Search for the $K_s \to 3\pi^0$ decay with the KLOE detection setup

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- Introduction
- Search for the $K_S \to \pi^0\pi^0\pi^0$ decay
- Background studies Monte Carlo calibration
- Preliminary result
- Summary & outlook

MESON 2012, Kraków, 31.05 - 05.06 2012

Introduction

➢ Time evolution of the $K^0 \leftrightarrow \overline{K^0}$ system in the rest frame:

$$i\frac{\partial}{\partial t}\begin{pmatrix} |K^0> \\ |\overline{K^0}> \end{pmatrix} = \mathbf{H}\begin{pmatrix} |K^0> \\ |\overline{K^0}> \end{pmatrix} = \left[\boldsymbol{M} - \frac{i}{2}\boldsymbol{\Gamma}\right]\begin{pmatrix} |K^0> \\ |\overline{K^0}> \end{pmatrix}$$

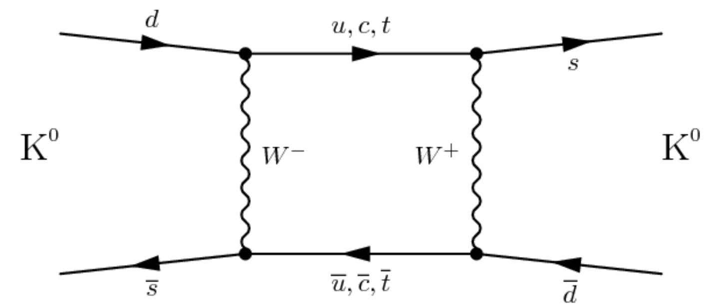
$$\boldsymbol{M} = \begin{pmatrix} M_{11} & M_{12} \\ M^*_{12} & M_{22} \end{pmatrix}$$

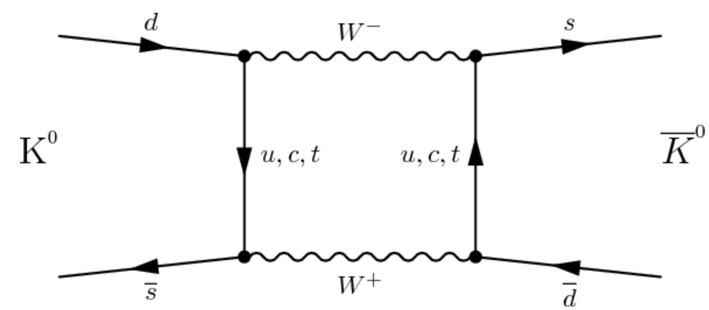
$$\boldsymbol{\Gamma} = \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma^*_{12} & \Gamma_{22} \end{pmatrix}$$

➢ In the basis of the CP operator:

$$|K_1> = \frac{1}{\sqrt{2}}(|K^0> + |\overline{K^0}>) \qquad (\mathrm{CP} = 1)$$

$$|K_2> = \frac{1}{\sqrt{2}}(|K^0> - |\overline{K^0}>) \qquad (\mathrm{CP} = -1)$$





➢ The eigenstates of **H**:

$|K_S>$ (t = 0.9 $\cdot 10^{-10}$ s; ct = 2.68 cm)

$|K_L>$ (t = 5.1 $\cdot 10^{-8}$ s; ct = 15.5 m)

➢ The main hadronic decay modes:

$$|K_S> \to \pi^+\pi^- \qquad |K_S> \to 2\pi^0 \qquad (\mathrm{CP} = 1)$$

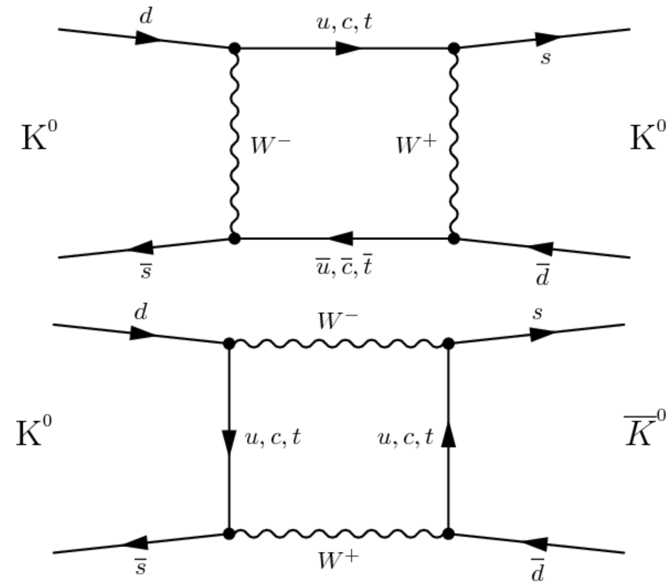
$$|K_L> \to \pi^0\pi^+\pi^- \qquad |K_L> \to 3\pi^0 \qquad (\mathrm{CP} = -1)$$

Introduction

- But K_S and K_L are not CP eigenstates:

$$BR(K_L \to \pi^+ \pi^-) = 1.97 \cdot 10^{-3}$$
$$BR(K_L \to \pi^0 \pi^0) = 8.65 \cdot 10^{-4}$$

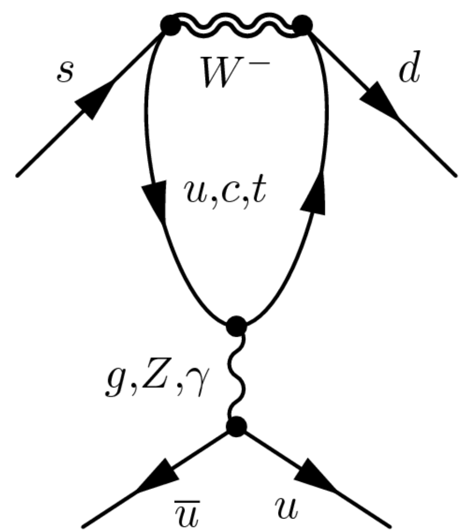
(K. Nakamura et al. (Particle Data Group), J. Phys. G 37, 075021 (2010))



- CP violation in mixing (ΔS=2):

$$|K_S> = \frac{1}{\sqrt{1+|\varepsilon_S|^2}}(\,|K_1> + \varepsilon_S|K_2>\,)$$
$$|K_L> = \frac{1}{\sqrt{1+|\varepsilon_L|^2}}(|K_2> + \varepsilon_L|K_1>)$$

$\varepsilon_S \neq \varepsilon_L \Rightarrow$ CPTV



- CP violation directly in the decay (ΔS=1):

$$|K_1> \to 2\pi, \quad |K_2> \to 3\pi$$

Introduction

➢ We can define the following amplitude ratios (assuming the CPT invariance):

$$\eta_{+-} = \frac{\langle \pi^+\pi^- | H | K_L \rangle}{\langle \pi^+\pi^- | H | K_S \rangle} = \varepsilon + \varepsilon' \qquad \eta_{00} = \frac{\langle \pi^0\pi^0 | H | K_L \rangle}{\langle \pi^0\pi^0 | H | K_S \rangle} = \varepsilon - 2\varepsilon'$$

➢ These parameters can be measured using the interference between $K_S \to \pi^+\pi^-$ and $K_L \to \pi^+\pi^-$ decay:

$$N_{\pi^+\pi^-} \sim [\, e^{-\Gamma_S} + |\eta_{+-}|^2 e^{-\Gamma_L} + 2|\eta_{+-}| \cos(\Delta m \cdot t \; + \varphi_{+-})\, e^{-\frac{1}{2}(\Gamma_S + \Gamma_L)t} \,]$$

$|\eta_{+-}| = (2.232 \pm 0.011) \cdot 10^{-3}$; $\varphi_{+-} = (43.51 \pm 0.05)^{\circ}$

$|\eta_{00}| = (2.221 \pm 0.011) \cdot 10^{-3}$; $\varphi_{00} = (43.52 \pm 0.05)^{\circ}$

(*K. Nakamura et al. (Particle Data Group), J. Phys. G 37, 075021 (2010)*)

Introduction

➢ For the $|K_S> \rightarrow 3\pi$ decay modes:

$$\eta_{000} = \frac{\langle \pi^0\pi^0\pi^0|H|K_S\rangle}{\langle \pi^0\pi^0\pi^0|H|K_L\rangle} = \varepsilon + \varepsilon'_{000} \qquad \eta_{+-0} = \frac{\langle \pi^+\pi^-\pi^0|H|K_S\rangle}{\langle \pi^+\pi^-\pi^0|H|K_L\rangle} = \varepsilon + \varepsilon'_{+-0}$$

➢ In the lowest order of the χPT: $\varepsilon'_{000} = \varepsilon'_{+-0} = -2\varepsilon'$

$$Im(\eta_{+-0}) = -0.002 \pm 0.009; \qquad Im(\eta_{000}) = (-0.1 \pm 1.6) \cdot 10^{-2}$$

$$|\eta_{000}| = \sqrt{\frac{\tau_L\, BR(K_S \rightarrow 3\pi^0)}{\tau_S\, BR(K_L \rightarrow 3\pi^0)}} < 0.018 \text{ @ } 90\%\ C.L.$$

(F. Ambrosino et al., Phys. Lett. B 619, 61 (2005))

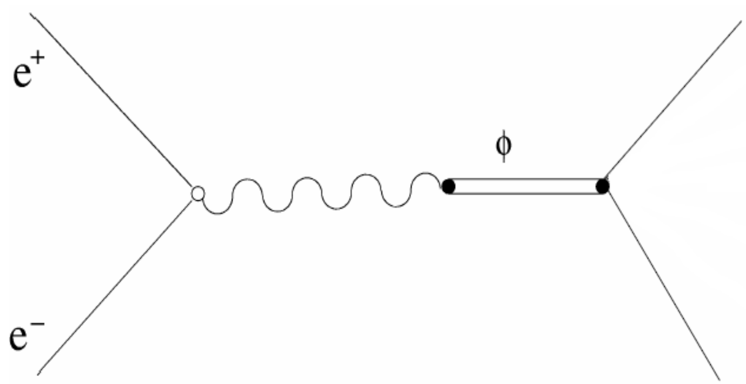
➢ Previous measurements of η_{000}:

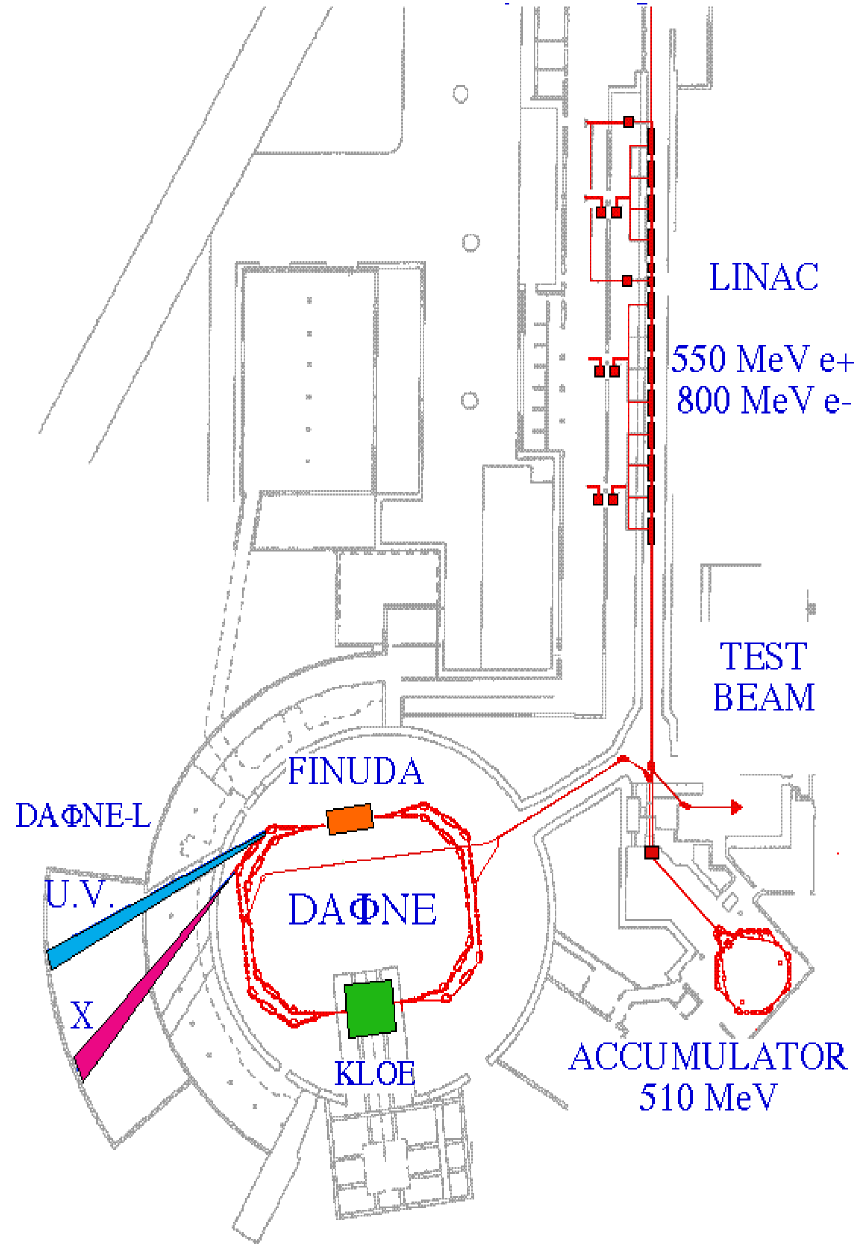
SND (direct search) :	$BR(K_S \rightarrow 3\pi^0) < 1.4 \cdot 10^{-5}$
NA48 (interference measurement):	$BR(K_S \rightarrow 3\pi^0) < 7.4 \cdot 10^{-7}$
KLOE	$\mathbf{BR(K_S \rightarrow 3\pi^0) < 1.2 \cdot 10^{-7}}$

Standard Model prediction: $\mathbf{BR(K_S \rightarrow 3\pi^0) = 1.9 \cdot 10^{-9}}$

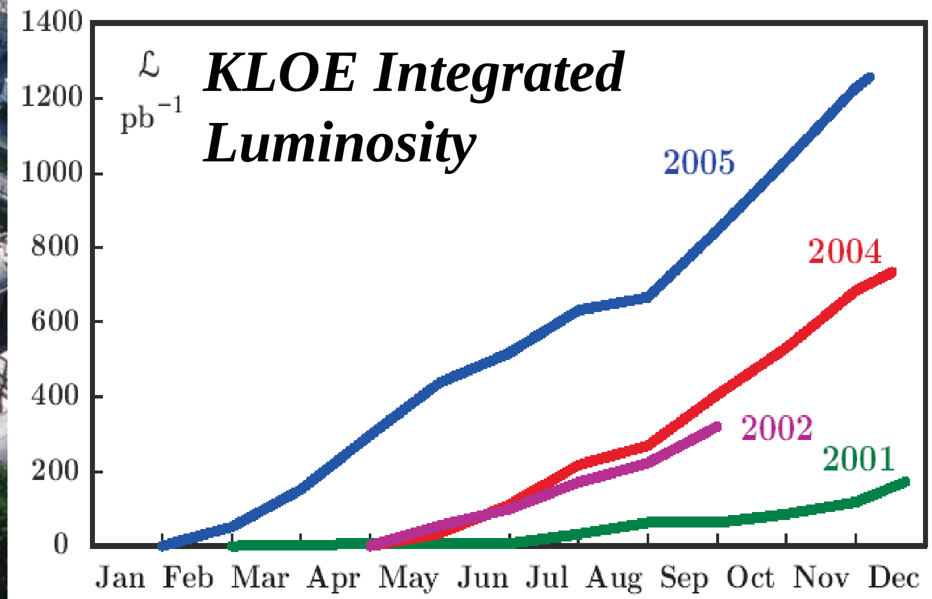
The DAFNE Φ-factory

- e^+e^- collider @ $\sqrt{s} = M_\varphi = 1019.4$ MeV
- LAB momentum $p_\varphi \sim 13$ MeV/c
- $\sigma_{peak} \sim 3\ \mu b$
- Separate e^+e^- rings to reduce beam-beam interaction
- Beams crossing angle: 12.5 mrad
- Peak luminosity $1.5{\times}10^{32}\ cm^{-2}s^{-1}$





DAΦNE Luminosity history



KLOE run:

- Daily performance: 7-8 pb^{-1}
- Best month $\int$L dt ~ 200 pb^{-1}
- Total KLOE $\int$L dt ~ 2400 pb^{-1} at φ mass peak + 250 pb^{-1} off peak (@ 1 GeV)

BR's for selected Φ decays	
K^+K^-	49.1%
K_SK_L	**34.1%**
$\rho\pi + \pi^+\pi^-\pi^0$	15.5%

KLOE (K LOng Experiment)

Large cylindrical drift chamber

- Uniform tracking and vertexing in all volume
- Helium based gas mixture (90% He – 10% $IsoC_4H_{10}$)
- Stereo wire geometry

$\sigma_p/p = 0.4\ \%$

$\sigma_{xy} = 150\ \mu m$; $\sigma_z = 2\ mm$

$\sigma_{vtx} \sim 3\ mm$

$\sigma(M_{\pi\pi}) \sim 1\ MeV$

Lead/scintillating-fiber calorimeter

- Hermetical coverage
- High efficiency for low energy photons

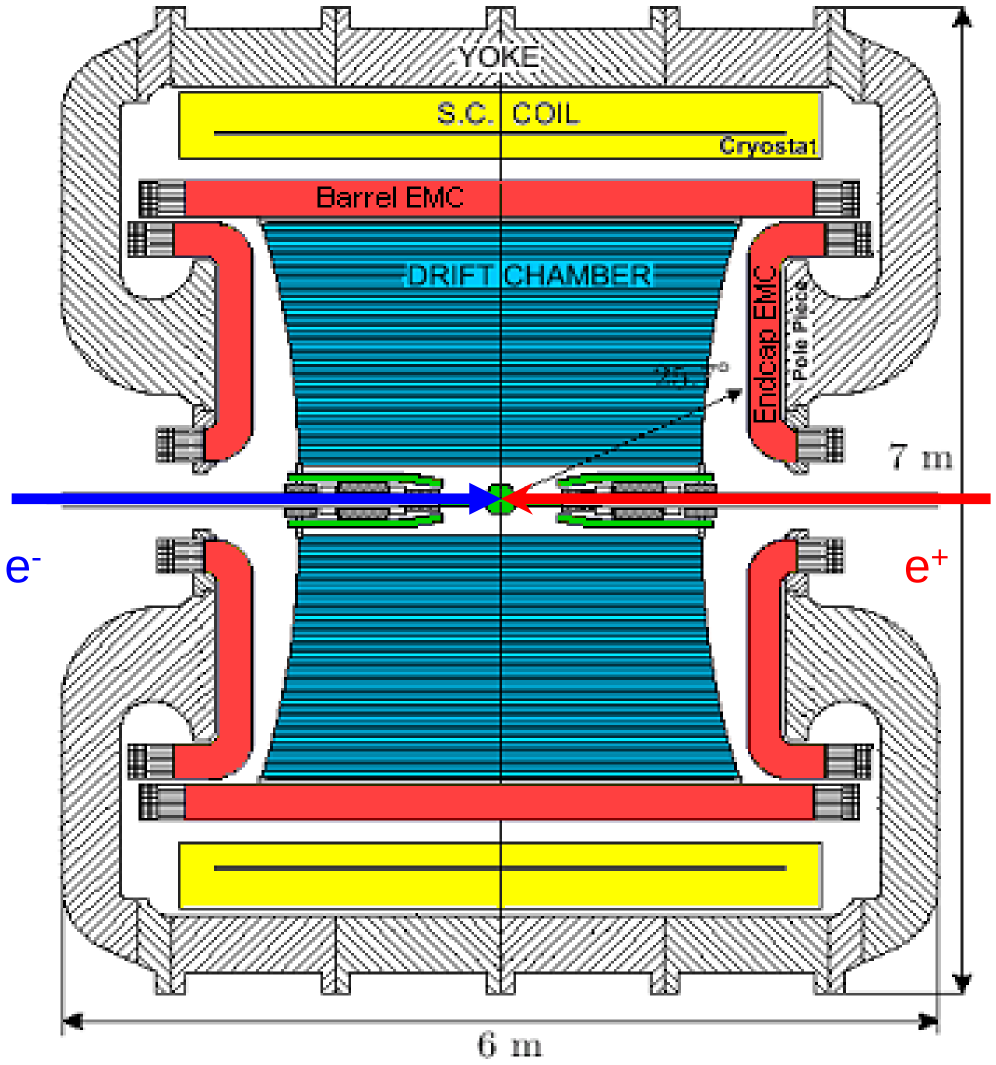
$\sigma_E/E = 5.7\% /\sqrt{E(GeV)}$

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

$\sigma_{vtx}(\gamma\gamma) \sim 1.5\ cm$

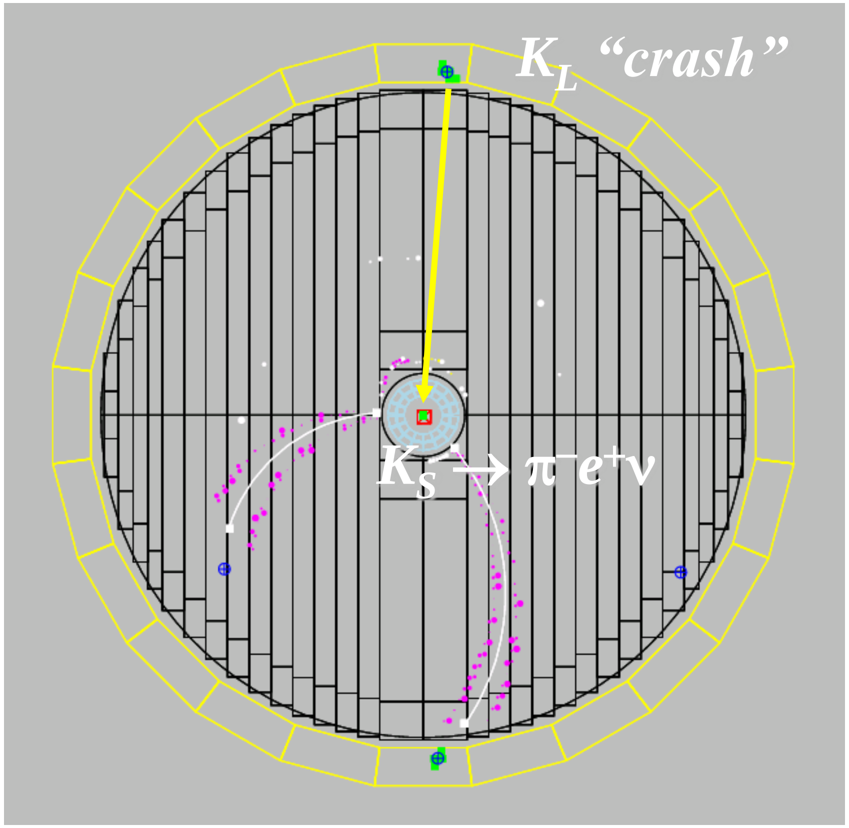
Superconducting coil

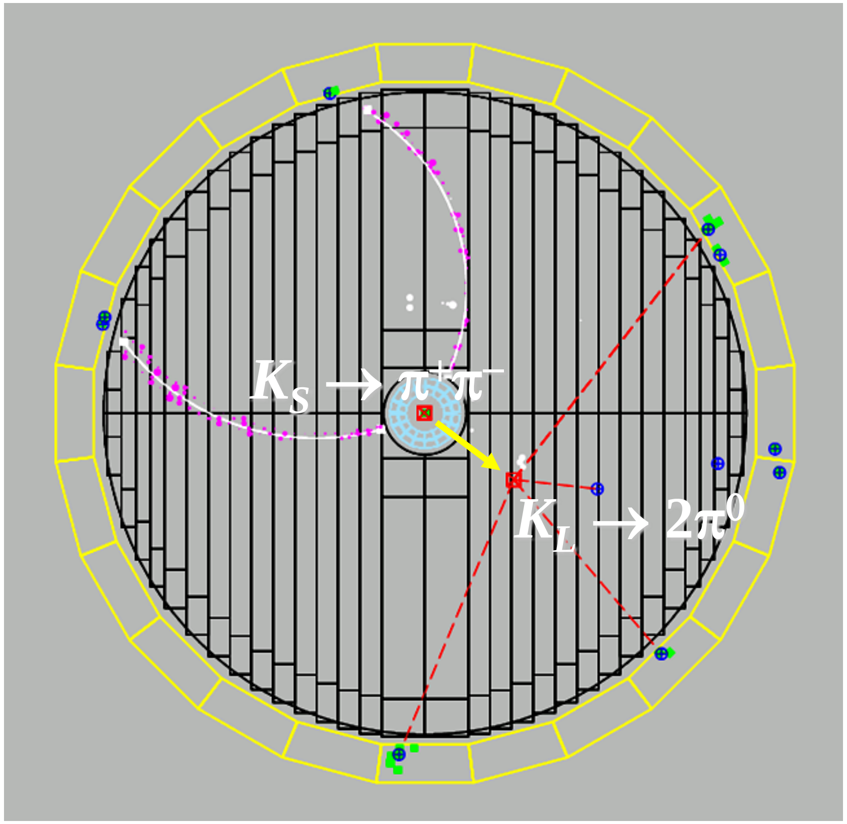
B = 0.52 T



K_S and K_L tagging

A Φ-factory offers the possibility to select pure kaon beams:





K_S tagged by K_L interaction in EmC

Efficiency ~ 30%

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

K_S momentum resolution: ~ 2 MeV

K_L tagged by $K_S \to \pi^+\pi^-$ vertex at IP

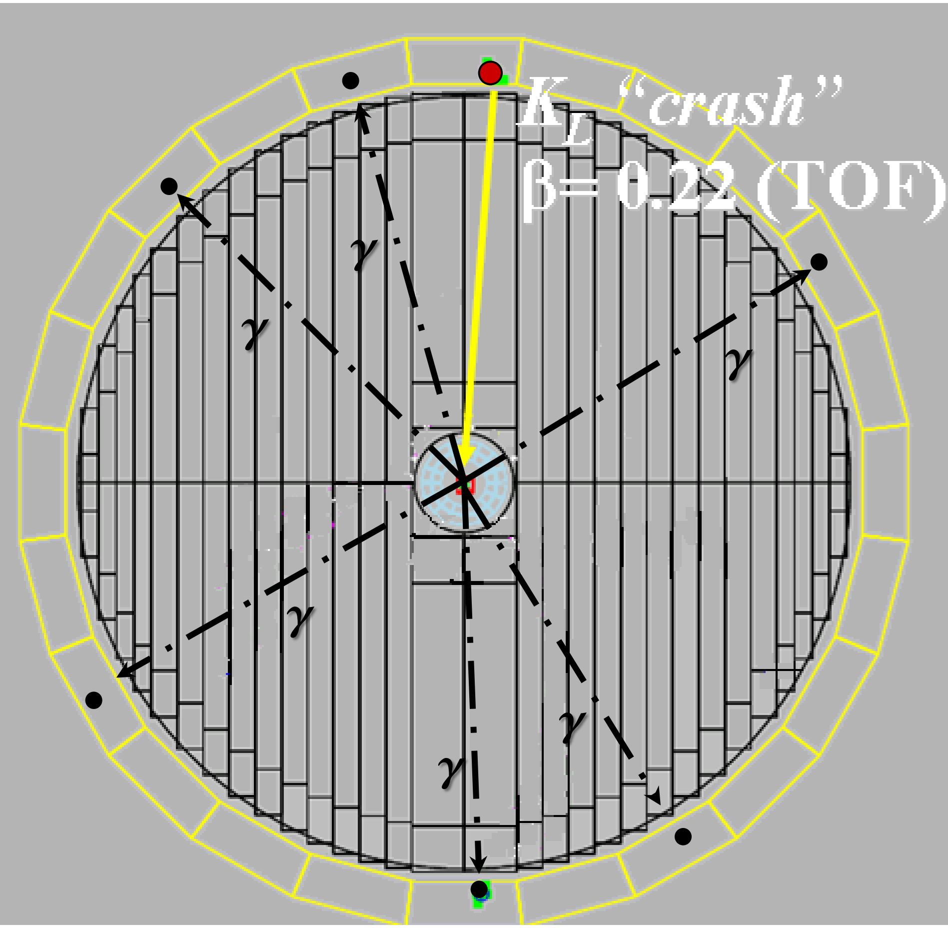
Efficiency ~ 70%

K_L angular resolution: ~ 1°

K_L momentum resolution: ~ 2 MeV

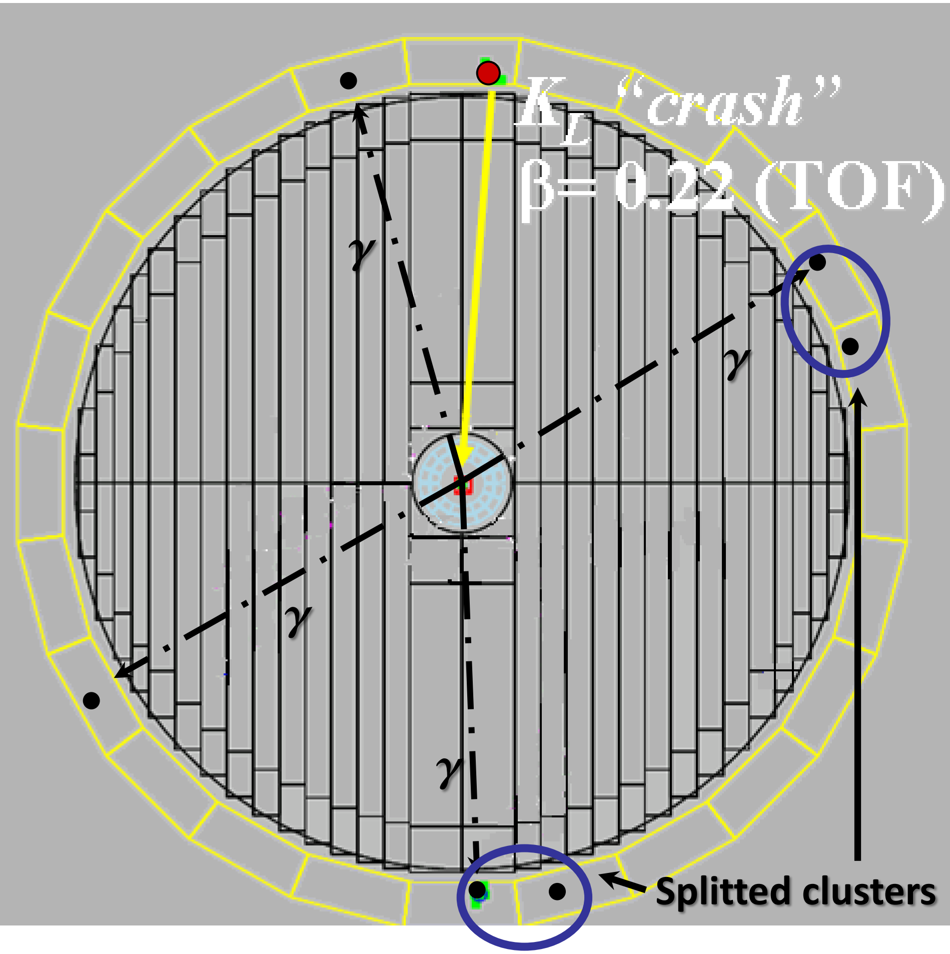
Search for the $K_S \to \pi^0\pi^0\pi^0$ decay

SIGNAL



$K_S \to 3\pi^0 \to 6\gamma$

BACKGROUND

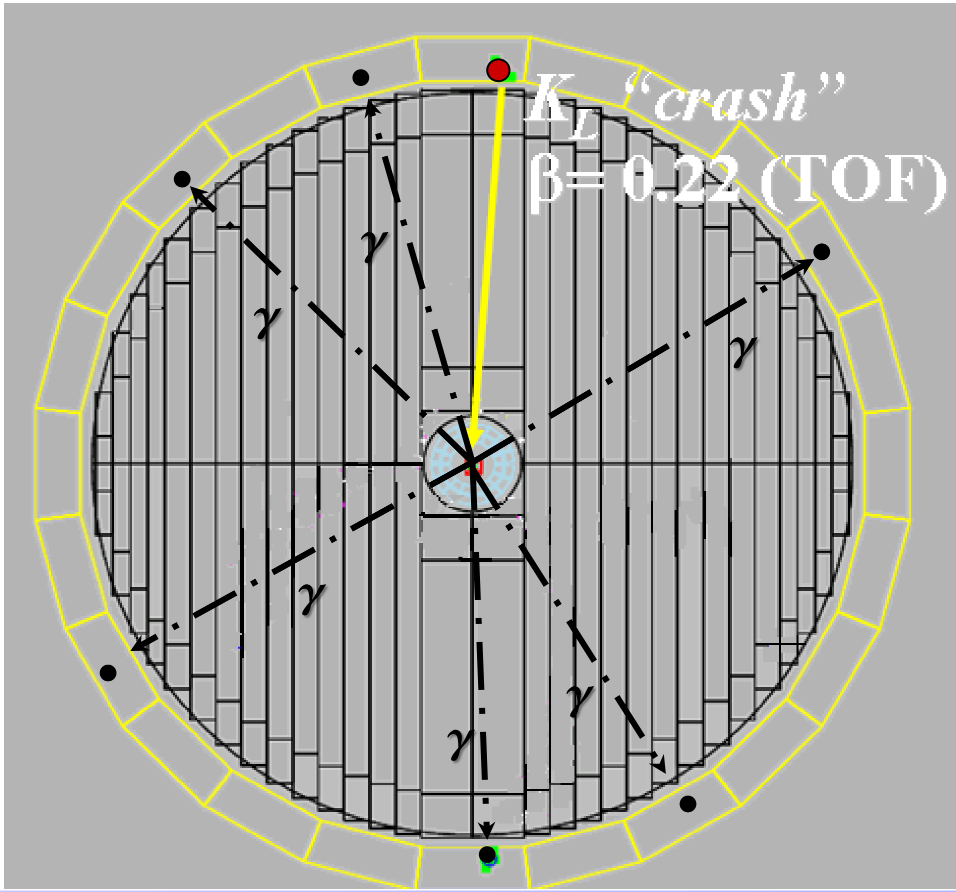


$K_S \to 2\pi^0$ + accidental/splitted clusters

$K_L \to 3\pi$, $K_S \to \pi^+ \pi^-$ („fake K_L-crash")

Search for the $K_S \to \pi^0\pi^0\pi^0$ decay

- 2004-2005 data ($\sim 7.53 \cdot 10^7$ K_L tags) & MC($\sim 1.59 \cdot 10^8$ K_L tags)
- Expected number of the $K_s \to 3\pi^0$ decays: $N_{SM} \sim 3.8$
- Preselected signal sample (K_L-crash + 6 photons) ~ **56000 events**



- Acceptance cuts:
  - K_L-crash: $\varepsilon \approx 28\%$
  - prompt photon: $\varepsilon \approx 48\%$

Background composition

2 Accidental
(24.16%)

2 Splitting
(59.15%)

1 Splitting + 1 Accidental
(5.83%)

„Fakes” (2.28%)

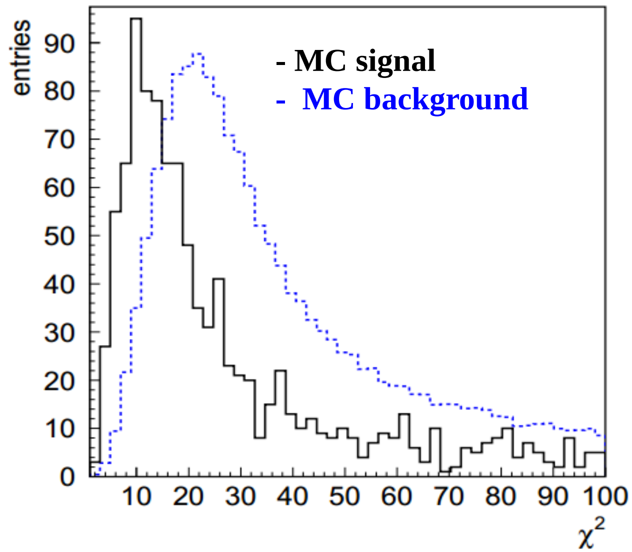
$K_L \to 3\pi^0$; $K_S \to \pi^+\pi^-$
$\varphi \to K^+K^-, \pi^+\pi^-\pi^0, \ldots$

Others (8.3%)

Accidental > 2 (0.92%)
Splitting >2 (2.45%)
1 Accidental + 0 Splitting (0,88%)
0 Accidental + 1 Splitting (4,05%)

Search for the $K_S \to \pi^0\pi^0\pi^0$ decay

Track Veto → χ^2_{fit} → $\Delta E/\sigma_E$ → Sbox → R_{min} → counting



- **Rejection of events with charged paricles**

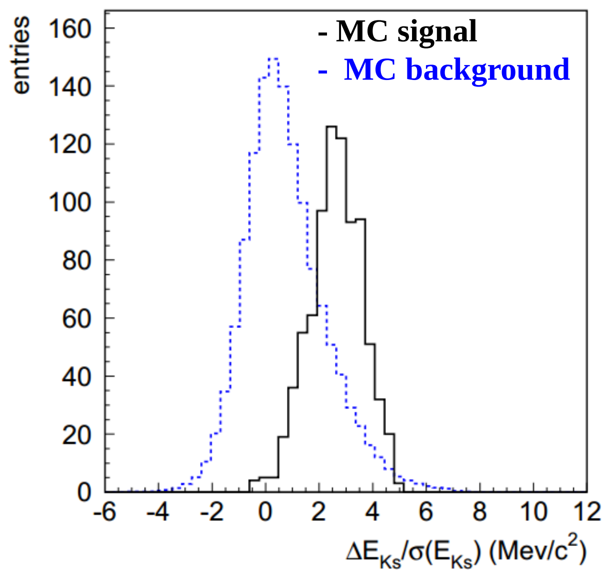
  events with at least one track from the Interaction Point (ρ_{PCA} < 4 cm & $|z_{PCA}|$ < 10 cm)

- **Kinematical fit**

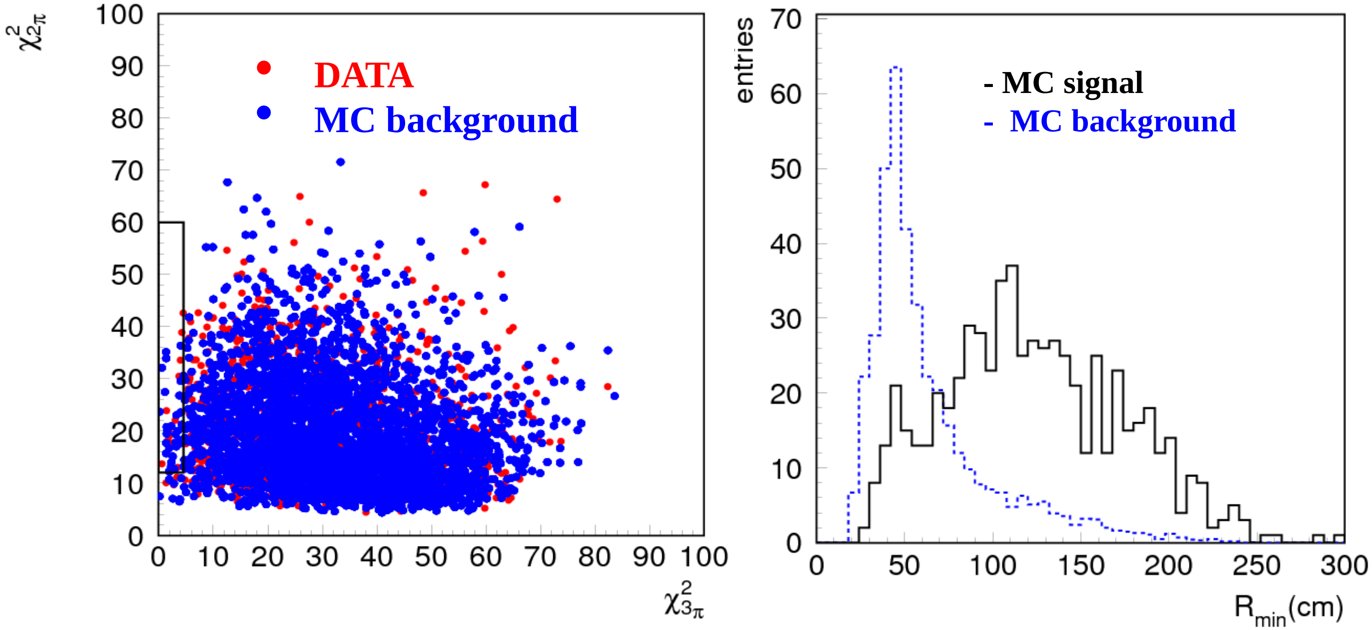
  K_S mass, total 4-momentum conservation, consistency between the measured time and position of each cluster

- **$\Delta E/\sigma_E$ cut**

  $\Delta E = E_{Ks} - \Sigma E_\gamma$



Search for the $K_S \to \pi^0\pi^0\pi^0$ decay



- **Signal region definition**

  $\chi^2_{2\pi}$: pairing of 4 out of 6 photons (π^0 masses, E_{Ks}, P_{Ks}, angle between π^0's)

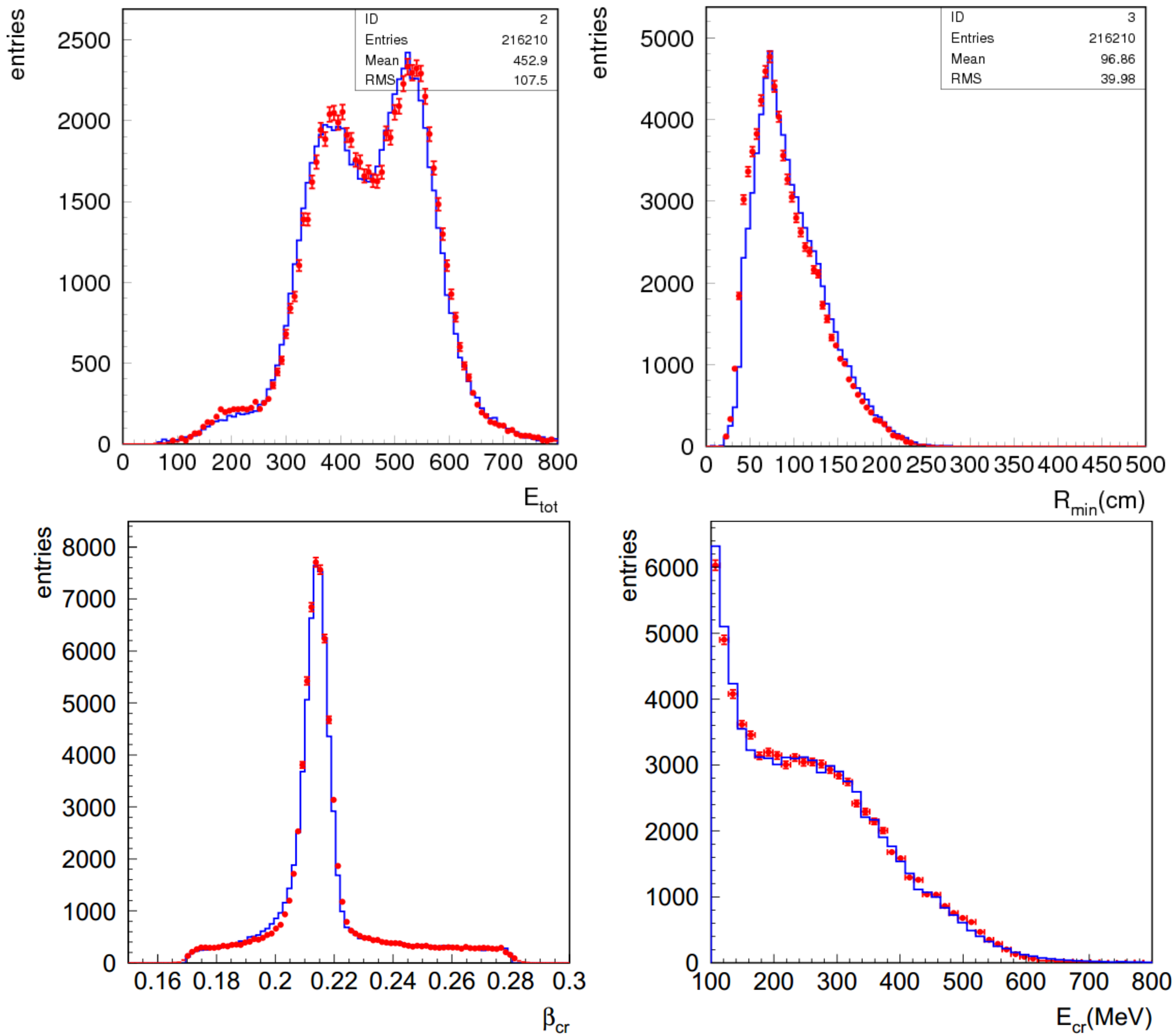
  $\chi^2_{3\pi}$: pairing of 6 clusters with best π^0 mass estimates

- **R_{min}**

  The minimum distance between clusters

Track Veto → **χ^2_{fit}** → **$\Delta E/\sigma_E$** → **Sbox** → **R_{min}** → **counting**

Monte Carlo calibration

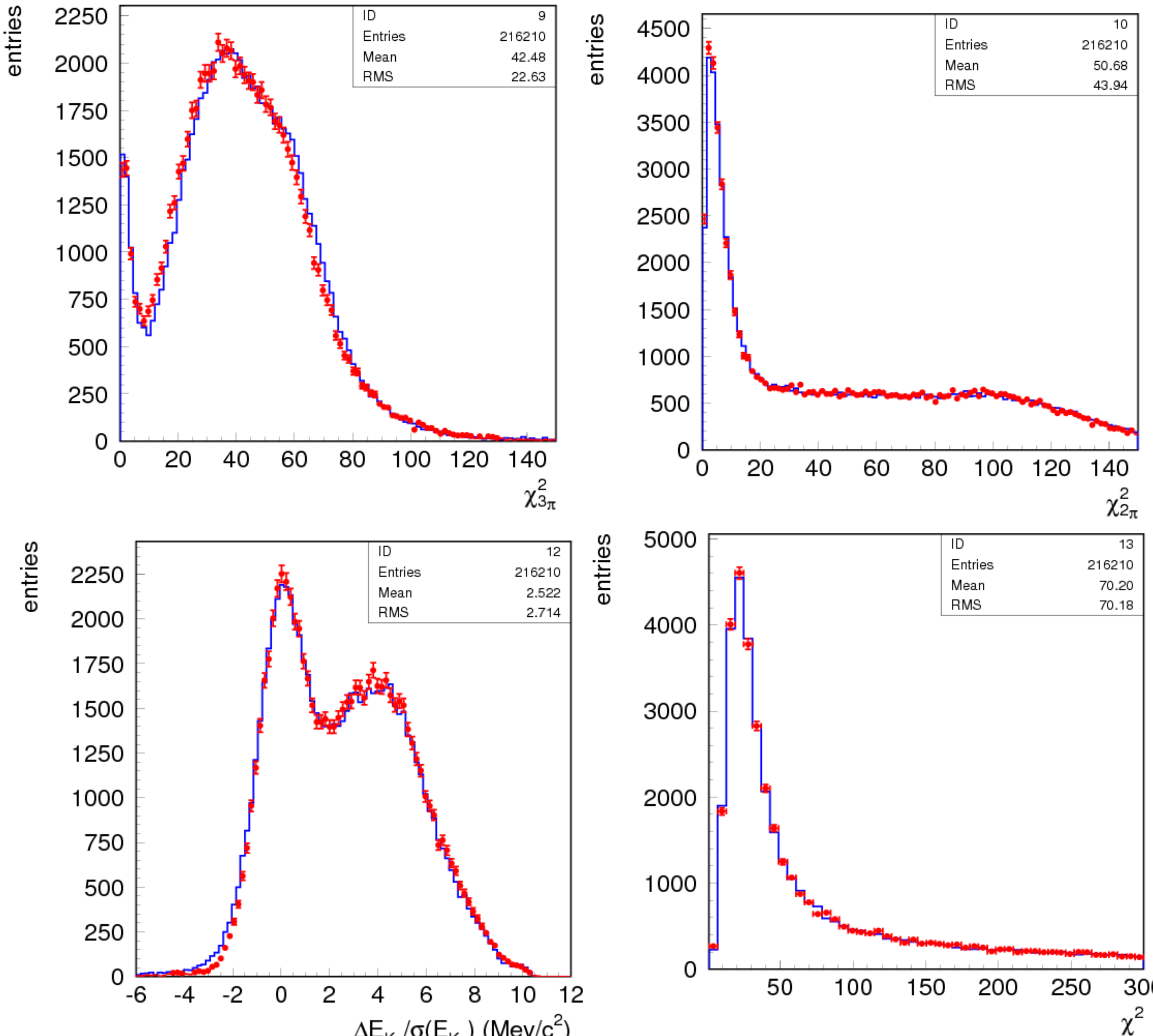


● DATA
● MC

Monte Carlo calibration

DATA

MC



Search for the $K_S \to \pi^0\pi^0\pi^0$ decay

- At the end of the analysis we count N_{obs} **=0 event selected as a signal and** N_{exp}**=0 events in MC**
- **SM prediction:** 1 event after tagging ⇒ 0.2 after selection
- The selection efficiency for $K_S \to 2\pi^0$ decay: $\varepsilon_{2\pi} \sim 0.66$
- Normalization sample: $N_{2\pi} = 1.36 \cdot 10^8$
- The selection efficiency for $K_S \to 3\pi^0$ signal: $\varepsilon_{3\pi} = 0.19 \pm 0.012$
- Upper limit on signal events: $N_{3\pi} < 13$ (90% C.L.)

PRELIMINARY

$$BR(K_S \to 3\pi^0) = \frac{N_{3\pi}/\varepsilon_{3\pi}}{N_{2\pi}/\varepsilon_{2\pi}} \times BR(K_S \to 2\pi^0) < 2.9 \times 10^{-8}$$

PRELIMINARY

Summary & outlook

- With the whole KLOE statistic we have obtained **the best upper limit on the BR($K_s \rightarrow 3\pi^0$) ≤ 2.9 10^{-8}**
- **This result points to the feasibility of the first observation at KLOE-2**
- Future: KLOE-2 @ Upgraded DAφNE (talk by A. Kupść)

THANK YOU FOR ATTENTION

SPARES

Introduction

- We can define the following amplitude ratios (assuming the CPT invariance):

$$\eta_{+-} = \frac{\langle \pi^+\pi^- | H | K_L \rangle}{\langle \pi^+\pi^- | H | K_S \rangle} = \varepsilon + \varepsilon' \qquad \eta_{00} = \frac{\langle \pi^0\pi^0 | H | K_L \rangle}{\langle \pi^0\pi^0 | H | K_S \rangle} = \varepsilon - 2\varepsilon'$$

where $\varepsilon = \frac{\langle \pi\pi(I=0)|H|K_L\rangle}{\langle \pi\pi(I=0)|H|K_S\rangle}$ and $\varepsilon' = \frac{\langle \pi\pi(I=2)|H|K_L\rangle}{\langle \pi\pi(I=2)|H|K_S\rangle} = ie^{i(\delta_2-\delta_0)} \frac{A_2}{\sqrt{2}A_0}\left(\frac{ImA_2}{A_2} - \frac{ImA_0}{A_0}\right)$

- These parameters can be measured using the interference between $K_S \to \pi^+\pi^-$ and $K_L \to \pi^+\pi^-$ decay:

$$N_{\pi^+\pi^-} \sim [e^{-\Gamma_S} + |\eta_{+-}|^2 e^{-\Gamma_L} + 2|\eta_{+-}|\cos(\Delta m \cdot t \ + \varphi_{+-}) e^{-\frac{1}{2}(\Gamma_S+\Gamma_L)t}]$$

$|\eta_{+-}| = (2.232 \pm 0.011)\cdot 10^{-3}$; $\varphi_{+-} = (43.51 \pm 0.05)^{o}$

$|\eta_{00}| = (2.221 \pm 0.011)\cdot 10^{-3}$; $\varphi_{00} = (43.52 \pm 0.05)^{o}$

(*K. Nakamura et al. (Particle Data Group), J. Phys. G 37, 075021 (2010)*)

Search for the $K_S \to \pi^0\pi^0\pi^0$ decay

- 2004-2005 data ($\sim 7.53 \cdot 10^7$ tags) & MC($\sim 1.59 \cdot 10^8$ tags)
- Expected number of the $K_s \to 3\pi^0$ decays: $N_{SM} \sim 3.8$
- Acceptance cuts:

- K_L-crash:

$$\left.\begin{array}{l} E_{cr} > 129\ \mathrm{MeV} \\ 0.196 \leq \beta_{cr} \leq 0.25 \\ 40^0 \leq \theta_{cr} \leq 140^0 \end{array}\right\} \varepsilon \approx 28\%$$

- prompt photon:

$$\left.\begin{array}{l} E_{cl} > 7\ \mathrm{MeV} \\ |\cos\theta_{cl}| \leq 0.915 \\ |\Delta T_{cl}| \leq \mathrm{Min}(3.5 \cdot \sigma_T(E_{cl}), 2\ \mathrm{ns}) \end{array}\right\} \varepsilon \approx 48\%$$

- Preselected signal sample (K_L-crash + 6 photons) ~ **56000 events**

Search for the $K_S \rightarrow \pi^0\pi^0\pi^0$ decay

- **Signal region definition**

  $\chi^2_{2\pi}$: pairing of 4 out of 6 photons

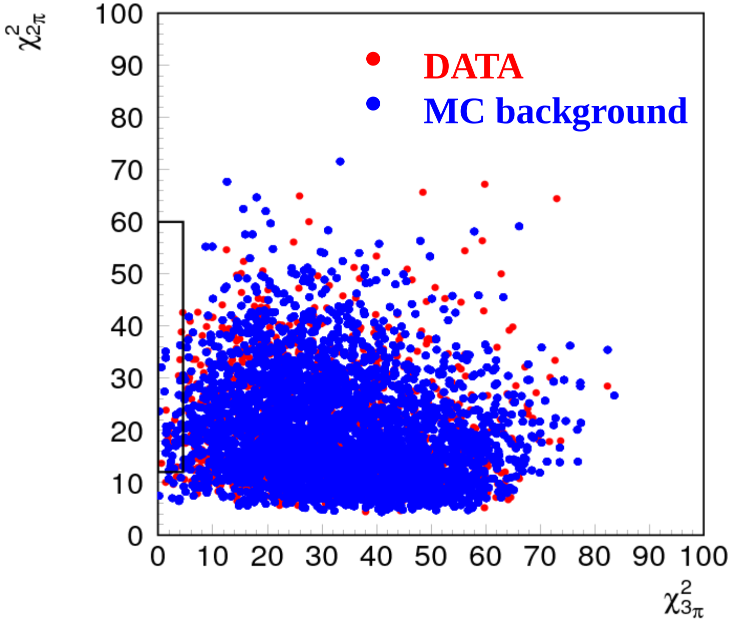
  (π^0 masses, E_{Ks}, P_{Ks}, angle between π^0's)

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

$$\chi^2_{2\pi} = \frac{\left(M_{\pi_1} - M_{pdg}\right)^2}{\sigma^2_{\pi_1}} + \frac{\left(M_{\pi_2} - M_{pdg}\right)^2}{\sigma^2_{\pi_2}} + \frac{\left(E_{K_S} - \sum E_{\gamma_i}\right)^2}{\sigma^2_E}$$

$$+ \frac{\left(P^x_{K_S} - \sum P^x_{\gamma_i}\right)^2}{\sigma^2_{P^x}} + \frac{\left(P^y_{K_S} - \sum P^y_{\gamma_i}\right)^2}{\sigma^2_{P^y}} + \frac{\left(P^z_{K_S} - \sum P^z_{\gamma_i}\right)^2}{\sigma^2_{P^z}} + \frac{\left(\pi - \vartheta_{\pi\pi}\right)^2}{\sigma^2_{\vartheta_{\pi\pi}}}$$

$$\chi^2_{3\pi} = \sum_{i=1}^{3} \frac{\left(M_{\pi_i} - M_{pdg}\right)^2}{\sigma^2_{\pi_i}}$$



- MC signal
- MC background

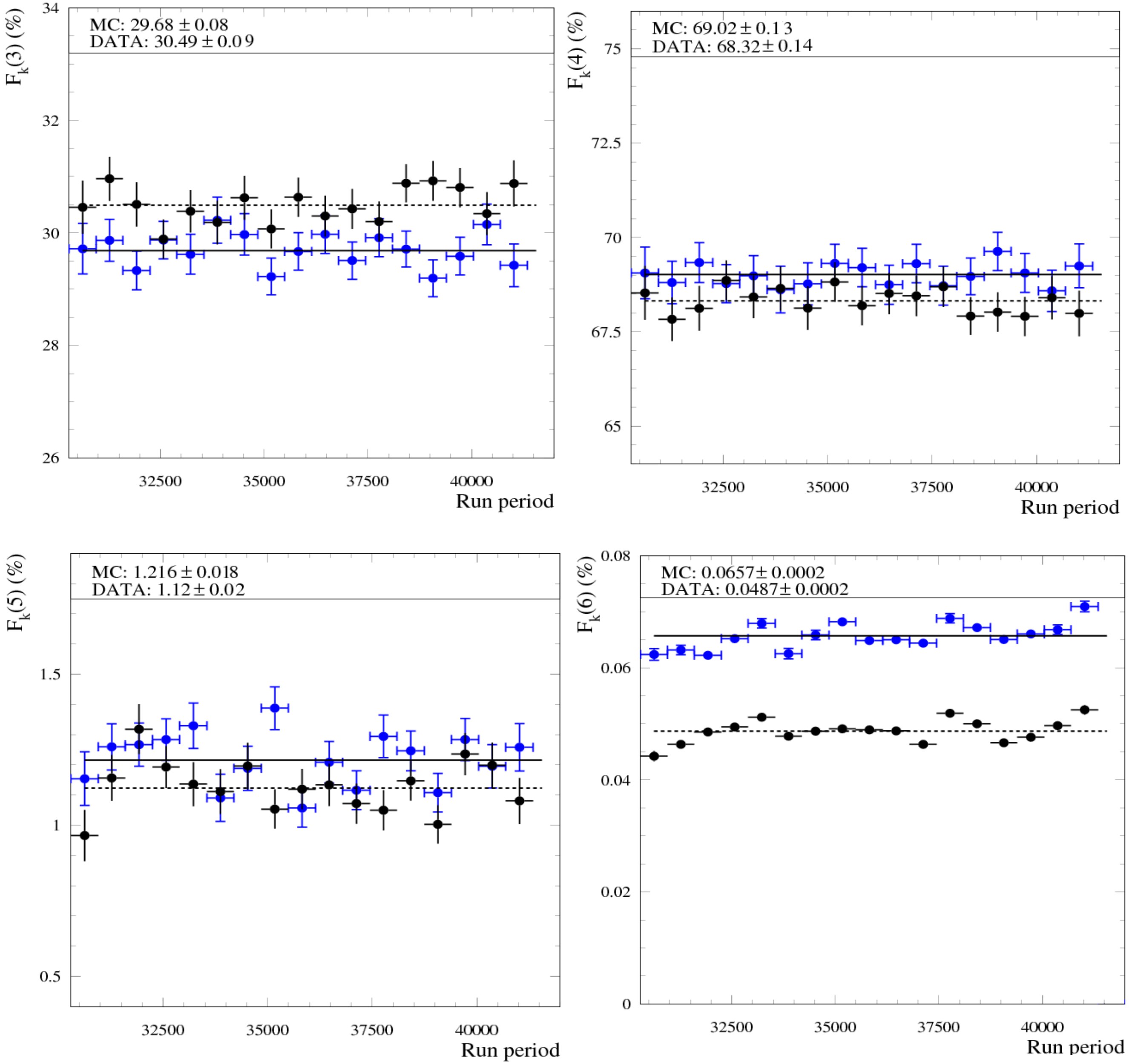
- **R_{min}**

  The minimum distance between clusters

Background studies

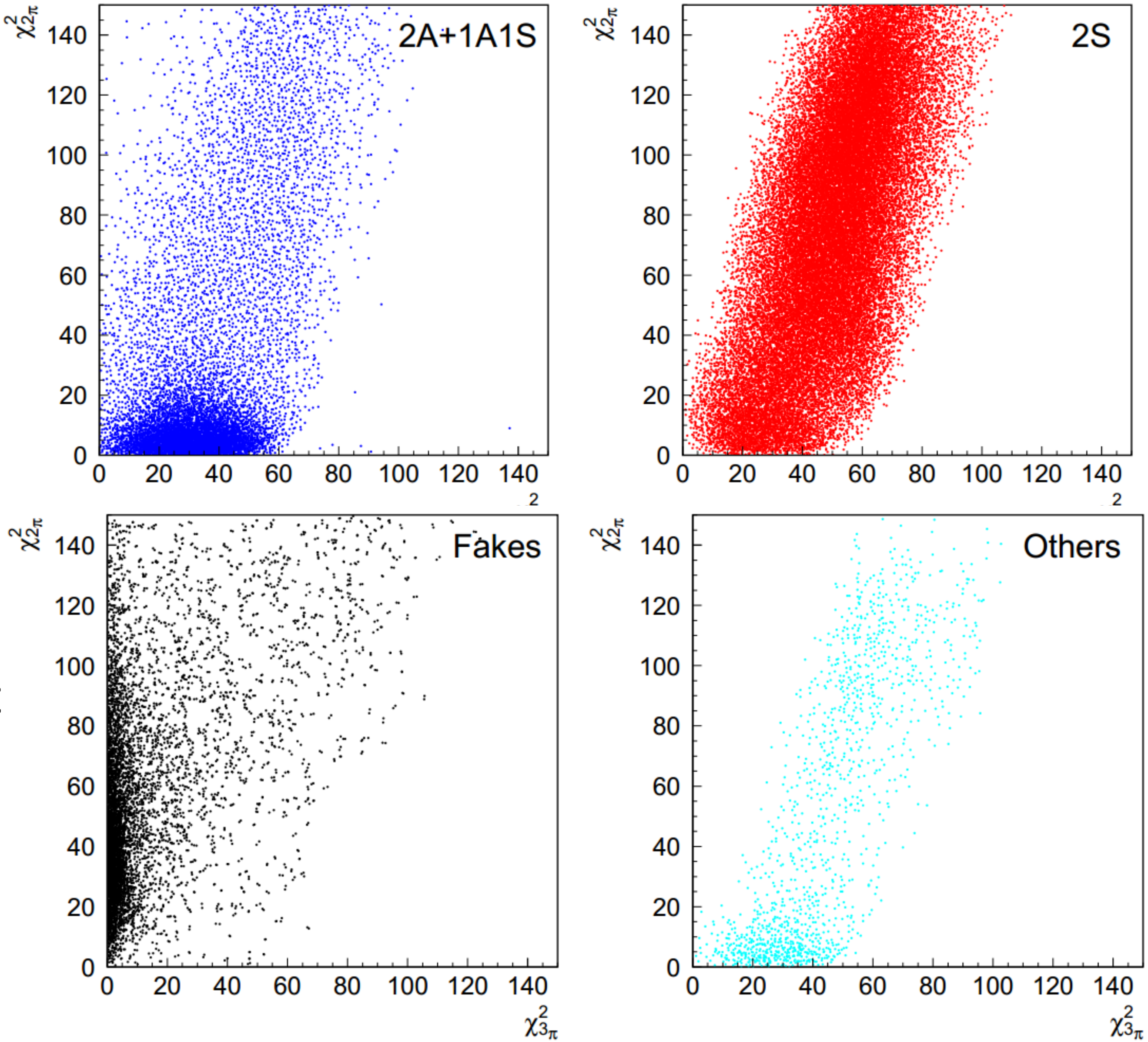
- DATA
- MC

$$F_k = \frac{N_{ev}(N_\gamma = k)}{\sum_{i=3}^{6} N_{ev}(N_\gamma = i)}$$

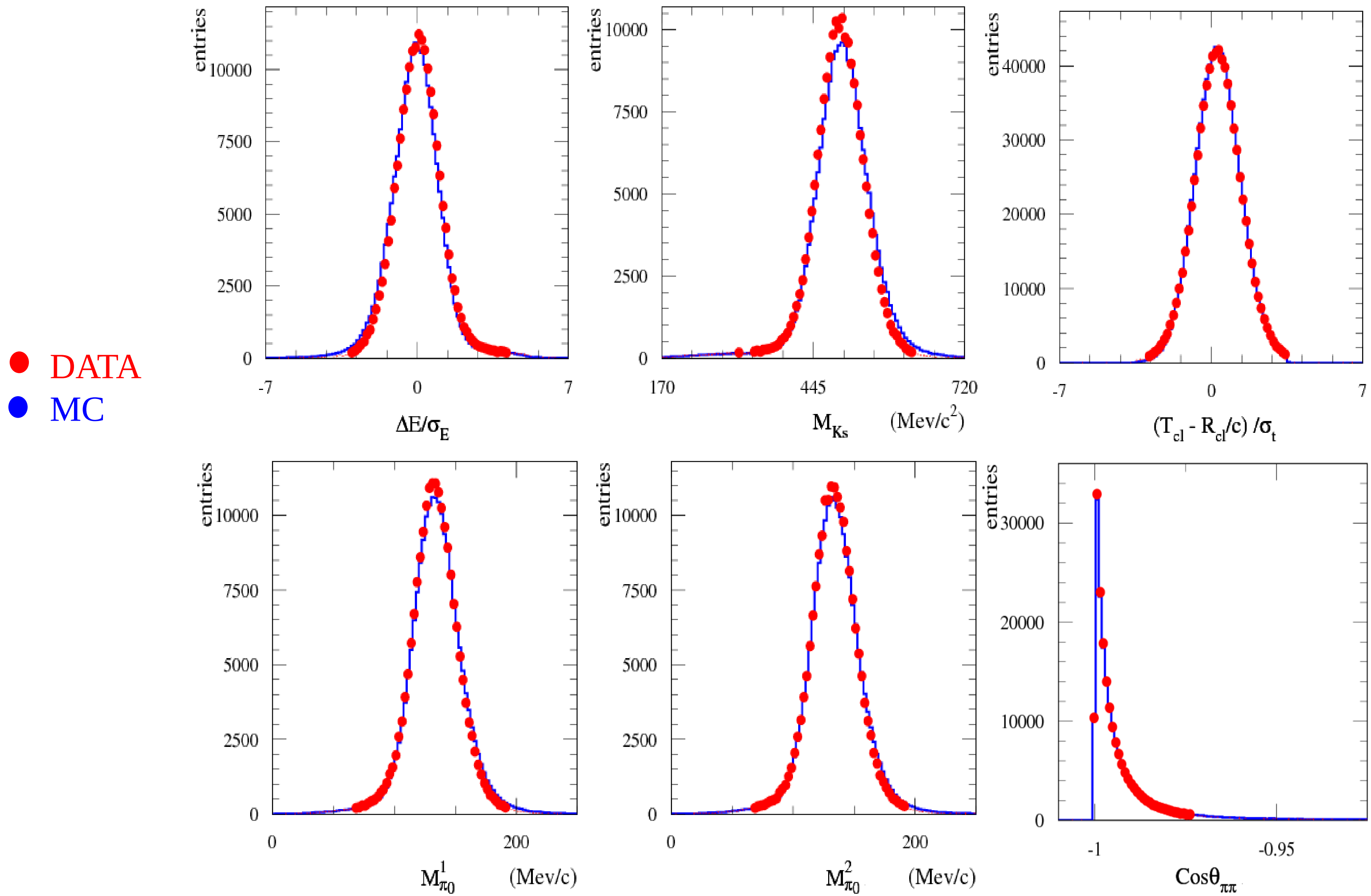


Monte Carlo calibration

- Using shapes of the MC categories we have fitted the ($\chi^2_{2\pi}$ $\chi^2_{3\pi}$) distribution
- Results of the fit are then used to weight MC events



Monte Carlo calibration



Search for the $K_S \to \pi^0\pi^0\pi^0$ decay

- Using the following set of cuts:

$$\left.\begin{array}{l} E_{cr} > 129 \text{ MeV} \\ 0.196 \leq \beta_{cr} \leq 0.25 \end{array}\right\} \varepsilon_{cr} \approx 28\%$$

$$\left.\begin{array}{l} \chi^2_{fit} < 35 \\ \Delta E/\sigma_E \geq 1.7 \\ 12.1 \leq \chi^2_{2\pi} \leq 60 \\ \chi^2_{3\pi} \leq 4.6 \\ R_{min} > 65 \text{ cm} \end{array}\right\} \varepsilon_{3\pi} = \mathbf{0.19 \pm 0.012}$$

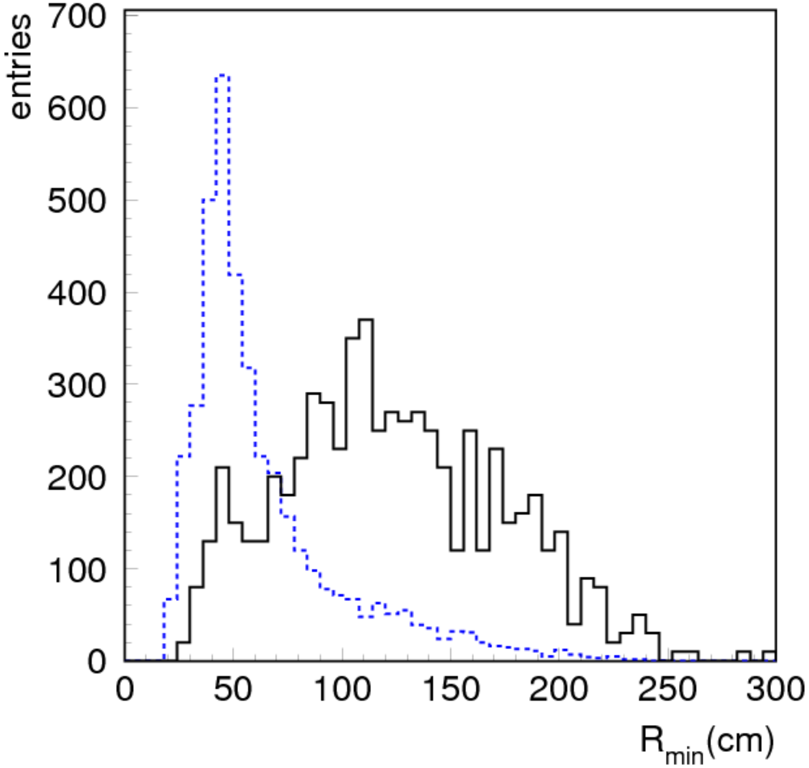
We count N_{obs} **=0 event selected as a signal and** N_{exp}**=0 events in MC**

- **SM prediction:** 1 event after tagging ⇒ 0.2 after selection
- The selection efficiency for $K_S \to 2\pi^0$ decay: $\varepsilon_{2\pi} \sim 0.66$
- Upper limit on signal events: $N_{3\pi} < 13$ (90% C.L.)
- Normalization sample: $N_{2\pi} = 90062000/\ \varepsilon_{2\pi} = 1.4 * 10\hat{}8$

PRELIMINARY

$$BR(K_S \to 3\pi^0) = \frac{N_{3\pi}/\varepsilon_{3\pi}}{N_{2\pi}/\varepsilon_{2\pi}} \times BR(K_S \to 2\pi^0) < 2.9 \times 10^{-8}$$

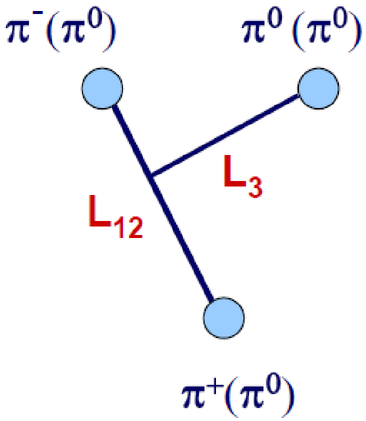
PRELIMINARY


entries
700
600
500
400
300
200
100
0
0
50
100
150
200
250
300
R_{min}(cm)

Introduction

- If the CP symmetry is conserved the allowed nonleptonic decays are: $K_S \rightarrow 2\pi$ and $K_L \rightarrow 3\pi$

- Two pion system:
  L - the angular momentum of the system



P$(\pi^0\pi^0) = P_\pi^2(-1)^L = 1$ (spin of kaon is zero); **C** $(\pi^0\pi^0) = C_\pi^2 = 1$,

CP$(\pi^0\pi^0) = 1$

P$(\pi^+\pi^-) = P_\pi^2(-1)^L$; **C** $(\pi^+\pi^-) = (-1)^L = 1$

CP$(\pi^+\pi^-) = 1$

- Three pion system:
  L12 – the angular momentum of a pair of pions in their center of mass frame
  L3 – the angular momentum of the third pion on the rest frame of kaon

P$(\pi^0\pi^0\pi^0) = P_\pi^3(-1)^{L12}(-1)^{L3} = -1$ $(L12+L3 = 0)$; **C** $(\pi^0\pi^0\pi^0) = C_\pi^3 = 1$,

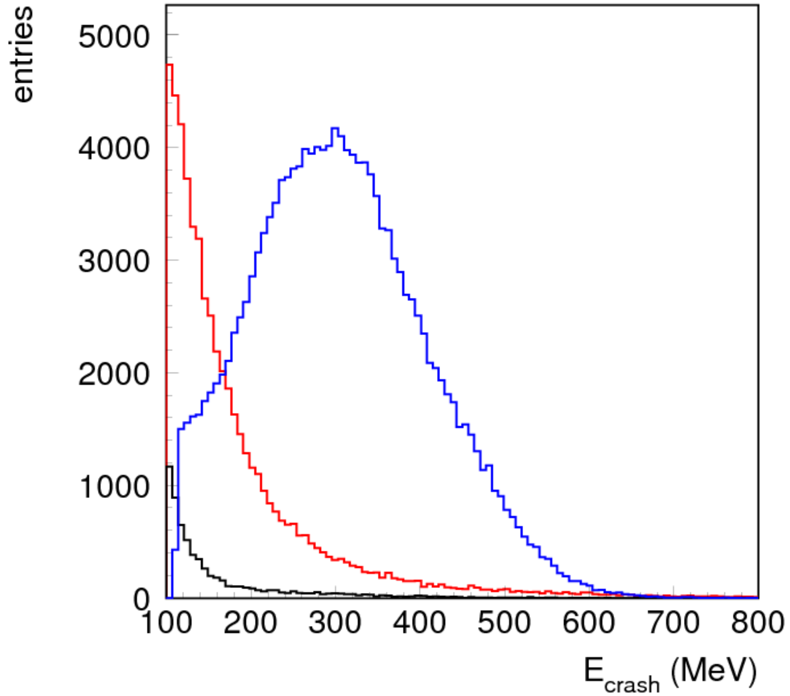
CP$(\pi^0\pi^0\pi^0) = -1$

P$(\pi^+\pi^-\pi^0) = P_\pi^3(-1)^{L12}(-1)^{L3} = -1$; **C** $(\pi^+\pi^-\pi^0) =$ **C**(π^0) **C** $(\pi^+\pi^-) = (-1)^{L12}$

CP$(\pi^+\pi^-) = (-1)^{L12+1} = -1$ $(L12=0)$

Fixing the MC K_L-crash energy

- We then fit to the energy distribution using shapes of True K_L crash, K_L passed through and Fake.
- For the Real K_L –crash events we apply a 12% correction to the energy
- The results of both fits:



	Weight	Number of events expected in data
2ACC+ 1A1S	0,424 ± 0,038	27495 ± 247
2S	0,314 ± 0,023	40160 ± 429
FAKE	1,27 ± 0.18	7222 ± 158
OTHERS	0,102 ± 0,01	1810 ± 432
True K_L crash	0.317 ± 0.024	49038 ± 318
K_L passed through	0.405 ± 0.037	22264 ± 260