From Wigner distributions of photons to dilepton production in semicentral heavy ion collisions

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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,
  Centrality dependence of dilepton production via $\gamma\gamma$ processes from Wigner distributions of photons in nuclei,
  Phys. Lett. **B814** (2021) 136114.

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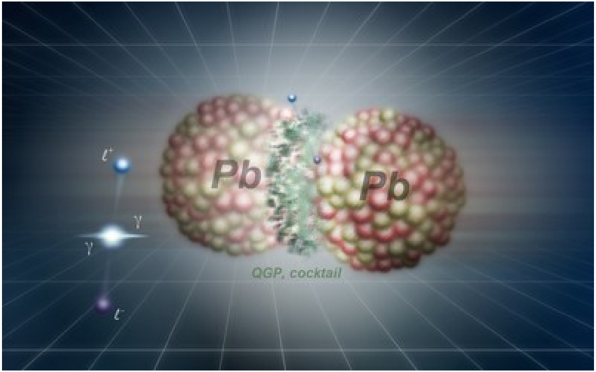
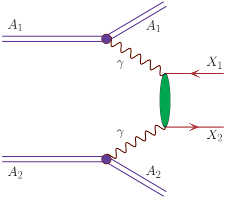
OUTLINE



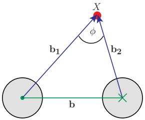
- From ultraperipheral to semicentral collisions $\rightarrow$ dilepton sources
  - $\gamma\gamma$ fusion mechanism
- Invariant mass
  - SPS (NA60 data)
  - RHIC (STAR data)
  - LHC (ALICE data)
- Low-P_T dilepton spectra
  - RHIC (STAR data)
  - LHC (ALICE data)
- Acoplanarity
  - LHC (ATLAS data)

NUCLEAR CROSS SECTION - IMPACT PARAMETER SPACE

The transverse momentum P_T of the pair is neglected



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



Definition in the centrality class

$$\frac{dN_{ll}[\mathcal{C}]}{dM} = \frac{1}{f_{\mathcal{C}} \cdot \sigma_{\mathrm{AA}}^{\mathrm{in}}} \int_{b_{\min}}^{b_{\max}} db \int dy_+ dy_- dp_t^2\, \delta(M - 2\sqrt{\omega_1\omega_2})\, \frac{d\sigma_{A_1 A_2 \to A_1 A_2 l^+ l^-}}{dy_+ dy_- dp_t^2\, db}\Bigg|_{\mathrm{cuts}},$$

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

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

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

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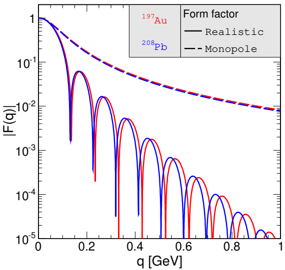
ELECTRIC FIELD VS FORM FACTOR

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

- point-like $F(\mathbf{q}^2) = 1$
- monopole $F(\mathbf{q}^2) = \frac{\Lambda^2}{\Lambda^2 + |\mathbf{q}|^2}$; $\sqrt{\langle r^2 \rangle} = \sqrt{\frac{6}{\Lambda^2}} = 1$ fm $A^{1/3}$
- realistic $F(\mathbf{q}^2) = \frac{4\pi}{|\mathbf{q}|} \int \rho(r) \sin(|\mathbf{q}|\, r)\, r dr$



$$\boldsymbol{E}(\omega, \boldsymbol{q}) = Z \sqrt{\frac{\alpha_{em}}{\pi}} \frac{\boldsymbol{q} F_{ch}(\boldsymbol{q}^2 + \frac{\omega^2}{\gamma^2})}{\boldsymbol{q}^2 + \frac{\omega^2}{\gamma^2}} ,$$

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

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

$$= \int d^2\boldsymbol{s} \exp[i\boldsymbol{q}\boldsymbol{s}]\, E_i\Big(\omega, \boldsymbol{b} + \frac{\boldsymbol{s}}{2}\Big) E_j^*\Big(\omega, \boldsymbol{b} - \frac{\boldsymbol{s}}{2}\Big),$$

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

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

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DIELECTRON INVARIANT-MASS SPECTRA - RHIC

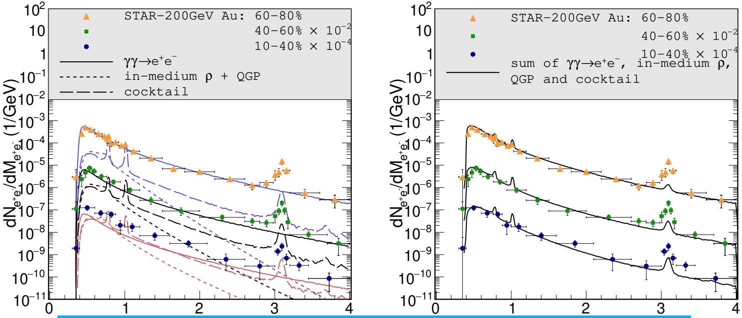
$p_t > 0.2$ GeV,

$|\eta_e| < 1$

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

- ✔ $\gamma\gamma$-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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DIMUON INVARIANT-MASS SPECTRA - SPS

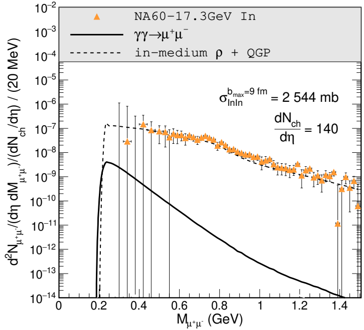
$P_T < 0.2$ GeV,

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

✔ $\gamma\gamma$-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

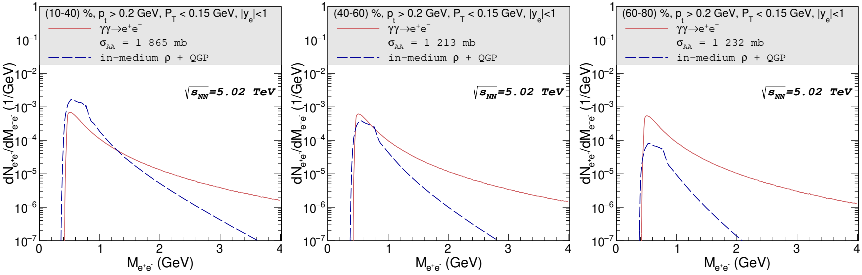
$p_t > 0.2$ GeV,

$|y_e| < 1$

$P_T < 0.15$ 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

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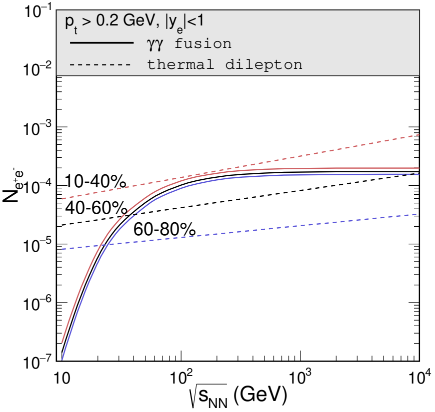
EXCITATION FUNCTION OF LOW-P_T



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

➡ k_t-factorization

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

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

➡ Exact calculation

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

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

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PAIR TRANSVERSE MOMENTUM - RHIC & LHC

$p_t > 0.2$ GeV,
$|\eta_e| < 1$
c=(60-80)%
$|y_{ee}| < 1$

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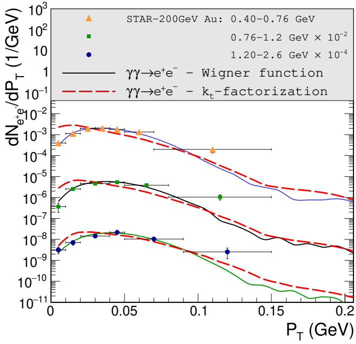
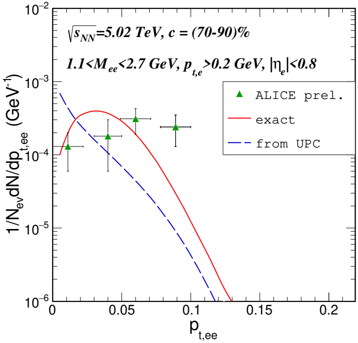
$p_t > 0.2$ GeV,
$|\eta_e| < 0.8$
c=(70-90)%
$M_{e^+e^-}$ =(1.1-2.7) GeV

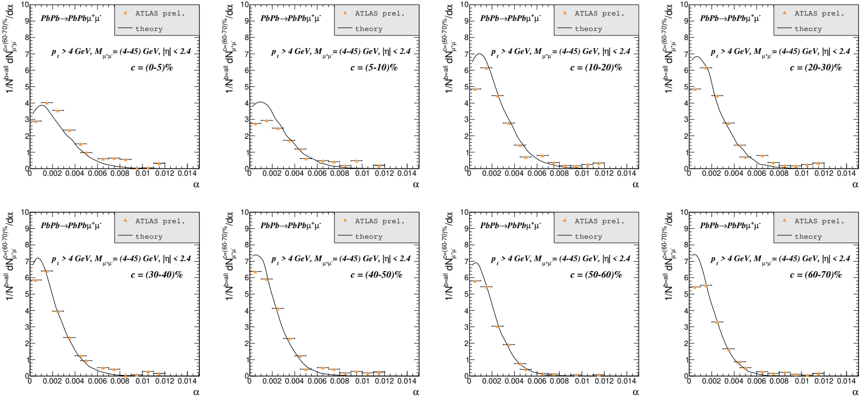




Small correction to the STAR decription & much better situation for LHC

Acoplanarity - ATLAS data

From central to peripheral collisions



$p_t > 4$ GeV,

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

$|\eta_\mu| < 2.4$

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

A correct normalization and shape of the distributions

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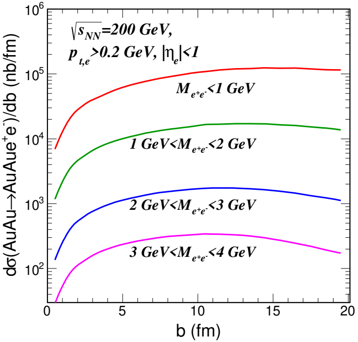
IMPACT PARAMETER

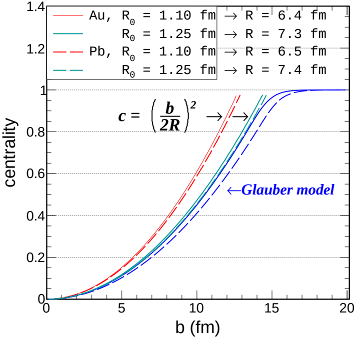
$p_t > 0.2$ GeV,

$|\eta_\mu| < 1$

Centrality & nuclear radius

$$R_A = R_0 A^{1/3}$$

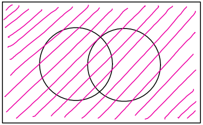




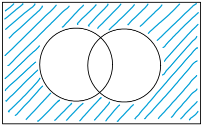
Distribution shape depends on the dielectron invariant mass range

Comparison with ALICE experimental data

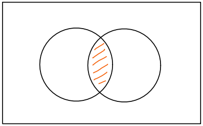
Full impact parameter space

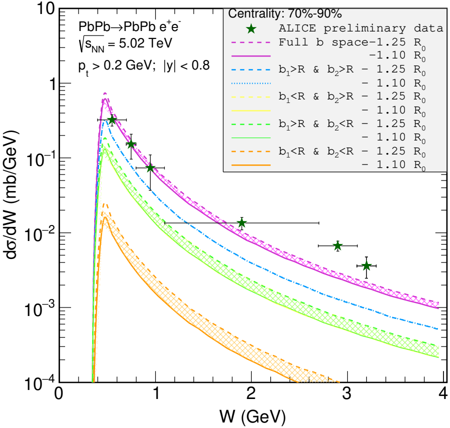


$b_1 > R$ and $b_2 > R$

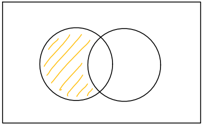


$b_1 < R$ and $b_2 < R$

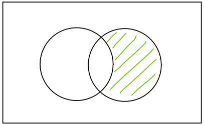




$b_1 < R$ and $b_2 > R$



$b_1 > R$ and $b_2 < R$



Excellent agreement with ALICE experimental data for $M_{e^+e^-} < 2.5$ GeV.

The ratio of e^+e^- production inside and outside of the nuclei ≈ 1.

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** (but taking into account **Wigner distribution**) 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