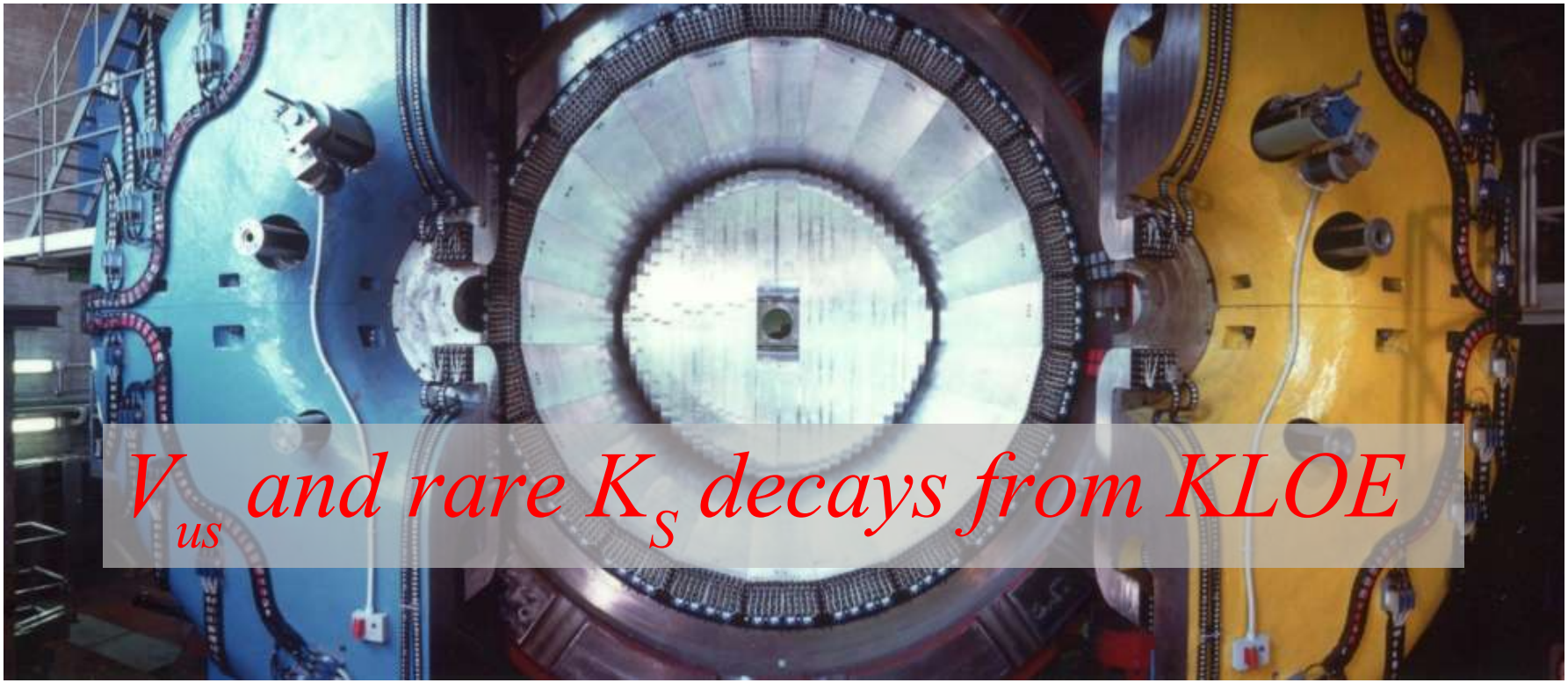


V_{us} and rare K_S decays from KLOE

M.Antonelli (INFN/Frascati)
for the KLOE collaboration

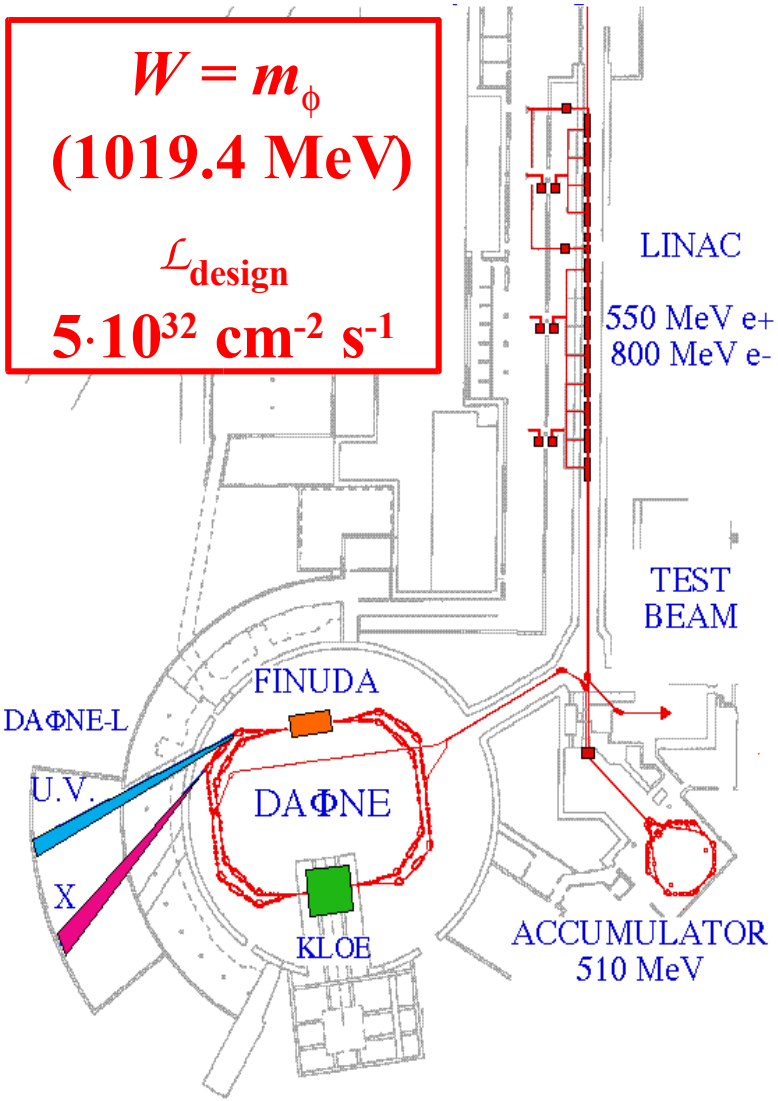
ICHEP 2004

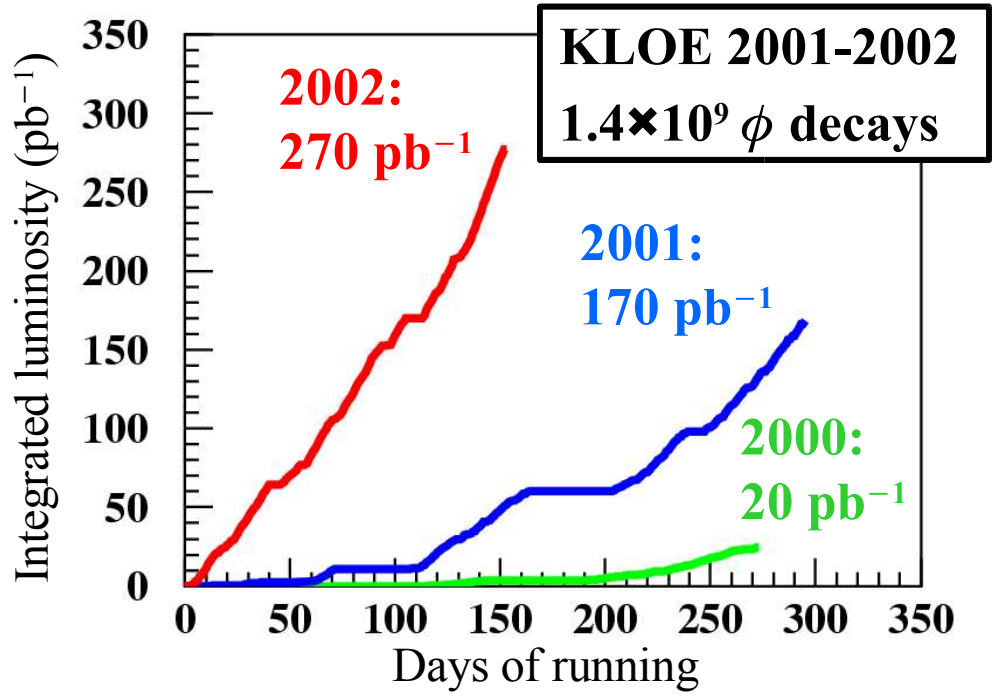
Beijing, 15-23 August

DAΦNE: the Frascati ϕ factory

$W = m_\phi$
(1019.4 MeV)

$\mathcal{L}_{design}$
$5 \cdot 10^{32}$ cm^{-2} s^{-1}





Machine upgrades for 2004:

$\mathcal{L} > 10^{32}$ cm^{-2} s^{-1} → 2 fb^{-1}/yr

2004 best $\mathcal{L}_{peak}$ 8.5×10^{31} cm^{-2} s^{-1}

2004 avg $\mathcal{L}$ $\sim 6 \times 10^{31}$ cm^{-2} s^{-1}

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

$$K_S\,(K^+) \longleftarrow \Phi \longrightarrow K_L\,(K^-)$$

Contamination $\approx 10^{-10}$

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

- **Tagging:** observation of $K_{S,L}$ signals presence of $K_{L,S}$

  - precision measurement of absolute BR's

- Interference measurements of K_SK_L system

K^+K^-

1.5×10^6 /pb^{-1}

p* = 127 MeV/c

$\lambda_\pm$= 95 cm

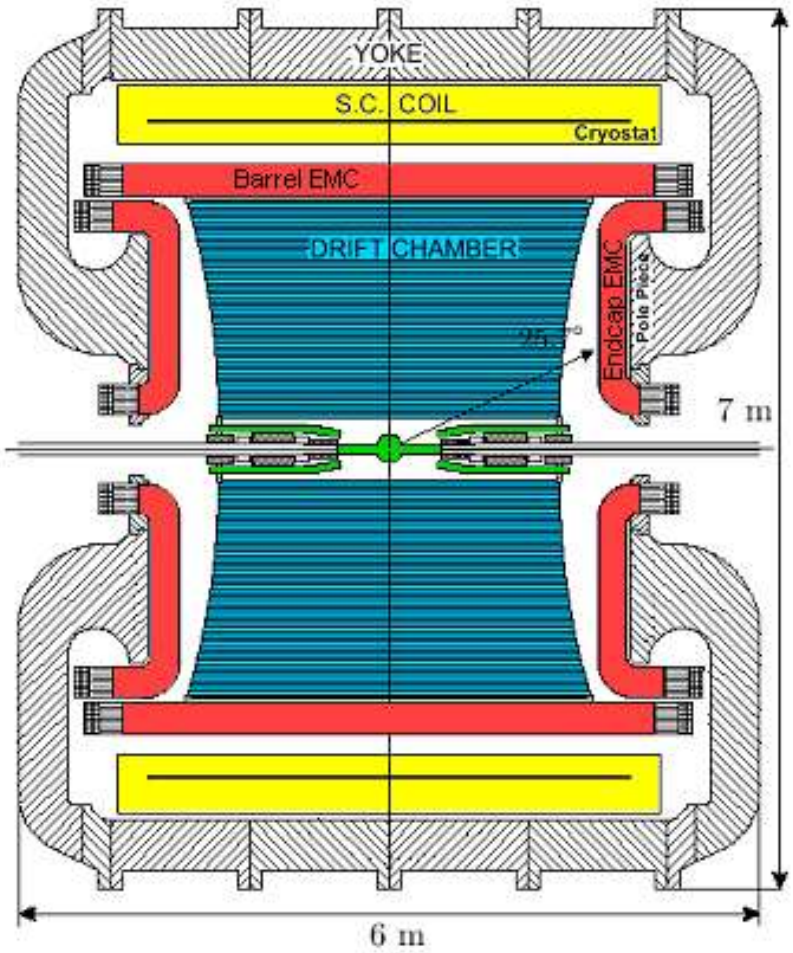
K_LK_S

10^6 /pb^{-1} ; p* = 110 MeV/c

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

λ_L = 3.4 m **Large detector to keep reasonable acceptance for K_L decays (~0.5 λ_L)**

The KLOE experiment



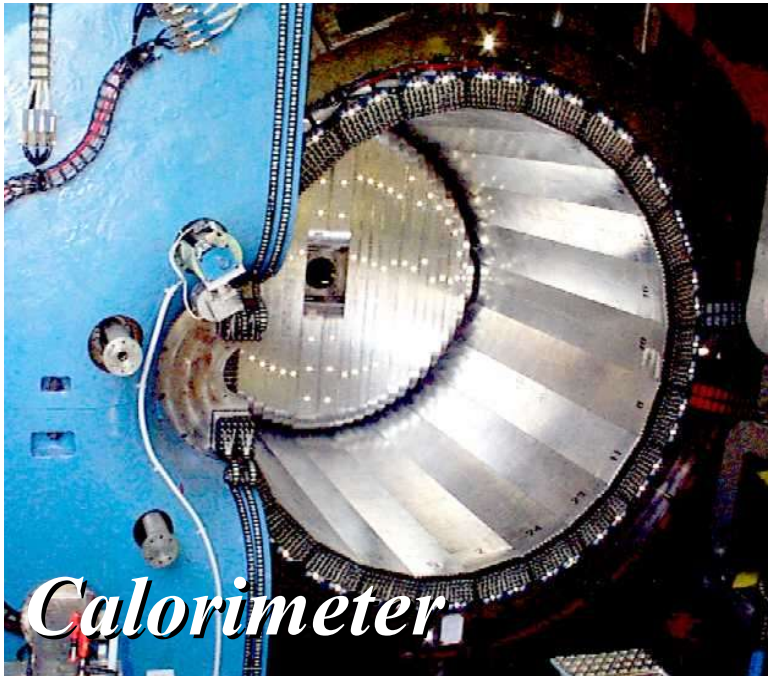
Be beam pipe (0.5 mm thick)
Instrumented permanent magnet quadrupoles (32 PMT's)

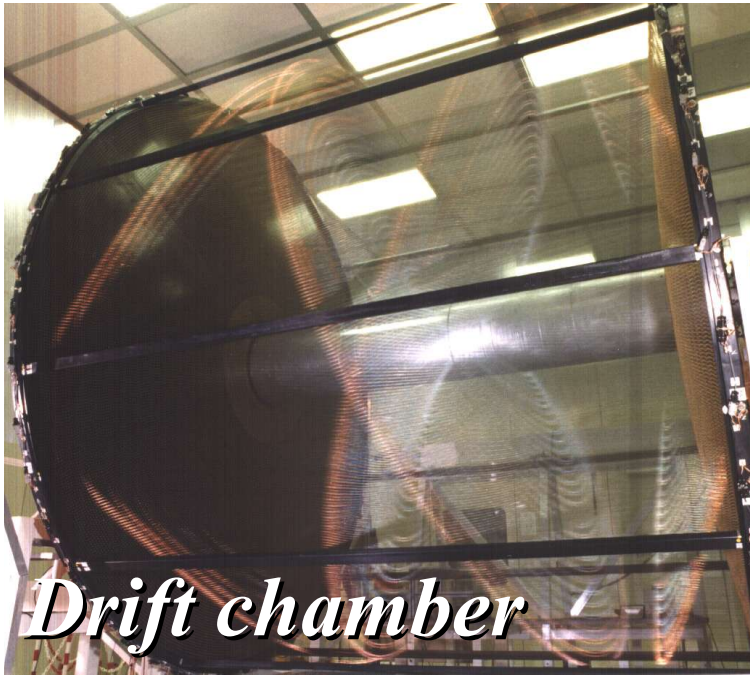
Drift chamber (4 m ∅ × 3.3 m)
90% He + 10% IsoB, CF frame
12582 stereo sense wires

Electromagnetic calorimeter
Lead/scintillating fibers
4880 PMT's

Superconducting coil (5 m bore)
$B = 0.52$ T ($\int B\, dl = 2$ T ▪m)

KLOE detector specifications





σ_E/E **5.7% /√*E*(GeV)**

σ_t **54 ps /√*E*(GeV) ⊕ 50 ps**

(relative time between clusters)

$\sigma_L(\gamma\gamma)$ **~2 cm** (π^0 from $K_L \rightarrow \pi^+\pi^-\pi^0$)

σ_p/p **0.4 %** (tracks with $\theta > 45°$)

σ_x^{hit} **150 μm (*xy*), 2 mm (*z*)**

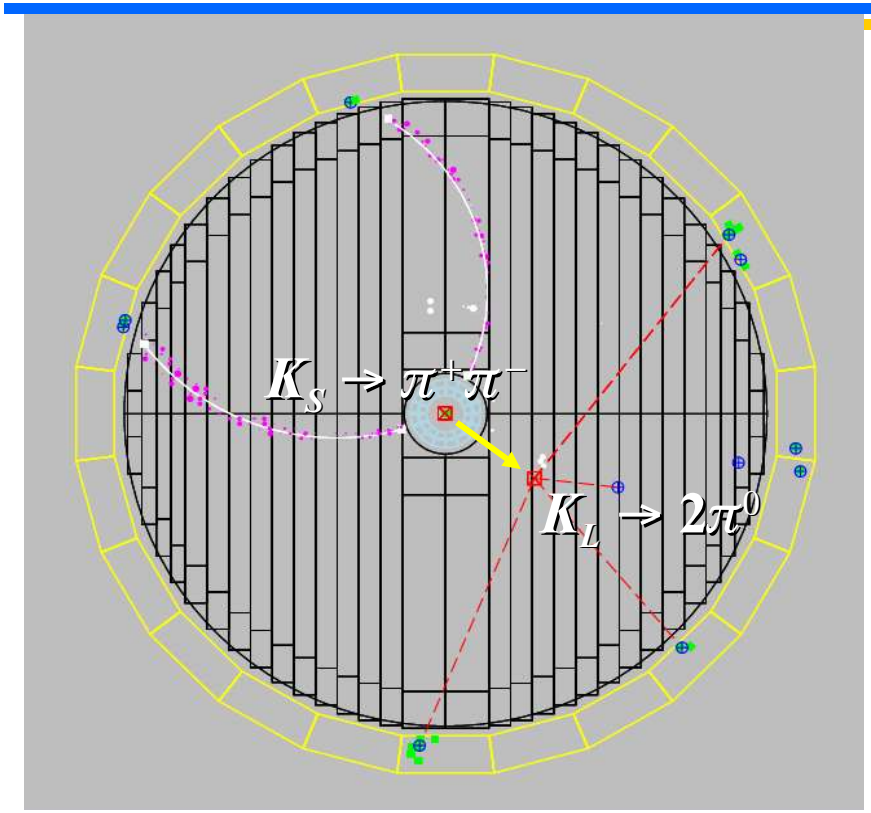
σ_x^{vertex} **~1 mm**

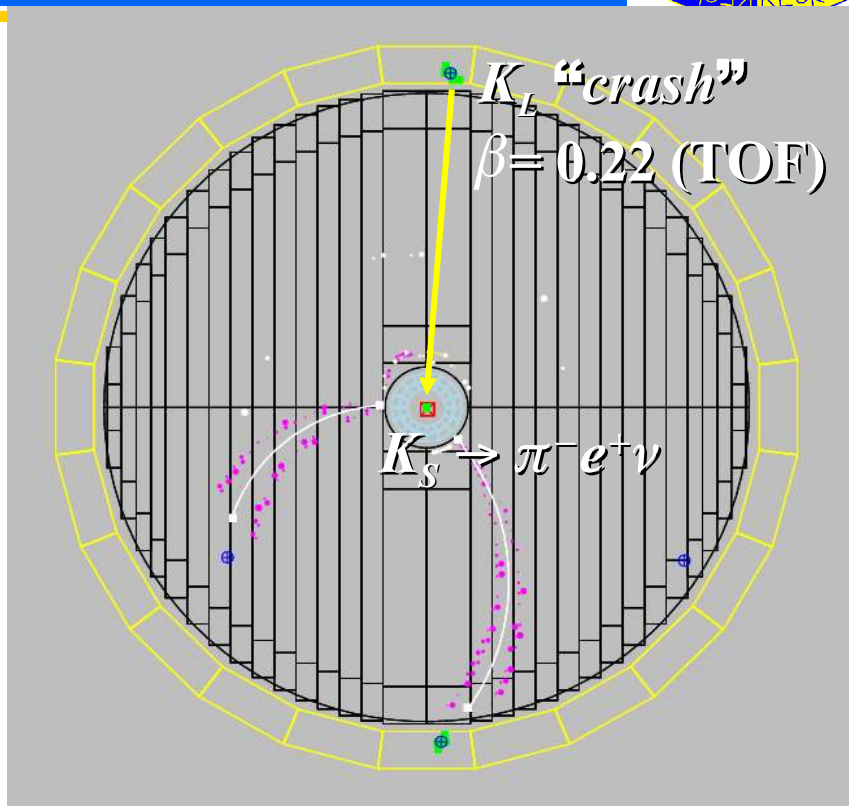
$\sigma(M_{\pi\pi})$ **~1 MeV**

Kaon physics at KLOE

⇒ $K_S \to \pi^0\pi^0\pi^0$	**Preliminary results**
$K_S \to \pi^+\pi^-(\gamma)$ $K_S \to \pi^0\pi^0$	***Phys. Lett.* B538 21 (2002)** Update with '01-'02 data in progress
⇒ $K_S \to \pi e \nu$	***Phys. Lett.* B535 37 (2002)** **Preliminary update with '01-'02 data**
K^0 **mass**	KLOE Note 181 (http://www.lnf.infn.it/kloe)
$K_L \to \gamma\gamma / K_L \to 3\pi^0$	***Phys. Lett.* B566 61 (2003)**
⇒ $K_L \to \pi\mu\nu, \pi e\nu, \pi^+\pi^-\pi^0\ 3\pi^0$	**Preliminary results**
⇒ K_L **mean life**	**Preliminary results**
⇒ V_{us} **from** K_L ***and*** K_S	**Preliminary results**
CP violation & interference	**In progress**
V_{us} **from** $K^{+/-}$	**In progress**
$K^+ \to \pi^+\pi^0\pi^0$	**hep-ex/0307054 accepted by *Phys. Lett.* B**

Tagged K_L and K_S "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

$4 \cdot 10^5$ tags/pb^{-1}

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

$3 \cdot 10^5$ tags/pb^{-1}

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

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

If *CPT* conserved: $\Gamma_S = \Gamma_L |\varepsilon + \varepsilon'_{000}|^2$ **BR($K_S \to 3\pi^0$) ~ 2 × 10^{-9}**

Best results: BR < 1.4 × 10^{-5} 90% CL SND '99

BR < 1.4 × 10^{-6} 90% CL NA48 '03 preliminary

Uncertainty on $K_S \to 3\pi^0$ amplitude currently limits precision on Im δ

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

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

Best results: Im δ = (2.4 ± 5.0) × 10^{-5} CPLEAR '99

Im δ = (−1.2 ± 3.0) × 10^{-5} NA48 '03 preliminary

A limit on BR($K_S \to 3\pi^0$) at 10^{-7} level would limit:

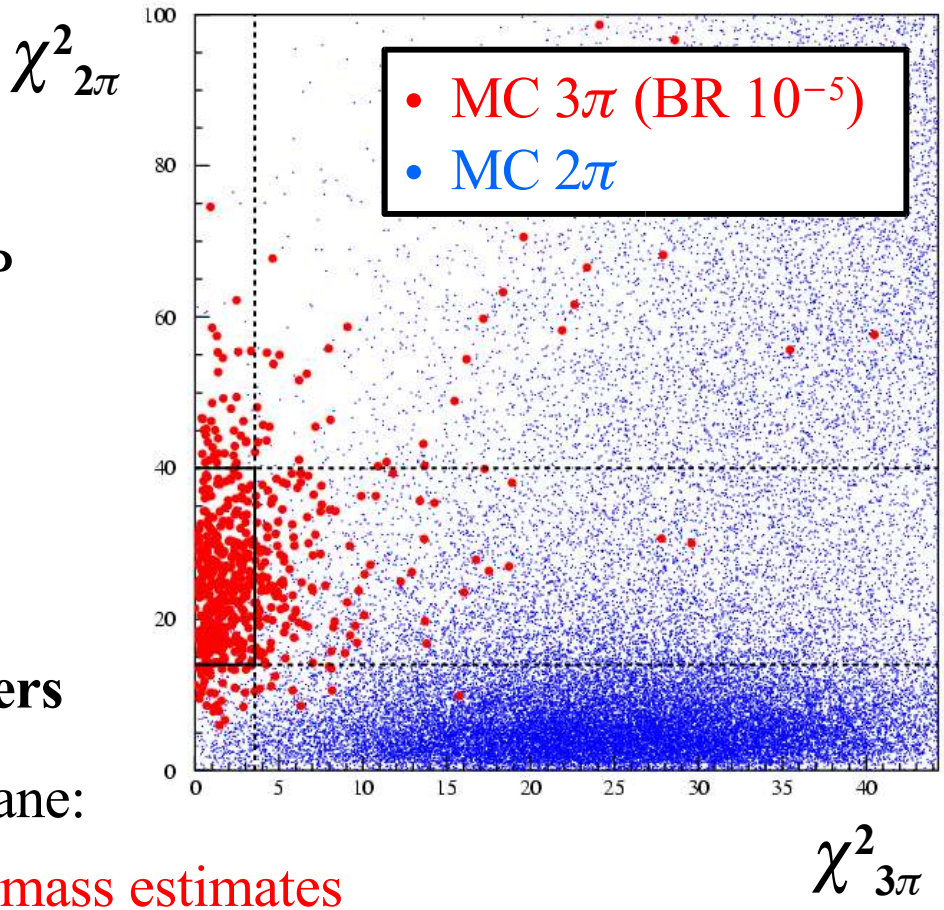
$|\mathrm{Im}\,\delta| < \sim 2 \times 10^{-5}$ ⇒ $\dfrac{m_{K^0} - m_{\bar{K}^0}}{\langle m_K \rangle} < \sim 8 \times 10^{-19}$

Compare:
$m_K/m_{\mathrm{Planck}} = 4 \times 10^{-20}$

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

Preselection:

- K_S tagged by K_L crash
- 6 photon clusters, no tracks from IP
- Kinematic fit to refine cluster parameters



Rejection of background:

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

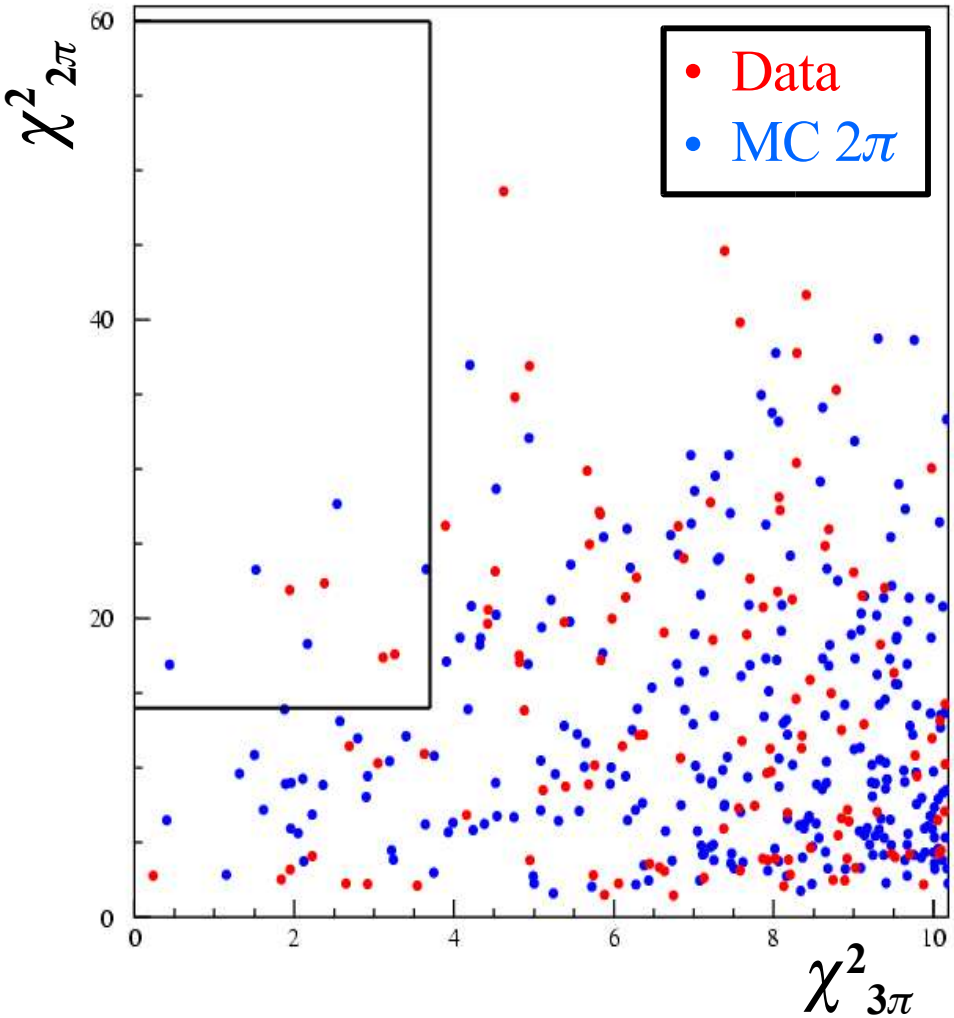
- Define signal box in $\chi^2_{3\pi}$ vs. $\chi^2_{2\pi}$ plane:

  $\chi^2_{3\pi}$ 3 cluster pairs with best π^0 mass estimates

  $\chi^2_{2\pi}$'' pair 4 clusters using π^0 masses, $E(K_S)$, $\mathbf{p}(K_S)$, angle between π^0's

- Final cut on residual K_S energy: $E(K_S) - \Sigma E_\pi$

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



analysis optimization:
minimization of expected upper limit

$\varepsilon_{3\pi} =$ 22.6%
(events with K_L crash)

N_{bkg}(MC) = 3.2 ± 1.4 ± 0.5

$N_{obs} = 4$

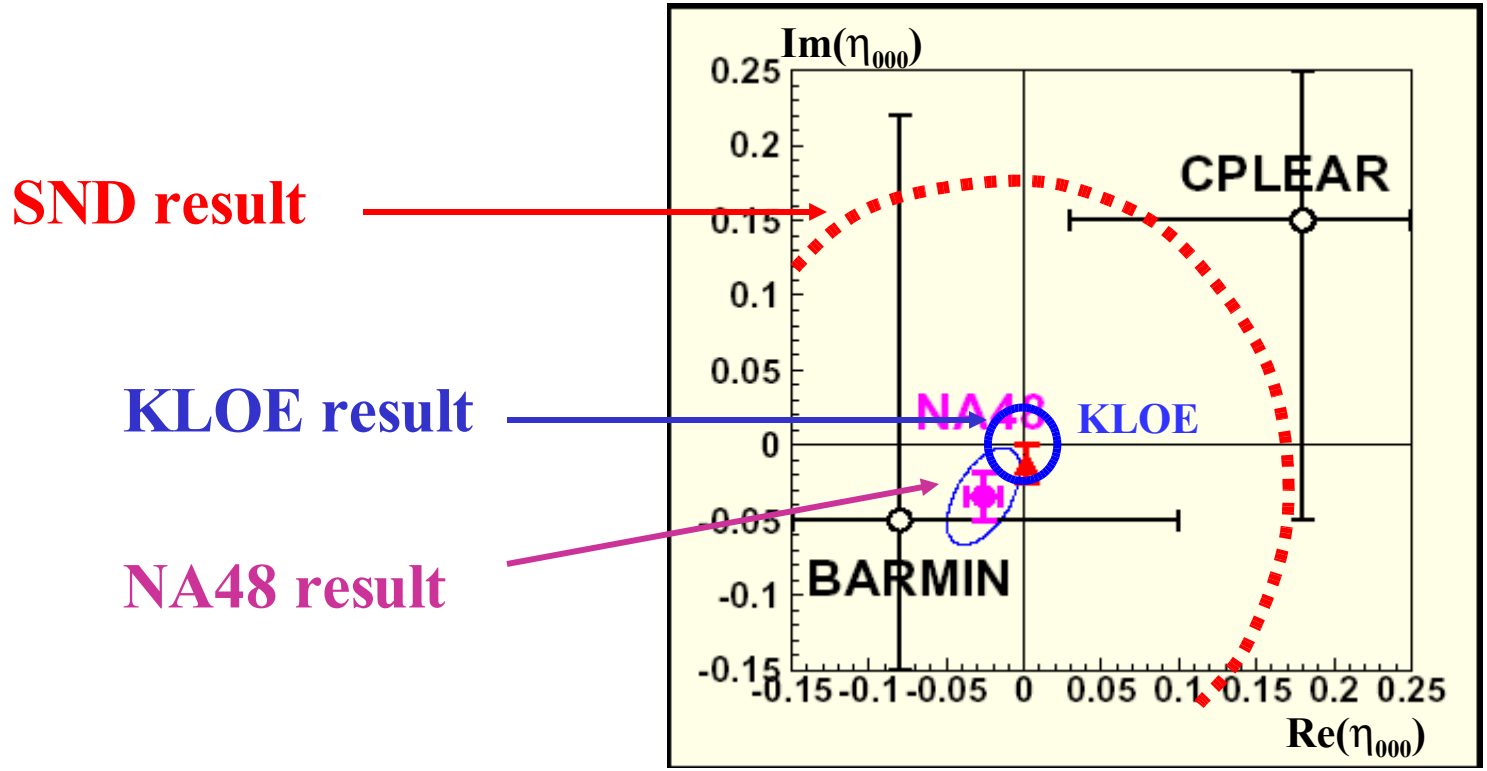
KLOE preliminary
450 pb^{-1} '01+'02 data

BR($K_S \to \pi^0\pi^0\pi^0$)
$\leq 2.1 \times 10^{-7}$ 90% CL

Constraints for η^{000}

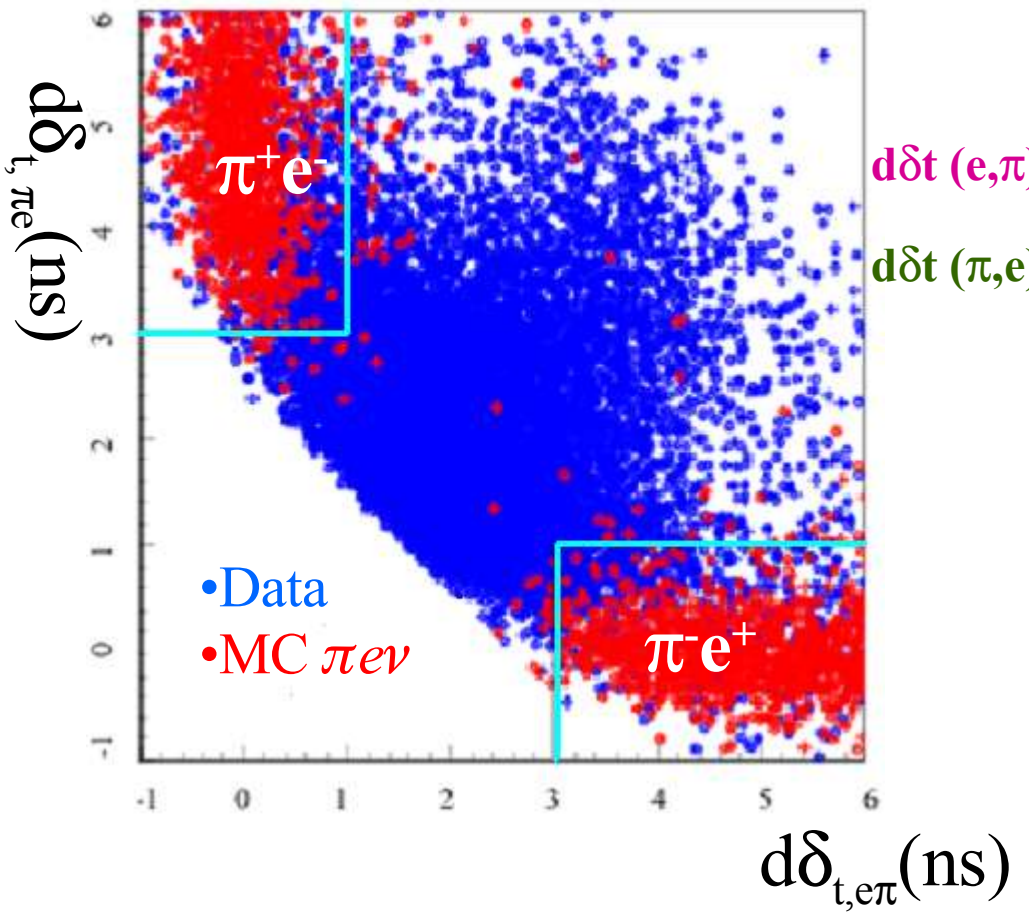
Using the PDG values and our limit we have:

$$|\eta^{000}| = \frac{A(K_S \to 3\pi^0)}{A(K_L \to 3\pi^0)} \sqrt{\frac{\tau_L}{\tau_S} \frac{B(K_S \to 3\pi^0)}{B(K_L \to 3\pi^0)}}$$



Analysis of $K_S \to \pi e \nu$ decays

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



$d\delta t\ (e,\pi) = [t_-^{CLU} - t_+^{CLU}] - [L_1 / c\ \beta(e) - L_2 / c\ \beta(\pi)]$

$d\delta t\ (\pi,e) = [t_-^{CLU} - t_+^{CLU}] - [L_1 / c\ \beta(\pi) - L_2 / c\ \beta(e)]$

$\varepsilon_{2trk} \cong 33\%$

$\varepsilon_{tof} \cong 70\%$

$K_S \to \pi^- e^+ \nu, \pi^+ e^- \nu$

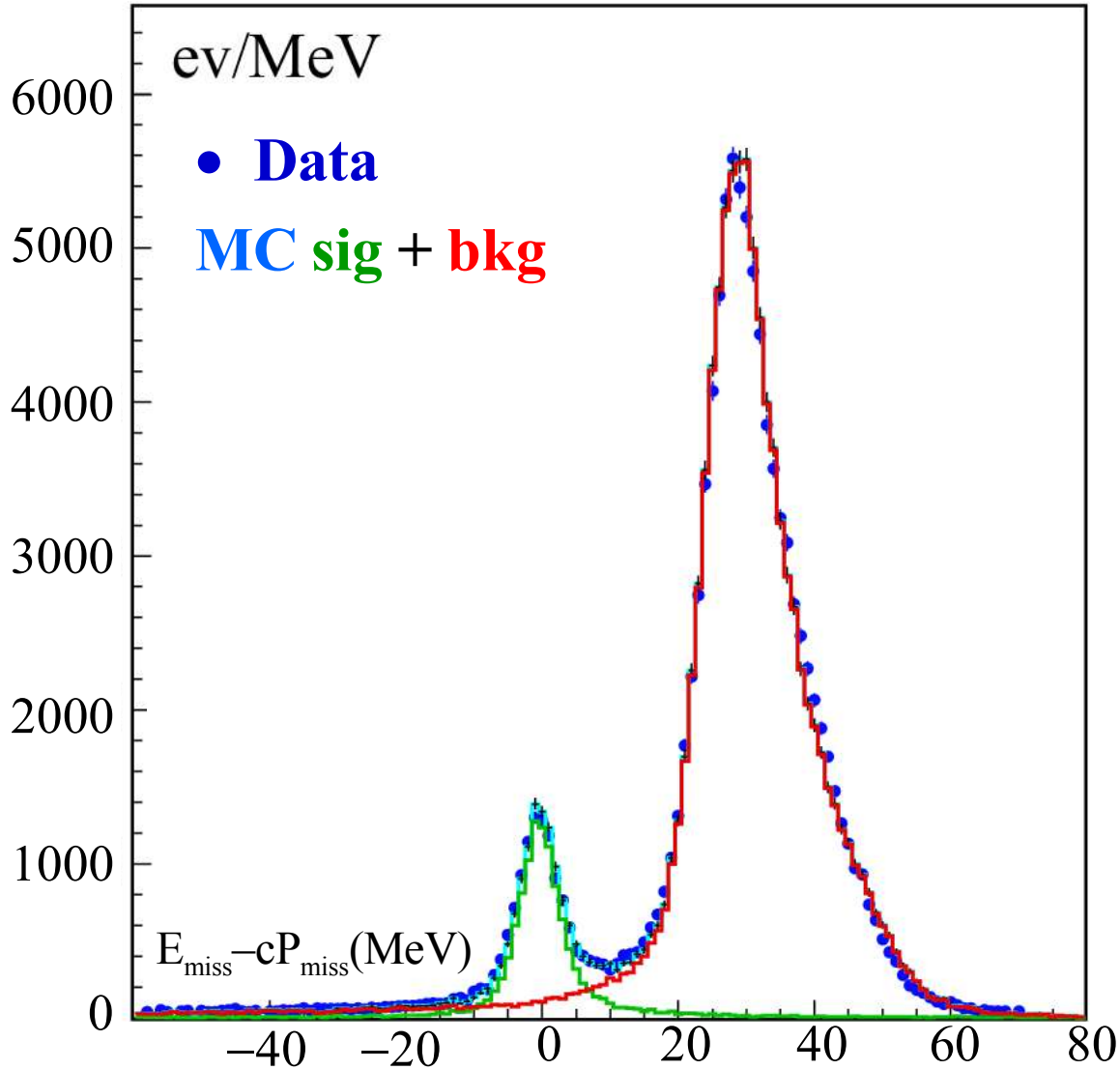
Kinematic closure: use K_L to obtain K_S momentum $\mathbf{P_K}$ and test for presence of neutrino:

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

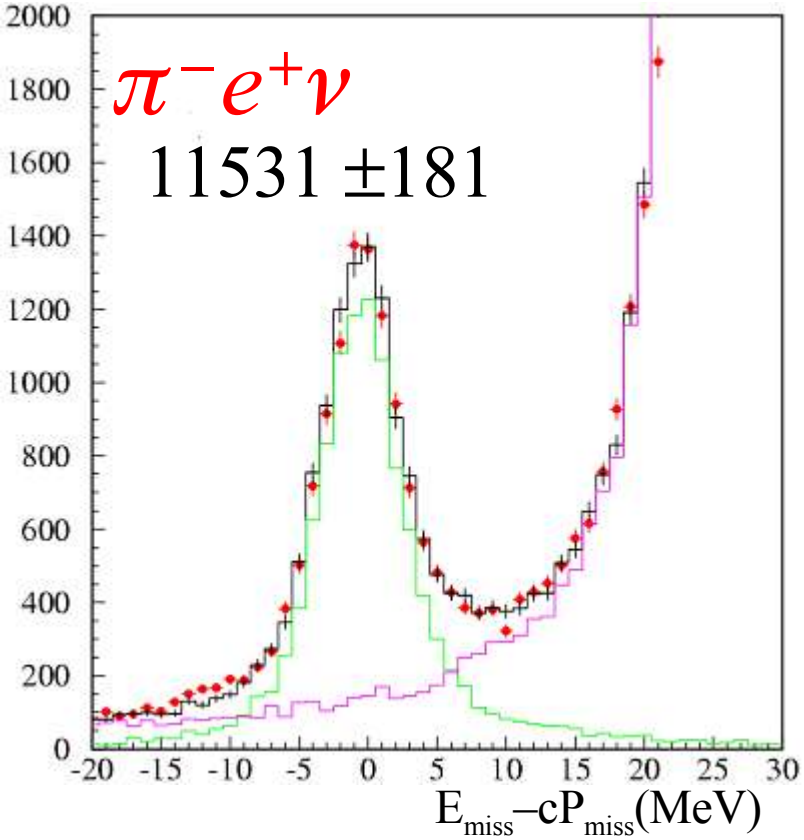
$$P_{miss} = |\mathbf{P_K} - \mathbf{P}_\pi - \mathbf{P_e}|$$

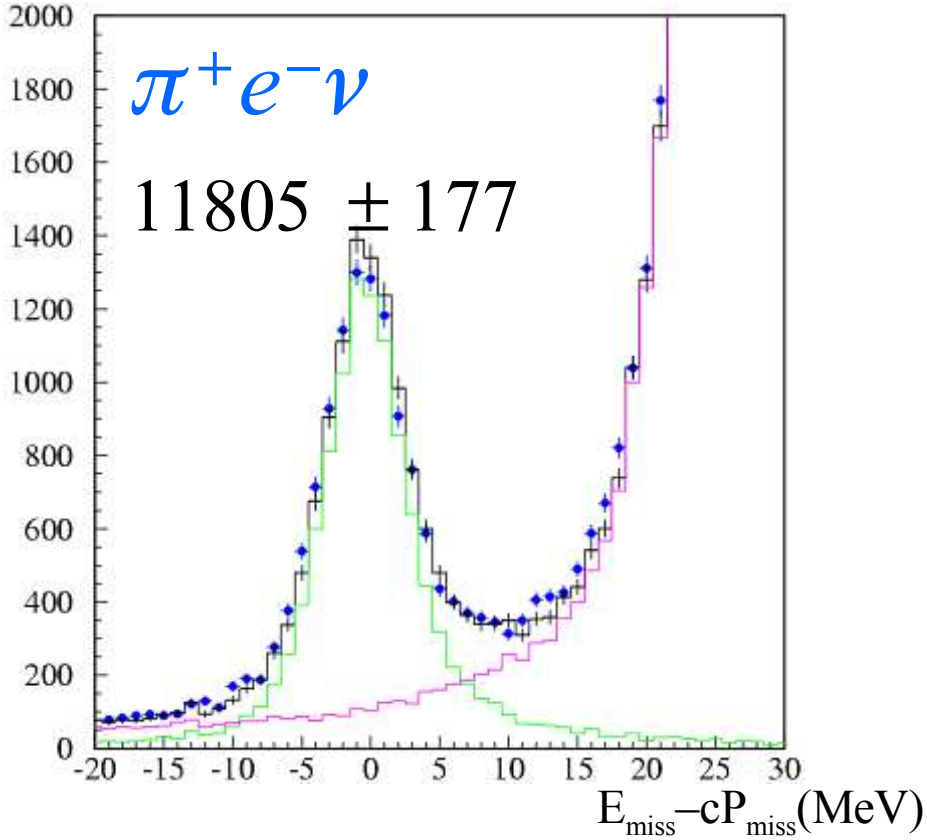
number of signal counts by fitting data to a linear combination of MC spectra for signal and background ($\pi^+\pi^-$)

IR-finite treatment of radiative effects in MC (no energy cutoff)



$K_S \to \pi^- e^+ \nu, \pi^+ e^- \nu$





Result sensitivity to fit interval well below present statistical uncertainty

Normalize signal counts to $K_S \to \pi\pi(\gamma)$ counts in the same data set

(use PDG03 for BR($K_S \to \pi\pi(\gamma)$), dominated by KLOE measurement)

$K_S \to \pi^- e^+ \nu, \pi^+ e^- \nu$

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

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

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

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

preliminary

evaluation of the systematics near completion

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

(Published result: $(6.91 \pm 0.34_{stat} \pm 0.15_{syst})\ 10^{-4}$ Phys.Lett.B535:3742,2002)

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

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

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

future: **next year run** $2\ fb^{-1} \to \sigma(A_S) \sim 3 \cdot 10^{-3}$

K_L decays

Precisely measure **absolute** branching ratios, with rel. accuracy < 1%

$410 pb^{-1} \Rightarrow (13 \cdot 10^6$ tagged K_L) x 4

- K_L decay vertex in a fiducial volume in DC (given a $K_S \rightarrow \pi^+\pi^-$ tag)
- Kinematic identification for charged decays using reconstructed momenta
- photons counting for $K_L \rightarrow 3\pi^0$

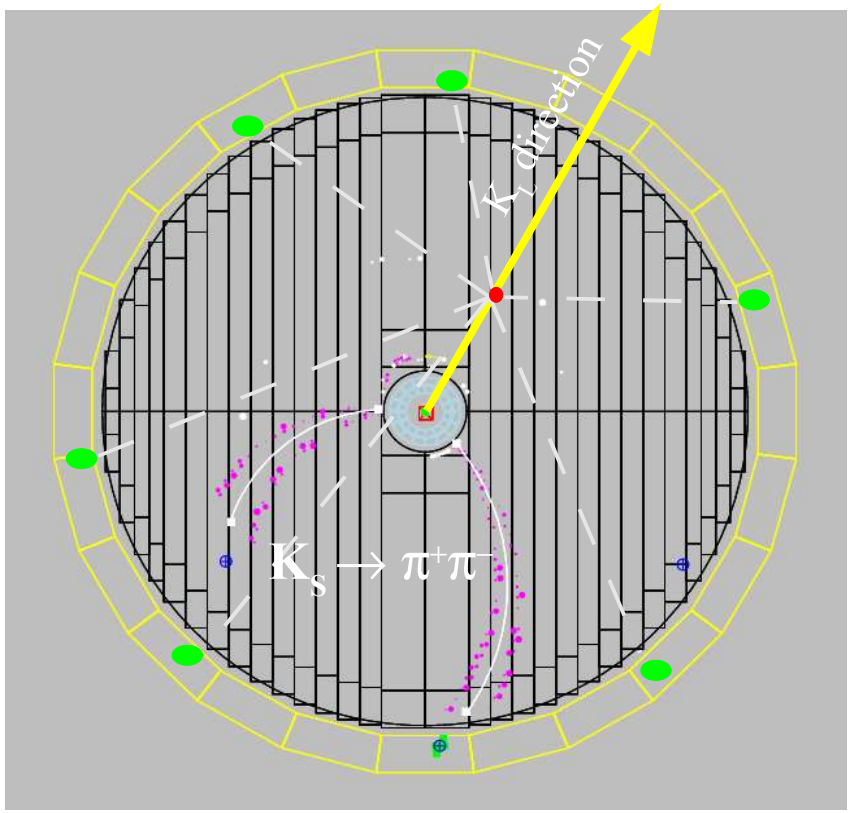
$$BR(K_L \rightarrow X) = \frac{N_{sig}/(\varepsilon_{rec.}^{X} \cdot \varepsilon_{F.V.} \cdot \varepsilon_{Tag}^{X})}{N_{Tag}/\varepsilon_{Tag}^{all}}$$

Tag bias $\frac{\varepsilon_{Tag}^{X}}{\varepsilon_{Tag}^{all}} \approx 1$

		$K_{\ell 3}$	$\pi^+\pi^-\pi^0$	$3\pi^0$
Reconstruction efficiency	$\varepsilon_{rec.}^{X}$	≈ 60%	45%	100%
Fiducial volume acceptance	$\varepsilon_{F.V.}$	≈ 26%		

K_L decays: Tag bias

Slightly different Tagging efficieny among K_L topologies

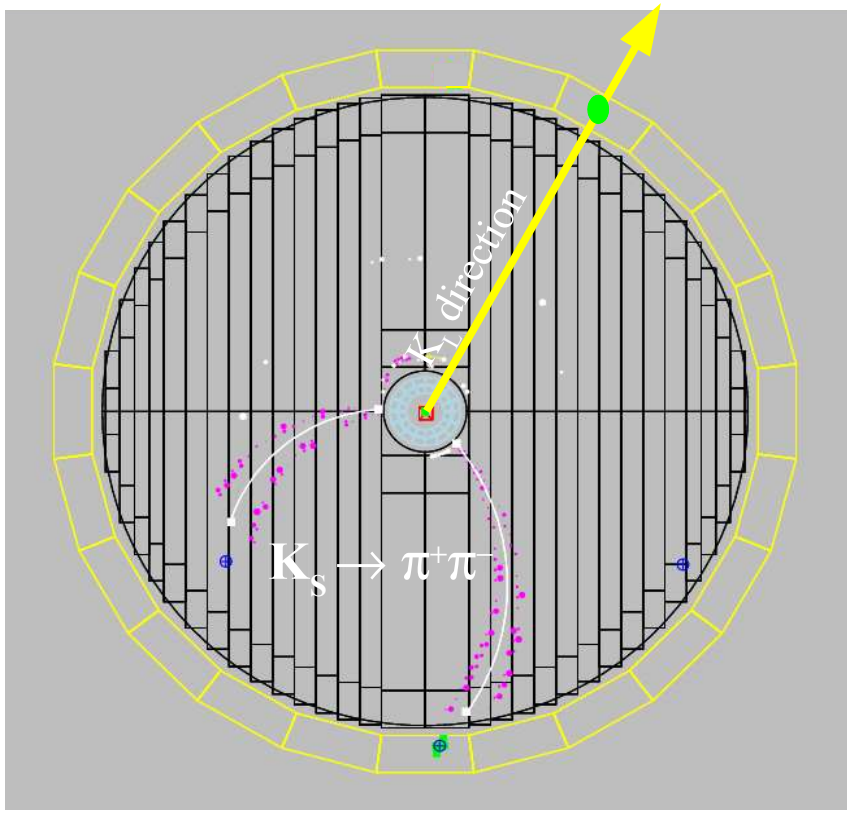


$K_L \rightarrow$ neutrals

- ~ 100% trigger efficiency
  good data/MC agreement

K_L decays: Tag bias

Slightly different Tagging efficieny among K_L topologies



$K_L \rightarrow$ interaction fraction

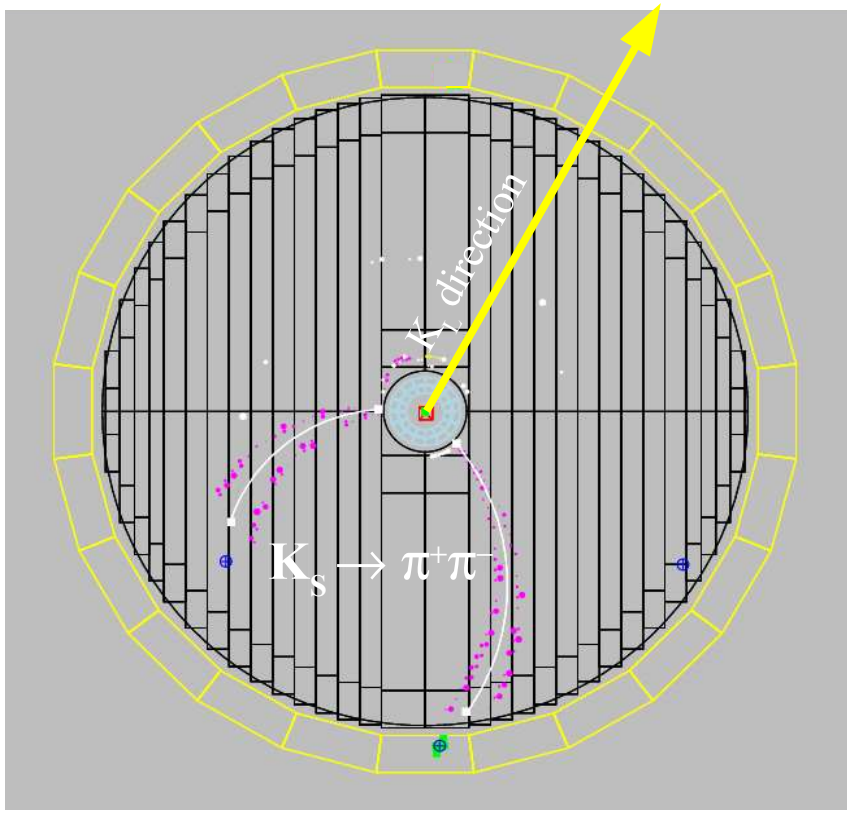
30%

trigger efficiency

85%

K_L decays: Tag bias

Slightly different Tagging efficieny among K_L topologies



$K_L \rightarrow$	interaction,	punch-trough
fraction	30%	17%
trigger efficiency	85%	65%

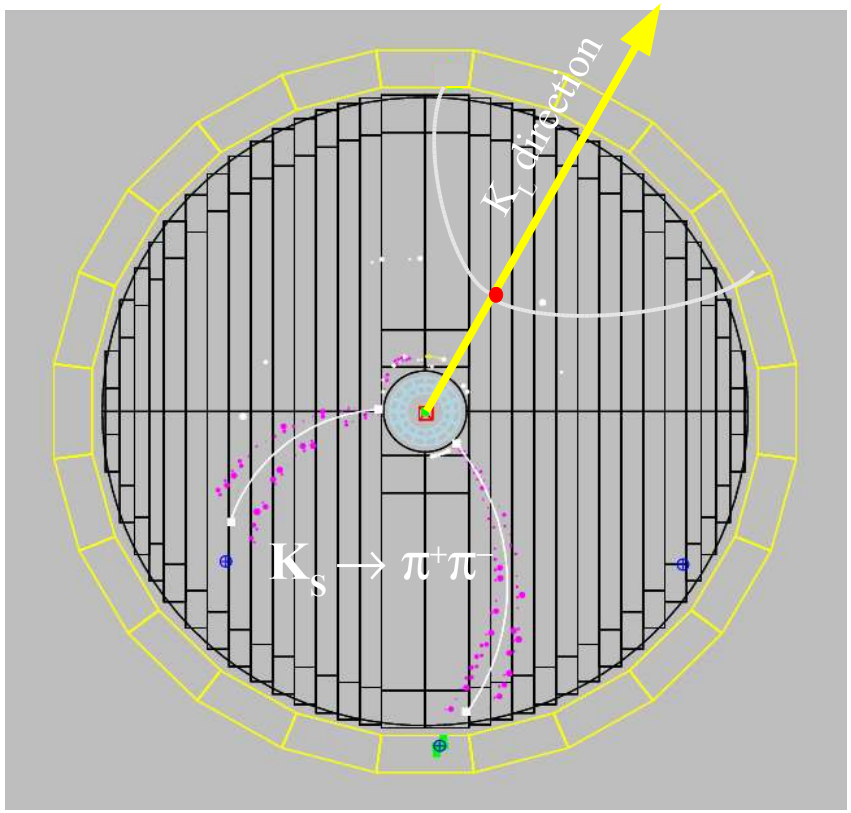
data/MC agreement at ~ 10%

possible source of systematic uncertainty at ~ 1-2%

Tagging with K_S autoTrigger ε~20%

K_L decays: Tag bias

Sligthely different Tagging efficicieny among K_L topologies



$K_L \to$ charged

- Few % decrease of $K_S \to \pi^+\pi^-$ reconstrucion efficiency at small R_{KL}

  good data/MC agreement

  typical correction 0.5% ± 0.1%

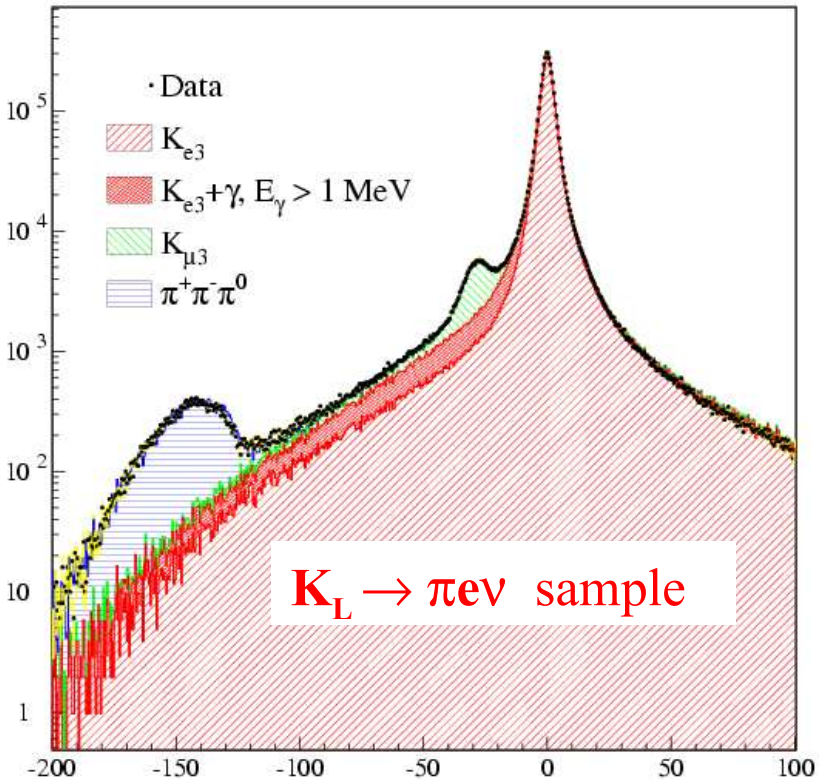
Typical biases for K_S autoTrigger Tag

charged	neutrals
0.985	1.02

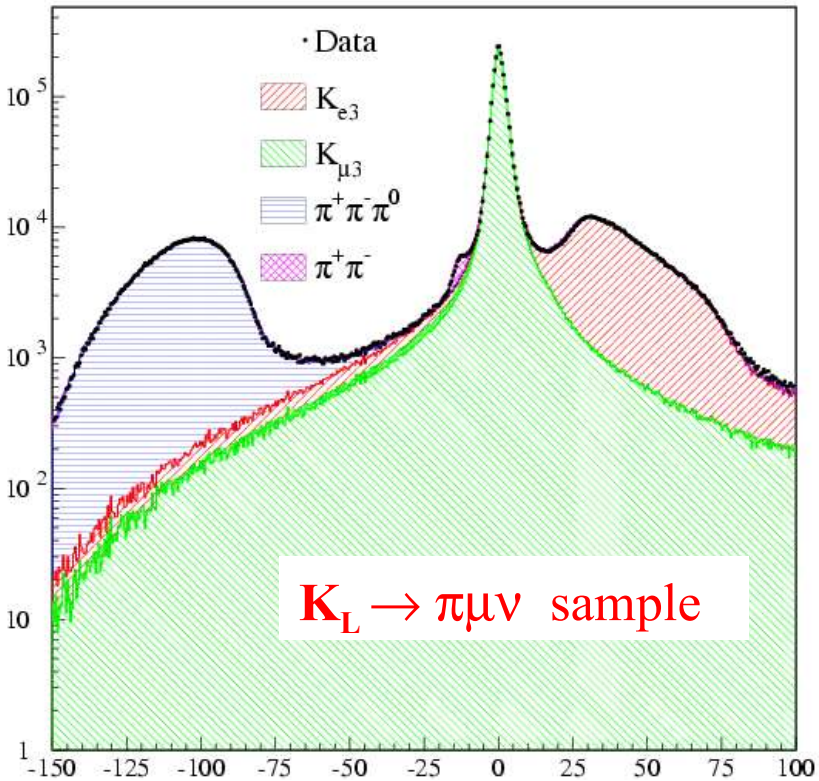
K_L decays: Kinematics

Charged K_L decay modes selected by kinematics: $\mathbf{P_{miss} - E_{miss}}$

$\mathbf{P_{miss} - E_{miss}}$ distribution very sensitve to radiation and momentum resolution → Check with independent selection by PiD



Lesser of $\mathbf{P_{miss} - E_{miss}}$ in πe or $e\pi$ hyp. (MeV)



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

K_L decays: Preliminary results

- Preliminary results:

$BR(K_L \to \pi e \nu) = 0.3994 \pm 0.0006 \pm 0.0034$

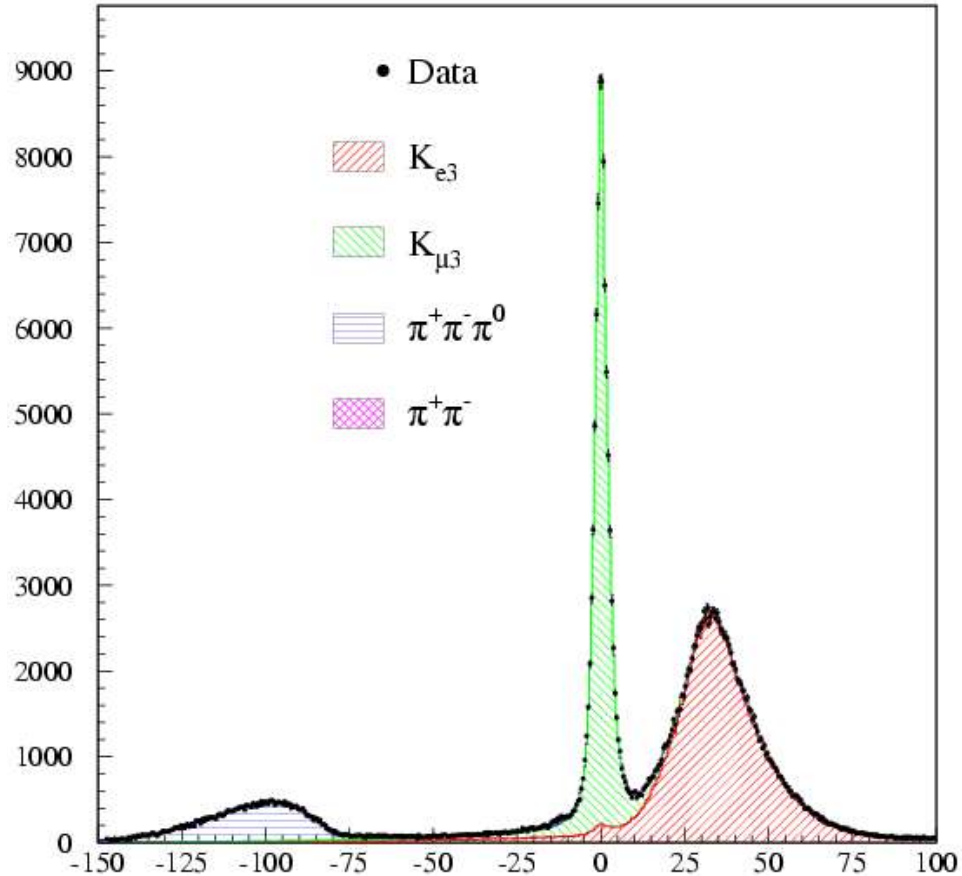
$BR(K_L \to \pi \mu \nu) = 0.2708 \pm 0.0005 \pm 0.0025$

$BR(K_L \to 3\pi^0) = 0.2014 \pm 0.0003 \pm 0.0022$

$BR(K_L \to \pi^+\pi^-\pi^0) = 0.1271 \pm 0.0004 \pm 0.0010$

- Preliminary systematics:

	$\pi e \nu$	$\pi \mu \nu$	$\pi^+\pi^-\pi^0$	$3\pi^0$
Selection	0.0004	0.0003	0.0002	0.0015
Shape	0.0010	0.0008	-	-
Tag bias	0.0022	0.0016	0.0006	0.0011
Lifetime	0.0023	0.0017	0.0007	0.0012



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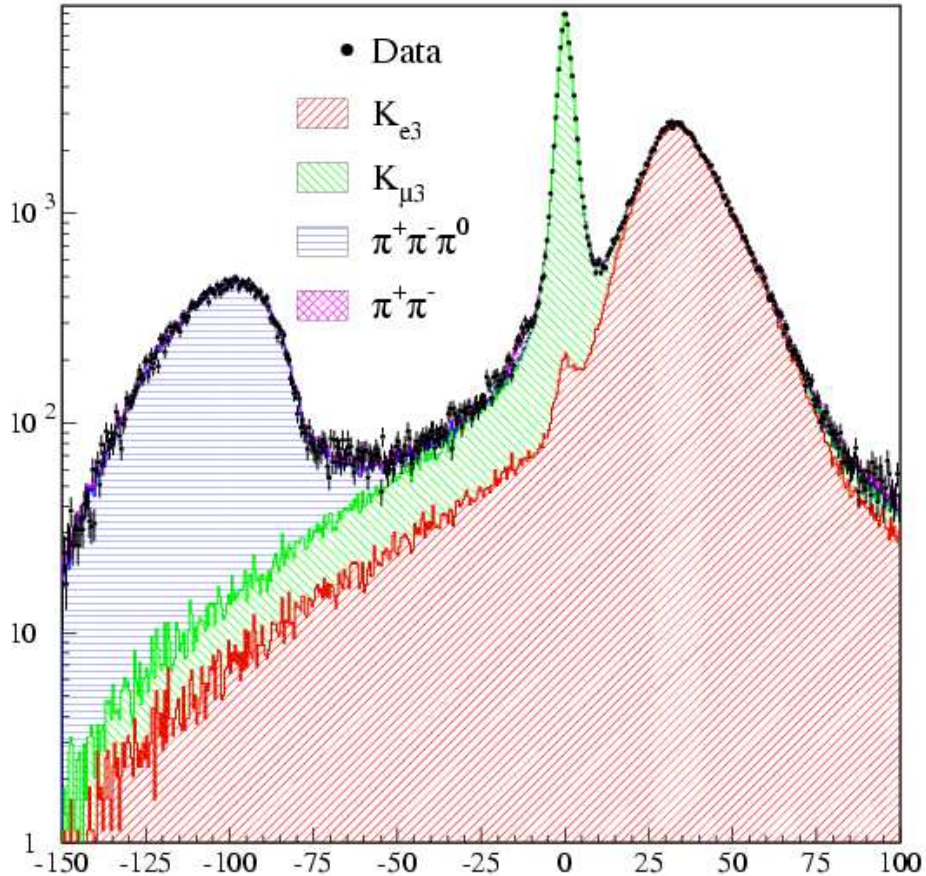
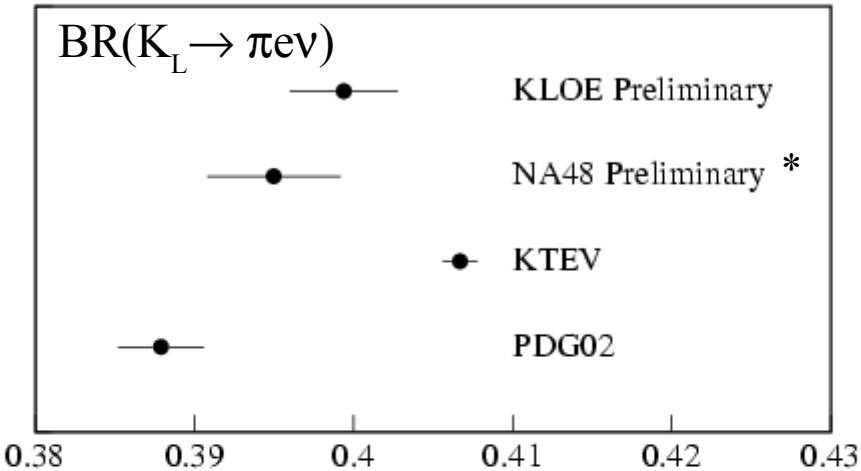
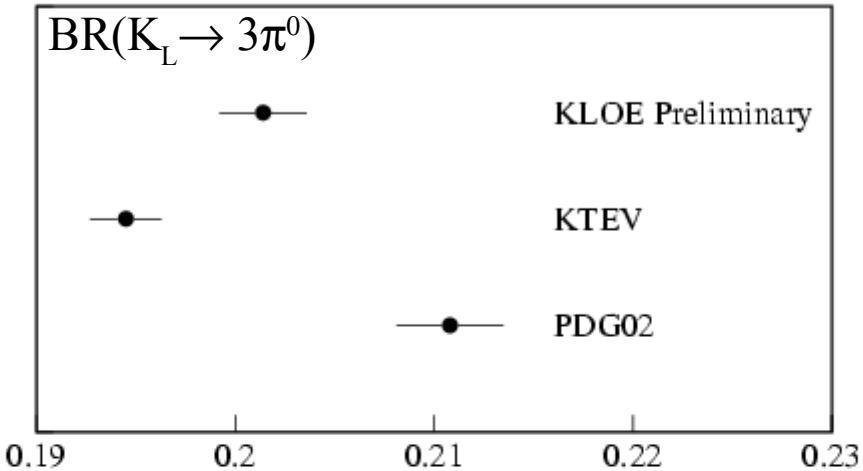
Lifetime	0.0023	0.0017	0.0007	0.0012

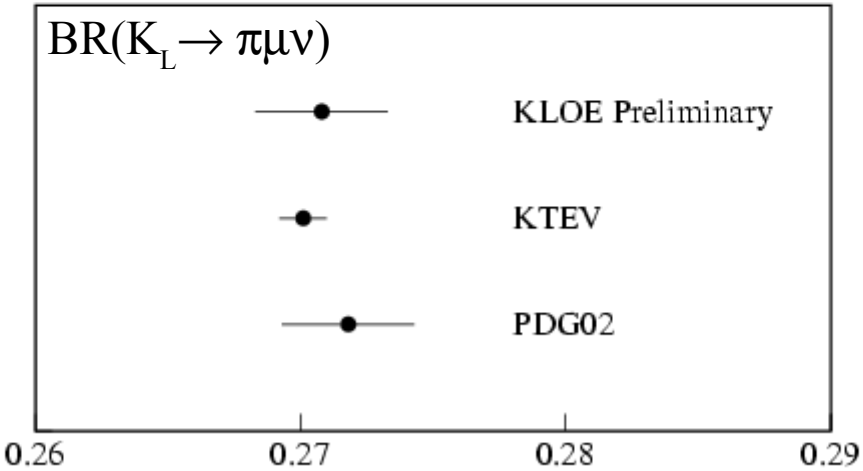


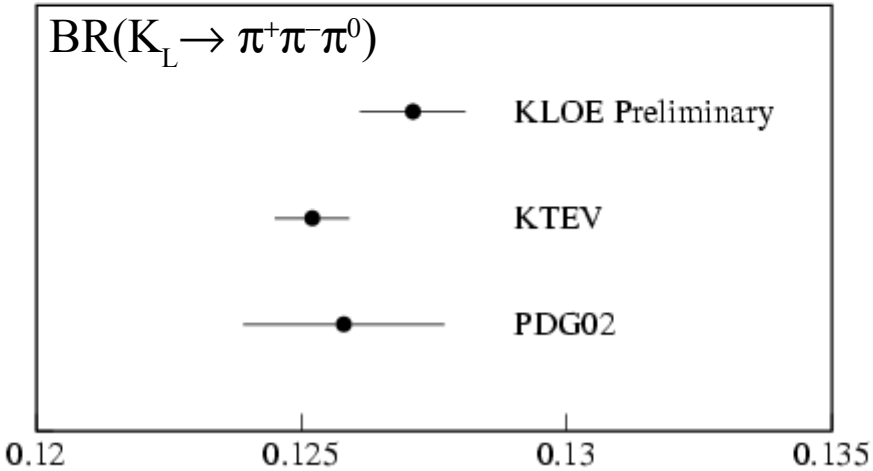
Lesser of $\mathbf{P_{miss}} - \mathbf{E_{miss}}$ in $\pi\mu$ or $\mu\pi$ hyp. (MeV)

K_L decays: results comparison









* Will go up using KLOE/KTEV BR($K_L \to 3\pi^0$)

K_L decays: lifetime from unitarity

- sum of absolute branching fractions:

$$\Sigma\, BR(K_L \rightarrow \mathbf{X}) = 1.0023 \pm 0.0009 \pm 0.0077$$ Rare decays from PDG

Upper limit on K_L invisible BR $1.05 \cdot 10^{-2}$ @90 C.L.

- K_L FV acceptance depends on K_L lifetime

Assuming $\Sigma\, BR(K_L \rightarrow \mathbf{X}) = 1$ $\lambda_{KL} = 51.35 \pm 0.05 \pm 0.26$ ns

K_L lifetime from $K_L \to \pi^0\pi^0\pi^0$

tag with $K_S \to \pi^-\pi^+$

at least 3 neutral clusters in EMC

neutral vertex reconstruction and $3\pi^0$ selection

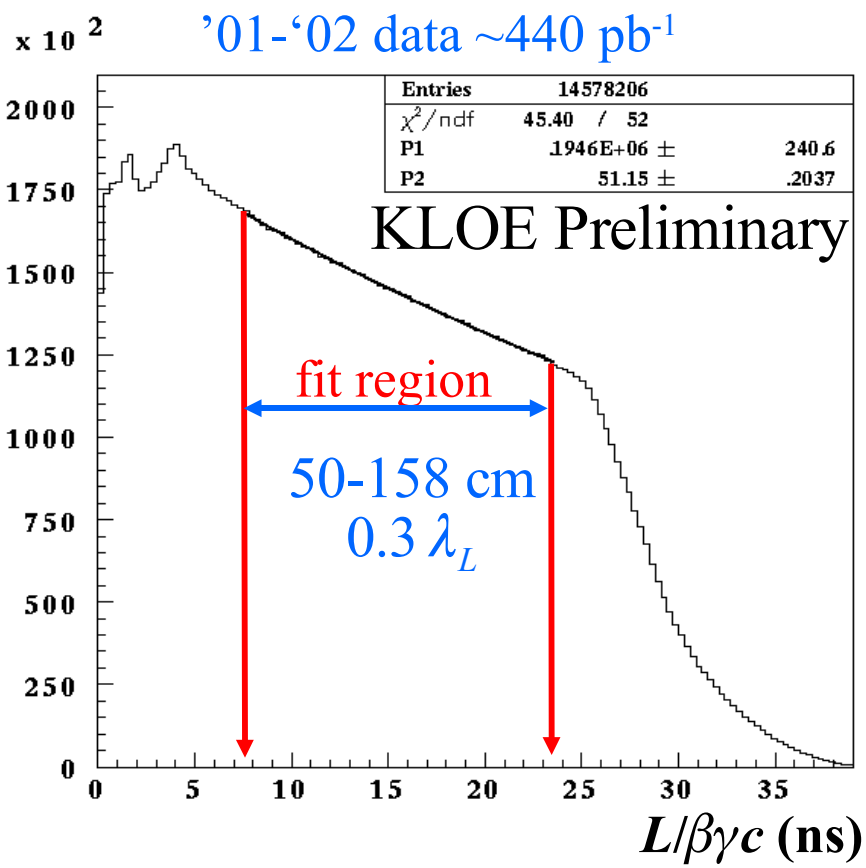
14.5 Mevents selected

checks with data for:

neutral vertex calibration, resolution

and photon efficiency

using $K_L \to \pi^+\pi^-\pi^0$



τ (PDG) (fit) = (51.7 ± 0.4) ns

τ (Vosburg, 1972) = (51.54 ± 0.44) ns - 0.4 Mevents

τ (KLOE) = (51.15 ± 0.20stat) ns - 14.5 Mevents – 440 pb^{-1}

Preliminary Systematics 0.6%

Unitarity test of CKM matrix – V_{us}

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

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

$$\Delta = 0.0042 \pm 0.0019 \quad \text{PDG02}$$

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

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

$|V_{us}|$ from neutral K_{l3} partial decay widths

$$|V_{us}| \times f_+^{K^0\pi^-}(0) = \left[\frac{128\pi^3 \Gamma_K^\ell}{G_F^2 M_K^5 S_{ew} I_K^\ell(\lambda_+, \lambda_0)} \right]^{1/2} \frac{1}{1+\delta_{em}^{K\ell}}$$

$f_+^{K0\pi-}(0)$ form factor at zero momentum transfer: pure theory calculation (χPT, lattice)

$I_K^\ell(\lambda_+, \lambda_0)$ phase space integral, S_{ew} short distance corrections (1.0232)

λ_+, λ_0 slopes (momentum dependence of the vector and scalar form factors)

$\delta_{em}^{K\ell}$ electromagnetic correction (amplitude and phase space)

KLOE measurements of $V_{us} f_+^{K\pi}(0)$

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

use quadratic parametrization

$$f_i(t) = f_i(0)\left[1 + \lambda_i \frac{t}{m_{\pi^+}^2} + \frac{\lambda_i'}{2}\frac{t^2}{m_{\pi^+}^4}\right]$$

$\lambda_+ = 0.0206 \pm 0.0018$

$\lambda'_+ = 0.0032 \pm 0.0007$ from KTeV

$\lambda_0 = 0.0137 \pm 0.0013$

average K_L lifetime from KLOE and WA(Vosburgh '72, Devlin '67)

$\lambda_{KL} = 51.35 \pm 0.25$ ns

K_L BR's assuming unitarity

Preliminary KLOE results:

$|V_{us}| f_+^{K\pi}(0)(K_{Se3}) = 0.2171 \pm 0.0017$

$|V_{us}| f_+^{K\pi}(0)(K_{Le3}) = 0.2147 \pm 0.0014$

$|V_{us}| f_+^{K\pi}(0)(K_{L\mu3}) = 0.2167 \pm 0.0015$

from unitarity (Marciano):

$(1-|V_{ud}|^2)^{1/2} f_+^{K\pi}(0) = 0.2177 \pm 0.0028$

$f_+^{K\pi}(0)$ from Leutwyller-Roos **0.961(8)**

confirmed by D. Becirevic et al. (Lattice+CHPT) **0.960(9)**

KLOE measurements of $V_{us} f_+^{K\pi}(0)$

Compare **our measurements of $V_{us} f_+^{K\pi}(0)$**

$\Gamma(K_S \to \pi e \nu)$ from KLOE

$\Gamma(K_L \to \pi \ell \nu)$ from KLOE

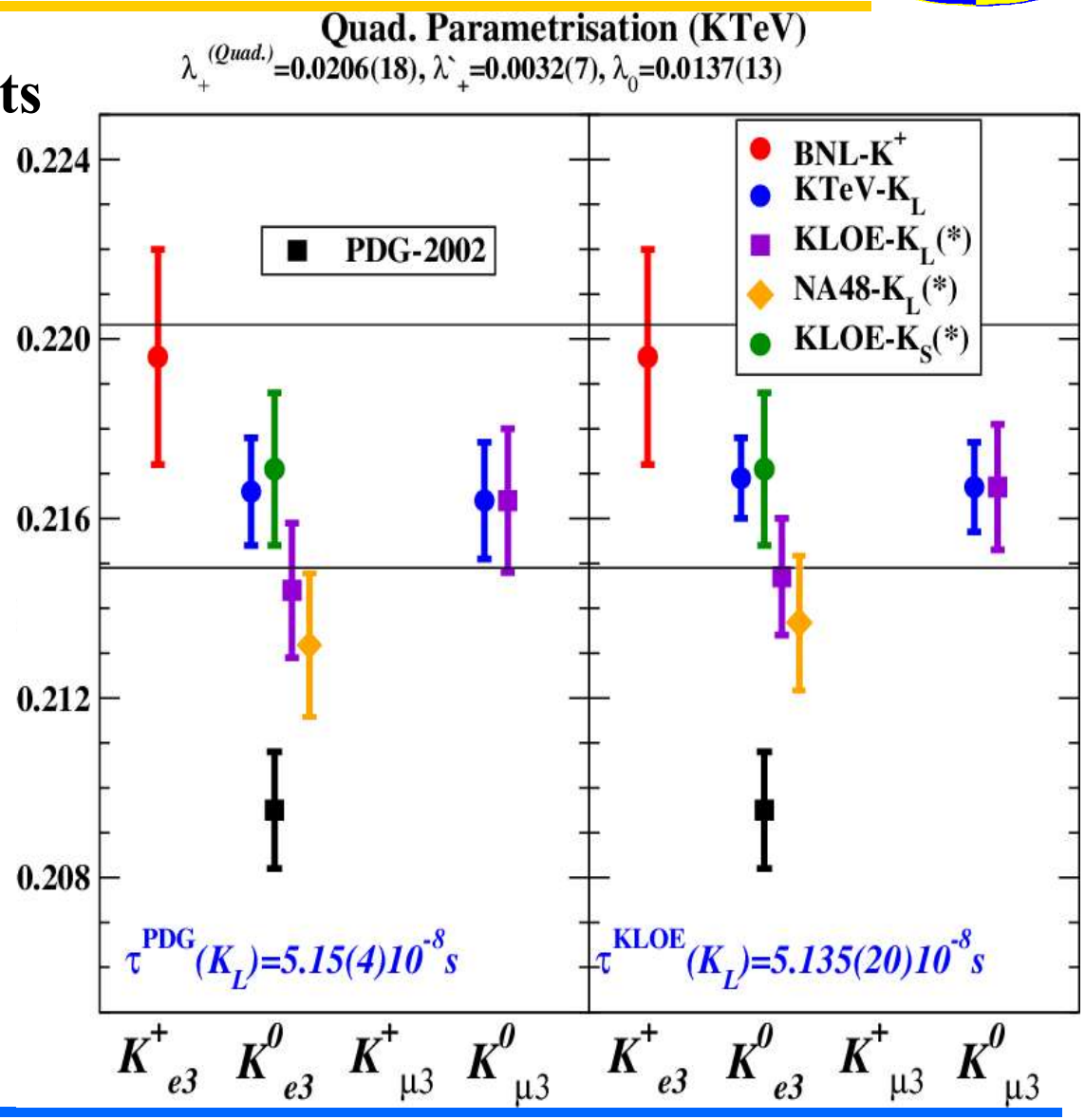
with:

$\Gamma(K^+ \to \pi^0 e^+ \nu)$ from E865

$\Gamma(K_L \to \pi \ell \nu)$ from KTEV

$\Gamma(K_L \to \pi e \nu)$ from NA48

$\Gamma(K_L \to \pi e \nu)$ from PDG02



Summary

KLOE is analyzing a unique data sample: 500 pb^{-1} of ϕ decays

- Best upper limit on $K_S \rightarrow \pi^0\pi^0\pi^0$

  important contributions to the measurement of V_{us}
- K_S semileptonic BR measured for first time with 1.4% accuracy
- Preliminary measurements of dominat K_L BR's with 0.9% accuracy
- Preliminary measurements of K_L lifetime with 1%-0.5% accuracy
- Analysis of $K^{\pm}$, BR's, and lifetime in progress
- Analysis of K_L semileptonic form factor slopes in progress

KLOE expects to collect 2 fb^{-1} in 2004-2005

- improved analyses of rare decays and interference studies