Modeling of coherent production in hadronic collisions II

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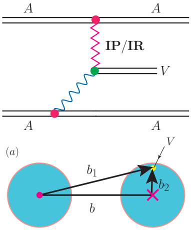
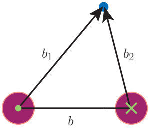


Photoproduction

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

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

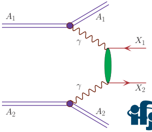
$\gamma\gamma$ fusion



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

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

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



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Equivalent Photon Flux vs. Form Factor

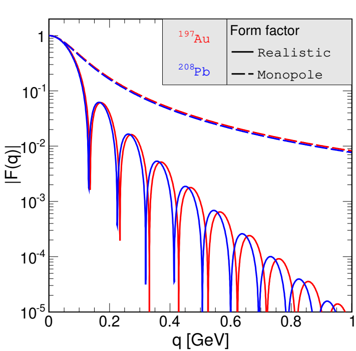
$$N(\omega, b) = \frac{Z^2 \alpha_{em}}{\pi^2 \beta^2} \frac{1}{\omega} \frac{1}{b^2} \times \left| \int \mathrm{d}\chi\, \chi^2 \frac{F\left(\frac{\chi^2+u^2}{b^2}\right)}{\chi^2 + u^2} J_1(\chi) \right|^2$$

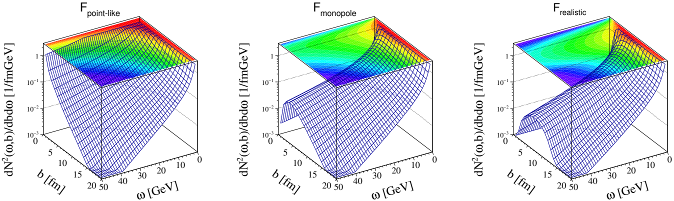
$$\beta = \frac{p}{E},\ \gamma = \frac{1}{\sqrt{1-\beta^2}},\ u = \frac{\omega b}{\gamma \beta},\ \chi = k_\perp b$$

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

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

- monopole $F\left(\mathbf{q}^2\right) = \frac{\Lambda^2}{\Lambda^2 + |\mathbf{q}|^2},\ \sqrt{\left\langle r^2 \right\rangle} = \sqrt{\frac{6}{\Lambda^2}} = 1\ \text{fm}\ A^{1/3}$
- realistic $F\left(\mathbf{q}^2\right) = \frac{4\pi}{|\mathbf{q}|} \int \rho(r) \sin(|\mathbf{q}|\, r)\, r \mathrm{d}r$





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J/ψ - UPC

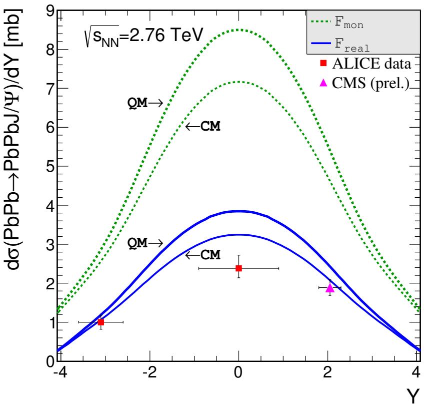
$$\sigma_{\gamma A\to J/\psi A} = \frac{d\sigma_{\gamma A\to J/\psi A}(t=0)}{dt}\int_{-\infty}^{t_{max}} \mathrm{d}t\, |F_A(t)|^2$$

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

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

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

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



$2.5 < y < 4, p_t < 0.3 GeV$	σ_{tot} [mb]
theory^{PL}	10.350
theory^{MON}	0.398
theory^{REAL}	0.111

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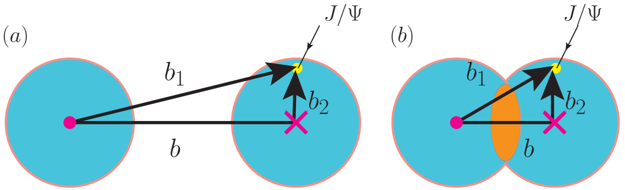
Charmonium photoproduction

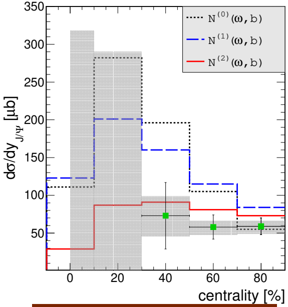


The inclusion of the absorption effect by modifying effective photon fluxes in the impact parameter space.

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

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

$$\sigma(N, UPC) = \sigma(N^{(1)}, UPC) = \sigma(N^{(2)}, UPC)$$



ALICE data, $\sqrt{s_{NN}}$ = 2.76 TeV

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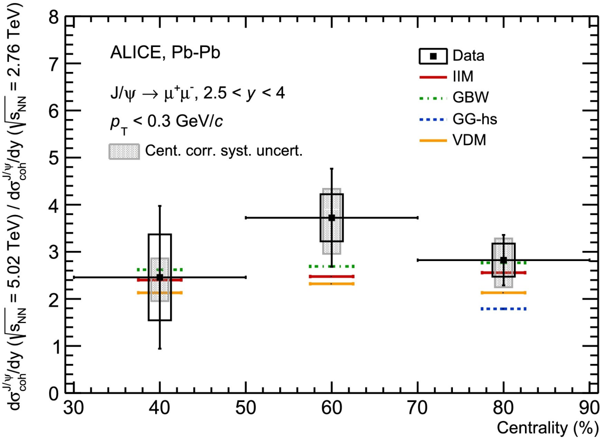
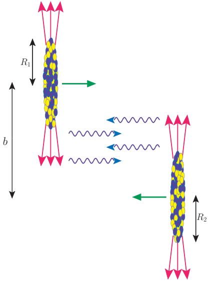
ALICE DATA VS. THEORY

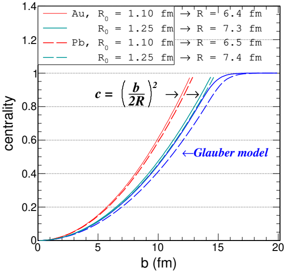


Ratio of the measurements at $\sqrt{s_{NN}} = 5.02$ TeV and $\sqrt{s_{NN}}$=2.76 TeV

Are we using the correct impact parameter interval?

Impact parameter





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

- geometrical model

$$c = \frac{b^2}{4R_A^2}$$

$$c(N) \approxeq \pi b^2(N)/\sigma_{in}, \quad \sigma_{in} = \pi (2R)^2$$

- Glauber model

$$\sigma_{AB}^{\rm in} = \int d^2b \left(1 - e^{-\sigma_{\rm NN}^{\rm in} T_{\rm AB}(b)}\right)$$

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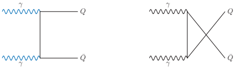
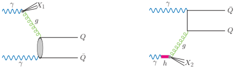
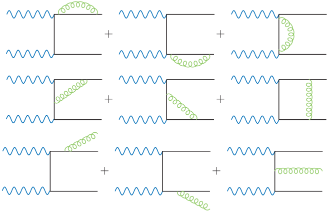
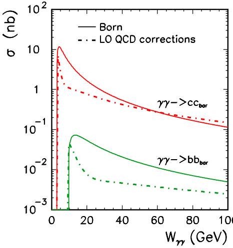
Elementary cross section

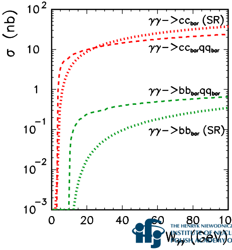

The Born amplitudes.


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


The single-resolved mechanism.

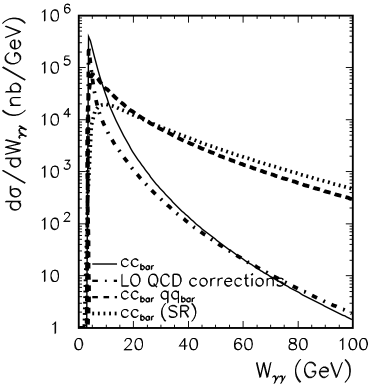

The leading-order QCD corrections.





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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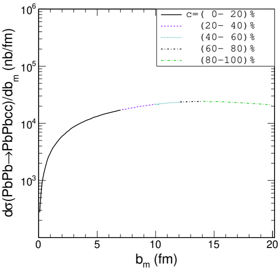
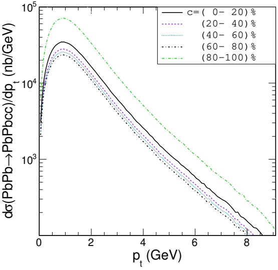
Nuclear cross section

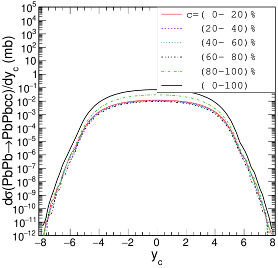
Impact parameter



Transverse momentum



Rapidity



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

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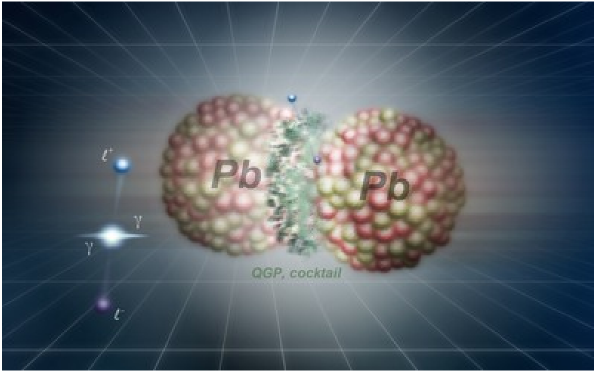
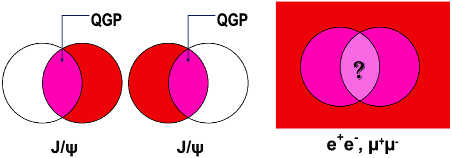
DILEPTON PRODUCTION



- From ultraperipheral to semicentral collisions
  - $\gamma\gamma$ fusion



Dielectron invariant-mass spectra - RHIC

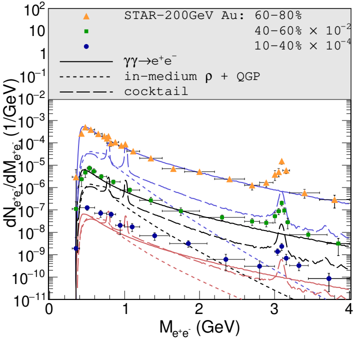
$p_t > 0.2$ GeV,

$|\eta_e| < 1$

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

- ✔ $\gamma\gamma$-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

$$\sigma_{A_1A_2\to A_1A_2\ell^+\ell^-} = \int N(\omega_1,\mathbf{b_1})\,N(\omega_2,\mathbf{b_2})\,\delta^{(2)}(\mathbf{b}-\mathbf{b}_1-\mathbf{b}_2)\int d^2\mathbf{b}_1\,d^2\mathbf{b}_2\,d^2\mathbf{b}\,dy_{\ell^+}\,dy_{\ell^-}\,dp_{t,\ell}^2\,\frac{d\sigma(\gamma\gamma\to\ell^+\ell^-;\hat{s})}{d(-\hat{t})}$$

➯ **k_t-factorization**

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

➯ **Exact calculation**

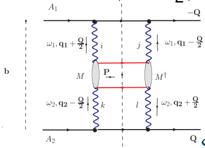
$$\frac{d\sigma[\mathcal{C}]}{d^2\mathbf{P}_T^{\ell^+\ell^-}} = \int\frac{d^2\boldsymbol{Q}}{2\pi}w(Q;b_{\rm max},b_{\rm min})\int\frac{d^2\boldsymbol{q}_1}{\pi}\frac{d^2\boldsymbol{q}_2}{\pi}\delta^{(2)}(\mathbf{P}_T^{\ell^+\ell^-}-\mathbf{q}_1-\boldsymbol{q}_2)\int\frac{d\omega_1}{\omega_1}\frac{d\omega_2}{\omega_2}$$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

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

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

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

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



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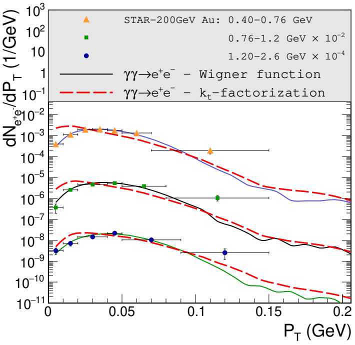
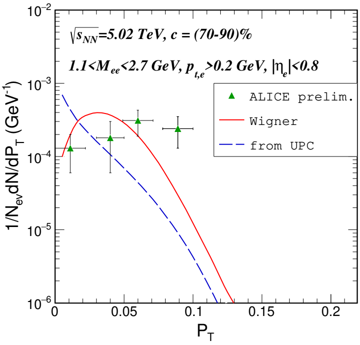
PAIR TRANSVERSE MOMENTUM - RHIC & LHC

$p_t > 0.2$ 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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Pair transverse momentum - RHIC & LHC

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

- - - - - - PLB**790** (2019) 339
vs.
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$p_t > 0.2$ GeV,
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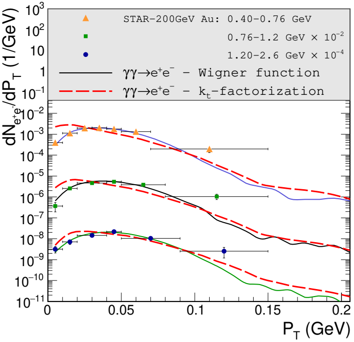
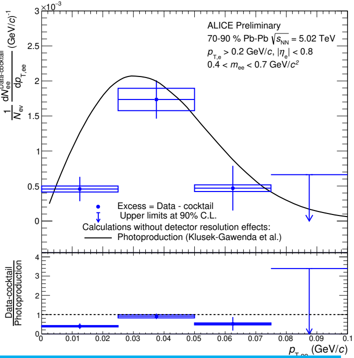
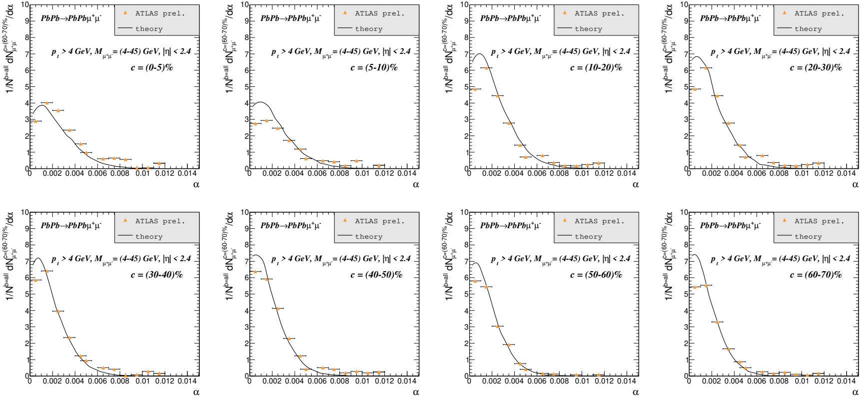




Small correction to the STAR description & much better situation for LHC



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,

$|\eta_\mu| < 2.4$

Conclusion

- EPA in the impact parameter space
- Ultraperipheral & semicentral heavy-ion collisions
- Fourier transform of the charge distribution
- Multidimensional integrals $\to$ differential cross section
- Description of experimental data for UPC and semicentral events
  - 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
  - $PbPb \to PbPbc\bar{c}$
  - $pp \to c\bar{c}$
  - $pn \to c\bar{c}$
  - $np \to c\bar{c}$
  - $nn \to c\bar{c}$

  $\to$ *D* meson production
- Wigner function and J/ψ photoproduction...
- Centrality vs. impact parameter...

Thank you

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