Photon induced processes from semi-central to ultraperipheral collisions: Introduction

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Interplay of hard and soft QCD probes for collectivity in heavy-ion collisions
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Outline

Peripheral/ultraperipheral collisions

Weizsäcker-Williams fluxes of equivalent photons
electromagnetic dissociation of heavy nuclei

"Soft to hard" in the diffractive photoproduction of vector mesons

diffractive dissociation
color dipole approach
J/ψ photoproduction on the proton

Diffractive processes on the nuclear target & multiple scattering expansion

Coherent exclusive & incoherent diffraction with breakup of nucleus
production in ultraperipheral HI collisions

From ultraperipheral to semicentral collisions

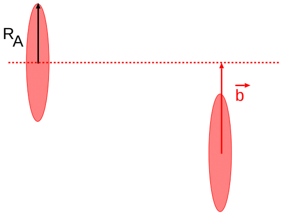
dileptons from $\gamma\gamma$ production vs thermal dileptons from plasma phase
diffractive J/ψ in semi-central collisions

A. Łuszczak and W. S., Phys. Rev. C **97** (2018) no.2, 024903 [arXiv:1712.04502 [hep-ph]].

A. Łuszczak and W. S., arXiv:1901.07989 [hep-ph].

M. Kłusek-Gawenda, R. Rapp, W. S. and A. Szczurek, Phys. Lett. B **790** (2019) 339 [arXiv:1809.07049 [nucl-th]].

Centrality



- e.g. from optical limit of Glauber:

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

  $\sigma_{\rm AA}^{\rm in} \sim 7\,{\rm barn}$ for Pb at LHC.
- fraction of inelastic hadronic events contained in the centrality class $\mathcal{C}$,

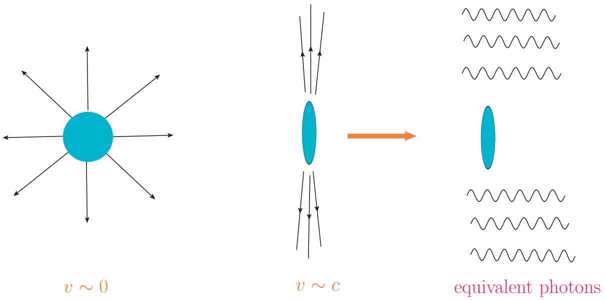
$$f_{\mathcal{C}} = \frac{1}{\sigma_{\rm AA}^{\rm in}} \int_{b_{\rm min}}^{b_{\rm max}} db \frac{d\sigma_{\rm AA}^{\rm in}}{db} .$$

- experimentally, centrality is determined by binning in multiplicity and/or transverse energy.
- Probability of no inelastic interaction:

$$P_{\rm surv}(\boldsymbol{b}) = \exp[-\sigma_{\rm NN}^{\rm in} T_{\rm AA}(b)] \sim \theta(b - 2R_A)$$

Fermi-Weizsäcker-Williams equivalent photons

Heavy nuclei Au, Pb **have** $Z \sim 80$



- ion at rest: source of a Coulomb field, the highly boosted ion: sharp burst of field strength, with $|\boldsymbol{E}|^2 \sim |\boldsymbol{B}|^2$ and $\boldsymbol{E} \cdot \boldsymbol{B} \sim 0$. (See e.g. J.D Jackson textbook).
- acts like a flux of "equivalent photons" (photons are collinear partons).

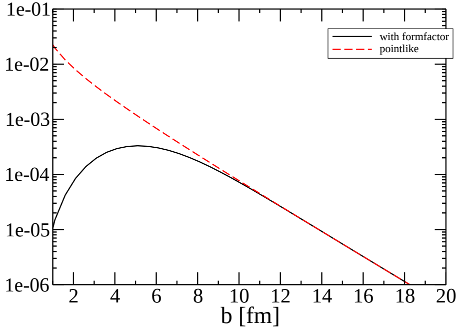
$$\boldsymbol{E}(\omega, \boldsymbol{b}) = -i \, \frac{Z\sqrt{4\pi\alpha_{em}}}{2\pi} \, \frac{\boldsymbol{b}}{b^2} \, \frac{\omega b}{\gamma} K_1\left(\frac{\omega b}{\gamma}\right) \; ; N(\omega, \boldsymbol{b}) = \frac{1}{\omega} \frac{1}{\pi} \left| \boldsymbol{E}(\omega, \boldsymbol{b}) \right|^2$$

$$\sigma(AB) = \int d\omega d^2\boldsymbol{b} \, N(\omega, \boldsymbol{b}) \, \sigma(\gamma B; \omega)$$

Finite size of particle $\to$ charge form factor

$bN(\omega, \boldsymbol{b})\ [fm^{-1}]$

$\omega = 1\,\mathrm{GeV}\,,\ \gamma = 100$



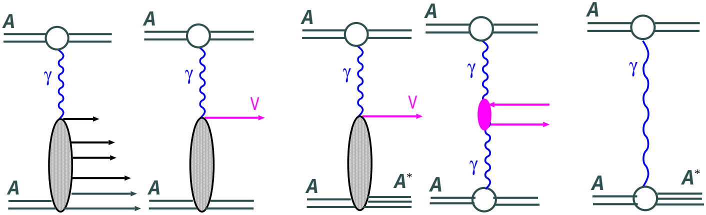
$$\boldsymbol{E}(\omega, \boldsymbol{b}) = Z\sqrt{4\pi\alpha_{em}} \int \frac{d^2\boldsymbol{q}}{(2\pi)^2} \exp[-i\boldsymbol{b}\boldsymbol{q}]\ \frac{\boldsymbol{q}}{\boldsymbol{q}^2 + \omega^2/\gamma^2}\ F_{em}(\boldsymbol{q}^2 + \omega^2/\gamma^2)$$

$$F_{em}(Q^2) = \exp[-R^2_{\rm ch}Q^2/6]\ ,\ \ Q^2 \ll \frac{1}{R^2_{\rm ch}}\ .$$

- Seen from a large distance, the ion indeed acts like a pointlike charge.
- When we come closer, the finite-size charge distribution important. Sometimes its effect is simulated by a sharp lower cutoff in b.

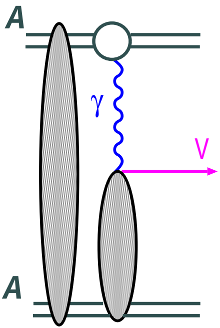
Ultraperipheral collisions

some examples of ultraperipheral processes:



- photoabsorption on a nucleus
- diffractive photoproduction with and without breakup/excitation of a nucleus
- $\gamma\gamma$-fusion.
- electromagnetic excitation/dissociation of nuclei. Excitation of Giant Dipole Resonances.
- the intact nuclei in the final state are not measured. Each of the photon exchanges is associated with a large rapidity gap.
- very small p_T of the photoproduced system.

Absorption corrected flux of photons



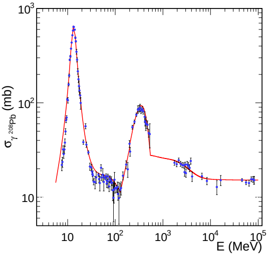
$$\sigma(A_1 A_2 \to A_1 A_2 V; s) = \int d\omega N^{\mathrm{eff}}_{A_1}(\omega)\, \sigma(\gamma A_2 \to V A_2; 2\omega\sqrt{s}) + (1 \leftrightarrow 2)$$

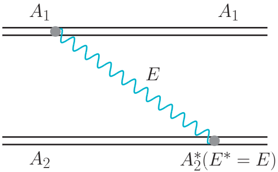
$$N^{eff}(\omega) = \int d^2\boldsymbol{b}\, P_{\mathrm{surv}}(\boldsymbol{b}) N(\omega, \boldsymbol{b})$$

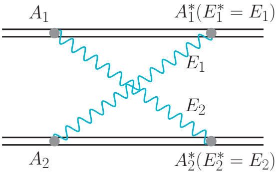
- survival probability:

$$P_{\mathrm{surv}}(\boldsymbol{b}) = S^2_{el}(\boldsymbol{b}) = \exp\Big(-\sigma_{NN} T_{A_1 A_2}(\boldsymbol{b})\Big) \sim \theta(|\boldsymbol{b}| - (R_1 + R_2))$$

Electromagnetic excitation of heavy ions





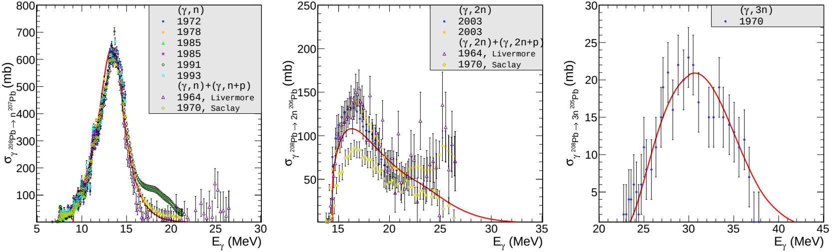


$$\bar{n}_{A_2}(\boldsymbol{b}) \equiv \int_{E_{\min}}^{\infty} dE\, N_{A_1}(E, \boldsymbol{b})\sigma_{\rm tot}(\gamma A_2; E)\,.$$

$$\sigma_{\rm tot}(A_1 A_2 \to A_1 A_2^*; E_{\max}) \approx \int d^2\boldsymbol{b} P_{\rm surv}(\boldsymbol{b}) \exp[-\bar{n}_{A_2}(\boldsymbol{b})] \int_{E_{\min}}^{E_{\max}} dE\, N_{A_1}(E, \boldsymbol{b})\sigma_{\rm tot}(\gamma A_2; E)\,.$$

- Huge peak in the photoabsorption cross section – Giant Dipole Resonance.

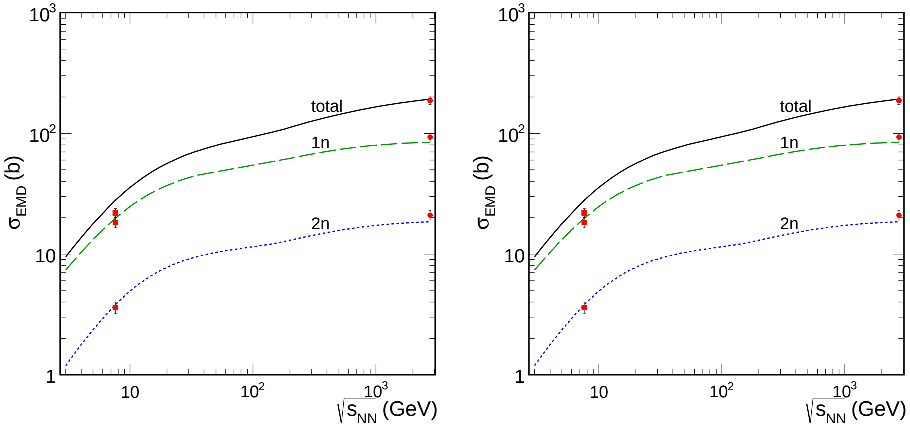
Electromagnetic excitation of heavy ions



- Giant dipole resonance decays through emission of few neutrons.
- experimental data on excitation functions for the reactions $\gamma^{208}\mathrm{Pb} \to \mathrm{k\,neutrons} + \mathrm{Pb}$ allow us to calculate the fractions $f(E,k)$ of a final state with $k = 1,2,3$ neutrons.
- we can calculate "topological cross sections" with given numbers of neutrons in the forward region of either ion.
- Monte Carlo Code "Gemini" for evaporation of neutrons based on Hauser-Feshbach Theory.

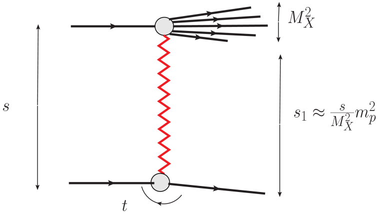
$$\sigma(A_1 A_2 \to (m\mathrm{N}, X)(k\mathrm{N}, Y)) = \int d^2\boldsymbol{b}\, P_{\mathrm{surv}}(\boldsymbol{b})\, P^{\mathrm{exc}}_{A_1}(\boldsymbol{b}, m)\, P^{\mathrm{exc}}_{A_2}(\boldsymbol{b}, k)\,.$$

Electromagnetic excitation of heavy ions

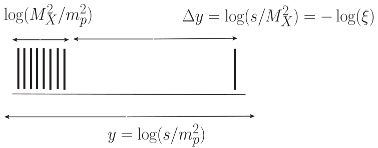


- electromagnetic dissociation cross section for ^{208}Pb. Data from SPS and LHC (ALICE).
- calculations from M. Kłusek-Gawenda, M. Ciemala, W. S. and A. Szczurek, Phys. Rev. C **89** (2014) 054907.
- cross section at LHC $\sim$ 200 barn!
- these processes play an important role as "triggers" for ultraperipheral processes.

Inelastic diffraction: kinematics & t-channel exchanges



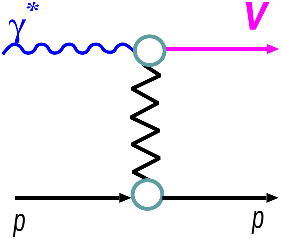
$$\frac{\Delta p_L}{p_L} \equiv \xi \sim \frac{M_X^2}{s} \ll 1$$

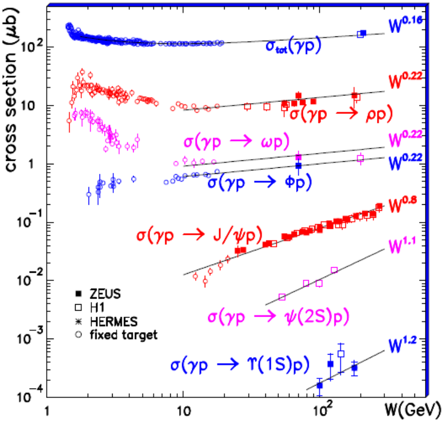


$$A(s_1, M_X^2, t) \propto \left(\frac{s_1}{m_p^2}\right)^{\alpha(t)} \propto \left(\frac{1}{\xi}\right)^{\alpha(t)} \implies \sigma \propto \exp[2(\alpha(0)-1)\cdot\Delta y]$$

- **To bridge a gap (say Δy ≥ 3) : α(0) ≥ 1** (Pomeron, C= +1; Odderon(??), C = -1).
- Exchange of secondary Reggeons: α(0)=0.5 for ρ,ω,f2,a1; α(0)=0 for pions **dies out exponentially with the gap size** (no exchange of color or charge over a large gap!).
- **Pomeron/Odderon**: ***multigluon exchanges***; **Reggeons**: ***$q\,\bar{q}$ - exchange***
- **Photons (J=1, C=-1) also qualify!**

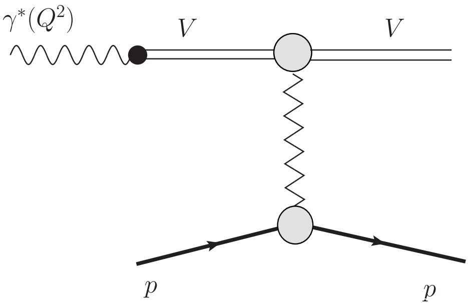
Total photoproduction cross sections





- From soft to hard diffraction in the photoproduction of vector mesons.
- Pomeron intercept depends on the meson...

Vector Meson Dominance



Extrapolate from the VM-pole to spacelike region:

$$A(\gamma^*(Q^2)p \to Vp; W, t) = \sqrt{\frac{3\Gamma(V^0 \to e^+e^-)}{M_V \alpha_{em}}} \frac{M_V^2}{Q^2 + M_V^2} A(Vp \to Vp; W, t)$$

Vector Meson Dominance

Extrapolate from the VM-pole to spacelike region:

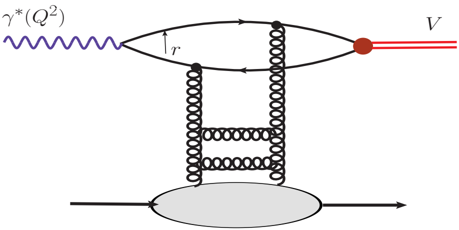
$$A(\gamma^*(Q^2)p \to Vp; W, t) = \sqrt{\frac{3\Gamma(V^0 \to e^+e^-)}{M_V \alpha_{em}}} \frac{M_V^2}{Q^2 + M_V^2} A(Vp \to Vp; W, t)$$

- hadronic structure of the photon
- parameters of $A(Vp \to Vp; W, t)$ can be taken from πN elastic scattering

$$\begin{aligned} \Im m A(Vp \to Vp; W, t = 0) &= s \cdot \sigma_{\rm tot}(Vp) \\ \sigma_{\rm tot}(\rho^0 p) &= \sigma_{\rm tot}(\omega p) = \frac{1}{2}(\sigma_{\rm tot}(\pi^+ p) + \sigma_{\rm tot}(\pi^- p)) \\ \sigma_{\rm tot}(\phi p) &= \sigma_{\rm tot}(K^+ p) + \sigma_{\rm tot}(K^- n) - \sigma_{\rm tot}(\pi^+ p) \end{aligned}$$

- works well for photoproduction of ρ, ω,
- cannot be correct in the deeply spacelike region $Q^2 \gg M_V^2$
- connection to QCD degrees of freedom at large Q^2 ?
- heavy flavours ?

Color dipole/ $k_\perp$-factorization approach



Color dipole representation of forward amplitude:

$$A(\gamma^*(Q^2)p \to Vp; W, t=0) = \int_0^1 dz \int d^2\boldsymbol{r}\, \psi_V(z,\boldsymbol{r})\, \psi_{\gamma^*}(z,\boldsymbol{r},Q^2)\, \sigma(x,\boldsymbol{r})$$

$$\sigma(x,\boldsymbol{r}) = \frac{4\pi}{3}\alpha_S \int \frac{d^2\boldsymbol{\kappa}}{\boldsymbol{\kappa}^4} \frac{\partial G(x,\boldsymbol{\kappa}^2)}{\partial \log(\boldsymbol{\kappa}^2)} \left[1 - e^{i\boldsymbol{\kappa}\boldsymbol{r}}\right],\ x = M_V^2/W^2$$

- impact parameters and helicities of high-energy q and $\bar{q}$ are conserved during the interaction.
- scattering matrix is "diagonal" in the color dipole representation. Color dipoles as "Good-Walker states".

When do small dipoles dominate ?

- the photon shrinks with Q^2 - photon wavefunction at large r:

$$\psi_{\gamma^*}(z, \boldsymbol{r}, Q^2) \propto \exp[-\varepsilon r]\,,\; \varepsilon = \sqrt{m_f^2 + z(1-z)Q^2}$$

- the integrand receives its main contribution from

$$r \sim r_S \approx \frac{6}{\sqrt{Q^2 + M_V^2}}$$

Kopeliovich, Nikolaev, Zakharov '93

- a large quark mass (bottom, charm) can be a hard scale even at $Q^2 \to 0$.
- for small dipoles we can approximate

$$\sigma(x, r) = \frac{\pi^2}{3} r^2 \alpha_S(q^2) xg(x, q^2)\,,\; q^2 \approx \frac{10}{r^2}$$

- for $\varepsilon \gg 1$ we then obtain the asymptotics

$$A(\gamma^* p \to Vp) \propto r_S^2 \sigma(x, r_S) \propto \frac{1}{Q^2 + M_V^2} \times \frac{1}{Q^2 + M_V^2}\, xg(x, Q^2 + M_V^2)$$

- probes the gluon distribution, which drives the energy dependence.
- From DGLAP fits: $xg(x, \mu^2) = (1/x)^{\lambda(\mu^2)}$ with $\lambda(\mu^2) \sim 0.1 \div 0.4$ for $\mu^2 = 1 \div 10^2 \mathrm{GeV}^2$.

Input to a calculation of J/ψ photoproduction

Overlap of light-cone wave functions

$$\Psi_V^*(z,\boldsymbol{r})\Psi_\gamma(z,\boldsymbol{r}) = \frac{e_Q\sqrt{4\pi\alpha_{\rm em}}N_c}{4\pi^2 z(1-z)}\Big\{m_Q^2 K_0(m_Q r)\psi(z,r) -[z^2+(1-z)^2]m_Q K_1(m_Q r)\frac{\partial\psi(z,r)}{\partial r}\Big\}.$$

- "boosted Gaussian" wave functions as in Nemchik et al. ('94)

$$\psi(z,r) \propto z(1-z)\exp\left[-\frac{M_Q^2 R^2}{8z(1-z)} - \frac{2z(1-z)r^2}{R^2}\right]$$

- parameters m_Q, R & normalization as in Kowalski et al. (2006) for J/ψ and Cox et al. (2008) for Υ.

diffractive slope on a free nucleon:

$B = B_0 + 4\alpha' \log(W/W_0)$ with $W_0 = 90\,\mathrm{GeV}$, and $\alpha' = 0.164\,\mathrm{GeV}^{-2}$.
We take $B_0 = 4.88\,\mathrm{GeV}^{-2}$ for J/ψ and $B_0 = 3.68\,\mathrm{GeV}^{-2}$ for Υ.

Dipole cross section from Xfitter

BGK-form of the dipole cross section

$$\sigma(x,r) = \sigma_0 \left(1 - \exp\left[-\frac{\pi^2 r^2 \alpha_s(\mu^2) xg(x,\mu^2)}{3\sigma_0}\right]\right), \mu^2 = C/r^2 + \mu_0^2$$

- the *soft* ansatz, as used in the original BGK model

$$xg(x,\mu_0^2) = A_g x^{-\lambda_g}(1-x)^{C_g},$$

- the *soft* + *hard* ansatz

$$xg(x,\mu_0^2) = A_g x^{-\lambda_g}(1-x)^{C_g}(1 + D_g x + E_g x^2),$$

- fit I: BGK fit with fitted valence quarks for σ_r for H1ZEUS-NC data in the range $Q^2 \geq 3.5$ GeV^2 and $x \leq 0.01$. NLO fit. *Soft gluon*.
- fit II: BGK fit with valence quarks for σ_r for H1ZEUS-NC data in the range $Q^2 \geq 0.35$ GeV^2 and $x \leq 0.01$. NLO fit. *Soft* + *hard gluon*.
- fits from A. Łuszczak and H. Kowalski, Phys. Rev. D **95** (2017).

Corrections for real part and skewedness

numerically important corrections:

- real part of the diffractive amplitude:

$$\sigma(x,r) \to (1 - i\rho(x))\sigma(x,r)\,,\ \rho(x) = \tan\left(\frac{\pi\Delta_{\mathbf{P}}}{2}\right), \Delta_{\mathbf{P}} = \frac{\partial \log\left(\langle V|\sigma(x,r)|\gamma\rangle\right)}{\partial \log(1/x)}$$

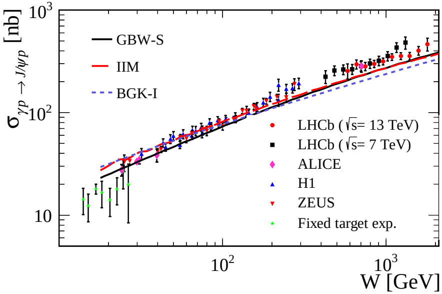
- amplitude is non-forward also in the longitudinal momenta. Correction factor (Shuvaev et al. (1999)):

$$R_{\mathrm{skewed}} = \frac{2^{2\Delta_{\mathbf{P}}+3}}{\sqrt{\pi}} \cdot \frac{\Gamma(\Delta_{\mathbf{P}} + 5/2)}{\Gamma(\Delta_{\mathbf{P}} + 4)}\,.$$

- apply K-factor to the cross section:

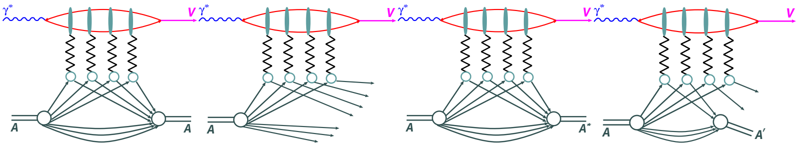
$$K = (1 + \rho^2(x)) \cdot R^2_{\mathrm{skewed}}\,.$$

Exclusive diffractive J/ψ photoproduction on the proton



- besides the BGK-fit of Łuszczak & Kowalski, we show to other dipole cross section fits which incorporate heavy quarks:
  1. 'IIM' (Iancu, Itakura & Munier, which is a parametrization inspired by BFKL/BK-asymptotics).
  2. a recent re-fit of the Golec-Biernat-Wüsthoff form of the dipole cross section obtained by Golec-Biernat & Sapeta (2018).
- the data at high energies were in fact extracted from exclusive diffraction in pp-collisions by LHCb.
- note: for our applications on nuclear targets, the region of $W \sim 30 \div 100\,\mathrm{GeV}$ is the most relevant.

Diffractive processes on the nuclear target



diffractive processes on nuclear targets:

- coherent diffraction – nucleus stays in the ground state
- complete breakup of the nucleus, final state free protons & neutrons
- intact nucleus, but an excited state
- partial breakup of the nucleus, a variety of possible fragments

they all have in common:

- large rapidity gap between vector meson and nuclear fragments
- lack of production of additional particles

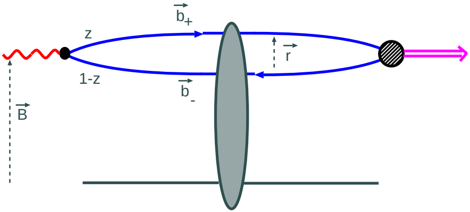
Off-forward amplitude

Amplitude at finite transverse momentum transfer $\boldsymbol{\Delta}$

$$\mathcal{A}(\gamma^* A_i \to V A_f^*; W, \Delta) = 2i \int d^2\boldsymbol{B} \exp[-i\boldsymbol{\Delta}\boldsymbol{B}] \langle V | \langle A_f^* | \hat{\Gamma}(\boldsymbol{b}_+, \boldsymbol{b}_-) | A_i \rangle | \gamma \rangle$$

$$= 2i \int d^2\boldsymbol{B} \exp[-i\boldsymbol{\Delta}\boldsymbol{B}] \int_0^1 dz \int d^2\boldsymbol{r} \Psi_V^*(z,\boldsymbol{r}) \Psi_\gamma(z,\boldsymbol{r}) \langle A_f^* | \hat{\Gamma}(\boldsymbol{B} - (1-z)\boldsymbol{r}, \boldsymbol{B} + z\boldsymbol{r}) | A_i \rangle .$$

$$\begin{aligned} \boldsymbol{r} &= \boldsymbol{b}_+ - \boldsymbol{b}_-, \;\; \boldsymbol{b} = (\boldsymbol{b}_+ + \boldsymbol{b}_-)/2\,, \\ \boldsymbol{B} &= z\boldsymbol{b}_+ + (1-z)\boldsymbol{b}_- = \boldsymbol{b} - (1-2z)\frac{\boldsymbol{r}}{2} \end{aligned}$$



Coherent diffraction – Glauber averages

$$\mathcal{A}(\gamma^* A_i \to V A_i; W, \Delta) = 2i \int d^2\boldsymbol{b} \exp[-i\boldsymbol{b}\boldsymbol{\Delta}] \int d^2\boldsymbol{r} \rho_{V\gamma}(\boldsymbol{r}, \boldsymbol{\Delta}) \langle A_i | \hat{\Gamma}(\boldsymbol{b} + \frac{\boldsymbol{r}}{2}, \boldsymbol{b} - \frac{\boldsymbol{r}}{2}) | A_i \rangle \,,$$

$$\rho_{V\gamma}(\boldsymbol{r}, \boldsymbol{\Delta}) = \int_0^1 dz \exp[i(1-2z)\frac{\boldsymbol{r}\boldsymbol{\Delta}}{2}] \Psi_V^*(z, \boldsymbol{r}) \Psi_\gamma(z, \boldsymbol{r}) \,.$$

$$\hat{\Gamma}(\boldsymbol{b}_+, \boldsymbol{b}_-) = 1 - \prod_{i=1}^{A} [1 - \hat{\Gamma}_{N_i}(\boldsymbol{b}_+ - \boldsymbol{c}_i, \boldsymbol{b}_- - \boldsymbol{c}_i)] \,,$$

in the limit of the dilute uncorrelated nucleus all we need are:

$$M(\boldsymbol{b}_+, \boldsymbol{b}_-) = \int d^2\boldsymbol{c}\, T_A(\boldsymbol{c}) \Gamma_N(\boldsymbol{b}_+ - \boldsymbol{c}, \boldsymbol{b}_- - \boldsymbol{c}) \approx \frac{1}{2}\sigma(\boldsymbol{r}) T_A(\boldsymbol{b})$$

$$\langle A_i | \hat{\Gamma}(\boldsymbol{b} + \frac{\boldsymbol{r}}{2}, \boldsymbol{b} - \frac{\boldsymbol{r}}{2}) | A_i \rangle = 1 - \left[1 - \frac{1}{A} M(\boldsymbol{b}_+, \boldsymbol{b}_-)\right]^A \approx 1 - \exp[-\frac{1}{2}\sigma(\boldsymbol{r}) T_A(\boldsymbol{b})]$$

Incoherent diffraction: summing over nuclear states

$$\frac{d\sigma_{\rm incoh}}{d\boldsymbol{\Delta}^2} = \sum_{A_f \neq A} \frac{d\sigma(\gamma A_i \to VA_f^*)}{d\boldsymbol{\Delta}^2} \,.$$

Closure in the sum over nuclear final states:

$$\sum_{A \neq A_f} |A_f\rangle\langle A_f| = 1 - |A\rangle\langle A|,$$

$$\frac{d\sigma_{\rm incoh}}{d\boldsymbol{\Delta}^2} = \frac{1}{4\pi} \int d^2\boldsymbol{r} d^2\boldsymbol{r}' \rho^*_{V\gamma}(\boldsymbol{r}', \boldsymbol{\Delta}) \rho_{V\gamma}(\boldsymbol{r}, \boldsymbol{\Delta}) \Sigma_{\rm incoh}(\boldsymbol{r}, \boldsymbol{r}', \boldsymbol{\Delta}) \,,$$

$$\Sigma_{\rm incoh}(\boldsymbol{r}, \boldsymbol{r}', \boldsymbol{\Delta}) = \int d^2\boldsymbol{b} d^2\boldsymbol{b}' \exp[-i\boldsymbol{\Delta}(\boldsymbol{b} - \boldsymbol{b}')] \mathcal{C}\left(\boldsymbol{b}' + \frac{\boldsymbol{r}'}{2}, \boldsymbol{b}' - \frac{\boldsymbol{r}'}{2}; \boldsymbol{b} + \frac{\boldsymbol{r}}{2}, \boldsymbol{b} - \frac{\boldsymbol{r}}{2}\right)$$

Only ground state nuclear averages:

$$\mathcal{C}(\boldsymbol{b}'_+, \boldsymbol{b}'_-; \boldsymbol{b}_+, \boldsymbol{b}_-) = \langle A|\hat{\Gamma}^\dagger(\boldsymbol{b}'_+, \boldsymbol{b}'_-)\hat{\Gamma}(\boldsymbol{b}_+, \boldsymbol{b}_-)|A\rangle - \langle A|\hat{\Gamma}(\boldsymbol{b}'_+, \boldsymbol{b}'_-)|A\rangle^* \langle A|\hat{\Gamma}(\boldsymbol{b}_+, \boldsymbol{b}_-)|A\rangle \,.$$

Nuclear averages as in Glauber & Matthiae

$$\hat{\Gamma}(\boldsymbol{b}_+,\boldsymbol{b}_-) = 1 - \prod_{i=1}^{A}[1 - \hat{\Gamma}_{N_i}(\boldsymbol{b}_+ - \boldsymbol{c}_i, \boldsymbol{b}_- - \boldsymbol{c}_i)]\,,$$

in the limit of the dilute uncorrelated nucleus all we need are:

$$M(\boldsymbol{b}_+,\boldsymbol{b}_-) = \int d^2\boldsymbol{c}\, T_A(\boldsymbol{c})\Gamma_N(\boldsymbol{b}_+ - \boldsymbol{c}, \boldsymbol{b}_- - \boldsymbol{c})$$

$$\Omega(\boldsymbol{b}'_+,\boldsymbol{b}'_-;\boldsymbol{b}_+,\boldsymbol{b}_-) = \int d^2\boldsymbol{c}\, T_A(\boldsymbol{c})\Gamma^*_N(\boldsymbol{b}'_+ - \boldsymbol{c}, \boldsymbol{b}'_- - \boldsymbol{c})\Gamma_N(\boldsymbol{b}_+ - \boldsymbol{c}, \boldsymbol{b}_- - \boldsymbol{c})$$

$$\begin{aligned}\mathcal{C}(\boldsymbol{b}'_+,\boldsymbol{b}'_-;\boldsymbol{b}_+,\boldsymbol{b}_-) &= \left[1 - \frac{1}{A}\Big(M^*(\boldsymbol{b}'_+,\boldsymbol{b}'_-) + M(\boldsymbol{b}_+,\boldsymbol{b}_-)\Big) + \frac{1}{A}\Omega(\boldsymbol{b}'_+,\boldsymbol{b}'_-;\boldsymbol{b}_+,\boldsymbol{b}_-)\right]^A \\ &\quad - \left[\Big(1 - \frac{1}{A}M^*(\boldsymbol{b}'_+,\boldsymbol{b}'_-)\Big)\Big(1 - \frac{1}{A}M(\boldsymbol{b}_+,\boldsymbol{b}_-)\Big)\right]^A\end{aligned}$$

Multiple scattering expansion of the incoherent cross section

Diffraction cone of the free nucleon: $B \ll R_A^2$

$$\sigma(x, \boldsymbol{r}, \boldsymbol{\Delta}) = \sigma(x, r) \exp[-\frac{1}{2} B \boldsymbol{\Delta}^2]$$

Multiple scattering expansion for $\boldsymbol{\Delta}^2 R_A^2 \gg 1$

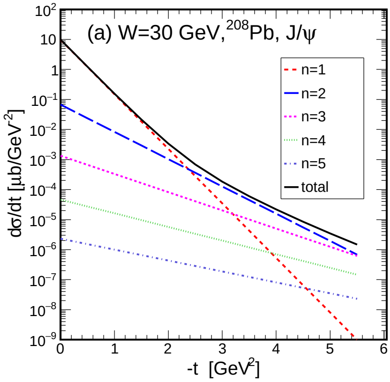
$$\frac{d\sigma_{\rm incoh}}{d\boldsymbol{\Delta}^2} = \sum_n \frac{d\sigma^{(n)}}{d\boldsymbol{\Delta}^2} = \frac{1}{16\pi} \sum_n w_n(\boldsymbol{\Delta}) \int d^2\boldsymbol{b}\, T_A^n(\boldsymbol{b}) |I_n(x, \boldsymbol{b})|^2 \,,$$

$$w_n(\boldsymbol{\Delta}) = \frac{1}{n \cdot n!} \cdot \left(\frac{1}{16\pi B} \right)^{n-1} \cdot \exp\left(-\frac{B}{n} \boldsymbol{\Delta}^2 \right) \,,$$

and

$$\begin{aligned} I_n(x, \boldsymbol{b}) &= \langle V | \, \sigma^n(x, r) \exp[-\frac{1}{2} \sigma(x, r) T_A(\boldsymbol{b})] | \gamma \rangle \\ &= \int_0^1 dz \int d^2\boldsymbol{r}\, \Psi_V^*(z, \boldsymbol{r}) \Psi_\gamma(z, \boldsymbol{r}) \, \sigma^n(x, r) \underbrace{\exp[-\frac{1}{2} \sigma(x, r) T_A(\boldsymbol{b})]}_{\text{nuclear absorption}} \,. \end{aligned}$$

Diffractive incoherent photoproduction on the nuclear target



$-t = \mathbf{\Delta}^2$, single scattering has the same diffractive slope as on the free nucleon, multiple scatterings have smaller slopes.

Incoherent diffraction at low $\boldsymbol{\Delta}^2$

at low $\boldsymbol{\Delta}^2$ the single scattering dominates, and one should rather use its exact form:

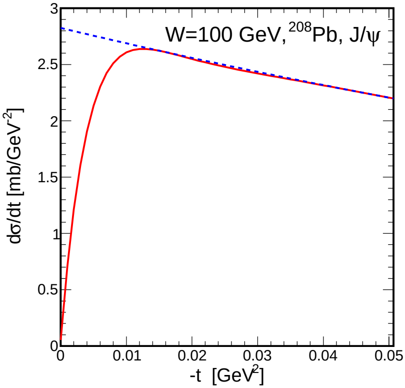
$$\frac{d\sigma_{\rm incoh}}{d\boldsymbol{\Delta}^2} = \frac{1}{16\pi}\left\{ w_1(\boldsymbol{\Delta}) \int d^2\boldsymbol{b}\, T_A(\boldsymbol{b}) |I_1(x,\boldsymbol{b})|^2 - \underbrace{\frac{1}{A}\left| \int d^2\boldsymbol{b} \exp[-i\boldsymbol{\Delta}\boldsymbol{b}]\, T_A(\boldsymbol{b}) I_1(x,\boldsymbol{b}) \right|^2}_{\text{vanishes for } \boldsymbol{\Delta}^2 \mathrm{R}_\mathrm{A}^2 \gg 1} \right\}.$$

$$I_1(x,\boldsymbol{b}) = \langle V | \sigma(x,r) \underbrace{\exp[-\frac{1}{2}\sigma(x,r) T_A(\boldsymbol{b})]}_{\text{nuclear absorption}} |\gamma\rangle$$

If we were to neglect intranuclear absorption, we would obtain for small $\boldsymbol{\Delta}^2$:

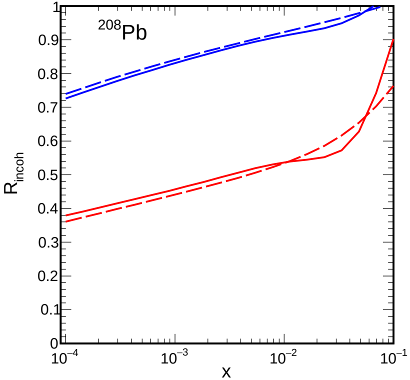
$$\frac{d\sigma_{\rm incoh}}{d\boldsymbol{\Delta}^2} = A \cdot \frac{d\sigma(\gamma N \to VN)}{d\boldsymbol{\Delta}^2}\bigg|_{\boldsymbol{\Delta}^2=0} \cdot \left\{ 1 - \mathcal{F}_A^2(\boldsymbol{\Delta}^2) \right\}.$$

Diffractive processes on the nuclear target



- solid line: exact single scattering
- dashed: large $|t|$-limit of single scattering
- exact result merges into the large $|t|$ limit quickly, the latter is a good approximation in a broad range of t.
- cross section dips, but does not vanish at $t \to 0$.
- note: in the small to intermediate t region nuclear correlations may play a role.

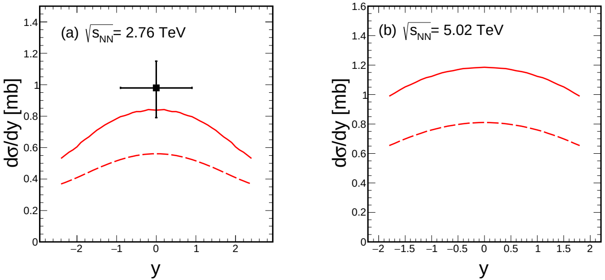
Diffractive processes on the nuclear target



- blue: Υ, red: J/ψ
- dashed line: dipole fit I (soft gluon),
- solid line: dipole fit II (soft+hard gluon)
- dependence on dipole cross section in its "applicability region" is rather small.
- nuclear absorption cannot be neglected, even for heavy vector mesons.

$$R_{\rm incoh}(x) = \frac{d\sigma_{\rm incoh}/d\boldsymbol{\Delta}^2}{A \cdot d\sigma(\gamma N \to VN)/d\boldsymbol{\Delta}^2} = \frac{\displaystyle\int d^2\boldsymbol{b}\, T_A(\boldsymbol{b}) \Big| \langle V | \sigma(x,r) \exp[-\frac{1}{2}\sigma(x,r) T_A(\boldsymbol{b})] | \gamma \rangle \Big|^2}{A \cdot \Big| \langle V | \sigma(x,r) | \gamma \rangle \Big|^2} .$$

Incoherent diffraction in ultraperipheral heavy ion collisions



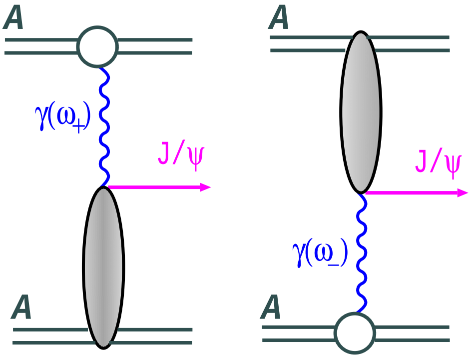
solid line: with skewedness/real part correction
dashed line: without corr.
data point from ALICE
Eur. Phys. J. C **73** (2013)

Cross section for AA collision uses Weizsäcker-Williams photon fluxes:

$$\frac{d\sigma_{\rm incoh}(AA \to VAX)}{dy} = n_{\gamma/A}(z_+)\sigma_{\rm incoh}(W_+) + n_{\gamma/A}(z_-)\sigma_{\rm incoh}(W_-)\,,$$

$$z_\pm = \frac{m_V}{\sqrt{s_{NN}}} e^{\pm y}, \;\; W_\pm = \sqrt{z_\pm s_{NN}}\,.$$

Coherent photoproduction of J/ψ in heavy ion collisions



- $\boldsymbol{p}_1, \boldsymbol{p}_2$ = transverse momenta of outgoing ions.
- Interference induces azimuthal correlation $(\boldsymbol{p}_1 \cdot \boldsymbol{p}_2)/(t_1 t_2)$.
- the interference is concentrated at very low p_T of J/ψ and can be neglected in rapidity distributions.

Energies available for photoproduction

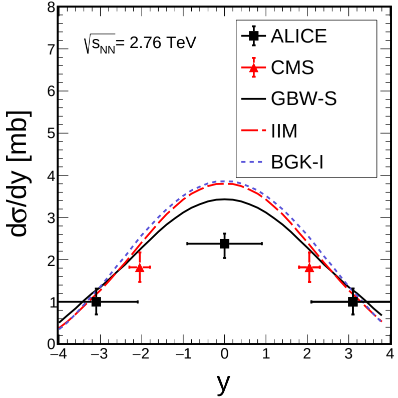
$\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$						
y	$W_+[\mathrm{GeV}]$	$W_-[\mathrm{GeV}]$	x_+	x_-	$n(\omega_+)$	$n(\omega_-)$
0.0	92.5	92.5	$1.12 \cdot 10^{-3}$	$1.12 \cdot 10^{-3}$	69.4	69.4
1.0	152	56.1	$4.13 \cdot 10^{-4}$	$3.05 \cdot 10^{-3}$	39.5	100
2.0	251	34.0	$1.52 \cdot 10^{-4}$	$8.29 \cdot 10^{-3}$	14.5	132
3.0	414	20.6	$5.59 \cdot 10^{-5}$	$2.25 \cdot 10^{-2}$	1.68	163
3.8	618	13.8	$2.51 \cdot 10^{-5}$	$5.02 \cdot 10^{-2}$	0.03	188

Table: Subenergies $W_\pm$ and Bjorken-x values $x_\pm$ for $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$ for a given rapidity y. Also shown are photon fluxes $n(\omega_\pm)$.

$\sqrt{s_{NN}} = 5.02\,\mathrm{TeV}$						
y	$W_+[\mathrm{GeV}]$	$W_-[\mathrm{GeV}]$	x_+	x_-	$n(\omega_+)$	$n(\omega_-)$
0.0	125	125	$6.17 \cdot 10^{-4}$	$6.17 \cdot 10^{-4}$	87.9	87.9
1.0	206	75.6	$2.27 \cdot 10^{-4}$	$1.68 \cdot 10^{-3}$	57.2	119
2.0	339	45.9	$8.35 \cdot 10^{-5}$	$4.56 \cdot 10^{-3}$	28.5	150
3.0	559	27.8	$3.07 \cdot 10^{-5}$	$1.24 \cdot 10^{-2}$	7.5	181
4.0	921	16.9	$1.13 \cdot 10^{-5}$	$3.37 \cdot 10^{-2}$	0.35	213
4.8	1370	11.3	$5.08 \cdot 10^{-6}$	$7.50 \cdot 10^{-2}$	0.001	238

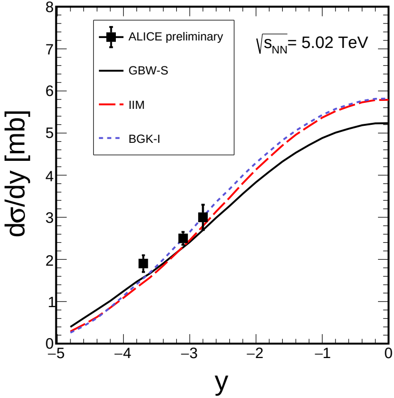
Table: Subenergies $W_\pm$ and Bjorken-x values $x_\pm$ for $\sqrt{s_{NN}} = 5.02\,\mathrm{TeV}$ for a given rapidity y.

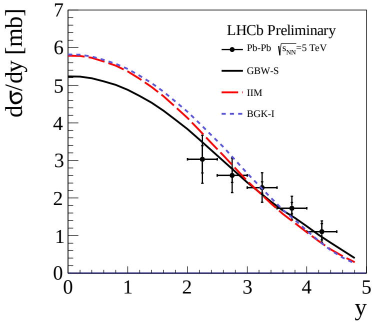
Coherent photoproduction of J/ψ in heavy ion collisions



- reasonable description of experimental data.
- the highest γN energy at $y = 0$, about $W = 100\,\mathrm{GeV}$.
- explicit higher Fock states, $c\bar{c}g, c\bar{c}gg$...?

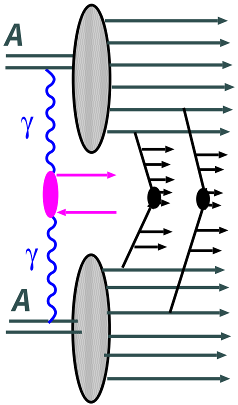
Coherent photoproduction of J/ψ in heavy ion collisions





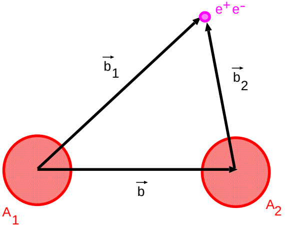
- Preliminary data from ALICE & LHCb.

Dilepton production in semi-central collisions



- Dileptons are a "classic" probe of the QGP.
- medium modifications of ρ, thermal dileptons
- dileptons from $\gamma\gamma$ fusion have peak at very low pair transverse momentum.
- can they be visible even in semi-central collisions?

Dilepton production in semi-central collisions



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

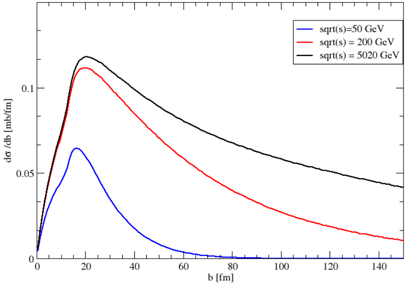
where the phase space element is $d\xi = dy_+ dy_- dp_t^2$ with $y_\pm$, p_t and m_l the single-lepton rapidities, transverse momentum and mass, respectively, and

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

- we adopt the impact parameter definition of centrality, of course...

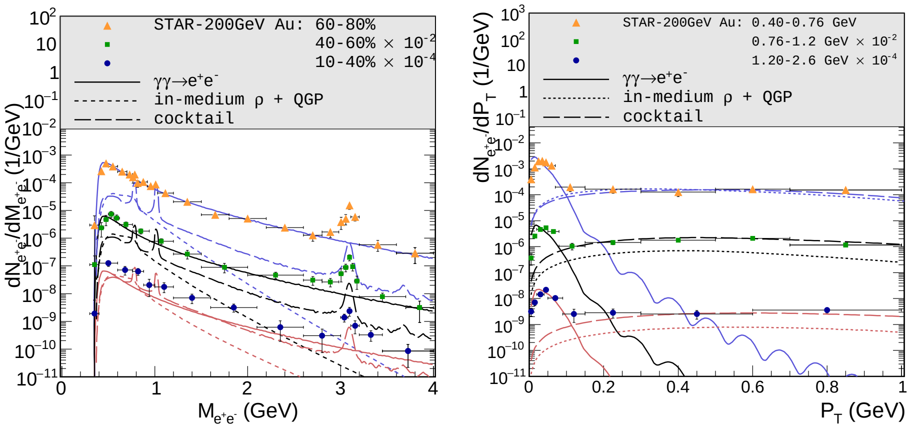
$$\frac{dN_{ll}[\mathcal{C}]}{dM} = \frac{1}{f_{\mathcal{C}} \cdot \sigma_{\rm AA}^{\rm in}} \int_{b_{\min}}^{b_{\max}} db \int d\xi\, \delta(M - 2\sqrt{\omega_1\omega_2})\, \frac{d\sigma_{ll}}{d\xi db}\bigg|_{\rm cuts} \;,$$

Dilepton production: impact parameter distribution



- semi-central collisions are situated on the left side of the distribution, below $b < 15\mathrm{fm}$.
- starting from RHIC energies, the contribution from coherent photons is practically energy-independent.
- also notice the long tails of the ultraperipheral part. Their importance rises with energy.

Dilepton production in semi-central collisions



- M. Kłusek-Gawenda, R. Rapp, W.S. & A. Szczurek, Phys.Lett. B790 (2019)
- electron pair $P_T < 150\,\mathrm{MeV}$: dileptons from coherent photons dominate over a large range of centralities.
- other mechanisms: medium modified ρ, thermal dileptons, Dalitz-decays ("cocktail").

From ultraperipheral to peripheral nuclear collisions

Recently, the ALICE collaboration has observed a large enhancement of J/ψ mesons carrying very small $p_T < 300\,\mathrm{MeV}$ in the centrality classes corresponding to peripheral collisions.

Centrality class $70 \div 90\%$:

$13\,\mathrm{fm} < b < 15\,\mathrm{fm}$, photon fluxes by Contreras Phys. Rev. C **96** (2017)

$$\begin{aligned} \frac{d\sigma_{\mathrm{incoh}}(AA \to VX|70 \div 90\%)}{dy} &= n_{\gamma/A}(z_+|70 \div 90\%)\sigma_{\mathrm{incoh}}(W_+|p_T < p_T^{\mathrm{cut}}) \\ &+ n_{\gamma/A}(z_-|70 \div 90\%)\sigma_{\mathrm{incoh}}(W_-|p_T < p_T^{\mathrm{cut}}) \\ &\approx 15\,\mu\mathrm{b}\,, \end{aligned}$$

The ALICE measurement is [Phys. Rev. Lett. **116** (2016)]:

$$\frac{d\sigma(AA \to VX|70 \div 90\%; 2.5 < |y| < 4.0)}{dy} = 59 \pm 11 \pm 8\,\mu\mathrm{b}\,.$$

For an estimate of the coherent contribution, see: M. Kłusek-Gawenda and A. Szczurek, Phys. Rev. C **93** (2016), **See talk by Antoni Szczurek on Friday.**

Instead of a summary

- Even when nuclei don't touch each other, they have very large inelastic cross sections. EM dissociation ~ 200 barn at LHC.
- Ultraperipheral heavy ion collisions give access to a lot of interesting processes. Photoproduction of J/ψ tells us about interaction of small dipoles with nuclear medium, potentially about the nuclear gluon distribution.
- Certain properties/phenomena can even carry over into the semi-central domain. Their exploration has just begun.