Anisotropy of photon production in magnetic field

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G. Basar, D. Kharzeev, V.S., arXiv:1206.1334
A. Bzdak, V.S., arXiv:1208.5502

Thermal radiation workshop; December 6, 2012

Outline

- motivation: photon puzzle
  measurements vs expectations

- possible solutions:
  “hadronic”
  “partonic” + magnetic field

- magnetic field in heavy-ion collisions:
  essential properties: magnitude, lifetime, b-dependence
  natural source of anisotropy

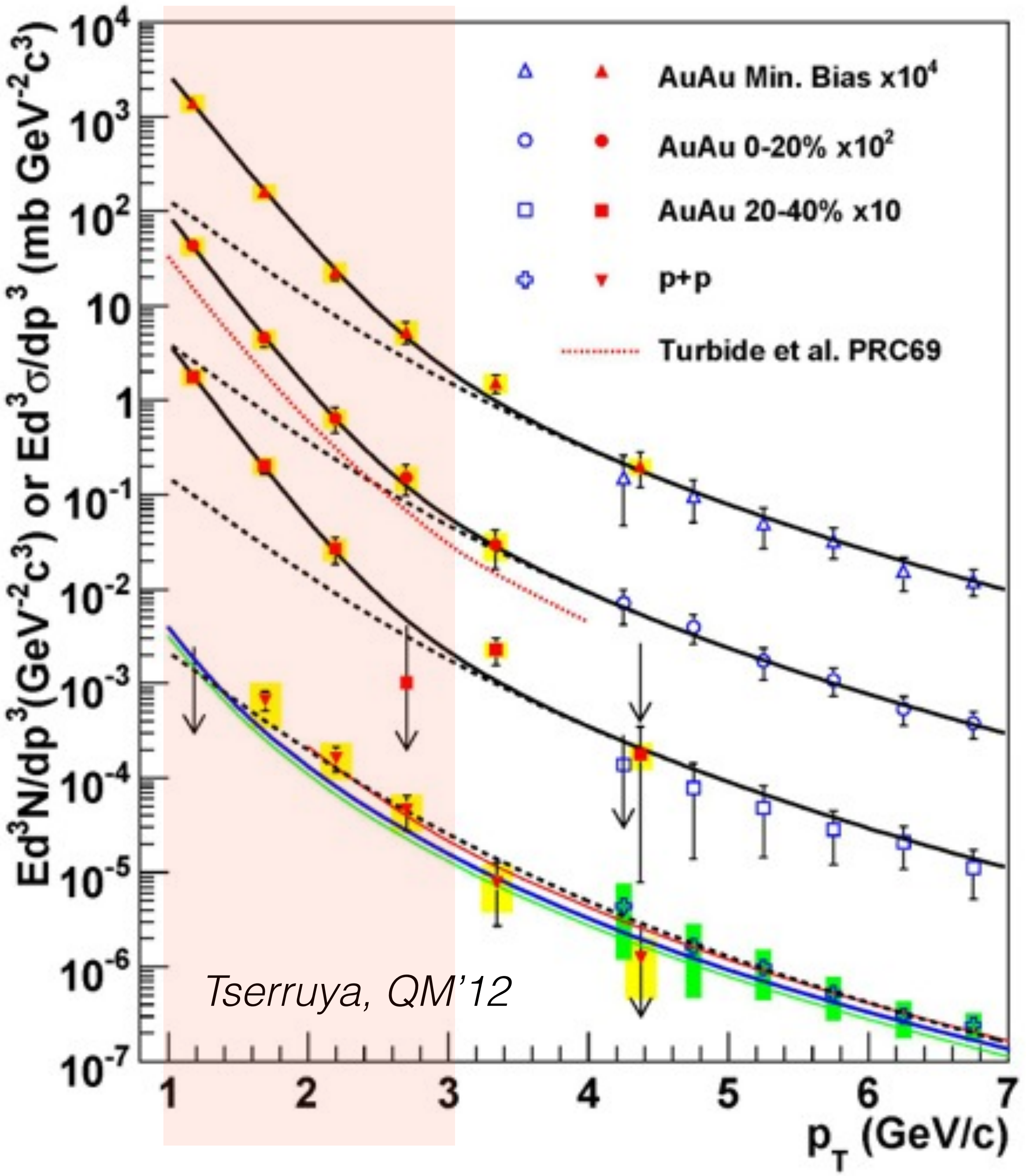
- photon production and magnetic field:
  results & possible experimental signatures

Experimental facts about γ

- transverse momentum spectrum

T_{ave} = 221 MeV ➞

T_{ini} = 300 to 600 MeV τ_0 = 0.15 to 0.6 fm/c

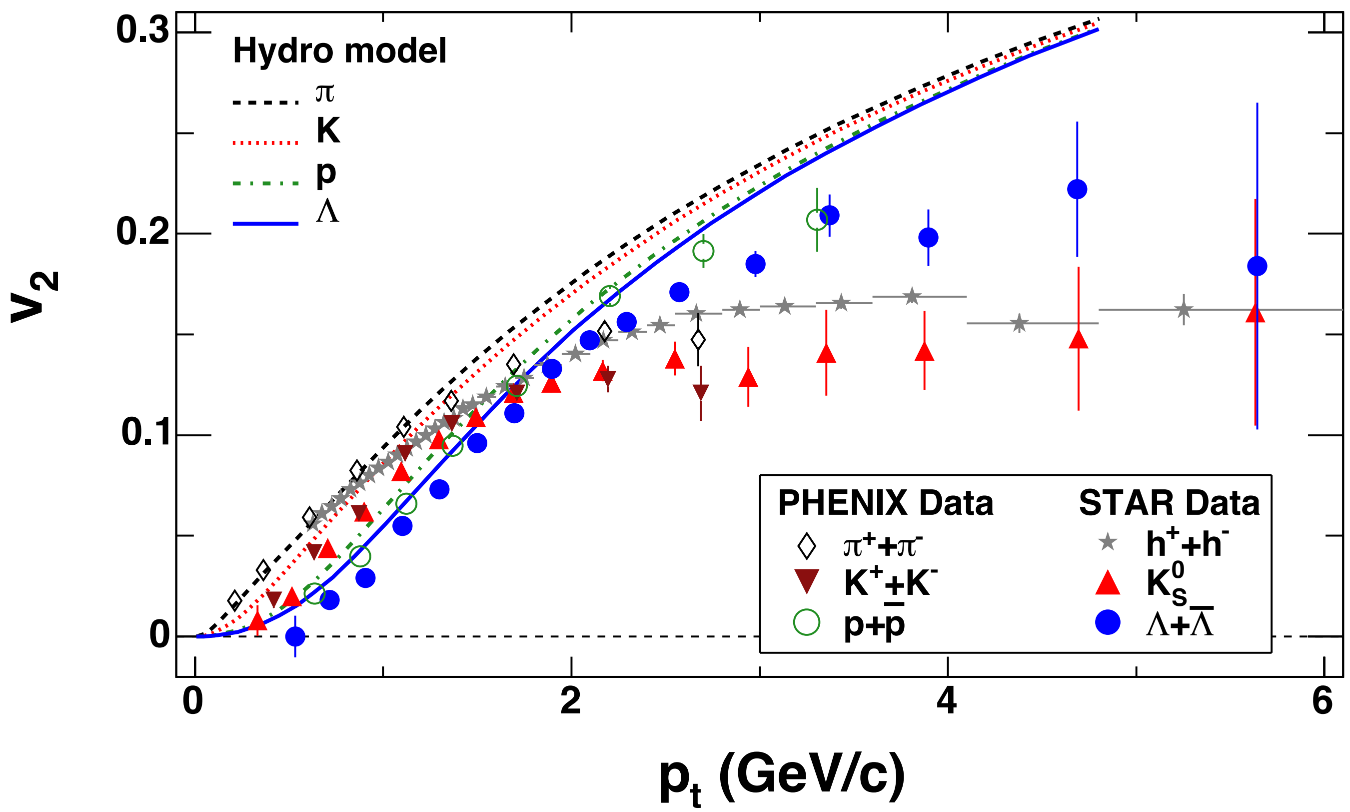


Azimuthal anisotropy

- Direct photons:

PHENIX

- Hadrons:



Azimuthal anisotropy

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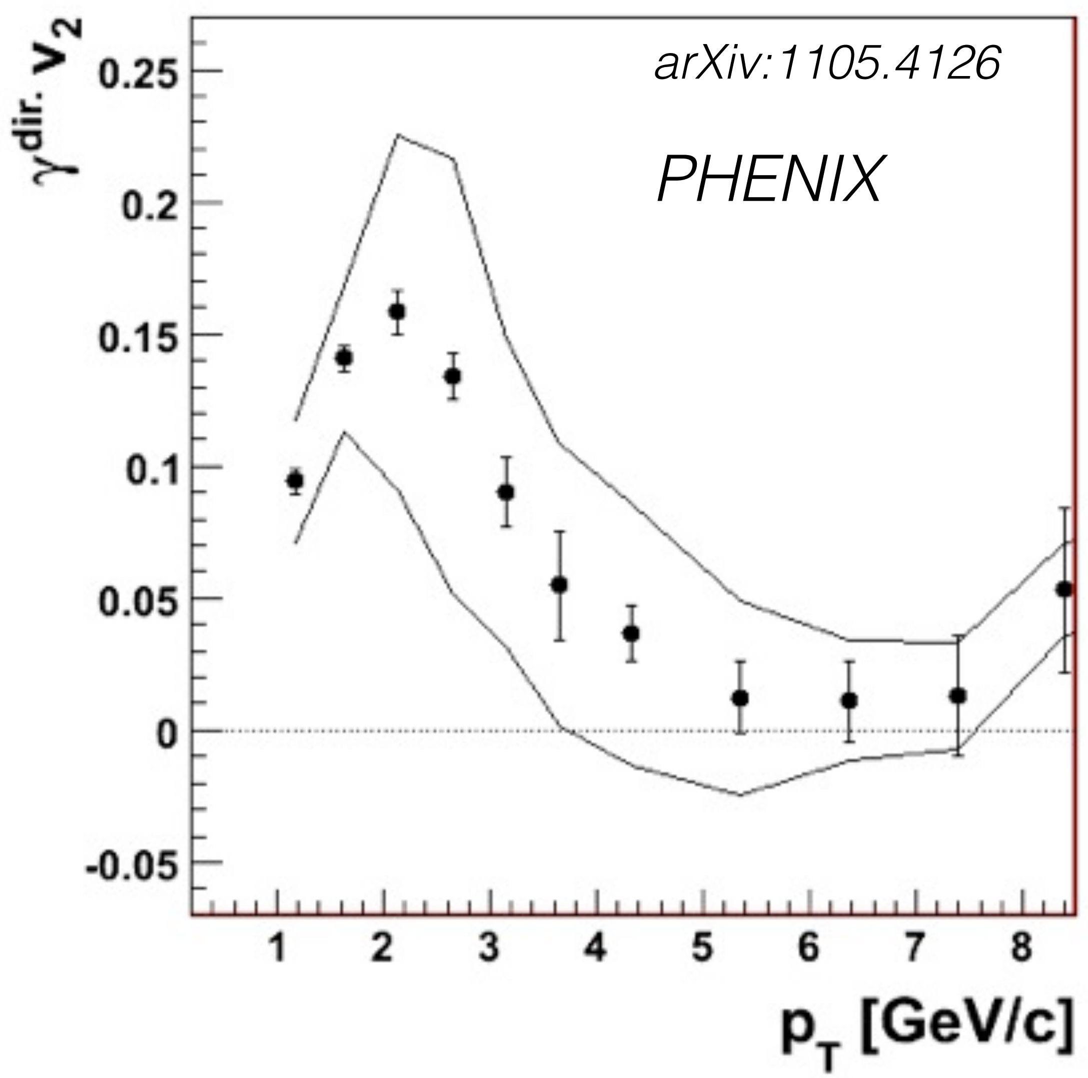
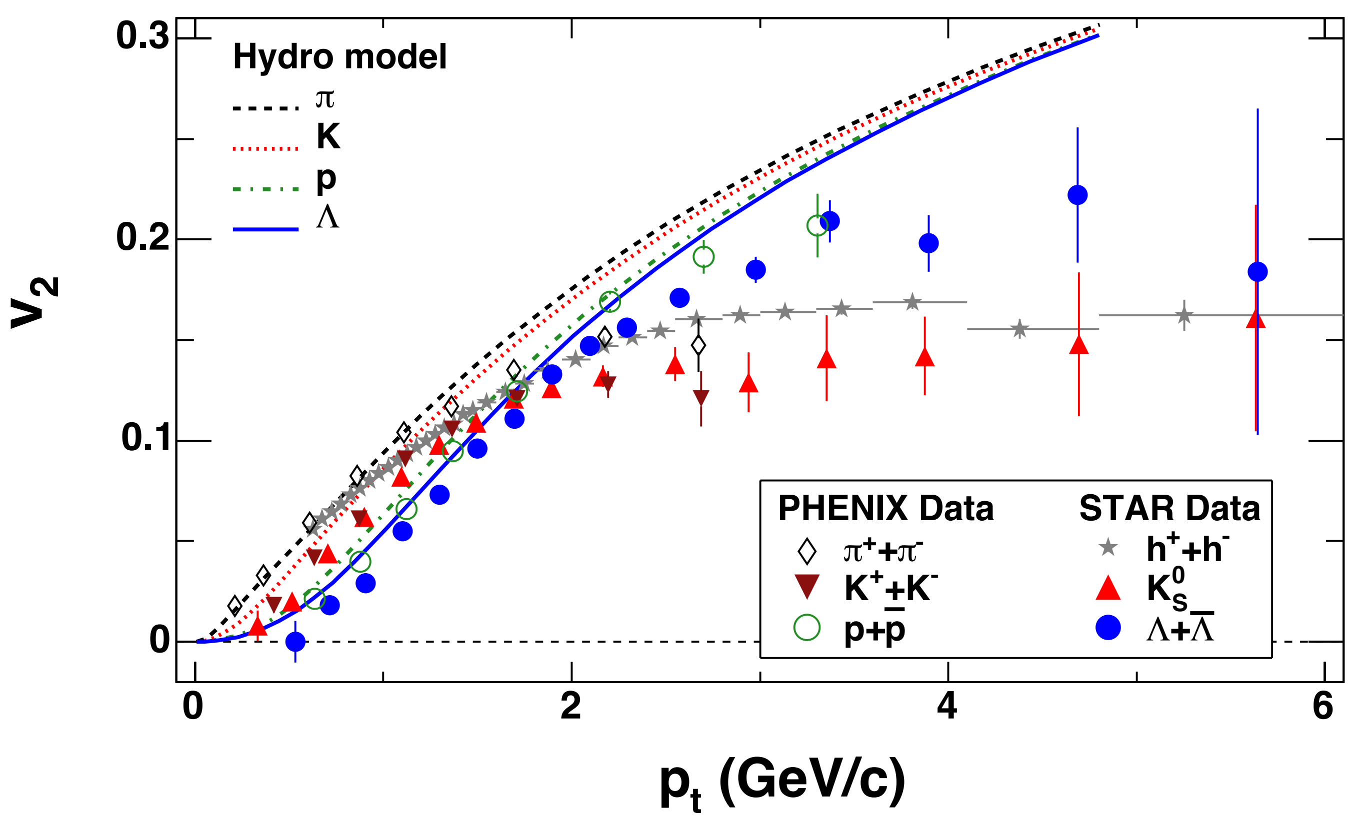
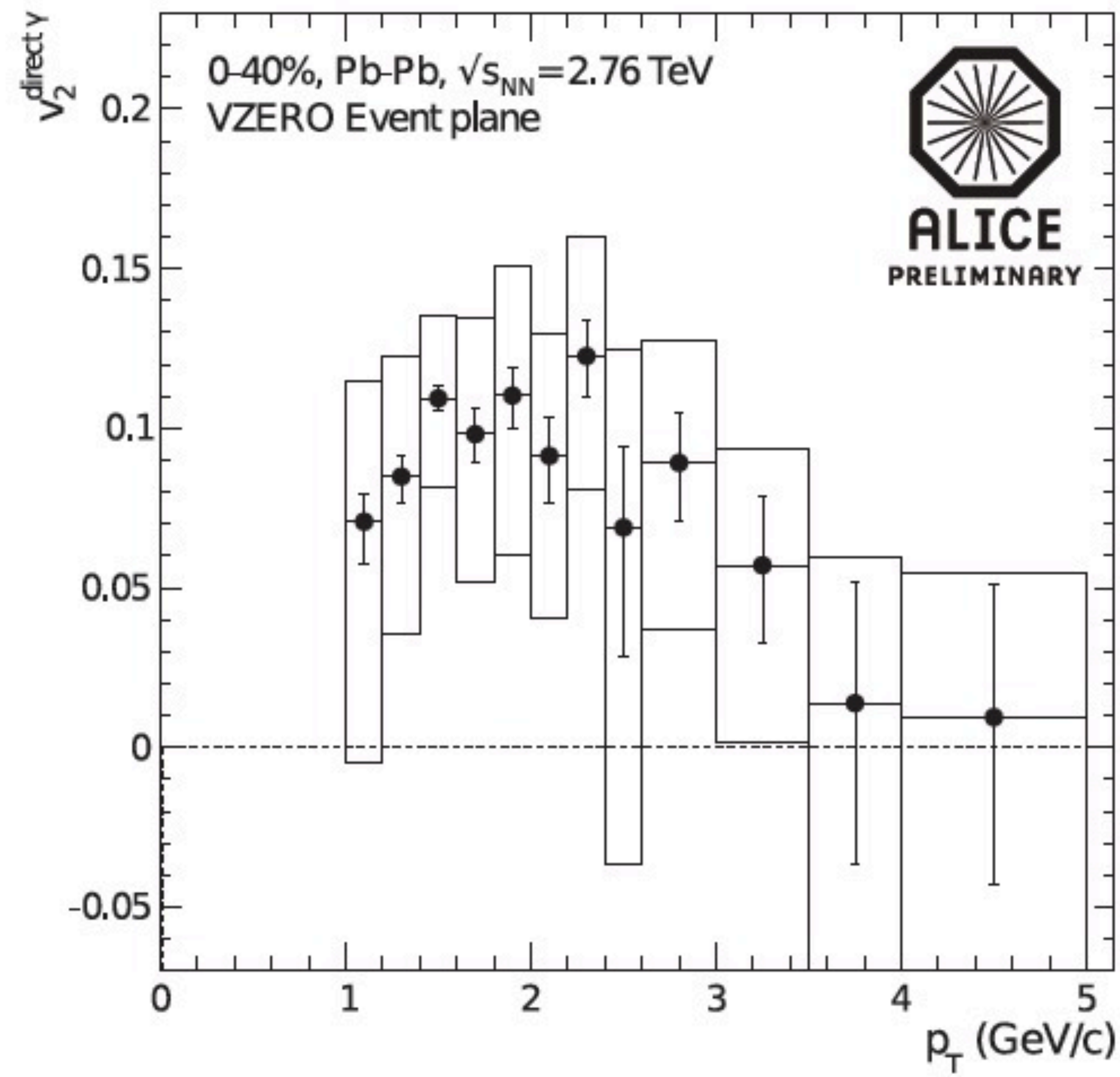


- Hadrons:

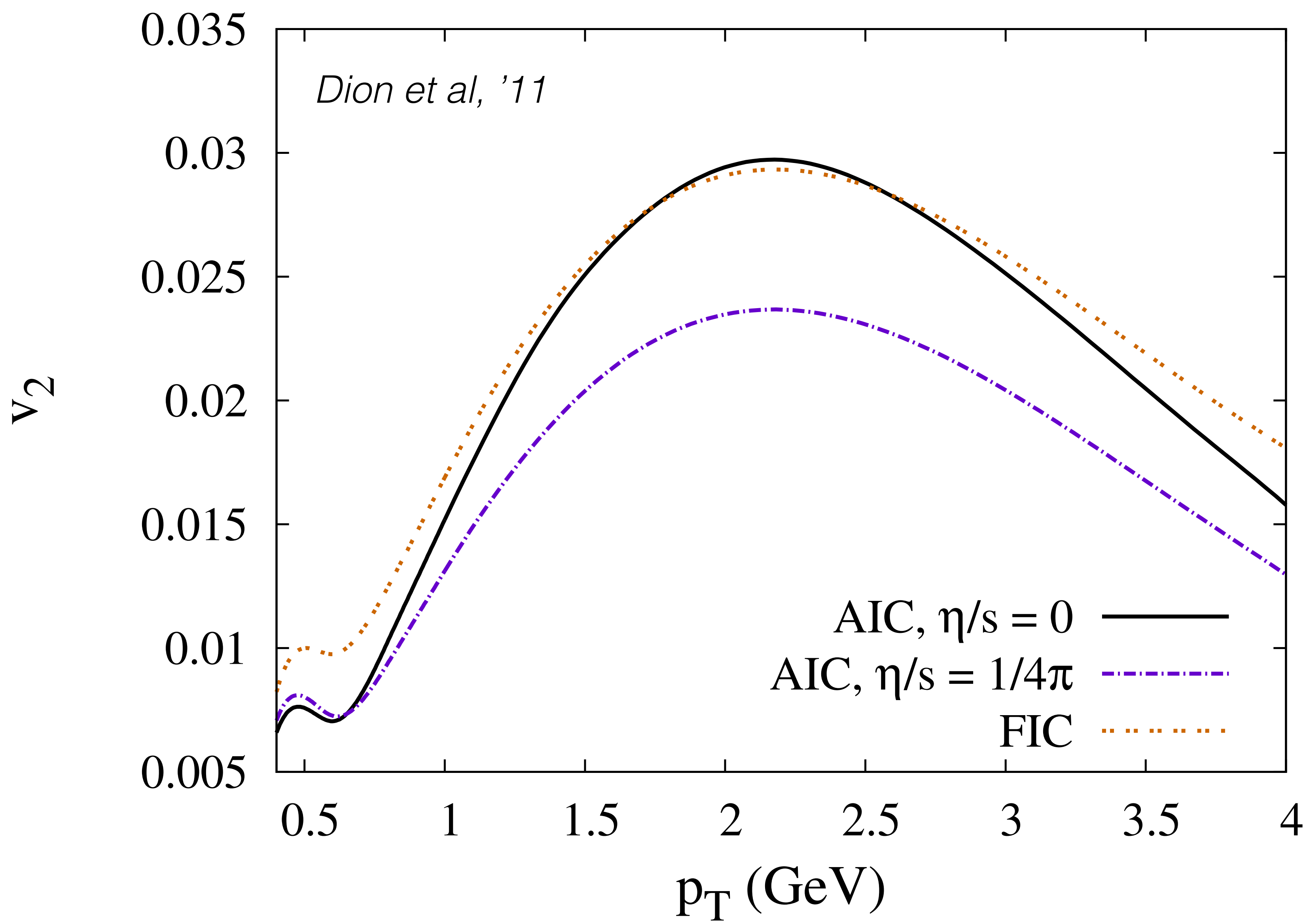


Azimuthal anisotropy:LHC



Daniel Lohner, Hot Quarks 2012

Theory: Hydrodynamics



Hydro:
5 times smaller v_2 then in experiment

AIC: averaged initial conditions
FIC: fluctuating initial conditions

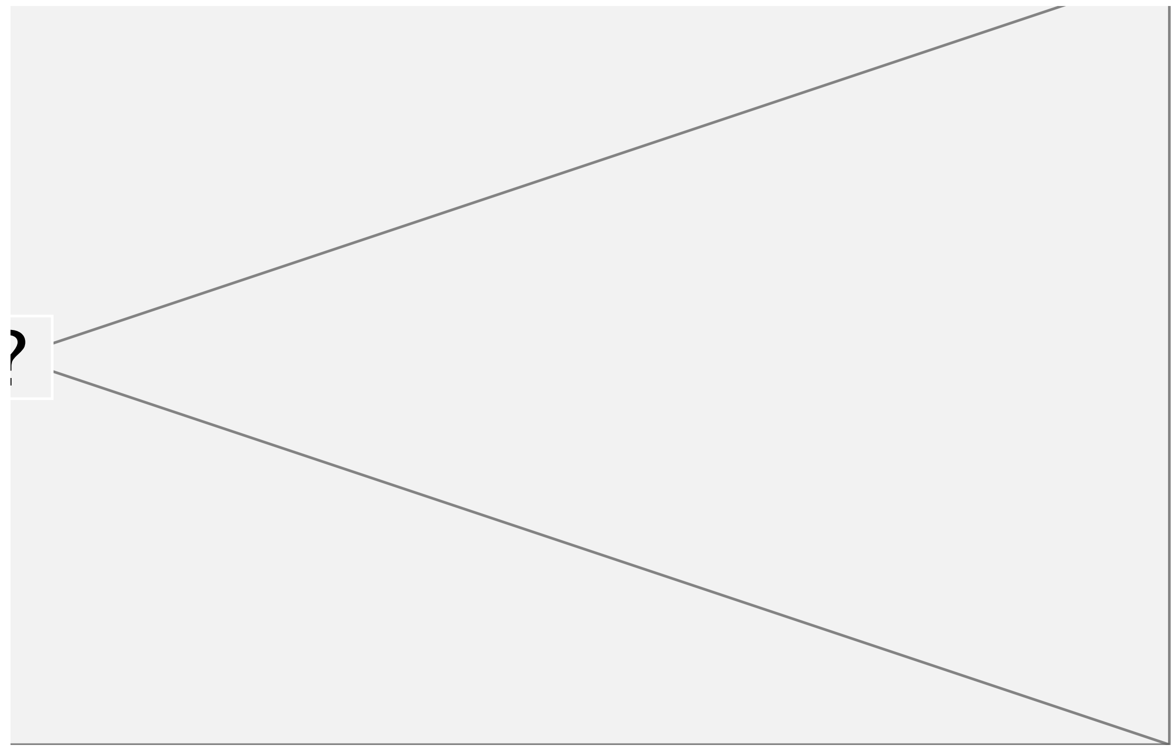
Large photon v_2 is difficult to explain with dominant QGP source

Another source of anisotropy?

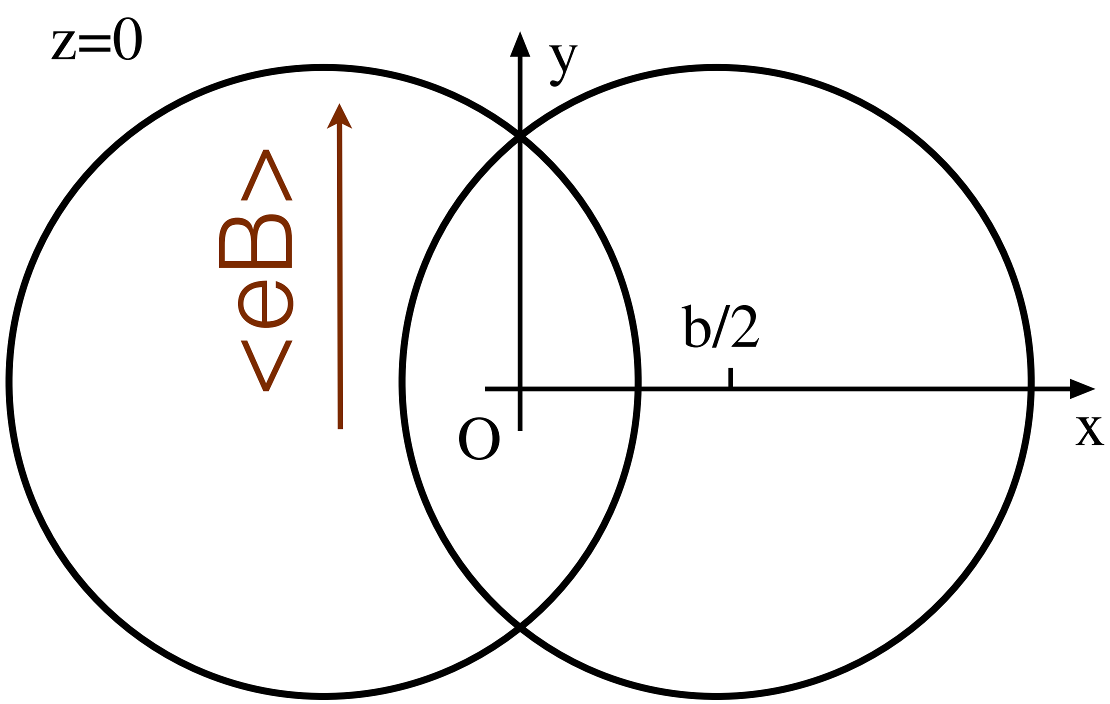
- anisotropy $\neq$ flow!
- other sources for anisotropy not related to flow?!
- magnetic field?! Perfect candidate for anisotropic photon production.

Magnetic field in HIC I

- spectators form two currents

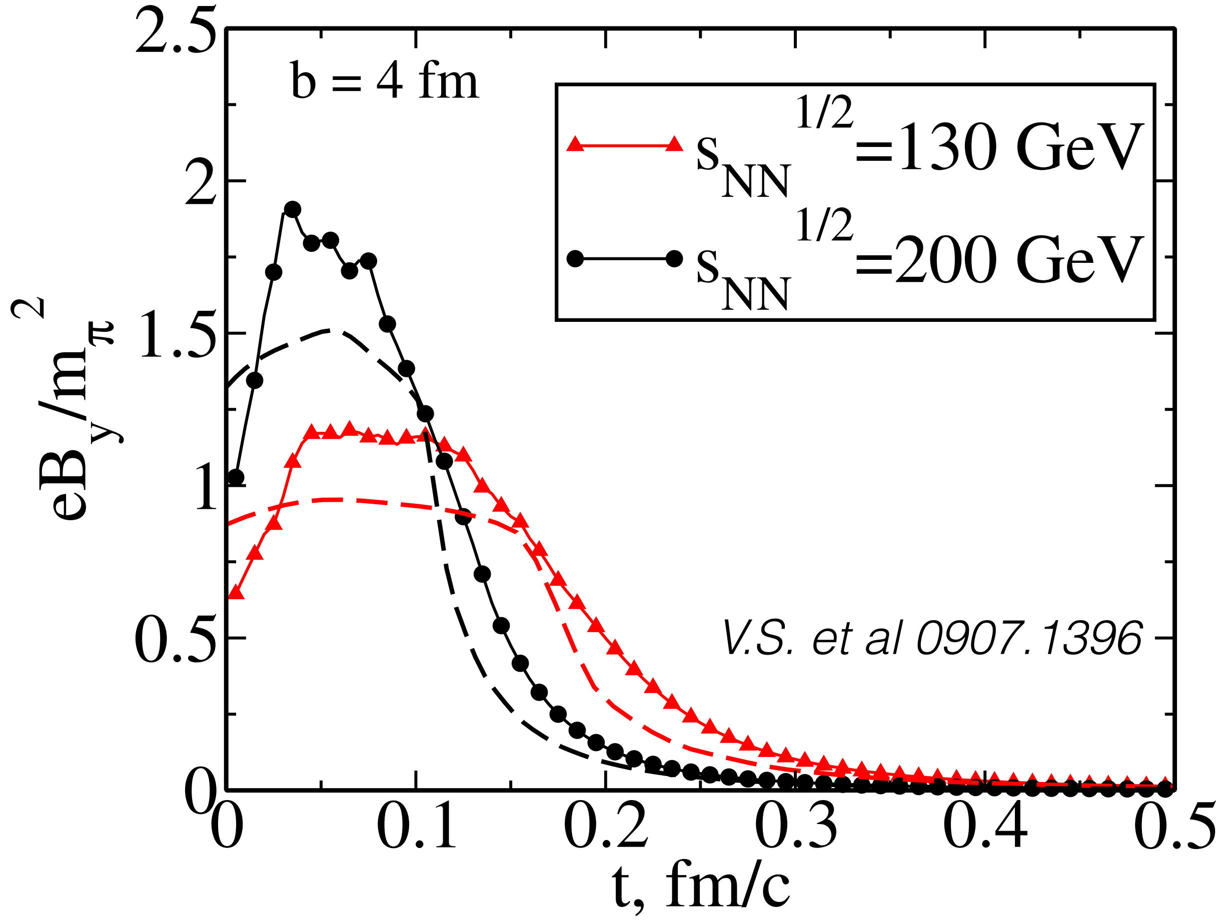


- resulting event average magnetic field
  $\langle eB_y \rangle \sim m_\pi^2$ (out-plane)
  $\langle eB_x \rangle \sim 0$ (in-plane)



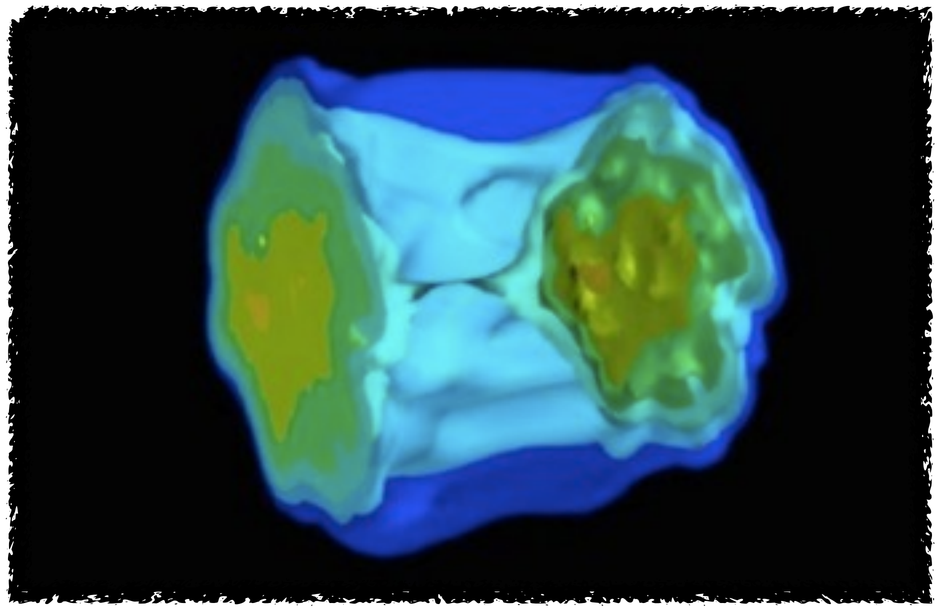
Magnetic field in HIC II

- maximal eB ~ √s
- maximum at t_M ~ 1/ √s
- life time t_{lt} ~ 1/ √s
- integral ~ const

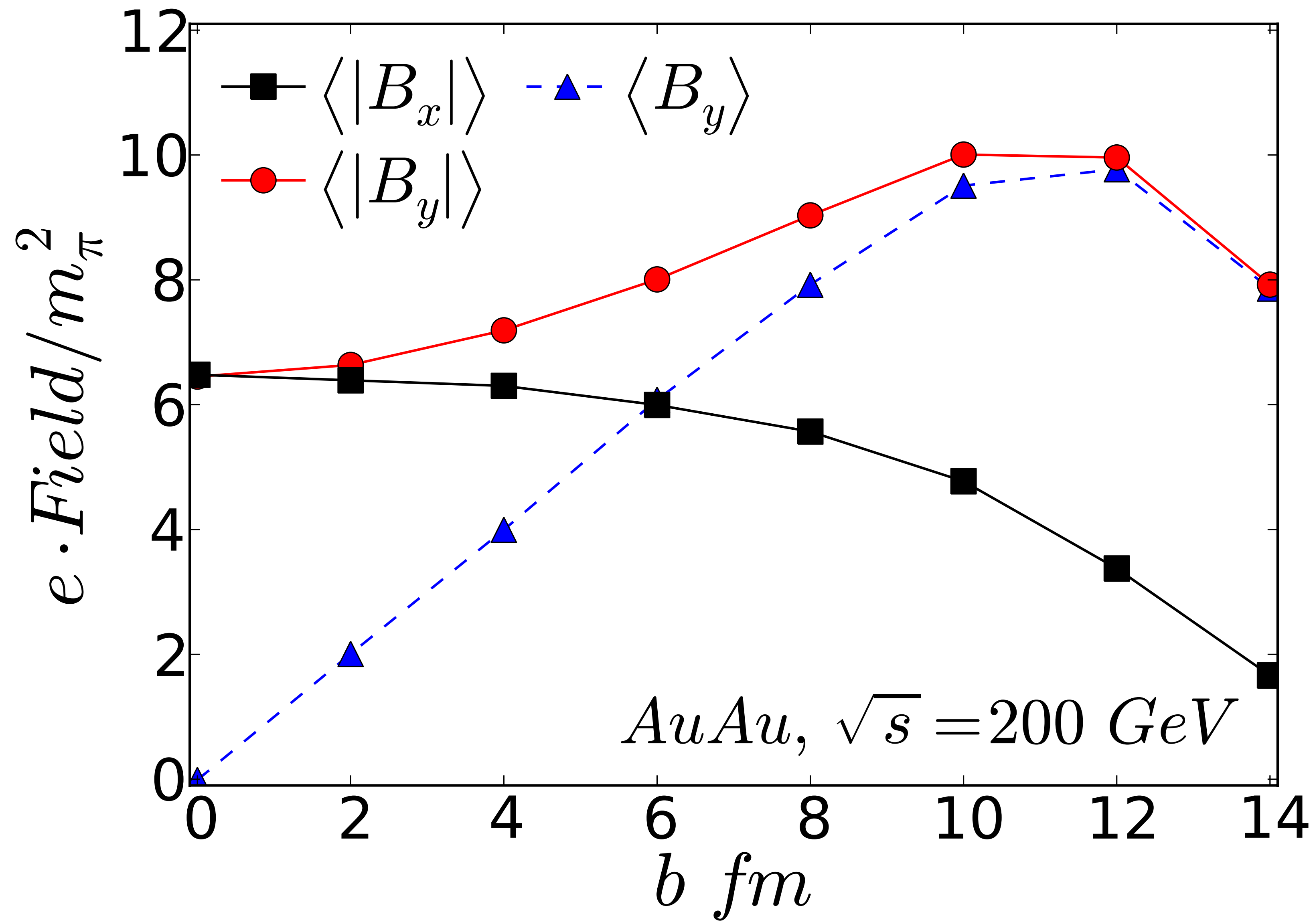


D. Kharzeev, L. McLerran,
H. Warringa, 0711.0950
V.S. et al, 0907.1396

Magnetic field in HIC III



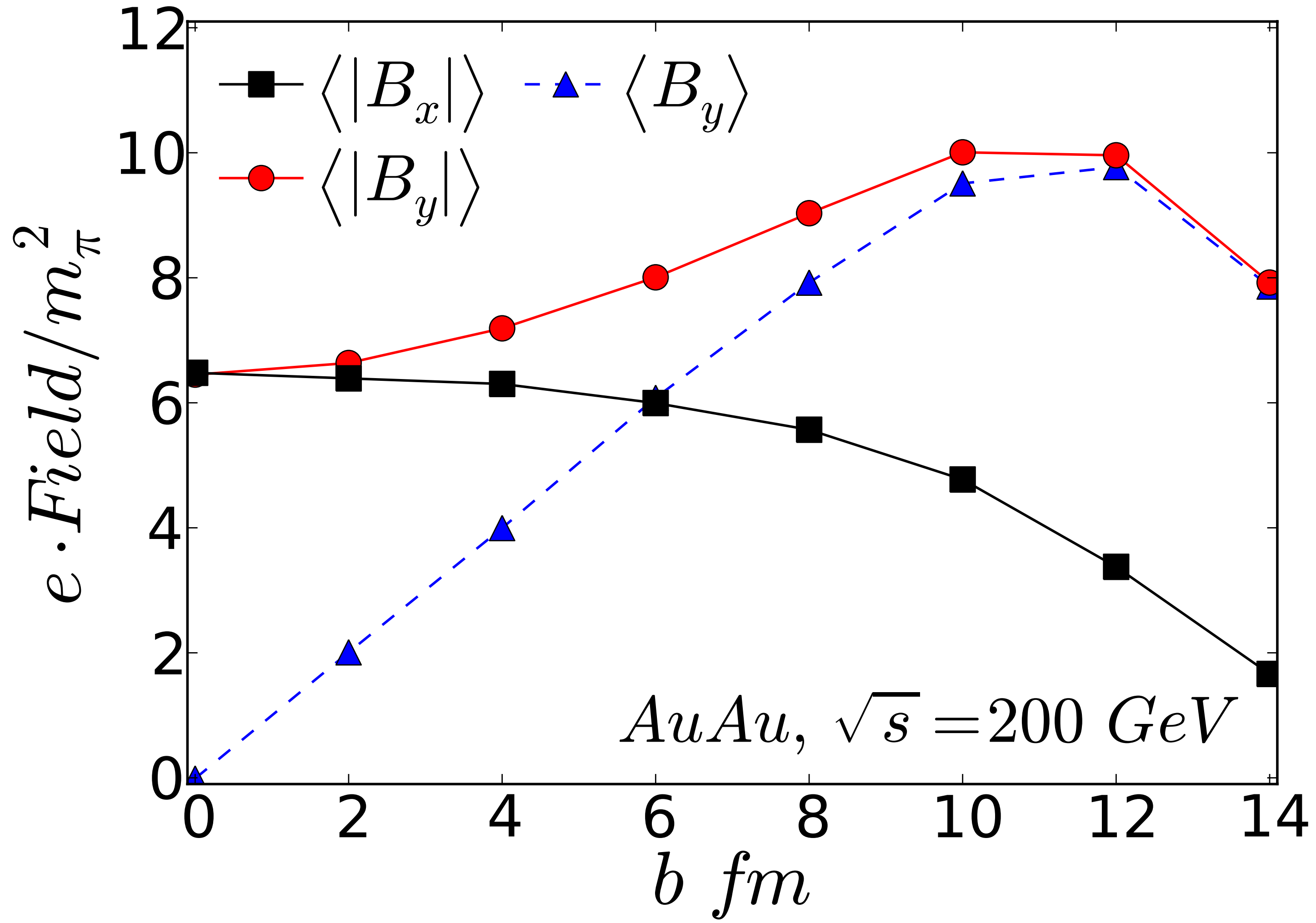
- fluctuations can play important role

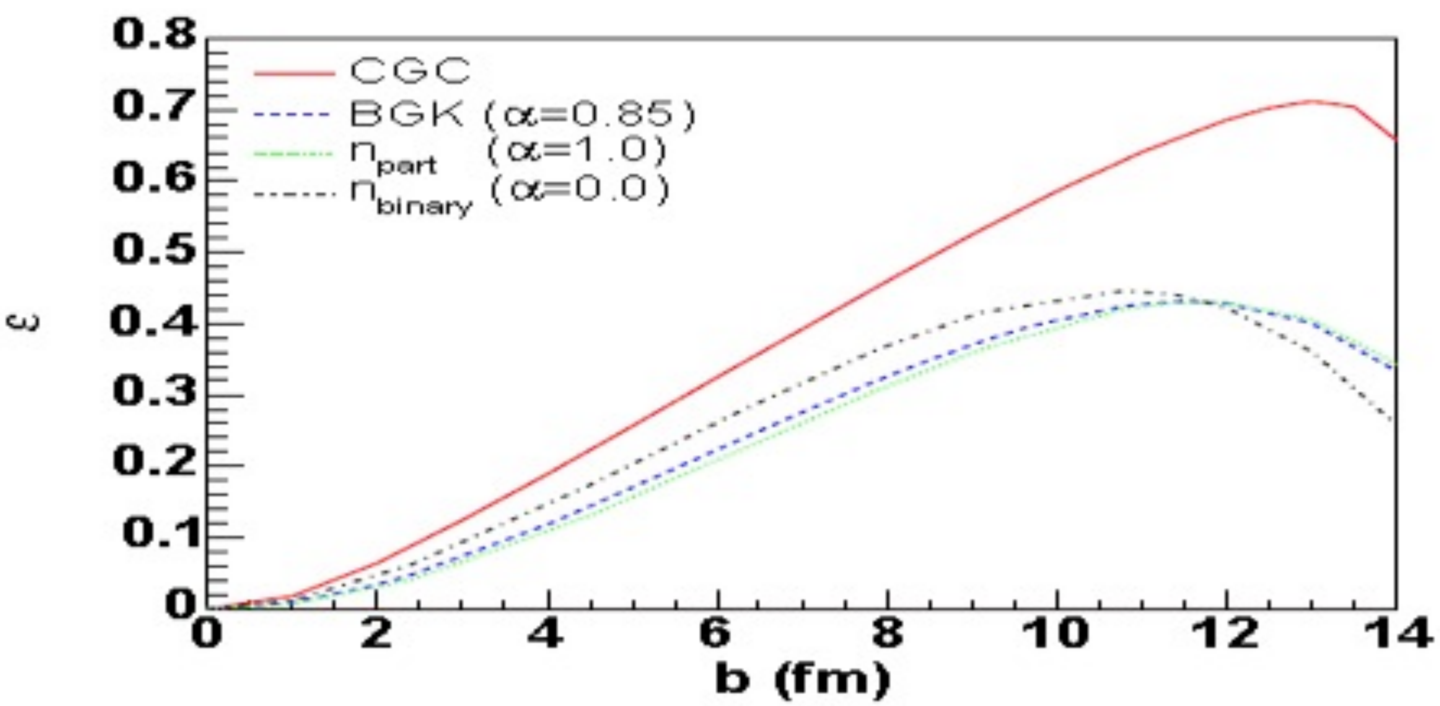


V.S. et al, 0907.1396;
A. Bzdak and V.S., 1111.1949

- lumpy distribution of electric charge in colliding nuclei results in nonzero randomly oriented magnetic field even in central collisions

Magnetic field in HIC IV





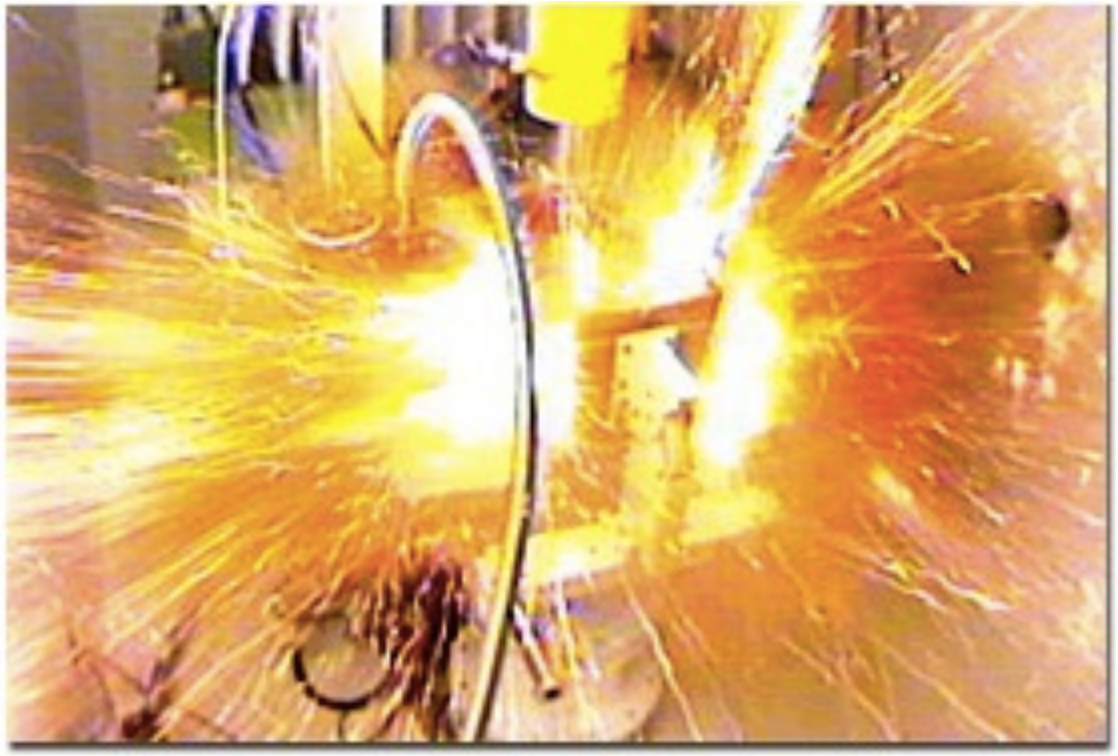
- $\langle eB_y \rangle$ is linear as a function of impact parameter
- this is common feature of $\langle eB \rangle$ and eccentricity $\boldsymbol{\varepsilon}_2$

Magnetic field in HIC V

eB in HIC compared to

- Hybrid magnet at
  National High Magnetic field Lab
  45 Tesla ~ $4.5\times10^{-13}\ m_\pi^2$

- Pulsed magnets:
  100 Tesla ~$10^{-12}\ m_\pi^2$



Watch an exploding pulsed magnet at work.

Vital Statistics

Strength	45 tesla
Type	Hybrid
Bore size	32 mm (~1.25 inches)
Online since	December 1999
Cost	$14.4 million
Weight	31,752 kg (35 tons)
Height	6.7 meters (22 feet)
Operating temperature	-271 ° C (-456 ° F)
Water used per minute	15,142 liters (4,000 gallons)
Power required	33 MW

Photo Credit: Larry Gordon

- Radio pulsars:
  10^{-6}-$10^{-5}\ m_\pi^2$

- Magnetars:
  10^{-4}-$10^{-3}\ m_\pi^2$

High eB... So what?

Effects, that can be potentially observed:

- modification of QCD phase diagram
  (not really, short lifetime of B)
- chiral magnetic effect
  (sphaleron transition rate?!)
- chiral magnetic wave
  (life time for magnetic field ~ 4 fm/c)
- Photon splitting, and many other in the next talk
- **photon production!**

Photon production from eB

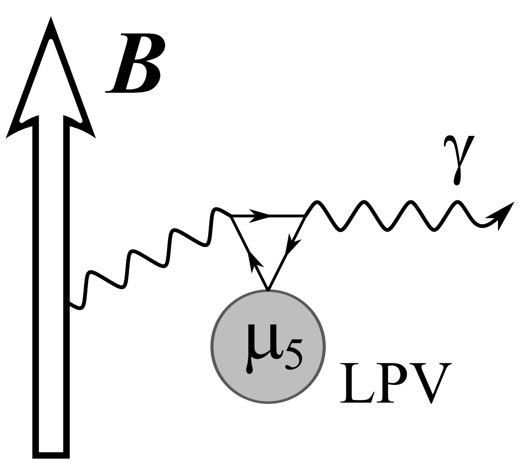
Several mechanisms:

- synchrotron radiation of quarks in eB (K. Tuchin)
  unknown: density and distribution function of quarks in early stage

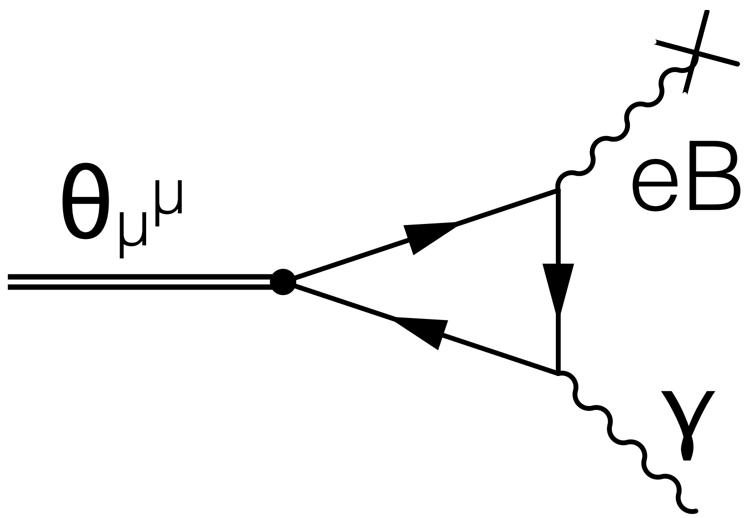
  R. Venugopalan and V.S. Quark production in Glasma

- axial anomaly (K. Fukushima)
  unknown: μ_5 and spectral function of $G\tilde{G}$

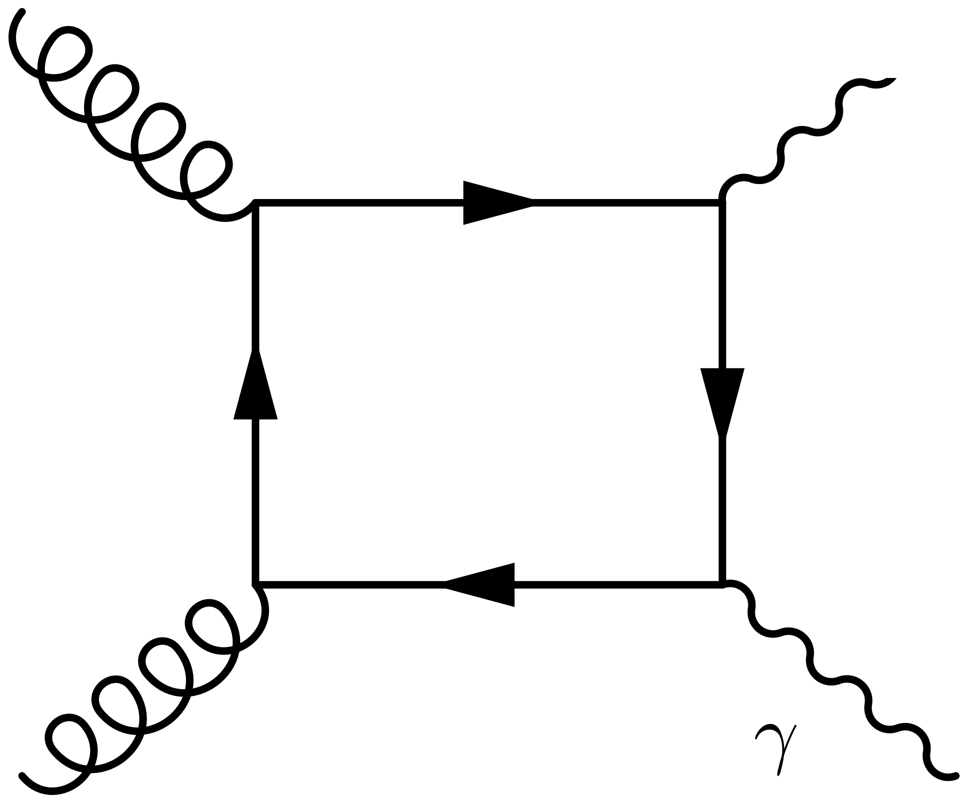
  G. Basar and D. Kharzeev



- **conformal anomaly**
  unknown?!: bulk viscosity



Simple explanation



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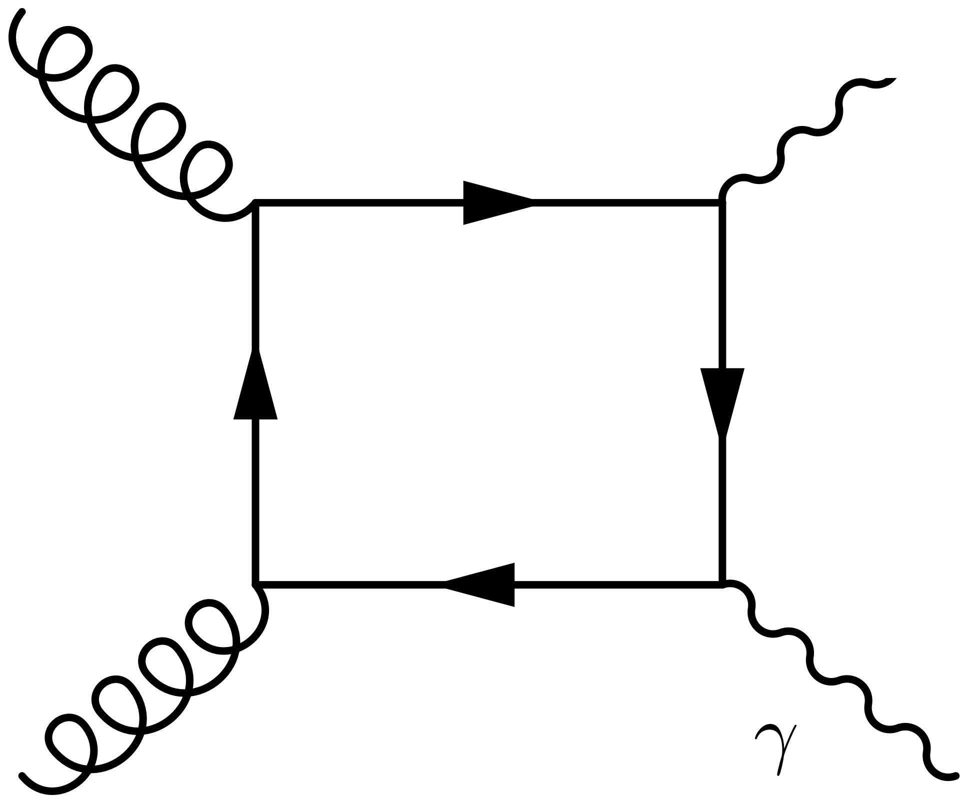
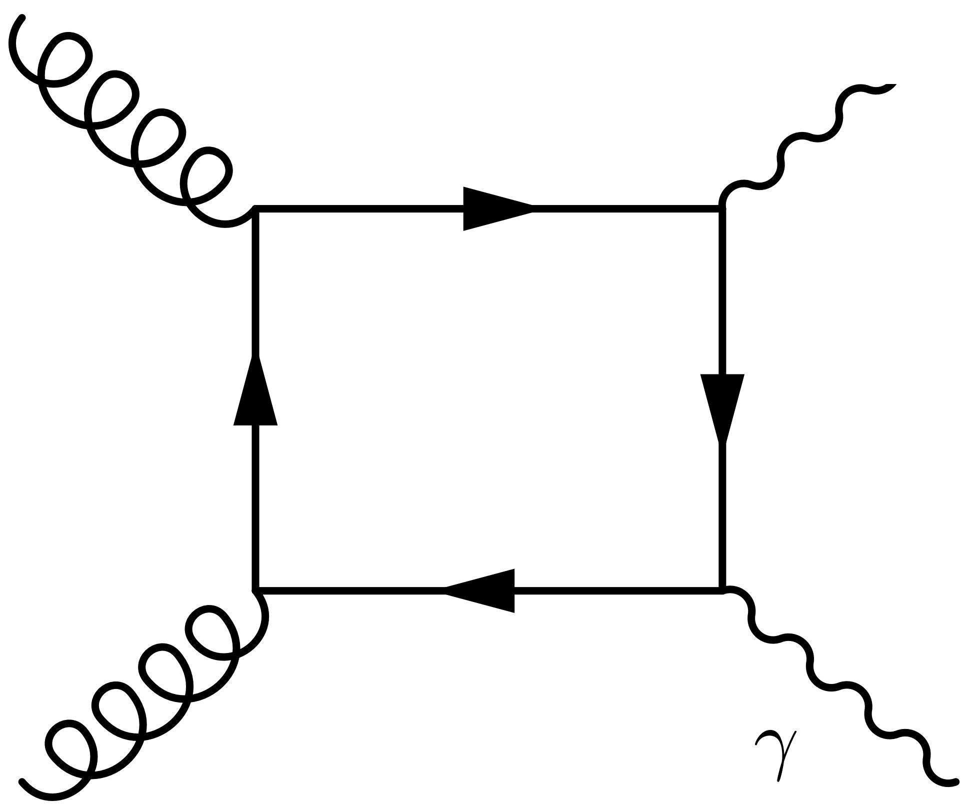
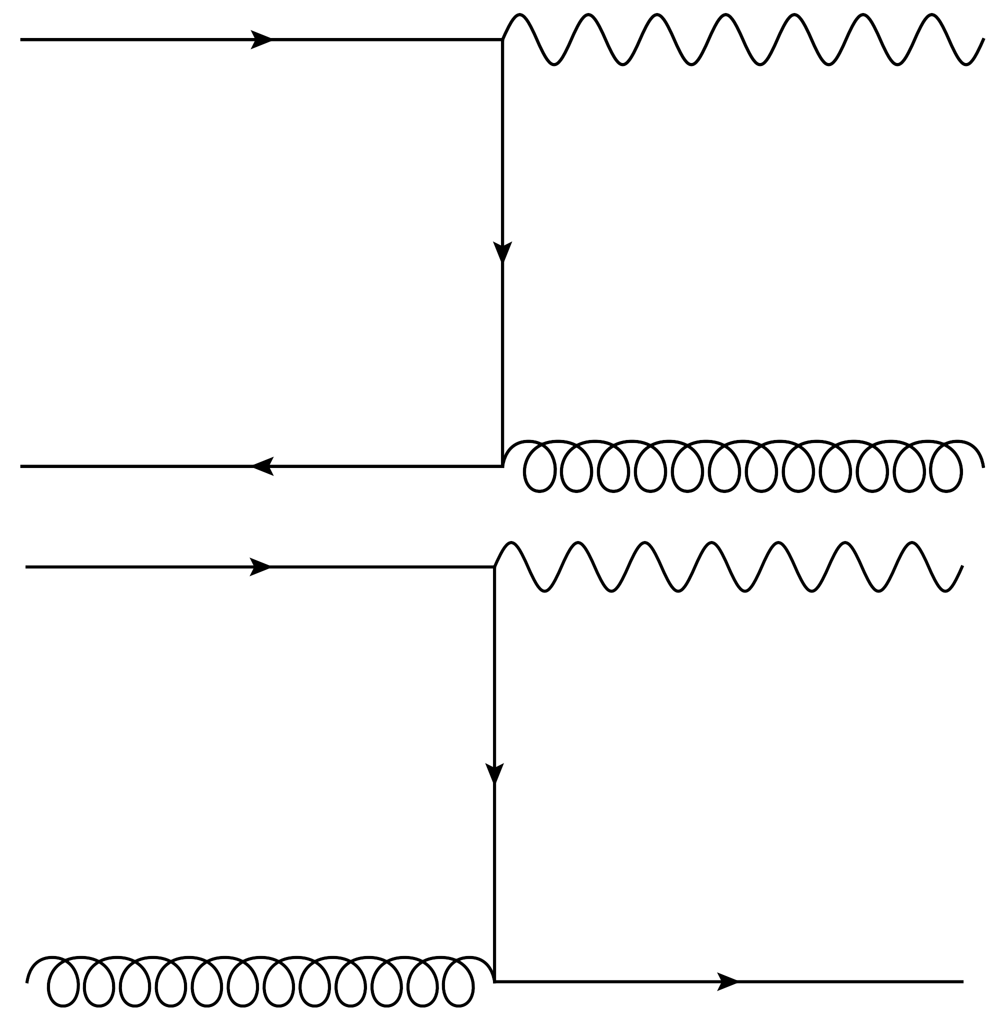


- Two photon production: $\alpha_s \alpha\ G^2 F^2$, $F^2 = F_{\mu\nu}F^{\mu\nu}$
  thus rate ~ α^2

- Replace one photon with eB
  rate ~ α

Simple explanation





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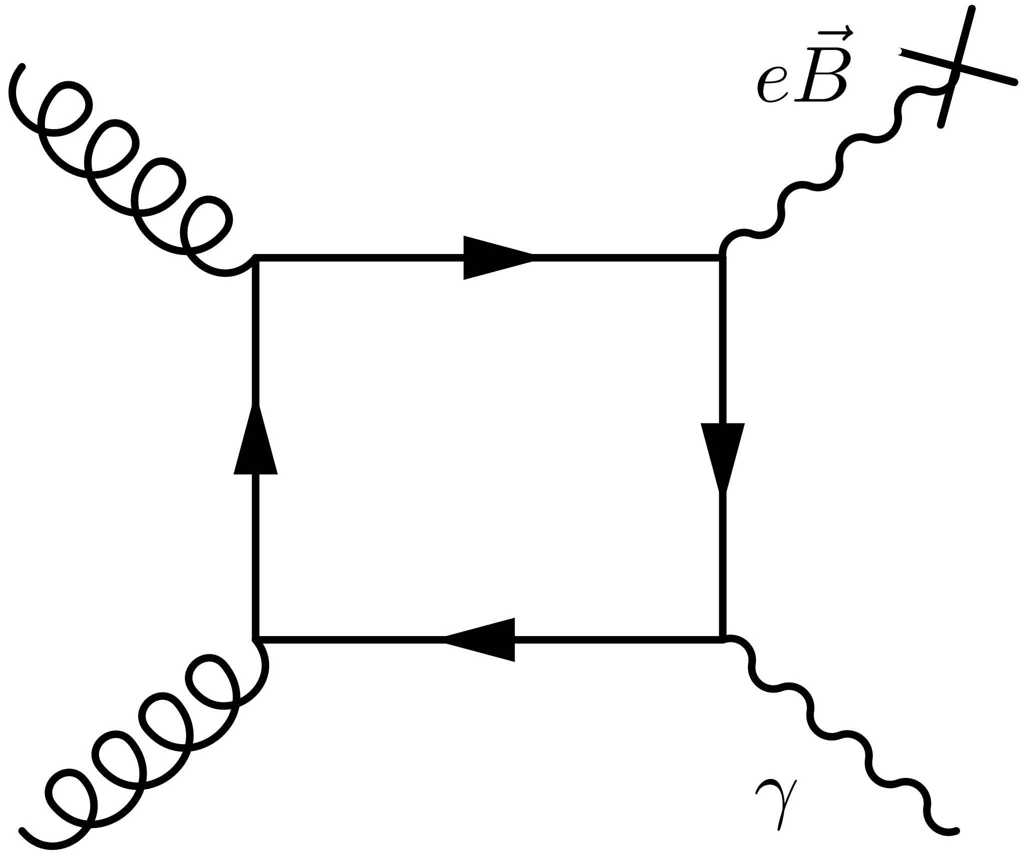

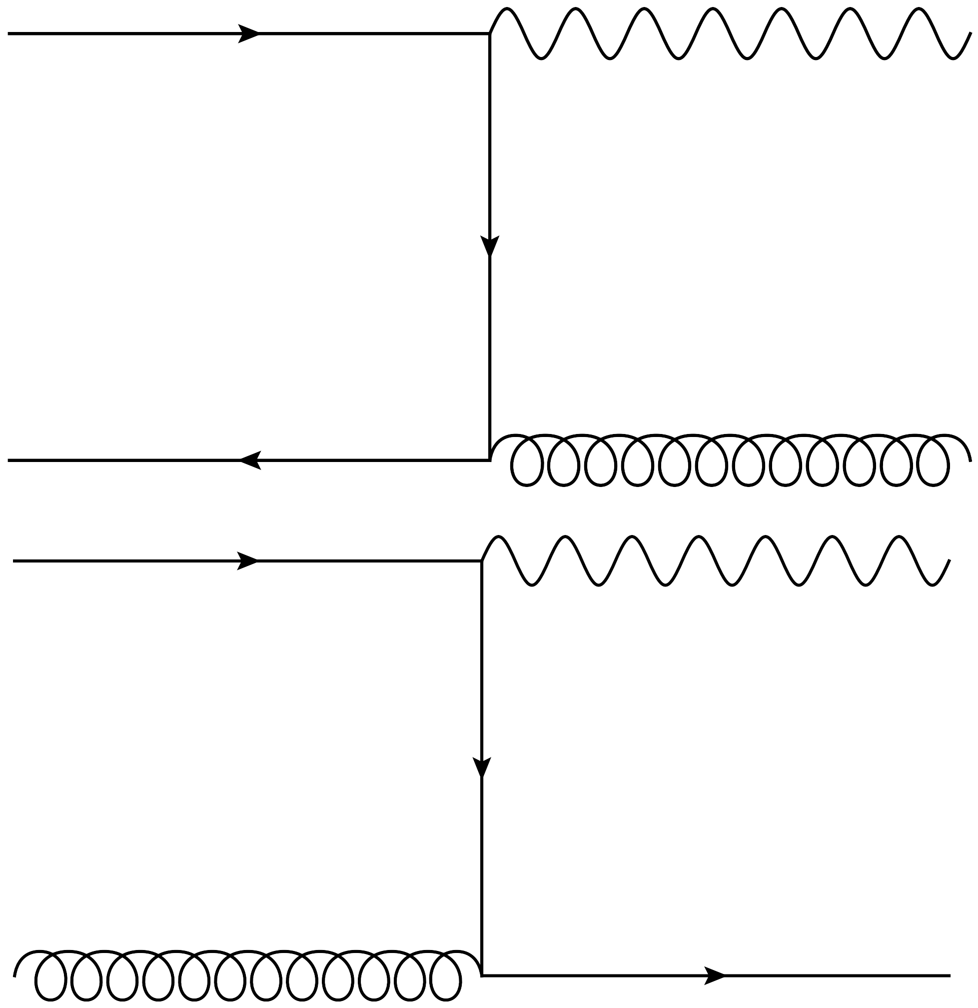

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Conformal anomaly

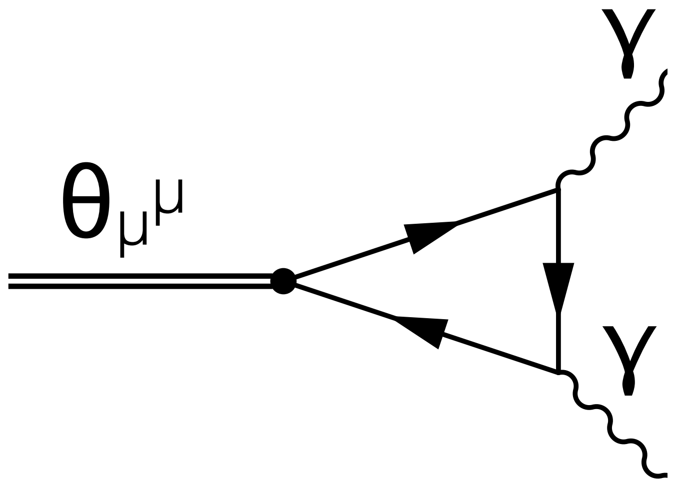
- divergence of dilatation current

$$\partial^\mu S_\mu = \theta^\mu_\mu = \frac{\beta(g)}{2g} G^{\mu\nu a} G_{\mu\nu a} + \sum_q m_q \left[1 + \gamma_m(g)\right] \bar{q} q$$

- color singlet states **$\sigma \sim \theta_\mu^\mu$** *Migdal, Shifman*

$$\langle 0|S^\mu|\sigma\rangle = i q^\mu f_\sigma; \quad \langle 0|\partial_\mu S^\mu|\sigma\rangle = m_\sigma^2 \, f_\sigma$$

- effective Lagrangian

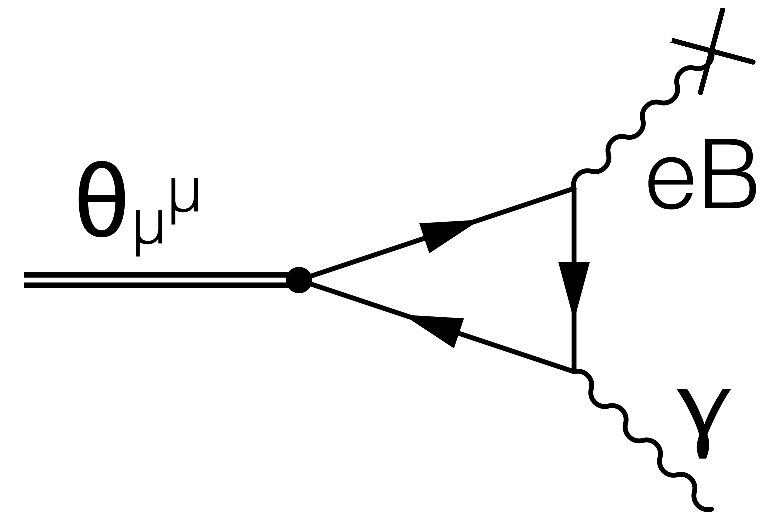


$$\mathcal{L}_{\sigma\gamma\gamma} = g_{\sigma\gamma\gamma} \, \sigma \, F_{\mu\nu} F^{\mu\nu}$$

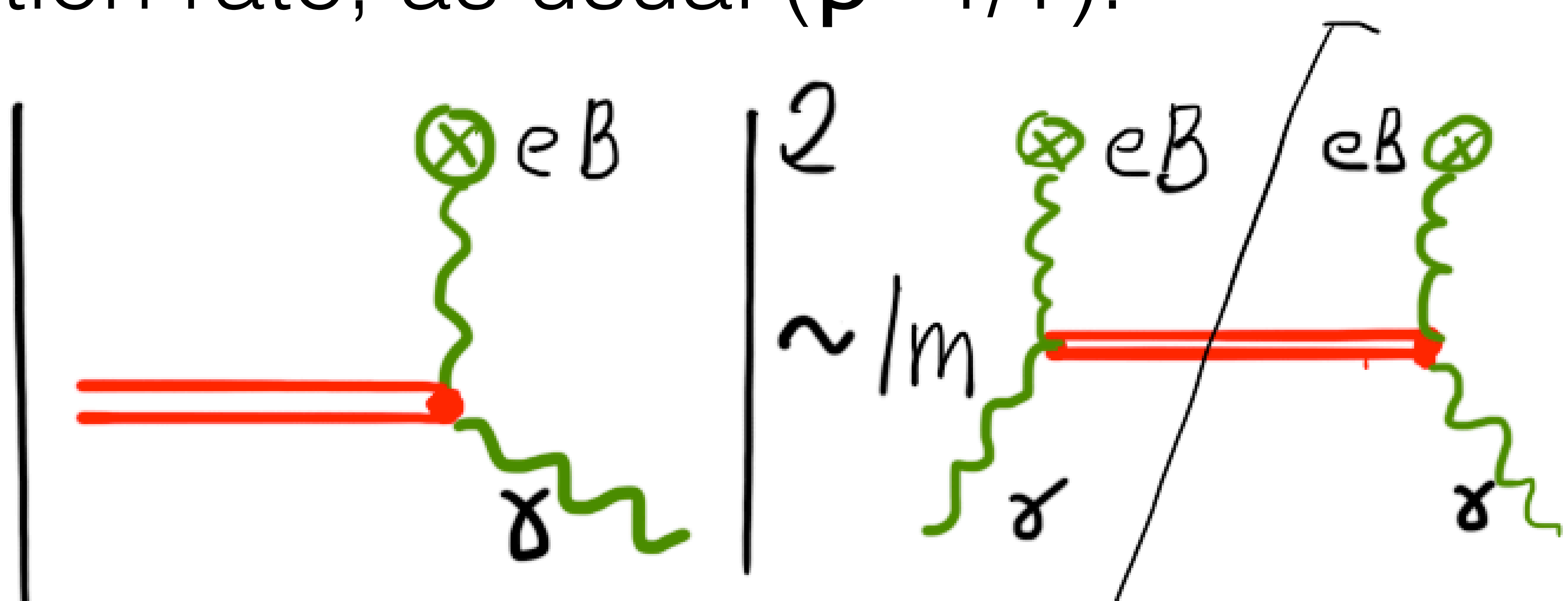
- $g_{\sigma\gamma\gamma} \cong 0.02 \text{ GeV}^{-1}$ *Ellis and Lanik; Crewther; Chanowitz*

Photon production rate

- one of the photons: classical field eB



- production rate, as usual (β=1/T):



$$q_0 \frac{d\Gamma_B}{d^3q} = 2 \left(\frac{g_{\sigma\gamma\gamma}}{\pi f_\sigma m_\sigma^2} \right)^2 \times \frac{(B_y^2 - B_x^2) q_x^2 + q_\perp^2 B_x^2}{\exp(\beta q_0) - 1} \rho_\theta(q_0 = |\vec{q}|).$$

Final answer

$$q_0 \frac{d\Gamma_B}{d^3q} = 2\left(\frac{g_{\sigma\gamma\gamma}}{\pi f_\sigma m_\sigma^2}\right)^2 \times \frac{(B_y^2 - B_x^2)q_x^2 + q_\perp^2 B_x^2}{\exp(\beta q_0) - 1} \rho_\theta(q_0 = |\vec{q}|).$$

Numerical coefficient; constrained by hadronic observables

Momentum dependence; β=1/T; if e-b-e fluc. of magnetic field are neglected:

$$\frac{B_y^2 q_x^2}{\exp(\beta q_0) - 1}$$

Spectral function for G^2, or trace of energy momentum tensor

Spectral function of $\theta_\mu{}^\mu$

- hydrodynamic approximation

$$\rho_\theta(q_0,\vec{q}) = \frac{1}{\pi}\mathcal{I}m[G_R^{\mu\mu,\nu\nu}(q_0,\vec{q})] = 9q_0\frac{\zeta}{\pi} + \frac{9}{\pi}(\epsilon+p)\left(\frac{1}{3}-c_s^2\right)^2 \frac{q_0\Gamma_s\,\vec{q}^4}{(q_0^2-c_s^2\,\vec{q}^2)^2+(q_0\Gamma_s\vec{q}^2)^2}$$

bulk viscosity

sound peak

- real photons, sound peak does not contribute:

$$\rho_\theta(q_0,\vec{q}) \approx 9q_0\frac{\zeta}{\pi}$$

$G\tilde{G}$

- Similar calculations can be done for $F\tilde{F}$ $G\tilde{G}$
- Spectral function $G\tilde{G}$ in hydro approximation is defined by sphaleron transition rate and was calculated in pQCD and AdS/CFT.

Bulk viscosity

- first principle Lattice QCD:
  H. Meyer SU(3) Yang Mills (YM)
  However, there are issues.

- approximations:

  $\zeta = C_\zeta\, \eta\, (1/3 - c_s^2)^2$ (vs ADS/QCD $\zeta \geqq 2\, \eta\, (1/3 - c_s^2)$)

  C_ζ = 15 in relaxation time appr. (S. Weinberg '71)
  C_ζ = 45 in NLO SU(3) YM (K. Dusling and T. Schafer '11)
  C_ζ = 2.5-5 phenomenological constraints
  in this talk: conservative C_ζ = 2.5-5

- also conservative $\eta/s = 1/(4\pi)$. Entropy, s, from matrix model fitted to YM SU(3) (R. Pisarski)

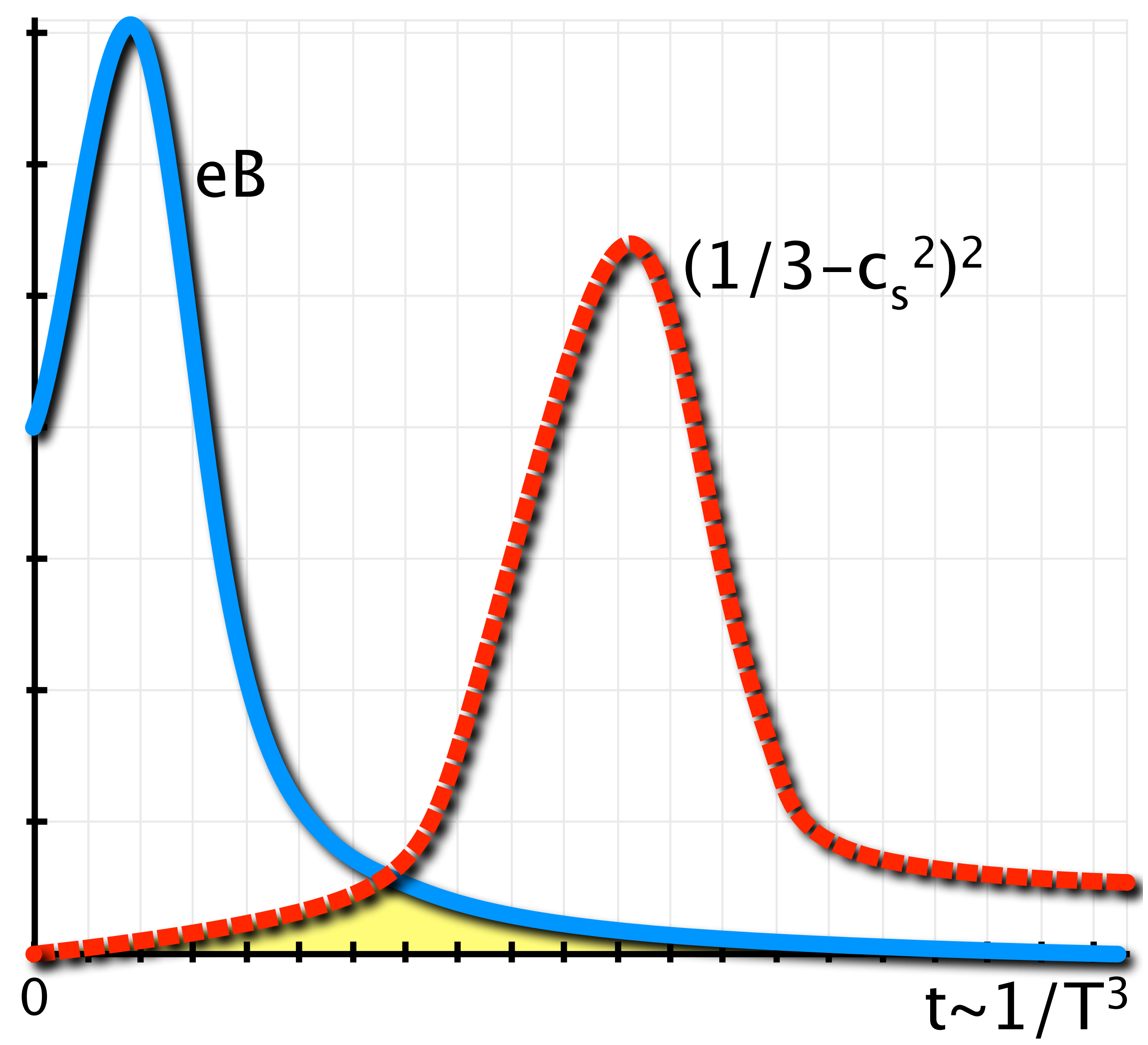
So one would expect...

$$q_0 \frac{d\Gamma_B}{d^3q} = 2\left(\frac{g_{\sigma\gamma\gamma}}{\pi f_\sigma m_\sigma^2}\right)^2 \times \frac{(B_y^2 - B_x^2)q_x^2 + q_\perp^2 B_x^2}{\exp(\beta q_0) - 1}\rho_\theta(q_0 = |\vec{q}|).$$

$$\rho_\theta(q_0, \vec{q}) \approx 9 q_0 \frac{\zeta}{\pi}$$

$\zeta = C_\zeta\, \eta\, (1/3 - c_s^2)^2$

- negligible contribution from this mechanism?! eB is non-zero at early stage where $(1/3\text{-}c_s^2)^2$ is small



However

- rate is proportional to $(1\text{-}c_s^2)^2\ T^3\ (eB)^2$

  rough estimate at early stage

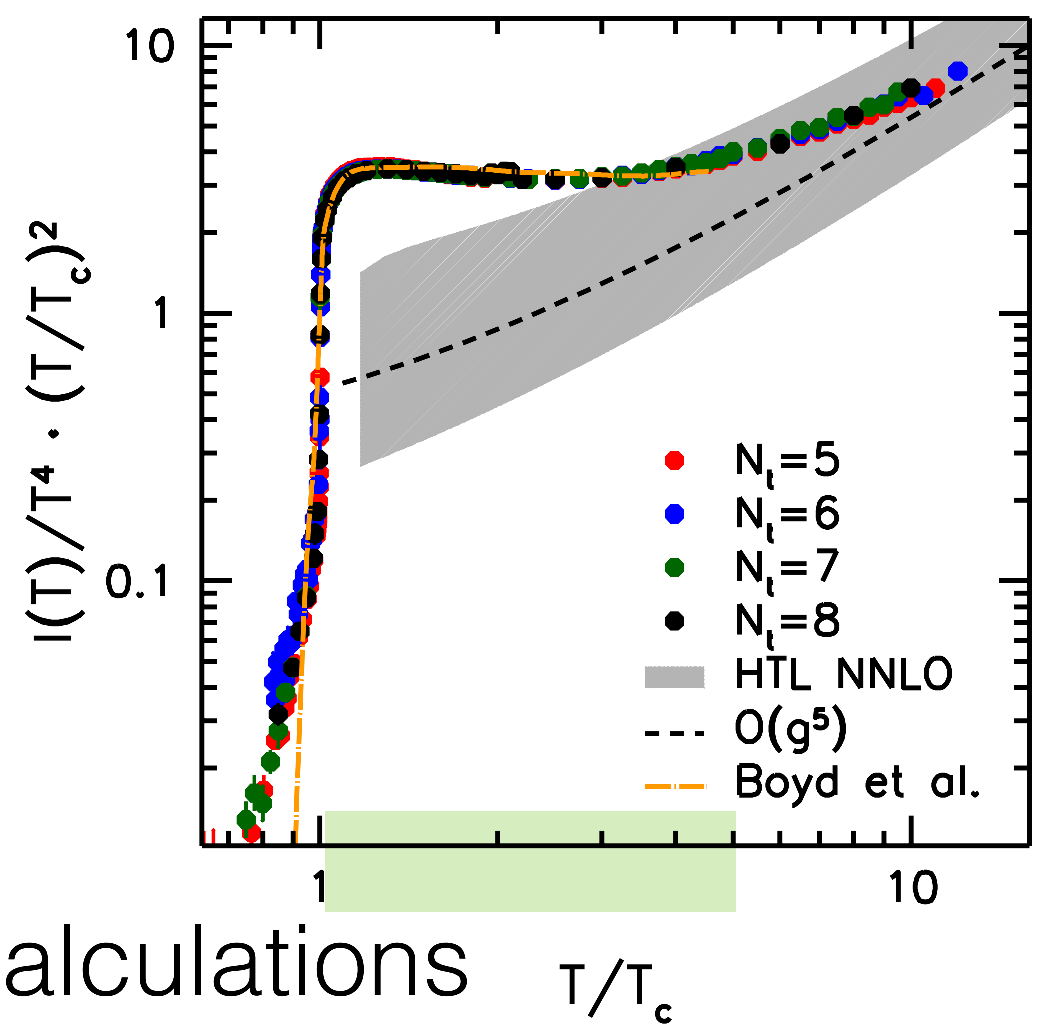
  $(1\text{-}c_s^2) \sim (\varepsilon\text{-}3p)/T^4 \sim$ (from LQCD) $\sim$ **1 / T^2** (talks by R. Pisarski)

  $(1\text{-}c_s^2)^2\ T^3 \sim$ **1 / T** $\sim$ (Bjorken expansion) $\sim t^{1/3}$

  while $eB \sim 1/(t^2+\text{const})$

stringy?
fuzzy bag?
quasiparticles?
monopoles?

$I = \varepsilon\text{-}3p$



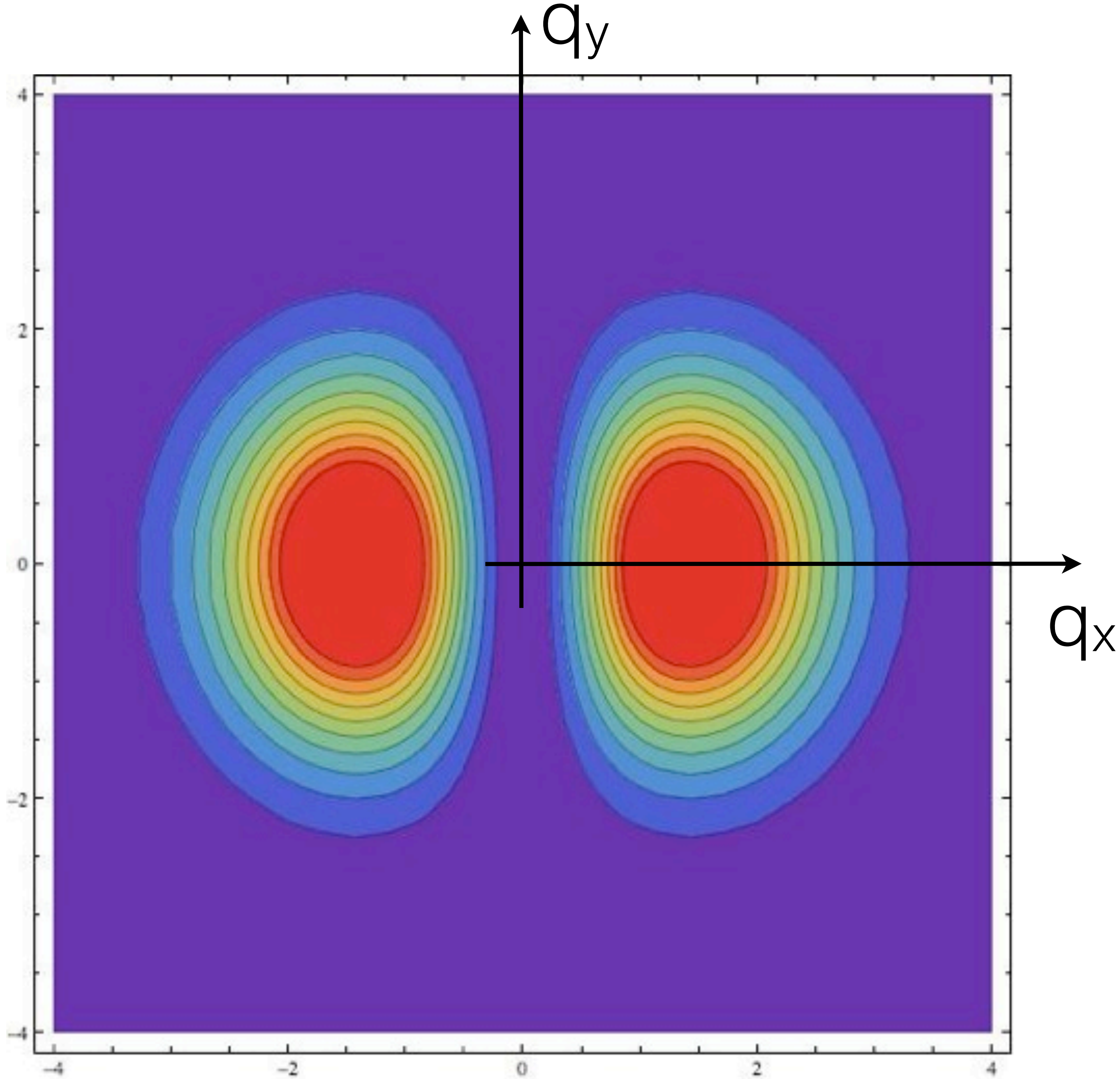
Sz. Borsanyi et at, 1204.6184

- rigorous answer: numerical calculations

Anisotropy of production rate

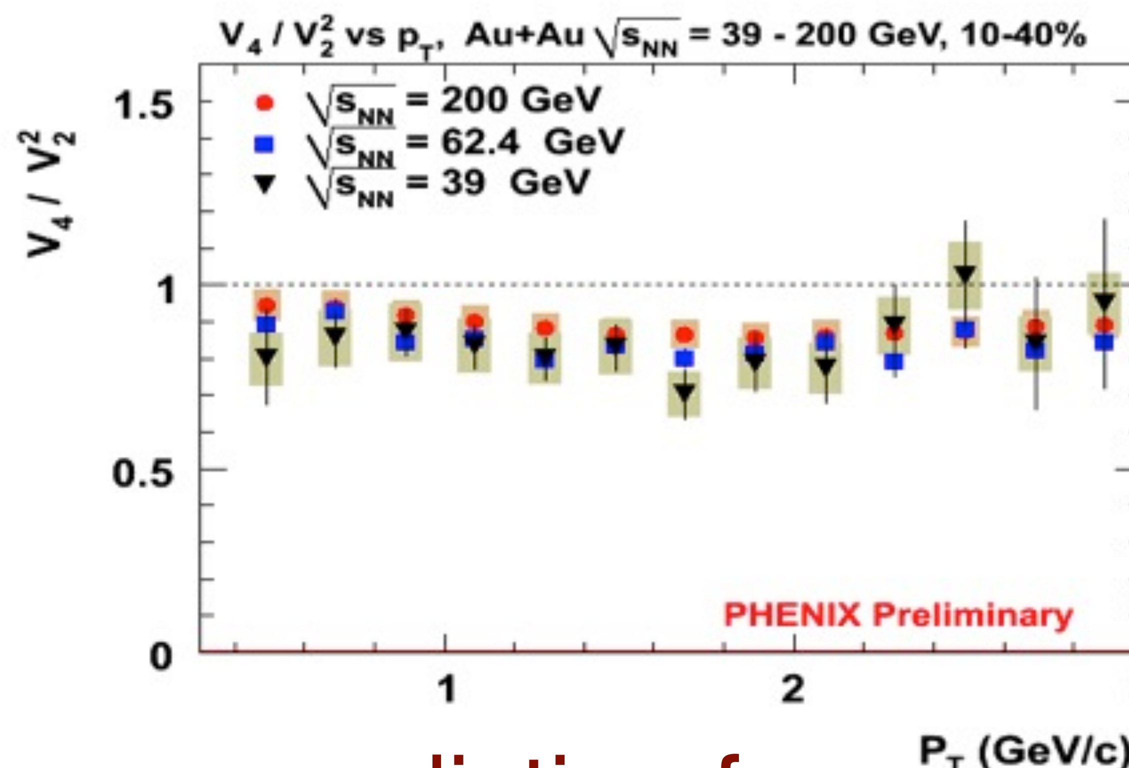
- in this mechanism:

$$dN/d\varphi \sim q_x^2 = q_T^2 \cos^2(\varphi) = q_T^2\,[1+\cos(2\varphi)]/2$$



consequently:

- non-zero v_2
- small v^{γ}_n, n=4,...
  in contrast to hadronic v_4
  PHENIX: $v_4/v_2^2 \sim 1$



our prediction for photons: $v_4/v_2^2 \ll 1$

Numerical calculations: v_2

- ingredients: thermal photons and photons from conformal anomaly +eB

- significant contribution to v_2

- higher $p_\perp$: prompt photons

G. Basar, D. Kharzeev, V.S., arXiv:1206.1334

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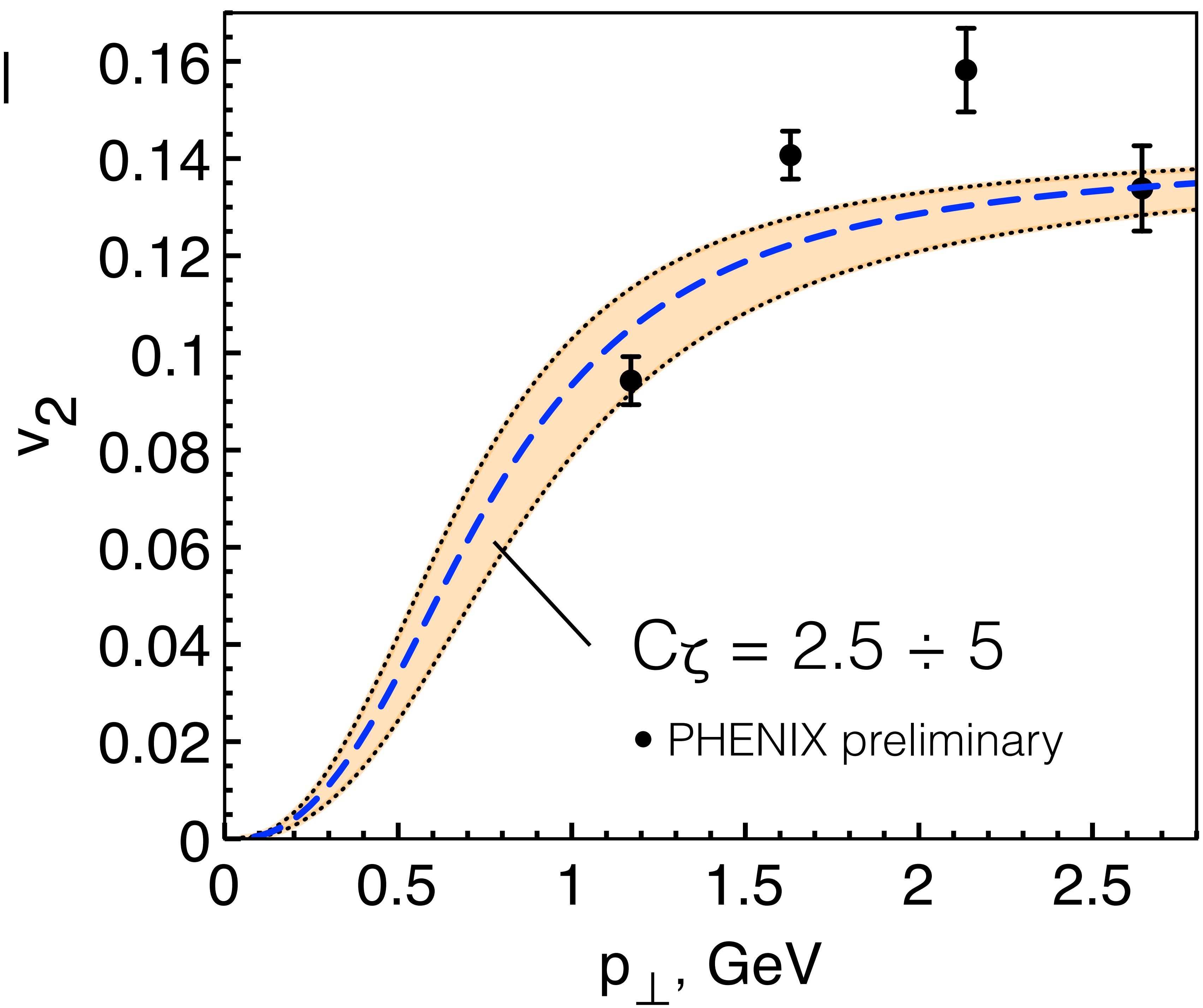

G. Basar, D. Kharzeev, V.S., arXiv:1206.1334

Other parameters

- initial temperature T = 400 MeV
- initial time τ=0.1 fm/c (no need for complete equilibrium, is to be discussed later)
- Bjorken expansion for T
- electromagnetic field from spectators only (with fluctuations taken into account). Possible induced magnetic field will only enhance production via this mechanism

Transverse momentum spectra

- conformal anomaly:
  $dN/dp_\perp \sim$ $\mathbf{p_\perp^2}$$/ [\exp(p_0/T)-1]$
  similar to effect of direct flow

- higher than thermal photons for $p_\perp > 1$ GeV

- higher $p_\perp$: prompt photons

G. Basar, D. Kharzeev, V.S., arXiv:1206.1334

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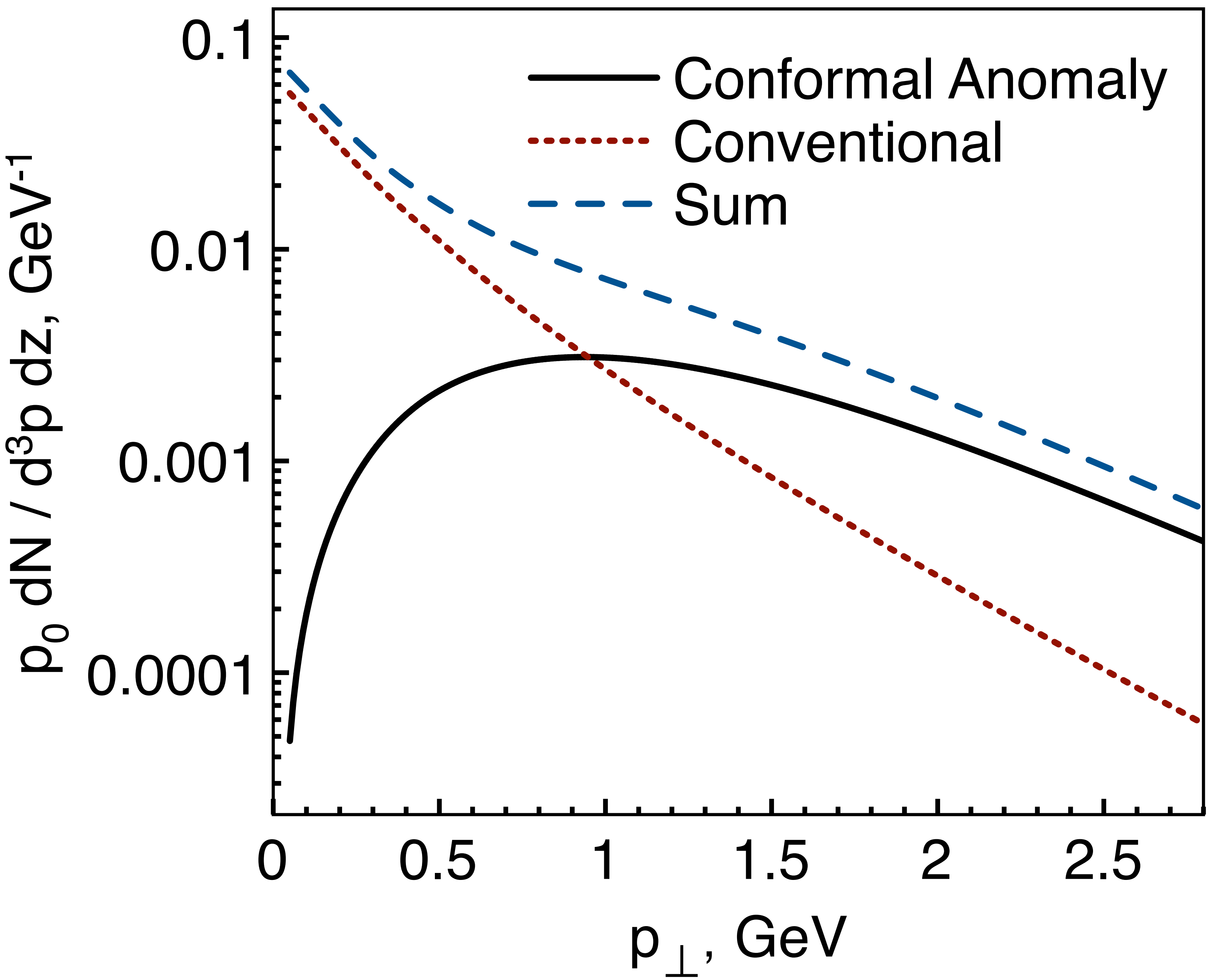


G. Basar, D. Kharzeev, V.S., arXiv:1206.1334

Experimental tests I

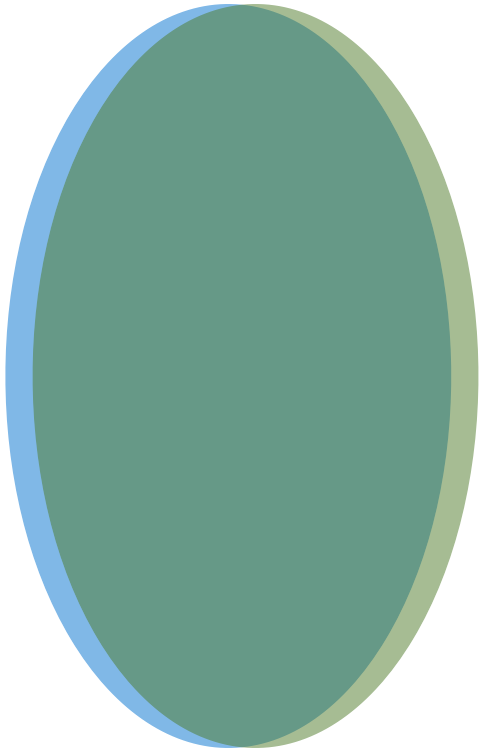
- **1) magnetic field B** is generated mostly by spectators
  thus, B is defined by centrality (measured by ZDC),
  reaction plane

  2) hadronic flow: initial eccentricity ε
  ε depends on details of hadron
  interaction (Glauber fluctuations,
  fluctuations of energy deposition);
  participant plane

- so switch off either **1)** or **2)**

Switching of B

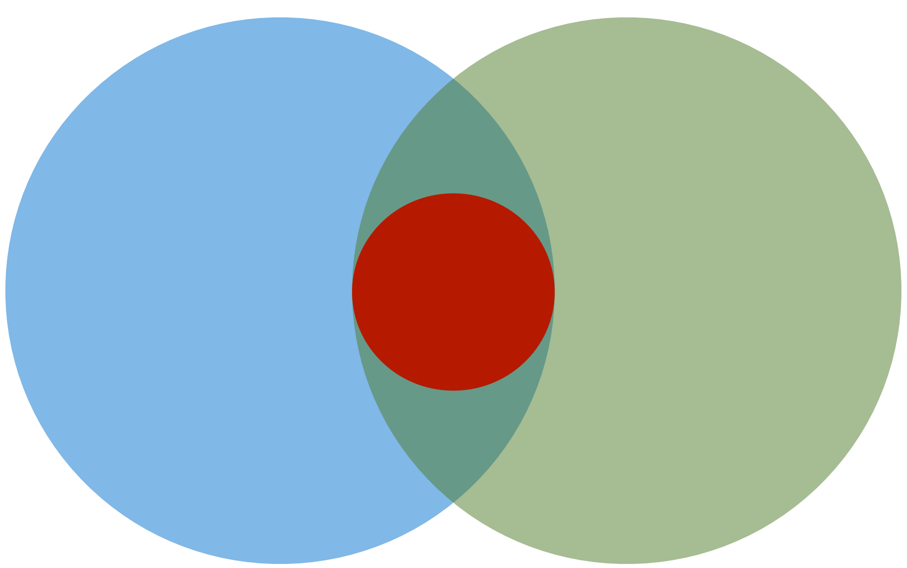
- central U+U collisions
  U is deformed ion:
  events with (almost) no particles in ZDC: **B=0**, **ε≠0**;
  if photon v_2 is the same as the one of hadrons,
  our mechanism is ruled out



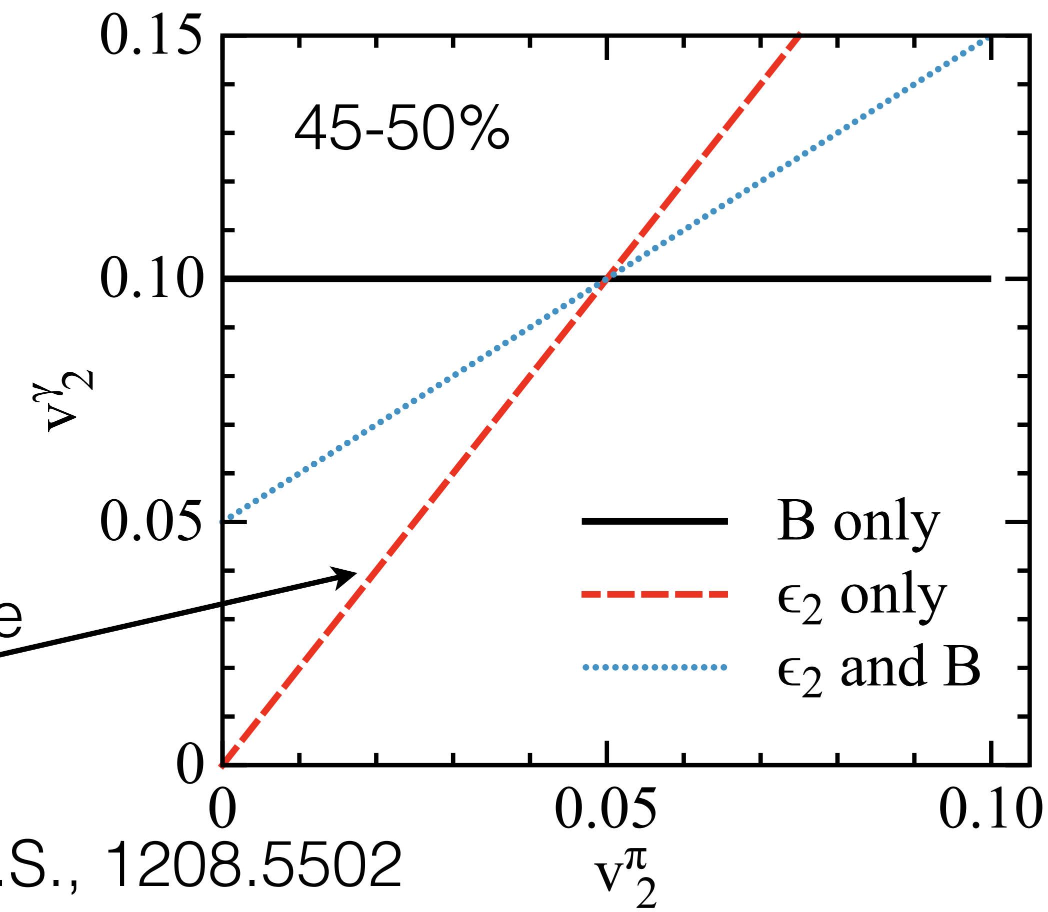
Switching of ε

- non-central collisions: fluctuations of eccentricity

  in given centrality class (e.g. 45-50% defined by ZDC), **B = const**; while hadronic v_2 fluctuates because of initial eccentricity fluctuations.
  Limiting case:
  non-central collisions (→ eB≠0) with zero **v_2**.
  thus in such events anisotropy of photon production is due to eB.



Our mechanism will be ruled out, if



A. Bzdak and V.S., 1208.5502

Experimental tests II

- small v_4; violation of scaling $v_4 \sim v_2^2$
- number of photons $N_{in\text{-}plane} > N_{out\text{-}plane}$
  $(N_{in\text{-}plane} - N_{out\text{-}plane}) \sim eB^2$ and thus is quadratic function of impact parameter
- in-plane polarization of photons

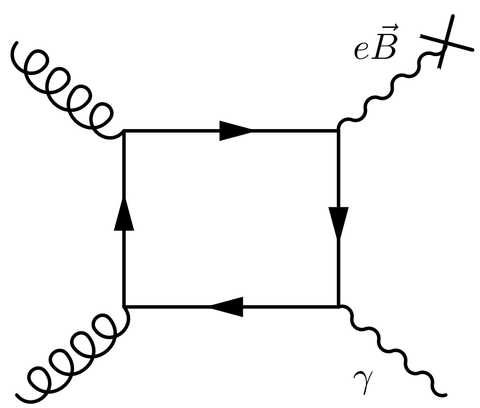
Outlook:LHC energies

- Higher initial temperatures → lower bulk viscosity
  T_{ave} = 304 MeV

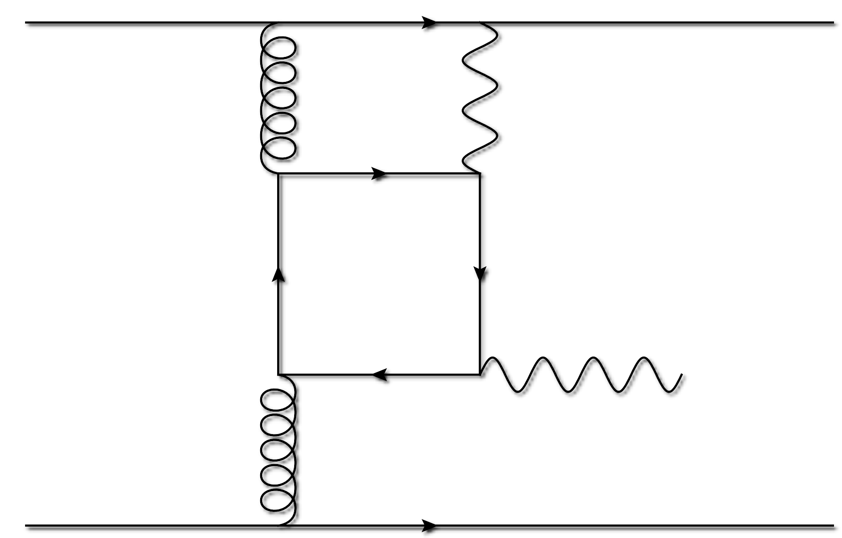
- Large γ → short time scales for non-zero magnetic field (modulo plasma response)
  $t_{LHC} = t_{RHIC}\, \gamma_{RHIC} / \gamma_{LHC} \rightarrow t_{LHC} \propto 0.01$ fm/c vs $t_{RHIC} \propto 0.1$ fm/c

- LHC data can be described by:
  $T^{init}_{LHC} / T^{init}_{RHIC} = Q^{sat}_{LHC} / Q^{sat}_{RHIC}$ and $\tau_0^{LHC} / \tau_0^{RHIC} = Q^{sat}_{RHIC} / Q^{sat}_{LHC}$

- No need for equilibrium
  - production from Glasma:



  - production from CGC:



Outlook:RHIC low energy scan

- lower energies -> lower eB, but longer time scales
- in equilibrium: bulk viscosity, ζ, is divergent at critical point (CP)
- in reality (HIC): at CP $\zeta \sim \xi^{2.8}$, ξ is correlation length
- on O(4) line: $\zeta \sim \xi^2$ (while shear viscosity is finite)
  see *E. Nakano, V.S. and B. Friman, arXiv:1109.6822*
- rather speculative: small eB can compensate large ζ

MAGNETO-HYDRO

Summary

- photon v_2 puzzle:

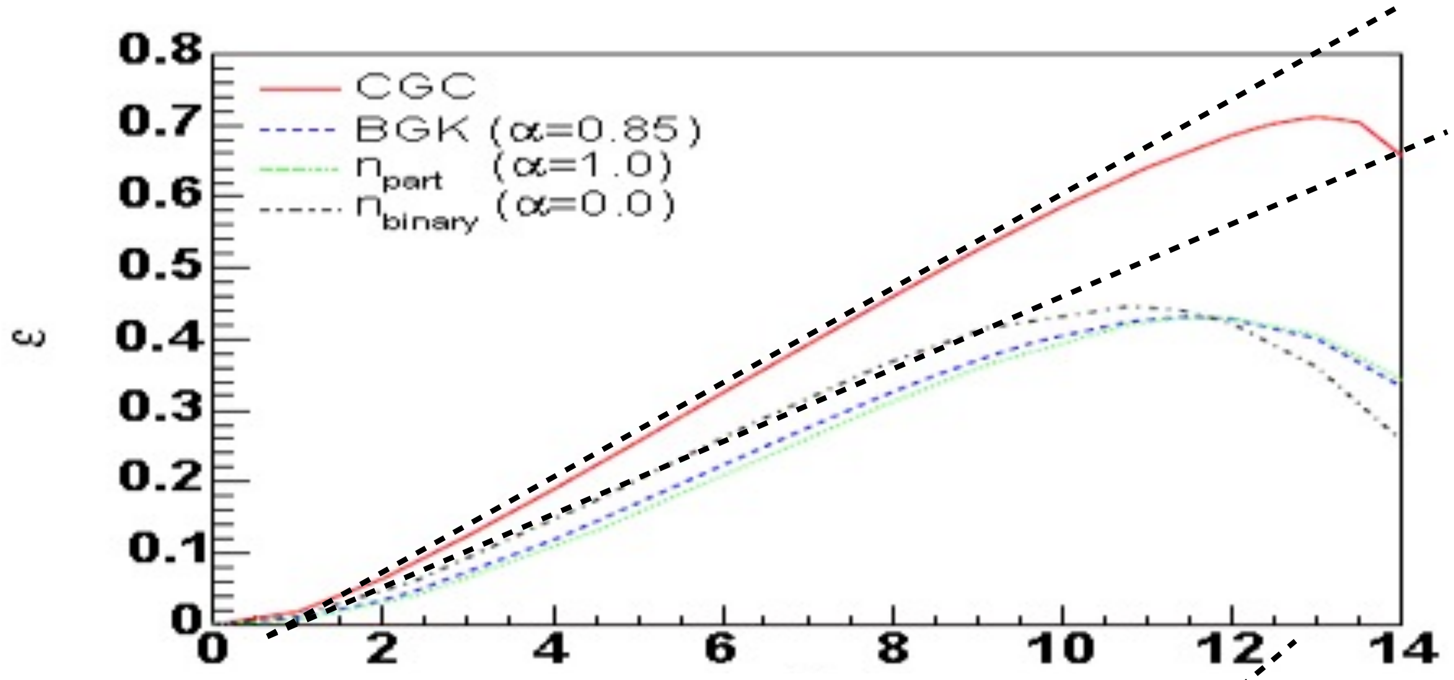
  - hadronic physics?!

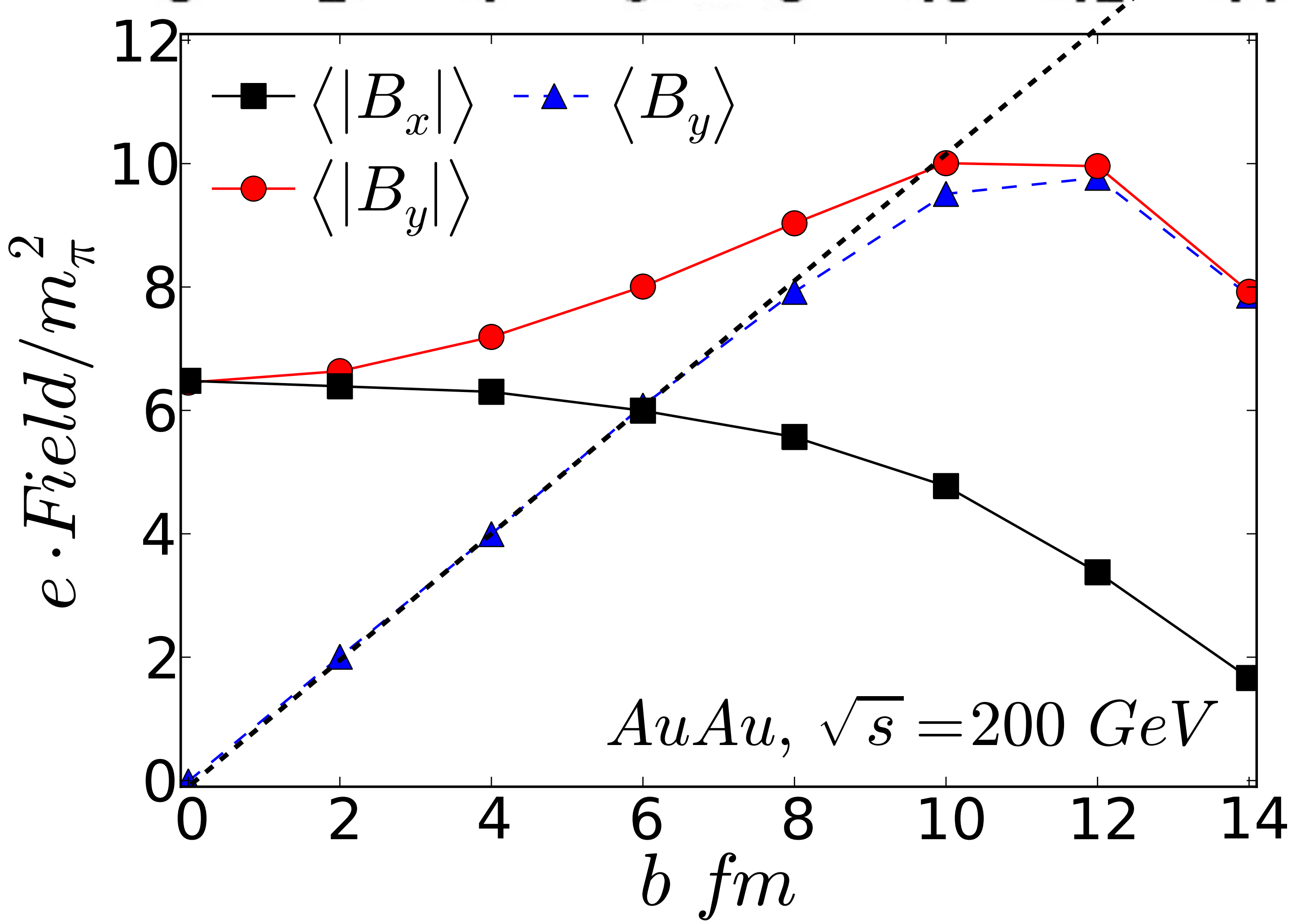
  - or effect of non-zero magnetic field?!

- there are ways to discriminate between hadronic and magnetic field related mechanisms of v_2!

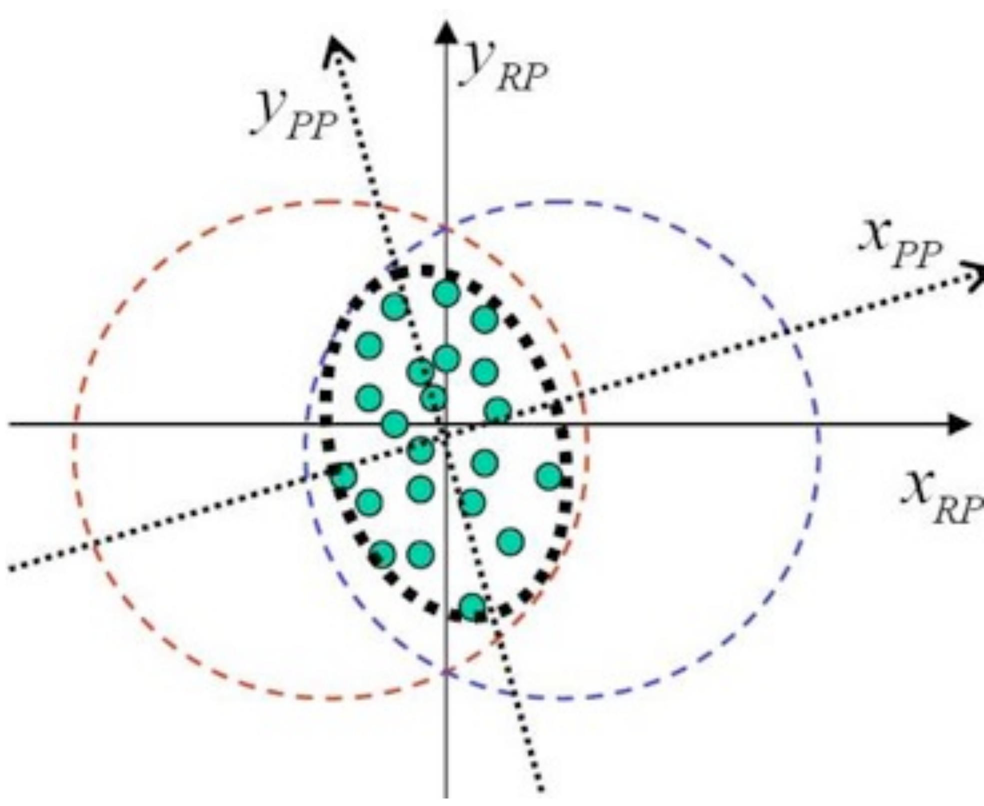
- axial anomaly: similar effect, but unknown μ_5 (similar to CME); synchrotron radiation: similar effect, but unknown quark distribution in initial state

Backup

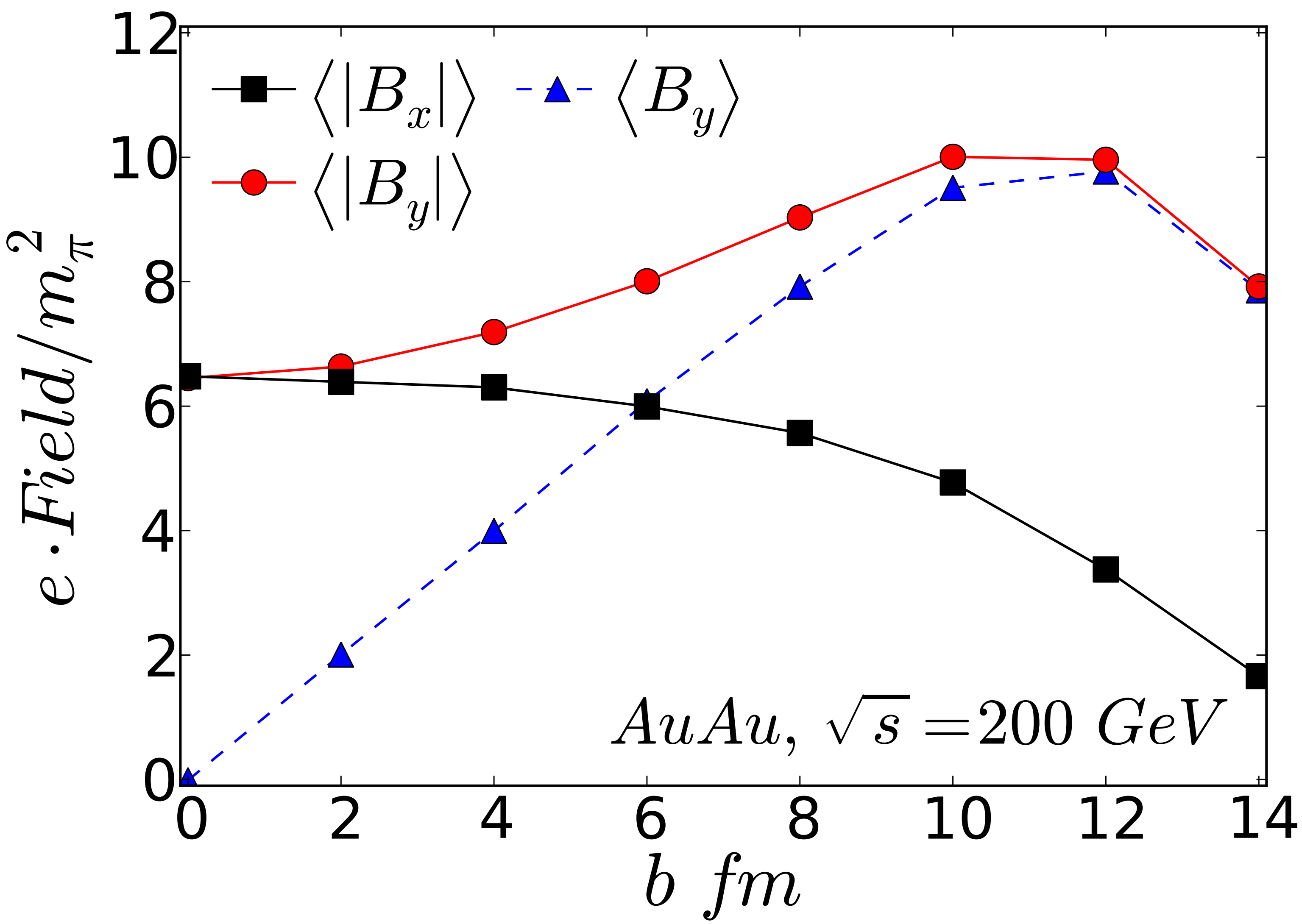




Drescher Dumitru Hayashigaki Nara, nucl-th/0605012



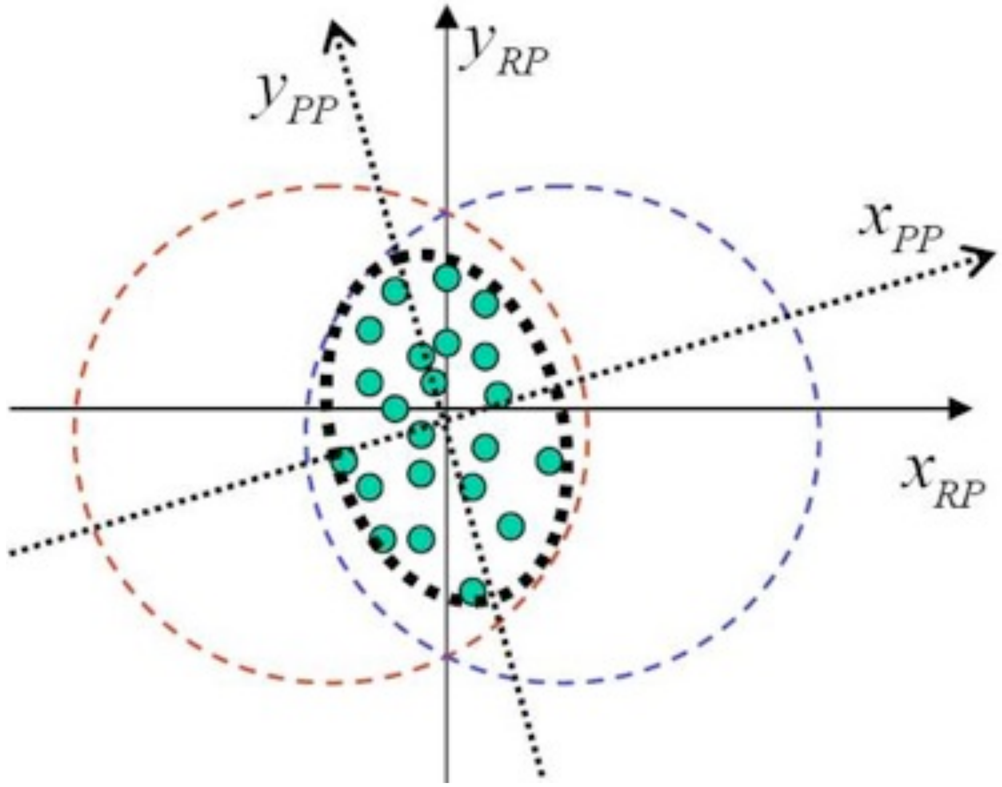
Fluctuations of eB



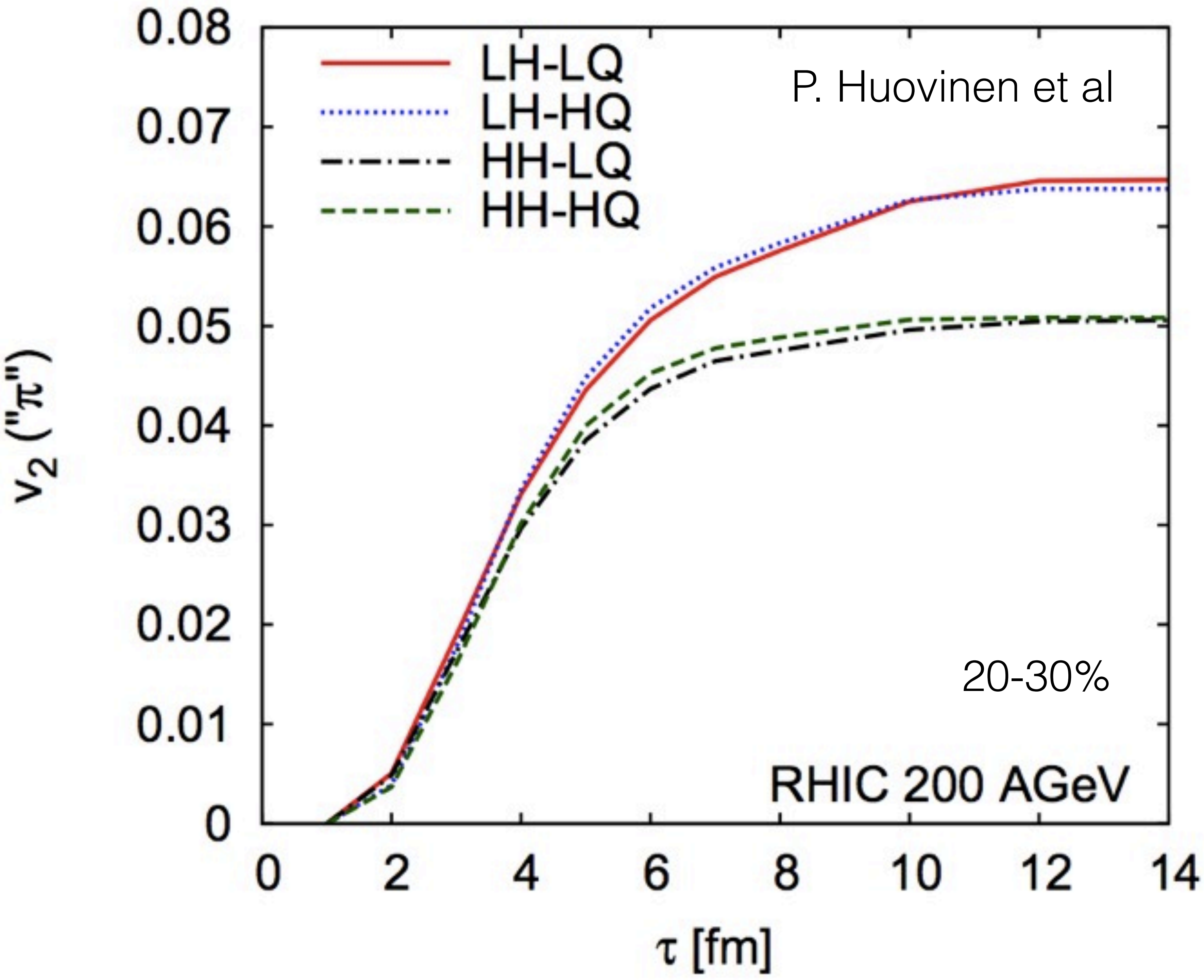
- for observables <eB> is not as significant as as <|eB$_y$ - eB$_x$|>

A. Bzdak and V.S., 1111.1949

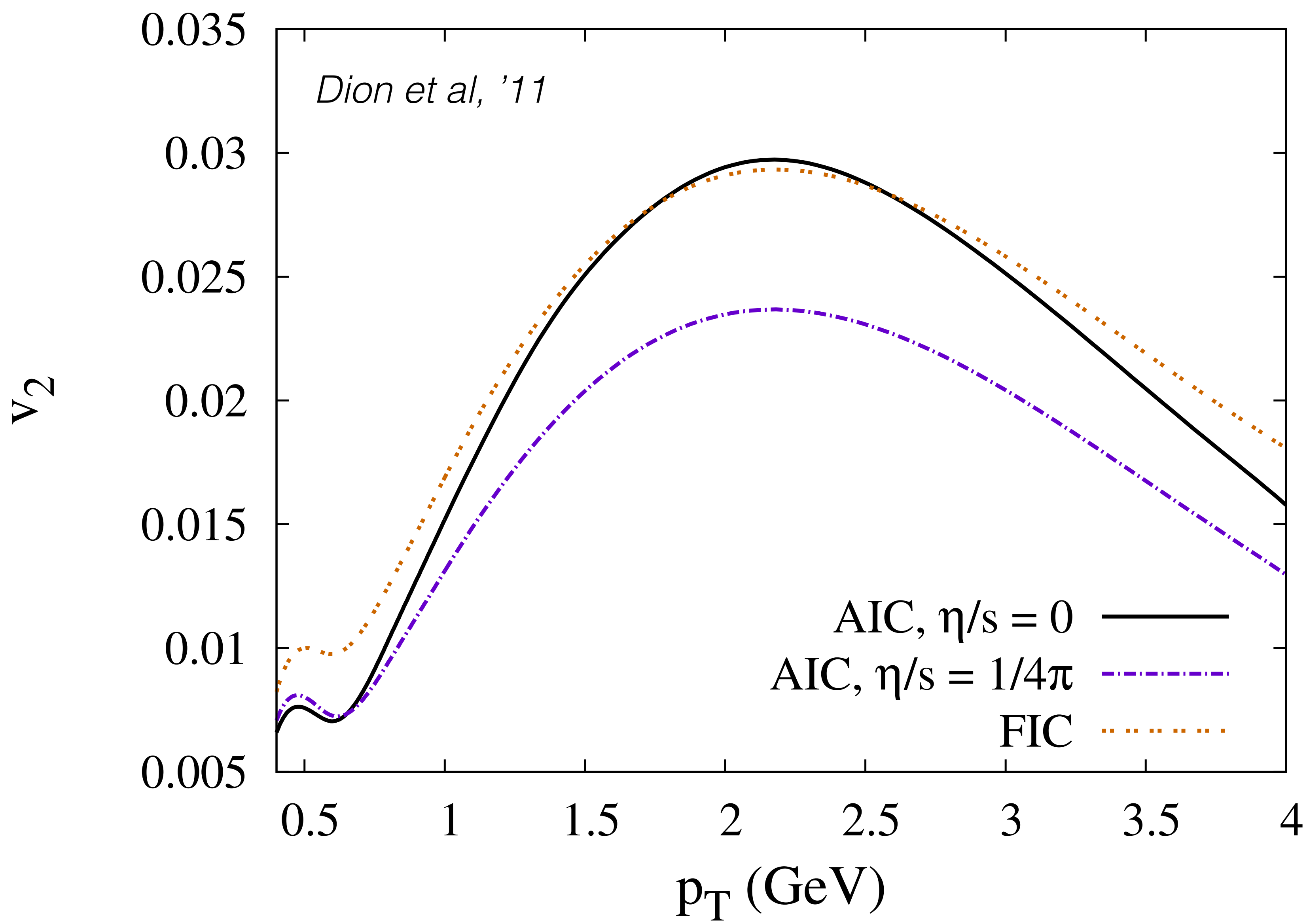
- azimuthal fluctuations of eB relative to orientation of participant plane: J. Bloczynski et al1209.6594



Development of hadronic flow



Theory: Hydrodynamics II



Hydro:
5 times smaller v_2 then in experiment

AIC: averaged initial conditions
FIC: fluctuating initial conditions

Large photon v_2 is difficult to explain with dominant QGP source