The direct photon puzzle and the weak magnetic photon emission

Li Yan

Institute of Modern Physics at Fudan University

Mar. 23, 2023 @ USTC

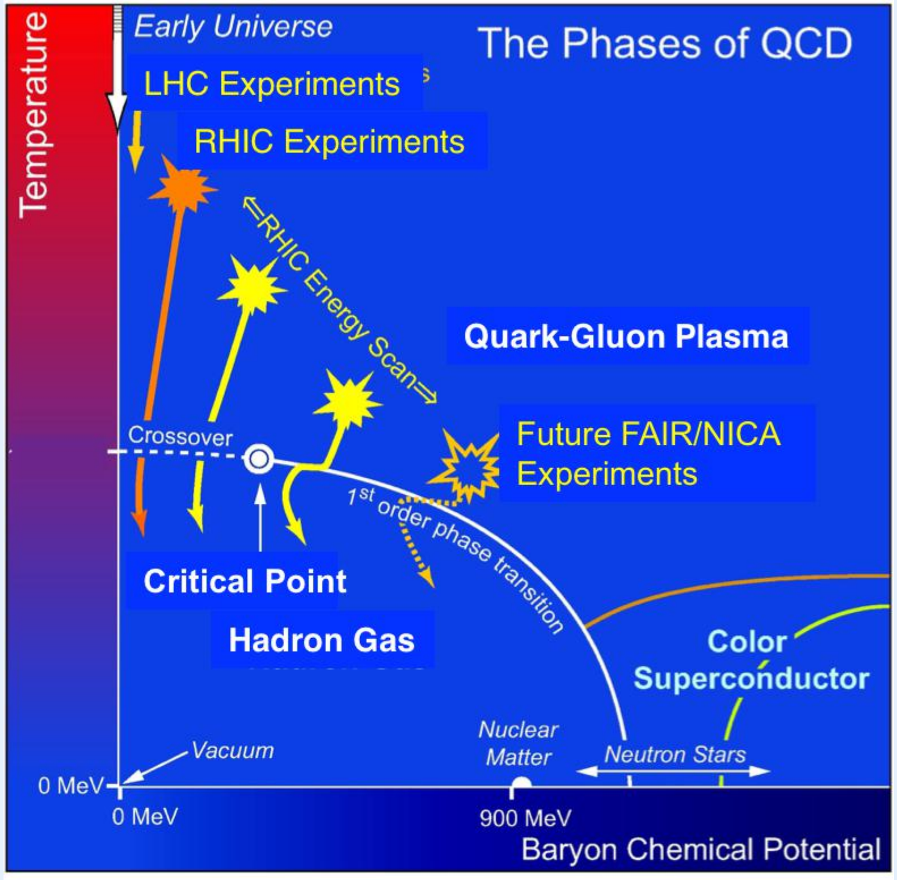
with Jing-An Sun, arXiv: 2302.07696

Outline

- Direct photons and direct photon puzzle in heavy-ion experiments.
- Magnetic field in heavy-ion collisions.
- Weak magnetic photon emission (WMPE).

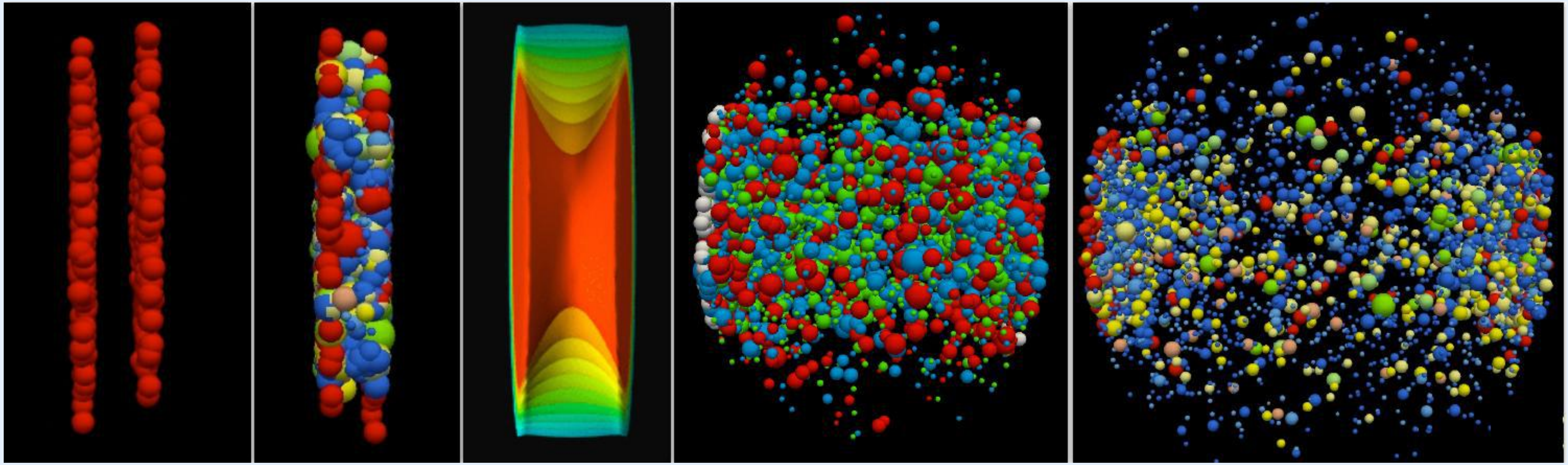
Standard picture of Heavy-ion collisions

- QCD phase diagram



Standard picture of Heavy-ion collisions

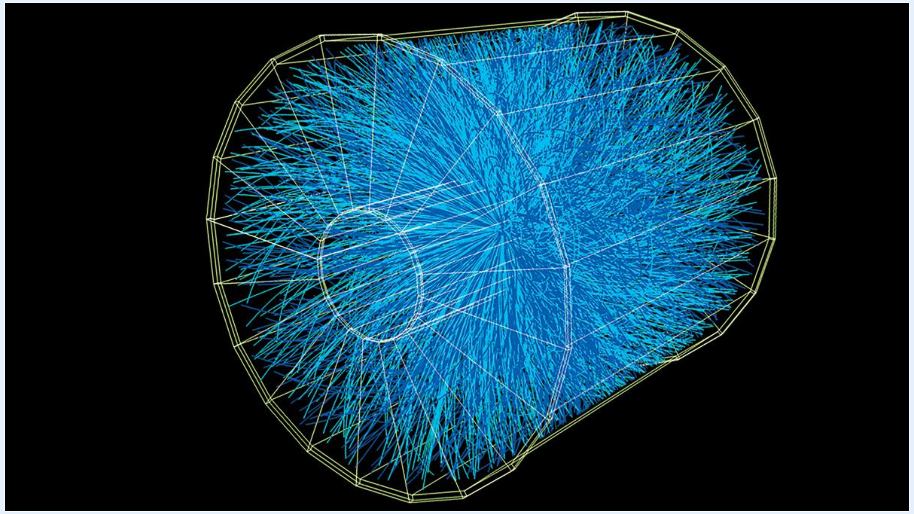
- Different stages in one heavy-ion collision event



initial stage (pre-equilibrium) + QGP + Hadron Gas + freeze out

Hadron probes

- Hadron spectra: pions, kions, protons, etc.,

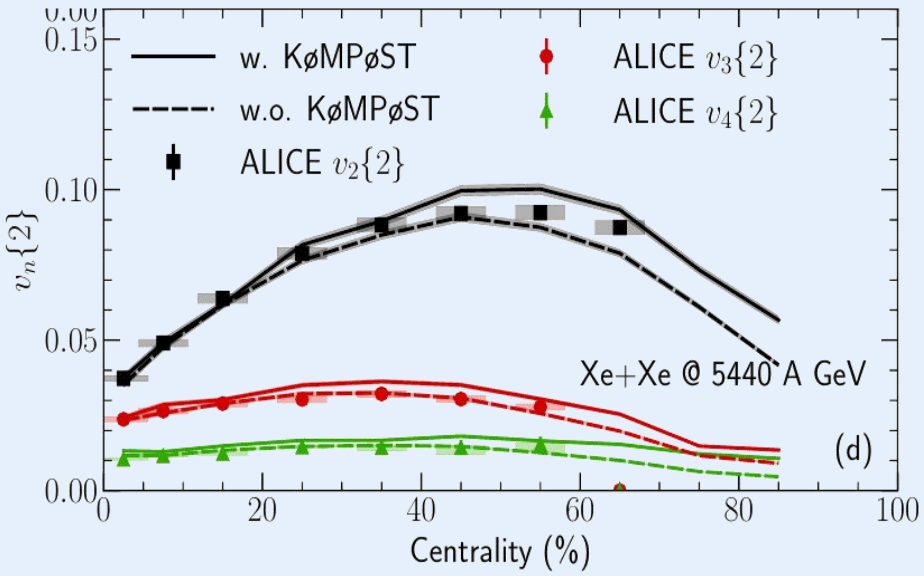


$$E\frac{dN}{d^3\vec{p}} \propto \frac{dN}{dp_T dy}[1+2v_1\cos(\phi_p-\Psi_1) \\ +2v_2\cos 2(\phi_p-\Psi_2) \\ +2v_3\cos 3(\phi_p-\Psi_3) \\ +\ldots]$$

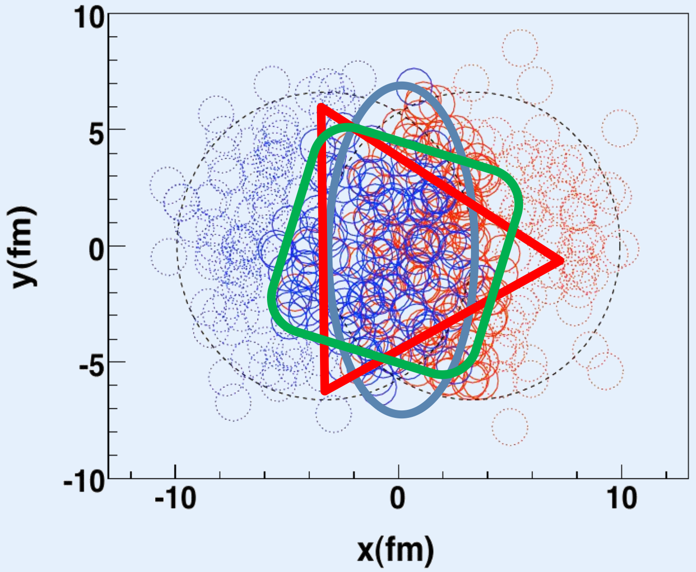
where v_n (n-th order flow) contains information of QGP collective flow. v_n of charged hadrons has been measured precisely for n<6. Flow provides probes of transport properties of QGP, e.g., η/s, ζ/s.

Hadron probes from hydro (*standard model*)

- Hydro: initial condition + hydro EoM + QCD EoS + hadronization
- Hadron spectra and flow paradigm: medium response to geometry



[C. Gale et al, 2016.00216]

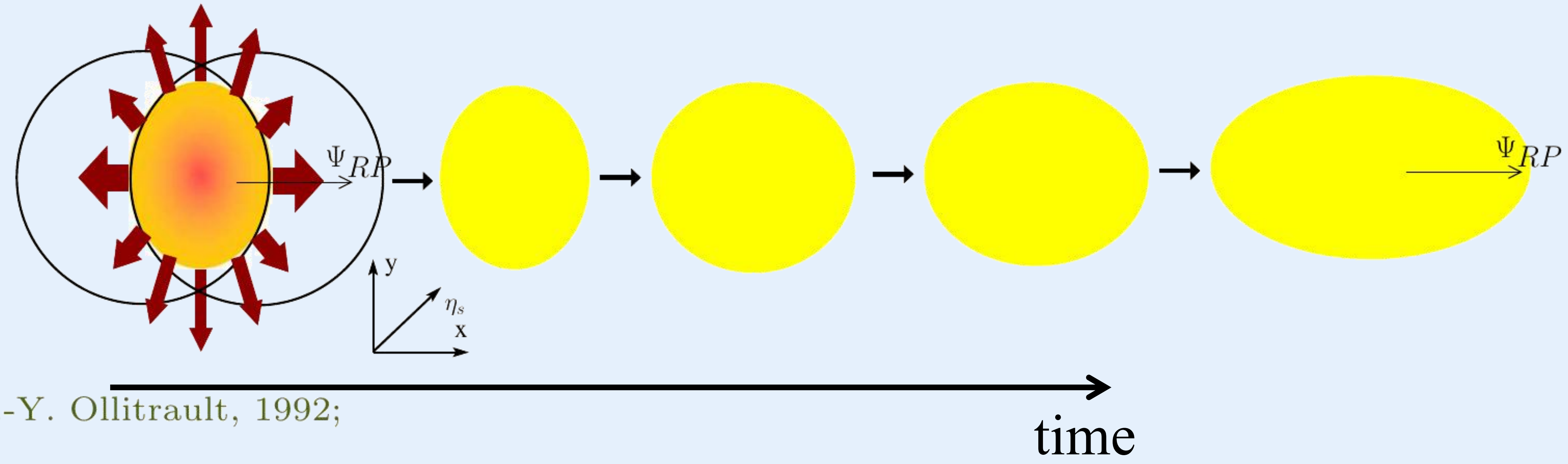


[PHOBOS MC-Glauber, C. Loizides et al, 1408.2549]

Flow paradigm

- Anisotropic flow developped as system expands,

Initial density has an elliptic geometry (overlapped region in collisions)

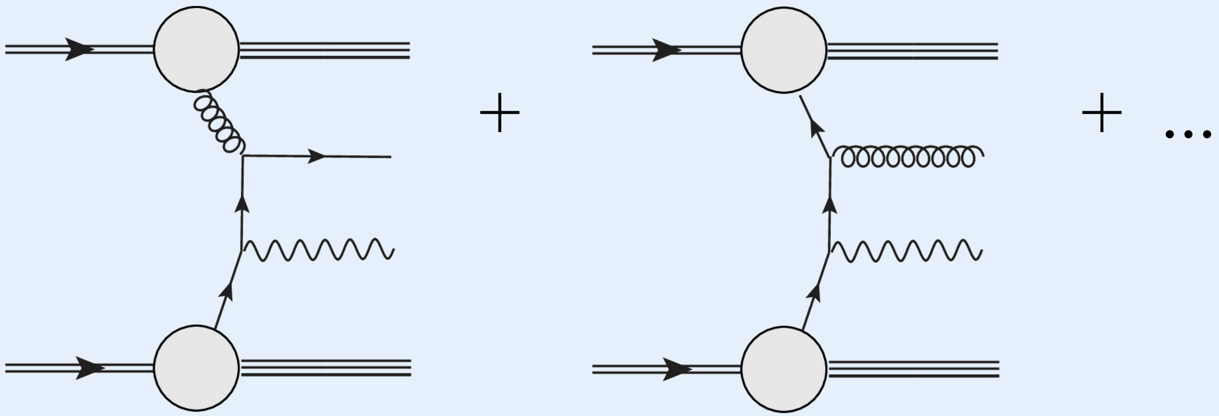


J.-Y. Ollitrault, 1992;

- A finite time scale is required.

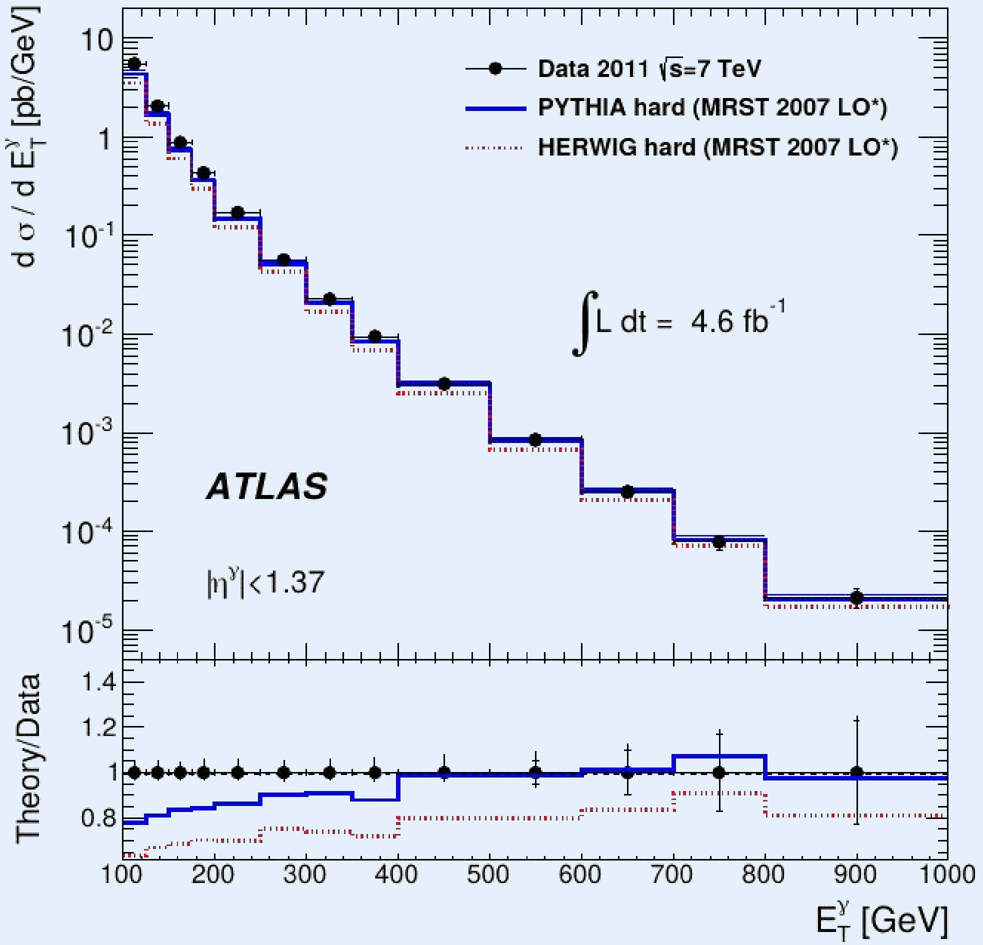
Direct photons in hadron colliders: e.g., $pp \to \gamma X$

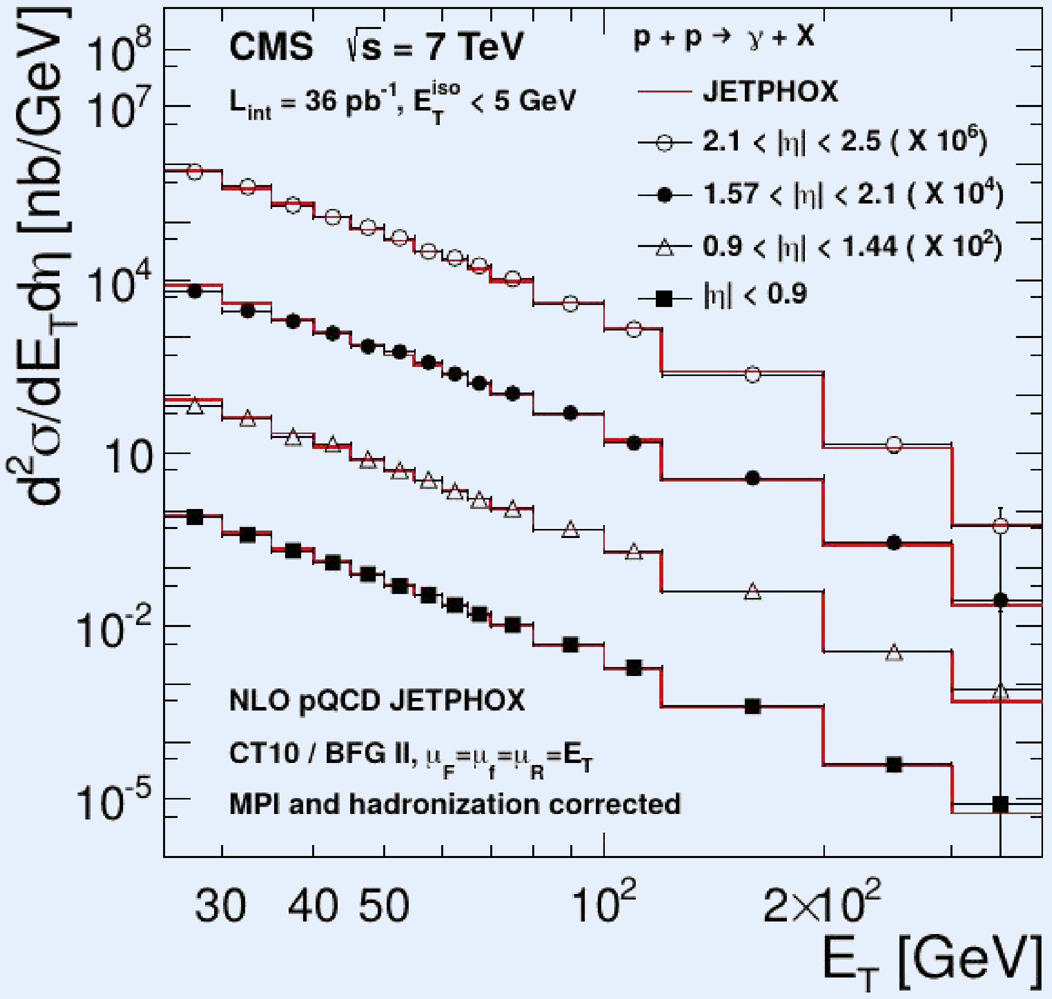
- Photons from partonic scatterings (subtract secondary decays).
- Can be calculated via pQCD,



- cross-section ~ $\sum_{ab} f_a \otimes f_b \otimes \hat{\sigma}_{ab}$, access to gluon PDF in hadron
- Isotropic emmission.

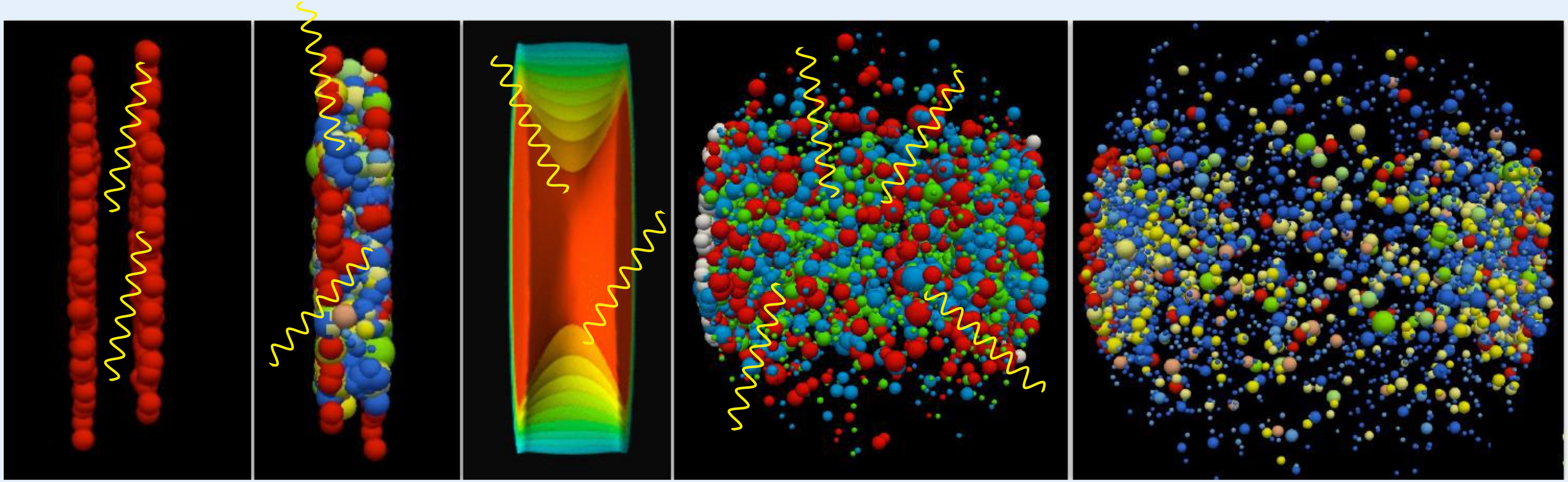
Direct photon cross section in pp





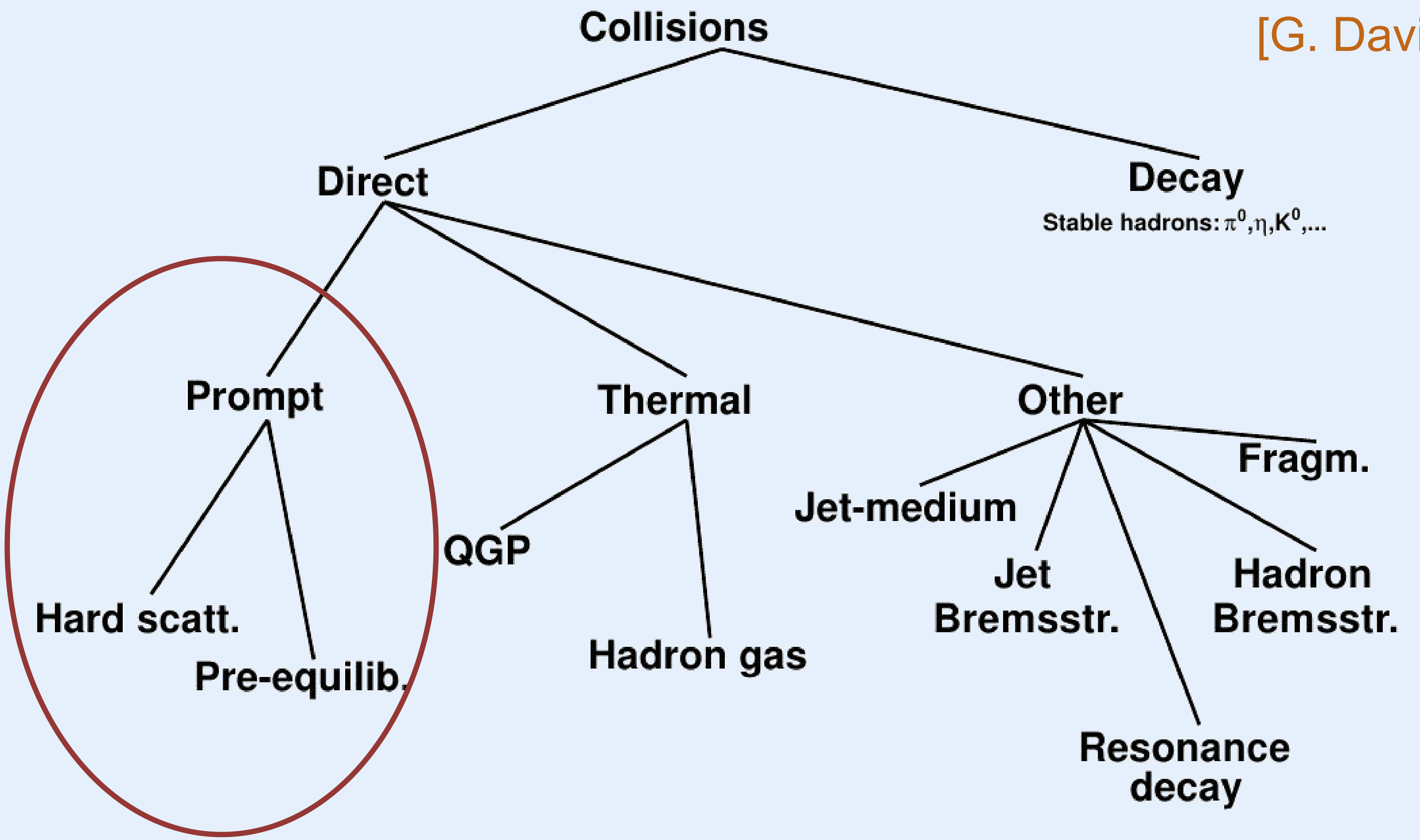
Direct photons in heavy-ion collisions

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



probe access to information of different evolution stages! “historian”

Direct photon production in heavy-ion collisions

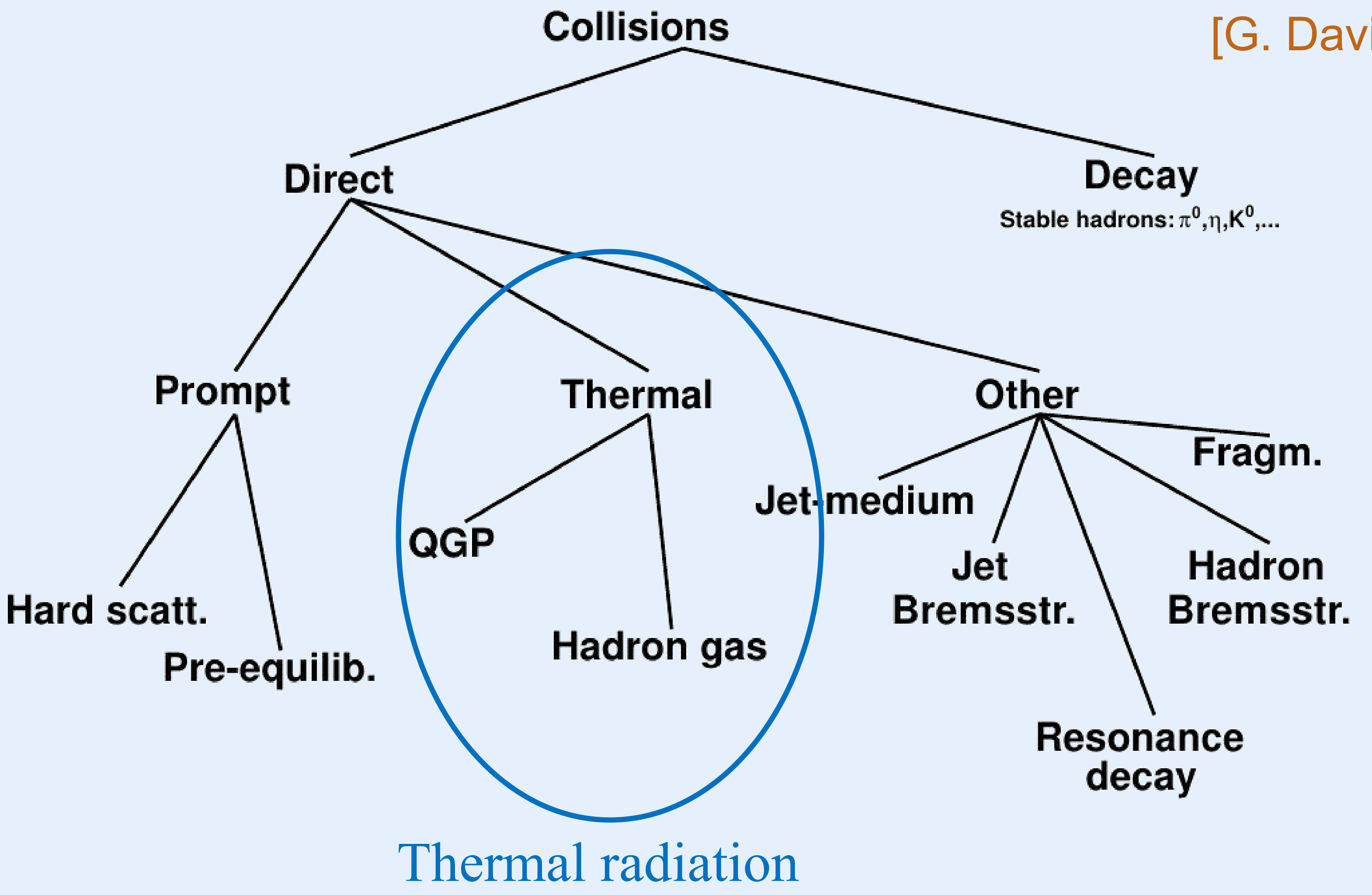


[G. David, 1907.08893]

Hard production: pp $\otimes$ N_{coll}

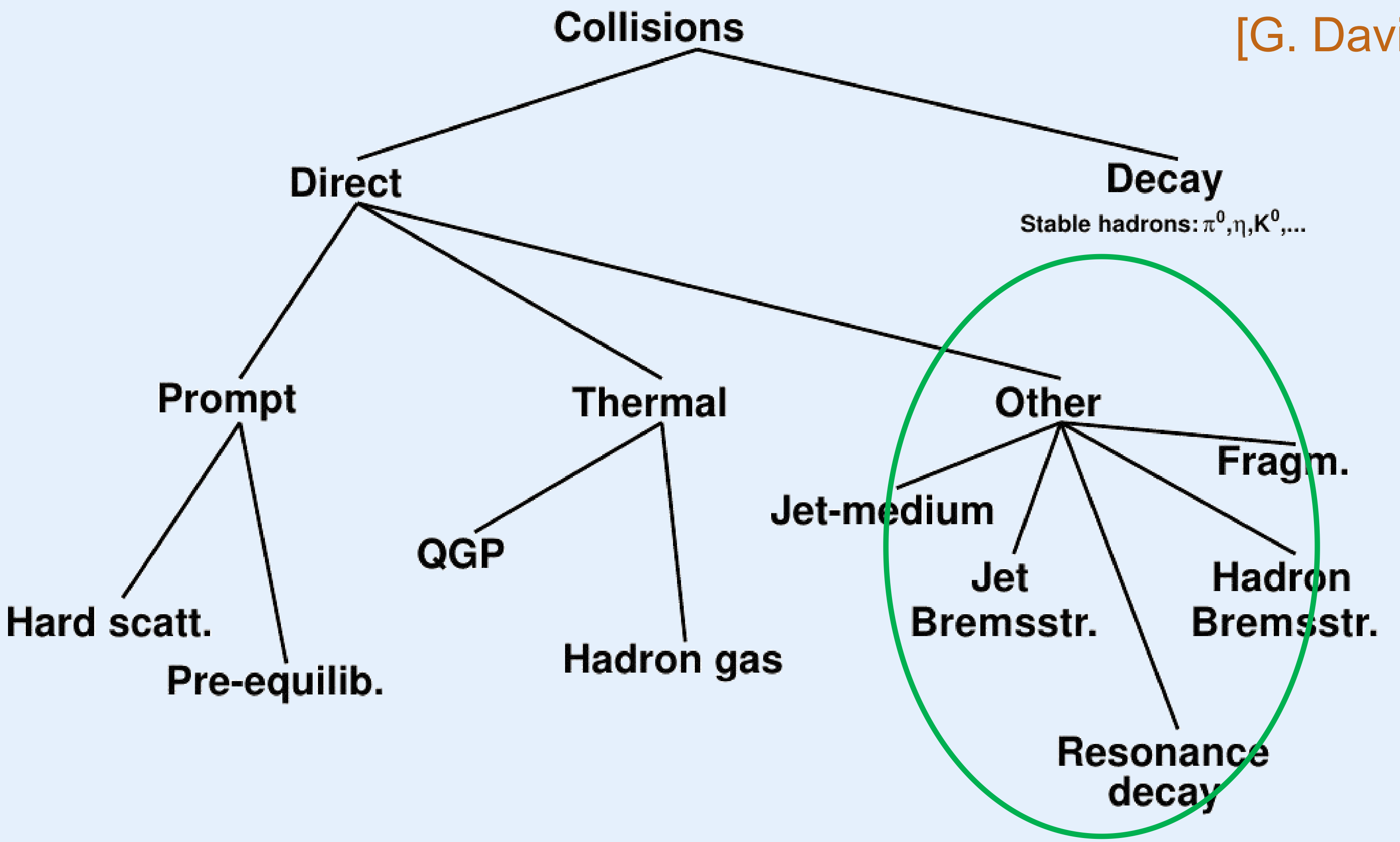
Direct photon production in heavy-ion collisions

[G. David, 1907.08893]



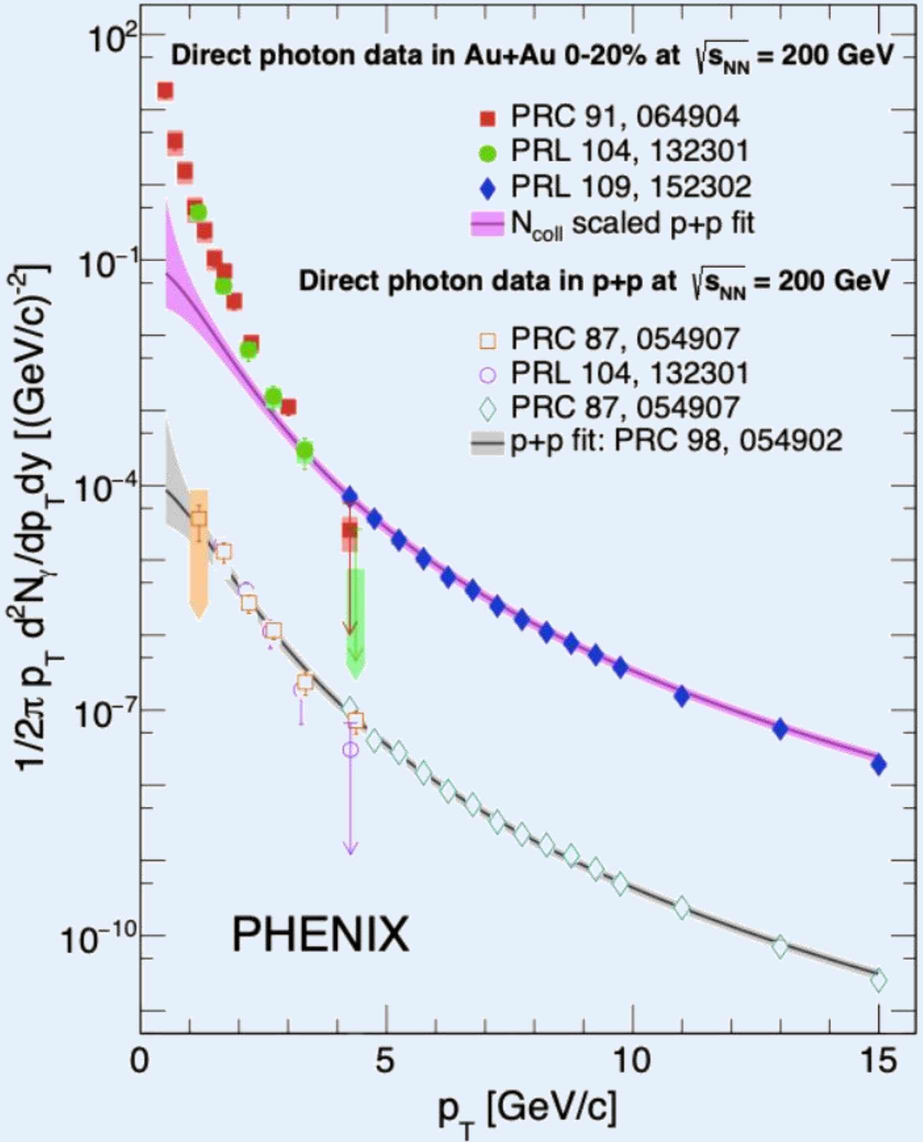
Direct photon production in heavy-ion collisions

[G. David, 1907.08893]



Jet conversion, etc.

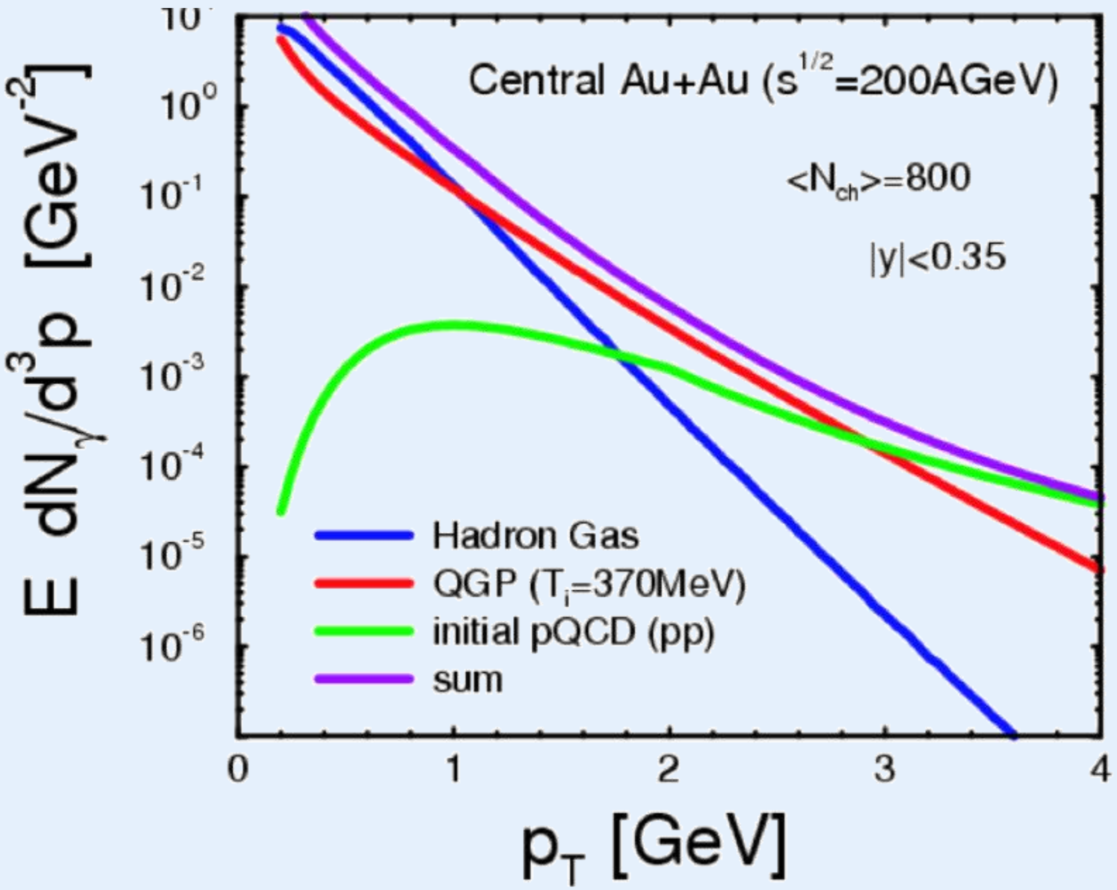
Direct photon yields from heavy-ion collisions



- Hard process dominates at large p_T
- Excess of direct γ above pQCD scaled expectation at small p_T: thermal radiations.
- Non-prompt (direct - pQCD scaled photons) spectrum used to estimate QGP temperature.
- We focus on the QGP thermal radiation

[PHENIX collaboration, 2203.12354]

Direct photon yields from heavy-ion collisions



[Turbide et al, PRC 69 014902 (2004)]

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- Excess of direct γ above pQCD scaled expectation at small p_T: thermal radiations.
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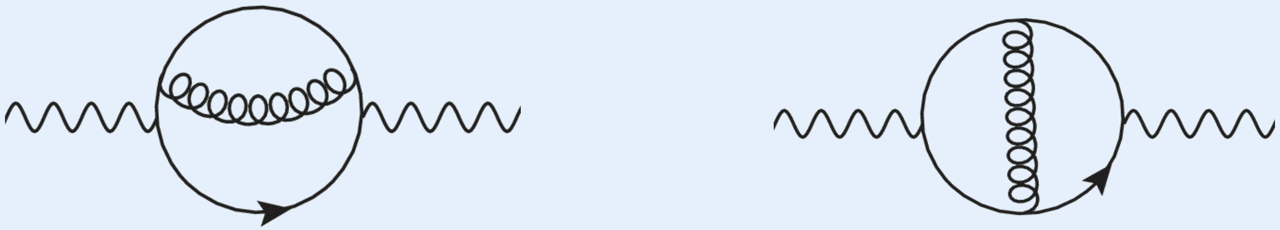
Thermal radiation from equilibriated QGP

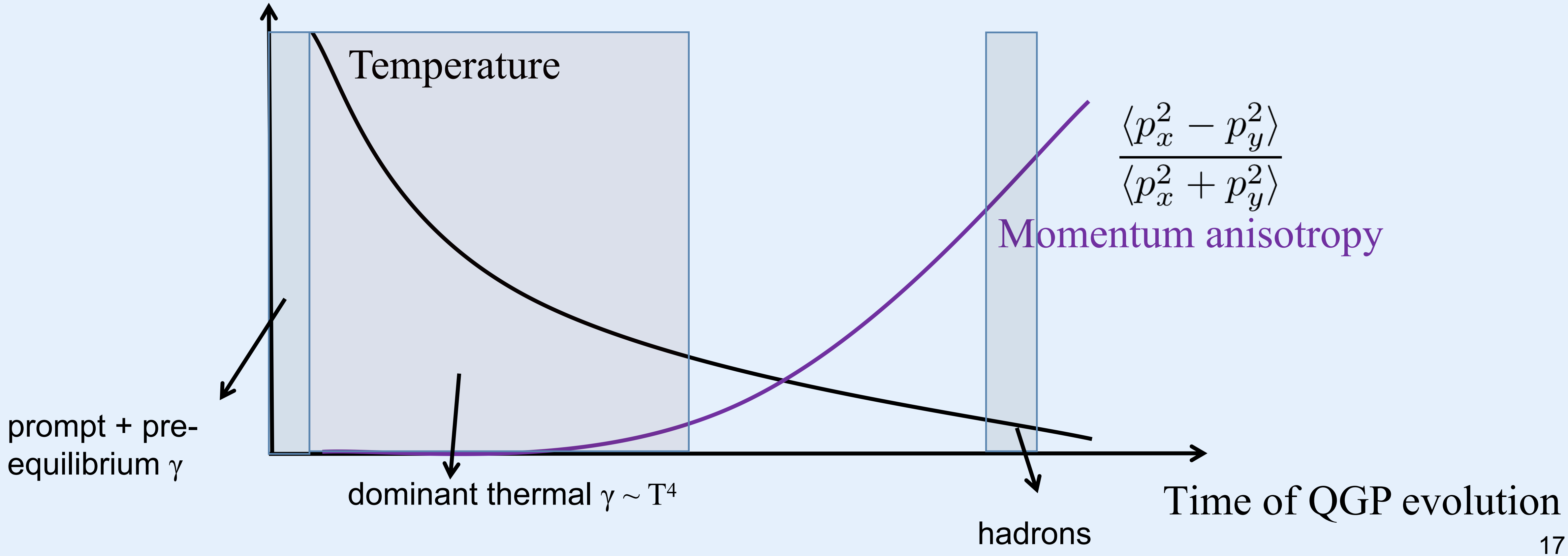


- Leading order radiation: $q\bar{q} \to g\gamma$ and $qg \to q\gamma$
- Production rate: $E\frac{dR}{d^3p} \propto \frac{1}{e^{E/T}-1}\mathrm{Im}\,\Pi^{R,\mu}_{\mu} \propto T^4$
- Photon spectrum requires space-time integral: require medium info.

$$E\frac{d^3N^\gamma}{d^3p} = \int_{tV} E\frac{dR}{d^3p} \propto \frac{dN^\gamma}{dp_T}(1 + 2v_2^\gamma \cos 2\phi + \ldots)$$

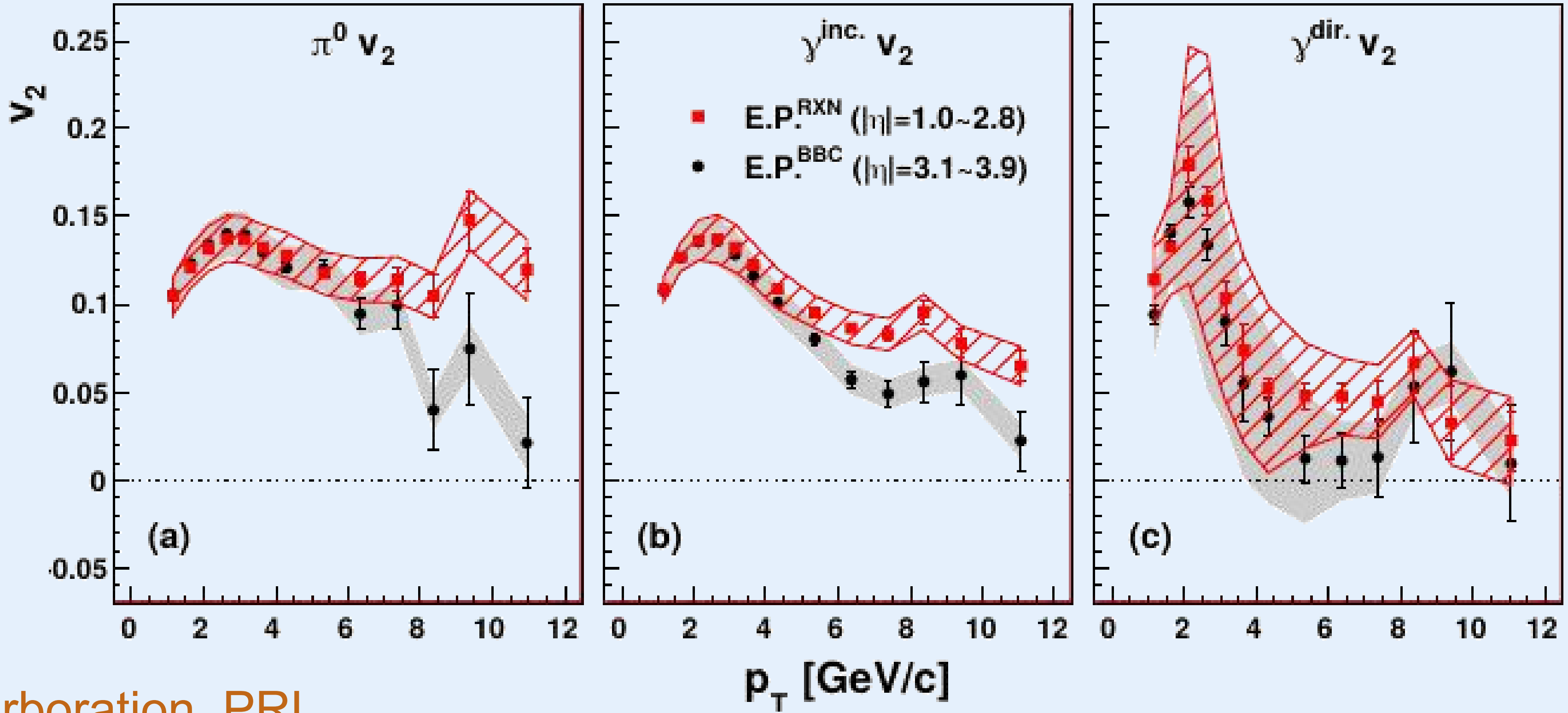
Direct photon elliptic flow (before 2011)

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



Direct photon elliptic flow (after 2011)

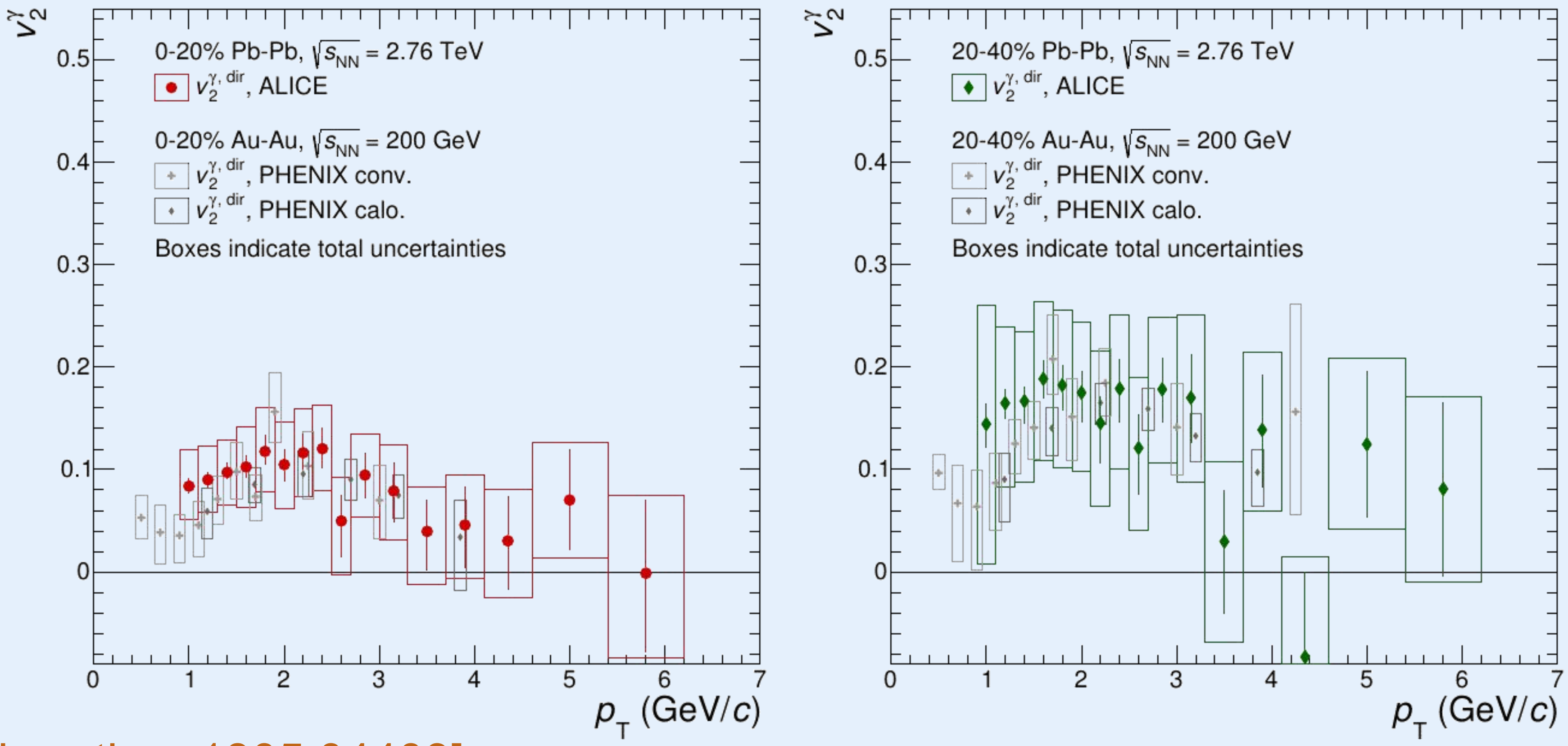
- Experimental observation: $v_2^{\gamma} \approx v_2^{\text{hadron}}$



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

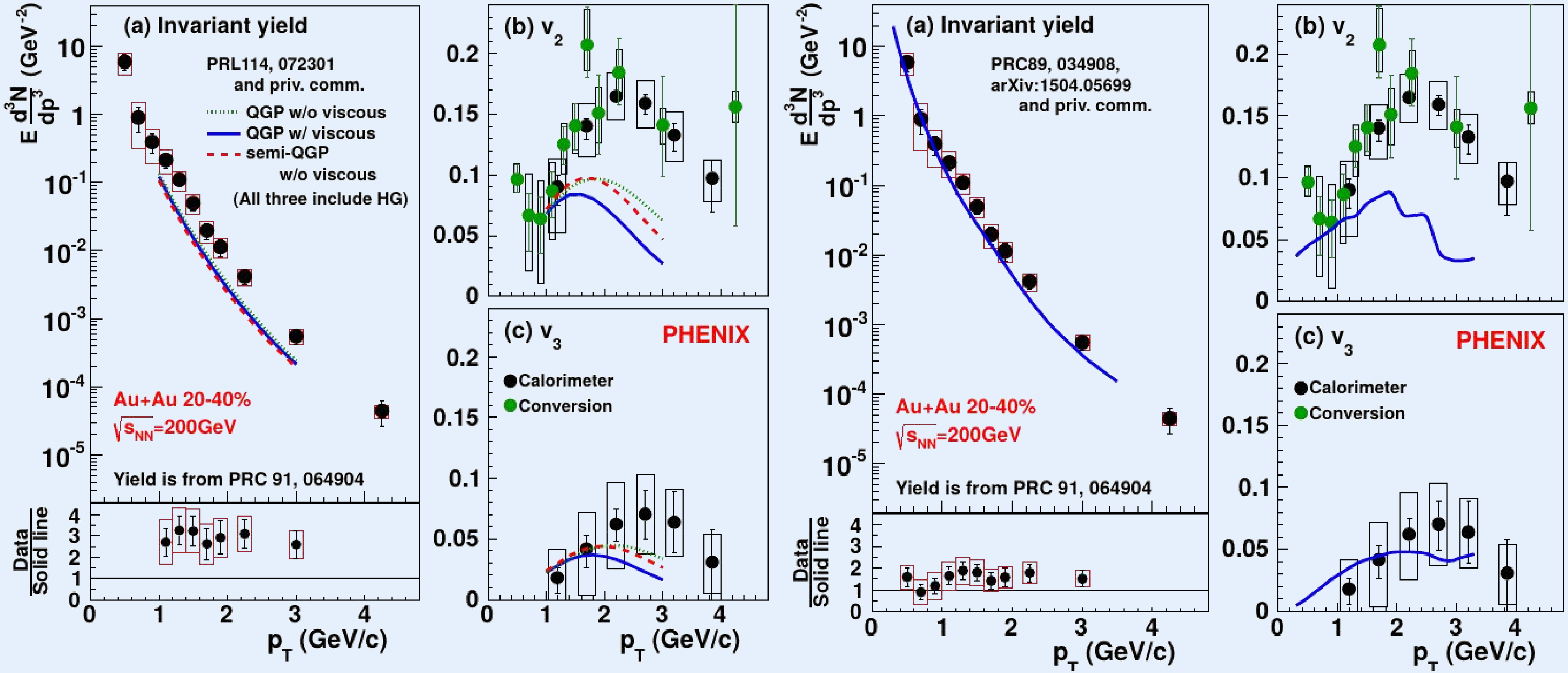
Direct photon elliptic flow (after 2011)

- Confirmation at the LHC: $v_2^\gamma \approx v_2^{\mathrm{hadron}}$



[ALICE collarboration, 1805.04403]

Experiments vs theories



[PHENIX, 1509.07752, R. Ryu et al, PRL 115 132301(2015), J. Paquet et al, PRC 93 044906 (2016), O. Linnyk et al, PRC 92, 054914 (2015)]

Direct photon puzzle

- PHENIX collarboration, PRL 109, 122302 (2012):

anisotropy is interpreted in terms of a path-length dependence for parton energy loss. In this measurement with the PHENIX detector at the Relativistic Heavy Ion Collider we find that for $p_T > 4$ GeV$/c$ the anisotropy for direct photons is consistent with zero, which is as expected if the dominant source of direct photons is initial hard scattering. However, in the $p_T < 4$ GeV$/c$ region dominated by thermal photons, we find a substantial direct-photon v_2 comparable to that of hadrons, whereas model calculations for thermal photons in this kinematic region underpredict the observed v_2.

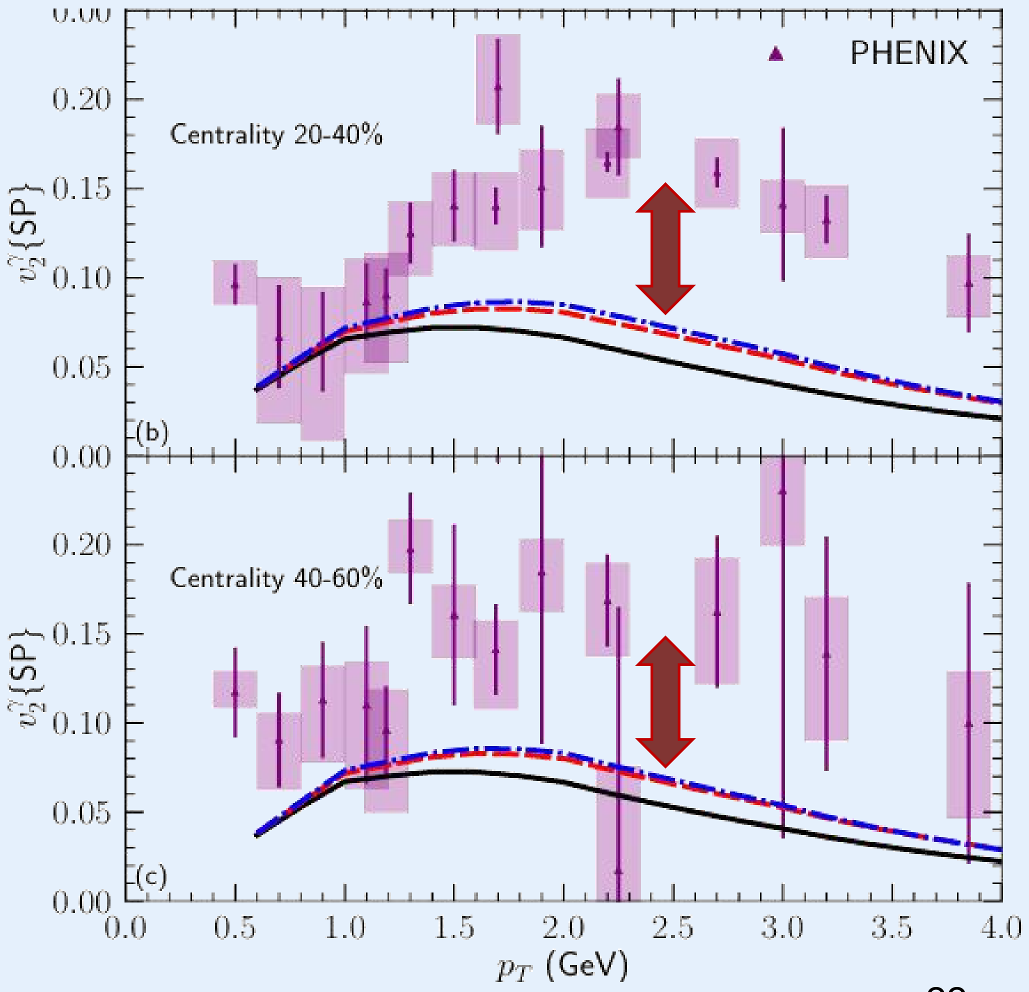
- Direct photon puzzle: "*Not too much of a puzzle left for yields.*"

[K. Reygers, Quark Matter 2022 plenary talk]

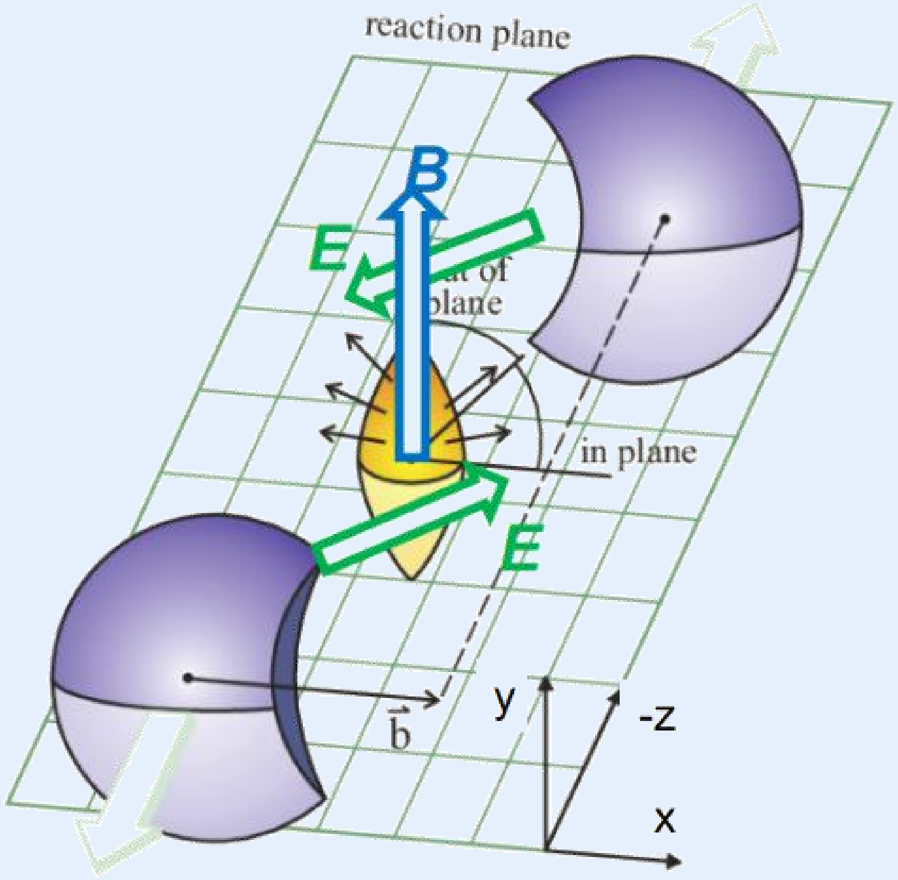
Up-to-date (conventional) hydro prediction

[C. Gale et al, 2016.00216]

- Chemical equilibration in QGP
- EbE 2+1D hydro for medium expansion
- NNLO pQCD for prompt photons
- LO thermal rate (AMY) with also dissipative corrections: $f + \delta f$
- Hadron gas γ production
- But, no magnetic field!



Electromagnetic field in heavy-ion collisions



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

- From the relativistic motion of nucleus
- B field is dominated out of plane,

$$\vec{B} \parallel \hat{y}$$

- B field is extremely strong ***initially***,

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

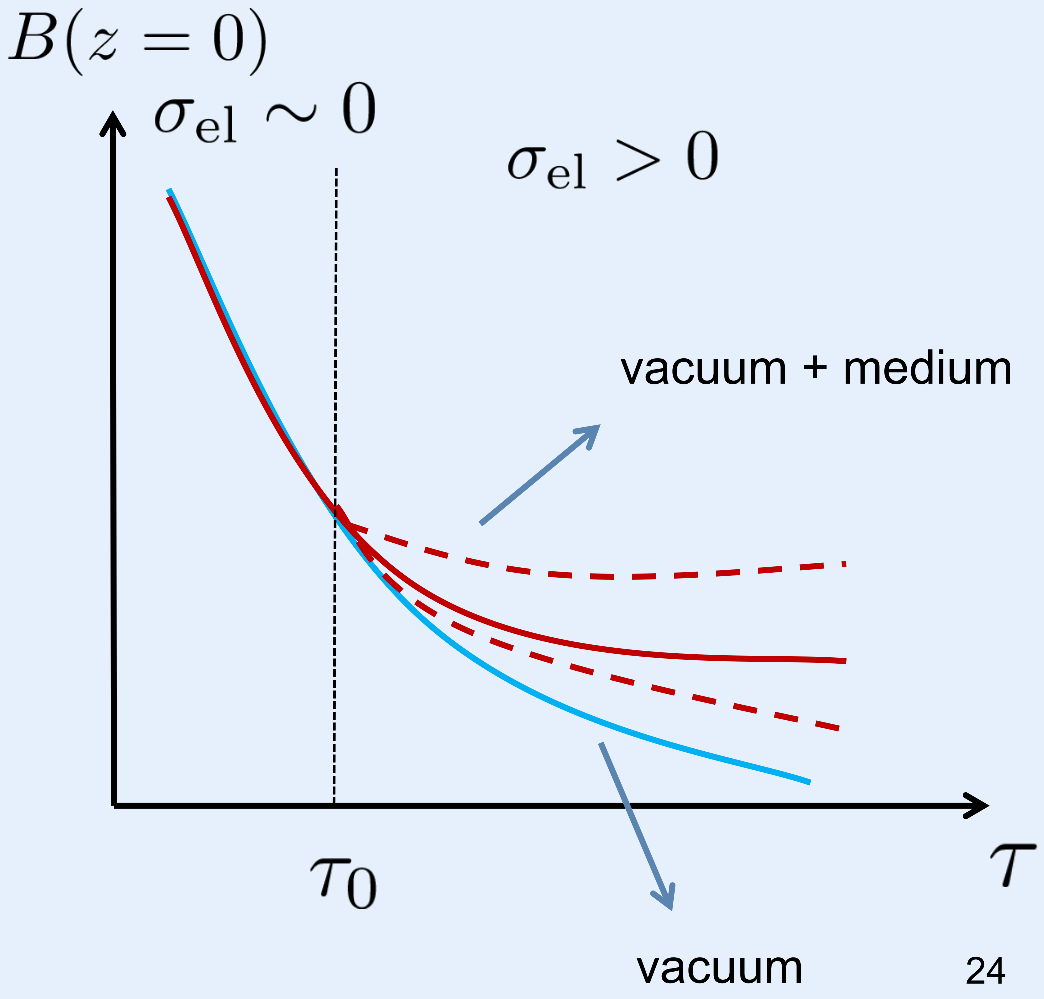
which has lead to many novel effects.

- Life time of B is crucial, but unknown.

Theoretically expected decay of magnetic field

A brief summary:

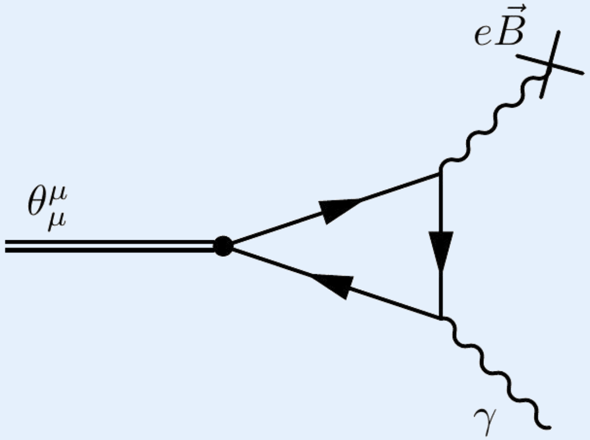
- Vacuum evolution of B is well solved, as well as B before tau_0.
- Medium contribution is uncertain, due to the electrical conductivity, as well as B after tau_0.
- tau_0 is related to chemical equilibration of QGP, approximately, tau_0 ~ 1 fm/c.
- Life time of B is extremely short unless with a unreasonbly large conductivity.



[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]

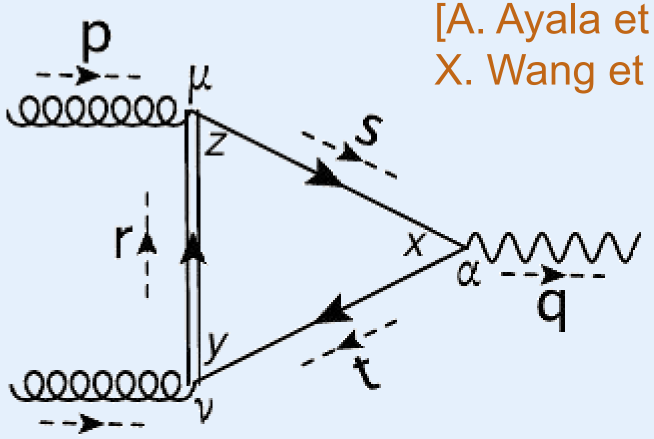
Strong Magnetic field and direct photon v_2

- Conformal anomaly [G. Basar et al., 2012]



- Quark with Landau level excitations

[A. Ayala et al, 1704.02433, X. Wang et al, 2006.16254]



- Some other mechanism involving induced inelastic emission (synchrotron-like), etc. [K. Tuchin, PRC 91, 014902., 2015, B. Zakharov, EPJC 76 (2016)]
- Strong magnetic field only exists at very early times: tau~0.1fm/c.
- Charged carriers in QGP (quarks) needs time to generate: tau>tau_0.

Magnetic field: strong vs weak

- Strong B leads to MHD: B becomes hydro d.o.f.

$$|eB| \gg T^2 \sim \sqrt{\epsilon}$$

- Strong B alters dynamics of quark scattering amplitudes, (Landau levels)

$$|eB| \gg g^2T^2 \sim m_T^2$$

- In realistic HIC, these conditions reduce to a criterion, $|eB| \sim m_\pi^2$, thus weak field condition,

$$|eB| \ll m_\pi^2$$

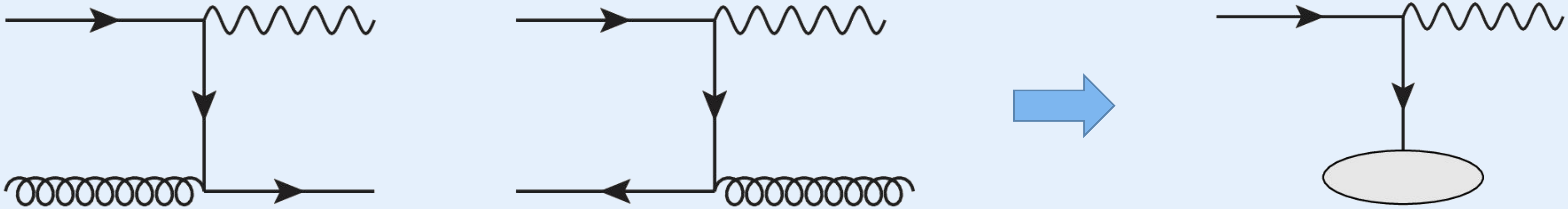
Weak magnetic photon emission (WMPE) in QGP

- Weak field strength assumption: $|eB|/m_\pi^2 \ll 1$
- Dynamical evolution of QGP follows hydro, instead of MHD.
- However, QGP is slightly off-equilibrium due to weak B field.
- Photon production via quark scatterings not changed substantially.

- Our goal:

1. find a novel mechanism of photon emission in weak B field.
2. photon emission must be significantly anisotropic.
3. do not change direct photon yields substantially.

Weak magnetic photon emission in QGP

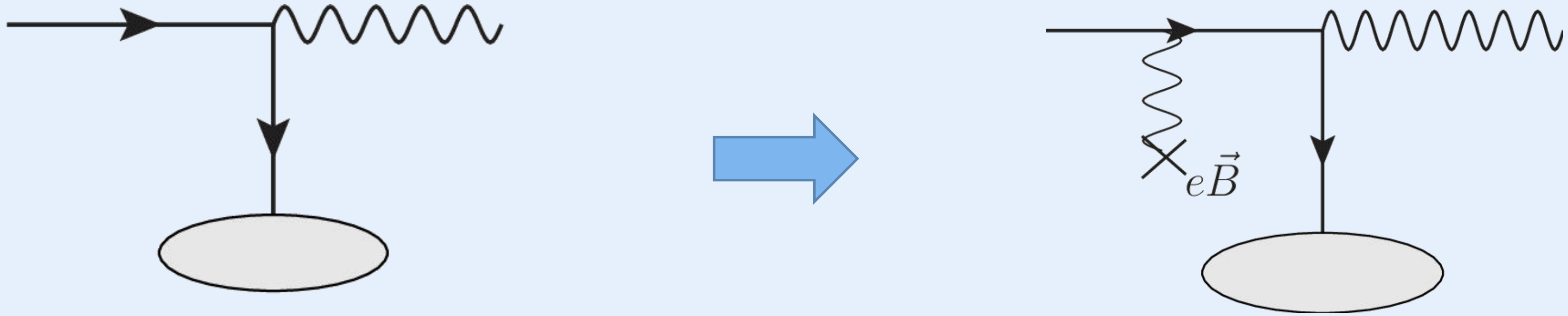


1. Start with the production rate from kinetic theory*:

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

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

Weak magnetic photon emission in QGP



2. Shift in f_q due to the presence of a weak B field:

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

where in background rate quark distribution also gets corrected by viscosities.

Weak magnetic photon emission in QGP

3. Determining f_{EM} according to electrical conductivity of QGP,

$$f_{\mathrm{EM}} = \frac{c}{8\alpha}\frac{\sigma_{\mathrm{el}} n_{\mathrm{eq}}(1-n_{\mathrm{eq}})}{T^3 p\cdot u} eQ_f F^{\mu\nu} p_\mu u_\nu \qquad \propto \frac{|eB|}{T^2}$$

Weak magnetic photon emission in QGP

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properties of background QGP

properties of external E&B field,
e.g., $B_y p_T u^z \cos\phi_p$

Origin of photon elliptic emission anisotropy

- External B field naturally contains a dipole moment,

$$\cos\phi_p \in F^{\mu\nu} p_\mu u_\nu$$

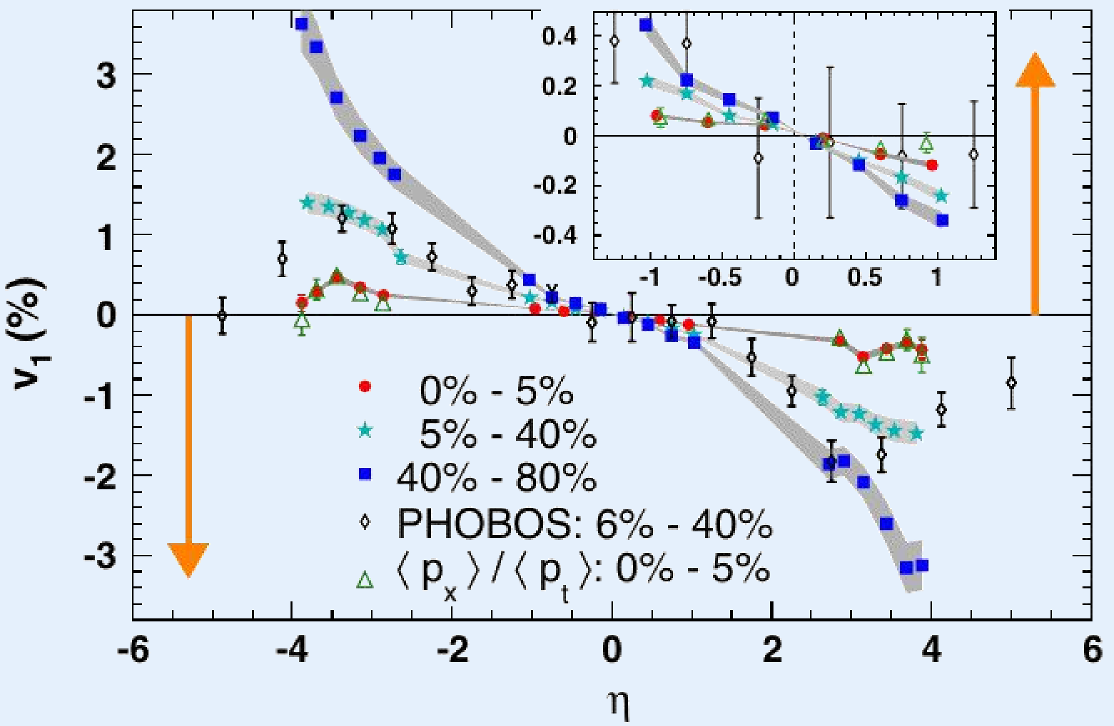
- An extra dipole moment comes from background QGP, e.g., a tilted fireball,

[P. Bozek et al., 1101.3354]

$$A(\tau, p_T, \eta_s, Y)\cos\phi_p \in n_{\text{eq}} \quad \leftrightarrow v_1$$

- Coupled effects give rise to

$$\cos 2\phi_p \sim v_2^{\text{EM}}$$



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

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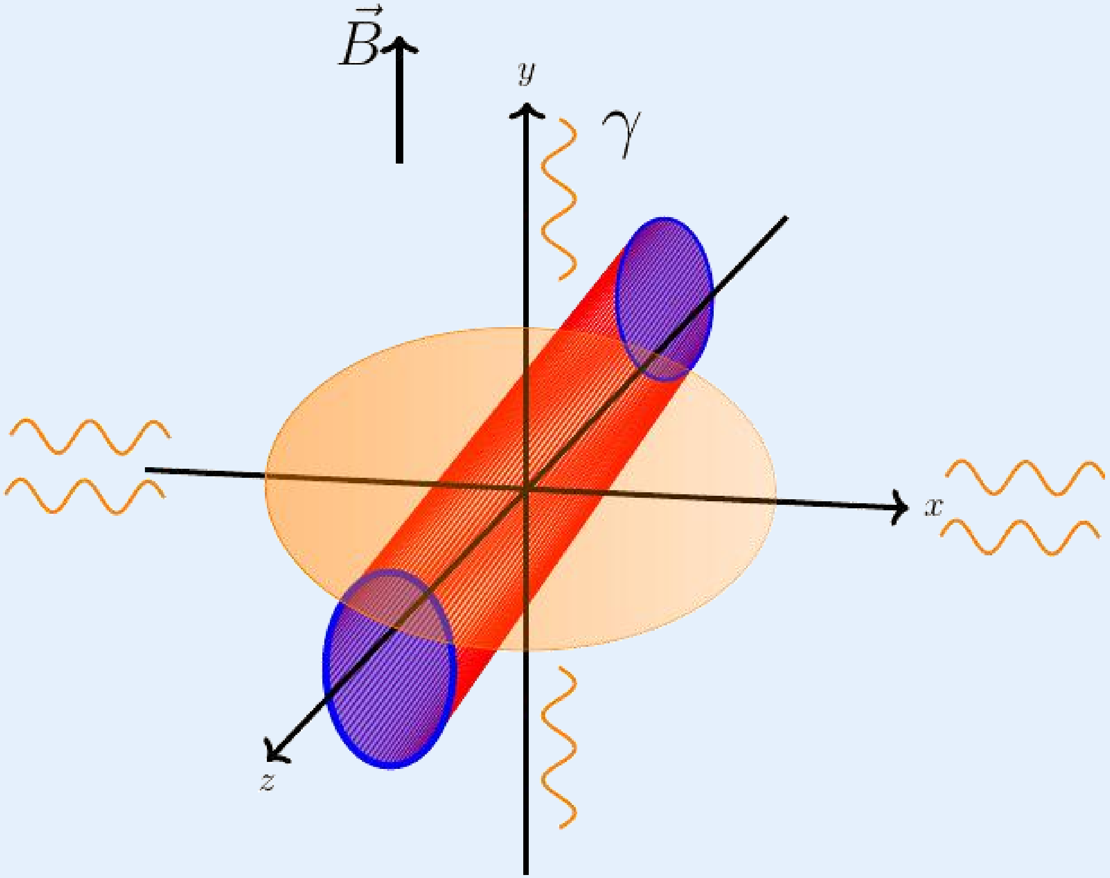


WMPE on top of Bjorken flow

- Bjorken flow: boost invariant along z, analytical but unphysical.

$$u^\mu = (\cosh\eta_s, 0, 0, \sinh\eta_s) \qquad n_{\rm eq} = A_0(\tau,\eta_s,p_T,Y) + A_1(\tau,\eta_s,p_T,Y)\cos\phi_p$$

- Correction of quark distribution due to B field,

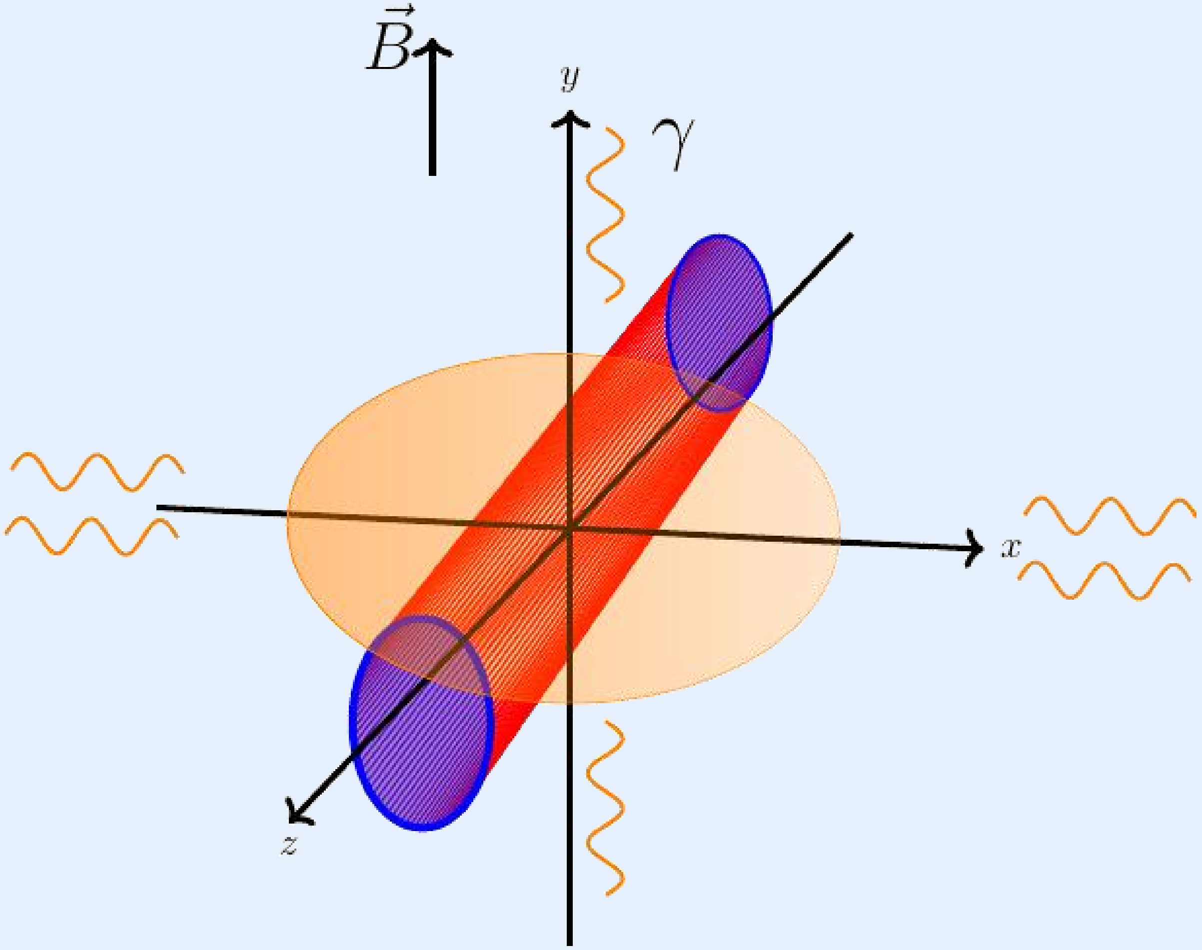
$$f_{\rm EM} \propto QB_y\frac{\tau_R}{T}\frac{\sinh\eta_s}{\cosh(y-\eta_s)}\left[\frac{A_1}{2} + A_0\cos\phi + \frac{A_1}{2}\cos 2\phi\right]$$

which implies already $v_2^{\rm EM} = 0.5$, irrespective of magnitude of B_y

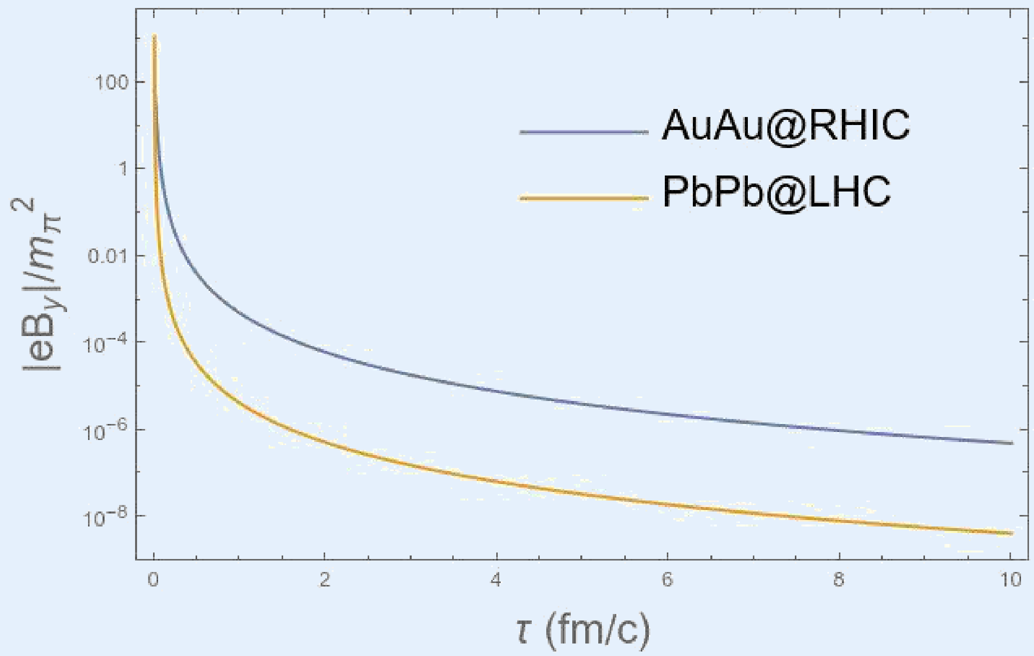
- After integral over space-time and even rapidity window as experiments, only odd components remain, so here for photons v_1=0.

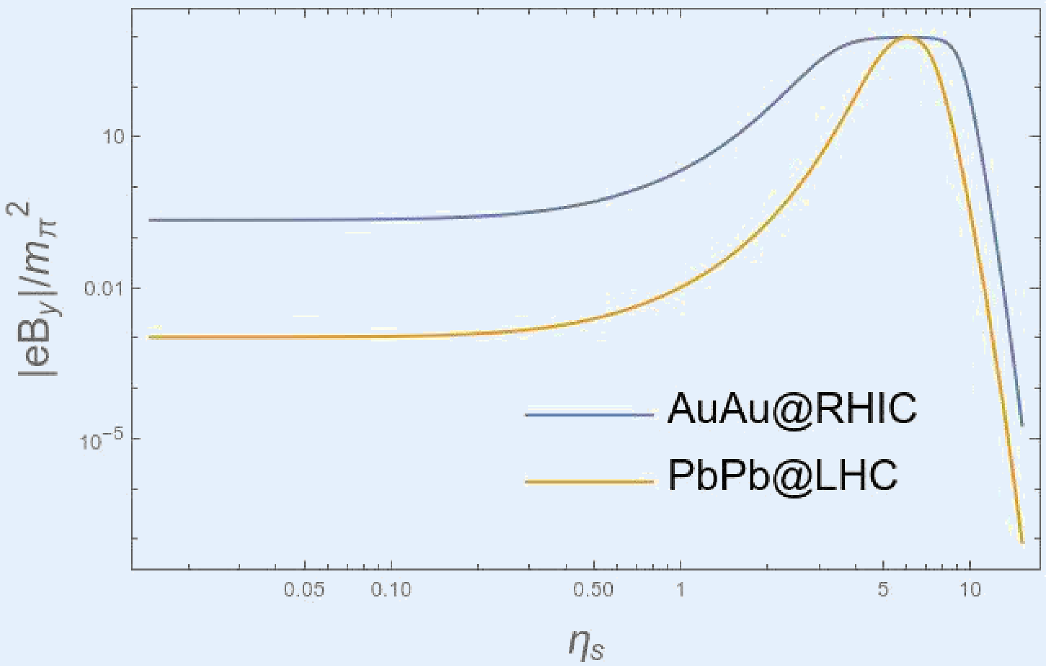
WMPE under realistic conditions

- Electrical conductivity = LO pQCD evaluation (AMY), to be consistent with background photon results.
- One tilted fireball initial condition, which has been used to reproduce charged hadron v_1 : *single-shot*
- Solving medium evolution using 3+1 D hydro (MUSIC), with finite shear/bulk viscosities, from tau0=0.4 fm/c.



WMPE under realistic conditions





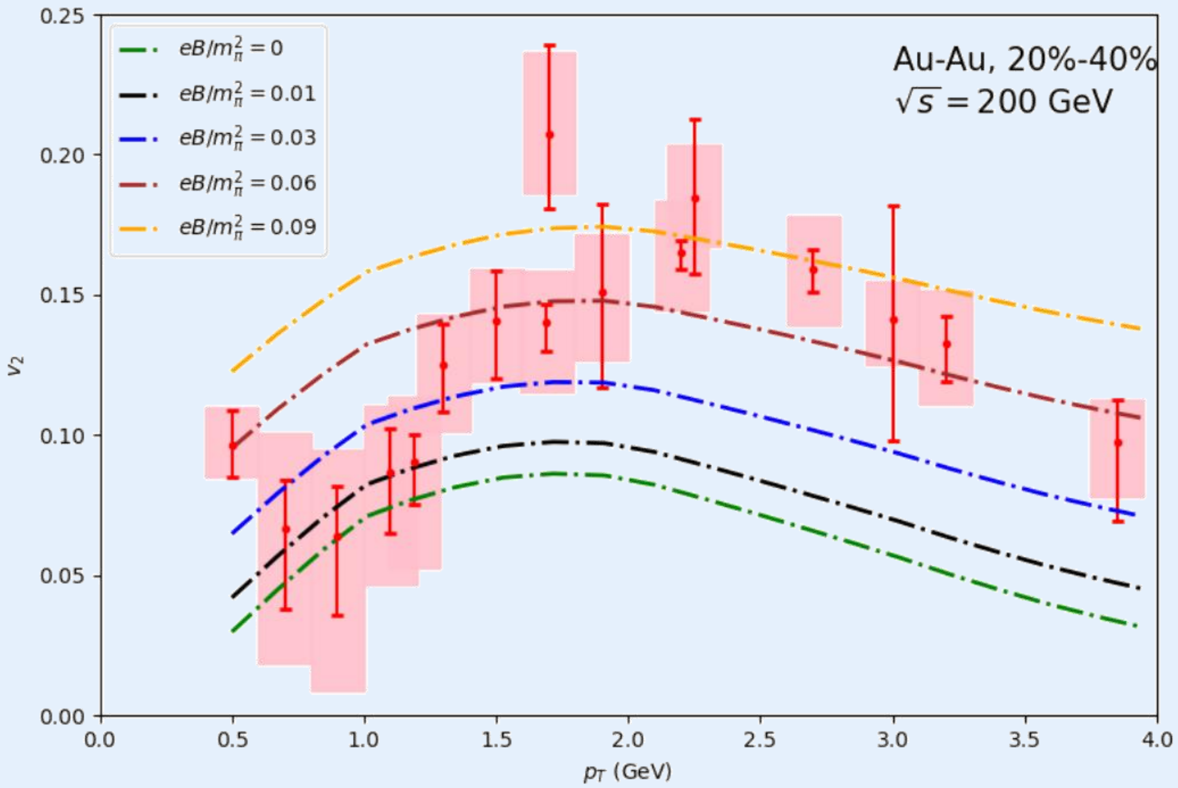
- Space-time profile of external B field as in vacuum: “worst-case” scenario

[K. Hattori and X. Huang, 1609.00747]

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

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

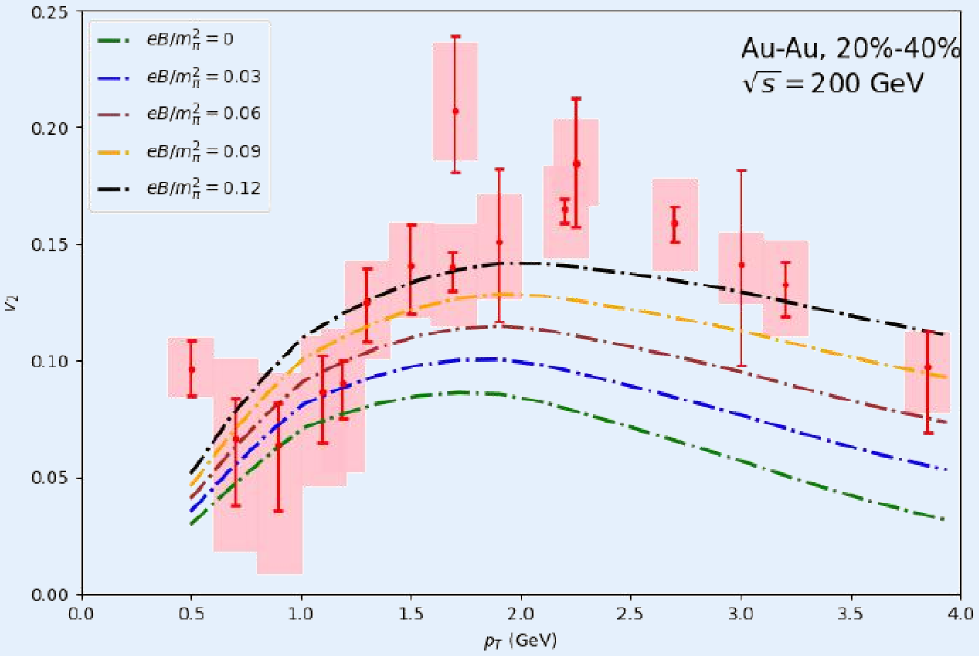
Ideal hydro and weak field condition

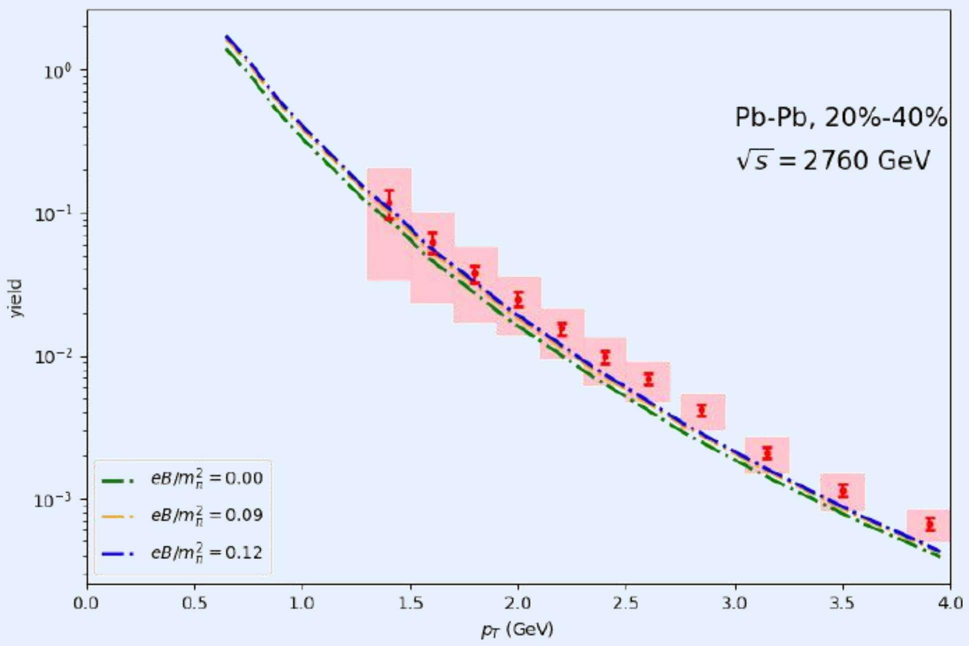


$$|eB_y^0|/m_\pi^2 < 0.1$$

- Weak B field indeed gives rise to a large elliptic flow of direct photons!

Viscous hydro and WMPE

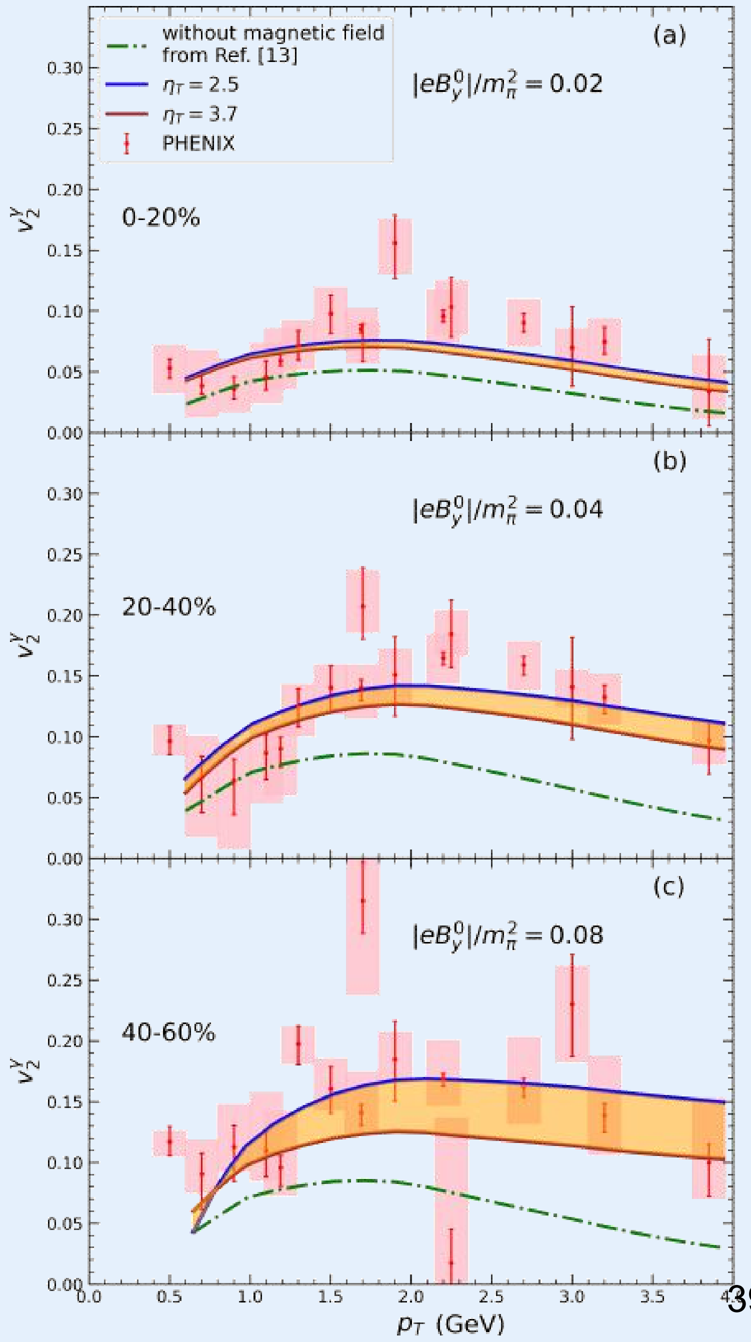




- Detailed shape of elliptic flow is sensitive to viscosity.
- Experimental data of elliptic flow can be reproduced!
- Direct photon yields receive small enhancement (~10%) .

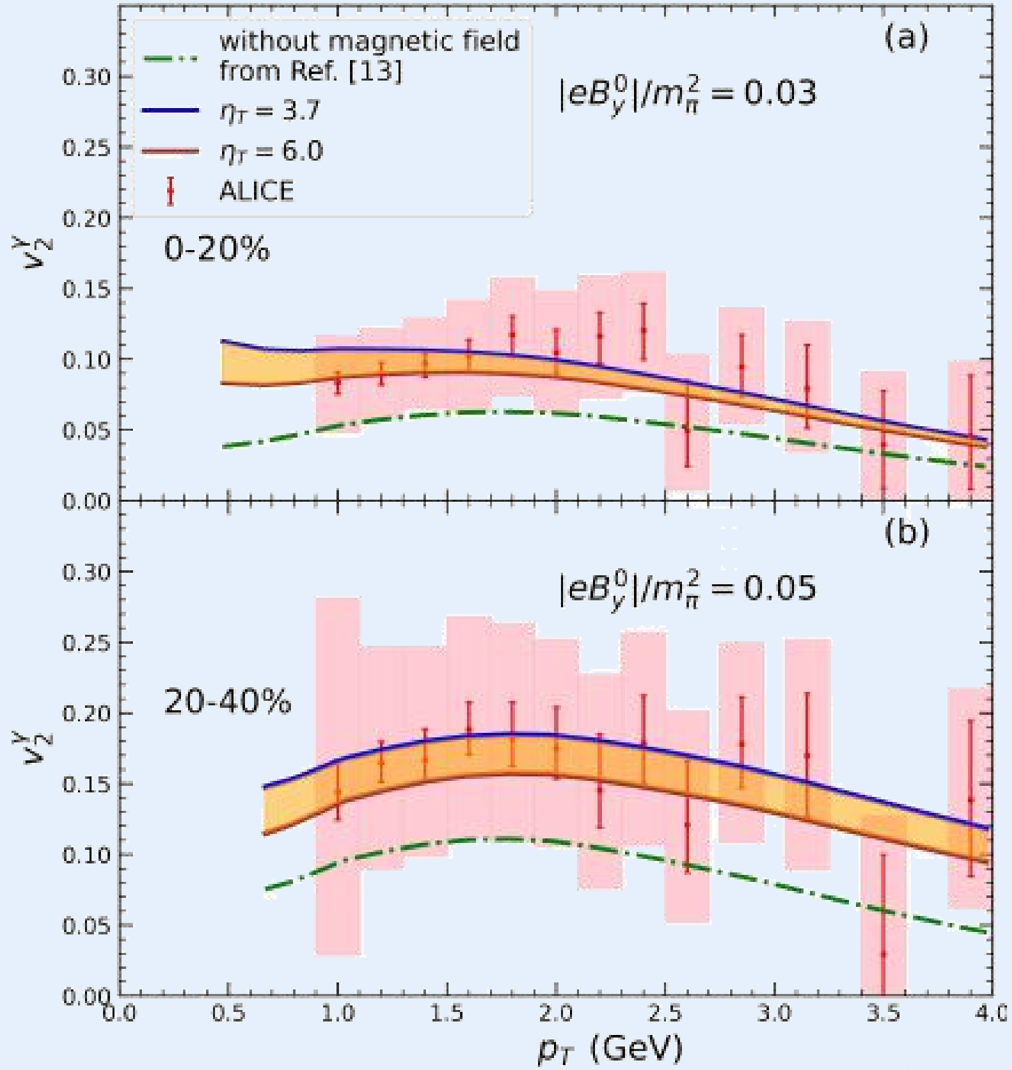
Confronts experiment at RHIC

- Good agreement for all centralities.
- Initial field strength extracted and grows as centrality increases: correct trend!

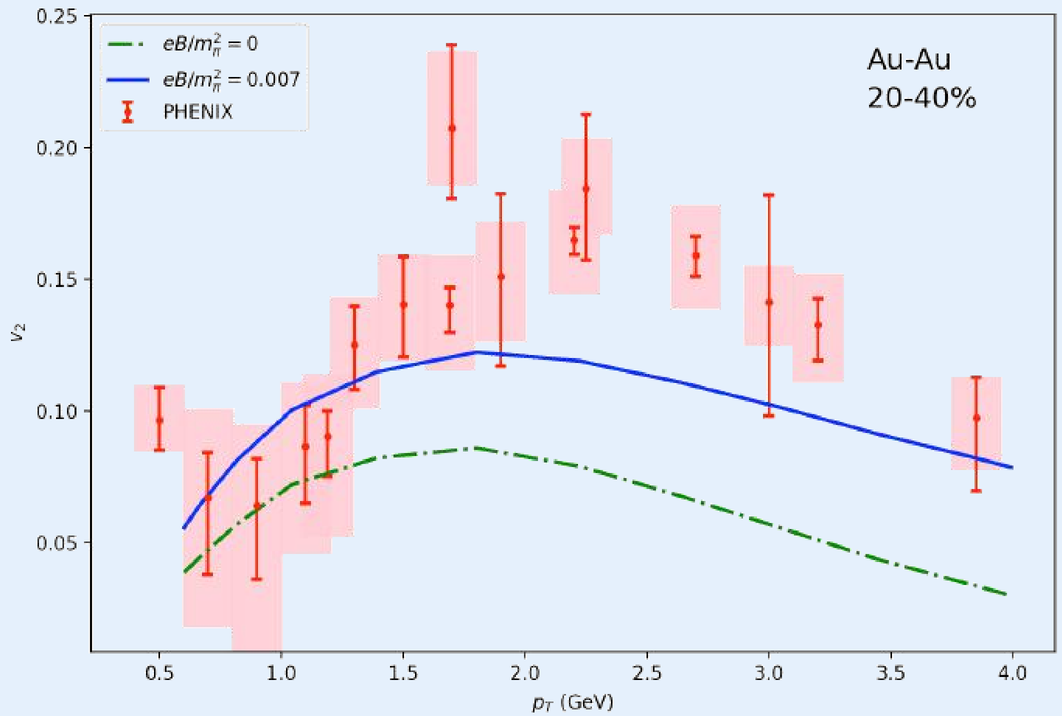


Confronts experiment at LHC

- Good agreement for all centralities.
- Initial field strength extracted and grows as centrality increases: correct trend!



Event-by-event simulations (preliminary)



- Extract initial field strength is reduced significantly: $|eB_y^0|/m_\pi^2 \approx 0.007$
- Surprisingly, vacuum evolution of B(t=0.4 fm/c) gives $|eB_y|/m_\pi^2 \approx 0.007$

Summary

- Weak magnetic photon emission can be a solution to "direct photon puzzle"!
- A weak magnetic field evolves along with QGP in HIC.
- Direct photon spectrum can be used to extract B field strength at early time.