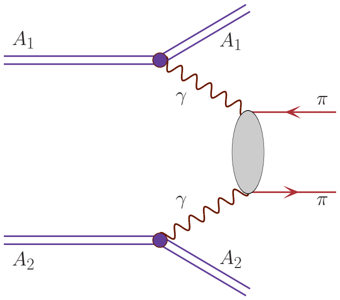
Institute of Nuclear Physics PAN, PL-31-342 Cracow, Poland

Exclusive production of pion pairs in large invariant mass in nucleus-nucleus collisions

Mariola Kłusek–Gawenda

In collaboration with prof. A. Szczurek



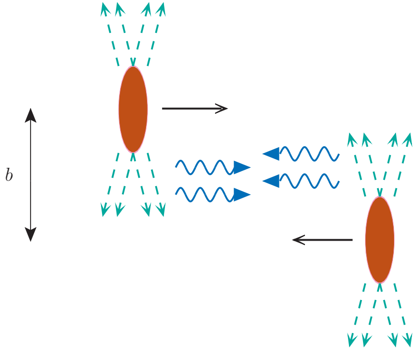
$\mathrm{PbPb} \rightarrow \mathrm{PbPb}\pi^0\pi^0$
$\mathrm{PbPb} \rightarrow \mathrm{PbPb}\pi^+\pi^-$

Accelerator LHC:

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

1. Equivalent photon approximation
   - Form factor
     - Realistic
     - Monopole
2. $\gamma\gamma \longrightarrow \pi\pi$
   - pQCD Brodsky-Lepage
   - Hand-bag
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.

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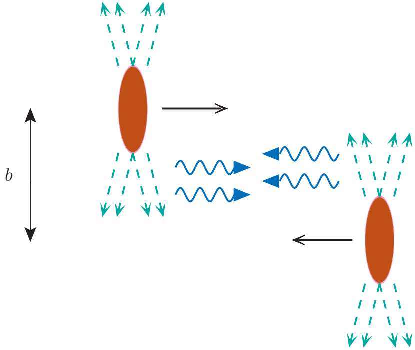

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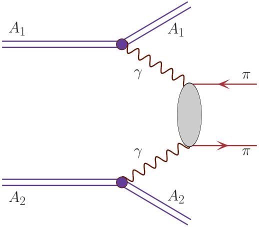
Peripheral collisions:

$b > R_1 + R_2 \cong 14$ fm

The total cross section in EPA

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



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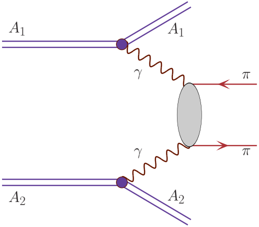

- $x_{1,2} = \frac{\omega_{1,2}}{\gamma M_A}$

Photons flux

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

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

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

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

The cross section in EPA

Nuclear cross section – EPA

$$\sigma\left(PbPb \to \pi\pi PbPb; s_{NN}\right) =$$

$$= \int \hat{\sigma}\left(\gamma\gamma \to \pi\pi; W_{\gamma\gamma}\right)\theta\left(|\mathbf{b}_1 - \mathbf{b}_2| - 2R_A\right)$$

$$x \quad N\left(\omega_1, \mathbf{b}_1\right) N\left(\omega_2, \mathbf{b}_1\right) 2\pi b_m \, \mathrm{d}b_m \, \mathrm{d}\overline{b}_x \, \mathrm{d}\overline{b}_y \, \frac{W_{\gamma\gamma}}{2} \mathrm{d}W_{\gamma\gamma} \mathrm{d}Y$$

The details of derivation:

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"

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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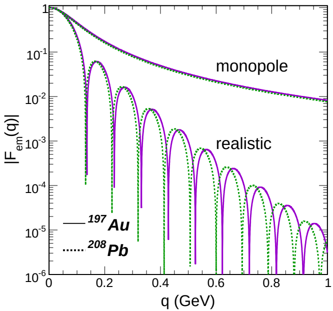
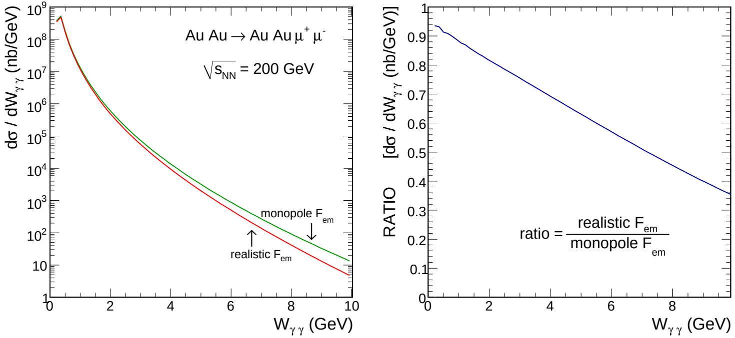


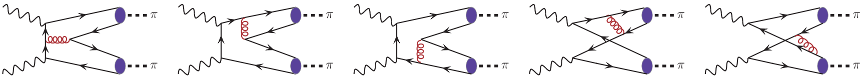
Realistic vs monopole form factor



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

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

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



- $\mu_x = min(x, 1-x)\sqrt{s(1-z^2)}$,
- $z = \cos\theta$, ↪A. Szczurek, J. Speth, Nucl.Phys.**A728**(2003)182
- $F_{reg}^{pQCD}(t, u) = \left[1 - \exp\left(\frac{t - t_m}{\Lambda_{reg}^2}\right)\right]\left[1 - \exp\left(\frac{u - u_m}{\Lambda_{reg}^2}\right)\right]$

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

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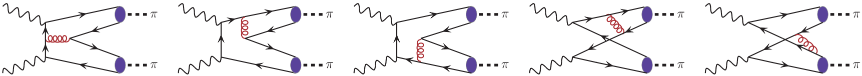

Total cross section

$$\sigma(\gamma\gamma \rightarrow \pi\pi) = \int \frac{2\pi}{4 \cdot 64\pi^2 W^2} \frac{p}{q} \sum_{\lambda_1,\lambda_2} \left|\mathcal{M}(\lambda_1, \lambda_2)\right|^2 dz$$

The quark distribution amplitude of the pion

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

$$a_n\left(\mu^2\right) = \frac{2}{3}\frac{2n+3}{\left(n+1\right)\left(n+2\right)}\left(\frac{\alpha_s\left(\mu^2\right)}{\alpha_s\left(\mu_0^2\right)}\right)^{-\frac{C_F}{\beta_0}\left[3+\frac{2}{(n+1)(n+2)}-4\sum_{k=1}^{n+1}\frac{1}{k}\right]} \times \int_0^1 dx C_n^{3/2}\left(2x-1\right) \phi_\pi\left(x,\mu_0^2\right)$$

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

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*
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(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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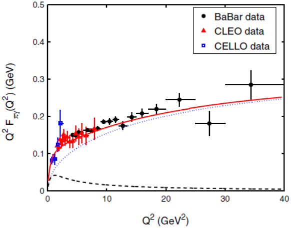

FIG. 5 (color online). $Q^2 F_{\pi\gamma}(Q^2)$ with the model wave function (3) by taking $m_q = 0.30$ GeV and $B = 0.60$. The solid, the dotted, and the dashed lines are for the total contribution, the leading valence quark contribution, and the nonvalence quark contribution to the form factor, respectively.

$$F_{\pi\gamma}(Q^2) = F^{(V)}_{\pi\gamma}(Q^2) + F^{(NV)}_{\pi\gamma}(Q^2)$$

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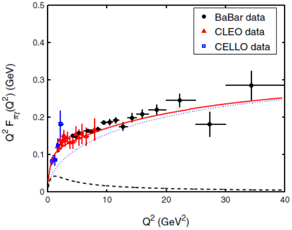

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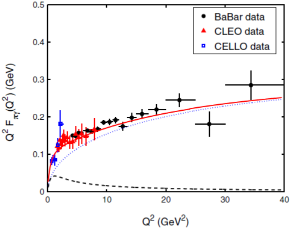

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Based on the BHL prescription:

$$\Psi^R_{q\bar{q}}(x, \mathbf{k}_\perp) = A\, \varphi_\pi(x) \times \exp\left[-\frac{\mathbf{k}_\perp + \mathbf{m}_\mathbf{q}^2}{8\beta^2 x(1-x)}\right]$$

- $\varphi_\pi(x) = \left(1 + B\, C_2^{3/2}(2x-1)\right)$

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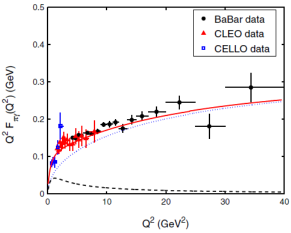

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$$\phi_\pi(x, \mu_0^2) = \frac{2\sqrt{3}}{f_\pi} \int_{|\mathbf{k}_\perp|^2 \le \mu_0^2} \frac{d^2\mathbf{k}_\perp}{16\pi^3} \Psi_{q\bar{q}}(x, \mathbf{k}_\perp)$$

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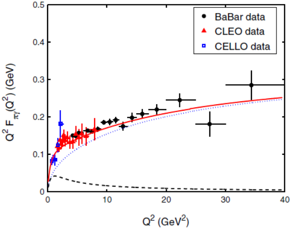

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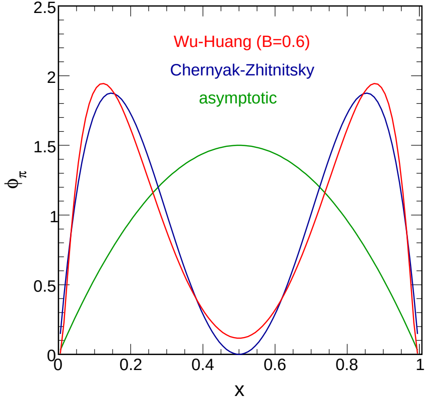
$$\phi_\pi\left(x,\mu_0^2\right)_{WH} = \frac{\sqrt{3}A\, m_q \beta}{2\sqrt{2}\pi^{3/2} f_\pi}\sqrt{x(1-x)} \times \left(1 + B \times C_2^{3/2}(2x-1)\right) \times \left(\mathrm{erf}\left[\sqrt{\frac{m_q^2+\mu_0^2}{8\beta^2 x(1-x)}}\right] - \mathrm{erf}\left[\sqrt{\frac{m_q^2}{8\beta^2 x(1-x)}}\right]\right)$$

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

The quark distribution amplitude of the pion

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



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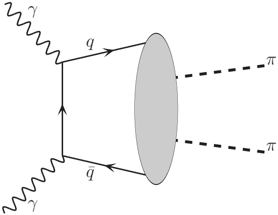
Hand-bag model



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

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Phys. Lett. **B683** (2010) 165.

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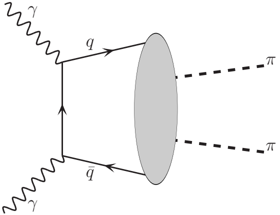

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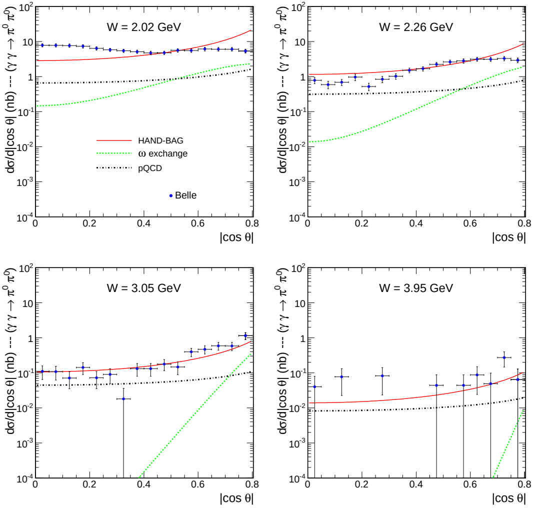
$$\mathcal{A}_{+-} = \mathcal{A}_{-+} = -4\pi_{em}\frac{s^2}{tu}R_{\pi\pi}(s) \propto \frac{1}{\sin^2\theta}$$

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

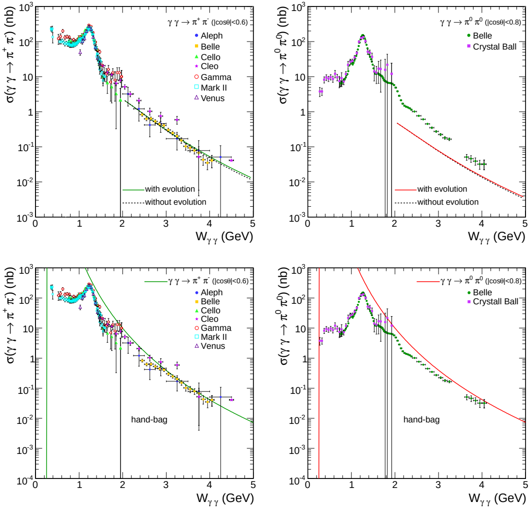
- $s_0 = 9\ \text{GeV}^2$
- $a_u = 1.375\ \text{GeV}^2$
- $n_u = 0.4175$
- $a_s = 0.5025\ \text{GeV}^2$
- $n_s = 1.195$

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

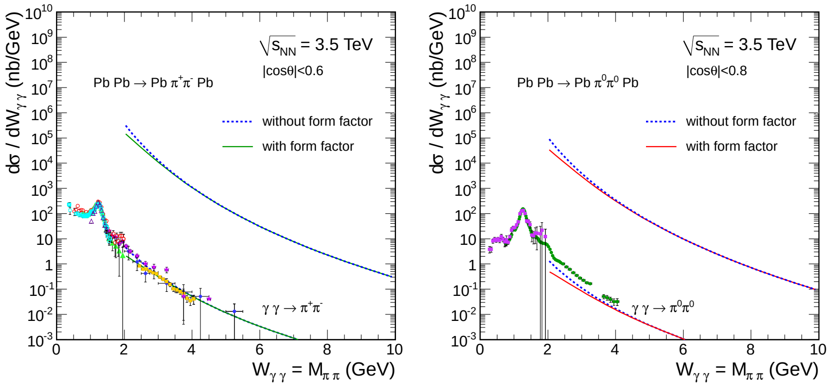
$\frac{d\sigma(\gamma\gamma\to\pi^0\pi^0)}{dz} \Longrightarrow$ pQCD vs hand-bag vs ω exchange



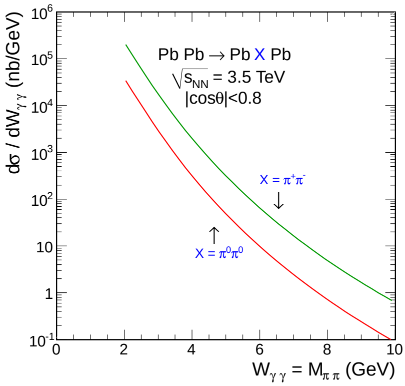
$\sigma(\gamma\gamma \to \pi^+\pi^-)$ & $\sigma(\gamma\gamma \to \pi^0\pi^0)$ $\Longrightarrow$ pQCD vs hand-bag



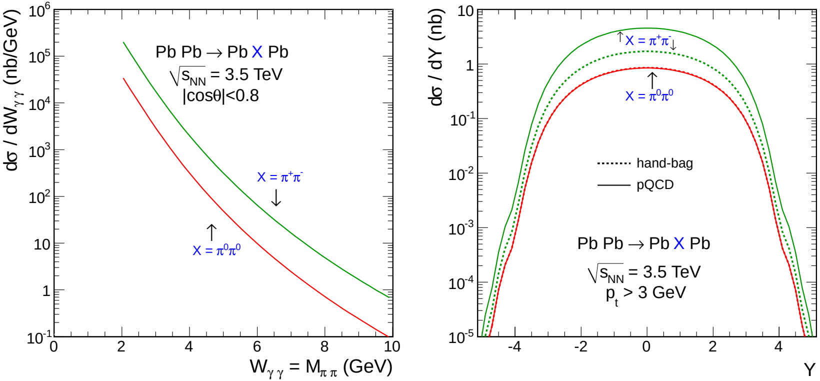
Nuclear cross section



Nuclear cross section



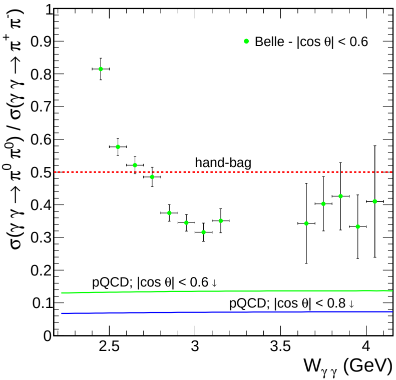
Nuclear cross section



Conclusions

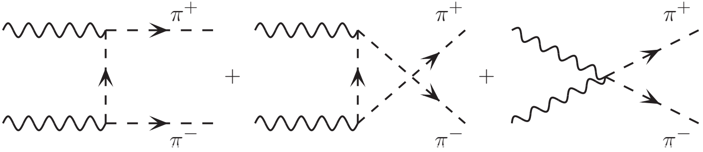
$$\frac{\sigma(\gamma\gamma\to\pi^0\pi^0)}{\sigma(\gamma\gamma\to\pi^+\pi^-)}$$

pQCD vs hand-bag mechanism

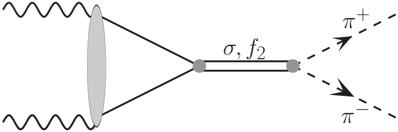


Other mechanisms

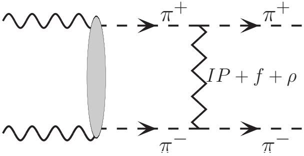
- Pion exchange



- Resonances

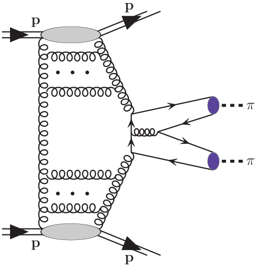


- High-energy $\pi\pi$ rescattering

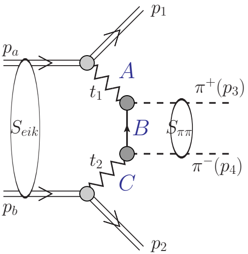


Some other related works

- A new pQCD mechanism:
  L. A. Harland-Lang,
  V. A. Khoze,
  M. G. Ryskin and
  W. J. Stirling,
  arXiv: 1105.1626 [hep-ph]



- But here
  non-perturbative mechanism:
  P. Lebiedowicz,
  R. Pasechnik and
  A. Szczurek,
  arXiv: 1103.5642 [hep-ph]



Thank You For Attention