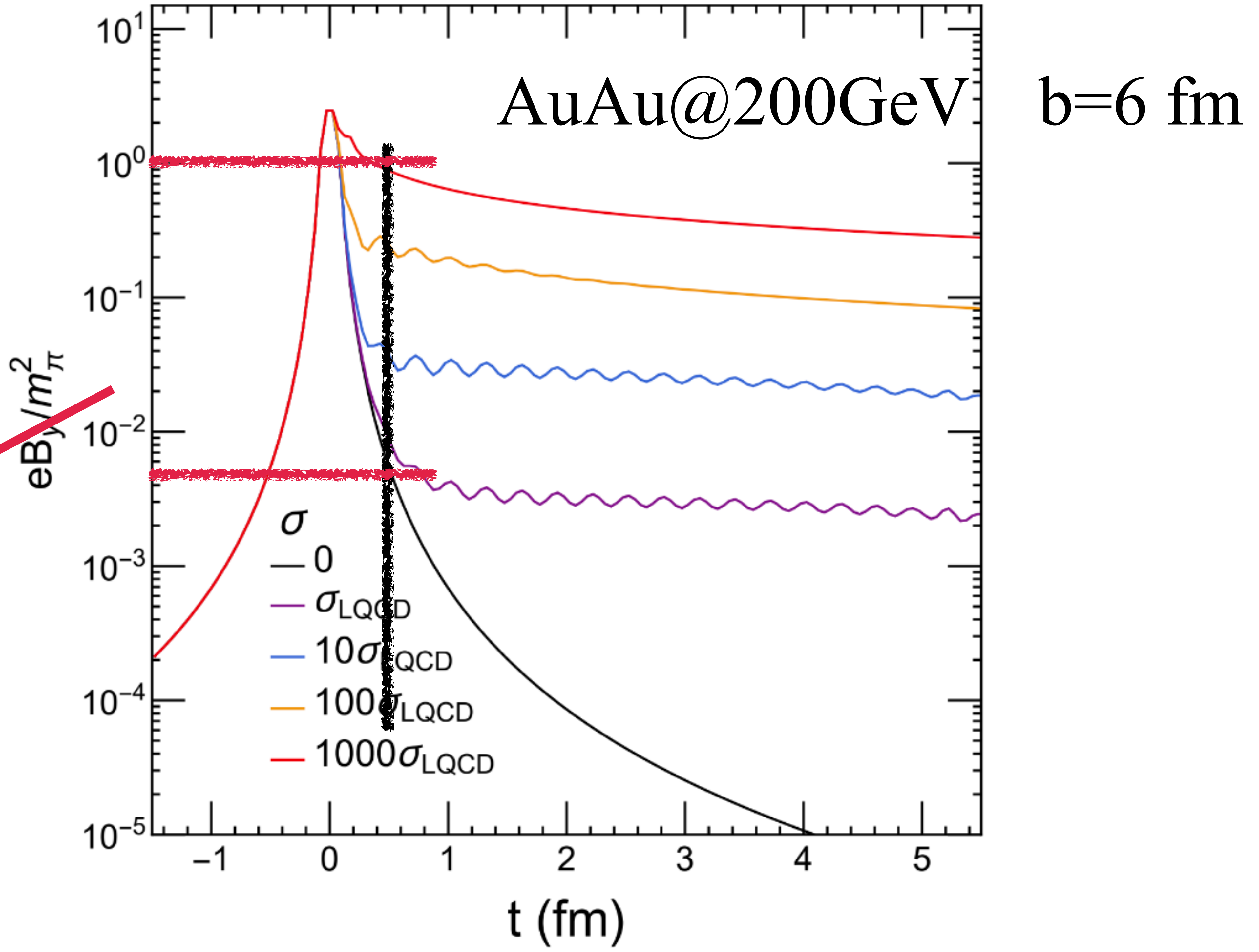


- The weak magnetic photon emission also has significant effect on the triangle flow.

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

Estimated B field at $\tau = 0.4$ fm 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

$\frac{\sigma}{T} \in [0.2,2]$ Cover the experimental elliptic flow data

F.Stefan arxiv: 2112.12497

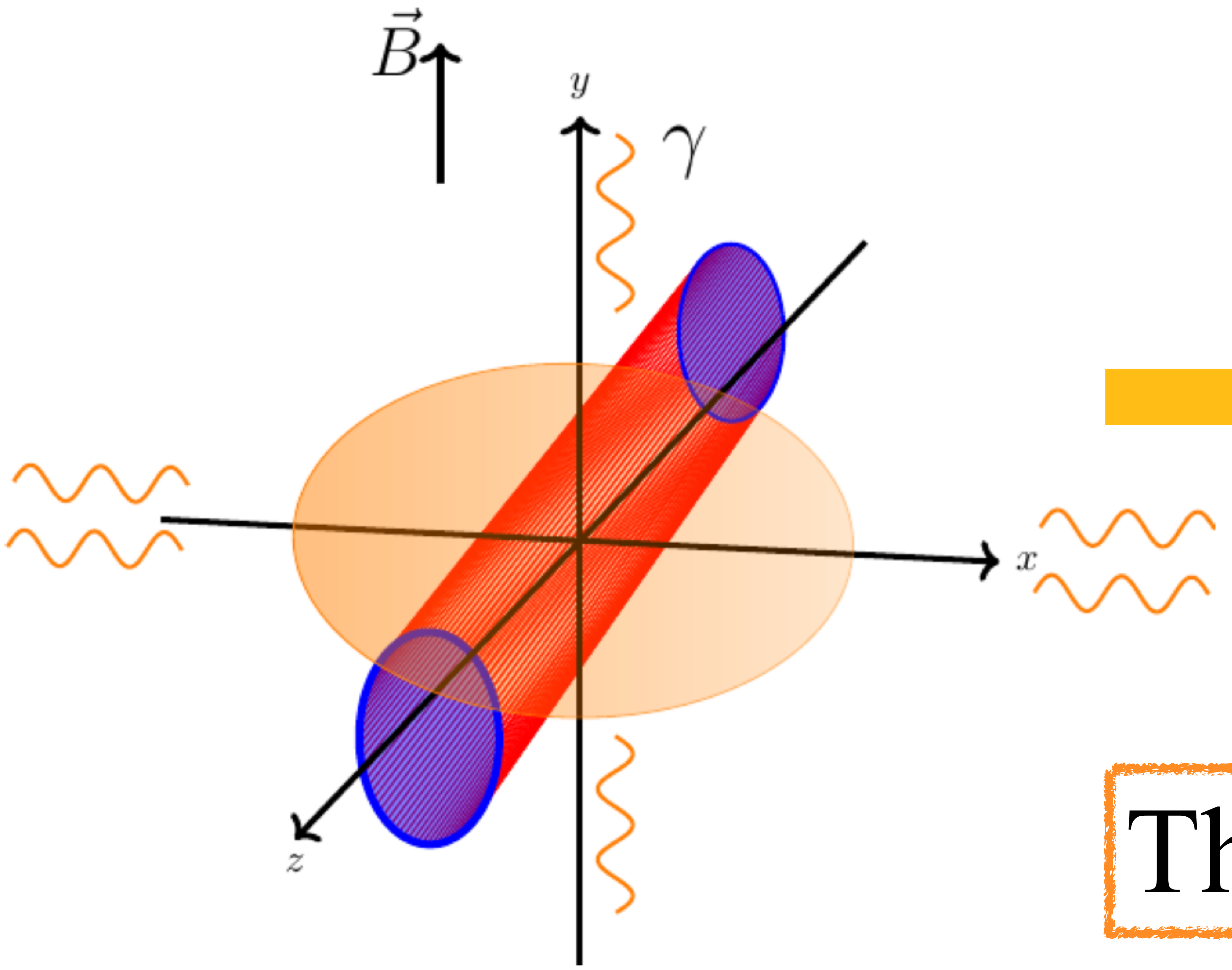
Summary

- **Weak magnetic photon emission:**

  Weak magnetic field + the non-trivial longitudinal dynamics of fireball.

- The elliptic flow of photons at RHIC and LHC are **reproduced for the first time**.
- **The initial B field** can be extracted from photon spectra.

arXiv: 2302.07696



Towards direct photon puzzle.

Thanks for your attention!

ATHIC2023

Back up

$$\mathcal{R}^\gamma = \bar{\mathcal{R}}^\gamma + \mathcal{R}^\gamma_{\rm EM}$$

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

$$E_p \frac{d^3N_{\rm EM}}{d^3\mathbf{p}} = \int_V \mathcal{R}^\gamma_{\rm EM}(P,X) = v_0^{\rm EM}(1+2v_2^{\rm EM}\cos 2\phi_p)$$

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

Small angle approximation for photon production rate

For the process $1+2 \longrightarrow 3+\gamma$

$$\begin{aligned} \omega\frac{d^3R_\gamma}{d^3k} =& \frac{1}{2(2\pi)^3}\int \frac{d^3p_1}{2p_1^0(2\pi)^3}\frac{d^3p_2}{2p_2^0(2\pi)^3}\frac{d^3p_3}{2p_3^0(2\pi)^3} \times (2\pi)^4\delta^4(P_1+P_2-P_3-K)\,|\mathcal{M}|^2 \\ &\times f_{B/F}(p_1)\,f_{B/F}(p_2)\left[1+\sigma_{B/F}f_{B/F}(p_3)\right] \\ &\propto f_q(k) \end{aligned}$$

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

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.

$$\Rightarrow \quad v_2^{EM} \propto \int \frac{\sinh\eta_s}{\cosh(y-\eta_s)} A_1$$

Rapidity-odd!

Must be Rapidity-odd

A Rapidity-odd directed flow for background medium is required for non-zero v_2^{EM}

Hydrodynamic simulation

Reweight participants of the forward and backward-going nuclei in the two component Glauber model

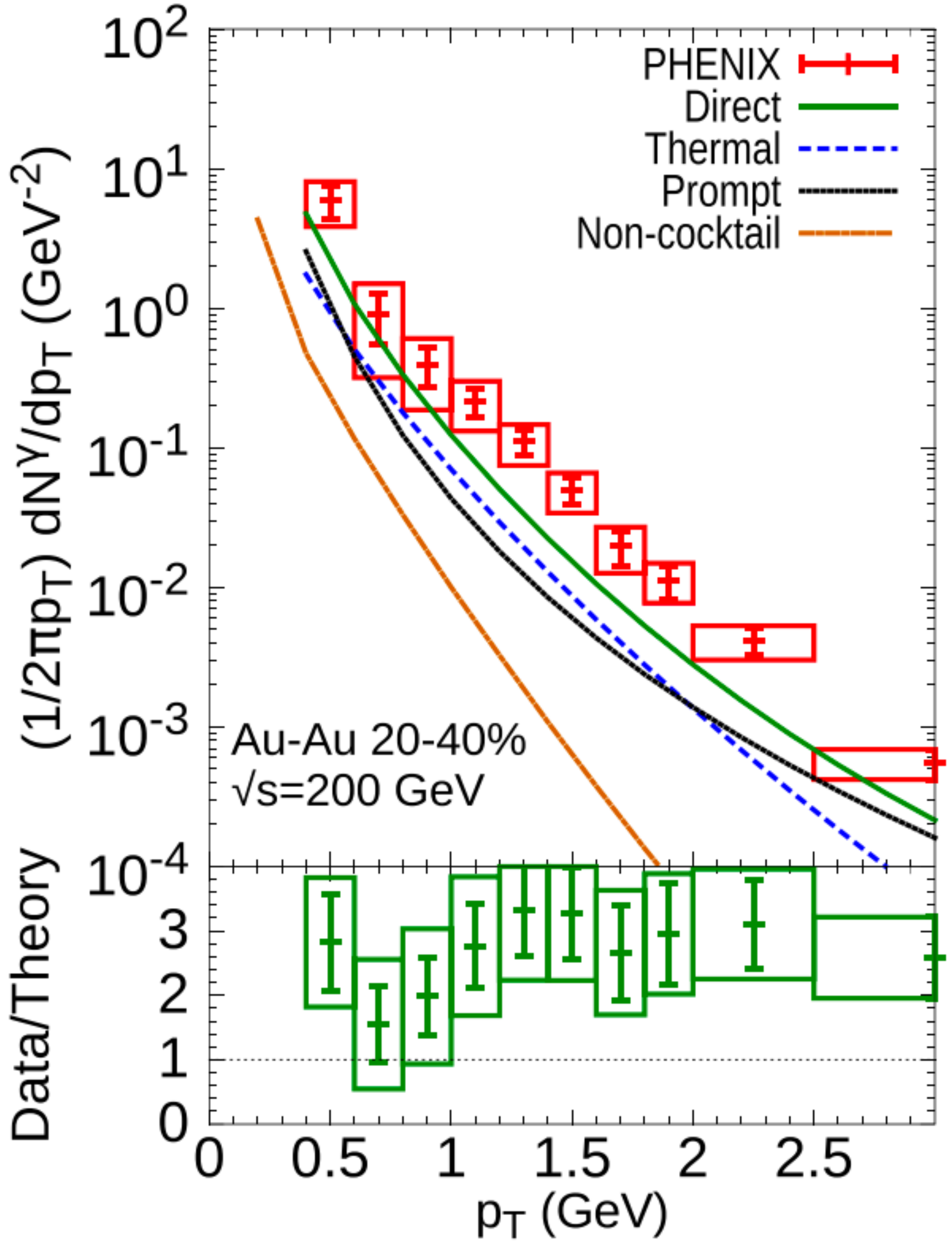
$$s(\tau_0, x_\perp, \eta_s) \propto w(\eta_s)[\alpha N_{\rm coll} + (1-\alpha)(N^+_{\rm part} w^+(\eta_s) + N^-_{\rm part} w^-(\eta_s))]$$

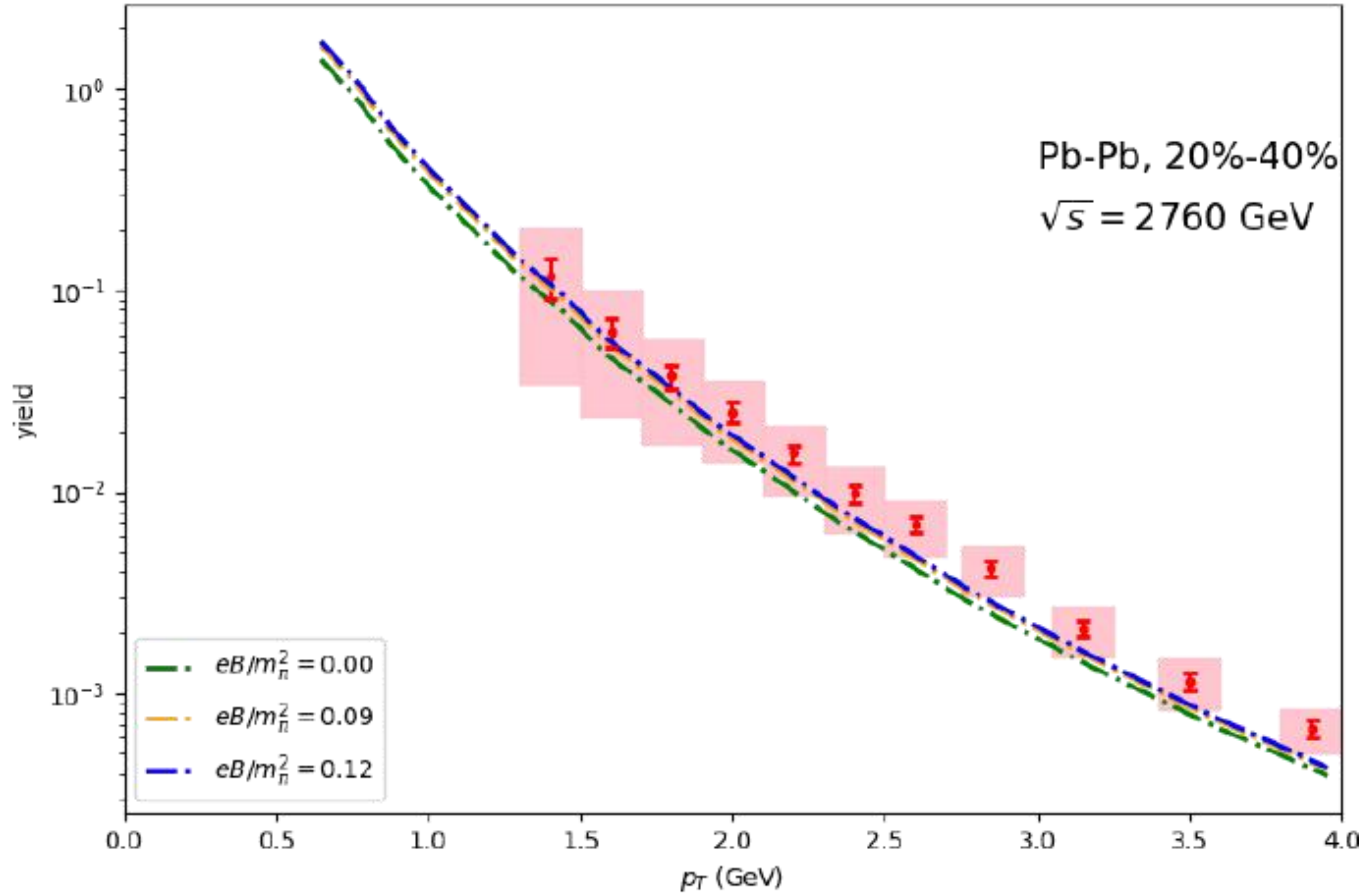
S. Chatterjee and P. Boz˙ek, Phys. Rev. Lett. 120, 192301 (2018)

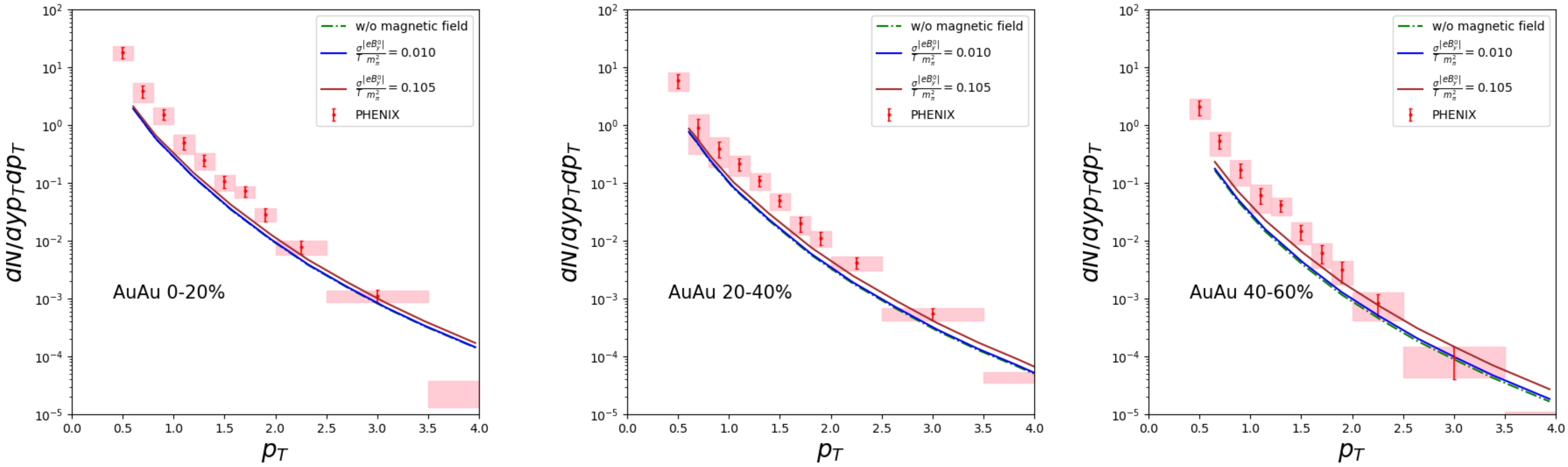
$$w^+(\eta_s) = \begin{cases} 0\,, & \eta_s < -\eta_T \\ \frac{\eta_T+\eta_s}{2\eta_T}\,, & -\eta_T \le \eta_s \le \eta_T \\ 1\,, & \eta_s > \eta_T \end{cases}$$

η_T determines the extent to which the fireball is tilted.

Yield of photons







w/o magnetic field
$\frac{\sigma}{T}\frac{|eB_y^0|}{m_\pi^2} = 0.010$
$\frac{\sigma}{T}\frac{|eB_y^0|}{m_\pi^2} = 0.105$
PHENIX
AuAu 0-20%
AuAu 20-40%
AuAu 40-60%
dN/dyp_Tdp_T
p_T