Photon production from gluon splitting and fusion induced by a magnetic field of arbitrary strength in relativistic heavy-ion collisions

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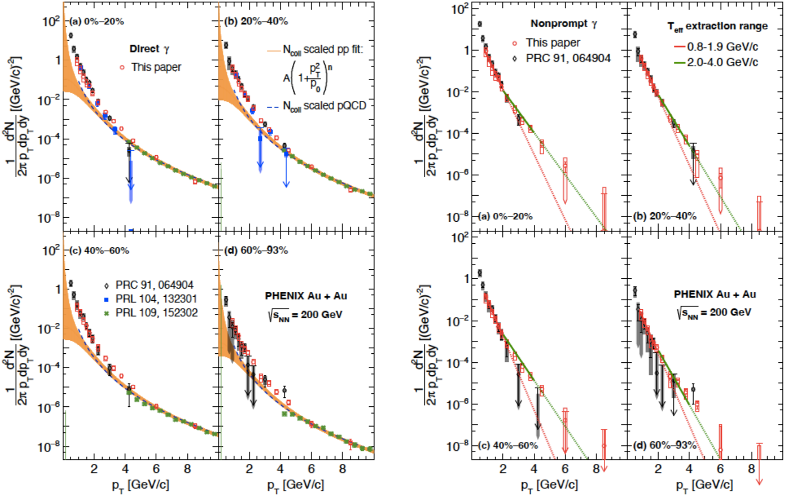
Overview

Direct Photon Puzzle

Direct Photon Puzzle: Unexpectedly large yield together with sizable elliptic flow v_2 compared to conventional baselines (prompt + thermal QGP + hadronic gas) tuned to other EM probes ($\pi^0 \to \gamma\gamma$, dileptons).

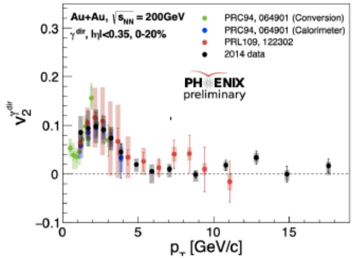
Question: Can the earliest stage of the collision simultaneously produce extra photons and a large positive v_2, before substantial hydrodynamic flow has developed? What is the role of magnetic fields that are also at its highest intensity during this stage?

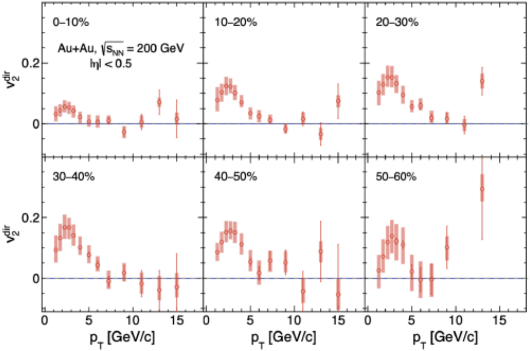
PHENIX direct and nonprompt photon yield



Phys. Rev. D 98, 054902 (2018)

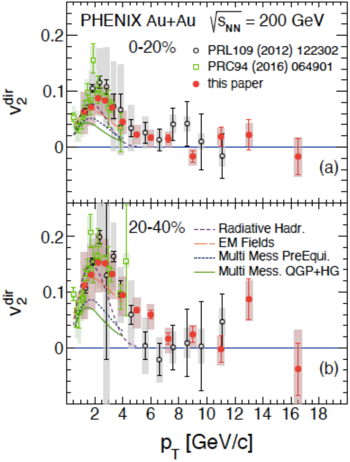
PHENIX photon v_2





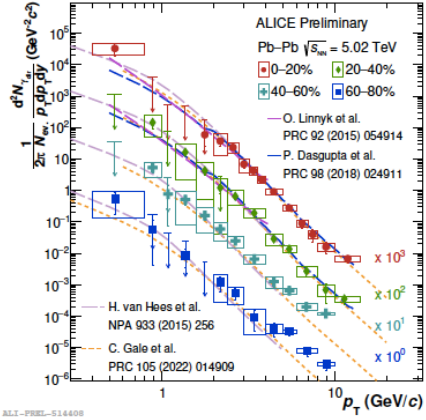
Phys. Rev. D 98, 054902 (2018)

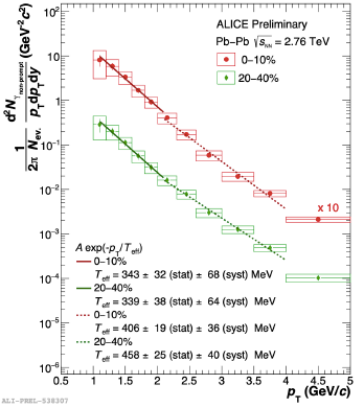
PHENIX photon v_2 2026



Phys. Rev. C 114, 024903 (2026)

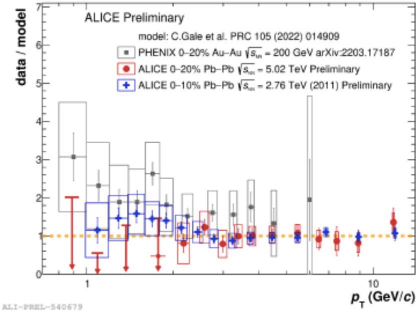
ALICE photon yield

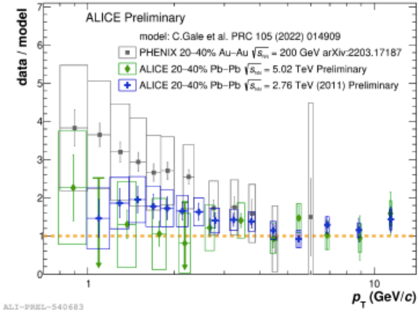




PoS HardProbes2023 (2024) 061

ALICE photon v_2





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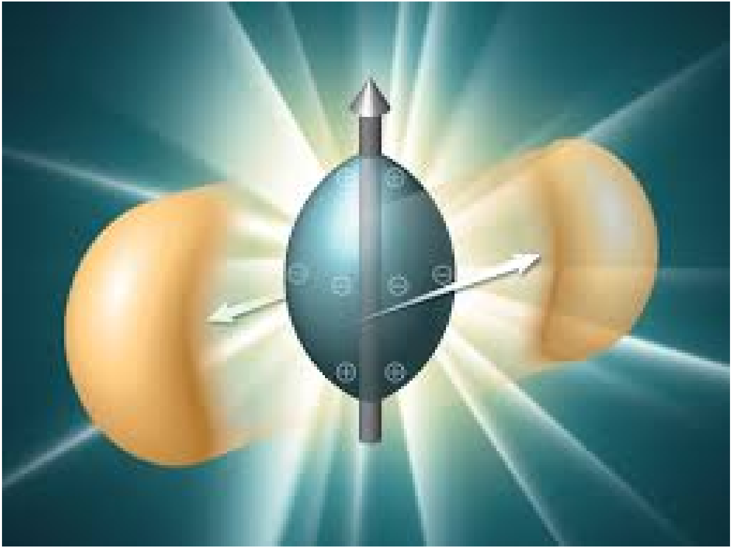
Photon puzzle summary

- At RHIC energies (Au+Au, $\sqrt{s_{NN}} = 200$ GeV) the photon puzzle is still difficult to describe, PHENIX's new releases (2026) confirm a strong low-p_T component and non-zero v_2 that tends toward zero at high p_T
- At LHC energies (Pb+Pb, $\sqrt{s_{NN}} = 2.76$–5.02 TeV) the yield picture has improved. ALICE's Run-2 measurements report direct-photon spectra that are consistent with state-of-the-art calculations once prompt plus pre-equilibrium contributions are included; a significant signal is seen for $p_T \geq 2$ GeV/c, and the very-low-p_T signal at 5.02 TeV is small as those models predict. (The ALICE updates emphasize yields; precision v_2 at low p_T is still limited and not yet showing a RHIC-like tension.)

Beyond the baseline (prompt + thermal QGP + HG rates)

- Pre-equilibrium/early-time radiation and different thermalization scenarios (helps yield at intermediate p_T without killing v_2).
- Jet–medium (conversion/bremsstrahlung) photons that carry flow from path-length biases and medium response.
- Radiative hadronization and hadronic many-body updates (extra late-time photons $\to$ larger v_2).
- Semi-QGP, glasma, and non-equilibrium enhancements, plus viscous/e-by-e hydrodynamics with updated rates.
- **Magnetic field–related channels (early-time anisotropies).**

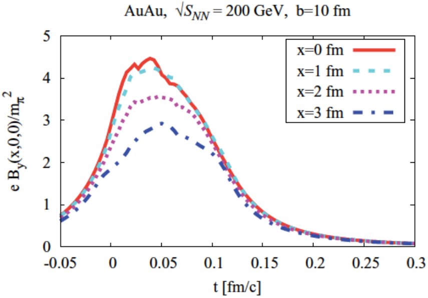
Magnetic field generated in peripheral HICs

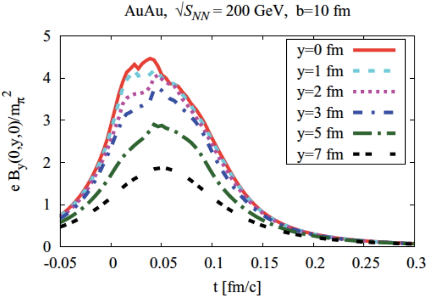


Magnetic-field–based mechanisms

- Quark synchrotron (magneto-bremsstrahlung) in the QGP [K. Tuchin, Phys. Rev. C 91, 014902 (2015)].
- Anomaly-induced photons (QCD$\times$QED conformal anomaly in a B-background. [G. Başar, D. Kharzeev, V. Skokov, Phys. Rev. Lett. 109, 202303 (2012)].
- Magneto-sono-luminescence (MSL): coupling of stress-tensor fluctuations to photons in B-background [G. Başar, D. E. Kharzeev, E. V. Shuryak, Phys. Rev. C 90, 014905 (2014)].
- Viscous dynamics and rates and thus dissipative/transport effects can be modified in a weak external within hydro B-fields [J.-A. Sun et al., Phys. Rev. C 109, 034917 (2024)].
- **Hybrid scenarios (anomaly/MSL/transport + conventional thermal + jet-medium) can increase the low–mid-p_T yield and v_2 without overproducing high-p_T photons.**

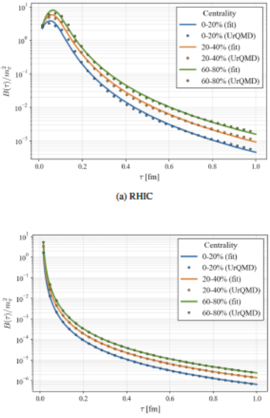
Magnetic field generated in peripheral HICs





Phys. Rev. C 83, 054911 (2011)

Magnetic field generated in peripheral HICs



(a) RHIC

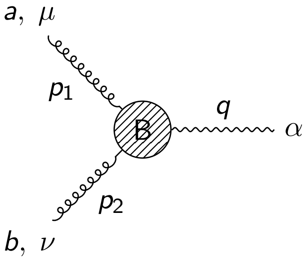
(b) LHC

2609.05923 [nucl-th]

Two-gluon one-photon vertex in a magnetic field

Why gluons?: During pre-equilibrium $n_g \gg n_q$
Gluon rich pre-equilibrium + very strong B
$\Longrightarrow gg \to \gamma$ **and** $g \to g\gamma$ **become important channels**

$$\Gamma^{\mu\nu\alpha}_{ab}(p_1, p_2, q) \;=$$



A.A., S. Bernal-Langarica, J. Jaber-Urquiza, J.J. Medina-Serna,
Phys. Rev. D 110, 076021 (2024)

Symmetry constraints

Third rank tensor constrained by symmetry properties

- **First**, gauge invariance requires that this tensor be transverse when contracted with the momentum carrying the Lorentz index corresponding to the vertex index assigned to the given particle, namely,

$$\begin{aligned} p_{1\mu}\Gamma^{\mu\nu\alpha}_{ab}(p_1,p_2,q) &= 0 \\ p_{2\nu}\Gamma^{\mu\nu\alpha}_{ab}(p_1,p_2,q) &= 0 \\ q_{\alpha}\Gamma^{\mu\nu\alpha}_{ab}(p_1,p_2,q) &= 0 \end{aligned}$$

- **Second**, since the gluons are indistinguishable, the vertex needs to be symmetric under the exchange of the gluon indexes and momenta, namely,

$$\Gamma^{\mu\nu\alpha}_{ab}(p_1,p_2,q) = \Gamma^{\nu\mu\alpha}_{ba}(p_2,p_1,q)$$

Symmetry constraints

- **Third**, in the B-background (C) and parity (P) conjugation are each broken. The vertex transforms under C and P as

$$
\begin{aligned}
\hat{C}\,\Gamma_{ab}^{\mu\nu\alpha}\hat{C}^{-1} &= (-1)^3\Gamma_{ab}^{\mu\nu\alpha} \\
\hat{P}\,\Gamma_{ab}^{\mu\nu\alpha}\hat{P}^{-1} &= (-1)^3\Gamma_{ab}^{\mu\nu\alpha}
\end{aligned}
$$

However, notice that the above relations imply that the vertex is invariant under the combined action of the CP transformation.

Tensor basis

- These general properties need to be translated into the properties of the chosen tensor basis and its coefficients to span the vertex.
- The basis can be constructed out of the external product of suitably chosen polarization vectors.
- To find the tensor basis, let us first concentrate in the photon leg.
- We introduce a **tetrad**, namely, a set of four linearly independent vectors that span the four-dimensional Minkowski space-time and that also account for the presence of the external field.

Tensor basis

- We start by choosing one of this vectors as the photon momentum and the other three as the general polarization vectors.
- We choose the **Ritus basis**

$$
\begin{aligned}
q^\mu & \\
l_q^\mu &\equiv \hat{F}^{\mu\beta} q_\beta \\
l_q^{*\mu} &\equiv \hat{F}^{*\mu\beta} q_\beta \\
k_q^\mu &\equiv \frac{q^2}{l_q^2} \hat{F}^{\mu\beta} \hat{F}_{\beta\sigma} q^\sigma + q^\mu
\end{aligned}
$$

where

$\hat{F}^{\mu\beta} \equiv F^{\mu\beta}/|B|$, $F^{\mu\beta}$ the EM strength tensor and $F^{*\mu\beta}$ its dual

Tensor basis

- The polarization vectors l_q^μ, $l_q^{*\mu}$ and k_q^μ satisfy

$$q_\mu l_q^\mu = q_\mu l_q^{*\mu} = q_\mu k_q^\mu = 0$$

  and therefore are transverse to the photon momentum q^μ.
- They form an orthogonal basis and satisfy

$$g^{\mu\nu} = \frac{q^\mu q^\nu}{q^2} + \frac{l_q^\mu l_q^\nu}{l_q^2} + \frac{l_q^{*\mu} l_q^{*\nu}}{l_q^{*2}} + \frac{k_q^\mu k_q^\nu}{k_q^2}$$

- For on-shell photons $q^2 = 0$, and thus the vector k^μ becomes

$$k_q^\mu \to q^\mu,$$

  showing that there are only two polarization vectors for real photons: l_q^μ and $l_q^{*\mu}$.

Tensor basis

The vertex is expressed as the external product of the polarization vectors corresponding to each of the vector particles

$$\begin{aligned} \text{photon } \alpha &\rightarrow q^\alpha,\ l_q^\alpha,\ l_q^{*\alpha},\ k_q^\alpha \\ \text{gluon } \mu,\ a &\rightarrow p_{1a}^\mu,\ l_{p_1 a}^\mu,\ l_{p_1 a}^{*\mu},\ k_{p_1 a}^\mu \\ \text{gluon } \nu,\ b &\rightarrow p_{2b}^\nu,\ l_{p_2 b}^\nu,\ l_{p_2 b}^{*\nu},\ k_{p_2 b}^\nu \end{aligned}$$

- Therefore, in general the i-th basis element $\Gamma_{ab\ i}^{\mu\nu\alpha}(p_1, p_2, q)$ corresponds to one of the products of three polarization vectors, where each factor is taken from one of the sets of polarization vectors for each particle. Working with the set of normalized polarization vectors, schematically we have

$$\Gamma_{ab\ i}^{\mu\nu\alpha}(p_1, p_2, q) \in \left\{ \left[\hat{l}_{p_1 a}^\mu,\ \hat{l}_{p_1 a}^{*\mu},\ \hat{k}_{p_1 a}^\mu\right] \otimes \left[\hat{l}_{p_2 b}^\nu,\ \hat{l}_{p_2 b}^{*\nu},\ \hat{k}_{p_2 b}^\nu\right] \otimes \left[\hat{l}_q^\alpha,\ \hat{l}_q^{*\alpha},\ \hat{k}_q^\alpha\right] \right\}$$

Tensor basis

- A further simplification can be made by noticing that for on-shell gauge bosons, conservation of energy-momentum

$$\begin{aligned} \omega_q &= \omega_{p_1} + \omega_{p_2} \\ \vec{q} &= \vec{p}_1 + \vec{p}_2 \end{aligned}$$

requires that the gauge bosons are collinear and therefore

$$\begin{aligned} p_1^\mu &= (\omega_{p_1}/\omega_q)\, q^\mu \\ p_2^\mu &= (\omega_{p_2}/\omega_q)\, q^\mu \end{aligned}$$

where we chose to express the gluon momenta in terms of the photon momentum.

- Consequence: all Lorentz structures, odd with respect to either or both $\hat{C}$ and $\hat{P}$, are not available to express the on-shell effective vertex.

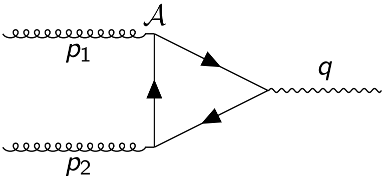
Tensor basis

- Putting all this together we can finally write

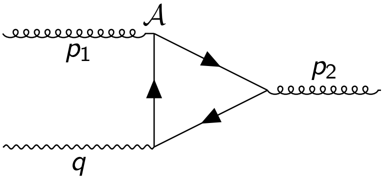
$$
\begin{aligned}
\Gamma^{\mu\nu\alpha}_{ab}(p_1, p_2, q)_{\text{on-shell}} &= a_1^{++}\,\hat{l}^{\mu}_{p_1\,a}\hat{l}^{\nu}_{p_2\,b}\hat{l}^{\alpha}_{q} + a_2^{++}\,\hat{l}^{*\mu}_{p_1\,a}\hat{l}^{*\nu}_{p_2\,b}\hat{l}^{\alpha}_{q} \\
&+ \frac{a_3^{++}}{\sqrt{2}}\left(\hat{l}^{\mu}_{p_1\,a}\hat{l}^{*\nu}_{p_2\,b} + \hat{l}^{*\mu}_{p_1\,a}\hat{l}^{\nu}_{p_2\,b}\right)\hat{l}^{*\alpha}_{q}
\end{aligned}
$$

which shows that only three independent tensor structures, together with their corresponding coefficients, are needed to span the on-shell effective two-gluon one-photon vertex.

Gluon fusion and splitting



Gluon fusion



Gluon splitting

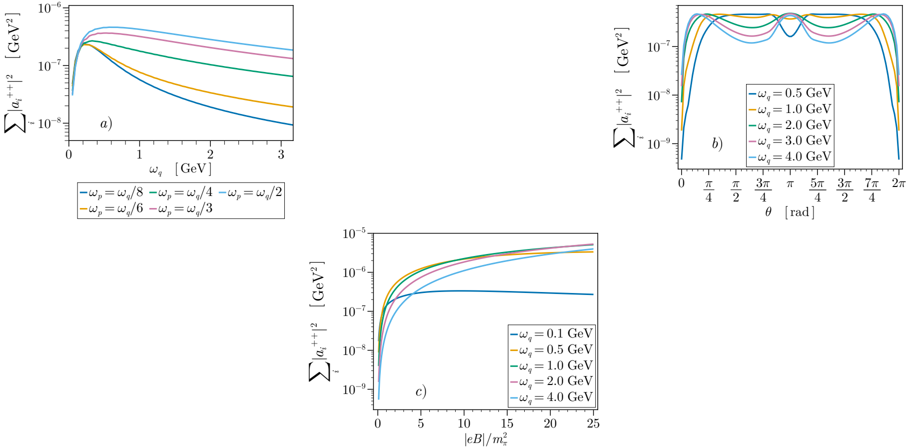
One-loop gluon fusion/splitting vertex

After a lengthy but straightforward calculation we get

$$\begin{aligned}
\Gamma^{\mu\nu\alpha}_{ab} &= -i\frac{g^2 q_f^2 B}{(2\pi^2)}\mathrm{Tr}[t_a t_b]\delta^4(p_1+p_2-q) \\
&\times \int_0^\infty \frac{ds_1 ds_2 ds_3}{c_1^2 c_2^2 c_3^2}\left(\frac{1}{t_1 t_2 t_3 - t_1 - t_2 - t_3}\right)\left(\frac{e^{-ism_f^2}}{s}\right) \\
&\times e^{-\frac{i}{s}\left(s_1 s_3 \omega_{p_1}^2 + s_2 s_3 \omega_{p_2}^2 + s_1 s_2 \omega_q^2\right)\frac{q_\perp^2}{\omega_q^2}} \\
&\times e^{-\frac{i}{\omega_q^2}\frac{q_\perp^2}{|q_f B|}\left(\frac{1}{t_1 t_2 t_3 - t_1 - t_2 - t_3}\right)\left(t_1 t_3 \omega_{p_1}^2 + t_2 t_3 \omega_{p_2}^2 + t_1 t_2 \omega_q^2\right)} \\
&\times \sum_{j=1}^{19}\left(T^{\mu\nu\alpha}_{\mathcal{A}j} + T^{\mu\nu\alpha}_{\mathcal{B}j}\right)
\end{aligned}$$

where $s = s_1 + s_2 + s_3$ and the traces over Dirac space corresponding to diagrams $\mathcal{A}$ and $\mathcal{B}$

Matrix element squared



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Invariant photon momentum distribution

$$
\begin{aligned}
\omega_q \frac{dN^{\rm mag}}{d^3q} &= \frac{\mathcal{V}\Delta\tau}{2(2\pi)^3}\int\frac{d^3p_1}{(2\pi)^3 2\omega_{p_1}}\int\frac{d^3p_2}{(2\pi)^3 2\omega_{p_2}}\\
\times\quad & (2\pi)^4\Bigg\{\delta^{(4)}\left(q-k-p\right) n(\omega_p) n(\omega_k)\overline{\sum_{\rm c,s,f}}|\Gamma_{gg\to\gamma}|^2\\
& +\delta^{(4)}\left(q+k-p\right) n(\omega_p)\left[1+n(\omega_k)\right]\overline{\sum_{\rm c,s,f}}|\Gamma_{g\to g\gamma}|^2\Bigg\}
\end{aligned}
$$

Test two possible initial distributions

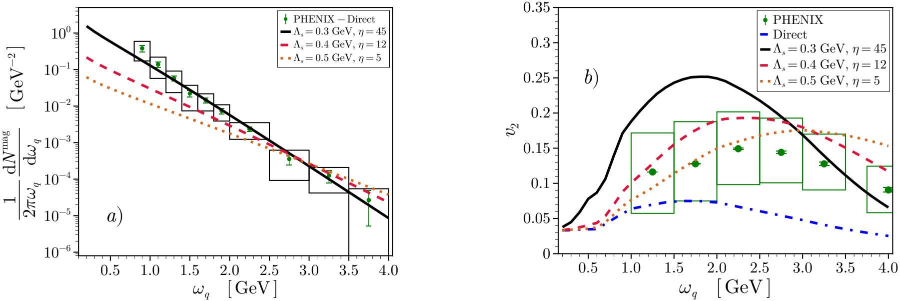
First consider $n(\omega)$ as a **isotropic** distribution of gluons coming from the shattered glasma.

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

where η and Λ_s represent a high gluon occupation factor and saturation momentum, respectively.

Next, consider an **anisotropic** distribution accounting for the different initial expansion rates in the beam and transverse directions

$$n(\omega) = \frac{\eta}{e^{\omega/\Lambda_s} - 1} \to \frac{A\langle p_T\rangle e^{-2(\xi^2 p_L^2 + p_\perp^2)/3\langle p_T\rangle^2}}{\sqrt{\xi^2 p_L^2 + p_\perp^2}}$$



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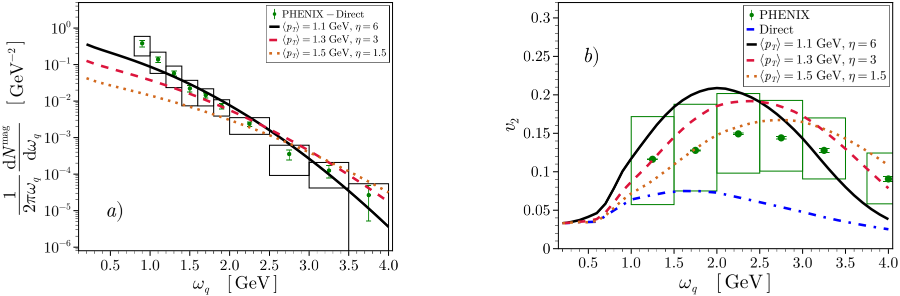
Anisotropic gluon distribution $|eB| = 3m_\pi^2$



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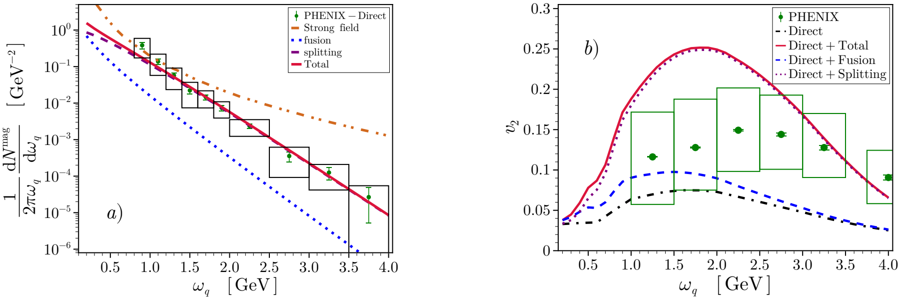
Isotropic BE-like initial gluon distribution $|eB| = (1-3)m_\pi^2$



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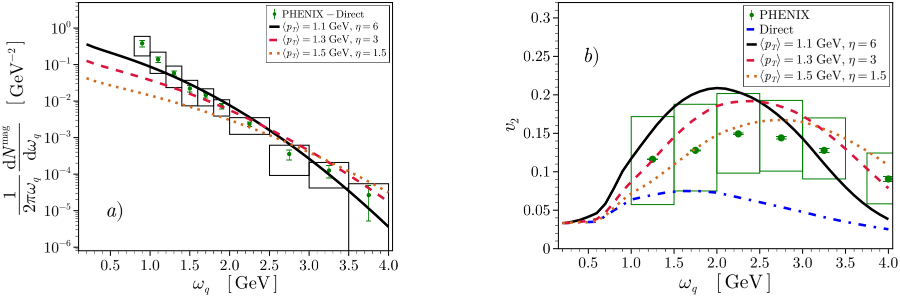
Anisotropic gluon distribution $|eB| = (1-3)m_\pi^2$



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Conclusions

- The photon puzzle has not disappeared; instead, increasingly sophisticated calculations suggest that the observed photons probably encode several stages of the collision, with pre-equilibrium and electromagnetic-field-driven mechanisms playing a potentially important role.
- Intense magnetic field effects during the very early stages of a Relativistic Heavy-Ion Collision.
- High gluon occupation number during early stages together with the magnetic field opens up gluon fusion/splitting channel for photon production.
- Photon yield excess and v_2 magnitude and shape well described with magnetic field effects for semi-central Au + Au collisions.

THANKS

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dgapa

BACKUP

Tensor basis

- To write the coefficients a_i, $i = 1, \ldots, 18$, we have to our disposal Lorentz scalars also with definite properties under C and P. Expressing any of the momentum vectors p_1^μ, p_2^μ, q^μ as p_m^μ, $m = 1, 2, 3$, the available Lorentz scalars are

$$
\begin{aligned}
S_{1\ mn}^{++} &= (p_m \cdot p_n) \\
S_{2\ mn}^{++} &= (p_m \cdot p_n)_\perp \\
S_{3\ mn}^{-+} &= p_m^\mu \hat{F}_{\mu\nu} p_n^\nu \\
S_{4\ mn}^{--} &= p_m^\mu \hat{F}^*_{\mu\nu} p_n^\nu
\end{aligned}
$$

- where the notation $S_{j\ mn}^{CP}$, emphasizes the properties under the C and P transformations, respectively, of the corresponding Lorentz scalar of the kind $j = 1, \ldots, 4$.