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Production of two pions and two ρ^0 mesons in peripheral ultrarelativistic heavy-ion collisions

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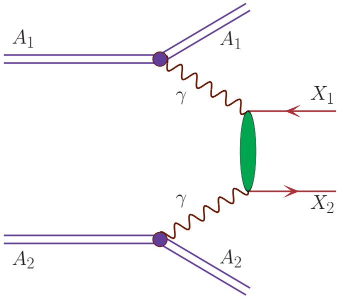
In collaboration with prof. A. Szczurek



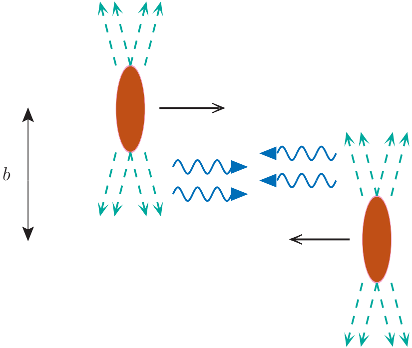
$PbPb \to PbPb\pi^0\pi^0$
$PbPb \to PbPb\pi^+\pi^-$
$PbPb \to PbPb\,(\rho^0\rho^0 \to 4\pi)$

1. Equivalent photon approximation
   - Form factor
2. $\gamma\gamma \to \pi\pi$
   - soft two-pion continuum
   - resonances
   - pion-pion rescattering
   - BL pQCD
   - hand-bag
3. $\rho^0\rho^0$ production
4. Nuclear cross section
5. Conclusions

Accelerator LHC:

- nuclei: Pb–Pb
- $\sqrt{s_{NN}} = 3.5$ TeV
- $\gamma_{cm} = 2\ 932$ GeV

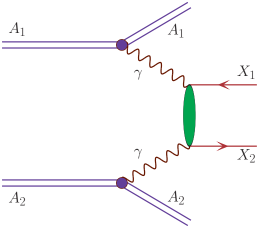
Equivalent photon approximation (EPA)



The strong electromagnetic field is used as a source of photons to induce electromagnetic reactions.

Peripheral collisions:

$b > R_1 + R_2 \cong 14$ fm



$$\sigma\left(PbPb \to PbPbX_1X_2; s_{NN}\right)$$
$$= \int \hat{\sigma}\left(\gamma\gamma \to X_1X_2; x_1x_2s_{NN}\right) \mathrm{d}n_{\gamma\gamma}\left(x_1, x_2, \mathbf{b}\right)$$

- $x_{1,2} = \frac{\omega_{1,2}}{\gamma M_A}$

$$\mathrm{d}n_{\gamma\gamma}\left(x_1, x_2, \mathbf{b}\right) = \int \frac{1}{\pi}\mathrm{d}^2\mathbf{b}_1 |\mathbf{E}\left(x_1, \mathbf{b}_1\right)|^2 \frac{1}{\pi}\mathrm{d}^2\mathbf{b}_2 |\mathbf{E}\left(x_2, \mathbf{b}_2\right)|^2$$
$$x \quad S^2_{abs}\left(\mathbf{b}\right)\delta^{(2)}(\mathbf{b} - \mathbf{b}_1 + \mathbf{b}_2)\frac{\mathrm{d}x_1}{x_1}\frac{\mathrm{d}x_2}{x_2}$$

- $\mathbf{E}\left(x, \mathbf{b}\right) = Z\sqrt{4\pi\alpha_{em}} \int \frac{\mathrm{d}^2\mathbf{q}}{(2\pi^2)} e^{-i\mathbf{bq}} \frac{\mathbf{q}}{\mathbf{q}^2 + x^2M_A^2} F_{em}\left(\mathbf{q}^2 + x^2M_A^2\right)$
- $S^2_{abs}\left(\mathbf{b}\right) \cong \theta\left(\mathbf{b} - 2R_A\right)$

- $\frac{1}{\pi}\int \mathrm{d}^2\mathbf{b}|\mathbf{E}\left(x, \mathbf{b}\right)|^2 = \int \mathrm{d}^2\mathbf{b} N\left(\omega, \mathbf{b}\right)$
- $\mathrm{d}\omega_1\mathrm{d}\omega_2 \to \mathrm{d}W_{\gamma\gamma}\mathrm{d}Y_{X_1X_2}$

The cross section in EPA

Nuclear cross section – EPA

$$\sigma\left(PbPb \to PbPbX_1X_2; s_{NN}\right) =$$
$$= \int \hat{\sigma}\left(\gamma\gamma \to \pi\pi; W_{\gamma\gamma}\right)\, \theta\left(|\mathbf{b}_1 - \mathbf{b}_2| - 2R_A\right)$$
$$x \quad N\left(\omega_1, \mathbf{b}_1\right) N\left(\omega_2, \mathbf{b}_1\right) 2\pi b_m \, \mathrm{d}b_m \, \mathrm{d}\overline{b}_x \, \mathrm{d}\overline{b}_y \frac{W_{\gamma\gamma}}{2} \mathrm{d}W_{\gamma\gamma} \mathrm{d}Y$$

The details of derivation:

A. Szczurek, M. K-G; Phys. Rev. **C82** (2010) 014904,
"Exclusive muon-pair productions in ultrarelativistic heavy-ion collisions: Realistic nucleus charge form factor and differential distributions"

Form factor

MONOPOLE F_{em}

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

REALISTIC F_{em}

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

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

- $^{197}Au \Rightarrow \sqrt{< r^2 >} = 5.3\ fm$, $\Lambda = 0.091\ GeV$,
- $^{208}Pb \Rightarrow \sqrt{< r^2 >} = 5.5\ fm$, $\Lambda = 0.088\ GeV$.

In the literature:

$\Lambda = (0.08 - 0.09)\ GeV$

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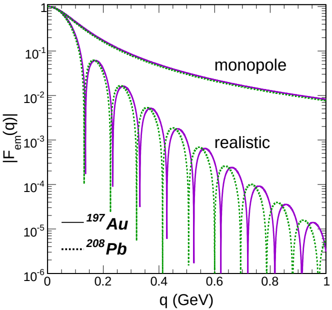
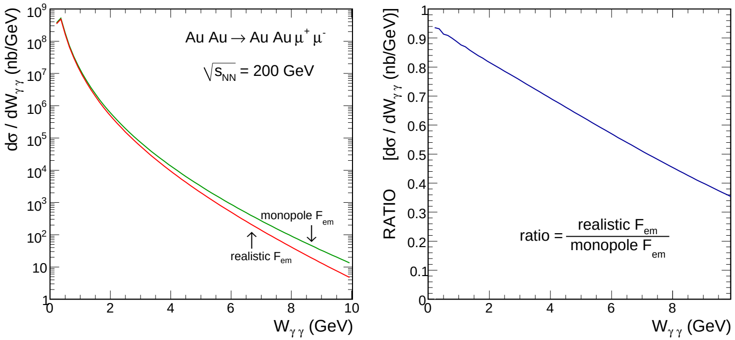
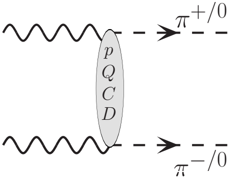


Realistic vs monopole form factor

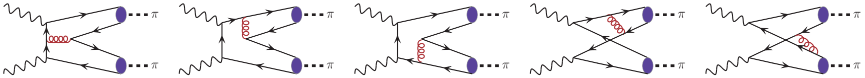


Perturbative QCD approach



A. Szczurek, M. K-G;
Phys. Lett. **B700** (2011) 322,
"Exclusive production of large invariant mass pion pairs in ultraperipheral ultrarelativistic heavy ion collisions"

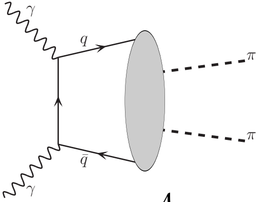
The $\gamma\gamma \to (q\bar{q})(q\bar{q}) \to \pi\pi$ amplitude in the LO pQCD:



$$\mathcal{M}(\lambda_1, \lambda_2) = \int_0^1 dx \int_0^1 dy\, \phi_\pi(x, \mu_x^2)\, T_H^{\lambda_1 \lambda_2}(x, y, \mu^2)\, \phi_\pi(y, \mu_y^2) \times F_{reg}^{pQCD}(t, u)$$

Elementary cross section for $\gamma\gamma \to \pi\pi$

Hand-bag model



M. Diehl, P. Kroll and C. Vogt, Phys. Lett. **B532** (2002) 99;

M. Diehl and P. Kroll, Phys. Lett. **B683** (2010) 165.

$$\mathcal{A}_{+-} = \mathcal{A}_{-+} = -4\pi\alpha_{em}\frac{s^2}{tu}R_{\pi\pi}(s)$$

$$R_{\pi\pi}(s) = \frac{5}{9s}a_u\left(\frac{s_0}{s}\right)^{n_u} + \frac{1}{9s}a_s\left(\frac{s_0}{s}\right)^{n_s}$$

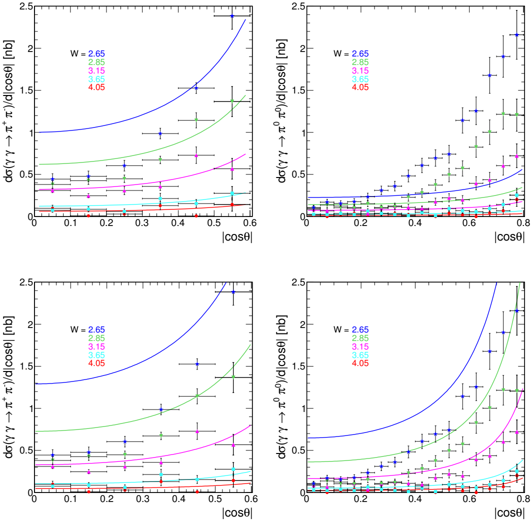
- $s_0 = 9\ \mathrm{GeV}^2$
- $a_u = 1.375\ \mathrm{GeV}^2$
- $n_u = 0.4175$
- $a_s = 0.5025\ \mathrm{GeV}^2$
- $n_s = 1.195$

$$\sigma\left(\gamma\gamma \to \pi^+\pi^-\right) = \frac{4\pi\alpha_{em}^2}{s}\left(\frac{\cos\theta_0}{\sin^2\theta_0} + \frac{1}{2}\ln\frac{1+\cos\theta_0}{1-\cos\theta_0}\right)|R_{\pi\pi}(s)|^2$$

Angular distributions for the $\gamma\gamma \to \pi\pi$

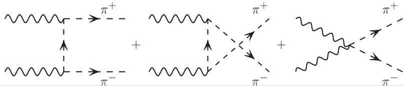
pQCD

hand-bag

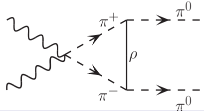


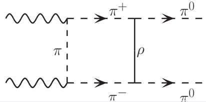
Other continuum processes

The $\gamma\gamma \to \pi^+\pi^-$ continuum - the Born term matrix elements



$\gamma\gamma \to \pi^0\pi^0$ in a simple coupled-channel model





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

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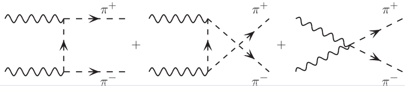
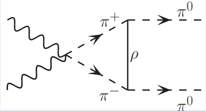
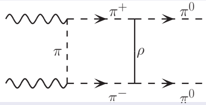


$\gamma\gamma \to \pi^0\pi^0$ in a simple coupled-channel model





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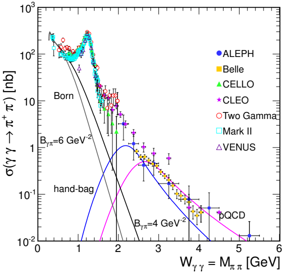
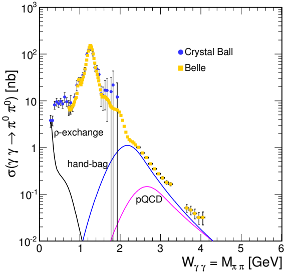
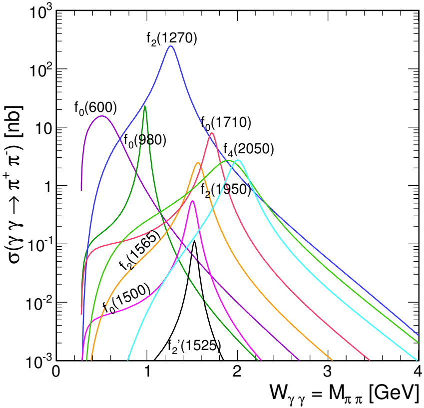
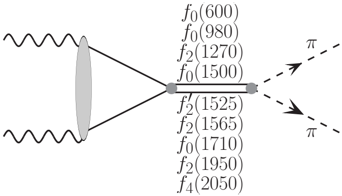




Elementary cross section for $\gamma\gamma \to \pi\pi$

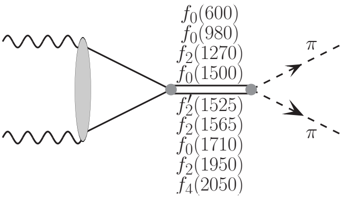
s-channel $\gamma\gamma \to$ resonances





$$\Gamma_R(W) = \Gamma_R \frac{\sqrt{\frac{W^2}{4} - m_\pi^2}}{\sqrt{\frac{m_R^2}{4} - m_\pi^2}} F^J(W,R)$$

$F^J(W,R)$ - Blatt-Weisskopf ff

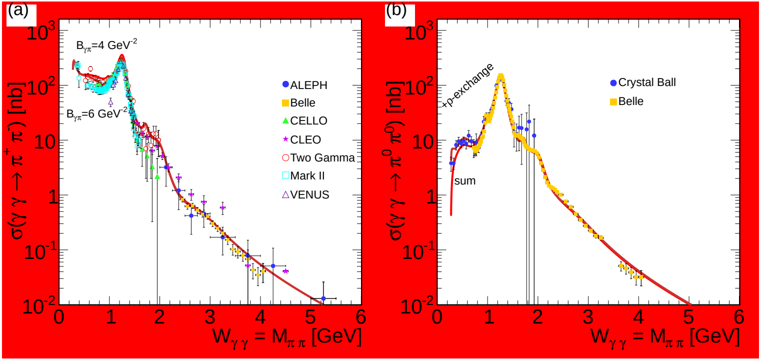


$$\mathcal{M}(\lambda_1,\lambda_2) = \frac{\sqrt{64\pi^2 W^2 \times 8\pi(2J+1)\left(\frac{m_R}{W}\right)^2 \Gamma_R \Gamma_R(W) Br(R\to\gamma\gamma) Br\left(R\to\pi^{+/0}\pi^{-/0}\right)}}{W^2 - m_R^2 + i m_R \Gamma_R(W)} e^{i\varphi_R}$$

$$\times\sqrt{2}\delta_{\lambda_1,\lambda_2} \left\{ \begin{array}{l} Y_0^0;\ \text{dla}\ f_0 \\ Y_2^2;\ \text{dla}\ f_2(1270), f_2'(1525), f_2(1950) \\ Y_2^0;\ \text{dla}\ f_2(1565) \\ Y_4^0;\ \text{dla}\ f_4(2050) \end{array} \right\}$$

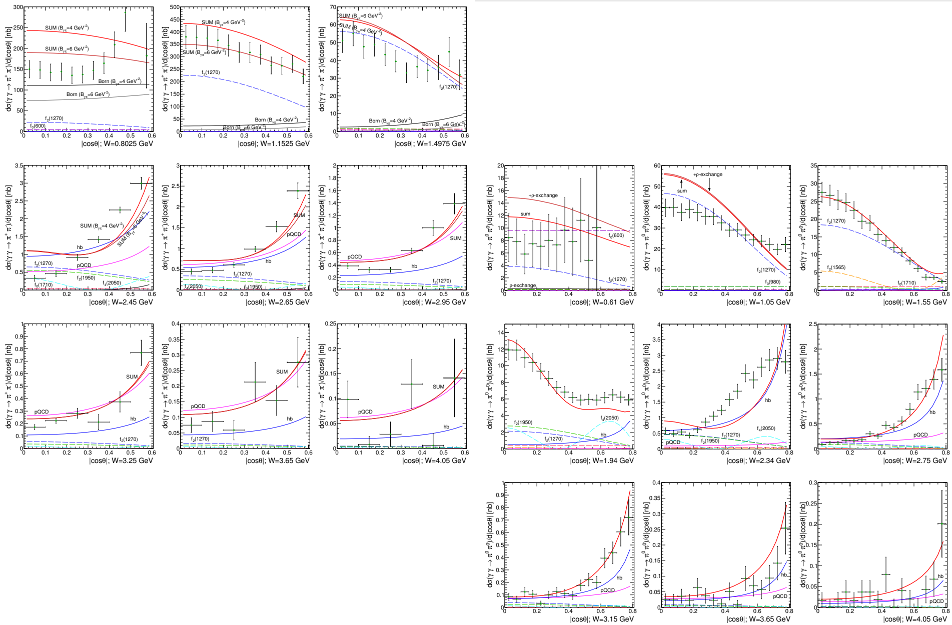
$$\times \exp\left(\frac{-(W-m_R)^2}{\Lambda_R^2}\right)$$

Total cross section for the $\gamma\gamma \to \pi\pi$

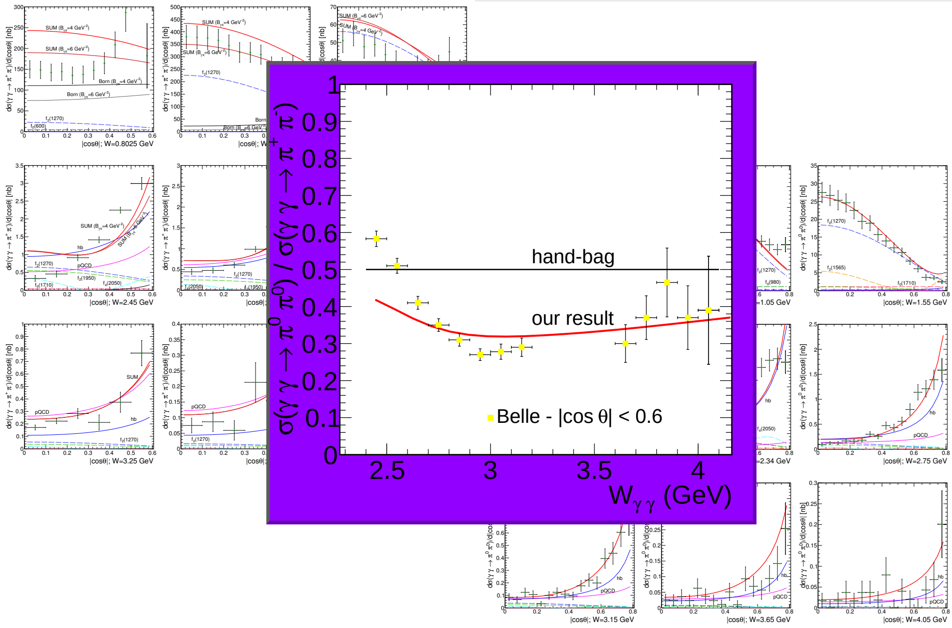


$|\cos\theta| < 0.6$ $\qquad$ $|\cos\theta| < 0.8$

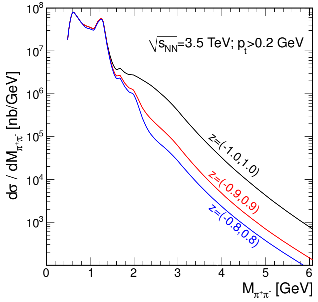
Angular distributions for the $\gamma\gamma \to \pi\pi$

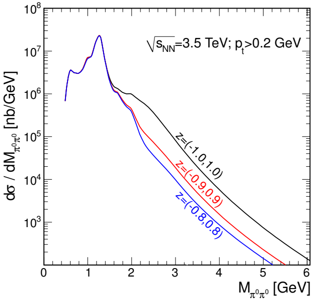


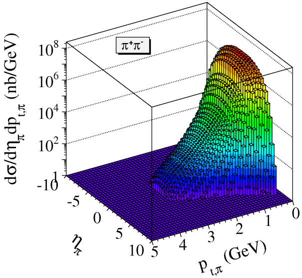
Angular distributions for the $\gamma\gamma \to \pi\pi$

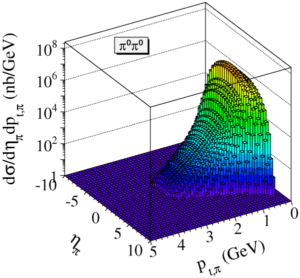


Pb Pb $\rightarrow$ Pb Pb $\pi\pi$; $\sqrt{s_{NN}} = 3.5$ TeV



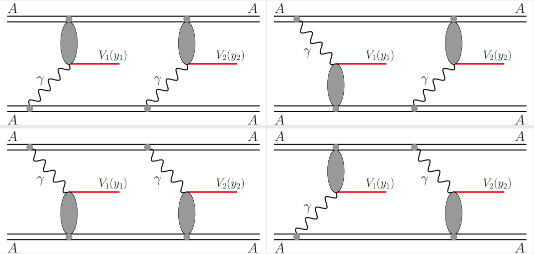






$\rho^0\rho^0$ production

Double scattering mechanism



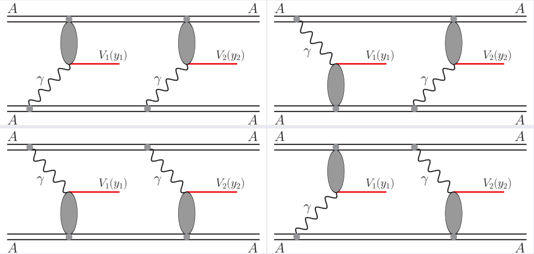
$$\sigma_{AA\to AAV_1V_2}(\sqrt{s_{NN}}) = C \int P_{V_1}(b,\sqrt{s_{NN}}) P_{V_2}(b,\sqrt{s_{NN}}) d^2b$$

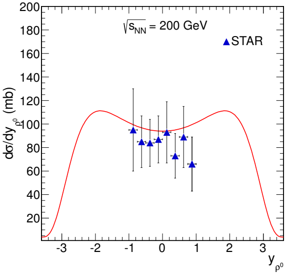
$C = 1$ or $1/2$ $(V_1 = V_2)$

$$P_V(b,\sqrt{s_{NN}}) = \frac{d\sigma_{AA\to AAV}(b;\sqrt{s_{NN}})}{2\pi b db}$$

$\rho^0\rho^0$ production

Double scattering mechanism





$$\sigma_{AA\to AAV_1V_2}(\sqrt{s_{NN}}) = C \int P_{V_1}(b,\sqrt{s_{NN}})\, P_{V_2}(b,\sqrt{s_{NN}})\, d^2b$$

Our result $\to$ 596 mb,

original model* $\to$ 590 mb.

$C = 1$ or $1/2$ $(V_1 = V_2)$

$$P_V(b,\sqrt{s_{NN}}) = \frac{d\sigma_{AA\to AAV}(b;\sqrt{s_{NN}})}{2\pi b db}$$

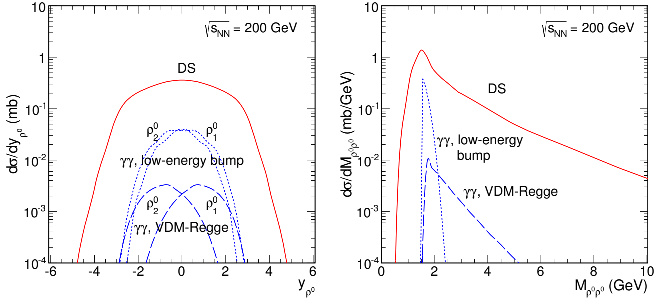
*S.R. Klein and J. Nystrand, Phys. Rev. **C60** (1999) 014903

$\rho^0\rho^0$ production

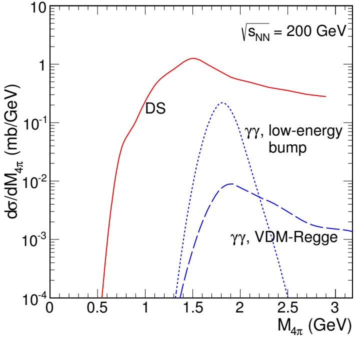
$$\frac{d\sigma_{AA\to AAV_1V_2}}{dy_1 dy_2} = C \int d^2b S_{el}^2(b)$$

$$\left(\frac{dP_1{}^{\gamma\boldsymbol{P}}(b, y_1; \sqrt{s_{NN}})}{dy_1} + \frac{dP_1{}^{\boldsymbol{P}\gamma}(b, y_1; \sqrt{s_{NN}})}{dy_1} \right)$$

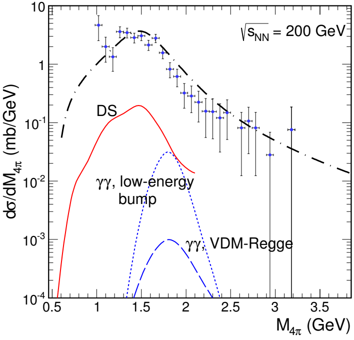
$$\left(\frac{dP_2{}^{\gamma\boldsymbol{P}}(b, y_2; \sqrt{s_{NN}})}{dy_2} + \frac{dP_2{}^{\boldsymbol{P}\gamma}(b, y_2; \sqrt{s_{NN}})}{dy_2} \right)$$



Au Au $\rightarrow$ Au Au $\pi^+\pi^-\pi^+\pi^-$

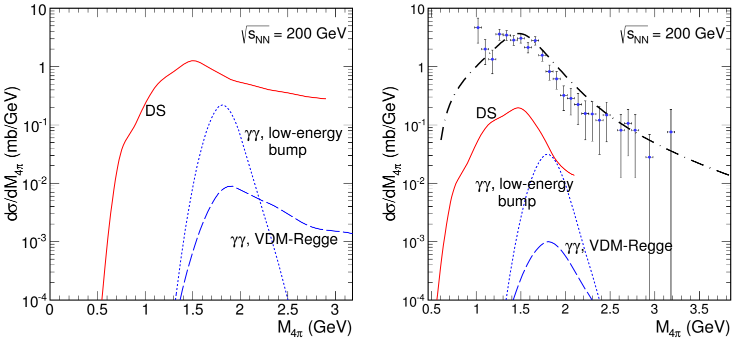


Full phase space



$|\eta_\pi| < 1$

Au Au $\rightarrow$ Au Au $\pi^+\pi^-\pi^+\pi^-$



Full phase space

$|\eta_\pi| < 1$

$\rho^0(1700) \rightarrow 4\pi$???

$\rho^0\rho^0$ production

Cross sections (in mb) for single ρ^0 production and double scattering and photon-photon mechanisms of $\rho^0\rho^0$ production for fixed and smeared mass of ρ^0 meson.

PAPER IN PREPARATION Energy	$m_{\rho^0} =$ $= 0.77549$ GeV	Mass smearing
RHIC ($\sqrt{s_{NN}} = 200$ GeV), ρ^0	596	
LHC ($\sqrt{s_{NN}} = 3.5$ TeV), ρ^0	4000	
LHC ($\sqrt{s_{NN}} = 5.5$ TeV), ρ^0	4795	
RHIC ($\sqrt{s_{NN}} = 200$ GeV), DS	1.5	1.55
LHC ($\sqrt{s_{NN}} = 3.5$ TeV), DS		15.25
RHIC, DS, $\lvert\eta_\pi\rvert < 1$		0.15
LHC, DS, $\lvert\eta_\pi\rvert < 1$		0.3
RHIC, $\gamma\gamma$, VDM-Regge	$7.5\ 10^{-3}$	
RHIC, $\gamma\gamma$, low-energy bump	$95\ 10^{-3}$	
RHIC, $\gamma\gamma$, VDM-Regge, $\lvert\eta_\pi\rvert < 1$	$0.5\ 10^{-3}$	
RHIC, $\gamma\gamma$, low-energy bump, $\lvert\eta_\pi\rvert < 1$	$14.6\ 10^{-3}$	

Conclusions

- We describe the word data for $\gamma\gamma \to \pi\pi$ for the first time both for the total cross section and for angular distributions for $\gamma\gamma \to \pi^+\pi^-$ and $\gamma\gamma \to \pi^0\pi^0$ reactions simultaneously at all experimentally available energies (from the kinematical threshold ($W=2m_\pi$) up to $W_{\gamma\gamma} \approx 6$ GeV). We show that different mechanisms contribute:
  1. several resonanses,
  2. soft continuum,
  3. pion-pion rescattering,
  4. pQCD mechanisms proposed by Brodsky and Lepage,
  5. the hand-bag mechanism proposed by Diehl, Kroll and Vogt.
- Cross section for different lower cuts on pion transverse momenta at the LHC energy.

$p_{t,min}$ (GeV)	$\pi^+\pi^-$ (mb)	$\pi^0\pi^0$ (mb)
0.2	46.7	8.7
0.5	12.1	5.1
1.0	0.08	0.05

- We calculate differential distributions for two ρ^0 mesons production in exclusive ultraperipheral, ultrarelativistic collisions via a double scattering mechanism.