15. ZIMÁNYI WINTER SCHOOL ON HEAVY ION PHYSICS

HEAVY ION UPC PHYSICS

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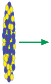
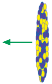
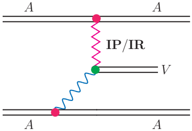
UltraPeripheral Collisions

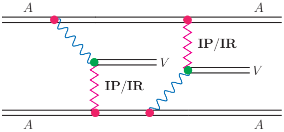




Photoproduction

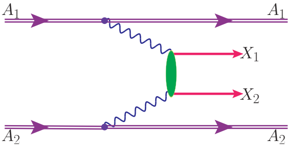


- $\rho^0 \& J/\psi$



- $\rho^0\rho^0 \& J/\psi J/\psi$

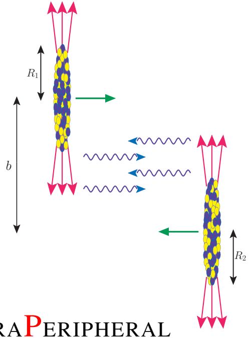
$\gamma\gamma$ fusion



- $\mu^+\mu^-$
- $\rho^0\rho^0$
- $\pi^+\pi^- \& \pi^0\pi^0$

Predictions for ultraperipheral processes that could be studied experimentally.

Equivalent Photon Approximation



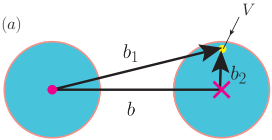
The strong electromagnetic field is a source of photons that can induce electromagnetic reactions in ion-ion collisions.

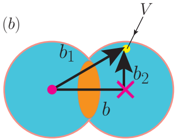
UltraPeripheral Collisions

semi-CENTRAL Collisions

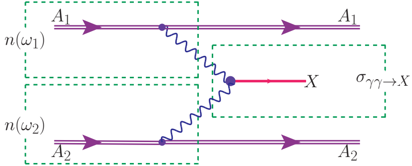
$$b > R_{min} = R_1 + R_2$$

$$b \leq R_{min}$$



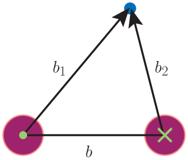


$AA \to AAX_1X_2$ - $\gamma\gamma$ FUSION



$$n(\omega) = \int_{R_{min}}^{\infty} 2\pi b \mathrm{d}b \, N(\omega, b) \qquad (1)$$

$$\begin{aligned} \sigma_{A_1A_2 \to A_1A_2X} &= \int \mathrm{d}\omega_1 \, \mathrm{d}\omega_2 \, n(\omega_1) n(\omega_2) \sigma_{\gamma\gamma\to X}(\omega_1, \omega_2) \\ &= \ldots \\ &= \int N(\omega_1, \mathbf{b_1}) \, N(\omega_2, \mathbf{b_2}) S^2_{abs}(\mathbf{b}) \\ &\times \ \sigma_{\gamma\gamma\to X}\left(\sqrt{s_{A_1A_2}}\right) \\ &\times \ 2\pi b \mathrm{d}b \, \mathrm{d}\bar{b}_x \, \mathrm{d}\bar{b}_y \, \frac{W_{\gamma\gamma}}{2} \mathrm{d}W_{\gamma\gamma} \, \mathrm{d}Y_X \qquad (2) \end{aligned}$$

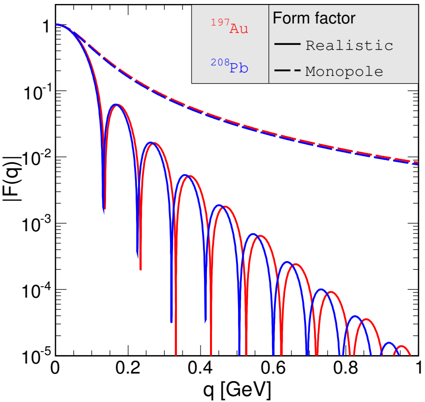


FORM FACTOR

$N\left(\omega_{1/2}, \mathbf{b}_{1/2}\right)$ depends on the form factor

REALISTIC F_{em}

$$F(q) = \frac{4\pi}{q} \int \rho(r) \sin(qr)\, r dr$$



MONOPOLE F_{em}

$$F(q^2) = \frac{\Lambda^2}{\Lambda^2 + q^2}$$

$$\Lambda = \sqrt{\frac{6}{<r^2>}}$$

- $^{197}Au \Rightarrow \sqrt{< r^2 >} = 5.3$ fm, $\Lambda = 91$ MeV,
- $^{208}Pb \Rightarrow \sqrt{< r^2 >} = 5.5$ fm, $\Lambda = 88$ MeV.

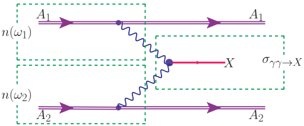
In the literature:

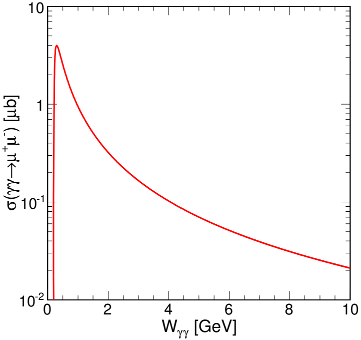
$\Lambda = (80 - 90)$ GeV

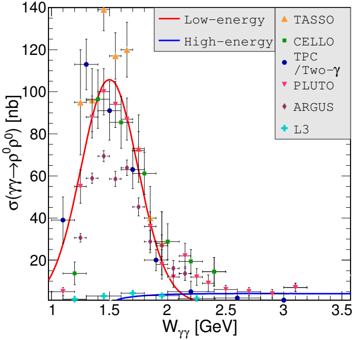
POINT-LIKE F_{em}

$$F(q^2) = 1$$

ELEMENTARY CROSS SECTION

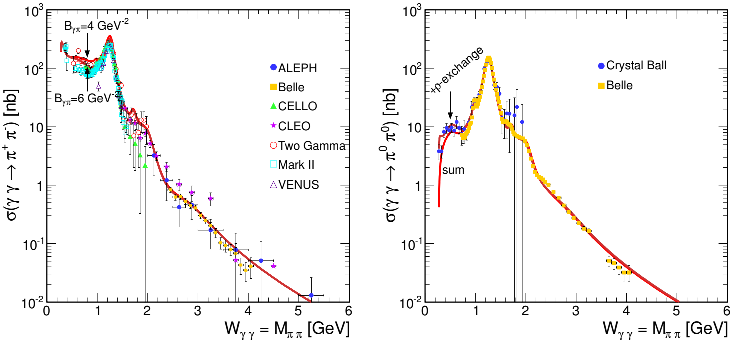






Ref.
M. Kłusek-Gawenda and A. Szczurek, Phys. Rev. **C82** (2010) 014904,
"Exclusive muon-pair productions in ultrarelativistic heavy-ion collisions – realistic nucleus charge form factor and differential distributions"

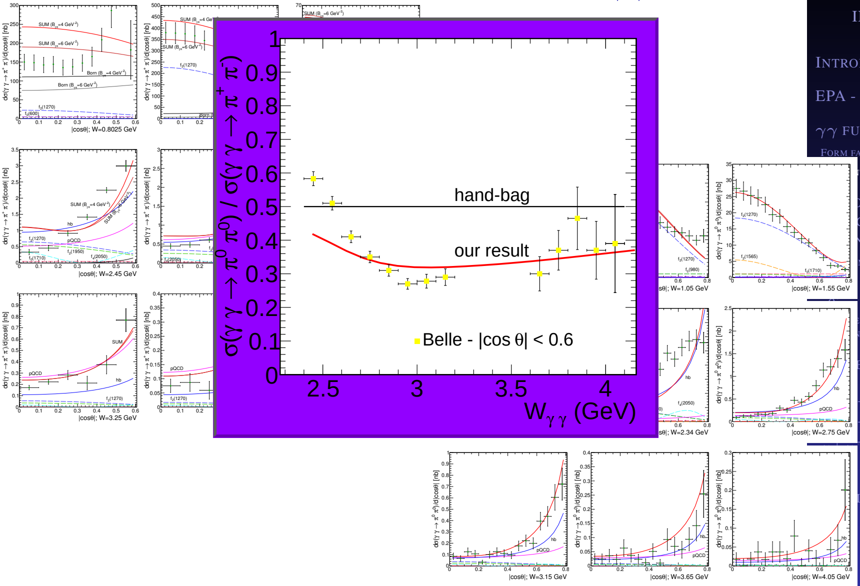
Ref.
M. Kłusek, W. Schäfer and A. Szczurek, Phys.Lett. **B674** (2009) 92,
"Exclusive production of $\rho^0\rho^0$ pairs in $\gamma\gamma$ collisions at RHIC"



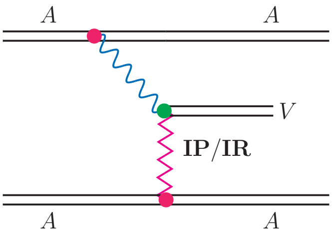
Ref.

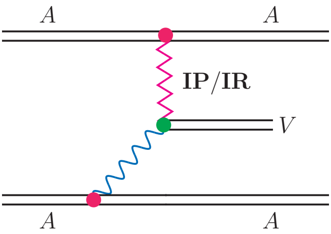
M. Kłusek and A. Szczurek, Phys. Rev. **C87** (2013) 054908,
"$\pi^+\pi^-$ and $\pi^0\pi^0$ pair production in photon-photon and in ultraperipheral ultrarelativistic heavy ion collisions"

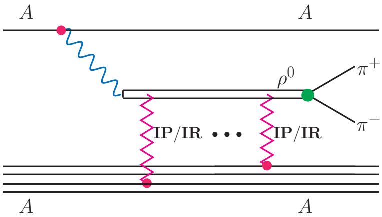
ANGULAR DISTRIBUTIONS FOR THE $\gamma\gamma \to \pi\pi$

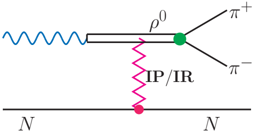


Photoproduction of vector meson



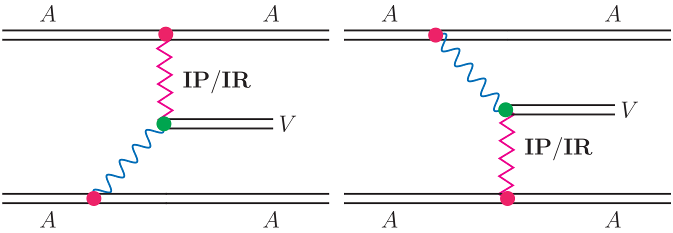






Parameters fixed to describe HERA data
we expect: $\frac{d\sigma(\gamma n \to Vn)}{dt} \approx \frac{d\sigma(\gamma p \to Vp)}{dt}$

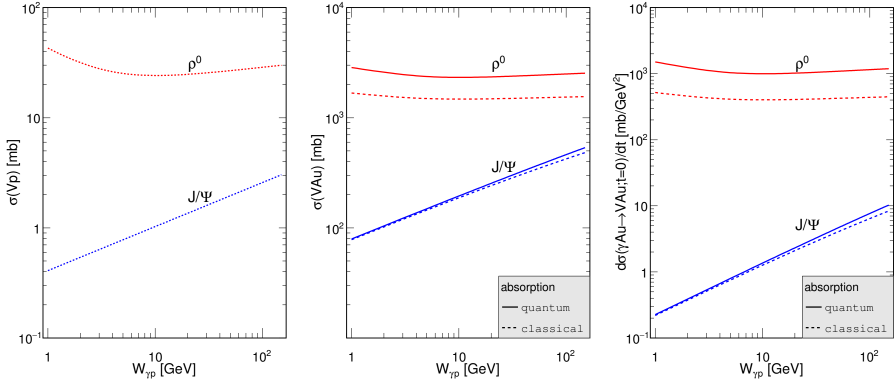
SINGLE VECTOR MESON PRODUCTION



$$\frac{d\sigma_{A_1 A_2 \to A_1 A_2 V}}{d^2 b dy} = \frac{dP_{\gamma \mathbf{P}}(b, y)}{dy} + \frac{dP_{\mathbf{P}\gamma}(b, y)}{dy} \quad (3)$$

$$\frac{dP_{1/2}(b, y)}{dy} = \omega_{1/2} N(\omega_{1/2}, b) \sigma_{\gamma A_{2/1} \to V A_{2/1}}(W_{\gamma A_{2/1}}) \quad (4)$$

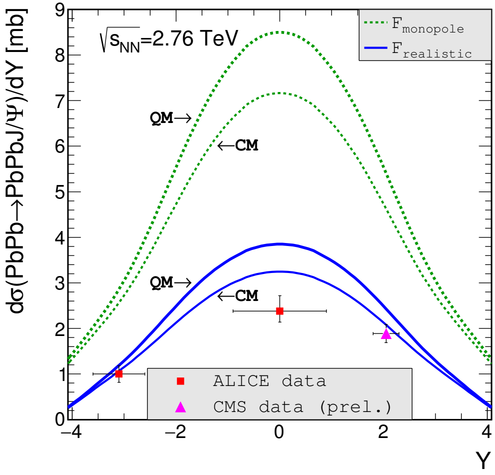
$\frac{d\sigma_{\gamma p \to Vp}(t=0)}{dt}$ ← HERA data



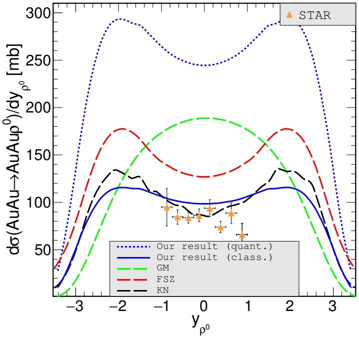
- $\sigma^{CM}_{tot}(VA) = \int d^2\mathbf{r}\,\left(1 - \exp\left(-\sigma_{tot}(Vp)\,T_A(\mathbf{r})\right)\right)$
- $\sigma^{QM}_{tot}(VA) = 2\int d^2\mathbf{r}\,\left(1 - \exp\left(-\frac{1}{2}\sigma_{tot}(Vp)\,T_A(\mathbf{r})\right)\right)$

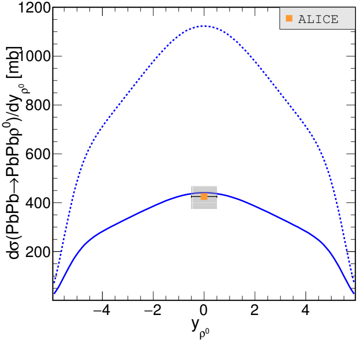
$$\sigma_{\gamma A \to VA}(W_{\gamma A_{2/1}}) = \frac{d\sigma_{\gamma A \to VA}(t=0)}{dt} \int_{-\infty}^{t_{max}} dt\, \left| F_A(t) \right|^2$$

J/ψ MESON PRODUCTION



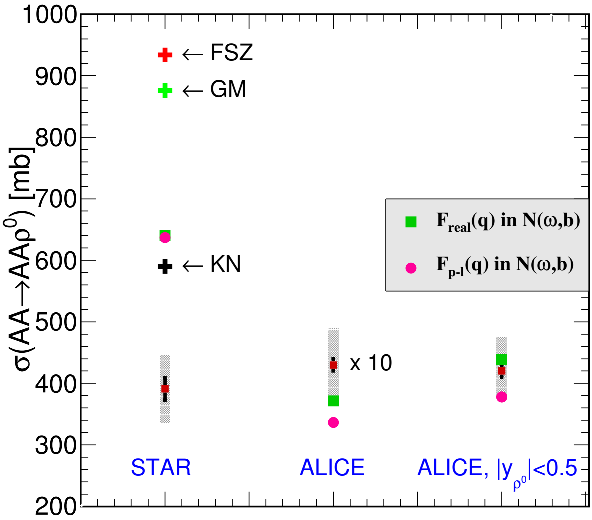
ρ^0 meson production



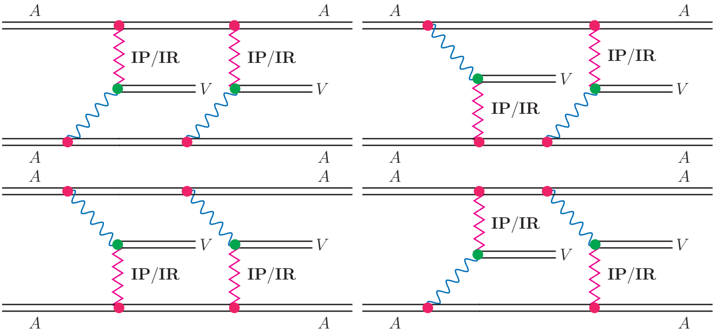


GM - V.P. Gonçalves and M.V.T. Machado, "The QCD pomeron in ultraperipheral heavy ion collisions. IV. Photonuclear production of vector mesons", Eur. Phys. J. **C40** (2005) 519,
FSZ - L. Frankfurt, M. Strikman and M. Zhalov, "Signals for black body limit in coherent ultraperipheral heavy ion collisions", Phys. Lett. **B537** (2002) 51,
KN - S. Klein and J. Nystrand, "Exclusive vector meson production in relativistic heavy ion collisions", Phys. Rev. **C60** (1999) 014903

Single ρ^0 meson production

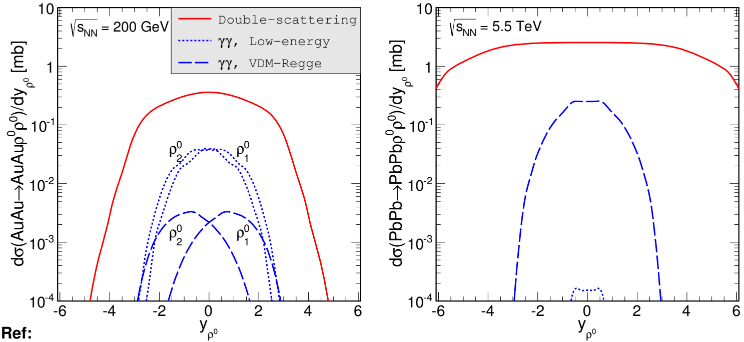


DOUBLE-SCATTERING MECHANISM



$$\frac{d\sigma_{A_1A_2\to A_1A_2\rho^0\rho^0}}{dy_1 dy_2} = \frac{1}{2}\int\left(\frac{dP_{\gamma\mathbf{P}}(b,y_1)}{dy_1} + \frac{dP_{\mathbf{P}\gamma}(b,y_1)}{dy_1}\right) \times \left(\frac{dP_{\gamma\mathbf{P}}(b,y_2)}{dy_2} + \frac{dP_{\mathbf{P}\gamma}(b,y_2)}{dy_2}\right) d^2b$$

DOUBLE-SCATTERING MECHANISM VS $\gamma\gamma$ FUSION

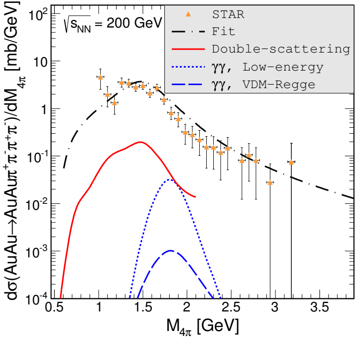


Ref:
M. Kłusek-Gawenda and A. Szczurek, Phys. Rev. **C89** (2014) 024912
"Double-scattering mechanism in the exclusive $AA \to AA\rho^0\rho^0$ reaction in ultrarelativistic collisions",

$$\mathrm{Br}(\rho^0\rho^0 \to \pi^+\pi^-\pi^+\pi^-) \simeq 100\%$$

$\pi^+\pi^-\pi^+\pi^-$ PRODUCTION @ RHIC

$|\eta_\pi| < 1$



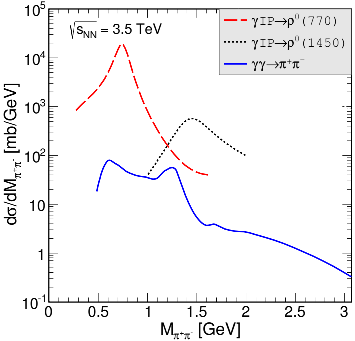
missing mechanisms:

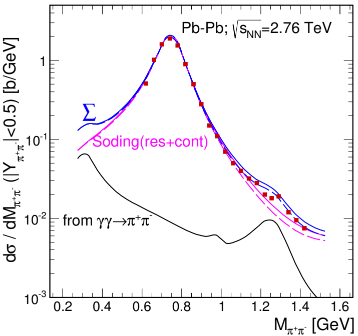
$AA \to AA\rho^0(1450) \to 4\pi$

$AA \to AA\rho^0(1700) \to 4\pi$

?

TWO-PION PRODUCTION





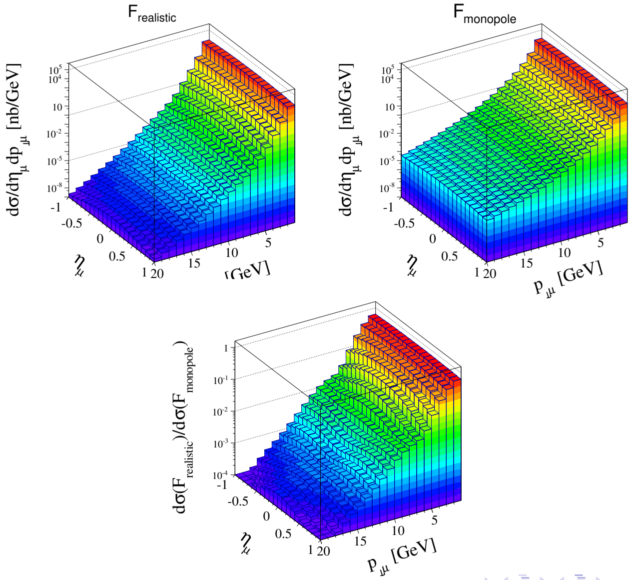
Drell-Söding+$f_2(1270)$

colored solid lines - $\Gamma_{\rho^0} = 150.2$ MeV

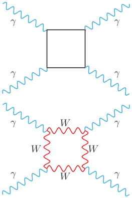
colored dashed lines - $\Gamma_{\rho^0} = 140$ MeV

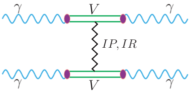
ALICE data: JHEP 1509 (2015) 095

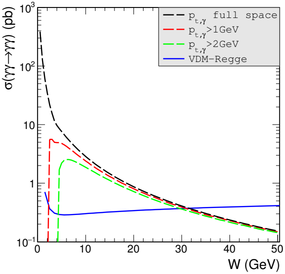
DIMUONS PRODUCTION

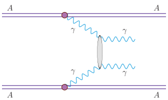


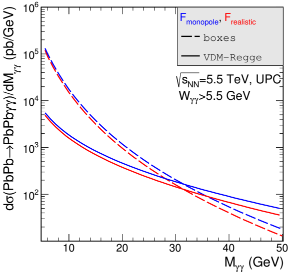
$\gamma\gamma$ PRODUCTION

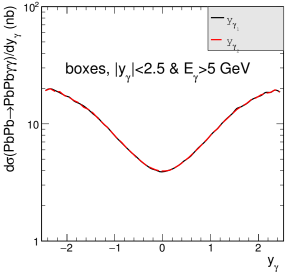












Conclusions

- EPA in the impact parameter space
- Realistic form factor (two-parameter Fermi model)
- Elementary cross section
  - $\gamma\gamma \to \mu^+\mu^-$
  - $\gamma\gamma \to \rho^0\rho^0$ low-energy parametrization & VDM-Regge model
  - $\gamma\gamma \to \pi^{+/0}\pi^{-/0}$ continuum, resonances, QCD mechanisms
    Both for the total cross section and for angular distributions
    both for $\gamma\gamma \to \pi^{+/0}\pi^{-/0}$ reactions simultaneously
    for all experimentally available energies.
- Good description of
  - STAR and ALICE data for $\rho^0(770)$ production
  - CMS and ALICE data for J/ψ production
- Comparison of four-pion production via $\rho^0\rho^0$ production
  - $\gamma\gamma$ fusion
  - nuclear double-photoproduction (very large)

  with STAR data $\rho^0(1450) \to 4\pi$ or/and $\rho^0(1700) \to 4\pi$??
- $\pi^+\pi^-$ photoproduction & $\gamma\gamma \to f_2(1270) \to \pi^+\pi^-$

Conclusions

- PbPb→PbPb$\gamma\gamma$; $\sqrt{s_{NN}} = 5.5$ TeV

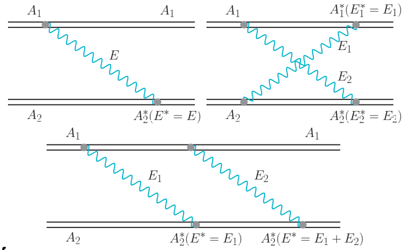
BOXES, $\sigma_{tot}[nb]$ cuts	our results $F_{realistic}$	our results $F_{monopole}$	Ref. [1]
$W_{\gamma\gamma} > 5.0$ GeV	311		35±7
$W_{\gamma\gamma} > 5.5$ GeV	254	294	
$W_{\gamma\gamma} > 5.5$ GeV, $p_{t,\gamma} > 2$ GeV	138	160	
$W_{\gamma\gamma} > 4.5$ GeV, $\lvert\eta_\gamma\rvert < 2.5$	286		
$W_{\gamma\gamma} > 5.5$ GeV, $\lvert\eta_\gamma\rvert < 2.5$	162		
$E_\gamma > 5$ GeV, $\lvert\eta_\gamma\rvert < 2.5$	54		

VDM-Regge model cuts	our results $F_{realistic}$	our results $F_{monopole}$
$W_{\gamma\gamma} > 1$ GeV,	199	
$W_{\gamma\gamma} > 2$ GeV,	74	
$W_{\gamma\gamma} > 5$ GeV,	28	32
$W_{\gamma\gamma} > 5$ GeV, $\lvert\eta_\gamma\rvert < 2.5$	20	
$E_\gamma > 5.5$ GeV	11	13
$E_\gamma > 3$ GeV, $\lvert\eta_\gamma\rvert < 2.5$	0.07	

[1] D. d'Enterria and G.G. da Silveira, Phys. Rev. Lett. **111** (2013) 080405 "Observing light-by-light scattering at the Large Hadron Collider"

CONCLUSIONS

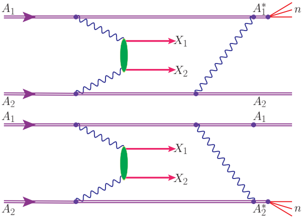
- Multiple Coulomb excitations



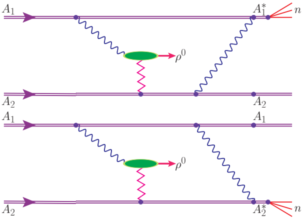
Ref.
M. Kłusek-Gawenda, M. Ciemała, W. Schäfer and A. Szczurek, Phys. Rev. **C89** (2014) 054907,
"Electromagnetic excitation of nuclei and neutron evaporation in ultrarelativistic ultraperipheral heavy ion collisions"

associated with $\rho^0\rho^0$ or ρ^0 production may cause additional excitation of one or both nuclei to the giant resonance region

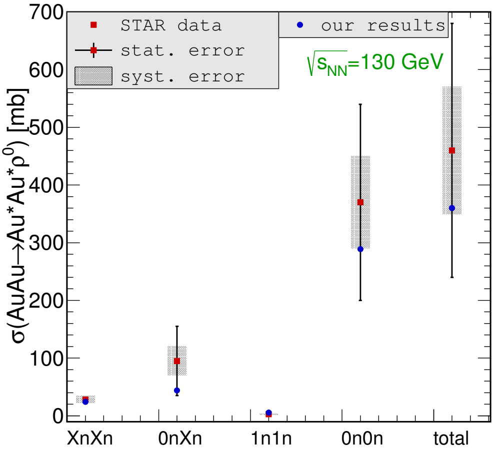
$$AA \to AA^*(kn)X_1X_2$$



$$AA \to AA^*(kn)\rho^0$$



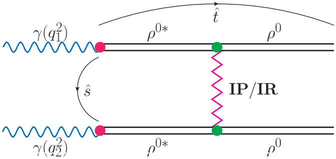
ρ^0 production in heavy ion UPC with nuclear excitation



Back-up slides

ELEMENTARY CROSS SECTION $\gamma\gamma \to \rho^0\rho^0$

$$\sigma^{\text{high-energy}}_{\gamma\gamma\to\rho^0\rho^0} = \int\limits_{\hat{t}_{min}(\hat{s})}^{\hat{t}_{max}(\hat{s})} \frac{d\sigma^{\text{high-energy}}_{\gamma\gamma\to\rho^0\rho^0}}{d\hat{t}} d\hat{t} \quad (5)$$



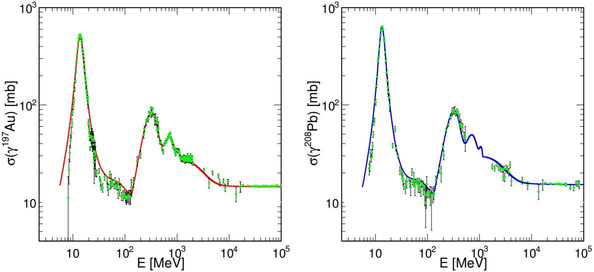
$$\frac{d\sigma^{\text{high-energy}}_{\gamma\gamma\to\rho^0\rho^0}}{d\hat{t}} = \frac{1}{16\pi\hat{s}} \left|\mathcal{M}_{\gamma\gamma\to\rho^0\rho^0}\left(\hat{s},\hat{t};q_1,q_2\right)\right|^2 \quad (6)$$

$$\mathcal{M}_{\gamma\gamma\to\rho^0\rho^0}\left(\hat{s},\hat{t};q_1,q_2\right) = C_{\gamma\to\rho^0} C_{\gamma\to\rho^0} \mathcal{M}_{\rho^{0*}\rho^{0*}\to\rho^0\rho^0}\left(\hat{s},\hat{t};q_1,q_2\right) \quad (7)$$

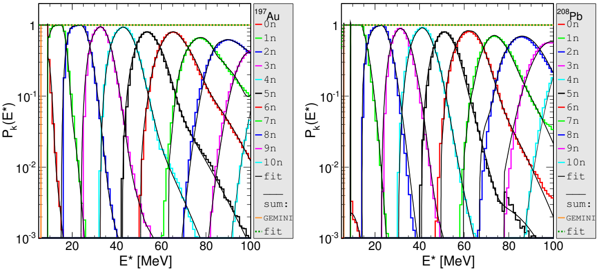
$$\mathcal{M}_{\rho^{0*}\rho^{0*}\to\rho^0\rho^0}\left(\hat{s},\hat{t};q_1,q_2\right) = \left(\eta_{\mathbf{P}}\left(\hat{s},\hat{t}\right) C_{\mathbf{P}} \left(\frac{\hat{s}}{s_0}\right)^{\alpha_{\mathbf{P}}\left(\hat{t}\right)-1} + \eta_{\mathbf{R}}\left(\hat{s},\hat{t}\right) C_{\mathbf{R}} \left(\frac{\hat{s}}{s_0}\right)^{\alpha_{\mathbf{R}}\left(\hat{t}\right)-1}\right)$$

$$\times \hat{s}\, F\left(\hat{t}; q_1^2 \approx 0\right) F\left(\hat{t}; q_2^2 \approx 0\right) \quad (8)$$

Photoabsorption $\sigma(\gamma A \to A) \downarrow$



Probability of neutron multiplicity $\downarrow$



Excitation function $\gamma^{A}X \rightarrow kn^{A-1}X\downarrow$