Search for the the CP violating $K_s \rightarrow 3\pi^0$ decay with the KLOE detector

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on behalf of the KLOE/KLOE-2 collaboration

- Introduction
- Search for the $K_S \rightarrow \pi^0\pi^0\pi^0$ decay
- Background studies
- Results of the measurement
- Summary & outlook

DISCRETE 2012, Lisbon, 3-7 December 2012

Introduction

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

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

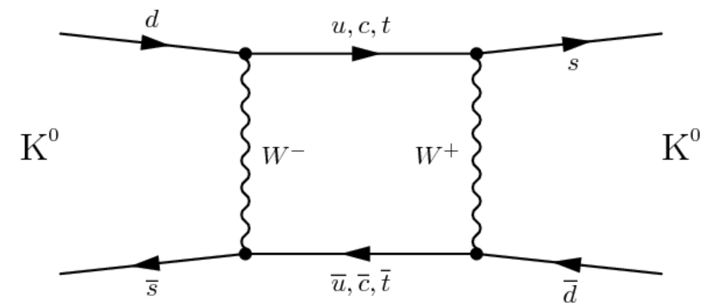
$$\boldsymbol{M} = \begin{pmatrix} M_{11} & M_{12} \\ M^*_{12} & M_{22}\end{pmatrix}$$

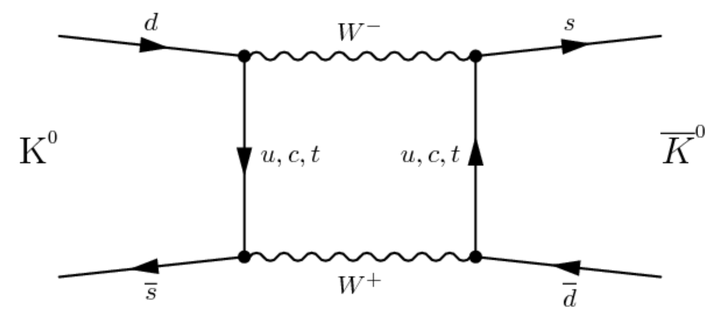
$$\boldsymbol{\Gamma} = \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma^*_{12} & \Gamma_{22}\end{pmatrix}$$

- In the basis of the CP operator:

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

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





- 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:

$|K_S> \rightarrow \pi^+\pi^-$
$|K_S> \rightarrow 2\pi^0$ (CP = 1)

$|K_L> \rightarrow \pi^0\pi^+\pi^-$ (CP = -1 for I=0, 2, ...)
$|K_L> \rightarrow 3\pi^0$ (CP = -1)

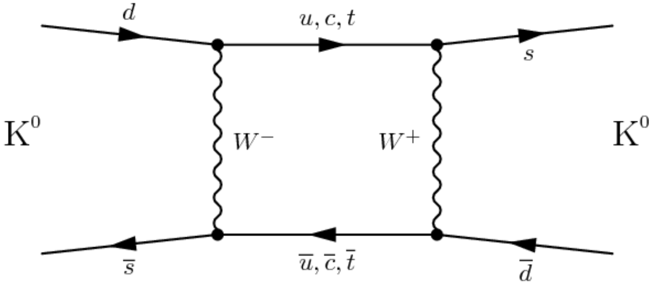
Introduction

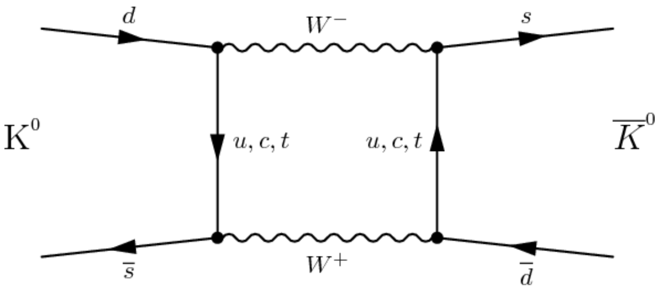
- But K_S and K_L are not CP eigenstates:

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

(J. Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012))

- CP violation in mixing (ΔS=2):



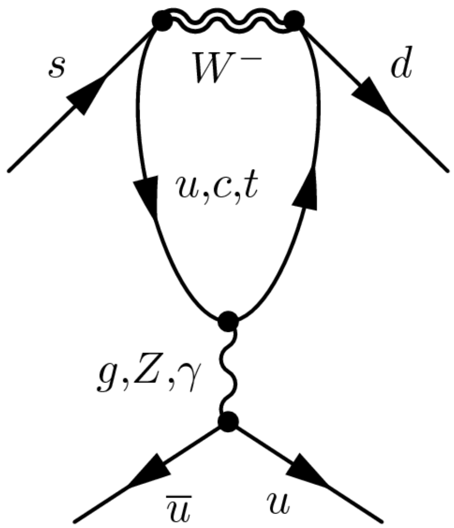


$$|K_S> = \frac{1}{\sqrt{1+|\varepsilon_S|^2}}(\,|K_1> + \varepsilon_S|K_2>\,) \quad \boldsymbol{\varepsilon_S \neq \varepsilon_L \Rightarrow \mathbf{CPTV}}$$

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

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

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



- 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:

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

$|\eta_{+-}| = (2.232 \pm 0.011) \cdot 10^{-3}$; $\varphi_{+-} = (43.51 \pm 0.05)^o$
$|\eta_{00}| = (2.221 \pm 0.011) \cdot 10^{-3}$; $\varphi_{00} = (43.52 \pm 0.05)^o$

(*J. Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012)*)

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))

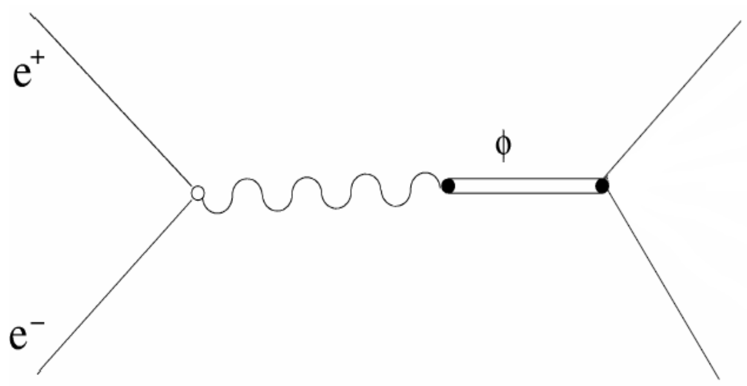
- Previous measurements of η_{000}:

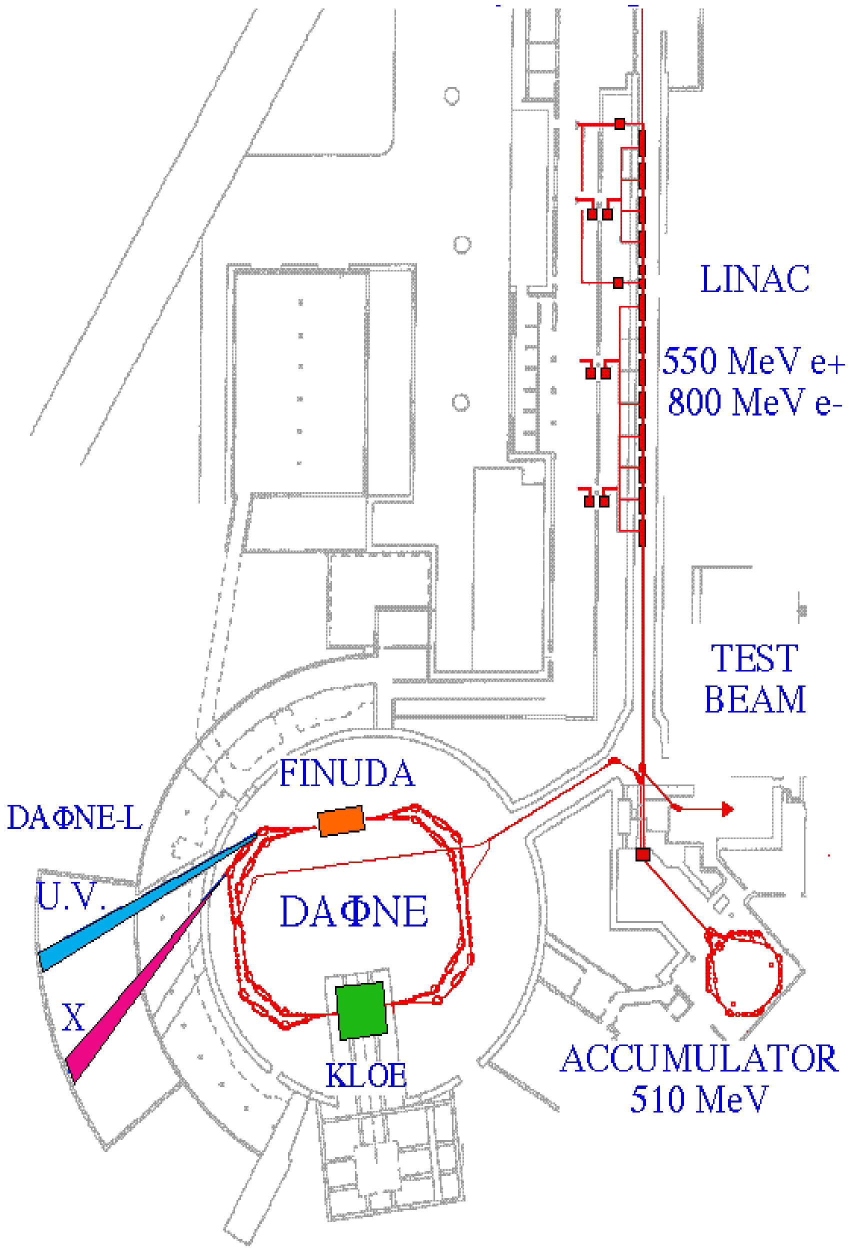
SND (direct search) :	$BR(K_S \rightarrow 3\pi^0) < 1.4 \cdot 10^{-5}$
NA48 (interference measurement):	$BR(K_S \rightarrow 3\pi^0) < 7.4 \cdot 10^{-7}$
KLOE	**$BR(K_S \rightarrow 3\pi^0) < 1.2 \cdot 10^{-7}$**

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

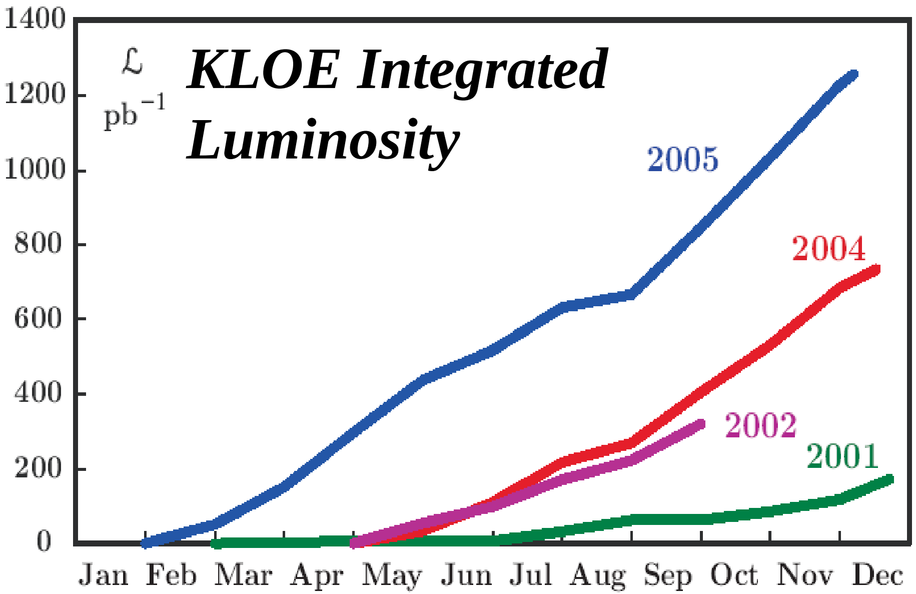
The DAFNE Φ-factory

- 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 $1.5\times10^{32}\ cm^{-2}s^{-1}$





DAΦNE Luminosity history



KLOE run:

- ❑ Daily performance: 7-8 pb^{-1}
- ❑ Best month $\int L\,dt \sim 200$ pb^{-1}
- ❑ Total KLOE $\int L\,dt \sim 2400$ 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

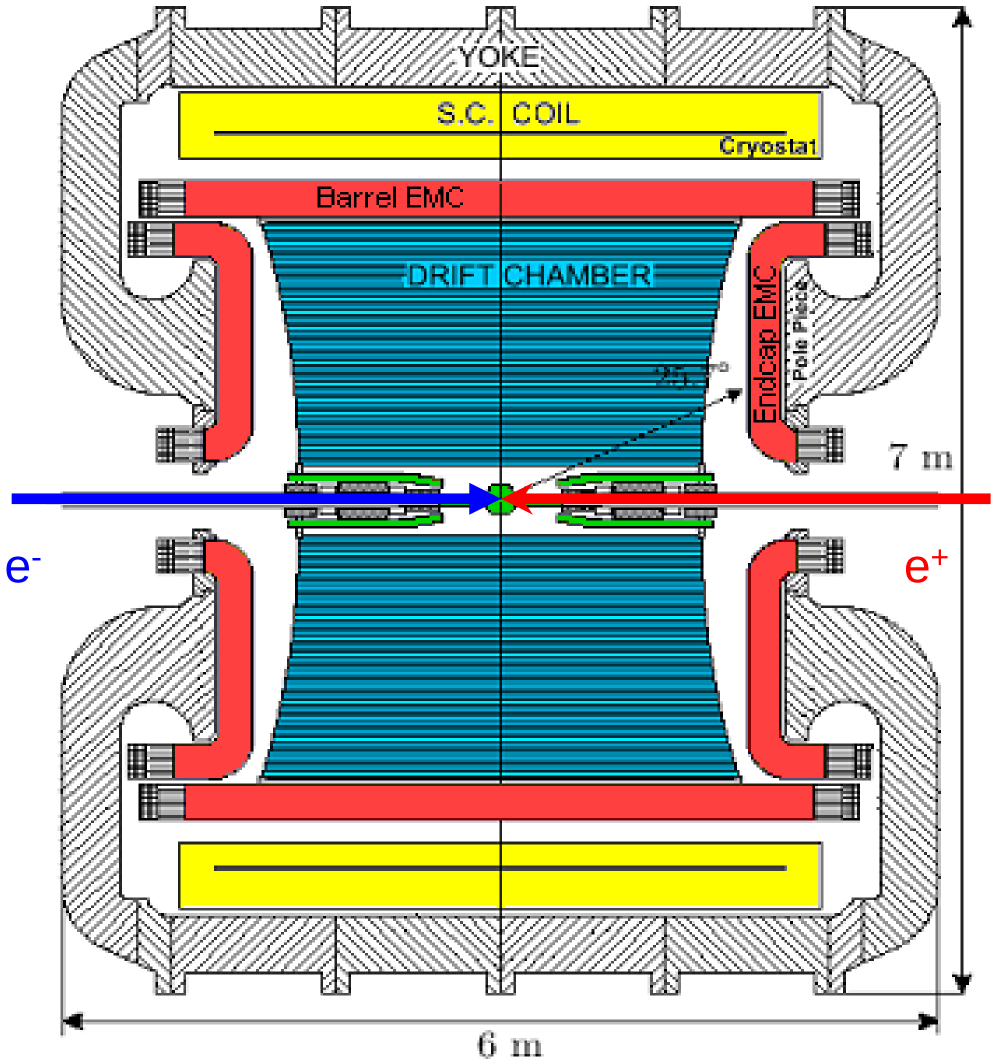
$\sigma_E/E = 5.7\% / \sqrt{E(GeV)}$

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

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

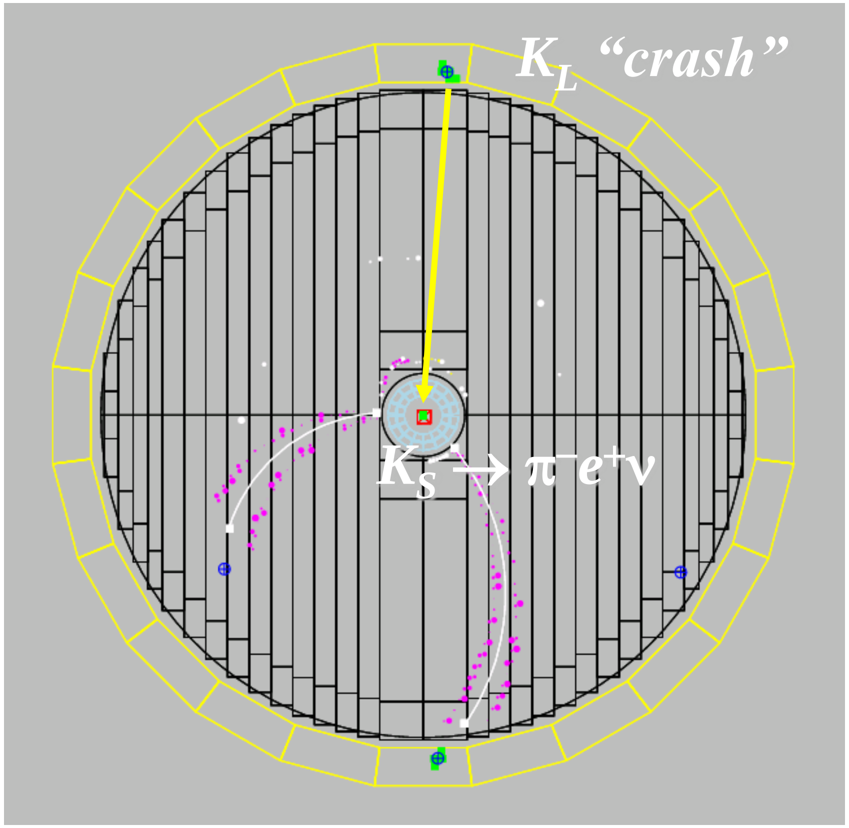
Superconducting coil

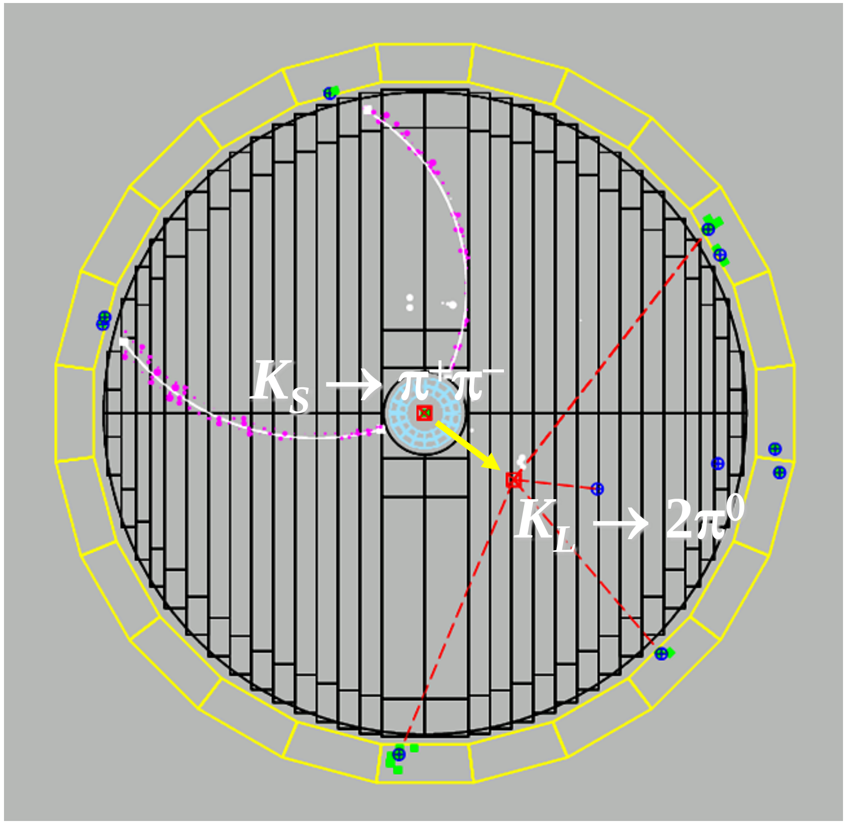
B = 0.52 T



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 $K_S \rightarrow \pi^+\pi^-$ vertex at IP

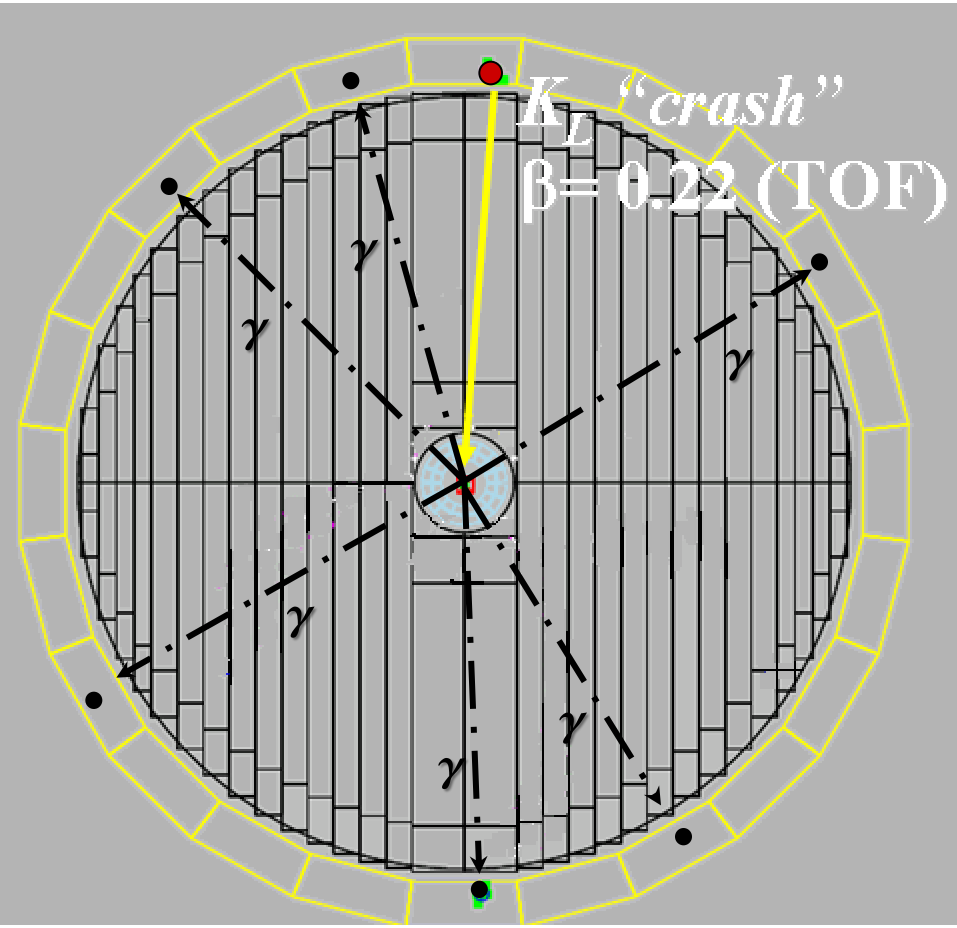
Efficiency ~ 70%

K_L angular resolution: ~ 1°

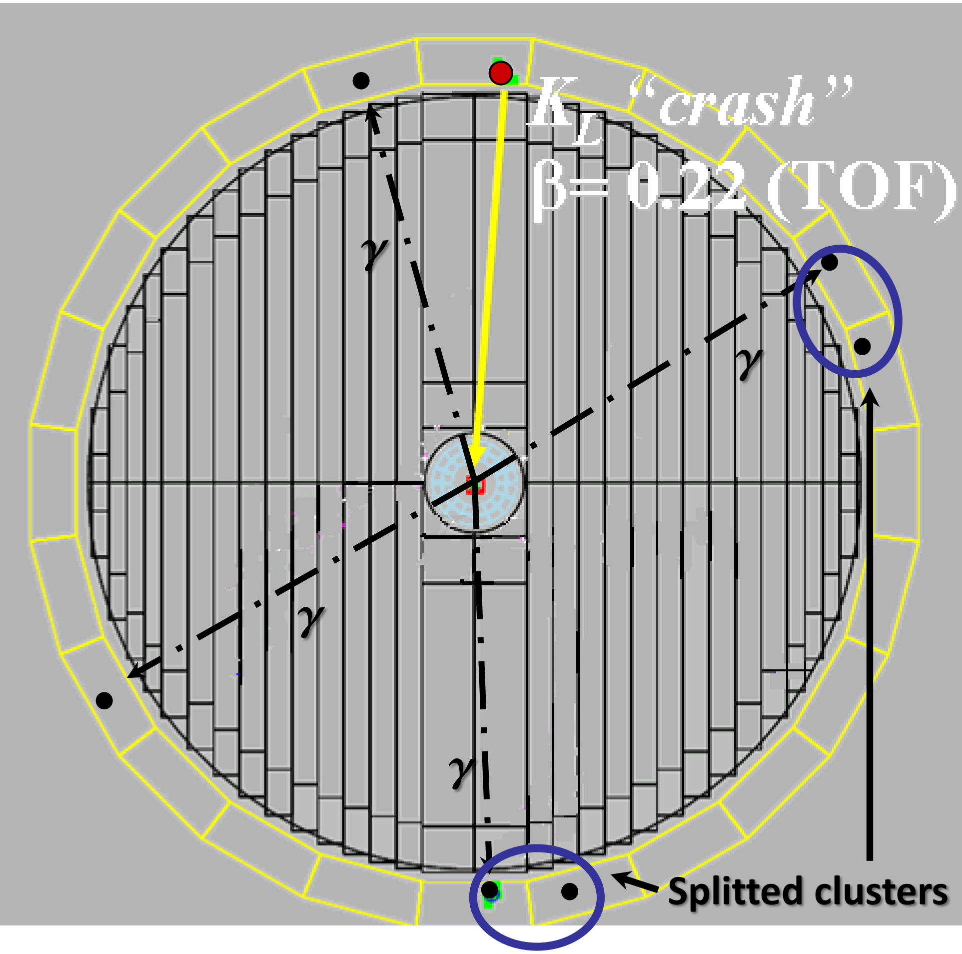
K_L momentum resolution: ~ 2 MeV

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

SIGNAL



BACKGROUND



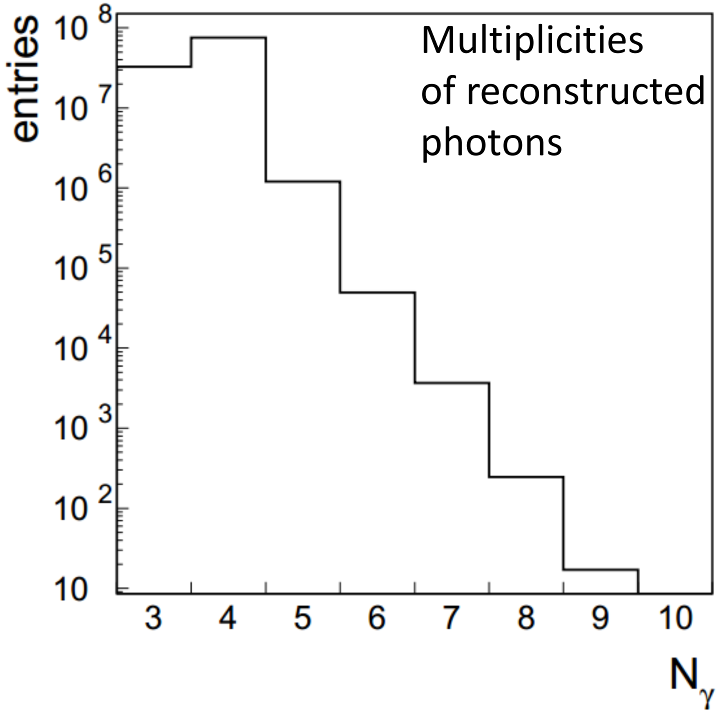
$K_S \to 3\pi^0 \to 6\gamma$

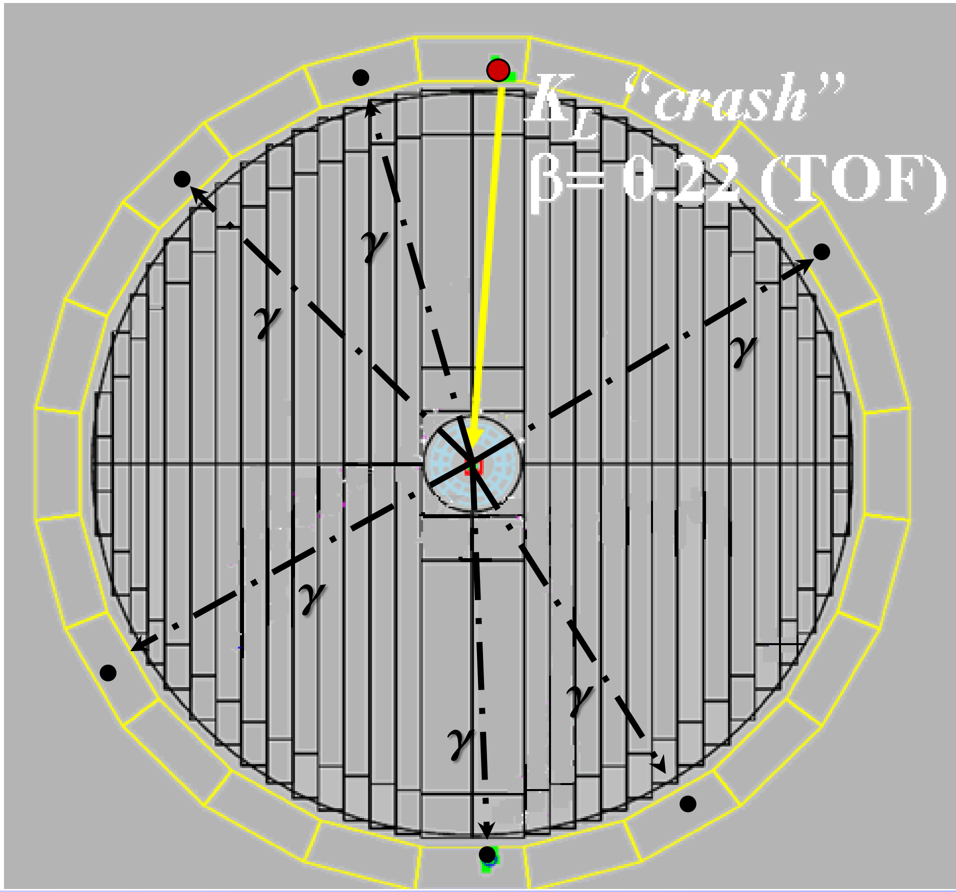
$K_S \to 2\pi^0$ + accidental/splitted clusters

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

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

- K_L interactions in the calorimeter tag K_s decay
- Preselected signal sample (K_L-crash + 6 photons) ~ **77000 events**
- $K_S \rightarrow 2\pi^0$ (4 prompt photons) used for normalization
  - K_L-crash: $\varepsilon_{cr} \approx 23\%$
  - prompt photon: $\varepsilon_{ph} \approx 48\%$



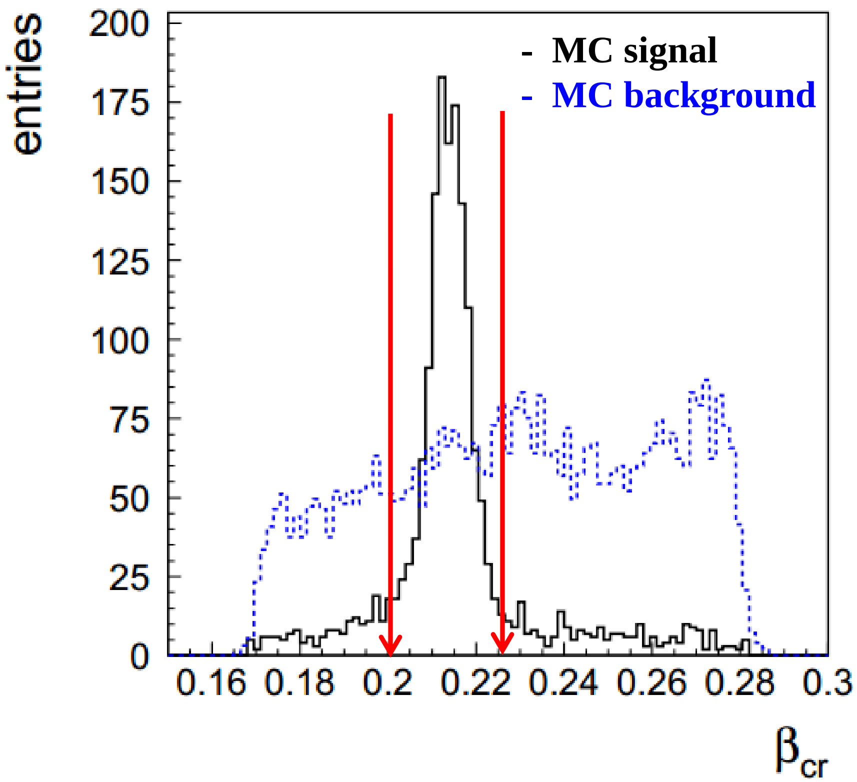


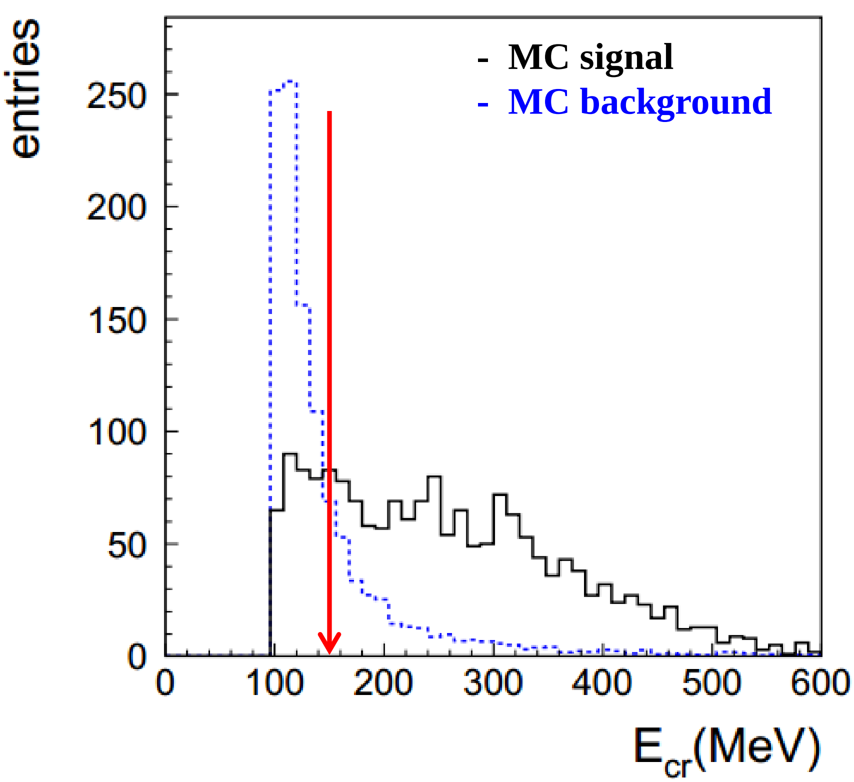
Search for the $K_S \to \pi^0\pi^0\pi^0$ decay

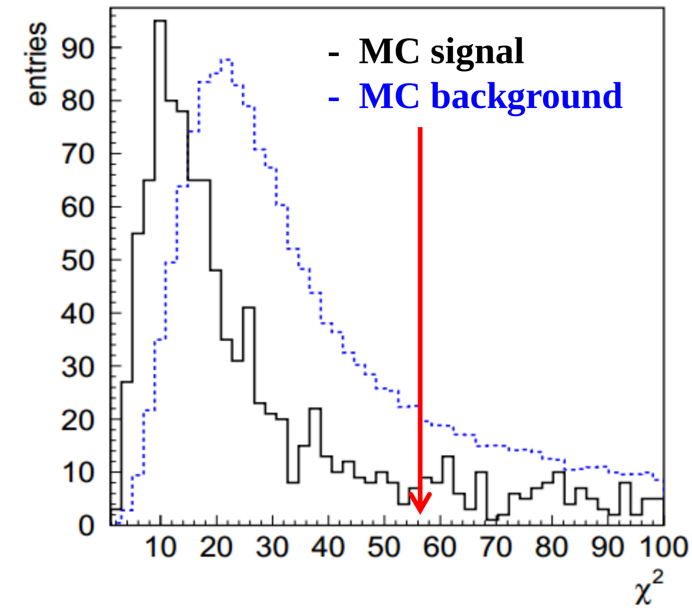
❑ Rejection of events with charged paricles

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

- cuts on the velocity of the tagging K_L meson in the Φ rest frame (β_{cr}) and energy (E_{cr}) of the K_L cluster





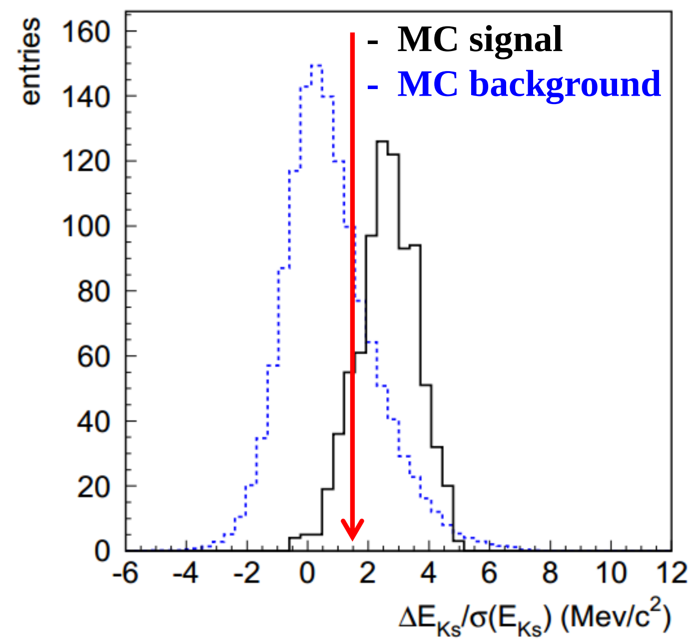


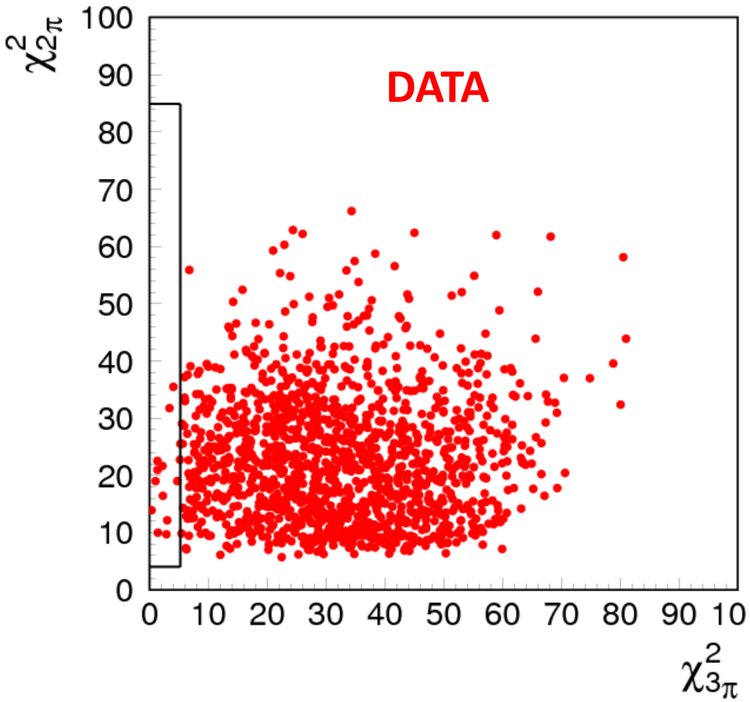
- **Kinematical fit**

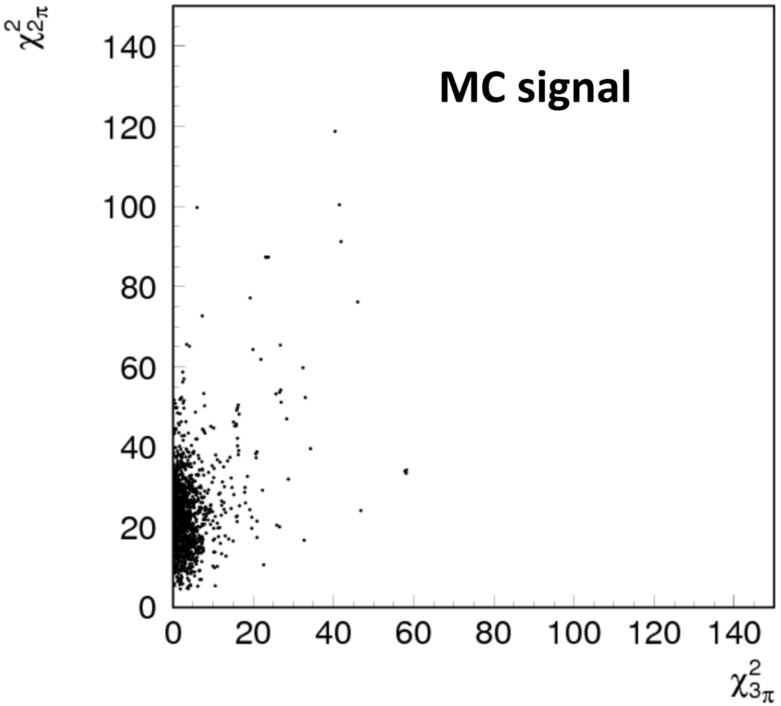
  K_S mass, total 4-momentum conservation, consistency between the measured time and position of each cluster

- **$\Delta E/\sigma_E = (E_{Ks} - \Sigma E_\gamma)/\sigma_E$ cut**

  Consistency between the K_S energy reconstructed by tagging and the sum of energies of four „best" gamma quanta





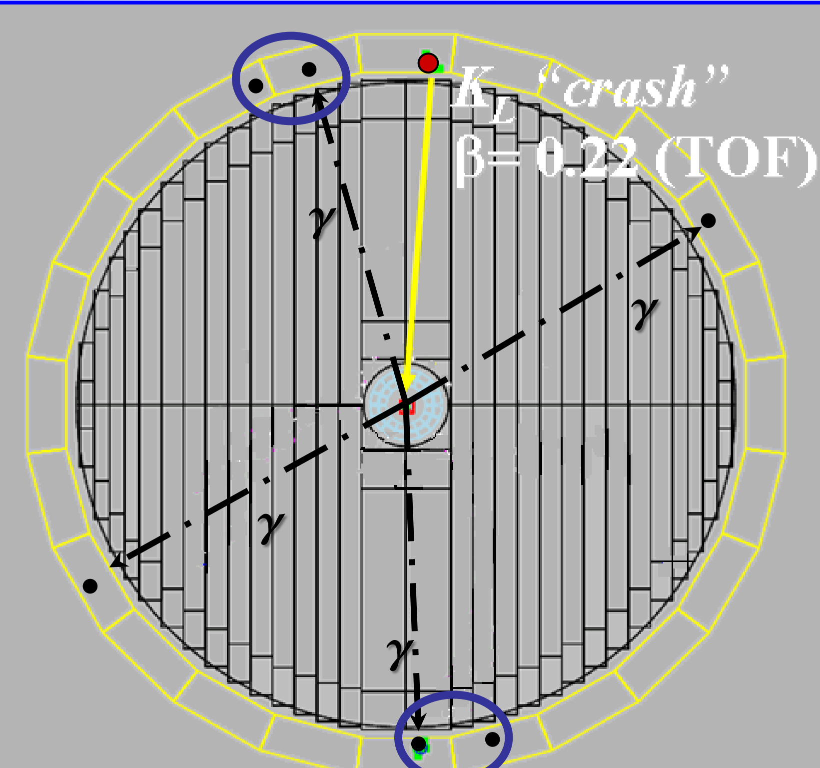


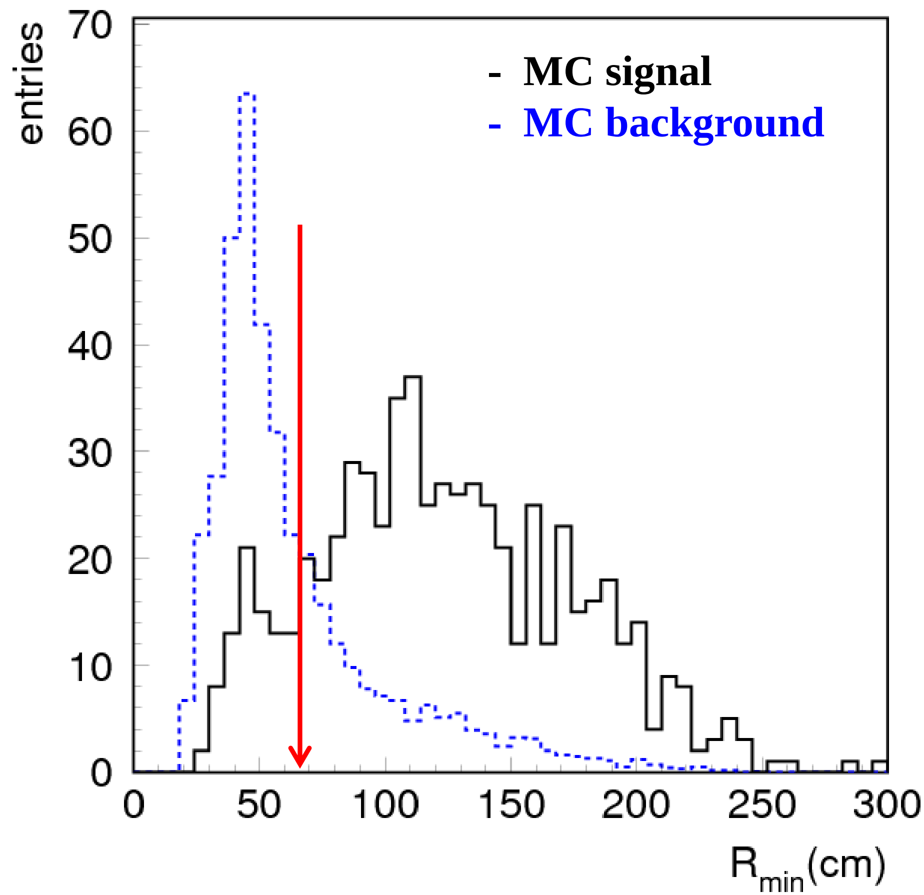
- **Signal region definition**

  $\chi^2_{2\pi}$: 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

Analysis scheme





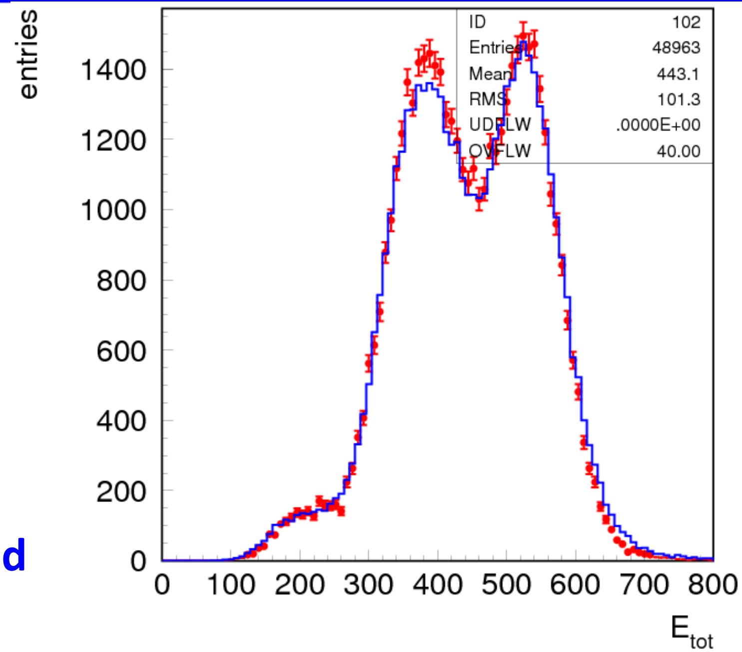
- **R_{min}**

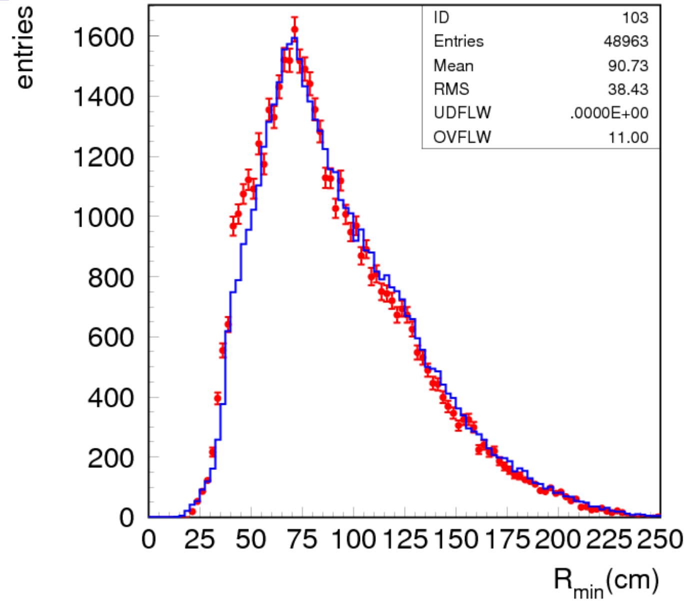
  The minimum distance between clusters

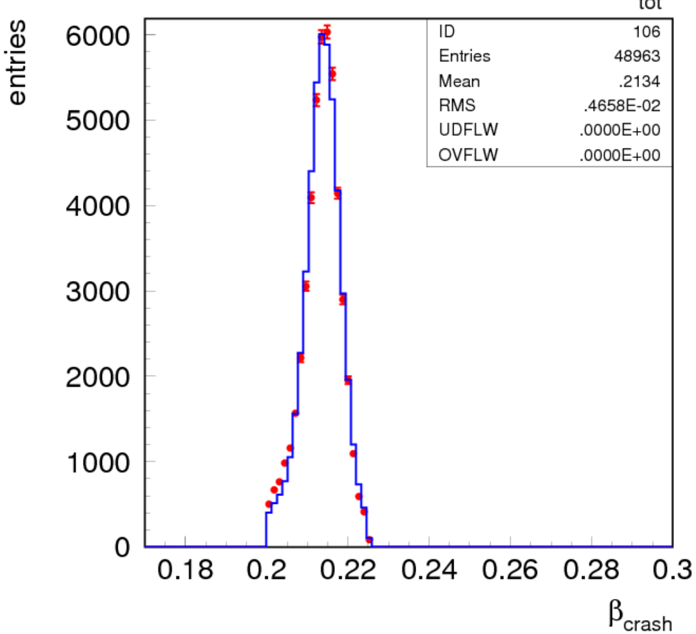
Track Veto → **χ^2_{fit}** → **$\Delta E/\sigma_E$** → **Sbox** → **R_{min}** → **counting**

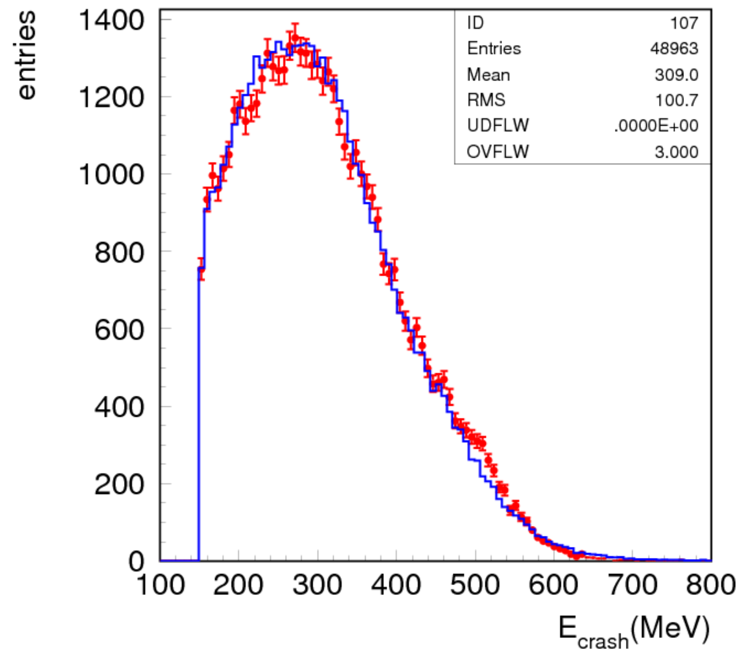
Simulations vs data: Inclusive distributions

- **DATA**
- **MC background**









Simulations vs data: Inclusive distributions

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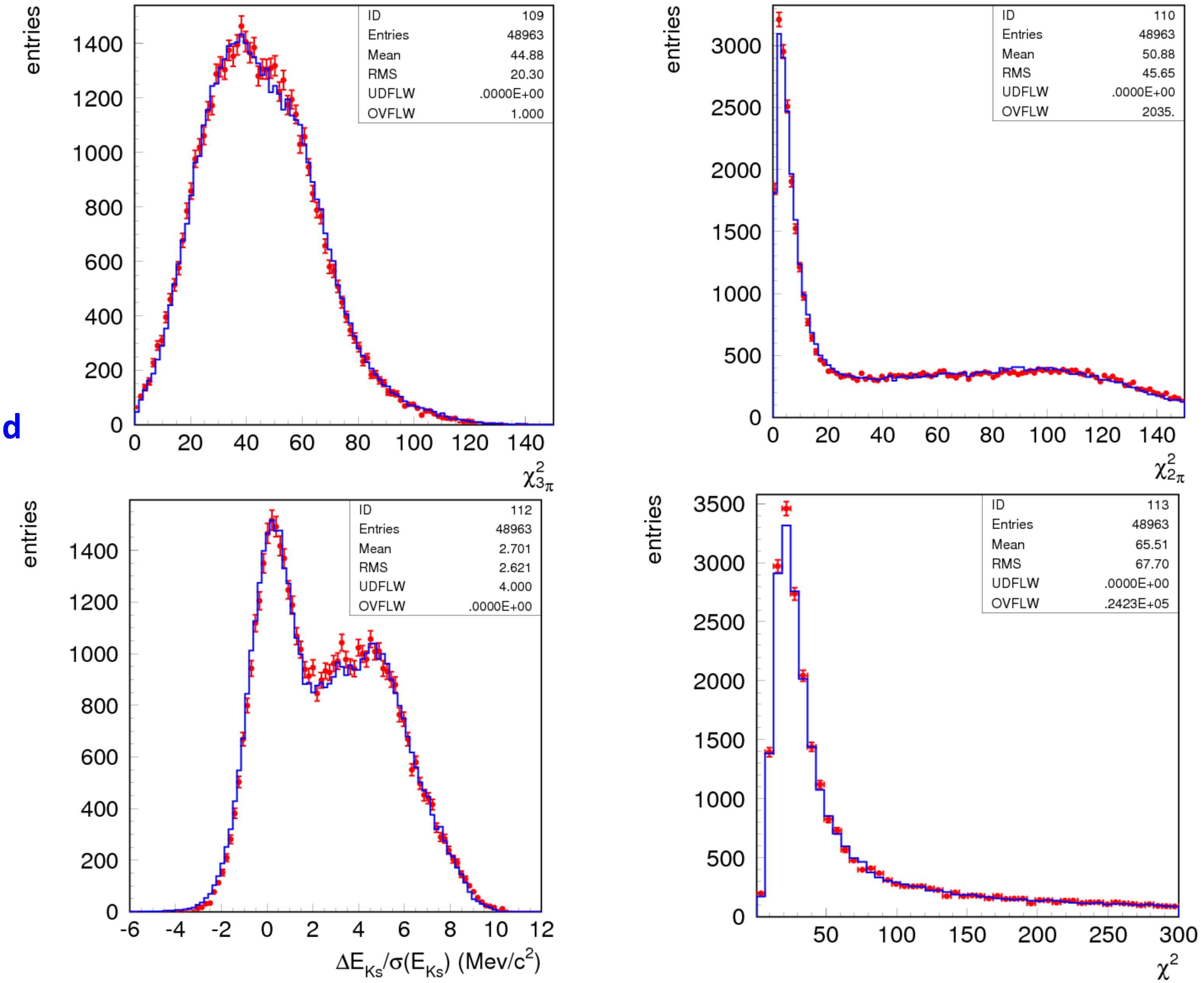
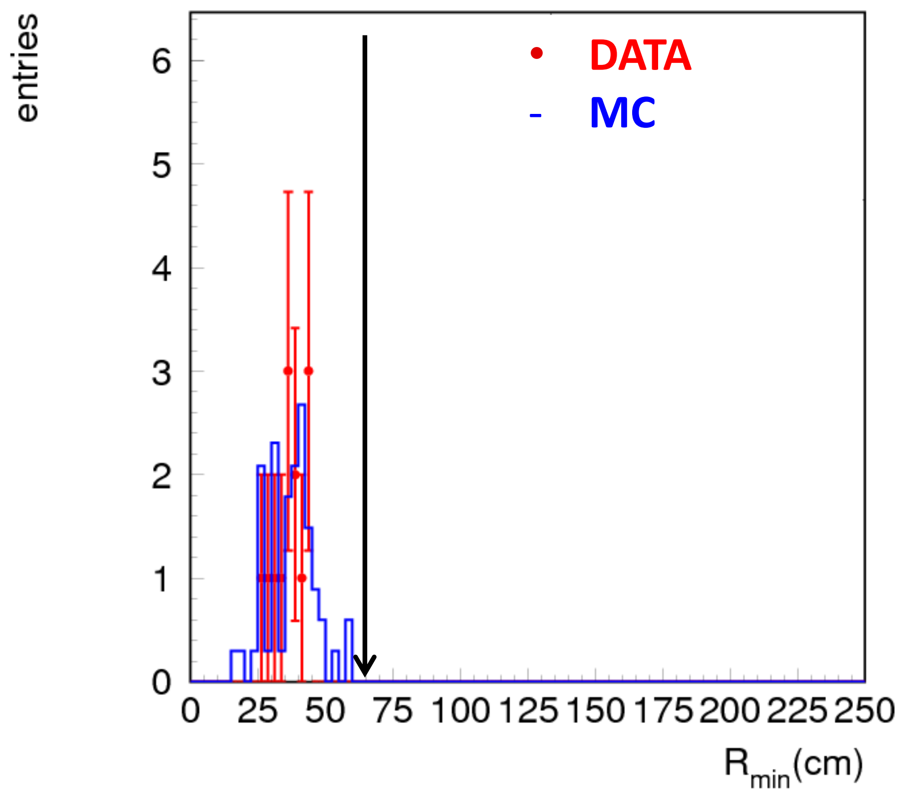


Results of the analysis

- At the end of the analysis we count N_{obs} **=0 events selected as a signal and** N_{exp}**=0 events in MC**



- Systematic error estimation:
  - ✓ Normalization sample selection
  - ✓ Background estimation
  - ✓ Signal selection

Results of the analysis

- ✓ **Normalization sample selection**

  (Acceptance, background filter)

- ✓ **Background estimation**

  (Energy scale and resolution of the calorimeter for data and simulations, variation of cuts on β_{cr}, E_{cr}, χ^2_{fit}, $\Delta E/\sigma_E$, R_{min})

- ✓ **Signal selection**

  (Acceptance, background filter, energy scale and resolution of the calorimeter for data and simulations, variation of cuts on χ^2_{fit}, $\Delta E/\sigma_E$, R_{min})

SOURCE	$\Delta\varepsilon_{2\pi}/\varepsilon_{2\pi}$ [%]	$\Delta\varepsilon_{3\pi}/\varepsilon_{3\pi}$ [%]
Acceptance	1.60	0.21
Background filter	0.46	0.30
Calorimeter energy scale	—	1.00
Calorimeter energy resolution	—	1.10
χ^2_{fit}	—	1.46
R_{min}	—	0.90
TOTAL	1.65	2.30

Summary & outlook

- At the end of the analysis we count N_{obs} **=0 events selected as a signal and** N_{exp}**=0 events in MC**
- The selection efficiency for $K_S \to 2\pi^0$ decay: $\varepsilon_{2\pi} = 0.660 \pm 0.002_{stat} \pm 0.010_{syst}$
- Normalization sample: $N_{2\pi} / \varepsilon_{2\pi} = (1.14130 \pm 0.00011) \cdot 10^8$
- The selection efficiency for $K_S \to 3\pi^0$ signal: $\varepsilon_{3\pi} = 0.233 \pm 0.012_{stat} \pm 0.006_{sys}$
- **The upper limit at 90% C.L. :**

$$BR(K_S \to 3\pi^0) = \frac{N_{3\pi}/\varepsilon_{3\pi}}{N_{2\pi}/\varepsilon_{2\pi}} \times BR(K_S \to 2\pi^0) < 2.64 \times 10^{-8}$$

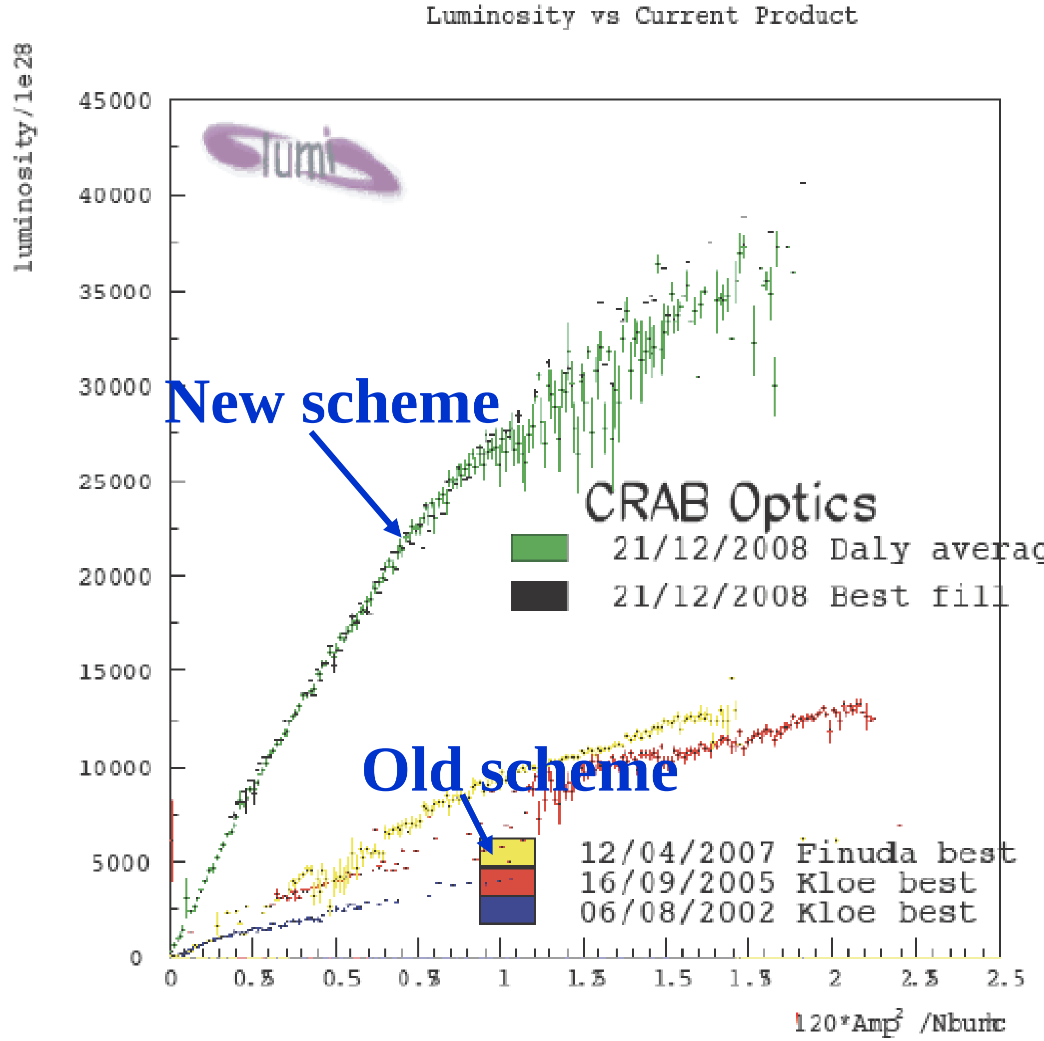
$$|\eta_{000}| = \sqrt{\frac{\tau_L\, BR(K_S \to 3\pi^0)}{\tau_S\, BR(K_L \to 3\pi^0)}} < 0.0088$$

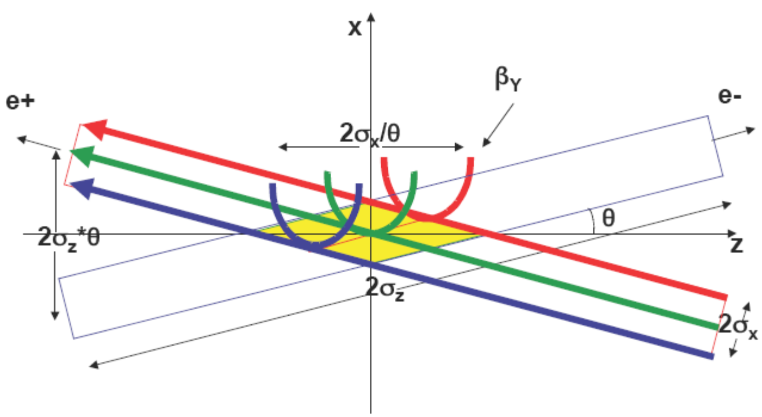
- **This result points to the feasibility of the first observation at KLOE-2**
- Future: KLOE-2 @ Upgraded DAΦNE

DAΦNE upgrade

New interaction scheme implemented: large beam crossing angle + sextupoles for crabbed waist optics

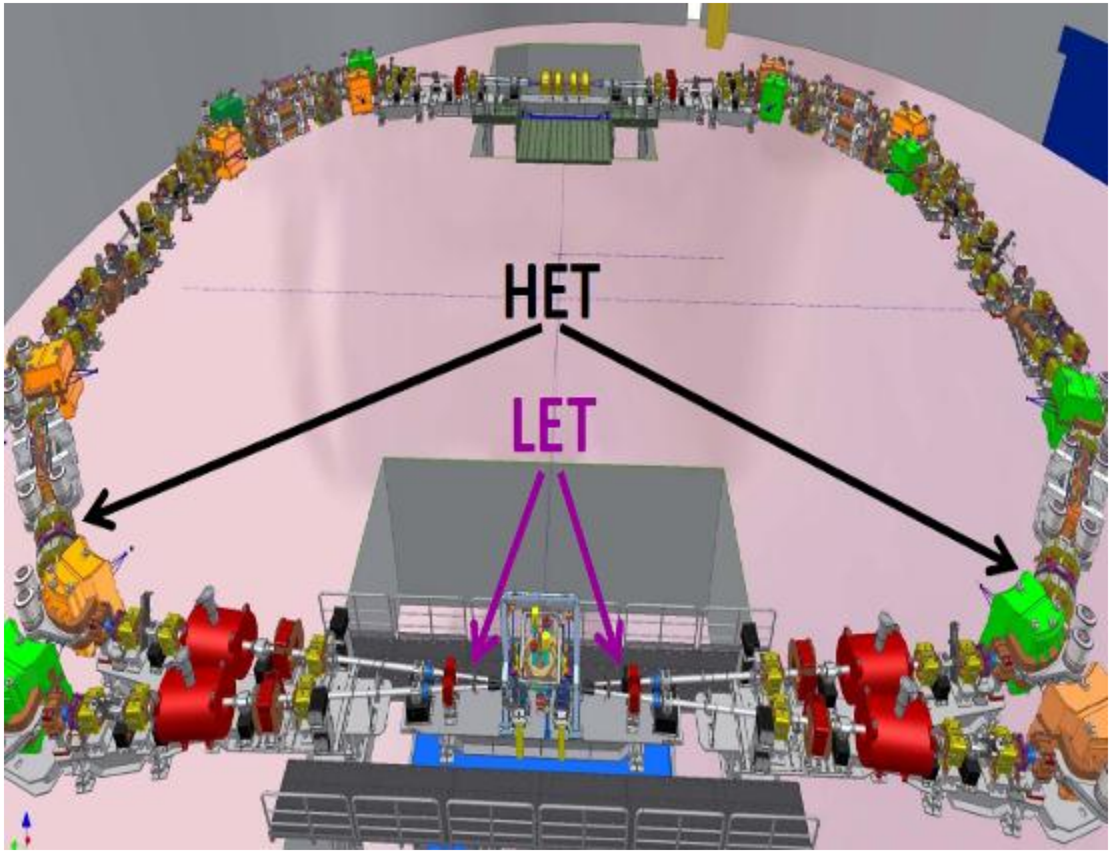
- **$L_{new} \sim 3 \times L_{old}$**
- **$\int L\,dt = 1\ pb^{-1}$/hour**





KLOE upgrades: $\gamma\gamma$ taggers

Measurement of leptons momenta in $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-X$



LET: E_e ~ 160-230 MeV

- **Inside KLOE detector**
- **LYSO+SiPM**
- **σ_E<10% for E>150 MeV**

HET: E_e > 400 MeV

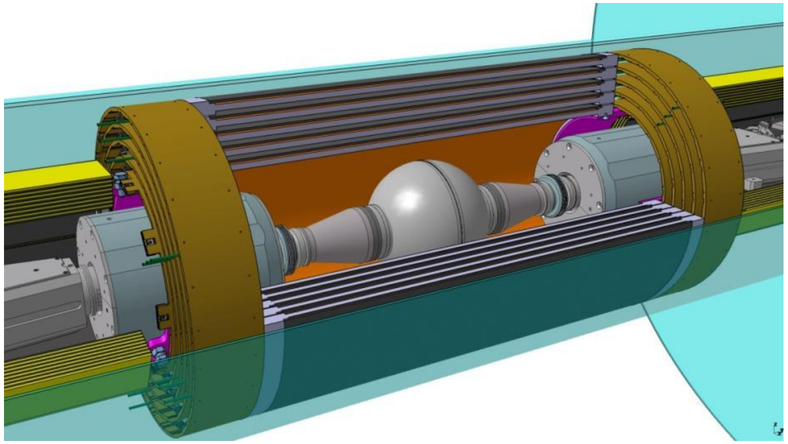
- **11 m from IP**
- **Scintillator hodoscopes**
- **σ_E ~ 2.5 MeV**
- **σ_T ~ 200 ps**

$\gamma\gamma$ taggers are installed and ready for the first KLOE-2 run

KLOE upgrades: IR detectors

INNER TRACKER

- 4 layers of cylindrical triple GEM
- Better vertex reconstruction near IP
- Larger acceptance for low p_t tracks

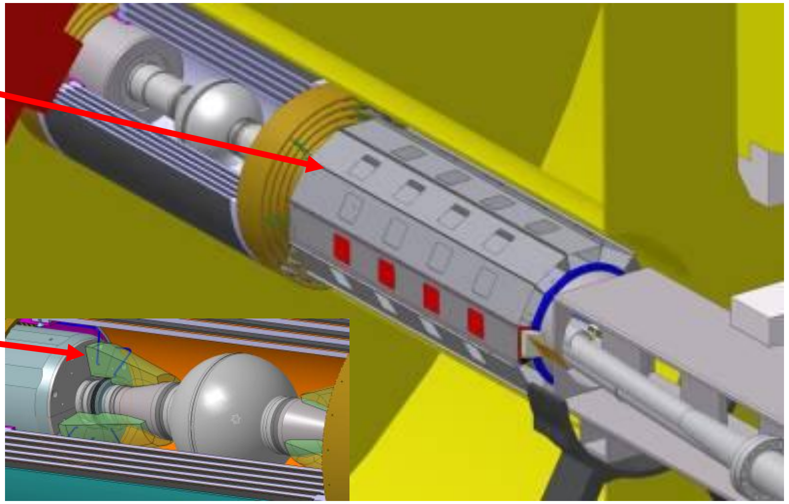


QCALT

- W + scintillator tiles + SiPM/WLS
- Low-beta quadrupoles: coverage for K_L decays

CCALT

- LYSO + APD
- Increase acceptance for γ's from IP (21° →10°)



Increasing the statistics and acceptance of the detector while significantly reducing the background gives the realistic chances to observe the $K_S \rightarrow 3\pi^0$ decay for the first time in the near future.

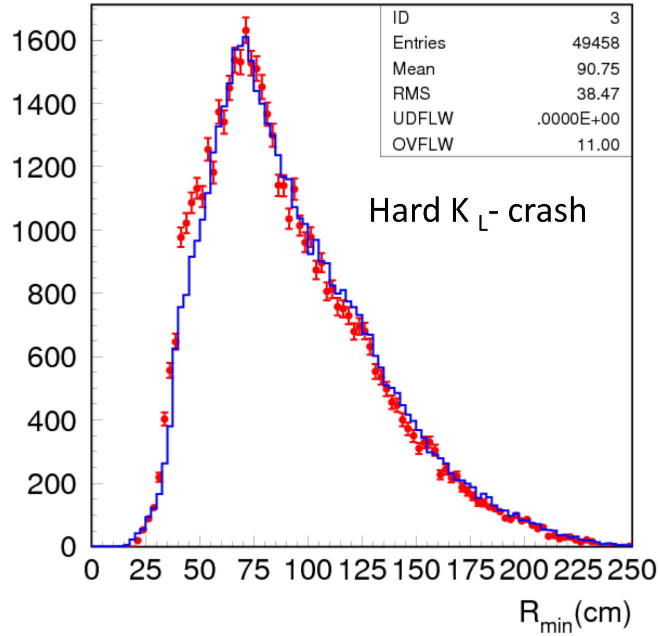
THANK YOU

FOR

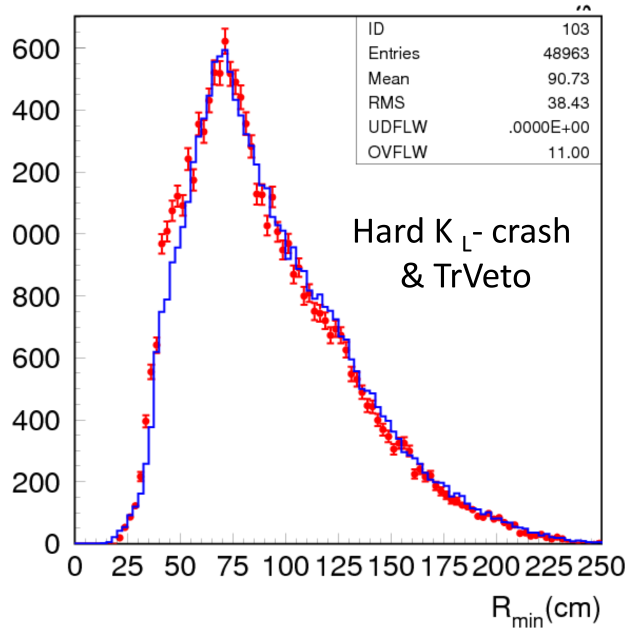
ATTENTION

SPARES

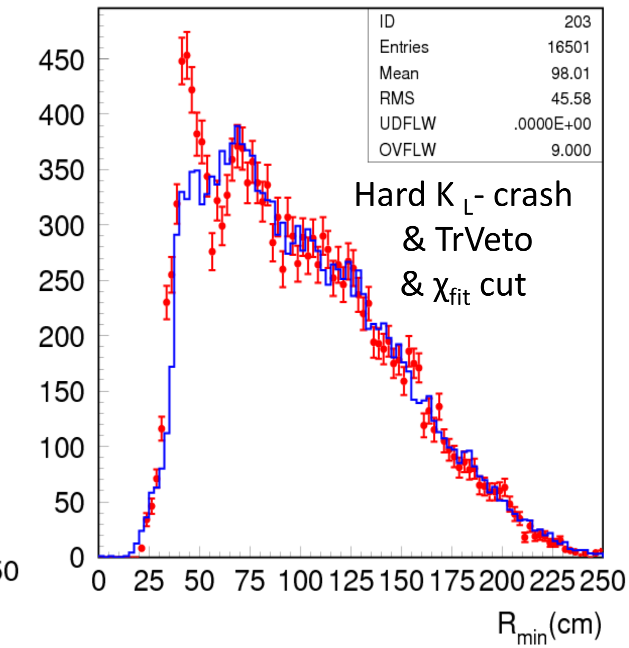
R_{min}



ID 3
Entries 49458
Mean 90.75
RMS 38.47
UDFLW .0000E+00
OVFLW 11.00
Hard K L- crash
R min (cm)



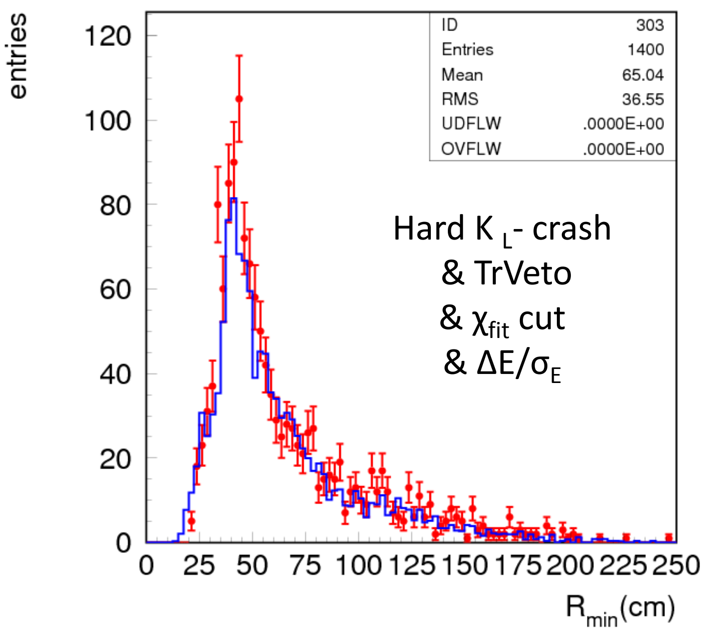
ID 103
Entries 48963
Mean 90.73
RMS 38.43
UDFLW .0000E+00
OVFLW 11.00
Hard K L- crash
& TrVeto
R min (cm)



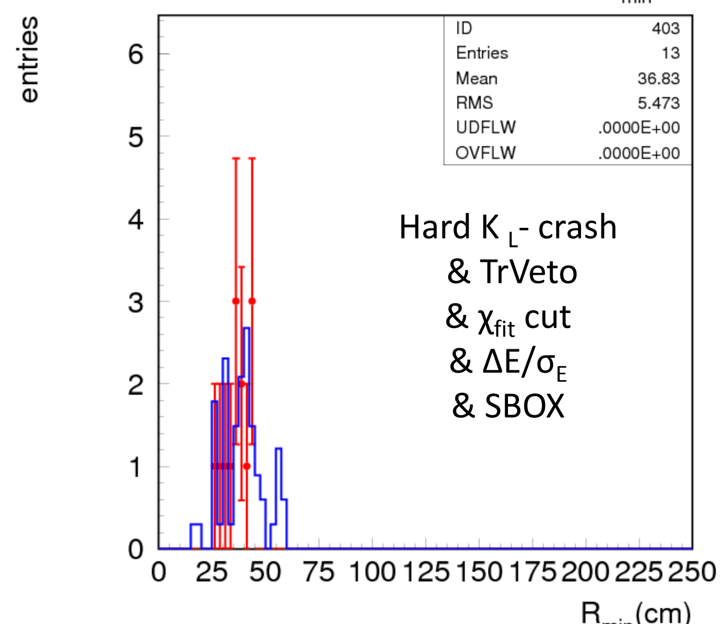
ID 203
Entries 16501
Mean 98.01
RMS 45.58
UDFLW .0000E+00
OVFLW 9.000
Hard K L- crash
& TrVeto
& χfit cut
R min (cm)

• DATA

\- MC

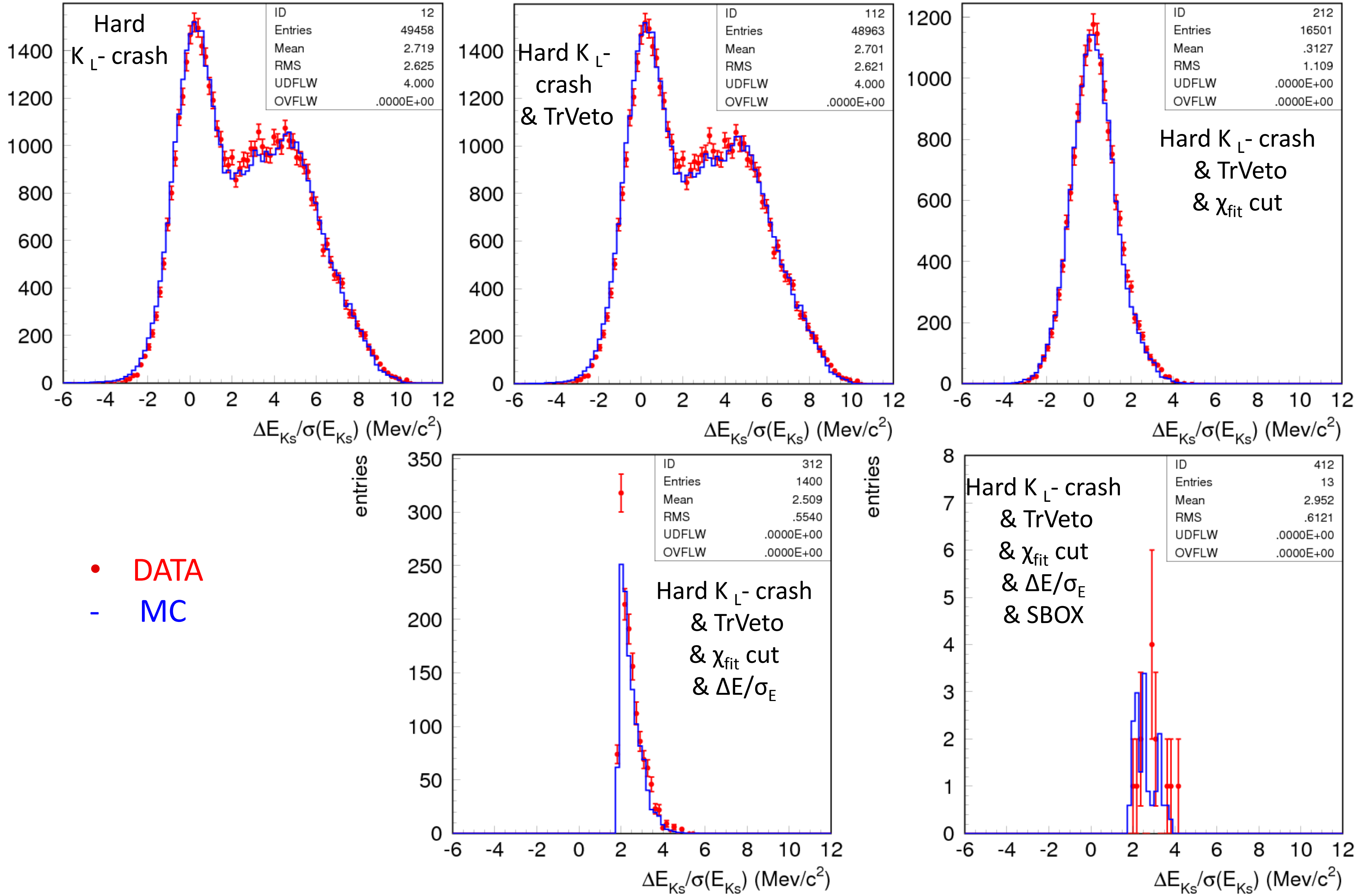


entries
ID 303
Entries 1400
Mean 65.04
RMS 36.55
UDFLW .0000E+00
OVFLW .0000E+00
Hard K L- crash
& TrVeto
& χfit cut
& ΔE/σE
R min (cm)

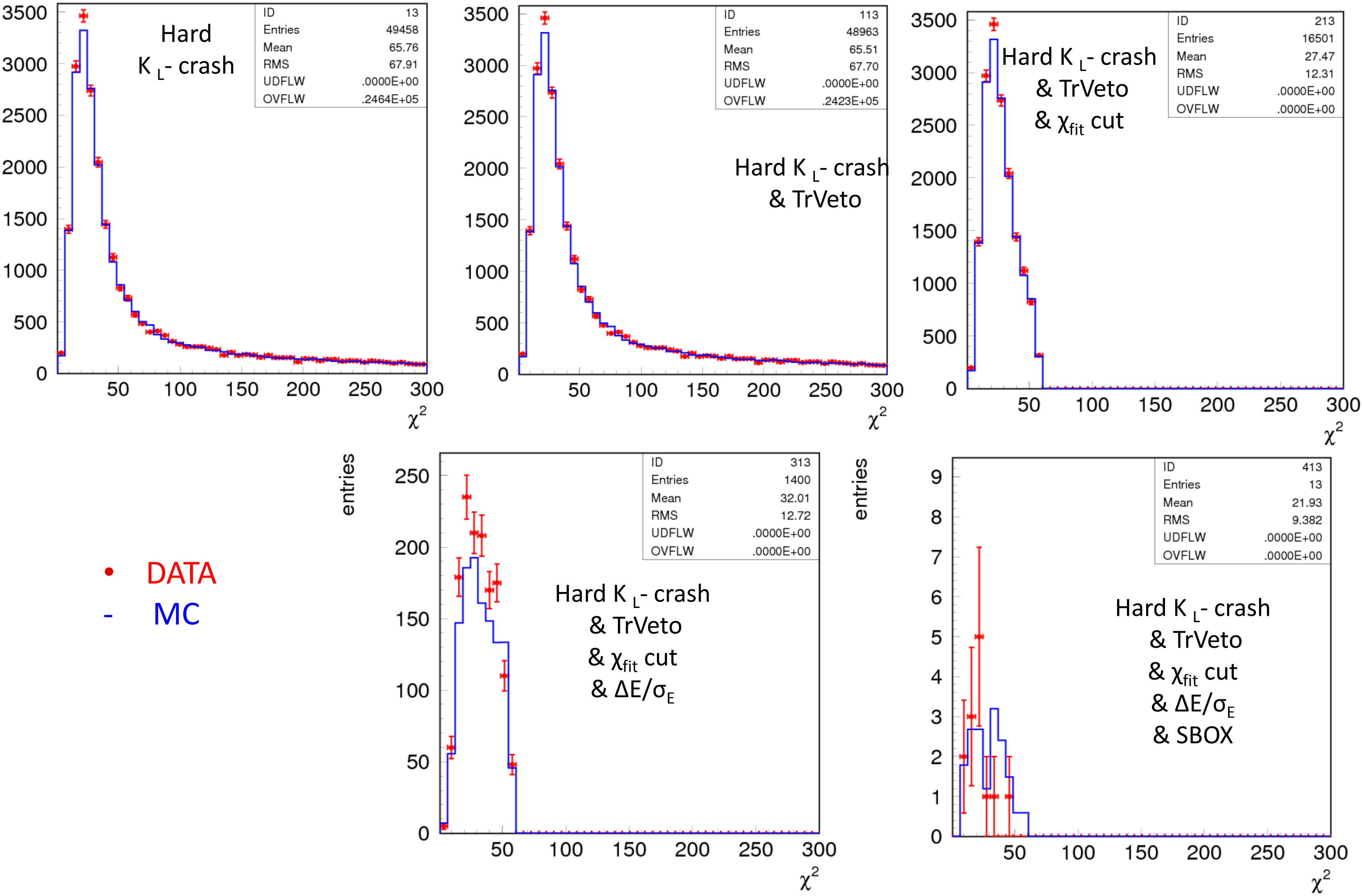


entries
ID 403
Entries 13
Mean 36.83
RMS 5.473
UDFLW .0000E+00
OVFLW .0000E+00
Hard K L- crash
& TrVeto
& χfit cut
& ΔE/σE
& SBOX
R min (cm)

$\Delta E/\sigma_E$

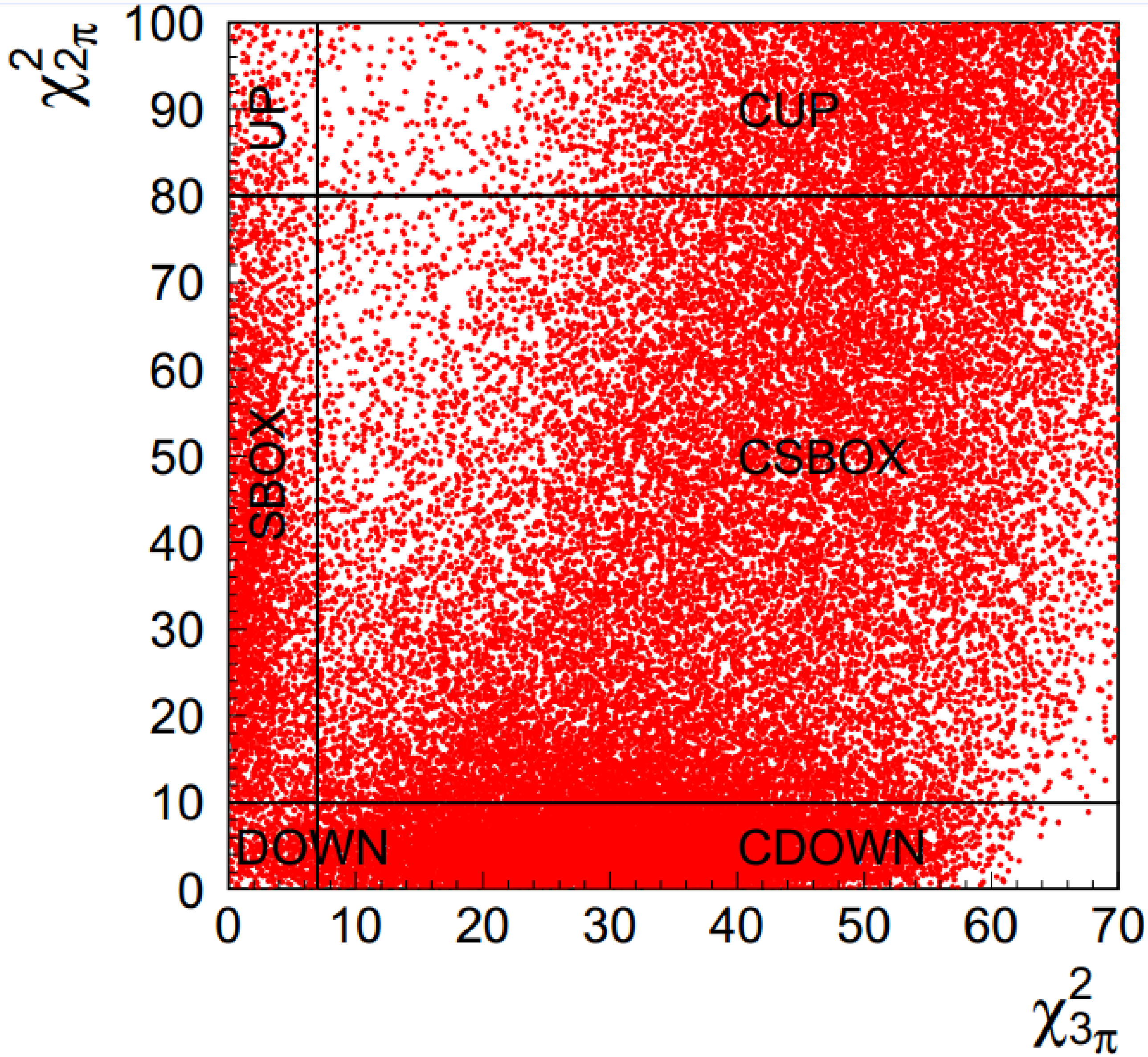


$\chi^2{}_{fit}$



ID 13
Entries 49458
Mean 65.76
RMS 67.91
UDFLW .0000E+00
OVFLW .2464E+05
Hard K L- crash
ID 113
Entries 48963
Mean 65.51
RMS 67.70
UDFLW .0000E+00
OVFLW .2423E+05
Hard K L- crash & TrVeto
ID 213
Entries 16501
Mean 27.47
RMS 12.31
UDFLW .0000E+00
OVFLW .0000E+00
Hard K L- crash & TrVeto & χfit cut
ID 313
Entries 1400
Mean 32.01
RMS 12.72
UDFLW .0000E+00
OVFLW .0000E+00
Hard K L- crash & TrVeto & χfit cut & ΔE/σE
ID 413
Entries 13
Mean 21.93
RMS 9.382
UDFLW .0000E+00
OVFLW .0000E+00
Hard K L- crash & TrVeto & χfit cut & ΔE/σE & SBOX
entries
χ2
• DATA
- MC

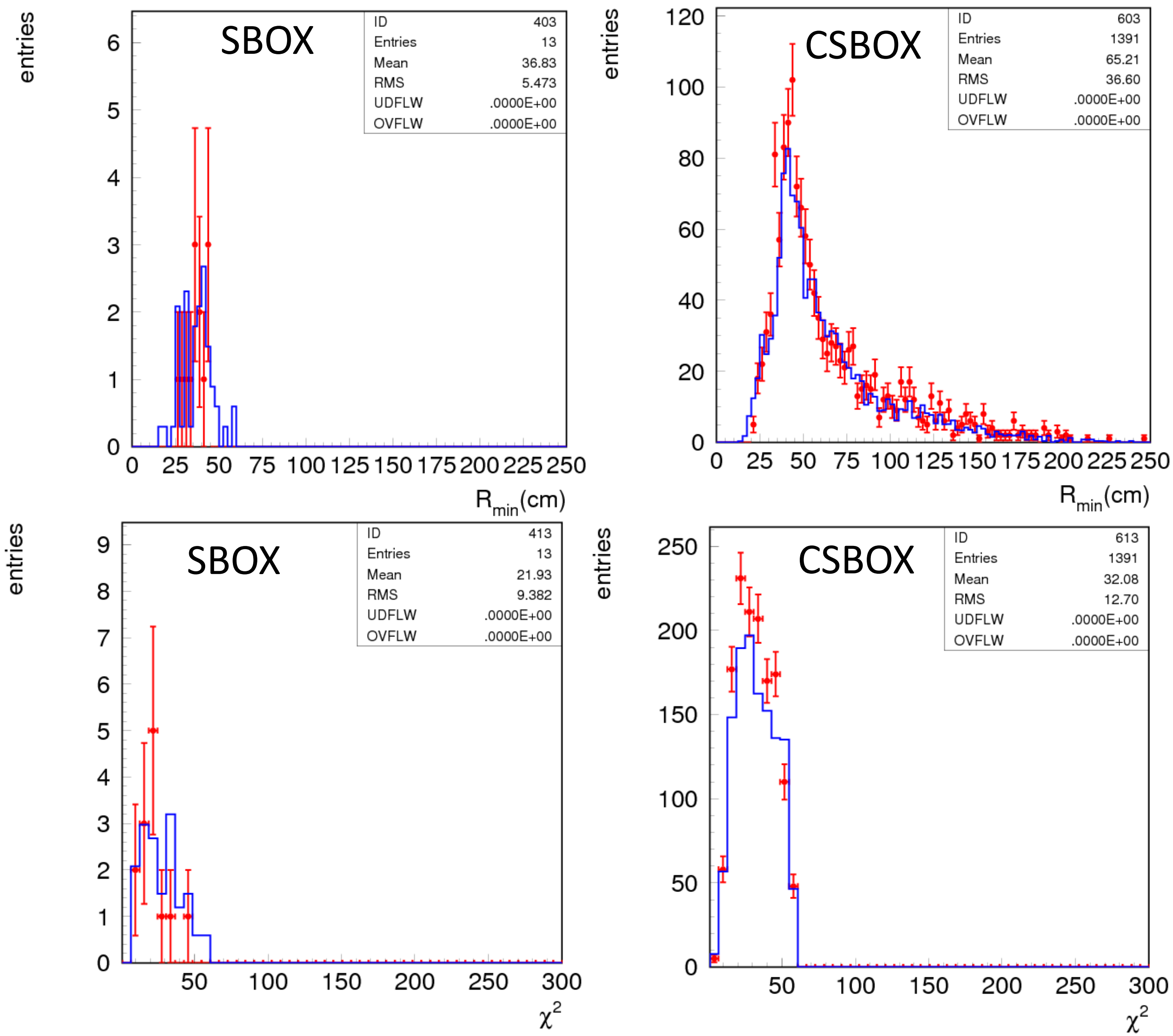
Distributions in the $\chi^2_{2\pi}$ vs $\chi^2_{3\pi}$ boxes



$\chi^2_{2\pi}$ vs $\chi^2_{3\pi}$ boxes: Hard K_L - crash & TrV & χ_{fit} cut & $\Delta E/\sigma_E$

(Only SBOX and CSBOX control regions are populated at this stage of analysis)

- • DATA
- \- MC



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:

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

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

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

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

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

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

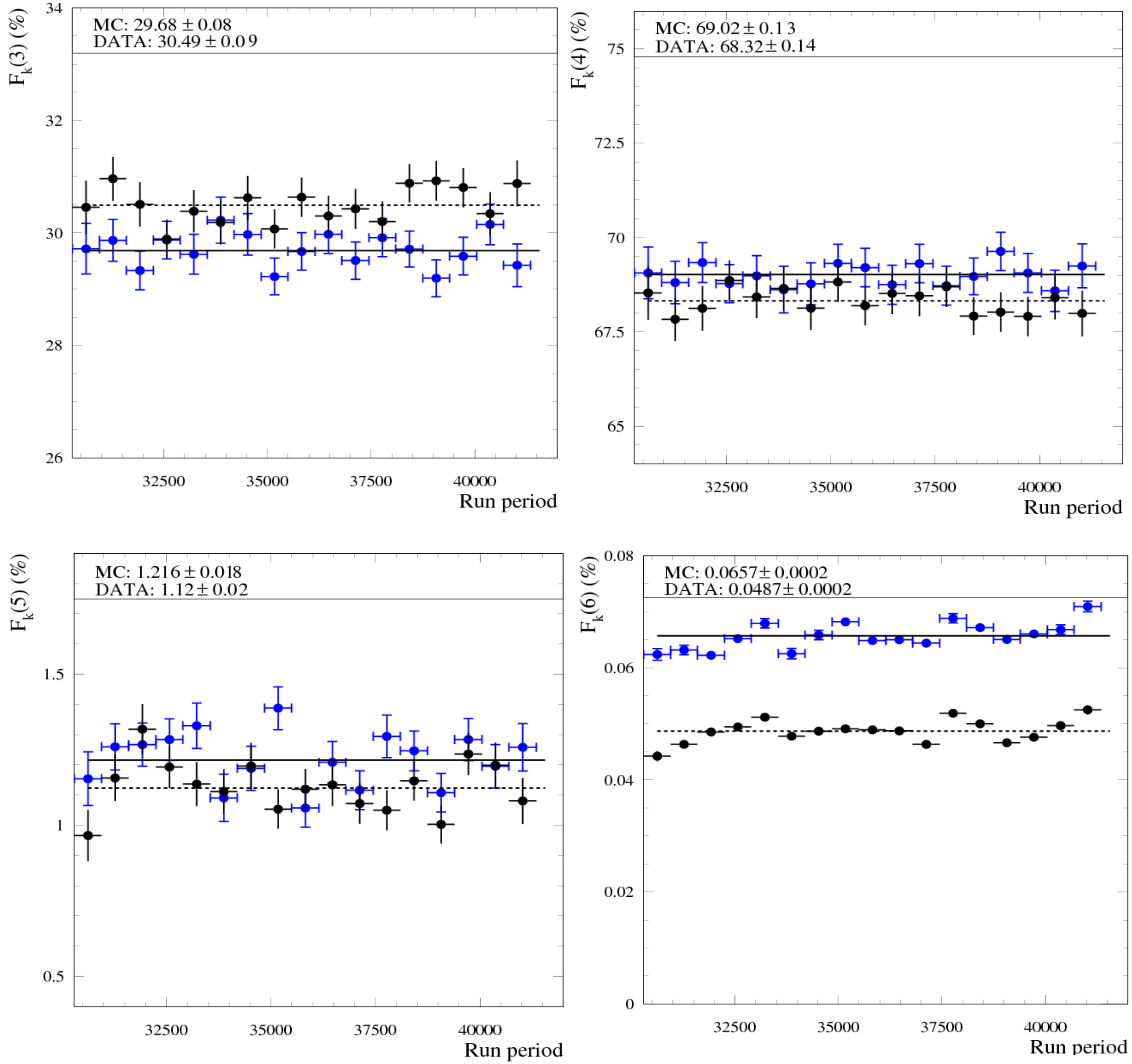
$$+ \frac{(P^x_{K_S} - \sum P^x_{\gamma_i})^2}{\sigma^2_{P^x}} + \frac{(P^y_{K_S} - \sum P^y_{\gamma_i})^2}{\sigma^2_{P^y}} + \frac{(P^z_{K_S} - \sum P^z_{\gamma_i})^2}{\sigma^2_{P^z}} + \frac{(\pi - \vartheta_{\pi\pi})^2}{\sigma^2_{\vartheta_{\pi\pi}}}$$

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

Background studies

- DATA
- MC

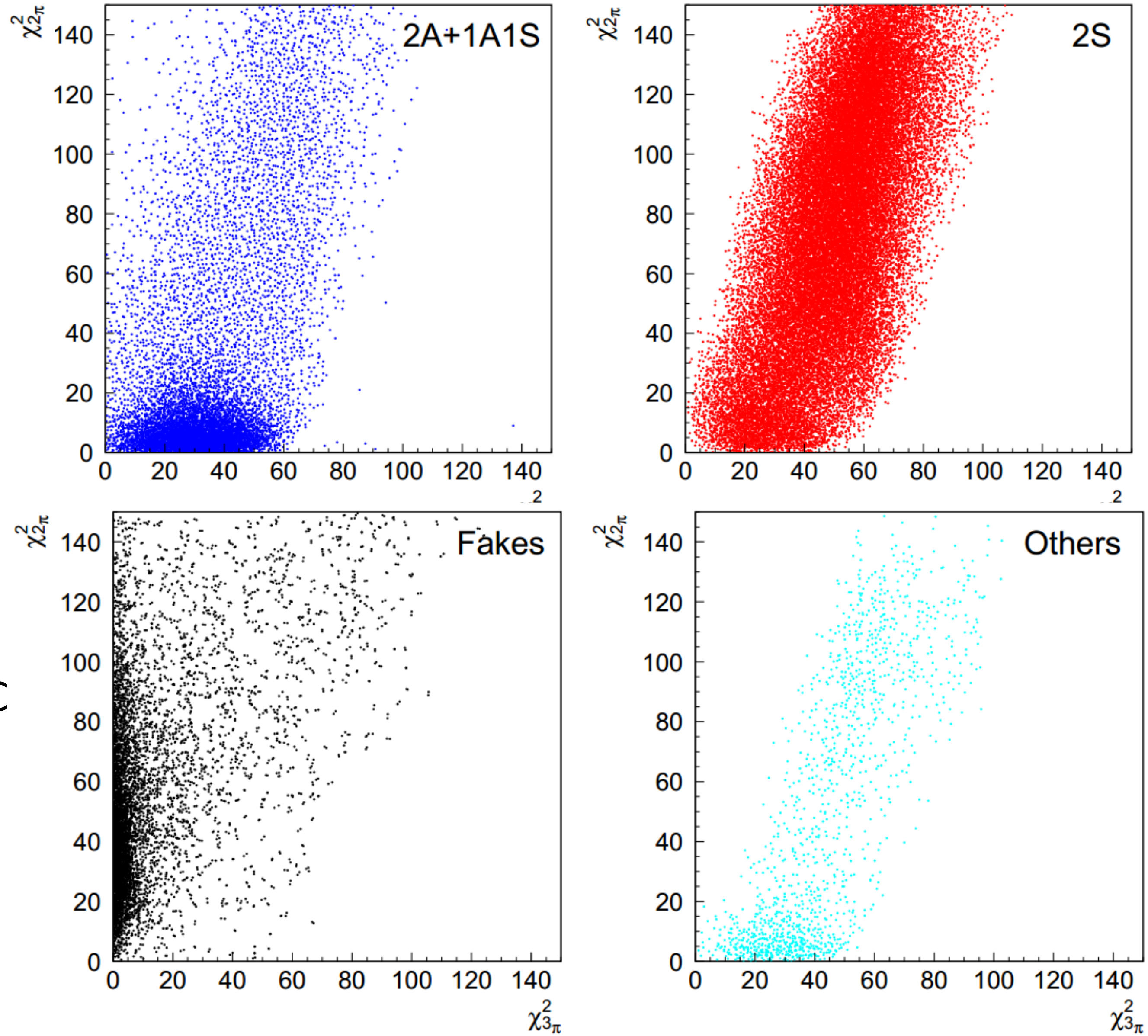
$$F_k = \frac{N_{ev}(N_\gamma = k)}{\sum_{i=3}^{6} N_{ev}(N_\gamma = i)}$$



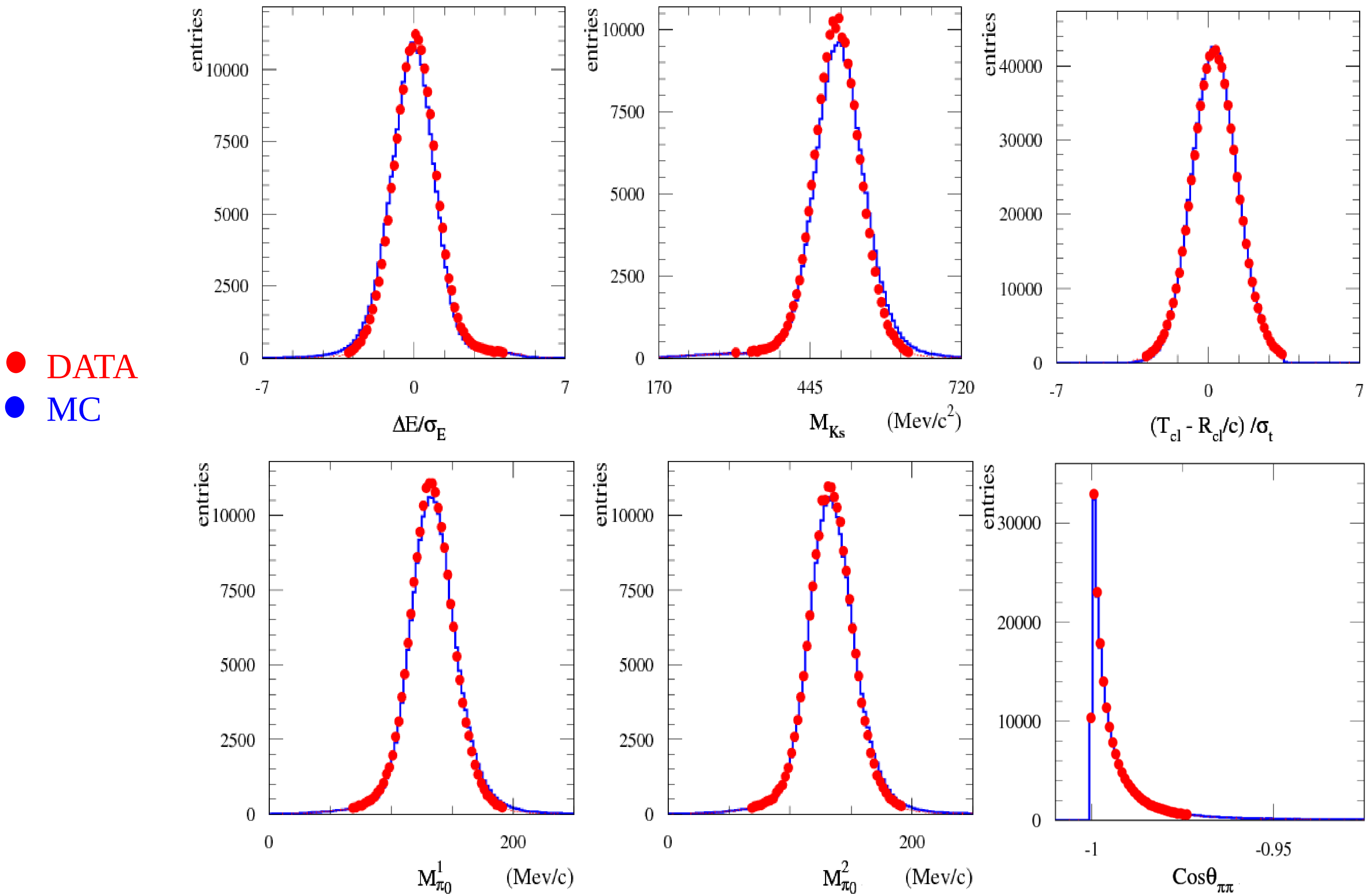
Monte Carlo calibration

- 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



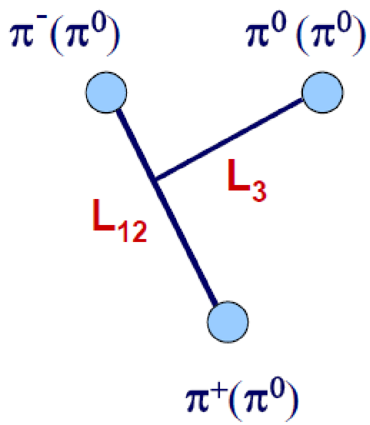
Monte Carlo calibration



Introduction

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

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



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

$$\mathbf{CP(\pi^0\pi^0) = 1}$$

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

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

- 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

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

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

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

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