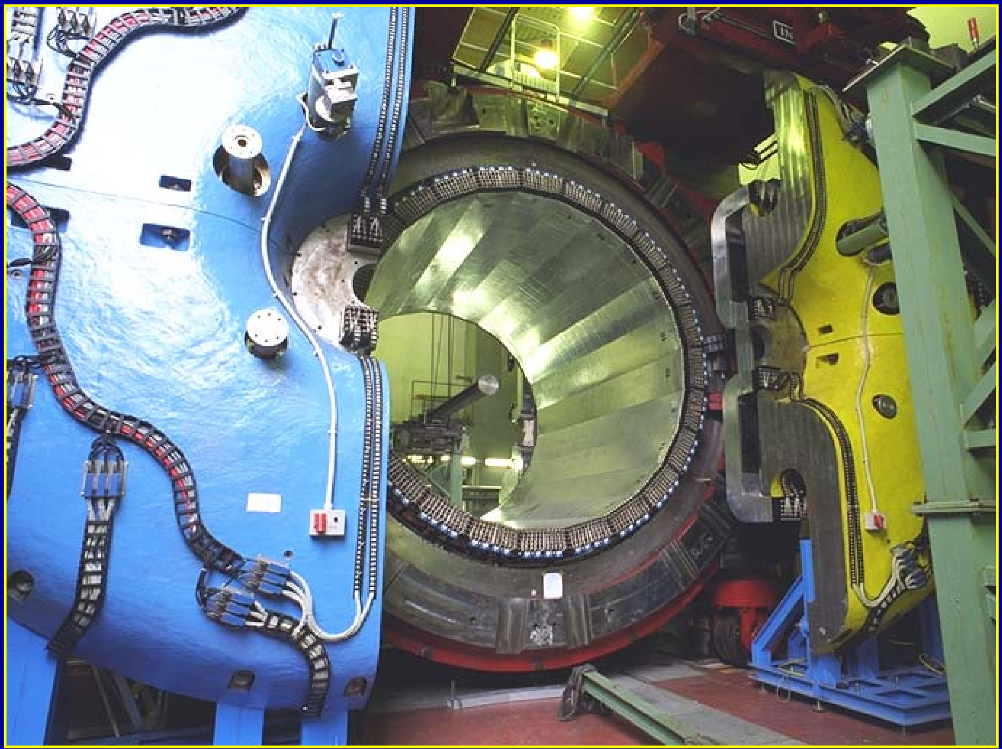
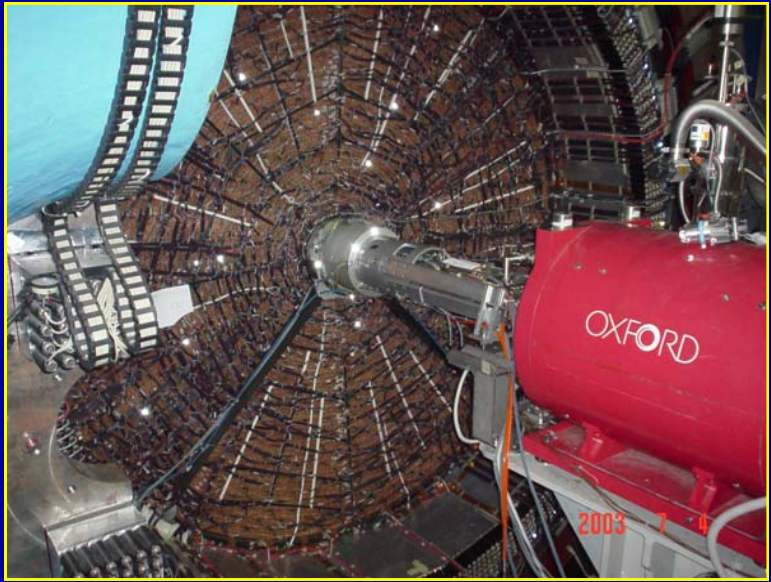
Recent results from KLOE at DAΦNE





Barbara Sciascia
INFN Laboratori Nazionali di Frascati
representing the KLOE Collaboration

KLOE: physics at a ϕ - factory

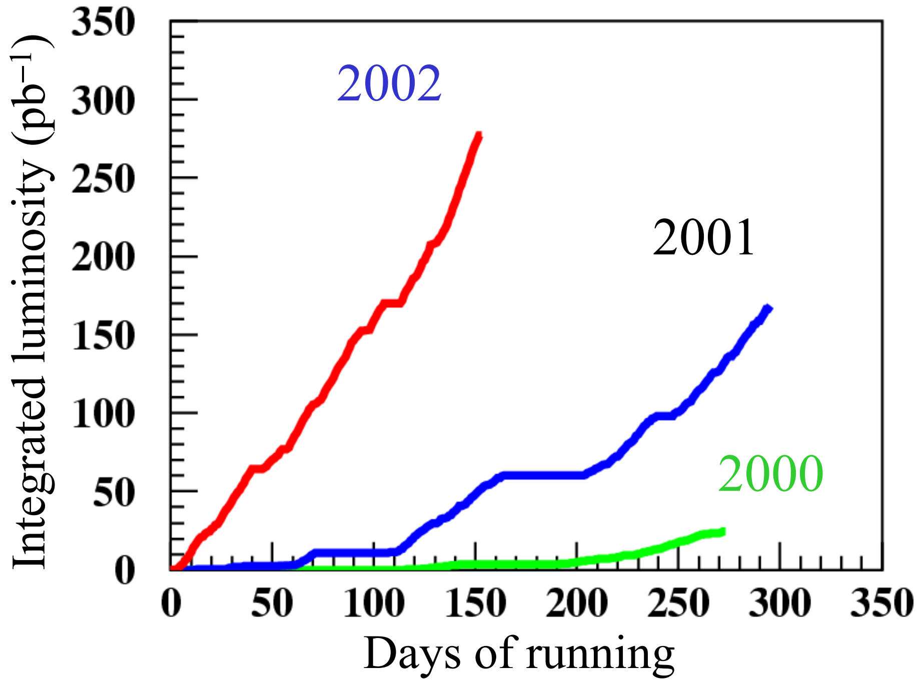
Kaon physics

- CP: double ratio/interferometry
- CPT tests: **semileptonic K_S**, K_L charge asymmetries
- **V_{us}** : kaon form factors from semileptonic $K_{S,L}$,$K^{\pm}$ decays
- Rare $K_{S,L}$ decays: **$K_S \rightarrow 3\pi^0$**, $\pi^+\pi^-\pi^0$, $K_L \rightarrow \gamma\gamma$

Non Kaon Physics

- radiative ϕ decays (scalars,pseudoscalars + photon)
- $\rho\pi$ final states
- rare η decays
- **hadronic cross section: see D.Leone talk**

KLOE data taking



2000: 25 pb^{-1}

$80 \bullet 10^6$ ϕ decays

First published results

2001: 176 pb^{-1}

$550 \bullet 10^6$ ϕ decays

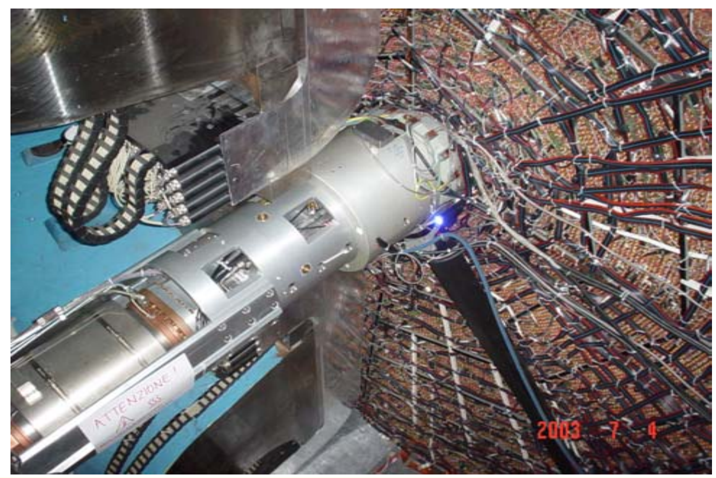
2002: 296 pb^{-1}

$920 \bullet 10^6$ ϕ decays

Analysis in progress

Goal for 2004-5: L > 1 fb^{-1}

- New interaction region
- Injection efficiency improved
- Wiggler magnets modified



The KLOE detector

- **Al-Be beam pipe**

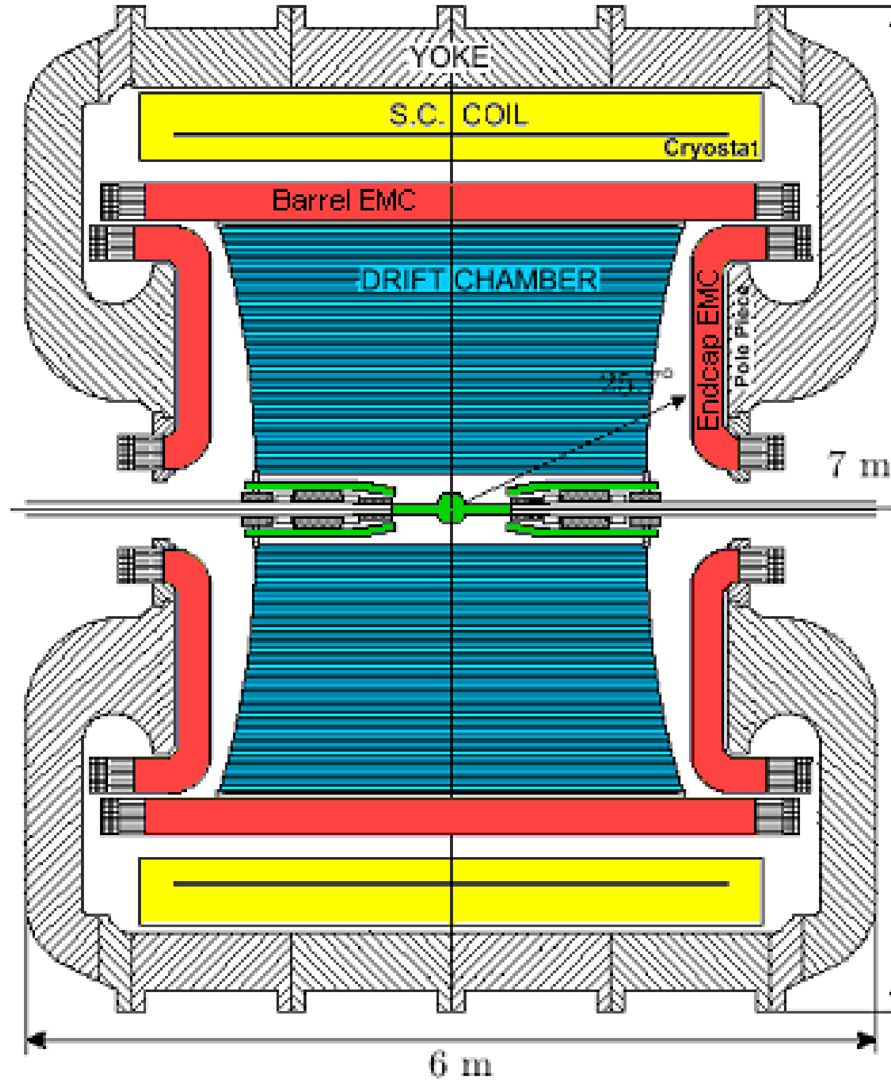
(spherical, 10 cm ∅, 0.5 mm thick)

- **Instrumented permanent magnet quadrupoles** (32 PMT's)

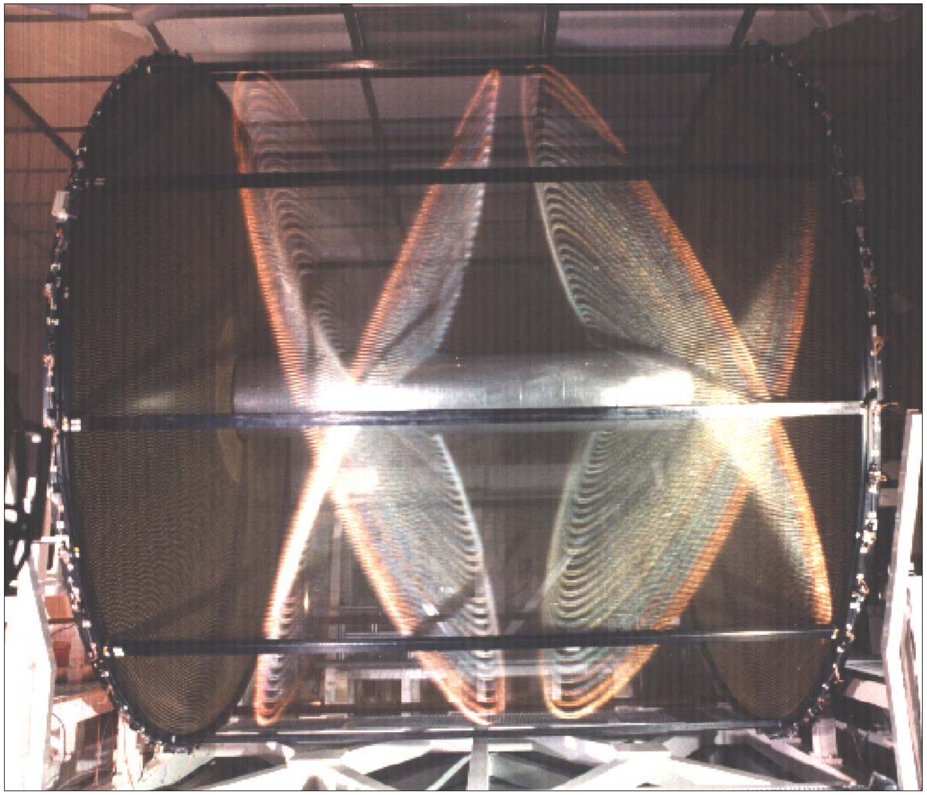
- **Drift chamber**
  - Gas mixture: 90% He + 10% C_4H_{10}
  - 4 m ∅ × 3.75 m, CF frame
  - 12582 stereo–stereo sense wires
  - almost squared cells

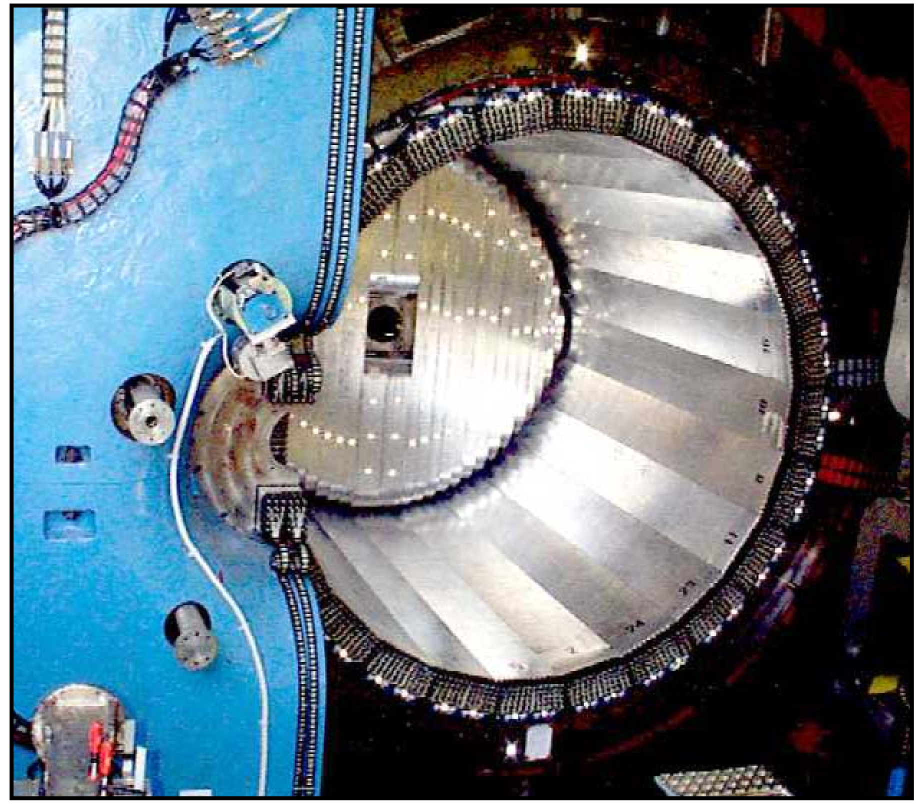
- **Electromagnetic calorimeter**
  - lead/scintillating fibers (1 mm ∅), 15 X_0
  - 4880 PMT's
  - 98% solid angle coverage

- **Superconducting coil** (B = 0.52 T)



Detector performance





$\sigma_p/p = 0.4\ \%$ (tracks with $\theta > 45°$)
$\sigma_x^{hit} = 150\ \mu m\ (xy),\ 2\ mm\ (z)$
$\sigma_x^{vertex} \sim 1\ mm$
$\sigma(M_{\pi\pi}) \sim 1\ MeV$

$\sigma_E/E = 5.7\% / \sqrt{E(GeV)}$
$\sigma_t = 54\ ps / \sqrt{E(GeV)} \oplus 50\ ps$
$\sigma_{vtx}(\gamma\gamma) \sim 1.5\ cm$ (π^0 from $K_L \to \pi^+\pi^-\pi^0$)

Kaon properties

Production:

$K_S K_L$ (K^+K^-) produced in pure $J^{PC} = 1^{--}$ state:

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

Observation of $\boldsymbol{K_{S,L}}$ signals presence of $\boldsymbol{K_{L,S}}$

$$\frac{1}{\sqrt{2}}\left(|K_L,\mathbf{p}\rangle|K_S,-\mathbf{p}\rangle - |K_L,-\mathbf{p}\rangle|K_S,\mathbf{p}\rangle\right)$$

Allows precision measurement of absolute BR's

Allows interference measurements of $K_S K_L$ system

Properties:

λ_S **= 6 mm:** K_S decays near interaction point

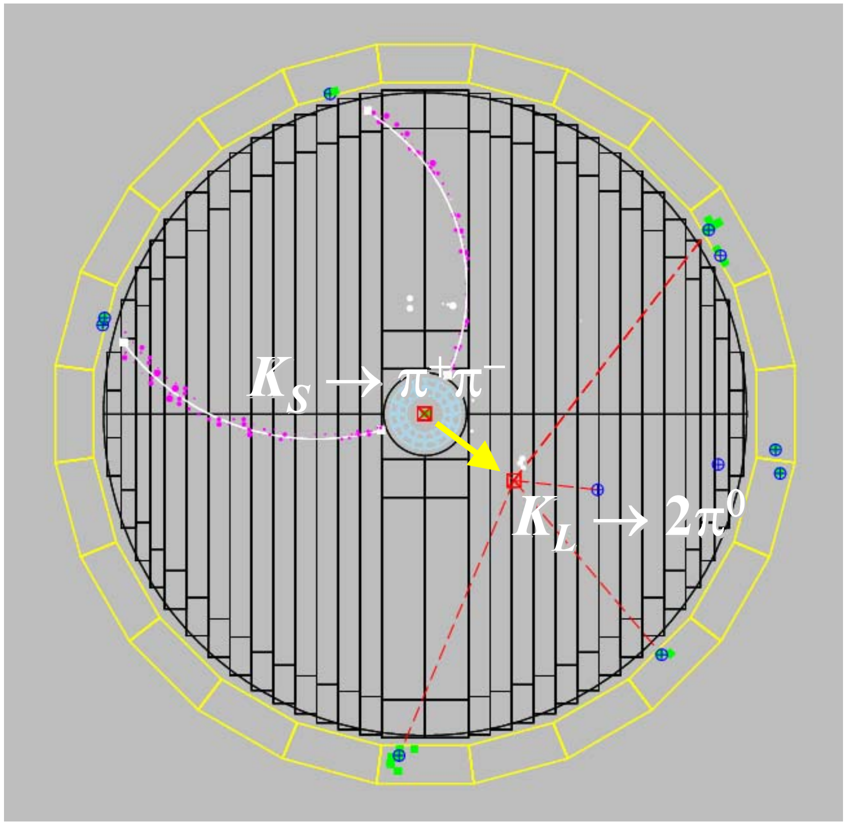
λ_L **= 3.4 m:** Appreciable acceptance for K_L ($\sim 0.5\lambda_L$)

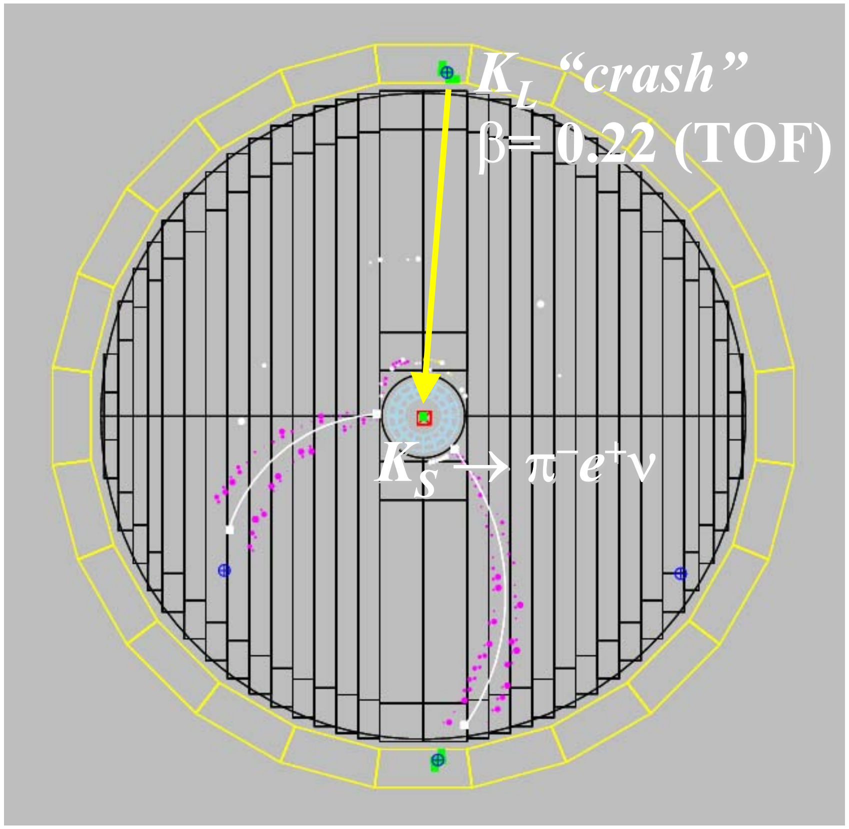
$N_{SL} \sim 10^6$ /pb^{-1} ; p* = 110 MeV/c

$\lambda_\pm$ **= 0.9 m:** 60% acceptance for kaon tracking

$N_{+-} \sim 1.5\times10^6$ /pb^{-1} ; p* = 127 MeV/c

Tagging of K_S and K_L "beams"





K_L tagged by $K_S \to \pi^+\pi^-$ vertex at IP
Efficiency ~ 70% (mainly geometrical)
K_L angular resolution: ~ 1°
K_L momentum resolution: ~ 1 MeV

K_S tagged by K_L interaction in EmC
Efficiency ~ 30% (largely geometrical)
K_S angular resolution: ~ 1° (0.3° in ϕ)
K_S momentum resolution: ~ 1 MeV

$K_S \to \pi^0\pi^0\pi^0$ – Test of CP and CPT

- **Observation of $K_S \to 3\pi^0$ signals CP violation in mixing and/or in decay:**

  SM prediction: $\Gamma_S = \Gamma_L|\varepsilon|^2$, giving $BR(K_S \to 3\pi^0) = 1.9\ 10^{-9}$

  Present published results: $BR(K_S \to 3\pi^0) < 1.4\ 10^{-5}$ (90% CL)

- **Uncertainty on $K_S \to 3\pi^0$ amplitude limits precision of CPT test:**

  from unitarity:

$$(1 + i \tan\phi_{SW})\mathrm{Re}\,\varepsilon - \Sigma_f A^*(K_S \to f)\, A(K_L \to f)/\Gamma_S = (-i + \tan\phi_{SW})\,\mathrm{Im}\,\delta$$

$(\varepsilon_{S,L} = \varepsilon \pm \delta)$

- **A limit on $BR(K_S \to 3\pi^0)$ at 10^{-7} level translates into a 2.5-fold improvement on the accuracy of Im δ ($5\times10^{-5} \to 2\times10^{-5}$), *i.e.***

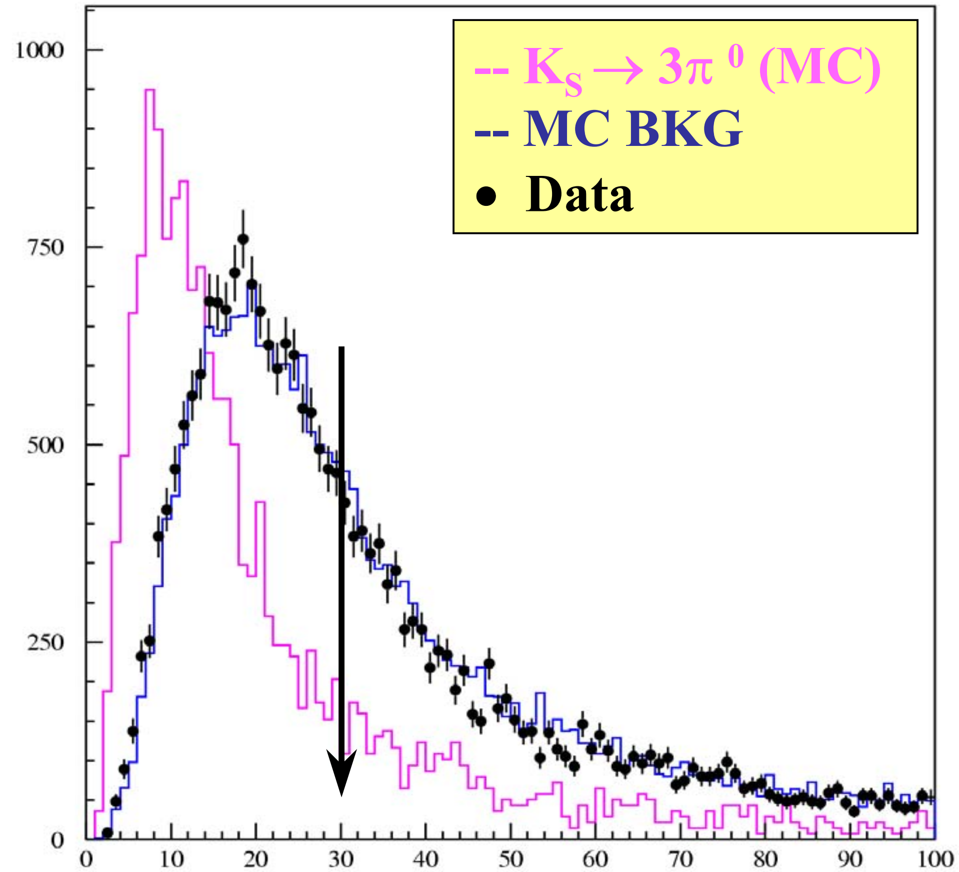
$$\frac{\delta(M_{K0} - M_{\overline{K0}})}{M_K} \sim 5\ 10^{-19}$$

$(\Gamma_{K0} = \Gamma_{\overline{K0}}$ assumed $)$

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

- K_S's tagged by K_{crash} identification ($1.5 \cdot 10^8$ events)
- 6 photons (neutral clusters, TOF consistent with $\beta = 1$)
- No charged tracks from IP
- Kinematic fit:

> • Impose K_S mass and energy-momentum conservation, $\beta = 1$ for each γ
>
> • Estimate E_γ, $\mathbf{r}_\gamma$, t_γ, $\sqrt{s}$, p_ϕ



χ^2_{Fit}

Rejection power of χ^2_{fit} not sufficient to eliminate main background due to $\mathbf{K_S \to \pi^0\pi^0 + 2}$ **fake** γ**'s**

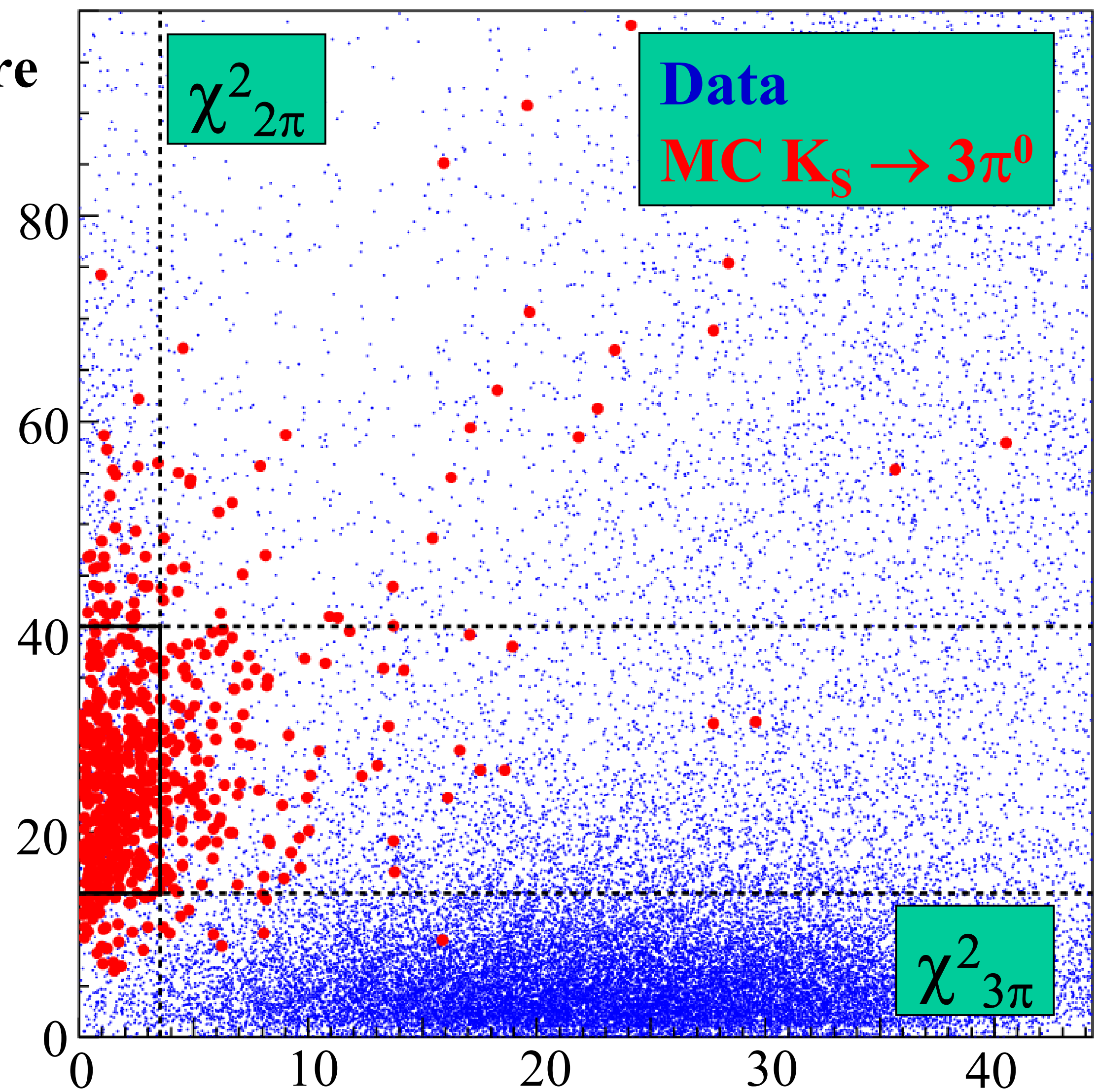
Search for $K_S \to \pi^0\pi^0\pi^0$ – $2\pi^0$ vs $3\pi^0$

To reject background compare 3π *vs* 2π hypotheses :

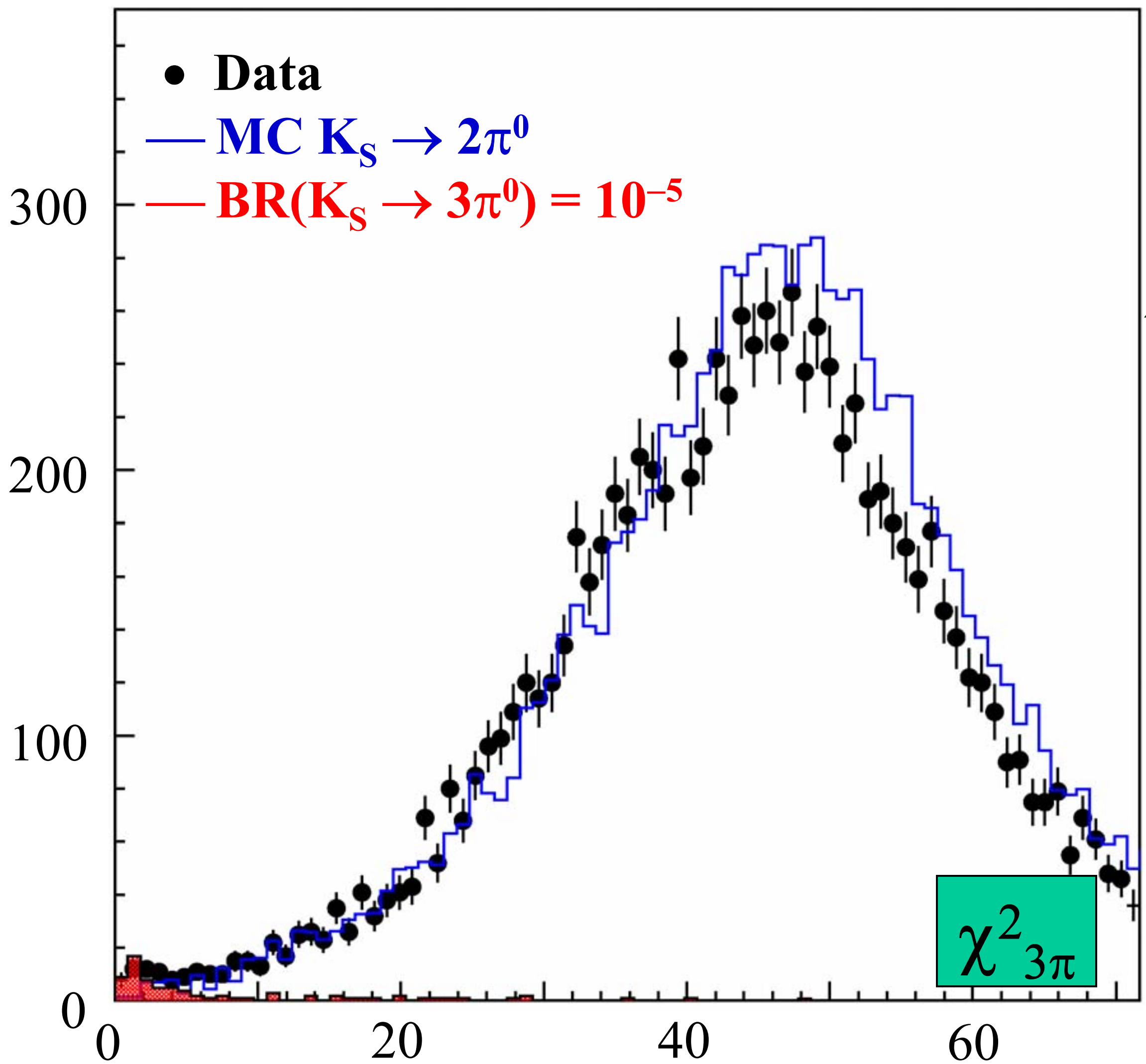
$\chi^2_{3\pi}$ – pairing of 6γ clusters with best π^0 mass estimates

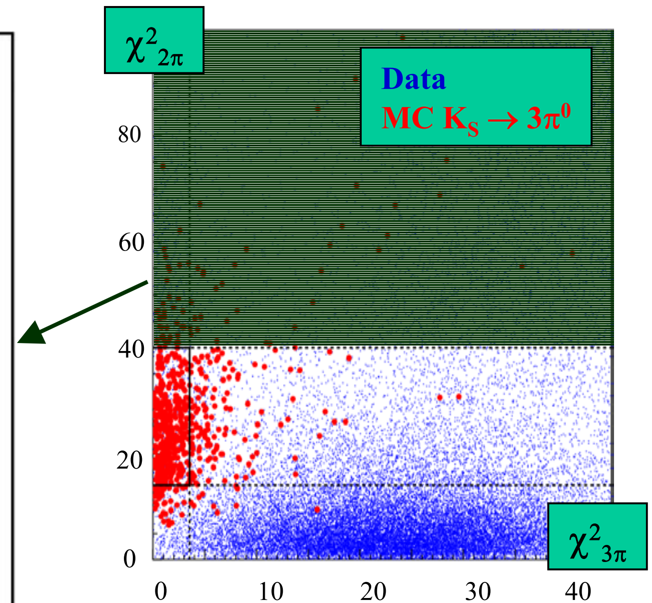
$\chi^2_{2\pi}$ – best pairing of 4γ's out of 6: π^0 masses, $E(K_S)$, $P(K_S)$, c.m. angle between π^0's

Definition of the signal box obtained from analysis of 6-pb^{-1}-equivalent MC subsample



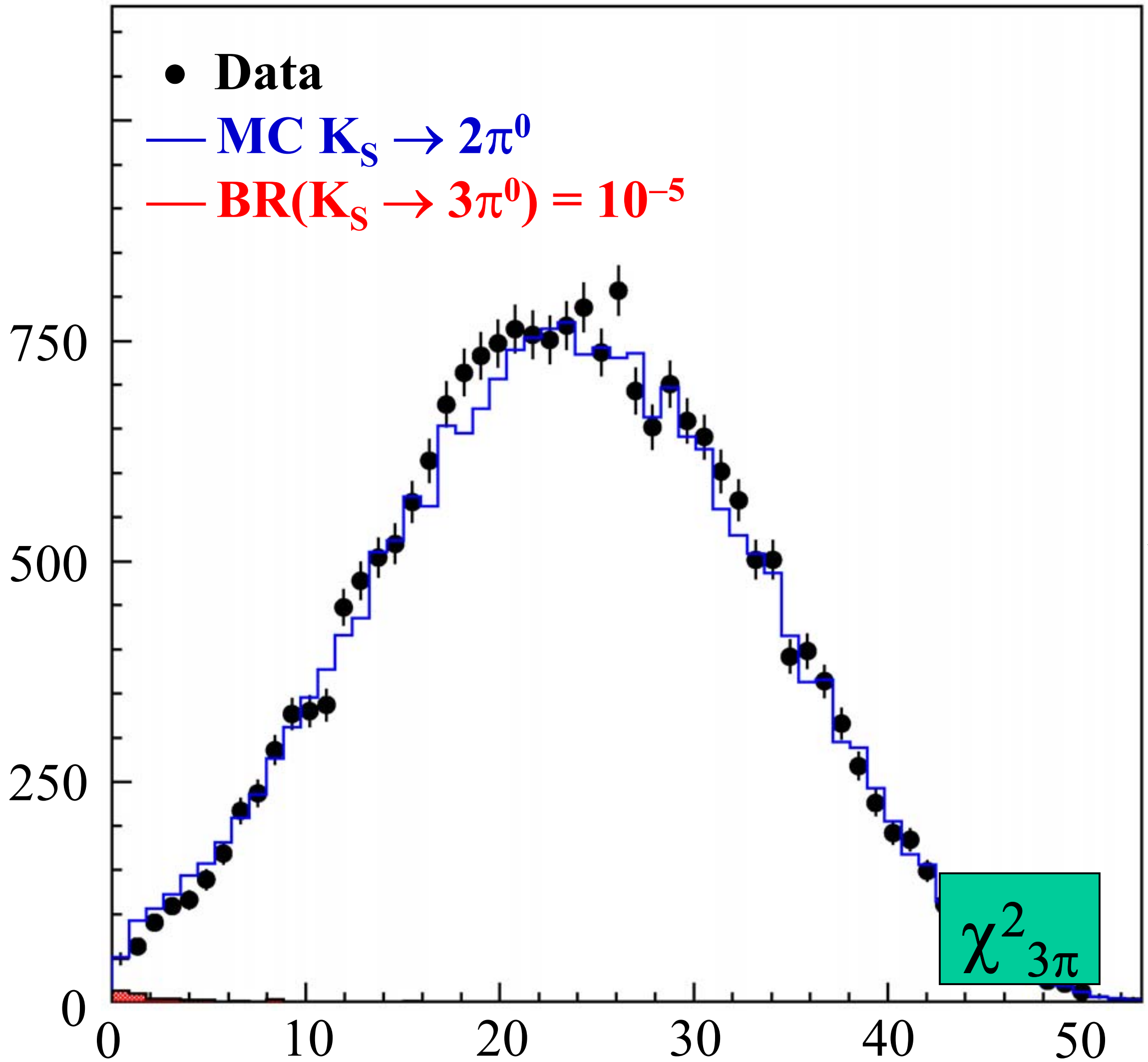
Search for $K_S \to \pi^0 \pi^0 \pi^0$ - sidebands

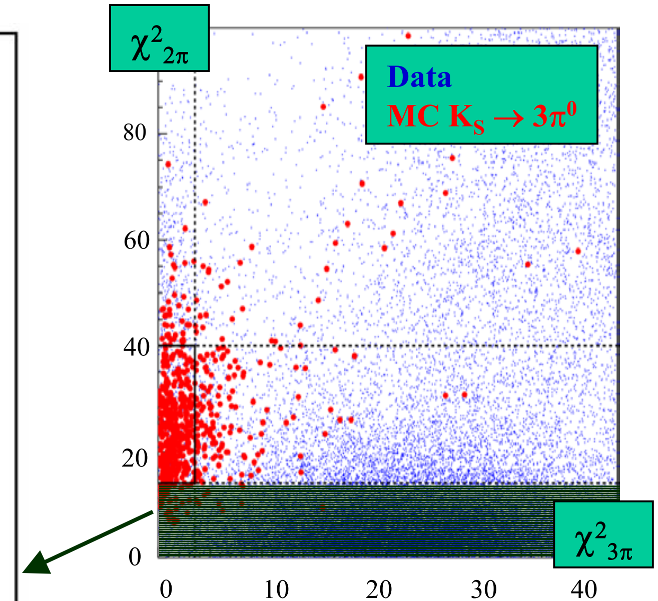




$K_S \to 3\pi^0$ decay switched on during MC production of 450 pb^{-1} equivalent data, with BR equal to the present upper limit

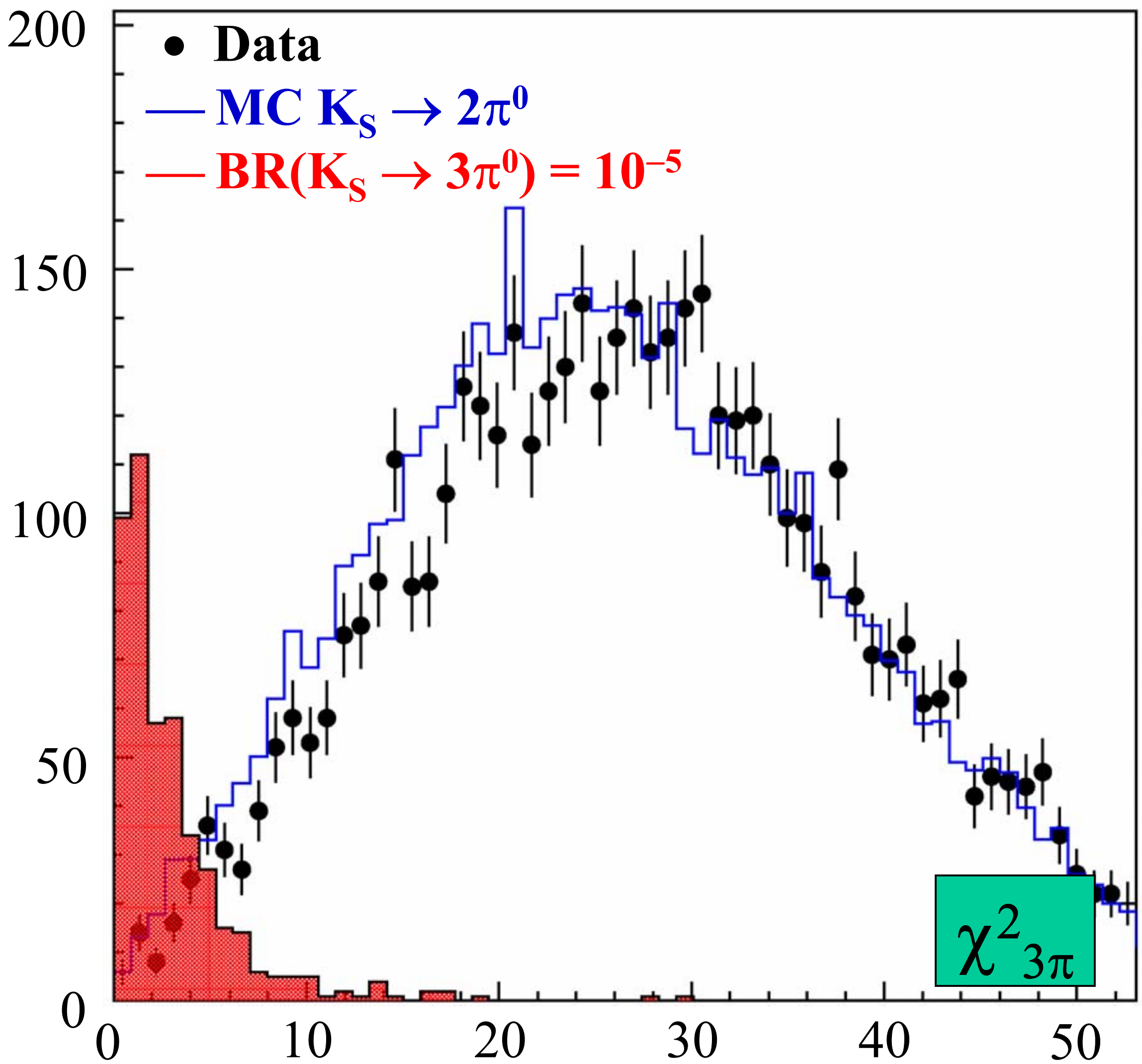
Search for $K_S \rightarrow \pi^0\pi^0\pi^0$ - sidebands

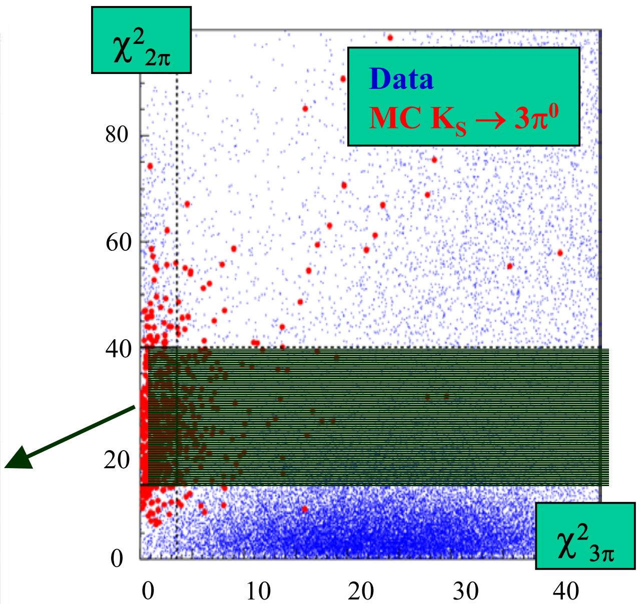




Absolute BKG normalization better than 10% in all control boxes

Search for $K_S \rightarrow \pi^0 \pi^0 \pi^0$ – signal region





$K_S \to \pi^0\pi^0\pi^0$ – Preliminary results

N_{sel}(data) = 4 events selected as signal, with efficiency $\varepsilon_{3\pi} = 23\%$

N_{sel}(bkg) = 3±1.3 ±0.2 bkg events expected from MC, use $N_{sel}(bkg) = 1.6$

Can state: **$N_{3\pi} < 5.83$ with a 90% CL**

Normalize signal counts to $K_S \to \pi^0\pi^0$ count in the same data set:

$$\mathbf{BR(K_S \to \pi^0\pi^0\pi^0) = \frac{N_{3\pi} / \varepsilon_{3\pi}}{N_{2\pi} / \varepsilon_{2\pi}} BR(K_S \to \pi^0\pi^0) < 2.1\ 10^{-7},}$$

Which translates into a limit on $|\eta_{000}| = \left| \frac{A(K_S \to \pi^0\pi^0\pi^0)}{A(K_L \to \pi^0\pi^0\pi^0)} \right| < 2.4\ 10^{-2}$

$K_S \to \pi e \nu$ decays – Physics issues

Sensitivity to CPT violating effects through charge asymmetry:

$$A_{S,L} = \frac{\Gamma(K_{S,L} \to \pi^- e^+ \nu) - \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})}{\Gamma(K_{S,L} \to \pi^- e^+ \nu) + \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})}$$

If CPT holds, $A_S = A_L$

$A_S \neq A_L$ signals CPT violation in mixing and/or decay with $\Delta S \neq \Delta Q$

Sensitivity to CP violation in K^0-$\bar{K}^0$ mixing:

$A_S = 2\mathrm{Re}\,\varepsilon$ (CPT symmetry assumed)

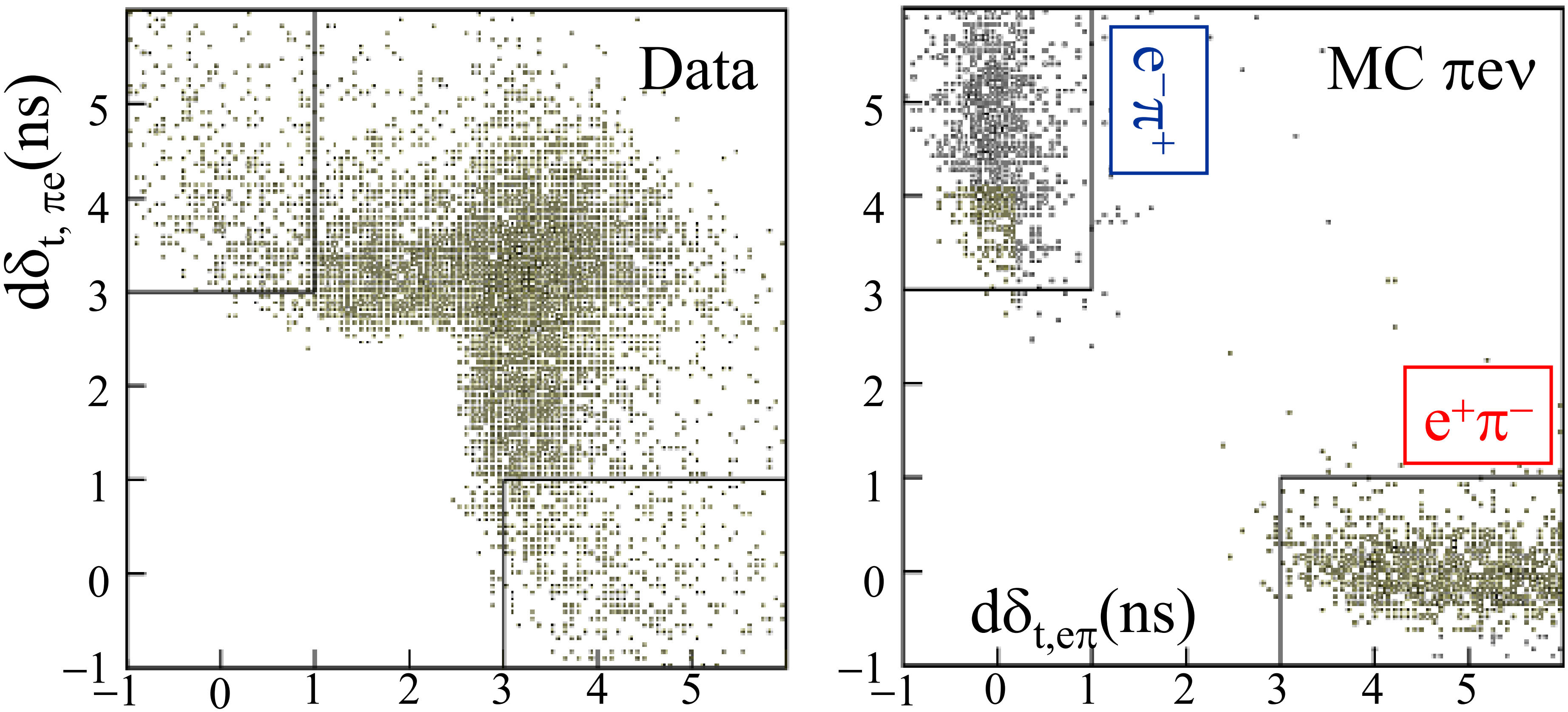
A_S never measured before

Can extract $|V_{us}|$ via measurement of BR($K_S \to \pi e \nu$)

$K_S \rightarrow \pi e \nu$ decay – Analysis outline

- ♦ K_{crash} tag + 2 tracks from IP with $M_{\pi\pi} < 490$ MeV (reject $K_S \rightarrow \pi\pi(\gamma)$)
- ♦ **TOF identification:** compare π-e expected flight times, reject ππ,πμ bkg

$$\mathbf{d\delta_{t,\,\pi e} = \delta t(m_\pi) - \delta t(m_e)} \qquad (\delta t(m) = t_{cluster} - t.o.f.)$$



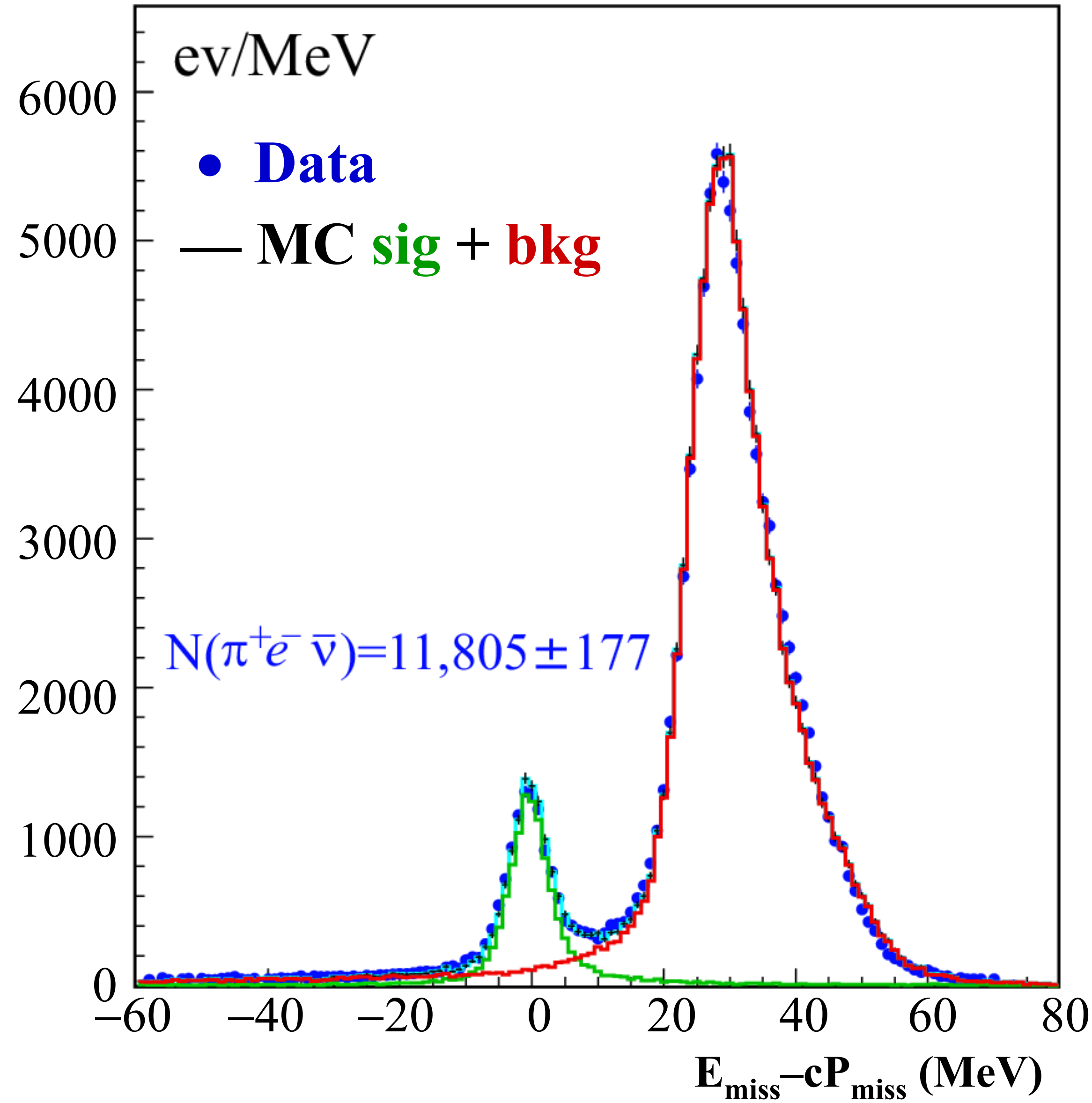
$K_S \to \pi e \nu$ decay – Events counting

Kinematic closure: use K_L to obtain K_S momentum $\mathbf{P}_K$ and test for presence of neutrino:

$$E_{miss} = \sqrt{M_K^2 + P_K^2} - E_\pi - E_e$$

$$P_{miss} = |\mathbf{P}_K - \mathbf{P}_\pi - \mathbf{P}_e|$$

Determine number of signal counts by fitting data to a linear combination of MC spectra for signal and background

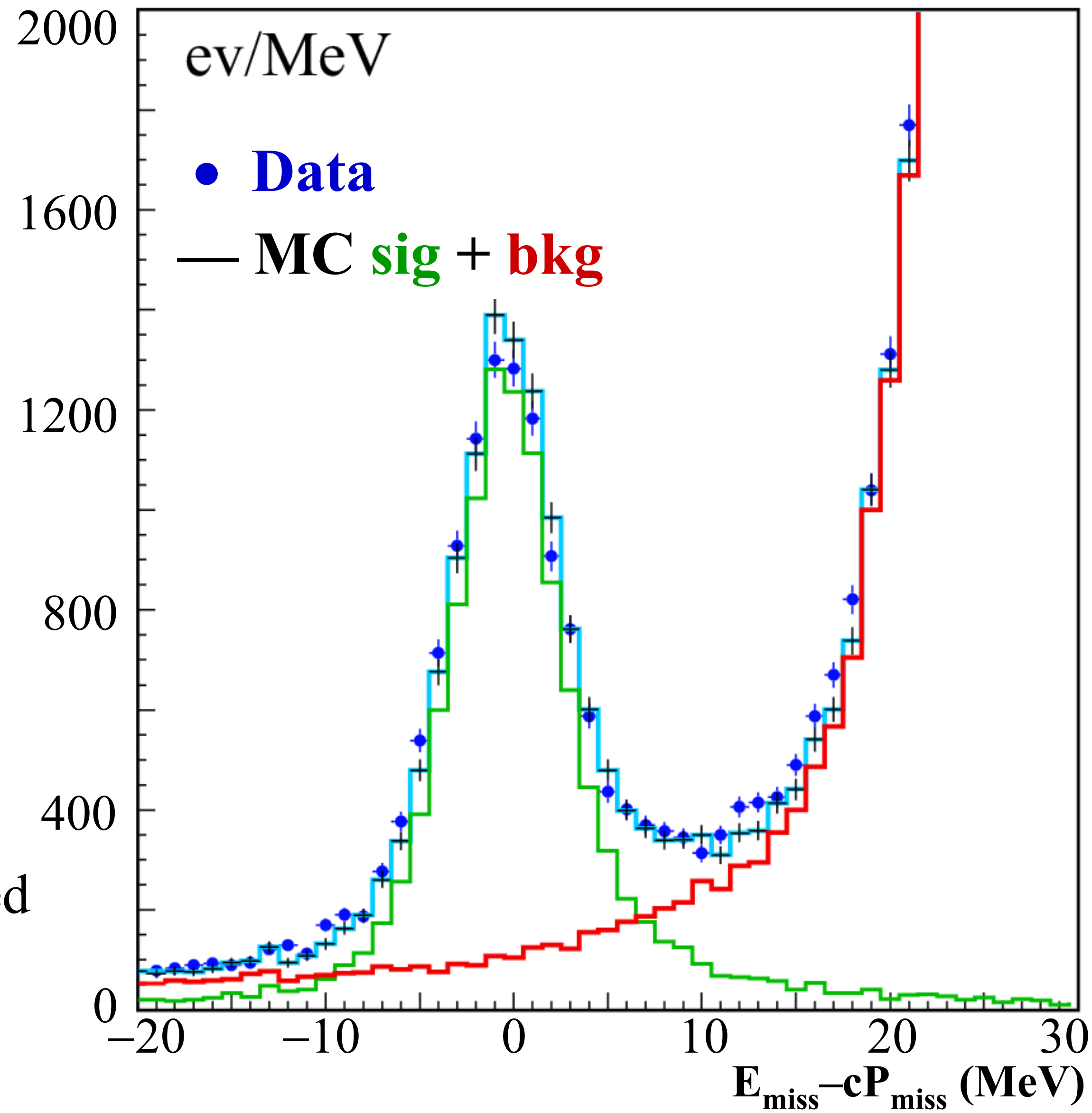


$K_S \rightarrow \pi e \nu$ *decay – Events counting*

Signal spectrum sensitive to the presence of a photon in the final state

Include radiative effects through an IR-finite treatment in MC (no energy cutoff)

Normalize signal counts to $K_S \rightarrow \pi\pi(\gamma)$ counts in the same data set (use PDG03 for BR($K_S \rightarrow \pi\pi(\gamma)$), dominated by KLOE measurement)



$K_S \rightarrow \pi e \nu$ decay – BR and A_S

Selection efficiency (given the tag) is evaluated by charge, using data control sample of $K_L \rightarrow \pi e \nu$ decaying close to IP:

$\varepsilon(\pi^- e^+) = (24.1 \pm 0.1 \pm 0.2)\%$; $\varepsilon(\pi^+ e^-) = (23.6 \pm 0.1 \pm 0.2)\%$

$BR(K_S \rightarrow \pi^- e^+ \nu) = (3.54 \pm 0.05_{stat} \pm 0.05_{syst})\ 10^{-4}$

$BR(K_S \rightarrow \pi^+ e^- \nu) = (3.54 \pm 0.05_{stat} \pm 0.04_{syst})\ 10^{-4}$

$BR(K_S \rightarrow \pi e \nu) = (7.09 \pm 0.07_{stat} \pm 0.08_{syst})\ 10^{-4}$

preliminary

evaluation of the systematics near completion

(Published result: $(6.91 \pm 0.34_{stat} \pm 0.15_{syst})\ 10^{-4}$, **Phys.Lett.B535:37-42,2002**)

$A_S^e = (-2 \pm 9_{stat} \pm 6_{syst})\ 10^{-3}$ **(never measured before)**

($A_L = (3.322 \pm 0.058 \pm 0.047)\ 10^{-3}$, KTeV 2002)

future:

2004-5 run: 2 $fb^{-1} \rightarrow \sigma(A_S^e) \sim 3\times10^{-3}$

CPT test: 20 fb^{-1} needed to reach $\sigma(Re\delta_K) = \frac{1}{4}\,\sigma(A_S^e) = 3\times10^{-4}$

Unitarity test of CKM matrix – V_{us}

Most precise test of unitarity possible at present comes from 1st row:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \sim |V_{ud}|^2 + |V_{us}|^2 \equiv 1 - \Delta$$

Can test if $\Delta = 0$ at few 10^{-3} : PDG02 $\Delta = 0.0042 \pm 0.0019$

from super-allowed $0^+ \rightarrow 0^+$ Fermi transitions, n β-decays: $2|V_{ud}|\delta V_{ud} = 0.0015$

from semileptonic kaon decays (PDG 2002 fit): $2|V_{us}|\delta V_{us} = 0.0011$

To extract $|V_{us}|$ from K^0_{e3} decays, have to include EM effects:

$$\Gamma(K^0 \rightarrow \pi e \nu(\gamma)) \propto |V_{us}\, f_+^{K0\pi-}(0)\,|^2\; I(\lambda_t)\,(1 + \Delta I(\lambda_t,\alpha))\;(1 + \delta_{EM})$$

Fractional contributions to the uncertainty:

$$\frac{\delta|V_{us}|}{|V_{us}|} = 0.5\,\frac{\delta\Gamma}{\Gamma} \oplus 0.05\,\frac{\delta\lambda_t}{\lambda_t} \oplus \frac{\delta f_+^{K0\pi-}(0)}{f_+^{K0\pi-}(0)}$$

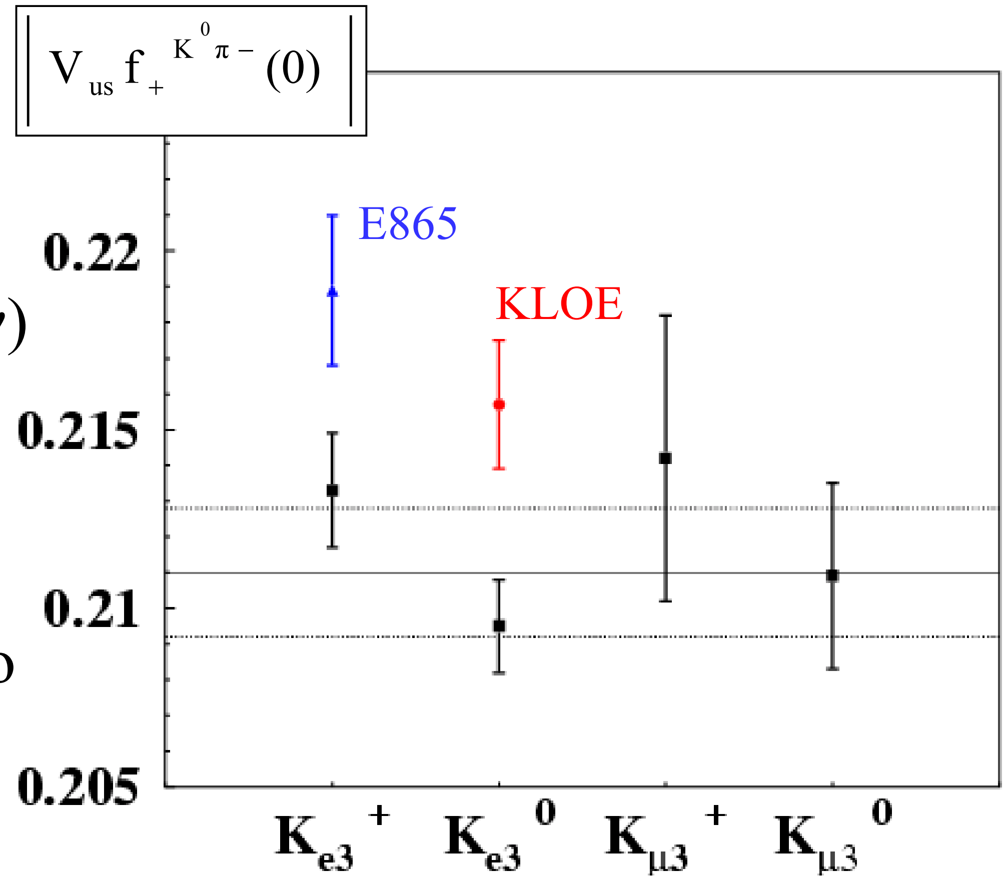
$$0.5\% \oplus 0.3\% \oplus 1\%$$

$K_S \to \pi e \nu$ decay – $V_{us} f_+^{K\pi}(0)$

Compare **our K_s measurement of V_{us} $f_+^{K\pi}(0)$** with:

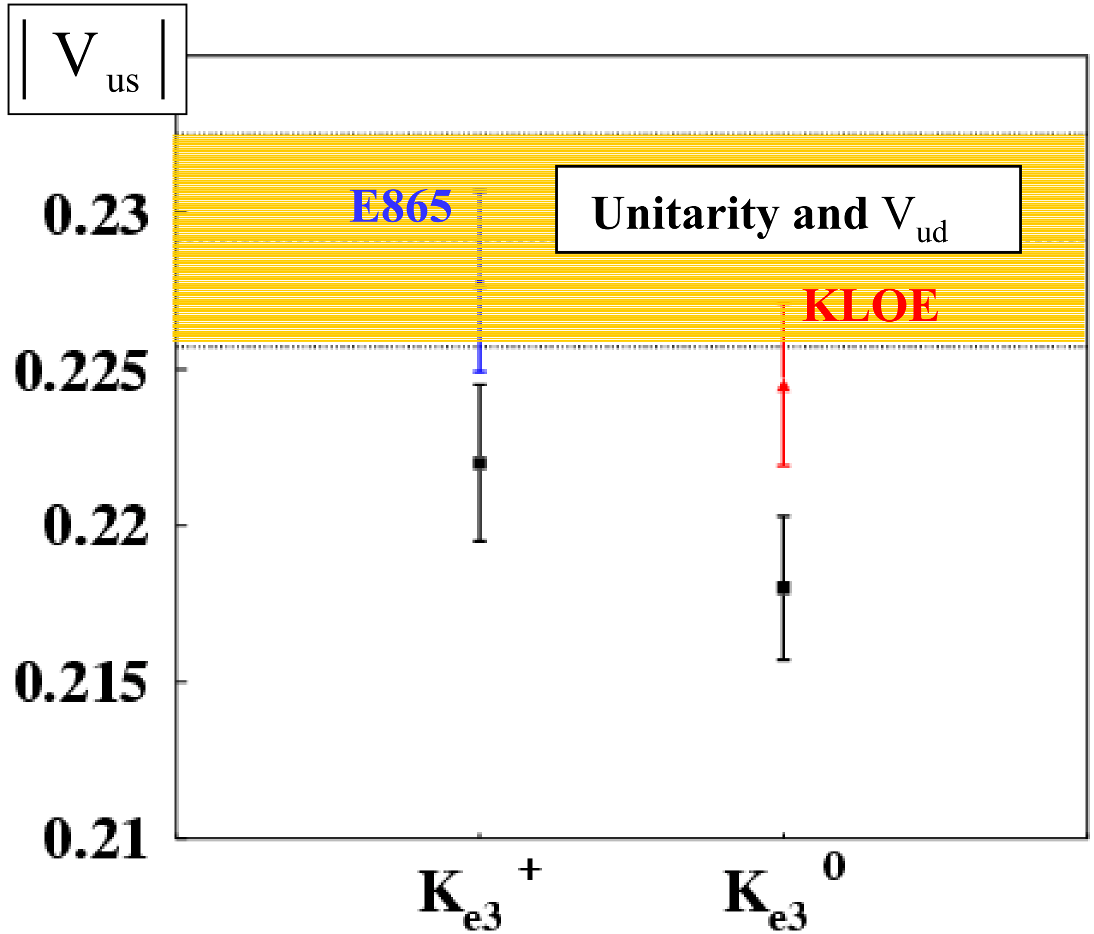
- **PDG02** fit results for $\Gamma(K^+ \to \pi^0 l^+ \nu)$ and $\Gamma(K_L \to \pi^- l^+ \nu)$ (radiation effects not known)
- **$\Gamma(K^+ \to \pi^0 e^+ \nu)$ from E865 experiment (uses PDG fits)**

- CKMwg prescription is used to extract $\mathbf{V_{us}\ f_+^{K\pi}(0)}$ from the partial decay width



Our **preliminary** result agrees better with latest K^+ data, while showing a appreciable deviation from old K^0_{e3}

$K_S \rightarrow \pi e \nu$ decay – V_{us} determination



PDG02, CKMwg use:

$$f_+^{K^0\pi^-}(0) = 0.961 \pm 0.008$$

from **Leutwyler, Roos** **Z.Phys. C 25 1984,** χPT to O(p^4), **confirmed by a lattice calculation (hep-ph 0403217)**

A recent determination of $f_+(0)$ (**Cirigliano et al. hep-ph 0401173**) differs by +2%; the same authors suggest to use experimental ratio $\Gamma(K^0_{e3})/\Gamma(K^+_{e3})$ to improve the theoretical estimate of $f_+^{K\pi}$

K_L decays – Present knowledge

Knowledge of 4 main K_L BR's at present dominated by 3 measurements:

$$\frac{\Gamma(K_L \to \pi^0\pi^0\pi^0)}{\Gamma(K_L \to \pi e \nu)} \text{ and } \frac{\Gamma(K_L \to \pi^0\pi^0\pi^0)}{\Gamma(K_L \to \pi^+\pi^-\pi^0)}$$, with ~2% relative uncertainty [NA31]

$$R_{\mu/e} = \frac{\Gamma(K_L \to \pi\mu\nu)}{\Gamma(K_L \to \pi e \nu)} = 0.702 \pm 0.011$$ [Argonne HBC 1980]

3-σ discrepancy (**~4%**) between measurement and expectation for $R_{\mu/e}$:

$R_{\mu/e} = 0.671 \pm 0.002$, direct measurement for K^+, from KEK-E246 2001

$R_{\mu/e}$ calculable from the slopes λ_+ and λ_0 of vector and scalar form factors:

0.670 ± 0.002, if $\lambda_0 = 0.0183 \pm 0.0013$, from ISTRA+ 2003

0.668 ± 0.006, if $\lambda_0 = 0.017 \pm 0.004$, from one-loop χPt

K_L decays – Status and objectives

Have to precisely measure **absolute** branching ratios, with rel. accuracy < 1%

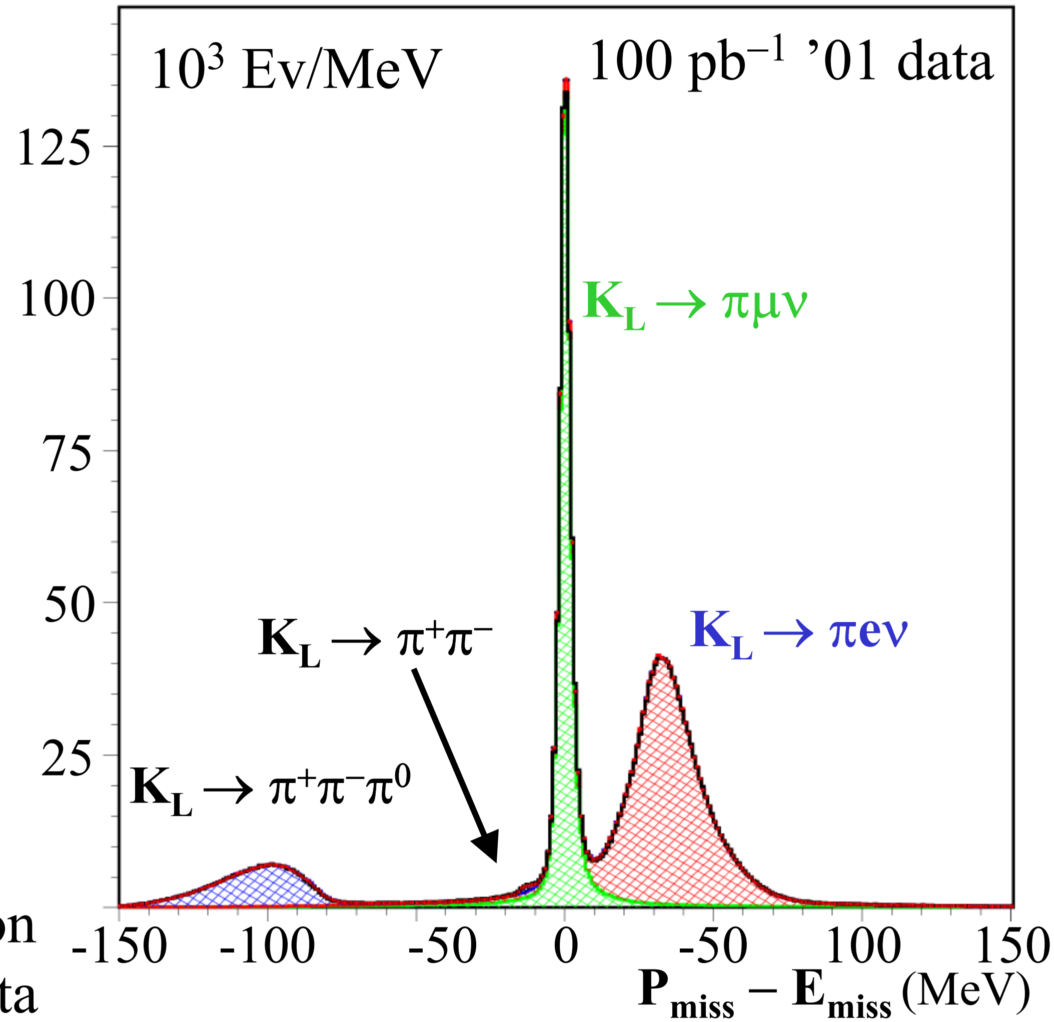
K_L beam tagged by identification of $K_S \to \pi^+\pi^-$

K_L decay vertex in a given fiducial volume in DC

Kinematic identification using reconstructed momenta

$450 pb^{-1} \Rightarrow 3 \bullet 10^6$ K_{e3} events

In progress:
* New detailed MC with radiation and $\pi-\mu-K_L$ response
* Selection efficiency as a function of K_L vertex position and momenta of decay products

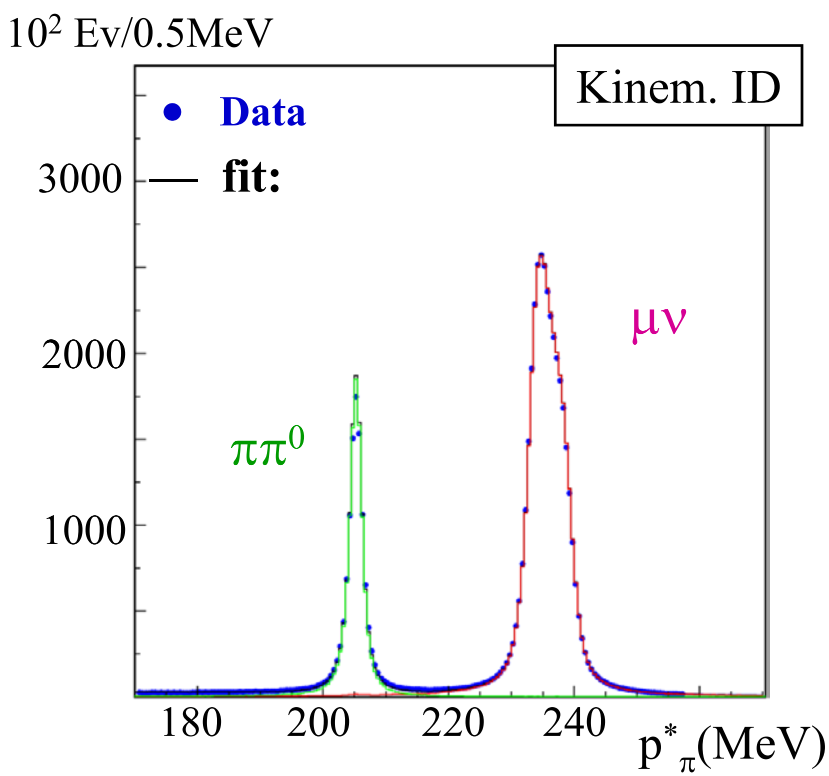


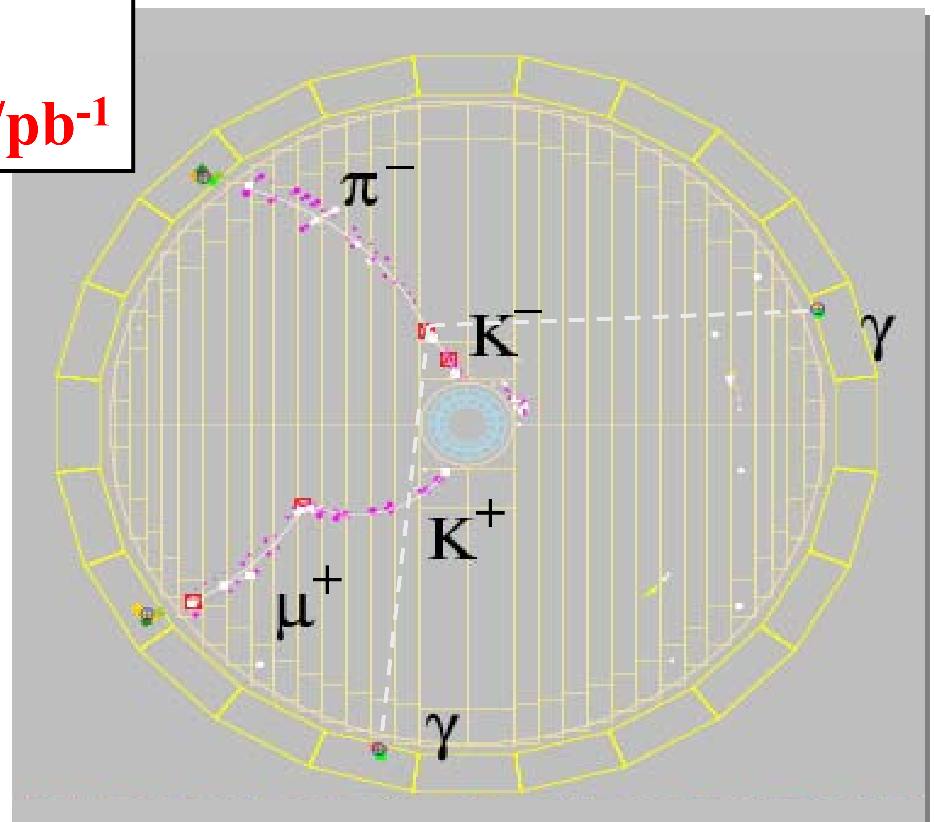
Lesser of ($P_{miss} - E_{miss}$) in $\pi\mu$ or $\mu\pi$ hyp.

Charged kaons – Tagging

Measurement of absolute BR's: K^+ beam tagged from $K^- \rightarrow \pi^-\pi^0$, $\mu^-\nu$

- Two-body decays identified as peaks in the momentum spectrum of secondary tracks in the kaon rest frame: **$6 \cdot 10^5$ tags/pb^{-1}**





$K^+ \rightarrow \mu^+\nu_\mu \quad K^- \rightarrow \pi^-\pi^0$

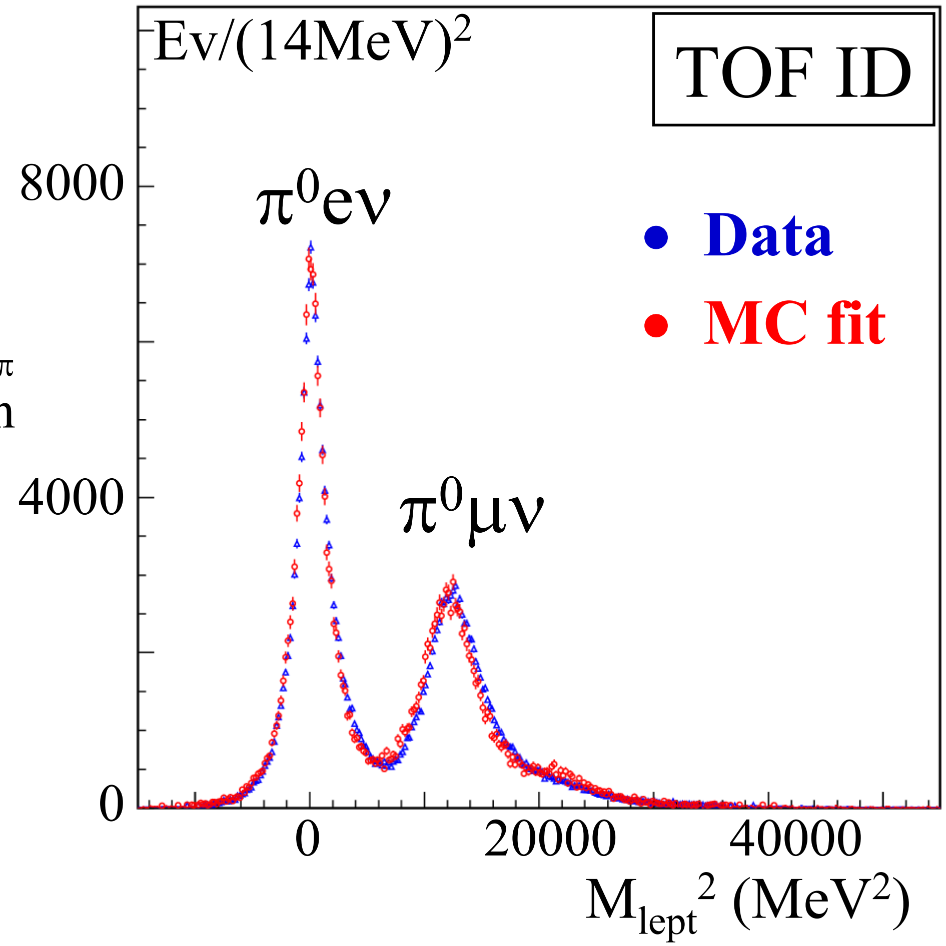
Charged kaons – $K^{\pm}_{l3}$ decays

After tag a dedicated reconstruction of $K^{\pm}$ tracks is performed, correcting for charged kaon dE/dx in the DC walls

K_{l3} selection:

- 1-prong kaon decay vertex in a given fiducial volume in DC
- Reject two-body decays by cutting on P^{*}_{π}
- π^0 search: 2 neutral clusters in EmC, with tof matching the K decay vertex
- Obtain charged daughter mass spectrum from TOF measurement:

$$t^{decay}_{K} = t_{lept} - L_{lept}/(\beta_{lept}c) = \langle t_{\gamma} - L_{\gamma}/c \rangle$$



$450pb^{-1} \Rightarrow 3 \cdot 10^5$ K_{e3} events

Outlook

Present status - K_S:

Sensitivity to BR's at the 10^{-7} level (preliminary UL for $K_S \to 3\pi^0$)

Measurement of K_{e3} mode at the % level, 10^{-2} accuracy on A_S

Expect 2 fb^{-1} of integrated luminosity in 2004-5, would allow:

A_S with a total accuracy of $4\ 10^{-3}$, first test of SM prediction $A_S = 2\ \mathrm{Re}\ \varepsilon$

Sensitivity to $K_S \to 3\pi^0$ at 10^{-8} level

A measurement of BR($K_S \to \pi^+\pi^-\pi^0$) with 20% relative uncertainty

- First **direct** measurement
- Test of the χPt prediction, BR($K_S \to \pi^+\pi^-\pi^0$) = $(2.4 \pm 0.7)\ 10^{-7}$

In progress:

Measurement of BR's for semileptonic K_L and K^+ decays

- Huge statistics, uncertainty will be limited by systematics
- Will clarify the situation concerning the experimental parameters for the determination of V_{us}