Pseudoscalar meson transition form factors in nonperturbative QCD approach

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Introduction

BABAR data and puzzles

Nonperturbative approach to PS meson transition form factors

Conclusions

The theory of hard exclusive processes was formulated within the factorization approach to perturbative quantum chromodynamics (pQCD) in 1977-1981

[1] A. V. Radyushkin, (1977), hep-ph/0410276.

[2] G. P. Lepage and S. J. Brodsky, Phys. Lett. **B87**, 359 (1979).

[3] A. V. Efremov and A. V. Radyushkin, Theor. Math. Phys. **42**, 97 (1980).

[4] A. V. Efremov and A. V. Radyushkin, Phys. Lett. **B94**, 245 (1980).

[5] A. V. Efremov and A. V. Radyushkin, Submitted to 19th Int. Conf. on High Energy Physics, Tokyo, Japan, Aug 23-30, 1978.

[6] G. P. Lepage and S. J. Brodsky, Phys. Rev. **D22**, 2157 (1980).

[7] S. J. Brodsky and G. P. Lepage, Phys. Rev. **D24**, 1808 (1981).

V.L. Chernyak, A.R. Zhitnitsky

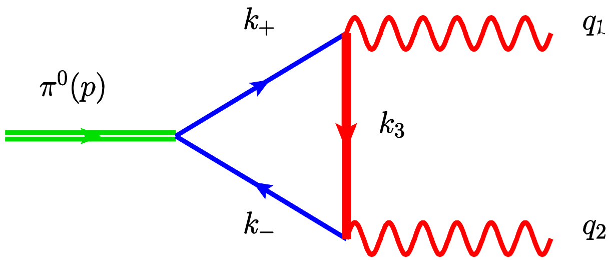
The photon-pion transition $\gamma^*\gamma^* \to \pi^0$ is of special interest

a)it is the simplest process for theory;

b)related to the axial anomaly when both photons are real;

c)At large photon virtualities has simple asymptotics [6,7]

Photon-pion transition form factor:
In the pQCD factorization approach



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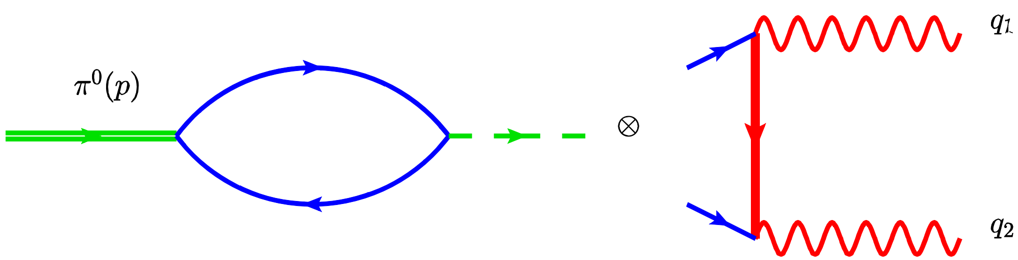


Factorization $f_\pi\, J^*\, 1/Q^2$

and it settle in at ~ 1 GeV^2

$$F^{pQCD}_{\pi\gamma^*\gamma}(Q^2,0)=\frac{2f_\pi}{3Q^2}J,\ \text{where } f_\pi = 92.4\ \text{MeV}$$

$$J=\int_0^1 \frac{\varphi_\pi(x)}{x}dx$$

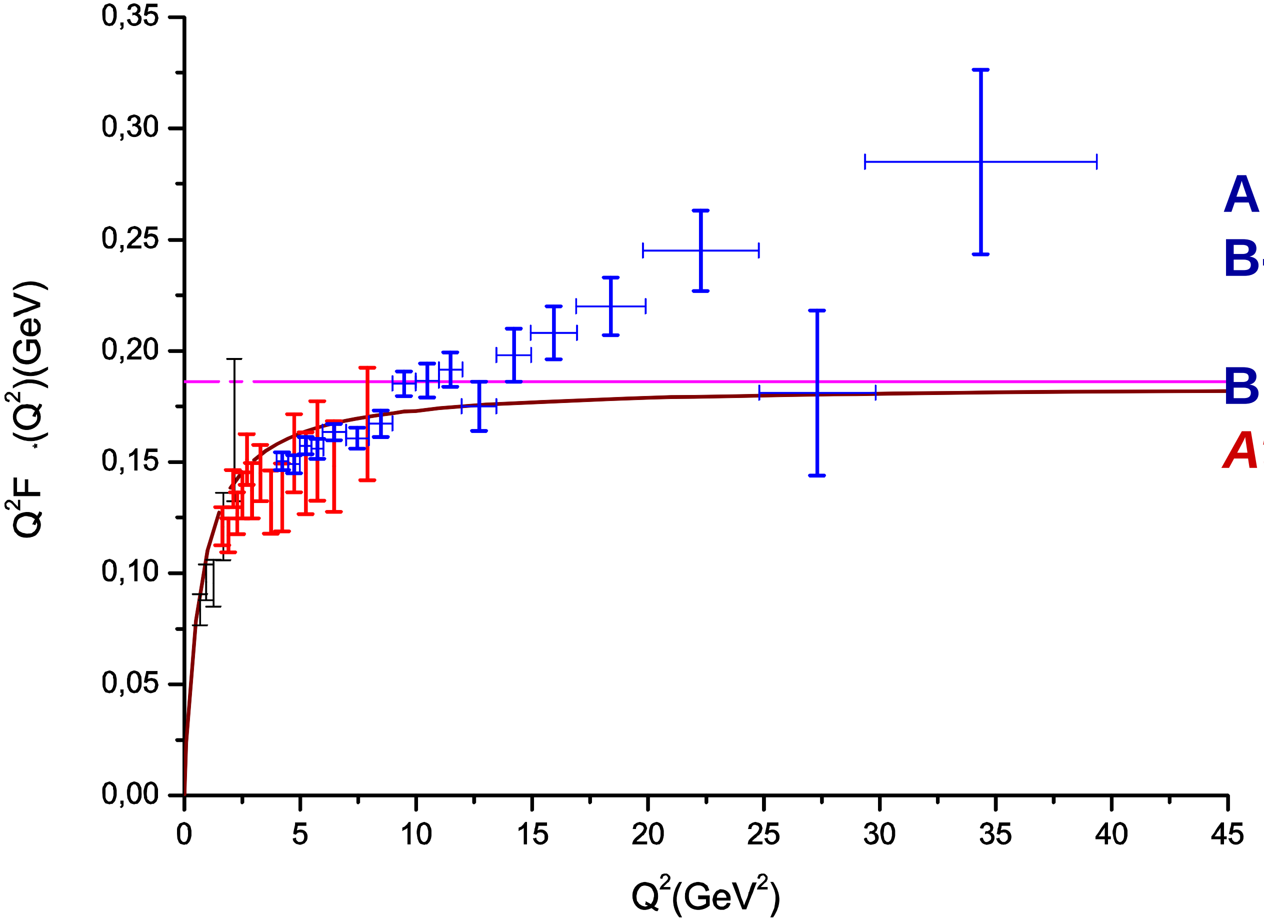
$$F^{pQCD,As}_{\pi\gamma^*\gamma}(Q^2,0)=2f_\pi\frac{1}{Q^2},\ \text{for } \varphi^{As}_\pi(x)=6x(1-x)$$

Asymmetric kinematics (measured by BABAR)

$$F^{pQCD}_{\pi\gamma^*\gamma^*}(Q^2,Q^2)=\frac{1}{Q^2}\frac{2f_\pi}{3}$$

Symmetric kinematics

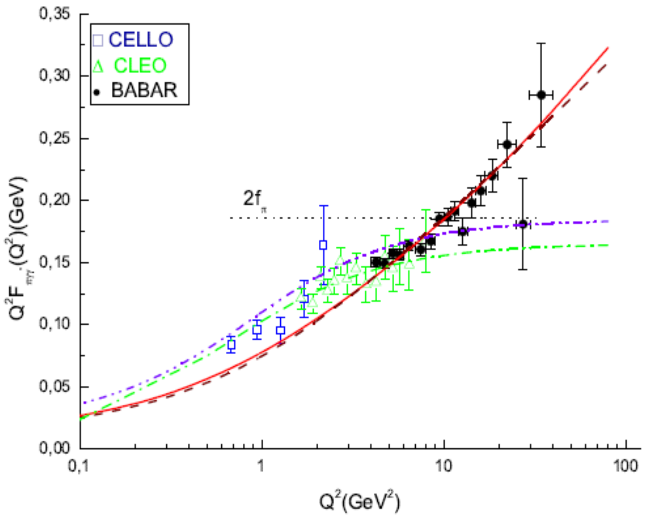
BABAR surprise 2009
(and CELLO-1991, CLEO-1997) data



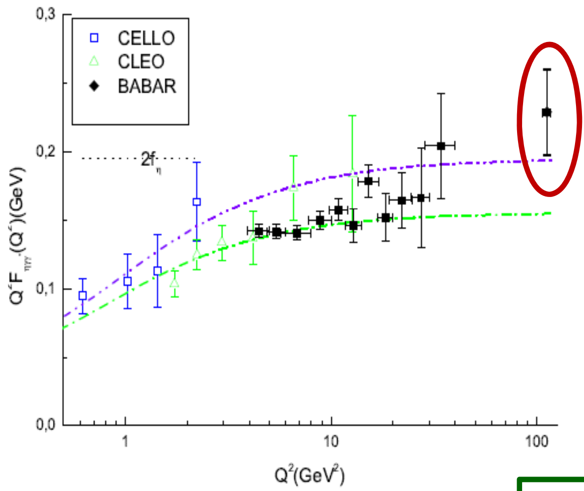
A. Data higher than B-L asymptotic limit,

B. They are ***GROWing!*** ***At large Q^2***

$\pi \to \gamma\gamma^*$



$\eta \to \gamma\gamma^*$

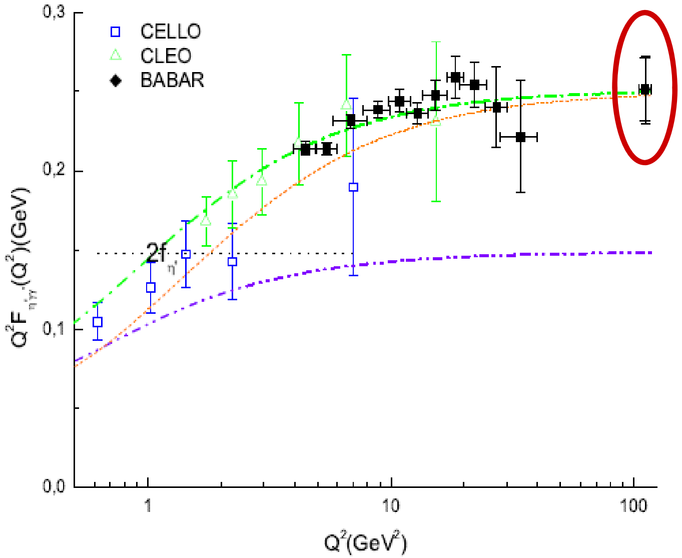


BABAR triumph in 2009-11 and puzzles

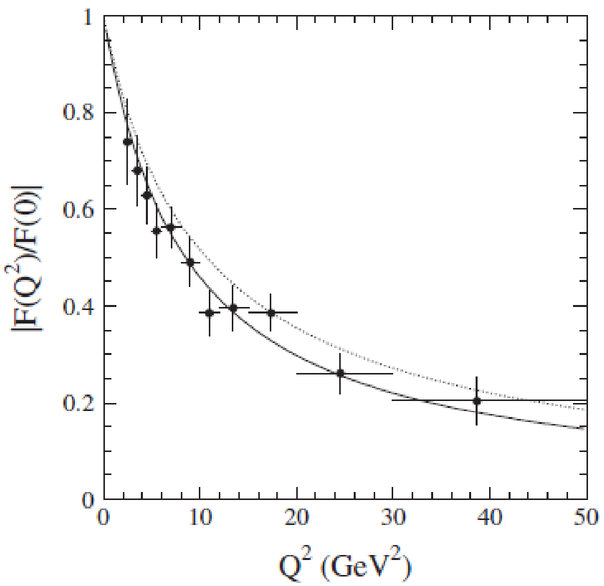
$$\Lambda_\pi = 776 \pm 22 \text{ MeV}$$

$$\Lambda_\eta \approx 866 \text{ MeV}$$

$\eta' \to \gamma\gamma^*$



$\eta_c \to \gamma\gamma^*$



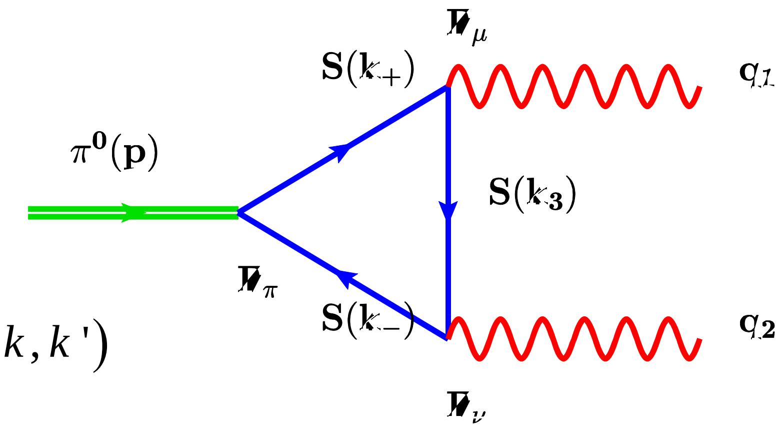
$$F^{\text{CLEO}}_{\pi\gamma\gamma^*}(Q^2,0) = \frac{1}{4\pi^2 f_P}\frac{1}{1+Q^2/\Lambda_P^2}$$

CLEO fit

$$\Lambda_{\eta'} = 859 \pm 28 \text{ MeV}$$

$$\Lambda_{\eta_c} = 2.92 \pm 0.16 \text{ GeV}$$

Nonperturbative Nonlocal QCD Approach to $\pi\gamma$ Form Factor And its asymptotic properties AED JETP Lett. (2003)



Quark Propagator

$$\frac{\not k}{k^2} \Rightarrow \boxed{S(k) = \frac{\not k + m(k^2)}{D(k^2)}} \xrightarrow{k^2 \to \infty} \frac{\not k}{k^2}$$

Quark-Photon Vertex

$$\gamma_\mu \Rightarrow \boxed{\Gamma_\mu = \gamma_\mu} + \Delta\Gamma_\mu(k,k') \xrightarrow{k^2 \to \infty} \gamma_\mu, \text{ where } \Delta\Gamma_\mu(k,k')$$

guarantes WTI $(k' = k + q)$: $q_\mu \Gamma_\mu = S^{-1}(k') - S^{-1}(k)$

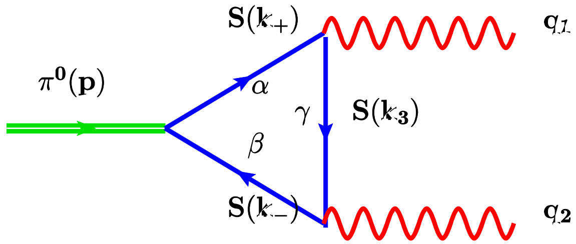
Quark-Pion vertex

$$\frac{1}{f_\pi}\gamma_5 \Rightarrow \boxed{\Gamma_\pi = \frac{1}{f_\pi}\gamma_5 F(k,k')} \overset{k'^2 \to \infty,\ k^2 \to \infty}{=} 0$$

The vertex F is equivalent of the light-cone pion WF

We use for the Dynamical Quark Mass the model

$$m(k^2) = M_q \exp(-2\Lambda k^2)$$



$$F_{P\gamma^*\gamma^*}\left(p^2;q_1^2,q_2^2\right)=\frac{N_c}{6\pi^2 f_P}\int_0^\infty \frac{d\left(\alpha\beta\gamma\right)}{\Delta^3} e^{-\frac{1}{\Delta}\left[\alpha\beta p^2+\gamma\left(\alpha q_1^2+\beta q_2^2\right)\right]}\left[d_\gamma\left(\alpha G^{m,0}_{\alpha,\beta}+\beta G^{0,m}_{\alpha,\beta}\right)+\gamma G^{0,0}_{\alpha,\beta}\right]$$

We are interested by kinematics $q_1^2 = Q^2 \to \infty, q_2^2 \approx 0$

Meson mass--shell condition $p^2 = -M_M^2$

The dynamics depends on the parameters:

Dynamical Quark Mass **M_q ,**
And Nolocality Scale **L**

The basic result for asymptotic

AED JETP Lett 2010

$$F_{P\gamma^*\gamma^*}\left(p^2; q_1^2 \to \infty, q_2^2 \approx 0\right) \approx \frac{2 f_P}{3} \int_0^1 dx \frac{\varphi_P(x)}{D\left(x q_1^2\right)},$$

where $D\left(k^2\right)$ is the nonperturbative quark propagator

with properties $D\left(k^2 \to \infty\right) = k^2$ and $D\left(k^2 = 0\right) = M_q^2$

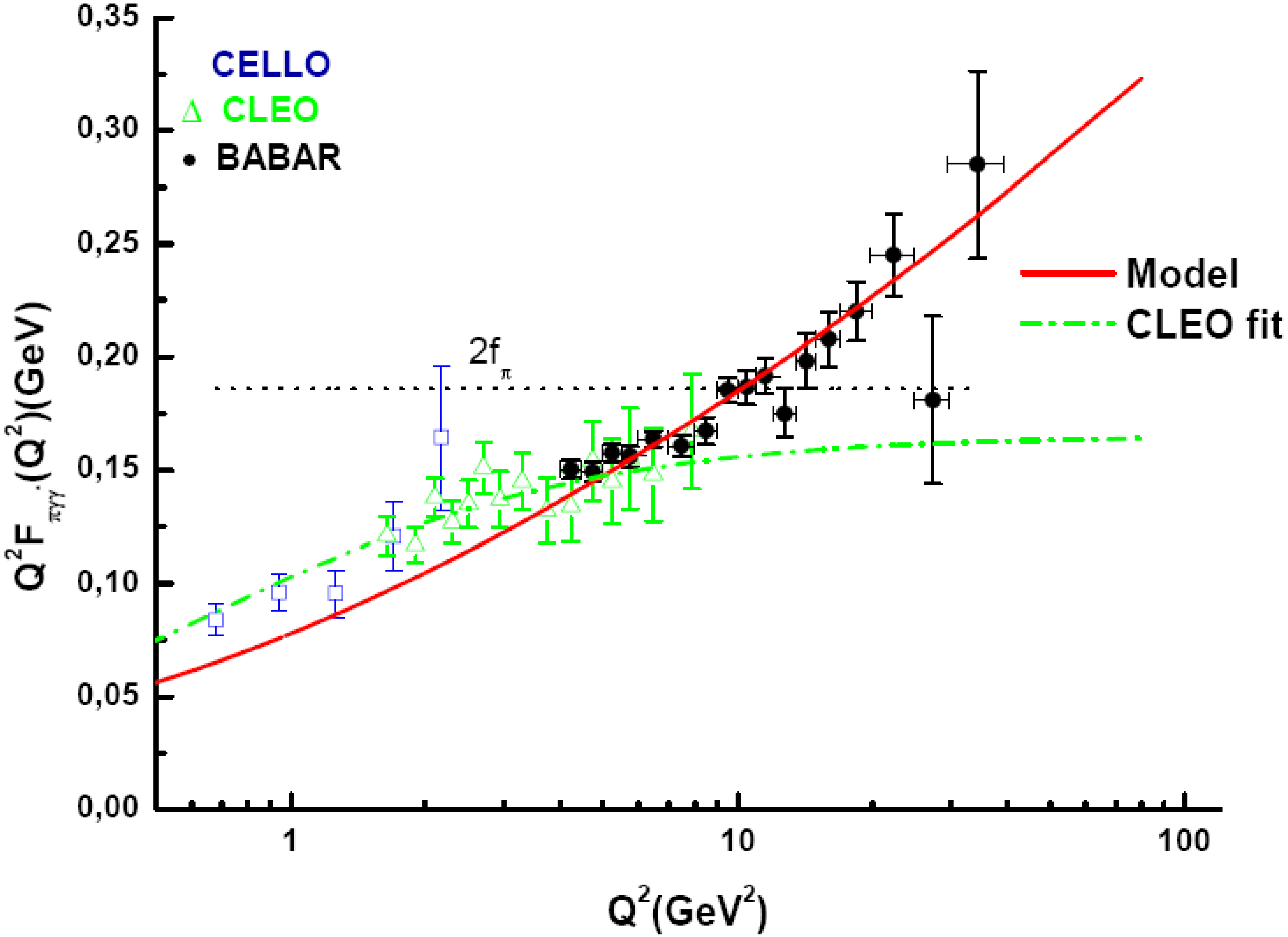
The Distribution Amplitude is

$$\varphi_P(x) = \frac{N_C}{4\pi^2 f_P^2} \int_0^\infty dL e^{x(1-x)M_P^2} \left[x G^{m,0}\left(xL, (1-x)L\right) + (1-x) G^{0,m}\left(xL, (1-x)L\right) \right]$$

$$F_{P\gamma^*\gamma^*}\left(p^2; q_1^2 \to \infty, q_2^2 \approx 0\right) \to \begin{cases} \dfrac{1}{q_1^2} & \text{for } \varphi_P(x) \text{ well suppressed at } x \to 0, \\ \dfrac{1}{q_1^2} \ln\left(\dfrac{q_1^2}{M_q^2}\right) & \text{for } \varphi_P(x) \text{ flat, "badly" suppressed at } x \to 0, \end{cases}$$

The latter scenario is from **AED PEPAN Lett 2009,**
AV Radyushkin PRD 2009
MV Polyakov JETP Lett 2009

The pion transition form factor (2009)



Growing !

$M_q = 135 \text{ MeV}$

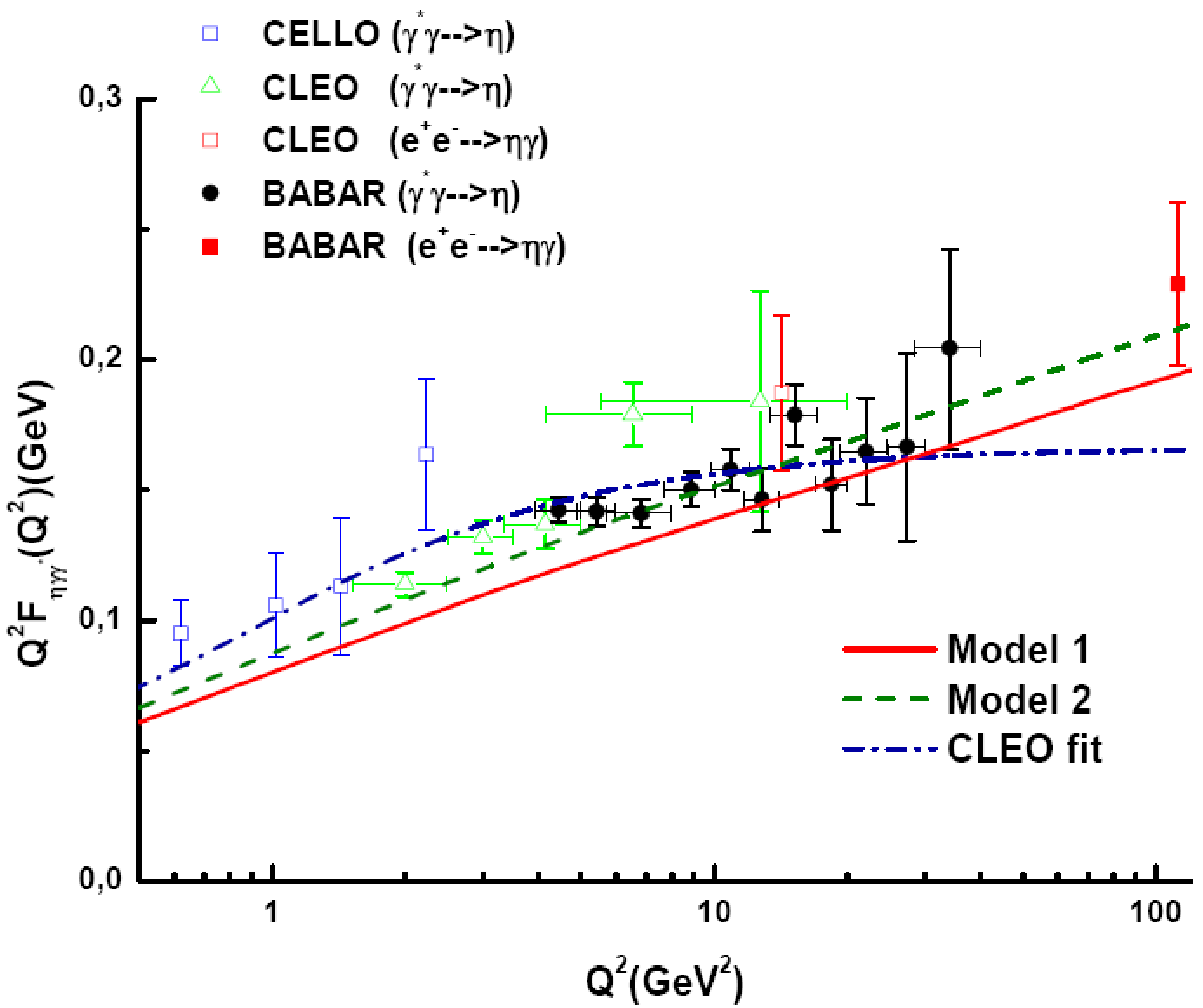
$$F_{\eta\gamma^*\gamma}\left(m_\eta^2;Q^2,0\right)=\frac{1}{3\sqrt{3}}\Big[\Big(5F_u\left(m_\eta^2;Q^2,0\right)-2F_s\left(m_\eta^2;Q^2,0\right)\Big)\cos\theta\left(m_\eta^2\right)-$$
$$-\sqrt{2}\Big(5F_u\left(m_\eta^2;Q^2,0\right)+F_s\left(m_\eta^2;Q^2,0\right)\Big)\sin\theta\left(m_\eta^2\right),$$

$$F_{\eta'\gamma^*\gamma}\left(m_{\eta'}^2;Q^2,0\right)=\frac{1}{3\sqrt{3}}\Big[\Big(5F_u\left(m_{\eta'}^2;Q^2,0\right)-2F_s\left(m_{\eta'}^2;Q^2,0\right)\Big)\sin\theta\left(m_{\eta'}^2\right)+$$
$$+\sqrt{2}\Big(5F_u\left(m_{\eta'}^2;Q^2,0\right)+F_s\left(m_{\eta'}^2;Q^2,0\right)\Big)\cos\theta\left(m_{\eta'}^2\right),$$

Very strong meson mass--shell dependence!

It is misleading that from BABAR data possible to extract separately nonstrange and strange form factors!!!

The eta transition form factor (2011)



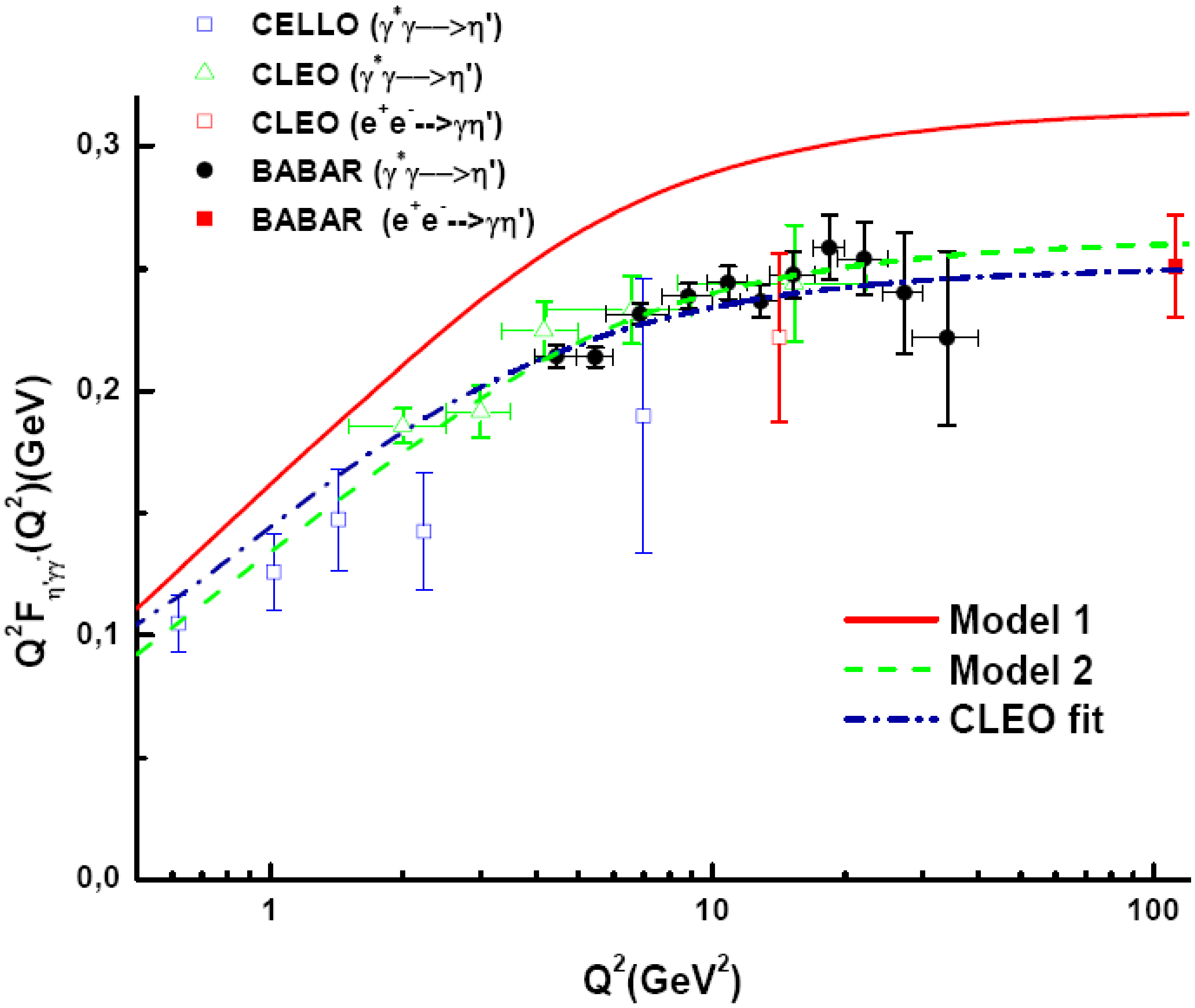
Still Growing !

$$M_q = 135 \text{ MeV}$$

$$M_s = 250 \text{ MeV}$$

$$\theta\left(m_\eta^2\right) \approx 5^o$$

The eta' transition form factor (2011)



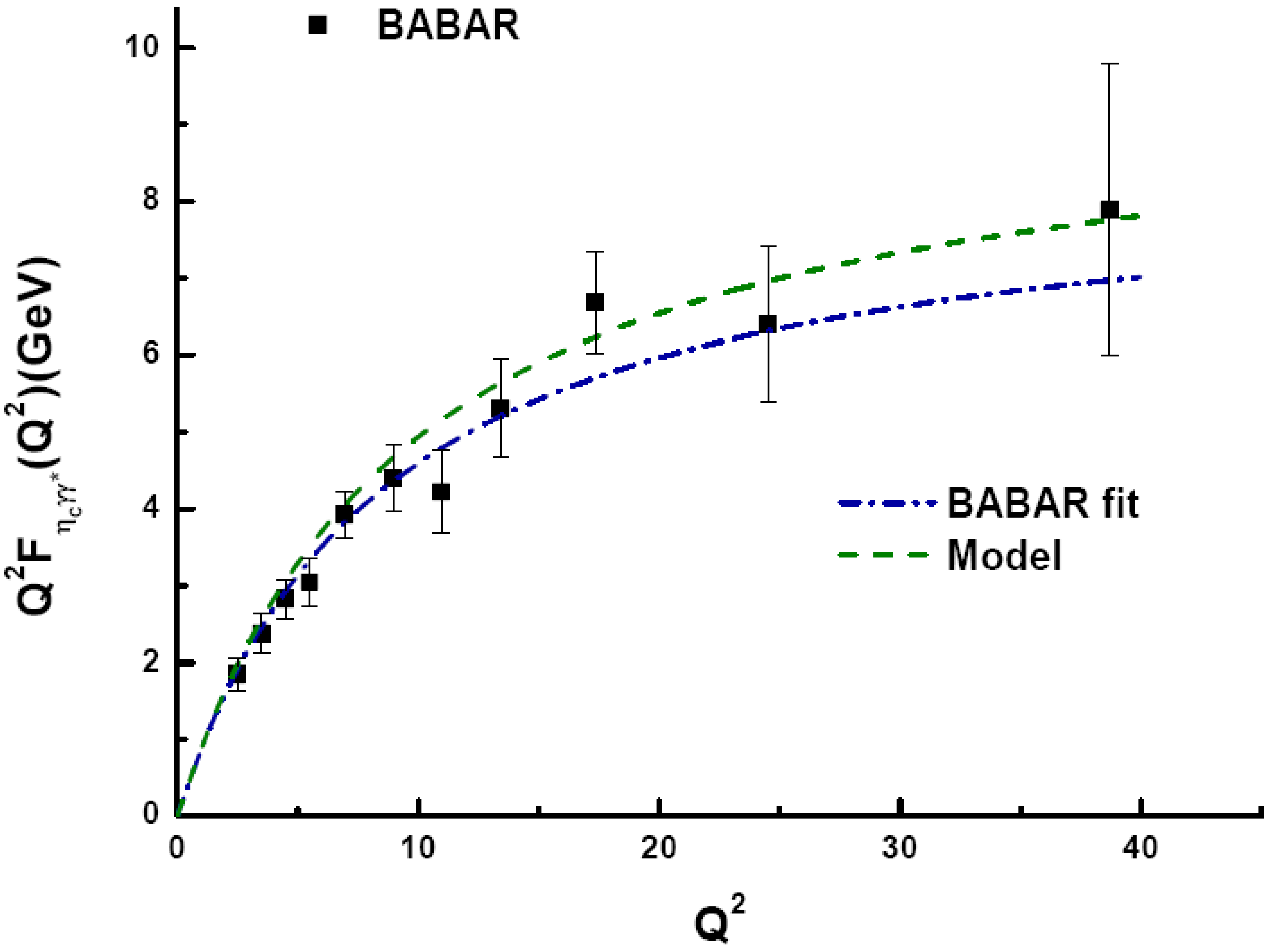
Saturating !

$$M_q = 135 \text{ MeV}$$

$$M_s = 250 \text{ MeV}$$

$$\theta\left(m_{\eta'}^2\right) \approx -50^o$$

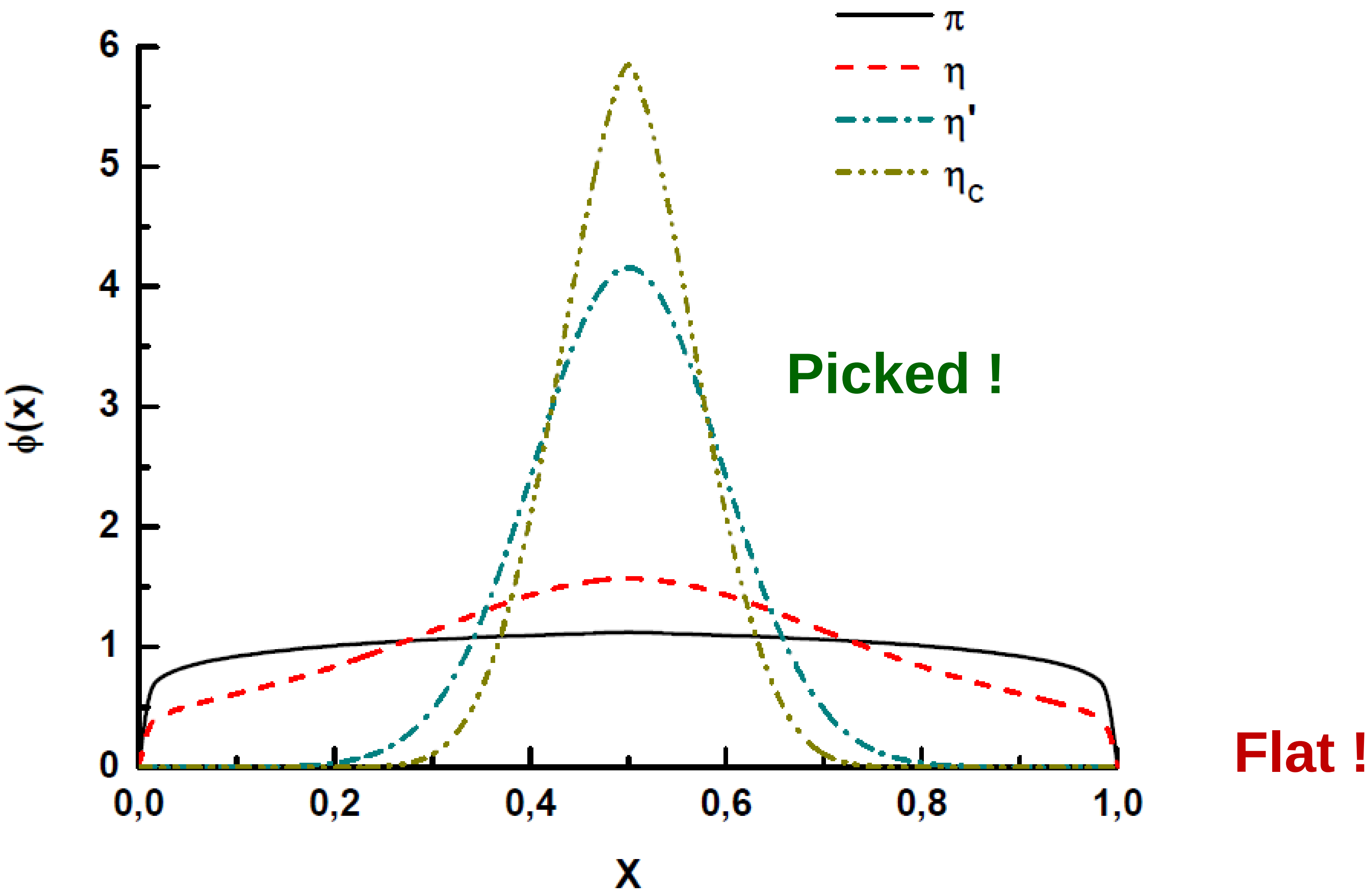
The eta$_C$ transition form factor (2011)



Saturating !

$M_C = 1550$ MeV

The PS meson Distribution Amplitudes



CONCLUSIONS

1. BABAR measured photon-pion form factor at large Q^2 in wide kinematical region and found that the data for $Q^2F(Q^2)$ exceed the asymptotic Brodsky-Lepage limit and, moreover, continue to growth – BABAR puzzle

2. BABAR measured photon-PS form factors (PS = η,η',η_c) and found that this growth absent or not evident (for η) – BABAR puzzle 2

3. The growth of the pion FF is explained within the nonlocal chiral quark model that generates the flat-like Distribution Amplitude and then $Q^2F(Q^2) \sim \ln(Q^2)$

4. *By using the same model and parameters we are able to explain all BABAR data simultaneously*

5. *Pion and Eta DAs are flat-like and FF grow,*
   Eta' and EtaC are strongly peaked and FF are saturated

6. BABAR data, if will be confirmed, point out on specific properties of quark dynamics in the pion and of the underlying QCD vacuum