E2-2003-85

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CLEO AND **E791** DATA: A SMOKING GUN FOR THE PION DISTRIBUTION AMPLITUDE?

Submitted to «Physics Letters B»

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Dedicated to Prof. D. V. Shirkov's 75th Birthday

The recent high-precision CLEO results [1] for the $\pi\gamma$ transition form factor gave rise to dedicated theoretical investigations [2, 3, 4, 5, 6, 7, 8, 9]. These experimental data are of particular importance because they can provide crucial quantitative information on nonperturbative parameters of the pion DA and – as we pointed out in [9] – on the QCD vacuum nonlocality parameter λ_q^2, which specifies the average virtuality of the vacuum quarks. In the absence of a direct solution of the nonperturbative sector of QCD, we are actually forced to extract related information from the data, relying upon a theoretical analysis as complete and as accurate as currently possible.

It was shown by Khodjamirian [5] that the most appropriate tool to analyze the CLEO data is provided by the light-cone QCD sum-rule (LCSR) method. Schmedding and Yakovlev (SY) [6] applied these LCSRs to the NLO of QCD perturbation theory. More recently [9], we have taken up this sort of data processing in an attempt to (i) account for a correct ERBL [10] evolution of the pion DA to each measured momentum scale, (ii) estimate more precisely the contribution of the (next) twist-4 term, and (iii) improve the error estimates in determining the 1- and 2-σ error contours.

The main outcome of these theoretical analyses can be summarized as follows: (i) the asymptotic pion DA [10] and the Chernyak–Zhitnitsky (CZ) [11] one are both outside the 2-σ error regions; (ii) the extracted parameters a_2 and a_4 are rather sensitive to the strong radiative corrections and to the size of the twist-4 contribution; (iii) the CLEO data allow us to estimate the correlation scale in the QCD vacuum, λ_q^2, to be $\lesssim 0.4$ GeV^2.

The present note gives a summary of our lengthy analysis [9] extending it a step further in an attempt to obtain from the CLEO data a direct estimate for the inverse moment of the pion DA that plays a crucial role in electromagnetic/transition form factors of the pion. Moreover, we take into account the variation of the twist-4 contribution and treat the threshold effects in the strong running coupling more accurately. The predictive power of our refined analysis lies in the fact that the value of the inverse moment obtained from an *independent* sum rule is compatible with that extracted from the CLEO data, referring in both cases to the same low momentum scale. As a result, the pion DA obtained from QCD sum rules with nonlocal condensates is within the 1-σ error region, while the asymptotic and the CZ pion DAs are clearly excluded, as being well outside the 2-σ region. Our prediction for the pion DA is confirmed by the Fermilab E791 data [12].

Below, we sketch the improved NLO procedure for the data processing, developed in [9]. Let us recall that this procedure is based on LCSRs for the transition form factor $F^{\gamma^*\gamma\pi}(Q^2, q^2 \approx 0)$ [5, 6]. Accordingly, the main expression for the form factor follows from the dispersion relation

$$\begin{aligned} F_{\rm LCSR}^{\gamma^*\gamma\pi}(Q^2) &= \int_0^{s_0} \frac{ds}{m_\rho^2}\,\rho(Q^2, s; \mu^2) e^{(m_\rho^2 - s)/M^2} + \int_{s_0}^{\infty} \frac{ds}{s}\,\rho(Q^2, s; \mu^2)\,; \qquad (1) \\ \rho(Q^2, s; \mu^2) &\equiv \mathbf{Im}\left[\frac{1}{\pi}\,F_{\rm QCD}^{\gamma^*\gamma^*\pi}(Q^2, s; \mu^2)\right], \end{aligned}$$

$F_{\rm QCD}^{\gamma^*\gamma^*\pi}(Q^2, q^2; \mu^2)$ on the r.h.s. of (1) is calculated by virtue of the factorization theorem for the form factor at Euclidean photon virtualities $q_1^2 = -Q^2 < 0$, $q_2^2 = -q^2 \leq 0$ [10, 13], with $M^2 \approx 0.7$ GeV^2 being the Borel parameter, whereas m_ρ is the ρ-meson mass, and $s_0 = 1.5$ GeV^2 denotes the effective threshold in the ρ-meson channel. The factorization scale μ^2 is fixed by SY at $\mu^2 = \mu_{SY}^2 = 5.76$ GeV^2. Moreover, $F_{\rm QCD}^{\gamma^*\gamma^*\pi}(Q^2, q^2; \mu^2)$ contains a twist-4 contribution, which is proportional to the coupling $\delta^2(\mu^2)$. This contribution has been calculated for the asymptotic twist-4 DAs of the pion [5].

We set $\mu^2 = Q^2$ in $F_{\rm QCD}^{\gamma^*\gamma^*\pi}(Q^2, q^2; \mu^2)$ and use the complete 2-loop expression for the form factor, absorbing the logarithms into the coupling constant and the pion DA evolution at the NLO [9] so that $\alpha_s(\mu^2) \stackrel{\rm RG}{\longrightarrow} \alpha_s(Q^2)$ (RG denotes the renormalization group) and

$$\varphi_\pi(x; \mu^2) \stackrel{\rm ERBL}{\longrightarrow} \varphi_\pi(x; Q^2) = U(\mu^2 \to Q^2)\varphi_\pi(x; \mu^2).$$

Then, we use the spectral density $\rho(Q^2, s) = \mathbf{Im}\left[F_{\rm QCD}^{\gamma^*\gamma^*\pi}(Q^2, q^2; Q^2)/\pi\right]$, derived in [6] at $\mu^2 = \mu_{\rm SY}^2$, in Eq. (1) to obtain $F^{\gamma^*\gamma\pi}(Q^2)$ and fit the CLEO data over the probed momentum range, denoted by $\{Q_{\rm exp}^2\}$. In our recent analysis [9] the evolution $\varphi_\pi(x; Q^2) = U(\mu_{\rm SY}^2 \to Q^2)\varphi_\pi(x; \mu_{\rm SY}^2)$ was performed *for every point* $Q_{\rm exp}^2$, with the aim to return to the normalization scale $\mu_{\rm SY}^2$ and to extract the DA parameters $(a_2,\ a_4)$ at this reference scale for the sake of comparison with the previous SY results [6]. Stated differently, for every measurement, $\{Q_{\rm exp}^2, F^{\gamma^*\gamma\pi}(Q_{\rm exp}^2)\}$, its own factorization/renormalization scheme has been used so that the NLO radiative corrections were taken into account in a complete way. The accuracy of this procedure is still limited mainly by the uncertainties of the twist-4 scale parameter [9], $k \cdot \delta^2$, where the factor k expresses the deviation of the twist-4 DAs from their asymptotic shapes. (Another source of uncertainty is owing to the mixing of the NLO approximations for the leading twist and that for the twist-4 contribution at LO, see [9].)

To summarize, the focal points of our procedure of the CLEO data processing are (i) $\alpha_s(Q^2)$ is the exact solution of the 2-loop RG equation with the threshold $M_q = m_q$ taken at the quark mass m_q, rather than adopting the approximate popular expression in [14] that was used in the SY analysis. This is particularly important in the low-energy region $Q^2 \sim 1$ GeV^2, where the difference between these two couplings reaches about 20%. (ii) All logarithms $\ln(Q^2/\mu^2)$ appearing in the coefficient function are absorbed into the evolution of the pion DA, performed separately at each experimental point $Q_{\rm exp}^2$. (iii) The value of the parameter δ^2 has been re-estimated in [9] to read $k \cdot \delta^2(1\text{GeV}^2) = 0.19 \pm 0.02$ GeV^2 (with $k = 1$). The present study differs from the SY approach in all these points and extends our recent analysis [9] with respect to points (i) and (iii) yielding to significant improvements of the results. It turns out that the effect of varying the value of δ^2, as well as the shapes of the twist-4 DAs, exerts a quite strong influence which entails k to deviate from 1. In the absence of reliable information on higher twists, one may assume that this uncertainty is of the same order as that for the leading twist case. Therefore we set $k = 1 \pm 0.1$. As a result, the final (rather conservative) accuracy estimate for the twist-4 scale parameter can be expressed in terms of $k \cdot \delta^2(1\text{GeV}^2) = 0.19 \pm 0.04$ GeV^2. To produce the complete 2σ- and 1σ-contours, corresponding to these uncertainties, we need to unite a number of contours, resulting from the processing of the CLEO data at different values of the scale parameter $k \cdot \delta^2$ within this admissible range. This is discussed in technical detail in [9]. Here we only want to emphasize that our contours are more stretched then the SY ones.

The obtained results for the asymptotic DA (◆), the BMS model (✖) [7], the CZ DA (■), the SY best-fit point (●) [6], a recent transverse lattice result (▼) [15], and two instanton-based models, viz., (★) [16] and (✦) (using in this latter case $m_q = 325$ MeV,

Table 1: Models/fits for different values of $k \cdot \delta^2$ (see text).

$k \cdot \delta^2$	0.23 GeV^2		0.15 GeV^2	
Models/fits	$(a_2, a_4)\vert_{\mu^2_{\rm SY}}$	χ^2	$(a_2, a_4)\vert_{\mu^2_{\rm SY}}$	χ^2
best fit	(+0.28, −0.29)	0.47	(+0.16, −0.16)	0.47
●	(+0.19, −0.14)	1.0	(+0.19, −0.14)	0.57
✖	(+0.14, −0.09)	1.7	(+0.14, −0.09)	0.52
◆	(−0.003, +0.00)	5.9	(−0.003, +0.00)	2.2
■	(+0.40, −0.004)	4.0	(+0.40, −0.004)	7.0
▼	(+0.06, +0.01)	3.8	(+0.06, +0.01)	1.2
★	(+0.03, +0.005)	4.7	(+0.03, +0.005)	1.6
✦	(+0.06, −0.01)	3.6	(+0.06, −0.01)	1.1

$n = 2$, and $\Lambda = 1$ GeV) [17], are compiled in Table 1 for the maximal and the minimal twist-4 scale parameter. For the middle $k \cdot \delta^2$ value (0.19 GeV^2) – discussed in [9] – the corresponding values of the best-fit point (✚) are $a_2(\mu^2_{\rm SY}) = +0.22$, $a_4(\mu^2_{\rm SY}) = -0.22$, and $\chi^2 = 0.47$.

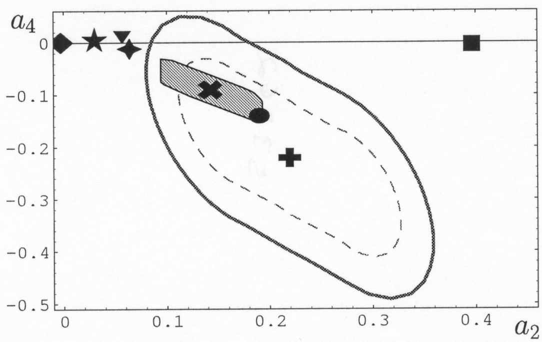

Figure 1: Analysis of the CLEO data on $F_{\pi\gamma^*\gamma}(Q^2)$ in terms of error ellipses in the (a_2,a_4) plane contrasted with various theoretical models explained in the text. The solid line denotes the 2σ-contour; the broken line stands for the 1σ-contour. The slanted shaded rectangle represents the constraints on (a_2, a_4) posed by the NLC QCD SRs [7] for the value $\lambda_q^2 = 0.4$ GeV2. All constraints are evaluated at $\mu^2_{\rm SY} = 5.76$ GeV^2 after NLO ERBL evolution.

We turn now to the important topic of whether or not the set of CLEO data is consistent with the non-local QCD SR results for φ_π. We present in Fig. 1 the results of the data analysis for the twist-4 scale parameter $k \cdot \delta^2$ varied in the interval $[0.15 \leq k \cdot \delta^2 \leq 0.23]$ GeV^2. We have established in [7] that a two-parameter model $\varphi_\pi(x; a_2, a_4)$ factually enables us to fit all the moment constraints that result from NLC QCD SRs (see [18] for more details). The only parameter entering the NLC SRs is the correlation scale λ_q^2 in the QCD vacuum, known from nonperturbative calculations and lattice simulations [19, 20]. A whole bunch of admissible pion DAs resulting from the NLC QCD SR analysis associated with $\lambda_q^2 = 0.4$ GeV^2 at $\mu_0^2 \approx 1$ GeV^2 [7] was determined, with the optimal one given analytically by

$$\varphi_\pi^{\rm BMS}(x) \;=\; \varphi_\pi^{\rm as}(x)\Big[1 + a_2^{\rm opt}\cdot C_2^{3/2}(2x-1) + a_4^{\rm opt}\cdot C_4^{3/2}(2x-1)\Big]\,, \qquad (2)$$

where $\varphi_\pi^{\rm as}(x) = 6x(1-x)$ and $a_2^{\rm opt} = 0.188$, $a_4^{\rm opt} = -0.13$ are the corresponding Gegenbauer coefficients. From Fig. 1 we observe that the NLC QCD SR constraints encoded in the slanted shaded rectangle are in rather good overall agreement with the CLEO data at the 1σ-level. This agreement could eventually be further improved adopting smaller values of λ_q^2, say, 0.3 GeV^2, which however are not supported by the QCD SR method and lattice calculations [20]. On the other hand, as it was demonstrated in [9], the agreement between QCD SRs and CLEO data fails for larger values of λ_q^2, e. g., 0.5 GeV^2.

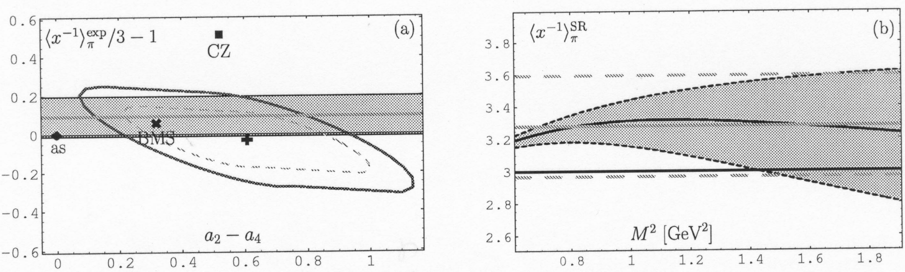

Figure 2: (a) The result of the CLEO data processing for the quantity $\langle x^{-1}\rangle_\pi^{\rm exp}/3-1$ at the scale $\mu_0^2 \approx 1$ GeV^2 in comparison with three theoretical models. The thick solid-line contour corresponds to the union of 2σ-contours, while the thin dashed-line contour denotes the union of 1σ-contours. The light solid line with the hatched band indicates the mean value of $\langle x^{-1}\rangle_\pi^{\rm SR}/3-1$ and its error bars in the second part of the Figure. (b) The inverse moment $\langle x^{-1}\rangle_\pi^{\rm SR}$ shown as a function of the Borel parameter M^2 from the NLC SR at the same scale μ_0^2 [7]; the light solid line is the estimate for $\langle x^{-1}\rangle_\pi^{\rm SR}$; the dashed lines correspond to its error-bars.

In the present study we have processed the CLEO data in such a way as to obtain an experimental constraint on the value of $\langle x^{-1}\rangle_\pi = \int_0^1 \varphi_\pi(x)x^{-1}dx$ that appears in different perturbative calculations of pion form factors. This is illustrated in Fig. 2(a). A "daughter SR" has been previously constructed directly for this quantity by integrating the r.h.s. of the SR for $\varphi_\pi(x)$ with the weight x^{-1}, (for details, see [21, 7]). Due to the smooth behavior of the NLC at the end points $x = 0, 1$, this integral is well defined, supplying us with an *independent* SR, with a rather good stability behavior of $\langle x^{-1}\rangle_\pi^{\rm SR}(M^2)$, as one sees from Fig. 2(b). We have estimated $\langle x^{-1}\rangle_\pi^{\rm SR}(\mu_0^2 \approx 1\ {\rm GeV}^2) = 3.28 \pm 0.31$ at the value $\lambda_q^2 = 0.4$ GeV^2 of the non-locality parameter. It should be emphasized that this estimate is not related to the pion DA, $\varphi_\pi^{\rm BMS}(x; a_2, a_4)$, constructed within the same framework. Nevertheless, the value obtained with the "daughter" QCD SR and those calculated using the bunch of pion DAs, mentioned above, match each other.

On the other hand, from the CLEO data one obtains a constraint on the value of $a_2 + a_4 = \langle x^{-1}\rangle_\pi^{\rm exp}/3 - 1$ at the low point $\mu_0^2 \approx 1$ GeV^2 that complies with the NLC SR estimate. In Fig. 2(a) we demonstrate the united regions, corresponding to the merger of the 2σ-contours (solid thick line) and the 1σ-contours (thin dashed line), which have been obtained for values of the twist-4 scale parameter within the determined range. This resulting admissible region is strongly stretched along the $(a_2 - a_4)$ axis, demonstrating the poor accuracy for this combination of DA parameters, while more restrictive constraints are obtained for $\langle x^{-1}\rangle_\pi^{\rm exp}$. One appreciates that the NLC SR result, $\langle x^{-1}\rangle_\pi^{\rm SR}$, with its error bars appears in good agreement with the constraints to $\langle x^{-1}\rangle_\pi^{\rm exp}$ at the 1σ-level, as one sees from the light solid line within the hatched band in Fig. 2(a). In particular, the 1σ-constraint obtained at the central value $k \cdot \delta^2 = 0.19$ GeV^2 exhibits the same good agreement with the corresponding SR estimate because the theoretical uncertainty of the twist-4 scale parameter affects only the $(a_2 - a_4)$ constraint. Moreover, the estimate $\langle x^{-1}\rangle_\pi^{\rm SR}$ practically coincides with that obtained in the data analysis on the electromagnetic pion form factor in the framework of a different LCSR method in [22]. These three independent estimates are in good agreement to each other, giving robust support that the CLEO data processing and the theoretical calculations are mutually consistent.

More importantly, the end-point contributions to the $\langle x^{-1}\rangle_\pi^{\rm SR}$ are suppressed, the range of suppression being controlled by the value of the parameter λ_q^2. The larger this parameter, at fixed resolution scale $M^2 > \lambda_q^2$, the stronger the suppression of the NLC contribution. Similarly, an excess of the value of $\langle x^{-1}\rangle_\pi$ over 3 (asymptotic DA) is also controlled by the value of λ_q^2, becoming smaller with increasing λ_q^2. Therefore, to match the value $\langle x^{-1}\rangle_\pi^{\rm SR}$ to the CLEO best-fit point (✚) in Fig. 2(a), would ask to use larger values of λ_q^2 than 0.4 GeV^2. But this is in breach of the (a_2, a_4) error ellipses. A window of about 0.05 GeV^2 exists to vary λ_q^2: any smaller and one is at the odds with QCD SRs and lattice calculations [20]; any larger and the NLC QCD SRs rectangle can tumble out of the CLEO data region.

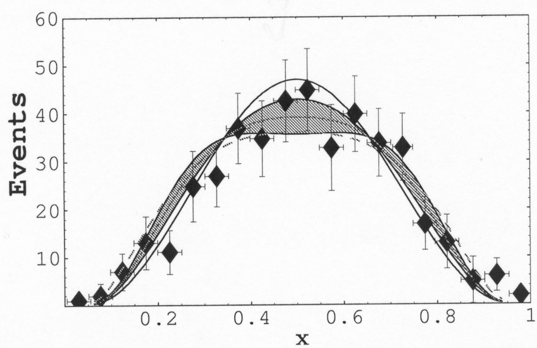

Figure 3: Comparison of $\varphi^{\rm as}$ (solid line), $\varphi^{\rm CZ}$ (dashed line), and the BMS bunch of pion DAs (strip, [9]) with the E791 data [12].

Before we come to the Fermilab experiment [12], let us summarize our findings. They have been obtained by refining the CLEO data analysis in the following points. We corrected the mass thresholds in the running strong coupling and incorporated the variation of the twist-4 contribution more properly. In addition, the CLEO data were used to extract a direct constraint on the inverse moment $\langle x^{-1}\rangle_\pi(\mu_0^2)$ of the pion DA – at the core of form-factor calculations. This has relegated the asymptotic and CZ pion DAs beyond the 2σ level (95%), with the SY best-fit point still belonging to the 1σ deviation region (68%) in the parameter space of (a_2, a_4), while providing compelling argument in favor of our model [7].

To compare our model DA for the pion [7] with the E791 di-jet events, we adopt the convolution approach developed in [23] having also recourse to [24]. The results are displayed in Fig. 3 making evident that, though the data from E791 are not that sensitive as to exclude other shapes for the pion DA, also displayed for comparison, they are in good agreement with our prediction.

As a conclusion, both analyzed experimental data sets (CLEO [1] and Fermilab E791 [12]) converge to the conclusion that the pion DA is not everywhere a convex function, like the asymptotic one, but has instead two maxima with the end points ($x = 0, 1$) strongly suppressed – in contrast to the CZ DA. These two key features are controlled by the QCD vacuum correlation length λ_q^2, whose value suggested by the CLEO data analysis here and in [9] is approximately 0.4 GeV^2 in good compliance with the QCD SR estimates and lattice computations [20].

Acknowledgments. This work was supported in part by the Russian Foundation for Fundamental Research (contract 03-02-16816), INTAS-CALL 2000 N 587, the Heisenberg–Landau Programme (grants 2002 and 2003), the COSY Forschungsprojekt Jülich/Bochum, and the DFG.

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Received on April 25, 2003.

Бакулев А. П., Михайлов С. В., Стефанис Н. Г. E2-2003-85

Действительно ли данные экспериментов CLEO и E791 позволяют определить пионную амплитуду распределения?

Анализируются экспериментальные данные CLEO по переходу $\gamma^*\gamma \to \pi$ в $O(\alpha_s)$-правилах сумм (ПС) на световом конусе. Обработка результатов CLEO усовершенствованным нами методом Ходжамиряна–Шмеддинга–Яковлева дала новые ограничения на параметры пионной амплитуды распределения (АР) — коэффициенты Гегенбауэра a_2 и a_4, а также на ее обратный момент $\langle x^{-1}\rangle_\pi$. Первые определяют АР пиона в низкой точке нормировки, последний входит в пертурбативные КХД-формулы для формфакторов пиона. Мы исследовали чувствительность полученных для коэффициентов a_2 и a_4 ограничений к вариации вклада твиста-4 и показали, что данные эксперимента CLEO подтверждают модели АР пиона, следующие из КХД ПС с нелокальными конденсатами. В то же время как асимптотическая АР, так и АР Черняка–Житницкого исключены ими полностью. Мы также проверили, что спектр пионных АР, построенных ранее в КХД ПС с нелокальными конденсатами, хорошо согласуется с данными эксперимента E791 по образованию двух струй в дифракционных πA-взаимодействиях. Таким образом, на поставленный в заголовке вопрос мы отвечаем утвердительно.

Работа выполнена в Лаборатории теоретической физики им. Н. Н. Боголюбова ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 2003

Bakulev A. P., Mikhailov S. V., Stefanis N. G. E2-2003-85

CLEO and E791 Data: A Smoking Gun for the Pion Distribution Amplitude?

The CLEO experimental data on the $\pi\gamma$ transition are analyzed to NLO in QCD perturbation theory using light-cone QCD sum rules. By processing the data along the lines proposed by Khodjamiryan, Schmedding and Yakovlev, and recently revised by us, we obtain new constraints for the Gegenbauer coefficients a_2 and a_4, as well as for the inverse moment $\langle x^{-1}\rangle_\pi$ of the pion distribution amplitude (DA). The former determine the pion DA at low momentum scale, the latter is crucial in calculating pion form factors. From the results of our analysis we conclude that the data confirm the shape of the pion DA we previously obtained with QCD sum rules and nonlocal condensates, while the exclusion of the asymptotic and the Chernyak–Zhitnitsky DA is reinforced. We also investigate the sensitivity of the calculated coefficients in this analysis to the twist-4 contribution and check out pion DA against the di-jets data of the E791 experiment, providing credible evidence for our results far more broadly. Thus, our answer to the question in the title is positive.

The investigation has been performed at the Bogoliubov Laboratory of Theoretical Physics, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna, 2003

Макет *Т. Е. Попеко*

Подписано в печать 17.06.2003.
Формат 60 × 90/16. Бумага офсетная. Печать офсетная.
Усл. печ. л. 0,68. Уч.-изд. л. 1,20. Тираж 415 экз. Заказ № 53962.

Издательский отдел Объединенного института ядерных исследований
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