J/ψ PHOTOPRODUCTION
IN SEMI-PERIPHERAL HEAVY-ION COLLISIONS

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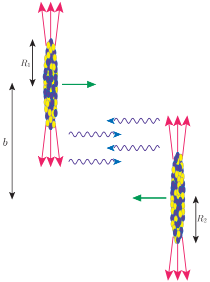

Centrality (for ^{208}Pb):

- central collisions: b $\approx$ (0 fm $+\triangle b$);
- semi-central collisions: b $\approx$ (5 $-$ 10) fm;
- semi-peripheral collisions: b $\approx$ (10 $-$ 12) fm;
- peripheral collisions: b $\approx$ (12 fm $-(R_1 + R_2)$);
- ultraperiperal collisions: b $> (R_1 + R_2)$;

where $R = R_0 A^{1/3}$.

The strong electromagnetic field is a source of photons that can induce electromagnetic reactions in ion-ion collisions.
Electromagnetism is a long-range force, so electromagnetic interactions occur even at relatively large ion-ion separations.

Photon energy: $\omega = \frac{\gamma}{b} \approx \gamma \times 15$ MeV

Virtuality: $Q^2 = \frac{1}{R^2} \approx 0.0008$ GeV^2

1 M. Kłusek-Gawenda, A. Szczurek, M. V. T. Machado, V. G. Serbo, *Double-photon exclusive processes with heavy-quark–heay-antiquark pairs in high-energy Pb-Pb collisions at energies available at the CERN Large Hadron Collider*, Phys. Rev. **C83** (2011) 024903;

2 M. Kłusek-Gawenda, A. Szczurek, *Photoproduction of J/ψ mesons in peripheral and semicentral heavy ion collisions*, Phys. Rev. **C93** (2016) 044912.

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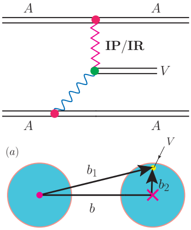
Equivalent Photon Approximation - UPC



Photoproduction

$$\frac{d\sigma_{A_1 A_2 \to A_1 A_2 V}}{d^2 b dy} = \frac{dP_{\gamma \mathbf{P}/\mathbf{R}}(y,b)}{dy} + \frac{dP_{\mathbf{P}/\mathbf{R}\gamma}(y,b)}{dy}$$

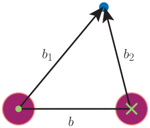
$$\frac{dP_{\gamma \mathbf{P}/\mathbf{P}\gamma}(y,b)}{dy} = \omega_{1/2} N\left(\omega_{1/2}, b\right) \sigma_{\gamma A_{2/1} \to V A_{2/1}}(W_{\gamma A_{2/1}}) S_{abs}(b)$$

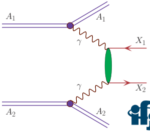
$\gamma\gamma$ fusion

$$\sigma_{A_1 A_2 \to A_1 A_2 X_1 X_2} = \int \sigma_{\gamma\gamma \to X_1 X_2}\left(W_{\gamma\gamma}\right) N(\omega_1, \mathbf{b_1}) N(\omega_2, \mathbf{b_2}) S^2_{abs}(\mathbf{b}) \frac{W_{\gamma\gamma}}{2} dW_{\gamma\gamma}\, dY_{X_1 X_2}\, d\bar{b}_x\, d\bar{b}_y\, d^2 b$$

$$= \int \frac{d\sigma_{\gamma\gamma \to X_1 X_2}\left(W_{\gamma\gamma}\right)}{d\cos\theta} N(\omega_1, \mathbf{b_1}) N(\omega_2, \mathbf{b_2}) S^2_{abs}(\mathbf{b}) \frac{W_{\gamma\gamma}}{2} dW_{\gamma\gamma}\, dY_{X_1 X_2}\, d\bar{b}_x\, d\bar{b}_y\, d^2 b$$

$$\times \frac{d\cos\theta}{dy_{X_1}\, dy_{X_2}\, dp_t} \times dy_{X_1}\, dy_{X_2}\, dp_t\,.$$





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Equivalent Photon Flux vs. Form Factor

$$N(\omega,b) = \frac{Z^2\alpha_{em}}{\pi^2\beta^2}\frac{1}{\omega}\frac{1}{b^2} \times \left| \int d\chi\, \chi^2 \frac{F\left(\frac{\chi^2+u^2}{b^2}\right)}{\chi^2+u^2} J_1(\chi) \right|^2$$

$$\beta = \frac{p}{E},\ \gamma = \frac{1}{\sqrt{1-\beta^2}},\ u = \frac{\omega b}{\gamma\beta},\ \chi = k_\perp b$$

- point-like $F(\mathbf{q}^2) = 1$

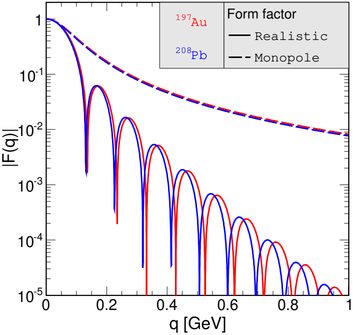
$$N(\omega,b) = \frac{Z^2\alpha_{em}}{\pi^2\beta^2}\frac{1}{\omega}\frac{1}{b^2} \times u^2\left[K_1^2(u) + \frac{1}{\gamma^2}K_0^2(u)\right]$$

- monopole $F(\mathbf{q}^2) = \frac{\Lambda^2}{\Lambda^2+|\mathbf{q}|^2}$

$$\sqrt{\langle r^2\rangle} = \sqrt{\frac{6}{\Lambda^2}} = 1 \text{ fm } A^{1/3}$$

- realistic

$$F(\mathbf{q}^2) = \frac{4\pi}{|\mathbf{q}|}\int \rho(r)\sin(|\mathbf{q}|\,r)\,r\,dr$$



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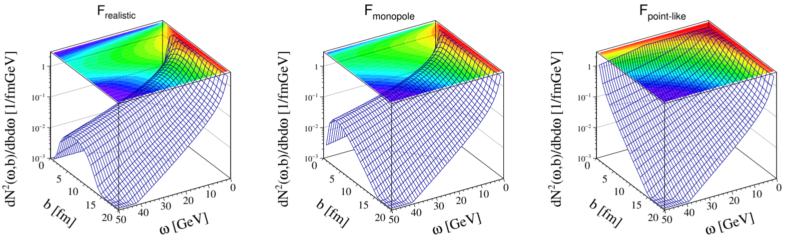
Photon flux



Standard photon fluxes.

J/ψ - UPC

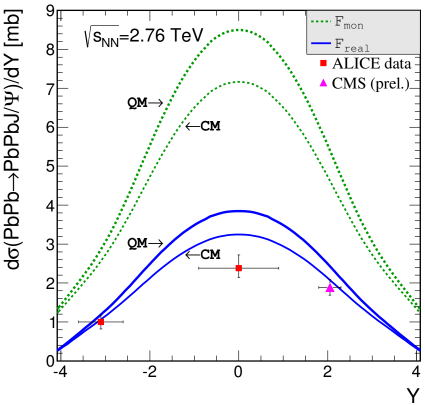
$$\sigma_{\gamma A \to J/\psi A} = \frac{d\sigma_{\gamma A \to J/\psi A}(t=0)}{dt} \int_{-\infty}^{t_{max}} dt\, |F_A(t)|^2$$

$$= \frac{\alpha_{em}}{4 f^2_{J/\psi}} \sigma^2_{tot,J/\psi A} \int_{-\infty}^{t_{max}} dt\, |F_A(t)|^2$$

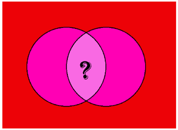
$$t = -q^2 = -(m^2_{J/\psi} / (2\omega_{lab}))^2$$

$$\sigma^{QM}_{tot}(J/\psi A) = 2 \int d^2\mathbf{r} \left(1 - \exp\left(-\frac{1}{2}\sigma_{tot}(J/\psi p)\, T_A(\mathbf{r})\right)\right)$$

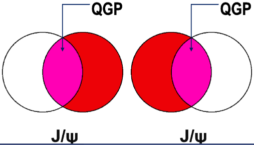
$$\sigma^{CM}_{tot}(J/\psi A) = \int d^2\mathbf{r}\, (1 - \exp(-\sigma_{tot}(J/\psi p)\, T_A(\mathbf{r})))$$



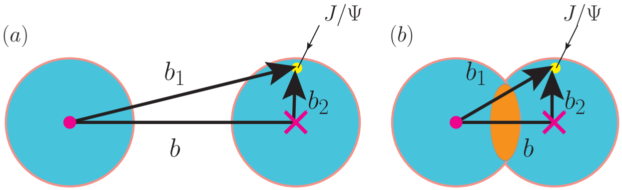
UPC → semi-central collision



e^+e^-, $\mu^+\mu^-$



CHARMONIUM PHOTOPRODUCTION

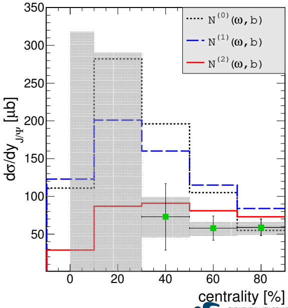


The inclusion of the absorption effect by modifying effective photon fluxes in the impact parameter space.

$$N^{(1)}(\omega_1, b) = \int N(\omega_1, b_1) \frac{\theta(R_A - (|\mathbf{b}_1 - \mathbf{b}|))}{\pi R_A^2} \mathrm{d}^2 b_1$$

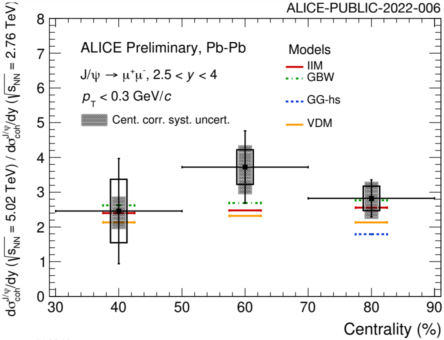
$$N^{(2)}(\omega_1, b) = \int N(\omega_1, b_1) \frac{\theta(R_A - (|\mathbf{b}_1 - \mathbf{b}|))(b_1 - R_A)}{\pi R_A^2} \mathrm{d}^2 b_1$$

A successful description of ALICE data, $\sqrt{s_{NN}}$ = 2.76 TeV



Coherent J/ψ cross section at forward rapidity

NEW



- Ratio of the measurements at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV and $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV shows no centrality dependence within uncertainties
- Fair agreement of the measured ratio to models (except GG-hs) within uncertainties

Quark Matter 2022 - A. Neagu 19

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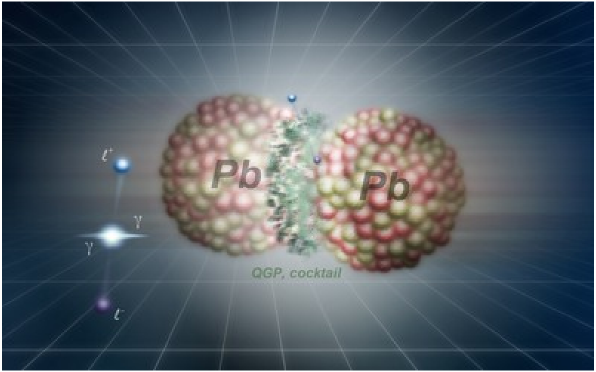
DILEPTON PRODUCTION



- ➢ From ultraperipheral to semicentral collisions → dilepton sources
  - ➢ $\gamma\gamma$ fusion mechanism

DIELECTRON INVARIANT-MASS SPECTRA - RHIC

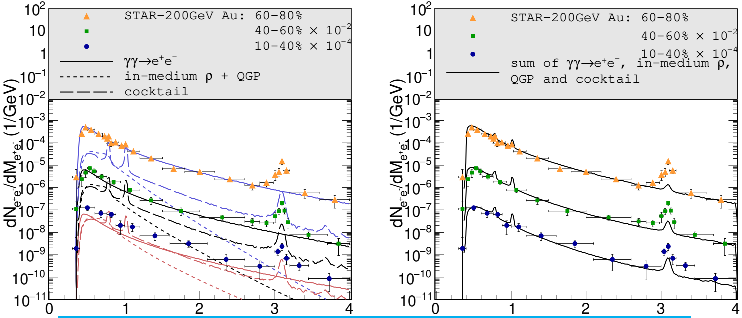
$p_t > 0.2$ GeV,

$|\eta_e| < 1$

$|y_{e^+e^-}| < 1$

- ✔ $\gamma\gamma$-fusion
- ✔ thermal radiation
- ✔ hadronic cocktail

3 centrality classes



The coherent emission dominates for the two peripheral samples

and is comparable to the cocktail and thermal radiation yields in semi-central collisions.

EPA in the impact parameter space - the pair transverse momentum $P_T^{\ell^+\ell^-}$ is neglected

$$\sigma_{A_1 A_2 \to A_1 A_2 \ell^+\ell^-} = \int N(\omega_1, \mathbf{b_1})\, N(\omega_2, \mathbf{b_2})\, \delta^{(2)}(\mathbf{b} - \mathbf{b}_1 - \mathbf{b}_2) \int d^2\mathbf{b}_1\, d^2\mathbf{b}_2\, d^2\mathbf{b}\, dy_{\ell^+}\, dy_{\ell^-}\, dp_{t,\ell}^2 \frac{d\sigma(\gamma\gamma \to \ell^+\ell^-; \hat{s})}{d(-\hat{t})}$$

➫ **k_t-factorization**

$$\frac{dN_{ll}}{d^2\mathbf{P}_T^{\ell^+\ell^-}} = \int \frac{d\omega_1}{\omega_1} \frac{d\omega_2}{\omega_2} d^2\boldsymbol{q}_{1t} d^2\boldsymbol{q}_{2t} \frac{dN(\omega_1, q_{1t}^2)}{d^2\boldsymbol{q}_{1t}} \frac{dN(\omega_2, q_{2t}^2)}{d^2\boldsymbol{q}_{2t}} \delta^{(2)}(\boldsymbol{q}_{1t} + \boldsymbol{q}_{2t} - \mathbf{P}_T^{\ell^+\ell^-})\hat{\sigma}(\gamma\gamma \to \ell^+\ell^-)\Big|_{\text{cuts}},$$

➫ **Exact calculation**

$$\frac{d\sigma[\mathcal{C}]}{d^2\mathbf{P}_T^{\ell^+\ell^-}} = \int \frac{d^2\boldsymbol{Q}}{2\pi} w(Q; b_{\max}, b_{\min}) \int \frac{d^2\boldsymbol{q}_1}{\pi} \frac{d^2\boldsymbol{q}_2}{\pi} \delta^{(2)}(\mathbf{P}_T^{\ell^+\ell^-} - \mathbf{q}_1 - \boldsymbol{q}_2) \int \frac{d\omega_1}{\omega_1} \frac{d\omega_2}{\omega_2}$$
$$\times \quad E_i\left(\omega_1, \boldsymbol{q}_1 + \frac{\boldsymbol{Q}}{2}\right) E_j^*\left(\omega_1, \boldsymbol{q}_1 - \frac{\boldsymbol{Q}}{2}\right) E_k\left(\omega_2, \boldsymbol{q}_2 - \frac{\boldsymbol{Q}}{2}\right) E_l^*\left(\omega_2, \boldsymbol{q}_2 + \frac{\boldsymbol{Q}}{2}\right) \frac{1}{2\hat{s}} \sum_{\lambda\bar{\lambda}} M_{ik}^{\lambda\bar{\lambda}} M_{jl}^{\lambda\bar{\lambda}\dagger}\, d\Phi(\ell^+\ell^-)\,.$$

The factorization formula is written in terms of the Wigner function:

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

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

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

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PAIR TRANSVERSE MOMENTUM - RHIC & LHC

$p_t > 0.2$ GeV,

$|\eta_e| < 1$

c=(60-80)%

$|y_{ee}| < 1$

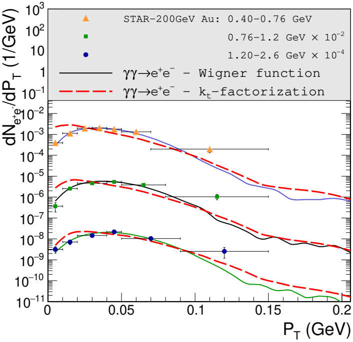
- - - - - - PL**B790** (2019) 339
vs.
—— PL**B814** (2021) 136114

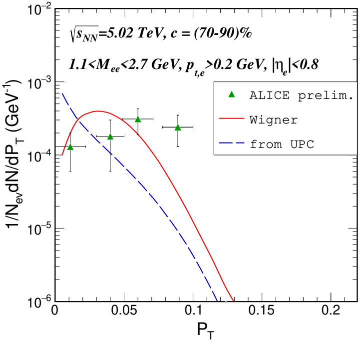
$p_t > 0.2$ GeV,

$|\eta_e| < 0.8$

c=(70-90)%

$M_{e^+e^-}$ =(1.1-2.7) GeV





Small correction to the STAR description & much better situation for LHC

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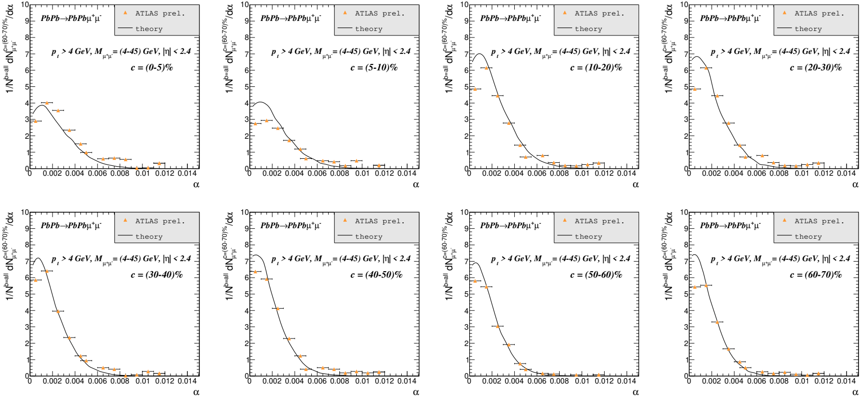
ACOPLANARITY - ATLAS DATA



A successful description of ATLAS data by $\gamma\gamma$-fusion alone

A correct normalization and shape of the distributions

$p_t > 4$ GeV,

$M_{\mu^+\mu^-}$ =(4-45) GeV,

$|\eta_\mu| < 2.4$

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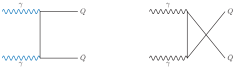
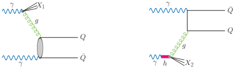
HEAVY-QUARK

Elementary cross section

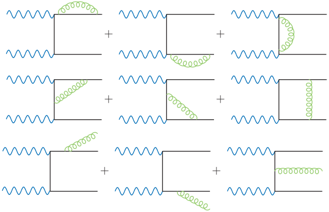


The Born amplitudes.

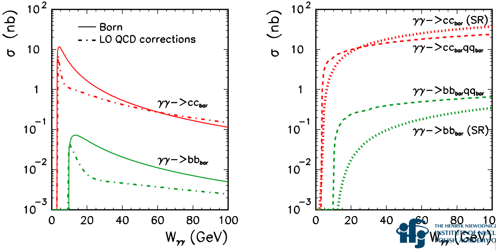
$Q\bar{Q}q\bar{q}$ production.



The single-resolved mechanism.

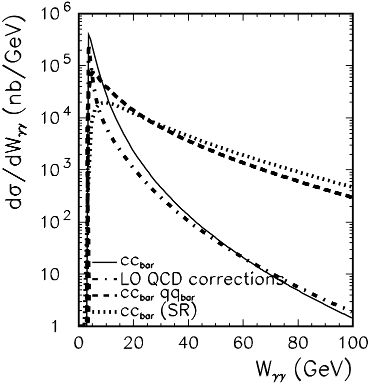


The leading-order QCD corrections.



Nuclear cross section

$\gamma - \gamma$ subsystem energy



Partial contributions of different mechanisms.

	σ_{tot}	Born	QCD-corrections
$c\bar{c}$	2.47 *mb*	42.5 %	14.6 %
		4-quark	Single-resolved
		27.1 %	15.8 %

UPC results ($\sqrt{s_{NN}}$ = 5.5 TeV) for $c\bar{c}$ production

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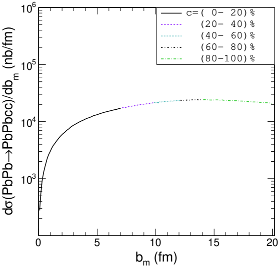
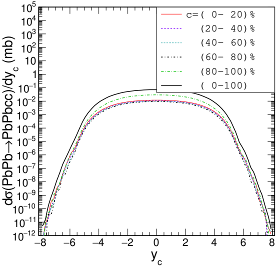
$c\bar{c}$ VS. CENTRALITY

Nuclear cross section

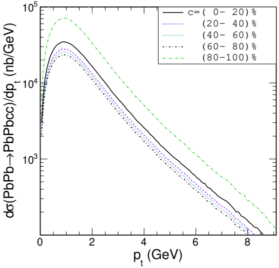
Impact parameter



Rapidity



Transverse momentum



Non-UPC results ($\sqrt{s_{NN}}$ = 5.02 TeV)

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CONCLUSION

- EPA in the impact parameter space
- Ultraperipheral & semicentral heavy-ion collisions
- Fourier transform of the charge distribution
- Multidimensional integrals $\rightarrow$ differential cross section
- Description of experimental data for UPC and semicentral events
  - First description of ALICE data for J/ψ production; centrality $<$ 100%
  - Description of STAR and ALICE data for Dilepton production - J/ψ contribution is missing
- $c\bar{c}$ production
  - $PbPb \rightarrow PbPbc\bar{c}$
  - $pp \rightarrow c\bar{c}$
  - $pn \rightarrow c\bar{c}$
  - $np \rightarrow c\bar{c}$
  - $nn \rightarrow c\bar{c}$

$\rightarrow$ D meson production

Thank you