

Impact parameter dependence of dilepton production: Wigner function approach and the role of photon polarizations

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- 1 Peripheral/ultraperipheral collisions
 - Weizsäcker-Williams equivalent photons
 - a part of the partonic structure of charged particles
- 2 From ultraperipheral to semicentral collisions
 - dileptons from $\gamma\gamma$ production vs thermal dileptons from plasma phase
 - Wigner function generalization of the Weizsäcker-Williams approach
- 3 Diffractive production of $c\bar{c}$ pairs in pA UPCs
 - elliptic gluon GTMD and angular correlations



M. Kłusek-Gawenda, R. Rapp, W. S. and A. Szczurek, "Dilepton Radiation in Heavy-Ion Collisions at Small Transverse Momentum," Phys. Lett. B **790** (2019) 339 [arXiv:1809.07049 [nucl-th]].

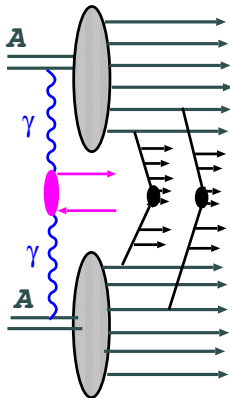


M. Kłusek-Gawenda, W. S. and A. Szczurek, "Centrality dependence of dilepton production via $\gamma\gamma$ processes from Wigner distributions of photons in nuclei," Phys. Lett. B **814** (2021), 136114 [arXiv:2012.11973 [hep-ph]].



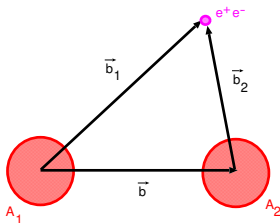
B. Linek, A. Łuszczak, M. Łuszczak, R. Pasechnik, W. S. and A. Szczurek, "Probing proton structure with $c\bar{c}$ correlations in ultraperipheral pA collisions," JHEP **10** (2023), 179 [arXiv:2308.00457 [hep-ph]].

Dilepton production in semi-central collisions



- dileptons from $\gamma\gamma$ fusion have peak at very low pair transverse momentum.
- can they be visible even in semi-central collisions?
- WW photons are a coherent “parton cloud” of nuclei, which can collide and produce particles. Nuclei create an “underlying event, in which e.g. plasma can be formed.
- Early considerations in N. Baron and G. Baur, Z. Phys. C **60** (1993).
- Dileptons are a “classic” probe of the QGP: medium modifications of ρ , thermal dileptons... What is the competition between the different mechanisms? Very soft dileptons as a probe of the conductivity of the plasma?
- dependence on **centrality/ impact parameter?**
- role of photon polarizations

Dilepton production in semi-central collisions



$$\frac{d\sigma_{ll}}{d\xi d^2\mathbf{b}} = \int d^2\mathbf{b}_1 d^2\mathbf{b}_2 \delta^{(2)}(\mathbf{b} - \mathbf{b}_1 - \mathbf{b}_2) N(\omega_1, b_1) N(\omega_2, b_2) \frac{d\sigma(\gamma\gamma \rightarrow l^+l^-; \hat{s})}{d(-\hat{t})},$$

where the phase space element is $d\xi = dy_+ dy_- dp_t^2$ with y_{\pm} , p_t and m_l the single-lepton rapidities, transverse momentum and mass, respectively, and

$$\omega_1 = \frac{\sqrt{p_t^2 + m_l^2}}{2} (e^{y_+} + e^{y_-}), \quad \omega_2 = \frac{\sqrt{p_t^2 + m_l^2}}{2} (e^{-y_+} + e^{-y_-}), \quad \hat{s} = 4\omega_1\omega_2.$$

- we adopt the impact parameter definition of centrality

$$\frac{dN_{ll}[C]}{dM} = \frac{1}{f_C \cdot \sigma_{AA}^{\text{in}}} \int_{b_{\text{min}}}^{b_{\text{max}}} db \int d\xi \delta(M - 2\sqrt{\omega_1\omega_2}) \left. \frac{d\sigma_{ll}}{d\xi db} \right|_{\text{cuts}},$$

Thermal dilepton production

- The calculation of thermal dilepton production from a near-equilibrated medium follows the approach of R. Rapp and E. V. Shuryak, Phys. Lett. B **473** (2000); J. Ruppert, C. Gale, T. Renk, P. Lichard and J. I. Kapusta, Phys. Rev. Lett. **100** (2008). R. Rapp and H. van Hees, Phys. Lett. B **753** (2016) 586.
- To compute dilepton invariant-mass spectra an integration of the thermal emission rate over the space-time evolution of the expanding fireball is performed,

$$\frac{dN_{ll}}{dM} = \int d^4x \frac{M d^3P}{P_0} \frac{dN_{ll}}{d^4x d^4P} ,$$

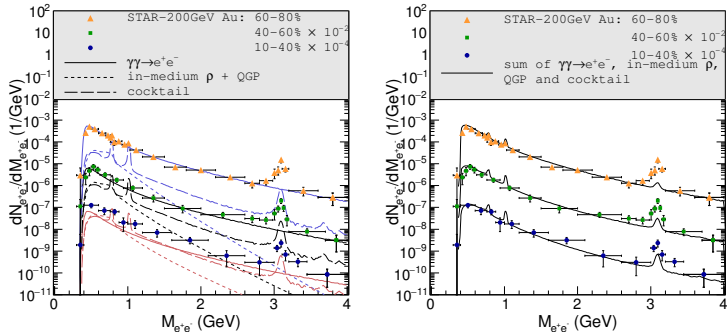
where (P_0, \vec{P}) and $M = \sqrt{P_0^2 - P^2}$ are the 4-vector ($P = |\vec{P}|$) and invariant mass of the lepton pair, respectively.

- The thermal emission rate is expressed through the EM spectral function,

$$\frac{dN_{ll}}{d^4x d^4P} = \frac{\alpha_{\text{EM}}^2 L(M)}{\pi^3 M^2} f^B(P_0; T) (-g_{\mu\nu}) \text{Im} \Pi_{\text{EM}}^{\mu\nu}(M, P; \mu_B, T) ,$$

- The fireball evolves through both QGP and hadronic phases. For the respective spectral functions we employ in-medium quark-antiquark annihilation and in-medium vector spectral functions in the hadronic sector.
- Different centrality classes for different colliding systems are characterized by the measured hadron multiplicities and appropriate initial conditions for the fireball.

Dilepton production in semi-central collisions



Left panel: Dielectron invariant-mass spectra for pair- $P_T < 0.15$ GeV in Au+Au ($\sqrt{s_{NN}} = 200$ GeV) collisions for 3 centrality classes including experimental acceptance cuts ($p_t > 0.2$ GeV, $|\eta_e| < 1$ and $|y_{e^+e^-}| < 1$) for $\gamma\gamma$ fusion (solid lines), thermal radiation (dotted lines) and the hadronic cocktail (dashed lines); right panel: comparison of the total sum (solid lines) to STAR data [1].

[1] data from J. Adam *et al.* [STAR Collaboration], Phys. Rev. Lett. **121** (2018) 132301.

- also added is a contribution from decays of final state hadrons "cocktail" supplied by STAR.
- the J/ψ contribution has been described e.g. in W. Zha, L. Ruan, Z. Tang, Z. Xu and S. Yang, Phys. Lett. B **789** (2019), 238-242 [arXiv:1810.02064 [hep-ph]].

Pair transverse momentum distribution

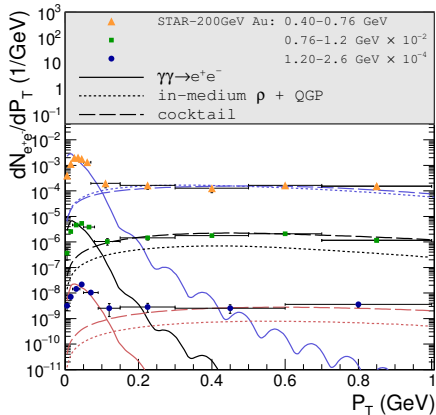
- Here we perform a simplified calculation by using b -integrated **transverse momentum dependent photon fluxes**,

$$\frac{dN(\omega, q_t^2)}{d^2\vec{q}_t} = \frac{Z^2 \alpha_{EM}}{\pi^2} \frac{q_t^2}{[q_t^2 + \frac{\omega^2}{\gamma^2}]^2} F_{\text{em}}^2(q_t^2 + \frac{\omega^2}{\gamma^2}).$$

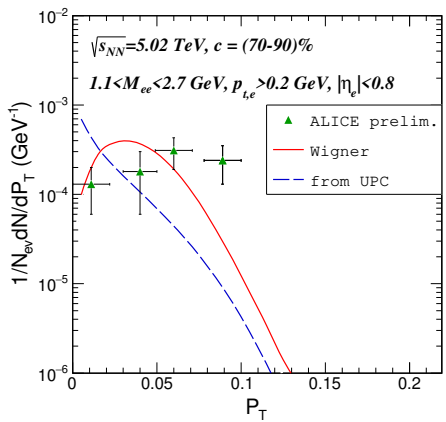
$$\frac{d\sigma_{ll}}{d^2\vec{P}_T} = \int \frac{d\omega_1}{\omega_1} \frac{d\omega_2}{\omega_2} d^2\vec{q}_{1t} d^2\vec{q}_{2t} \frac{dN(\omega_1, q_{1t}^2)}{d^2\vec{q}_{1t}} \frac{dN(\omega_2, q_{2t}^2)}{d^2\vec{q}_{2t}} \delta^{(2)}(\vec{q}_{1t} + \vec{q}_{2t} - \vec{P}_T) \hat{\sigma}(\gamma\gamma \rightarrow l^+l^-) \Big|_{\text{cut}}$$

- analogous to **TMD-factorization** in hard processes. Note that experiment includes a cut $p_t(\text{lepton}) > 0.2 \text{ GeV}$. Formfactors ensure that photon virtualities are much smaller than this “hard scale”. We can thus treat them as **on-shell** in the $\gamma\gamma \rightarrow e^+e^-$ cross section.
- notice the extremely sharp peak in q_t , which is cut off only by ω/γ . The peak will move towards smaller q_t as the boost γ increases.
- This approach does not account for **photon polarization** nor **impact parameter dependence**.

Dilepton production in semi-central collisions



P_T spectra of the individual contributions (line styles as in the previous figure) in 3 different mass bins for 60-80% central Au+Au collisions ($\sqrt{s_{NN}}=200$ GeV), compared to STAR data [1].



P_T distribution of the pair against ALICE data.

[1] J. Adam *et al.* [STAR Collaboration], Phys. Rev. Lett. **121** (2018) 132301.

- We need to find a generalization of photon fluxes (or parton distributions), that contain information on both impact parameter and transverse momentum. This is achieved by the **Wigner function**.
- We also have to take into account photon polarizations, so in fact we obtain a **density matrix** of Wigner functions:

$$N_{ij}(\omega, \mathbf{b}, \mathbf{q}) = \int \frac{d^2\mathbf{Q}}{(2\pi)^2} \exp[-i\mathbf{b}\mathbf{Q}] E_i\left(\omega, \mathbf{q} + \frac{\mathbf{Q}}{2}\right) E_j^*\left(\omega, \mathbf{q} - \frac{\mathbf{Q}}{2}\right)$$

- when summed over polarizations it reduces to the well-known WW flux after integrating over \mathbf{q} , and to the TMD photon flux after integrating over \mathbf{b} :

$$N(\omega, \mathbf{q}) = \delta_{ij} \int d^2\mathbf{b} N_{ij}(\omega, \mathbf{b}, \mathbf{q}) = \delta_{ij} E_i(\omega, \mathbf{q}) E_j^*(\omega, \mathbf{q}) = \left| \mathbf{E}(\omega, \mathbf{q}) \right|^2,$$

$$N(\omega, \mathbf{b}) = \delta_{ij} \int \frac{d^2\mathbf{q}}{(2\pi)^2} N_{ij}(\omega, \mathbf{b}, \mathbf{q}) = \delta_{ij} E_i(\omega, \mathbf{b}) E_j^*(\omega, \mathbf{b}) = \left| \mathbf{E}(\omega, \mathbf{b}) \right|^2.$$

- Field strength vector:

$$\mathbf{E}(\omega, \mathbf{q}) \propto \frac{\mathbf{q}F(q^2)}{q^2 + \frac{\omega^2}{\gamma^2}}$$

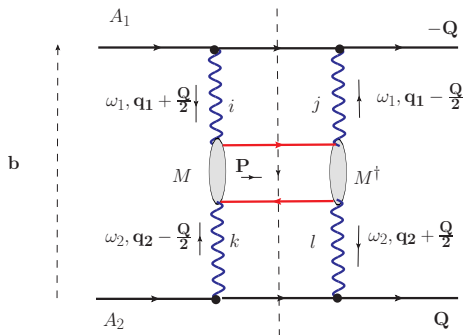
- The Wigner function is the Fourier transform of a generalized transverse momentum distribution (GTMD), and in some sense (at small- x) the most general function in the zoo of parton correlators. For the photon case, see S. Klein, A. H. Mueller, B. W. Xiao and F. Yuan, Phys. Rev. D **102** (2020) no.9, 094013.
- Recently, there has been a lot of interest in the gluon Wigner distributions, which has applications in exclusive diffractive processes. See e.g. Y. Hagiwara, Y. Hatta, R. Pasechnik, M. Tasevsky and O. Teryaev, Phys. Rev. D **96** (2017) no.3, 034009.
Review: R. Pasechnik, M Tasevsky (2023)
- In our case we have the simple factorization formula for the cross section:

$$\frac{d\sigma}{d^2b d^2P} = \int d^2\mathbf{b}_1 d^2\mathbf{b}_2 \delta^{(2)}(\mathbf{b} - \mathbf{b}_1 + \mathbf{b}_2) \int \frac{d\omega_1}{\omega_1} \frac{d\omega_2}{\omega_2} d^2\mathbf{q}_1 d^2\mathbf{q}_2 \delta^{(2)}(\mathbf{P} - \mathbf{q}_1 - \mathbf{q}_2) \\ \times N_{ij}(\omega_1, \mathbf{b}_1, \mathbf{q}_1) N_{kl}(\omega_2, \mathbf{b}_2, \mathbf{q}_2) \frac{1}{2\hat{s}} M_{ik} M_{jl}^\dagger d\Phi(l^+ l^-).$$

- no independent sum over photon polarizations!
- other approaches: M. Vidovic, M. Greiner, C. Best and G. Soff, Phys. Rev. **C47** (1993); K. Hencken, G. Baur and D. Trautmann, Phys. Rev. C **69** (2004) 054902; S. Klein et al. (2020).

Wigner function approach

$$\begin{aligned}
 \frac{d\sigma}{d^2b d^2P} &= \int \frac{d^2Q}{(2\pi)^2} \exp[-i\mathbf{b}Q] \int \frac{d\omega_1}{\omega_1} \frac{d\omega_2}{\omega_2} \int \frac{d^2q_1}{\pi} \frac{d^2q_2}{\pi} \delta^{(2)}(\mathbf{P} - \mathbf{q}_1 - \mathbf{q}_2) \\
 &\times E_i\left(\omega_1, \mathbf{q}_1 + \frac{Q}{2}\right) E_j^*\left(\omega_1, \mathbf{q}_1 - \frac{Q}{2}\right) E_k\left(\omega_2, \mathbf{q}_2 - \frac{Q}{2}\right) E_l^*\left(\omega_2, \mathbf{q}_2 + \frac{Q}{2}\right) \\
 &\times \frac{1}{2\hat{s}} \sum_{\lambda\bar{\lambda}} M_{ik}^{\lambda\bar{\lambda}} M_{jl}^{\lambda\bar{\lambda}\dagger} d\Phi(l+l^-).
 \end{aligned}$$



$$\begin{aligned}
 \frac{d\sigma}{d^2b d^2P} &= \int \frac{d^2Q}{(2\pi)^2} \exp[-i\mathbf{b}Q] \int \frac{d\omega_1}{\omega_1} \frac{d\omega_2}{\omega_2} \int \frac{d^2q_1}{\pi} \frac{d^2q_2}{\pi} \delta^{(2)}(\mathbf{P} - \mathbf{q}_1 - \mathbf{q}_2) \\
 &\times E_i\left(\omega_1, \mathbf{q}_1 + \frac{Q}{2}\right) E_j^*\left(\omega_1, \mathbf{q}_1 - \frac{Q}{2}\right) E_k\left(\omega_2, \mathbf{q}_2 - \frac{Q}{2}\right) E_l^*\left(\omega_2, \mathbf{q}_2 + \frac{Q}{2}\right) \\
 &\times \frac{1}{2\hat{s}} \sum_{\lambda\bar{\lambda}} M_{ik}^{\lambda\bar{\lambda}} M_{jl}^{\lambda\bar{\lambda}\dagger} d\Phi(l^+l^-).
 \end{aligned}$$

with

$$\begin{aligned}
 \sum_{\lambda\bar{\lambda}} M_{ik}^{\lambda\bar{\lambda}} M_{jl}^{\lambda\bar{\lambda}\dagger} &= \delta_{ik} \delta_{jl} \sum_{\lambda\bar{\lambda}} \left| M_{\lambda\bar{\lambda}}^{(0,+)} \right|^2 + \epsilon_{ik} \epsilon_{jl} \sum_{\lambda\bar{\lambda}} \left| M_{\lambda\bar{\lambda}}^{(0,-)} \right|^2 \\
 &+ P_{ik}^{\parallel} P_{jl}^{\parallel} \sum_{\lambda\bar{\lambda}} \left| M_{\lambda\bar{\lambda}}^{(2,-)} \right|^2 + P_{ik}^{\perp} P_{jl}^{\perp} \sum_{\lambda\bar{\lambda}} \left| M_{\lambda\bar{\lambda}}^{(2,+)} \right|^2 + \text{interferences}
 \end{aligned}$$

$$\delta_{ik} = \hat{x}_i \hat{x}_k + \hat{y}_i \hat{y}_k, \quad \epsilon_{ik} = \hat{x}_i \hat{y}_k - \hat{y}_i \hat{x}_k, \quad P_{ik}^{\parallel} = \hat{x}_i \hat{x}_k - \hat{y}_i \hat{y}_k, \quad P_{ik}^{\perp} = \hat{x}_i \hat{y}_k + \hat{y}_i \hat{x}_k$$

- In the $\gamma\gamma$ CM, colliding photons can be in the $J_z = 0, \pm 2$ states.

- Wigner function is not necessarily a non-negative function. One may doubt, whether our cross section is manifestly positive, i.e. well-defined. To this end, we can introduce:

$$G_{ik}(\omega_1, \omega_2, \mathbf{P}; \mathbf{b}) \equiv \int \frac{d^2 \mathbf{k}}{2\pi^2} \exp[-i\mathbf{b}\mathbf{k}] E_i(\omega_1, \mathbf{k}) E_k(\omega_2, \mathbf{P} - \mathbf{k}),$$

so that our cross section takes the form

$$\frac{d\sigma}{d^2 \mathbf{b} d^2 \mathbf{P}} = \int \frac{d\omega_1}{\omega_1} \frac{d\omega_2}{\omega_2} G_{ik}(\omega_1, \omega_2, \mathbf{P}; \mathbf{b}) G_{jl}^*(\omega_1, \omega_2, \mathbf{P}; \mathbf{b}) \frac{1}{2\hat{s}} \sum_{\lambda \bar{\lambda}} M_{ik}^{\lambda \bar{\lambda}} M_{jl}^{\lambda \bar{\lambda} \dagger} d\Phi(l^+ l^-).$$

from which we obtain the cross section as a sum of squares which is manifestly positive:

$$\begin{aligned} \frac{d\sigma}{d^2 \mathbf{b} d^2 \mathbf{P}} &= \int \frac{d\omega_1}{\omega_1} \frac{d\omega_2}{\omega_2} \left\{ |G_{xx} + G_{yy}|^2 \sum_{\lambda \bar{\lambda}} \left| M_{\lambda \bar{\lambda}}^{(0,+)} \right|^2 + |G_{xy} - G_{yx}|^2 \sum_{\lambda \bar{\lambda}} \left| M_{\lambda \bar{\lambda}}^{(0,-)} \right|^2 \right. \\ &+ \left. |G_{xx} - G_{yy}|^2 \sum_{\lambda \bar{\lambda}} \left| M_{\lambda \bar{\lambda}}^{(2,+)} \right|^2 + |G_{xy} + G_{yx}|^2 \sum_{\lambda \bar{\lambda}} \left| M_{\lambda \bar{\lambda}}^{(2,-)} \right|^2 \right\} \frac{d\Phi(l^+ l^-)}{2\hat{s}}. \end{aligned}$$

- The Wigner function would be most conveniently decomposed into the $O(2)$ tensors introduced before.
- A popular GTMD parametrization is (e.g. Boer et al. 2018):

$$\begin{aligned} \mathcal{G}_{ij}(x, \mathbf{q}, \mathbf{Q}) &= \delta_{ij} \mathcal{G}_1(x, \mathbf{q}, \mathbf{Q}) + (2q_i q_j - \mathbf{q}^2 \delta_{ij}) \mathcal{G}_2(x, \mathbf{q}, \mathbf{Q}) \\ &+ (2Q_i Q_j - \mathbf{Q}^2 \delta_{ij}) \mathcal{G}_3(x, \mathbf{q}, \mathbf{Q}) + (q_i Q_j - Q_i q_j) \mathcal{G}_4(x, \mathbf{q}, \mathbf{Q}) \end{aligned}$$

- in the forward limit $\mathbf{Q} \rightarrow 0$, we have the TMD limits $\mathcal{G}_1 \rightarrow f_1(x, \mathbf{q})$, $\mathcal{G}_2 \rightarrow h_1^\perp(x, \mathbf{q})$.
- "Fierz transformation" to convert contractions $P_{ik} P_{jl}$ to $P_{ij} P_{kl}$:

$$\left(\begin{array}{c} \mathbb{I} \otimes \mathbb{I} \\ \varepsilon \otimes \varepsilon \\ P^\parallel \otimes P^\parallel \\ P^\perp \otimes P^\perp \end{array} \right) \Big|_{s\text{-channel}} = \frac{1}{2} \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & 1 & -1 \\ 1 & -1 & -1 & 1 \end{pmatrix} \left(\begin{array}{c} \mathbb{I} \otimes \mathbb{I} \\ \varepsilon \otimes \varepsilon \\ P^\parallel \otimes P^\parallel \\ P^\perp \otimes P^\perp \end{array} \right) \Big|_{t\text{-channel}}$$

- for small- x photons all the GTMDs are proportional to each other.

Photon polarization dependence

- Decompose the $\gamma\gamma \rightarrow l^+l^-$ amplitude into channels of total angular momentum projection $J_z = 0, \pm 2$ and even and odd parity, $z =$ LF momentum fraction of lepton.

$$M_{\uparrow\uparrow}^{(0,+)} = \frac{mk_{\perp} e^{-i\phi}}{k_{\perp}^2 + m^2}, \quad M_{\downarrow\downarrow}^{(0,+)} = \frac{-mk_{\perp} e^{i\phi}}{k_{\perp}^2 + m^2},$$

$$M_{\uparrow\downarrow}^{(0,+)} = \frac{m^2(2z-1)}{k_{\perp}^2 + m^2}, \quad M_{\downarrow\uparrow}^{(0,+)} = \frac{m^2(2z-1)}{k_{\perp}^2 + m^2},$$

$$M_{\uparrow\uparrow}^{(0,-)} = \frac{mk_{\perp} e^{-i\phi}}{k_{\perp}^2 + m^2}, \quad M_{\downarrow\downarrow}^{(0,-)} = \frac{mk_{\perp} e^{i\phi}}{k_{\perp}^2 + m^2},$$

$$M_{\uparrow\downarrow}^{(0,-)} = \frac{-m^2}{k_{\perp}^2 + m^2}, \quad M_{\downarrow\uparrow}^{(0,-)} = \frac{m^2}{k_{\perp}^2 + m^2},$$

$$M_{\uparrow\uparrow}^{(2,+)} = \frac{-mk_{\perp} e^{i\phi}}{k_{\perp}^2 + m^2}, \quad M_{\downarrow\downarrow}^{(2,+)} = \frac{mk_{\perp} e^{-i\phi}}{k_{\perp}^2 + m^2},$$

$$M_{\uparrow\downarrow}^{(2,+)} = \frac{-k_{\perp}^2 (ze^{i2\phi} - (1-z)e^{-i2\phi})}{k_{\perp}^2 + m^2}, \quad M_{\downarrow\uparrow}^{(2,+)} = \frac{k_{\perp}^2 ((1-z)e^{i2\phi} - ze^{-i2\phi})}{k_{\perp}^2 + m^2},$$

$$M_{\uparrow\uparrow}^{(2,-)} = \frac{mk_{\perp} e^{i\phi}}{k_{\perp}^2 + m^2}, \quad M_{\downarrow\downarrow}^{(2,-)} = \frac{mk_{\perp} e^{-i\phi}}{k_{\perp}^2 + m^2},$$

$$M_{\uparrow\downarrow}^{(2,-)} = \frac{-k_{\perp}^2 (ze^{i2\phi} + (1-z)e^{-i2\phi})}{k_{\perp}^2 + m^2}, \quad M_{\downarrow\uparrow}^{(2,-)} = \frac{k_{\perp}^2 ((1-z)e^{i2\phi} + ze^{-i2\phi})}{k_{\perp}^2 + m^2},$$

- all amplitudes have a common factor $g_{\text{em}}^2 / \sqrt{z(1-z)}$.

Polarization structure & angular dependence in the massless case

- for the massless case, only amplitudes for $J_z = \pm 2, S_z = 0$ with $L_z = \pm 2$ contribute!

-

$$\begin{aligned} \sum_{\lambda\bar{\lambda}} M_{ik}^{\lambda\bar{\lambda}} M_{jl}^{\lambda\bar{\lambda}\dagger} &\implies P_{ik}^{\parallel} P_{jl}^{\parallel} \sum_{\lambda=-\bar{\lambda}} \left| M_{\lambda\bar{\lambda}}^{(2,-)} \right|^2 + P_{ik}^{\perp} P_{jl}^{\perp} \sum_{\lambda=-\bar{\lambda}} \left| M_{\lambda\bar{\lambda}}^{(2,+)} \right|^2 \\ &= \frac{2}{k_{\perp}^2} \left\{ \frac{z^2 + (1-z)^2}{z(1-z)} \left(P_{ik}^{\parallel} P_{jl}^{\parallel} + P_{ik}^{\perp} P_{jl}^{\perp} \right) \right. \\ &\quad \left. + 2 \cos(4\phi) \left(P_{ik}^{\parallel} P_{jl}^{\parallel} - P_{ik}^{\perp} P_{jl}^{\perp} \right) \right\} \end{aligned}$$

- $\cos(4\phi)$ modulation from **difference between \parallel and \perp linear polarizations** of “ s -channel” photons. (“**vacuum birefringence**”)
- from Fierz transformation

$$\begin{aligned} \left(P^{\parallel} \otimes P^{\parallel} + P^{\perp} \otimes P^{\perp} \right) \Big|_{s\text{-channel}} &= \left(\mathbb{I} \otimes \mathbb{I} - \varepsilon \otimes \varepsilon \right) \Big|_{t\text{-channel}} \\ \left(P^{\parallel} \otimes P^{\parallel} - P^{\perp} \otimes P^{\perp} \right) \Big|_{s\text{-channel}} &= \left(P^{\parallel} \otimes P^{\parallel} - P^{\perp} \otimes P^{\perp} \right) \Big|_{t\text{-channel}} \end{aligned}$$

- In the b -integrated cross section, the $\cos(4\phi)$ modulation comes from the **linearly polarized TMD** $h_{1\perp}^{\perp}(x, q_{\perp}^2)$ (C. Li, J. Zhou, Y. Zhou (2019)).

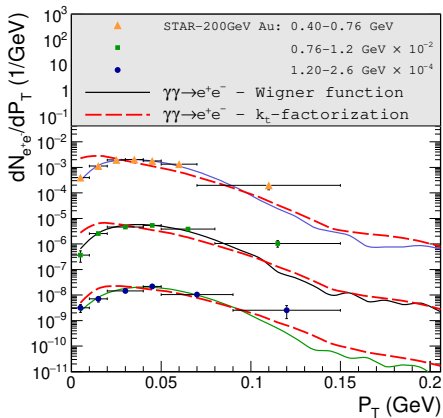
Polarization structure & angular dependence, massive case

- In the massive case, relevant to invariant masses close to the threshold, **interferences** between $J_z = 0$ and $J_z = \pm 2$ amplitudes of equal parity can induce the $\cos(2\phi)$ modulation.

$$\begin{aligned} \sum_{\lambda\bar{\lambda}} M_{ik}^{\lambda\bar{\lambda}} M_{jl}^{\lambda\bar{\lambda}\dagger} &\supset \delta_{ik} P_{jl}^{\parallel} \sum_{\lambda\bar{\lambda}} M_{\lambda\bar{\lambda}}^{(0,+)} M_{\lambda\bar{\lambda}}^{(2,+)\dagger} + P_{ik}^{\parallel} \delta_{jl} \sum_{\lambda\bar{\lambda}} M_{\lambda\bar{\lambda}}^{(2,+)} M_{\lambda\bar{\lambda}}^{(0,+)\dagger} \\ &+ \epsilon_{ik} P_{jl}^{\perp} \sum_{\lambda\bar{\lambda}} M_{\lambda\bar{\lambda}}^{(0,-)} M_{\lambda\bar{\lambda}}^{(2,-)\dagger} + P_{ik}^{\perp} \epsilon_{jl} \sum_{\lambda\bar{\lambda}} M_{\lambda\bar{\lambda}}^{(2,-)} M_{\lambda\bar{\lambda}}^{(0,-)\dagger} \end{aligned}$$

- We can expect a different dependence on centrality of the $\cos(2\phi)$ and $\cos(4\phi)$ contributions.
- In the t -channel coupling, the b -integrated cross section will contain the product of unpolarized & linearly polarized TMD's: $f_1(x_1, q_{1\perp}^2) h_1^{\perp}(x_2, q_{2\perp}^2) + (x_1, q_{1\perp} \leftrightarrow x_2, q_{2\perp})$.
- In **diffractive photoproduction of $q\bar{q}$ pairs** $\cos(2n\phi)$ correlations are induced by "elliptic" gluon GTMD/Wigner function (and higher harmonics). The dominant correlation here is $\cos(2\phi)$.

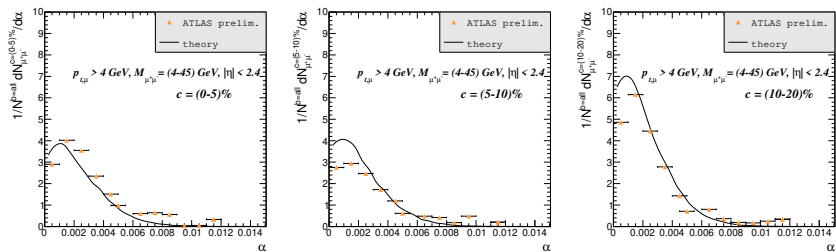
Dilepton production in semi-central collisions



P_T spectra for 60-80% central Au+Au collisions ($\sqrt{s_{NN}}=200$ GeV).

- Improved description of RHIC data in Wigner-function approach.

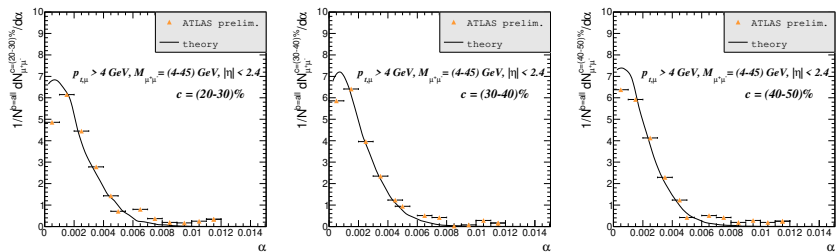
Acoplanarity distributions at LHC energies ($\sqrt{s_{NN}} = 5 \text{ TeV}$)



Data from ATLAS, Phys.Rev.C 107 (2023) 5, 054907.

- acoplanarity distribution of dimuons $\alpha = 1 - \frac{\Delta\phi}{\pi}$ in different bins of centrality

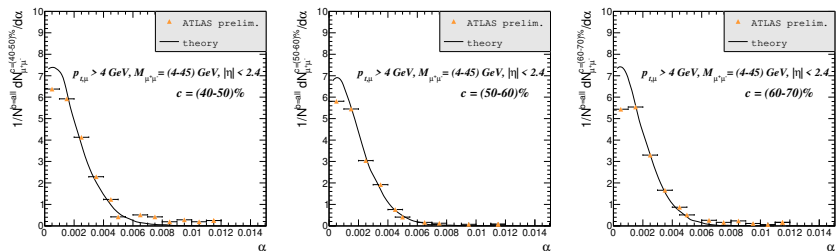
Acoplanarity distributions at LHC energies ($\sqrt{s_{NN}} = 5$ TeV)



Data from ATLAS, Phys.Rev.C 107 (2023) 5, 054907 .

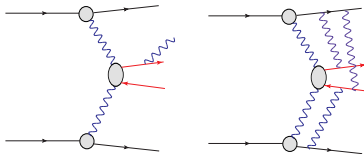
- acoplanarity distribution of dimuons $\alpha = 1 - \frac{\Delta\phi}{\pi}$ in different bins of centrality

Acoplanarity distributions at LHC energies ($\sqrt{s_{NN}} = 5 \text{ TeV}$)



Data from ATLAS, Phys.Rev.C 107 (2023) 5, 054907 .

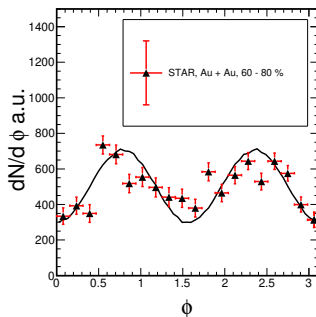
- acoplanarity distribution of dimuons $\alpha = 1 - \frac{\Delta\phi}{\pi}$ in different bins of centrality
- possible corrections: 1. photon emission/Sudakov resummation, genuine **strong field effects**: multiphoton exchanges are enhanced $\propto (Z\alpha)^{n_1+n_2}$, but suppressed for small-size electric dipoles.



Azimuthal angle distribution

- azimuthal angle between **sum** and **difference** of lepton transverse momenta.

$$\cos \phi = \frac{\mathbf{P} \cdot (\mathbf{p}_- - \mathbf{p}_+)}{|\mathbf{P}| |\mathbf{p}_- - \mathbf{p}_+|} \approx \frac{\mathbf{P} \cdot \mathbf{k}}{|\mathbf{P}| |\mathbf{k}|}, \quad \mathbf{k} = z_+ \mathbf{p}_- - z_- \mathbf{p}_+.$$



Data from STAR, Phys. Rev. Lett. 127 (2021); experimental cuts: $0.45 < M < 0.76$ GeV, $P_T < 0.1$ GeV.

- $\cos 4\phi$ modulation reflects orbital angular momentum $L_z = 2$ of e^+e^- pair.
- Calculation from Wigner function approach, M. Kłusek-Gawenda, W.S., A. Szczurek, in preparation.

- Angular distribution decomposed in harmonics:

$$\frac{dN}{d\phi} \propto 1 + A_2 \cos 2\phi + A_4 \cos 4\phi + \dots$$

$\sqrt{s_{NN}} = 200 \text{ GeV}$	Wigner	Wigner	STAR	STAR
centrality	A_4	$\sqrt{\langle P_T^2 \rangle} \text{ MeV}$	$ A_4 $	$\sqrt{\langle P_T^2 \rangle} \text{ MeV}$
60-80 %	-0.39	47.7	0.27 ± 6	50.9 ± 2.5
40-60 %	-0.49	51.0	-	-
20-40 %	-0.62	54.8	-	-
0-20%	-0.77	59.6	-	-

Table: Centrality dependence of angular coefficient and mean P_T of e^+e^- -pair.

Diffractive production of $c\bar{c}$ pairs in pA UPC

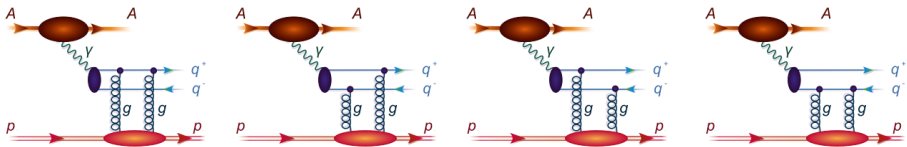


Figure: Feynman diagrams for the diffractive photoproduction of $q\bar{q}$ pairs in nucleus-proton collisions, discussed in the present paper.

$$\frac{d\sigma(\gamma p \rightarrow Q\bar{Q}p; s_{\gamma p})}{dz d^2\vec{P}_{\perp} d^2\vec{\Delta}_{\perp}} = \overline{\sum_{\lambda\gamma, \lambda, \bar{\lambda}}} \left| \int \frac{d^2\vec{b}_{\perp} d^2\vec{r}_{\perp}}{(2\pi)^2} e^{-i\vec{\Delta}_{\perp} \cdot \vec{b}_{\perp}} e^{-i\vec{P}_{\perp} \cdot \vec{r}_{\perp}} N(Y, \vec{r}_{\perp}, \vec{b}_{\perp}) \Psi_{\lambda\bar{\lambda}}^{\lambda\gamma}(z, \vec{r}_{\perp}) \right|^2.$$

- Jet momentum \vec{P}_{\perp} , pair transverse momentum $\vec{\Delta}_{\perp}$.
- Dipole amplitude \Leftrightarrow GTMD; dependence on $\cos\phi = \vec{P}_{\perp} \cdot \vec{\Delta}_{\perp} / (P_{\perp} \Delta_{\perp})$ induced by **elliptic gluon TMD**.

$$N(Y, \vec{r}_{\perp}, \vec{b}_{\perp}) = \int d^2\vec{q}_{\perp} d^2\vec{\kappa}_{\perp} f\left(Y, \frac{\vec{q}_{\perp}}{2} + \vec{\kappa}_{\perp}, \frac{\vec{q}_{\perp}}{2} - \vec{\kappa}_{\perp}\right) \exp[i\vec{q}_{\perp} \cdot \vec{b}_{\perp}] \\ \times \left\{ \exp\left[i\frac{1}{2}\vec{q}_{\perp} \cdot \vec{r}_{\perp}\right] + \exp\left[-i\frac{1}{2}\vec{q}_{\perp} \cdot \vec{r}_{\perp}\right] - \exp[i\vec{\kappa}_{\perp} \cdot \vec{r}_{\perp}] - \exp[-i\vec{\kappa}_{\perp} \cdot \vec{r}_{\perp}] \right\}.$$

•

$$f\left(Y, \frac{\vec{q}_{\perp}}{2} + \vec{\kappa}_{\perp}, \frac{\vec{q}_{\perp}}{2} - \vec{\kappa}_{\perp}\right) = f_0(Y, \kappa_{\perp}, q_{\perp}) + 2 \cos(2\phi_{q\kappa}) f_2(Y, \kappa_{\perp}, q_{\perp}).$$

Diffractive production of $c\bar{c}$ pairs in pA UPC

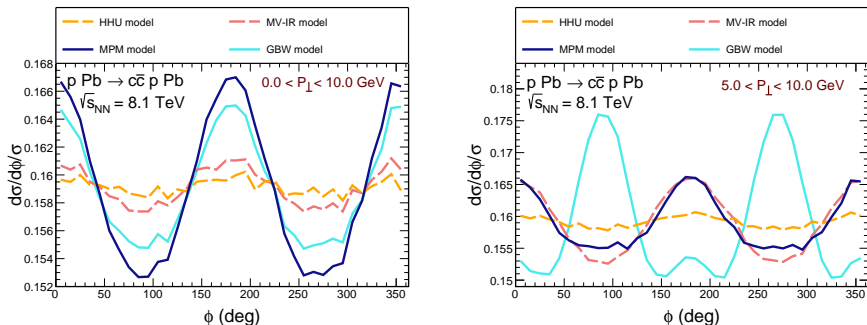


Figure: Distributions in the azimuthal angle ϕ between \vec{P}_\perp and $\vec{\Delta}_\perp$ normalised to the total cross section for $0.01 < P_\perp < 10.0$ GeV on the left and for $5.0 < P_\perp < 10.0$ GeV on the right.

- calculations from B.Linek et al. JHEP **10** (2023), 179.
- in impact parameter space: angular modulation due to dependence on relative orientation of \vec{b}_\perp and \vec{r}_\perp !. Can have dynamical origin, as well as a simple geometric one.

Summary

- We have studied low- P_T dilepton production in ultrarelativistic heavy-ion collisions, by a systematic comparisons of **thermal radiation** and **photon-photon fusion** within the coherent fields of the incoming nuclei.
- Comparison to recent **STAR data**: good description of low- P_T dilepton data in Au-Au($\sqrt{s_{NN}}=200$ GeV) collisions in three centrality classes, for invariant masses from threshold to ~ 4 GeV.
- Coherent emission dominant for the two peripheral samples, and comparable to the cocktail and thermal radiation yields in semi-central collisions.
- Impact-parameter dependent dilepton P_T distribution is described by a **Wigner function density matrix generalization of the Weizsäcker-Williams fluxes**. Different weights of $J_z = 0, \pm 2$ channels of the $\gamma\gamma$ -system. For e^+e^- pairs the $J_z = \pm 2$ channels dominate.
- We obtain an improved description of RHIC data.
- Proper account for the b -dependence is crucial at LHC energies.
- We obtain a very good description of ATLAS azimuthal decorrelations, our predictions agree well with recent ALICE data.
- the azimuthal $\cos 4\phi$ correlation measured by STAR is well reproduced, and can be traced to **orbital angular momentum of leptons**. Photon polarizations play an important role.
- Angular coefficient rises for more central collisions.
- in diffractive heavy quark production, the parton-level $\cos 2\phi$ azimuthal correlations induced by the elliptic Wigner function are much smaller than the ones in the QED process.