PHOTON 2015

DOUBLE SCATTERING PRODUCTION OF TWO ρ^0 MESONS AND FOUR PIONS IN ULTRAPERIPHERAL HEAVY ION COLLISIONS

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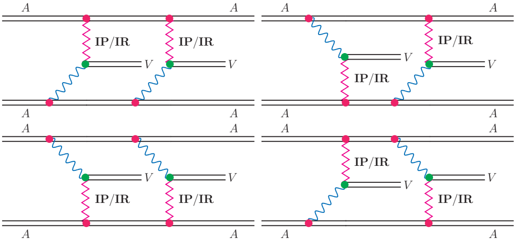
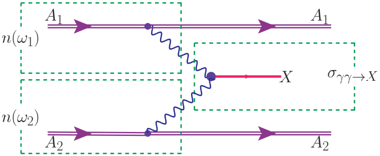
MAIN GOAL - ρ^0 MESONS PRODUCTION

- Double-scattering mechanism



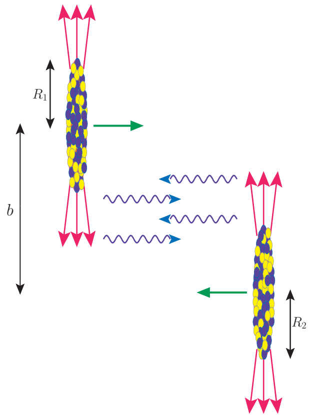
- $\gamma\gamma$ fusion



$\Rightarrow$ two-component of the $\sigma_{elementary}\left(\gamma\gamma \to \rho^0\rho^0\right)$

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

EQUIVALENT PHOTON APPROXIMATION

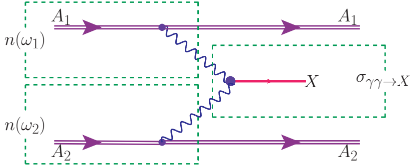


The strong electromagnetic field is a source of photons that can induce electromagnetic reactions in ion-ion collisions.

ULTRAPERIHERAL COLLISIONS

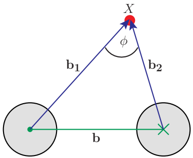
$$b > R_{min} = R_1 + R_2$$

NUCLEAR CROSS SECTION

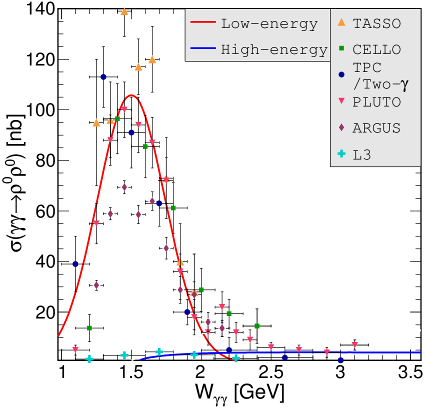


$$n(\omega) = \int_{R_{min}}^{\infty} 2\pi b \mathrm{d}b \, N(\omega, b) \qquad (1)$$

$$\begin{aligned}\sigma_{A_1 A_2 \to A_1 A_2 X} &= \int \mathrm{d}\omega_1 \, \mathrm{d}\omega_2 \, n(\omega_1) n(\omega_2) \sigma_{\gamma\gamma\to X}(\omega_1, \omega_2) \\ &= \dots \\ &= \int N(\omega_1, \mathbf{b_1}) \, N(\omega_2, \mathbf{b_2}) S^2_{abs}(\mathbf{b}) \\ &\times \sigma_{\gamma\gamma\to X}\left(\sqrt{s_{A_1 A_2}}\right) \\ &\times 2\pi b \mathrm{d}b \, \mathrm{d}\bar{b}_x \, \mathrm{d}\bar{b}_y \, \frac{W_{\gamma\gamma}}{2} \mathrm{d}W_{\gamma\gamma} \, \mathrm{d}Y_X \qquad (2)\end{aligned}$$



ELEMENTARY CROSS SECTION



Reference:

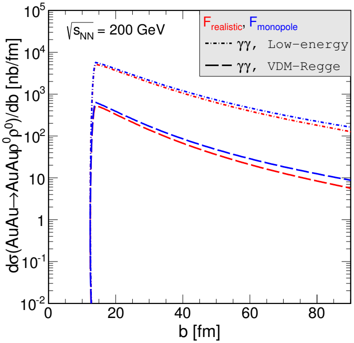
M. Kłusek, W. Schäfer and A. Szczurek, Phys.Lett. **B674** (2009) 92
"Exclusive production of $\rho^0\rho^0$ pairs in $\gamma\gamma$ collisions at RHIC"

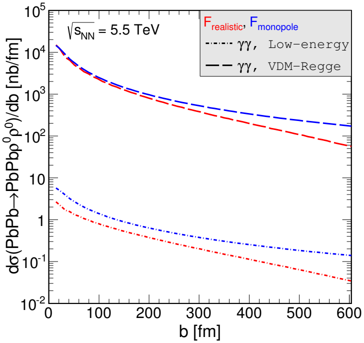
+ back-up slide

$AA \to AA\rho^0\rho^0$ - FORM FACTOR

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

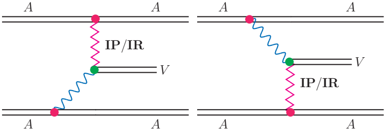
- realistic
- monopole



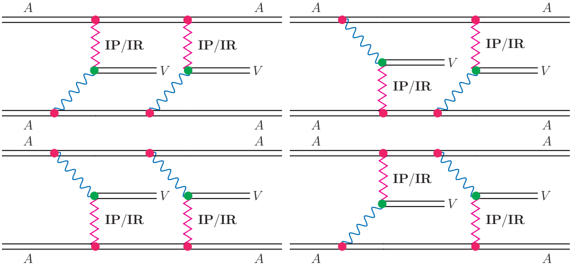


PHOTOPRODUCTION OF ρ^0 MESONS

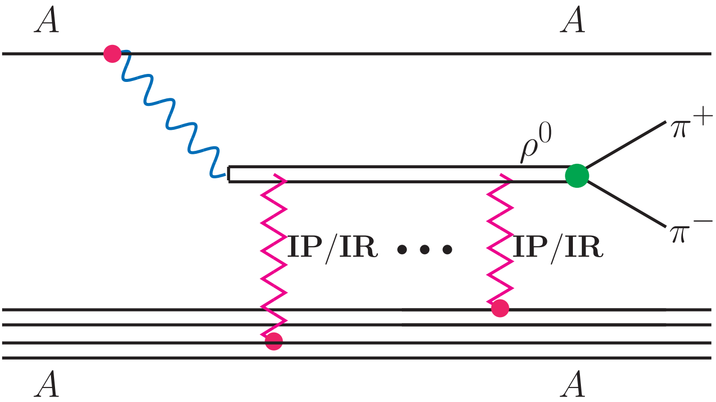
- Single ρ^0 meson production



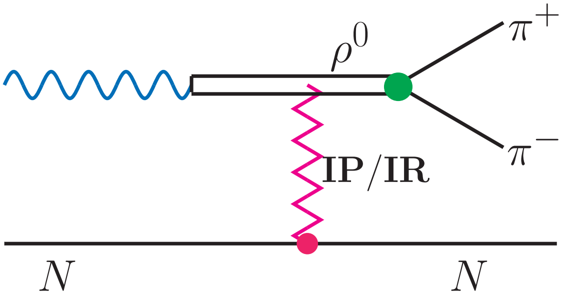
- Double-scattering mechanism



$AA \to AA\rho^0$



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

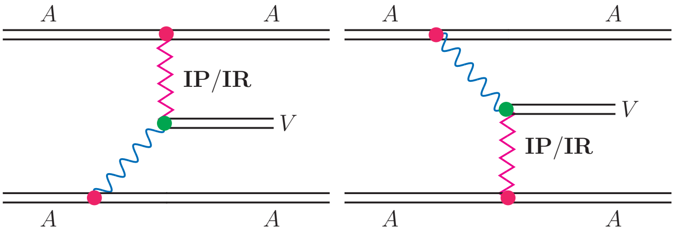


$N = n, p$

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



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

$$P_{1/2}(b,y) = \omega_{1/2}\tilde{N}(\omega_{1/2},b)\,\sigma_{\gamma A_{2/1} \to V A_{2/1}}(W_{\gamma A_{2/1}}) \qquad (4)$$

$$\sigma_{\gamma A \to \rho^0 A} = \frac{d\sigma_{\gamma A \to \rho^0 A}(t=0)}{dt} \int_{-\infty}^{t_{max}} \mathrm{d}t \, |F_A(t)|^2 \qquad (5)$$

SMEARING OF ρ^0 MASS

$$\frac{d\sigma_{AA\to AA\rho_0}}{dm\,dy} = f(m)\frac{d\sigma_{AA\to AA\rho_0}(y,m)}{dy} \qquad (6)$$

$$f(m) = \frac{|\mathcal{A}(m)|^2 N_{orm}}{\int |\mathcal{A}(m)|^2 N_{orm} dm} \qquad (7)$$

$$\int N_{orm}\,|\mathcal{A}(m)|^2\,dm = 1 \qquad (8)$$

=.

Drell-Söding contribution:

$$\mathcal{A}(m) = \mathcal{A}_{\mathcal{BW}}\frac{\sqrt{m m_{\rho^0}\Gamma_{\rho^0}(m)}}{m^2 - m_{\rho^0}^2 + i m_{\rho^0}\Gamma_{\rho^0}(m)} + \mathcal{B}_{\pi\pi} \qquad (9)$$

running width: $\Gamma_{\rho^0}(m) = \Gamma_{\rho^0}\frac{m_{\rho^0}}{m}\left(\frac{m^2 - 4m_\pi^2}{m_{\rho^0}^2 - 4m_\pi^2}\right)^{3/2} \qquad (10)$

Smearing of ρ^0 mass

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

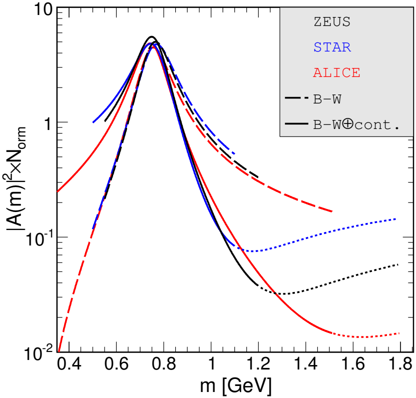
$$\Gamma_{\rho^0}(m) = \Gamma_{\rho^0} \frac{m_{\rho^0}}{m} \left(\frac{m^2 - 4m_\pi^2}{m_{\rho^0}^2 - 4m_\pi^2} \right)^{3/2}$$

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
$\left\lvert \frac{\mathcal{B}_{\pi\pi}}{\mathcal{A}_{\mathcal{BW}}} \right\rvert$ [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

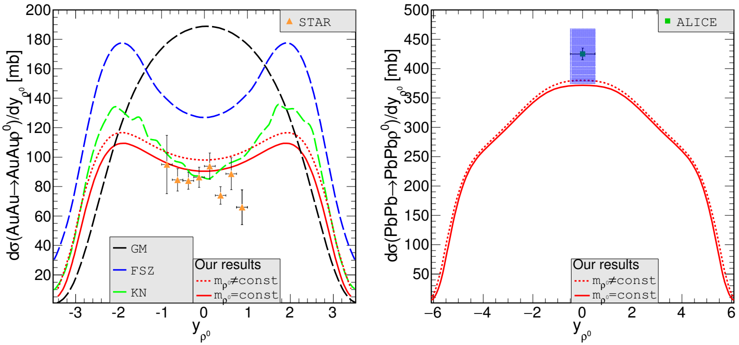
$\mathcal{A}$ … $+ \mathcal{B}_{\pi\pi}$

3/2



Paramete…			ALICE
m_{ρ^0} [GeV…		…3	0.761 ± 0.0023
Γ_{ρ^0} [GeV…		…7	0.1502 ± 5.5
$\left\|\frac{\mathcal{B}_{\pi\pi}}{\mathcal{A}_{\mathcal{BW}}}\right\|$ [G…			0.5 ± 0.04
m [GeV]	$(0.55 - 1.2)$	$(0.5 - 1.1)$	$(0.28 - 1.512)$

SINGLE ρ^0 MESON PRODUCTION

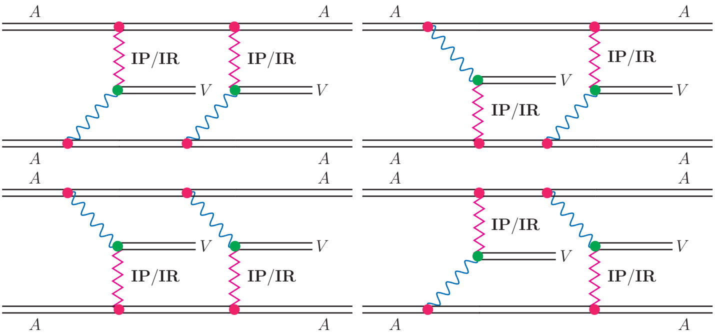


SINGLE ρ^0 MESON PRODUCTION

GM	FSZ	KN	Our result $m_{\rho^0} = \text{const}$	Our result $m_{\rho^0} \neq \text{const}$	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	$4200 \pm 100^{+500}_{-600}$
$\sqrt{s_{NN}} = 2.76$ TeV; $\lvert y_{\rho^0}\rvert < 0.5$					ALICE
			371	380	$425 \pm 10^{+42}_{-50}$

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

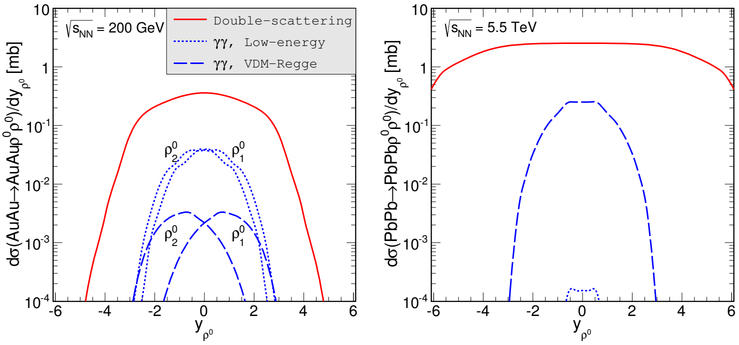
DOUBLE-SCATTERING MECHANISM



$$\frac{d\sigma_{A_1 A_2 \to A_1 A_2 \rho^0 \rho^0}}{dy_1 dy_2} = \frac{1}{2} \int \left(\frac{dP_{\gamma \mathbf{P}}(b, y_1)}{dy_1} + \frac{dP_{\mathbf{P}\gamma}(b, y_1)}{dy_1} \right) \times \left(\frac{dP_{\gamma \mathbf{P}}(b, y_2)}{dy_2} + \frac{dP_{\mathbf{P}\gamma}(b, y_2)}{dy_2} \right) d^2 b$$

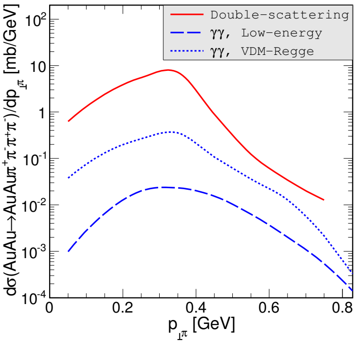
(ρ^0's have negligibly small transverse momenta)

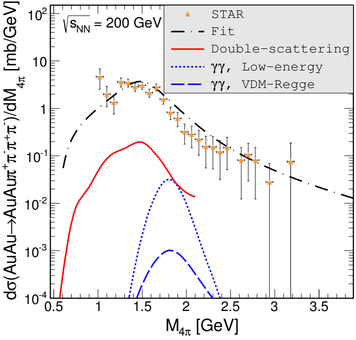
DOUBLE-SCATTERING MECHANISM VS $\gamma\gamma$ FUSION



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

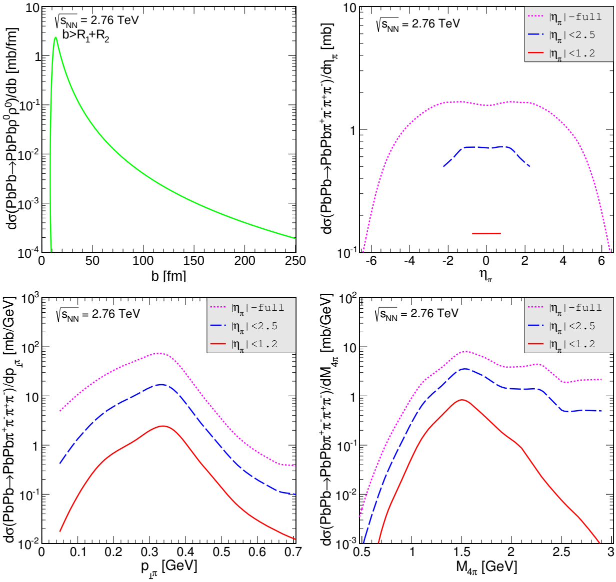
$|\eta_\pi| < 1$





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

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

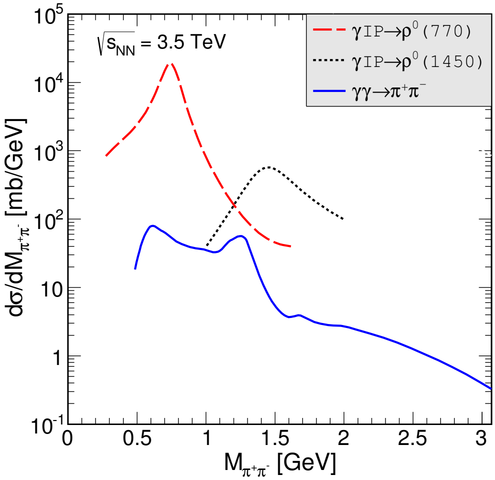


Comparison of the mechanisms

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, Phys. Rev. **C89** (2014) 024912 ”Double-scattering mechanism in the exclusive $AA \to AA\rho^0\rho^0$ reaction in ultrarelativistic collisions”,

TWO-PION PRODUCTION



Reference:
M. Kłusek-Gawenda 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",

CONCLUSION

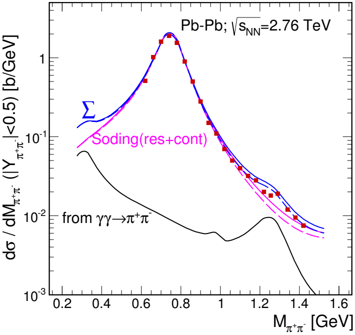
- Impact parameter space approach
- Smearing of ρ^0 meson
- Good description of STAR and ALICE data for single-$\rho^0(770)$ production

Drell-Söding+$f_2(1270)$

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

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

ALICE data arXiv:1503.09177



CONCLUSIONS

- 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)

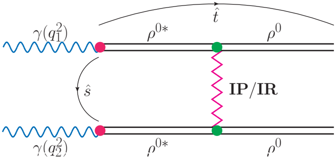
  Reference:
  M. Kłusek-Gawenda, M. Ciemała, W. Schäfer and A. Szczurek, Phys. Rev. **C89** (2014) 054907,
  "Electromagnetic excitation of nuclei and neutron evaporation in ultrarelativistic ultraperipheral heavy ion collisions"

More details: PhD thesis `http://www.ifj.edu.pl/msd/rozprawy_dr/rozpr_Klusek.pdf`

Back-up slides

Elementary cross section $\gamma\gamma \to \rho^0\rho^0$

$$\sigma^{\text{high-energy}}_{\gamma\gamma\to\rho^0\rho^0} = \int_{\hat{t}_{min}(\hat{s})}^{\hat{t}_{max}(\hat{s})} \frac{d\sigma^{\text{high-energy}}_{\gamma\gamma\to\rho^0\rho^0}}{d\hat{t}} d\hat{t} \tag{11}$$



$$\frac{d\sigma^{\text{high-energy}}_{\gamma\gamma\to\rho^0\rho^0}}{d\hat{t}} = \frac{1}{16\pi\hat{s}} \left| \mathcal{M}_{\gamma\gamma\to\rho^0\rho^0}\left(\hat{s},\hat{t};q_1,q_2\right)\right|^2 \tag{12}$$

$$\mathcal{M}_{\gamma\gamma\to\rho^0\rho^0}\left(\hat{s},\hat{t};q_1,q_2\right) = C_{\gamma\to\rho^0} C_{\gamma\to\rho^0} \mathcal{M}_{\rho^{0*}\rho^{0*}\to\rho^0\rho^0}\left(\hat{s},\hat{t};q_1,q_2\right) \tag{13}$$

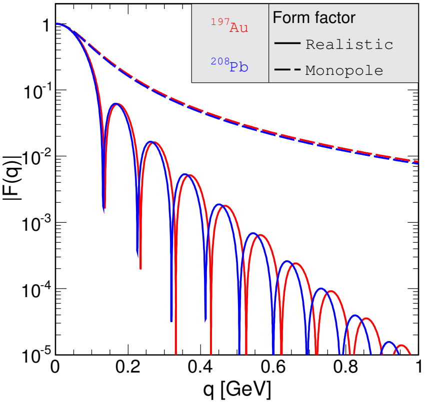
$$\mathcal{M}_{\rho^{0*}\rho^{0*}\to\rho^0\rho^0}\left(\hat{s},\hat{t};q_1,q_2\right) = \left(\eta_{\mathbf{P}}\left(\hat{s},\hat{t}\right) C_{\mathbf{P}} \left(\frac{\hat{s}}{s_0}\right)^{\alpha_{\mathbf{P}}\left(\hat{t}\right)-1} + \eta_{\mathbf{R}}\left(\hat{s},\hat{t}\right) C_{\mathbf{R}} \left(\frac{\hat{s}}{s_0}\right)^{\alpha_{\mathbf{R}}\left(\hat{t}\ri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

$$\times \hat{s}\, F\left(\hat{t};q_1^2\approx 0\right) F\left(\hat{t};q_2^2\approx 0\right) \tag{14}$$

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

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

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

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

- 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:

$$\sigma^{qm}_{tot}(\rho^0 A) = 2 \int \mathrm{d}^2\mathbf{r} \left(1 - \exp\left(-\frac{1}{2}\sigma_{tot}(\rho^0 p)\, T_A(\mathbf{r})\right)\right)$$

nucleus thickness:

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

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

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

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

AA→AAρ^0 vs Glauber model