Magnetic field effect on photon production

Vladimir Skokov

Western Michigan University

Conformal anomaly: G. Basar, D. Kharzeev, V.S., Phys. Rev. Lett. 109, 202303, 2012
Axial anomaly: K. Fukushima, K. Mameda, Phys.Rev. D 86, 071501, 2012
Experimental test:A. Bzdak, V.S., Phys. Rev. Lett. 110, 192301, 2013
Life time of magnetic field and conductivity: L. McLerran, V.S., Nuclear Physics A 929,184, 2014
Magneto-sono-luminescence: G. Basar, D. Kharzeev, E. Shuryak, Phys.Rev. C90 (2014) 014905
Prompt photons and synchrotron radiation in magnetic field: K.Tuchin, arXiv:1406.5097

Outline

- introduction: v_2-puzzle

- magnetic field

  - lifetime (key parameter)

- photon production in magnetic field:

  - synchrotron radiation

  - axial anomaly

  - conformal anomaly

Punchline

- In HIC we do have

  1) high magnetic field right after collision

  $eB\sim 1\text{-}10\ m_\pi^2$ ($m_\pi^2 = 10^{18}$ Gauss)

  2) photon (dilepton) production with azimuthal anisotropy owing to interactions with eB

  This can be tested in experiment in model-independent way

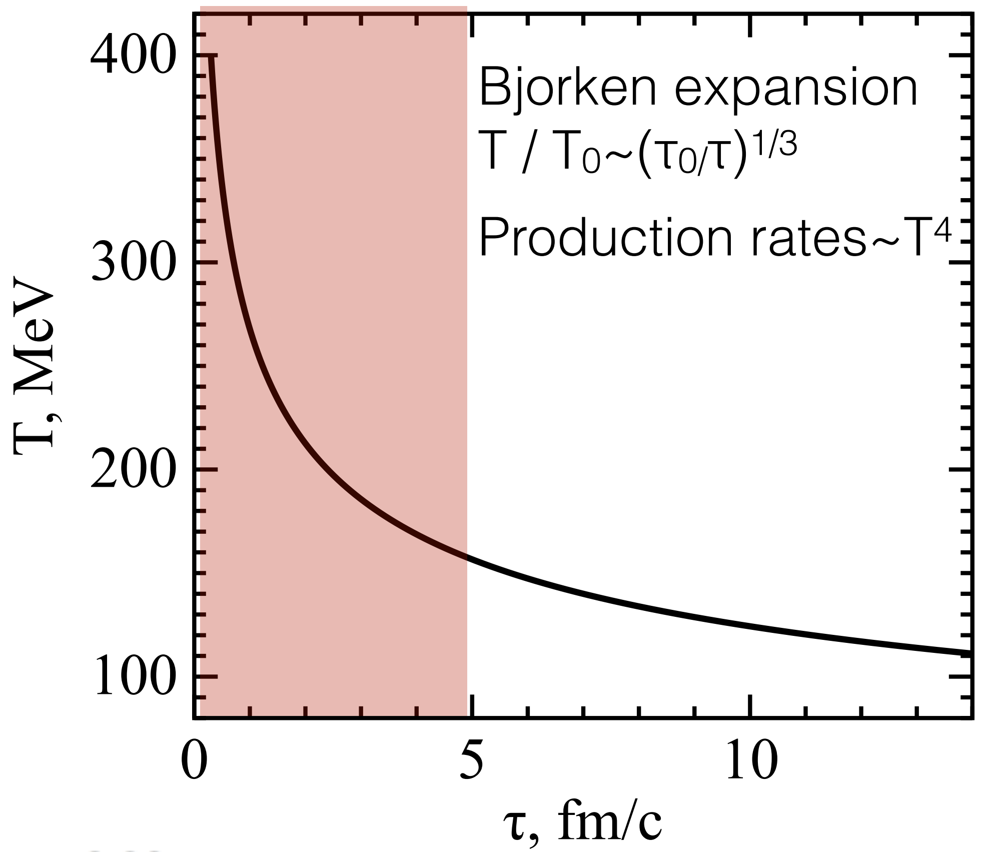
- v_2(photons) = v_2(pions) can be described with magnetic field

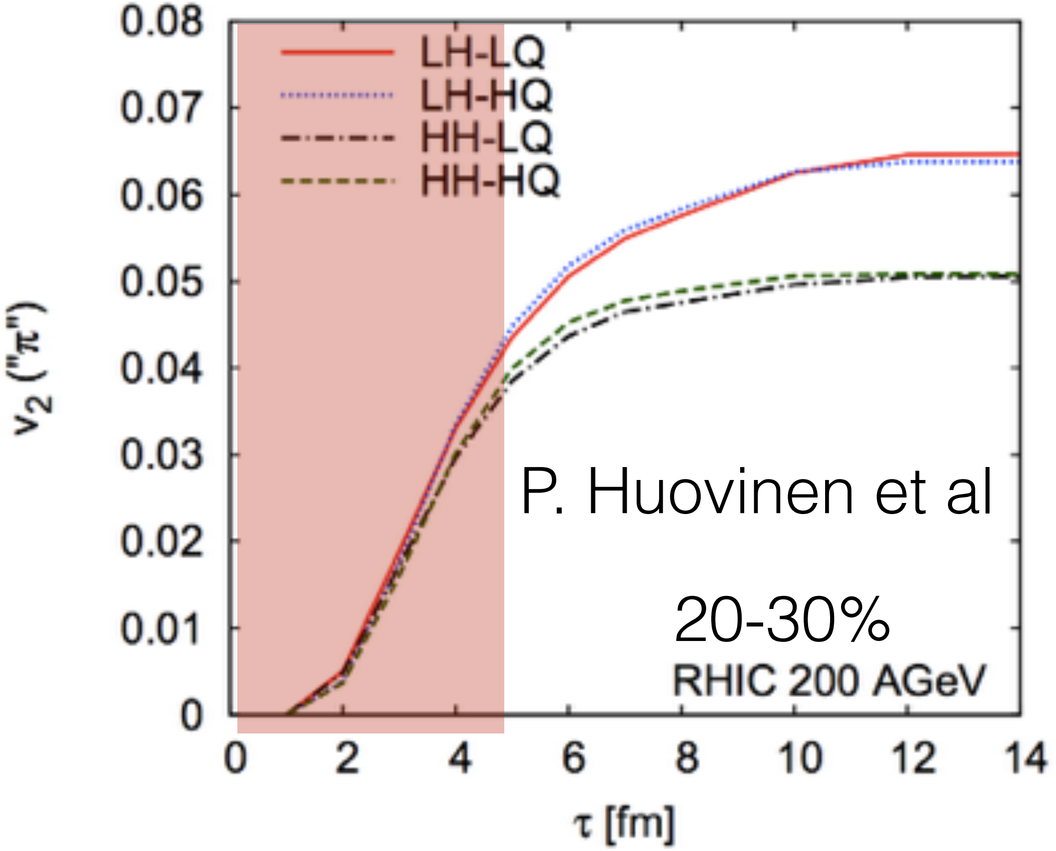
- v_2(photons) dependence on centrality consistent with PHENIX data

- v_3(photons) = v_3(pions) is challenging to get with magnetic field

Naive expectations

- Photon production rate is proportional to T^4 (according to pQCD)
- Large emission from early (hottest) stage of HIC
- At early stage: small hadronic flow (according to hydro)
- Photon v_2 is expected to be smaller than the one for hadrons
- If photons are produced from late stage: they would inherit flow of hadrons



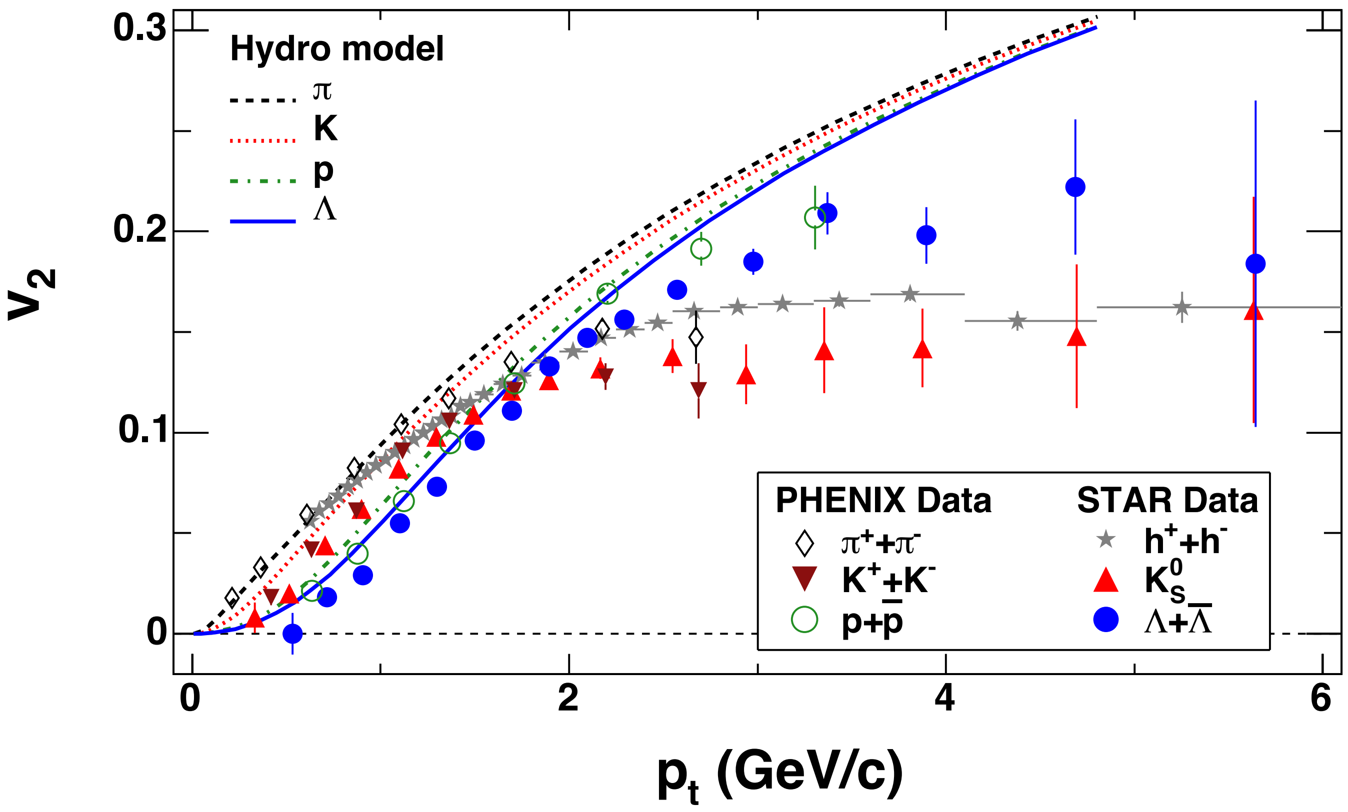


Azimuthal anisotropy

- Direct photons:

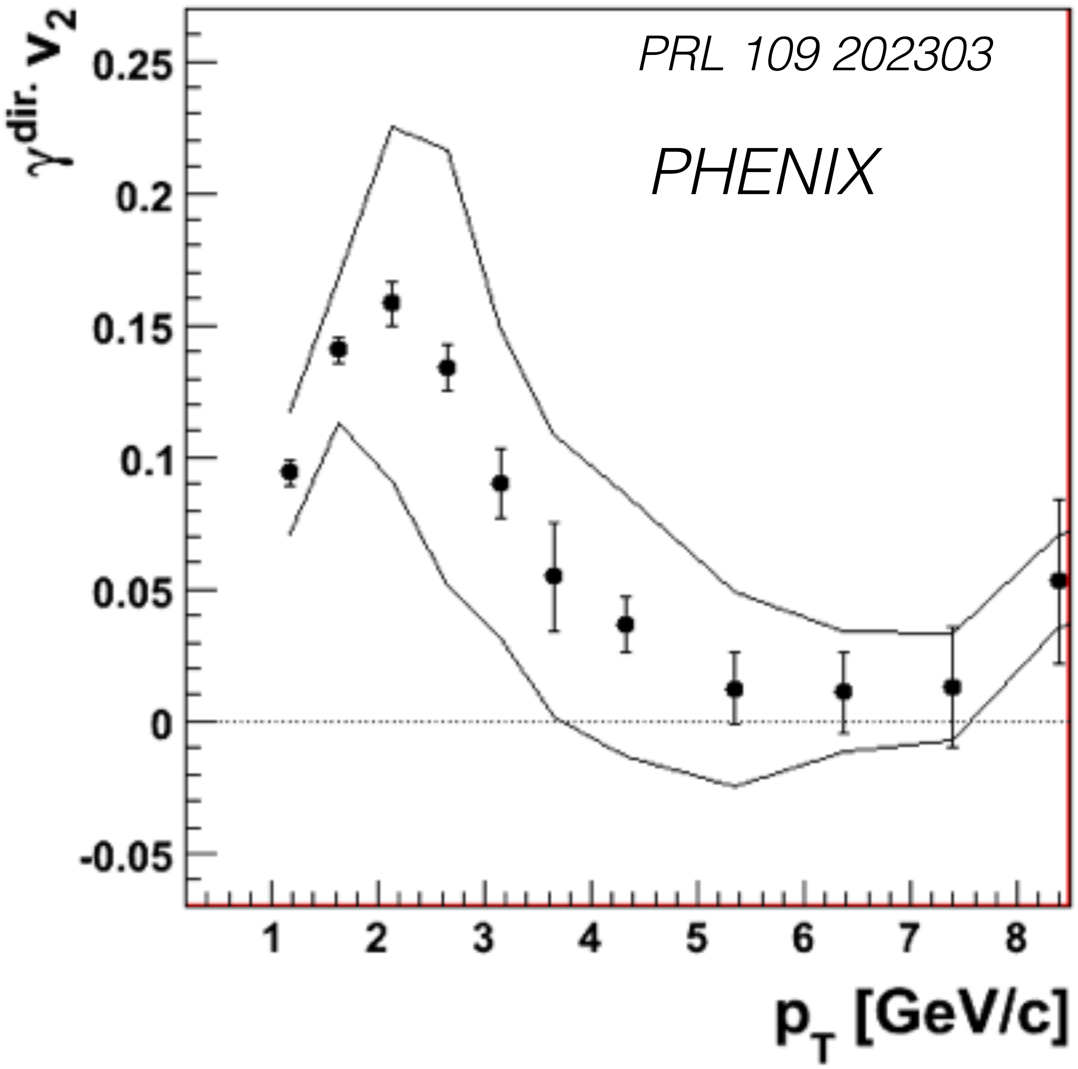
PHENIX

- Hadrons:

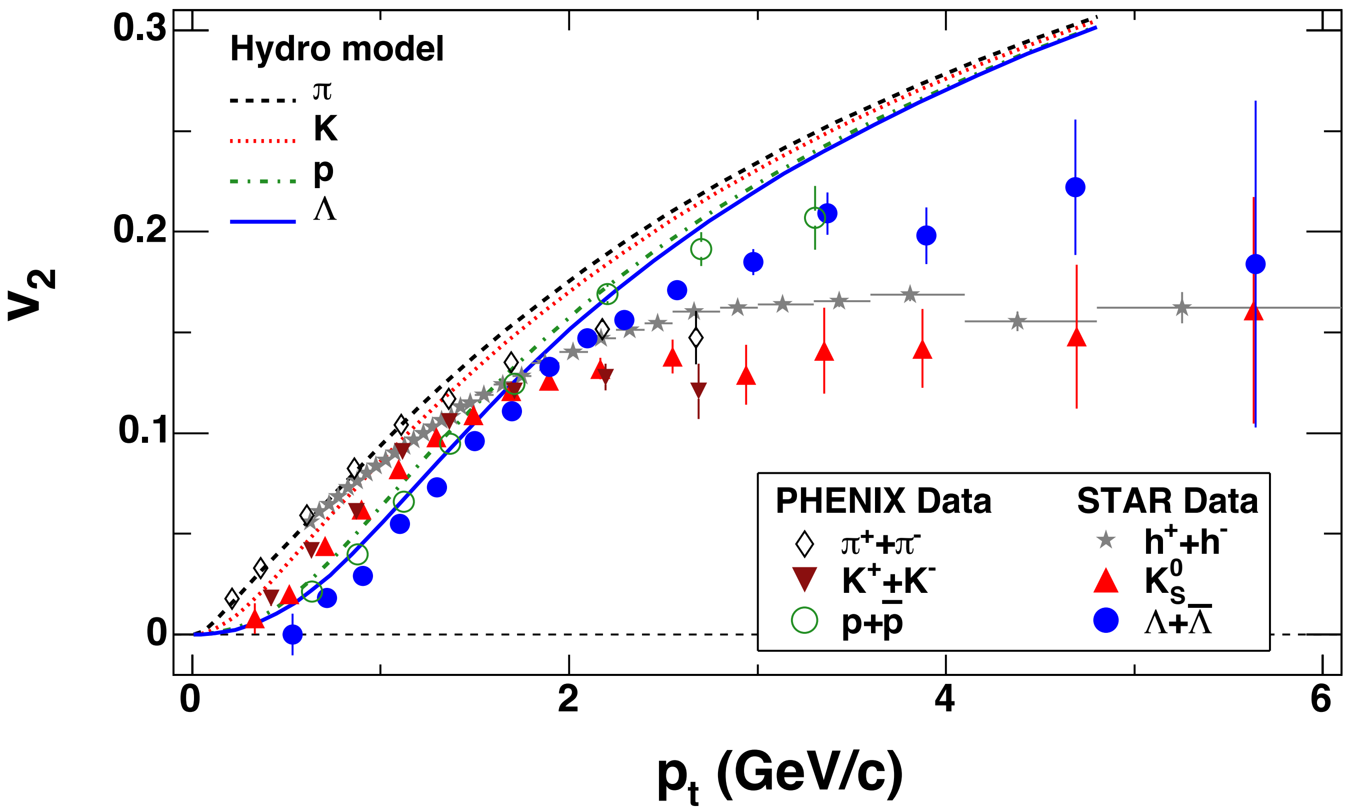


Azimuthal anisotropy

- Direct photons:



- Hadrons:



Possible resolutions

A) Large fraction of photons is produced at the early stage and they do carry anisotropy

1) Hadronic anisotropy from the early stage also?! Hydrodynamic interpretation is incorrect?!

Size scales (2 GeV)$^{-1}$ ~ 0.1 fm

2) Correlation between initial and final state, i.e. correlation between early time anisotropy of photons and late time anisotropy of hadrons. Photons from magnetic field! Magnetic field is correlated with initial eccentricity and thus with hadronic flow (according to hydrodynamical interpretation)

B) Large fraction of photons is produced at the late stage and they inherit anisotropy of hadrons

1) Suppression of production at early times (high T)

2) Enhancement of production at late stage (close to deconfinement?!)

Magnetic field

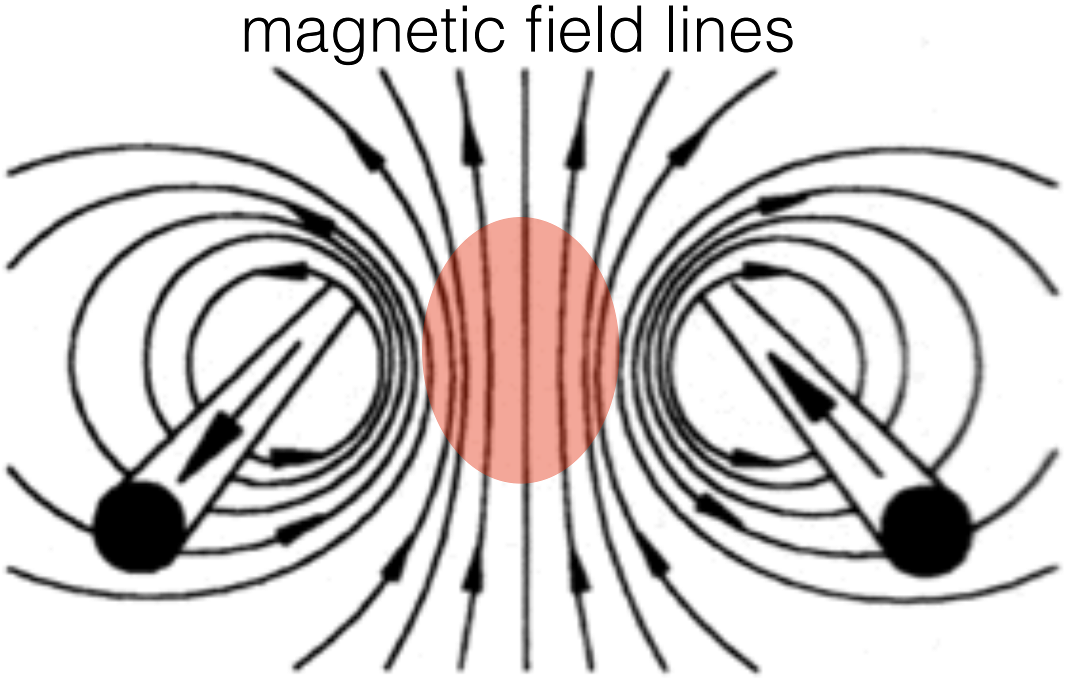
- anisotropy ≠ hydrodynamic flow!
- other sources of anisotropy not related to flow?!
- magnetic field!

Magnetic field in HIC I

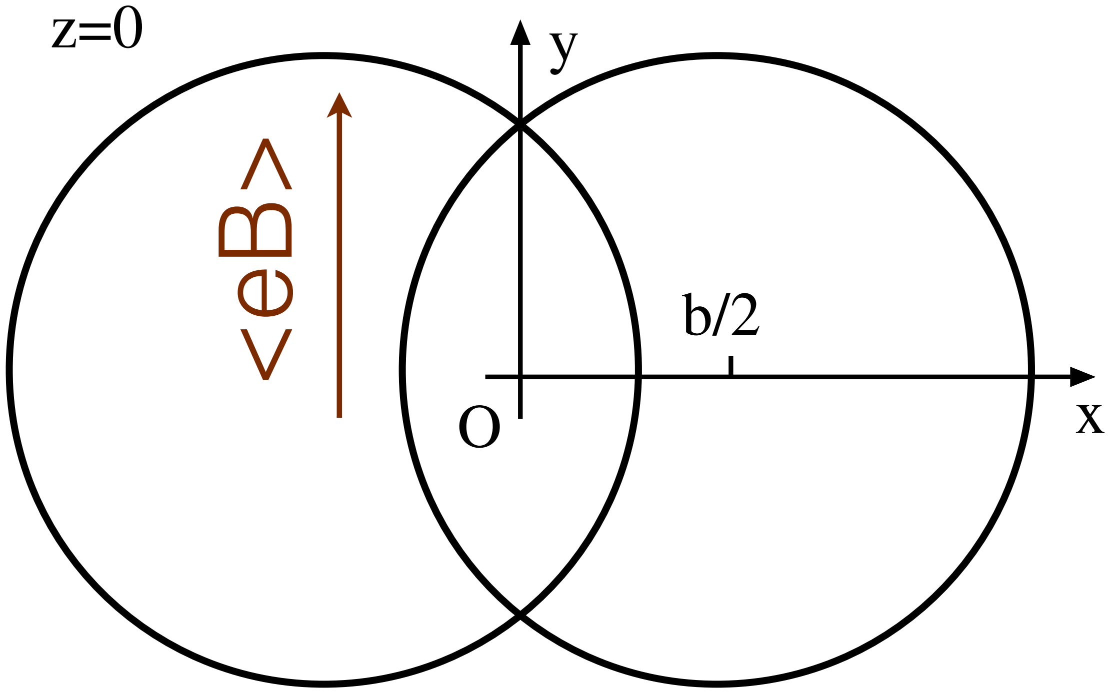
- spectators form two currents

For HIC:

J. Rafelski and B. Müller, PRL, 36, 517, 1976

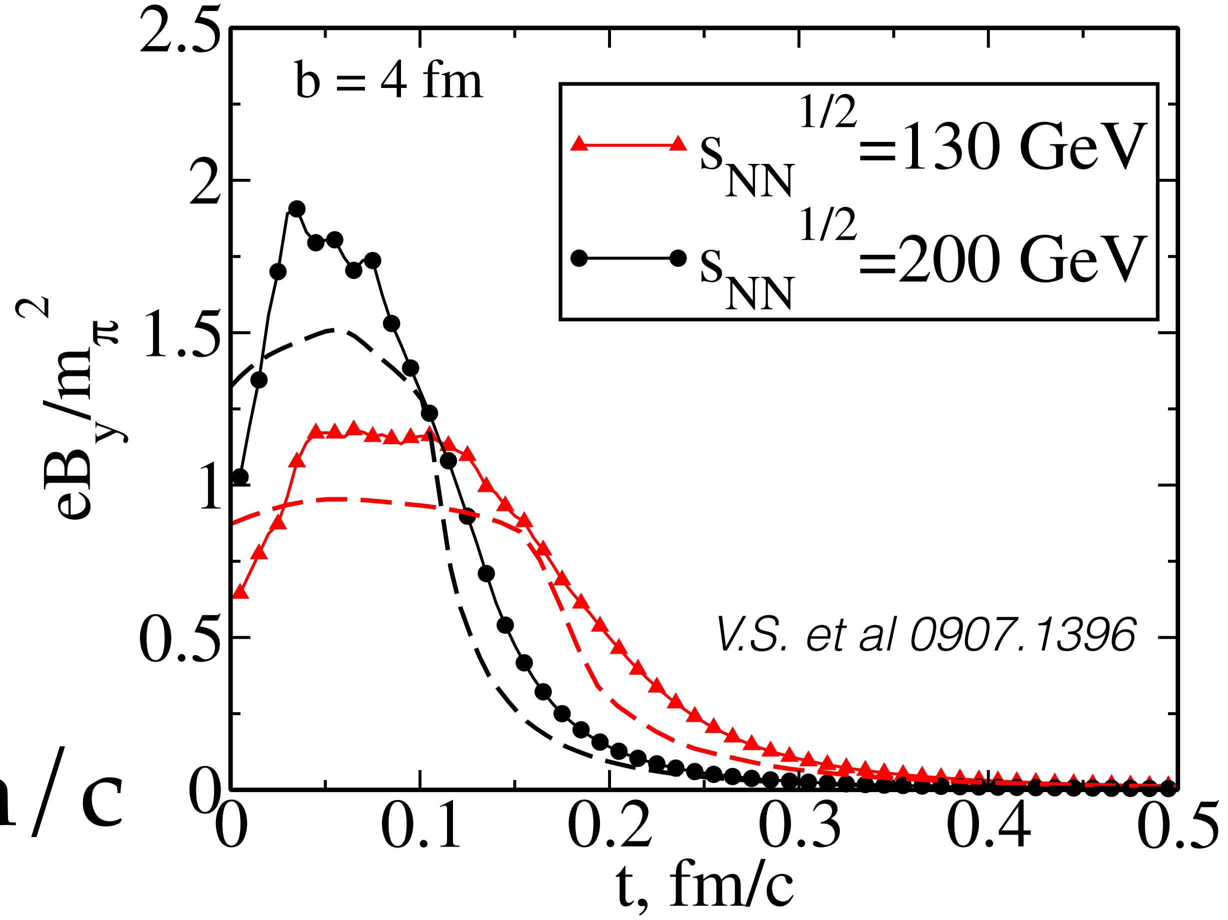


- resulting event
average magnetic field
$\langle eB_y \rangle \sim m_\pi^2$ (out-plane)
$\langle eB_x \rangle \sim 0$ (in-plane)



Magnetic field in HIC II

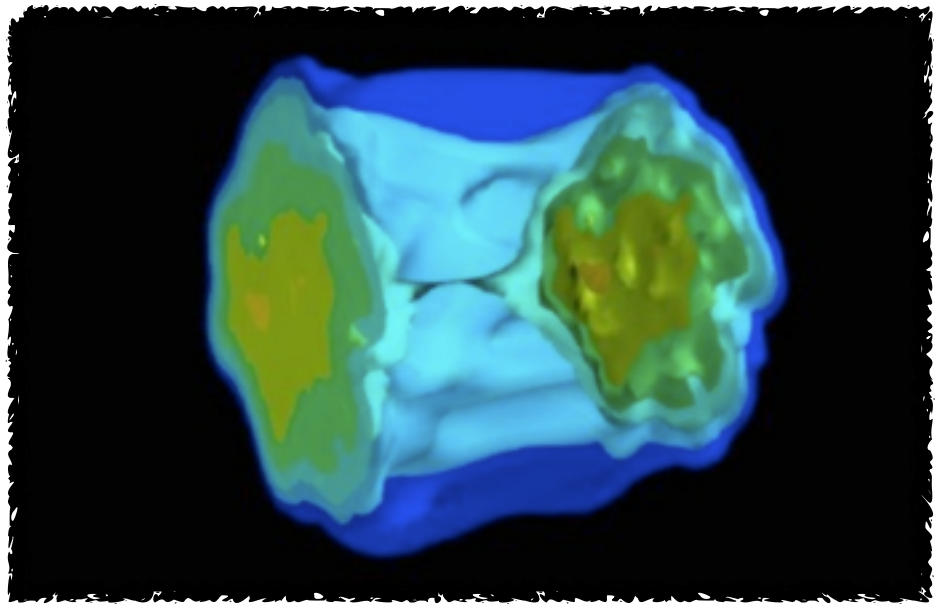
- maximal eB ~ √s
- maximum at t_M ~ 1/ √s
- lifetime t_{lt} ~ 1/ √s
- integral ~ const
- t_{lt} at LHC energies ~ 0.01 fm/c



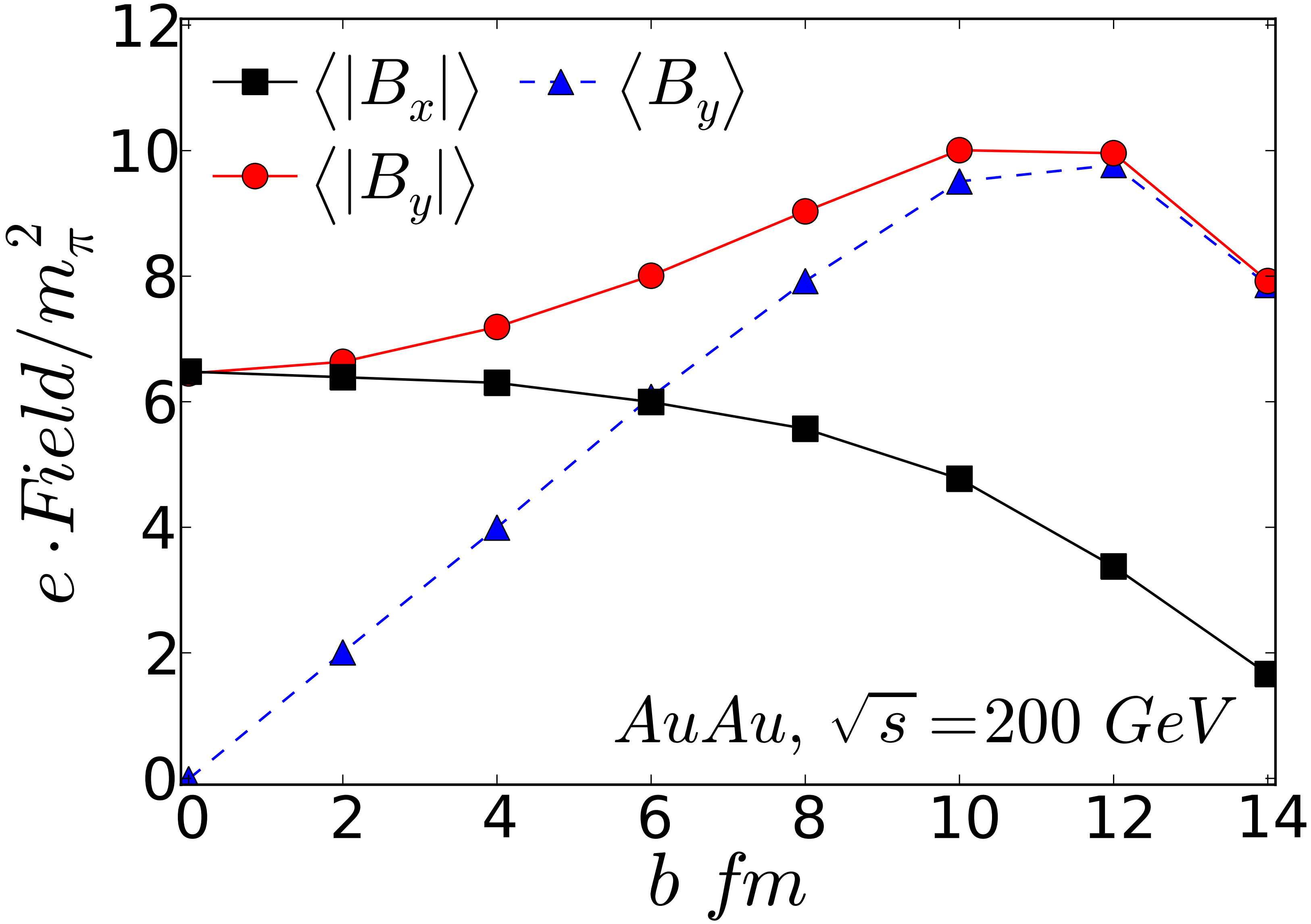
D. Kharzeev, L. McLerran, H. Warringa, 0711.0950

V.S. et al, 0907.1396

Magnetic field in HIC III



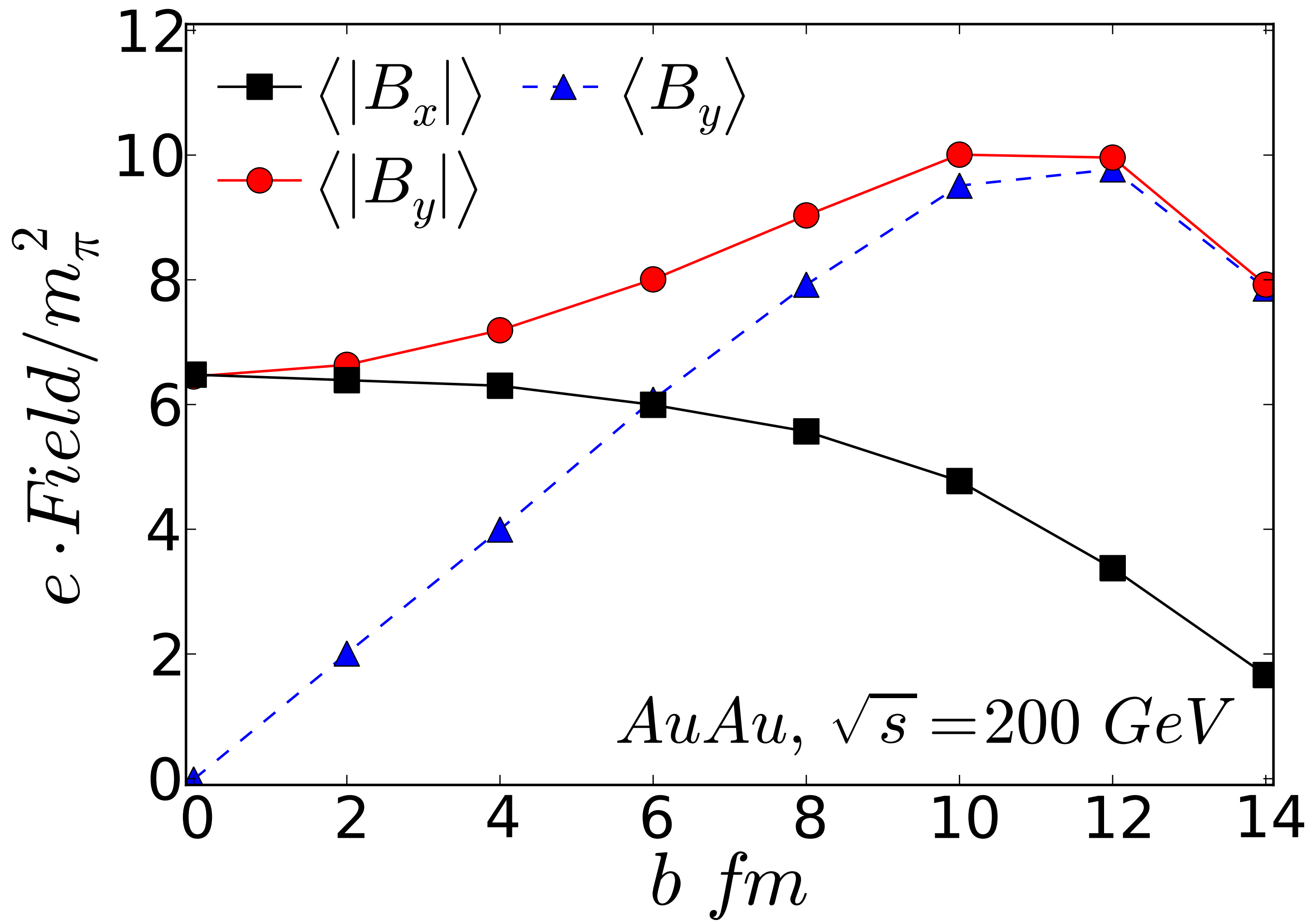
- fluctuations can play important role

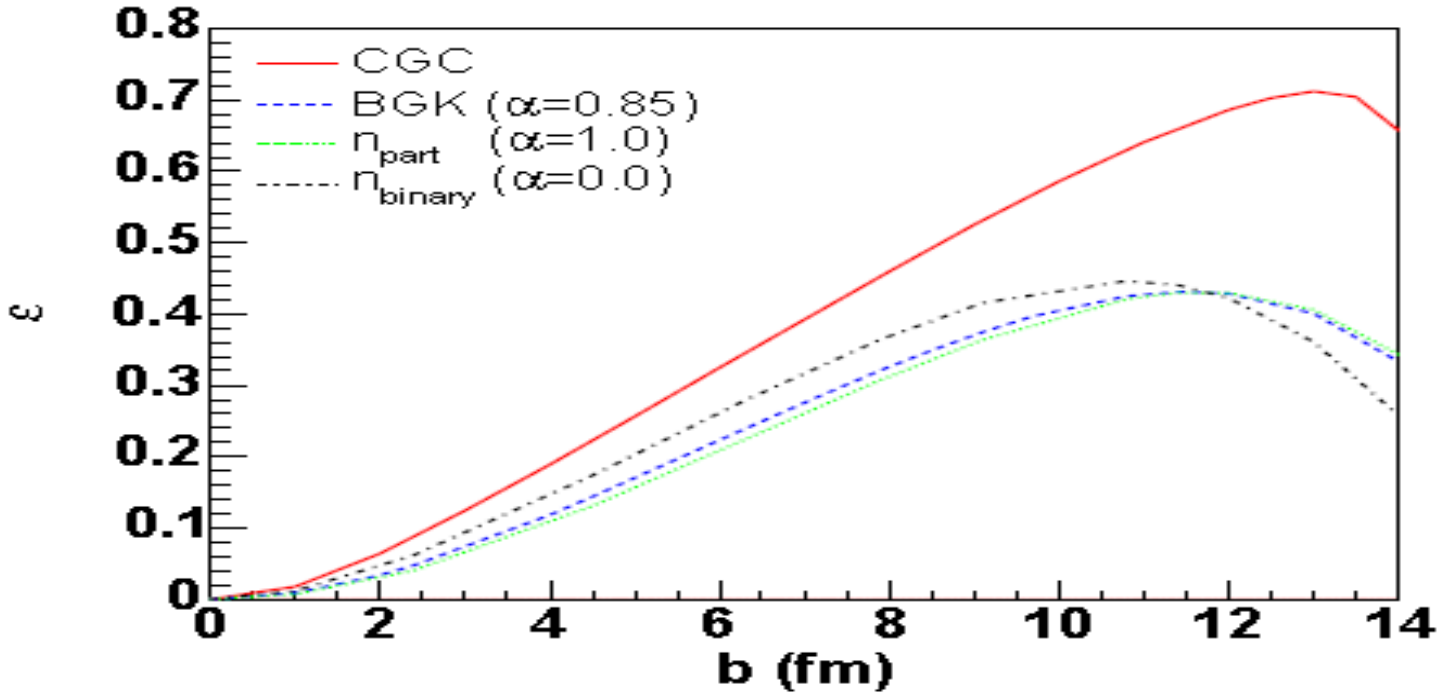


- lumpy distribution of electric charge in colliding nuclei results in nonzero randomly oriented magnetic field even in central collisions

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

Magnetic field in HIC IV





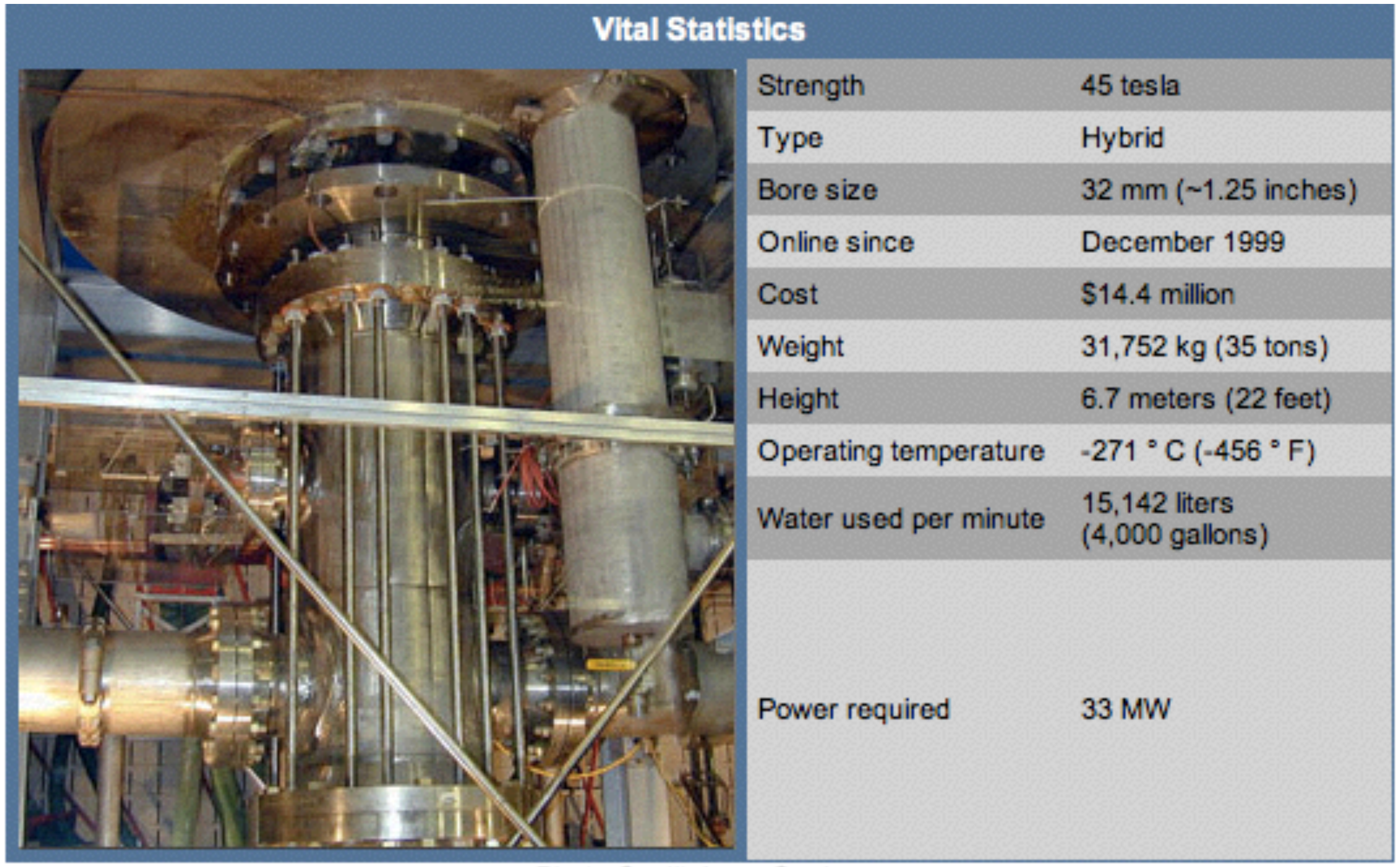
- <eB$_y$> is linear as a function of impact parameter

- linear correlations between <eB> and initial eccentricity ε_2

Comparing to

eB in HIC compared to

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

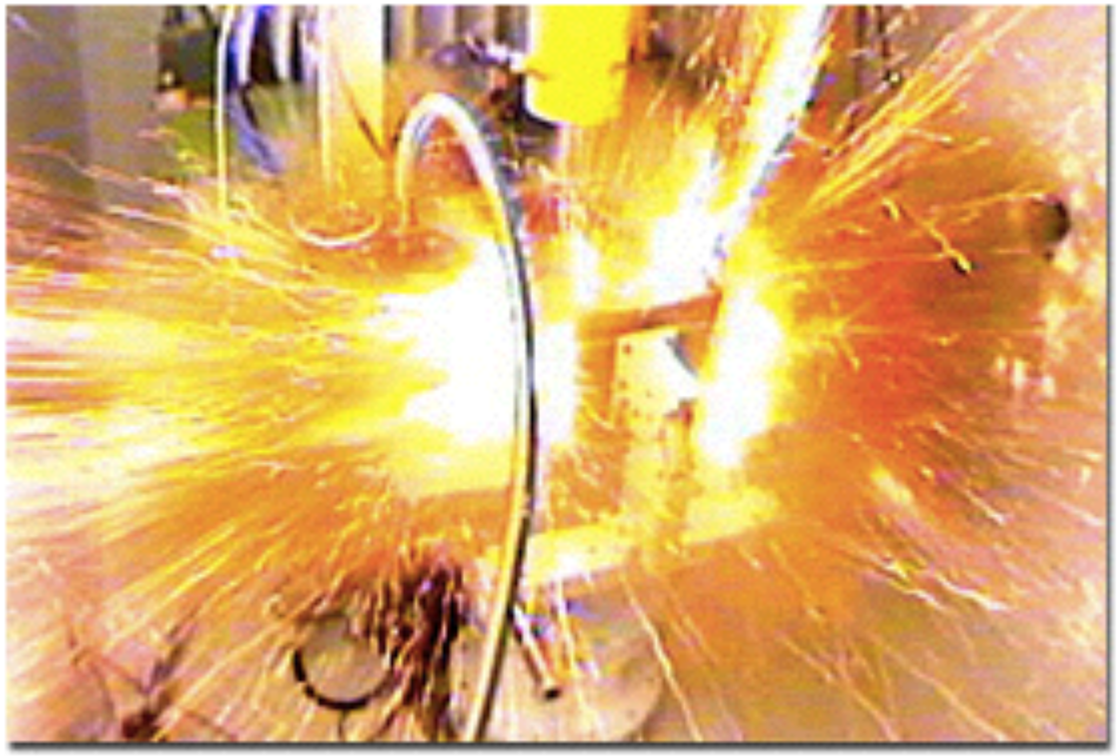


Vital Statistics

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

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



Watch an exploding pulsed magnet at work.

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

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

Lifetime of magnetic field I

Only spectators:

RHIC ($\sqrt{s}$=200 GeV) lifetime ~ **0.1 fm/c**

LHC lifetime ~ **0.01 fm/c**

Conductivity may increase lifetime of magnetic field

$\mathbf{j} = \sigma_{Ohm}\,\mathbf{E} + \sigma_{\chi}\,\mathbf{B}$,

electric conductivity σ_{Ohm}

chiral-magnetic conductivity σ_{χ} (D. Kharzeev and H. Warringa 0907.5007)

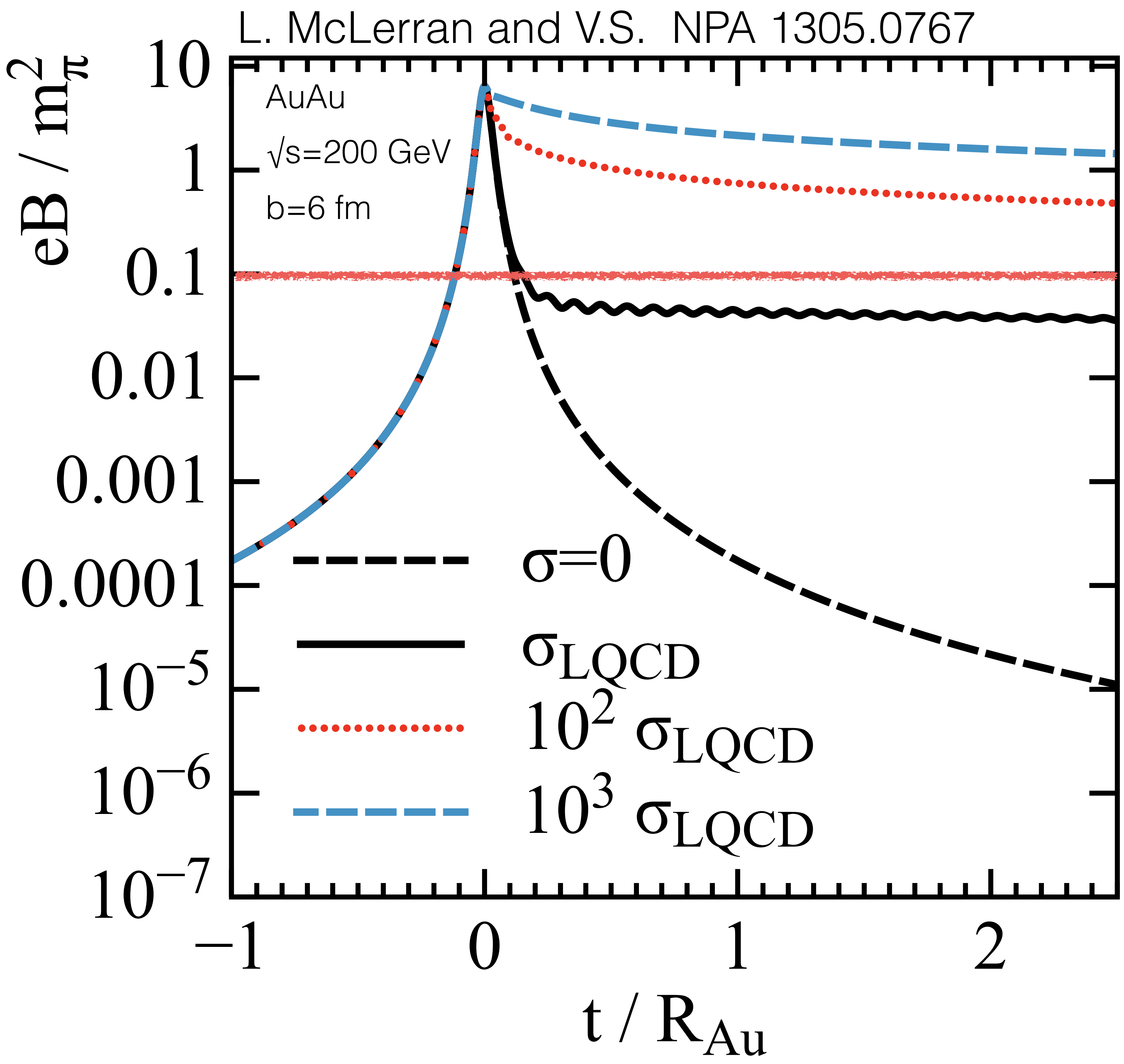
Electric conductivity:

σ_{Ohm}=(5.8±2.9)T/T$_c$ MeV (H.T. Ding et. al. 1012.4963)

Chiral magnetic conductivity (D. Kharzeev and H. Warringa 0907.5007):

$\sigma_{\chi} = (N_c\, e^2/2\pi \sum_f q_f^2)\ \mu_5$; for $\mu_5 \sim 1$ GeV $\sigma_{\chi} \sim 15$ MeV

Lifetime of magnetic field II



Optimistic scenario

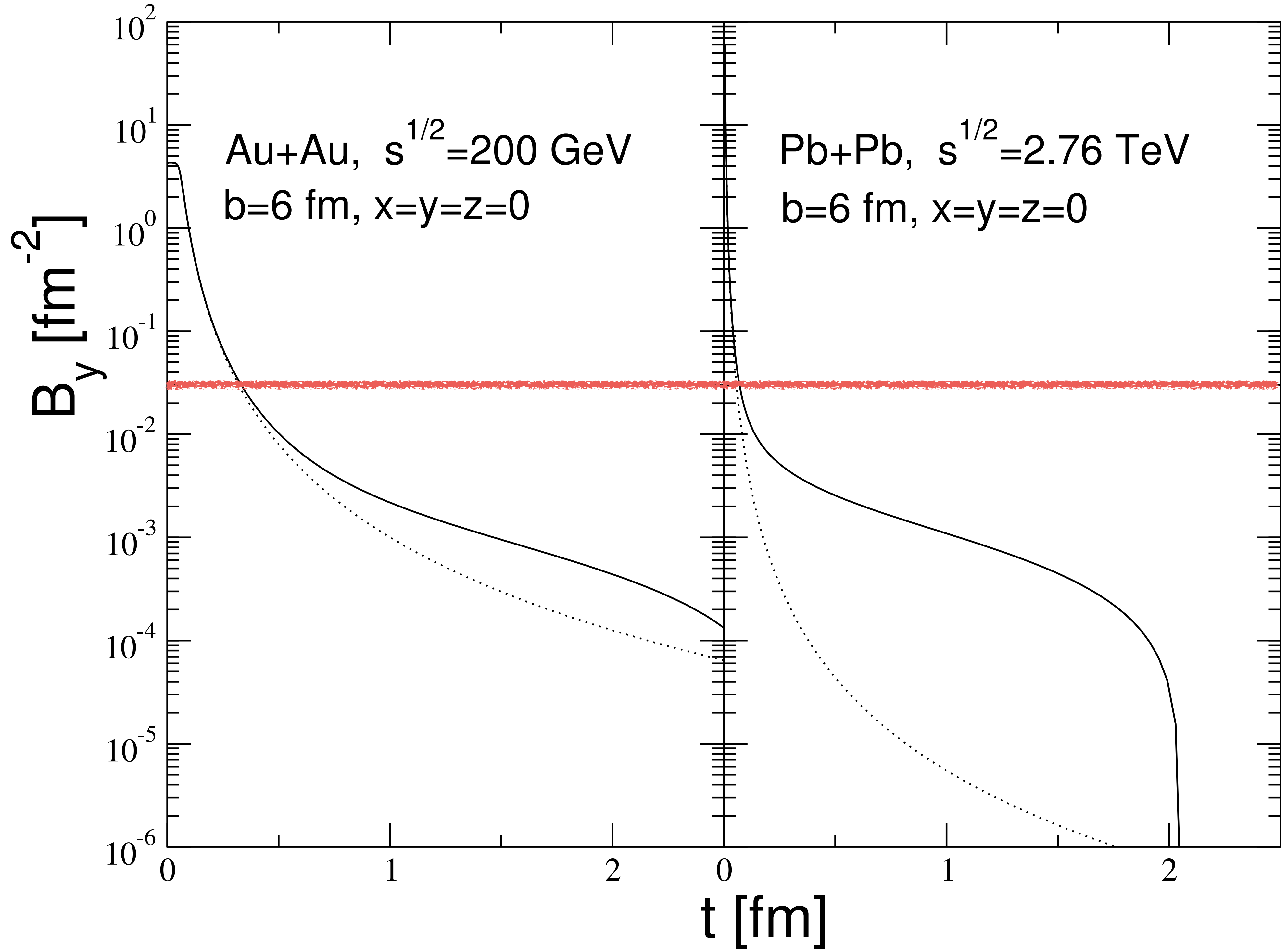
σ_{LQCD} ~15 MeV (at t=0)

Results are almost independent on σ_χ

For $eB \gtrsim m_\pi^2$
σ=0 is a very good approximation in agreement with naïve expectations

K. Tuchin's analytical results obtained for σ_{Ohm}=const ($\sigma_{Ohm} \neq 0$ before collision)

Lifetime of magnetic field III



A more realistic scenario by B. Zakharov, 1404.5047 (expanding geometry)
The same conclusion: conductivity does not change magnetic field lifetime

Conclusion: spectators define B, σ is not important for the lifetime

Observables

Effects, that can be potentially observed:

- modification of QCD phase diagram
  (however, probably irrelevant for HIC)
- chiral magnetic effect
- chiral magnetic wave
  (phenomenological constraints:
  life time for magnetic field $>$ **4 fm/c**)
- Dilepton production via photon splitting (K. Tuchin)

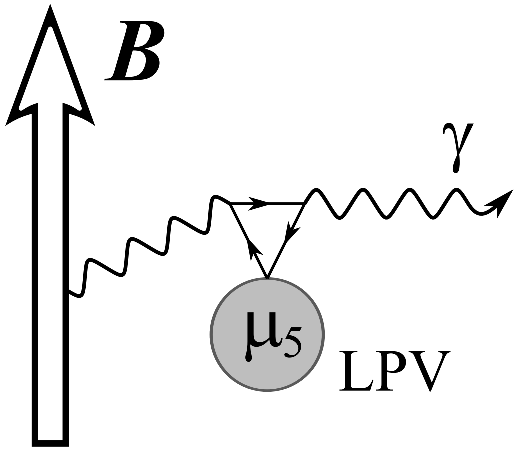
Photon production from eB

Several mechanisms:

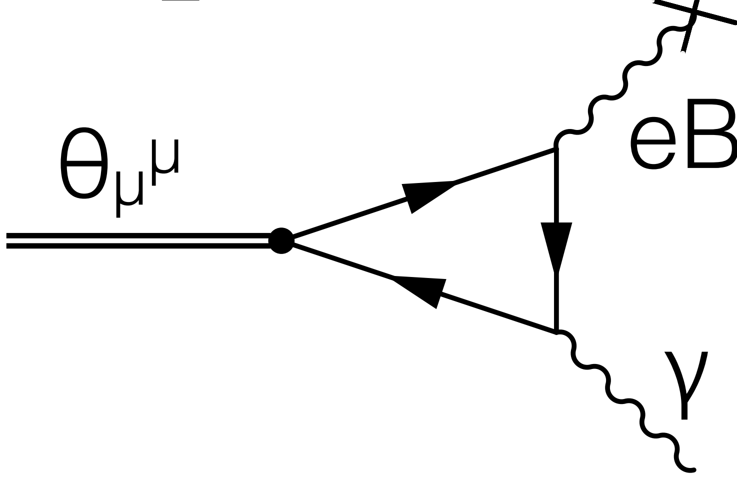
- synchrotron radiation of quarks in eB (K. Tuchin)
  $v_2 = 4/7$, $v_3 = 0$, $v_4 = 1/10$, higher order are negligible

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

  G. Basar and D. Kharzeev, G. Moore



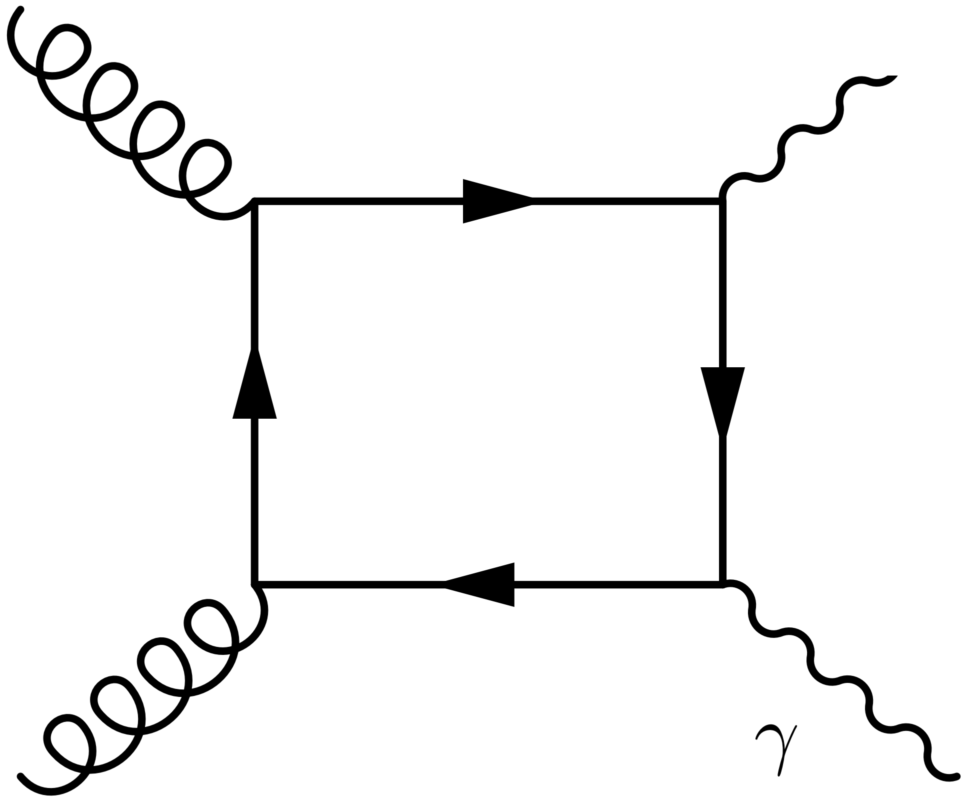
- **conformal anomaly (details in this talk)**



- Magneto-luminescence

  (G. Basar, D. Kharzeev and E. Schuryak, 2014)

Diagrammatic explanation



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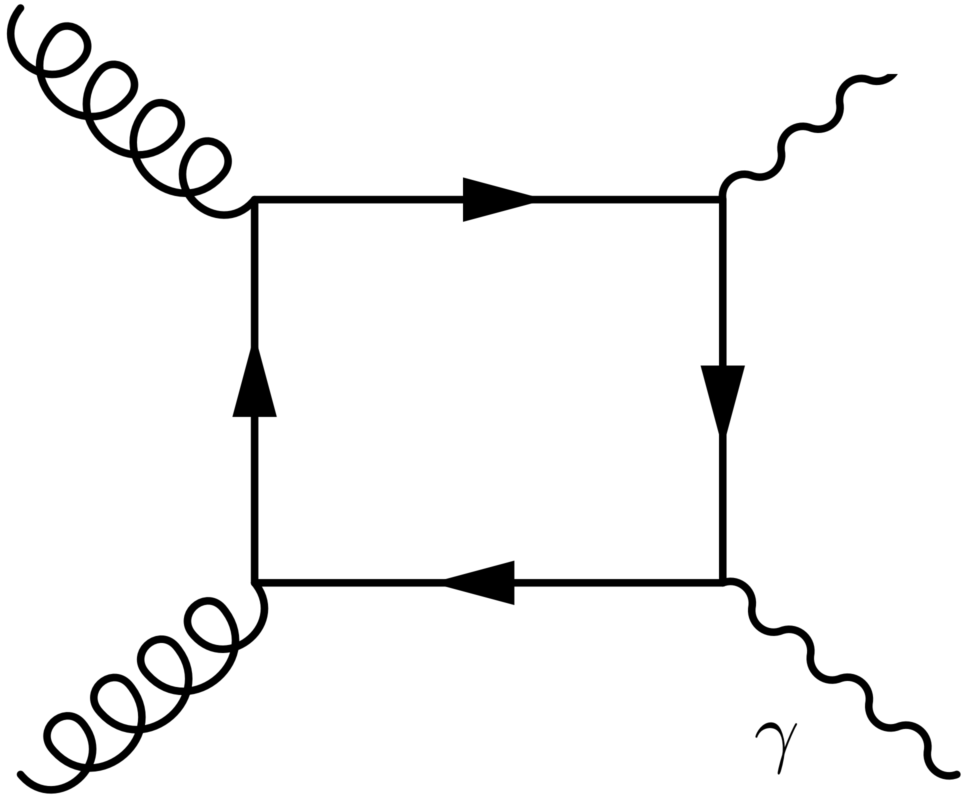
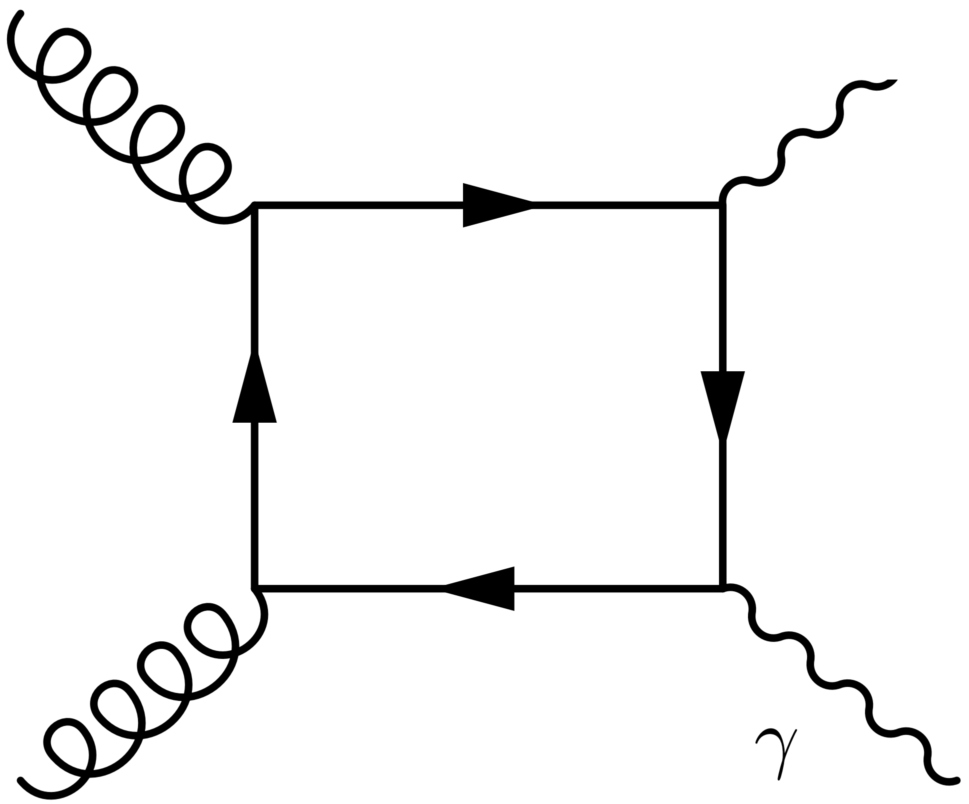
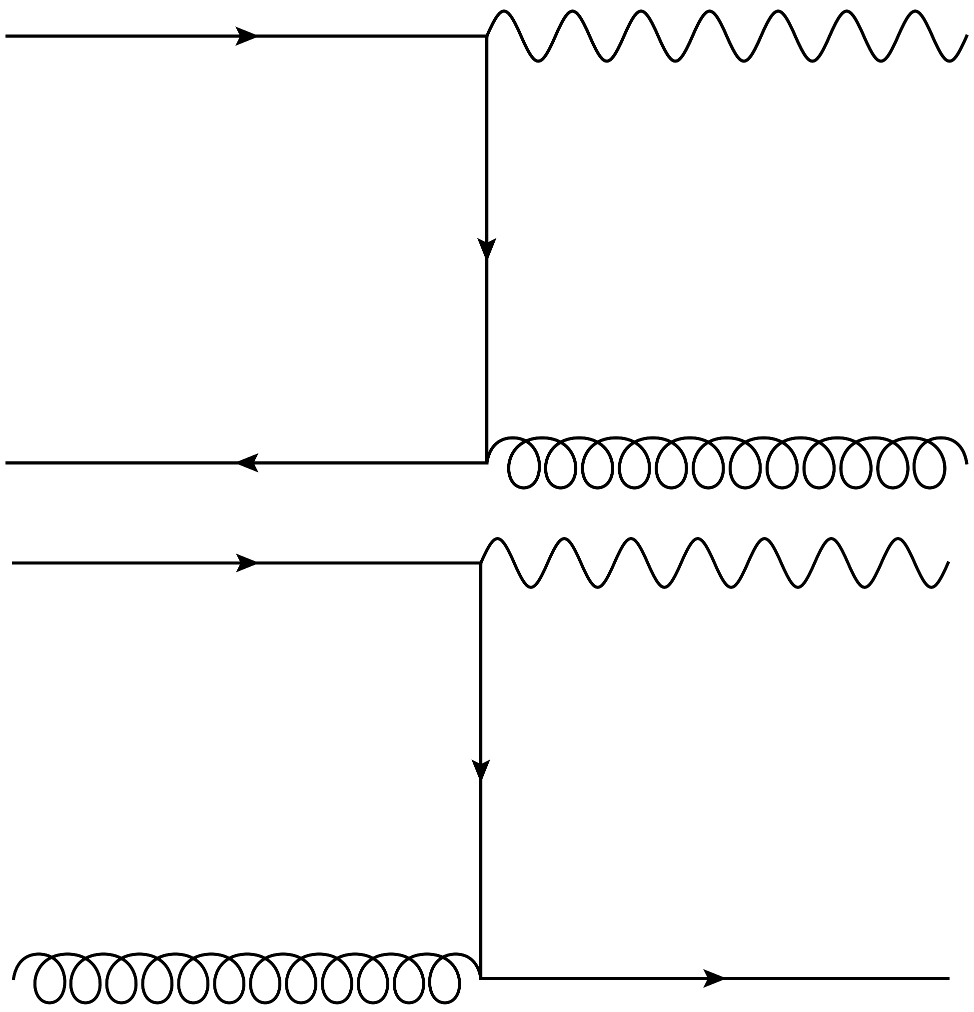


- Two photon production: $\alpha_s \alpha\ G^2 F^2$, $F^2 = F_{\mu\nu}F^{\mu\nu}$
  thus rate ~ α^2

- Replace one photon with eB
  rate ~ α

Diagrammatic explanation





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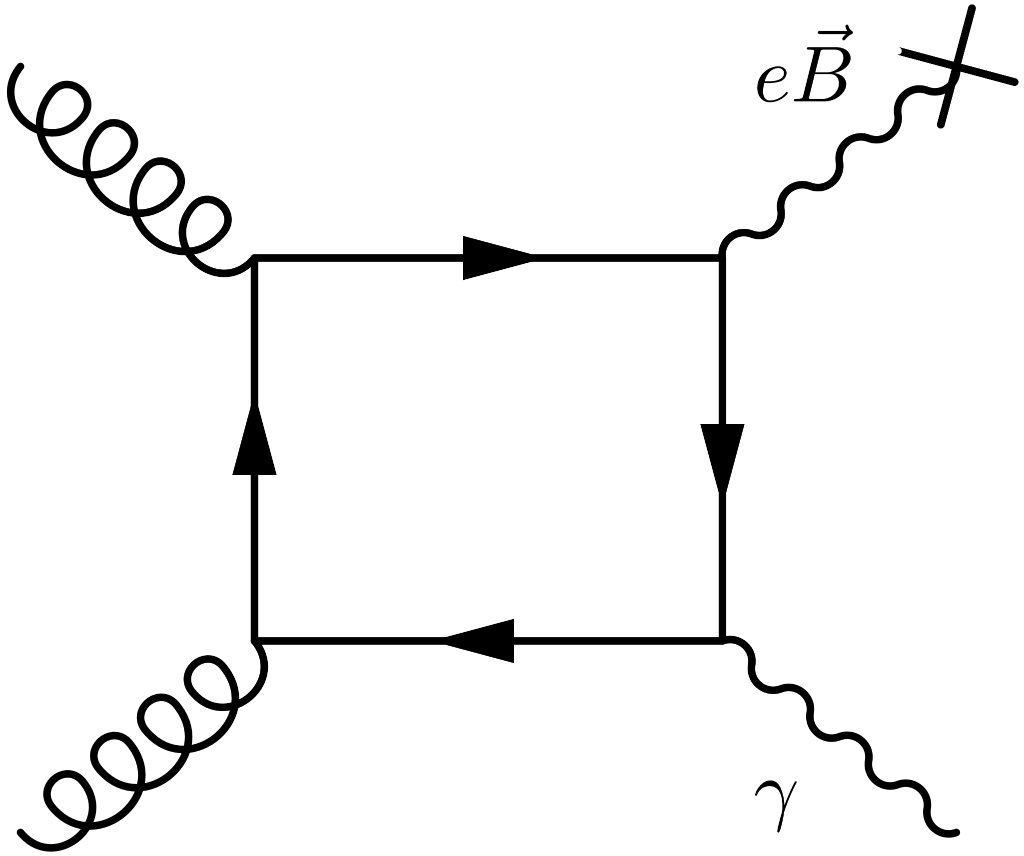

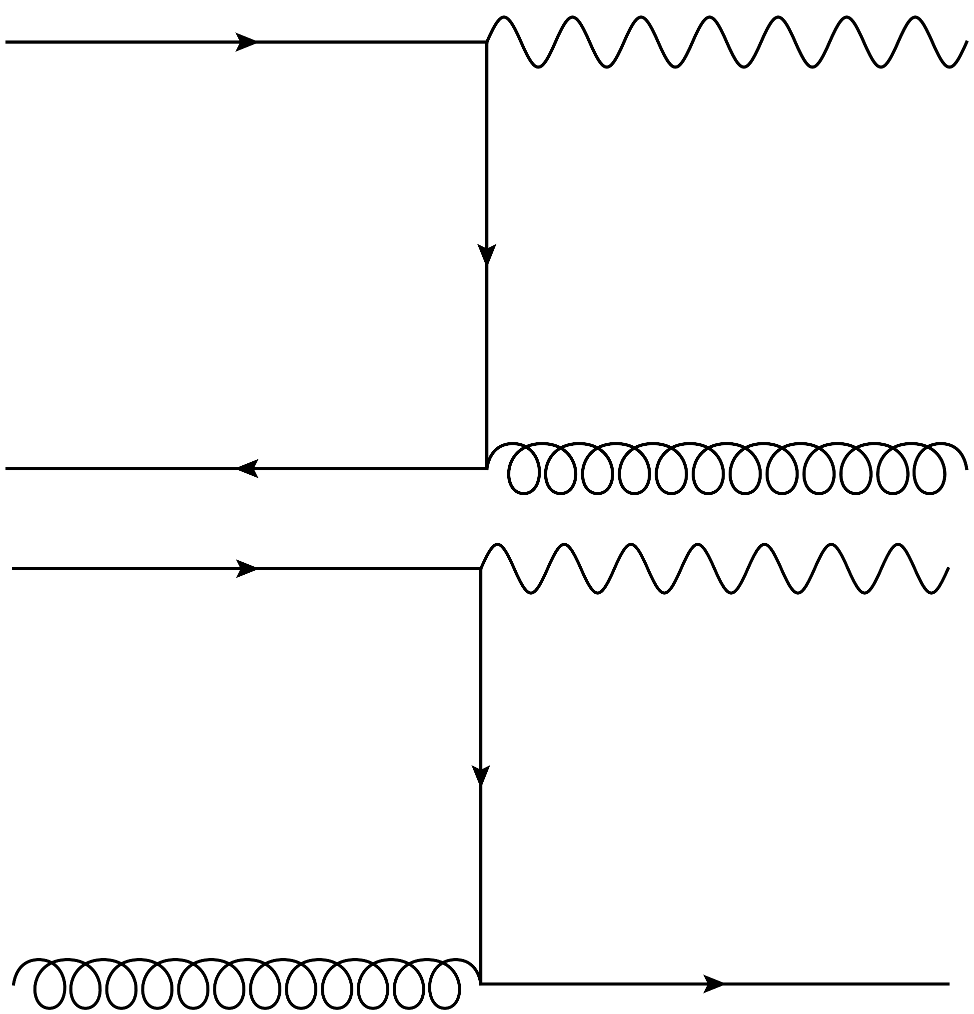

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  rate ~ α

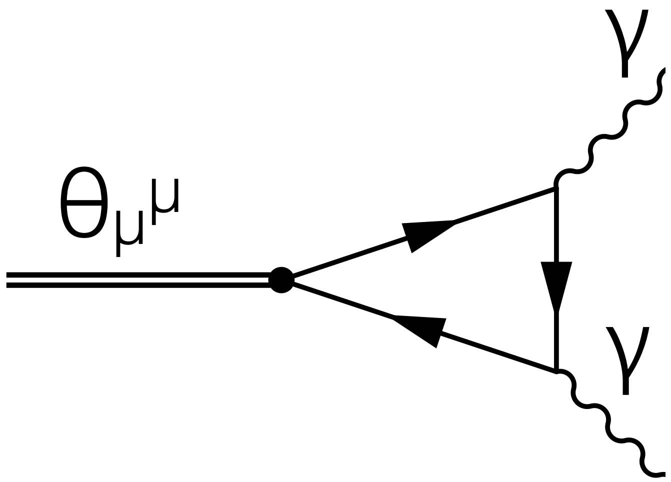
Conformal anomaly

- 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*

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



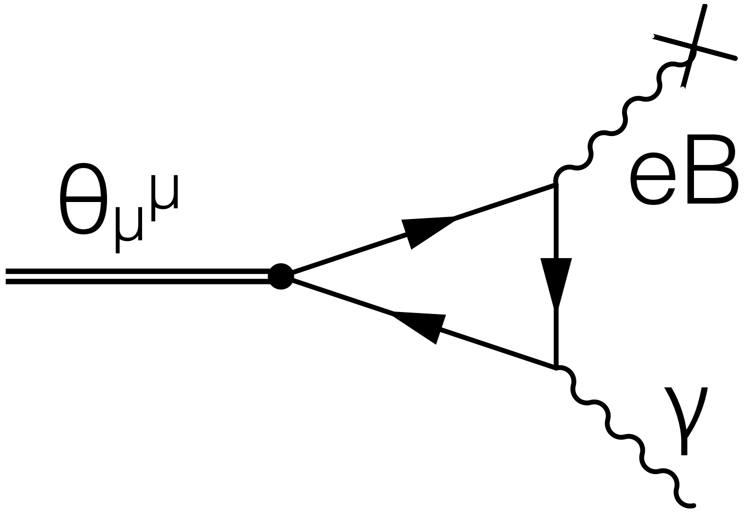
- effective Lagrangian

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

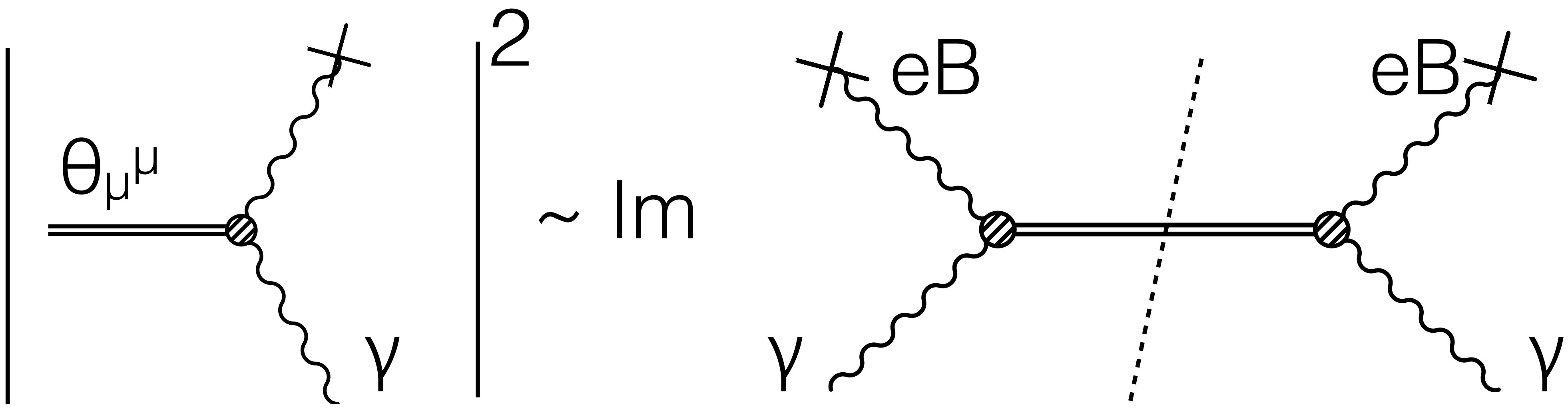
- $g_{\sigma\gamma\gamma} \cong 0.02$ GeV^{-1} *Ellis and Lanik; Crewther; Chanowitz*

Photon production rate

- one of the photons: classical field eB



- production rate, as usual (β=1/T):



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

The rate

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

Numerical coefficient;
constrained by hadronic
observables

Momentum dependence;
$\beta=1/T$; 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:

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

A more general approach

- 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.

- G. Basar, D. Kharzeev, E. Shuryak, 2014: Effective Lagrangian

$$g_T T^{\mu\nu}_{glue} T^{\mu\nu}_{\gamma\gamma} + g_S F^2 T^{\mu}_{\mu\ glue}$$

not taken
into account in this talk

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 $\zeta \geqq 2 \eta (1/3-c_s^2)$)

  $C_\zeta = 15$ in relaxation time approximation (S. Weinberg '71)

  $C_\zeta = 45$ in LO SU(3) YM (K. Dusling and T. Schafer '11)

  $C_\zeta = 2.5$-5 phenomenological constraints

  in this talk: conservative $C_\zeta = 2.5$-5

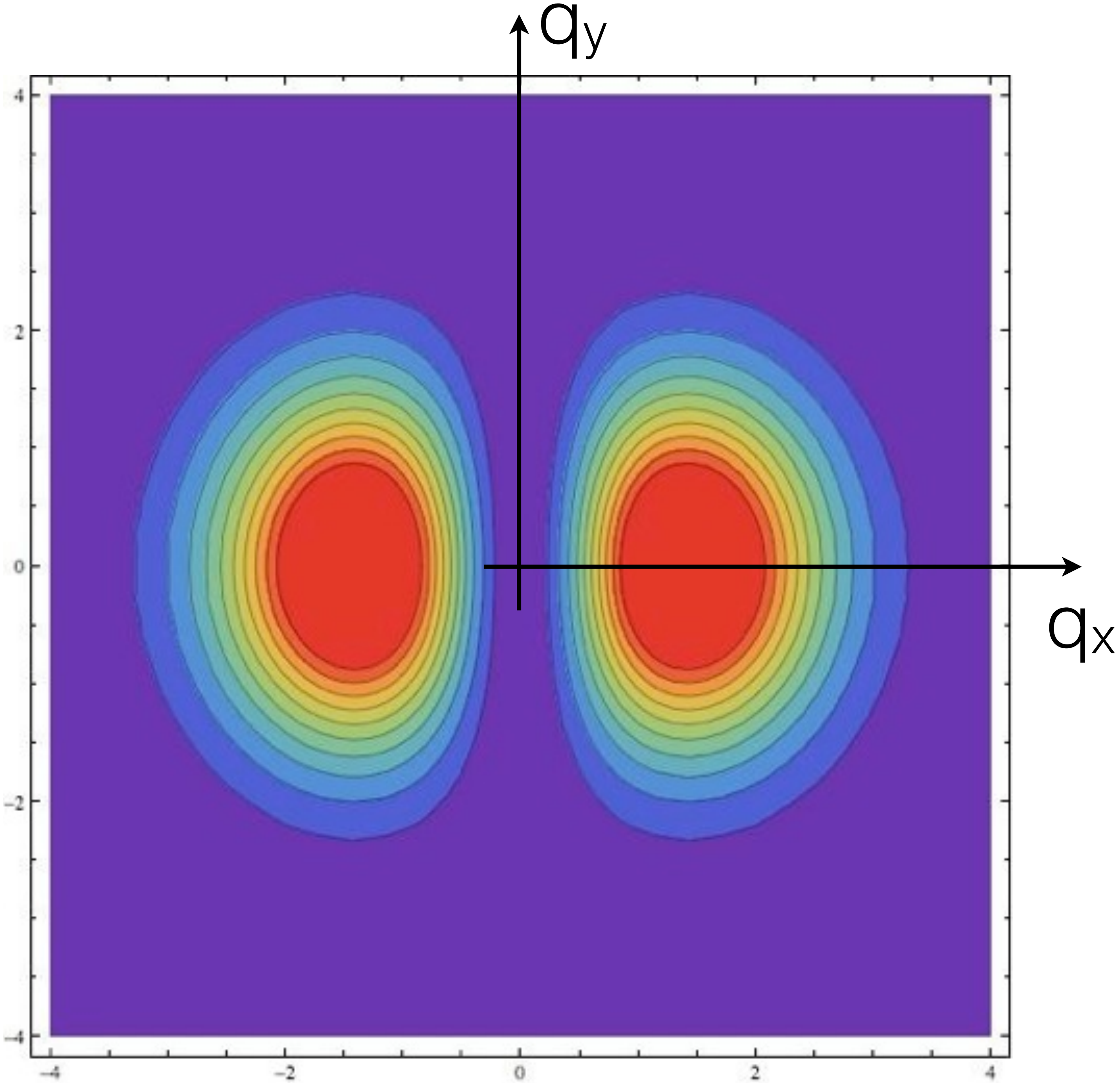
- also conservative $\eta/s=1/(4\pi)$.

- Entropy, s, from matrix model fitted to YM SU(3)

Anisotropy of production rate

- in this mechanism:

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

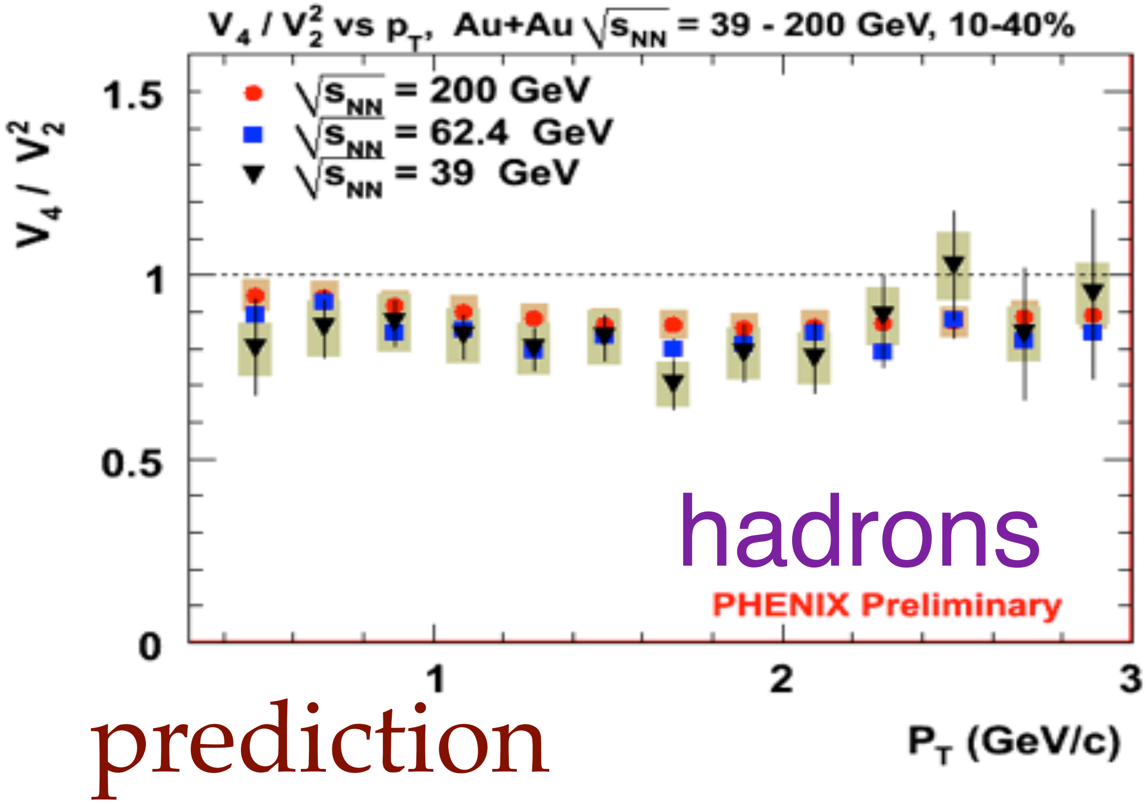


consequently:

- non-zero v_2, **zero** v_3
- small v^{γ}_n, n=4,...

  in contrast to hadronic v_4

  PHENIX: $v_4/v_2^2 \sim 1$



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 (not taken into account in these calculations)

- **more realistic simulations are required**

G. Basar, D. Kharzeev, V.S., 2011

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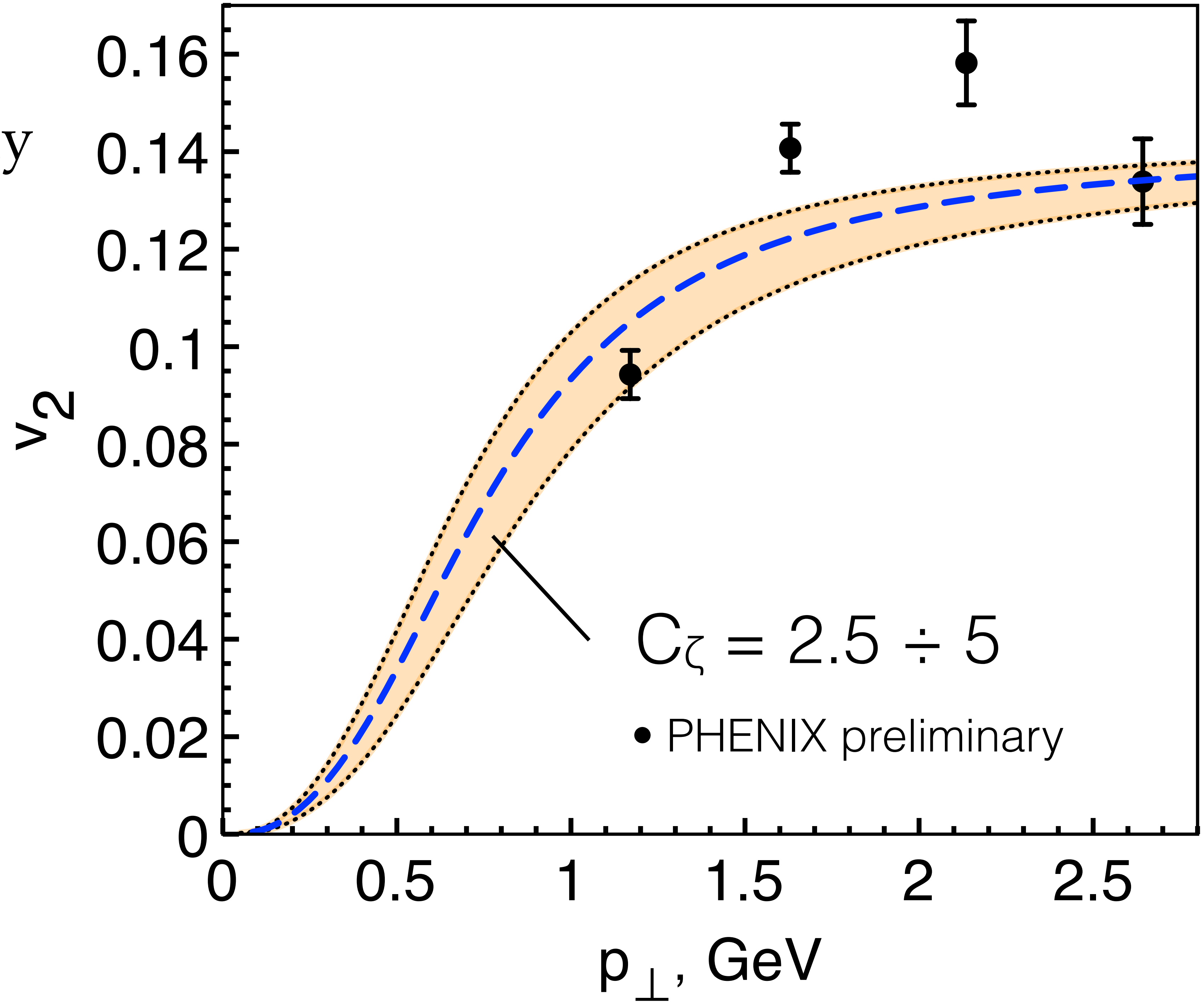
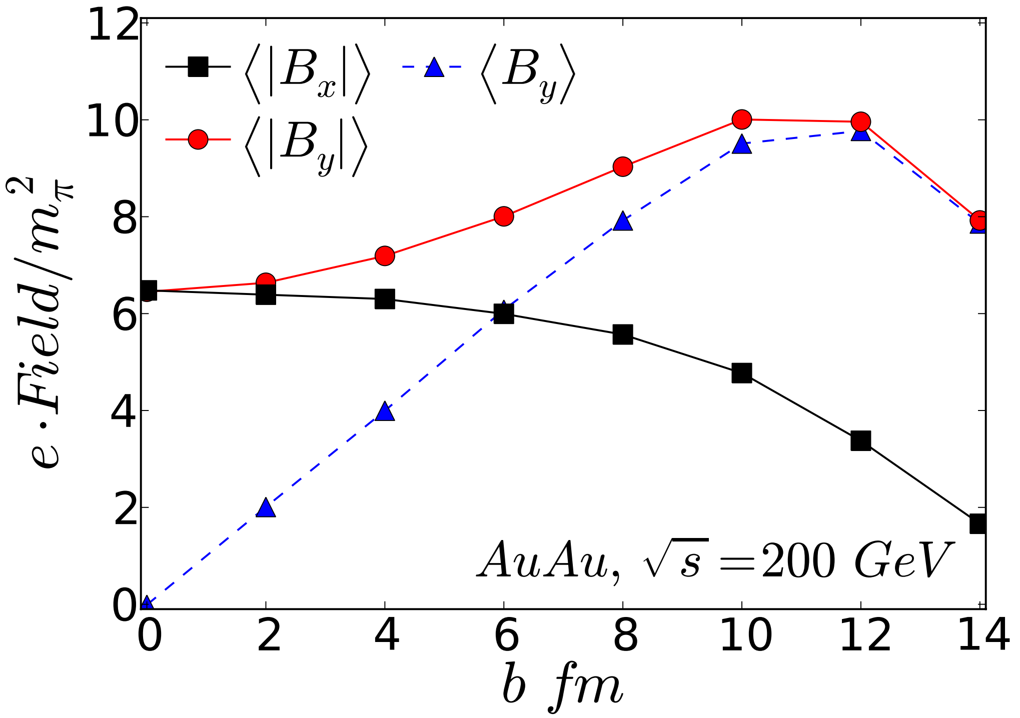
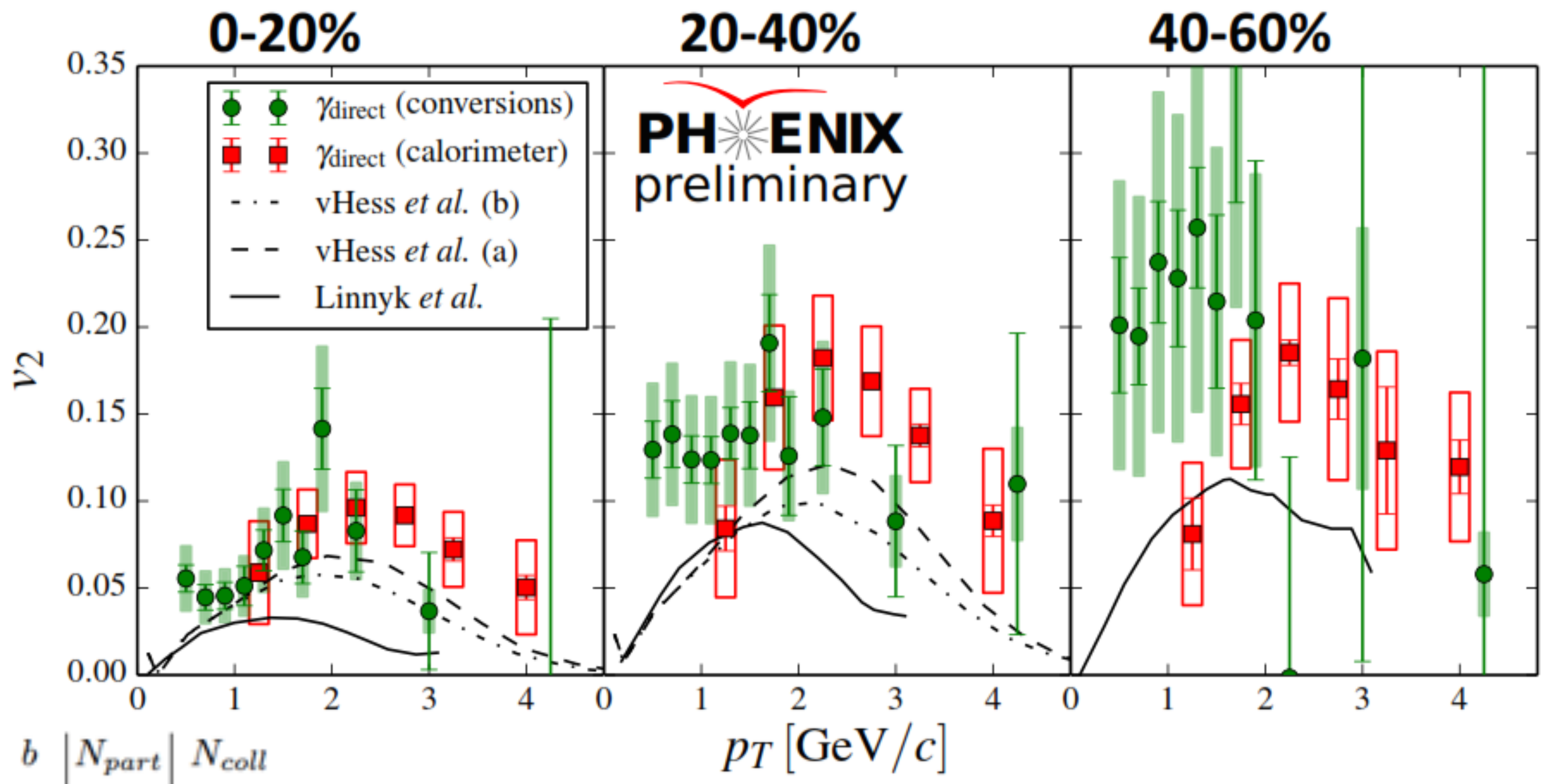


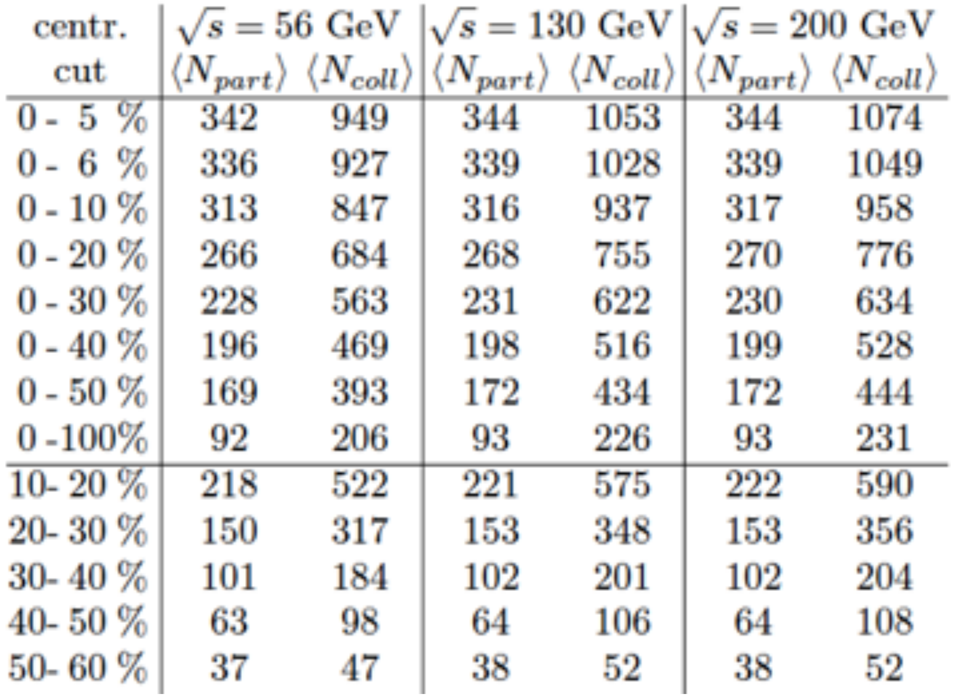
G. Basar, D. Kharzeev, V.S., 2011

Centrality dependence

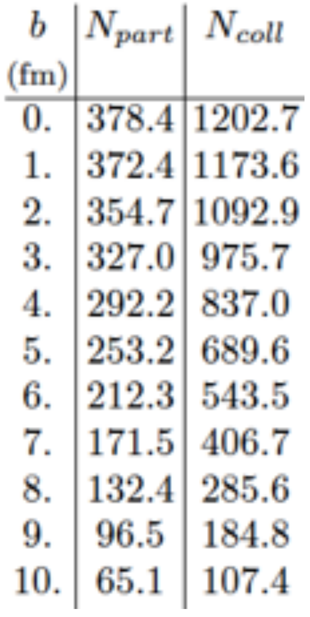
- Centrality dependence owing to dependence of magnetic field on impact parameter







centr. cut	$\sqrt{s} = 56$ GeV $\langle N_{part}\rangle$	$\sqrt{s} = 56$ GeV $\langle N_{coll}\rangle$	$\sqrt{s} = 130$ GeV $\langle N_{part}\rangle$	$\sqrt{s} = 130$ GeV $\langle N_{coll}\rangle$	$\sqrt{s} = 200$ GeV $\langle N_{part}\rangle$	$\sqrt{s} = 200$ GeV $\langle N_{coll}\rangle$
0 - 5 %	342	949	344	1053	344	1074
0 - 6 %	336	927	339	1028	339	1049
0 - 10 %	313	847	316	937	317	958
0 - 20 %	266	684	268	755	270	776
0 - 30 %	228	563	231	622	230	634
0 - 40 %	196	469	198	516	199	528
0 - 50 %	169	393	172	434	172	444
0 -100%	92	206	93	226	93	231
10- 20 %	218	522	221	575	222	590
20- 30 %	150	317	153	348	153	356
30- 40 %	101	184	102	201	102	204
40- 50 %	63	98	64	106	64	108
50- 60 %	37	47	38	52	38	52



b (fm)	N_{part}	N_{coll}
0.	378.4	1202.7
1.	372.4	1173.6
2.	354.7	1092.9
3.	327.0	975.7
4.	292.2	837.0
5.	253.2	689.6
6.	212.3	543.5
7.	171.5	406.7
8.	132.4	285.6
9.	96.5	184.8
10.	65.1	107.4

• Centrality	Magnetic field
0-20%	4 m_π^2
20-40%	8 m_π^2
40-40%	10 m_π^2

Uncertainties

- Hadronic Rates
- Evolution
- Initial time for gluon equilibration
- GG spectral function, application of the hydrodynamical approximation at k~2 GeV

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

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

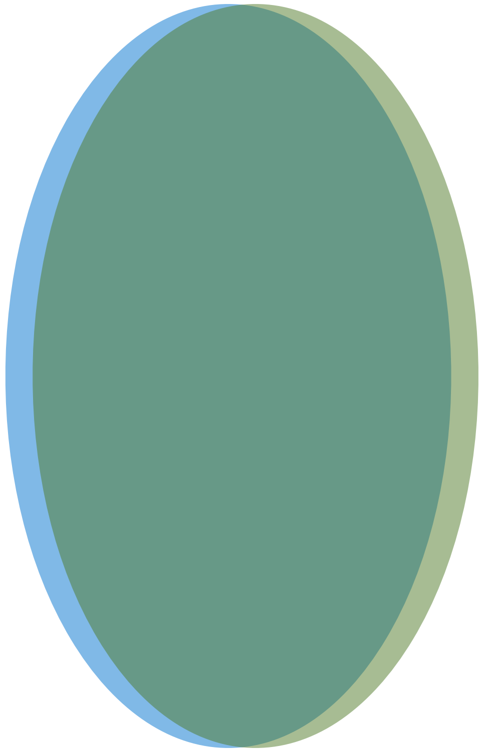
- central U+U collisions

  U is deformed ion:

  events with (almost) no particles in ZDC: **$B=0$**, **$\varepsilon\neq 0$**;

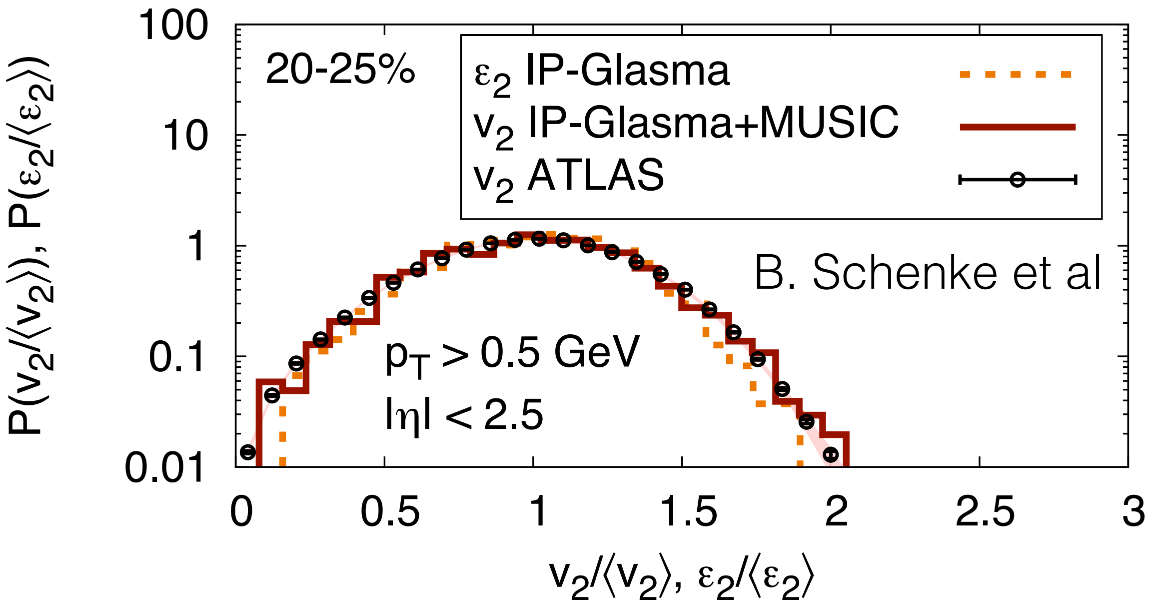
  if photon v_2 is the same as the one of hadrons,

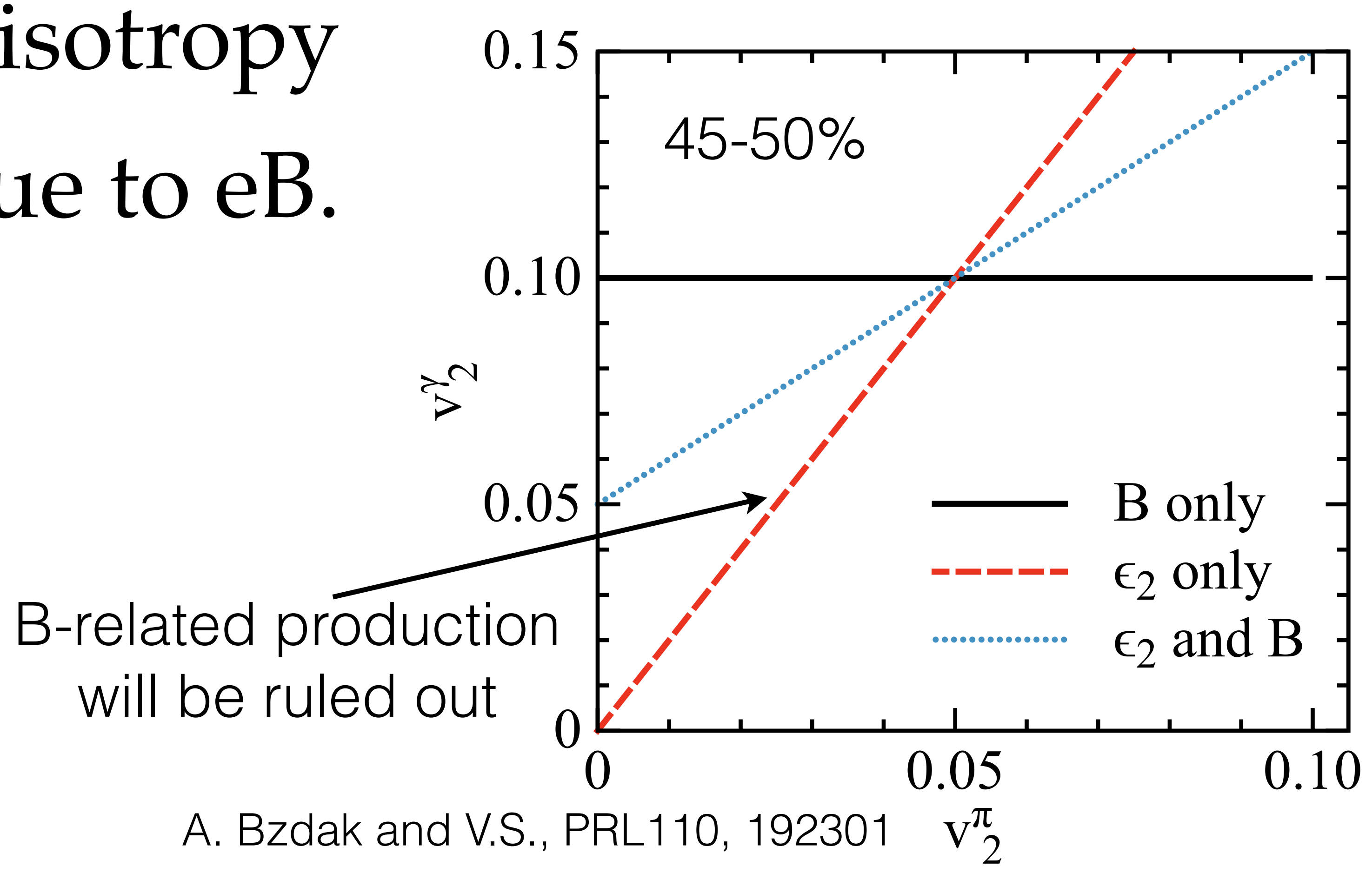
  our mechanism is ruled out



Switching of ε

- non-central collisions: fluctuations of eccentricity in given centrality class (e.g. 40-50% 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.





B-related production will be ruled out

A. Bzdak and V.S., PRL110, 192301

Outlook:LHC energies

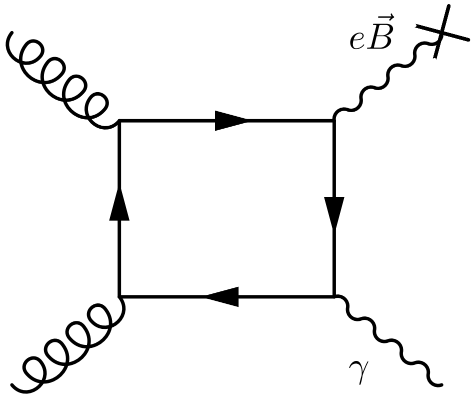
- Higher initial temperatures → lower bulk viscosity

- Large γ → short time scales for non-zero magnetic field

  $t_{LHC} = t_{RHIC}\, \Upsilon_{RHIC} / \Upsilon_{LHC} \rightarrow t_{LHC} \propto 0.01\ \mathrm{fm/c}$ vs $t_{RHIC} \propto 0.1\ \mathrm{fm/c}$

- No need for equilibrium

  - production from Glasma:



Summary

- In HIC we do have

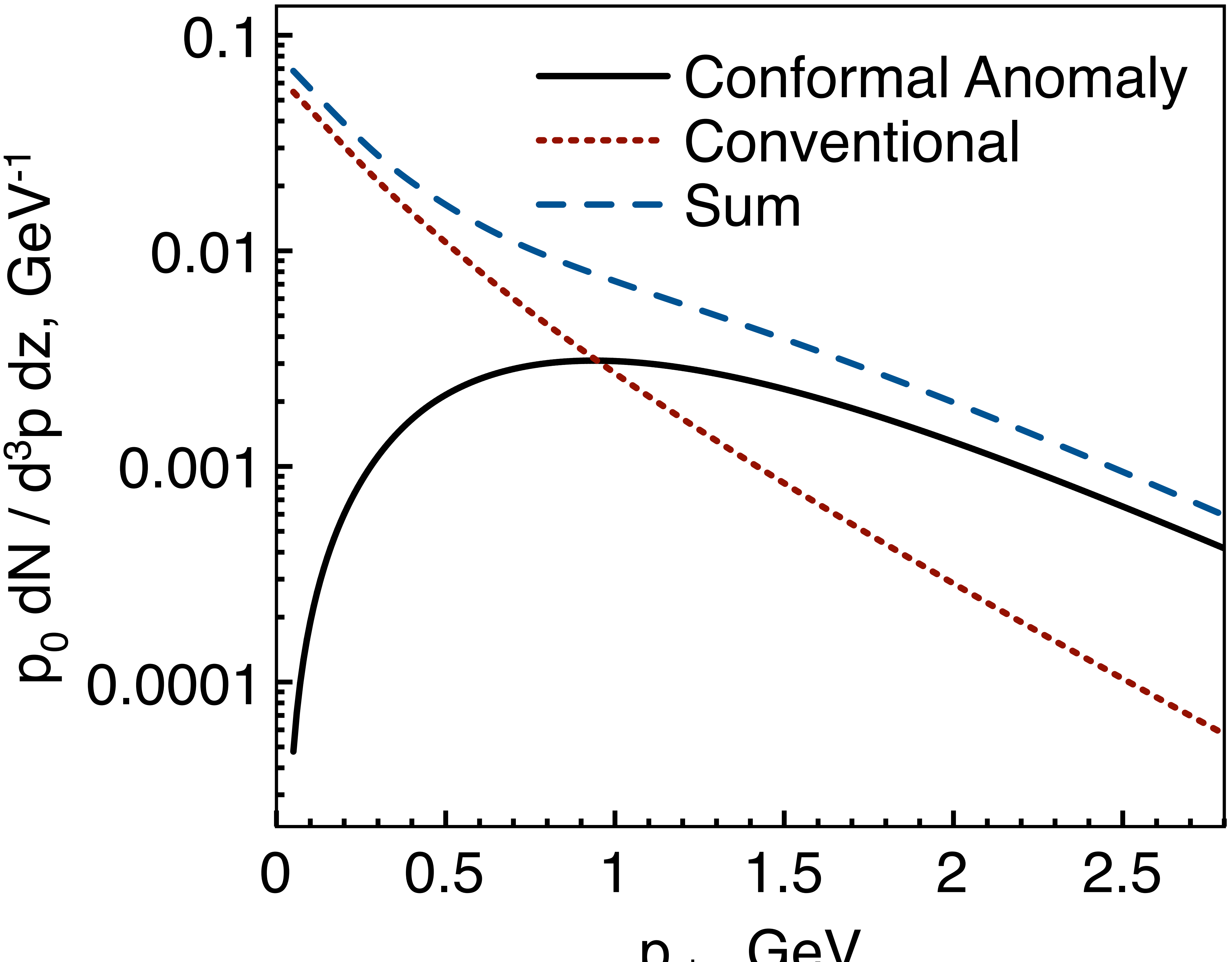
  1) high magnetic field right after collision

  eB~1-10 m_π^2 (m_π^2=10^{18} Gauss)

  2) photon (dilepton) production with azimuthal anisotropy owing to interactions with eB

  3) can be tested in experiment in model-independent way

Back up


Conformal Anomaly
Conventional
Sum
0.1
0.01
0.001
0.0001
0
0.5
1
1.5
2
2.5
p_0 dN / d^3p dz, GeV^{-1}
p GeV