Antikaon-nucleon/nuclei interaction studies at low energies the AMADUES project

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ANTIKAONIC
MATTER
AT
DAΦNE: AN
EXPERIMENT
WITH **U**NRAVELING
SPECTROSCOPY

AMADEUS collaboration
116 scientists from 14 Countries and 34 Institutes

lnf.infn.it/esperimenti/siddharta
and
LNF-07/24(IR) Report on lnf.infn.it web-page (Library)

AMADEUS started in 2005 and was presented and discussed in all the LNF Scientific Committees

HadronPhysics2
Study of Strongly Interacting Matter

EU Fundings FP7 – I3HP2:
Network WP9 – LEANNIS;
WP24 (SiPM JRA);
WP28 (GEM JRA)

CONTENTS

Scientific case

- The experimental investigation of the low energy interaction of antikaons (S = -1) with nucleons and nuclei is fundamental in understanding how spontaneous and explicit breaking of chiral $SU(3)_L \times SU(3)_R$ symmetry in QCD occurs in nuclear environment.

- The isospin (I = 0) s-wave $\bar{K}N$ interaction is quite strongly attractive around the $\bar{K}N$ threshold (from kaonic hydrogen data), unlike the weakly repulsive kaon – nucleon (S = +1) interaction.

- Chiral perturbation theory is not directly applicable to the sector with baryon number (B = 1) and strangeness (S = -1) due to the formation of the $\Lambda(1405)$ about 30 MeV below the $K^- p$ threshold.

- Different theoretical approaches are followed ..

- conclusive **experimental data are necessary to set** more **stringent constraints**.

Scientific case

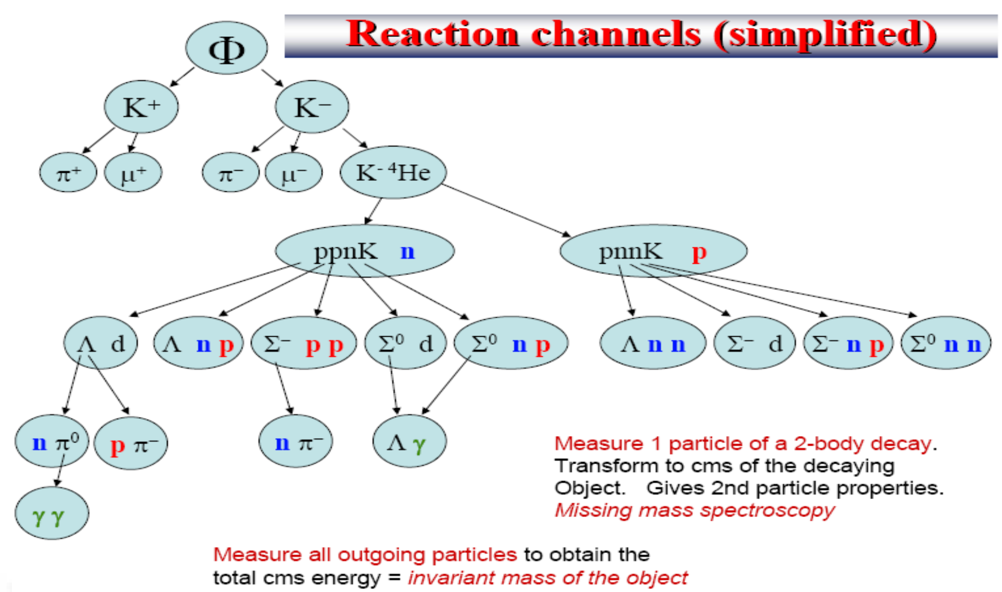
Deeply bound Kaonic nuclear states requires the presence of a strong attractive $\bar{K}N$ interaction in the isospin I=0 channel ($\Lambda\pi$ channel closed for isospin selection, $\Sigma\pi$ channel energetically closed)

The pillars of the existence of narrow $\bar{K}$ - nuclear states are:

- The low energy $\bar{K}N$ scattering data
- The kaonic hydrogen shift and with of the ground state
- The binding energy and decay with of $\Lambda(1405)$ regarded as an isospin

  I = 0 bound state of $\bar{K}$ + N

Example of the possible formation of tribaryonic kaonic nuclear states by stopping K^- in ^4He →



Scientific case and state of the experimental search

- DBKNS were firstly suggested by **Wycech**. **Y. Akaishi and T. Yamazaki** '*nuclear bound states in light nuclei*' with binding energies (up to 120 MeV) and narrow with (about 20 MeV) (for K^-ppn systems).

(S. Wycech, Nucl. Phys. A450 (1986) 399c) *(Phys. Rev. C65 (2002) 044005)*

- **Possible experimental indications** of the formation of kaonic nuclear states have received **alternative explanations** in the framework of known processes

- Recent calculations of K^-pp systems suggests relatively moderate bindings and larger widths

N. V. Sevchenko, A. Gal, J. Mares, J. Revai, Phys. Rev. C 76, 044004 (2007)
A. Dote, T. Hyodo, W. Weise, Nucl. Phys. A 804, 197 (2008)

Performed experiments: E471, E549, E570 @ KEK, FINUDA @ DAΦNE, FOPI @ GSI, OBELIX

future experiments: FOPI @ GSI, E15 @ J-PARC, FAIR @ GSI … and AMADEUS

- Possibility to **explore the nature of the Λ(1405)** (resonance, quasibound state emerging from the coupling between the KN and the Σπ channels ?) **produced by KN reactions** in various targets, also observing the porly explored **clean $\Sigma^0\pi^0$ decay channel**.

'*Kaon induced Λ(1405) production on a deuteron target at DAFNE*'
D. Jido, E. Oset, T. Sekihara Eur.Phys.J.A47:42,2011.

Experimental program

- AMADEUS aims to confirm or deny the existence of such exotic states performing a **full acceptance, high precision measurement of DBKNS both in formation and in the decay process**, implementing the KLOE detector with an inner AMADEUS dedicated setup:
  Study of the (most) fundamental antikaon deeply bound nuclear systems, the **kaonic dibaryon states: ppK^- and (pnK^-)** produced in a ^{3}He gas target, in formation and decay processes. As next step **kaonic 3-baryon states: $ppnK^-$ and $pnnK^-$** produced in a ^{4}He gas target.

- The important state **Λ(1405)** and its behaviour in the nuclear medium could be better understood with high statistics.

- **Measurement of the low-energy charged kaon cross sections** on H, d, Helium(3 and 4), for K^- momentum lower than 100 MeV/c (missing today).

- Study of the **K^- nuclear interactions in Helium** (poorly known, based on one paper from 1970 …)

Setup performance requirements

Formation processes

$K^{-}_{stopped} + {}^{4}He \rightarrow p + (K^{-}pnn)$

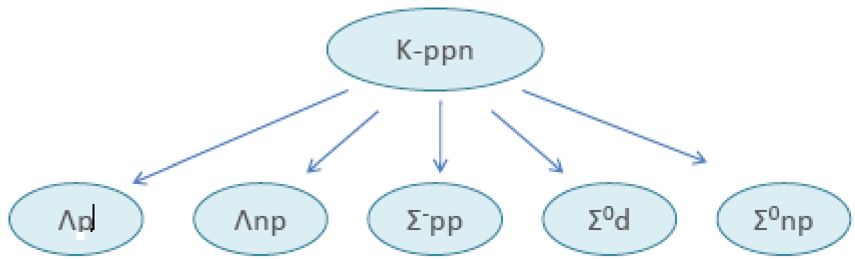
$K^{-}_{stopped} + {}^{4}He \rightarrow n + (K^{-}ppn)$

Study of the exotic states by the energy/momentum distribution of the ejected protons and neutrons. The setup should be able to measure:

- position of K^{-} stop: primary vertex and K^{+} tracking (trigger)
- outgoing neutrons and protons

Setup performance requirements

Decay processes



Invariant mass spectroscopy

this requires:

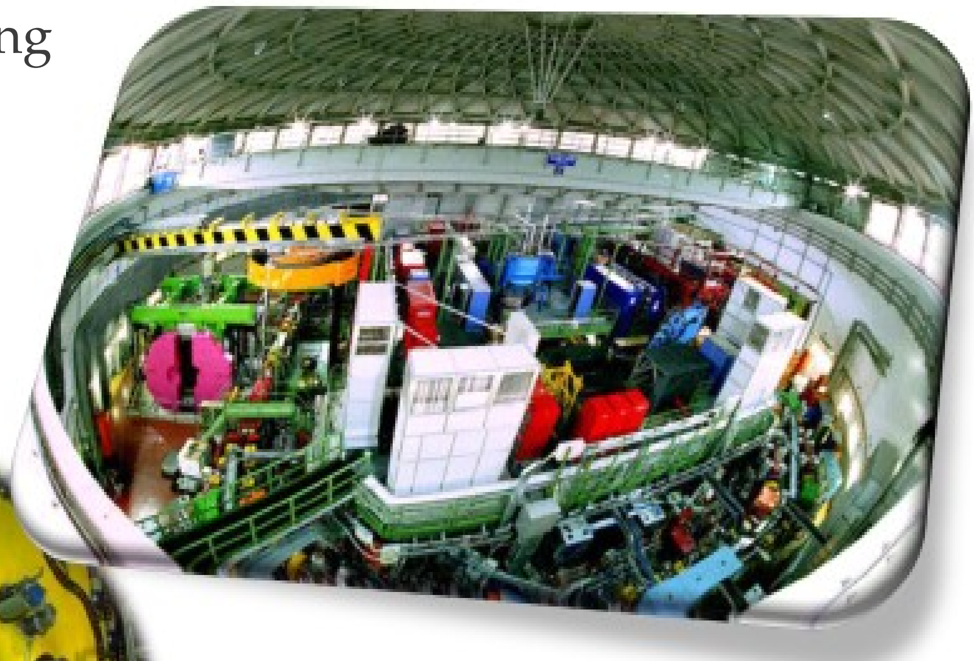
- identification of all decay products, including protons neutrons and pions from hyperons decay
- measurement of 4-momenta of charged and neutral particles
  - protons 200 – 800 Mev/c ; pions 50 – 200 Mev/c ; neutrons 200 – 800 Mev/c ; deuterons ...

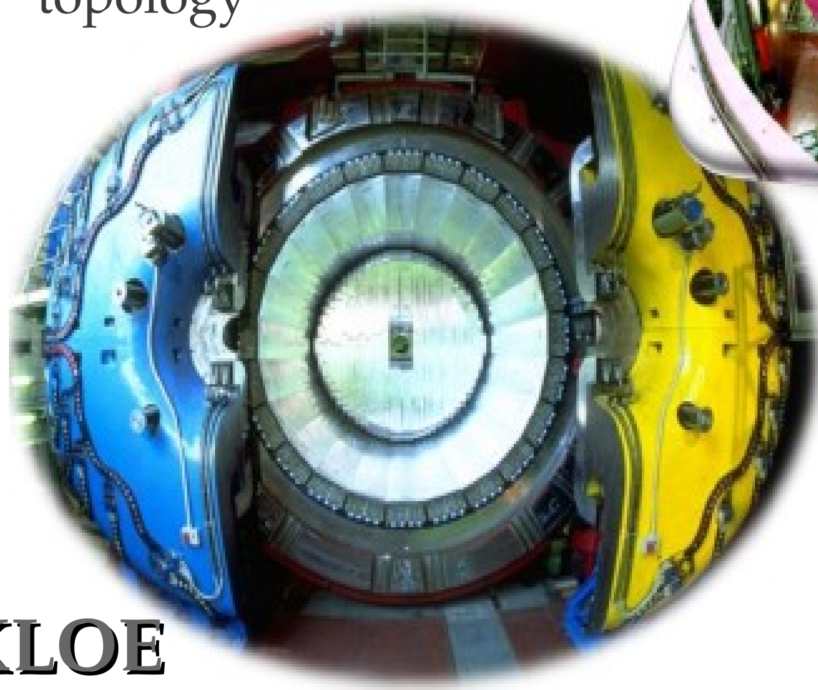
requirements satisfied by..

double ring $e^+ e^-$ collider working in C. M. energy of φ, producing ≈ 600 $K^+ K^-$ /s

- **low momentum** Kaons ≈ 127 Mev/c
- **back to back** $K^+ K^-$ topology

DAΦNE





KLOE

- 96% acceptance,
- optimized in the energy range of all charged particles involved
- good performance in detecting neutrons checked by kloNe group

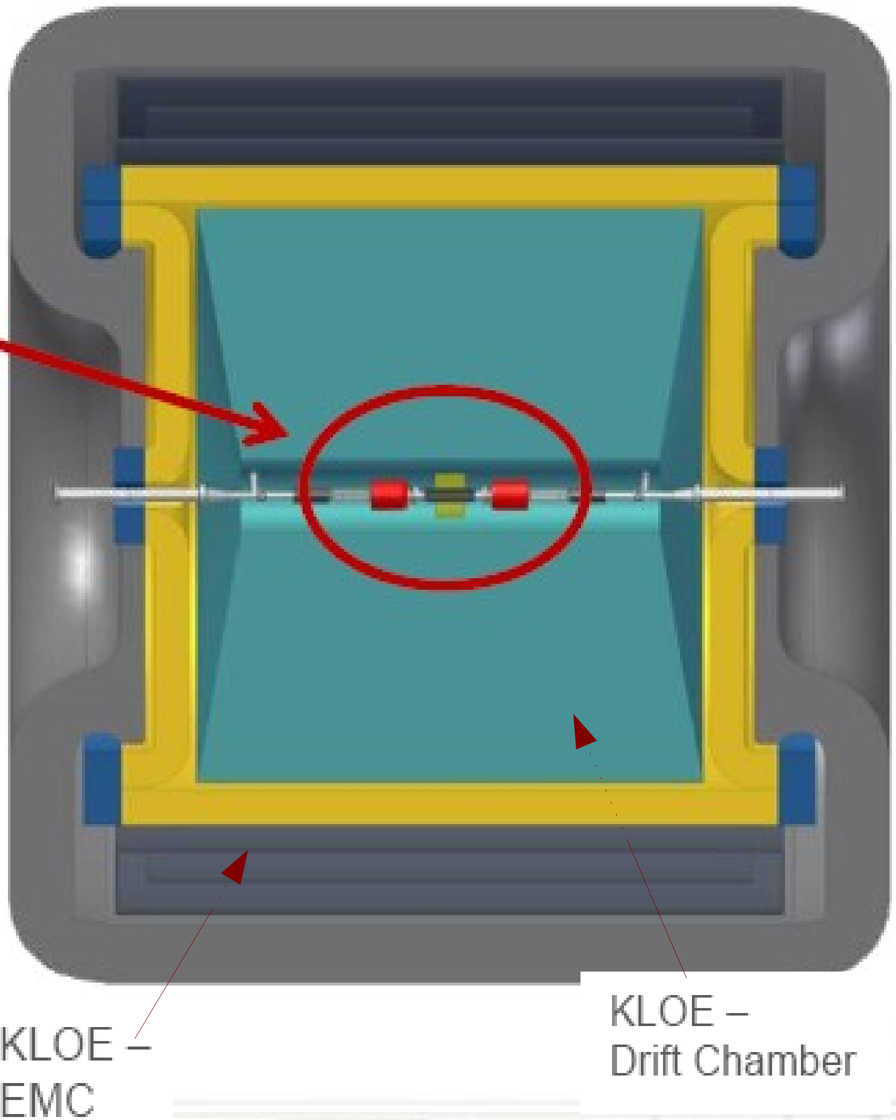
M. Anelli et al., Nucl. Instr. Meth. A 581, 368 (2007)

The experimental setup of AMADEUS

•The AMADEUS setup will be implemented in the 50 cm. gap in KLOE DC around the beam pipe:

•**Target** (A gaseous He target for a first phase of study)

•**Trigger** (1 or 2 layers of ScFi surrounding the interaction point)

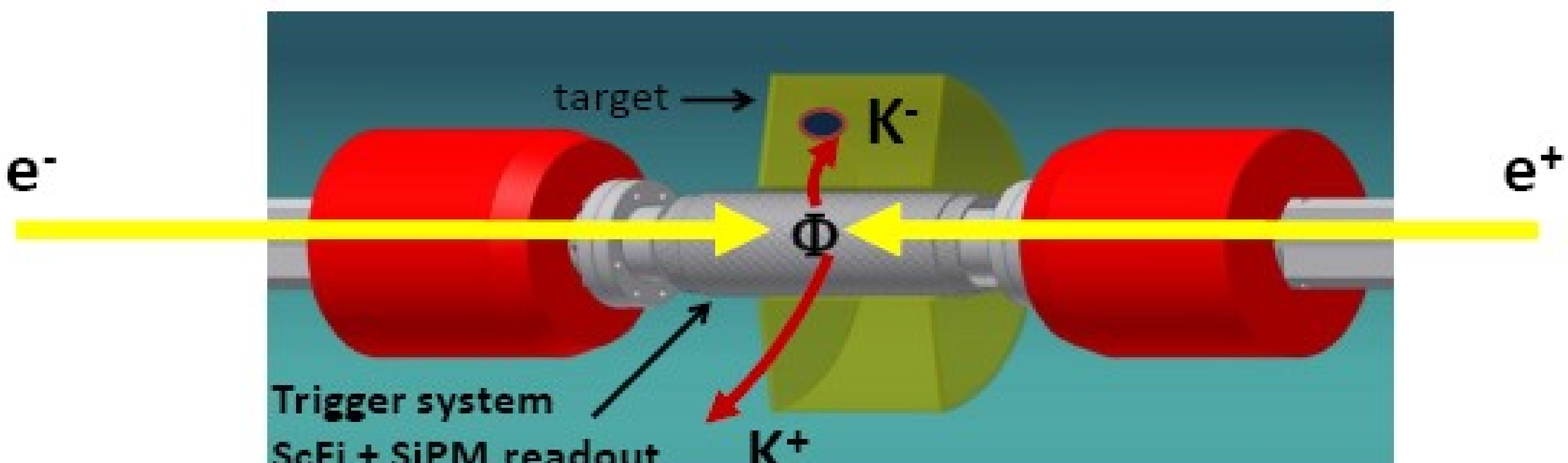


experimental setup: trigger system

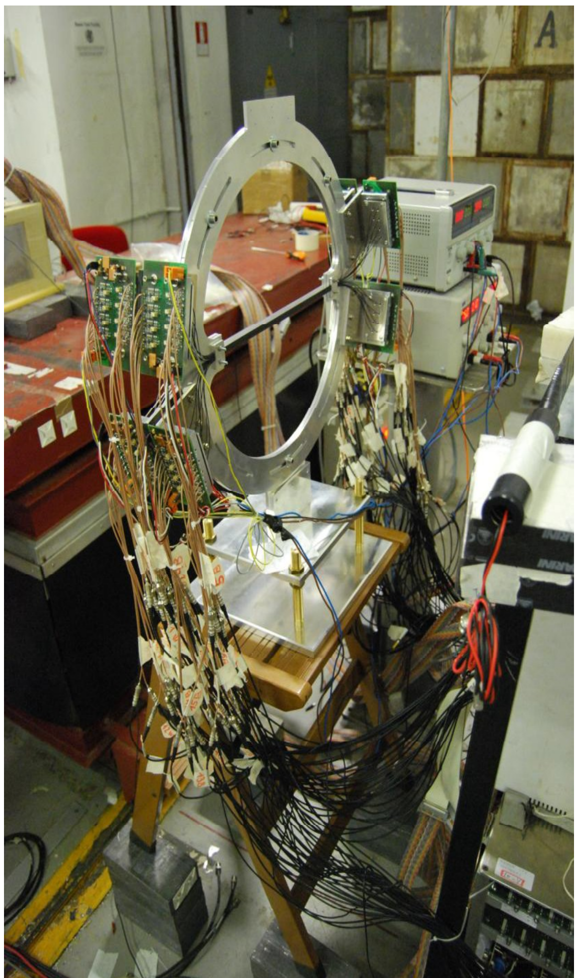
- **Cilindrical layer of scintillating fibers** surrounding the beam pipe to **trigger $K^+ K^-$ in opposite directions**
- Single or double layer

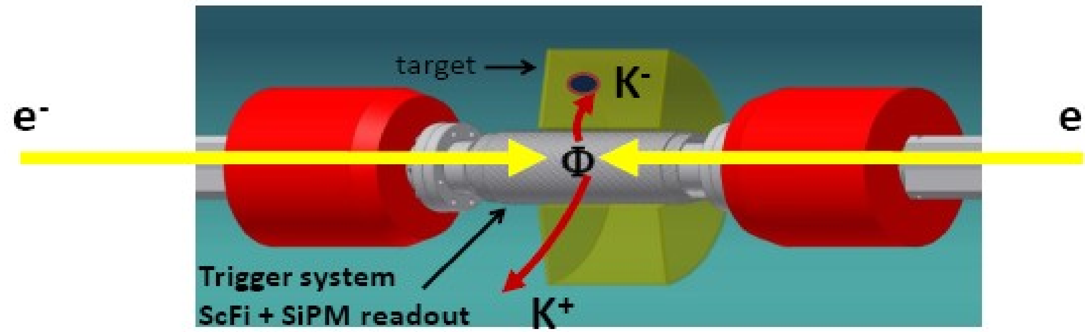
  In this case possibility of perform tracking as well: X-Y measurement with high granularity layers

- **Readout** to be done by **SiPM (silicon photo-multipliers)**



experimental setup: trigger system



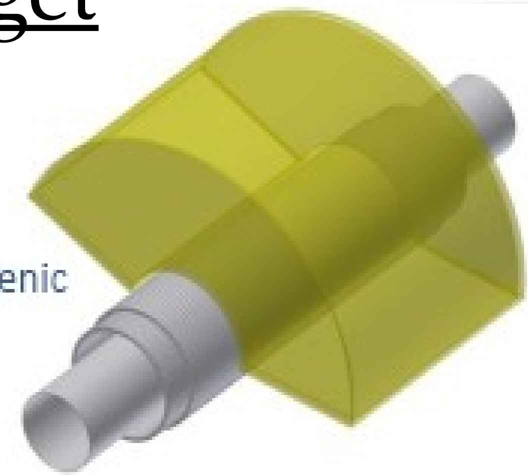


R&D activity is going on

prototipe of the trigger system
layers of BCF-10 fibers double cladded
free to rotate
read at both sides by Hamamatsu S10362-11-050-U SiPM

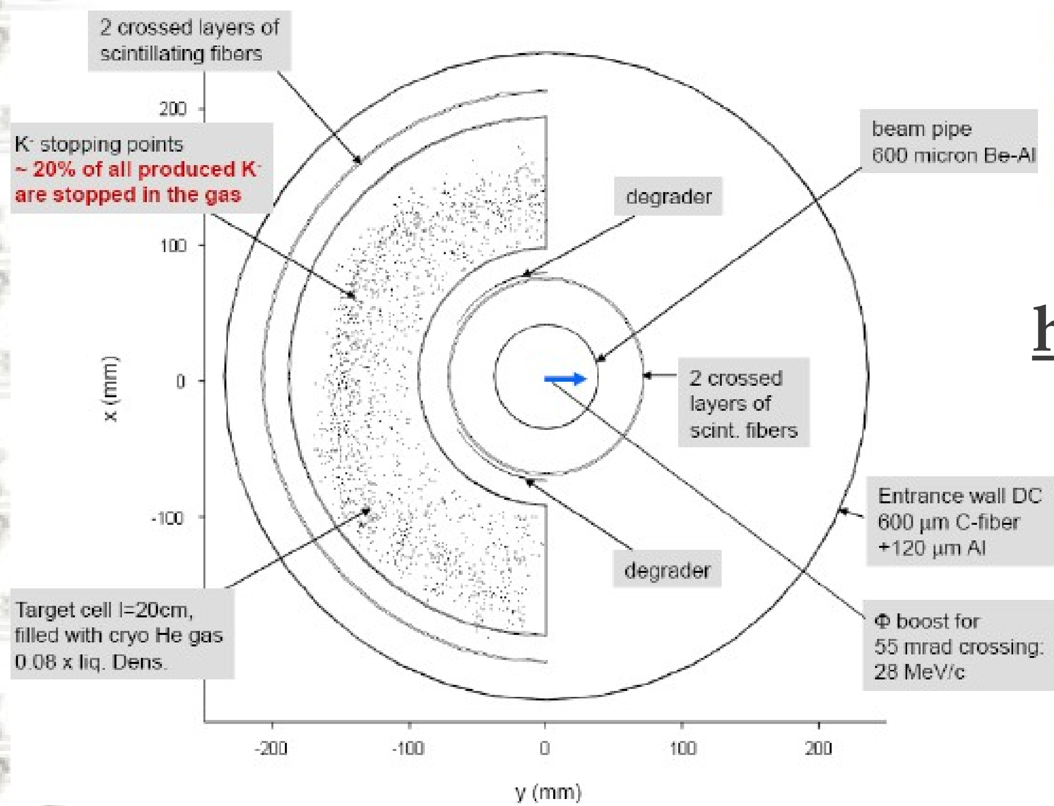
time resolution obtained (σ) for kaons 300ps
(Nuclear Inst. and Methods in Physics Research, A (2012), pp. 125-128).

experimental setup: target



Low-mass cryogenic gas target cell:
T = 10 K
P = 1.0 bar
Rin = 5 cm
Rout = 15 cm
L = 20 cm

AMADEUS Monte Carlo



half-toroidal cryogenic target cell

inside a vacuum chamber,
and
two more layers of fibers

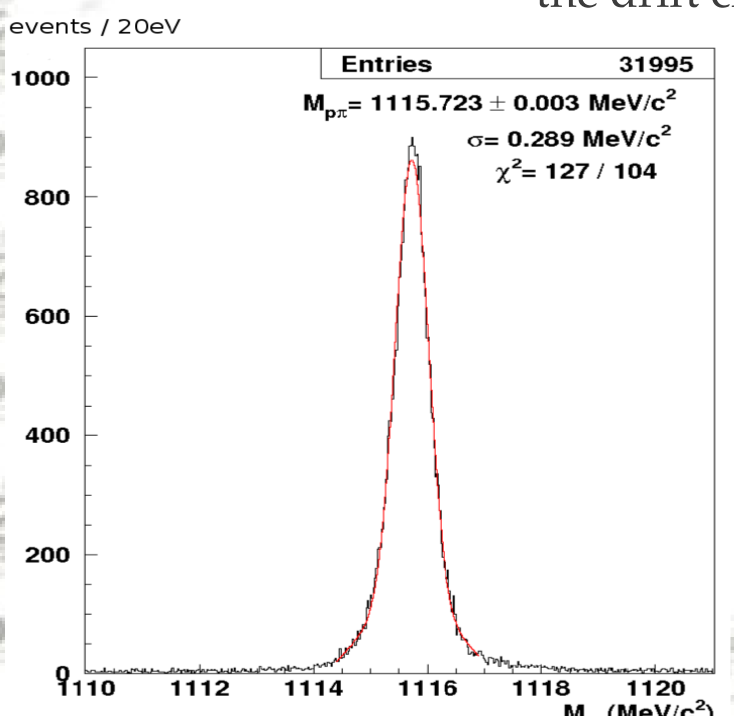
KLOE data analysis

... BUT much can be already done by analyzing the 2002-2005 collected KLOE data INDEED ...

The **drift chamber** of KLOE **contains mainly ^{4}He** (90% helium, 10% isobutane).

From the Monte Carlo simulation **0.1% of K^-** from DAΦNE should **stop in the DC inner volume**.

We can then study the interaction of K^- with ^{4}He filling the chamber (or with C from the drift chamber entrance wall carbon fiber).



•The **reconstruction capability for Λ's and Σ's** was **already tested**

Excellent results were obtained in

- **Λ(1116) + p** and **Λ(1116) + d** events
- **Λ(1405) → $\Sigma^0\pi^0$**

Concluding remarks

- The AMADEUS collaboration aims to perform a **complete search for DBKNS** and to study the **low energy interaction of K^- with light nuclei**, by implementing a dedicated AMADEUS setup in KLOE.

- A **unic opportunity** is offered by the special features of the **DAΦNE** collider and the **KLOE** detector implemented with a specific **AMADEUS setup** !

- **R&D** activity is **presently going on** for the trigger and target system.

- The **KLOE reconstruction capability** for the AMADEUS channels is already being tested by anlyzing 2002-2005 KLOE data,

preliminary results of the analysis already promise exciting prospectives.

Spare slides

KLOE data analysis: study of the Λ(1405) through its neutral decay channel

- The distribution shape of the Λ(1405) depends on the observed decay channel ($\Sigma^+\pi^-$, $\Sigma^-\pi^+$,$\Sigma^0\pi^0$) and on the production mechanism. It is of **great importance to explore the** Λ(1405) **production in KN reactions decaying in $\Sigma^0\pi^0$ channel** (Σ^0 decays electromagnetically in Λγ). This is a **golden, still poorly explored, channel** since the main source of background **Σ(1385) can not decay in $\Sigma^0\pi^0$** for isospin selection.

- We searched for signal of Λ(1405) produced by interaction of K^- with a proton in the DC entrance wall or in the gas filling the DC (up to now a total luminosity of 1.2 fb^{-1} was analyzed), according to the reaction:

$$K^-p \to \Lambda(1405) \to \Sigma^0\pi^0 \to (\Lambda\gamma)(\gamma\gamma) \to (p\pi^-)3\gamma.$$

- To this end a MC simulation was created in which K^- is stopped in the inner DC volume, here interacts with a proton of ^{4}He forming an object with mass 1432 MeV, and momentum equal to the Fermi momentum of the proton in ^{4}He nucleus.

- Such object subsequently decays according to the reaction:

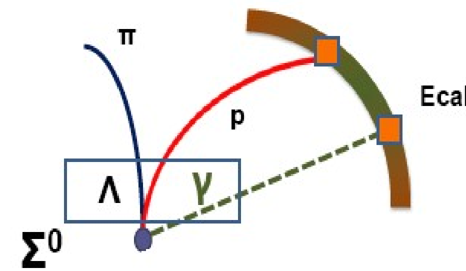
$$K^-p \to \Sigma^0\pi^0 \to (\Lambda\gamma_3)(\gamma_1\gamma_2) \to (p\pi^-)\gamma_1\gamma_2\gamma_3.$$

- As first we identify Λ(1116) through its charged decay in a pion and a proton as shortly described below..

<u>KLOE data analysis:</u> Selection criteria for the Λ(1116)

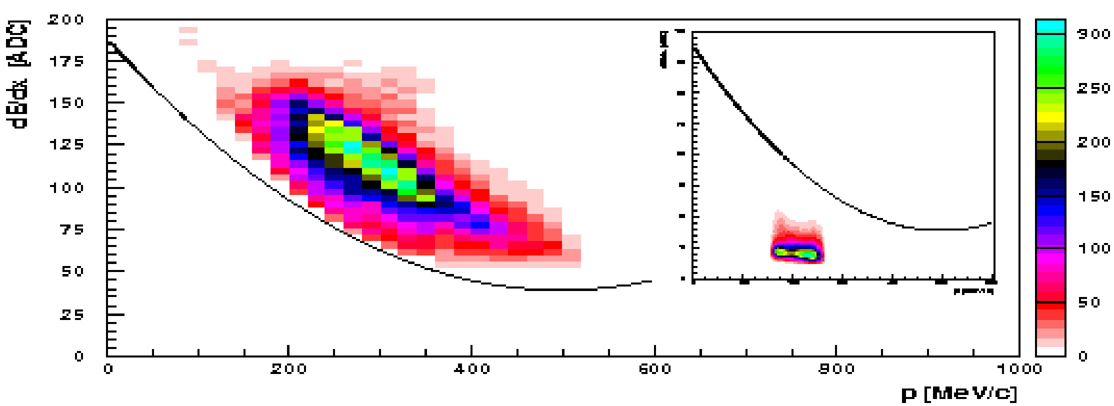
- Reconstruction of Λ decay vertex:

$$\Lambda \rightarrow p\,\pi^{-} \qquad (BR \sim 64\%)$$



requests:
vertex with at last two opposite charged particles
spatial position of vertex inside DC, or in DC entrance wall
negative tracks with dE/dx < 95 ADC counts.

Positive tracks with the last DC measurement near the calorimeter, and dE/dx > a – bp + cp^2 are identified as protons (the coefficients were optimized using dE/dx v.s. p distribution of protons already identified using the energy released in the calorimeter) (see also KLOE Memo 330 September 2006)



A clear separation with respect to pions (from K^+ two body decay) is evident.

KLOE data analysis: selection of the photon clusters

- We select those events in which there are at least three neutral clusters (with not associated track in the DC) not coming from K^+ decay $K^+ \to \pi^+\pi^0$
- A chi square variable χ_t^2 based on time-of-flight is calculated for each couple of selected neutral clusters in order to identify the three photons.
- In order to distinguish the photon clusters coming from π^0 decay, from γ_3 (due to Σ^0 decay) we select the triple which minimizes a chi square variable $\chi_{\pi\Sigma}^2$ based on the combined masses of π^0 and Σ^0.
- Specific cuts were optimized over χ_t^2 and $\chi_{\pi\Sigma}^2$ based on MC results.
- In order to avoid the selection of splitted clusters or background for π^0, the following cut was introduced (see KLOE memo 311 9 June 2006):

$$R \geq \frac{a}{E_{\gamma_i} + E_{\gamma_j} + b} \quad \text{dove } a = 15000\, MeV\, cm \ \text{ e } b = 1\, MeV$$

Where R (cm), E_i, E_j (MeV) are the distance between the clusters and the energies of the two clusters.

- According to MC true information, the algorithm has an **efficiency ~100% in recognizing photon clusters and more than 80% in recognizing the right photons triple!**

Identification of neutrons through K^- interaction in the KLOE DC entrance wall (DCEW)

The aim of this work is to test the reconstruction capability of neutron clusters (in the KLOE calorimeter) which is of **great importance** in the study of **missing**, as well as **invariant, mass** spectroscopy in the search for **K^-pp** and **K^-ppn DBKNS** (presently studied by Dr. Vasquez Doce).

At this end a MC simulation was created in which K^- interacts with a p in the DCEW (much statistic) giving rise to the reaction:

$$K^- p \to \Sigma^0 \pi^0 \to (\Lambda\gamma_3)(\gamma_1\gamma_2) \to (n\pi^0)\gamma_1\gamma_2\gamma_3 \to n(\gamma_4\gamma_5)\gamma_1\gamma_2\gamma_3.$$

(Σ^0 decays electromagnetically in $\Lambda\gamma$, $\Lambda \to n\pi^0$ (BR=36%))

compared to data analysis results for the same channel.

PROBLEMS:

6 neutral clusters in each event !

No track in the calorimeter, **no** decay **vertex** !

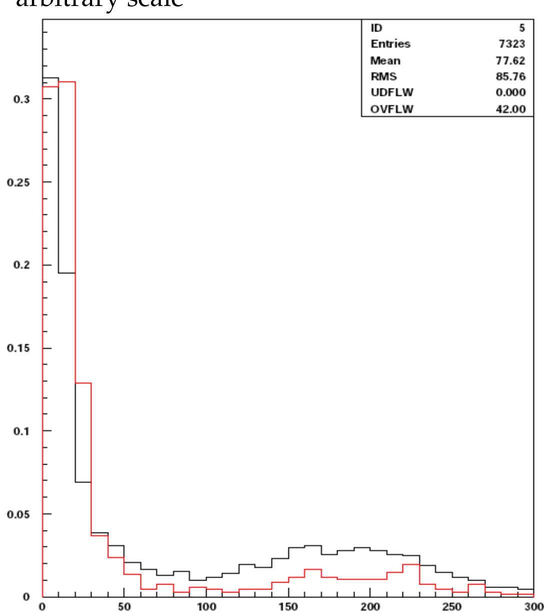
Events are retained in which **K^+ is tagged**, **K^- is not tagged**. **K^+ track is extapolated backword** so to obtain the K^- - DCEW interaction point $\mathbf{r_K}$. The χ_t^2 variable is applied **searching for 5 photon candidates**. **The algorithm has an efficiency of ~ 96% in selecting photons** (MC true information)!

Identification of neutrons through K$^-$ interaction in the KLOE DC entrance wall

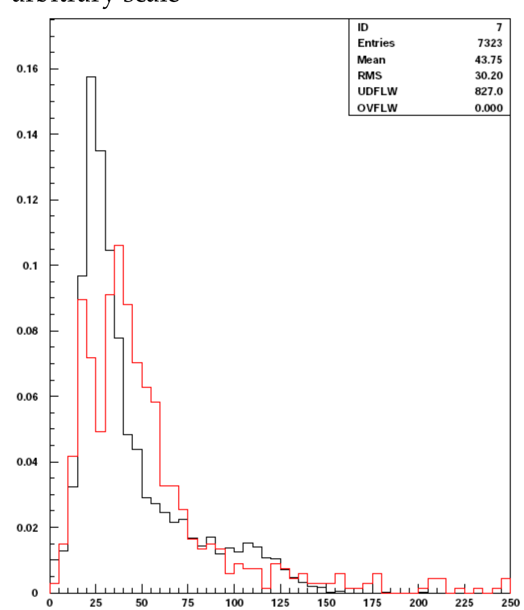
For each couple a new chi square variable is calculated based on the invariant mass of four photons in order to identify the two couples of photons coming from π^0 decay.

Many sources of background were taken into account: 1) **cluster splitting** 2) presence of a **negative kaons not tagged** by dE/dx or 2 - body decay 3) $\mathbf{K^- \rightarrow \pi^- \pi^0 \pi^0}$ (BR ~ 1.8%) 4) Events in which $\mathbf{\Lambda \rightarrow p \pi^-}$ (BR ~ 64%) while $\mathbf{K^+ \rightarrow \pi^+ \pi^0 \pi^0}$.

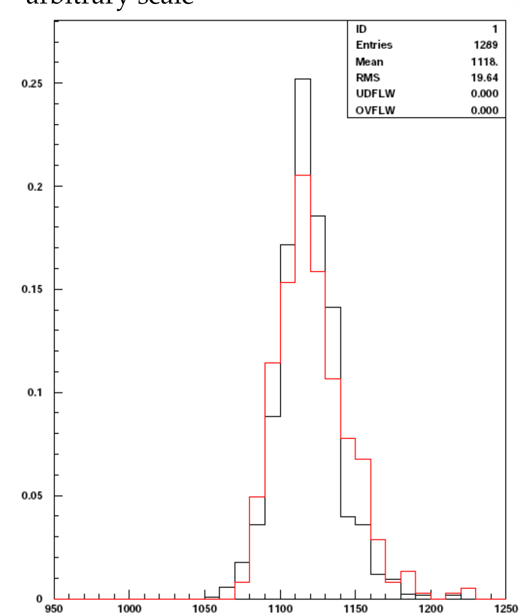
To conclude, for each identified π^0 a new chi square variable is calculated based on the Λ invariant mass to identify, among the two π^0s, the one coming from Λ decay.



E_n (MeV), MC red, data black



T_n (ns), MC red, data black



$m_{n\,\pi 0}$ (MeV/c^2), MC red, data black

Identification of neutrons through K^- interaction in the KLOE DC entrance wall (concluding remarks)

The width in the invariant mass of the Λ is due to the resolution of the calorimeter and shows the difficulty in performing invariant mass spectroscopy in the case of totally neutral channels.

The capability in neutron identification of our algorithm turns instead to be very interesting, and can give important informations in the study of $\Lambda - p$ or $\Lambda - d$ events (produced as a consequence of K^- interaction in ^4He) when Λ decays through its charged channel, in the search for DBKNS.

Scientific case Λ(1405)

- Λ(1405) is a negative parity baryon resonance (spin = 1/2, isospin = 0, strangeness = -1) located slightly below the $\bar{K}N$ threshold, decaying into the $\Sigma\pi$ channel trough the strong interaction.

- The quark model picture has some difficulties to reproduce the Λ(1405). According to its negative parity, one of the quarks has to be exited to the $l = 1$ orbit. Similar to the nucleon sector, where one of the lowest negative parity baryon is the N(1535), the expected mass of the Λ^* is around 1700 MeV (since it contains one strange quark). Another difficulty is the energy splitting observed between the Λ(1405) and the Λ(1520), if is interpreted as the spin-orbit partner ($J^p = 3/2^-$).

- R. Dalitz and collaborators first suggested to interpret Λ(1405) as an $\bar{K}N$ quasibound state.

- In the context of chiral theories the Λ(1405) is explained as an I = 0 quasibound state emerging from the coupling between the $\bar{K}N$ and the $\Sigma\pi$ channels.

- the distribution shape depends on the observed decay channel ($\Sigma^+\pi^-$, $\Sigma^-\pi^+$, $\Sigma^0\pi^0$) and on the production mechanism. **Great importance to explore the Λ(1405) production in $\bar{K}N$ reactions**.

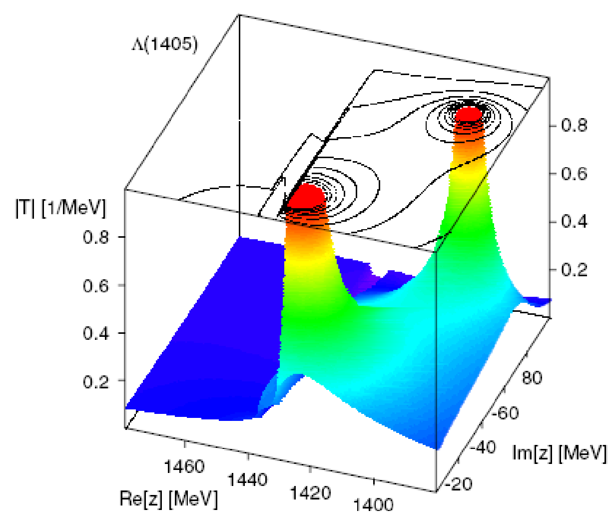
Scientific case

In the context of chiral theories the $\Lambda(1405)$ is explained as an I = 0 quasibound state emerging from the coupling between the $\bar{K}N$ and the $\Sigma\pi$ channels. Here comes out that there are two poles in the neighborhood of the $\Lambda(1405)$, both contributing to the final experimental invariant mass distribution.

One pole has a mass of ~1390 MeV and a width of ~130 MeV and is strongly coupled to the $\Sigma\pi$ channel.

A second pole has a mass 1420-1430 MeV, a width of 30 MeV and mostly couples to the $\bar{K}N$ channel.

As a consequence, the distribution shape depends on the observed decay channel ($\Sigma^+\pi^-$, $\Sigma^-\pi^+$, $\Sigma^0\pi^0$) and on the production mechanism.



We then see the **great importance to explore the $\Lambda(1405)$ production in $\bar{K}N$ reactions decaying in $\Sigma^0\pi^0$ channel** (Σ^0 decays electromagnetically in $\Lambda\gamma$). This is a **golden, still poorly explored, channel** since the main source of background **$\Sigma(1385)$ can not decay in $\Sigma^0\pi^0$** for isospin selection.

Selection of the photon clusters

We select those events in which there are at least three neutral clusters (with not associated track in the DC) not coming from K^+ decay $K^+ \to \pi^+\pi^0$

In order to identify the three photon clusters, a chi square variable is calculated for each couple of selected clusters, based on the difference $t = t_i - t_j$ where..

$$t_i = t_{cli} - \frac{r_i}{c}$$

$$r_i = \sqrt{(x_\Lambda - x_{cli})^2 + (y_\Lambda - y_{cli})^2 + (z_\Lambda - z_{cli})^2}$$

→

$$\chi_t^2 = t^T V_t^{-1} t$$

The three couples of photon candidates (in time from Λ decay vertex $\mathbf{r}_\Lambda$) minimizing this variable are selected (a check controls that each cluster appears two times in the three couples).

In order to distinguish the photon clusters coming from π^0 decay, from γ_3 (due to Σ^0 decay) we select the triple which minimizes:

$$\chi^2_{\pi\Sigma} = \frac{(m_{\pi^0} - m_{ij})^2}{\sigma^2_{ij}} + \frac{(m_{\Sigma^0} - m_{k\Lambda})^2}{\sigma^2_{k\Lambda}}$$

Where σ_{ij} $\sigma_{k\Lambda}$ are respectively the variances of the invariant mass of two photons and one photon with the Λ

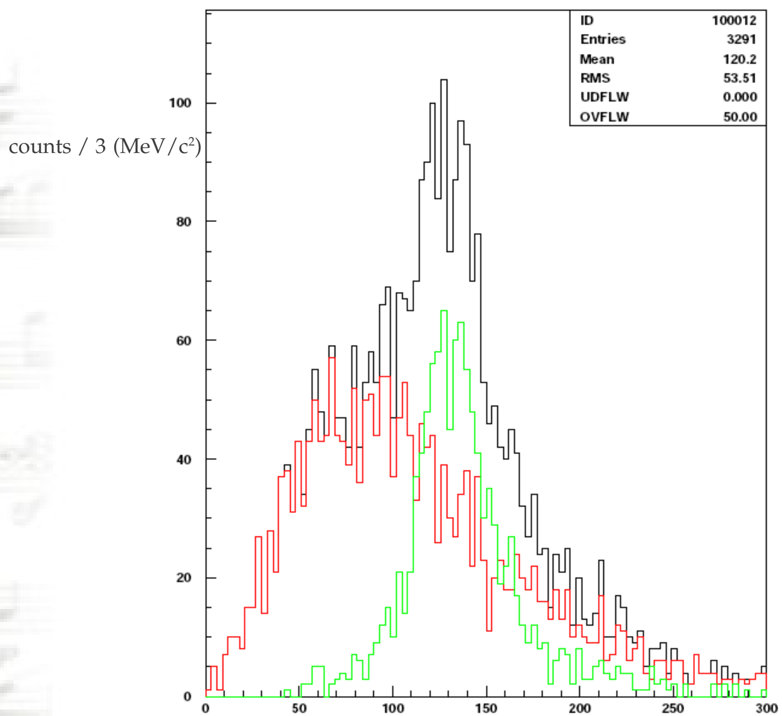
Specific cuts were optimized over χ_t^2 and $\chi_{\pi\Sigma}^2$ based on MC results.

Selection of the photon clusters

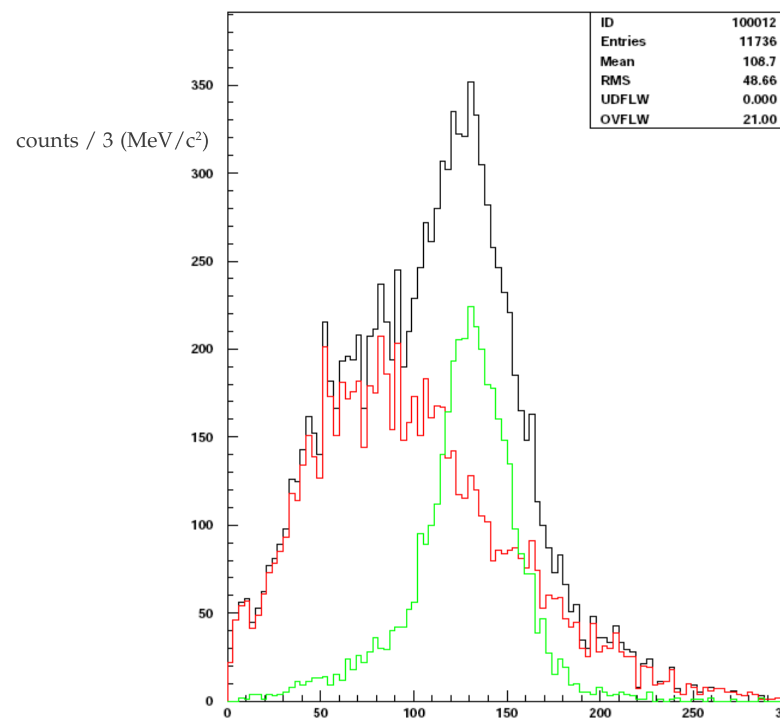
In order to avoid the selection of splitted clusters or background for π^0, the following cut was introduced (see KLOE memo 311 9 June 2006):

$$R \geq \frac{a}{E_{\gamma_i} + E_{\gamma_j} + b} \quad \text{dove } a = 15000\,MeV\,cm \text{ e } b = 1\,MeV$$

Where R (cm), E_i, E_j (MeV) are the distance between the clusters and the energies of the two clusters.



MC events. In black: invariant mass of the three couples of photons (MeV/c²), in red: $m_{\gamma3\gamma2}$, $m_{\gamma2\gamma1}$ (MeV/c²), in green: $m_{\gamma2\gamma1}$ (MeV/c²)



Data. In black: invariant mass of the three couples of photons (MeV/c²), in red: $m_{\gamma3\gamma2}$, $m_{\gamma2\gamma1}$ (MeV/c²), in green: $m_{\gamma2\gamma1}$ (MeV/c²)

According to MC true information, the algorithm has an **efficiency more than 80% in recognizing the right photons triple!**