COHERENT J/ψ PHOTOPRODUCTION FROM PERIPHERAL TO CENTRAL HEAVY-ION COLLISIONS

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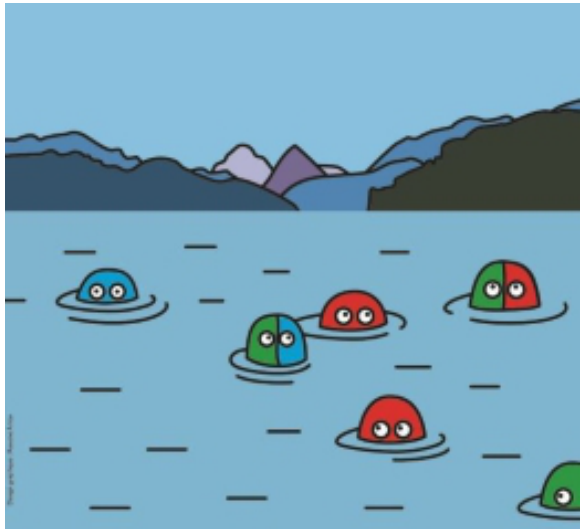

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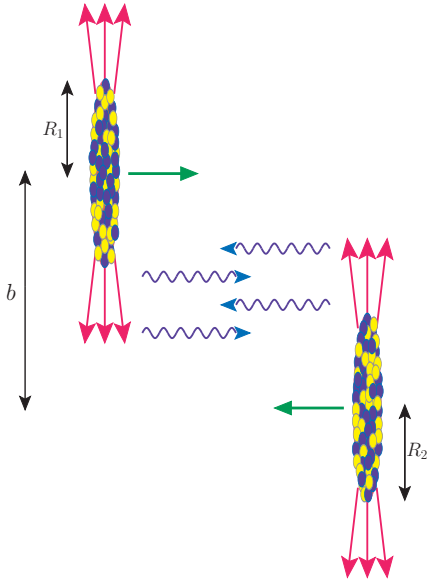


Centrality (for ^{208}Pb):

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

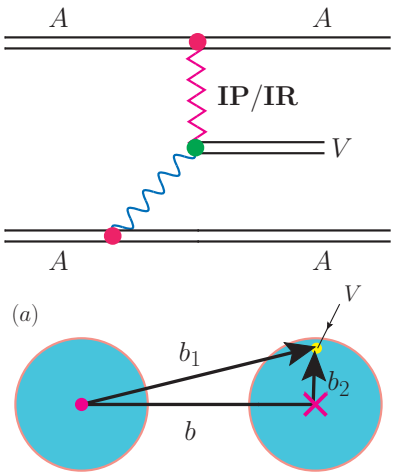
The strong electromagnetic field is a source of photons that can induce electromagnetic reactions in ion-ion collisions.
Electromagnetism is a long-range force, so electromagnetic interactions occur even at relatively large ion-ion separations.

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

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

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

Equivalent Photon Approximation - UPC



Photoproduction

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

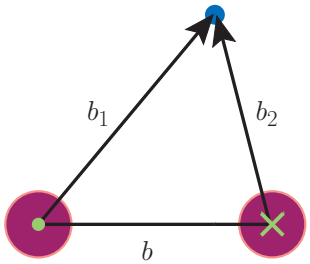
$$\frac{dP_{\gamma \mathbf{P}/\mathbf{P}\gamma}(y,b)}{dy} = \omega_{1/2} N\left(\omega_{1/2}, b\right) \sigma_{\gamma A_{2/1} \to V A_{2/1}}(W_{\gamma A_{2/1}}) S_{abs}(b)$$

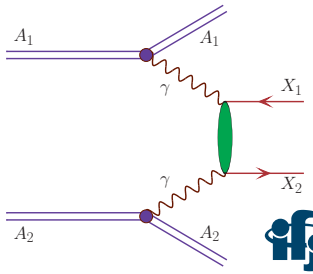
$\gamma\gamma$ fusion

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

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

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





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

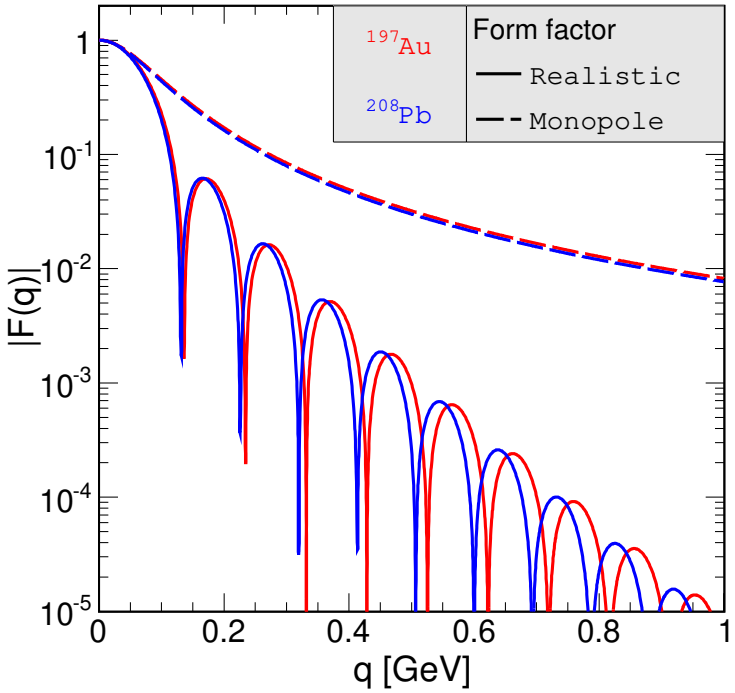
$$N(\omega, b) = \frac{Z^2 \alpha_{em}}{\pi^2 \beta^2} \frac{1}{\omega} \frac{1}{b^2} \times u^2 \left[K_1^2(u) + \frac{1}{\gamma^2} K_0^2(u)\right]$$

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

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

- realistic

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



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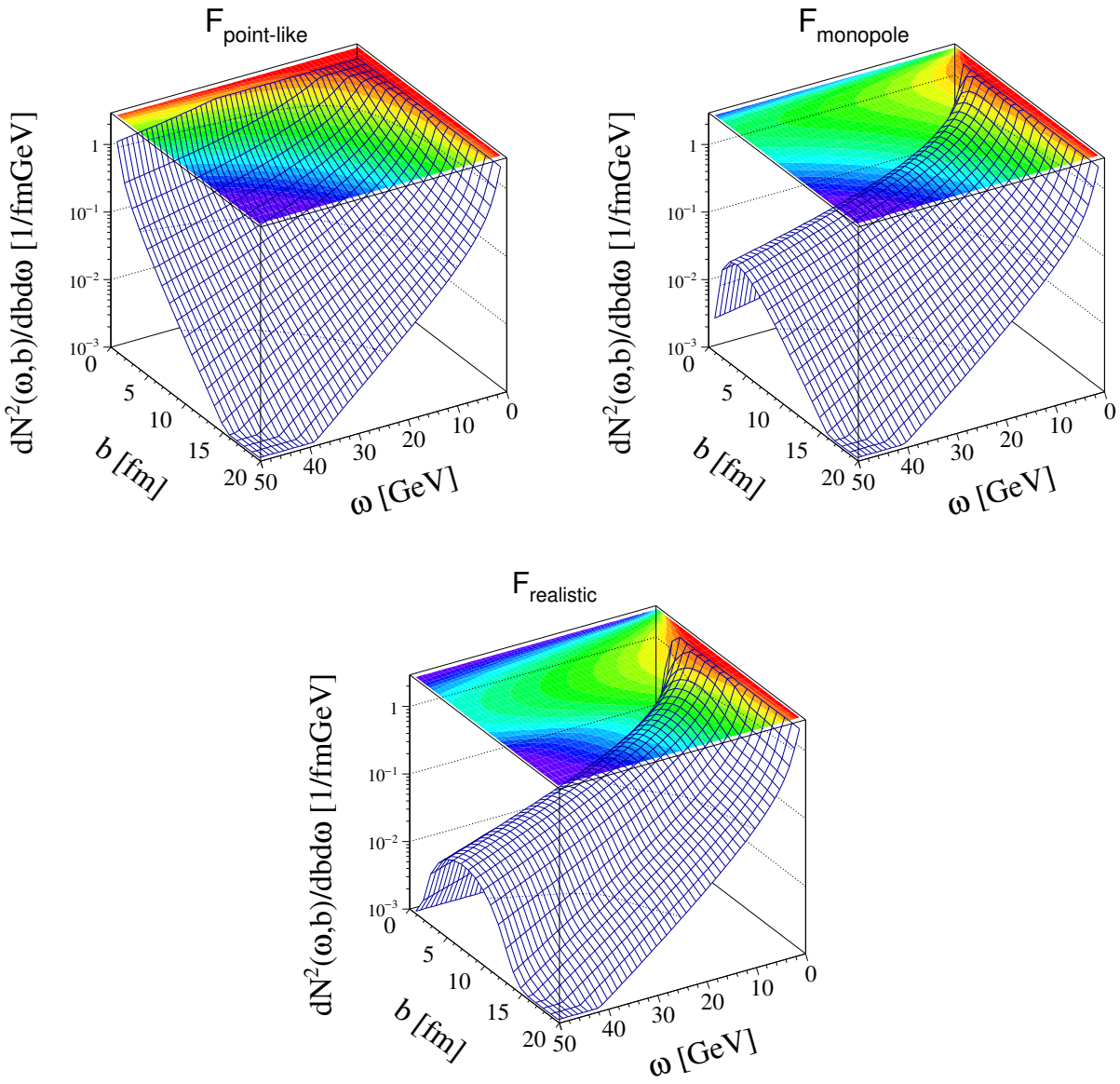
Photon flux


F point-like
F monopole
F realistic
dN²(ω,b)/dbdω [1/fmGeV]
b [fm]
ω [GeV]

J/ψ photoproduction - UPC

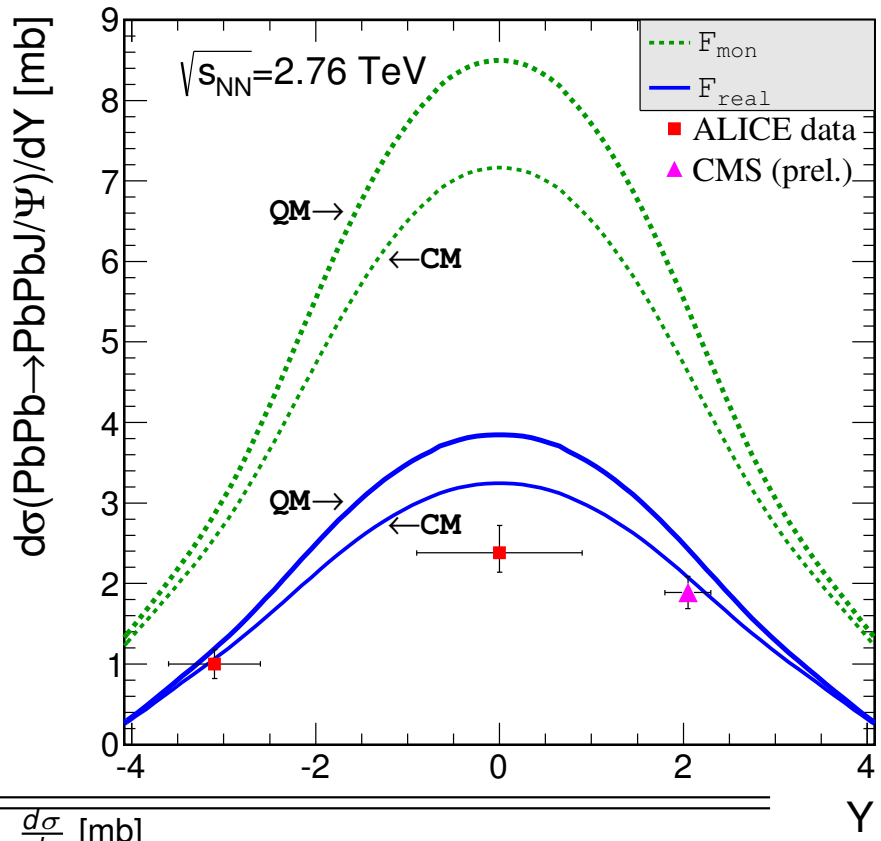
$$\sigma_{\gamma A \to J/\psi A} = \frac{d\sigma_{\gamma A \to J/\psi A}(t=0)}{dt} \int_{-\infty}^{t_{max}} dt\, |F_A(t)|^2$$

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

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

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

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



UPC	$\frac{d\sigma}{dy}$ [mb] $-3.6 < y < -2.3$	$\lvert y\rvert < 0.9$	$1.8 < y < 2.3$
theory$^{MON}_{QM}$	3.24	8.29	5.41
theory$^{MON}_{CM}$	2.61	6.99	4.62
theory$^{REAL}_{QM}$	1.37	3.75	2.43
theory$^{REAL}_{CM}$	**1.21**	**3.17**	**2.07**
ALICE exp.	-	*[ALICE:2013wjo]*$2.38^{+0.34}_{-0.24}$	*[ALICE:2012yye]*1.0 ± 0.3
CMS exp.	*[CMS:2016itn]*1.82 ± 0.3	-	

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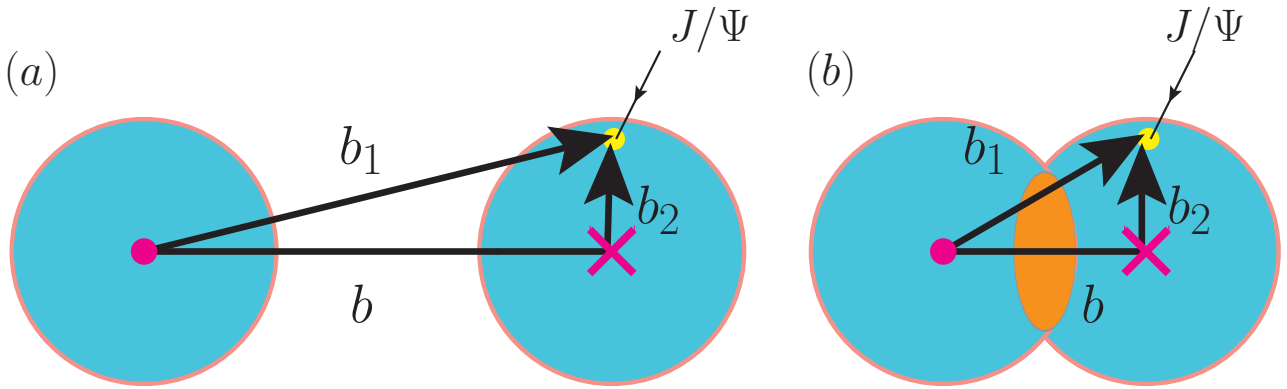
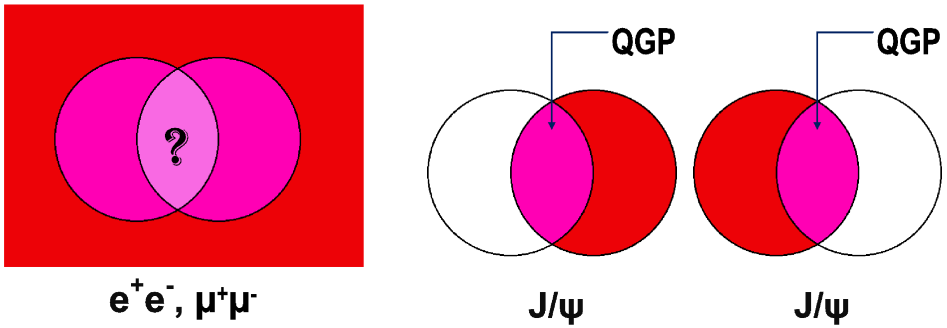
UPC → semi-central collision

Impact parameter space



J/ψ photoproduction for (a) ultraperipheral and (b) central heavy ion collisions.

EFFECTIVE PHOTON FLUX

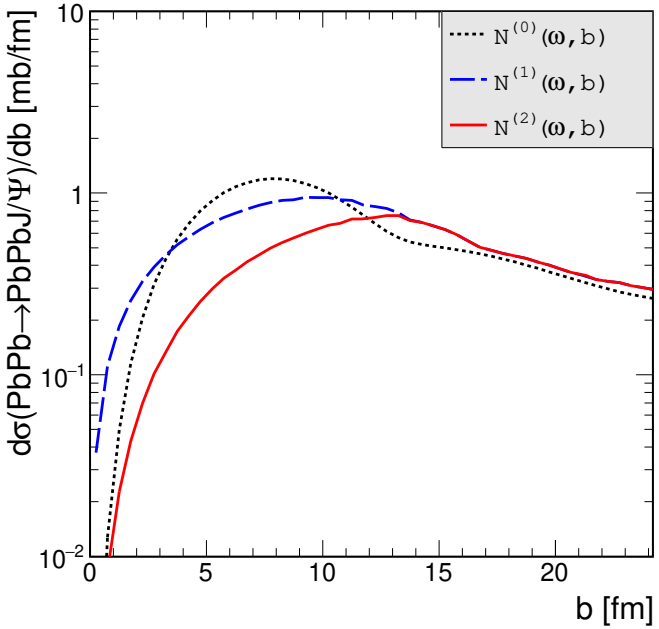


The inclusion of the absorption effect by modifying effective photon fluxes in the impact parameter space.

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

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

$$\boxed{\sigma(N^{(0)}, UPC) = \sigma(N^{(1)}, UPC) = \sigma(N^{(2)}, UPC)}$$



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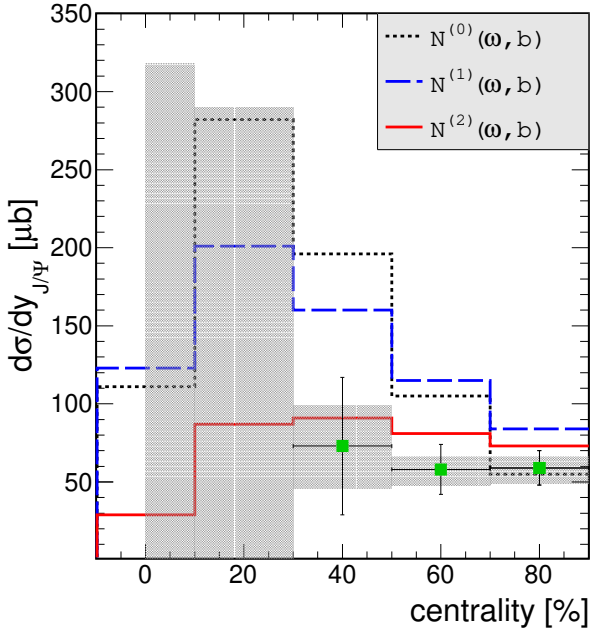
J/ψ PHOTOPRODUCTION - SEMI-CENTRAL REGION

Cross section in [μb] per rapidity unit for nuclear photoproduction of J/ψ meson in $Pb - Pb$ collision at $\sqrt{s_{NN}}$ = 2.76 TeV

Flux	$\frac{d\sigma_{tot}}{dy}$ [μb]	Centrality range [%]					
		0-10	10-30	30-50	50-70	70-90	UPC
$N^{(0)}(\omega, b)$	theory^{PL}	9 984	579	185	92	58	10 350
	theory^{MON}	398	358	158	86	56	2 393
	theory^{REAL}	111	282	196	105	55	947
$N^{(1)}(\omega, b)$	theory^{REAL}	123	201	160	116	84	947
$N^{(2)}(\omega, b)$	theory^{REAL}	**30**	**88**	**91**	**82**	**72**	947
	ALICE (2015)	< 318	< 290	73 ± 52	58 ± 20	59 ± 16	-



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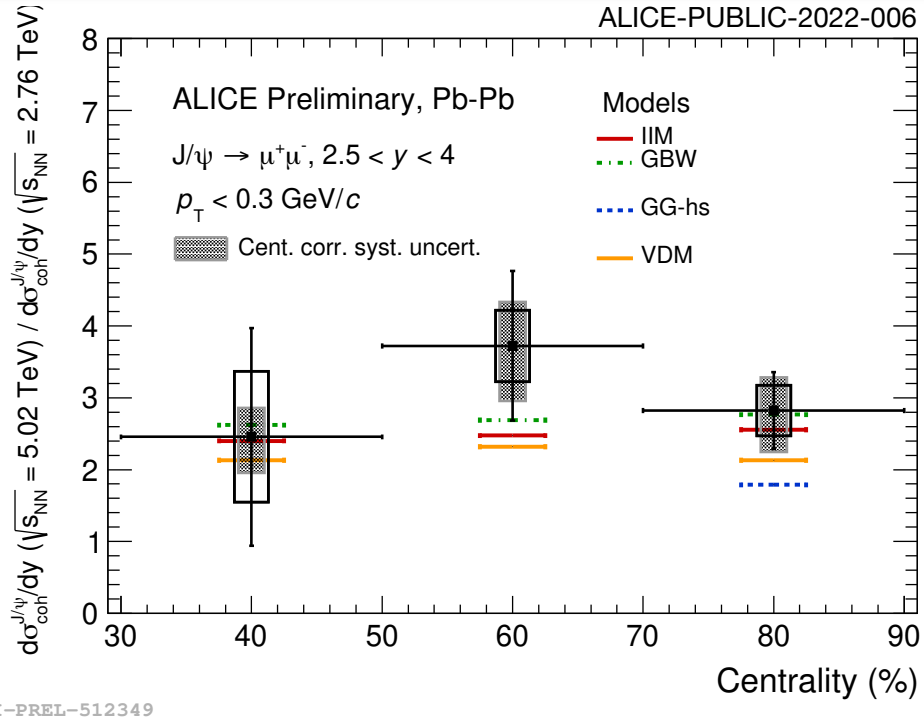
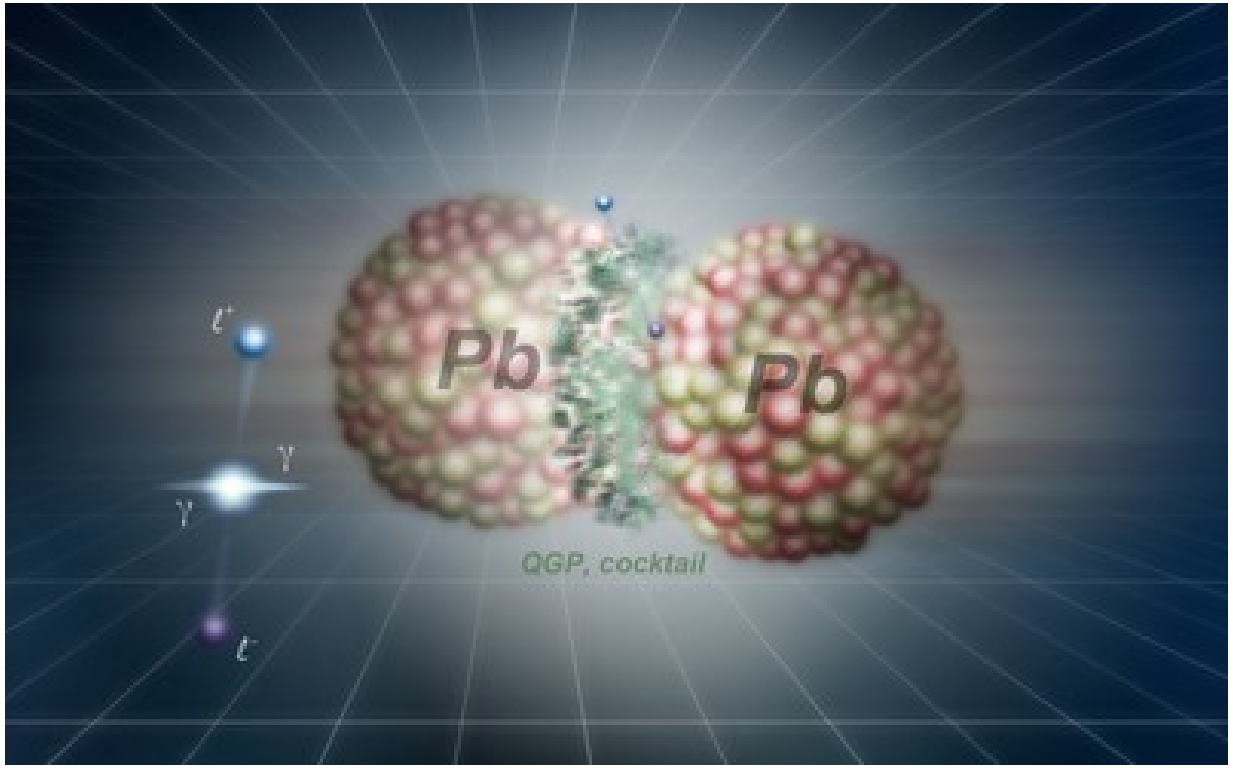
Coherent J/ψ cross section at forward rapidity

NEW



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

DILEPTON PRODUCTION



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

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DIELECTRON INVARIANT-MASS SPECTRA - RHIC

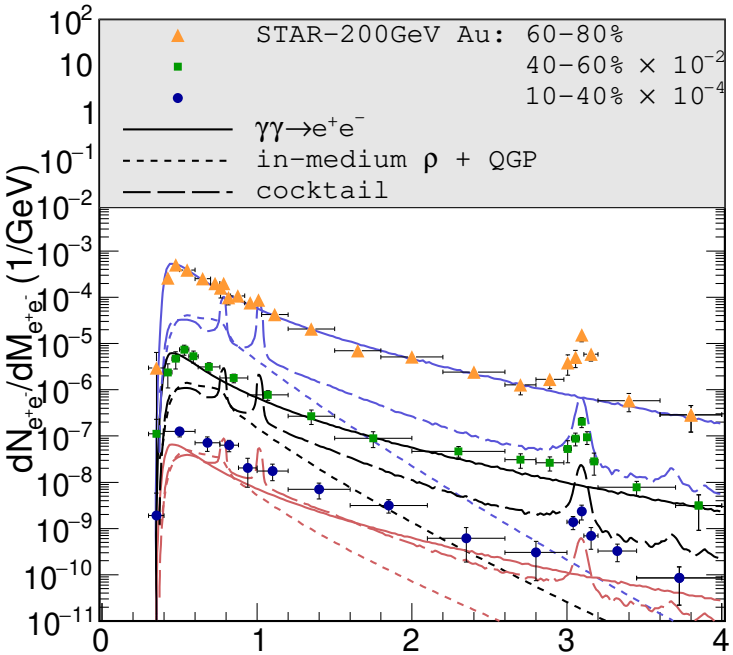
p_t >0.2 GeV,

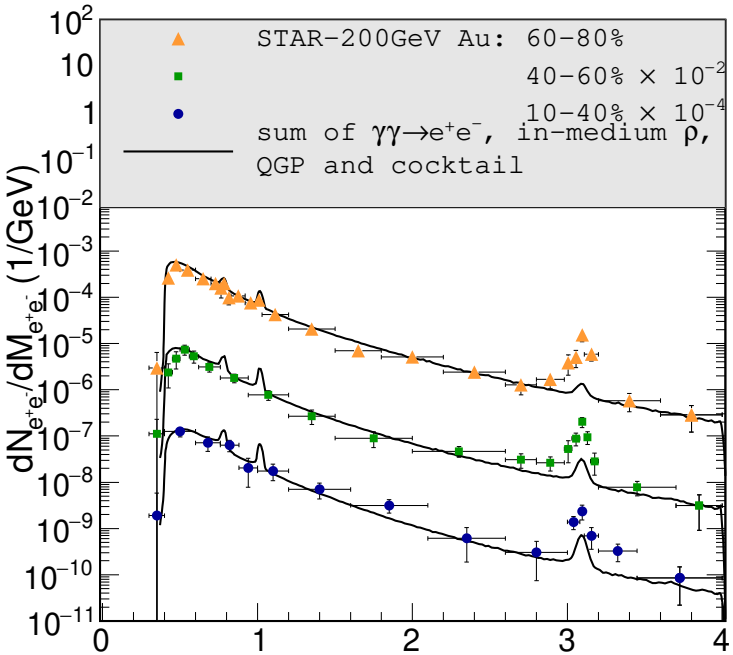
$|\eta_e|$<1

$|y_{e^+e^-}|$<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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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
  - ALICE data for J/ψ production; centrality $< 100\%$
  - STAR and ALICE data for dilepton production - J/ψ contribution is missing

Thank you

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

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

➪ 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:

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

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

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

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