Dilepton production via photon-photon fusion in semicentral heavy-ion collisions at small transverse momentum

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✓ M. K-G, R. Rapp, W. Schäfer and A. Szczurek,
Dilepton Radiation in Heavy-Ion Collisions at Small Transverse Momentum,
Phys. Lett. **B790** (2019) 339,

✓ M. K-G, W. Schäfer and A. Szczurek,
Wigner distributions of photons in nuclei and dilepton production via photon-photon fusion in semicentral ultrarelativistic nucleus-nucleus collisions,
in preparation.

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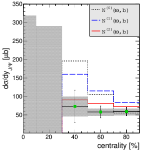
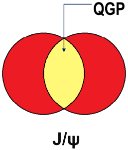
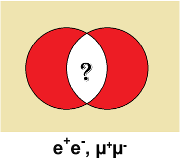
OUTLINE

✓ M. K-G and A. Szczurek,
Photoproduction of $J/\psi J/\psi$ mesons in peripheral and semicentral heavy-ion collisions,
Phys. Rev. **C93** (2016) 044912

✓ ALICE Collaboration, J. Adam et al.,
Measurement of an excess in the yield of J/ψ at very low p_T in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV,
Phys. Rev. Lett. 116 (2016) 22.







✘ Dileptons from $\gamma\gamma$ fusion have peak at very low P_T
✘ Nuclei create event in which e.g. plasma can be formed
✘ Dileptons are a classical probe of the QGP

- Ultraperipheral collisions
- From ultraperipheral to semicentral collisions → dilepton sources
  - Initial $\gamma\gamma$ fusion mechanism
  - Thermal dileptons
- Low-P_T dilepton spectra
  - SPS
  - RHIC

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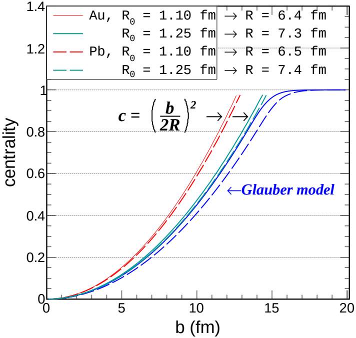
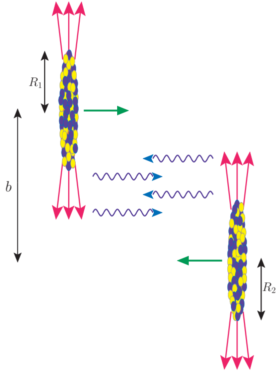
Equivalent Photon Approximation

The strong electromagnetic field is a source of photons that can induce electromagnetic reactions in ion-ion col



UltraPeripheral collisions

$b > R_{min} = R_1 + R_2 \approx 14$ fm



Centrality

$$c = f_{\text{Geo}}(b) = \frac{1}{\sigma_{AA}^{in}} \int_0^b \mathrm{d}b \frac{\mathrm{d}\sigma_{AA}^{in}}{db}$$

$$c = \left(\frac{b}{2R}\right)^2$$

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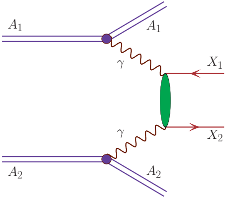
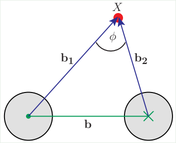
Nuclear cross section - UPC



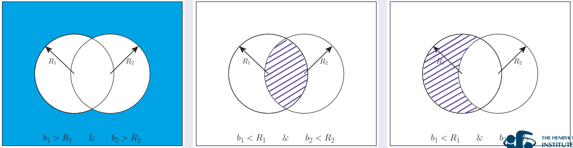
$$\sigma_{A_1 A_2 \to A_1 A_2 l^+ l^-} = \int N(\omega_1, \mathbf{b_1})\, N(\omega_2, \mathbf{b_2})\, \delta^{(2)}(\boldsymbol{b} - \boldsymbol{b}_1 - \boldsymbol{b}_2) \times \int d^2\boldsymbol{b}_1 d^2\boldsymbol{b}_2 d^2\boldsymbol{b}\, dy_+ dy_- dp_t^2 \frac{d\sigma(\gamma\gamma \to l^+ l^-; \hat{s})}{d(-\hat{t})}$$

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

UPC



Semicentral collisions



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Equivalent Photon Flux vs Form Factor

$$N(\omega, b) = \frac{Z^2 \alpha_{\rm EM}}{\pi^2} \left| \int_0^\infty dq_t \frac{q_t^2 F_{\rm em}(q_t^2 + \frac{\omega^2}{\gamma^2})}{q_t^2 + \frac{\omega^2}{\gamma^2}} J_1(bq_t) \right|^2 ,$$

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

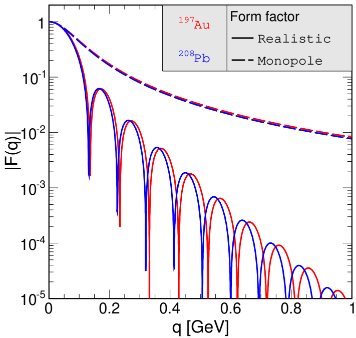
$$N(\omega, b) = \frac{Z^2 \alpha_{em}}{\pi^2 \beta^2} \frac{1}{\omega} \frac{1}{b^2} \times u^2 \left[K_1^2(u) + \frac{1}{\gamma^2} K_0^2(u) \right]$$

- 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

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



DIELECTRON INVARIANT-MASS YIELD

Definition in the centrality class

➯ Initial $\gamma\gamma$ fusion mechanism

$$\frac{dN_{ll}[\mathcal{C}]}{dM} = \frac{1}{f_{\mathcal{C}} \cdot \sigma_{\rm AA}^{\rm in}} \int_{b_{\min}}^{b_{\max}} db \int dy_+ dy_- dp_t^2 \, \delta(M - 2\sqrt{\omega_1\omega_2}) \frac{d\sigma_{A_1A_2 \to A_1A_2 l^+ l^-}}{dy_+ dy_- dp_t^2 db}\Big|_{\rm cuts},$$

$$f_{\mathcal{C}} = \frac{1}{\sigma_{\rm AA}^{\rm in}} \int_{b_{\min}}^{b_{\max}} db \frac{d\sigma_{\rm AA}^{\rm in}}{db} \to \text{fraction of inelastic hadronic event}$$

$$\frac{d\sigma_{\rm AA}^{\rm in}}{db} = 2\pi b (1 - e^{-\sigma_{\rm NN}^{\rm in} T_{\rm AA}(b)}) \to \text{optical Glauber model}$$

$$T_{\rm AA}(b) = \int d^3\vec{r}_1 d^3\vec{r}_2 \, \delta^{(2)}(\boldsymbol{b} - \boldsymbol{r}_{1\perp} - \boldsymbol{r}_{2\perp}) \, n_{\rm A}(r_1) n_{\rm A}(r_2) \to \text{Nuclear thickness function}$$

➯ Thermal dilepton production

The calculation of thermal dilepton production from a near-equilibrated medium

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

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

$\to$ Thermal emission rate

- ✓ Phys. Lett. **B473** (2000)
- ✓ Phys. Rev. Lett. 100 (2008)
- ✓ Phys. Lett. **B753** (2016) 586

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DIELECTRON INVARIANT-MASS SPECTRA - RHIC

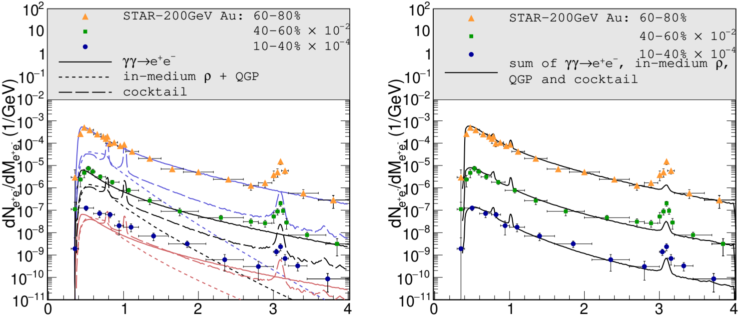
$p_t > 0.2$ GeV,

$|\eta_e| < 1$

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

- ✔ $\gamma\gamma$-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.

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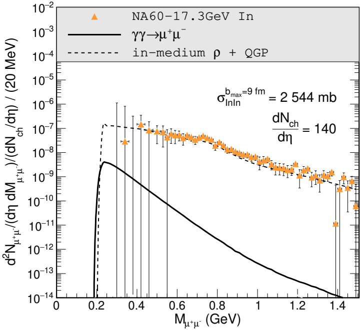
DIELECTRON INVARIANT-MASS SPECTRA - SPS

$P_T < 0.2$ GeV,

$3.3 < Y_{\mu^+\mu^-,LAB} < 4.2$

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

In-In @ $\sqrt{s_{NN}} = 17.3$ GeV



The $\gamma\gamma$ contribution is small and plays some role at small $M_{\mu^+\mu^-}$ where data run out of precision

DIELECTRON INVARIANT-MASS SPECTRA - LHC

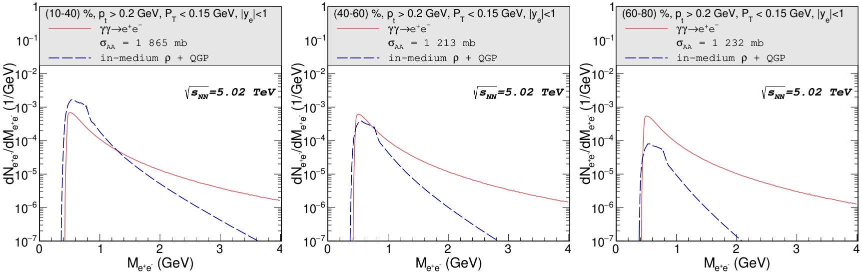
$p_t > 0.2$ GeV,

$|y_e| < 1$

$P_T < 0.15$ GeV

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

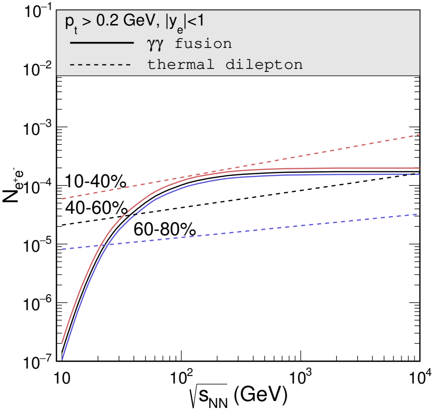
3 centrality classes



The total $\gamma\gamma$ cross section keeps rising at high collision energies,

the main contributions arise from large impact parameters $b \gg 2R_A$

EXCITATION FUNCTION OF LOW-P_T



A≃200

$P_t < 0.15$ GeV,

$|y_e| < 1$

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

3 centrality classes

$\gamma\gamma$ is subleading @SPS & keeps rising @ RHIC or LHC

DIELECTRON PAIR TRANSVERSE MOMENTUM

➩ from UPC

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

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

➩ Exact calculation

$$\frac{d\sigma[\mathcal{C}]}{dy_1 dy_2 d^2\boldsymbol{p}_1 d^2\boldsymbol{p}_2} = \int \frac{d^2\boldsymbol{Q}}{2\pi} w(Q; b_{\mathrm{max}}, b_{\mathrm{min}}) \int \frac{d^2\boldsymbol{q}_1}{\pi}\frac{d^2\boldsymbol{q}_2}{\pi} \delta^{(2)}(\boldsymbol{p}_1 + \boldsymbol{p}_2 - \boldsymbol{q}_1 - \boldsymbol{q}_2)$$

$$\times \quad E_i\left(\omega_1, \boldsymbol{q}_1 + \frac{\boldsymbol{Q}}{2}\right) E_j^*\left(\omega_1, \boldsymbol{q}_1 - \frac{\boldsymbol{Q}}{2}\right) E_k\left(\omega_2, \boldsymbol{q}_2 - \frac{\boldsymbol{Q}}{2}\right) E_l^*\left(\omega_2, \boldsymbol{q}_2 + \frac{\boldsymbol{Q}}{2}\right)$$

$$\times \quad \frac{1}{16\pi^2\hat{s}^2} \sum_{\lambda\bar{\lambda}} M_{ik}^{\lambda\bar{\lambda}} M_{jl}^{\lambda\bar{\lambda}\dagger}$$

$$w(Q; b_{\mathrm{max}}, b_{\mathrm{min}}) \equiv \int_{b_{\mathrm{min}}}^{b_{\mathrm{max}}} db\, bJ_0(bQ) = \frac{1}{Q^2}\Big(Qb_{\mathrm{max}}J_1(Qb_{\mathrm{max}}) - Qb_{\mathrm{min}}J_1(Qb_{\mathrm{min}})\Big)$$

A summation over photon polarizations i, j, k, l was implied

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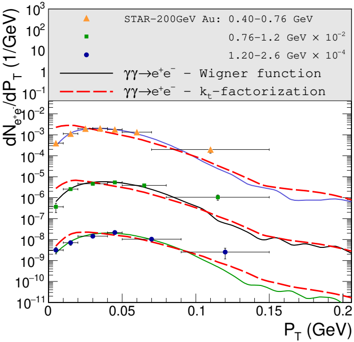
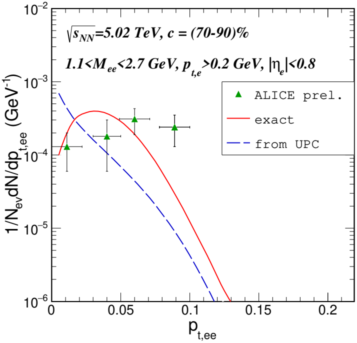
PAIR TRANSVERSE MOMENTUM - RHIC & LHC

Old vs. New one

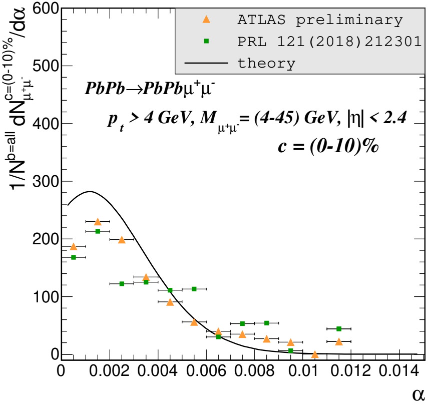
Old (RHIC)	New (LHC)
$p_t > 0.2$ GeV,	$p_t > 0.2$ GeV,
$\lvert\eta_e\rvert < 1$	$\lvert\eta_e\rvert < 0.8$
c=(60-80)%	c=(70-90)%
$\lvert y_{ee}\rvert < 1$	$M_{e^+e^-}$ =(1.1-2.7) GeV





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

ACOPLANARITY - ATLAS



$p_t > 4$ GeV,

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

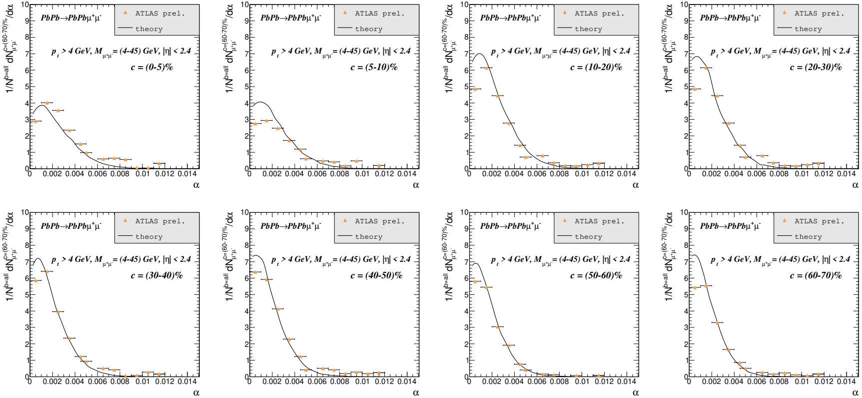
$|\eta_\mu| < 2.4$

✔ $\gamma\gamma$-fusion

c= (0-10)%

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

ACOPLANARITY - ATLAS



Very good description of the data having

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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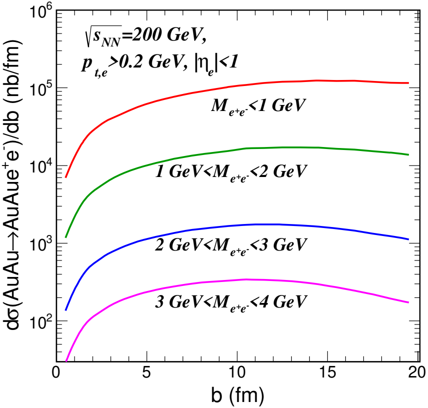
IMPACT PARAMETER



p_t >0.2 GeV,

$|\eta_\mu|<1$

✔ $\gamma\gamma$-fusion

Shape depends on the dielectron mass window

CONCLUSION

- ✓ The interplay of **thermal radiation with the initial photon annihilation process** triggered by the coherent electromagnetic fields of the incoming nuclei was presented.
- ✓ We **first** verify that the combination of photon fusion, thermal radiation, and final-state hadron decays gives a fair description of the low-P_T dilepton mass spectra and dilepton transverse momentum distribution as measured by the STAR collaboration for different centrality classes, including experimental acceptance cuts.
- ✓ STAR, ALICE and ATLAS experimental data show that **without free parameters** very good agreement with the data is achieved without including rescattering of leptons in quark-gluon plasma.
- ✓ Recently the CMS collaboration has measured modification of α distributions correlated with **neutron multiplicity**. A very new ATLAS study also presents the dimuon cross section in the presence of forward and/or backward neutron production. We plan to study it in the future.

Thank you