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Latest results from KLOE-2

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Abstract. The KLOE/KLOE-2 Collaboration ended its data taking in 2018, about 20 years after the detector was turned on. In two different periods of data-taking about 8 fb^{-1} at the peak of the $\phi(1020)$ resonance have been collected. During the years many results of the study of the light mesons have been published. The analysis of this unique data sample continues and the results of the latest measurements concerning kaons, and vector and pseudoscalar mesons are presented in this paper.

1 Introduction

The KLOE experiment has been carried on at the e^+e^- collider DAΦNE in Frascati. From 2001 to 2006, 2.5 fb^{-1} of data at the peak of the $\phi(1020)$ resonance, plus 250 pb^{-1} off-peak, have been collected. In 2008, a new interaction region has been installed in DAΦNE, to increase the luminosity, and from November 2014 to March 2018 a second data-taking campaign, referred to as the KLOE-2 experiment, has been carried out collecting 5.5 fb^{-1} of data at the peak of the $\phi(1020)$. The total KLOE+KLOE-2 data sample is the largest worldwide sample collected at a ϕ-factory, and it amounts to about 2.4×10^{10} ϕ mesons produced.
The KLOE detector consisted of a large volume Drift Chamber (DCH) surrounded by a hermetic Calorimeter, both immersed in an axial magnetic field of 0.52 T. The DCH, filled with a gas mixture of He - isobutane, provided a momentum resolution $\sigma_{p_t}/p_t = 0.4\%$ and a space resolution of 150 μm in the plane transverse to the beam line, and 2 cm along the beam direction. The Electromagnetic Calorimeter (EMC), made of Pb-scintillating fibers, covered 98% of the whole solid angle, and had energy resolution $\sigma_E/E = 5.7\%/\sqrt{E(\mathrm{GeV})}$ and time resolution $\sigma_t = 55$ ps$/\sqrt{E(\mathrm{GeV})} \oplus 100$ ps.
For the KLOE-2 data-taking the detector has been upgraded with the insertion of an Inner Tracker close to the DAΦNE Interaction Point (IP), made of four layers of cylindrical GEMs, and new small angle calorimeters, the QCALT (tungsten and scintillator tiles with SiPMs) as instrumentation of the DAΦNE quadrupoles, and the CCALT (LYSO crystals with SiPMs) to improve the acceptance for small angle particles. A tagging system for scattered electrons in $\gamma\gamma$ processes consisting of two different detectors was also installed: a High Energy Tagger (HET, scintillator hodoscopes readout by PMTs) placed after the first bending magnet of the machine, and a Low Energy Tagger (LET, LYSO crystal calorimeters with SiPMs) placed 1 m far from the IP.
The latest results obtained both in kaon physics and in light hadron spectroscopy are presented.

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2 T and CPT tests in neutral kaon transitions

T and CPT are described in Quantum Mechanics by antiunitary operators, then direct tests of the two symmetries require the study of transitions in which the *in* and *out* states are exchanged, and also all spins and momenta are reversed. This is possible in KLOE by exploiting the entanglement of the meson-antimeson pairs, $K^0 - \bar{K}^0$, produced at the ϕ-factory DAΦNE. Considering the decay $e^+e^- \to \phi \to K^0\bar{K}^0$, the initial state is fully antisymmetric and can be written in terms of any pair of orthogonal states[1, 2]:

$$|i>= \frac{1}{\sqrt{2}}(|K^0>|\bar{K}^0> - |\bar{K}^0>|K^0>) = \frac{1}{\sqrt{2}}(|K_+>|K_-> - |K_->|K_+>)$$

Assuming the rule $\Delta S = \Delta Q$, $|K^0>$ and $|\bar{K}^0>$ can be identified through their semileptonic decay into a positive or negative lepton, respectively. $|K_->$ and $|K_+>$ are neutral kaon states tagged by the observation of the partner decay into the CP=+1 eigenstate $\pi\pi$ and CP=-1 eigenstate $3\pi^0$, respectively. They are orthogonal if one neglets direct CP violation effects (of the order of ε')[1, 2].
Starting from the $K^0 \to K_-$, the following transitions can be considered: $\bar{K}^0 \to K_-$ (CP-conjugate), $K_- \to K^0$ (T-conjugate), and $K_- \to \bar{K}^0$ (CPT-conjugate).
The first decaying kaon (at time t_1) is used to tag the second one, and its decay (at time t_2 greater than t_1) is used to filter the final state. In the case of the ϕ-factory, considering the region where $\Delta t = t_2 - t_1 >> \tau_S$ (τ_S being the K_S lifetime), the first decaying kaon is essentially a K_S while the second is a K_L, then the following processes must be considered: $\phi \to K_S K_L \to \pi^\mp e^\pm \nu, 3\pi^0$ and $\phi \to K_S K_L \to \pi^+\pi^-, \pi^\mp e^\pm \nu$.
Different ratios of decay rates, $I(f_1, f_2, \Delta t)$, sensitive to the different symmetries, can be measured:

$$R_2^T(\Delta t) = \frac{I(\pi^+e^-\bar{\nu}, 3\pi^0, \Delta t)}{I(\pi^+\pi^-, \pi^-e^+\nu, \Delta t)}\frac{1}{D} \qquad R_4^T(\Delta t) == \frac{I(\pi^-e^+\nu, 3\pi^0, \Delta t)}{I(\pi^+\pi^-, \pi^+e^-\bar{\nu}, \Delta t)}\frac{1}{D}$$

$$R_2^{CPT}(\Delta t) = \frac{I(\pi^+e^-\bar{\nu}, 3\pi^0, \Delta t)}{I(\pi^+\pi^-, \pi^+e^-\bar{\nu}, \Delta t)}\frac{1}{D} \qquad R_4^{CPT}(\Delta t) = \frac{I(\pi^-e^+\nu, 3\pi^0, \Delta t)}{I(\pi^+\pi^-, \pi^-e^+\nu, \Delta t)}\frac{1}{D}$$

$$R_2^{CP}(\Delta t) = \frac{I(\pi^+e^-\bar{\nu}, 3\pi^0, \Delta t)}{I(\pi^-e^+\nu, 3\pi^0, \Delta t)} \qquad R_4^{CP}(\Delta t) = \frac{I(\pi^+\pi^-, \pi^-e^+\nu, \Delta t)}{I(\pi^+\pi^-, \pi^+e^-\bar{\nu}, \Delta t)}$$

where:

$$D = \frac{|<3\pi^0|K_->|^2}{|<\pi^+\pi^-|K_+>|^2} \simeq \frac{Br(K_L \to 3\pi^0)\Gamma_L}{Br(K_S \to \pi\pi)\Gamma_S}$$

Also the double ratios can be constructed:

$$\frac{R_2^T}{R_4^T}(\Delta t) = \frac{I(\pi^+e^-\bar{\nu}, 3\pi^0, \Delta t)I(\pi^+\pi^-, \pi^+e^-\bar{\nu}, \Delta t)}{I(\pi^-e^+\nu, 3\pi^0, \Delta t)I(\pi^+\pi^-, \pi^-e^+\nu, \Delta t)}$$

$$\frac{R_2^{CPT}}{R_4^{CPT}}(\Delta t) = \frac{I(\pi^+e^-\bar{\nu}, 3\pi^0, \Delta t)I(\pi^+\pi^-, \pi^-e^+\nu, \Delta t)}{I(\pi^+e^-\bar{\nu}, 3\pi^0, \Delta t)I(\pi^+\pi^-, \pi^+e^-\bar{\nu}, \Delta t)}$$

To select $\phi \to K_S K_L \to \pi^\mp e^\pm \nu, 3\pi^0$ events, two tracks of opposite charge with a vertex close to the IP are required, and the $\pi^+\pi^-$ background is rejected with a Time-of-Flight technique. The $3\pi^0$ vertex is reconstructed from the arrival time of the 6 photons in the EMC. To select $\phi \to K_S K_L \to \pi^+\pi^-, \pi^\mp e^\pm \nu$ events two pairs of tracks with opposite charge are required, one

close to the IP, and the second, for the semileptonic decay, within the DCH.
The measured ratios for $\Delta t >> \tau_S$ are reported in Fig.1. They all show a flat behaviour and are fitted to a constant[3].

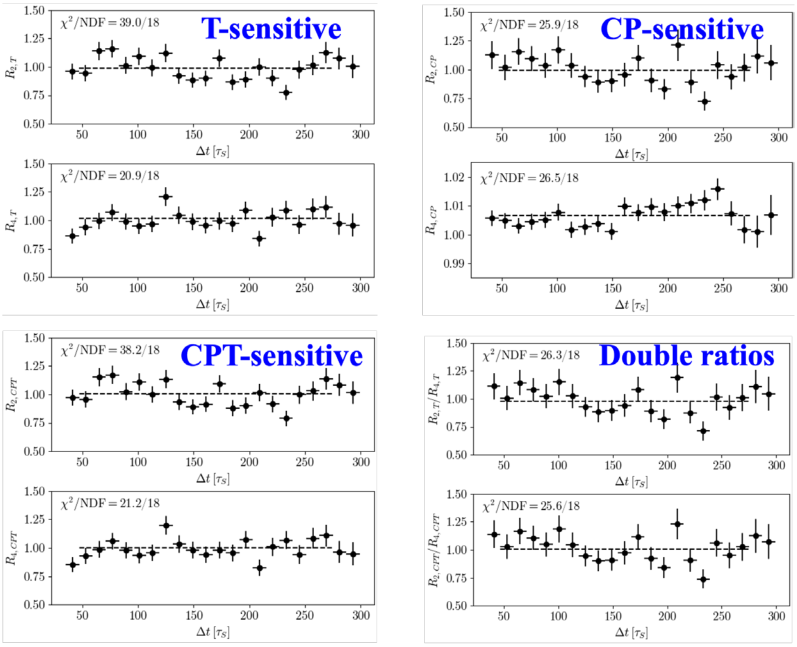

Figure 1. Measured ratios as functions of Δt, the dashed lines are constant fits[3].

The results are summarized in Fig.2[3], and compared to the theoretical expectations assuming CPT invariance and T violation equal to CP violation in mixing[4].

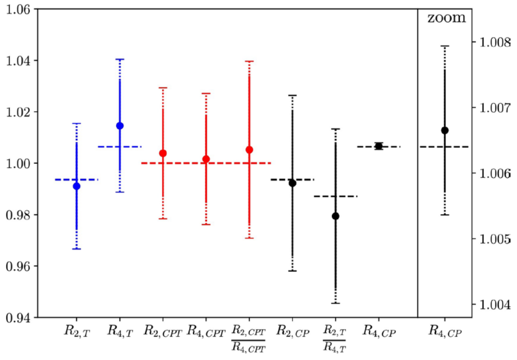

Figure 2. Comparison of the measured ratios to the theoretical expectations (dashed lines), the solid error bars correspond to the statistical uncertainty, the dotted bars show the total uncertainties. The last point on the right is the zoom of R_4^{CP} which has smaller uncertainty due to higher statistics[3].

3 $\eta \to \pi^0\gamma\gamma$

The rare decay $\eta \to \pi^0\gamma\gamma$ provides a good test of Chiral Perturbation Theory (ChPT), since the tree level contributions at $O(p^2)$ and $O(p^4)$ vanish because neutral mesons are involved, and the $O(p^4)$ contributions from kaon or pion loops are suppressed. Therefore it is directly sensitive to the $O(p^6)$ terms of the chiral lagrangian. The two most recent measurements of this decays have been performed with essentially the same detector, the Crystal Ball, at the AGS in Brookhaven, $Br = (2.21 \pm 0.24 \pm 0.47) \times 10^{-4}$ [5], and at MAMI in Mainz by the A2 Collaboration, $Br = (2.52 \pm 0.25) \times 10^{-4}$ [6]. These two values are significantly higher than the KLOE old result $Br = (0.84 \pm 0.27 \pm 0.14) \times 10^{-4}$ based on 68 signal events[7], from the analysis of a sample of 450 pb^{-1} of data.
Recently a sample of 1.7 fb^{-1} of KLOE data has been analyzed, looking for five prompt photon events from the decay $\phi \to \eta\gamma$ with $\eta \to \pi^0\gamma\gamma$. The main source of background is from the decay $\phi \to \eta\gamma$ with $\eta \to 3\pi^0$, that mimics five prompt photon events when photons are lost or are merged in the EMC. In Fig.3-left it is reported the final distribution of invariant mass of the four photons from the η decay; a clear evidence of the signal is visible in correspondence to the η mass, superimposed to a large irreducible background. The yield

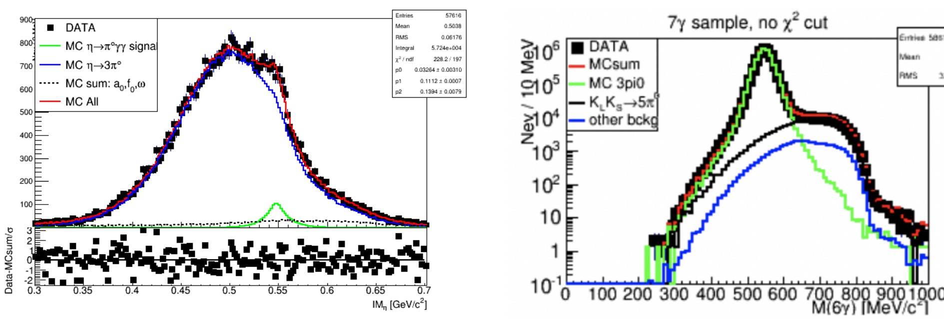

Figure 3. Left: Four photon invariant mass distribution, signal (green) and $\eta \to 3\pi^0$ background (blue), the red histogram is the sum of all the contributions. Right: six photon invariant mass for the normalization sample, compared to the MC simulation.

of signal events is 1246 ± 133, which, normalized to the very clean and abundant sample of seven prompt photon events from $\phi \to \eta\gamma$ with $\eta \to 3\pi^0$(Fig.3-right), gives:

$$Br(\eta \to \pi^0\gamma\gamma) = (0.99 \pm 0.11_{stat} \pm 0.24_{syst}) \times 10^{-4}$$

This result is consistent with the old KLOE result, and confirms the discrepancy with the two measurements obtained with the Crystal Ball, now set at the level of four standard deviations. In fig.4 the invariant mass distributions of the two photons not coming from the π^0 is shown, the hole at about 150 MeV is due to the veto for events with two π^0's from the event selection.
By performing the analysis in bins of the squared two-photon invariant mass (Fig. 5) the differential decay rate has been obtained.
In Fig.6 the differential decay rate measured by KLOE is compared with the measurements from refs.[5, 6]. The superimposed curve is a calculation based on Vector Meson Dominance and Linear Sigma Model[8].

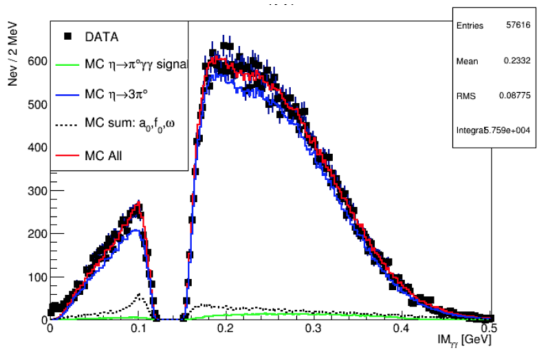

Figure 4. Invariant mass distribution of the two photons not coming from π^0.

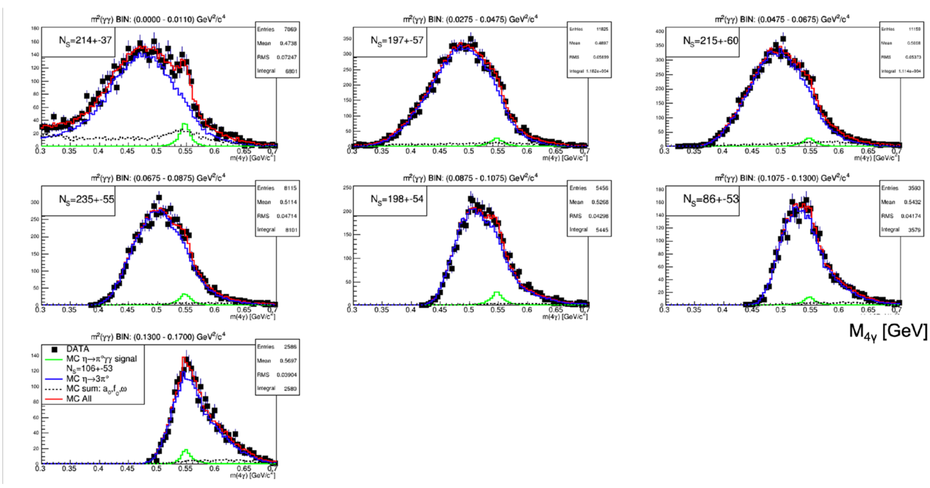

Figure 5. Four photon invariant mass distribution for different bins of two photon invariant mass.

4 $\phi \to \eta\mu^+\mu^-$

By measuring the invariant mass spectra of the lepton pairs produced in the Dalitz decays $V \to P\ell^+\ell^-$, the Transition Form Factors (TFF) at time-like momentum transfers can be determined. While the decay of $\phi \to \eta e^+e^-$ has been extensively studied, being the most recent result from KLOE in 2015 [9], for the decay into muon pairs, $\phi \to \eta\mu^+\mu^-$, only an upper limit on the branching fraction by the CMD-2 Collaboration exists, $Br < 9.4 \times 10^{-6}$ at 90% C.L.[10]. This decay can be studied at KLOE by selecting events with two charged tracks and two or six prompt photons from the $\eta \to \gamma\gamma$ and $\eta \to 3\pi^0$ decay channels, respectively. About 1.7 fb^{-1} of data are analyzed, and in Fig.7.left the invariant mass of the $\gamma\gamma$ pair is reported, showing a clear peak corresponding to the η mass. The second peak on the right is from the decay $\phi \to \eta\pi^+\pi^-$, that can also be studied with the same data sample, shifted with respect to the true η mass value due to the assumption that the charged tracks are muons. In Fig.7.right the signal from the $\eta \to 3\pi^0$ decay is shown. From a fit to the peak region, the preliminary values of the branching fraction have been obtained, see Fig.8: $Br(\phi \to \eta\mu^+\mu^-) = (5.65 \pm 0.11_{stat}) \times 10^{-6}$ for $\eta \to \gamma\gamma$ and $Br(\phi \to \eta\mu^+\mu^-) = (5.76 \pm 0.19_{stat}) \times 10^{-6}$ for $\eta \to 3\pi^0$.

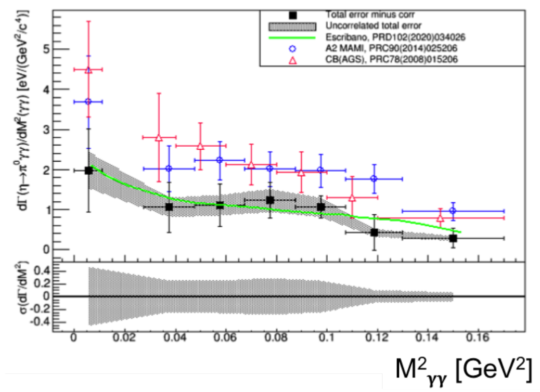

Figure 6. Differential decay rate as a function of the invariant mass of the two photons not coming from π^0, compared to previous experiments and to the latest theoretical prediction[8]; in gray the uncertainty band is shown.

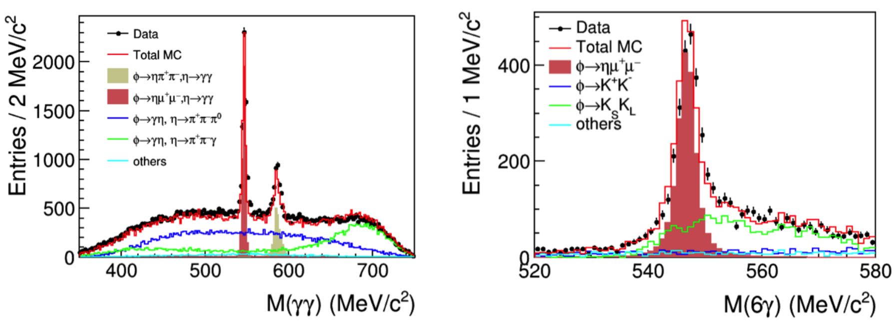

Figure 7. Left: Invariant mass of the $\gamma\gamma$ pair; right: invariant mass of the six prompt photons from $\eta \to 3\pi^0$.

Only the statistical uncertainties are reported, the systematics are under evaluation.
The TFF $F_{\phi\eta}(q^2)$ can be extracted from the $\mu^+\mu^-$ invariant mass distribution ($q^2 = M^2_{\mu\mu}$) according to:

$$\frac{1}{\Gamma(\phi \to \eta\gamma)} \frac{d\Gamma(\phi \to \eta\mu^+\mu^-)}{dq^2} = \left|F_{\phi\eta}(q^2)\right|^2 \frac{\alpha}{3\pi q^2} \sqrt{1 - \frac{4m_\mu^2}{q^2}} \left(1 + \frac{2m_\mu^2}{q^2}\right) \times \\ \times \left[\left(1 + \frac{q^2}{M_\phi^2 - M_\eta^2}\right)^2 - \frac{4M_\phi^2 q^2}{(M_\phi^2 - M_\eta^2)^2}\right]^{\frac{3}{2}}$$

The preliminary values of the form factor slope $\Lambda^{-2} = \frac{dF_{\phi\eta}}{dq^2}$ have been extracted: $\Lambda^{-2} = (3.01 \pm 0.10)\ \mathrm{GeV}^{-2}$ for $\eta \to \gamma\gamma$ and $\Lambda^{-2} = (2.90 \pm 0.20)\ \mathrm{GeV}^{-2}$ for $\eta \to 3\pi^0$.

5 $\gamma^*\gamma^* \to \pi^0$

The HET, installed for the second phase of data-taking to detect the scattered electrons in $\gamma\gamma$ interactions, consisted of two scintillator hodoscopes read out with standard PMTs, placed

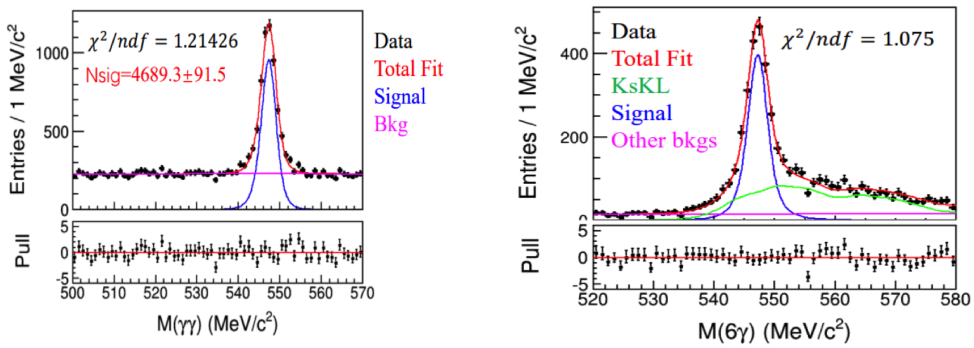

Figure 8. Fits to the $\gamma\gamma$ (left) and six photon (right) invariant masses for the two η decay modes under study in $\phi \to \eta\mu^+\mu^-$ events.

behind the first bending dipoles in each of the DAΦNE rings, which acted as spectrometers for the scattered particles. The goal is to measure the π^0 width at the few percent level, by detecting the π^0's produced in the process $e^+e^- \to e^+e^-\gamma^\star\gamma^\star \to e^+e^-\pi^0$.
The HET has been acquired asynchronously with respect to the central detector, and HET signals corresponding to 2.5 DAΦNE revolutions were recorded for each KLOE-2 trigger. The analysis is based on the comparison of the samples with the HET-KLOE coincidences ("A+", accidental plus signal sample) and without coincidences (pure accidental,"A" sample). Events with signal on one of the two HET stations in a time window of 40 ns around the KLOE-2 trigger, and with two neutral clusters in the EMC, are selected. The number of π^0's is estimated from a simultaneous fit to several variables (see example in Fig.9), and it is normalized to radiative Bhabha scattering events. By combining the two HET stations, a statistical uncertainty of 6.5% can be reached on the π^0 width. The evaluation of the systematics coming from the different detector acceptance for signal events and for radiative Bhabha scattering is in progress.

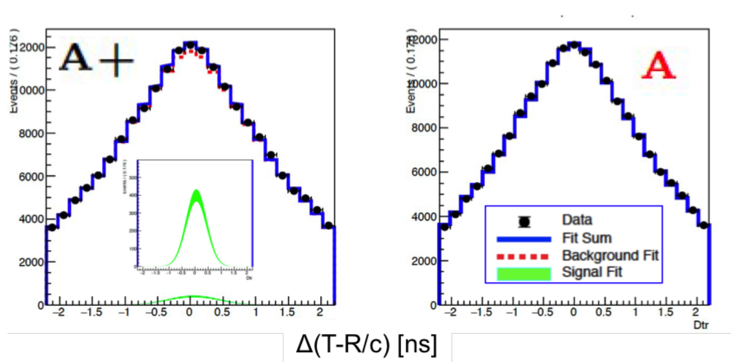

Figure 9. Example of simultaneous fit; the variable is the Time-of-Flight difference between the two clusters in the EMC. The inset in the left plot is the zoom of the signal (green histogram).

6 Conclusions

The KLOE/KLOE-2 Collaboration collected about 8 fb^{-1} of data at the peak of the $\phi(1020)$ resonance in two different data-taking periods. This is a unique worldwide data sample, from which many interesting physics processes have been studied in the past, and continue to be studied. In this paper the results on the latest analyses concerning kaons and light pseudoscalar mesons, like η and π^0, have been presented.

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