Double-scattering production of two ρ^0 mesons and four pions in heavy ion UPCs

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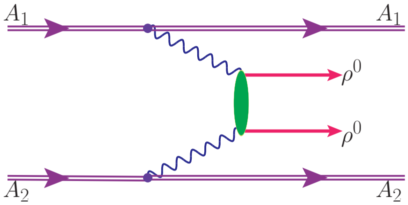
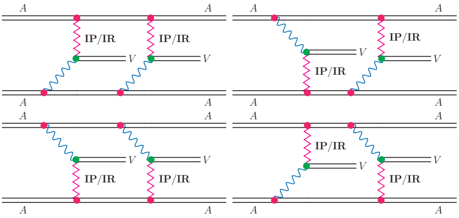
Introduction



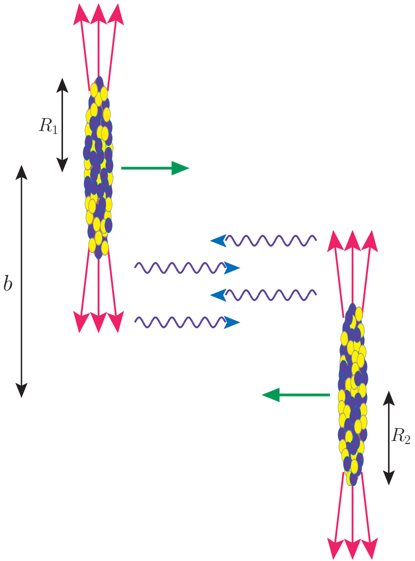
$\Uparrow$ $\gamma\gamma$ fusion

nuclear photoproduction $\Downarrow$



1. Equivalent photon approximation
   - $\gamma\gamma \to \rho^0 \rho^0$
     - low-energy bump
     - VDM-Regge
   - form factor
2. ρ^0 production
   - ρ^0 mass smearing
   - STAR & ALICE data
3. $\rho^0 \rho^0$ production $\to \pi^+\pi^-\pi^+\pi^-$
4. Conclusions

Equivalent photon approximation (EPA)



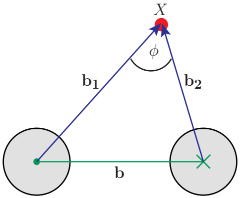
The strong electromagnetic field is a source of photons that induce electromagnetic reactions.

Peripheral collisions:

$b > R_1 + R_2 \cong 14$ fm

The cross section in EPA

$$\sigma_{A_1A_2\to A_1A_2X}\left(\sqrt{s_{A_1A_2}}\right) = \int \sigma_{\gamma\gamma\to X_1X_2}\left(\sqrt{s_{\gamma\gamma}}\right)$$
$$\times\quad N(\omega_1,\mathbf{b_1})\,N(\omega_2,\mathbf{b_2})\,S^2_{abs}(\mathbf{b})$$
$$\times\quad 2\pi b\mathrm{d}b\,\mathrm{d}\overline{b}_x\,\mathrm{d}\overline{b}_y\,\frac{W_{\gamma\gamma}}{2}\mathrm{d}W_{\gamma\gamma}\,\mathrm{d}Y_{X_1X_2}$$



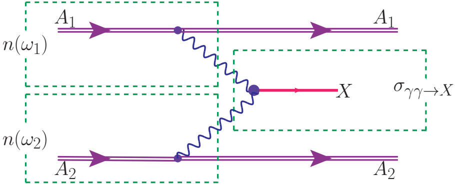
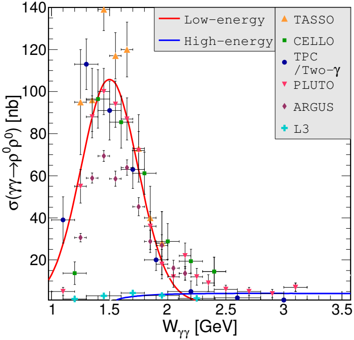


Diagram illustrates quantities in the impact parameter space. This is a view perpendicular to the direction of motion of two ions.

$$Y_{X_1X_2} = \frac{1}{2}\left(y_{X_1} + y_{X_2}\right)$$
$$W_{\gamma\gamma} = \sqrt{4\omega_1\omega_2}$$
$$\mathbf{b_1} = \left[\overline{b}_x + \frac{b}{2}, \overline{b}_y\right]$$
$$\mathbf{b_2} = \left[\overline{b}_x - \frac{b}{2}, \overline{b}_y\right]$$

Elementary cross section

- $\sigma^{\mathrm{low-energy}}_{\gamma\gamma\to\rho^0\rho^0}(W_{\gamma\gamma})$

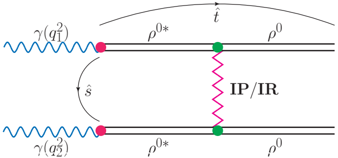


- $\sigma^{\mathrm{high-energy}}_{\gamma\gamma\to\rho^0\rho^0} = \int_{\hat{t}_{min}(\hat{s})}^{\hat{t}_{max}(\hat{s})} \frac{d\sigma^{\mathrm{high-energy}}_{\gamma\gamma\to\rho^0\rho^0}}{d\hat{t}} d\hat{t}$

$$\frac{d\sigma^{\mathrm{high-energy}}_{\gamma\gamma\to\rho^0\rho^0}}{d\hat{t}} = \frac{1}{16\pi\hat{s}} \Big| \overbrace{\mathcal{M}_{\gamma\gamma\to\rho^0\rho^0}(\hat{s},\hat{t};q_1,q_2)}^{C_{\gamma\to\rho^0}\,C_{\gamma\to\rho^0}\,\underbrace{\mathcal{M}_{\rho^{0*}\rho^{0*}\to\rho^0\rho^0}(\hat{s},\hat{t};q_1,q_2)}} \Big|^2$$

$$\left(\eta_{\mathbf{P}}(\hat{s},\hat{t})\, C_{\mathbf{P}} \left(\frac{\hat{s}}{s_0}\right)^{\alpha_{\mathbf{P}}(\hat{t})-1} + \eta_{\mathbf{R}}(\hat{s},\hat{t})\, C_{\mathbf{R}} \left(\frac{\hat{s}}{s_0}\right)^{\alpha_{\mathbf{R}}(\hat{t})-1}\right)$$

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



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

$AA \to AA\rho^0\rho^0$ - form factor

$$\sigma_{A_1A_2\to A_1A_2X}\left(\sqrt{s_{A_1A_2}}\right) = \int \sigma_{\gamma\gamma\to X_1X_2}\left(\sqrt{s_{\gamma\gamma}}\right)$$
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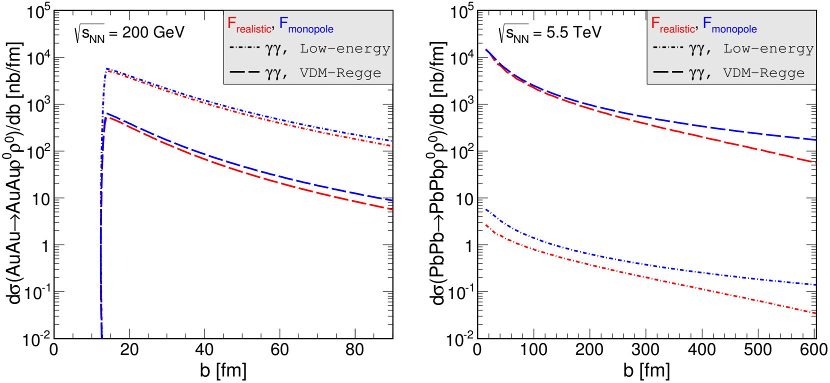
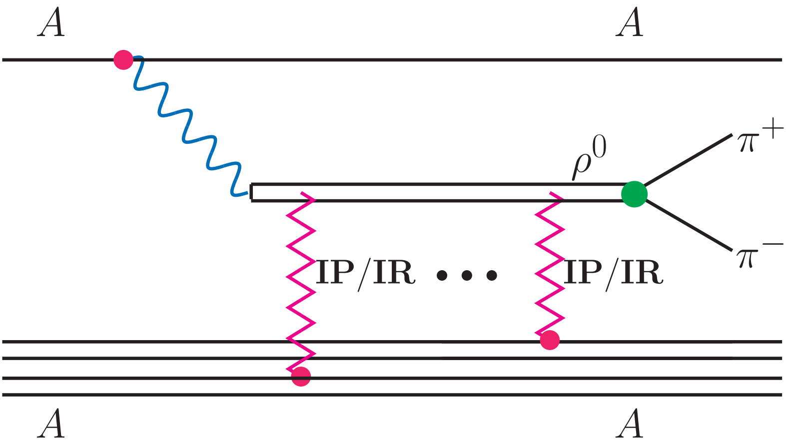
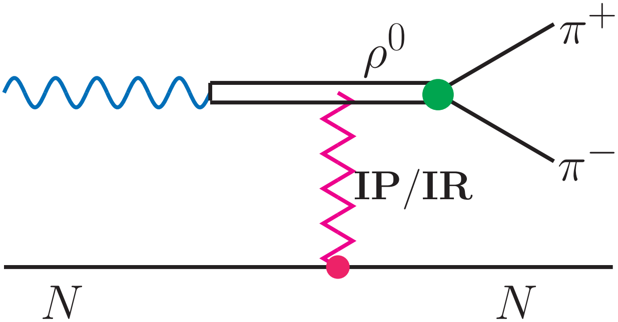
$$\times\quad 2\pi b\,\mathrm{d}b\,\mathrm{d}\overline{b}_x\,\mathrm{d}\overline{b}_y\,\frac{W_{\gamma\gamma}}{2}\mathrm{d}W_{\gamma\gamma}\,\mathrm{d}Y_{X_1X_2}$$



AA→AAρ^0



$\gamma N \to \rho^0 N$

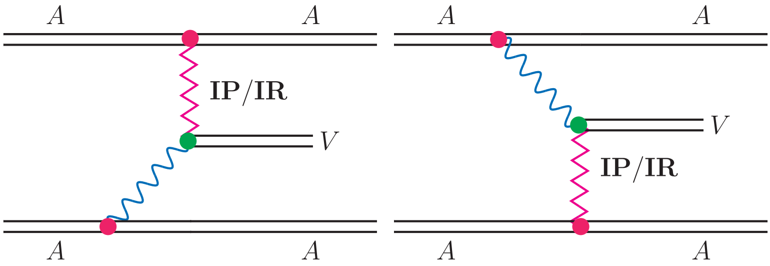


$N = n, p$

Parameters fixed to describe HERA data:

we expect: $\frac{d\sigma(\gamma n \to \rho^0 n)}{dt} \approx \frac{d\sigma(\gamma p \to \rho^0 n)}{dt}$

Single ρ^0 meson production



$$\frac{\mathrm{d}\sigma_{A_1A_2\to A_1A_2V}}{\mathrm{d}^2b\mathrm{d}y} = \frac{\mathrm{d}P_{\gamma \mathbb{P}}(b,y)}{\mathrm{d}y} + \frac{\mathrm{d}P_{\mathbb{P}\gamma}(b,y)}{\mathrm{d}y}$$

$$P_{1/2}(b,y) = \omega_{1/2}\tilde{N}(\omega_{1/2},b)\,\sigma_{\gamma A_{2/1}\to VA_{2/1}}(W_{\gamma A_{2/1}})$$

$$\sigma_{\gamma A\to\rho^0 A} = \frac{d\sigma_{\gamma A\to\rho^0 A}(t=0)}{dt}\int_{-\infty}^{t_{max}}\mathrm{d}t\left|F_A(t)\right|^2$$

$F_A(t)$ - nucleus form factor

A semi-classical model for $\gamma A \to \rho^0 A$ reaction

$$\sigma_{\gamma A \to \rho^0 A} = \frac{d\sigma_{\gamma A \to \rho^0 A}(t=0)}{dt} \int_{-\infty}^{t_{max}} \mathrm{d}t \left|F_A(t)\right|^2$$

$$\frac{d\sigma_{\gamma A \to \rho^0 A}(t=0)}{dt} = \frac{\alpha_{em}\sigma_{tot}^2(\rho^0 A)}{4 f_{\rho^0}^2}$$

- quasi-Glauber (classical Glauber):
  $$\sigma_{tot}(\rho^0 A) = \int \mathrm{d}^2\mathbf{r} \left(1 - \exp\left(-\sigma_{tot}(\rho^0 p)\, T_A(\mathbf{r})\right)\right)$$
- quantum mechanical Glauber:
  $$\sigma_{tot}^{qm}(\rho^0 A) = 2\int \mathrm{d}^2\mathbf{r} \left(1 - \exp\left(-\frac{1}{2}\sigma_{tot}(\rho^0 p)\, T_A(\mathbf{r})\right)\right)$$

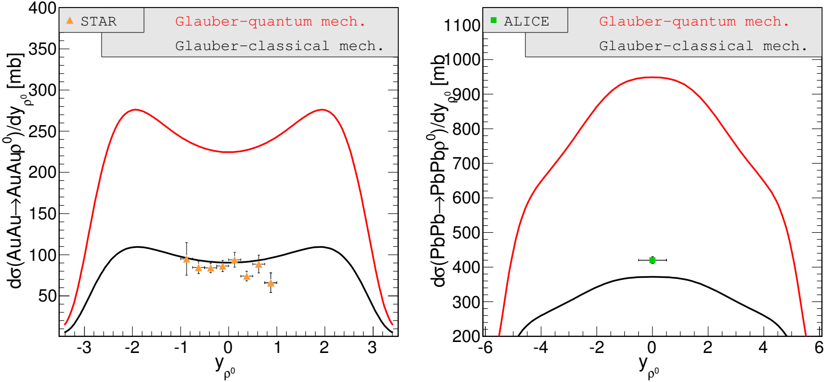
nucleus thickness: $T_A(\mathbf{r}) = \int \mathrm{d}z \rho_A\left(\sqrt{|\mathbf{r}|^2 + z^2}\right)$

$$\sigma_{tot}^2(\rho^0 p) = 16\pi \frac{\mathrm{d}\sigma_{\rho^0 p \to \rho^0 p}(t=0)}{\mathrm{d}t}$$

$$\frac{\mathrm{d}\sigma_{\rho^0 p \to \rho^0 p}(t=0)}{\mathrm{d}t} = \frac{f_{\rho^0}^2}{4\pi\alpha_{em}} \frac{\mathrm{d}\sigma_{\gamma p \to \rho^0 p}(t=0)}{\mathrm{d}t} \quad \text{(VDM)}$$

$$\frac{\mathrm{d}\sigma_{\gamma p \to \rho^0 p}(t=0)}{\mathrm{d}t} = B_{\rho^0}\left(XW^{\epsilon} + YW^{-\eta}\right) \quad \leftarrow \text{HERA data}$$

AA→AAρ^0 vs Glauber model



Smearing of ρ^0 mass

$$\frac{\mathrm{d}\sigma_{AA\to AA\rho_0}}{\mathrm{d}m\,\mathrm{d}y} = f(m)\frac{\mathrm{d}\sigma_{AA\to AA\rho_0}(y,m)}{\mathrm{d}y}$$

$$f(m) = \frac{|\mathcal{A}(m)|^2 N_{orm}}{\int |\mathcal{A}(m)|^2 N_{orm}\mathrm{d}m}$$

$$\int N_{orm}\,|\mathcal{A}(m)|^2\,\mathrm{d}m = 1$$

$$\mathcal{A}(m) = \mathcal{A}_{\mathcal{BW}}\frac{\sqrt{m m_{\rho^0}\Gamma_{\rho^0}(m)}}{m^2 - m_{\rho^0}^2 + i m_{\rho^0}\Gamma_{\rho^0}(m)} + \mathcal{B}_{\pi\pi}$$

running width: $\Gamma_{\rho^0}(m) = \Gamma_{\rho^0}\frac{m_{\rho^0}}{m}\left(\frac{m^2 - 4m_\pi^2}{m_{\rho^0}^2 - 4m_\pi^2}\right)^{3/2}$

Smearing of ρ^0 mass

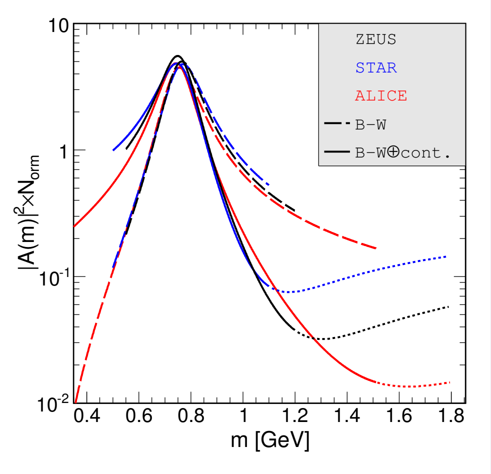
$$\mathcal{A}(m) = \mathcal{A}_{\mathcal{BW}} \frac{\sqrt{m m_{\rho^0} \Gamma_{\rho^0}(m)}}{m^2 - m_{\rho^0}^2 + i m_{\rho^0} \Gamma_{\rho^0}(m)} + \mathcal{B}_{\pi\pi}$$

$$\Gamma_{\rho^0}(m) = \Gamma_{\rho^0} \frac{m_{\rho^0}}{m} \left(\frac{m^2 - 4m_\pi^2}{m_{\rho^0}^2 - 4m_\pi^2} \right)^{3/2}$$

Parameter	ZEUS	STAR	ALICE
m_{ρ^0} [GeV]	0.77 ± 0.002	0.775 ± 0.003	0.761 ± 0.0023
Γ_{ρ^0} [GeV]	0.146 ± 0.003	0.162 ± 0.007	0.1502 ± 5.5
$\left\lvert \frac{\mathcal{B}_{\pi\pi}}{\mathcal{A}_{\mathcal{BW}}} \right\rvert$ [$\mathrm{GeV}^{-1/2}$]	0.669	0.89 ± 0.08	0.5 ± 0.04
m [GeV]	$(0.55 - 1.2)$	$(0.5 - 1.1)$	$(0.28 - 1.512)$

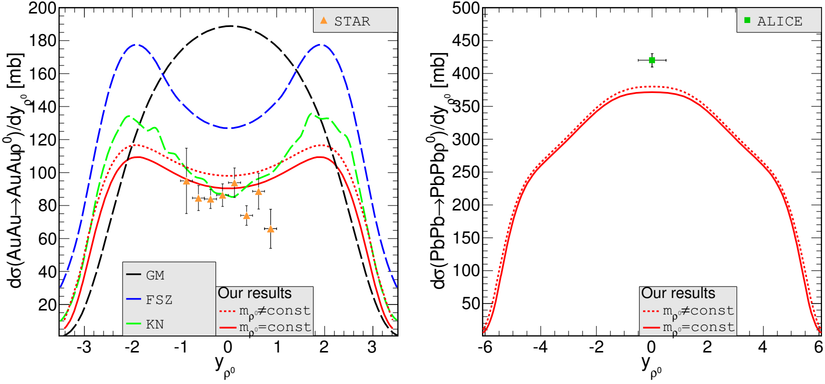
Smearing of ρ^0 mass

$$\mathcal{A}(m) = \mathcal{A}_{\mathcal{BW}} \frac{\sqrt{m m_{\rho^0} \Gamma_{\rho^0}(m)}}{m^2 - m_{\rho^0}^2 + i m_{\rho^0} \Gamma_{\rho^0}(m)} + \mathcal{B}_{\pi\pi}$$



Paramet	ALICE
m_{ρ^0} [Ge	0.761 ± 0.0023
Γ_{ρ^0} [Ge\	0.1502 ± 5.5
$\left\lvert \frac{\mathcal{B}_{\pi\pi}}{\mathcal{A}_{\mathcal{BW}}} \right\rvert$ [	0.5 ± 0.04
m [GeV]	$(0.28 - 1.512)$

Single ρ^0 meson production

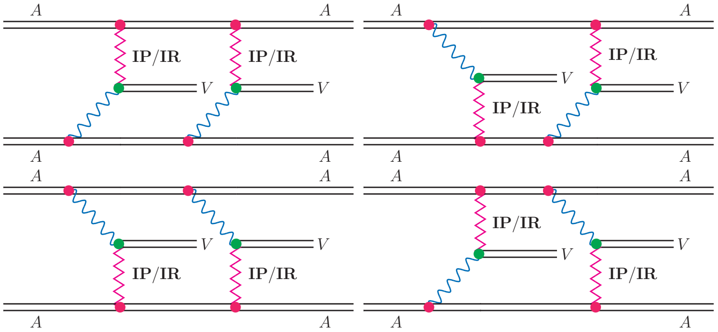


Single ρ^0 meson production

GM	FSZ	KN	Our result $m_{\rho^0} = const$	Our result $m_{\rho^0} \neq const$	Experimental data
$\sqrt{s_{NN}} = 130$ GeV; full $\lvert y_{\rho^0}\rvert$					STAR
	490		359	407	$370 \pm 170 \pm 80$
$\sqrt{s_{NN}} = 130$ GeV; $\lvert y_{\rho^0}\rvert < 1$					STAR
	140		130	143	$106 \pm 5 \pm 14$
$\sqrt{s_{NN}} = 200$ GeV; full $\lvert y_{\rho^0}\rvert$					STAR
876	934	590	590	646	$391 \pm 18 \pm 55$
$\sqrt{s_{NN}} = 2.76$ TeV; full $\lvert y_{\rho^0}\rvert$					ALICE
			3309	3405	$4300 \pm 100^{+600}_{-500}$
$\sqrt{s_{NN}} = 2.76$ TeV; $\lvert y_{\rho^0}\rvert < 0.5$					ALICE
			371	380	$420 \pm 10^{+39}_{-55}$

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

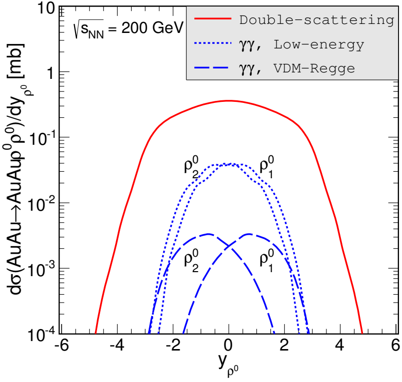
Double-scattering mechanism

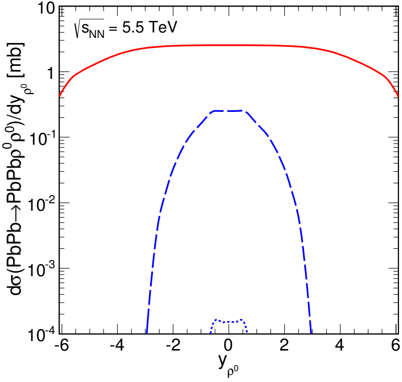


$$\frac{d\sigma_{A_1A_2\to A_1A_2\rho^0\rho^0}}{dy_1 dy_2} = \frac{1}{2}\int\left(\frac{dP_{\gamma\mathbb{P}}(b,y_1)}{dy_1} + \frac{dP_{\mathbb{P}\gamma}(b,y_1)}{dy_1}\right) \times \left(\frac{dP_{\gamma\mathbb{P}}(b,y_2)}{dy_2} + \frac{dP_{\mathbb{P}\gamma}(b,y_2)}{dy_2}\right) d^2b$$

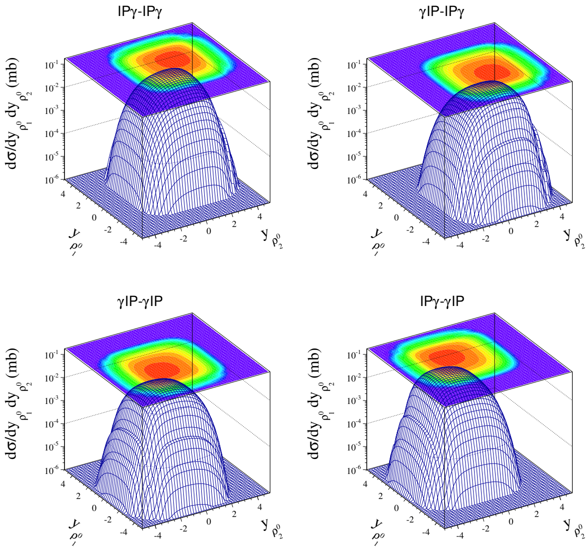
(ρ^0's have negligibly small transverse momenta)

Double-scattering mechanism vs $\gamma\gamma$ fusion

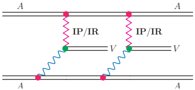




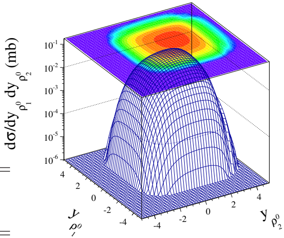
Double-scattering mechanism



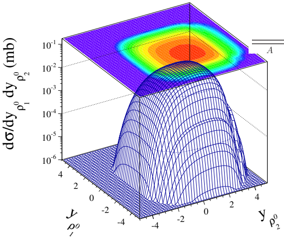
Double-scattering mechanism

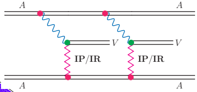


IPγ-IPγ

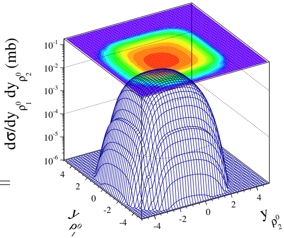


γIP-IPγ

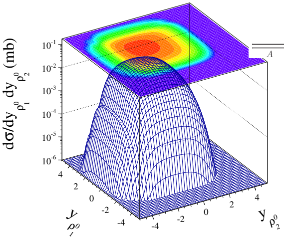


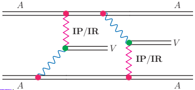


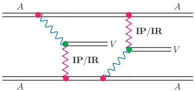
γIP-γIP



IPγ-γIP

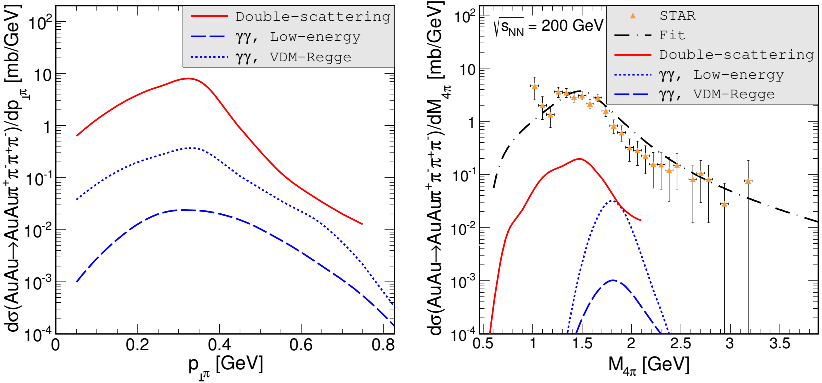






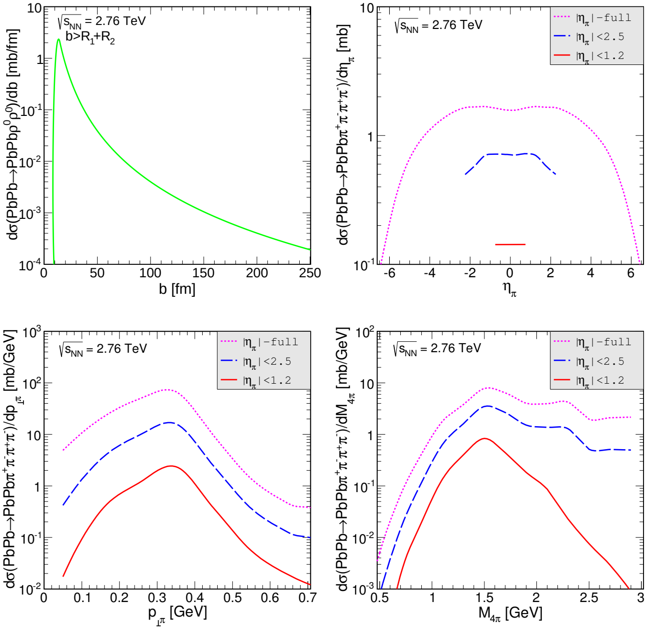
Double-scattering mechanism

$|\eta_\pi| < 1$



missing mechanisms: $AA \to AA\rho^0(1450) \to 4\pi$
$AA \to AA\rho^0(1700) \to 4\pi$?

Double-scattering mechanism at LHC

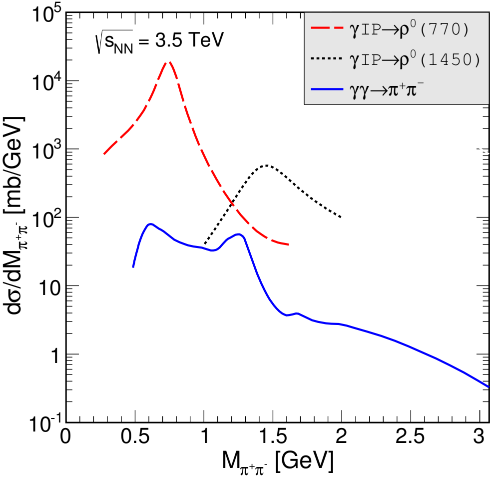


Comparison of the mechanisms

Energy	mechanism	σ_{tot} [mb]
RHIC ($\sqrt{s_{NN}} = 200$ GeV)	double-scattering	1.6
$-\|\|-$	$\rho^0\rho^0$ in $\gamma\gamma$ fusion	0.1
$-\|\|-$	$\pi^+\pi^-\pi^+\pi^-$ in $\gamma\gamma$ fusion	0.1

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

Two-pion production



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

Theoretical conclusions

- Impact parameter space approach
- Smearing of ρ^0 meson
- Good description of STAR and ALICE data for single-$\rho^0(770)$ production
- Comparison of four-pion production via $\rho^0\rho^0$ production
  - $\gamma\gamma$ fusion
  - nuclear double-photoproduction (very large)

  with STAR data
- Missing contributions (?)
  - $\rho^0(1450)$
  - $\rho^0(1700)$
- Multiple Coulomb excitations associated with $\rho^0\rho^0$ production may cause additional excitation of one or both nuclei to the giant resonance region (can be calculated)

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

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Thank You