Effect of weak magnetic field in QGP

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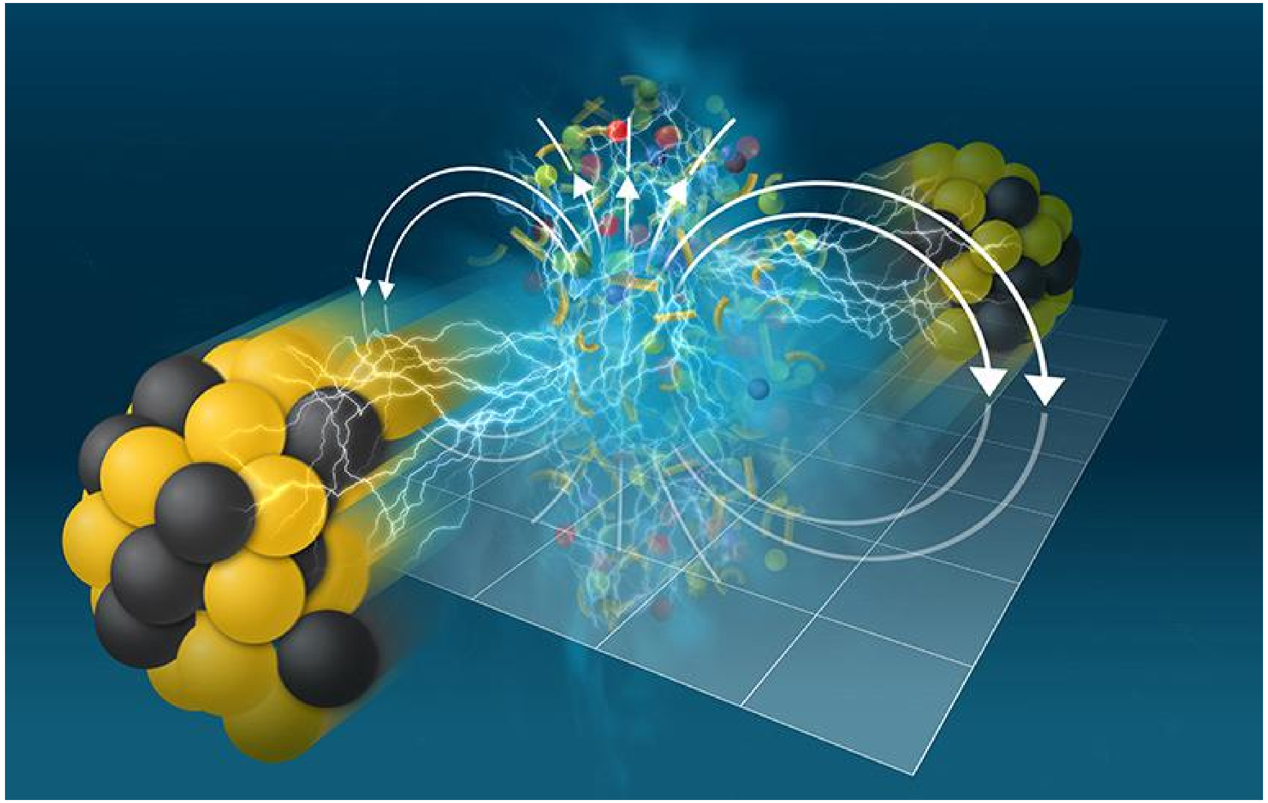
with Jing-An Sun, Minghua Wei, arXiv: 2302.07696, 2311.03929, 2401.07458, 2406.10041

Electromagnetic field in heavy-ion collisions



[T. Bowman and J. Abramowitz/Brookhaven National Laboratory]

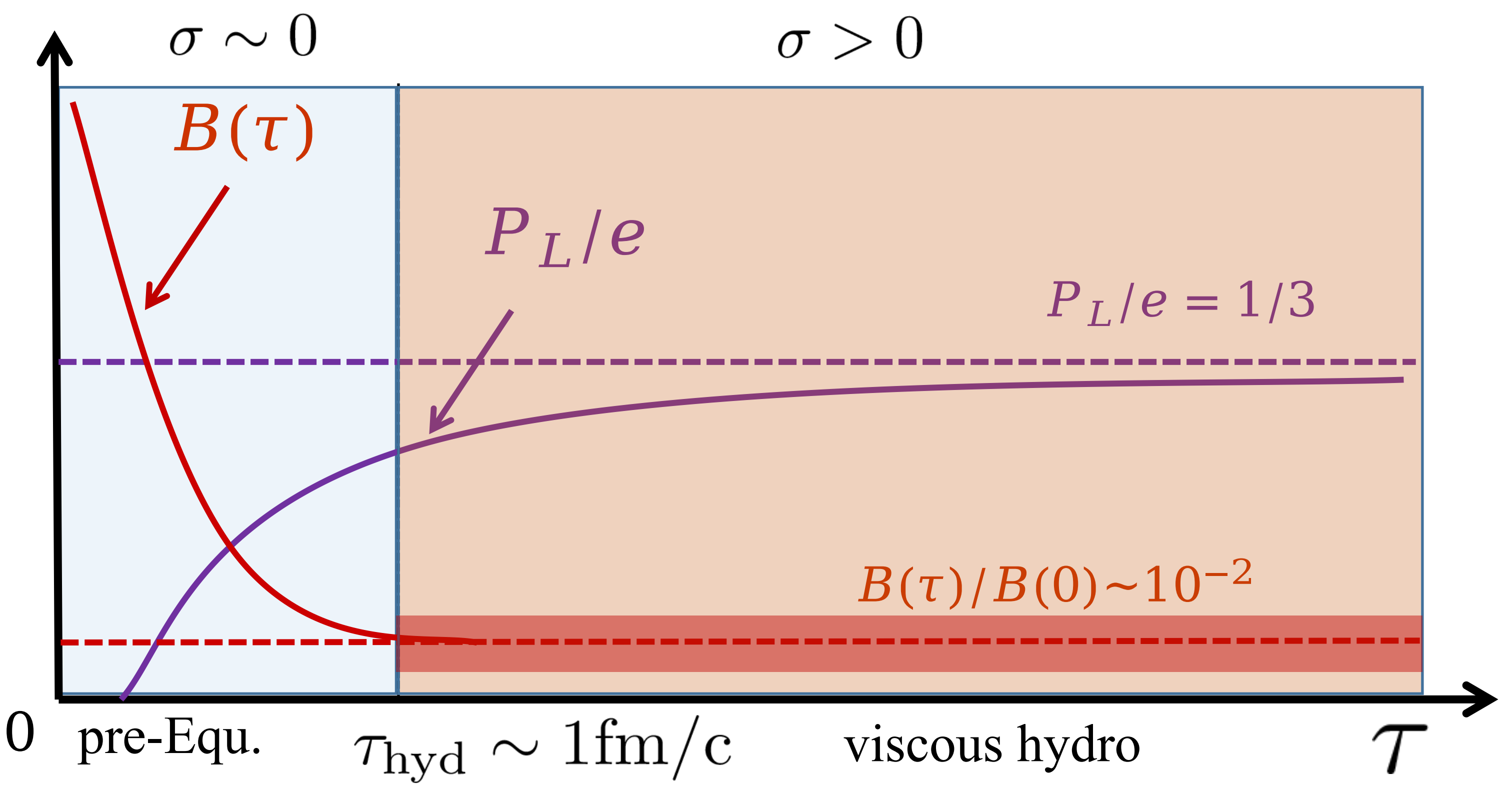
- Initially the field is strong,

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

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

- Generated from the relativistic motion of nucleus (spectators).
- From fluctuations of nucleons inside nucleus -- finite in central (small) collision.

Decay of B and thermalization of QGP



[Mclerran and Skokov, 1305.0774, A. Huang et al, 2212.08579, J-J. Zhang et al, 2201.06171, U. Gursoy et al, 1401.3805, L Yan and X. Huang, 2104.00831, K. Hattori and X. Huang, 1609.00747, and many others]

- EM fields become weak as QGP starts to evolve hydrodynamically,

$$eB(\tau > \tau_{\rm hyd})/m_\pi^2 \sim (0.01, 0.1)$$

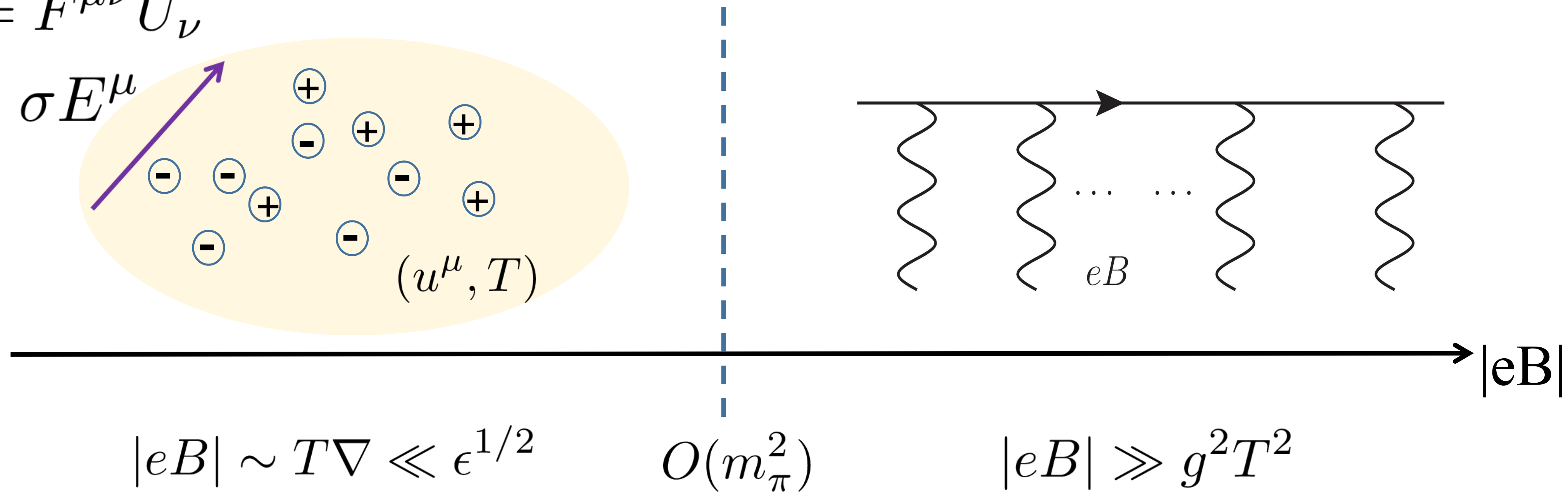
Weak field in terms of QCD scales, but still quite strong in nature!

Theory side: Magnetic field in QGP, weak vs. strong

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

$$E^\mu = F^{\mu\nu} U_\nu$$

$$j_c^\mu = \sigma E^\mu$$



[see Huang, Zhao and Zhuang, 2208.01407, for weak field vs. temperature]

Weak magnetic field corrects quark distribution

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

- Solving Boltzmann-Vlasov transport eq. using Chapman-Enskog method,

$$f = n_{\rm eq} + \delta f_{\rm EM}$$

- At leading order in $|eB|/T^2$ one finds solution (scalar),

$$\delta f_{\rm EM} \sim \tau_R Q F^{\mu\nu} p_\mu \frac{\partial}{\partial p^\nu} n_{\rm eq} \quad \leftrightarrow \quad \Delta j^\mu = \sigma_{\rm el} E^\mu = \sum Q_f \int \frac{d^3\mathbf{p}}{p^0} p^\mu \delta f_{\rm EM}$$

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

$$\delta\mathscr{F}_{\rm EM} = -\frac{\bar\tau}{T} Q F^{\mu\nu} p_\mu \frac{\partial}{\partial p^\nu} \mathscr{F}_{\rm eq} \qquad \Delta j^\mu = \sigma_{\rm el} E^\mu = \sum Q_f \int \frac{d^3\boldsymbol{p}}{p^0} p^\mu {\rm tr}_2[\delta\mathscr{F}_{\rm EM} - \delta\overline{\mathscr{F}}_{\rm EM}]\,,$$

Weak magnetic field and QGP dissipation: linear response

- dissipation due to shear force

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

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

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

- dissipation due to EM force

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

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

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

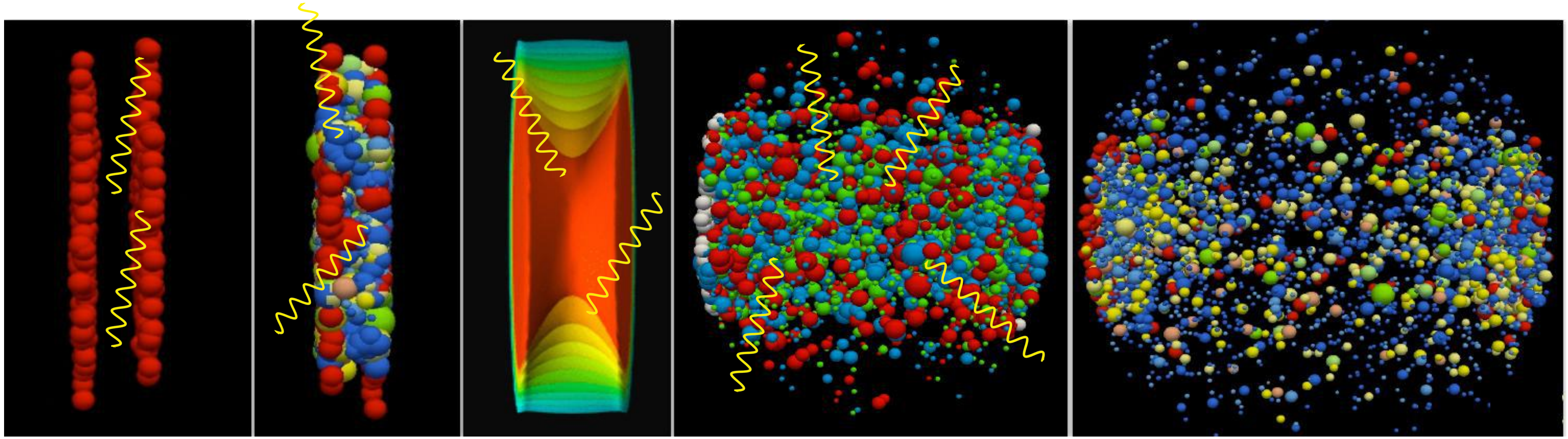
Weak magnetic effects in heavy-ion collisions

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

Direct photons in heavy-ion collisions

[cf., G. David, 1907.08893]

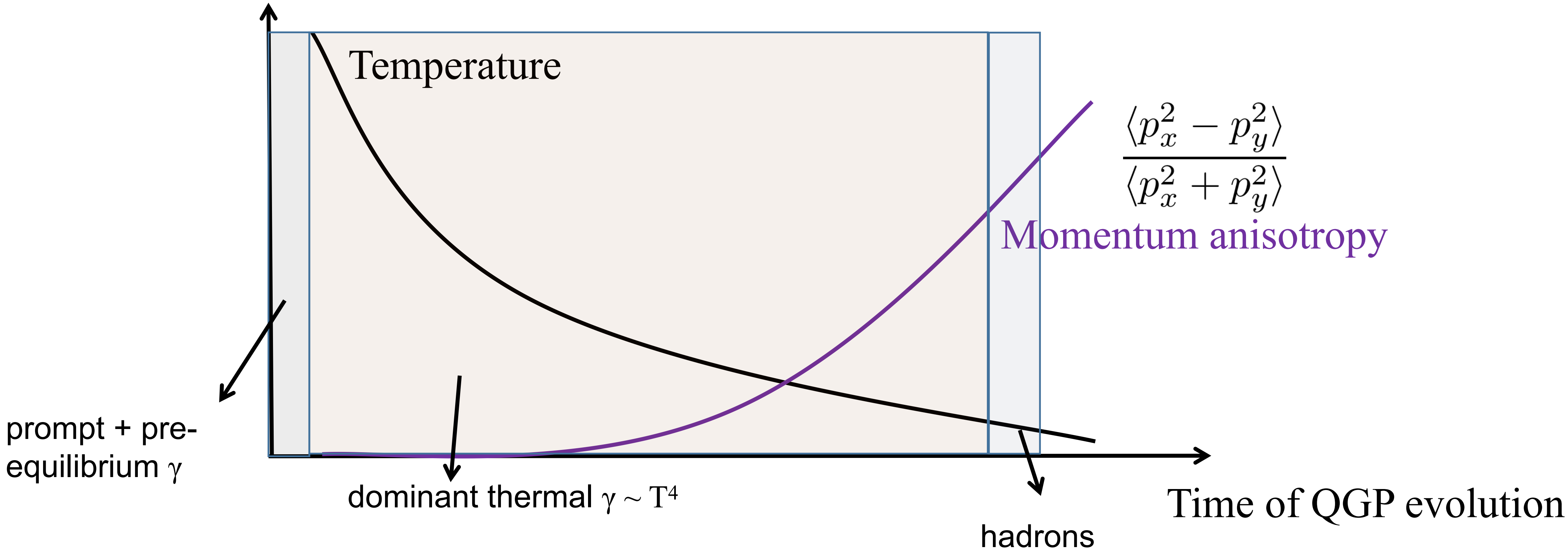
- Produced during the whole system evolution (exclude hadron decay)



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

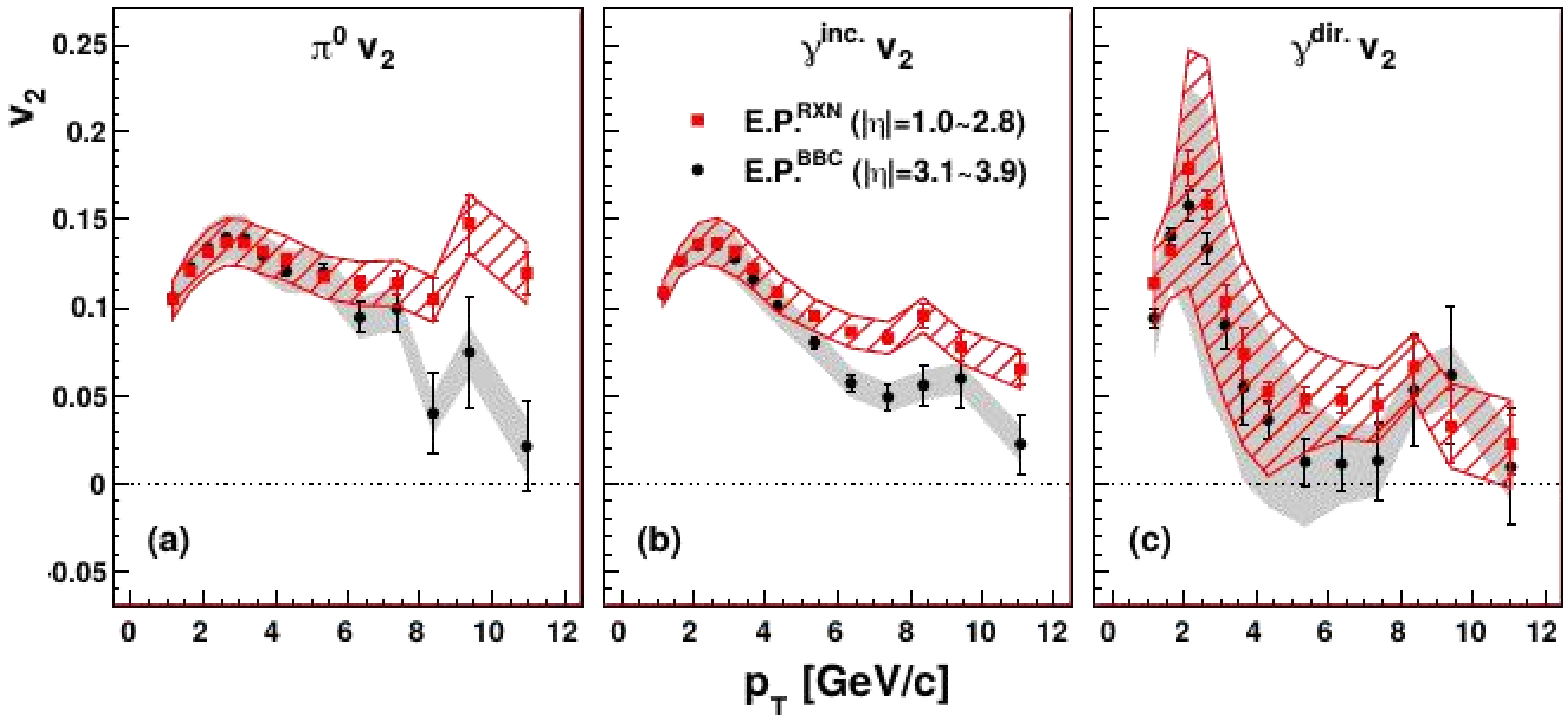
Direct photon elliptic flow (theory)

- Naive expectation: $v_2^{\gamma} < v_2^{\mathrm{hadron}}$



Direct photon puzzle

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

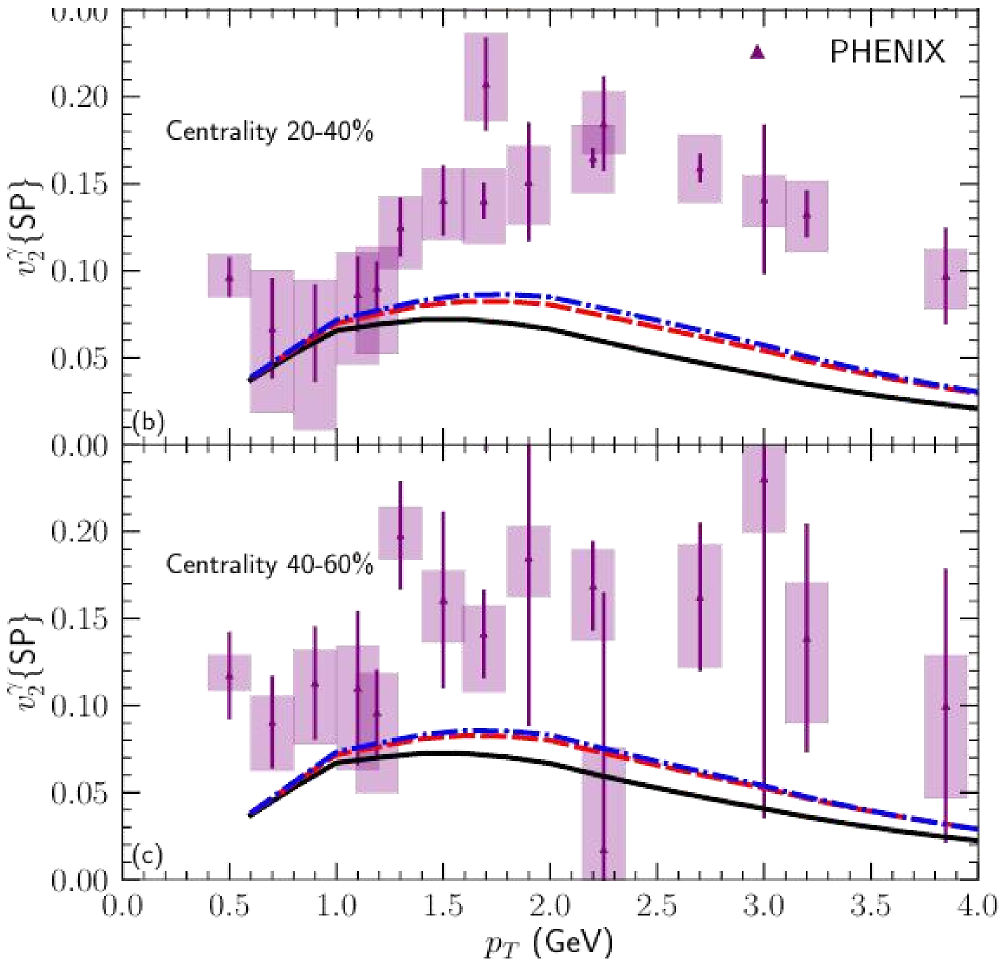


[PHENIX collaboration, PRL 109, 122302, (2012)]

Up-to-date realistic EbE hydro predictions

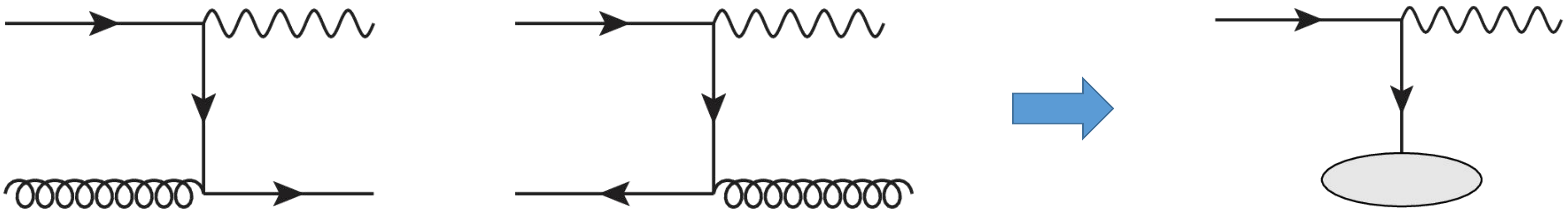
- QGP with elastic and inelastic processes
- NNLO pQCD for prompt photons
- LO thermal AMY rate
- Hadron gas photon productions
- Dissipative corrections from shear and bulk
- Chemical equilibration in QGP
- ...
- There is no EM field!

Direct photon puzzle



[C. Gale et al, 2016.00216, G. David, 1907.08893]

Weak magnetic photon emission from QGP (pQCD)

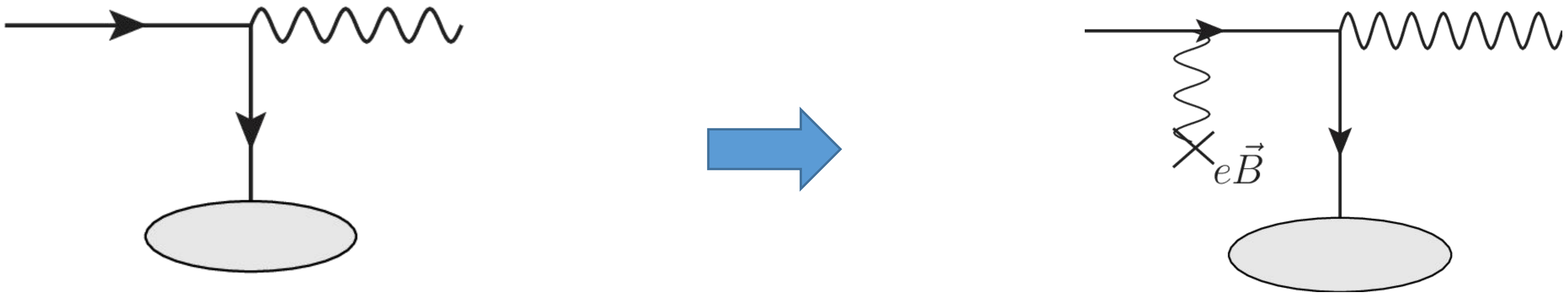


Correct production rate from kinetic theory (pQCD calculation)

$$R^{\gamma} \propto \sum_i \int d\Phi |\mathcal{M}_i|^2 f_{q/g} f_{q/g} (1 \pm f_{q/g}) \propto \alpha \alpha_s I_c f_q$$

NB: small angle approximation is not a necessary step, but good for illustration

Weak magnetic photon emission from QGP (pQCD)



Include all dissipative corrections, including correction by EM field

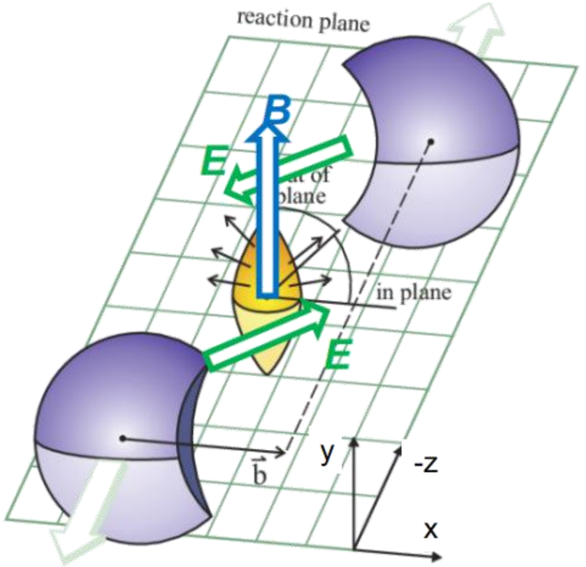
$$f_q \to \bar{f}_q + \delta f_{\mathrm{EM}} \quad \Rightarrow \quad R^\gamma = \bar{R}^\gamma + R^\gamma_{\mathrm{EM}}$$

the background rate quark distribution contains viscous corrections.

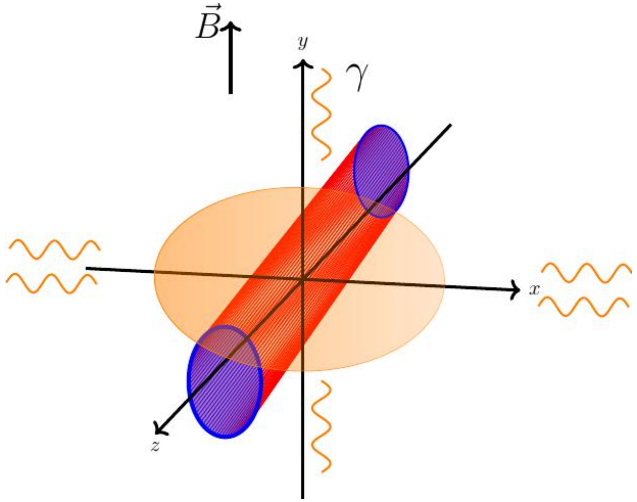
Weak magnetic photon emission is highly anisotropic

- Origin of momentum anisotropy:

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



properties of background QGP $\ni \cos n\phi_p$



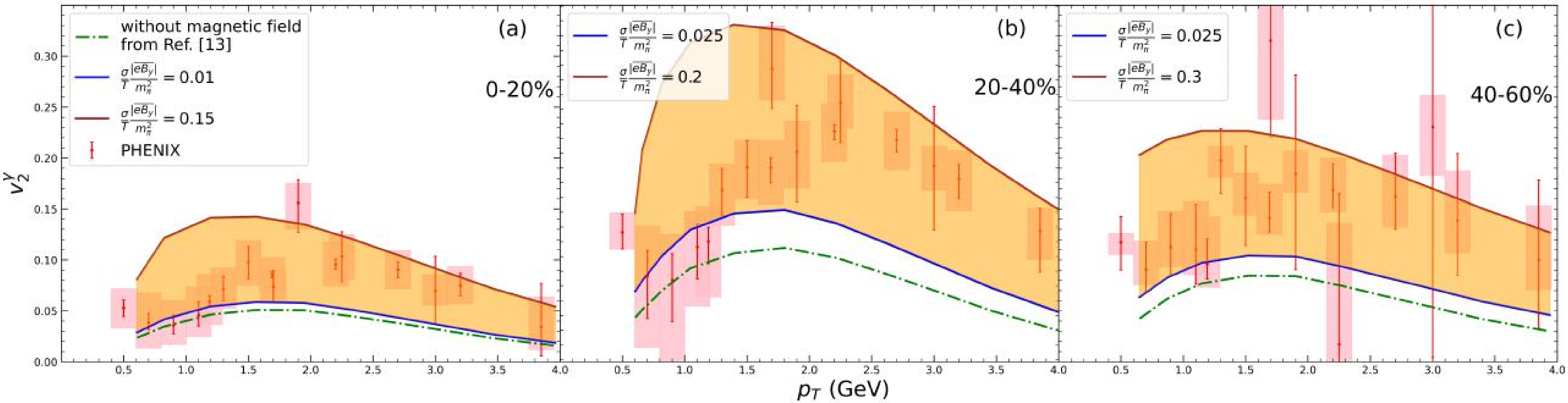
[P. Bozek et al, 1011.3354]

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

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

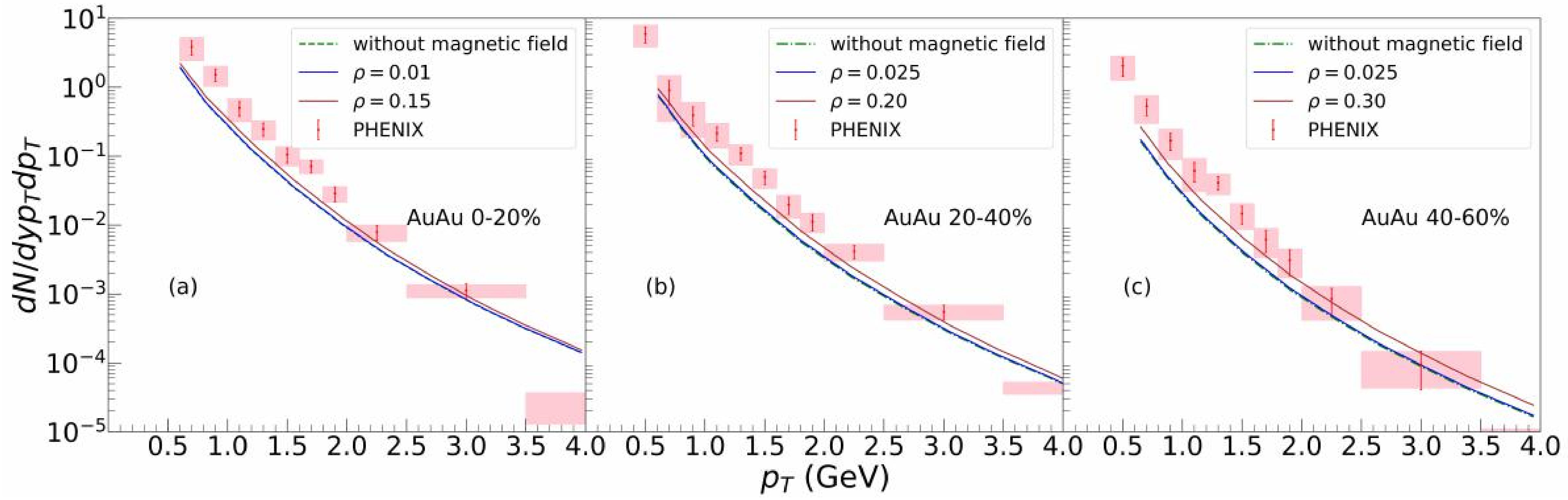
Longitudinal dynamics of QGP is essential, in addition to eB!

EbE hydro results: RHIC direct photon v2



- Numerical EbE hydro simulations: Trento3D + MUSIC + LEOS.
- 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 of the parameter according to photon v2.

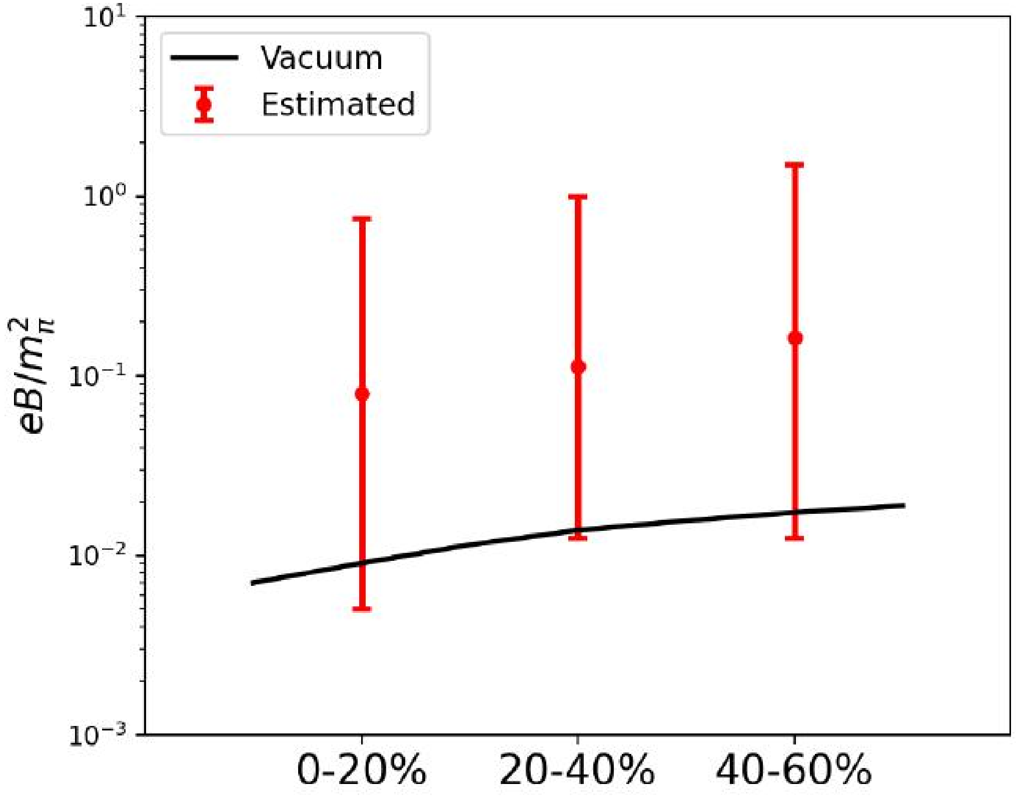
Direct photon yields

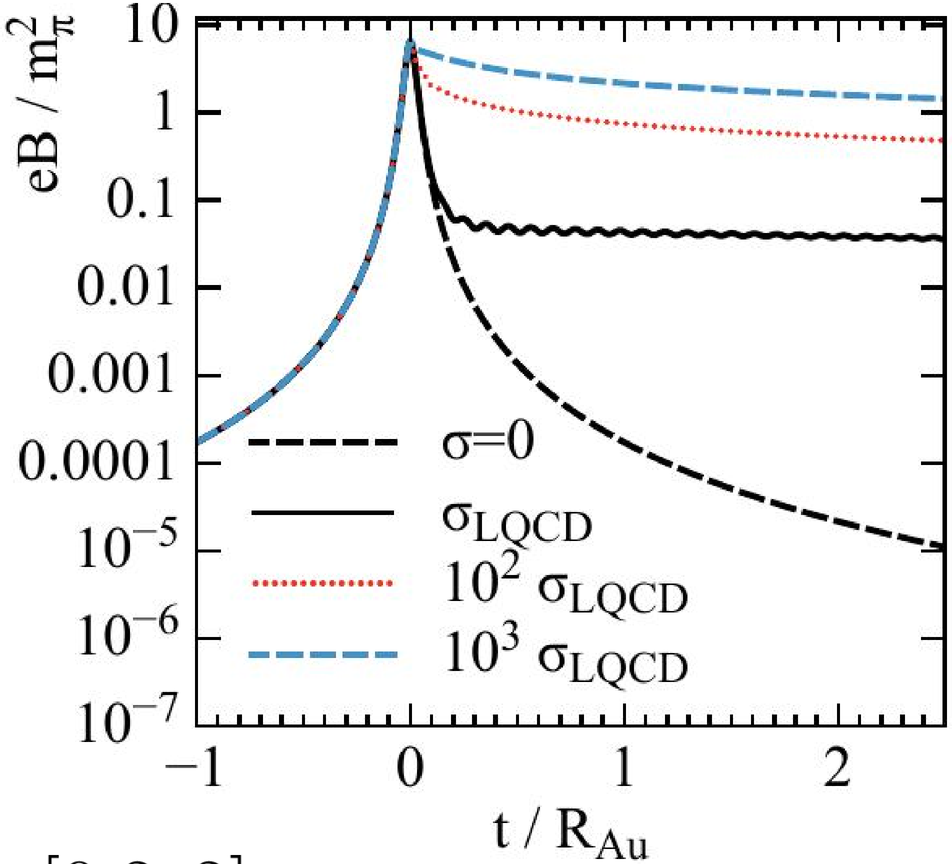


- Weak magnetic contribution to direct photon yields is marginal.

Estimate of the time averaged eB

[Skokov and Mclerran, 1305.0774]



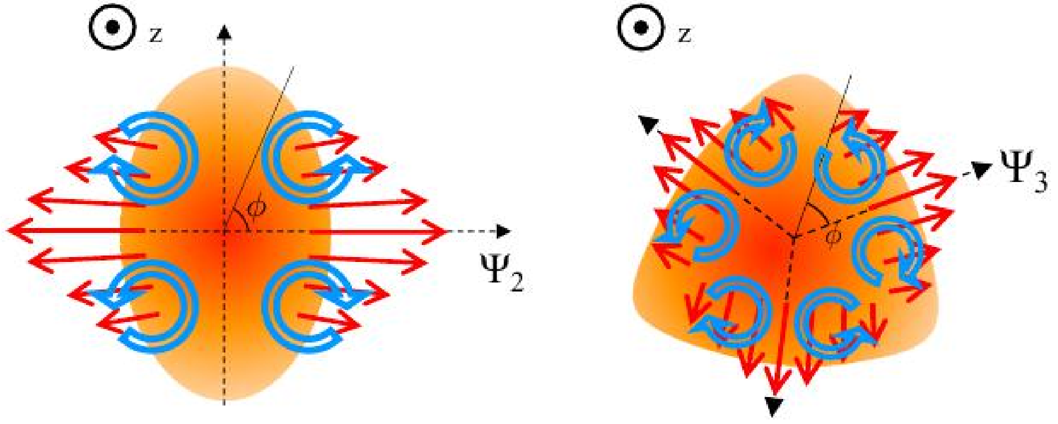


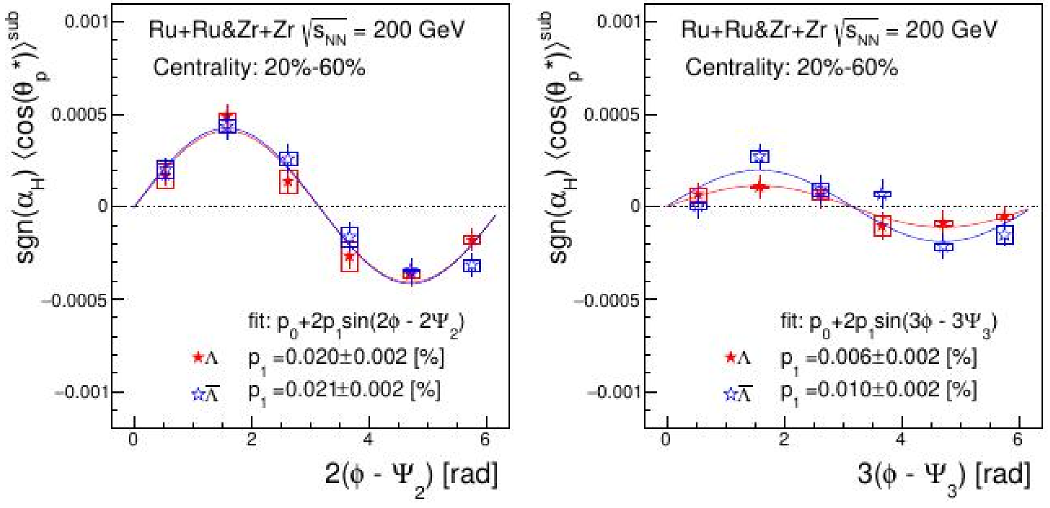
- Extract eB by direct photon v2, with $\sigma_{\mathrm{el}}/T \in [0.2, 2]$ [S Floerchinger et al., 2112.12497]
- This is only a rough estimate of the upper bound of realistic eB.

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

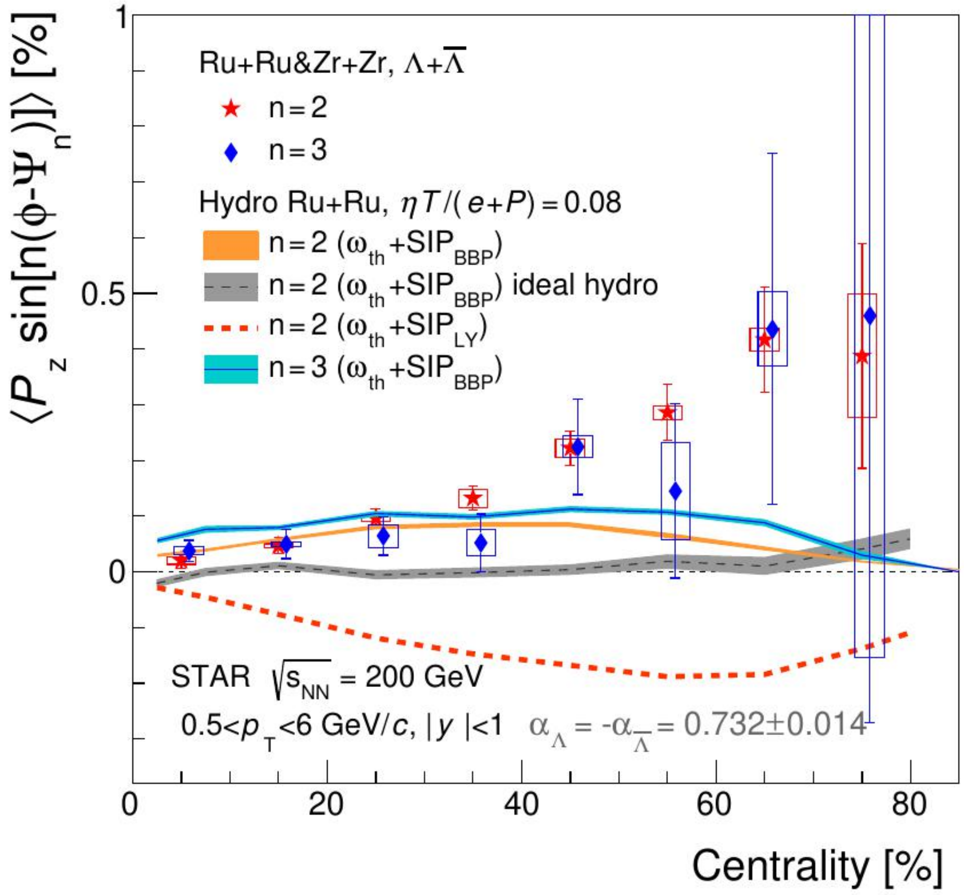




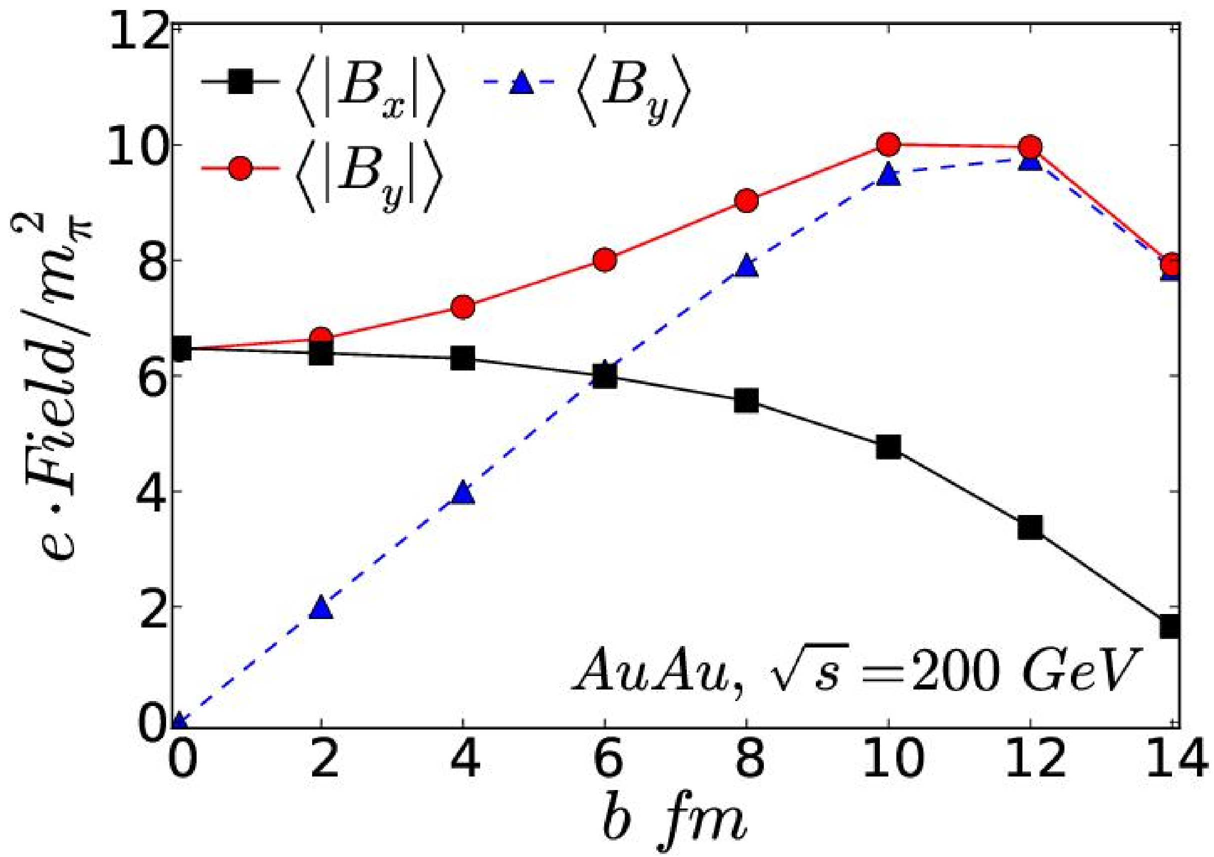
- In thermal equilibrium: spin ~ thermal vorticity generated owing to initial geometry.
- Sign observed against naive hydro expectation using thermal vorticity: sign problem

Motivation with eB: centrality dependence

[STAR collaboration, 2303.09074]



[A. Bzdak, V. Skokov, 1111.1949]



- Consistent entrality dependence between Pz and eB(b), at least qualitatively.

Polarized particle from QGP due to weak B

[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]

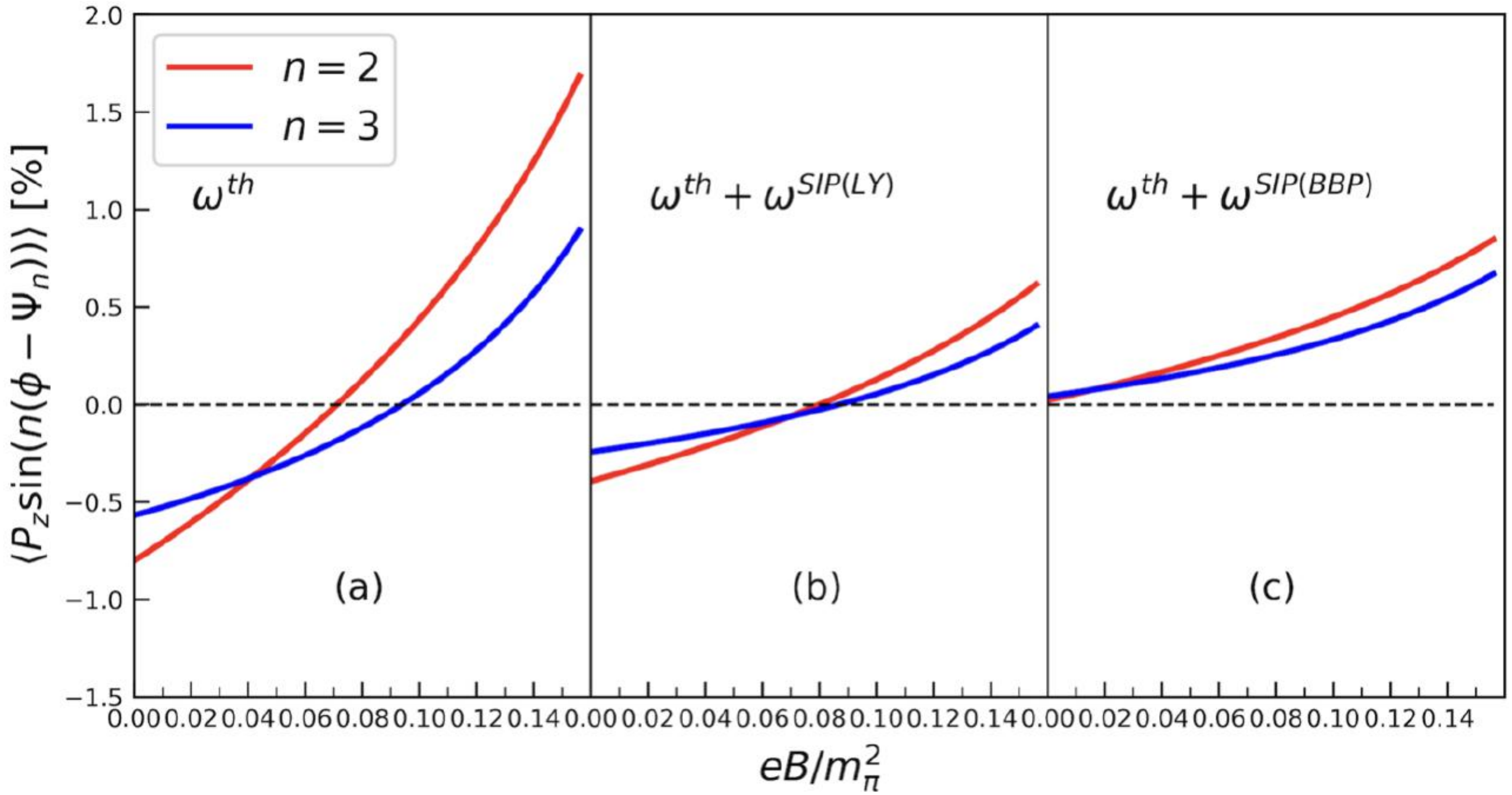
$$\bar{\omega}^{\rho\sigma} \to \bar{\omega}^{\rho\sigma} + \mathrm{SIP}$$

- With weak EM dissipative contribtion:

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

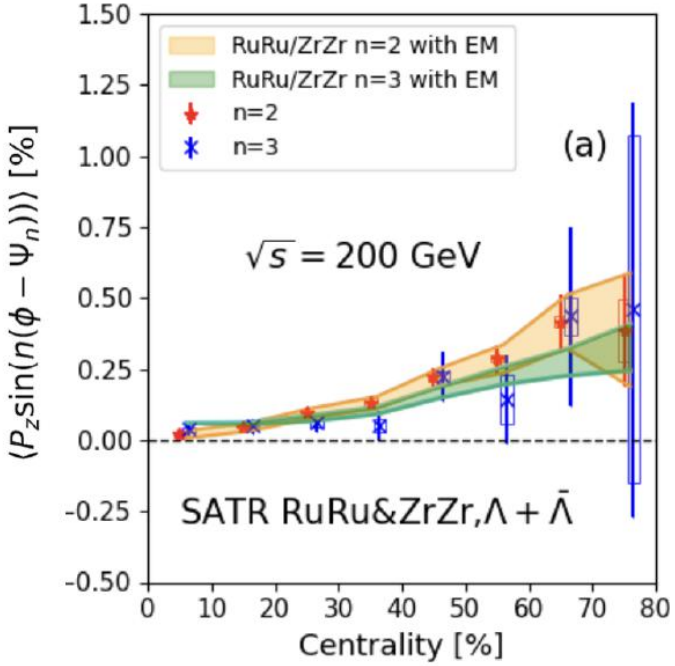
- Global polarization merely affected!

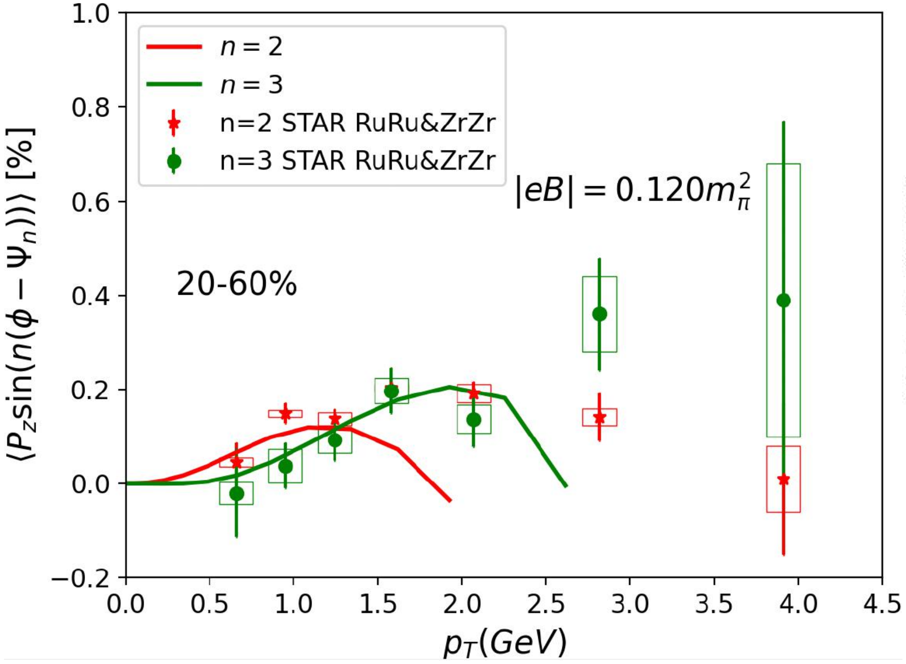
Local polarization and weak B field (fixed centrality)

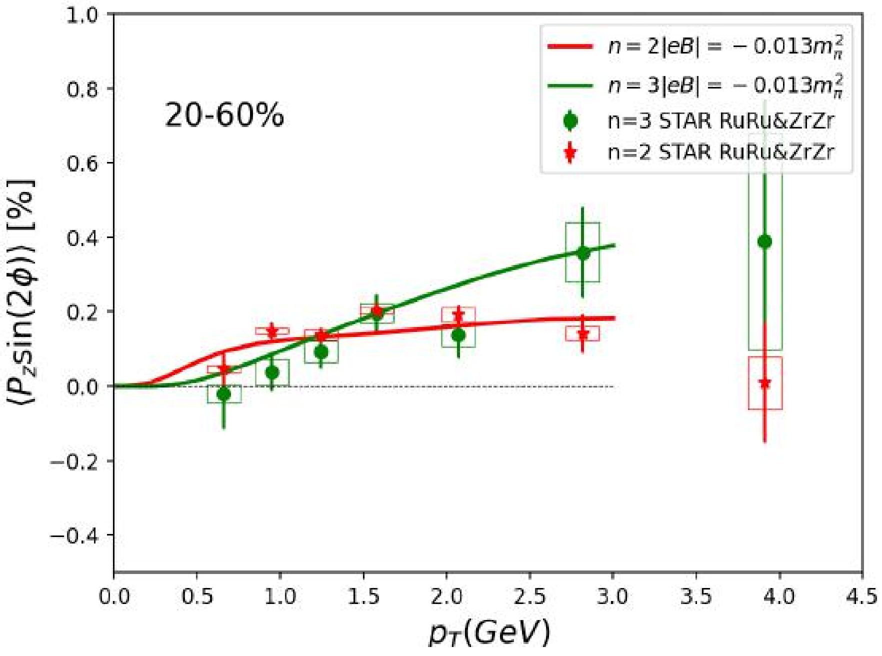


- Geometry does play a role, without eB (or other corrections): negative, and |n=2|>|n=3|.
- Sign problem can be solved by a weak B field, in addition to SIP.
- Flip of ordering between n=2 and n=3 can only be found with a finite B field.

Confront experimental data:





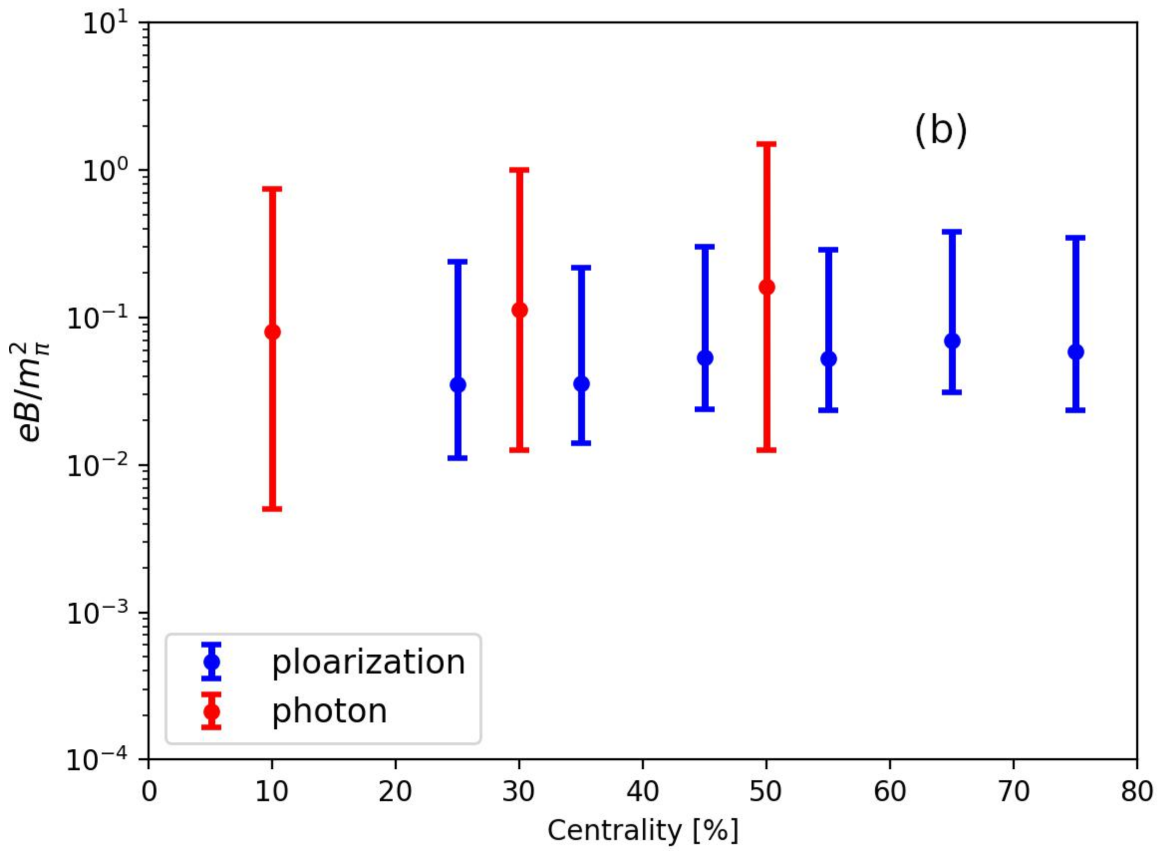


strangeness quark mass = 0.8 GeV

strangeness quark mass = 0.5 GeV

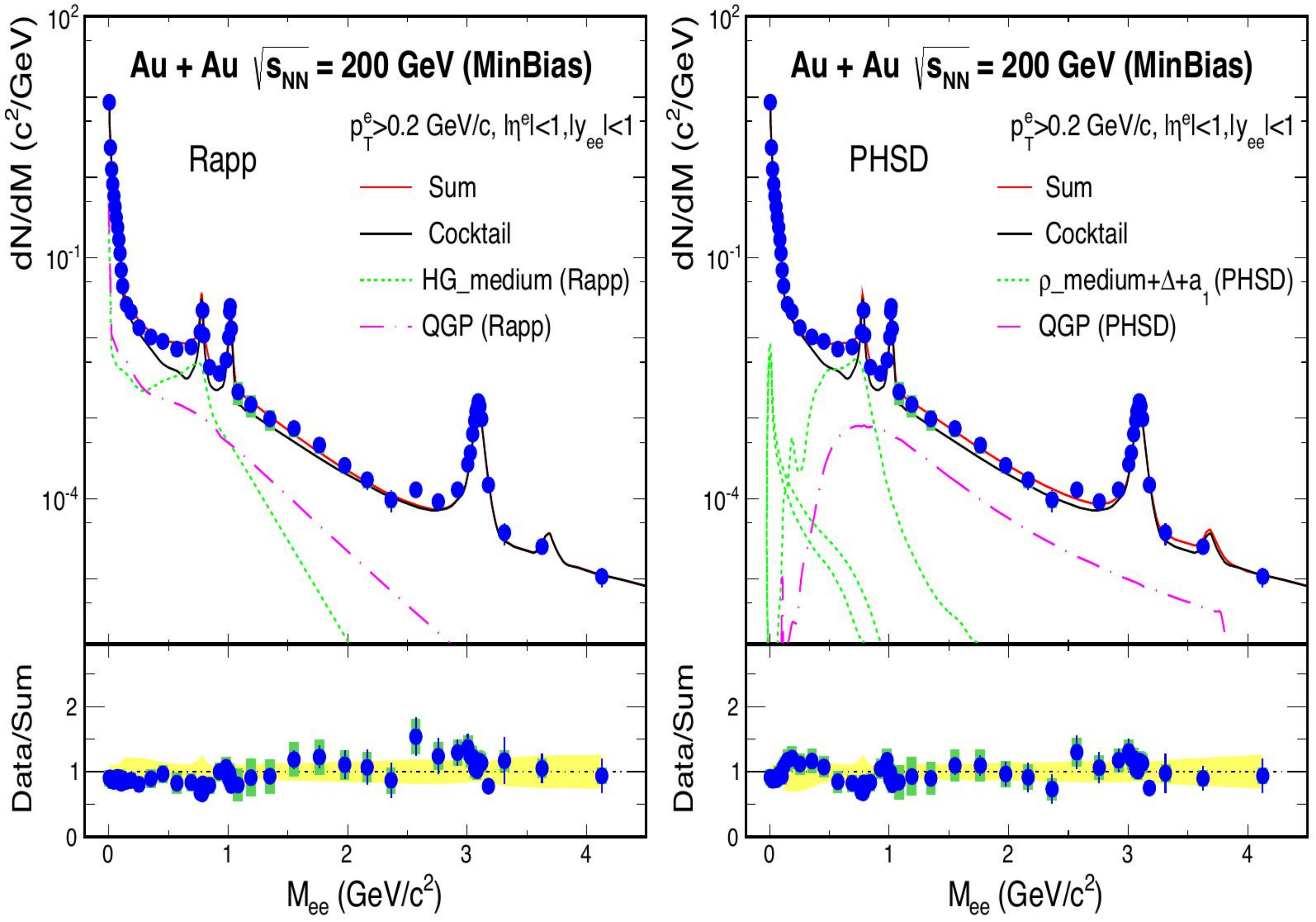
- s-quark mass is effectively a parameter due to Chiral symmetry breaking in Lambda.

Estimate of eB from Lambda polarization



- quantitatively consistency comparing to the values from direct photon elliptic flow.

Dilepton invariant mass spectrum at RHIC 200 GeV



[2005.14589]

- Thermal dileptons from QGP:

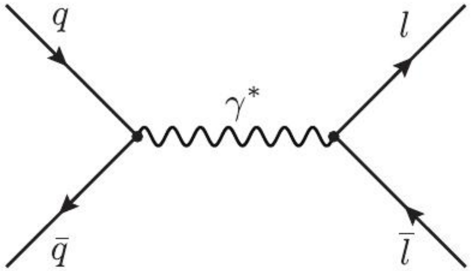
$$q\bar{q} \to \gamma^* \to l\bar{l}$$

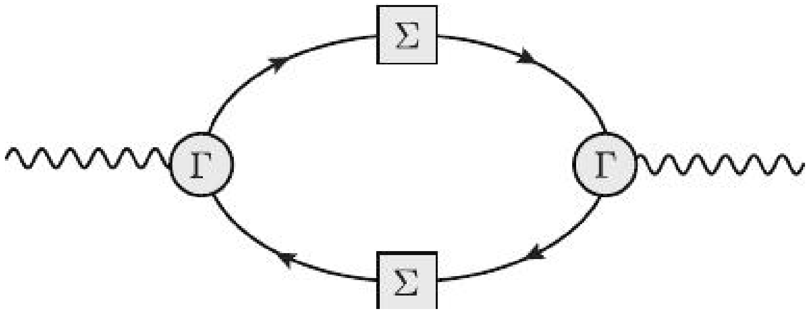
- Dominant source of dilepton at intermediate invariant mass.

- Could the dilepton (virtual photon) be polarized?

Thermal dilepton (in QGP virtual photon) polarization

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





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

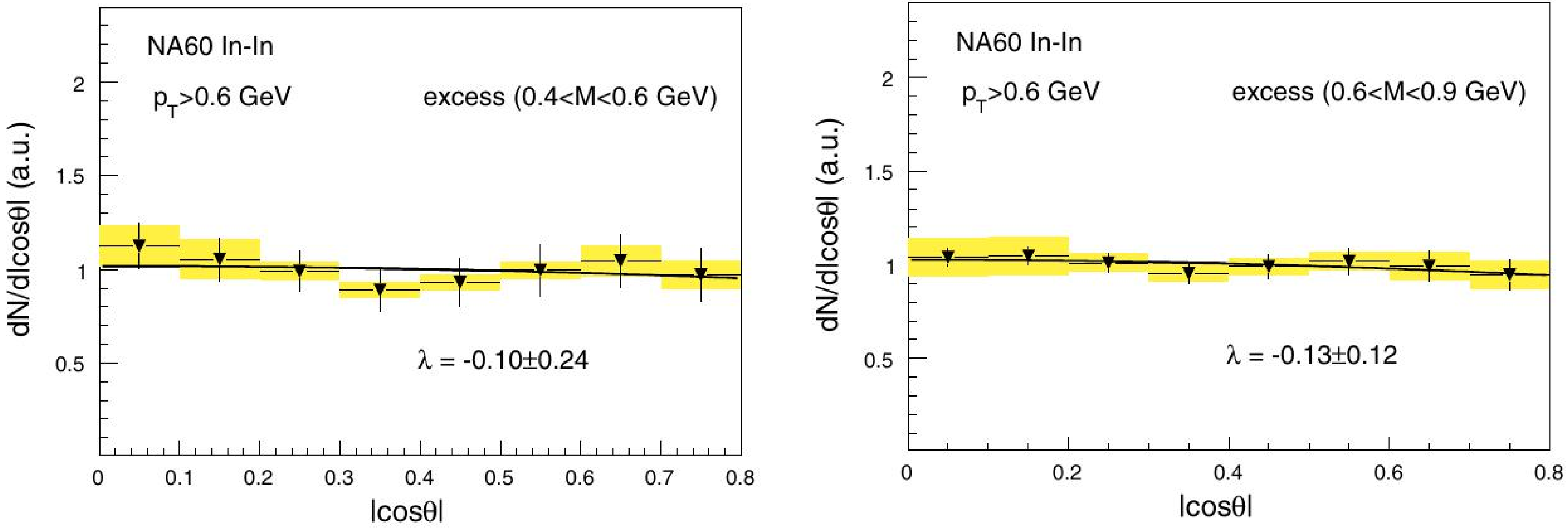
$$\frac{dR}{d^4Q d\Omega_l} \sim \mathcal{N}(1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta_l \cos 2\phi_l + \dots)$$

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

[cf. E. Speranza et al. PLB 782 (2018) 395–400]

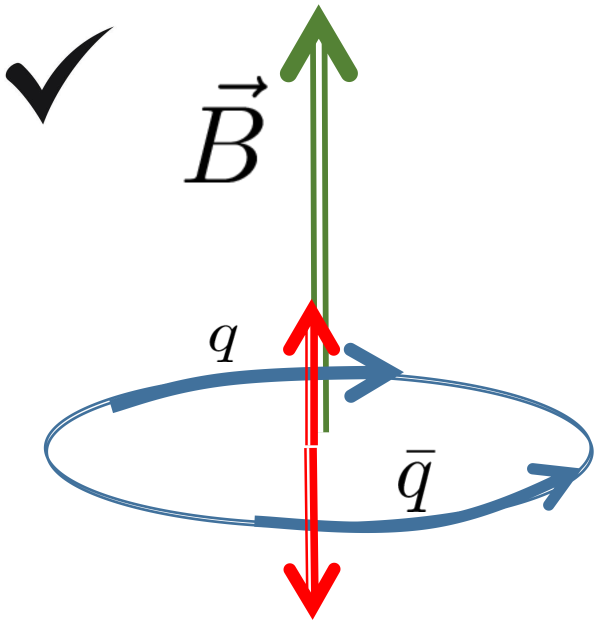
Early results from low energy collisions, 158A GeV In-In

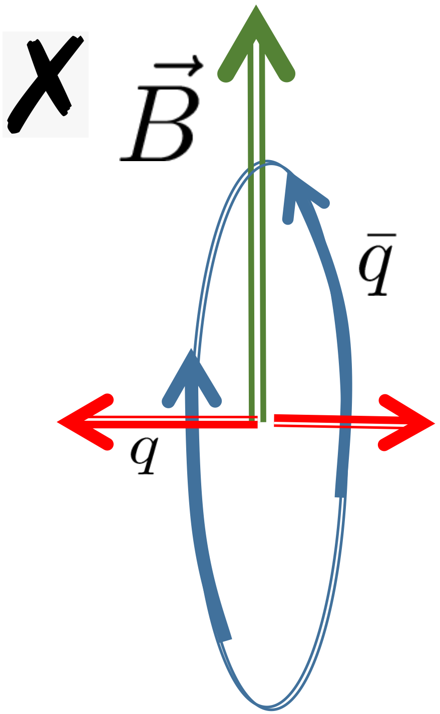
[NA60, PRL102.222301, (2009)]

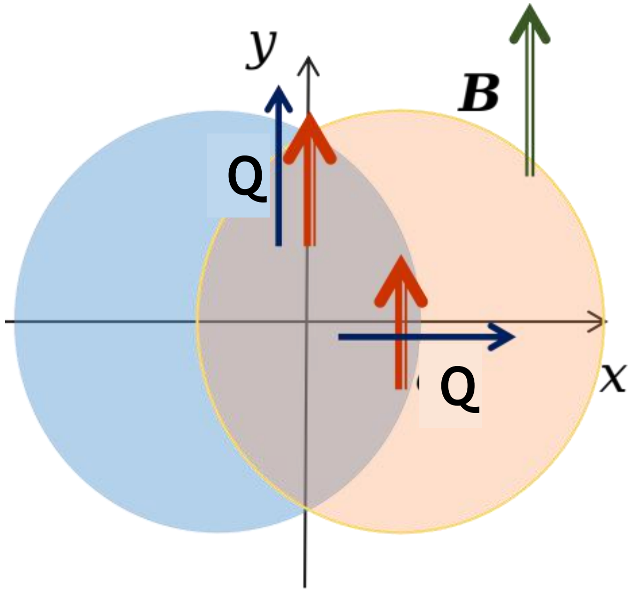


- Exp. measured dilepton polarization from NA60

QGP dilepton in the presence of an external eB



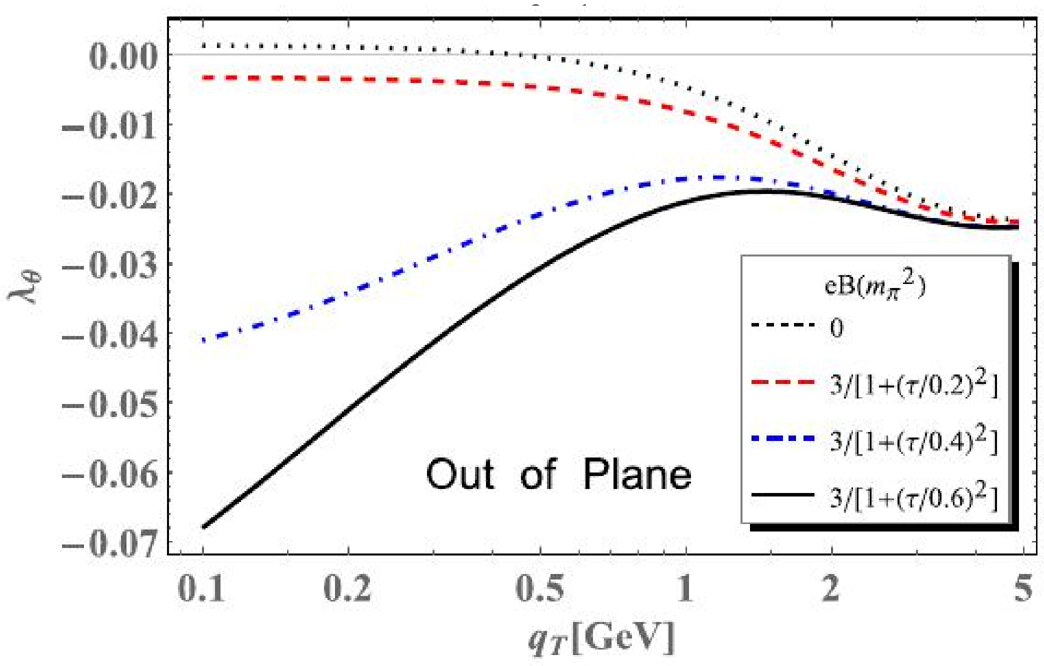


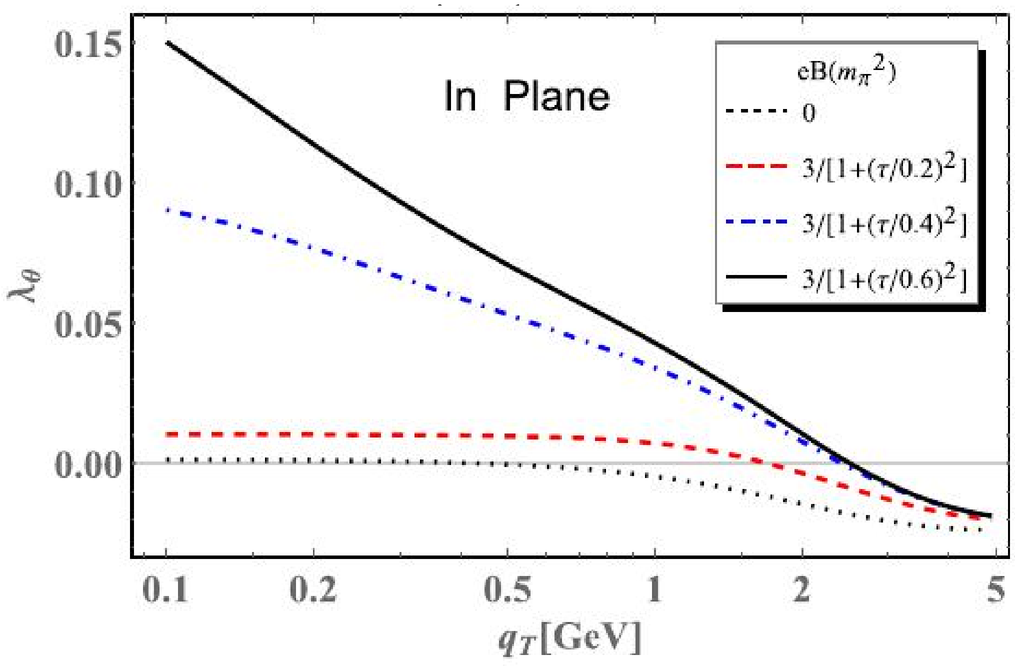


- The external eB induces extra polarization of the quark pair in QGP.

Numerical results for M_γ = 2 GeV (Bjorken flow)

- Effect is remarkable wrt. finite eB, and B field life time:





$\lambda_\theta < 0$ longitudinal polar. $\lambda_\theta > 0$ transverse polar.

Numerical results for M_γ = 2 GeV (Bjorken flow)

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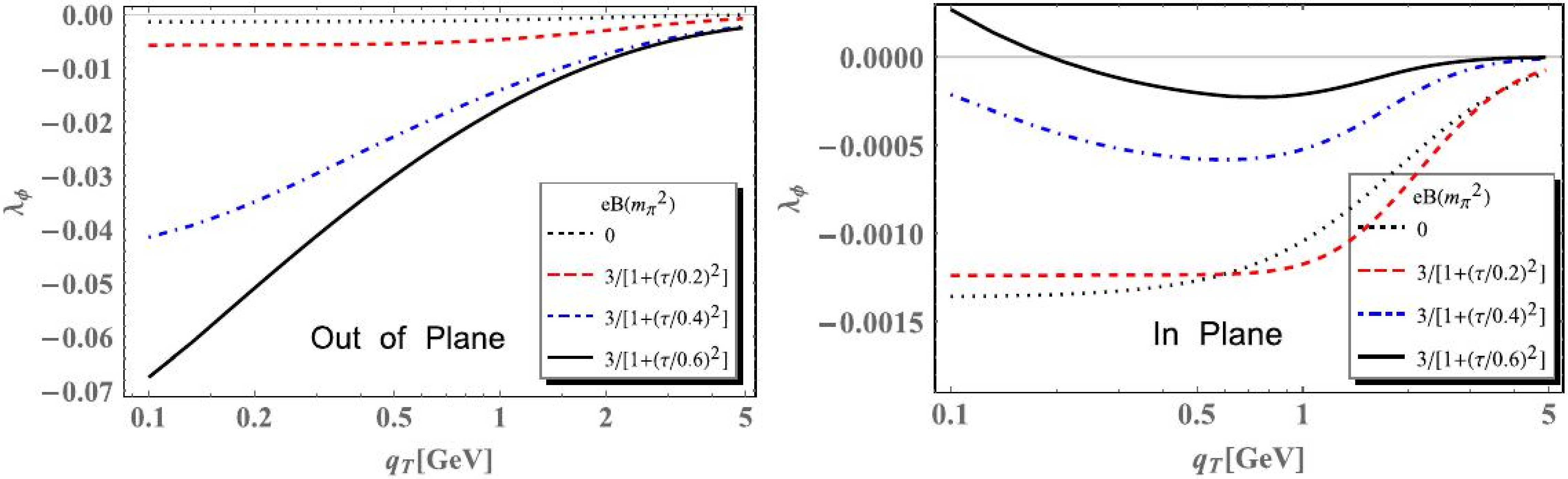


Summary

- 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. Expect: Splittings among charged v1, but needs to be verified.

Back-up slides

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,

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

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

$$\partial_{\mu} \Delta T^{\mu\nu} = J_{\mu} F^{\mu\nu} \rightarrow (e+P) D\Delta U^{\mu} = \frac{1}{2} Q_{+} E^{\mu} (n_{+} + n_{-}) + O(\nabla^2)$$

=> 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)]

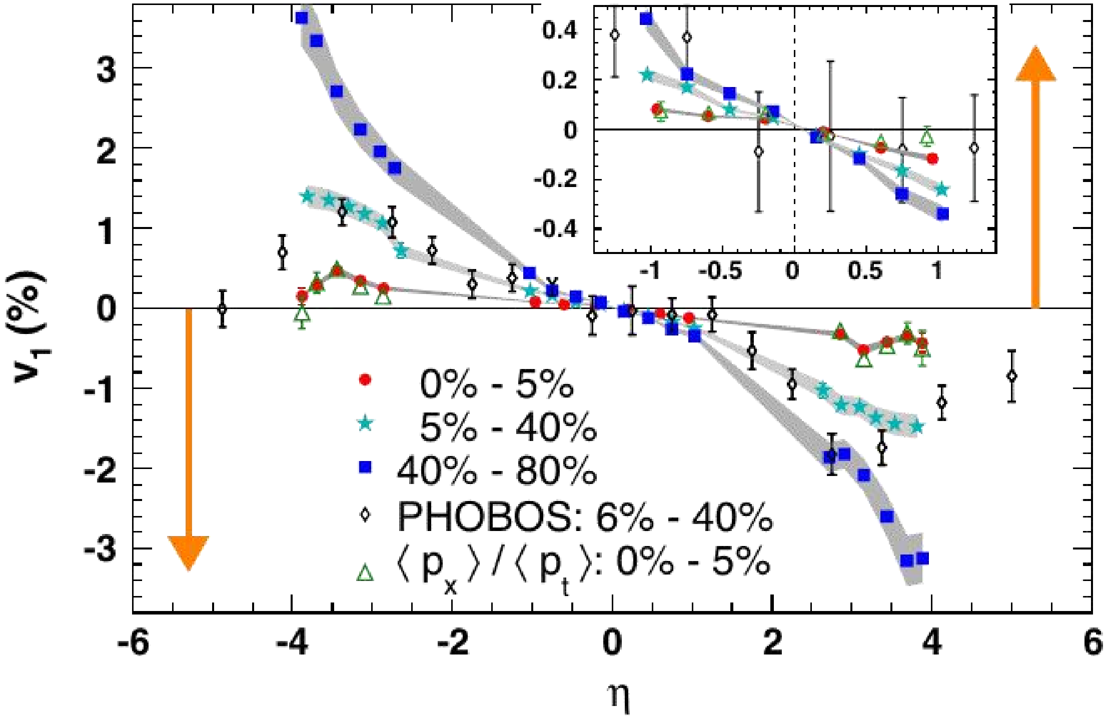
Photon elliptic flow and hadron v_1

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

  [P. Bozek et al., 1101.3354]

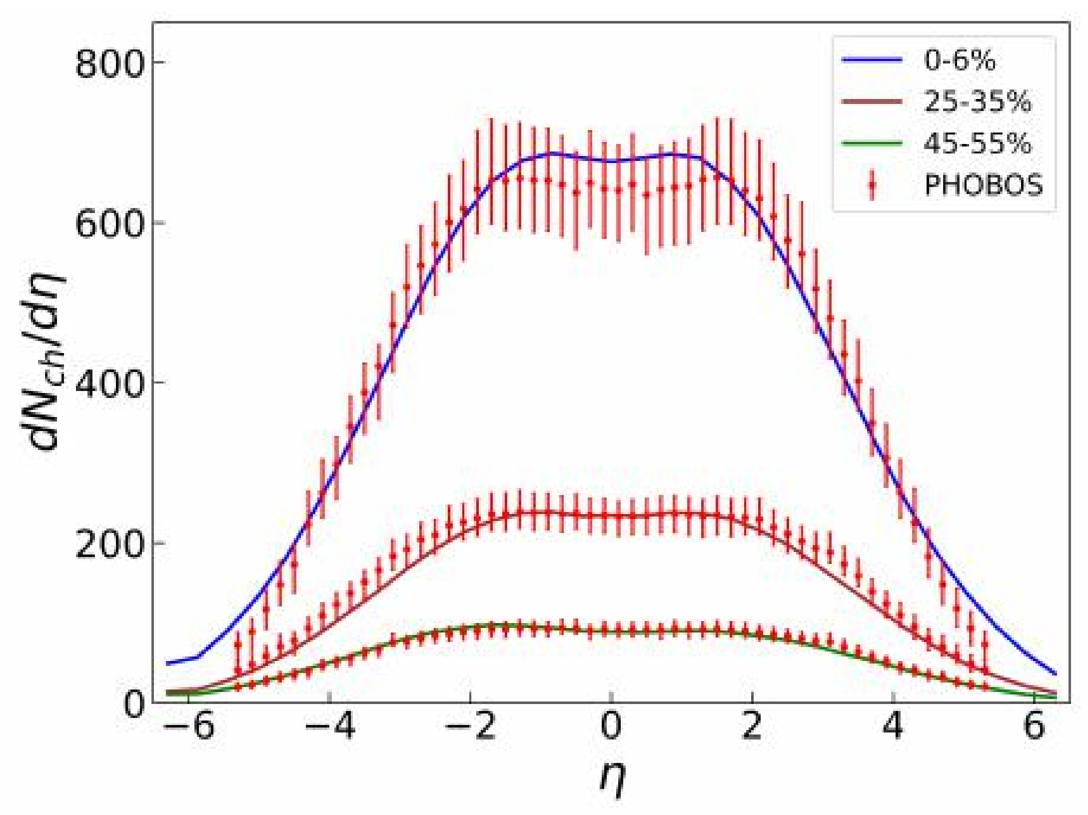
- Exp. measured photons in even rapidity window => one needs a rapidity-odd v_1 in the background.

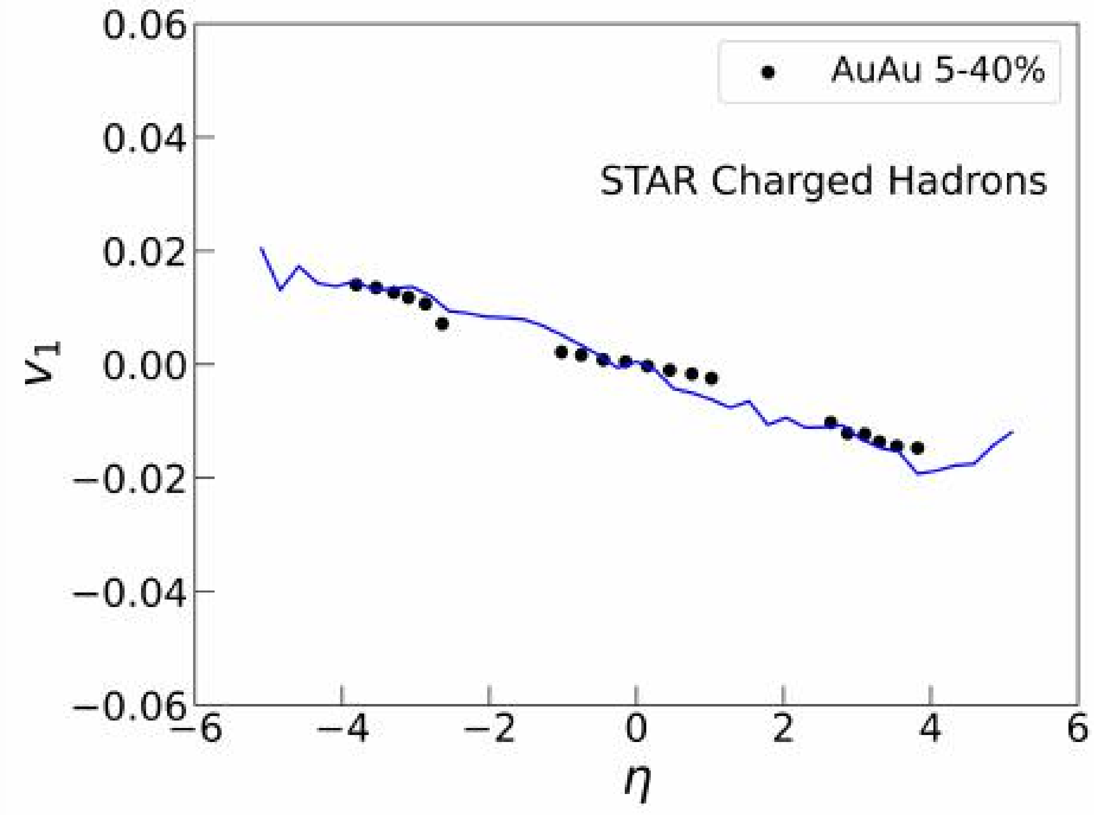
- Theory: EbE 3+1D hydro + weak B field to solve the direct photon puzzle.



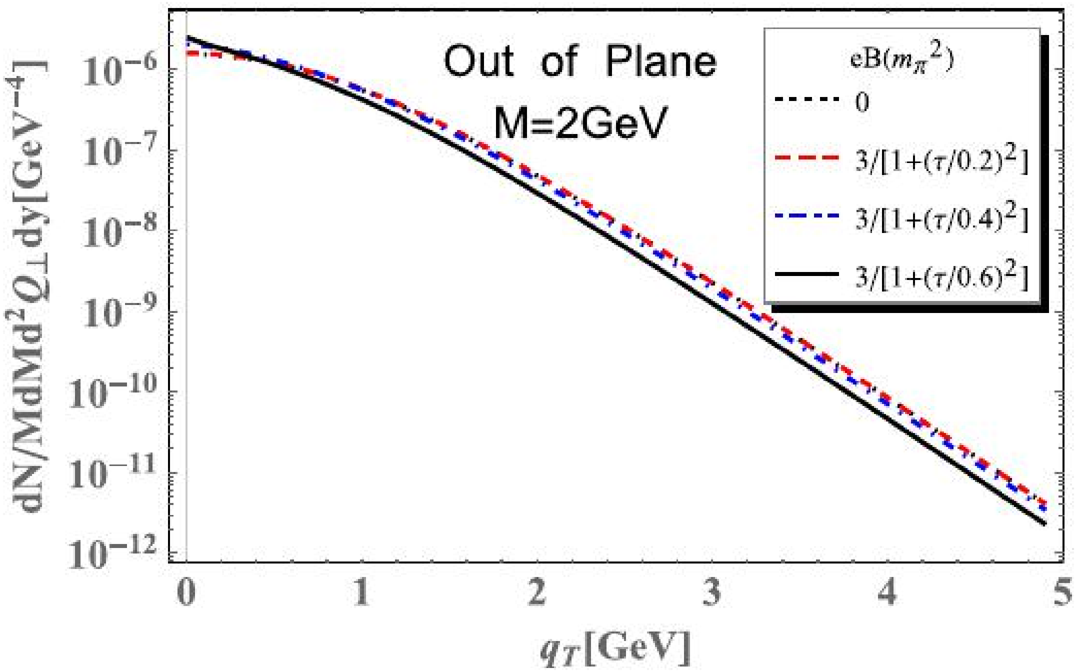
[STAR collaboration, PRL 101, 252301 (2008)]

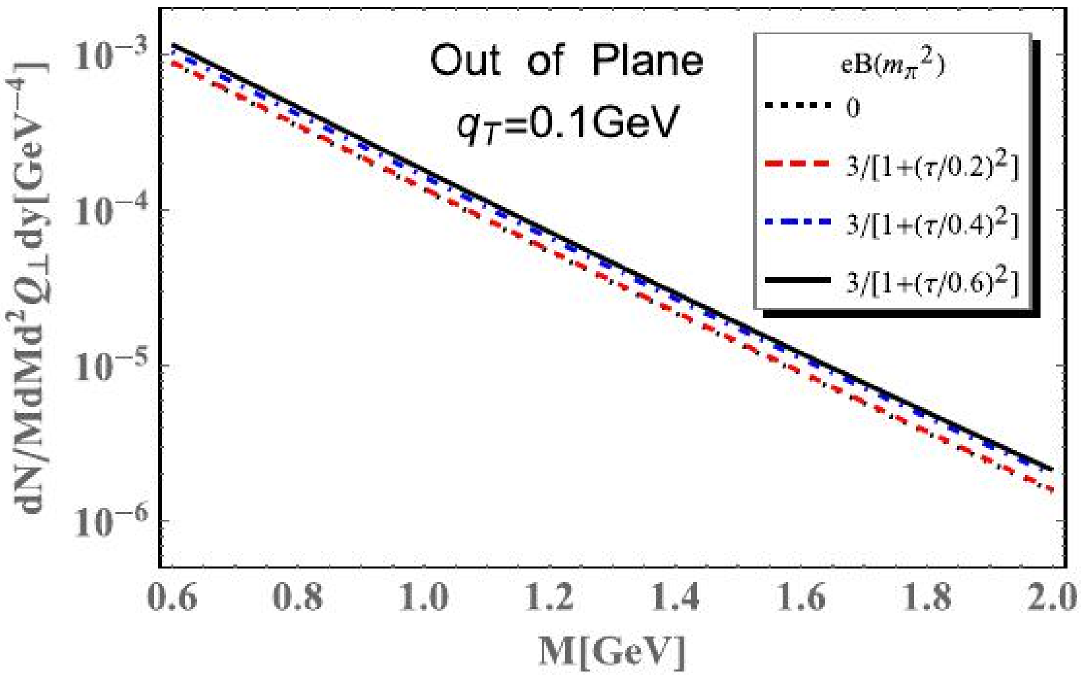
Longitudinal dynamics of QGP is essential

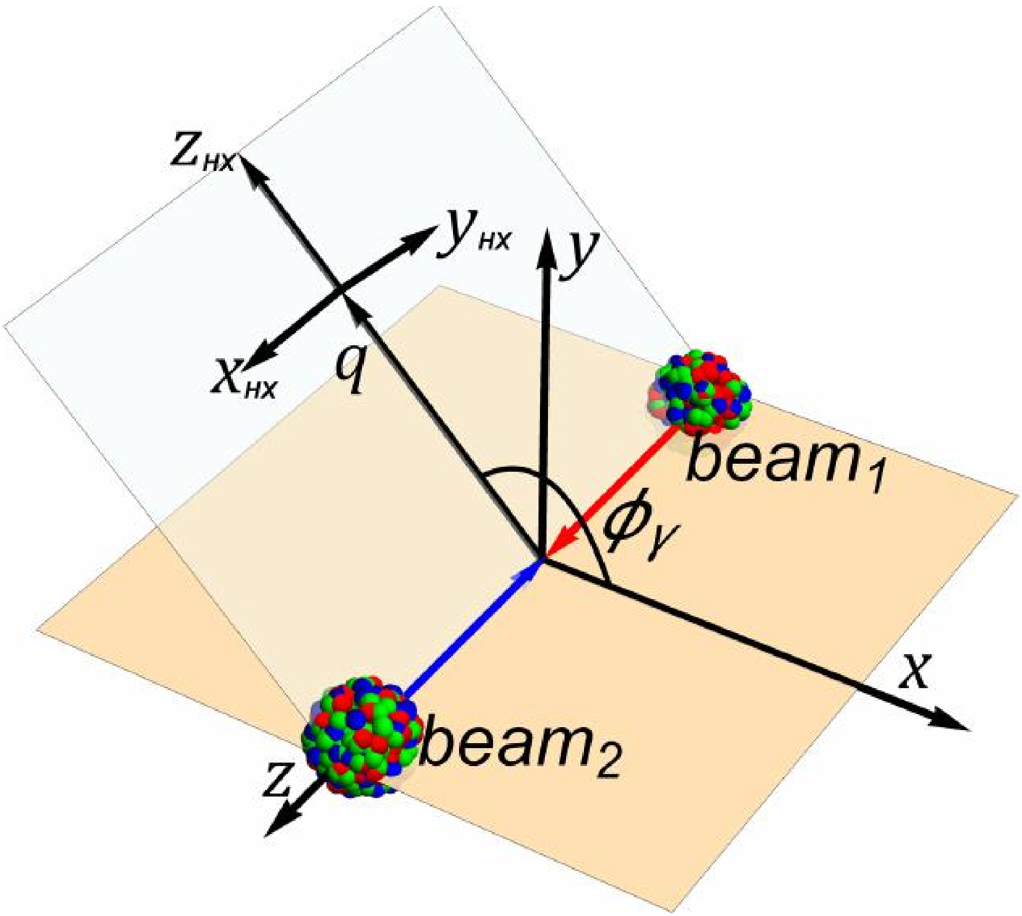




Dilepton yields



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y_{HX}
y
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q
$beam_1$
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