DIRAC EXPERIMENT AND TEST OF LOW-ENERGY QCD

M. PENTIA

NIPNE-HH, P.O.Box MG-6, 76900, Bucharest-Magurele, ROMANIA
E-mail: pentia@ifin.nipne.ro

on behalf of
"The DIRAC Collaboration"

B. Adeva[o], L. Afanasev[l], M. Benayoun[d], V. Brekhovskikh[n], G. Caragheorgheopol[m], T. Cechak[b], M. Chiba[j], S. Constantinescu[m], A. Doudarev[l], D. Dreossi[f], D. Drijard[a], M. Ferro-Luzzi[a], T. Gallas Torreira[a,o], J. Gerndt[b], R. Giacomich[f], P. Gianotti[e], F. Gomez[o], A. Gorin[n], O. Gortchakov[l], C. Guaraldo[e], M. Hansroul[a], R. Hosek[b], M. Iliescu[e,m], N. Kalinina[l], V. Karpoukhine[l], J. Kluson[b], M. Kobayashi[g], P. Kokkas[p], V. Komarov[l], A. Koulikov[l], A. Kouptsov[l], V. Krouglov[l], L. Krouglova[l], K.-I. Kuroda[k], A. Lanaro[a,e], V. Lapshine[n], R. Lednicky[c], P. Leruste[d], P. Levisandri[e], A. Lopez Aguera[o], V. Lucherini[e], T. Maki[i], I. Manuilov[n], L. Montanet[a], J.-L. Narjoux[d], L. Nemenov[a,l], M. Nikitin[l], T. Nunez Pardo[o], K. Okada[h], V. Olchevskii[l], A. Pazos[o], M. Pentia[m], A. Penzo[f], J.-M. Perreau[a], C. Petrascu[e,m], M. Plo[o], T. Ponta[m], D. Pop[m], A. Riazantsev[n], J.M. Rodriguez[o], A. Rodriguez Fernandez[o], V. Rykaline[n], C. Santamarina[o], J. Schacher[q], A. Sidorov[n], J. Smolik[c], F. Takeutchi[h], A. Tarasov[l], L. Tauscher[p], S. Trousov[l], P. Vazquez[o], S. Vlachos[p], V. Yazkov[l], Y. Yoshimura[g], P. Zrelov[l]

[a] CERN, Geneva, Switzerland ; [b] Czech Technical University, Prague, Czech Republic ; [c] Prague University, Czech Republic ; [d] LPNHE des Universites Paris VI/VII, IN2P3-CNRS, France ; [e] INFN - Laboratori Nazionali di Frascati, Frascati, Italy ; [f] Trieste University and INFN-Trieste, Italy ; [g] KEK, Tsukuba, Japan ; [h] Kyoto Sangyou University, Japan ; [i] UOEH-Kyushu, Japan ; [j] Tokyo Metropolitan University, Japan ; [k] Waseda University, Japan ; [l] JINR Dubna, Russia ; [m] National Institute for Physics and Nuclear Engineering NIPNE-HH, Bucharest, Romania ; [n] IHEP Protvino, Russia ; [o] Santiago de Compostela University, Spain ; [p] Basel University, Switzerland ; [q] Bern University, Switzerland

The low-energy QCD predictions to be tested by the DIRAC experiment are revised. The experimental method, the setup characteristics and capabilities, along with first experimental results are reported. Preliminary analysis shows good detector performance: alignment error via Λ mass measurement $m_\Lambda = 1115.6\ MeV/c^2$ with $\sigma = 0.92\ MeV/c^2$, $p\pi^-$ relative momentum resolution $\sigma_Q \approx 2.7\ MeV/c$, and evidence for $\pi^+\pi^-$ low momentum Coulomb correlation.

1 Introduction

Quantum Chromodynamics (QCD), responsible for the strong interaction sector of the Standard Model (SM) has successfully been tested only in the perturbative region of high momentum transfer ($Q > 1\ GeV$) or at short relative distance $\Delta r \sim \hbar/Q$ ($\Delta r < 0.2 fm$). Here the constituent quarks behave as weakly interacting, nearly massless particles. The QCD in the perturbative region, as any gauge theory with massless fermions, presents chiral symmetry.

In the nonperturbative region of low momentum transfer (low-energy), say $Q < 100\ MeV$, or equivalently at large distance ($\Delta r > 2 fm$), asymptotic freedom is absent, and quark confinement takes place. In the low energy region the chiral symmetry of QCD must be spontaneously broken.

The *Chiral Perturbation Theory* (ChPT)[1,2] seems to be the candidate theory for low energy processes. It exploits the mechanism of spontaneous breakdown of chiral symmetry (SBChS), or, in other words, the existence of a quark condensate. In order to test the existence of the quark condensate, the particularly significant symmetry breaking effect refers to the *S-wave $\pi\pi$ scattering lengths*. From the theoretical point of view, $\pi\pi$ scattering is a deeply studied problem. Within standard ChPT, Gasser and Leutwyler[1,2,3] and also Bijnens and collaborators[4] as well as within the *Generalized Chiral Perturbation Theory* (GChPT), Stern and collaborators[5,6], have obtained expressions for the $\pi\pi$ scattering amplitude in the chiral expansion.

The leading order expansion of the scattering amplitude is[6]

$$A(s;t,u) = \alpha \frac{M_\pi^2}{3F_\pi^2} + \frac{\beta}{F_\pi^2}\left(s - \frac{4}{3}M_\pi^2\right) + \mathcal{O}(p^4) \quad (1)$$

where α and β encode the information on the strength of the quark condensate. In the limit of a strong quark condensate, one has $\alpha \approx 1$, $\beta \approx 1$. A substantial departure of α from unity signals a much smaller value of the condensate.

The values predicted for the isospin $I = 0$ and $I = 2$ S-wave scattering lengths a_0^0 and a_0^2 can be confronted with the future experimental values of the DIRAC experiment. The available experimental data[7] for the scattering length is $a_0^0 = 0.26 \pm 0.05$. Based on these data there is no possibility to estimate the strength of the quark condensate and so to measure the extent of chiral symmetry breaking.

The DIRAC experiment[8] aims to determine the difference of the scattering lengths $\Delta = |a_0^0 - a_0^2|$ with 5% accuracy, by measuring the lifetime of pionium ($\pi^+\pi^-$ bound state). For the first time experimental evidence in favour of or against the existence of a strong quark condensate in the QCD vacuum could be within reach.

2 Pionium lifetime

Pionium is a metastable bound state, produced by π^+ and π^- electromagnetic interaction and decaying into $\pi^0\pi^0$ due to strong interaction. To obtain pion scattering lengths in a model independent way, a measurement of the lifetime of pionium has been proposed many years ago by Nemenov[9]. The measurement of the pionium lifetime (τ) will allow to determine the difference $|a_0^0 - a_0^2|$ of the strong S-wave $\pi\pi$-scattering lengths for isospin $I = 0$ and $I = 2$.

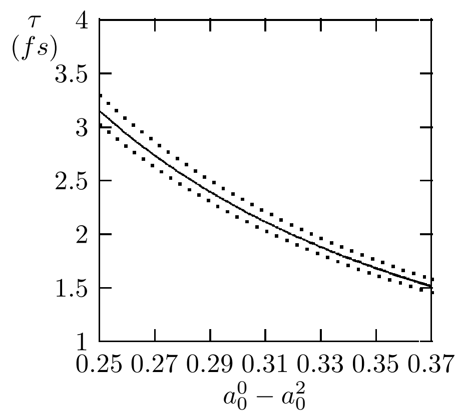

Figure 1. The pionium lifetime, in units of 10^{-15} s, as a function of the combination $(a_0^0 - a_0^2)$ of the S-wave scattering lengths. The band delineated by the dotted lines takes account of the uncertainties, coming from theoretical evaluations, low energy constants and a_1^1. (Thanks to H.Sazdjian hep-ph/9911520).

The general expression for the pionium decay width (Γ), according to ChPT[10] at leading and next-to-leading order in isospin breaking, is

$$\frac{1}{\tau} = \Gamma = \frac{2}{9} \cdot \alpha^3 \cdot p^* \cdot \left(a_0^0 - a_0^2 + \epsilon\right)^2 (1 + K)\,, \tag{2}$$

where α is the fine structure constant ;
$p^* = \left(M_{\pi^+}^2 - M_{\pi^0}^2 - \alpha^2 M_{\pi^+}^2/4\right)^{1/2}$ is the CM momentum of π^0 ;
$\epsilon = (0.58 \pm 0.16) \cdot 10^{-2}$; $K = 1.07 \cdot 10^{-2}$.

Using Eq.(2), $a_0^0 = 0.206$ and $a_0^2 = -0.0443$, Gasser et al.[10] have evaluated the pionium lifetime in the ground state $\tau = 3.25 \cdot 10^{-15} s$. In the isospin symmetry limit $\epsilon = 0$; $K = 0$, Eq.(2) becomes the Deser type formula[11].

Eq.(2) allows to get a relative error of the scattering lengths difference $\frac{\Delta\left(a_0^0 - a_0^2\right)}{\left(a_0^0 - a_0^2\right)} \approx 5\%$, if DIRAC measures the lifetime with a $\frac{\Delta\tau}{\tau} \approx 10\%$ error.

According to GChPT[13] the τ vs. $(a_0^0 - a_0^2)$ dependence is presented in Fig.1. Hence the experimental determination of the pionium lifetime could be interpreted in quark condensation terms for three different cases: First, if the central value of τ is close to 3×10^{-15} s, lying above 2.9×10^{-15} s, then the strong condensate assumption of ChPT is firmly confirmed, since its predictions of $(a_0^0 - a_0^2)$ lie between 0.250 and 0.258. Second, if the central value of τ lies below 2.4×10^{-15} s, it is the scheme of GChPT, which is confirmed, since the corresponding central value of α would lie above 2. The third possibility is the most difficult to interpret. If the central value of τ lies in the interval $2.4 \div 2.9 \times 10^{-15}$ s, then, because of the uncertainties, ambiguities in the interpretation may arise.

3 Experimental method

In an abundent production of oppositely charged pions the Coulomb interaction can form atomic $\pi^+\pi^-$ bound states. If the pions have a small relative momentum in their CM system ($Q \sim 1\ MeV/c$) and are much closer than the Bohr radius (387 fm), then pionium atoms are produced with a high production probability due to the large wave function overlap. Such pions originate from short-lived sources (ρ, ω, Δ), and not from long-lived ones (η, K_s^0), because in the latter case the separation of the two pions is in most cases larger than the Bohr radius.

The pionium production cross section is proportional to the double inclusive cross section $d\sigma_s^0/(d\vec{p}_1 d\vec{p}_2)$ for $\pi^+\pi^-$ pairs from short-lived sources, without Coulomb interaction in the final state[9], and to the squared atomic wave function of nS-states at the origin $|\psi_n(0)|^2$

$$\frac{d\sigma_n^A}{d\vec{p}_A} = (2\pi)^3 \frac{E_A}{M_A} |\psi_n(0)|^2 \frac{d\sigma_s^0}{d\vec{p}_1 d\vec{p}_2}\Big|_{\vec{p}_1=\vec{p}_2=\frac{\vec{p}_A}{2}} \tag{3}$$

where $\vec{p}_A, E_A$ and M_A are momentum, energy and mass of the pionium atom in the Lab system respectively; $\vec{p}_1$ and $\vec{p}_2$ are the π^+ and π^- momenta in the Lab system, and they must satisfy the relation $\vec{p}_1 = \vec{p}_2 = \vec{p}_A/2$ to form the atomic bound state. Atoms formed in this way are in a S-state.

After production in hadron-nucleus interaction relativistic pionium atoms ($2\ GeV/c < p_A < 6\ GeV/c$) are moving in the target. They can decay or, due to electromagnetic interaction with the target material, get excited or broken-up (ionized). Using atomic interaction cross sections, for a given target material and thickness, one can calculate the break-up probability for arbitrary values of pionium momentum and lifetime. In Fig.2 there are presented these dependencies for the pionium momentum $p = 4.7\ GeV/c$.

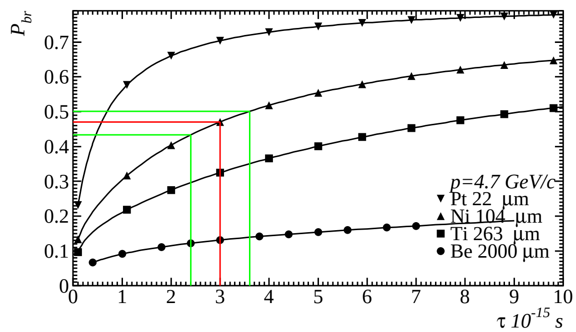

Figure 2. Probability of pionium break-up in the target.

Comparison of the measured break-up probability $P_{br} = n_A/N_A$ (ratio of broken-up - n_A and produced - N_A pionium atoms) with the calculated dependence of P_{br} on τ (see Fig.2) gives a value of the lifetime.

The break-up process gives characteristic $\pi^+\pi^-$ pairs, called *atomic pairs*. They have a small relative momentum in their CM system ($Q < 3\ MeV/c$), a small opening angle ($\theta_\pm \approx 6/\gamma \approx 0.35\ mrad$ for $p_A = 4.7\ GeV/c$) and nearly identical energies in the Lab system ($E_+ = E_-$ at 0.3 % level).

3.1 Determination of broken-up pionium atoms (n_A)

The measurement of broken-up n_A pionium atoms is realized through the analysis of the experimental distribution in Q of $\pi^+\pi^-$ pairs.

The free pion pair distribution can be written as the sum of the non-Coulomb (nC) (no final state interaction) and the Coulomb (C) pair distribution (Fig.3):

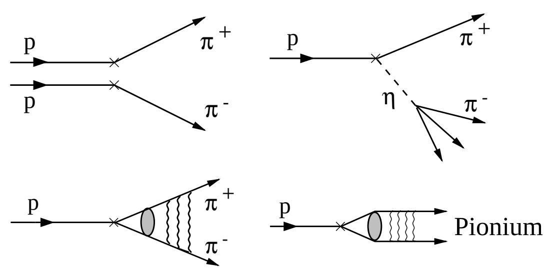

Figure 3. Accidental, non-Coulomb (long-lived sources) and Coulomb (short-lived sources) pion pair production and pionium production

$$\frac{dN^{free}}{dQ} = \frac{dN^{nC}}{dQ} + \frac{dN^{C}}{dQ}$$

$$\frac{dN^{nC}}{dQ} \sim \frac{dN^{exp}_{acc}}{dQ} \equiv \Phi(Q) \qquad ; \qquad \frac{dN^{C}}{dQ} \sim \Phi(Q)A_c(Q)(1+aQ)$$

where $A_c(Q)$ is the Coulomb and $(1+aQ)$ is the strong correlation factors.

Here we assumed that the non-Coulomb distribution of $\pi^+\pi^-$ pairs (without FSI) can be extracted from the experimental distribution of accidental pairs $\Phi(Q)$. The free pion pair distribution is then given by

$$\frac{dN^{free}}{dQ} = \frac{dN^{nC}}{dQ} + \frac{dN^{C}}{dQ} = N_0\Phi(Q)\left[f + A_c(Q)(1+aQ)\right], \qquad (4)$$

N_0, f, a - free parameters. In the region $Q > 3\ MeV/c$, there are mainly free pairs. This part of the distribution is fitted with the function (4) containing the experimental distribution $\Phi(Q)$ of $\pi^+\pi^-$ accidental pairs. The extrapolation of the approximation function to the region $Q < 2\ MeV/c$ yields the number of free pairs in this region. Hence the value n_A of atomic pairs is

$$n_A = \int\limits_{Q<2} \left(\frac{dN^{exp}}{dQ} - \frac{dN^{free}}{dQ}\right) dQ. \qquad (5)$$

From the measured break-up probability $P_{br} = n_A/N_A$, where N_A is the calculated total number (according to (3)) of produced pionium atoms, and from the dependence of P_{br} on the lifetime τ, one can derive a pionium ground state lifetime and hence a value for $\Delta = \left|a^0_0 - a^2_0\right|$.

4 Experimental setup

The experimental setup[12] (Fig.4) has been designed to detect pion pairs and to select atomic pairs at low relative momentum with a resolution better than 1 MeV/c. It was installed and commissioned in 1998 at the ZT8 beam area of the PS East Hall at CERN. After a calibration run in 1998, DIRAC has been collecting data since summer 1999.

The 24 GeV/c proton beam extracted from PS is focused on the target. The secondary particle channel, with an aperture of 1.2 msr, has the reaction plane tilted upwards at 5.7° relative to the horizontal plane. It consists of the following components: 4 planes of Micro Strip Gas Chambers (MSGC) with 4×512 channels; 2 planes Scintillation Fiber Detector (SciFi) with 2×240 channels; 2 planes Ionization Hodoscope (IH) with 2×16 channels; 1 Spectrometer Magnet of 2.3 Tm bending power. Downstream to the magnet

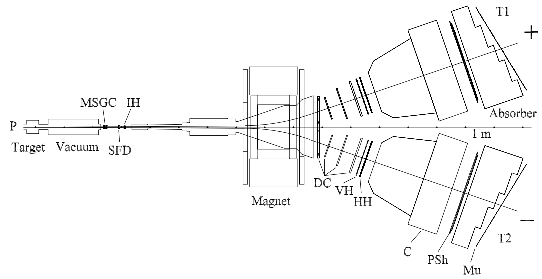

Figure 4. Experimental setup

the setup splits into two arms placed at $\pm 19°$, relative to the central axis. Each arm is equipped with a set of identical detectors: 4 Drift Chambers (DC), the first one common to both arms and with 6 planes and 800 channels, the other DC's have altogether per arm 8 planes and 608 channels; 1 Vertical scintillation Hodoscope (VH) plane with 18 channels; 1 Horizontal scintillation Hodoscope (HH) plane with 16 channels; 1 Cherenkov detectors (Ch) with 10 channels; 1 Preshower scintillation detector (PSh) plane with 8 channels; 1 Muon counter (Mu) plane with (28+8) channels.

For suppressing the large background rate a multilevel trigger was designed to select atomic pion pairs. The trigger levels are defined as follows: $T_0 = (VH \cdot PSh)_1 \cdot (VH \cdot PSh)_2 \cdot IH$, fast zero level trigger; $T_1 = (VH \cdot HH \cdot \overline{Ch} \cdot PSh)_1 \cdot (VH \cdot HH \cdot \overline{Ch} \cdot PSh)_2$, first level trigger from the downstream detectors; $T_2 = T_0 \cdot (IH \cdot SciFi)$, second level trigger from the upstream detectors, which selects particle pairs with small relative distance; T_3 is a logical trigger which applies a cut to the relative momentum of particle pairs. It handles the patterns of VH and IH detectors. T_3 did not so far trigger the DAQ system, but its decisions were recorded.

An incoming flux of $\sim 10^{11}$ protons/s would produce a rate of secondaries of about 3×10^6/s in the upstream detectors and 1.5×10^6/s in the downstream detectors. At the trigger level this rate is reduced to about 2×10^3/s, with an average event size of about 0.75 Kbytes.

With the 95 μm thin Ni target, the expected average pionium yield within the setup acceptance is $\sim 0.7\times10^{-3}$/s, equivalent to a total number of $\sim 10^{13}$ protons on target to produce one pionium atom.

5 First experimental results

The data taking has been done mainly with $\pi^+\pi^-$ and $p\pi^-$ pairs and also e^+e^- pairs for detector calibration. For the first data analysis only the most simple events were selected and processed, those with a single track in each arm, with signals in DC, VH and HH. The tracks in the DC's were extrapolated to the target plane crossing point of the proton beam. A cut was applied along X and Y distances between the extrapolated track and the hit fiber of the SciFi planes ($18mm$ divided by the particle momentum in GeV/c, to take into account the multiple scattering effect). Finally, these events were interpreted as $\pi^+\pi^-$ or $p\pi^-$ pairs produced in the target.

The difference in the time-of-flight Δt between the positive particle (left arm) and negative particle (right arm) of the pair at the level of VH is presented in Fig.5.

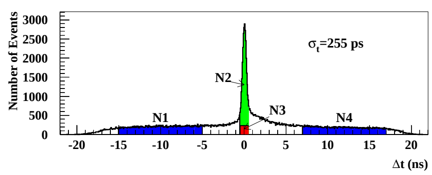

Figure 5. VH time-of-flight difference distribution for pair events

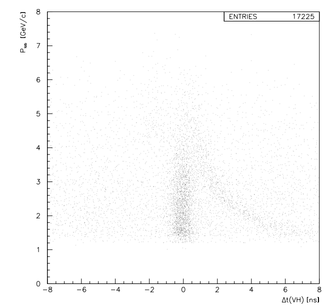

Figure 6. Positive particle momentum versus VH time-of-flight difference for particle pairs

The first interval $-20 < \Delta t < -0.5$ ns corresponds to accidental hadron pairs (mainly $\pi^+\pi^-$). In the second interval $-0.5 < \Delta t < 0.5$ ns one observes the peak of coincidence hits associated to correlated hadron pairs over the background of accidental pairs. The width of the correlated pair peak yields the time resolution of the VH ($\sigma_t \approx 250$ ps). The asymmetry on the right side of the peak is due to admixture of protons in the π^+ sample, that are $p\pi^-$ events. Hence the third interval $0.5 < \Delta t < 20$ ns contains both accidental pairs and $p\pi^-$ events.

This time-of-flight discrimination between $\pi^+\pi^-$ and $p\pi^-$ events is effective for momenta of positive particles below 4.5 GeV/c. This is demonstrated in Fig.6, where the scatter plot of positive particle momentum versus difference in time-of-flight Δt in VH is shown. The single particle momentum interval accepted by spectrometer is $1.3 \div 7.0$ GeV/c.

For correlated $\pi^+\pi^-$ pairs Coulomb interaction in the final state has to be considerated, because it increases noticeably the yield of $\pi^+\pi^-$ pairs with low relative momentum in CM ($Q < 5$ MeV/c). For accidental pairs this enhancement is absent.

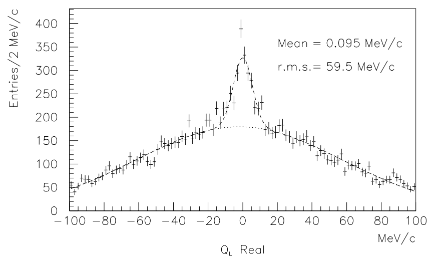

Figure 7. Correlated $\pi^+\pi^-$ pairs with positive particle momenta $p_{lab} <$ 4.5 GeV/c and $Q_T <$ 4 MeV/c.

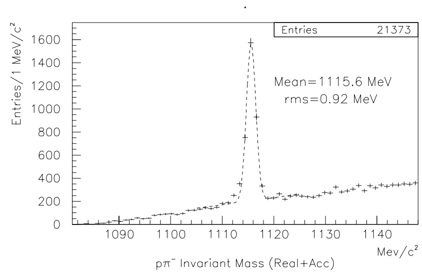

Figure 8. $p\pi^-$ invariant mass for proton momenta $p_{lab} >$ 3 GeV/c.

Fig.7 shows the distribution of the longitudinal component Q_L (the projection of Q along the total momentum of the pair) for correlated pairs. There are plotted pair events with positive particle momentum $p_{lab} < 4.5\ GeV/c$, occuring within the "correlated" Δt peak and with transversal component $Q_T < 4\ MeV/c$ to increase the fraction of low relative momentum pairs.

In the region $|Q_L| \leq 10\ MeV/c$ there is a noticeable enhancement of correlated $\pi^+\pi^-$ pairs due to Coulomb attraction in the final state.

The most important parameter for data analysis is the resolution in Q_L and Q_T. This has been measured by the reconstruction of the invariant mass of $p\pi^-$ pairs. The distribution of $p\pi^-$ invariant mass is presented in Fig.8. Positive particles are restricted to momenta larger than 3 GeV/c, and the time-of-flight must lie in $0.5 < \Delta t < 18\ ns$. A clear peak at the Λ mass $m_\Lambda = 1115.6\ MeV/c^2$ with a standard deviation $\sigma = 0.92\ MeV/c^2$ can be seen. These mass parameter values show a good detector calibration and coordinate detector alignment, with an accuracy in momentum reconstruction better than 0.5 % in the kinematic range of Λ decay products. This gives for the relative momentum resolution $\sigma_Q \sim 2.7\ MeV/c$. For $\pi^+\pi^-$ pairs a better resolution can be obtained, due to the different kinematics.

6 Conclusion

The DIRAC setup test and calibration have been done, and the DIRAC experiment began data taking. To achieve the goal - measurement of the pionium lifetime with 10% precision - we have to consider a number of at least 20000 recorded "atomic pairs". Improvements in hardware and software will continue this year. These will result in a better data quality.

References

1. J.Gasser and H.Leutwyler, Ann.Phys.158, (1984), 142.
2. J.Gasser and H.Leutwyler, Nucl.Phys.B250, (1985), 465.
3. J.Gasser and H.Leutwyler, Phys.Lett. B125, (1983), 325; J.Bijnens, G.Colangelo, G.Ecker. J.Gasser and M.E.Sainio, Phys.Lett. B374, (1996), 210.
4. J.Bijnens, G.Colangelo, G.Ecker, J.Gasser and M.Sainio, Nucl.Phys., B508, (1997), 263.
5. J.Stern, H.Sazdjian and N.H.Fuchs, Phys.Rev.D47, (1993), 3814.
6. M.Knecht, B.Moussallam, J.Stern and N.H.Fuchs, Nucl.Phys. B457, (1995), 513.
7. L.Rosselet et al., Phys.Rev. D15, (1977), 574; M.M.Nagels et al., Nucl.Phys. B147, (1979), 189.
8. B.Adeva et al., "Lifetime Measurement of $\pi^+\pi^-$ Atoms to Test Low Energy QCD Predictions", Proposal to the SPSLC, CERN/SPSLC 95-1, SPSLC/P 284, (1994).
9. L.L.Nemenov, Sov.J.Nucl.Phys. 41, (1985), 629.
10. A.Gall, J.Gasser, V.E.Lyubovitskij and A.Rusetsky, Phys.Lett. B462, (1999), 335.; J.Gasser, V.E.Lyubovitskij and A.Rusetsky, e-print hep-ph/9910438, (1999).
11. S.Deser, M.L.Goldberger, K.Baumann and W.Thiring, Phys.Rev. 96, (1954), 774.; J.L.Uretsky and T.R.Palfrey, Jr., Phys.Rev. 121, (1961), 1798.; S.M.Bilenky, Nguyen Van Hieu, L.L.Nemenov and F.G.Tkebuchava, Sov.J.Nucl.Phys. 10, (1969), 469.
12. A.Lanaro, e-print hep-ex/9912029, (1999).
13. H.Sazdjian, e-print hep-ph/9911520, (1999).
14. H.Jallouli and H.Sazdjian, Phys.Rev. D58, (1998), 014011.