# Weak magnetic effect in heavy-ion collision

Li Yan

Institute of Modern Physics, Fudan Univerity

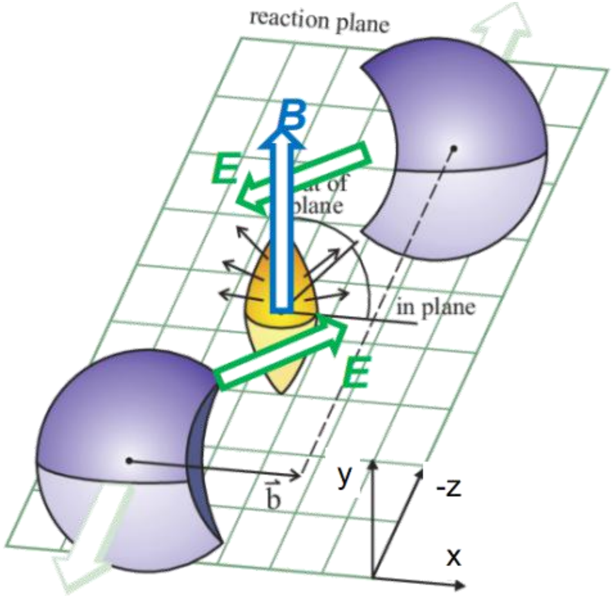
*Strong EM fields, UPC and EIC/EicC* , USTC, 2024, 04/13

with Jing-An Sun, Minghua Wei, arXiv: 2302.07696, 2311.03929, 2401.07458

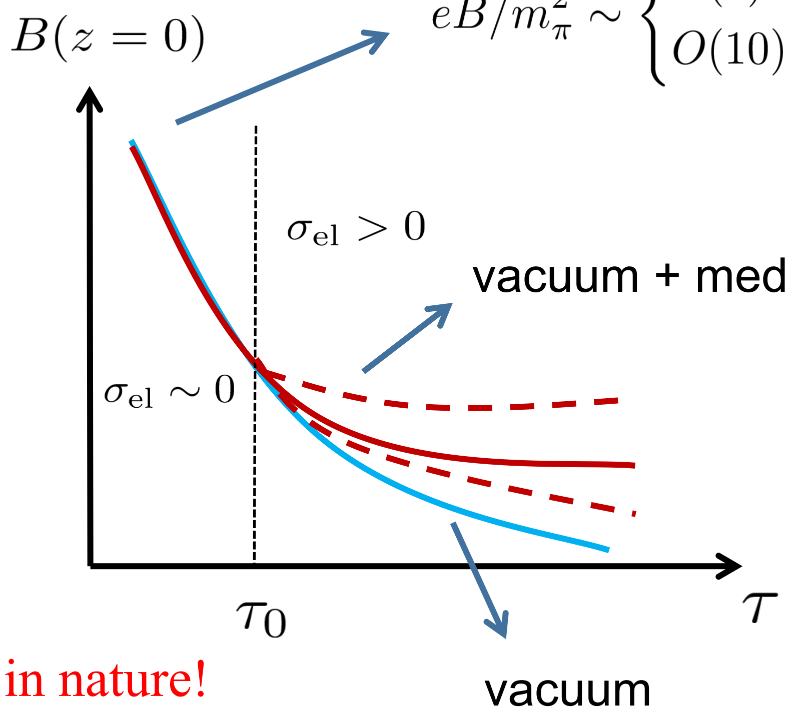
# Electromagnetic field in heavy-ion collisions

- Generated from the relativistic motion of nucleus.
- B field is extremely strong initially, but becomes weak as QGP evolves hydrodyamically.

[Skokov and Bzdak 2012, Deng and Huang 2012, Kharzeev 2008, Tuchin 2010, Skokov and Mclerann 2013, ...]



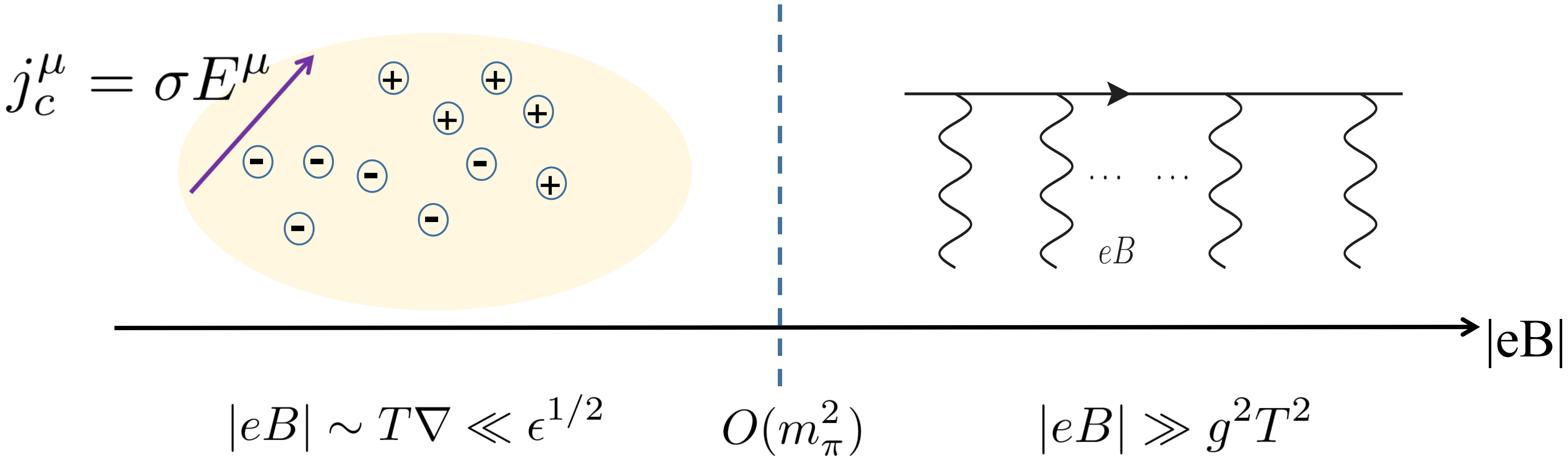

$$eB/m_\pi^2 \sim \begin{cases} O(1) & \text{RHIC} \\ O(10) & \text{LHC} \end{cases}$$




Weak field in terms of QCD scales, but still quite strong in nature!

# Magnetic field in QGP: strong vs. weak

- effect of eB in a charged medium, e.g., QGP




[Huang, Zhao and Zhuang, 2208.01407]

# Weak magnetic field and quark distribution

Solving transport eq. using Chapman-Enskog method,

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

at leading order in $eB/T^2$ one finds solution (scalar form solution),

$$\delta f_{\rm EM} \sim \tau_R q F^{\mu\nu} p_\mu \frac{\partial}{\partial p^\nu} n_{\rm eq} \quad \leftrightarrow \quad \Delta J^\mu_{\rm el} = \sigma_{\rm el} F^{\mu\nu} u_\nu$$

Concerning quark spin dof, it is similar but one needs to generalize $n_{eq}$ to $\mathcal{F}_{eq}$.

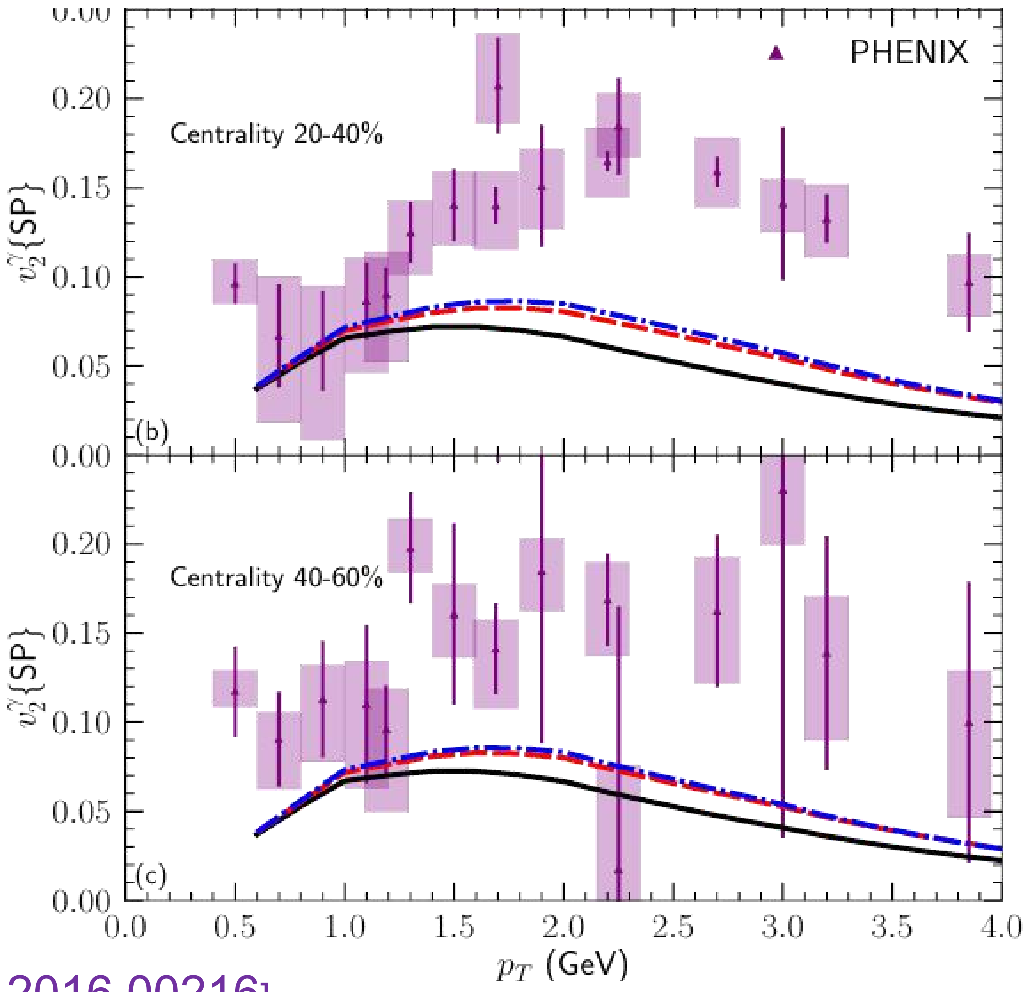
$$\delta \mathscr{F}_{\rm EM} = -\frac{\bar{\tau}}{T} Q F^{\mu\nu} p_\mu \frac{\partial}{\partial p^\nu} \mathscr{F}_{\rm eq}$$

# Weak magnetic effects in

1. Direct photon production
2. Lambda hyperon local polarization
3. Virtual photon polarization

# Up-to-date realistic eBe hydro predictions

- QGP with elastic and inelastic processes
- NNLO pQCD for prompt photons
- LO thermal AMY rate
- Hadron gas photon productions
- Dissipative corrections from shear and bulk
- Chemical equilibration in QGP
- ...
- There is no EM field!

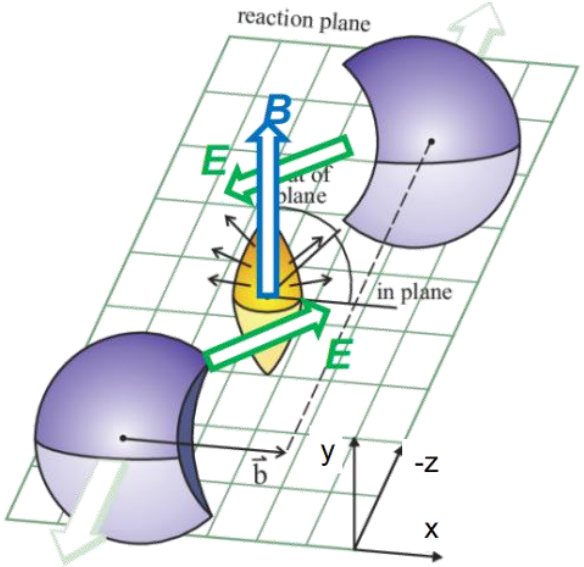



[C. Gale et al, 2016.00216]

# Weak magnetic photon emission from QGP

- Origin of momentum anisotropy:

$$R^{\gamma}_{\rm EM} \sim \ \delta f_{\rm EM} \sim \frac{n'_{\rm eq}}{\chi_n} p^\mu N_\mu = -\sigma_{\rm el} \frac{n'_{\rm eq}}{\chi_n} p^\mu u^\nu F_{\mu\nu}$$



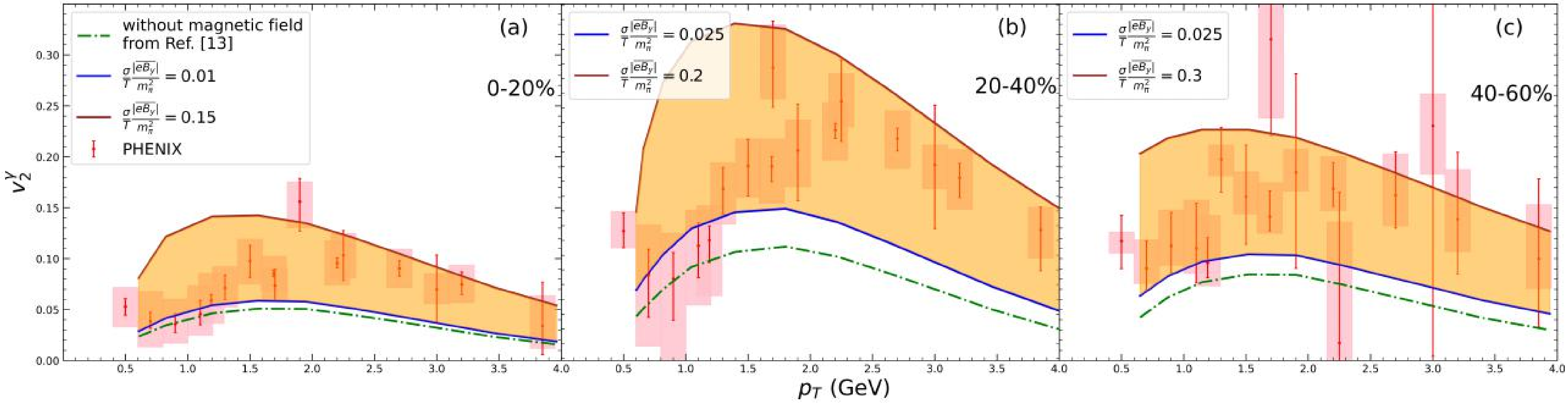

properties of background QGP

$$\ni \ \cos n\phi_p$$

properties of external E&B field, e.g.,

$$B_y p_T u^z \cos\phi_p$$

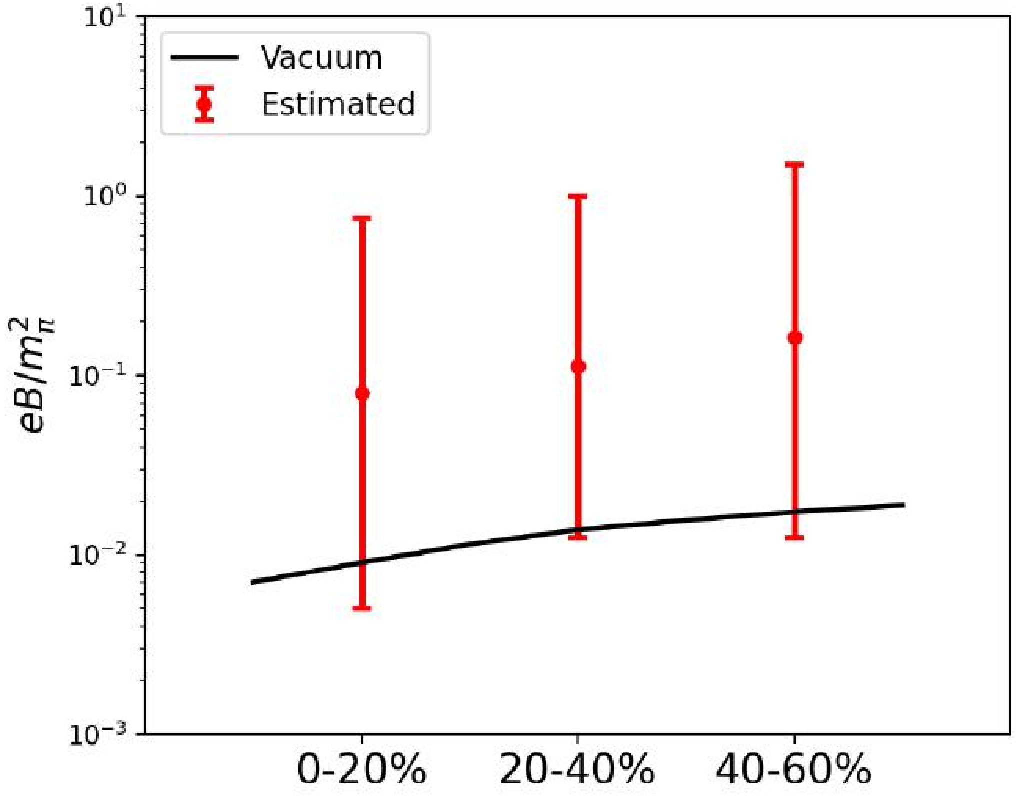
# EbE hydro results: RHIC direct photon v2

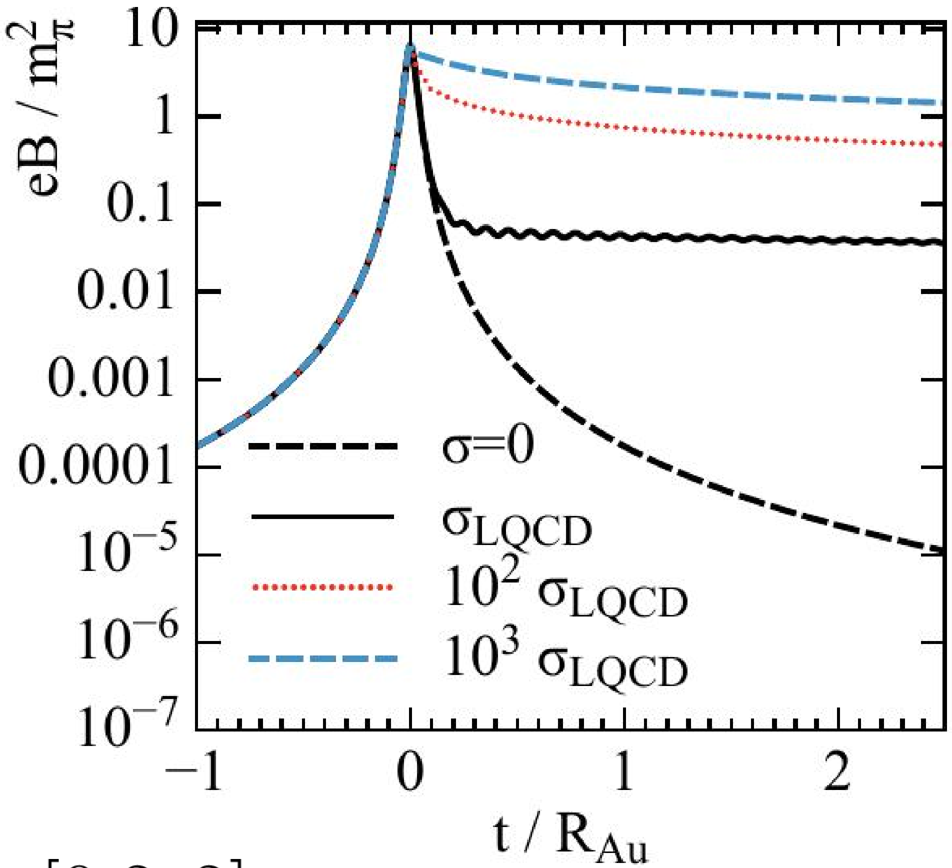



- Experimental data can be reproduced, with a proper parameter $\rho \equiv \frac{\sigma_{\rm el}}{T}\frac{\overline{eB_y}}{m_\pi^2}$
- There is a systematic increase in the parameter.

# Estimate of the time averaged eB

[Skokov and Mclerran, 1305.0774]



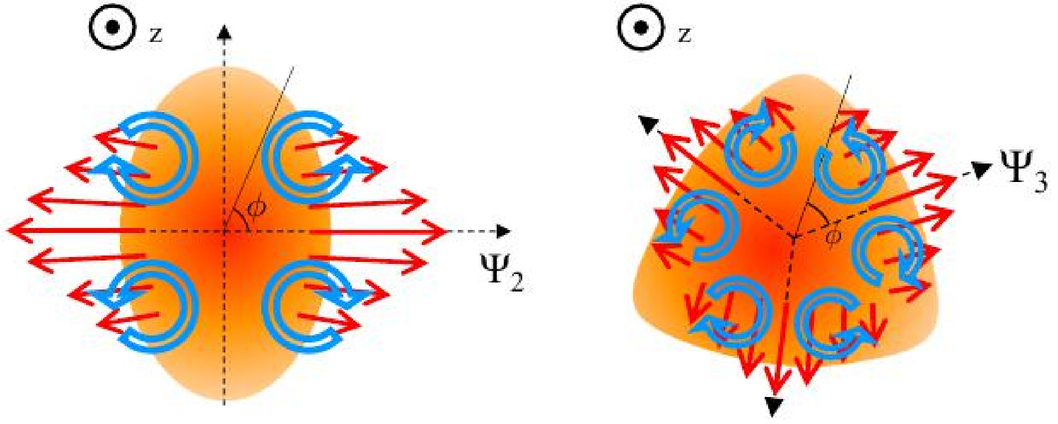



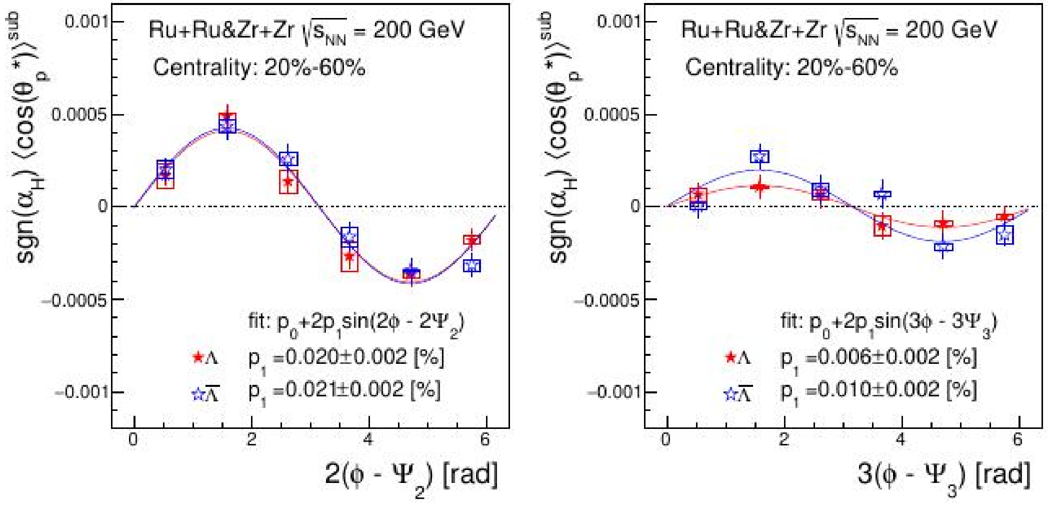

- Extract eB by direct photon v2, with $\sigma_{\mathrm{el}}/T \in [0.2, 2]$ [S Floerchinger et al., 2112.12497]
- This is only a rough estimate of the upper bound of realistic eB.

# Lambda hyperon polarization

[Liang and Wang, PRL 2006, The STAR collaboration, 2303.09074]

Local polarization along beam axis: spin of particles records rotating properties of QGP




- In thermal equilibrium: spin ~ thermal vorticity generated owing to initial geometry.
- Sign observed against naive hydro expectation using thermal vorticity: sign problem

# Polarized particle from QGP

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

Spin of particles emitted from fluid: converted from thermal vorticity, SIP, etc.

- In equilibrium solution:

$$P^{\mu}(p) = \frac{p_{\tau}}{2m}\epsilon^{\mu\nu\rho\sigma}\frac{\int d\Sigma\cdot p\; n_{\rm eq}\bar{\omega}^{\rho\sigma}}{\int d\Sigma\cdot p\; n_{\rm eq}}$$

- With also SIP contribution: (LY and BBP)

[S. Y. F. Liu and Y. Yin, JHEP 07, 188 (2021)
F. Becattini, et al, Plb 820, 136519 (2021), arXiv:2103.10917]

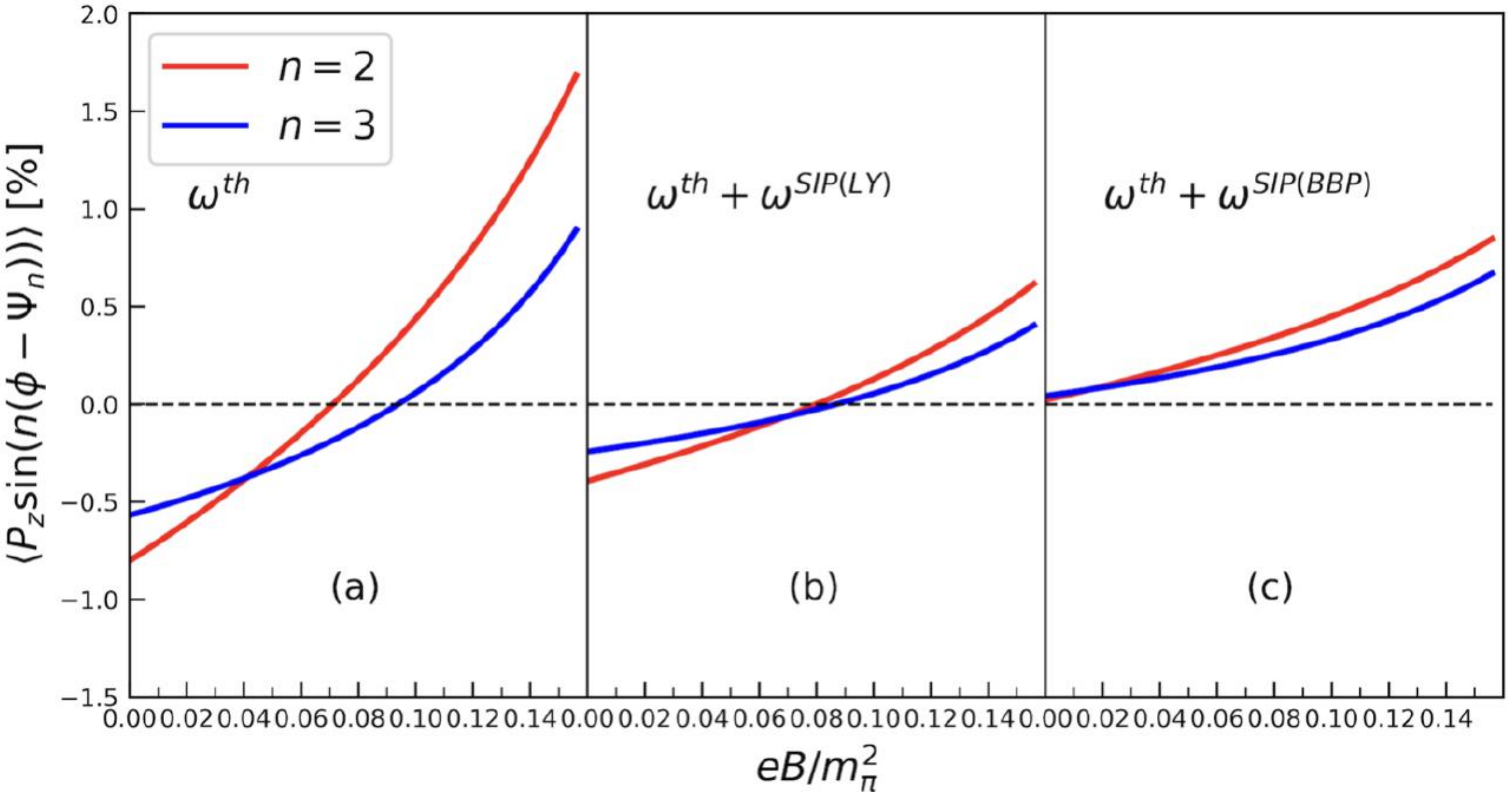
$$\bar{\omega}^{\rho\sigma} \to \bar{\omega}^{\rho\sigma} + \text{SIP}$$

- With weak EM dissipative contribtion:

$$P^{\mu}(\mathbf{p}) = -\frac{1}{8m}\epsilon^{\mu\alpha\beta\sigma}p_{\sigma}\frac{\int d\Sigma\cdot p\,[n_F(1-n_F)+(1-2n_F)\delta f_{\rm EM}]\,\omega_{\alpha\beta}}{\int d\Sigma\cdot p\,(n_F+\delta f_{\rm EM})}$$

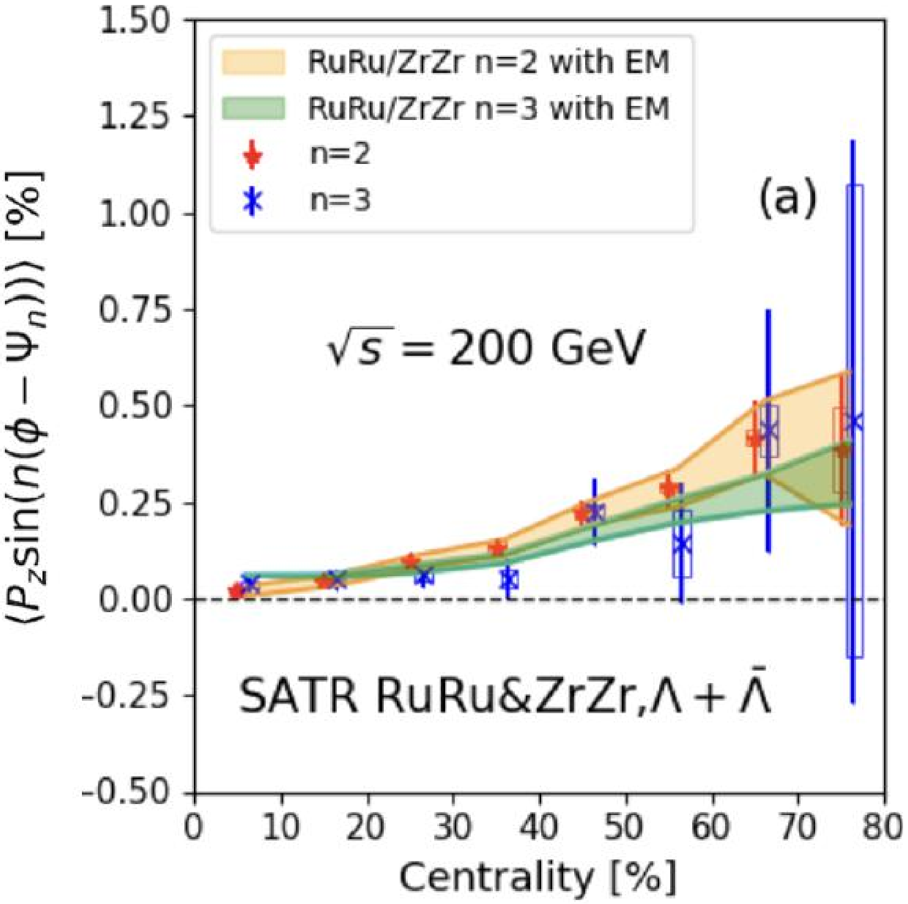
Global polarization merely affected!

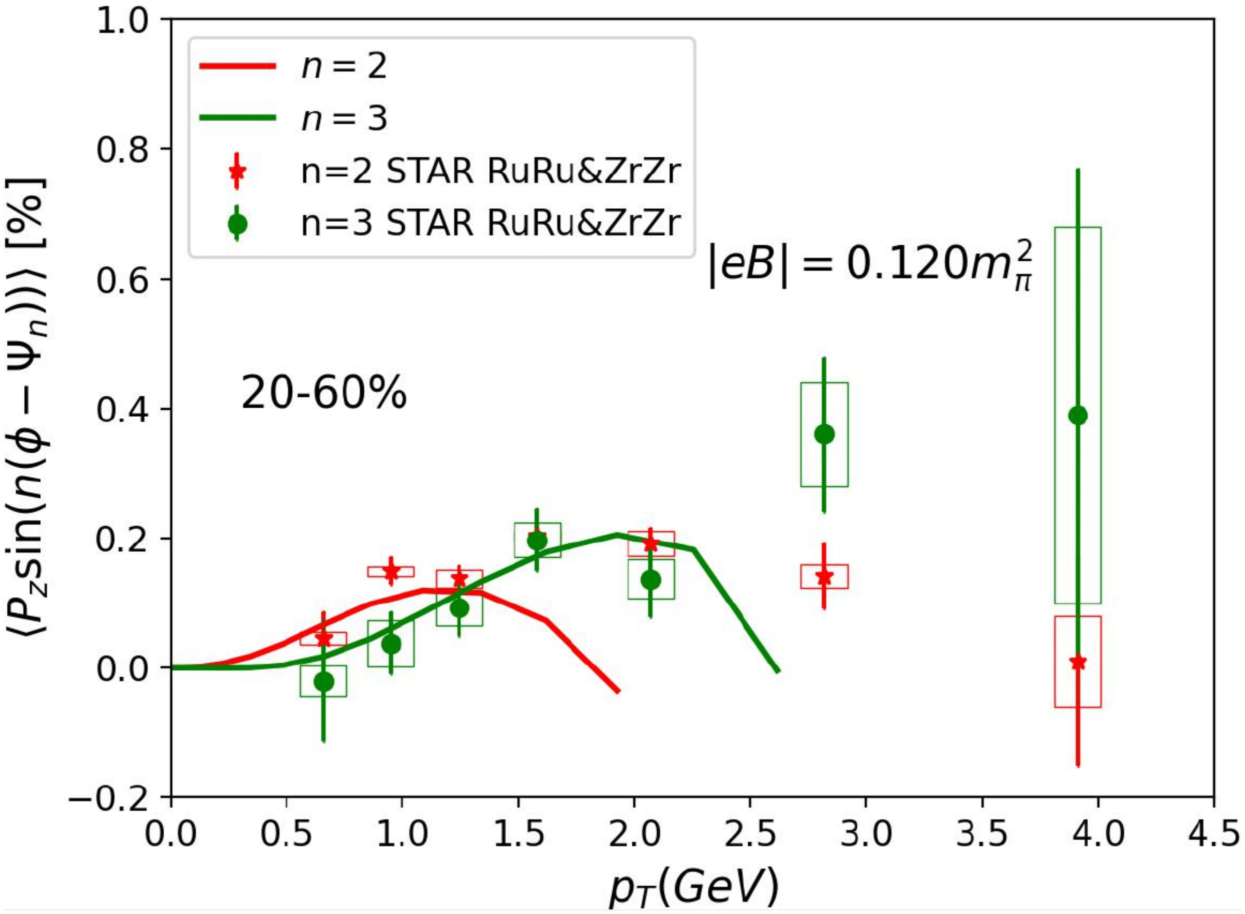
# Local polarization and weak B field (fixed centrality)




- Sign problem can be solved by a weak B field, in addition to SIP.
- Flip of ordering between n=2 and n=3 can only be found with a finite B field.

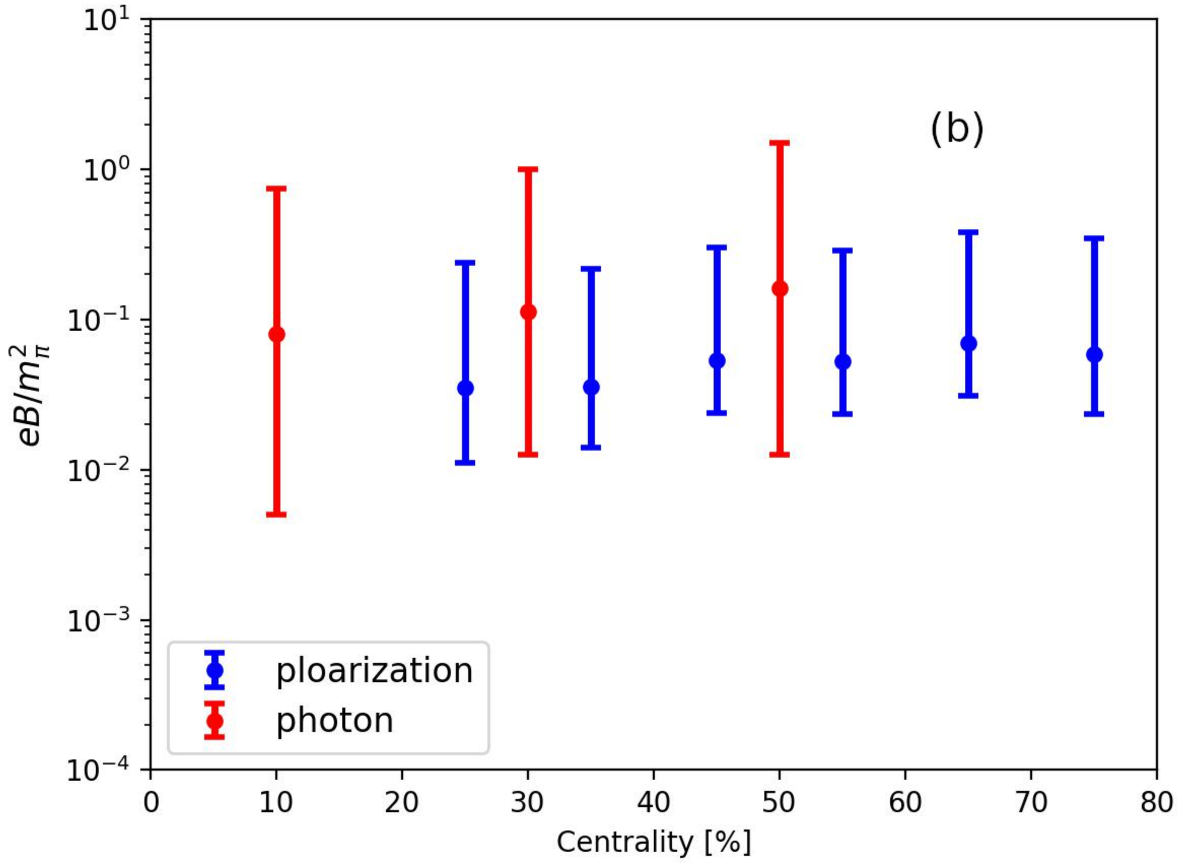
# Confront experimental data



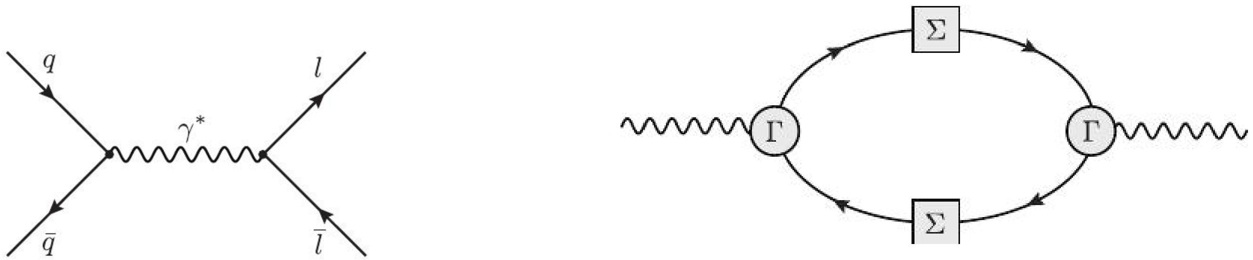

strangeness quark mass = 0.8 GeV

# Estimate of eB from Lambda polarization



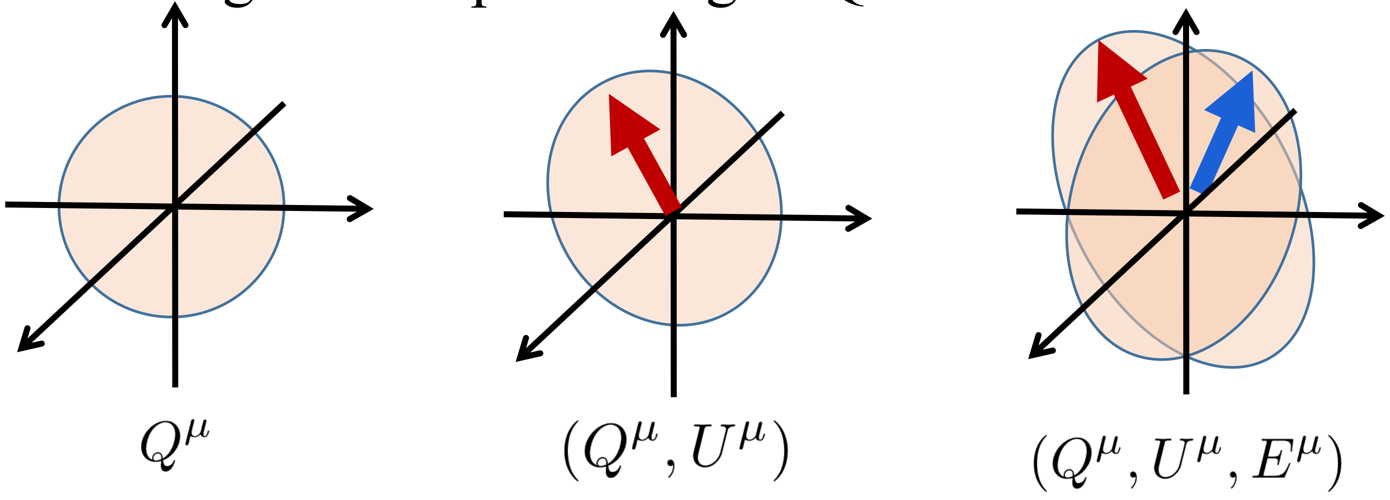

=> consistent with the values from direct photon elliptic flow.

# In QGP virtual photon polarization

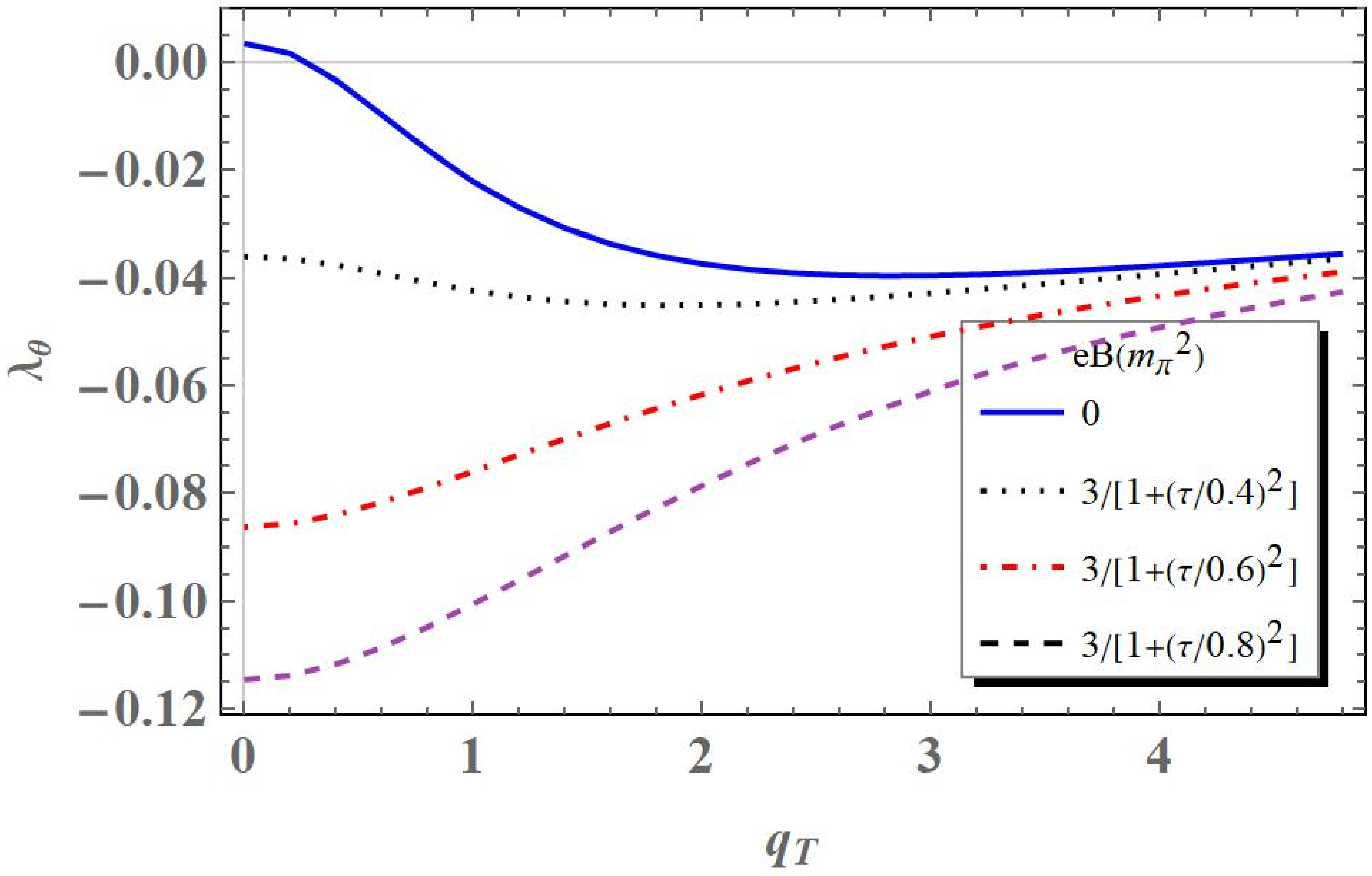



- Virtual photon approximates a intermediate massive spin-1 particle state.
- Polarization states of virtual photon determined by qqbar annihiliation in QGP.
- Induced by geometry breaking vectors presenting in QGP.

$$\rho_{ab}^{\gamma*} \sim \langle \Pi^{\mu\nu}(Q) \rangle$$



# Numerical results (Bjorken flow)




$$\lambda_\theta = \frac{\rho_{++} + \rho_{--} - 2\rho_{00}}{\rho_{++} + \rho_{--} + 2\rho_{00}}$$

Helicity frame lambda_theta

- \rho00 > 1/3 due to eB.
- Sensitive to eB life time.

# Summary

- There must be (at least) weak EM fields in QGP.
- Weak EM fields result in dissipative corrections in QGP fluid.
- Consequences:

1. A weak magnetic field can leads to significant direct photon $v_2$.
2. Change sign of local Lambda polarization
3. Extra polarization of virtual photons.
4. ...

# Back-up slides

# Weak magnetic field and QGP dissipation

- dissipation due to shear force

$$T^{\mu\nu} = T^{\mu\nu}_{\mathrm{ideal}} + \pi^{\mu\nu}$$

$$\pi_{\mu\nu} \sim 2\eta\nabla_{\langle\mu}u_{\nu\rangle}$$

$$\delta f_{\pi} \sim \frac{n'_{\mathrm{eq}}}{\chi_e} p^{\mu}p^{\nu}\pi_{\mu\nu}$$

- dissipation due to EM force

$$J^{\mu} = n_c u^{\mu} + \Delta J^{\mu}$$

$$\Delta J^{\mu} = \sigma_{\mathrm{el}} F^{\mu\nu} u_{\nu} = \sigma_{\mathrm{el}} E^{\mu}$$

$$\delta f_{\mathrm{EM}} \sim \frac{n'_{\mathrm{eq}}}{\chi_n} p^{\mu}\Delta J_{\mu}$$

# Weak magnetic field and collective dynamics

1. Weak EM field does not change background (neutrual) medium evolution.
2. Weak EM field leads to dissipative correction in conserved current,

$$J_{\rm el}^{\mu} = n_c U^{\mu} + \sigma_{\rm el} F^{\mu\nu} U_{\nu}$$

3. Charged components evolve slightly differently in weak EM field,

$$\partial_{\mu} \Delta T^{\mu\nu} = J_{\mu} F^{\mu\nu} \rightarrow \Delta u^{\mu} = u_{+}^{\mu} - u_{-}^{\mu} \sim O(QF^{\mu\nu}/T^2) \neq 0$$

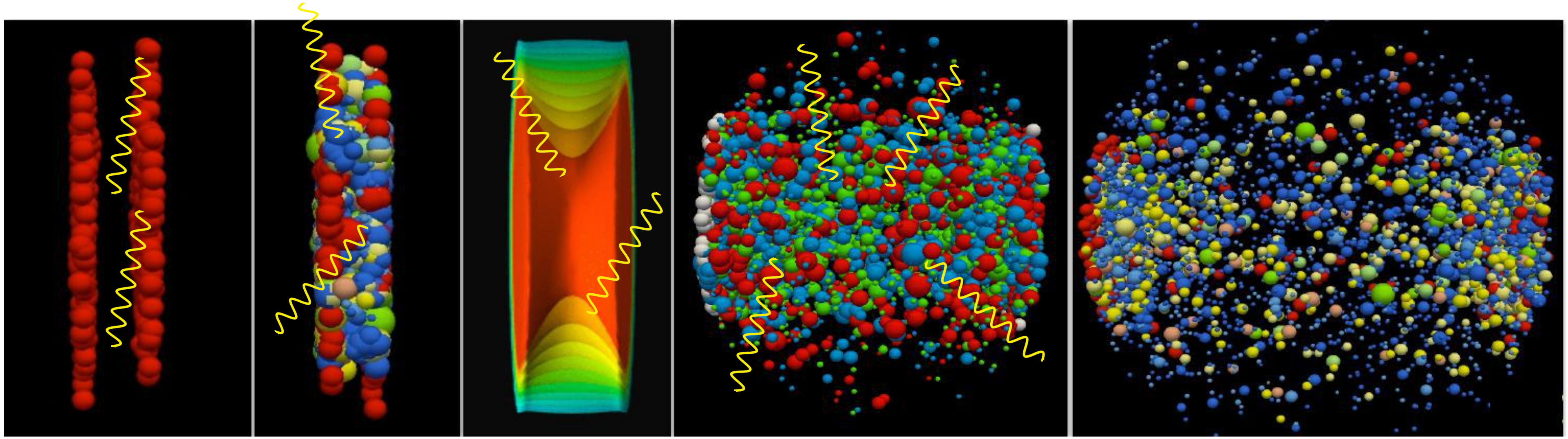
=> QGP bulk evolution is not affected, but charge dependent components feel the presence of the weak EM field, e.g., charged dependent flow

[The STAR collaboration, 2304,03430. U. Gursoy, D. Kharzeev, and K. Rajagopal, PRC 89, 054905 (2014)]

# Direct photons in heavy-ion collisions

[cf., G. David, 1907.08893]

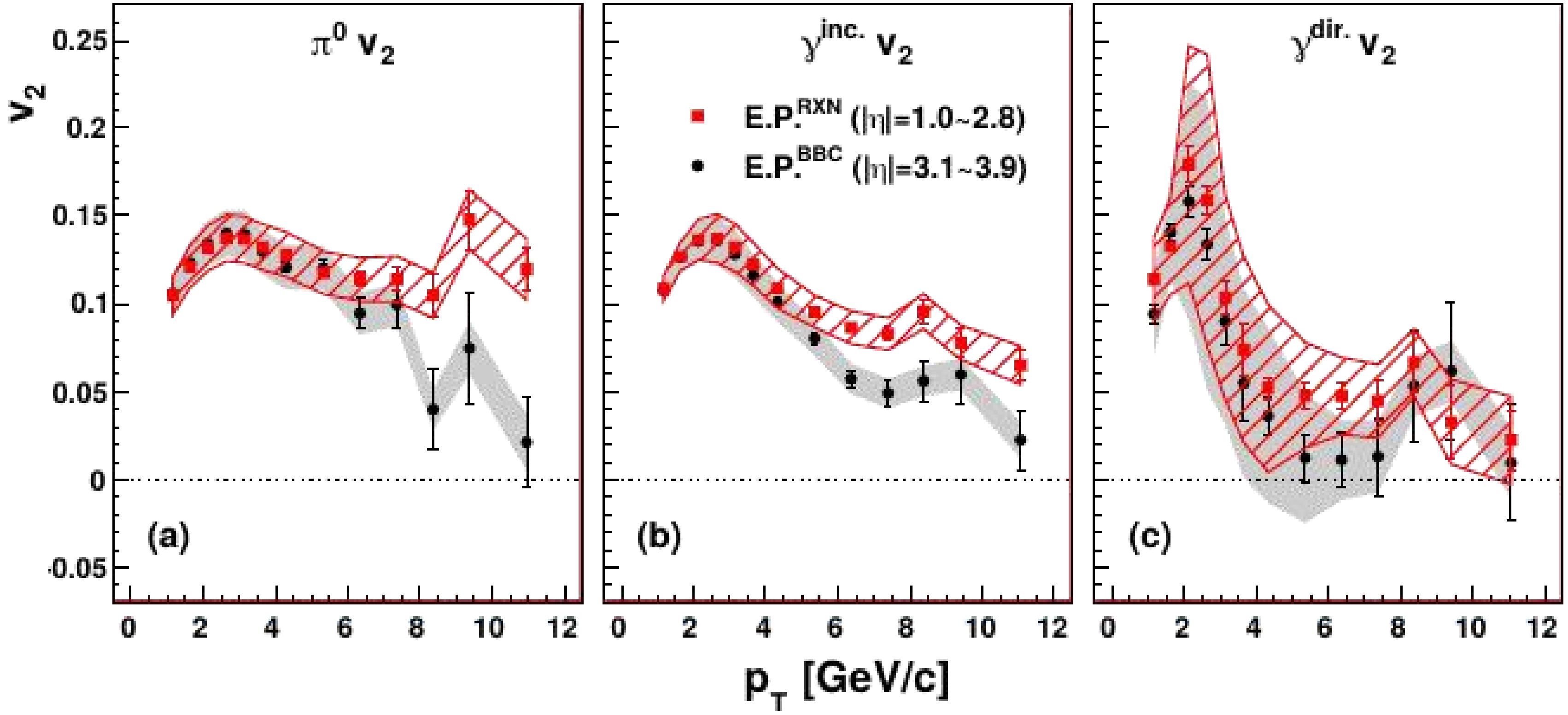
- Produced during the whole system evolution (exclude hadron decay)



- Direct photons = prompt + pre-equ.+ thermal from QGP and HG + jet etc.

# Direct photon puzzle

- Experimental observation: $v_2^{\gamma} \approx v_2^{\text{hadron}}$




[PHENIX collaboration, PRL 109, 122302, (2012)]

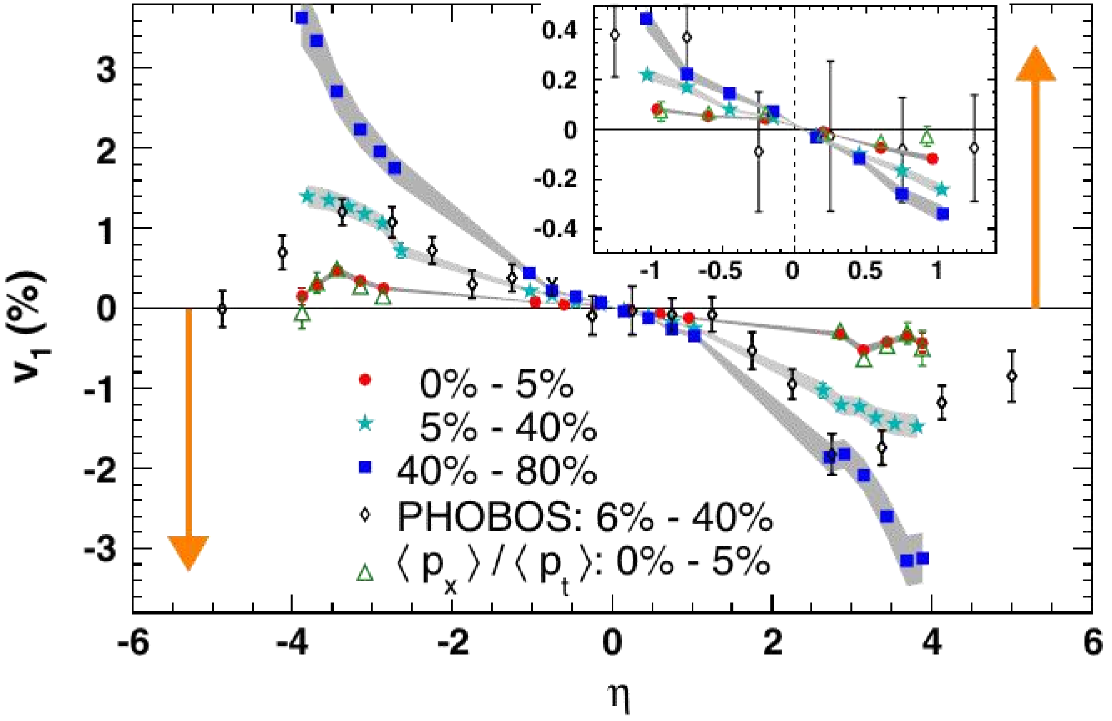
# Photon elliptic flow and hadron $v_1$

- Elliptic flow of photon then requires in the background QGP a $v_1$ component.

  [P. Bozek et al., 1101.3354]

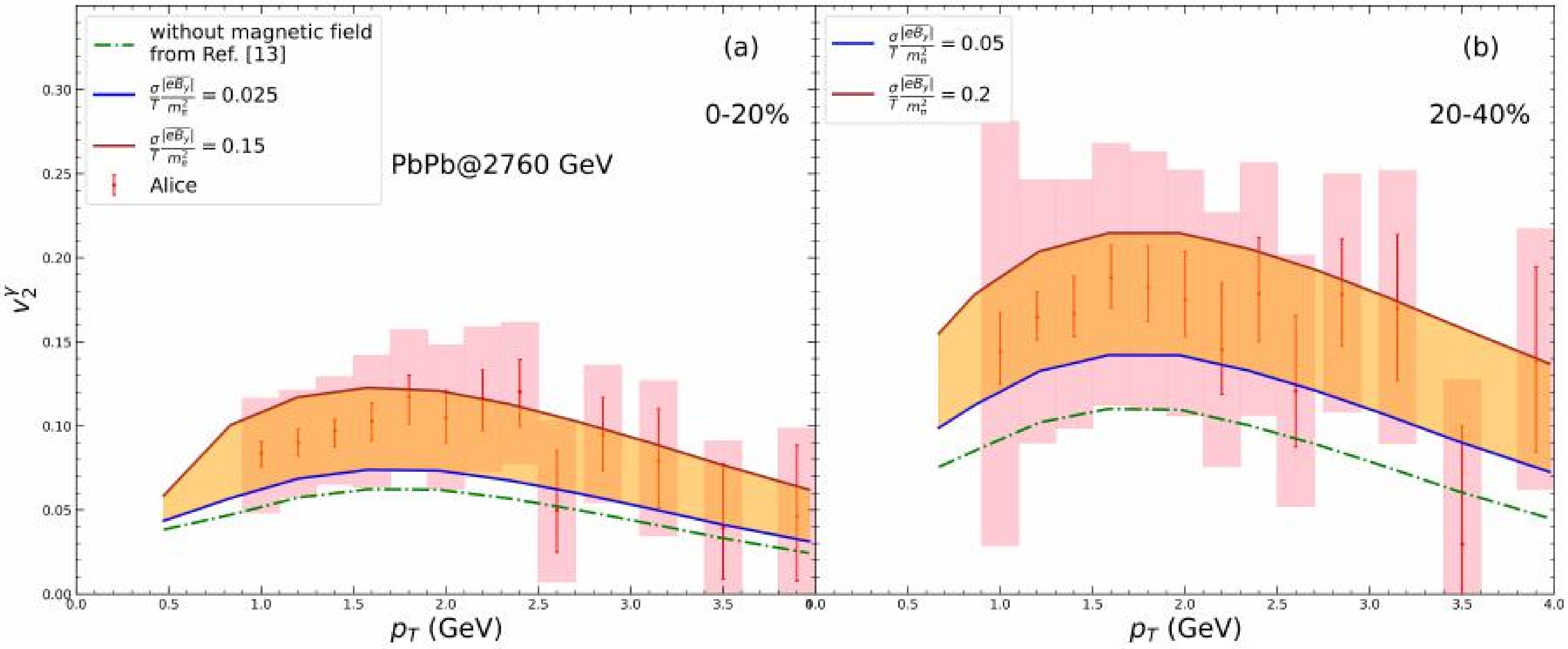
- Exp. measured photons in even rapidity window => one needs a rapidity-odd $v_1$ in the background.

- Theory: EbE 3+1D hydro + weak B field to solve the direct photon puzzle.

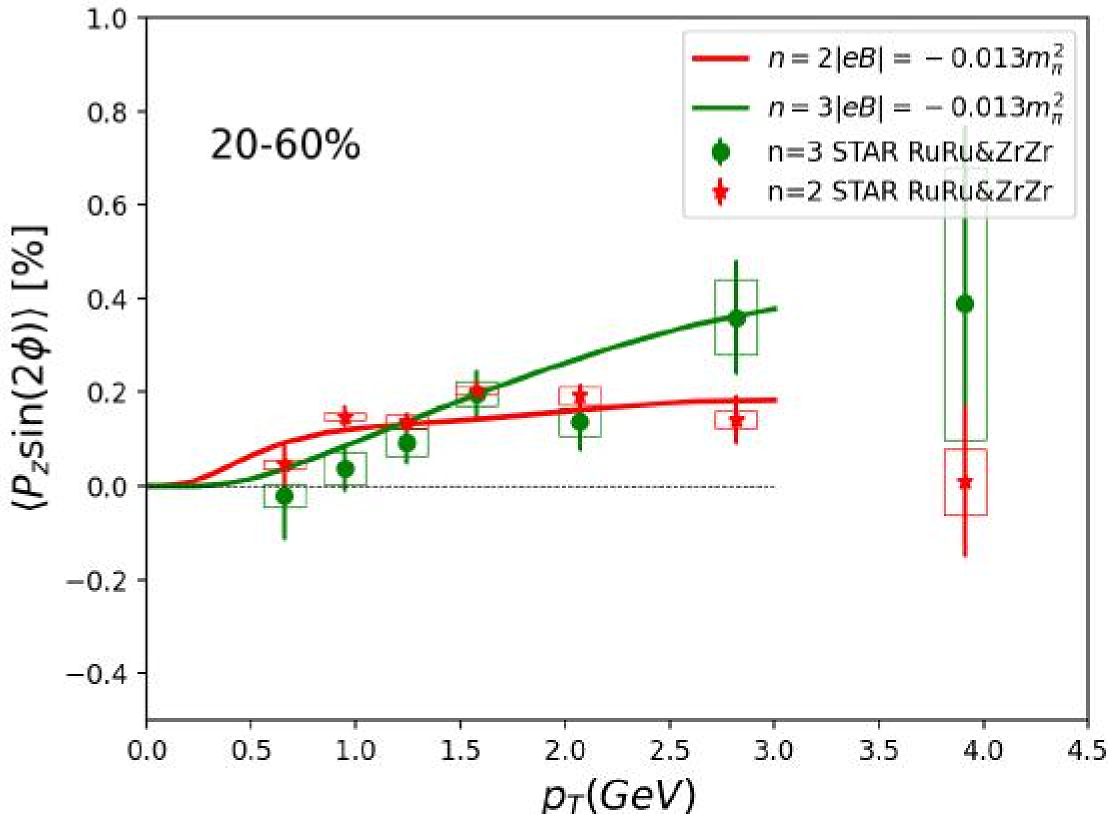



[STAR collaboration, PRL 101, 252301 (2008)]

# EbE hydro results: LHC direct photon v2



# Hydro results: differential local polarization




strangeness quark mass = 0.5 GeV