Recent results on BR(K -> πππ) at KLOE/KLOE-2

- the KLOE data sample & the kaon production
- CP violating decay $K_s \rightarrow 3\pi^0$
- absolute $K^+ \rightarrow \pi^+\pi^-\pi^+(\gamma)$ branching ratio

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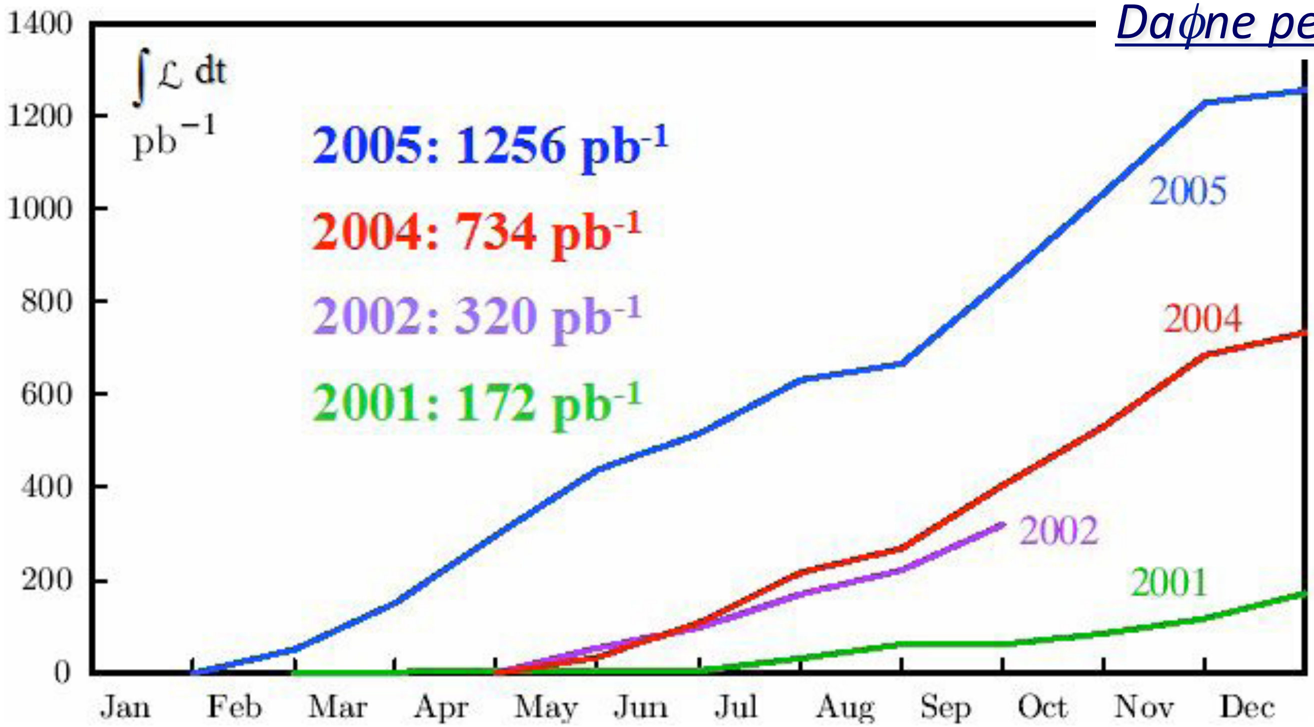
on behalf of the KLOE/KLOE-2 Collaboration

the KLOE data sample



Daϕne performance in 2004/05

≅ 105 $e^+ + e^-$ bunches

I^-_{peak} ~ 2.4 A, I^+_{peak} ~ 1.5 A

$\mathcal{L}_{peak} = 1.4 \times 10^{32}\ cm^{-2}\ s^{-1}$

$\mathcal{L}_{avg}$ month ≅ 200 pb^{-1}

2001 – 2005 **~ 2.5 fb^{-1}** *integrated @ $\sqrt{s}=M(\phi)$*

yielding **~ 2.5 x 10^9 K_SK_L** *and* **~ 3.6 x 10^9 K^+K^-** *pairs*

2006 *4-pt energy scan around ϕ peak + 250 pb^{-1} off peak data, $\sqrt{s}$=1GeV*

kaon production

the ϕ decay at rest provides monochromatic and pure kaon beams

the KK pairs in the final state have the same quantum numbers as the ϕ, *i.e.*, they are produced in a pure $J^{PC} = 1^{--}$ state

$\sigma(e^+e^- \rightarrow \phi) \approx 3\ \mu b$

K_S, K^+ ⟵ ϕ ⟶ **K_L, K^-**

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

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

$\Rightarrow$ allows precision measurements of absolute BRs

K^+K^-

BR ≅ 49%

p_{lab} = 127 MeV/c

$\lambda_\pm$ = 95 cm

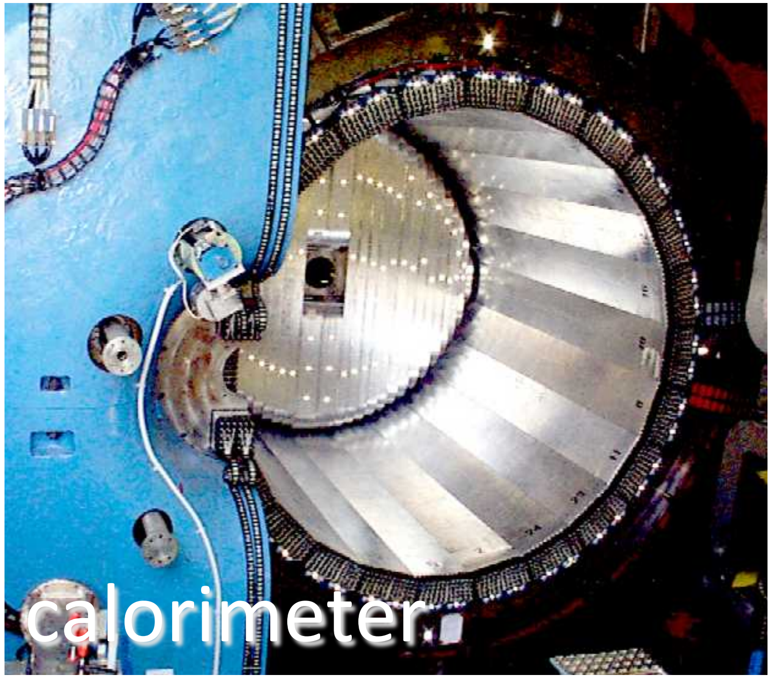
K_LK_S

BR ≅ 34% ; p_{lab} = 110 MeV/c

λ_S = 0.6 cm K_S decays near interaction point

λ_L = 340 cm Large detector to keep reasonable acceptance for K_L decays (~0.5 λ_L)

KLOE detector performance



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

$\sigma_t \cong 57$ ps $/\sqrt{E(GeV)} \oplus 140$ ps

(relative time between clusters)

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

$\sigma_p/p \cong 0.4$ % (tracks with $\theta > 45°$)

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

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

- CP violating decay $K_S \to \pi^0\pi^0\pi^0$

$K_S \rightarrow \pi^0\pi^0\pi^0$: search for a CP violating decay

$3\pi^0$ is a pure CP=-1 state; observation of $K_S \rightarrow 3\pi^0$ signals CP violation in mixing and/or decay

Li, Wolfenstein PRD21,178 (1980)

$$\eta_{000} = \frac{\langle \pi^0\pi^0\pi^0 | T | K_S \rangle}{\langle \pi^0\pi^0\pi^0 | T | K_L \rangle} = \varepsilon_S + \varepsilon'_{000}$$

to lowest order in χPT $\varepsilon'_{000} = -2\varepsilon'$

and, if CPT is conserved $\eta_{000} \approx \varepsilon$

therefore in the Standard Model ➔

BR($K_S \rightarrow 3\pi^0$) ~ 2×10^{-9}

BR ≤ 1.4×10^{-5} @ 90% CL SND '99 *direct measurement*

BR ≤ 7.4×10^{-7} @ 90% CL NA48 '04 *hep-ex/0408053* *indirect measurement*

Phys. Lett. B 619,61 (2005)

BR(K_S –> $3\pi^0$) ≤ 1.2×10^{-7} @ 90% CL
$|\eta_{000}| < 0.018$ @ 90% CL

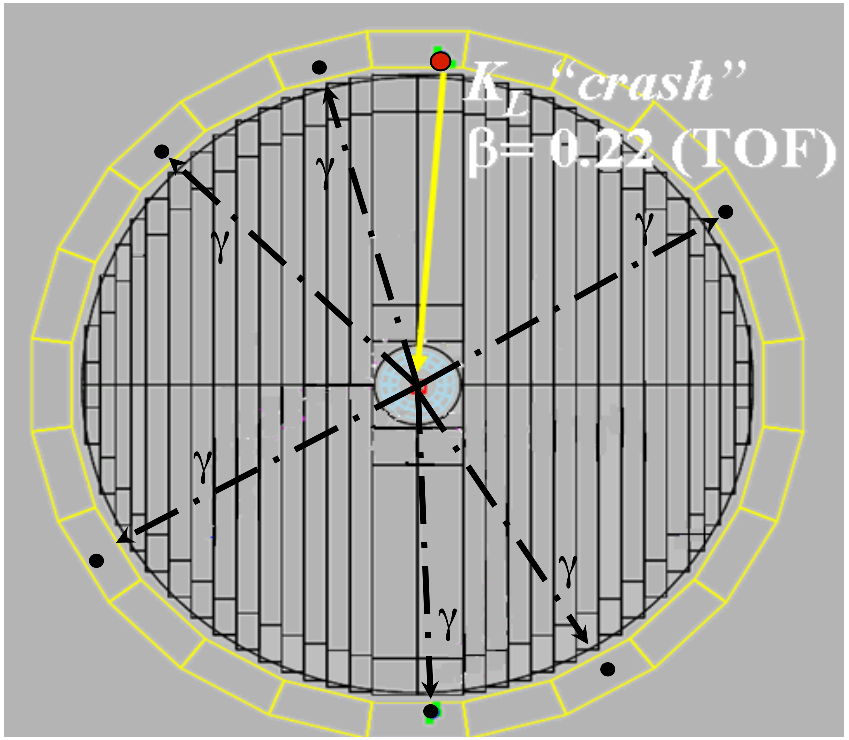
450 pb^{-1} of the KLOE data sample observed 2 candidates with an estimated backgrounf of 3.1 events in a tagged sample of 127×10^6 K_S decays

search for $K_S \rightarrow \pi^0\pi^0\pi^0$

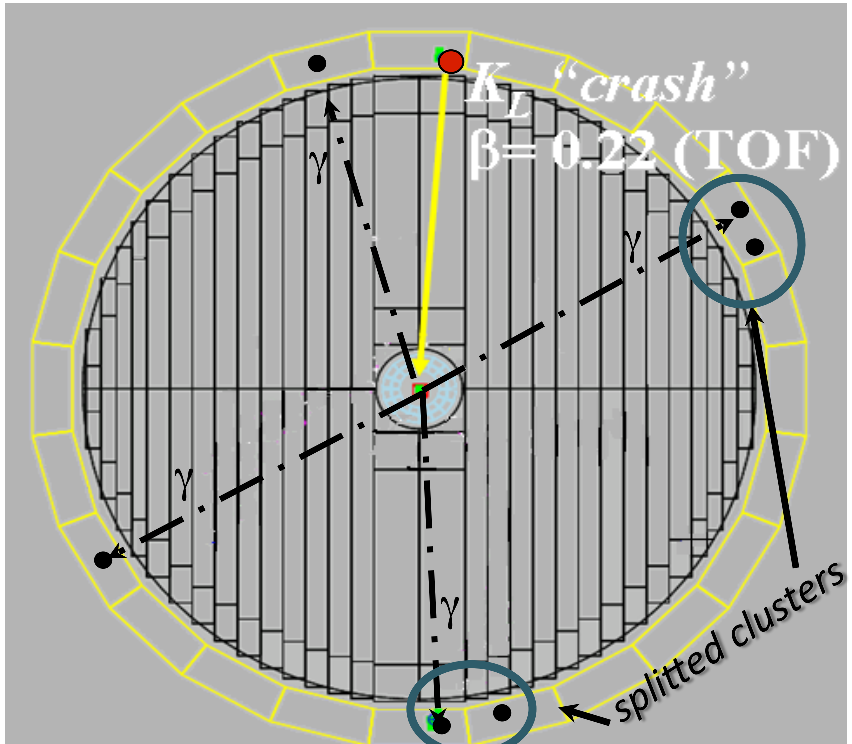
K_S tagged by K_L interaction in EmC ➔ **ε ~ 30%** (largely geometrical)

K_S angular resolution: ~ 1° (0.3° in ϕ)

K_S momentum resolution: ~ 1 MeV



signal $K_S \rightarrow 3\pi^0 \rightarrow 6\gamma$



dominant background

$K_S \rightarrow 2\pi^0$+ *accidental/splitted clusters*

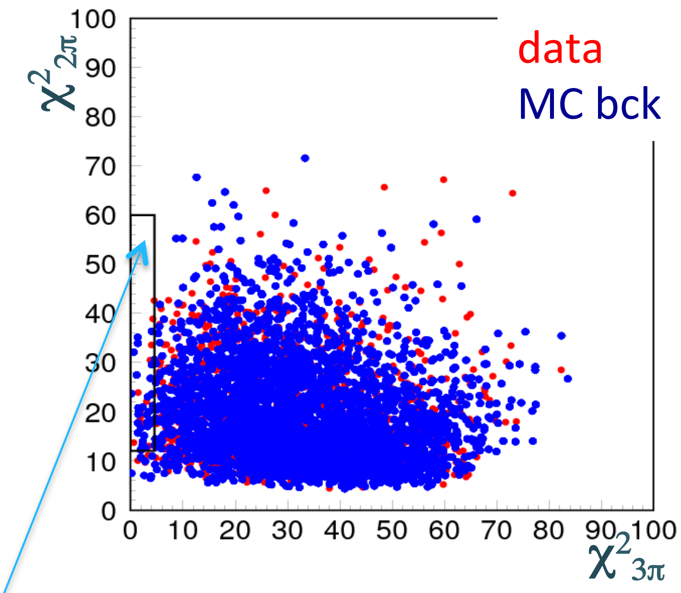
residual background

$K_L \rightarrow 3\pi^0$, $K_S \rightarrow \pi^+\pi^-$ *fake K_L crash*

search for $K_S \rightarrow \pi^0\pi^0\pi^0$

<u>*preselection*</u>

- ✓ K_S tagged by K_L crash
- ✓ 6 γ clusters, no tracks from IP
- ✓ kinematic fit to refine cluster parameters



<u>*to reject background compare 3π vs 2π hypothesis*</u>

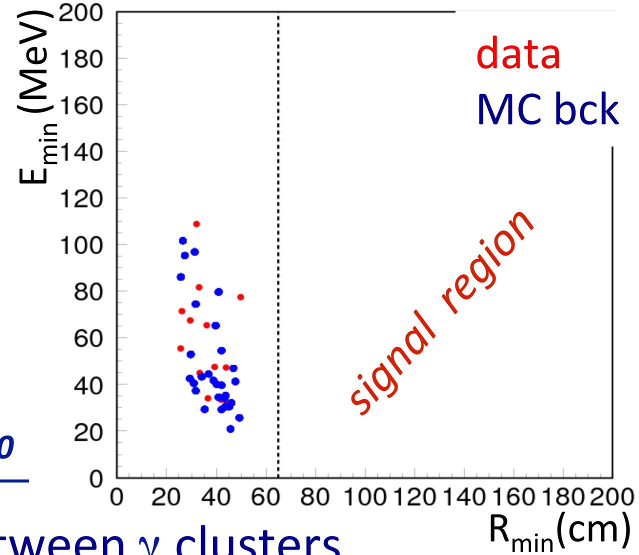
$\chi^2_{3\pi}$ – pairing of 6γ clusters with best π^0 mass estimates

$\chi^2_{2\pi}$ – best pairing of 4γ's out of 6: π^0 masses, $E(K_S)$, $P(K_S)$, c.m. angle between π^0s

✓ *to improve the quality of the γ's selection*

$$\Delta E = M_\phi/2 - \sum E_\pi \cong 0 \quad \text{if background}$$

signal box optimized using dedicated MC subsample
$4 < \chi^2_{2\pi} < 84.9$ and $\chi^2_{3\pi} < 5.2$



<u>***final cut on residual $K_S \rightarrow 2\pi^0$***</u>

✓ $R_{min} > 65.$ cm distance between γ clusters

search for $K_S \to \pi^0\pi^0\pi^0$: result

$N_{observed}$ = 0 events

$N_{bck}(MC)$ = 0 events *based on twice the data statistics*

$N_{expected}(SM)$ = 0.12 events

- assumption of no background ➔ UL ($N_{3\pi}$) = 2.3 @ 90% CL ($e_{3\pi}$= 0.23(1))
- normalize signal counts to $K_S \to 2\pi^0$ in the same data set

  $N_{2\pi} = N_{observed}/\varepsilon_{2\pi} = (1.142 \pm 0.005) \times 10^8$ ($\varepsilon_{2\pi} = 0.660(2)$)
- using the value $BR(K_S \to 2\pi^0) = 0.3069 \pm 0.0005$ *PDG 2012*

PLB 723 (2013) 54

$BR(K_S \to 3\pi^0) \leq 2.6 \times 10^{-8}$ @ 90% CL

$|\eta_{000}| < 0.0088$ @ 90% CL

1.7 fb^{-1} of the KLOE data sample

- *improvement of factor ~ 5*

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

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

- *this measurement completes the KLOE program of precise and fully inclusive $K^\pm$ dominant BR's*
- *this BR enters in the CUSP analysis to extract the $\pi\pi$ phase shift done by NA48,* ***PLB 633 (2006)***
- *needed to preform a global fit to $K^\pm$ BR's*

lifetime and absolute BRs by KLOE
(dBR/d$\tau^\pm$ and correlations available)

$K^+ \to \mu\nu$	0.6366(18)	0.3%	*PLB 632(2006)*
$K^+ \to \pi^+\pi^0$	0.2065(9)	0.5%	*PLB 666(2008)*
$K^\pm \to \pi^0 e^\pm \nu$	0.0497(5)	1.0%	*JHEP 02(2008)*
$K^\pm \to \pi^0 \mu^\pm \nu$	0.0324(4)	1.2%	*JHEP 02(2008)*
$K^\pm \to \pi^\pm\pi^0\pi^0$	0.0176(3)	1.7%	*PLB 597(2004)*
$\tau^\pm$	12.347(30) ns	0.24%	*JHEP 01 (2008)*

PLB 666 (2008)

BR($K^\pm \to \pi^\pm\pi^+\pi^-$)= 0.0568(22)

fit to $(1 - \Sigma BR_{KLOE})$

Flavianet fit '010 BR($K \to \pi^+\pi^-\pi^+$) = (5.73 ± 0.16)% $\Delta BR/BR = 2.7 \times 10^{-2}$

EPJC 69 (2010) 399

available measurement dates back to 72' (no informations on radiation cut-off)

CHIANG (2330 evts) BR($K \to \pi^+\pi^-\pi^+$) = (5.56 ± 0.20)% $\Delta BR/BR = 3.6 \times 10^{-2}$

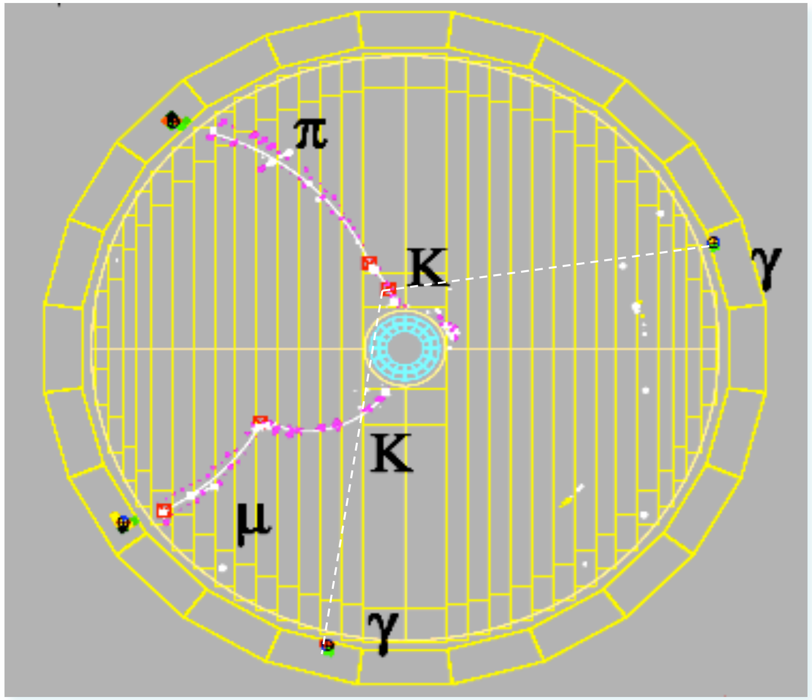
PRD 6 (1972) 1254

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

$K^\pm$ beam tagged from

$K^\pm \rightarrow \pi^\pm\pi^0,\ \mu^\pm\nu$ (85% of $K^\pm$ decays)

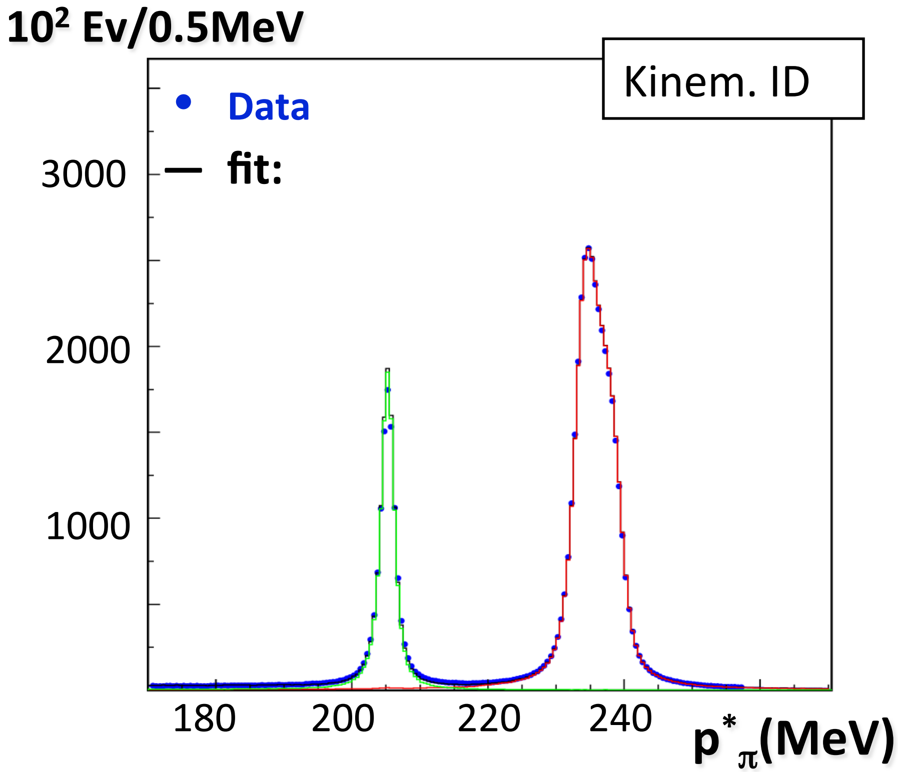
$\cong 1.5 \times 10^6\ K^+K^-$ evts/pb^{-1}



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 minimize 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 $\cong$ 75%
- the sample $N_{tag}(\mu\nu)$ is reduced by $\cong$ 35%

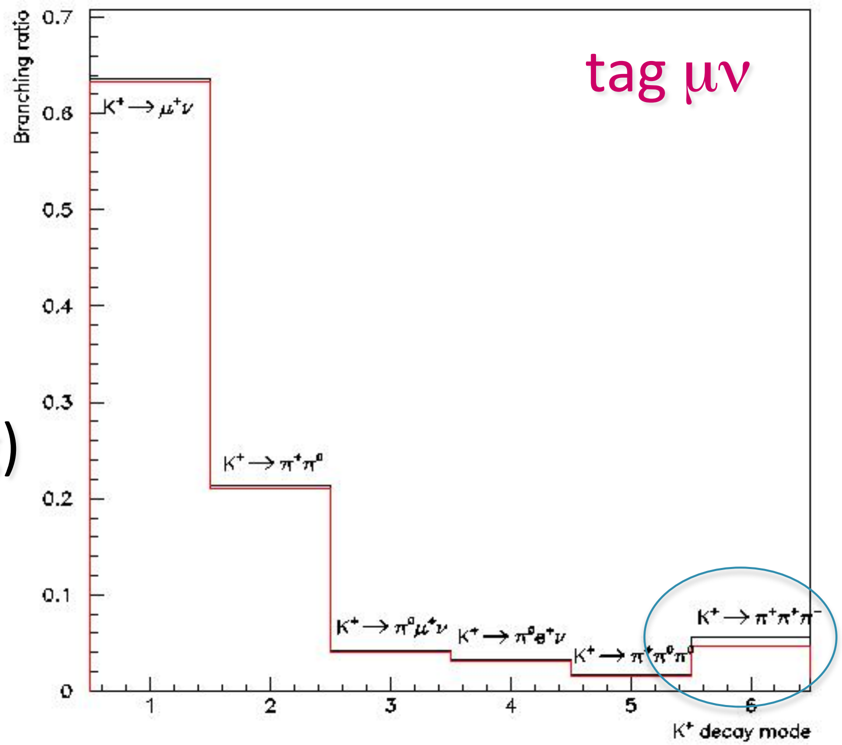
to measure BR's we must take into account a correction due to a bias on the tag selection induced by the signal ➔ *tag bias*

evaluated from MC $\Rightarrow$

C_{TB} = BR_{MC}(with tag) / BR_{MC}(without tag)

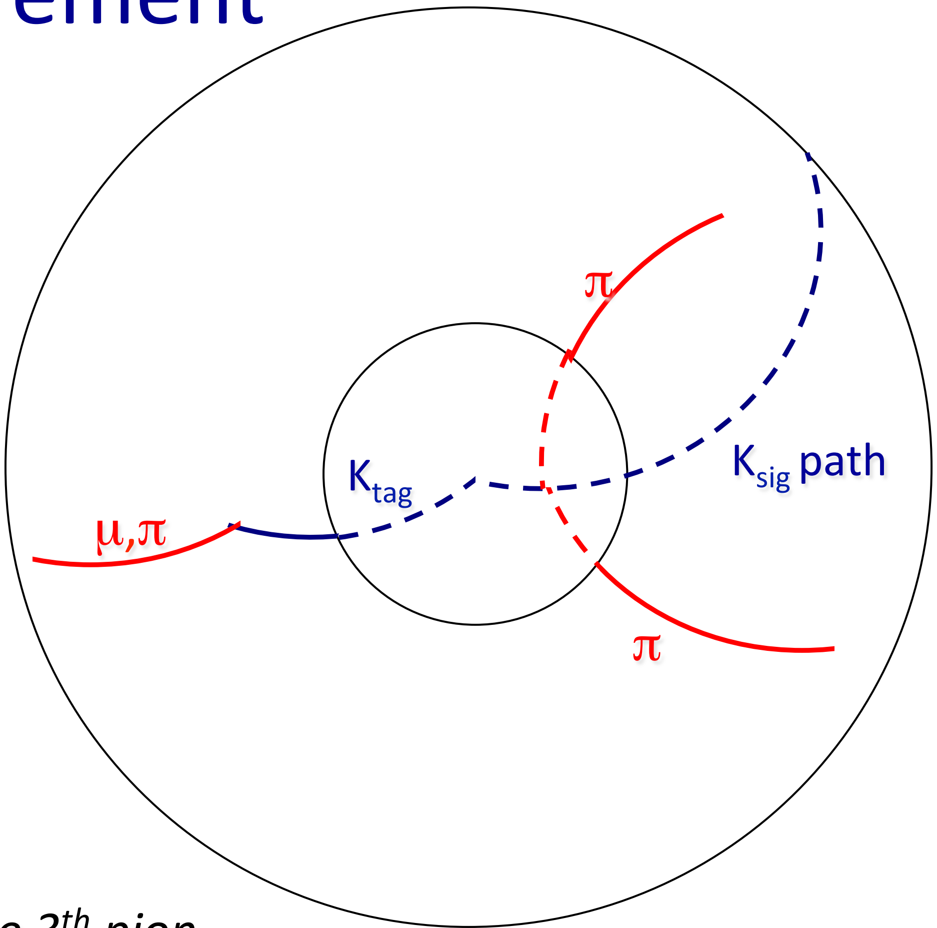
tag $\mu^-\bar{\nu}$, signal $\pi^+\pi^-\pi^+$

C_{TB} = .838681 ± .000971



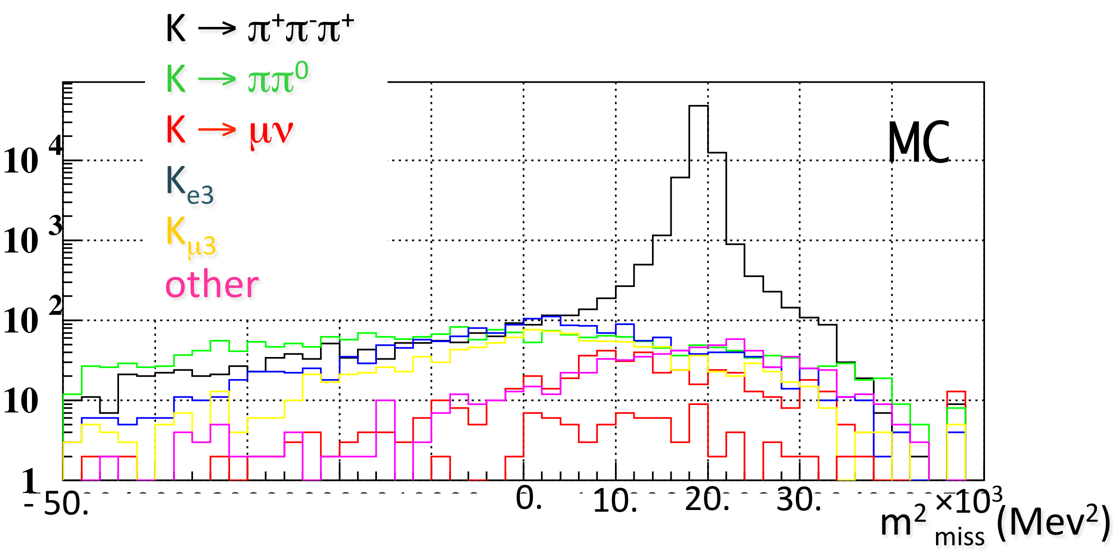
overview of the measurement

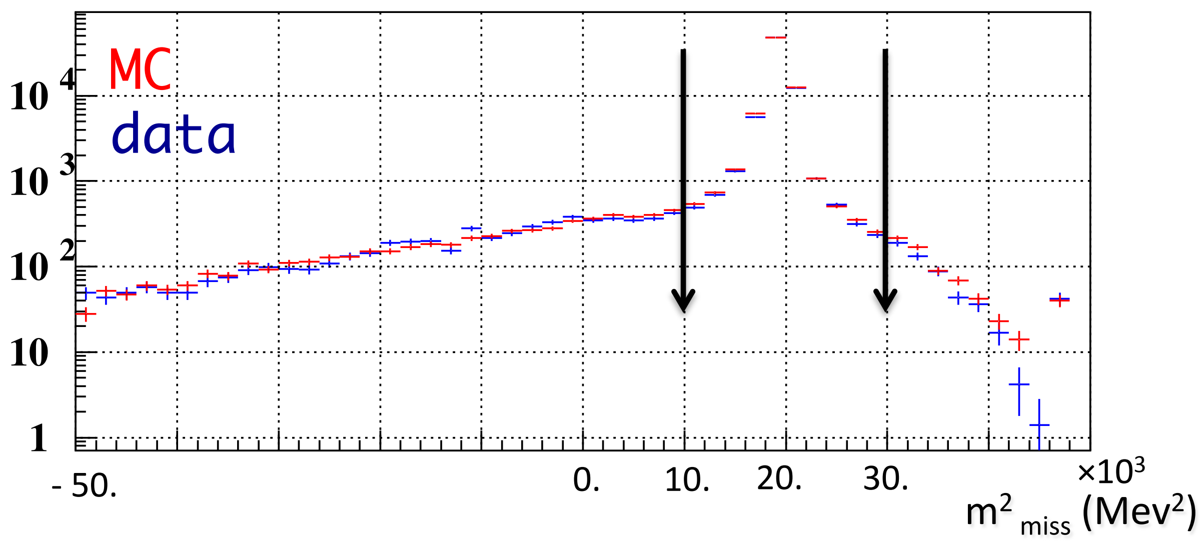
- triggering $\mu^{-}\nu$ tag on one side
- the virtual path of the signal K is given by the tag K track backward extrapolated to the I.P.
- in the signal hemisphere we require two reconstructed tracks making a vertex along the K path *before the inner wall of the DC* (R^{DC}_{inner} = 25 cm, $\alpha_{GEO} \cong$ 26 %)
- signal → *missing mass spectrum of the 3th pion*
- *selection efficiency* measured on MC, and corrected using data&MC control samples



first look at the signal sample

- tracks backward extrapolated with Distance of Closest Approach, DCA < 3. cm
- Distance of Closest Approach between two selected tracks, DCA_{tt} < 3. cm
- $p^* m_\pi$ < 190. MeV/c to remove 2 bodies decays
- ρ_{xy} < 24. cm
- NO charge requirements



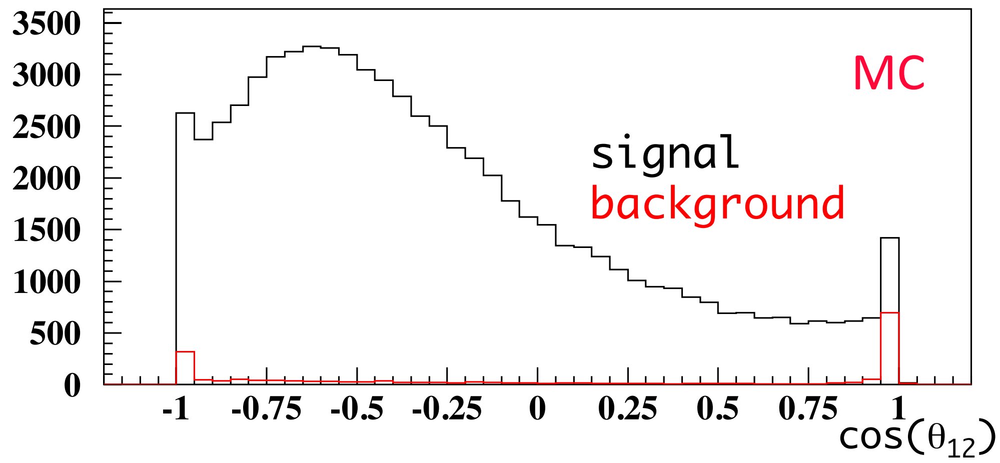


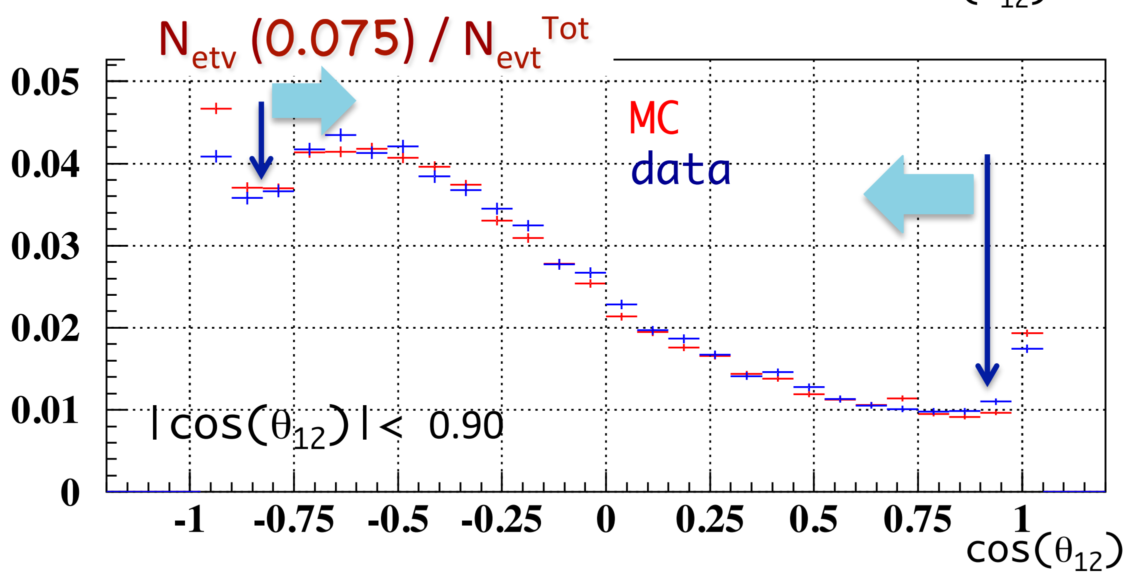
mass window ➔ (10000. < m^2_{miss} < 30000.) MeV^2

S/B ≅ 37.

residual background

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

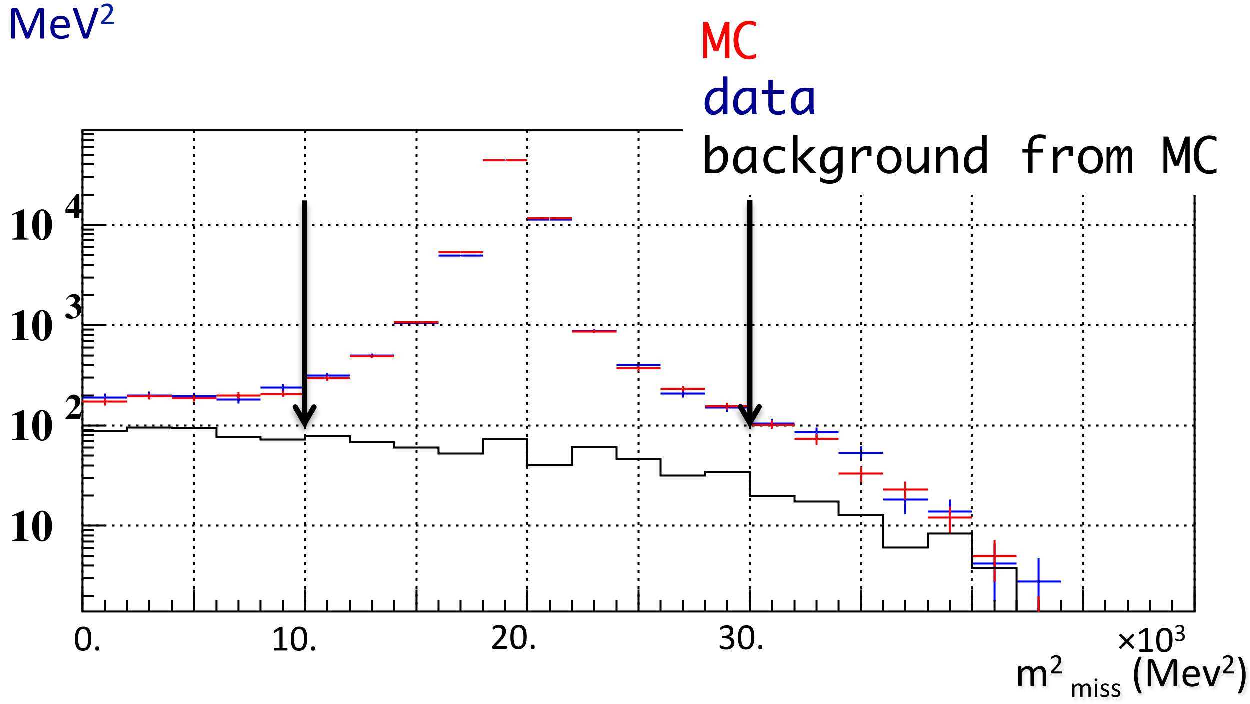




the signal (I)

- NO charge requirements
- N(selected tracks) = 2
- DCA < 3. cm
- DCA_{tt} < 3. cm
- p^*m_{π} < 190. MeV/c
- $|\cos(\theta_{12})| < 0.90$
- ρ_{xy} < 24. cm
- $10000. < m^2_{miss} < 30000.\ MeV^2$

S/B ≅ 88.4



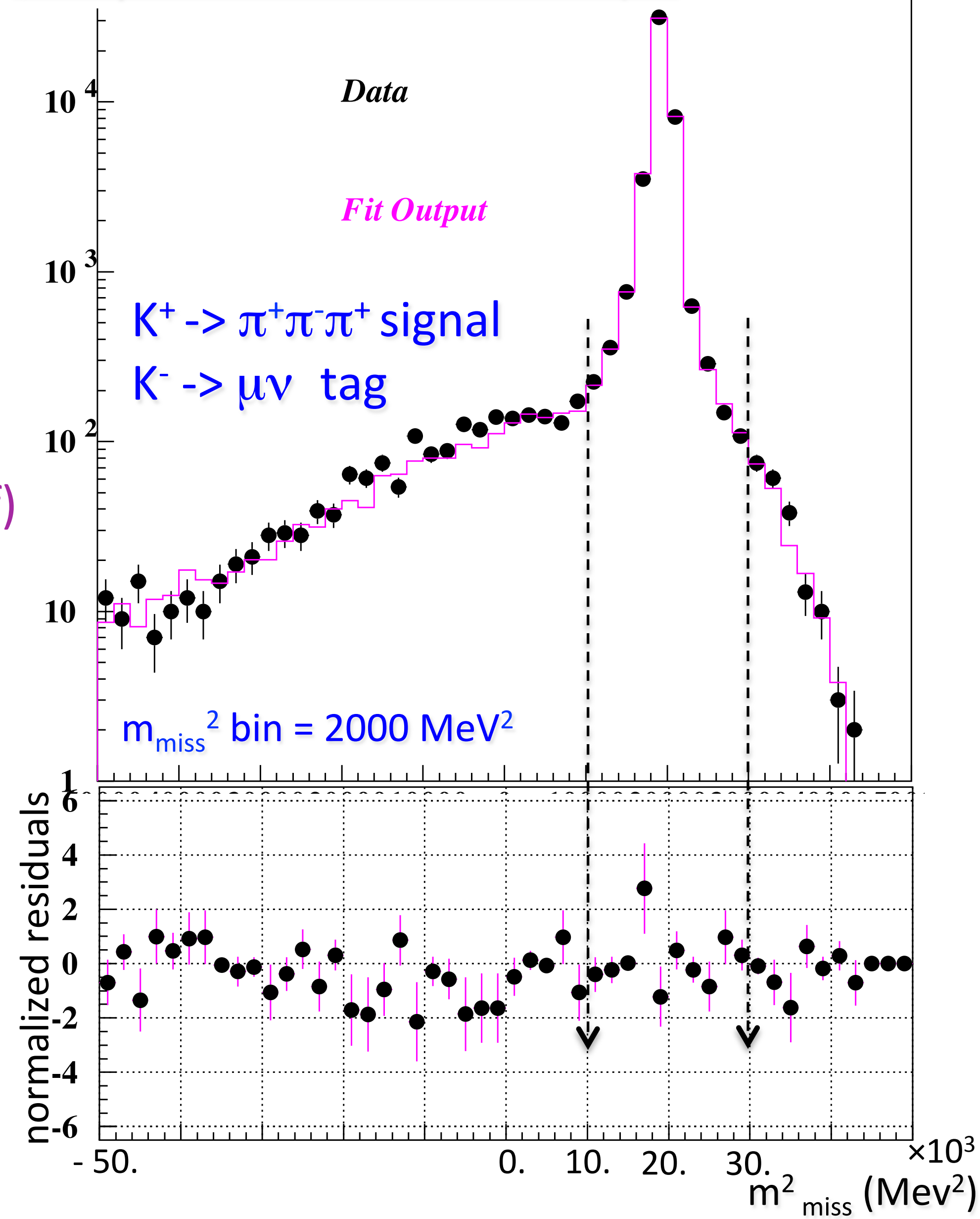
the signal (II)

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

$N(K^+ \to 3\pi)$	χ^2/ndf	$\mathcal{P}(\chi^2/ndf)$
45054.1 ± 212.2	47.6/45	.36

$N(K^- \to \mu\nu)$
12065087.0 ± 3473.4

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

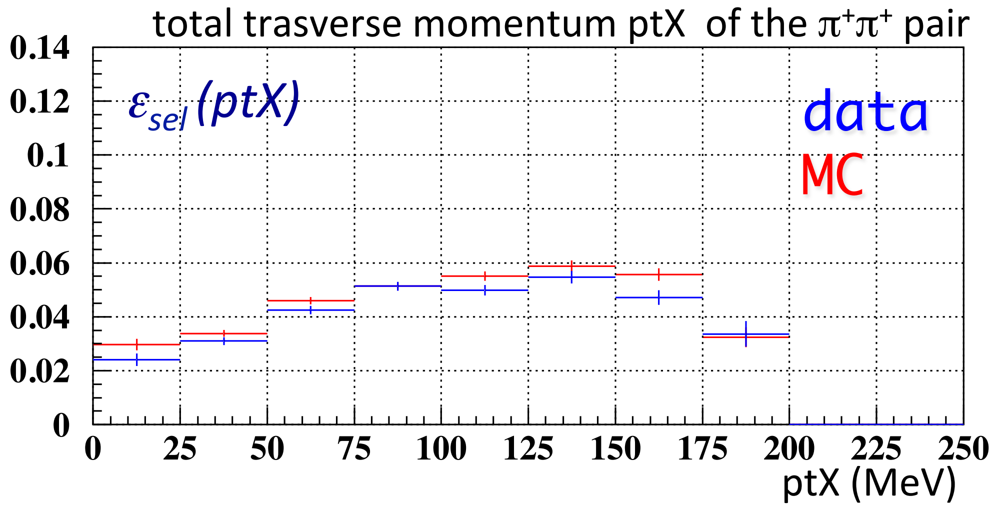


$K^+ \to \pi^- X$ control sample

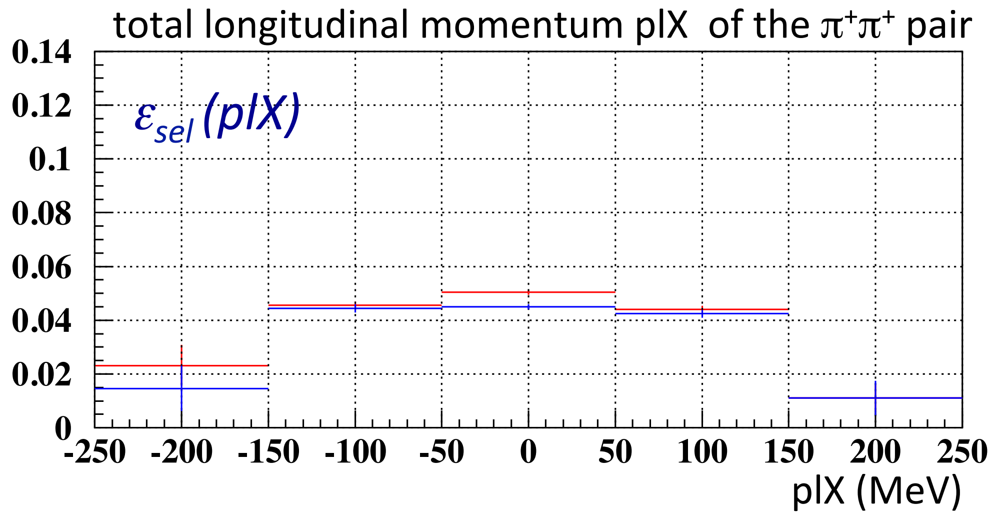
measurement of the double tracks reconstruction efficiency on data and MC

- neutral clusters (E > 30.MeV) in the "signal hemisfere" ≤ 1.
- $p^*m_\pi < 130.$ MeV
- $\cos(\theta_{K\pi}) > -0.85$
- DCA < 5.5 cm

➔ *bck contamination ≅ 10.%*



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



$$\varepsilon_{sel} = \varepsilon^{kine}_{sel}(K+ \to 3\pi) \times (\varepsilon^{data}_{sel} / \varepsilon^{MC}_{sel})$$

$$= 0.079370 \pm 0.000314$$

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

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

machine bck filter correction and cosmic veto correction

tag $K^- -> \mu^- \bar{\nu}$

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

KLOE preliminary

$BR(K^+ -> \pi^+\pi^-\pi^+(\gamma)) = (0.05526 \pm 0.00035_{stat} \pm 0.00036_{syst})$, $\Delta BR/BR = 9.2 \times 10^{-3}$

CHIANG (2330 evts) *PRD 6 (1972) 1254*	$BR(K\rightarrow\pi^+\pi^-\pi^+) = (5.56 \pm 0.20)\%$	$\Delta BR/BR = 3.6x10^{-2}$
KLOE fit '08 *PLB 666 (2008)*	$BR(K\rightarrow\pi^+\pi^-\pi^+) = (5.68 \pm 0.22)\%$	$\Delta BR/BR = 3.8x10^{-2}$
Flavianet fit '010 *EPJC 69 (2010) 399*	$BR(K\rightarrow\pi^+\pi^-\pi^+) = (5.73 \pm 0.16)\%$	$\Delta BR/BR = 2.7x10^{-2}$

conclusions

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

- new upper limit for BR($K_S \rightarrow 3\pi^0$)
  at KLOE-2 this analysis will benefit of the presence of new low θ calorimeters, and with the foreseen O(10fb^{-1}) it might be possible to have a first observation of the decay

- new preliminary measurement of the absolute BR($K^+ \rightarrow \pi^+\pi^-\pi^+(\gamma)$)
  this completes the KLOE program of precise and fully inclusive $K^\pm$ dominant BR's