Photon induced processes from semi-central to ultraperipheral heavy-ion collisions

Wolfgang Schäfer [1]

[1] Institute of Nuclear Physics, PAN, Kraków

XV Hadron Physics 2020,
13-17 September 2021
Sao Jose dos Campos, Brazil (virtual conference)

Outline

Peripheral/ultraperipheral collisions

Weizsäcker-Williams fluxes of equivalent photons

Coherent diffractive photoproduction of J/ψ

diffractive production on the free nucleon

production on nuclear target, comparison to UPC

From ultraperipheral to semicentral collisions

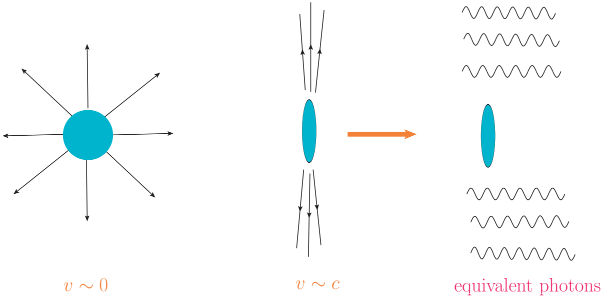
dileptons from $\gamma\gamma$ production vs thermal dileptons from plasma phase

density matrix/Wigner function generalization of the Weizsäcker-Williams approach

- A. Łuszczak and W. Schäfer, Phys. Rev. C **99** (2019) no.4, 044905 [arXiv:1901.07989 [hep-ph]].
- A. Łuszczak and W. Schäfer, [arXiv:2108.06788 [hep-ph]].
- M. Kłusek-Gawenda, R. Rapp, W. S. and A. Szczurek, Phys. Lett. B **790** (2019) 339 [arXiv:1809.07049 [nucl-th]].
- M. Kłusek-Gawenda, W. Schäfer and A. Szczurek, Phys. Lett. B **814** (2021), 136114 [arXiv:2012.11973 [hep-ph]].

Fermi-Weizsäcker-Williams equivalent photons

Heavy nuclei *Au*, *Pb* **have** $Z \sim 80$



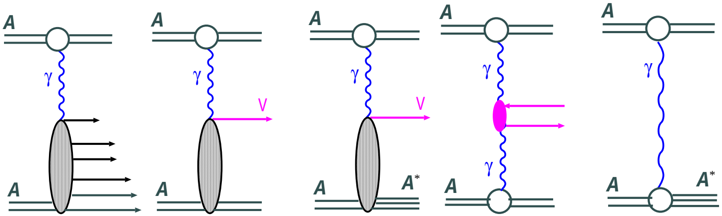
- ion at rest: source of a Coulomb field, the highly boosted ion: sharp burst of field strength, with $|\boldsymbol{E}|^2 \sim |\boldsymbol{B}|^2$ and $\boldsymbol{E} \cdot \boldsymbol{B} \sim 0$. (See e.g. J.D Jackson textbook).
- acts like a flux of "equivalent photons" (photons are collinear partons).

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

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

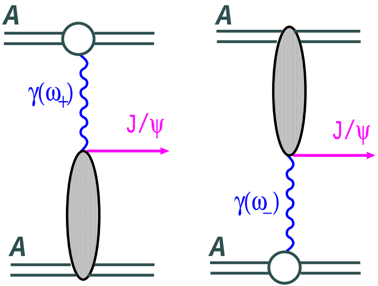
Ultraperipheral collisions

some examples of ultraperipheral processes:



- photoabsorption on a nucleus, at LHC we have $E = \sqrt{s_{NN}} = 2.76$ or $5\,\mathrm{TeV}$, so very high energy photon-nucleus subprocesses are possible.
- diffractive photoproduction with and without breakup/excitation of a nucleus
- $\gamma\gamma$-fusion.
- electromagnetic excitation/dissociation of nuclei. Excitation of Giant Dipole Resonances.
- the intact nuclei in the final state are not measured. Each of the photon exchanges is associated with a large rapidity gap.
- very small $p_T \sim 1/R_A$ of the photoproduced system.

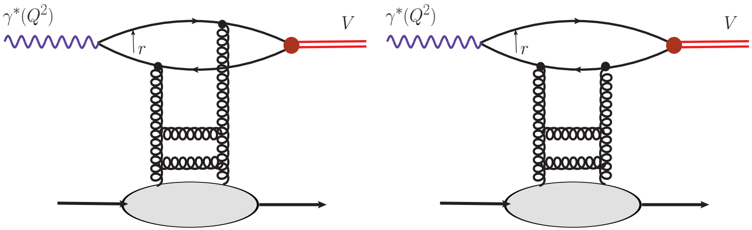
Coherent photoproduction of J/ψ in heavy ion collisions



- Exclusive vector meson production in HI collisions. Pioneering works: Klein & Nystrand ('99), Goncalves & Machado ('05). For the interfernce, see also Baur et al. ('06), WS & Szczurek ('07).
- Interference induces azimuthal correlation $(\boldsymbol{p}_1 \cdot \boldsymbol{p}_2)/(t_1 t_2)$, where $\boldsymbol{p}_1, \boldsymbol{p}_2 =$ transverse momenta of outgoing ions; concentrated at very low p_T of J/ψ and can be neglected in rapidity distributions.
- At midrapidity, the γA-cm energy W is $W = 92.5$ GeV for $\sqrt{s_{NN}} = 2.76$ TeV and $W = 125$ GeV for $\sqrt{s_{NN}} = 5$ TeV.
- The rapidity-dependent cross section for exclusive J/ψ production from the Weizsäcker-Williams fluxes of quasi-real photons $n(\omega)$ as:

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

Color dipole/ $k_\perp$-factorization approach



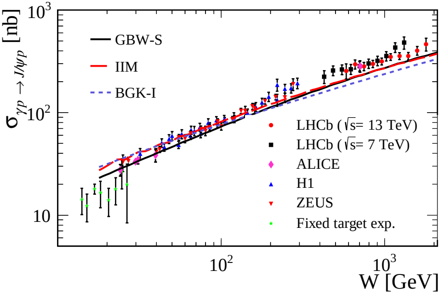
Color dipole representation of forward amplitude:

$$A(\gamma^*(Q^2)p \to Vp; W, t=0) = \int_0^1 dz \int d^2\boldsymbol{r}\, \psi_V(z, \boldsymbol{r})\, \psi_{\gamma^*}(z, \boldsymbol{r}, Q^2)\, \sigma(x, \boldsymbol{r})$$

$$\sigma(x, \boldsymbol{r}) = \frac{4\pi}{3}\alpha_S \int \frac{d^2\boldsymbol{\kappa}}{\boldsymbol{\kappa}^4} \frac{\partial xg(x, \boldsymbol{\kappa}^2)}{\partial \log(\boldsymbol{\kappa}^2)} \left[1 - e^{i\boldsymbol{\kappa}\boldsymbol{r}}\right], \; x = M_V^2/W^2$$

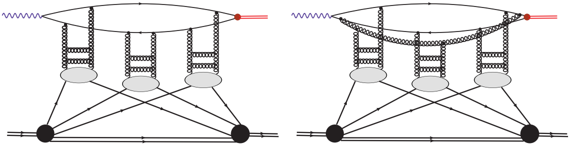
- impact parameters and helicities of high-energy q and $\bar{q}$ are conserved during the interaction.
- scattering matrix is "diagonal" in the color dipole representation. Color dipoles as "Good-Walker states".
- dipole cross section fitted to HERA DIS structure function data (the $\gamma^* p \to \gamma^* p$ forward amplitude.)
- corrections for real part, finite momentum transfer/"skewedness"

Exclusive diffractive J/ψ photoproduction on the proton



- besides the BGK-fit of Łuszczak & Kowalski, we show to other dipole cross section fits which incorporate heavy quarks:
  1. 'IIM' (Iancu, Itakura & Munier, which is a parametrization inspired by BFKL/BK-asymptotics).
  2. a recent re-fit of the Golec-Biernat-Wüsthoff form of the dipole cross section obtained by Golec-Biernat & Sapeta (2018).
- light-cone wave functions of J/ψ from Kowalski, Motyka & Watt ('06).
- the data at high energies were in fact extracted from exclusive diffraction in pp-collisions by LHCb.
- note: for our applications on nuclear targets, the region of $W \sim 30 \div 100\,\mathrm{GeV}$ is the most relevant.

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



- For the nuclear targets color dipoles can be regarded as eigenstates of the interaction and we can apply the standard rules of Glauber theory
- The Glauber form of the dipole scattering amplitude for $l_c \gg R_A$ (the coherence length is much larger than the nuclear size) is:

$$\Gamma_A(x, \boldsymbol{b}, \boldsymbol{r}) = 1 - \exp[-\frac{1}{2}\sigma(x, r) T_A(\boldsymbol{b})]$$

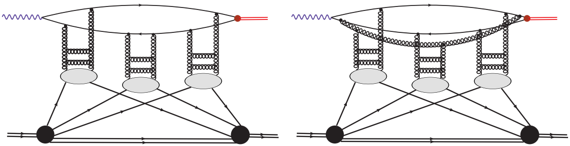
- at very high energies/small-x ($x \ll x_A \sim 0.01$) we need to take into account also the contribution of the $c\bar{c}g$-Fock state. The dipole cross section for the $q\bar{q}g$ state on the nucleon is (Nikolaev & Zakharov '93):

$$\sigma_{q\bar{q}g}(x, \boldsymbol{\rho}_1, \boldsymbol{\rho}_2, \boldsymbol{r}) = \frac{C_A}{2C_F}\Big(\sigma(x, \boldsymbol{\rho}_1) + \sigma(x, \boldsymbol{\rho}_2) - \sigma(x, \boldsymbol{r})\Big) + \sigma(x, \boldsymbol{r})$$

  Here $\boldsymbol{\rho}_{1,2}$ are the transverse $q - g$ and $\bar{q} - g$ distances, while $\boldsymbol{r}$ refers to the $q\bar{q}$ separation.
- Integrating over all variables but the dipole size $\boldsymbol{r}$, the effect of the gluon is a change of the $q\bar{q}$ dipole amplitude:

$$\Gamma_A(x, \boldsymbol{r}, \boldsymbol{b}) = \Gamma_A(x_A, \boldsymbol{r}, \boldsymbol{b}) + \log\left(\frac{x_A}{x}\right)\Delta\Gamma(x_A, \boldsymbol{r}, \boldsymbol{b})$$

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



- the $c\bar{c}g$ contribution contains the nonlinear piece associated with a triple-Pomeron vertex. Closely related to (one iteration of) Balitsky-Kovchegov equation.

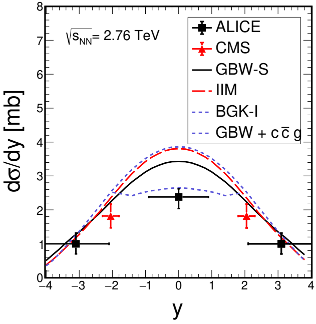
$q\bar{q}g$-contribution:

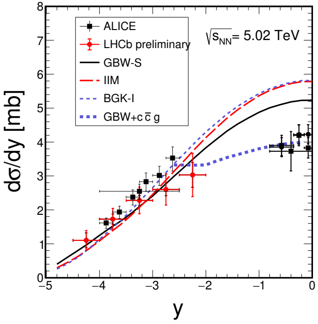
$$\Delta\Gamma(x_A, \boldsymbol{r}, \boldsymbol{b}) = \int d^2\boldsymbol{\rho}_1 |\psi(\boldsymbol{\rho}_1) - \psi(\boldsymbol{\rho}_2)|^2 \Big\{ \Gamma_A(x_A, \boldsymbol{\rho}_1, \boldsymbol{b} + \frac{\boldsymbol{\rho}_2}{2}) + \Gamma_A(x_A, \boldsymbol{\rho}_2, \boldsymbol{b} + \frac{\boldsymbol{\rho}_1}{2}) \\ - \Gamma_A(x_A, \boldsymbol{r}, \boldsymbol{b}) - \Gamma_A(x_A, \boldsymbol{\rho}_1, \boldsymbol{b} + \frac{\boldsymbol{\rho}_2}{2}) \Gamma_A(x_A, \boldsymbol{\rho}_2, \boldsymbol{b} + \frac{\boldsymbol{\rho}_1}{2}) \Big\}$$

- The quark $\to$ quark $+$ gluon light-cone wavefunction is probed in the nonperturbative regime.
- finite gluon propagation radius R_c, following color dipole phenomenology of Nikolaev, Zakharov & Zoller.

$$\psi(\boldsymbol{\rho}) = \frac{\sqrt{C_F \alpha_s}}{\pi} \frac{\boldsymbol{\rho}}{\rho R_c} K_1(\rho/R_c) \,\mathrm{with}\, R_c \sim 0.2 \div 0.3\,\mathrm{fm}.$$

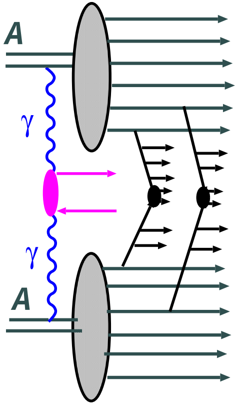
Color dipole/ $k_\perp$-factorization approach





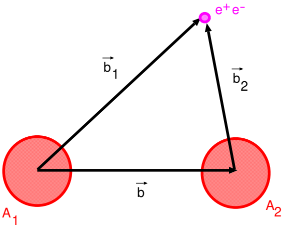
- Contribution of $c\bar{c}g$-state is related to nuclear gluon shadowing in other approaches (V. Guzey et al. '13, C. Henkels et al. '20).
- Glauber-Gribov rescattering of $c\bar{c}$ pair sums up nuclear higher twists & nonperturbative contributions.
- a rather small gluon propagation radius $R_c \sim 0.2$ fm is needed. This is *not a perturbation theory* calculation.
- NB: we are talking about a "hard" process with scale $Q^2 \sim 2.25\,\mathrm{GeV}^2$.

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).
- a first hint of the relevance of photoproduction mechanisms: a strong enhancement of J/ψ with $P_T < 300\,\mathrm{MeV}$ in peripheral reactions: J. Adam *et al.* [ALICE], Phys. Rev. Lett. **116** (2016) (for early estimates, see M. Kłusek-Gawenda and A. Szczurek, Phys. Rev. C **93** (2016)).
- Dileptons are a "classic" probe of the QGP: medium modifications of ρ, thermal dileptons... What is the competition between the different mechanisms?

Dilepton production in semi-central collisions

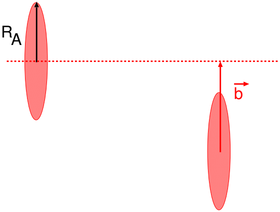


$$\frac{d\sigma_{ll}}{d\xi d^2\boldsymbol{b}} = \int d^2\boldsymbol{b}_1 d^2\boldsymbol{b}_2\, \delta^{(2)}(\boldsymbol{b} - \boldsymbol{b}_1 - \boldsymbol{b}_2) N(\omega_1, b_1) N(\omega_2, b_2) \frac{d\sigma(\gamma\gamma \to l^+ l^-; \hat{s})}{d(-\hat{t})} \;,$$

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

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

Centrality



- we adopt the impact parameter definition of centrality

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

- e.g. from optical limit of Glauber:

$$\frac{d\sigma_{\mathrm{AA}}^{\mathrm{in}}}{db} = 2\pi b (1 - e^{-\sigma_{\mathrm{NN}}^{\mathrm{in}} T_{\mathrm{AA}}(b)})$$

$\sigma_{\mathrm{AA}}^{\mathrm{in}} \sim 7\,\mathrm{barn}$ for Pb at LHC.

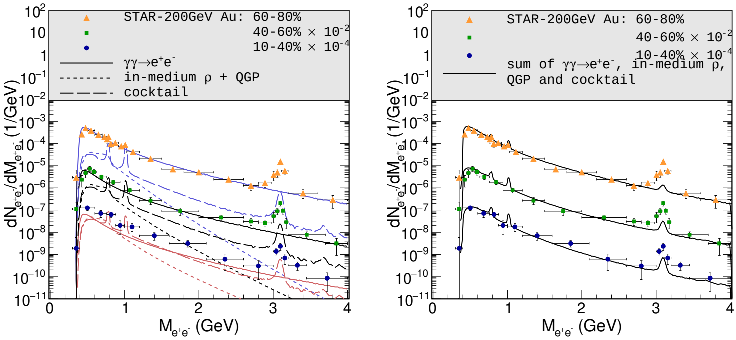
- fraction of inelastic hadronic events contained in the centrality class $\mathcal{C}$,

$$f_{\mathcal{C}} = \frac{1}{\sigma_{\mathrm{AA}}^{\mathrm{in}}} \int_{b_{\min}}^{b_{\max}} db \frac{d\sigma_{\mathrm{AA}}^{\mathrm{in}}}{db} .$$

- experimentally, centrality is determined by binning in multiplicity and/or transverse energy.

Dilepton production in semi-central collisions

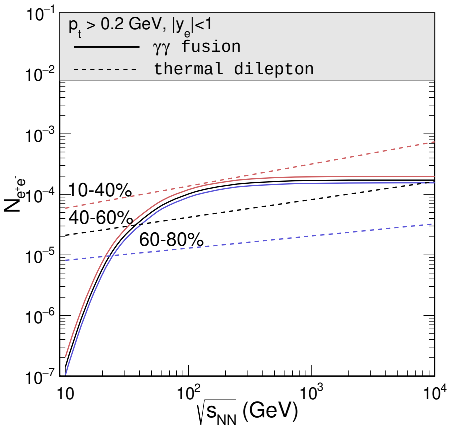
M. Kłusek-Gawenda, R. Rapp, WS & A. Szczurek, PLB 790 (2019).



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.

- data from J. Adam *et al.* [STAR Collaboration], Phys. Rev. Lett. **121** (2018) 132301.
- includes thermal QGP + in-medium ρ contribution (Rapp).
- 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]].

Dilepton production in semi-central collisions



Excitation function of low-P_T (<0.15 GeV) dilepton yields from $\gamma\gamma$ fusion (solid lines) and thermal radiation (dashed lines) in collisions of heavy nuclei (A$\simeq$200) around midrapidity in three centrality classes, including single-$e^{\pm}$ acceptance cuts.

Impact parameter dependence of P_T-distribution, M. Kłusek-Gawenda, WS & A. Szczurek, PLB 814 (2021)

- Electric field vector

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

- Then we introduce the Wigner-type density matrix

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

  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 $\boldsymbol{b}$.

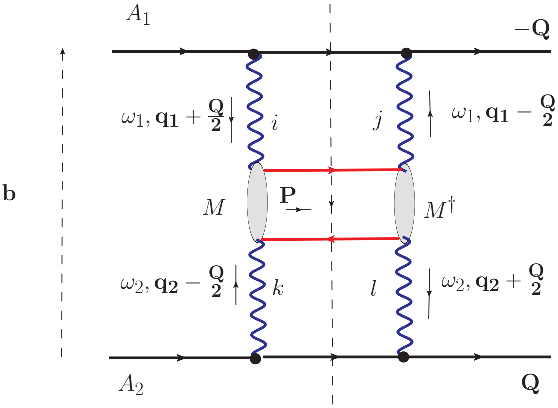
- cross section:

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

- 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, A.H. Mueller, B.-W. Xiao, F. Yuan, Phys.Rev.D 102 (2020).

Wigner function approach

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



Wigner function approach

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

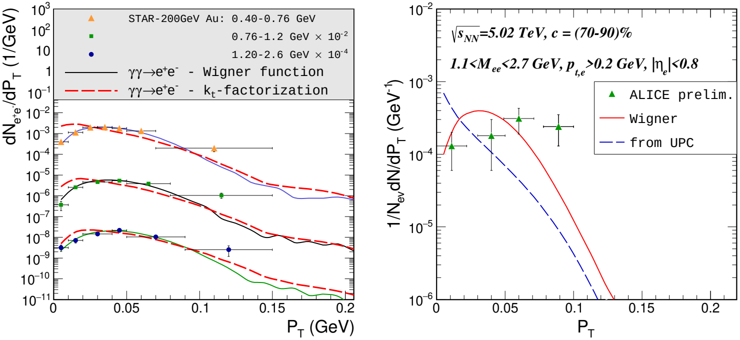
with

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

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

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

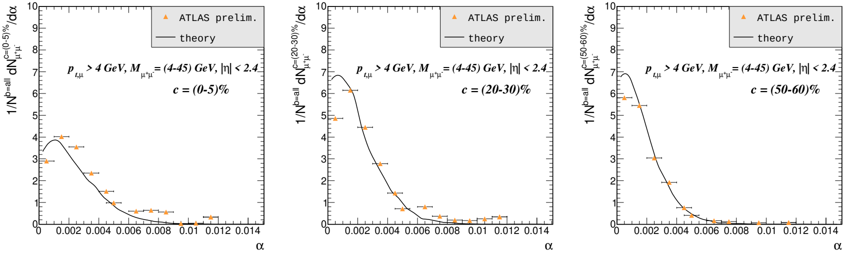
Dilepton production in semi-central collisions



P_T-pair spectrum of dielectrons, left: ($\sqrt{s_{NN}}$=200 GeV) for centralities 60 - 80 %, right: for 70-90% centrality Pb + Pb collisions at ($\sqrt{s_{NN}}$=5020 GeV).

- Wigner function approach leads to improvement of P_T-distribution at RHIC energy.
- At LHC energy it remedies a major failure of the naive b-integrated result: peak does not run away to $P_T \to 0$ with increasing energy, as in the distribution shown by dashed line "from UPC".

Dilepton production in semi-central collisions: acoplanarity distributions



Acoplanarity distributions (in bins of centrality) of dielectrons for Pb + Pb collisions at ($\sqrt{s_{NN}}$=5020 GeV).

- The dilepton system carries a finite total P_T, therefore dileptons are not back-to-back in the transverse plane.
- Acoplanarity: $\alpha = 1 - \frac{\Delta\phi}{\pi}$. Azimuthal decorrelation of electrons.
- N.B: no free parameters, only the known e.m. form factors/charge distributions of nuclei enter.
- Perhaps some room for additional decorrelation effects (multiphoton exchanges, bremsstrahlung ...) at larger α.
- Main features are very well described by the Wigner function approach.

Summary

- Exclusive diffractive J/ψ production in forward rapidity region is well described by Glauber-Gribov rescattering of $c\bar{c}$-dipoles. Dipole cross section fixed by HERA data.
- At midrapidity additional suppression is needed. Reasonable description is obtained after inclusion of $c\bar{c}g$ state, with a rather small gluon propagation radius $R_c \sim 0.2$ fm. The additional shadowing corresponds to a (moderate) shadowing of the nuclear glue.
- 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 $\sim$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 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.
- Parameter free Wigner function approach gives very good description of centrality dependence of pair transverse momentum and lepton azimuthal decorrelation.