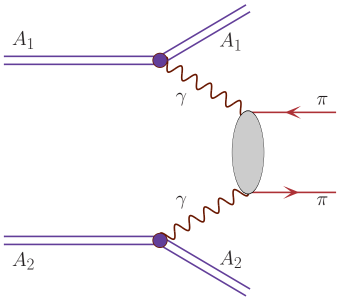
Institute of Nuclear Physics PAN, PL-31-342 Cracow, Poland

Exclusive production of $\pi^+\pi^-$ and $\pi^0\pi^0$ pairs in photon-photon and in ultrarelativistic heavy ion collisions

Mariola Kłusek–Gawenda

In collaboration with prof. A. Szczurek



Accelerator LHC:

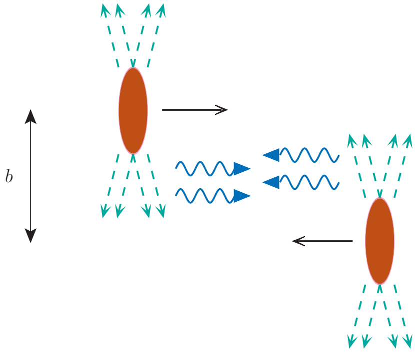
- nuclei: Pb–Pb
- $\sqrt{s_{NN}} = 3.5$ TeV
- $\gamma_{cm} = 2\ 932$ GeV

$PbPb \to PbPb\pi^0\pi^0$

$PbPb \to PbPb\pi^+\pi^-$

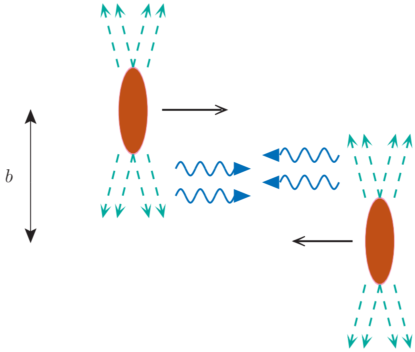
1. Equivalent photon approximation
   - Form factor
     - Realistic
     - Monopole
2. $\gamma\gamma \to \pi\pi$
   - dipion continuum
   - $\gamma\gamma \to$ resonances
   - pion-pion rescatterings
   - $\rho^{\pm}$ exchange
   - pQCD
3. Nuclear cross section
4. Conclusions

Equivalent photon approximation (EPA)



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

Equivalent photon approximation (EPA)



The strong
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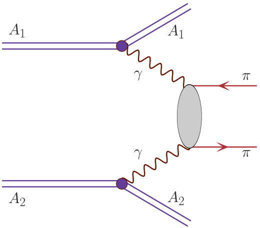
electromagnetic reactions.

Peripheral collisions:

$b > R_1 + R_2 \cong 14$ fm

The total cross section in EPA

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



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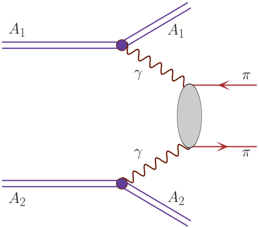

- $x_{1,2} = \frac{\omega_{1,2}}{\gamma M_A}$

Photons flux

$$\mathrm{d}n_{\gamma\gamma}(x_1, x_2, \mathbf{b}) = \int \frac{1}{\pi}\mathrm{d}^2\mathbf{b}_1 |\mathbf{E}(x_1, \mathbf{b}_1)|^2 \frac{1}{\pi}\mathrm{d}^2\mathbf{b}_2 |\mathbf{E}(x_2, \mathbf{b}_2)|^2$$

$$x \quad S^2_{abs}(\mathbf{b})\delta^{(2)}(\mathbf{b} - \mathbf{b}_1 + \mathbf{b}_2)\frac{\mathrm{d}x_1}{x_1}\frac{\mathrm{d}x_2}{x_2}$$

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

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

Form factor

MONOPOLE F_{em}

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

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

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

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In the literature:

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

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REALISTIC F_{em}

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

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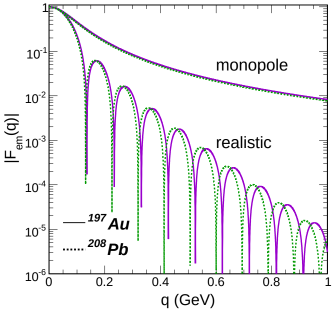


The cross section in EPA

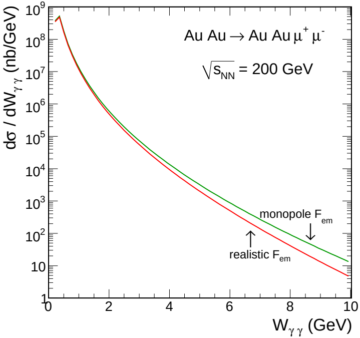
Nuclear cross section – EPA (impact parameter space)

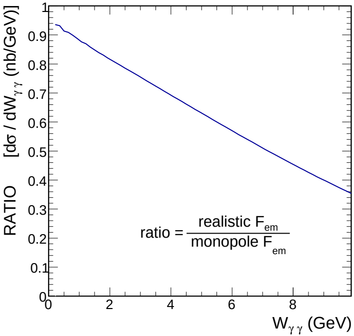
$$\sigma\left(PbPb \to \pi\pi PbPb; s_{NN}\right) =$$
$$= \int \hat{\sigma}\left(\gamma\gamma \to \pi\pi; W_{\gamma\gamma}\right) \theta\left(|\mathbf{b}_1 - \mathbf{b}_2| - 2R_A\right)$$
$$x \quad N\left(\omega_1, \mathbf{b}_1\right) N\left(\omega_2, \mathbf{b}_1\right) 2\pi b_m \, \mathrm{d}b_m \,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

The details of derivation:

Antoni 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”

Realistic vs monopole form factor





ELEMENTARY CROSS SECTION - $\gamma\gamma \to \pi\pi$

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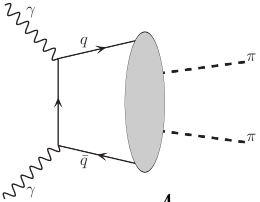
Hand-bag model



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

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

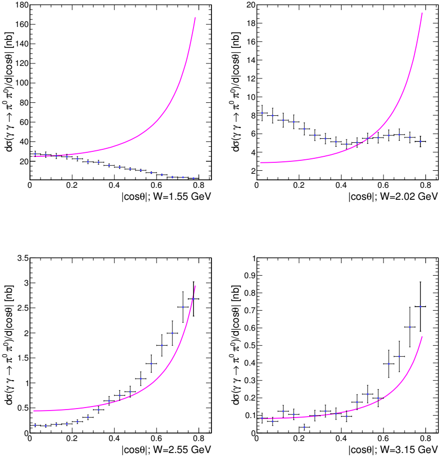
$$\mathcal{A}_{+-} = \mathcal{A}_{-+} = -4\pi\alpha_{em}\frac{s^2}{tu}R_{\pi\pi}(s)$$

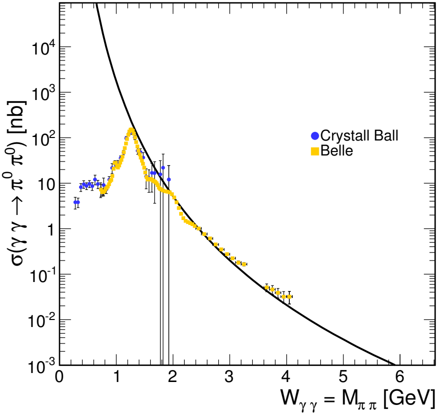
$$R_{\pi\pi}(s) = \frac{5}{9s}a_u\left(\frac{s_0}{s}\right)^{n_u} + \frac{1}{9s}a_s\left(\frac{s_0}{s}\right)^{n_s}$$

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

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

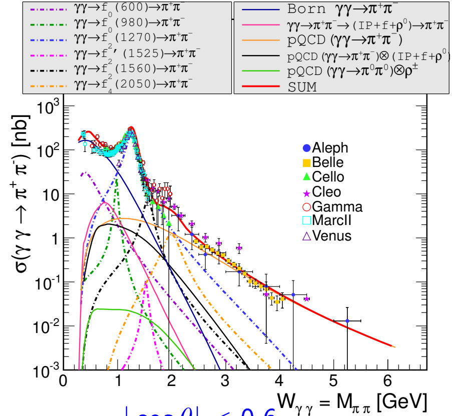
Hand-bag - PREDICTIONS



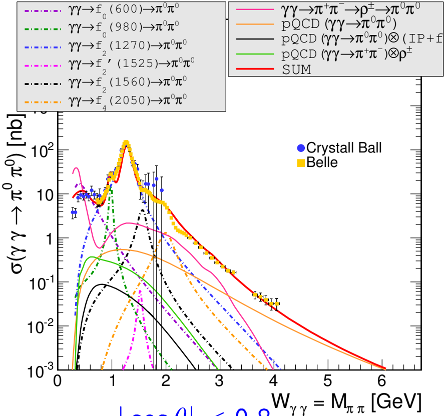


Elementary cross section for $\gamma\gamma \to \pi\pi$

Our description

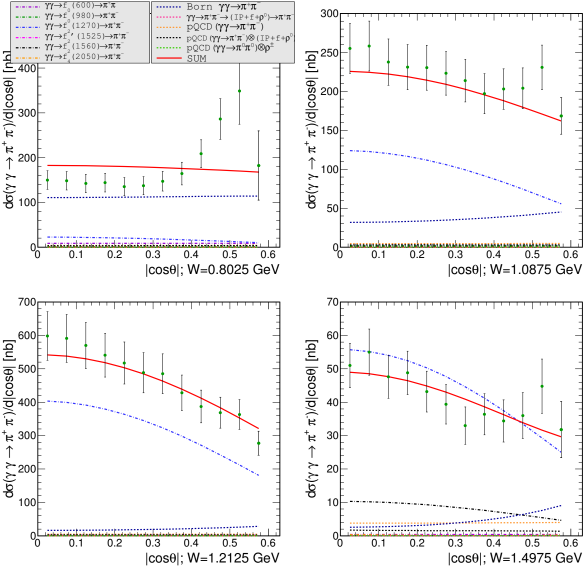


$|\cos\theta| < 0.6$

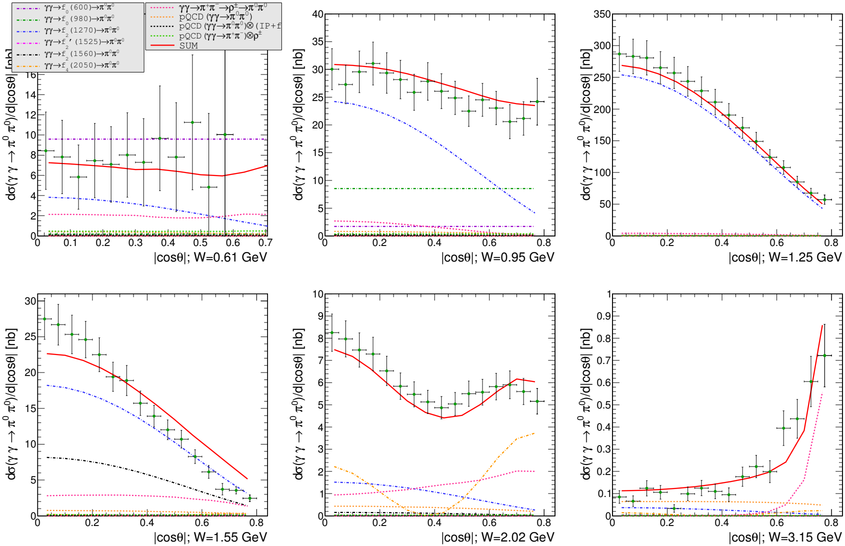


$|\cos\theta| < 0.8$

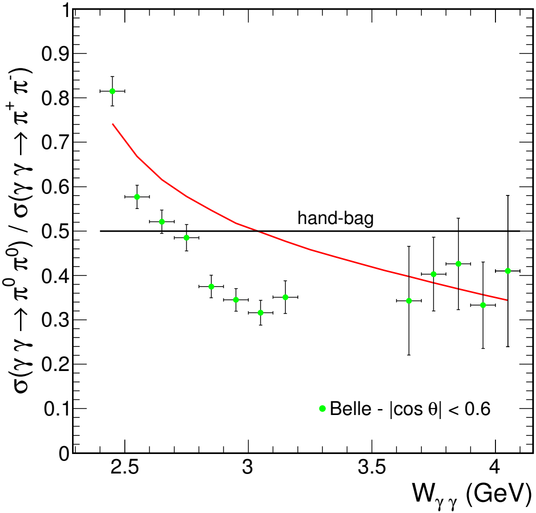
Angular Distribution - $\gamma\gamma \to \pi^+\pi^-$



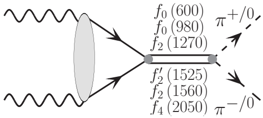
Angular Distribution - $\gamma\gamma \to \pi^+\pi^-$



our results vs hand-bag mechanism



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



$$\mathcal{M}(\lambda_1,\lambda_2) = \frac{\sqrt{64\pi^2 W^2 \times 8\pi(2J+1)\left(\frac{m_R}{W}\right)^2 \Gamma_R \,\Gamma_R(W)}}{W^2 - m_R^2 + i m_R \Gamma_R(W)}$$

$$\times \quad \sqrt{Br(R\to\gamma\gamma)\, Br\left(R\to\pi^{+/0}\pi^{-/0}\right)}\exp(i\varphi_R)\exp\left(\frac{-\left(W-m_R^2\right)^2}{\Lambda_R^2}\right)$$

$$\times \quad \sqrt{2}\delta_{\lambda_1,\lambda_2}\begin{cases} Y_0^0;\ \text{for } f_0(600), f_0(980) \\ Y_2^2;\ \text{for } f_2(1270), f_2'(1525), f_2(1560) \\ Y_4^2;\ \text{for } f_4(2050)\end{cases}$$

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

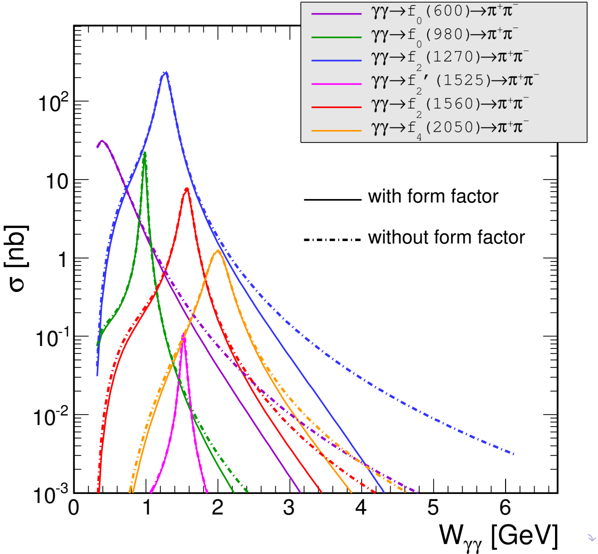
Form factor:

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

$\Lambda_R = 2.5$ GeV

- $\Gamma_{f_0(600)} = 0.8$ GeV
- $\Gamma_{f_0(980)} = 0.05$ GeV
- $\Gamma_{f_2(1270)} = 0.185$ GeV
- $\Gamma_{f_2'(1525)} = 0.073$ GeV
- $\Gamma_{f_2(1560)} = 0.16$ GeV
- $\Gamma_{f_4(2050)} = 0.3$ GeV

$\Gamma_R > 0.1$ GeV !



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

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

Blatt-Weisskopf form factors:

$$F^{J=0}(W,R) = 1,$$

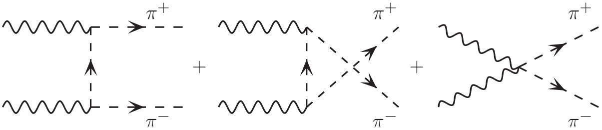
$$F^{J=2}(W,R) = \frac{(Rp_R)^4 + 3(Rp_R)^2 + 9}{(Rp)^4 + 3(Rp)^2 + 9},$$

$$F^{J=4}(W,R) =$$

$$= \frac{(Rp_R)^8 + 10(Rp_R)^6 + 135(Rp_R)^4 + 1575(Rp_R)^2 + 11025}{(Rp)^8 + 10(Rp)^6 + 135(Rp)^4 + 1575(Rp)^2 + 11025}$$

- R=5 GeV^{-1}

$\gamma\gamma \to \pi^+\pi^-$ continuum



$$\mathcal{M}^{\pi,c}_{\lambda_1\lambda_2}(q_1, q_2, p_{\pi^+}, p_{\pi^-}) = e^2 \sum 2g^{\mu,\nu}\varepsilon_\mu(\lambda_1)\varepsilon_\nu(\lambda_2)$$

$$\mathcal{M}^{\pi,t}_{\lambda_1\lambda_2}(q_1, q_2, p_{\pi^+}, p_{\pi^-}) =$$

$$= \quad e^2 \sum \left(2p^\mu_{\pi^-} - q^\mu_1\right)\varepsilon_\mu(q_1, \lambda_1)\left(2p^\nu_{\pi^+} - q^\nu_2\right)\varepsilon_\nu(q_2, \lambda_2)\frac{1}{t - m^2_\pi}$$

$$\mathcal{M}^{\pi,u}_{\lambda_1\lambda_2}(q_1, q_2, p_{\pi^+}, p_{\pi^-}) =$$

$$= \quad e^2 \sum \left(2p^\mu_{\pi^+} - q^\mu_1\right)\varepsilon_\mu(q_1, \lambda_1)\left(2p^\nu_{\pi^-} - q^\nu_2\right)\varepsilon_\nu(q_2, \lambda_2)\frac{1}{u - m^2_\pi}$$

$\gamma\gamma \to \pi^+\pi^-$ continuum

$$\mathcal{M}^{\pi}_{\lambda_1\lambda_2} = \left(\mathcal{M}^{\pi,c}_{\lambda_1\lambda_2} + \mathcal{M}^{\pi,t}_{\lambda_1\lambda_2} + \mathcal{M}^{\pi,u}_{\lambda_1\lambda_2}\right) \Omega\left(t,u,s\right)$$

$$\Omega\left(t,u,s\right) = \frac{F^2\left(t\right) + F^2\left(u\right)}{1 + F^2\left(-s\right)}$$

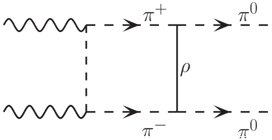
$$F(x) = exp\left(\frac{B_{\gamma\pi}}{4} x\right)$$

- $B_{\gamma\pi} = 4\ \mathrm{GeV}^{-2}$

$\gamma\gamma \to \pi^+\pi^- \to \rho^\pm \to \pi^0\pi^0$

$$\begin{aligned}
\mathcal{M}^t(\lambda_1,\lambda_2) = & \int \frac{eF(\kappa^2,k_1^2)}{\kappa_2^2 - m_\pi^2 + i\epsilon}\frac{F(\kappa_2^2,k_1^2)}{k_1^2 - m_\pi^2 + i\epsilon} \\
\times \quad & g_{\pi\pi\to\rho}\frac{F(\kappa^2,k_2^2)}{\kappa_2^2 - m_\rho^2 + i\epsilon} g_{\pi\pi\to\rho}\frac{eF(\kappa_2^2,k_2^2)}{k_2^2 - m_\pi^2 + i\epsilon} \\
\times \quad & (k_1^\alpha + p_{\pi^+}^\alpha)(-g_{\alpha,\beta})\left(k_2^\beta + p_{\pi^-}^\beta\right) \\
\times \quad & \epsilon_\mu(\lambda_1)(\kappa^\mu + k_1^\mu)\epsilon_\nu(\lambda_2)(\kappa^\nu - k_2^\nu)\, d\kappa_0 d\kappa_x d\kappa_y d\kappa_z \frac{1}{(2\pi)^2}
\end{aligned}$$

$$F(\kappa^2,k_1^2) = \exp\left(\frac{-\left|\kappa^2 - m_\pi^2\right|}{\Lambda_{BOX}{}^2}\right)\exp\left(\frac{-\left|k_1^2 - m_\pi^2\right|}{\Lambda_\pi{}^2}\right)$$

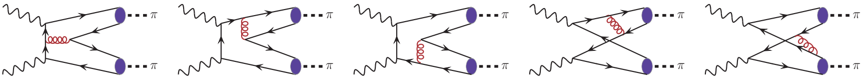


- $\Lambda_\pi = 2.7$ GeV
- $\Lambda_{BOX} = 1.05$ GeV

pQCD($\gamma\gamma \to \pi\pi$) [M.K-G and A.Szczurek, Phys. Lett **B 700** (2011) 322]

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

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



- $\mu_x = min\,(x, 1-x)\sqrt{s(1-z^2)}$,
- $z = \cos\theta$,
- $F_{reg}^{pQCD}(t, u) = \left[1 - \exp\left(\frac{t - t_m}{\Lambda_{reg}^2}\right)\right]\left[1 - \exp\left(\frac{u - u_m}{\Lambda_{reg}^2}\right)\right]$
  *A.Szczurek and J. Speth, Eur. Phys. J. **A18** (2003) 445

The quark distribution amplitude of the pion

$$\phi_\pi\left(x,\mu^2\right) = \frac{f_\pi}{2\sqrt{3}} 6x\left(1-x\right) \sum_{n=0}^{\infty\,\prime} C_n^{3/2}\left(2x-1\right) a_n\left(\mu^2\right)$$

$$a_n\left(\mu^2\right) = \frac{2}{3}\frac{2n+3}{\left(n+1\right)\left(n+2\right)}\left(\frac{\alpha_s\left(\mu^2\right)}{\alpha_s\left(\mu_0^2\right)}\right)^{-\frac{C_F}{\beta_0}\left[3+\frac{2}{(n+1)(n+2)}-4\sum_{k=1}^{n+1}\frac{1}{k}\right]}$$

$$\times \int_0^1 dx C_n^{3/2}\left(2x-1\right)\phi_\pi\left(x,\mu_0^2\right)$$

- $\alpha_s\left(\mu^2\right) = \frac{4\pi}{\beta_0 \ln\frac{\mu^2}{\Lambda^2_{QCD}}}$
- $\beta_0 = \frac{11}{3}C_A - \frac{2}{3}N_F$

The quark distribution amplitude of the pion

PHYSICAL REVIEW D **82**, 034024 (2010)

Implication on the pion distribution amplitude from the pion-photon transition form factor with the new *BABAR* data

Xing-Gang Wu*
Department of Physics, Chongqing University, Chongqing 400044, People's Republic of China

Tao Huang†
Institute of High Energy Physics and Theoretical Physics Center for Science Facilities, Chinese Academy of Sciences, Beijing 100049, People's Republic of China

(Received 19 May 2010; published 19 August 2010)

The new *BABAR* data on the pion-photon transition form factor arouses people's interest for the determination of the pion distribution amplitude. To explain the data, we take both the leading valence quark state's and the nonvalence quark state's contributions into consideration, where the valence quark part up to next-to-leading order is presented and the nonvalence quark part is estimated by a phenomenological model based on its limiting behavior at both $Q^2 \to 0$ and $Q^2 \to \infty$. Our results show that to be consistent with the new *BABAR* data at the large Q^2 region, a broader amplitude other than the asymptoticlike pion distribution amplitude should be adopted. The broadness of the pion distribution amplitude is controlled by a parameter B. It has been found that the new *BABAR* data at low and high energy regions can be explained simultaneously by setting B to be around 0.60, in which the pion distribution amplitude is closed to the Chernyak-Zhitnitsky form.

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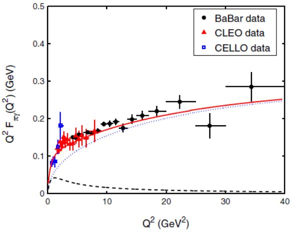


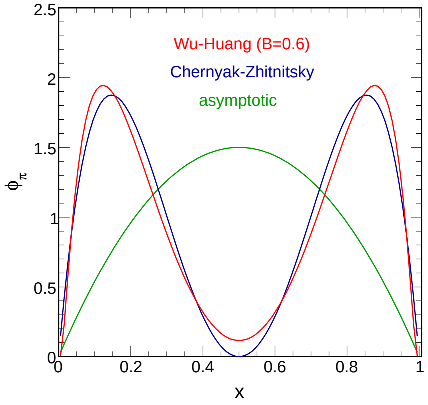
FIG. 5 (color online). $Q^2 F_{\pi\gamma}(Q^2)$ with the model wave function (3) by taking $m_q = 0.30$ GeV and $B = 0.60$. The solid, the dotted, and the dashed lines are for the total contribution, the leading valence quark contribution, and the nonvalence quark contribution to the form factor, respectively.

$$\phi_\pi\left(x,\mu_0^2\right)_{WH} = \frac{\sqrt{3}A\,m_q\beta}{2\sqrt{2}\pi^{3/2}f_\pi}\sqrt{x(1-x)} \times \left(1 + B \times C_2^{3/2}(2x-1)\right) \times \left(\operatorname{erf}\left[\sqrt{\frac{m_q^2+\mu_0^2}{8\beta^2 x(1-x)}}\right] - \operatorname{erf}\left[\sqrt{\frac{m_q^2}{8\beta^2 x(1-x)}}\right]\right)$$

- $B = 0.6$
- $m_q = 0.3$ GeV
- $A = 16.62$ GeV^{-1}
- $\beta = 0.745$ GeV

The quark distribution amplitude of the pion

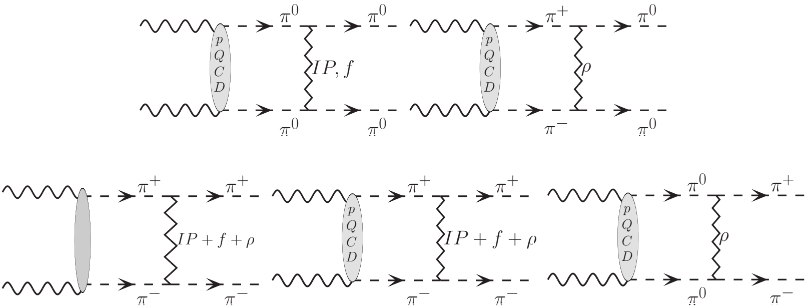
$$\phi_\pi(x)_{CZ} = 30x(1-x)(2x-1)^2$$
$$\phi_\pi(x)_{as} = 6x(1-x)$$



$$\phi_\pi\left(x,\mu_0^2\right)_{WH} = \frac{\sqrt{3}A\,m_q\beta}{2\sqrt{2}\pi^{3/2}f_\pi}\sqrt{x(1-x)} \times \left(1 + B\times C_2^{3/2}(2x-1)\right) \times \left(\mathrm{erf}\left[\sqrt{\frac{m_q^2+\mu_0^2}{8\beta^2 x(1-x)}}\right] - \mathrm{erf}\left[\sqrt{\frac{m_q^2}{8\beta^2 x(1-x)}}\right]\right)$$

- B = 0.6
- m_q = 0.3 GeV
- A = 16.62 GeV^{-1}
- β = 0.745 GeV

High energy pion-pion rescattering



$$
\begin{aligned}
\mathcal{M}_{\gamma\gamma\to\pi^+\pi^-} &= \sum_{\alpha} \mathcal{M}^{(\alpha)}_{\gamma\gamma\to\pi^+\pi^-} \\
&+ \sum_{ij}\sum_{\alpha,\beta} \frac{i}{16\pi^2 s} \int d^2\vec{k}_1 d^2\vec{k}_2 \delta^2\left(\vec{k} - \vec{k}_1 - \vec{k}_2\right) \\
&\times \mathcal{M}^{\alpha}_{\gamma\gamma\to ij}\left(s, \vec{k}_1\right) \mathcal{M}^{\beta}_{ij\to\pi^+\pi^-}\left(s, \vec{k}_2\right) + (\ldots)
\end{aligned}
$$

$IP + f + \rho$

$$\mathcal{M}^{t/u}_{IP+f+\rho}(\lambda_1,\lambda_2) = \sum_{X=IP,f,\rho} \left(C_X \varphi_X \left(\frac{s}{s_0}\right)^{\alpha_X(t/u)} \right) F^2(t/u)$$

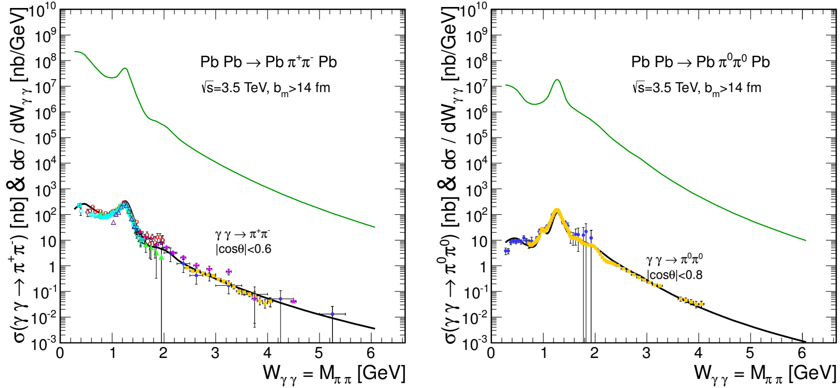
$F(t_{/u}) = \exp(\frac{B}{4} t_{/u})$

- B=4 GeV^{-2}
- $s_0 = 1\ \mathrm{GeV}^2$

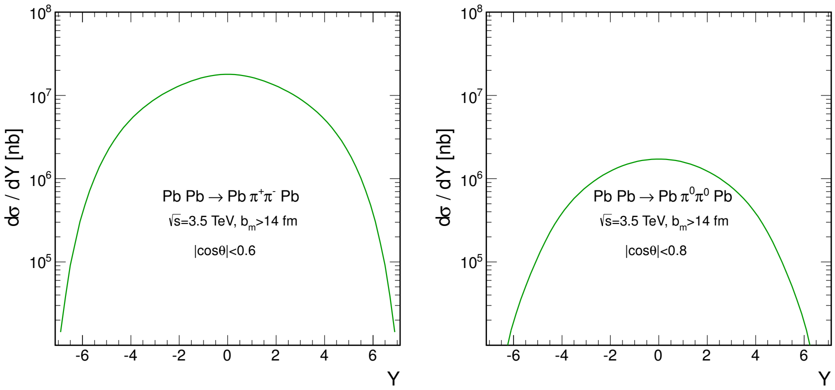
X	$\alpha_X(t_{/u}) = \alpha^0_X + \alpha' t_{/u}$	φ_X
IP	1.0808+(0.25 GeV^{-2})$t_{/u}$	i
f	0.5475+(0.93 GeV^{-2})$t_{/u}$	$\frac{-1}{\sin(\frac{\pi}{2}\alpha^0_f)} \exp\left(\frac{-i\pi}{2}\alpha_f\right)$
ρ	0.5475+(0.93 GeV^{-2})$t_{/u}$	$\frac{-i}{\cos(\frac{\pi}{2}\alpha^0_\rho)} \exp\left(\frac{-i\pi}{2}\alpha_\rho\right)$

*P. Lebiedowicz and A. Szczurek, Phys. Rev. **D83** (2011) 076002

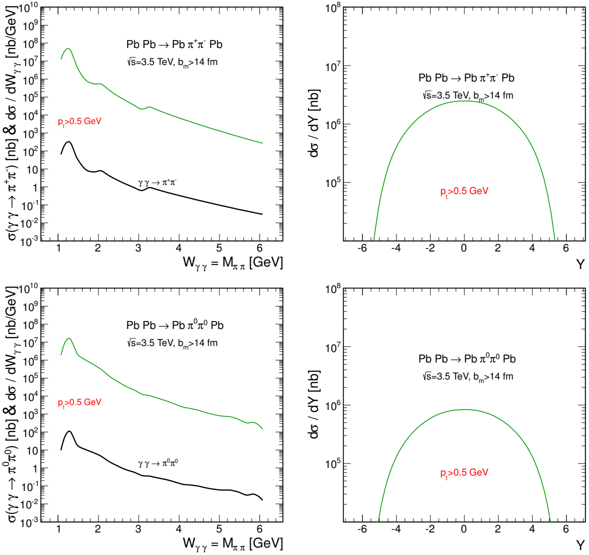
Results - NUCLEAR CROSS SECTION - $\frac{d\sigma}{dW_{\gamma\gamma}}$



Results - NUCLEAR CROSS SECTION - $\frac{d\sigma}{dY_{\pi\pi}}$



Results - $Pb + Pb \to Pb + Pb + \pi + \pi$ - $p_t > 0.5$ GeV



Conclusions

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

$\gamma\gamma \to \pi^+\pi^-$

- resonances
- $\gamma\gamma \to \pi^+\pi^- \to (IP + f + \rho^0) \to \pi^+\pi^-$
- $pQCD(\gamma\gamma \to \pi^+\pi^-)$
- $pQCD(\gamma\gamma \to \pi^+\pi^-) \otimes (IP + f + \rho^0)$
- $pQCD(\gamma\gamma \to \pi^0\pi^0) \otimes \rho^\pm$
- $\gamma\gamma \to \pi^+\pi^-$

$\gamma\gamma \to \pi^0\pi^0$

- resonances
- $\gamma\gamma \to \pi^+\pi^- \to \rho^\pm \to \pi^0\pi^0$
- $pQCD(\gamma\gamma \to \pi^0\pi^0)$
- $pQCD(\gamma\gamma \to \pi^0\pi^0) \otimes (IP + f)$
- $pQCD(\gamma\gamma \to \pi^+\pi^-) \otimes \rho^\pm$

Conclusions

Nuclear cross section:

$\sqrt{s} = 3.5$ TeV + peripheral collisions + realistic form factor

$PbPb \to PbPb\pi^+\pi^-$:		112 mb
$PbPb \to PbPb\pi^+\pi^-$	& $p_t > 0.5$ GeV:	14 mb
$PbPb \to PbPb\pi^0\pi^0$:		10 mb
$PbPb \to PbPb\pi^0\pi^0$	& $p_t > 0.5$ GeV:	5 mb

Background to the exclusive ρ^0 production

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Thank You For Attention