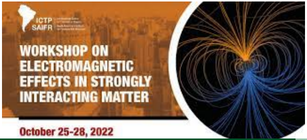
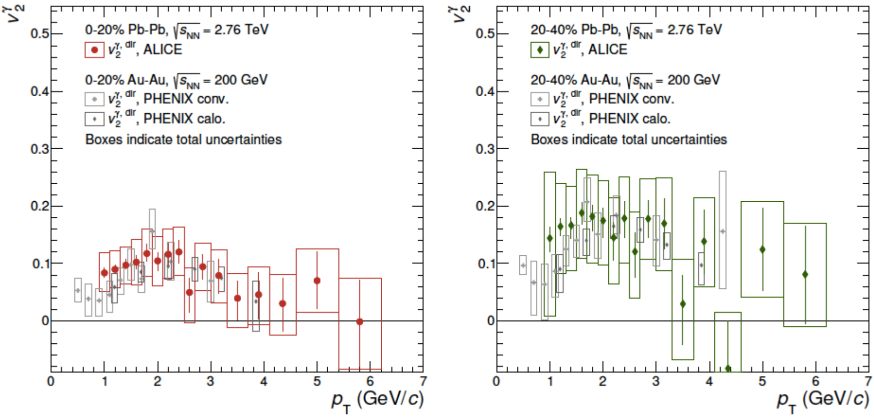
Anisotropic photon emission from gluon fusion and splitting in peripheral heavy-ion collisions with a strong magnetic background

Alejandro Ayala
Instituto de Ciencias Nucleares,
Universidad Nacional Autónoma de México and
Universidade Federal de Santa Maria, Brazil
In collaboration with: J. Castaño, L.A. Hernández, A.J. Mizher,
M.E. Tejeda-Yeomans, R. Zamora
e-Print:2209.09364 [hep-ph]



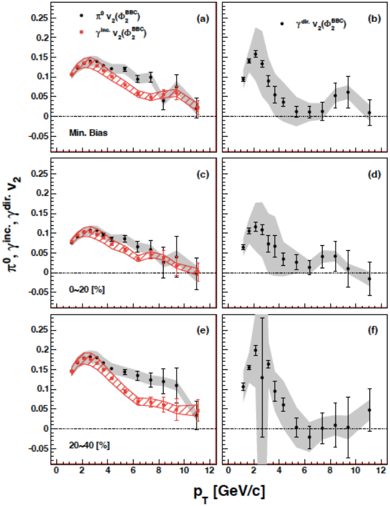
Overview

ALICE & PHENIX photon v_2



S. Acharya et al. (ALICE), Phys. Lett. B 789, 308 (2019).

PHENIX photon compared to π^0 v_2

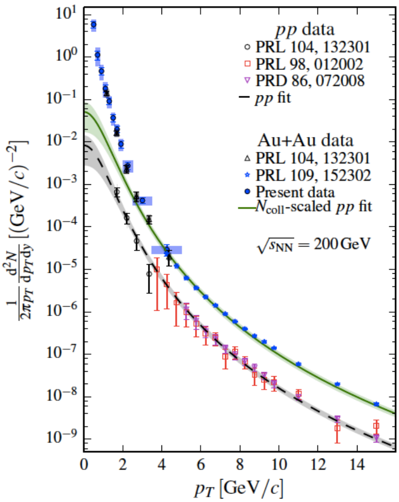


A. Adare et al. (PHENIX), Phys. Rev. Lett. 109, 122302 (2012).

Photon puzzle

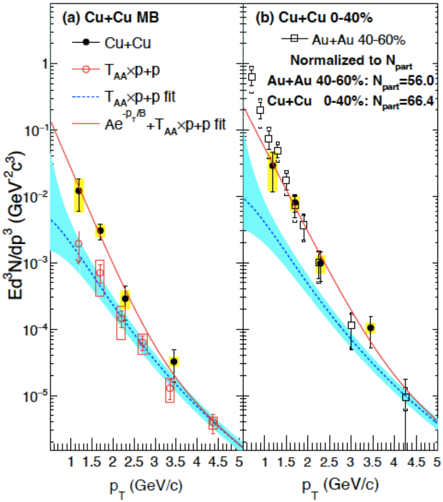
- For $p_T > 4$ GeV, v_2 for direct photons **is consistent with zero**
- This is to be expected if the **dominant source of direct photons is the initial hard scattering**
- However, for $p_T < 4$ GeV there is a **substantial direct photon v_2, even comparable to that of hadrons.**

PHENIX photon yield



A. Adare et al. (PHENIX), Phys. Rev. C 91, 064904 (2015).

PHENIX photon yield

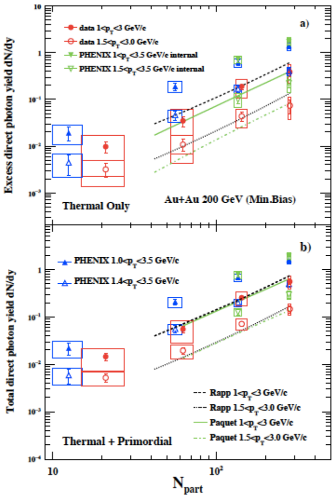


A. Adare et al. (PHENIX), Phys. Rev. C 98, 054902 (2018).

Thermal prompt photons?

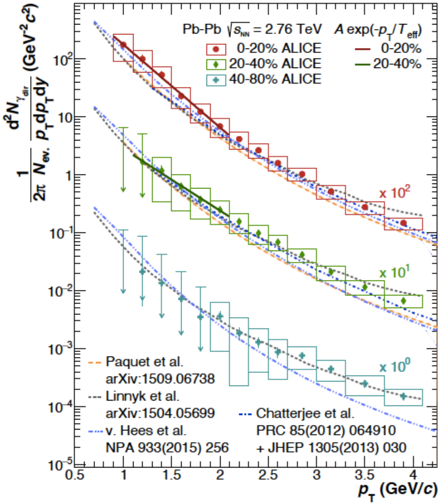
- Measurements at RHIC and at the LHC show that the production of high p_T direct photons in A+A is consistent with the p+p result scaled by the nuclear overlap function T_{AA}
- At low p_T the excess is attributed to a **thermal component**
- Inferred temperature $T \sim 220 - 300$ MeV. **(Early stages of thermal history?)**

Tension between PHENIX and STAR yields



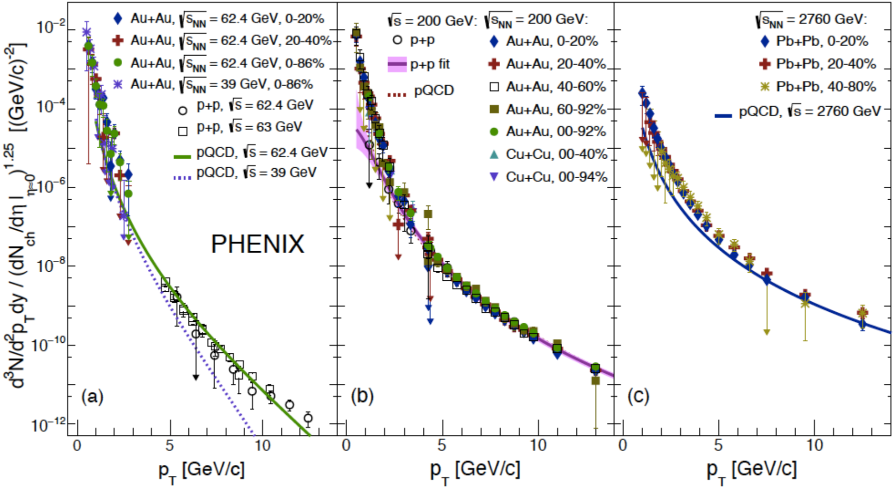
L. Adamczyk et al. (STAR), Phys. Lett. B 770, 451 (2017).

ALICE yields in better agreement with models



J. Adam et al. (ALICE), Phys. Lett. B 754, 235 (2016).

PHENIX scaled

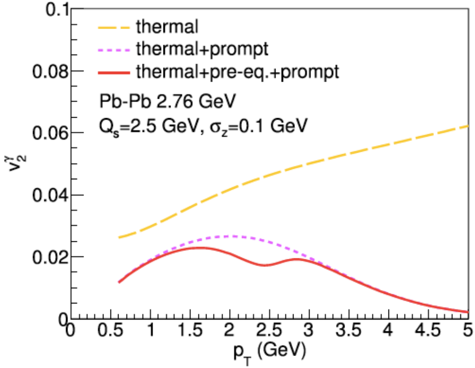


U.A. Acharya, et al. (PHENIX), arXiv:2203.12354 [nucl-ex].

Photons from pre-equilibrium?

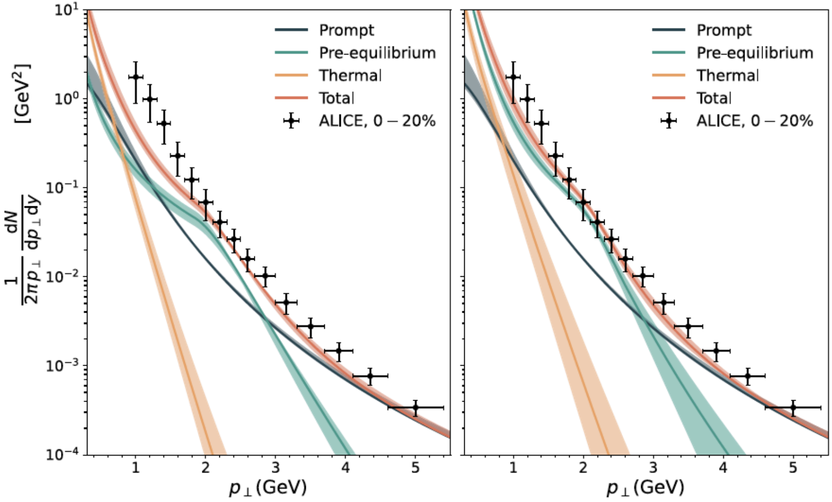
- In a heavy-ion collision, **pre-equilibrium** is the stage elapsed between nuclear overlap and soft partons dynamics dominance
- It is introduced in the context of the "bottom up" scenario for thermalization [R. Baier, A. H. Mueller, D. Schiff, D. T Son, Phys. Lett. B 502, 51 (2001)]
- The pre-equilibrium stage in nuclear collisions is not very well known, except for the fact that **it must contain a large number of gluons (glasma)** (and, parametricaly proportional to α_s, fewer quarks)
- Quark and gluon distributions are non-thermal and obey a self-similar scaling law motivated by a turbulent approach to thermalization scenario
- It is generally believed that $2 \to 2$ scattering processes involving quarks and gluons in this stage can give rise to an excess (over conventional sources) of photons
- The photon yield increases **but v_2 worsens**

Pre-equilibrium v_2



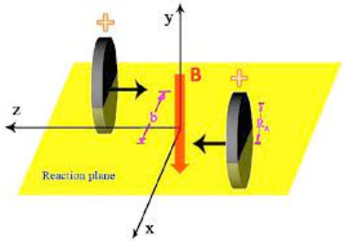
A. Monnai, J. Phys. G 47, 075105 (2020).

Pre-equilibrium yield



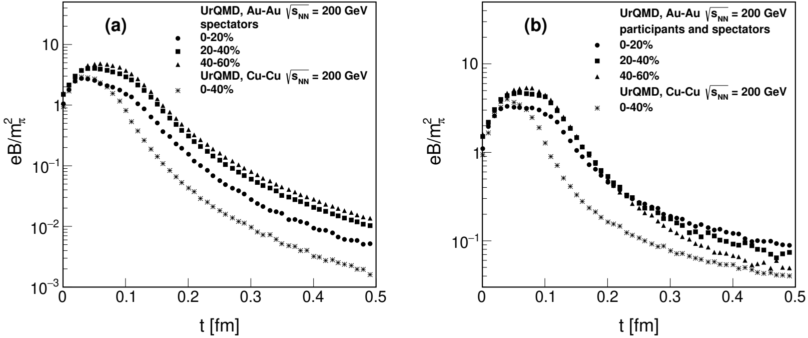
O. García-Montero, Ann. Phys. 443, 168984 (2022).

Magnetic field in HIC's



- Fast decreasing and even incomplete response of thermalized medium in late stages:
  Z. Wang, J. Zhao, C. Geiner, Z. Xu, P. Zhuang, Phys. Rev. C, 105, L041901 (2022),
  I. A. Shovkovy, e-Print:2210.00691 [nucl-th]
- **However, more intense during early (pre-equilibrium) stage**

Field strength as a function of time: Lienard-Wiechert potential UrQMD

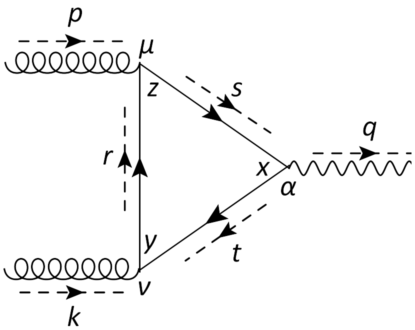


A. A., J.D. Castaño, I. Dominguez, L.A. Hernández, J. Salinas, M.E. Tejeda-Yeomans, Eur. Phys. J. A 56, 53 (2020).

New channels for photon producing processes at pre-equilibrium

Are there any new channels for photon production opened up by the presence of an intense magnetic field at pre-equilibrium?

Two-gluon one-photon on shell vertex



Two-gluon one-photon vertex: general structure

- The coupling between two gluons and one photon is made possible by the presence of the magnetic field
- The breaking of Lorentz invariance produces that space-time is separated into parallel and perpendicular pieces, with respect the magnetic field
- This is implemented by introducing the tensor metric components

$$g^{\mu\nu} = g_{\|}^{\mu\nu} + g_{\perp}^{\mu\nu}$$

- and the momentum components of the gluons and the photon, also in the parallel and perpendicular directions, namely,

$$p_{\|}^{\alpha},\ p_{\perp}^{\alpha},\ k_{\|}^{\alpha},\ k_{\perp}^{\alpha},\ q_{\|}^{\alpha},\ q_{\perp}^{\alpha},$$

Two-gluon one-photon vertex: general structure

- The kind of magnetic field hereby considered cannot transfer energy-momentum to the gluons and the photon. Thus, when also neglecting possibly medium induced modification on their dispersion properties, energy-momentum conservation imposes that for on-shell propagation all the four-momenta are parallel

$$q^\mu = p^\mu + k^\mu.$$

- Choosing q^μ as the reference four-momentum, we have

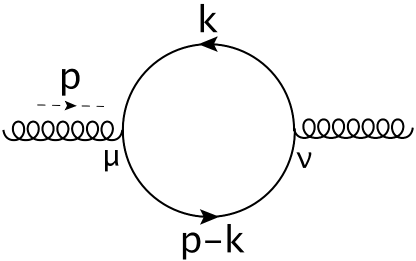
$$p^\mu = \left(\frac{\omega_p}{\omega_q}\right) q^\mu,$$

$$k^\mu = \left(\frac{\omega_k}{\omega_q}\right) q^\mu,$$

- where $\omega_p,\ \omega_k,\ \omega_q$ are the energies of the gluons and photon, respectively.

On-shell two-gluon one-photon vertex $\Gamma^{\mu\nu\alpha}$

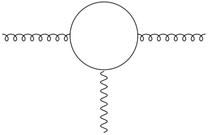
- Strategy: work in the strong field approximation and build $\Gamma^{\mu\nu\alpha}$ in a basis that accounts for the possible polarization states
- Starting from the two-gluon polarization tensor $\Pi^{\mu\nu}$ in the strong field limit



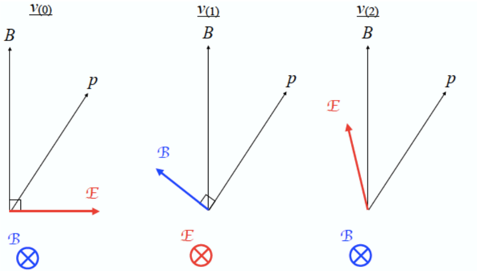
$$\Pi^{\mu\nu} \propto \left(g_{\parallel}^{\mu\nu} - \frac{p_{\parallel}^{\mu} p_{\parallel}^{\nu}}{p_{\parallel}^{2}} \right)$$

On-shell two-gluon one-photon vertex $\Gamma^{\mu\nu\alpha}$

- Add the photon line



- in one of the possible three states of polarization



Polarization vector basis

$$v_\mu^{(0)} = -\frac{1}{\sqrt{p^2 p_\parallel^2 p_\perp^2}}(p_\perp^2 p_0, p_\parallel^2 p_1, p_\parallel^2 p_2, p_\perp^2 p_3)$$

$$v_\mu^{(\perp)} = \frac{1}{\sqrt{p_\perp^2}}(0, -p_2, p_1, 0) = -\frac{\epsilon_{ij} p_i^\perp g_{j\mu}^\perp}{\sqrt{p_\perp^2}}$$

$$v_\mu^{(\parallel)} = \frac{1}{\sqrt{p_\parallel^2}}(p_3, 0, 0, p_0)$$

K Hattori and D. Satow, Phys. Rev. D 97, 014023 (2018)

- In particular

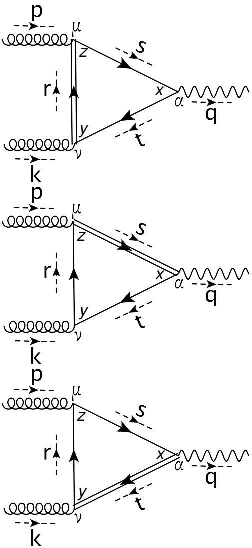
$$v_\mu^{(\parallel)} v_\nu^{(\parallel)} = g_{\mu\nu}^\parallel - \frac{p_\mu^\parallel p_\nu^\parallel}{p_\parallel^2}$$

Tensor structure in the strong field limit

- In the strong field case, **two of the external particles** need to be **longitudinally polarized**
- Conservation of angular momentum requires that the **third one be transversely polarized**
- The vertex is obtained by fully symmetrizing with respect to the Lorentz indices

$$
\begin{aligned}
\Gamma^{\mu\nu\alpha} &= \Gamma_1(\omega_q,\omega_k,q^2)\frac{\epsilon_{ij}q_\perp^i g_\perp^{j\mu}}{\sqrt{q_\perp^2}}\left(g_\parallel^{\nu\alpha}-\frac{q_\parallel^\nu q_\parallel^\alpha}{q_\parallel^2}\right)\\
&+ \Gamma_2(\omega_q,\omega_k,q^2)\frac{\epsilon_{ij}q_\perp^i g_\perp^{j\nu}}{\sqrt{q_\perp^2}}\left(g_\parallel^{\mu\alpha}-\frac{q_\parallel^\mu q_\parallel^\alpha}{q_\parallel^2}\right)\\
&+ \Gamma_3(\omega_q,\omega_k,q^2)\frac{\epsilon_{ij}q_\perp^i g_\perp^{j\alpha}}{\sqrt{q_\perp^2}}\left(g_\parallel^{\mu\nu}-\frac{q_\parallel^\mu q_\parallel^\nu}{q_\parallel^2}\right)
\end{aligned}
$$

One-loop vertex in the strong field limit



One-loop vertex in the strong field limit

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

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

$$iS(p) = ie^{-p_\perp^2/|eB|} \sum_{n=0}^{+\infty} \frac{(-1)^n D_n(|q_f B|, p)}{p_\parallel^2 - m_f^2 - 2n\,|q_f B| + i\epsilon}$$

$$\begin{aligned} D_n(|q_f B|, p) &= 2(\not{p}_\parallel + m_f)\mathcal{O}^- L_n^0\left(\frac{2p_\perp^2}{|q_f B|}\right) - 2(\not{p}_\parallel + m_f)\mathcal{O}^+ L_{n-1}^0\left(\frac{2p_\perp^2}{|q_f B|}\right) \\ &+ 4\not{p}_\perp L_{n-1}^1\left(\frac{2p_\perp^2}{|q_f B|}\right), \end{aligned}$$

One-loop vertex in the strong field limit

- $L_n^m(x)$ are the generalized Laguerre polynomials, and

$$\mathcal{O}^{\pm} = \frac{1}{2}\left[1 \pm \gamma^1\gamma^2 \text{sign}(q_f B)\right].$$

$$\begin{aligned}
\Gamma^{ab}_{\mu\nu\alpha} \;&=\; -\int d^4x d^4y d^4z \int \frac{d^4r}{(2\pi)^4}\frac{d^4s}{(2\pi)^4}\frac{d^4t}{(2\pi)^4}\\
&\times\; e^{-it\cdot(y-x)}e^{-is\cdot(x-z)}e^{-ir\cdot(z-y)}e^{-ip\cdot z}e^{-ik\cdot y}e^{iq\cdot x}\\
&\times\; \Big\{\text{Tr}\Big[iq_f\gamma_\alpha iS(s) ig\gamma_\mu t^a iS(r) ig\gamma_\nu t^b iS(t)\Big]\\
&+\; \text{Tr}\Big[iq_f\gamma_\alpha iS(t) ig\gamma_\nu t^b iS(r) ig\gamma_\mu t^a iS(s)\Big]\Big\}\\
&\times\; \Phi(x,y)\Phi(y,z)\Phi(z,x),
\end{aligned}$$

One-loop vertex in the strong field limit

$$A^\mu = \frac{B}{2}(0, -y, x, 0)$$

$$\Phi(x,y)\Phi(y,z)\Phi(z,x) = e^{-i\frac{|q_f B|}{2}\epsilon_{mj}(z-x)_m(x-y)_j}$$

$$iS_{\rm LLL}(p) = i\frac{e^{-p_\perp^2/|q_f B|}}{p_\parallel^2 - m_f^2 + \epsilon}(\not{p}_\parallel + m_f)\mathcal{O}^-,$$

$$\begin{aligned} iS_{\rm 1LL}(p) &= -2i\frac{e^{-p_\perp^2/|q_f B|}}{p_\parallel^2 - m_f^2 - 2\,|q_f B| + i\epsilon} \\ &\times \left[(\not{p}_\parallel + m_f)\left(1 - \frac{2p_\perp^2}{|q_f B|}\right)\mathcal{O}^- - (\not{p}_\parallel + m_f)\mathcal{O}^+ + 2\not{p}_\perp\right] \end{aligned}$$

One-loop vertex in the strong field limit

$$\Gamma^{\mu\nu\alpha(1-\text{loop})}_{ab} = -\delta^{(4)}(q-k-p)\text{Tr}\left[t_a t_b\right]\frac{8\pi^4 q_f g^2}{|q_f B|}q_\parallel^2 e^{f(p_\perp,k_\perp)}\sum_{i=1}^{3} D_i^{\mu\nu\alpha}$$

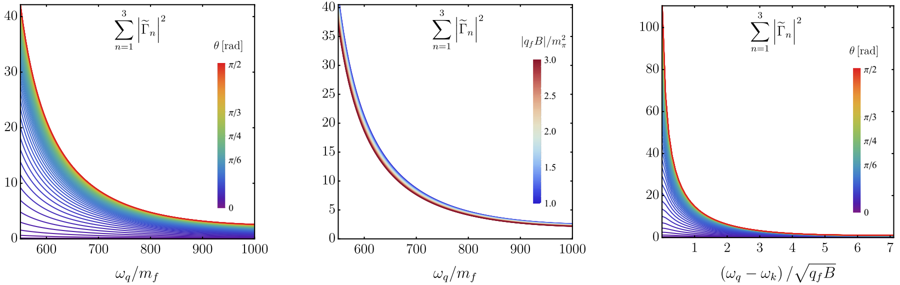
For $B \lesssim \omega_q^2$ tensor structure of $\Gamma^{\mu\nu\alpha(1-\text{loop})}$ **does not coincide with the expected structure** $\Gamma^{\mu\nu\alpha}$, which signals that calculation is incomplete

$$f\left(p_\perp, k_\perp\right) \;=\; \frac{1}{8|q_f B|}\left(p_m - k_m + i\epsilon_{mj}(p_j + k_j)\right)^2 \frac{1}{2}\left(p_m^2 + k_m^2 + 2i\epsilon_{jm}p_m k_j\right)$$

- Projecting onto the basis and defining

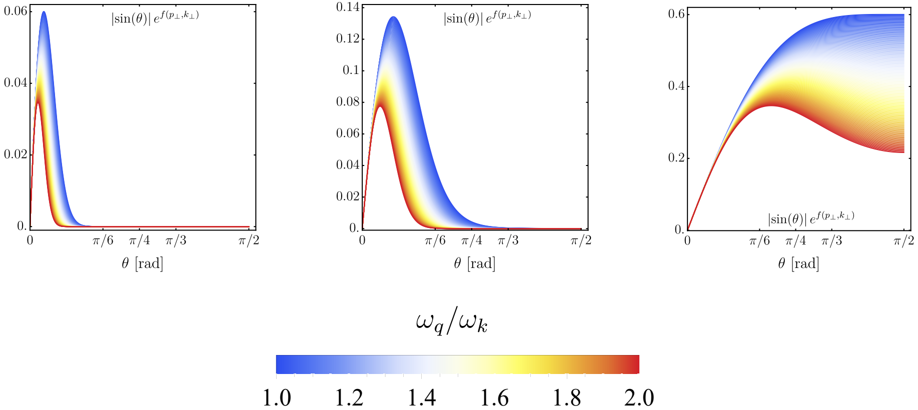
$$\Gamma_n \;\equiv\; \frac{8\pi^4 q_f g^2}{|q_f B|}e^{f(p_\perp,k_\perp)}\,|q_\perp|\,\widetilde{\Gamma}_n(\omega_q,\omega_k,\theta),$$

One-loop vertex in the strong field limit



Sum of squared amplitudes of $\widetilde{\Gamma}_n$, $n = 1, 2, 3$ as a function of: (a) the photon energy ω_q and the angle with respect to the magnetic field θ with $|q_f B| = m_\pi^2$, (b) the photon energy ω_q and the magnetic field strength with $\theta = \pi/2$, and (c) the ratio $(\omega_q - \omega_k)/\sqrt{|q_f B|}$ and the angle with respect to the magnetic field θ with $|q_f B| = m_\pi^2$. All the physical parameters are normalized with the quarks mass $m_f = 2 \times 10^{-3}$ GeV, having fixed $\omega_k = 1$ GeV.

One-loop vertex in the strong field limit



Angular dependence of the factor $|q_\perp|e^{f(p_\perp,k_\perp)}$ as a function of the photon's energy ω_q and the angle with respect to the magnetic field θ for fixed values of $|q_f B|$. (a) $\omega_k = 1$ GeV, $|q_f B| = m_\pi^2$. (b) $\omega_k = 1$ GeV, $|q_f B| = 5m_\pi^2$. (c) $\omega_k = 0.1$ GeV, $|q_f B| = m_\pi^2$

Main features

- The pre-factor peaks at small angles for large gluon energies. In this case the squared amplitude is highly suppressed for angles close to the reaction plane.
- For small gluon energies and/or a large field strength, the pre-factor is dominated by emission angles close to the reaction plane.
- Since at pre-equilibrium the largest gluon abundance happens for small energies, a positive v_2 coefficient may be expected.
- The pre-factor vanishes for $\theta = 0$, which prevents photons from being emitted along the direction of the magnetic field.

Conclusions

- The on-shell two-gluon one-photon vertex can be constructed by multiplying the longitudinal polarization tensor times a third polarization vector which is required to have components in the transverse plane, with respect to the magnetic field
- When the photon energy squared is allowed to be of order or larger than the magnetic field strength, this simple structure is spoiled
- In order to explore the bowels of this very complicated calculation, we have computed the one-loop contribution, placing two of the loop quarks in the LLL and the other one in the 1LL.
- For the case when the field strength is not the largest energy scale, the computation renders structures other than the ones obtained when the field strength is the largest of the scales.
- Possible improvements include accounting for the contribution from the three loop quarks occupying the lowest and first excited Landau levels such that, still working in the large field limit, a more complete description can be achieved when the photon energy increases.

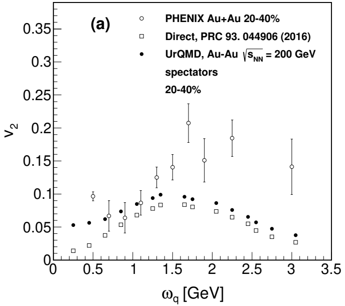
THANKS

BACKUP

Polarization basis in the strong field limit

- In the strong field approximation, the physical picture that emerges is as follows: It is well known that a strong magnetic field forces two of the vector particles to occupy parallel polarization states
- When the vertex involves a third vector particle, invariance under charge conjugation and conservation of angular momentum require that its polarization state is transverse.
- At the lowest perturbative order, this can be understood recalling that, when polarized in the same direction, the addition of the three spin $1/2$ quarks in the loop gives rise to a half-integer spin state that cannot describe the spin state of a combination of three vector particles.
- Therefore, one of the quarks that make up the loop needs to be placed not in the LLL but instead in the 1LL
- This in turn induces the emergence of a transverse mode to be occupied by one of the vector particles

Weighed v_2 average (direct and magnetic)



$$
v_2(\omega_q) = \frac{\sum_{i=1}^{m} \left[\frac{dN}{d\omega_q}\right]_i [v_2^{\mathrm{mag}}(\omega_q)]_i + \frac{dN^{\mathrm{direct}}}{d\omega_q}(\omega_q)\;\; v_2^{\mathrm{direct}}(\omega_q)}{\sum_{i=1}^{m} \left[\frac{dN}{d\omega_q}\right]_i + \frac{dN^{\mathrm{direct}}}{d\omega_q}(\omega_q)},
$$

A. A., J.D. Castaño, I. Dominguez, L.A. Hernández, J. Salinas, M.E. Tejeda-Yeomans, Eur. Phys. J. A 56, 53 (2020)