Measurement of BR($K^+ \rightarrow \pi^+\pi^-\pi^+(\gamma)$) at KLOE

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on behalf of the KLOE-2 Collaboration

DaΦne and KLOE

DaΦne: the frascati φ factory

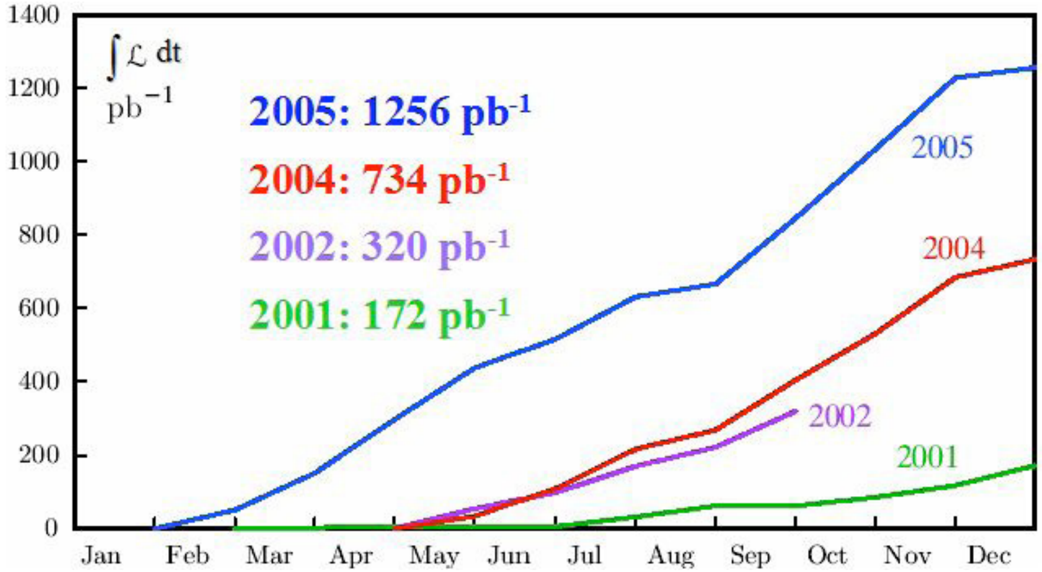
- e+e- collider @ $\sqrt{s}$ **= 1019.4 MeV**
- crossing angle ≈ 25 mrad

2.5 fb^{-1} integrated @ $\sqrt{s}$ = M(φ), yielding

~ 2.5 x 10^{9} $K_S K_L$

~ 3.6 x 10^{9} K^+K^-

250 pb^{-1} integrated @ $\sqrt{s}$ =1 GeV for physics in the continuum



- most of the infrastructures of the Frascati accelerator complex have been consolidated for physics run with KLOE-2
- beam interaction region upgraded

1) larger crossing angle
2) reduced beam size
3) crab-waist configuration

- the goal is to collect 5 fb^{-1} in 2 – 3 years

kaon production

the ϕs are produced with $\sigma(e^+e^- \rightarrow \phi) \approx 3\mu b$ and decay almost at rest ($p_x \approx 12.5$ MeV/c)

neutral and charged kaons are produced in pairs

collinear and monochromatic

$K_S, K^+ \longleftarrow \phi \longrightarrow K_L, K^-$

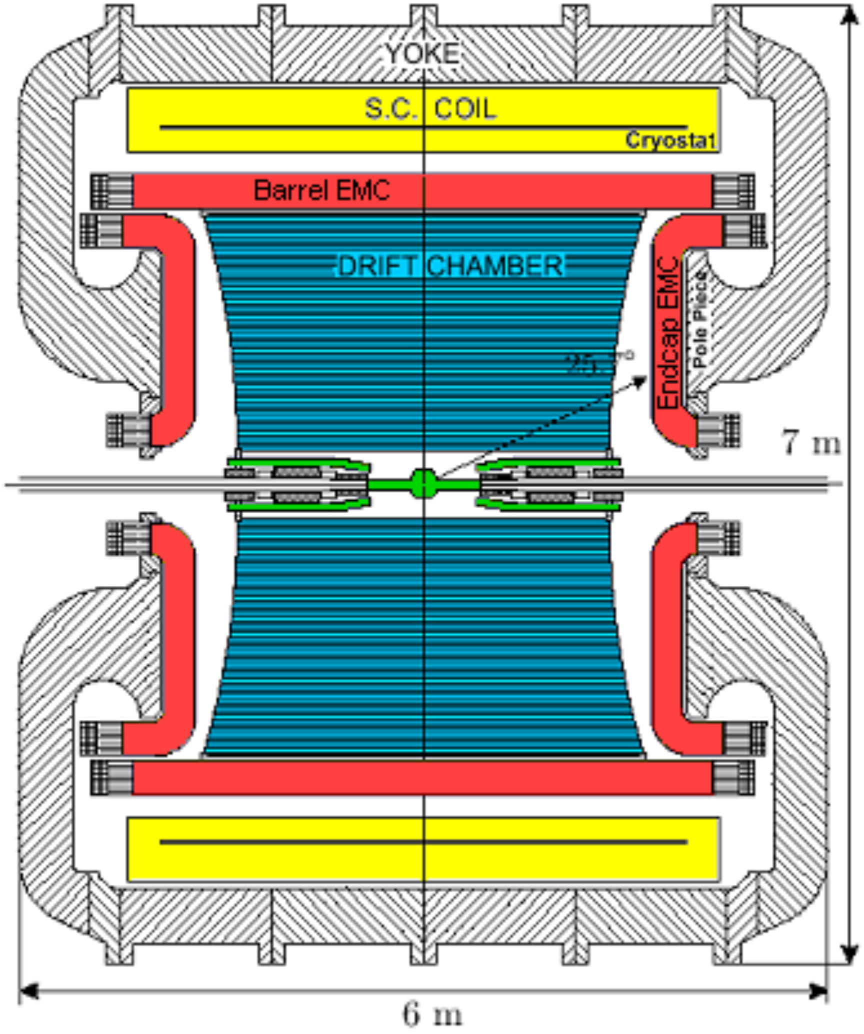
detection of a $K^-(K^+)$ guarantees the presence of a K^+ (K^-) with known momentum and direction (the same for K_SK_L) $\Rightarrow$ **tagging**

pure kaon beam obtained $\Rightarrow$ normalization (N_{tag}) sample

$\Rightarrow$ **allows precision measurements of absolute BRs**

K^+K^-	K_LK_S
BR ≅ 49%	BR ≅ 34%
p_{lab} = 127 MeV/c	p_{lab} = 110 MeV/c
$\lambda_\pm$ = 95 cm	λ_S = 0.6 cm, λ_L = 340 cm

the KLOE detector



Be beam pipe (0.5 mm thick),
r =10 cm (K_S fiducial volume)

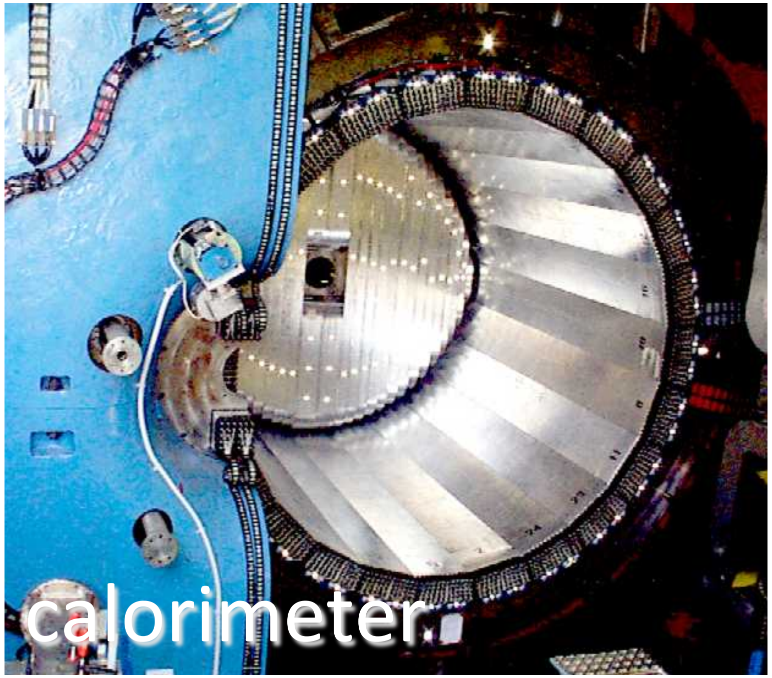
drift chamber (4 m Ø × 3.3 m),
90% He + 10% IsoB,
carbon-fiber structure,
12582 stereo sense wires

electromagnetic calorimeter
lead/scintillating fibers,
C-shaped end-caps for full
coverage → 98% of the solid angle

superconducting coil
B = 0.52 T ($\int Bdl = 2$ T·m)

loose trigger conditions to insure maximal acceptance for a wide topology of events

KLOE detector performance



$\sigma_E/E \cong 5.7\% /\sqrt{E(\mathrm{GeV})}$

$\sigma_t \cong 57$ ps $/\sqrt{E(\mathrm{GeV})} \oplus 100$ ps

$\sigma_{\gamma\gamma} \sim 2$ cm (π^0 from $K_L \rightarrow \pi^+\pi^-\pi^0$)

$\sigma_{pt}/p_t \cong 0.4$ % (tracks with $45^o < \theta < 135°$)

$\sigma_x^{hit} \cong 150$ μm (xy), 2 mm (z)

$\sigma_x^{vertex} \sim 3$ mm

the detector upgrades KLOE-2

✘ two stations of γ-γ taggers, for the detection of e^+ and e^-

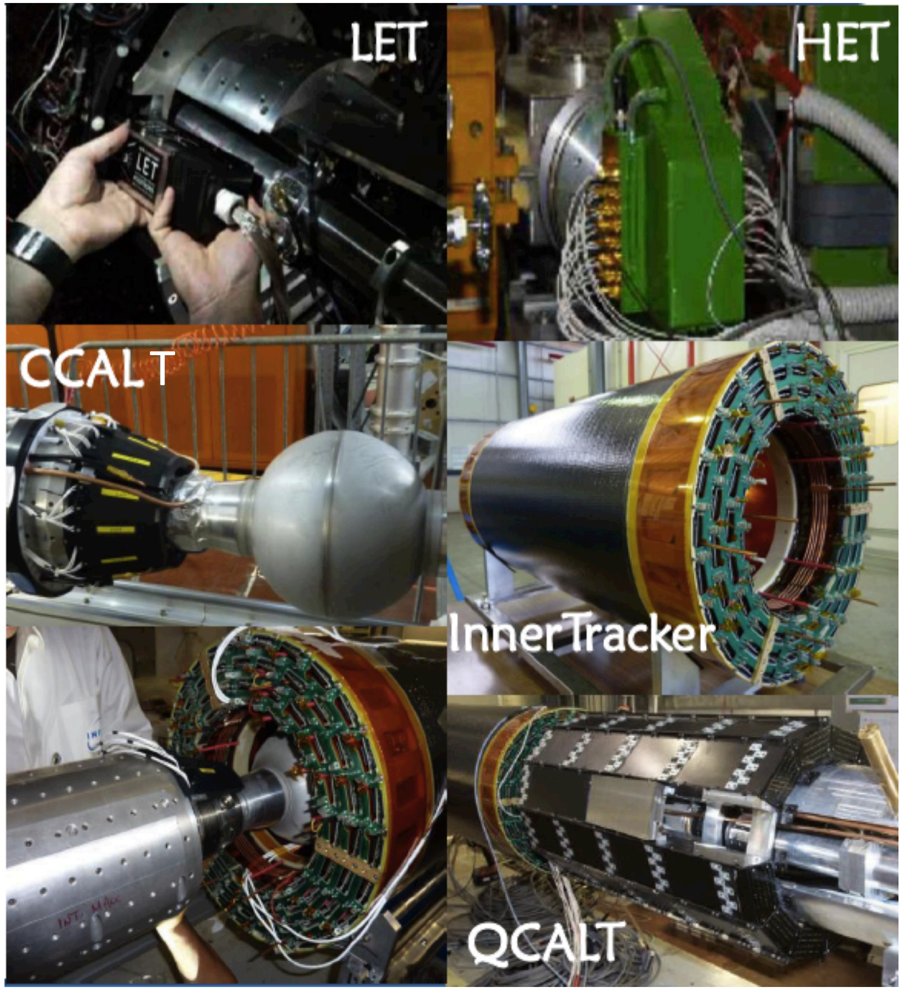
<u>High-Energy Taggers</u> (HET)

E_e > 400 MeV
11 m from IP
scintillators + PMTs

<u>Low-Energy Taggers</u> (LET)

130 < E_e < 300 MeV
inside KLOE
LYSO-crystals + SiPMs

✘ the Inner Tracker is the first cylindrical 3-GEM chamber ever built ➔ increase the acceptance for low p_t tracks and vertex resolution near IP



✘ CCALT LYSO-crystal calorimeter to increase acceptance for γs ($21^o \rightarrow 8^o$)

✘ QCALT is a sampling calorimeter to instrument the final focusing region

- absolute $K^+ \to \pi^+\pi^-\pi^+(\gamma)$ branching ratio

absolute BR($K^+ \rightarrow \pi^+\pi^-\pi^+(\gamma)$)

- *this measurement completes the KLOE program of precise and inclusive of FSR $K^\pm$ dominant BRs*

KLOE fit 2008 BR($K^\pm \rightarrow \pi^\pm\pi^-\pi^+$) = $(5.68 \pm 0.22)\%$ $\Delta BR/BR = 3.8\times10^{-2}$

PLB 666 (2008)

- *this BR enters in the CUSP analysis to extract the $\pi\pi$ phase shift, NA48* *PLB 633(2006)*
- *needed to perform a global fit to $K^\pm$ BRs*
- *available measurements dates back to 1972 (no informations on radiation cut-off)*

CHIANG (2330 evts) BR($K^\pm \rightarrow \pi^\pm\pi^-\pi^+$) = $(5.56 \pm 0.20)\%$ $\Delta BR/BR = 3.6\times10^{-2}$

PRD 6 (1972)1254

PDG fit 2012 BR($K^\pm \rightarrow \pi^\pm\pi^-\pi^+$) = $(5,59 \pm 0.04)\%$ $\Delta BR/BR = 7,1\times10^{-3}$

- *preliminary KLOE result presented at **KAON 2013** and **PHIPSI 2013***

KLOE$_{(45054\ \mathrm{evts})}$ BR($K^+ \rightarrow \pi^+\pi^-\pi^+(\gamma)$) = $(5.55 \pm 0.05)\%$ $\Delta BR/BR = 9.2\times10^{-3}$

tagging of K^+K^- beams (I)

$K^\pm$ beams tagged by $K^\pm \rightarrow \pi^\pm\pi^0$, $\mu^\pm\nu$

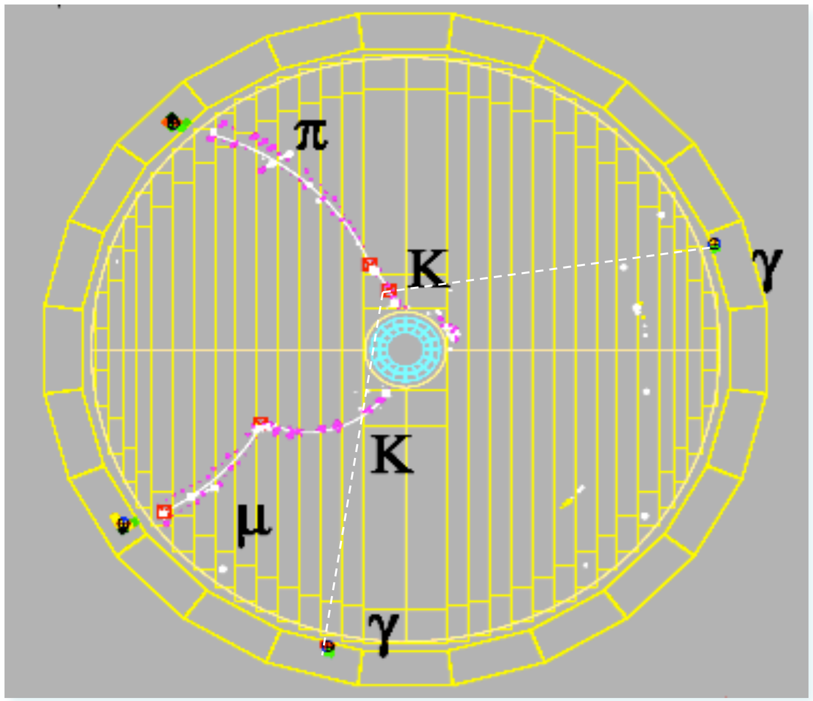
➔ $\cong 1.5 \times 10^6\ K^+K^-$ evts/pb^{-1}

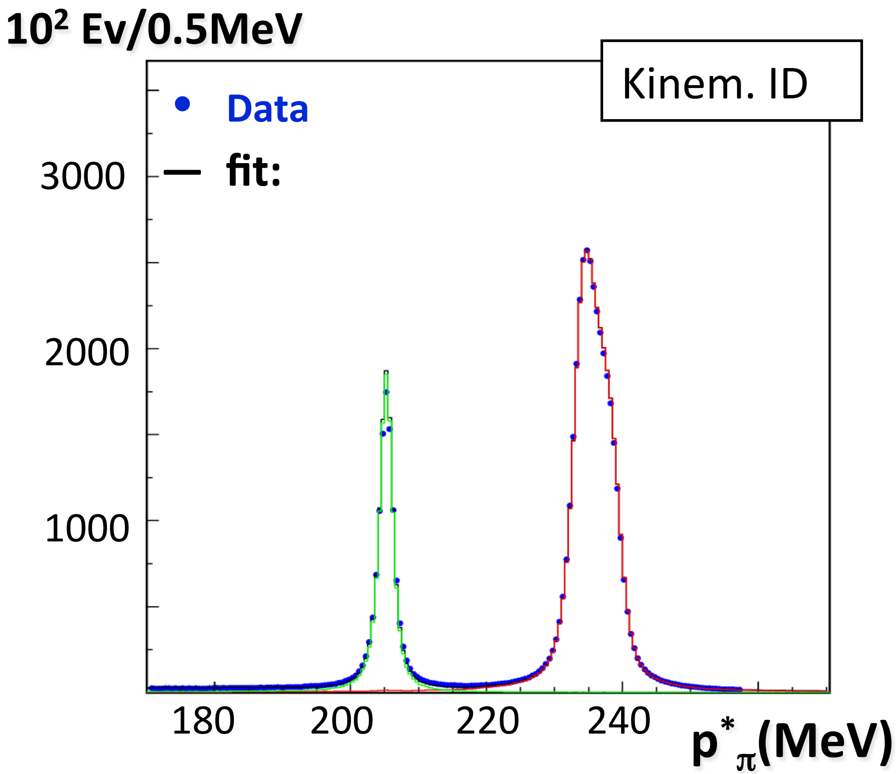
two indipendent samples of pure kaons

two-body decays identified as peaks in the momentum spectrum of secondary tracks in the kaon rest frame → $p^*(m_\pi)$

$\varepsilon_{tag} \cong 36\ \% \Rightarrow \cong 3.4 \times 10^5\ \mu\nu$ tags/pb^{-1}

$\cong 1.1 \times 10^5\ \pi\pi^0$ tags/pb^{-1}





tagging of K^+K^- beams (II)

to remove the impact of the trigger efficiency on the signal side we restrict our normalization sample N_{tag} to 2-body decays that provide themselves the EMC trigger of the event *self-triggering tags* *(EMC trigger given by 2 trigger sectors over threshold ~50 MeV)*

- the sample $N_{tag}(\pi\pi^0)$ is reduced by $\cong$ 40%
- the sample $N_{tag}(\mu\nu)$ is reduced by $\cong$ 35%

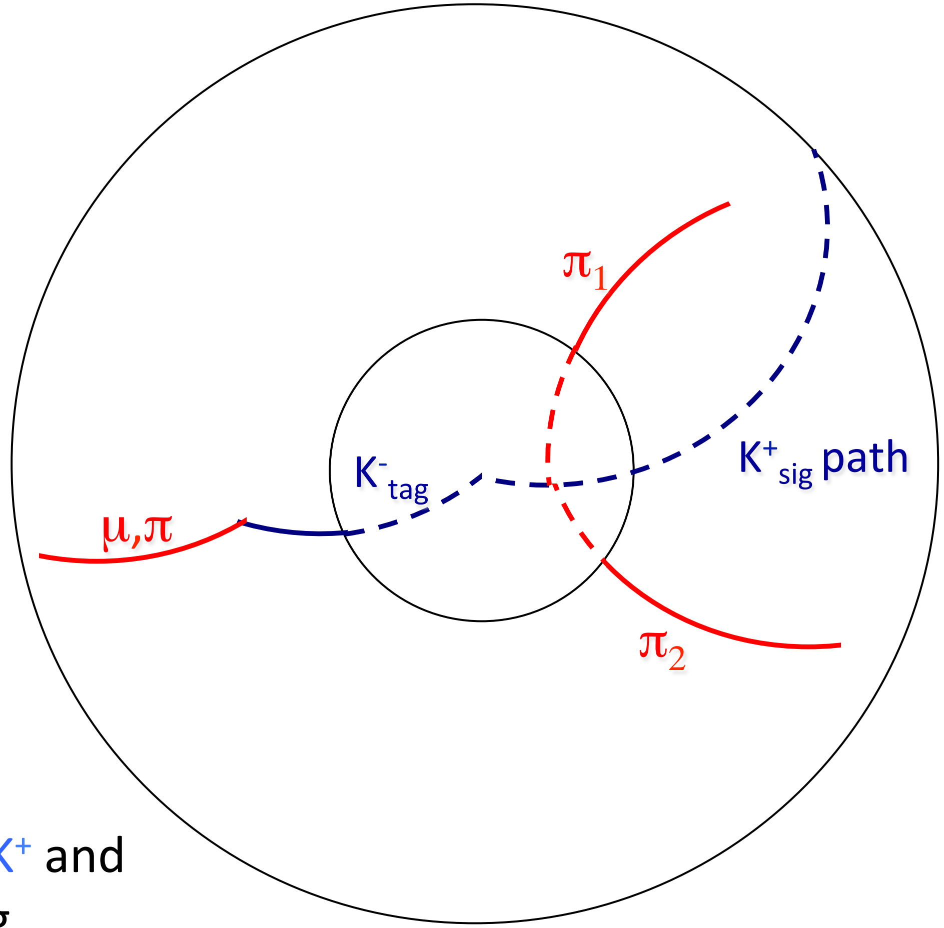
use K^- to tag and K^+ for signal search → to neglect correction to the BR($K \rightarrow 3\pi$) due to nuclear interactions of kaons ($\sigma_{NI}(K^+) \cong \sigma_{NI}(K^-)/10^3$ for $p_K \cong 100$ MeV/c)

to measure BR's we must take into account a correction due to a bias on the tag selection induced by the signal → *tag bias*

evaluated from MC $\Rightarrow$ $C_{TB} = BR_{MC}(\text{with tag}) / BR_{MC}(\text{without tag})$

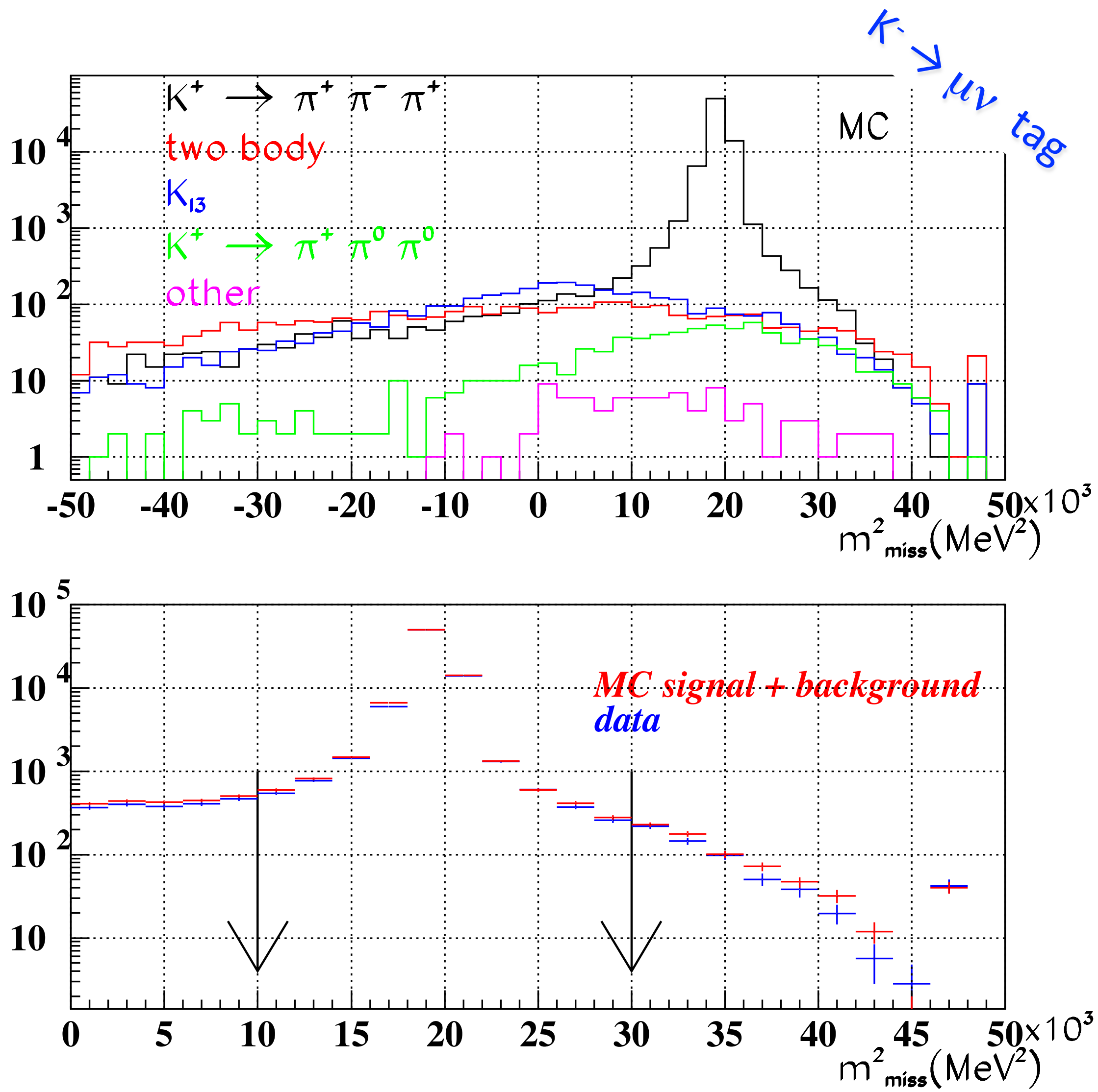
Overview

- self-triggering tag on one side
- the virtual path of the signal K^+ is given by the tagging K^- track backward extrapolated to the I.P.
- in the signal hemisphere we require two reconstructed tracks making a vertex along the K^+ path *before the DC sensitive volume* ($\alpha_{GEO} \cong 26\ \%$)
- the missing mass distribution from the K^+ and the two pions is used for event counting
- selection efficiency evaluated with MC and corrected using data&MC control samples



first look at the signal

- NO charge requests
- tracks backward extrapolated with Distance of Closest Approach, DCA < 3. cm
- p^*m_π < 190. MeV/c to remove 2-body decays
- N(selected tracks) = 2
- Distance of Closest Approach between two selected tracks, DCA_{12} < 3. cm
- fiducial volume, ρ_{xy} < 26. cm



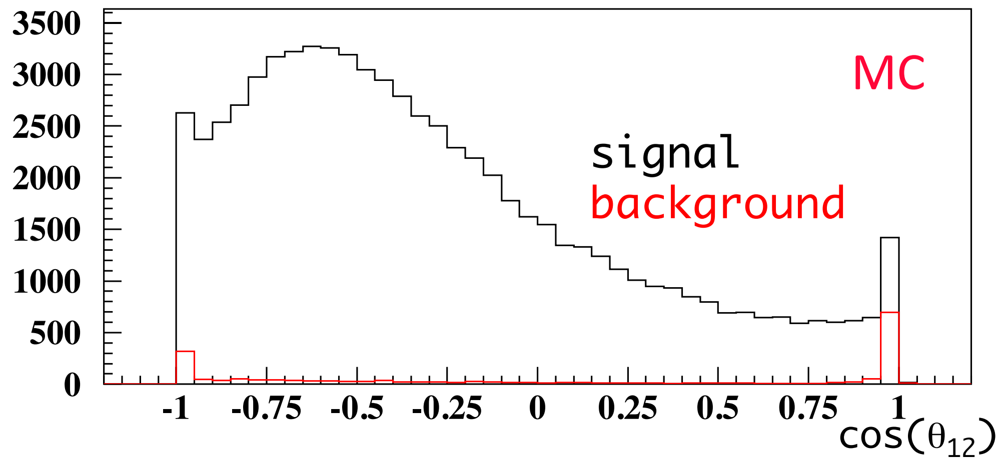
mass window ➔

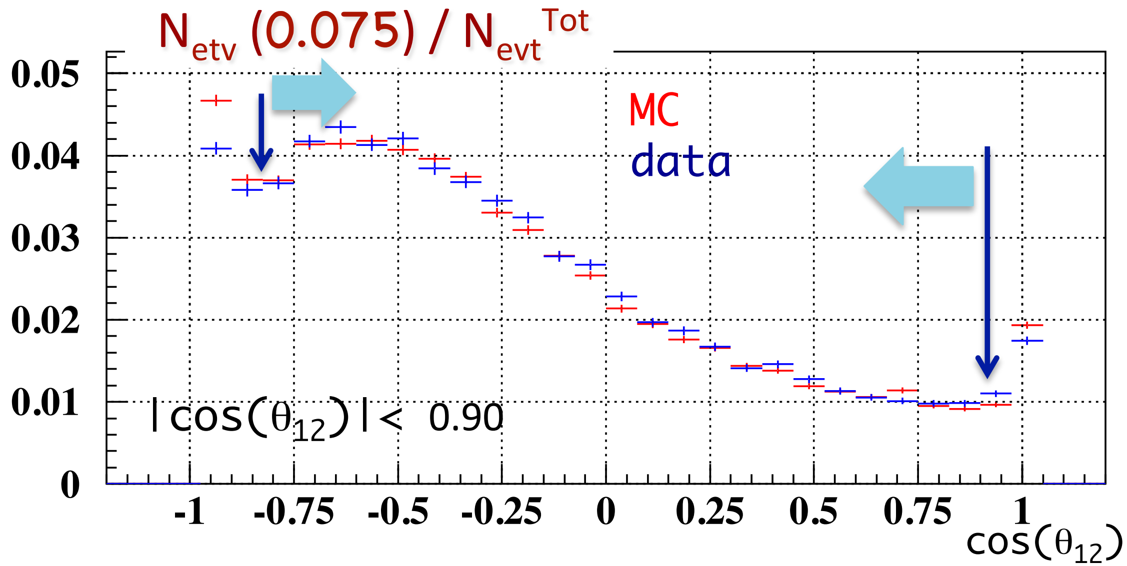
(10000. < m^2_{miss} < 30000.) MeV^2

S/B ≅ 37.

background

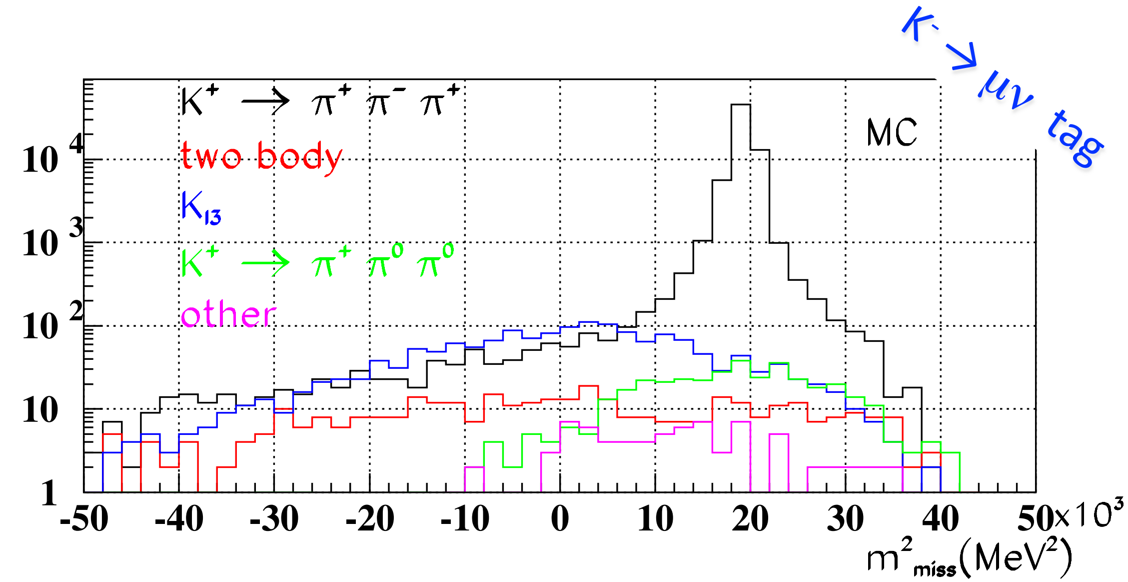
- mainly due to residual K tracks
- distributions of the opening angle between the two selected tracks ➔ $\cos(\theta_{12})$





the signal (I)

- NO charge requests
- $p^*m_\pi < 190.$ MeV/c
- DCA < 3. cm
- N(selected tracks) = 2
- $DCA_{12} < 3.$ cm
- $|\cos(\theta_{12})| < 0.90$
- fiducial volume, $\rho_{xy} < 26.$ cm



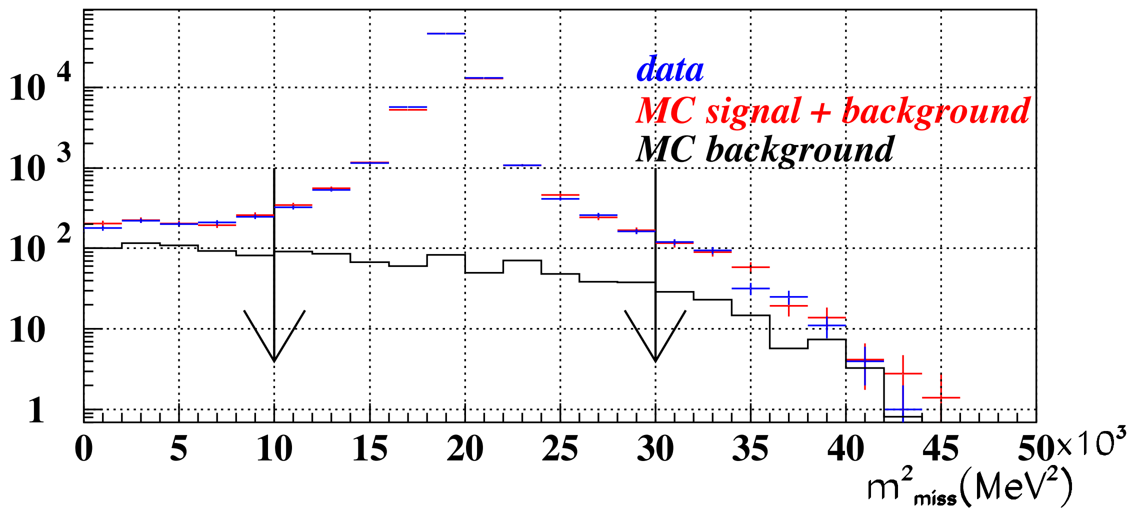
- $10000. < m^2_{miss} < 30000.$ MeV^2

S/B ≅ 88.

two body ≅ 0.1%

K_{l3} ≅ 0.5%

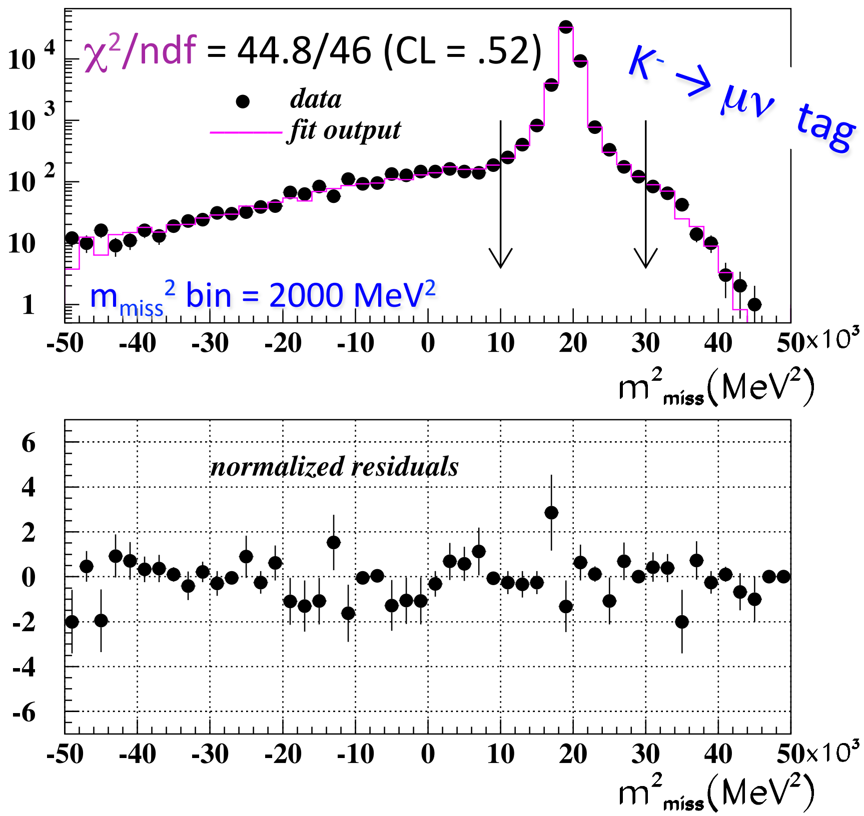
$K^+ \to \pi^+\pi^0\pi^0$ ≅ 0.4%

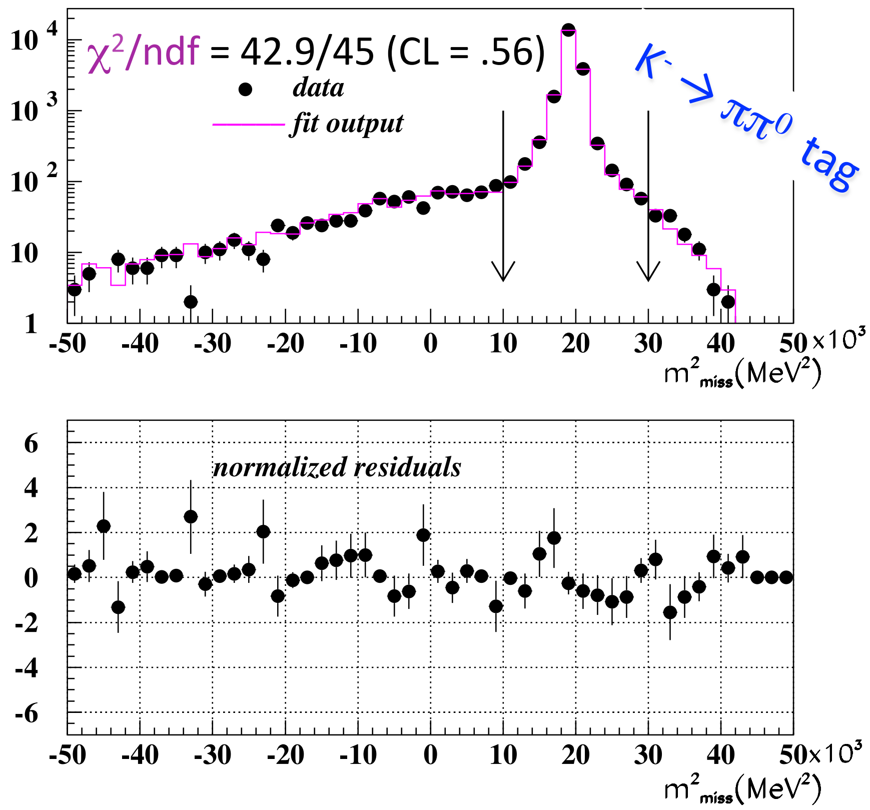


the signal (II)

to evaluate the background contribution ➔ fit the missing mass spectrum using MC signal and background shapes

174 pb^{-1} of the KLOE data sample





$N_{tag}(K^- \rightarrow \mu^- \nu) = 12065087$

$N(K^+ \rightarrow 3\pi) = 48032 \pm 286$

$N_{tag}(K^- \rightarrow \pi^- \pi^0) = 5171239$

$N(K^+ \rightarrow 3\pi) = 20063 \pm 186$

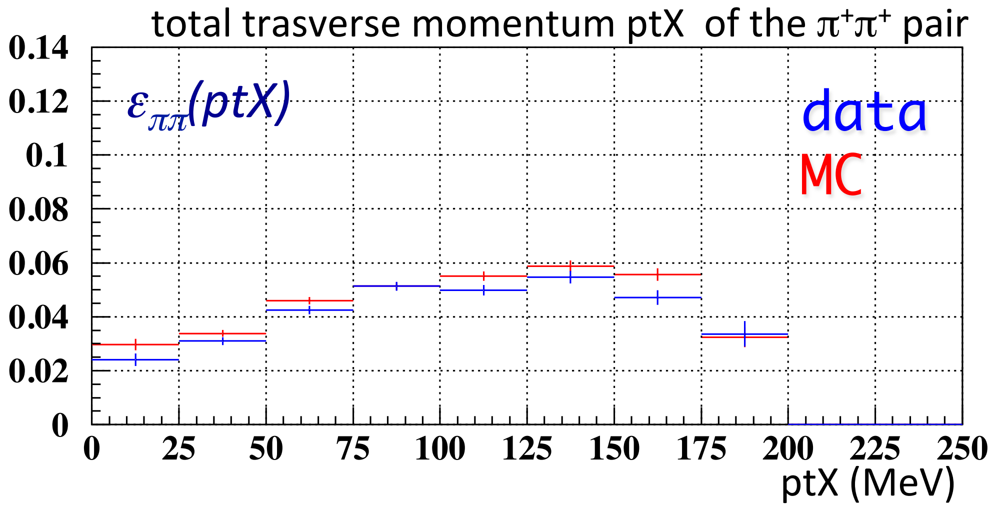
$K^+ \to \pi^- X$ control sample

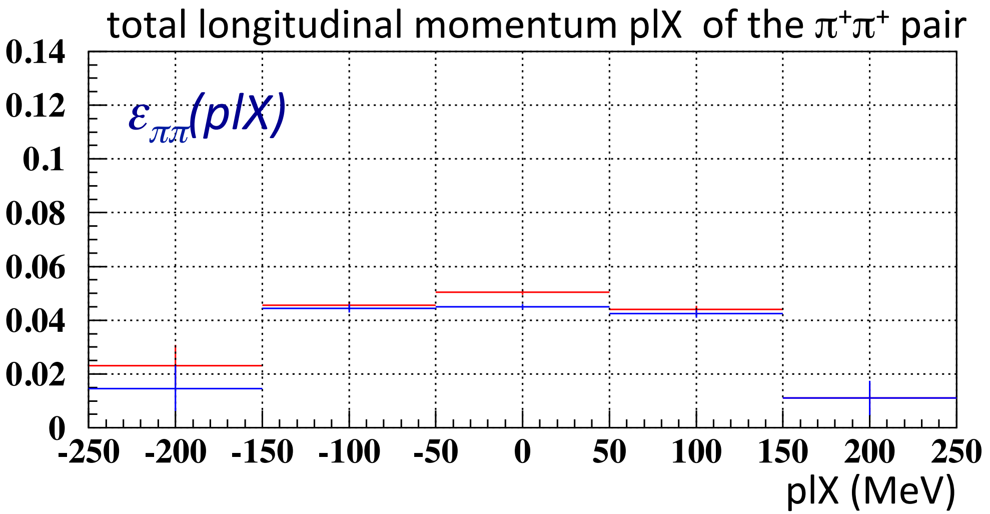
measurement of the double tracks reconstruction efficiency on data and MC

- neutral clusters (E > 30. MeV) in the signal hemisphere, $N_{clusters} \leq 1$
- $p^*m_\pi < 130.$ MeV
- $Cos(\theta_{K\pi}) > -0.85$
- $DCA_{\pi^-} < 7.$ cm

➔ *bck contamination ≅ 11.%*

then look for two reconstructed tracks that satisfy the complete set of the signal selection cuts ➔ $\varepsilon^{data}_{\pi\pi} / \varepsilon^{MC}_{\pi\pi}$





$K^- \to \mu\nu$ tag

$$\varepsilon_{sel} = \varepsilon^{MC}_{K+ \to 3\pi} \otimes (\varepsilon^{data}_{\pi\pi} / \varepsilon^{MC}_{\pi\pi}) = 0.0842 \pm 0.0003$$

$K^- \to \pi\pi^0$ tag

$$\varepsilon_{sel} = \varepsilon^{MC}_{K+ \to 3\pi} \otimes (\varepsilon^{data}_{\pi\pi} / \varepsilon^{MC}_{\pi\pi}) = 0.0866 \pm 0.0005$$

corrections to BR($K^+ \to \pi^+\pi^-\pi^+(\gamma)$)

$$BR(K^+ -> \pi^+\pi^-\pi^+(\gamma)) = \frac{N_{K->3\pi}}{N_{tag}} \times \frac{1}{\varepsilon_{sel} C_{TB} C_{SF} C_{CRV}}$$

- a cosmic-ray veto and a software filter to remove the machine background are implemented ➔ their effects C_{CRV} and C_{SF} have been evaluated with data acquired without cosmic-ray veto and software filter respectively
- C_{TB} is the correction for the tag bias evaluated with MC

Table of corrections	$K^-_{\mu 2}$ tags	$K^-_{\pi 2}$ tags
cosmic ray veto correction C_{CRV}	1.00125 ± 0.00002	1.00049 ± 0.00001
software filter correction C_{SF}	1.0144 ± 0.0013	1.0003 ± 0.0005
tag bias correction C_{TB}	0.839 ± 0.001	0.802 ± 0.002

systematic error contributions

Source of systematic uncertainties	$K^-_{\mu 2}$ tags (%)	$K^-_{\pi 2}$ tags (%)
DCA, DCA_{12}, $\cos(\theta_{12})$ cuts	0.52	0.41
$p^*_{m_\pi}$ cut	0.08	0.11
m^2_{miss} cut	0.05	0.14
fiducial volume	0.11	0.10
selection efficiency estimate	0.16	0.16
tag bias	0.16	0.32
$K^\pm$ lifetime	0.12	0.12
Total fractional systematic uncertainty	0.60	0.59

NOTE the analysis is fully inclusive of radiative decays, only ε_{sel} evaluation could be affected by a systematic uncertainty due to the cut $N_{clusters} \leq 1$ ➔ PHOTOS has been used to evaluate the fraction of decays removed by the cut, $\mathcal{O}(10^{-6})$

absolute BR($K^+ \to \pi^+\pi^-\pi^+(\gamma)$): result

174 pb^{-1} of the KLOE data sample

$$BR(K^+ \to \pi^+\pi^-\pi^+(\gamma))|_{TagK\mu2} = (0.05552 \pm 0.00034_{stat} \pm 0.00034_{syst})$$

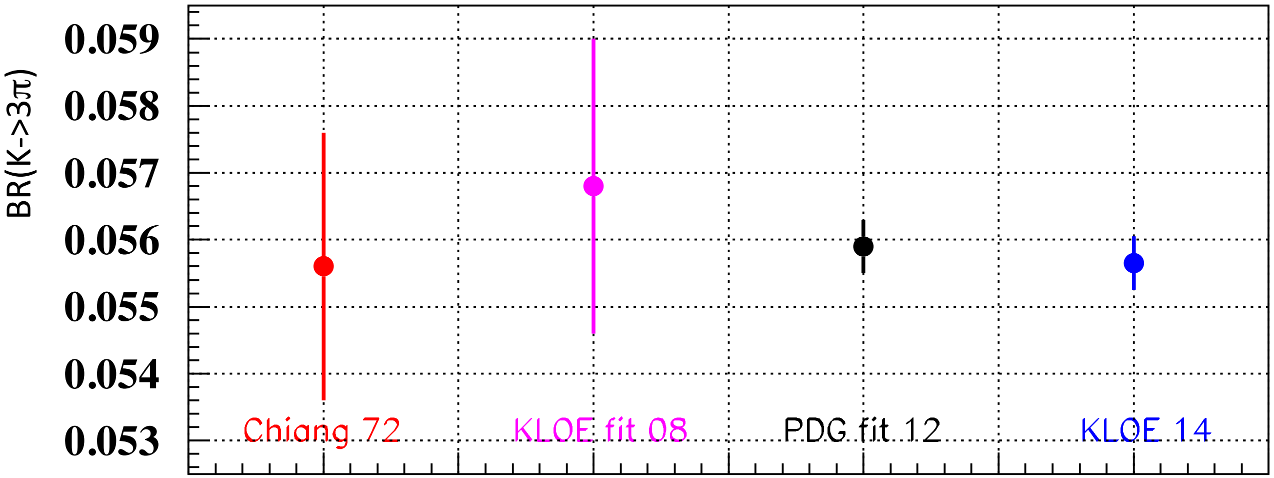
$$BR(K^+ \to \pi^+\pi^-\pi^+(\gamma))|_{TagK\pi2} = (0.05587 \pm 0.00053_{stat} \pm 0.00033_{syst})$$

and combining ➔

KLOE

$$BR(K^+ \to \pi^+\pi^-\pi^+(\gamma)) = (0.05565 \pm 0.00031_{stat} \pm 0.00025_{syst}), \quad \Delta BR/BR = 7.2 \times 10^{-3}$$

submitted to PLB arXiv:1407.2028



a factor ≅5 more precise with respect to the previous measurement *PRD 6 (1972) 1254*

absolute BR($K^+ \rightarrow \pi^+\pi^-\pi^+(\gamma)$): fit

lifetime and absolute BRs by KLOE

Parameter	BRs in	BRs out	Correlation coefficients					
BR($K^{\pm}_{\mu 2}$)	0.6366(17)	0.6372(11)						
BR($K^{\pm}_{\pi 2}$)	0.2065(9)	0.2070(9)	0.55					
BR($\pi^{\pm}\pi^{-}\pi^{+}$)	0.05565(39)	0.05577(39)	-0.23	-0.05				
BR($K^{\pm}_{e3}$)	0.0496(5)	0.0498(5)	0.42	-0.15	0.06			
BR($K^{\pm}_{\mu 3}$)	0.0323(4)	0.0324(4)	-0.39	0.14	-0.05	-0.58		
BR($\pi^{\pm}\pi^{0}\pi^{0}$)	0.01763(25)	0.01764(25)	-0.13	0.05	-0.02	0.04	-0.04	
$\tau_{K^{\pm}}$ (ns)	12.347(30)	12.344(29)	0.20	0.19	-0.14	0.05	-0.04	0.02

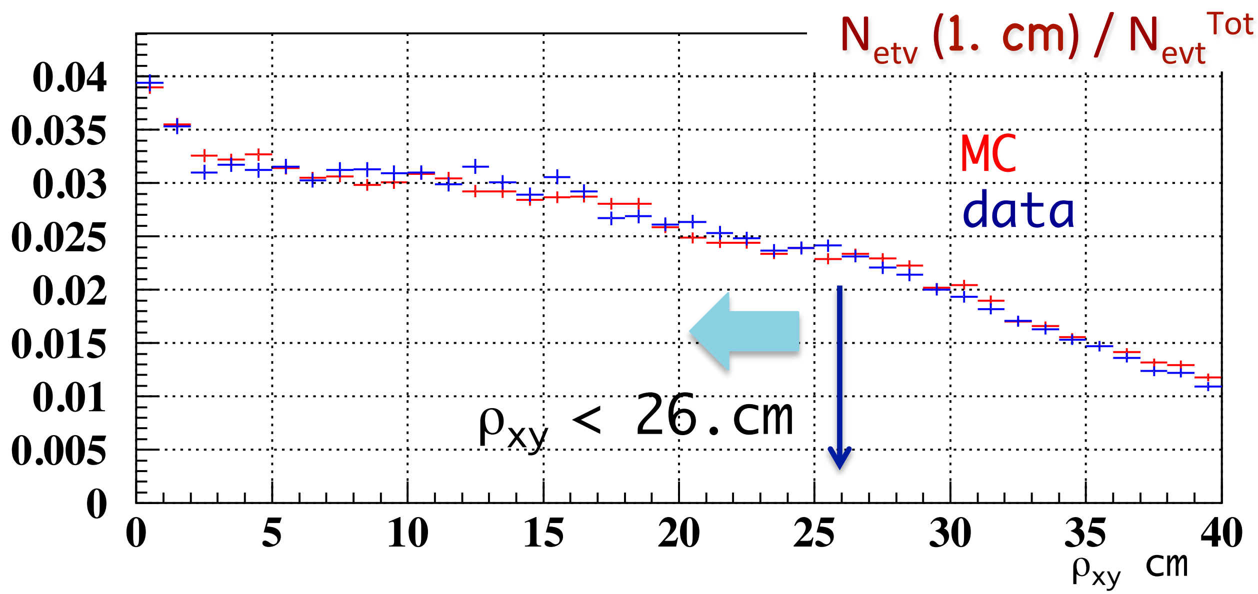
- the global fit to (1 – ΣBR_{KLOE}) taking into account the BRs dependence on $\tau_{K\pm}$ gives χ^2/ndf = 0.24/1 (CL = 0.63)
- KLOE provides consistent precision measurements of $\tau_{K\pm}$ and of the six largest $K^{\pm}$ branching fractions

Conclusions

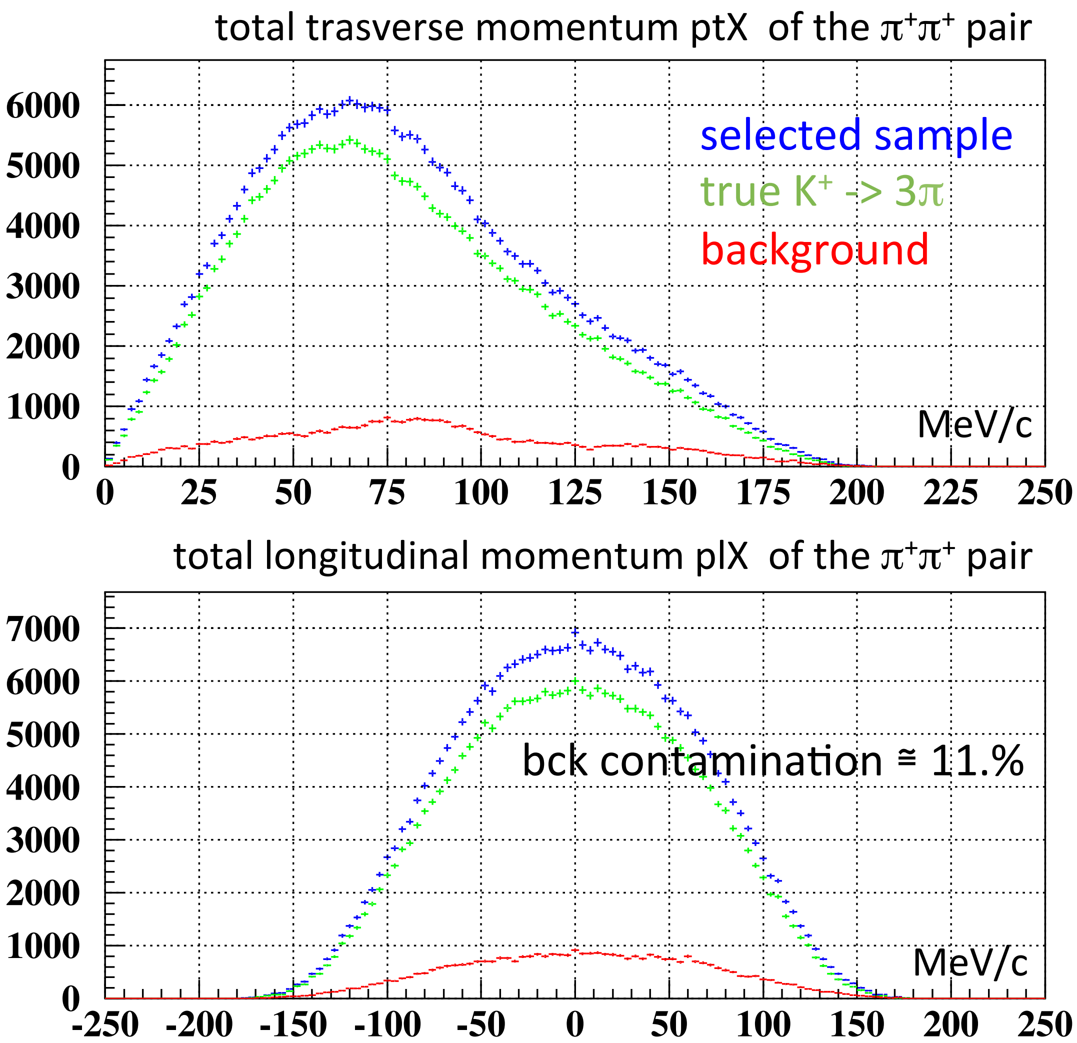
KLOE produced many interesting results in the recent years and it is still providing precise and competitive measurements in the kaon sector

- new measurement of the absolute BR($K^+ \rightarrow \pi^+\pi^-\pi^+(\gamma)$) completes the KLOE program of precise and fully inclusive of final-state radiation $K^{\pm}$ dominant BRs *backup slides*

fiducial volume

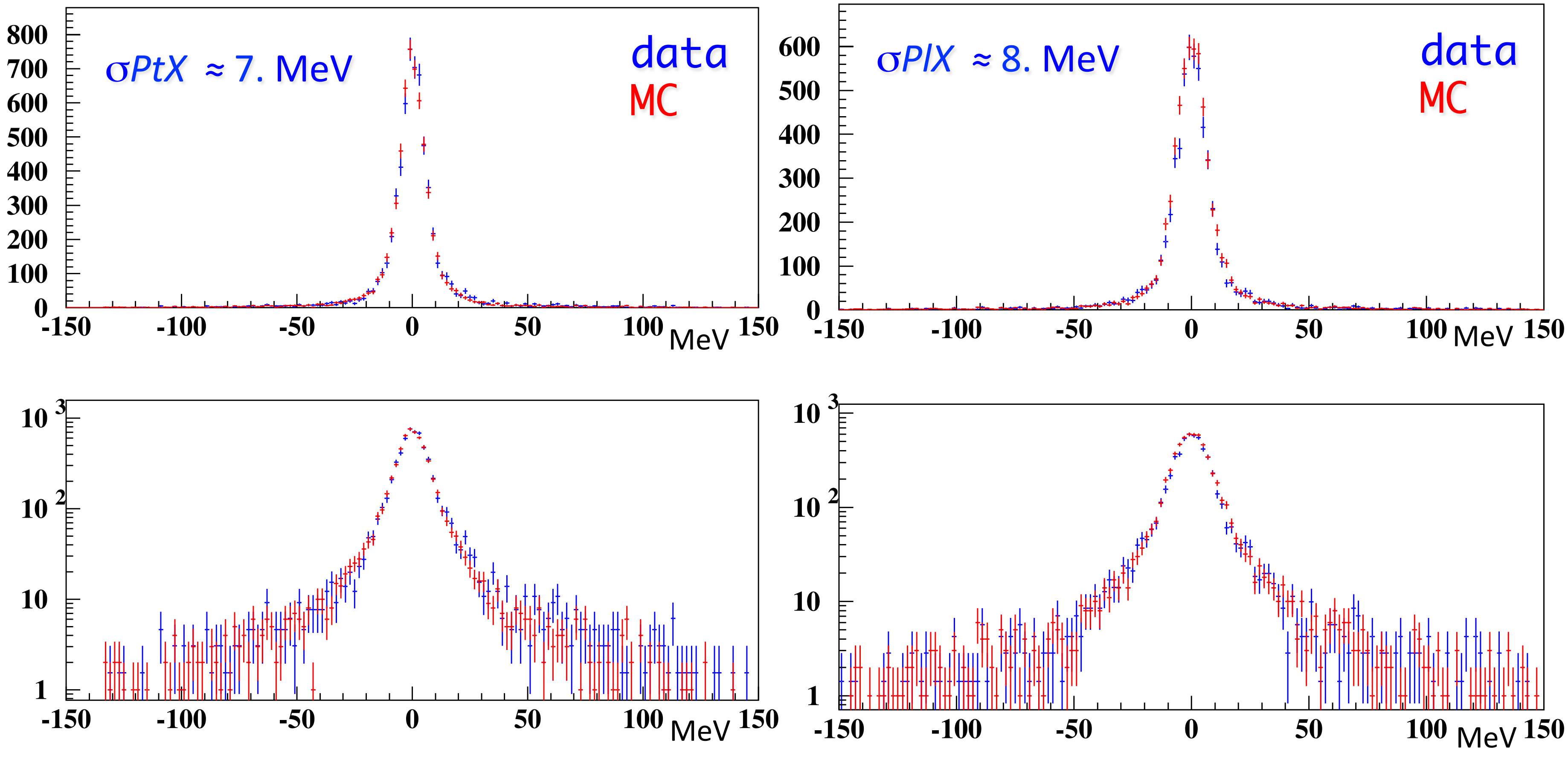


$K^+ \to \pi^- X$ control sample



$K^+ \to \pi^- X$ control sample

σPtX and σPlX respect to the reconstructed momentum of the $\pi^+\pi^+$ signal tracks



statistic and systematic error contributions

Source of statistical uncertainties	$K^-_{\mu 2}$ tags (%)	$K^-_{\pi 2}$ tags (%)
signal counting	0.45	0.70
selection efficiency	0.38	0.60
tag bias	0.11	0.18
software filter	0.13	0.05
cosmic ray veto	0.002	0.0005
Total fractional statistical uncertainty	0.62	0.95

Source of systematic uncertainties	$K^-_{\mu 2}$ tags (%)	$K^-_{\pi 2}$ tags (%)
DCA, DCA_{12}, $\cos(\theta_{12})$ cuts	0.52	0.41
$\mathrm{p}^*_{m_\pi}$ cut	0.08	0.11
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$K^\pm$ lifetime	0.12	0.12
Total fractional systematic uncertainty	0.60	0.59

Result (different data samples for BR and ε corrections measurements)

$$BR(K^+ -> \pi^+\pi^-\pi^+) = \frac{N_{K->3\pi}}{N_{tag}} \times \frac{1}{\varepsilon_{sel} C_{TB} C_f C_{crv}}$$

tag $K^- \to \mu\nu$

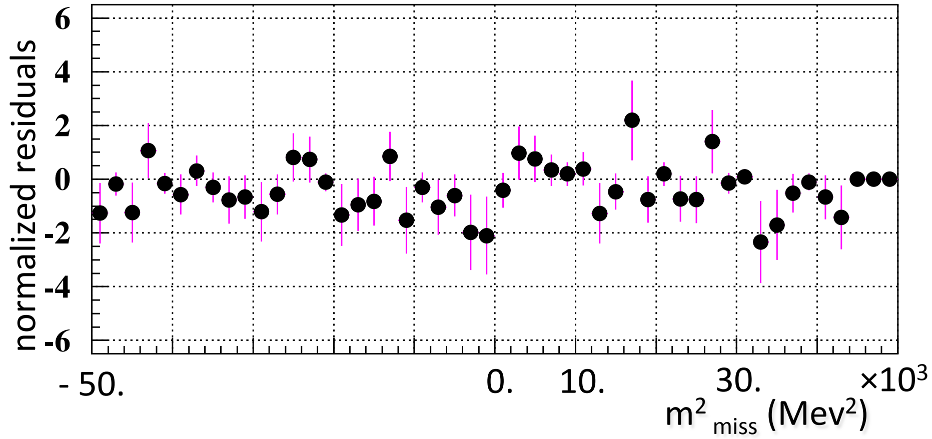
Using 88 pb^{-1} of the data sample

$N(K^+ \to 3\pi)$ = 22998.1 ± 151.6

$N(K^- \to \mu\nu)$ = 5768121.0 ± 2401.7

using 86 pb^{-1} of the data sample

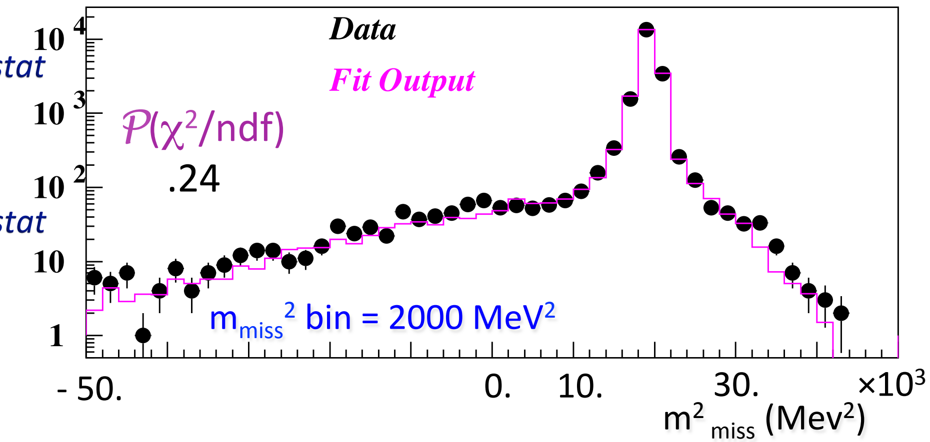
ε_{sel} = 0.08432 ± 0.00046



88 pb^{-1} $BR(K^+ \to \pi^+\pi^-\pi^+(\gamma)) = 0.05550 \pm 0.00048_{stat}$

174 pb^{-1} $BR(K^+ \to \pi^+\pi^-\pi^+(\gamma)) = 0.05551 \pm 0.00034_{stat}$

$\Delta BR/BR \approx 0.06$ %



$\pi\pi$ phase shift

NA48 observed in the $\pi^0\pi^0$ invariant mass distribution a cusp-like anomaly at $M_{00} = 2m_+$ *[PLB 633, 173 (2006)]* ➔ this has been interpreted by N. Cabibbo as the final state charge exchange scattering process $\pi^+\pi^- \to \pi^0\pi^0$ in $K^\pm \to \pi^\pm\pi^+\pi^-$ decay *[PRL 93, 121801 (2004)]*
a best fit to a rescattering model [JHEP 0503, 21 (2005)] provides a determination of $a_0 - a_2$ the difference between the S-wave $\pi\pi$ scattering lengths in the isospin I=0 and I=2 states

the main source of uncertainty is the ratio

$$\frac{A_{++-}}{A_{+00}} = \sqrt{\frac{BR(K^+ \to \pi^+\pi^+\pi^-)}{BR(K^+ \to \pi^+\pi^0\pi^0)}}\sqrt{\frac{\phi_{++-}}{\phi_{+00}}} = \sqrt{R}\sqrt{\frac{\phi_{+--}}{\phi_{+00}}}$$

NA48 evaluates $R = 3.175 \pm 0.050$ *using BR values from PDG 2008 [EPJ C 64 (2009) 589]*

using the BR($\pi^\pm\pi^+\pi^-$), BR($\pi^\pm\pi^0\pi^0$) and their correlation (-0.02) from our global fit, we obtain

$$R = 3.161 \pm 0.049$$