Thermal photon production from gluon fusion induced by magnetic fields in relativistic heavy-ion collisions

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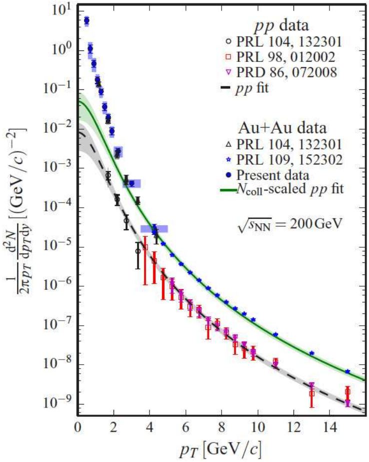
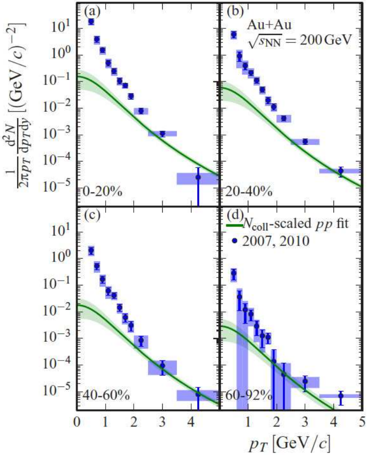
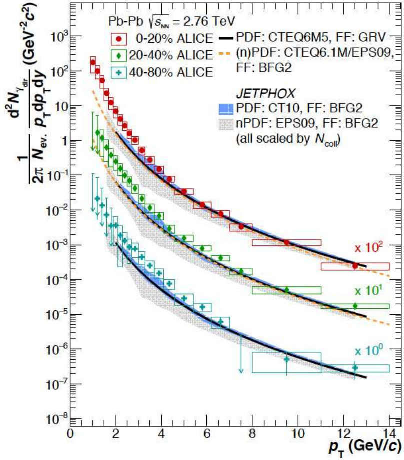
XLVI ISMD, Jeju Island South Korea, August, 2016

PHENIX, Phys. Rev. **C** 91, 064904 (2015)





ALICE, Phys. Lett. B **754**, 235-248 (2016)

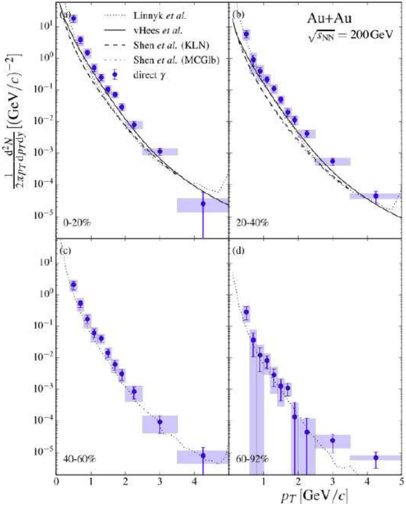


Outline

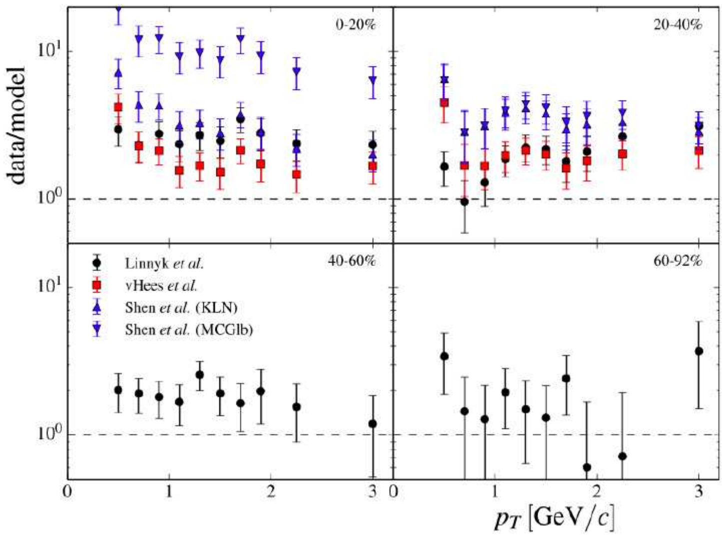
- Thermal photon excess as of 2014
- Current status: Data vs. models
- Magnetic field effects as a source of excess yield
- Gluon fusion into photons
- Conclusions

PHENIX compared to models as of 2014: Yield underestimated

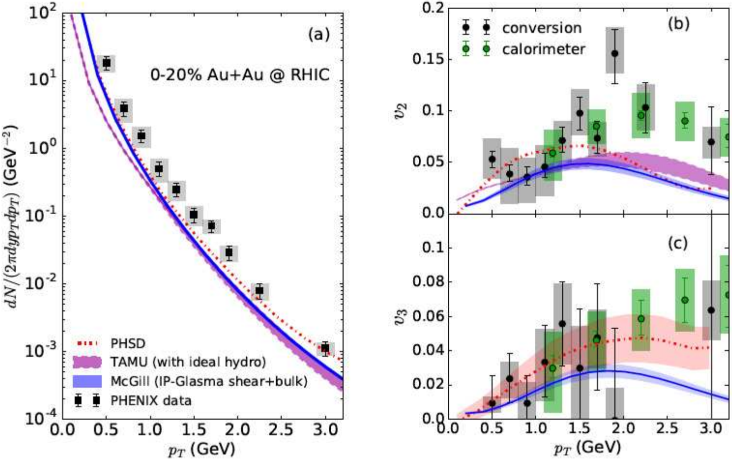
- Transport model: Linnyk, Cassing, Bratkovskaya, Phys. Rev. **C** 89, 034908 (2014)
- Fireball model: van Hees, Gale, Rapp, Phys. Rev. **C** 84, 054906 (2011)
- Hydro model: Shen, Heinz, Paquet, Gale, Phys. Rev. **C** 89, 044910 (2014)



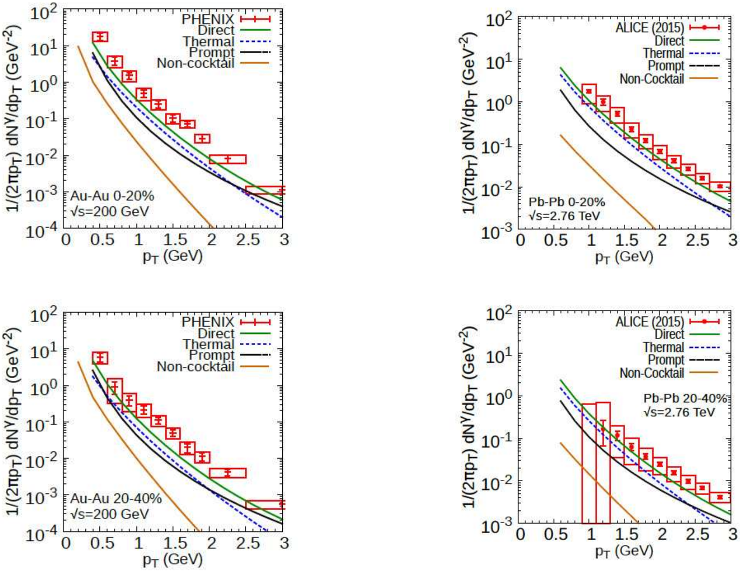
PHENIX compared to models as of 2014: Yield underestimated



PHENIX compared to models as of 2016: improvement
C. Shen e-Print: arXiv:1601.02563



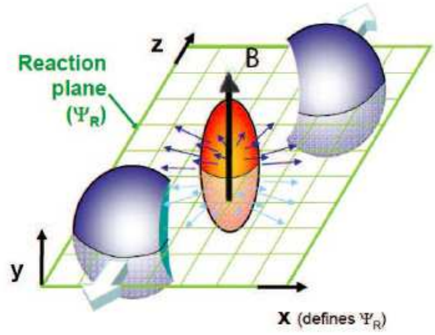
J.-F- Paquet *et al.*, arXiv:1509.06738



Summary of photon excess yield and flow:

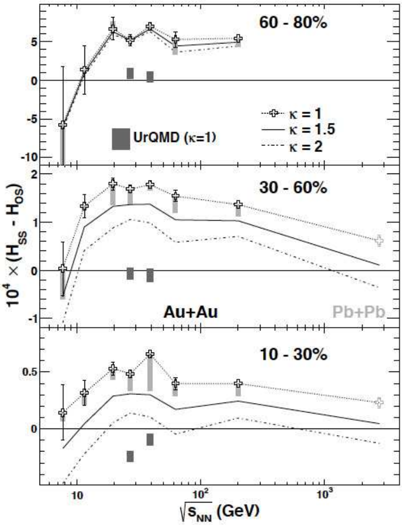
- Models have improved (including updated photon emission rates, viscosity, IP-Glasma)
- Models consistent with yield within the **(lower part of)** uncertainties
- v_2 still not well described
- v_3 better described than v_2

Magnetic field in heavy-ion collisions

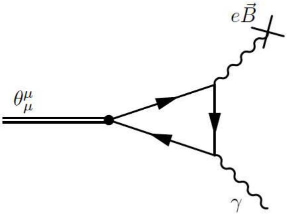


Charge separation along the magnetic field

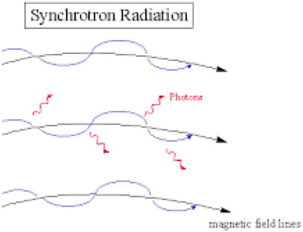
W. Broniowski, W. Florkowski, Phys. Rev. **C** 65, 024905 (2002)



Photons from magnetic field

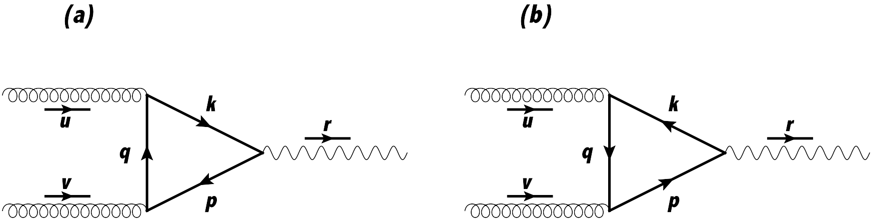


- Trace anomaly converts energy-momentum of gluon bulk into photons
  G. Basar, D. Kharzeev, V. Skokov
  Phys. Rev. Lett. **109**, 202303 (2012)



- Photon emission by quark synchrotron radiation
  K.Tuchin, Phys. Rev. C **91**, 014902 (2015)

Photon production from gluon fusion



- Gluons are far more abundant than quarks at early times
- Largest magnetic field intensities and largest temperatures at early times of the collision
- Diagrams have same relative sign in the presence of magnetic field

Fermion propagator in magnetic field

The fermion propagator in coordinate space cannot longer be written as a simple Fourier transform of a momentum propagator

$$S(x,x') = \Phi(x,x') \int \frac{d^4p}{(2\pi)^4} e^{-ip\cdot(x-x')} S(p)$$

where

$$\Phi(x,x') = \exp\left\{ iq_f \int_{x'}^{x} d\xi^\mu \left[A_\mu + \frac{1}{2} F_{\mu\nu}(\xi - x')^\nu \right] \right\}$$

is called the *phase factor*

Matrix element

$$\begin{aligned}
\mathcal{M}^{(a)} &= -\int d^4x \int d^4y \int d^4z \int \frac{d^4p}{(2\pi)^4} \int \frac{d^4q}{(2\pi)^4} \int \frac{d^4k}{(2\pi)^4} \\
&\times\ e^{-ip\cdot(y-x)} e^{-iq\cdot(z-y)} e^{-ik\cdot(x-z)} e^{-iu\cdot z} e^{-iv\cdot y} e^{ir\cdot x} \\
&\times\ \mathrm{Tr}\left[iq_f \gamma_\mu iS(k) ig\gamma_\alpha t^c iS(q) ig\gamma_\nu t^d iS(p) \right] \\
&\times\ \Phi(x,y)\Phi(y,z)\Phi(z,x)\epsilon^{*\mu}(\lambda_r)\epsilon^{\alpha}(\lambda_u)\epsilon^{\nu}(\lambda_v).
\end{aligned}$$

Fermion propagator in magnetic field: Intense field $\Longrightarrow$ Lowest Landau Level

The piece of the propagator $S(p)$ in momentum-space

$$
\begin{aligned}
iS(p) \quad &= \quad \int_0^\infty \frac{ds}{\cos(q_f Bs)} e^{is\left(p_\parallel^2 - p_\perp^2 \frac{\tan(q_f Bs)}{q_f Bs} - m_f^2 + i\epsilon\right)} \\
&\times \quad \left[\left(\cos(q_f Bs) + \gamma_1\gamma_2 \sin(q_f Bs)\right)\left(m_f + \not{p}_\parallel\right) - \frac{\not{p}_\perp}{\cos(q_f Bs)} \right] \\
\xrightarrow{LLL} &\quad 2ie^{-\frac{p_\perp^2}{q_f B}} \frac{\left(\not{p}_\parallel + m_f\right)}{p_\parallel^2 - m_f^2} \left[\frac{1 - i\gamma_1\gamma_2}{2} \right]
\end{aligned}
$$

The operator

$$
\mathcal{O}_\parallel = \left[1 - i\gamma_1\gamma_2\right]/2
$$

projects onto the longitudinal space. Therefore the **matrix element can be factorized into a product of transverse and longitudinal pieces**

Matrix element fractorizes into product of transverse and longitudinal pieces

$$\begin{aligned}
\mathcal{M}^{(a)} &= (2\pi)^4\delta^4(r-v-u)\mathcal{M}_{\perp}^{(a)}\mathcal{M}_{\parallel}^{(a)} \\
\mathcal{M}_{\perp}^{(a)} &= \left(\frac{4\pi}{q_f B}\right)^2 \int \frac{d^2p_\perp}{(2\pi)^2}\int \frac{d^2q_\perp}{(2\pi)^2}\int \frac{d^2k_\perp}{(2\pi)^2} \\
&\times\ e^{-\frac{k_\perp^2}{q_f B}} e^{-\frac{q_\perp^2}{q_f B}} e^{-\frac{p_\perp^2}{q_f B}} \prod_{i,j=1,2} e^{i\frac{2}{q_f B}\epsilon_{ij}(q-k+u)_i(q-p-v)_j} \\
&= \left(\frac{q_f B}{12\pi}\right) e^{-\frac{(u+v)_\perp^2}{3q_f B}}, \\
\mathcal{M}_{\parallel}^{(a)} &= -8\left(\frac{q_f g^2\delta^{cd}}{2}\right)\int \frac{d^2p_\parallel}{(2\pi)^2}\int \frac{d^2q_\parallel}{(2\pi)^2}\int \frac{d^2k_\parallel}{(2\pi)^2} \\
&\times\ (2\pi)^4\delta^2\left[(q-k+u)_\parallel\right]\delta^2\left[(q-p-v)_\parallel\right]\epsilon^{*\mu}(\lambda_r) \\
&\times\ \frac{\mathrm{Tr}\left[\gamma_\mu \not{k}_\parallel \mathcal{O}_\parallel \gamma_\alpha \not{q}_\parallel \mathcal{O}_\parallel \gamma_\nu \not{p}_\parallel \mathcal{O}_\parallel\right]}{k_\parallel^2 q_\parallel^2 p_\parallel^2}\epsilon^{\alpha}(\lambda_u)\epsilon^{\nu}(\lambda_v)
\end{aligned}$$

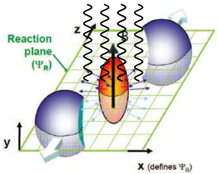
Early stages, gluons more abundant, quarks don't thermalize

- Hierarchy of energy scales $\sqrt{eB} > m$, $T > m$.
- Early stages gluons far more abundant than quarks
- Assume quarks do not yet thermalize.
- $m_f = 0$ since in the absence of thermal corrections, the light-quark vacuum masses are negligible.
- The trace contains the product of up to twelve gamma matrices. Upon squaring and summing over polarizations, only a small piece survives

$$\begin{aligned}
\mathrm{Tr}\left[\gamma_\mu \not{k}_\parallel \mathcal{O}_\parallel \gamma_\alpha \not{q}_\parallel \mathcal{O}_\parallel \gamma_\nu \not{p}_\parallel \mathcal{O}_\parallel\right] \quad &\longrightarrow \quad k_{\parallel\nu}(p_{\parallel\mu} q_{\parallel\alpha} - p_{\parallel\alpha} q_{\parallel\mu}) \\
&+ \quad k_{\parallel\mu}(p_{\parallel\nu} q_{\parallel\alpha} + p_{\parallel\alpha} q_{\parallel\nu}) \\
&+ \quad k_{\parallel\alpha}(p_{\parallel\nu} q_{\parallel\mu} - p_{\parallel\mu} q_{\parallel\nu})
\end{aligned}$$

Kinematical simplifications

- For photons emitted at mid-rapidity, **momentum components along the reaction plane are small.**
- Reaction plane is perpendicular to the magnetic field then $r_\perp = (u+v)_\perp \simeq 0$.
- Focus on photons with small momentum $r_3 = (v+u)_3 \simeq 0$.
- Focus on describing emission of real photons $r^2 = (u+v)^2 = 0$.
- The main thermal effect on low momentum gluons is the development of a **thermal mass** $m_g \sim gT$**.**



Photon yield $m_f = 0$, thermal gluons, low p_t photons

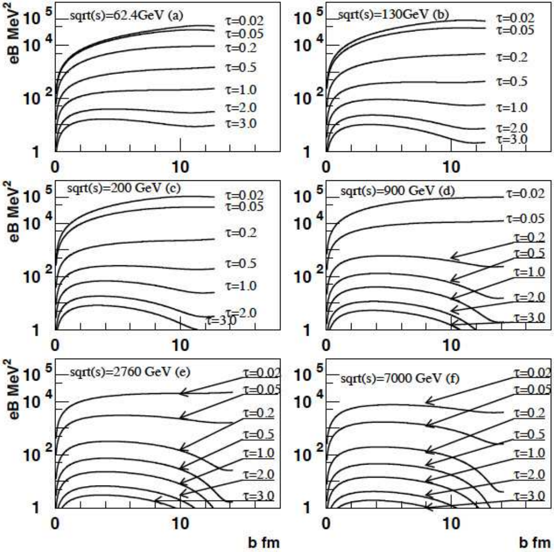
$$\begin{aligned}\frac{r_0 dN}{d^3r} &= \frac{1}{2(2\pi)^3}\int \frac{d^3u}{2u_0(2\pi)^3}\int \frac{d^3v}{2v_0(2\pi)^3} \\ &\times \sum_{\mathrm{pol},f} |\mathcal{M}|^2\, n(u_0)n(v_0)\end{aligned}$$

$$\frac{1}{2\pi N r_t dr_t}\frac{dN}{} = \frac{\left[\left(\frac{1}{3}\right)^4 e^{-2\frac{y_0^2 r_t^2}{eB}} + \left(\frac{2}{3}\right)^4 e^{-\frac{y_0^2 r_t^2}{eB}}\right]\frac{I(r_t/T)}{2\pi}}{\sqrt{3\pi eB/2}\left[\left(\frac{2}{3}\right)^{9/2} + \left(\frac{1}{3}\right)^{9/2}\right]\int_0^\infty dr_t I(r_t/T)}$$

$$I(z;\lambda) \equiv \int_0^z \frac{dx x^2 n\left(\sqrt{(z+x)^2-(2x)^2}\right)n(x)}{\left(\sqrt{x^2+\lambda^2}\right)\left(\sqrt{(z+x)^2-(2x)^2+\lambda^2}\right)}$$

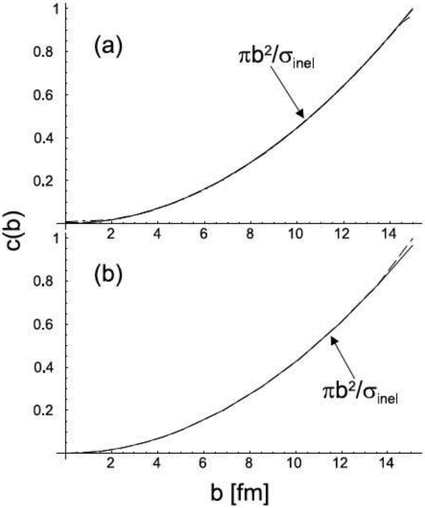
Magnetic field strength with time and impact parameter

Y. Zhong, C.-B. Yang, X. Cai, S.-Q. Feng, Adv. High Energry Phys. 2014, 193039 (2014)



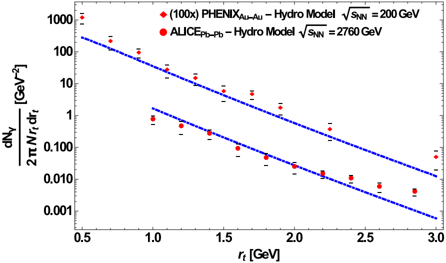
Centrality vs. impact parameter

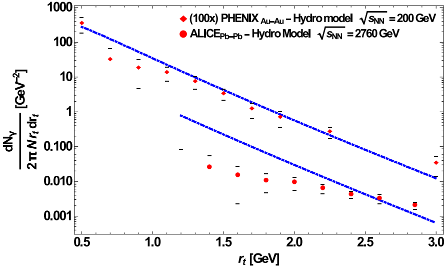
W. Broniowski, W. Florkowski, Phys. Rev. **C** 65, 024905 (2002)



Excess photon yield from magnetic field induced gluon fusion compared to McGuil hydro

A.A., J. Castaño-Yepes, C. A. Dominguez, L. Hernández, arXiv:1604.02713





- $T = 300$ MeV for $\sqrt{s_{NN}} = 200$ GeV (RHIC)
- $T = 350$ MeV for $\sqrt{s_{NN}} = 2.76$ TeV (LHC)
- $g = 1$
- $0.5 \times 10^4 < eB/(\text{MeV})^2 < 10^5$ for RHIC
- $eB/(\text{MeV})^2 \simeq 10^4$ for LHC

Conclusions

- Magnetic fields linked to observable phenomena in heavy-ion collisions
- Magnetic field induce processes otherwise now allowed such as emission of photons from gluon fusion
- Size of excess yield can be accounted for using reasonable values for eB, T and g.
- Magnetic fields naturally induce asymmetry (v_2).