Ultraperipheral Nucleus-Nucleus collisions

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Outline

Ultraperipheral collisions

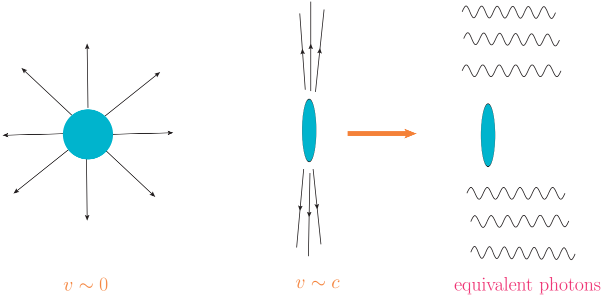
Weizsäcker-Williams equivalent photons
Production processes in UPC
Photon-photon scattering
Diffractive photoproduction of J/ψ as a probe of gluon saturation

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, $\gamma \gg 1$:
- $E_{\rm max} = Ze\gamma/b^2 \sim (5 \times 10^{16} \div 1.5 \times 10^{18})\,{\rm V/cm}$ from RHIC to LHC at $b = 15\,{\rm fm}$.
  Larger than Schwinger critical field $E_{\rm crit} = m_e^2 c^3/(e\hbar) \approx 1.3 \times 10^{16}\,{\rm V/cm}$!
  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).

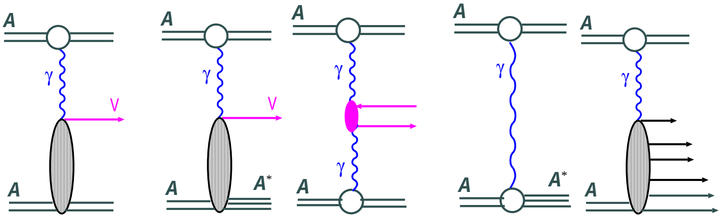
$$\boldsymbol{E}(\omega, \boldsymbol{b}) = -i\,\frac{Z\sqrt{4\pi\alpha_{em}}}{2\pi}\,\frac{\boldsymbol{b}}{b^2}\,\frac{\omega b}{\gamma} K_1\Big(\frac{\omega b}{\gamma}\Big)\ ;\ N(\omega, \boldsymbol{b}) \propto \frac{1}{\omega}\Big|\boldsymbol{E}(\omega, \boldsymbol{b})\Big|^2$$

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

realistic flux includes **charge distribution** of nucleus

Ultraperipheral collisions

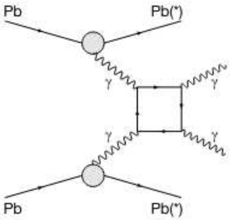
some examples of ultraperipheral processes:

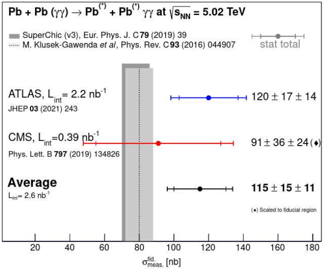


- **diffractive photoproduction** with and without breakup/excitation of a nucleus. Prominent final state: vector mesons $\rho, \omega, \phi, J/\psi, \psi', \Upsilon$. Mesasure the interaction of color dipoles with the nucleus.
- $\gamma\gamma$-**fusion**, mainly QED processes: $e^+e^-, \mu^+\mu^-, \tau^+\tau^-$ 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.

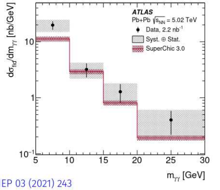
$\gamma\gamma$-scattering

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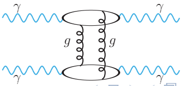
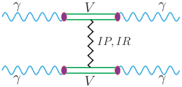
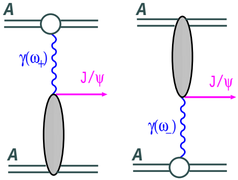
- Cross section dominated by SM box diagrams. Discrepancy wrt. theory prediction in lowest invariant mass bin.
- QCD effect? Quarkonium contribution? Recent speculation: Production of $T_{\psi\psi}(6900)$ resonance Biloshytskyi el al. 2207.13623.
- At large invariant masses: contribution of QCD Reggeon/Pomeron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

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

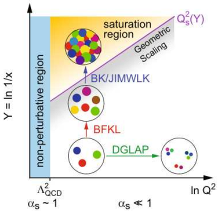
- On the **proton target**, at high γp cm-energies W, the diffractive process is decribed by the interction of a **color dipole** with the nucleon:

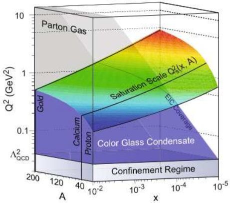
$$A(\gamma p \to J/\psi p; W, t = 0) = i\langle J/\psi|\sigma(x, \mathbf{r})|\gamma\rangle$$

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

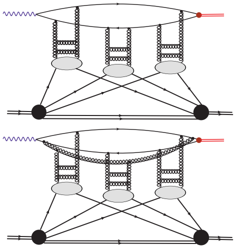
$$\sigma(x, \mathbf{r}) = \frac{\pi^2 \alpha_s(r)}{N_c} r^2 xg(x, "1/r^2")$$

- 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)





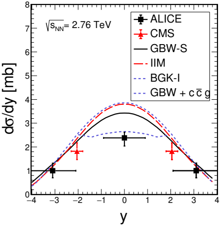
Glauber–Gribov theory for $c\bar{c}$ and $c\bar{c}g$ states

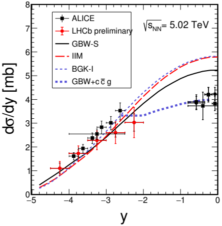


- We need to account for **rescattering** of $c\bar{c}$ and $c\bar{c}g$ Fock states of the photon.
- Partons propagate at fixed impact parameters, rescattering is a generalization of Glauber theory.
- $c\bar{c}$-state: **higher twist** effects
- $c\bar{c}g$ state: one iteration of Balitsky-Kovchegov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

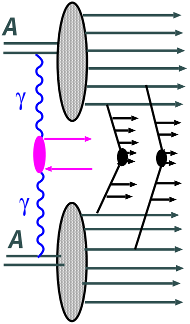
- Forward rapidities are well described by $c\bar{c}$ state alone.
- midrapidity data (smallest x!) need additional suppression from $c\bar{c}g$ contribution. Strongly dependent on infrared parameter $R_c \sim 0.2\,\mathrm{fm}$.

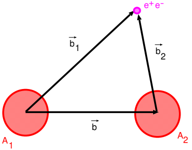
A. Łuszczak, WS, Phys Rev C 99 (2019), arXiv:2108.06788.





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**.

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

Thermal dilepton production

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

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

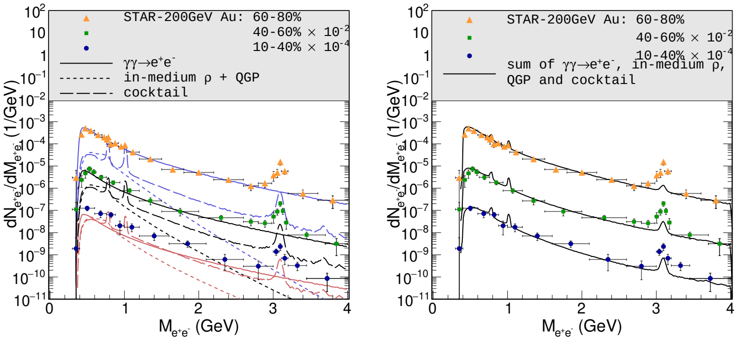
- To compute dilepton invariant-mass spectra an integration of the thermal emission rate over the space-time evolution of the expanding fireball is performed,

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

  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 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.

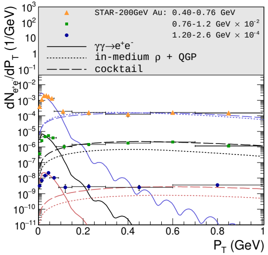
Pair transverse momentum distribution

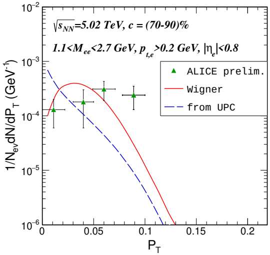
- Here we perform a simplified calculation by using b-integrated transverse momentum dependent photon fluxes,

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

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

- 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 $\boldsymbol{b}$:

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

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

- 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).

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:

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

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

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

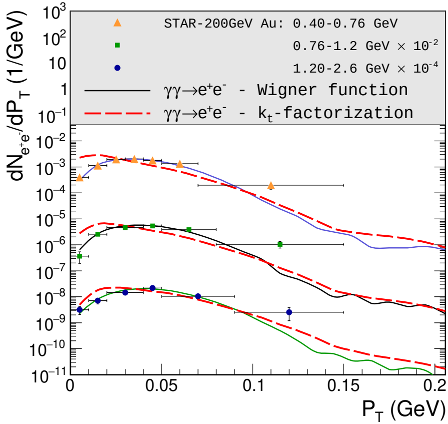
$$\sum_{\lambda\bar{\lambda}} \left| M^{(2,-)}_{\lambda\bar{\lambda}} \right|^2 = g^4_{\rm em} \frac{8\beta^2\sin^2\theta}{(1-\beta^2\cos^2\theta)^2} ,$$

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).

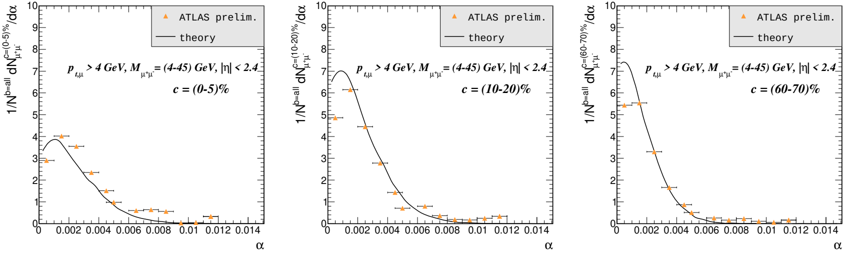
Dilepton production in semi-central collisions



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

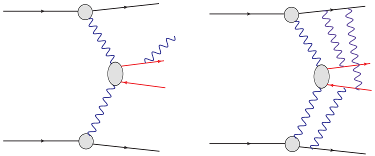
- Improved description of RHIC data in Wigner-function approach. No new free parameter.

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

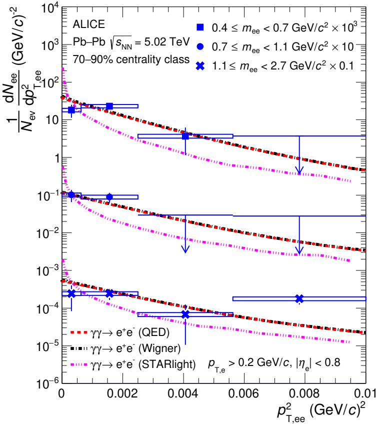


Data from ATLAS, ATLAS-CONF-2019-051

- 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: 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)).

	Mass range (GeV)	**Wigner**	STARLIGHT	ALICE data
$\sqrt{\langle p^2_{T,ee}\rangle}$	$0.4 \le M \le 0.7$	45 MeV	30 MeV	44 ± 28 (stat.) ± 6 (syst.) MeV
	$0.7 \le M \le 1.1$	48 MeV	38 MeV	45 ± 36 (stat.) ± 8 (syst.) MeV
	$1.1 \le M \le 2.7$	50 MeV	42 MeV	69 ± 36 (stat.) ± 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.