Photon production induced by magnetic fields in HICs: photon yield and elliptic flow.

Instituto de Ciencias Nucleares UNAM

Luis A. Hernandez

PHYSICAL REVIEW D **96,** 014023 (2017)

Prompt photon yield and elliptic flow from gluon fusion induced by magnetic fields in relativistic heavy-ion collisions

Alejandro Ayala,[1,2] Jorge David Castaño-Yepes,[1] C. A. Dominguez,[2] L. A. Hernández,[1] Saúl Hernández-Ortiz,[1] and María Elena Tejeda-Yeomans[3]

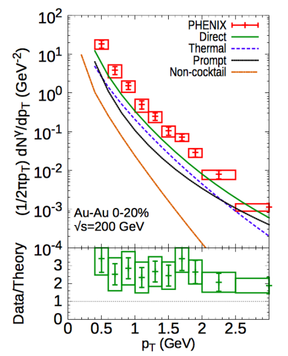
September 11, 2017

Instituto de Ciencias Nucleares, UNAM.

Outline

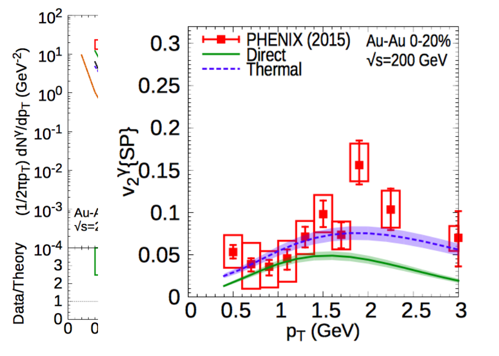
1. Motivation
2. Production of $\gamma' s$.
3. Results
4. Conclusion

Thermal photon puzzle.



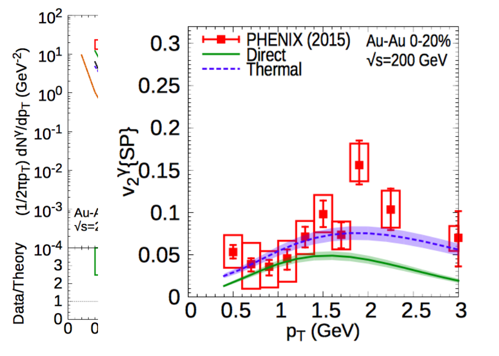
J-F Paquet *et al.*,Phys. Rev. C **93**, (2016) 044906

Thermal photon puzzle.



J-F Paquet *et al.*,Phys. Rev. C 93, (2016) 044906

Thermal photon puzzle.

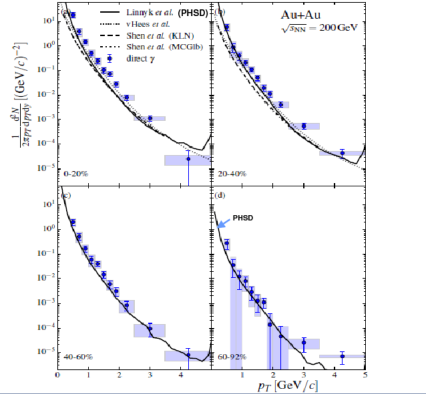


J-F Paquet *et al.*,Phys. Rev. C 93, (2016) 044906

- Data status of direct photons.
- Data/model comparisons.
- Excess at low p_t.
- New processes to explain the excess.

Data vs Models 2014

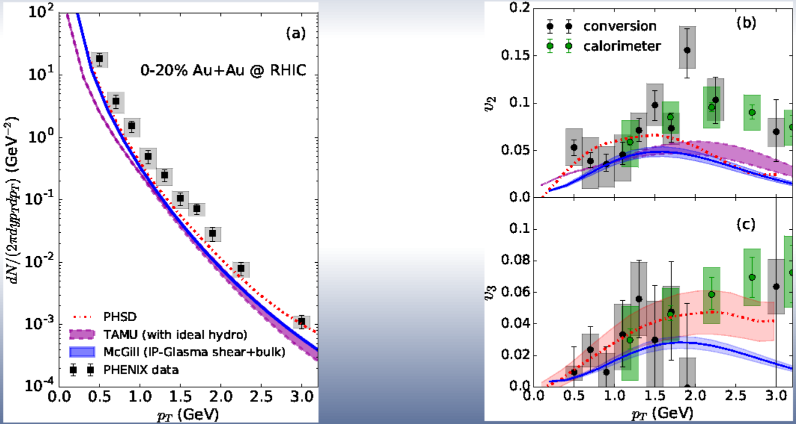
O. Linnyk, E. L. Bratkovskaya and W. Cassing, Prog. Part. Nucl. Phys. **87** (2016) 50-115.



- Transport model: O. Linnyk, E. L. Bratkovskaya and W. Cassing, Phys. Rev. C89, 034908 (2014).
- Fireball model: H. van Hees, C. Gale and R. Rapp, Phys. Rev. C84, 054906 (2011).
- Hydro model: C. Shen, U. W. Heinz, J.-F. Paquet and C. Gale, Phys. Rev. C89, 044910 (2014).

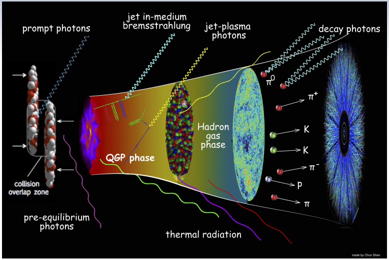
Update Data vs Models 2016

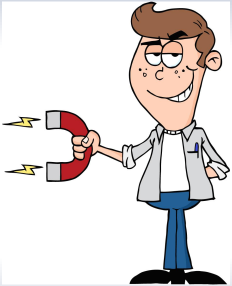
PHENIX compared to models.



C. Shen, arXiv:1601.02563.

Conditions for a new mechanism to produce γ's

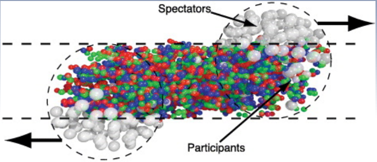




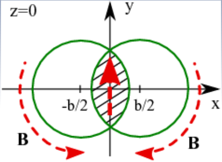
By Chun Shen

We compute the production of prompt photons from the perturbative fusion of low momentum gluons coming from the shattered glasma.

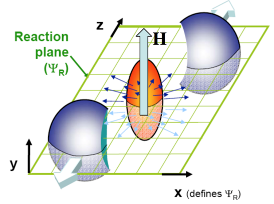
Magnetic fields in HICs.



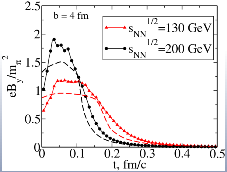
R. Snellings, J. Phys. 13, (2011) 055008



V. Voronyuk *et al.*,Phys. Rev. C **83**, 054911 (2011)



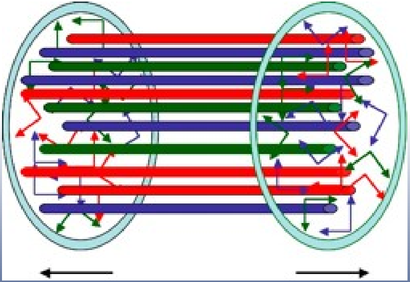
D. E. Kharzeev, L. D. McLerran and H. J. Warringa, Nucl. Phys. A **803**, 227 (2008)



V. Skokov, A. Y. Illarionov and V. Toneev, Int. J. Mod. Phys. A **24**, 5925 (2009)

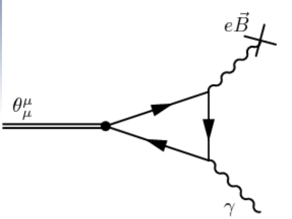
Nonequilibrate gluons.

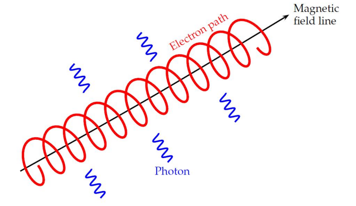
- Over-occupied initial state called the *glasma*.
- Saturation effects $\rightarrow$ times of order $\tau_s \sim 1/\Lambda_s$
- $\Lambda_s \equiv$ saturation scale.
- $\Delta\tau_s \simeq 1 - 1.5$fm



By Larry McLerran, ISMD2008

Photons from magnetic fields.





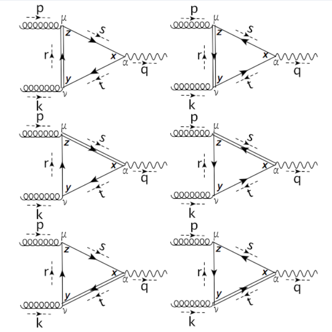
- Trace anomaly converts energy-momentum of gluon bulk into photons.

  G. Basar, D. Kharzeev and V. V. Skokov, Phys. Rev. Lett. **109**, 202303 (2012).

- Photon emission by quarks synchrotron radiation.

  K. Tuchin, Phys. Rev. C**91**, 0124902 (2015).

Gluon fusion induced by eB



The quark propagator is written in its coordinate space representation as

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

where

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

the Schwinger phase factor.

Strong magnetic fields.

The translational invariant part of the propagator is written in terms of Landau levels, since the strength of the magnetic fields is dominant, therefore we consider the Lowest Landau Level (LLL) or at most the first Landau Level (1LL)

$$
\begin{aligned}
S^{\mathrm{LLL}}(p) &= -2ie^{-\frac{p_\perp^2}{|q_f B|}} \frac{\not{p}_\parallel}{p_\parallel^2} \mathcal{O}_\parallel^+ , \\
S^{\mathrm{1LL}}(p) &= \frac{e^{-\frac{p_\perp^2}{|q_f B|}}}{p_\parallel^2 - 2|q_f B|} \left\{ \not{p}_\parallel \mathcal{O}_\parallel^+ \left[1 - \frac{2p_\perp^2}{|q_f B|} \right] - \not{p}_\parallel \mathcal{O}_\parallel^- + 4\not{p}_\perp \right\} .
\end{aligned}
$$

with

$$
\mathcal{O}_\parallel^\pm = \left[1 \pm (\mathrm{sign}(q_f B)) i\gamma_1\gamma_2 \right] / 2
$$

Notation

- $\boldsymbol{B} = B\hat{z}$.
- Vector potential $A^\mu = \frac{B}{2}(0, -y, x, 0)$ (*symmetric gauge*).
- $p_\perp^\mu \equiv (0, p_1, p_2, 0)$,
  $p_\parallel^\mu \equiv (p_0, 0, 0, p_3)$,
  $p_\perp^2 \equiv p_1^2 + p_2^2$ and
  $p_\parallel^2 \equiv p_0^2 - p_3^2$,
  therefore $p^2 = p_\parallel^2 - p_\perp^2$.

The amplitude for the process.

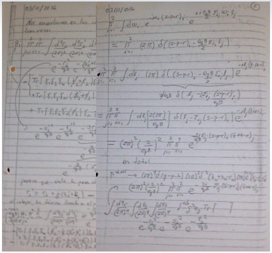
$$
\begin{aligned}
\widetilde{\mathcal{M}} &= -\int d^4x d^4y d^4z \int \frac{d^4r}{(2\pi)^4}\frac{d^4s}{(2\pi)^4}\frac{d^4t}{(2\pi)^4} \\
&\times\ e^{-it\cdot(y-x)}e^{-is\cdot(x-z)}e^{-ir\cdot(z-y)}e^{-ip\cdot z}e^{-ik\cdot y}e^{iq\cdot x} \\
&\times\ \left\{\mathrm{Tr}\left[iq_f\gamma_\alpha iS(s)ig\gamma_\mu t^c iS(r)ig\gamma_\nu t^d iS(t)\right]\right. \\
&+\ \left.\mathrm{Tr}\left[iq_f\gamma_\alpha iS(t)ig\gamma_\nu t^d iS(r)ig\gamma_\mu t^c iS(s)\right]\right\} \\
&\times\ \Phi(x,y)\Phi(y,z)\Phi(z,x)\epsilon^\mu(\lambda_p)\epsilon^\nu(\lambda_k)\epsilon^\alpha(\lambda_q)
\end{aligned}
$$

Three steps.

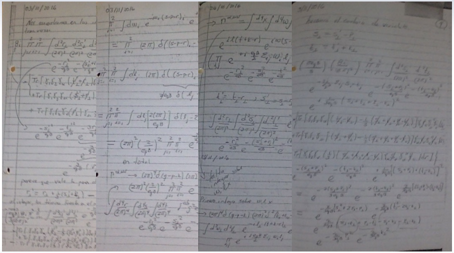
Compute:

1. Product of Schwinger phase factors/integrals over the space-time points.
2. Tensor structures.
3. Integrals over the momenta.

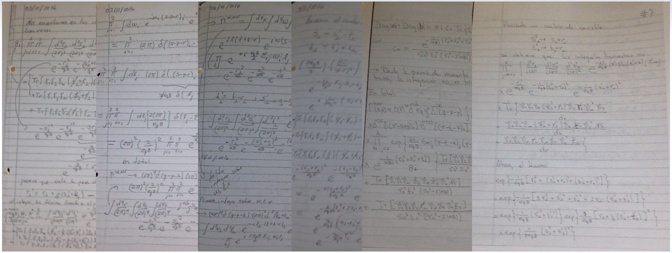
Computing process



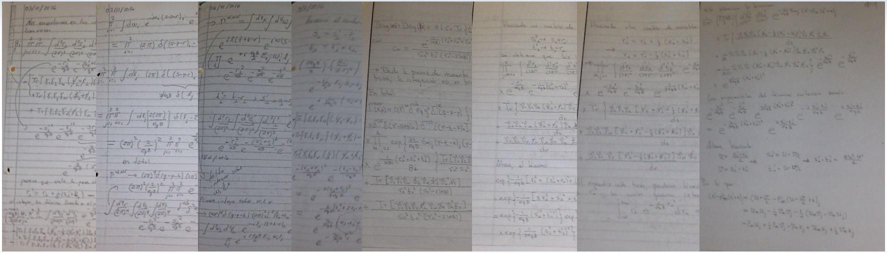
Computing process



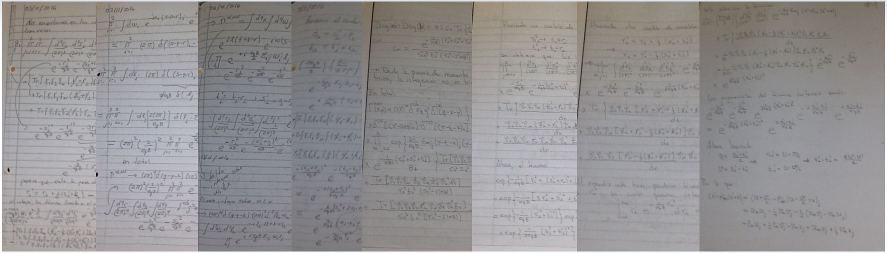
Computing process



Computing process



Computing process



to be continued...

Photon production probability.

$$\frac{1}{4}\sum_{\text{pol}}|\widetilde{\mathcal{M}}|^2 = (2\pi)^4\delta^{(4)}(q-k-p)\,\mathcal{V}\tau_s\frac{1}{4}\sum_{\text{pol}}|\mathcal{M}|^2,$$

- Average over the initial gluons.
- $\mathcal{V}\tau_s$ is the space-time volume

Explicitly

$$\frac{1}{4}\sum_{\text{pol}}|\mathcal{M}|^2 = \frac{q_f^2\alpha_{\text{em}}\alpha_s^2}{(2\pi)\omega_q^2}\left(\omega_p^2+3\omega_k^2\right)q_\perp^2\exp\left\{-\frac{q_\perp^2}{q_f B\omega_q^2}\left[\omega_p^2+\omega_k^2-\omega_p\omega_k\right]\right\}.$$

We have already used that the produced photon needs to move in the original gluon's direction.

$$\begin{aligned} p^\mu &= \omega_p(1,\hat{p}) = (\omega_p/\omega_q)\,q^\mu, \\ k^\mu &= \omega_k(1,\hat{k}) = (\omega_k/\omega_q)\,q^\mu. \end{aligned}$$

Invariant photon momentum distribution.

$$\omega_q \frac{dN^{\text{mag}}}{d^3q} = \frac{\chi \mathcal{V} \Delta\tau_s}{2(2\pi)^3} \int \frac{d^3p}{(2\pi)^3 2\omega_p} \int \frac{d^3k}{(2\pi)^3 2\omega_k} n(\omega_p) n(\omega_k)$$
$$\times \quad (2\pi)^4 \delta^{(4)}(q-k-p) \frac{1}{4} \sum_{\text{pol},f} |\mathcal{M}|^2.$$

- Three flavours.
- $n(\omega)$, distribution of gluons.
- χ, overlap region (semicentral collision).

High occupation gluon number

$$n(\omega) = \frac{\eta}{e^{\omega/\Lambda_s} - 1}.$$

- η high gluon occupation factor.
- Λ_s the saturation scale

We introduced a *flow velocity* factor, that is, $\omega_{p,k} \to (p,k) \cdot u$. With $u^\mu = \gamma(1,\beta)$ and $\gamma = 1/\sqrt{1-\beta^2}$

Elliptic flow coefficient

The azimuthal distribution with respect to the reaction plane can be given in terms of a Fourier decomposition as

$$\frac{dN^{\text{mag}}}{d\phi} = \frac{N^{\text{mag}}}{2\pi}\left[1 + \sum_{i=1}^{\infty} 2v_n(\omega_q)\cos(n\phi)\right],$$

with total number of photons, N^{mag} is

$$N^{\text{mag}} = \int \frac{d^3q}{(2\pi)^3}\frac{dN^{\text{mag}}}{d^3q}$$

Elliptic flow coefficient

$$v_2(\omega_q) = \frac{\frac{dN^{\text{mag}}}{d\omega_q}(\omega_q)\ v_2^{\text{mag}}(\omega_q) + \frac{dN^{\text{direct}}}{d\omega_q}(\omega_q)\ v_2^{\text{direct}}(\omega_q)}{\frac{dN^{\text{mag}}}{d\omega_q}(\omega_q) + \frac{dN^{\text{direct}}}{d\omega_q}(\omega_q)},$$

γ's invariant momentum distribution

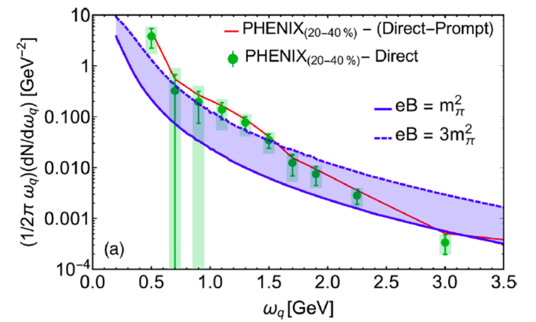


Figure: Difference between PHENIX photon invariant momentum distribution [1] and direct (points) or direct minus prompt (zigzag) photons from [2]

- $\alpha_s = 0.3$,
- $\Lambda_s = 2$ GeV,
- $\eta = 3$,
- $\Delta\tau_s = 1.5$ fm,
- $R = 7$ fm,
- $\beta = 0.25$ and
- $\chi = 0.8$

[1] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. C **91**, 064904 (2015).
[2] J.-F. Paquet, C. Shen, G. S. Denicol, M. Luzum, B. Schenke, S. Jeon, C. Gale, Phys. Rev. C **93**, 044906 (2016).

γ's invariant momentum distribution ($\beta = 0$)

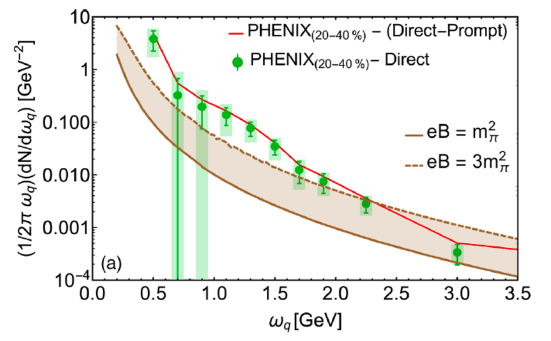


Figure: Difference between PHENIX photon invariant momentum distribution [1] and direct (points) or direct minus prompt (zigzag) photons from [2]

[1] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. C **91**, 064904 (2015).
[2] J.-F. Paquet, C. Shen, G. S. Denicol, M. Luzum, B. Schenke, S. Jeon, C. Gale, Phys. Rev. C **93**, 044906 (2016).

Coefficient v_2

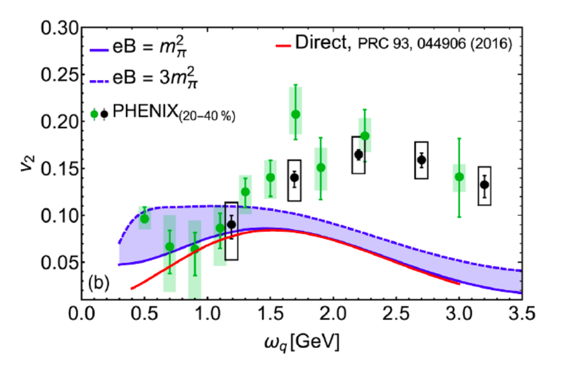


Figure: Harmonic coefficient v_2, using the direct photon result of [1] together with our calculation, also compared to PHENIX data [2]

[1] J.-F. Paquet, C. Shen, G. S. Denicol, M. Luzum, B. Schenke, S. Jeon, C. Gale, Phys. Rev. C **93**, 044906 (2016).
[2] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. C **94**, 064901 (2016).

Coefficient v_2 $(\beta = 0)$

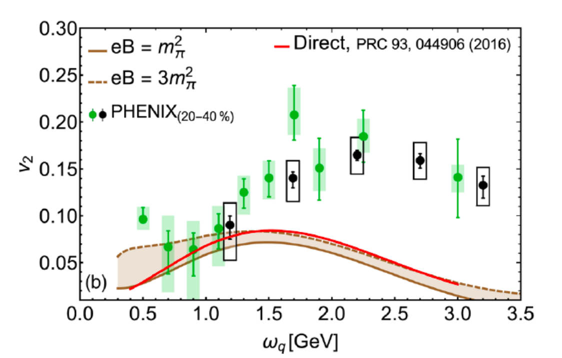


Figure: Harmonic coefficient v_2, using the direct photon result of [1] together with our calculation, also compared to PHENIX [2]

[1] J.-F. Paquet, C. Shen, G. S. Denicol, M. Luzum, B. Schenke, S. Jeon, C. Gale, Phys. Rev. C 93, 044906 (2016).
[2] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. C 94, 064901 (2016).

Summary

- In a semi-central HICs, a magnetic field of a large intensity is produced.
- When eB is the most intense are also the scales associated to the production of a large number of small momentum gluons.
- eB provides the mechanism to allow that gluons fuse and convert into photons in excess over other well studied mechanisms.
- eB also provides an initial asymmetry for the development of an azimuthal anisotropy quantified in terms of a substantial v_2 (particularly at low photon momenta).

Thank you!!!

Enjoy your stay in Tlaxcala!!!