Photon induced processes: from ultraperipheral to semicentral nuclear collisions

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Outline

Ultraperipheral collisions

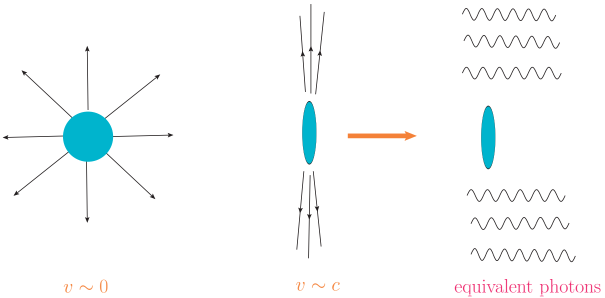
- Weizsäcker-Williams equivalent photons
- Production processes in UPC
- Photon-photon scattering
- Diffractive photoproduction of J/ψ as a probe of gluon saturation

From ultraperipheral to peripheral to semicentral collisions

- Dileptons from $\gamma\gamma$ production vs thermal dileptons from plasma phase
- Wigner function generalization of the Weizsäcker-Williams approach

Fermi-Weizsäcker-Williams equivalent photons

Heavy nuclei *Au*, *Pb* **have** $Z\alpha_{\rm em} \sim 0.6$



- ion at rest: source of a Coulomb field, the highly boosted ion, $\gamma \gg 1$:
- $E_{\max} = Ze\gamma/b^2 \sim (5 \times 10^{16} \div 1.5 \times 10^{18})\,\mathrm{V/cm}$ from RHIC to LHC at $b = 15\,\mathrm{fm}$. Larger than Schwinger critical field $E_{\rm crit} = m_e^2 c^3/(e\hbar) \approx 1.3 \times 10^{16}\,\mathrm{V/cm}$! But very short interaction time $\Delta t \sim b/\gamma$.
- Sharp burst of field strength, with $|\boldsymbol{E}|^2 \sim |\boldsymbol{B}|^2$ and $\boldsymbol{E} \cdot \boldsymbol{B} \sim 0$. (See e.g. J.D Jackson textbook) acts like a flux of "**equivalent photons**" (photons are collinear partons).

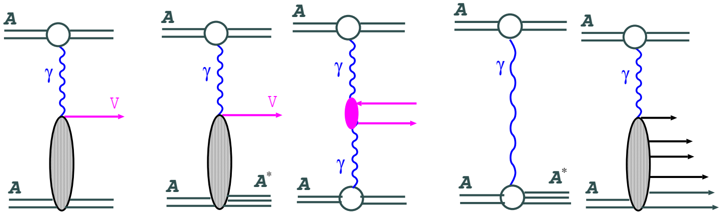
$$\boldsymbol{E}(\omega, \boldsymbol{b}) = -i\,\frac{Z\sqrt{4\pi\alpha_{em}}}{2\pi}\,\frac{\boldsymbol{b}}{b^2}\,\frac{\omega b}{\gamma} K_1\left(\frac{\omega b}{\gamma}\right)\;;\; N(\omega, \boldsymbol{b}) \propto \frac{1}{\omega}\Big|\boldsymbol{E}(\omega, \boldsymbol{b})\Big|^2$$

$$\sigma(AB) = \int d\omega d^2\boldsymbol{b}\, N(\omega, \boldsymbol{b})\, \sigma(\gamma B; \omega)$$

realistic flux includes **charge distribution** of nucleus

Ultraperipheral collisions

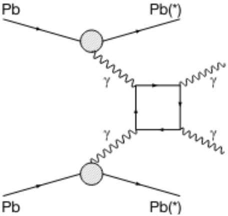
some examples of ultraperipheral processes:

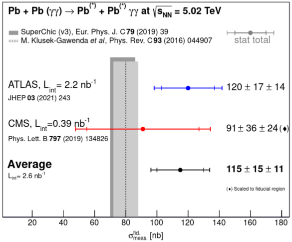


- **diffractive photoproduction** with and without breakup/excitation of a nucleus. Prominent final state: vector mesons $\rho, \omega, \phi, J/\psi, \psi', \Upsilon$. Mesasure the interaction of color dipoles with the nucleus.
- $\gamma\gamma$-**fusion**, mainly QED processes: $e^+e^-, \mu^+\mu^-, \tau^+\tau^-$ pairs. Bounds on anomalous magnetic moment of τ competitive with LEP. Measurement of $\gamma\gamma \to \gamma\gamma$.
- **Low energy nuclear physics:** electromagnetic excitation/dissociation of nuclei. Utilize the very low energy region of photon fluxes. Excitation of Giant Dipole Resonances. These processes may happen "on top" of the production processes above.
- the intact nuclei in the final state are not measured. Each of the photon exchanges is associated with a **large rapidity gap**. Veto on activity in very forward detectors or demand low number of neutrons in forward direction.
- **very small** $p_T \sim 1/R_A$ of the photoproduced system.

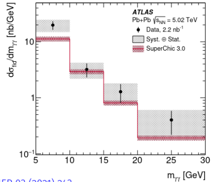
$\gamma\gamma$-scattering

First direct evidence by ATLAS: Nature Phys. **13** (2017) no.9, 852-858





recent measurements summarized in G. Krinitsas et al., arXiv:2204.02845



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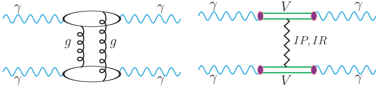
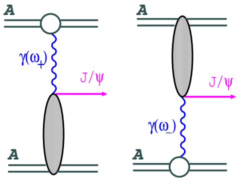
- Cross section dominated by SM box diagrams. Discrepancy wrt. theory prediction in lowest invariant mass bin.
- QCD effect? Quarkonium contribution? Recent speculation: Production of $T_{\psi\psi}(6900)$ resonance Biloshytskyi el al. 2207.13623.

- At large invariant masses: contribution of QCD Reggeon/Pomeron exchanges.
  M. Kłusek-Gawenda, WS, A. Szczurek, Phys Lett B 761 (2016).
- Measurable in the future ?



Diffractive photoproduction of J/ψ



- Each of the ions can be source of photon! Subtle interference effects at small P_T.
- rapidity distribution:

$$\frac{d\sigma(J/\psi)}{dy} = n(\omega_+)\sigma(\gamma A \to J/\psi A; W_+) + n(\omega_-)\sigma(\gamma A \to J/\psi A; W_-)$$

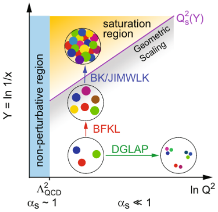
- On the **proton target**, at high γp cm-energies W, the diffractive process is decribed by the interction of a **color dipole** with the nucleon:

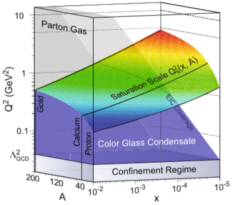
$$A(\gamma p \to J/\psi p; W, t=0) = i\langle J/\psi|\sigma(x,\mathbf{r})|\gamma\rangle$$

with the dipole cross section for **small dipoles**

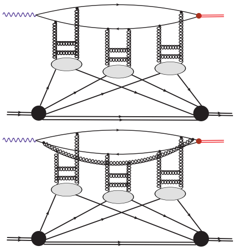
$$\sigma(x,\mathbf{r}) = \frac{\pi^2\alpha_s(r)}{N_c} r^2 xg(x, "1/r^2")$$

- We don't expect the proportionality to the leading-twist glue of the target to be relevant for the heavy nucleus.
- For J/ψ the color dipole analysis suggests scale $Q^2 \sim 2.25\,\mathrm{GeV}^2$. Ballpark of the **saturation scale**! A. Accardi et al. EPJA 52 (2016)





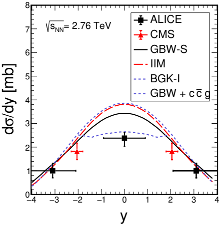
Glauber–Gribov theory for $c\bar{c}$ and $c\bar{c}g$ states

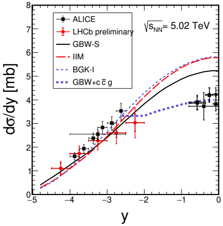


- We need to account for **rescattering** of $c\bar{c}$ and $c\bar{c}g$ Fock states of the photon.
- Partons propagate at fixed impact parameters, rescattering is a generalization of Glauber theory.
- $c\bar{c}$-state: **higher twist** effects
- $c\bar{c}g$ state: one iteration of Balitsky-Kovchegov eqn. Partially related to leading twist **gluon shadowing**.

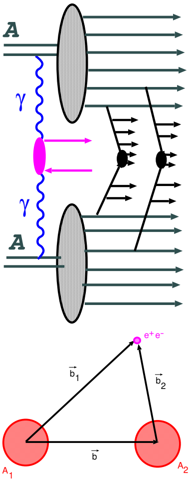
- Forward rapidities are well described by $c\bar{c}$ state alone.
- midrapidity data (smallest x!) need additional suppression from $c\bar{c}g$ contribution. Strongly dependent on infrared parameter $R_c \sim 0.2\,\mathrm{fm}$.

A.Łuszczak, WS, Phys Rev C 99 (2019), arXiv:2108.06788.





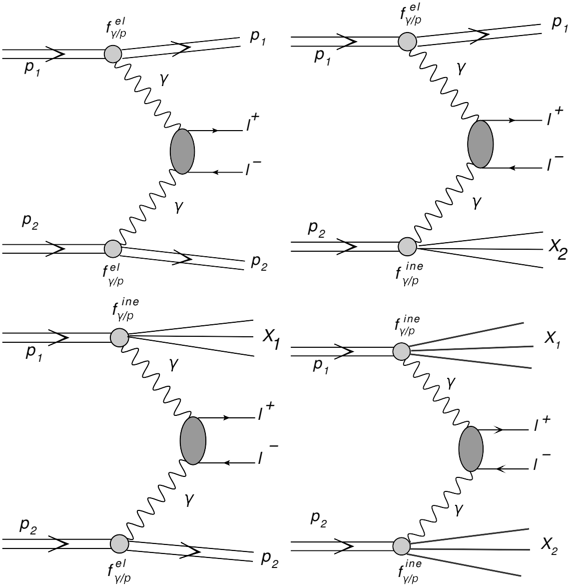
Dilepton production in semi-central collisions



- 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?
- Centrality dependence $\leftrightarrow$ cross section in **slices of impact parameter**.

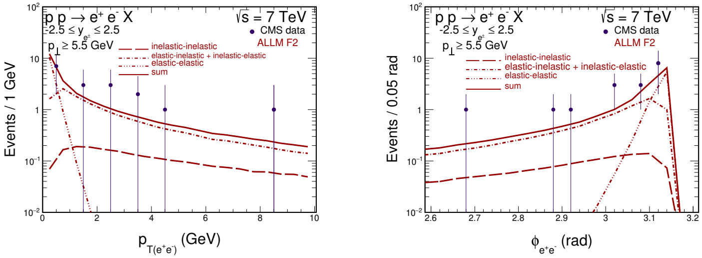
$$\frac{dN_{ll}[\mathcal{C}]}{dM} = \frac{1}{f_{\mathcal{C}} \cdot \sigma^{\rm in}_{\rm AA}} \int_{b_{\rm min}}^{b_{\rm max}} db \int d\xi \, \delta(M - 2\sqrt{\omega_1 \omega_2}) \, \frac{d\sigma_{ll}}{d\xi db}$$

Dileptons from $\gamma\gamma$-fusion in pp collisions



- M.Łuszczak, W.S., A. Szczurek, Phys.Rev.D 93 (2016) 7, 074018

Dileptons from $\gamma\gamma$-fusion in pp collisions



- from M.Łuszczak, W.S., A. Szczurek, Phys.Rev.D 93 (2016) 7, 074018
- "inelastic photon fluxes" correspond to the **standard photon parton distributions**. They can be calculated from proton structure functions F_2, F_L.
- "elastic" photon fluxes are the **coherent contribution to the photon parton distribution** in a proton. It can be calculated from e.m. form factors G_E, G_M.
- both are part of photon parton distributions like e.g. the k_T-factorization fluxes of ours, or e.g. LUX-QED fit.

Thermal dilepton production

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

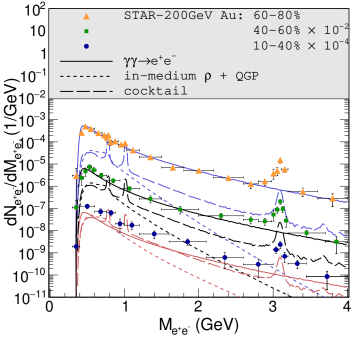
$$\frac{dN_{ll}}{d^4xd^4P} = \frac{\alpha_{\rm EM}^2 L(M)}{\pi^3 M^2}\, f^B(P_0;T)\,(-g_{\mu\nu}){\rm Im}\Pi^{\mu\nu}_{\rm EM}(M,P;\mu_B,T)\ ,$$

- To compute dilepton invariant-mass spectra an integration of the thermal emission rate over the space-time evolution of the expanding fireball is performed,

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

  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 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.
- Note: the low wavelength limit $P_0 \to 0$ at $\vec{P} = 0$ of the spectral function is related to the **conductivity of the medium**.
- 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.

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.
- Calculations from M. Kłusek-Gawenda, R. Rapp, W.S. and A. Szczurek, Phys. Lett. B **790** (2019), 339-344.

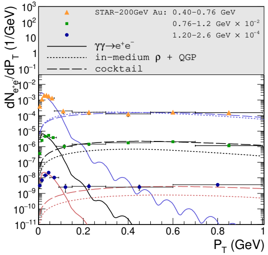
Pair transverse momentum distribution

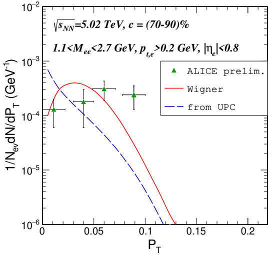
- Here we perform a simplified calculation by using b-integrated transverse momentum dependent photon fluxes,

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

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

- analogous to TMD-factorization in hard processes. Note that experiment includes a cut $p_t(\mathrm{lepton}) > 0.2\,\mathrm{GeV}$. Formfactors ensure that photon virtualities are much smaller then this "hard scale". We can thus treat them as on-shell in the $\gamma\gamma \to e^+e^-$ cross section.
- $dN/d^2\vec{q}_t$ has 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.





Wigner function approach

- 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 **polarization density matrix** of Wigner functions:

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

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

$$\begin{aligned} N(\omega, \boldsymbol{q}) &= \delta_{ij} \int d^2\boldsymbol{b}\, N_{ij}(\omega, \boldsymbol{b}, \boldsymbol{q}) = \delta_{ij}\, E_i(\omega, \boldsymbol{q}) E_j^*(\omega, \boldsymbol{q}) = \Big| \boldsymbol{E}(\omega, \boldsymbol{q}) \Big|^2 , \\ N(\omega, \boldsymbol{b}) &= \delta_{ij} \int \frac{d^2\boldsymbol{q}}{(2\pi)^2} N_{ij}(\omega, \boldsymbol{b}, \boldsymbol{q}) = \delta_{ij}\, E_i(\omega, \boldsymbol{b}) E_j^*(\omega, \boldsymbol{b}) = \Big| \boldsymbol{E}(\omega, \boldsymbol{b}) \Big|^2 . \end{aligned}$$

- Field strength vector:

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

Wigner function approach

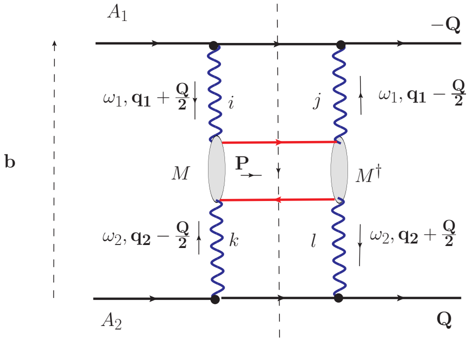
- The Wigner function is the Fourier transform of a **generalized transverse momentum distribution** (GTMD), and in some sense (at small-x) the most general function in the zoo of parton correlators. X.Ji Phys.Rev.Lett. 91 (2003); A.V. Belitsky, X. Ji and F.Yuan Phys.Rev.D 69 (2004)
For the photon case, 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.
- In our case we have the simple factorization formula for the cross section:

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

- no independent sum over photon polarizations! By fixing impact parameter of sources, the photon polarizations get entangled.
- 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

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



Positivity

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

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

so that our cross section takes the form

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

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

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

- Channels of different $J_z = \pm 2, 0$ and parity come with different weights!

Photon polarization dependence

- We have decomposed the $\gamma\gamma \to l^+ l^-$ amplitude into channels of total angular momentum projection $J_z = 0, \pm 2$ and even and odd parity. The explicit expressions for the squares of amplitudes, in terms of cm-scattering angle θ read:

$$\sum_{\lambda\bar{\lambda}} \left| M^{(0,+)}_{\lambda\bar{\lambda}} \right|^2 = g^4_{\rm em} \frac{8(1-\beta^2)\beta^2}{(1-\beta^2\cos^2\theta)^2} ,$$

$$\sum_{\lambda\bar{\lambda}} \left| M^{(0,-)}_{\lambda\bar{\lambda}} \right|^2 = g^4_{\rm em} \frac{8(1-\beta^2)}{(1-\beta^2\cos^2\theta)^2} ,$$

$$\sum_{\lambda\bar{\lambda}} \left| M^{(2,+)}_{\lambda\bar{\lambda}} \right|^2 = g^4_{\rm em} \frac{8\beta^2\sin^2\theta}{(1-\beta^2\cos^2\theta)^2} \left(1-\beta^2\sin^2\theta\right) ,$$

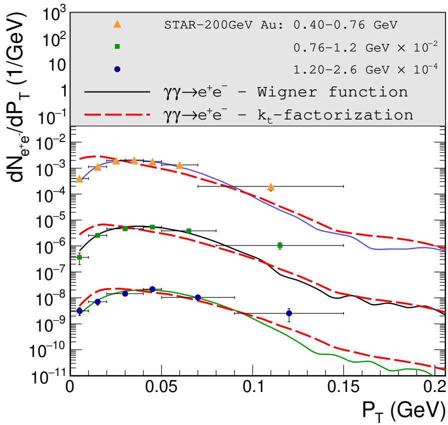
$$\sum_{\lambda\bar{\lambda}} \left| M^{(2,-)}_{\lambda\bar{\lambda}} \right|^2 = g^4_{\rm em} \frac{8\beta^2\sin^2\theta}{(1-\beta^2\cos^2\theta)^2} ,$$

where $g^2_{\rm em} = 4\pi\alpha_{\rm em}$, and

$$\beta = \sqrt{1 - \frac{4m_l^2}{M^2_{l^+l^-}}}$$

- is the lepton velocity in the dilepton cms-frame. Notice that in the ultrarelativistic limit $\beta \to 1$, the $|J_z| = 2$ terms dominate, while for $\beta \ll 1$, relevant for heavy fermions, the $J_z = 0$ components are the leading ones (pseudoscalar channel dominates).

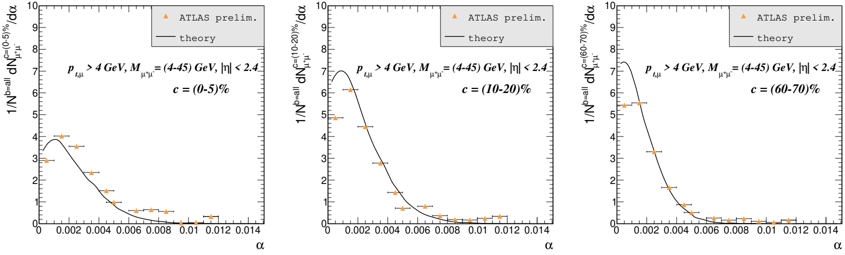
Dilepton production in semi-central collisions



P_T spectra for 60-80% central Au+Au collisions ($\sqrt{s_{NN}}$=200 GeV, 5020 GeV).

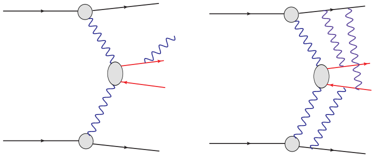
- Improved description of RHIC data in Wigner-function approach. No new free parameter.

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

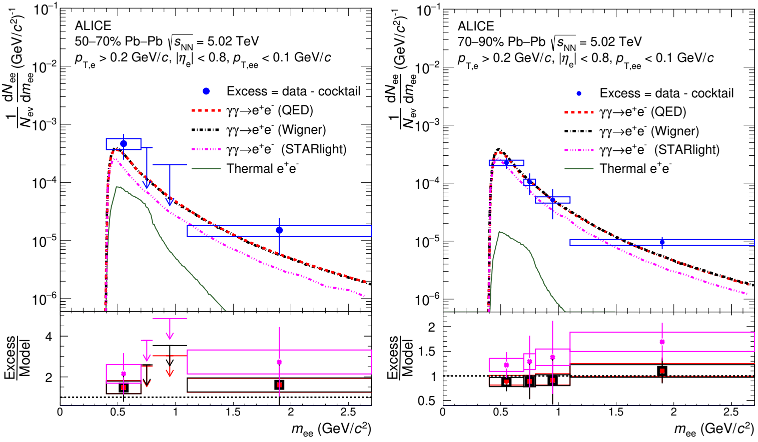


Data from ATLAS, ATLAS-CONF-2019-051

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



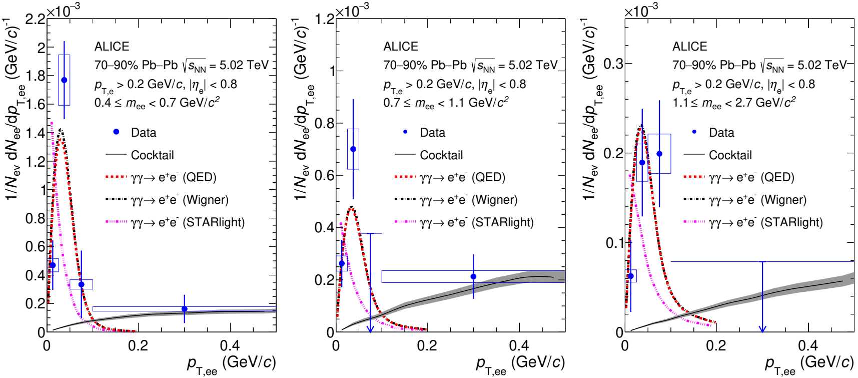
Our predictions against ALICE data: invariant mass



Data from ALICE, [arXiv:2204.11732 [nucl-ex]].

- our results: "Wigner", M. Kłusek-Gawenda, W. S. and A. Szczurek, Phys. Lett. B **814** (2021), 136114.
- also shown are the results of the STARLIGHT MC, as well as calculations by W. Zha, J. D. Brandenburg, Z. Tang and Z. Xu, Phys.Lett.B 800 (2020) 135089, Eur.Phys.J.A 57 (2021) 10, 299.

Our predictions against ALICE data: pair P_T



Data from ALICE, 'Dielectron production at midrapidity at low transverse momentum in peripheral and semi-peripheral Pb−Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV," [arXiv:2204.11732 [nucl-ex]].

- our results: "Wigner", M. Kłusek-Gawenda, W. S. and A. Szczurek, Phys. Lett. B **814** (2021), 136114.
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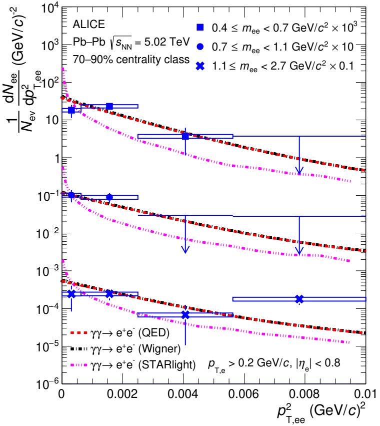
Our predictions against ALICE data: pair P_T



ALICE [arXiv:2204.11732 [nucl-ex]].

- Inclusion of the **impact-parameter-momentum correlation** leads to improvement of the description of pair-p_T distribution.
- $\sqrt{\langle p^2_{T,ee} \rangle}$ shows substantial broadening over the naive impact parameter-integrated result.
- rescattering of leptons in the plasma and/or magnetic field had been suggested as a source of broadening. (S. Klein et al. Phys Rev. Lett. 122 (2019)).

$\sqrt{\langle p^2_{T,ee} \rangle}$

Mass range (GeV)	**Wigner**	STARLIGHT	ALICE data
$0.4 \leq M \leq 0.7$	45 MeV	30 MeV	44 ± 28 (stat.) $\pm$ 6 (syst.) MeV
$0.7 \leq M \leq 1.1$	48 MeV	38 MeV	45 ± 36 (stat.) $\pm$ 8 (syst.) MeV
$1.1 \leq M \leq 2.7$	50 MeV	42 MeV	69 ± 36 (stat.) $\pm$ 8 (syst.) MeV

Summary

- **Weizsäcker-Williams photons** of highly boosted heavy ions open up a plethora of physics opportunities. From low-energy nuclear physics, to QED with strong fields, to high-energy QCD, to beyond the Standard Model physics.
- We have briefly discussed: the direct observation of **photon-photon scattering** by ATLAS and CMS collaborations. Slight underprediction of data: a hint at not fully understood QCD phenomena in $\gamma\gamma \to \gamma\gamma$?
- **Diffractive photoproduction of J/ψ on lead nuclei** probes the interaction of small color dipoles in the small-x regime close to the saturation scale. It gives a hint of a moderate **gluon shadowing** at small x.
- Coherent Weizsäcker-Williams photons **dominate the production of low-P_T dilepton pairs in peripheral collisions**. They are 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.
- **Wigner function approach** gives an improved description of RHIC data. Proper **account for the b-$\boldsymbol{P}_T$ correlation is crucial at LHC energies**.
- There appears to be no clear sign of a conjectured broadening of dilepton distributions from rescattering in (the magnetic field of) the plasma.
- many future applications: azimuthal correlation of $\boldsymbol{P} \cdot (\boldsymbol{p}_+ - \boldsymbol{p}_-)$ (starts at $\cos(4\phi)$), "flow" correlations $\boldsymbol{P} \cdot \boldsymbol{b}$, angular momentum of lepton pair, mass dependence thereof...