# *Exclusive* $\gamma^{(*)}\gamma$ *processes*

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# Introduction

The general formula for the leading power term of any hadron form factor in QCD was first obtained in [1] and has the form :

$$\langle p_1,\, s_1,\, \lambda_1;\, p_2,\, s_2,\, \lambda_2 | J_\lambda | 0 \rangle = C_{12} \left( 1/\sqrt{q^2} \right)^{|\lambda_1+\lambda_2|+(2n_{min}-3)} \qquad (1)$$

$n_{\rm min}$ is the minimal number of elementary constituents in a given hadron, $n_{min} = 2$ for mesons and $n_{min} = 3$ for baryons ;
$s_{1,2}$ and $\lambda_{1,2}$ are the hadron spins and helicities ,
the current helicity $\lambda = \lambda_1 - \lambda_2 = 0, \pm 1$ ;
the coefficient $C_{12}$ is expressed through the integral over the wave functions of both hadrons.

It is seen that the behavior is independent of hadron spins, but depends essentially on their helicities, and the QCD helicity selection rules are clearly seen: the largest form factors occur only for $\lambda_1 = \lambda_2 = 0$ mesons and $\lambda_1 = -\lambda_2 = \pm 1/2$ baryons of any spins.

The QCD logarithmic loop corrections to (1) were first calculated in [2].

[1] *V.L.Chernyak , A.R.Zhitnitsky , JETP Lett.* 25 (1977) 510

[2] *V.L.Chernyak , V.G.Serbo , A.R.Zhitnitsky , JETP Lett.* 26 (1977) 594

# $\gamma\gamma \to \overline{M}M$ *large angle scattering*

The QCD predictions for the leading terms of the large angle scattering cross sections $\gamma\gamma \to$ two mesons were considered in [1],[2]

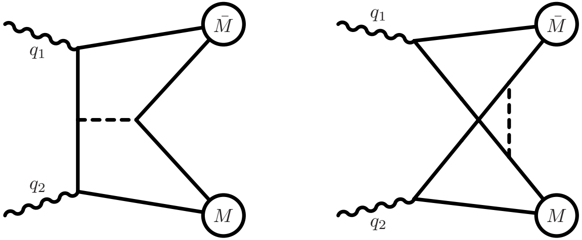



Fig.1 Two typical Feynman diagrams for the leading term hard QCD contributions to $\gamma\gamma \to \overline{M}M$, the broken line is the hard gluon exchange.


[1] *S.J.Brodsky, G.P.Lepage, Phys.Rev. D*24 (1981) 1808
[2] *M.Benayoun, V.L.Chernyak, Nucl.Phys. B*329 (1990) 285

$$\frac{d\sigma(\gamma\gamma \to M^\dagger M)}{d\cos\theta} = \frac{1}{32\pi W^2}\,\frac{1}{4}\sum_{\lambda_1\lambda_2}\left|A_{\lambda_1\lambda_2}\right|^2$$

$$A^{(lead)}_{\lambda_1\lambda_2}(W,\theta) = \frac{64\pi^2}{9W^2}\,\alpha\,\overline{\alpha}_s\,f_M^2\int_0^1 dx\,\phi_M(x)\int_0^1 dy\,\phi_M(y)\;T_{\lambda_1\lambda_2}(x,\,y,\,\theta)$$

$$T_{++} = T_{--} = (e_s - e_u)^2\,\frac{1}{\sin^2\theta}\,\frac{A}{D}\,, \qquad T_{+-} = T_{-+} =$$

$$= \frac{1}{D}\left[\frac{(e_s-e_u)^2}{\sin^2\theta}(1-A) + e_s e_u\,\frac{AC}{A^2 - B^2\cos^2\theta} + \frac{(e_s^2 - e_u^2)}{2}(y_s - x_u)\right]$$

$$A = (x_s y_u + x_u y_s)\,, \quad B = (x_s y_u - x_u y_s)\,, \quad C = (x_s x_u + y_s y_u)$$

$$D = x_u x_s y_u y_s\,, \quad x_s + x_u = 1\,, \quad e_u = 2/3, \quad e_s = e_d = -1/3$$

$f_M$ are the couplings: $f_\pi = 132\,\mathrm{MeV}$, $f_K = 165\,\mathrm{MeV}$

$\phi_M(x)$ is the leading twist meson wave function,

$x$ is the meson momentum fraction carried by quark inside the meson

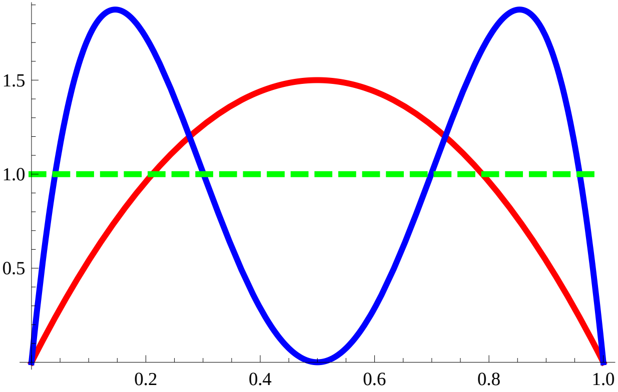



Fig.2

Different models for the leading twist pion wave function $\phi_\pi(x)$.

Red line : asymptotic wave function $\phi_\pi^{\rm asy}(x) = 6x(1-x)$ .
*Blue* line : CZ wave function (at the low scale normalization point)
$\phi_\pi^{cz}(x) = 30x(1-x)(2x-1)^2$ [1] .
Dashed line : flat wave function $\phi_\pi(x) = 1$.

[1] *V.L.Chernyak, A.R.Zhitnitsky, Nucl. Phys. B*201 (1982) 492

Cross sections for *charged mesons*: $\gamma\gamma \to \pi^+\pi^-,\ K^+K^-$ behave as:

$$\frac{d\sigma(\gamma\gamma \to \pi^+\pi^-)}{d\cos\theta} \sim \frac{f_\pi^4}{W^6 \sin^4\theta}\,, \qquad (2)$$

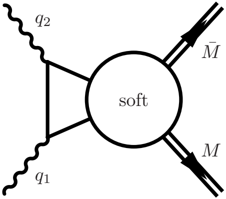
and the angular distribution $\sim 1/\sin^4\theta$ is nearly independent of the meson wave function form. But the absolute values of cross sections depend strongly on the form of $\phi_M(x)$ and are much larger for the wide wave functions.

For *neutral mesons*: $\gamma\gamma \to \pi^o\pi^o,\ \overline{K}_S K_S,\ \pi^o\eta,\ \eta\eta$ the coefficient of the formally leading term $\sim 1/W^6$ is very small, so that at present energies $W < 4\ GeV$ such amplitudes are dominated by the first power correction in the amplitude and the energy behavior is much steeper

$$\frac{d\sigma(\gamma\gamma \to \overline{K}_S K_S)}{d\cos\theta} \sim \frac{f_K^4}{W^{10}}\,\chi(\theta)\,, \qquad (3)$$

while, unlike (2), the angular dependence $\chi(\theta)$ and the overall coefficient in (3) are not predicted (at present) in a model independent way.

The main dynamical assumption of the "handbag model" [1] is that at present energies $W \leq 4\,GeV$ *all* $\gamma\gamma \to \overline{M}M$ amplitudes are still dominated by soft non-leading terms.



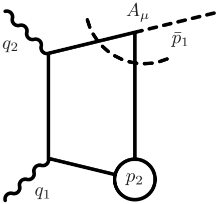




Fig.3a The overall picture of "the standard handbag"contribution [1]

Fig.3b The standard lowest order Feynman diagram for the QCD light cone sum rule [2]

[1] *M.Diehl, P.Kroll, C.Vogt, Phys.Lett. B*532 (2002) 99

[2] *V.L.Chernyak, Phys.Lett. B*640 (2006) 246; *hep* – *ph*/0605072

For all mesons, both charged and neutral, "the standard handbag" contribution (Fig.3) gives $d\sigma(\gamma\gamma \to \overline{M}M)/d\cos\theta \sim \mathrm{const}/W^{10}$ [2]. This angular behavior $\sim$ const disagrees with all data $\sim 1/\sin^4\theta$, and the energy behavior disagrees with the data $\sim 1/W^6$ for charged mesons.

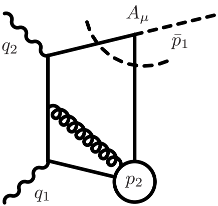



Fig.4 Typical additional Feynman diagram for "the extended handbag model" which includes contributions from 3-particle wave functions (the curly line is the soft non-perturbative gluon).

I expect that, in distinction with the standard contribution of Fig.3, such additional contributions will give

$$\left(\frac{d\sigma(\gamma\gamma\to\overline{M}M)}{d\cos\theta}\right)_{fig.3}\sim\frac{1}{W^{10}};\quad\left(\frac{d\sigma(\gamma\gamma\to\overline{M}M)}{d\cos\theta}\right)_{fig.4}\sim\frac{1}{W^{10}\sin^4\theta},$$

in better agreement with data for *neutral mesons* $M=\pi^o,\,K_S,\,\eta$. Unfortunately, such contributions are not yet calculated at present.

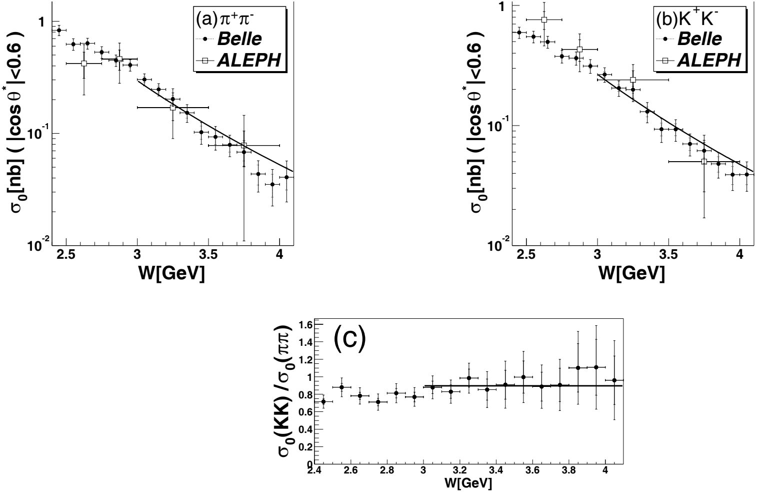



Fig.5 Cross sections $\sigma_o$ integrated over the angular region $|\cos\theta| < 0.6$.

a) $\gamma\gamma \to \pi^+\pi^-$, b) $\gamma\gamma \to K^+K^-$ , *together with* $\sim 1/W^6$ *dependence line*,

c) the cross section ratio $R = \sigma_o(K^+K^-)/\sigma_o(\pi^+\pi^-) \simeq 0.9$, the solid line is the result of the fit for the data above $3GeV$. Compare with the naive $R = (f_K/f_\pi)^4 \simeq 2.5$ .

*H. Nakazawa, S. Uehara et al., Belle Collaboration, Phys. Lett. B615 (2005) 39*

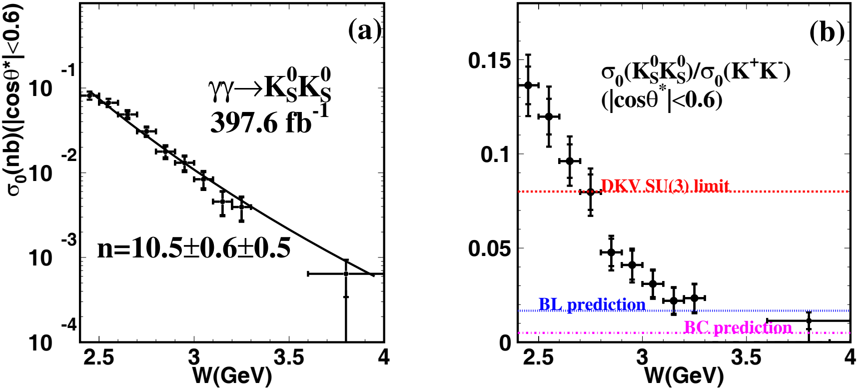
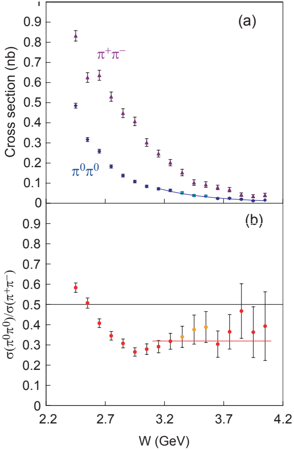



Fig.6 (a) The total cross section $\sigma_o(\gamma\gamma \to K_S K_S)$ in the c.m. angular region $|\cos\theta^*| < 0.6$. Here $n$ is the $W$-dependence $\sigma_o(W) \sim W^{-n}$,

(b) The ratio $\sigma_0(K_S K_S)/\sigma_0(K^+K^-)$ versus $W$.

The dotted line DKV = Diehl-Kroll-Vogt is the handbag model prediction with the $SU(3)$ -flavor symmetry assumption [2]; the dashed BL and dashed-dotted BC lines are the Brodsky-Lepage and Benayoun-Chernyak leading term QCD predictions (for sufficiently large energy $W$)

[1] *W.T.Chen et al., Belle Collaboration, Phys.Lett. B651 (2007) 15*
[2] *M.Diehl, P.Kroll, C.Vogt, Phys.Lett. B532 (2002) 99*




The QCD predictions for this range of energies:

$$\sigma(\pi^+\pi^-) \sim 1/W^6\,, \qquad \sigma(\pi^o\pi^o) \sim 1/W^{10}$$

$$R = \sigma(\pi^o\pi^o)/\sigma(\pi^+\pi^-) \sim 1/W^4$$

The handbag model prediction :

$$R = \sigma(\pi^o\pi^o)/\sigma(\pi^+\pi^-) = 0.5$$

Fig. 7 (a) *Cross sections* $\sigma_o(\gamma\gamma \to \pi^0\pi^0)$ and $\sigma_o(\gamma\gamma \to \pi^+\pi^-)$ for $|\cos\theta^*| < 0.6$ ;
(b) *their ratio*. The lines are the fits to the result in the region indicated.

*S.Uehara, Y.Watanabe et al., Belle Collaboration, Phys.Rev.* D78 (2008) 052004 ; *arXiv* : 0805.3387[*hep* − *ex*]; *arXiv* : 0810.0655[*hep* − *ex*]
*H.Nakazawa, S.Uehara et al., Belle Collaboration, Phys.Lett.* B615 (2005)39

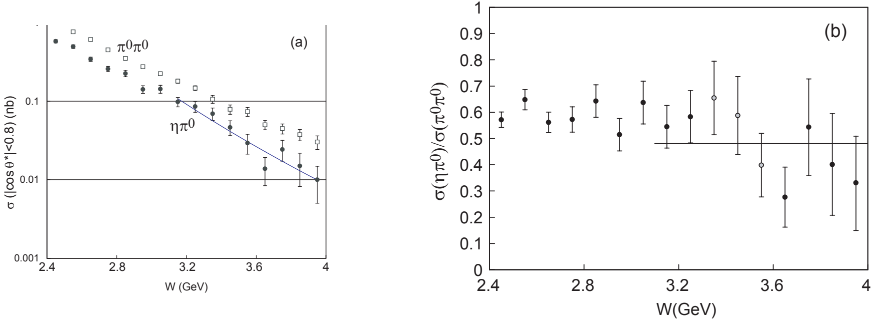



Fig.8 a) $W$ - dependence of cross sections $\gamma\gamma \to \pi^o\pi^o$ and $\gamma\gamma \to \pi^o\eta$, $(|\cos\theta^*| < 0.8)$.
The curve is the power-law fit : $\sigma(\pi^o\eta) \sim W^{-n}$, $n = (10.5 \pm 1.2 \pm 0.5)$.
b) $W$ - dependence of the cross section ratio $\sigma(\eta\pi^0)/\sigma(\pi^0\pi^0)$ $(|\cos\theta^*| < 0.8)$. The line is the average in the 3.1 - 4.0 GeV range (the charmonium region, 3.3 - 3.6 GeV, is omitted from calculation).

*S.Uehara, Y.Watanabe et al., Belle Collaboration, arXiv : 0906.1464*
*S.Uehara, Y.Watanabe et al., Belle Collaboration, Phys.Rev. D78 (2008) 052004*

The value of n in $\sigma_{\rm tot} \sim W^{-n}$ in various reactions fitted in the $W$ and $|\cos\theta^*|$ ranges indicated.

| Process | $n$ | $W$ range (GeV) | $\lvert\cos\theta^*\rvert$ range | Reference |
|---|---|---|---|---|
| $\pi^+\pi^-$ | $7.9 \pm 0.4 \pm 1.5$ | 3.0 — −4.1 | $< 0.6$ | [1] |
| $K^+K^-$ | $7.3 \pm 0.3 \pm 1.5$ | 3.0 — −4.1 | $< 0.6$ | [1] |
| $K^0_S K^0_S$ | $10.5 \pm 0.6 \pm 0.5$ | 2.4 – 4.0 (exclude 3.3 – 3.6) | $< 0.6$ | [2] |
| $\eta\pi^0$ | $10.5 \pm 1.2 \pm 0.5$ | 3.1 – 4.1 | $< 0.8$ | [3] |
| $\pi^0\pi^0$ | $8.0 \pm 0.5 \pm 0.4$ ? | 3.1 – 4.1 (exclude 3.3 – 3.6) | $< 0.8$ | [4] |

The QCD predictions (in the range $2.5 < W < 4\,GeV$):

$n \simeq 6$ for charged $\pi^+\pi^-$, $K^+K^-$; $n \simeq 10$ for neutral $K^o_S K^o_S$, $\eta\pi^o$, $\pi^o\pi^o$

The handbag model predictions: $n \simeq 10$ for all mesons


[1] *H. Nakazawa, S. Uehara et al., Belle Collaboration, Phys. Lett. B615 (2005) 39*

[2] *W. T. Chen et al., Belle Collaboration, Phys. Lett. B651 (2007) 15*

[3] *S. Uehara, Y. Watanabe et al., Belle Collaboration, arXiv : 0906.1464*

[4] *S. Uehara, Y. Watanabe et al., Belle Collaboration, Phys. Rev. D78 (2008) 052004*

## Conclusions on large angle cross sections $\gamma\gamma \to MM$

1) The leading term QCD predictions $d\sigma/d\cos\theta \sim 1/W^6 \sin^4\theta$ for charged mesons $\pi^+\pi^-$, $K^+K^-$ agree with data both in energy and angular dependence at energies $W > 2.5\, GeV$. The *absolute values* of cross sections agree with data *only* for *the wide pion (kaon) wave functions* like $\phi^{cz}_{\pi,K}(x)$, the asymptotic wave functions $\phi_{\pi,K}(x) \simeq \phi^{asy}(x)$ predict *much smaller* cross sections. The handbag model predictions for charged mesons disagree with data in energy dependence.

2) *For neutral mesons* the QCD leading terms have much smaller overall coefficients, so that the non-leading terms are expected to dominate at present energies and the energy dependence is steeper: $\sigma(\overline{M^o} M^o) \sim 1/W^{10}$. This agrees with data on $\sigma(\overline{K}_S K_s)$ and $\sigma(\pi^o\eta)$, while $\sigma(\pi^o\pi^o)$ is consistent with $\sim 1/W^{10}$ at $6 < W^2 < 10 GeV^2$, but behaves abnormally at $12 < W^2 < 16 GeV^2$ (may be due to contamination by the pure QED - background).

3) Predictions of "the standard handbag model" *disagree* with data either in energy and/or angular dependence, or in absolute values, but "the extended handbag model" (which includes contributions of 3-particle wave functions) is potentially capable to describe the cross sections of *neutral mesons* at intermediate energies $2.5 GeV < W < 4 GeV$.

## $\gamma^*\gamma \to \{\pi^o\,,\,\eta\,,\,\eta'\}$ *form factors* $F_{\gamma P}(Q^2)$

QCD predictions (P=pseudoscalar meson):

$$\int dz\, e^{iq_1 z}\langle P(p)|\,T\{J^{el}_\mu(z)J^{el}_\nu(0)\}|0\rangle = \Big(\epsilon_{\mu\nu\lambda\sigma}q_1^\lambda q_2^\sigma\Big)\,F_{\gamma P}(q_1^2, q_2^2)$$

At $q_2^2 = 0,\ -q_1^2 = Q^2 \gg 1\,GeV^2$ :

$$Q^2 F_{\gamma P}(Q^2) = \int_0^1 dx \frac{\phi_P(x,\mu^2 = Q^2)}{x}\Bigg(1 + O\Big(\alpha_s(Q^2)\Big) + O\Big(1/Q^2\Big)\Bigg),$$

where $\phi_P(x,\mu^2)$ is the leading twist pseudoscalar meson wave function,
$0 \le x \le 1$ is the meson momentum fraction carried by quark.
At asymptotically large $\mu^2 \to \infty$ the model independent QCD prediction is:

$$\phi_P(x,\mu^2 \to \infty) = \phi_P^{\rm asy}(x) = 6x(1-x)\,,$$

*but the logarithmic evolution with increasing* $\mu^2$ *is very slow*.

$$|\pi^o\rangle \to |(\bar{u}u - \bar{d}d)/\sqrt{2}\rangle, \quad |n\rangle \to |(\bar{u}u + \bar{d}d)/\sqrt{2}\rangle, \quad |s\rangle \to |\bar{s}s\rangle$$

$$|\eta\rangle = \cos\phi\,|n\rangle - \sin\phi\,|s\rangle\,, \quad |\eta'\rangle = \sin\phi\,|n\rangle + \cos\phi\,|s\rangle$$

$$f_\pi \simeq 132\ MeV\,, \quad f_n \simeq f_\pi, \quad f_s \simeq 1.3\, f_\pi, \quad \phi \simeq 40^o$$

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$$F_{\gamma\pi}(Q^2) = \frac{\sqrt{2}(e_u^2 - e_d^2)\, f_\pi}{Q^2} \int_0^1 dx \frac{\phi_\pi(x, \mu^2 = Q^2)}{x} \left(1 + O(\alpha_s) + O(1/Q^2)\right),$$

$$F_{\gamma n}(Q^2) = \frac{\sqrt{2}(e_u^2 + e_d^2)\, f_\pi}{Q^2} \int_0^1 dx \frac{\phi_\pi(x, \mu^2 = Q^2)}{x} \left(1 + O(\alpha_s) + O(1/Q^2)\right),$$

$$F_{\gamma s}(Q^2) = \frac{2e_s^2\, f_s}{Q^2} \int_0^1 dx \frac{\phi_s(x, \mu^2 = Q^2)}{x} \left(1 + O(\alpha_s) + O(1/Q^2)\right),$$

$$F_{\gamma\eta}(Q^2) = \left(\cos\phi\, F_{\gamma n}(Q^2) - \sin\phi\, F_{\gamma s}(Q^2)\right), \; F_{\gamma\eta'}(Q^2) = \left(\sin\phi\, F_{\gamma n}(Q^2) + \cos\phi\, F_{\gamma s}(Q^2)\right)$$

*T.Feldmann, P.Kroll, B.Stech, Phys. Rev. D58 (1998) 114006*

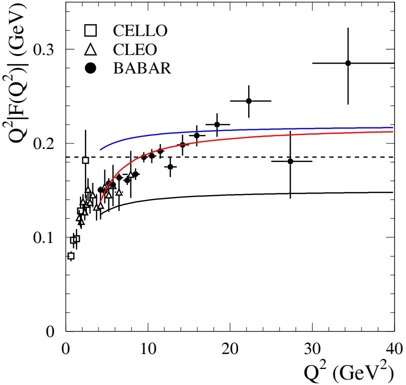


Fig.9 The form factor $\Phi \equiv Q^2 F_{\gamma\pi}(Q^2)$

Theory :

a) logarithmic loop corrections are calculated at NNLO order [1]

b) only the twist-4 part of the total power correction $\sim 1/Q^2$ is calculated at present,

$\delta\Phi_4 \simeq \sqrt{2} f_\pi (-0.6\, GeV^2/Q^2)$ [2]

(and it well may be that it is not even the main part of the total $\sim 1/Q^2$ correction)

c) the power correction $\sim 1/Q^4$ is unknown.

a) Black line, [1],[2]: $\phi_\pi(x) = \phi_{\rm asy}(x)$, $\Phi \simeq \sqrt{2} f_\pi \Big[ 0.81 - (0.6\, GeV^2/Q^2) \Big]$

b) *Blue line*, [1],[2]: $\phi_\pi(x) = \phi_{\rm cz}(x)$, $\Phi \simeq \sqrt{2} f_\pi \Big[ 1.18 - (0.6\, GeV^2/Q^2) \Big]$

c) *Red line* (example): $\phi_\pi(x) = \phi_{\rm cz}(x)$, $\Phi \simeq \sqrt{2} f_\pi \Big[ 1.18 - (1.5\, GeV^2/Q^2) - (1.2\, GeV^2/Q^2)^2 \Big]$

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Theory : [1] *B.Melic, D.Muller, K.Passek − Kumericki, Phys. Rev. D68* (2003) 014013
[2] *A.Khodjamirian, Eur. Phys. J. C6* (1998) 33, *hep − ph*/9712451

Experiment: V.P. Druzhinin , *arXiv* : 0909.3148 [*hep − ex*]
V.P. Druzhinin *et al*, *BaBar Collaboration*, *arXiv* : 0905.4778

The values of $F_{\gamma P}(Q^2)$ form factors at $Q^2 = 112\, GeV^2$ for various meson wave functions

| Wave functions | $Q^2 F_{\gamma^* \pi}(Q^2)$ | $Q^2 F_{\gamma^* \eta}(Q^2)$ | $Q^2 F_{\gamma^* \eta'}(Q^2)$ | Ref. |
|---|---|---|---|---|
| $\phi_n(x) \simeq \phi_s(x) \simeq \phi_{asy}(x) = 6x(1-x)$ | 0.15 | 0.14 | 0.22 | |
| $\phi_n(x) \simeq \phi_{cz}(x); \quad \phi_s(x) \simeq \phi_{asy}(x)$ | 0.22 | 0.23 | 0.29 | |
| $\phi_n(x) \simeq \phi_s(x) \simeq \phi_{cz}(x)$ | 0.22 | 0.21 | 0.32 | |
| $\phi_n(x) \simeq \phi_s(x) \simeq 1$ | 0.33 | 0.32 | 0.48 | [1] [2] |
| experiment | — | $0.23 \pm 0.03$ | $0.25 \pm 0.02$ | [3] |

[1] *A.V.Radyushkin, arXiv* : 0906.0323 [*hep* − *ph*]
[2] *M.V.Polyakov, arXiv* : 0906.0538 [*hep* − *ph*]

[3] *V.P.Druzhinin et al, BaBar Collaboration, Phys. Rev. D*74(2006)012002

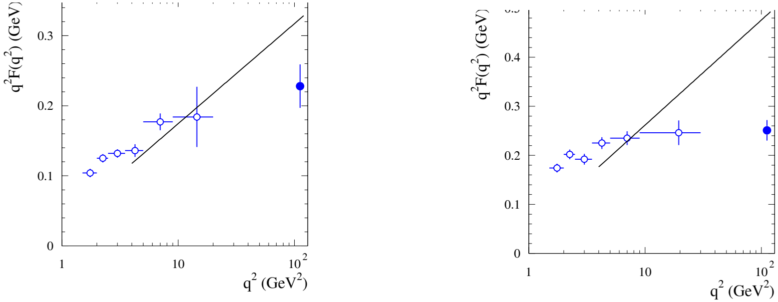


Fig.10 *Black points*: $\eta$ (left) and $\eta'$ (right) transition form factors at $q^2 = 112\ GeV^2$ :

$$q^2 F_{\gamma\eta}(q^2) = (0.229 \pm 0.030 \pm 0.008)\ GeV,$$
$$q^2 F_{\gamma\eta'}(q^2) = (0.251 \pm 0.019 \pm 0.008)\ GeV.$$

*V.P.Druzhinin et al., BaBar Collaboration, Phys.Rev. D74* (2006) 012002

*White points*: previous CLEO data at $2\ GeV^2 < (Q^2 = -q^2) < 20\ GeV^2$.

*V.Savinov et al., CLEO Collaboration, Phys.Rev. D57* (1998) 33

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Black lines: predictions for the form factors $q^2 F_{\gamma\eta}(q^2)$, $q^2 F_{\gamma\eta'}(q^2)$ with the flat pseudoscalar wave function $\phi_P(x) \simeq 1$ [1][2]


[1] *A.V.Radyushkin, arXiv* : 0906.0323 [*hep* − *ph*]

[2] *M.V.Polyakov, arXiv* : 0906.0538 [*hep* − *ph*]

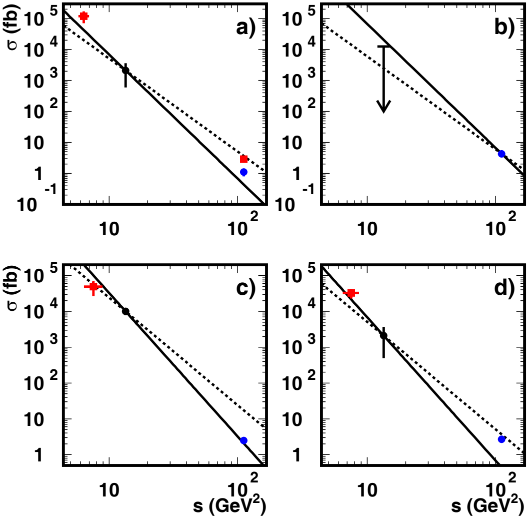


Fig.11 Solid lines correspond to $1/s^4$ dependence and dashed ones represent $1/s^3$.

**a)** $\sigma(e^+e^- \to \phi\eta)$ **b)** $\sigma(e^+e^- \to \phi\eta')$

**c)** $\sigma(e^+e^- \to \rho\eta)$ **d)** $\sigma(e^+e^- \to \rho\eta')$

The measured cross sections:

at $\sqrt{s} \simeq 2.5,\ 2.75\,GeV$ by BaBar,

at $\sqrt{s} = 3.67$ GeV by CLEO and

at $\sqrt{s} = 10.58$ GeV by BaBar and Belle

for various processes. BaBar measurements are represented by squares.

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*QCD predictions* :

$\sigma(e^+e^- \to VP) \sim 1/s^4$ for the end point suppressed pseudoscalar wave function like $\phi_P(x) \sim x(1-x)$

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$\sigma(e^+e^- \to VP) \sim 1/s^2$ for the flat pseudoscalar wave function $\phi_P(x) \sim 1$

The data agree with $1/s^4$ dependence and are in contradiction with $1/s^2$.

*K.Belous, M.Shapkin et al., Belle Collaboration arXiv : 0906.4214 [hep − ex]*

# *Conclusions on the form factors* $F_{\gamma P}(Q^2)$, $P = \{\pi^o, \eta, \eta'\}$ *and the* $P -$ *meson leading twist wave functions* $\phi_P(x)$

The *flat leading twist pseudoscalar wave function* $\phi_P(x) \simeq 1$ :
*a*) predicts the form factors $F_{\gamma\eta}(q^2)$ and $F_{\gamma\eta'}(q^2)$ at $q^2 = 112 GeV^2$ much larger than the BaBar results,
*b*) predicts the parametrical behavior of cross sections $\sigma(e^+e^- \to PV)$ at large $s$ as: $\sigma(e^+e^- \to PV) \sim 1/s^2$ , in contradiction with the data $\sigma(e^+e^- \to PV) \sim 1/s^4$ in the interval $\sim 8 GeV^2 < s < 112 GeV^2$.

The *asymptotic leading twist pion wave function* $\phi_\pi(x) \simeq 6x(1-x)$ :
*a*) predicts the form factors $F_{\gamma\pi^o}(Q^2)$, $F_{\gamma\eta}(Q^2)$ considerably smaller than data,
*b*) predicts branchings of charmonium decays: ${}^3P_0$, ${}^3P_2 \to \pi^+\pi^-$, $K^+K^-$, the pion electromagnetic form factor $F_\pi(q^2)$ at $q^2 = 10 - 15 GeV^2$, etc. much smaller than data.

The *CZ leading twist pion wave function* $\phi_\pi^{cz}(x) \simeq 30x(1-x)(2x-1)^2$
- leads to predictions in a reasonable agreement with all data available.