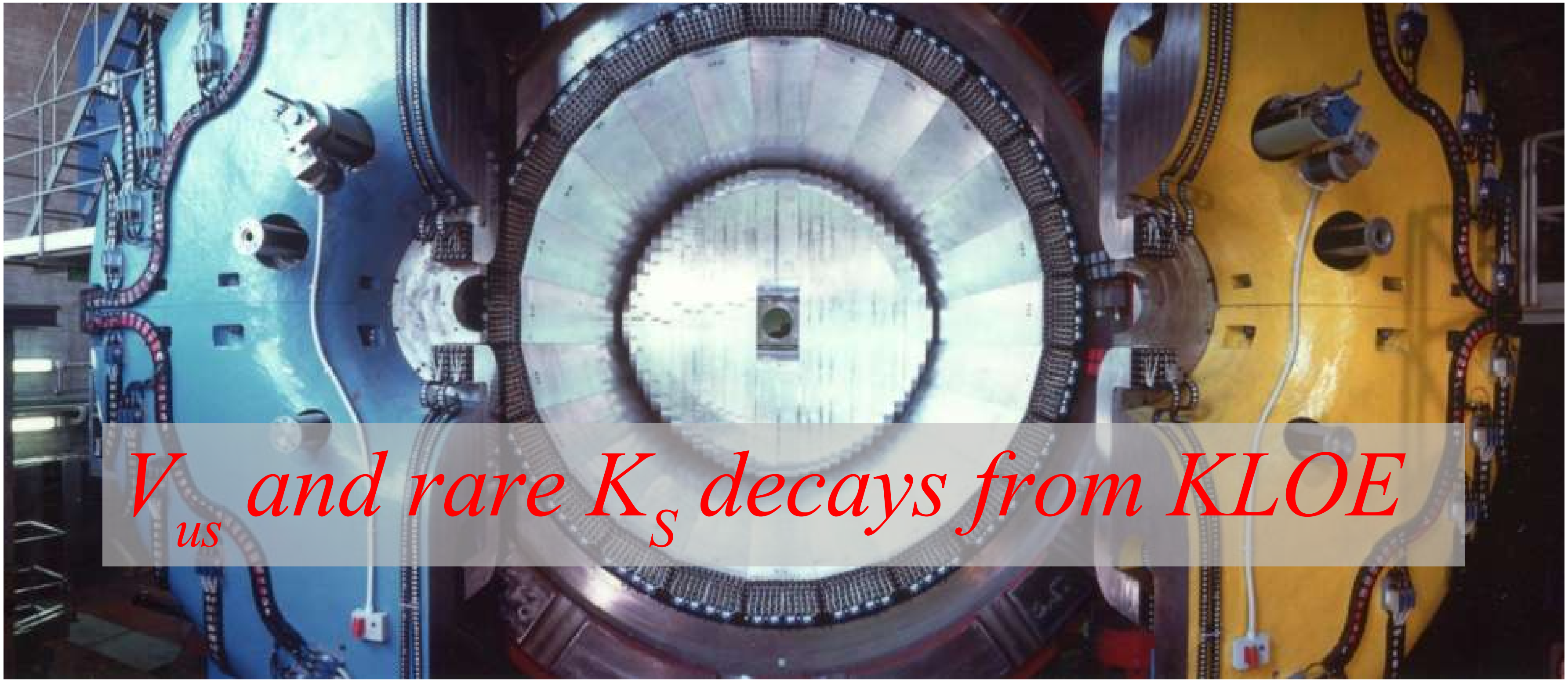


V_{us} and rare K_S decays from KLOE

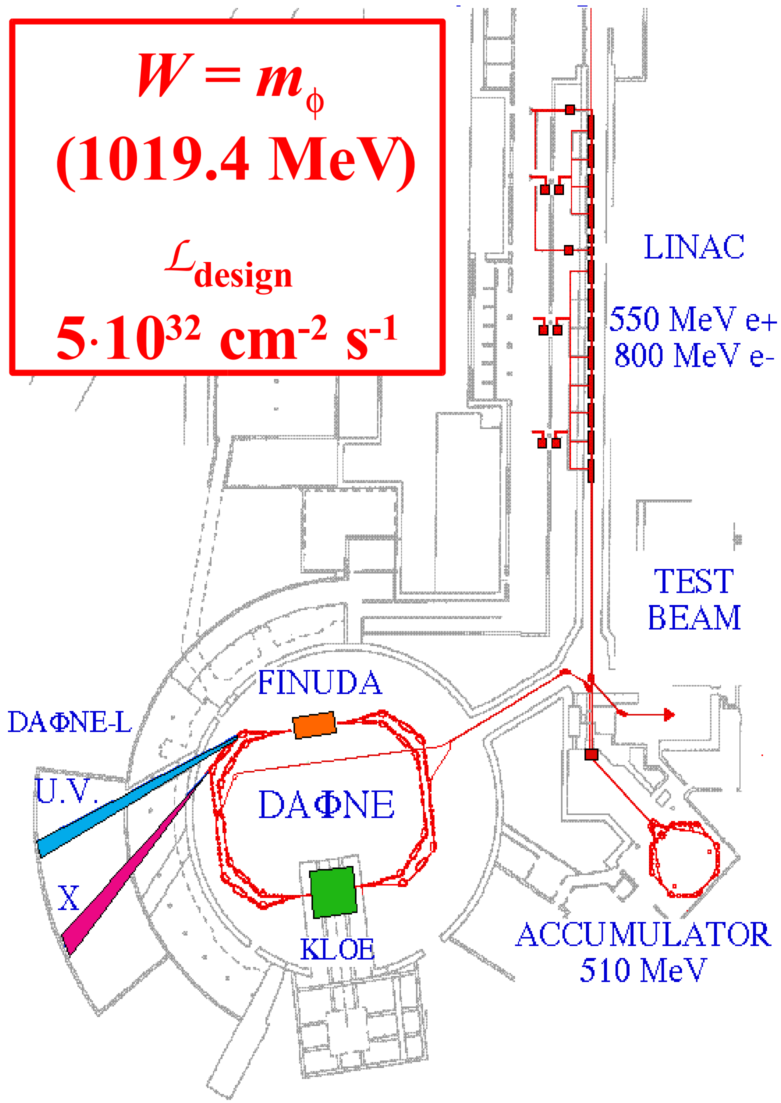
M.Antonelli (INFN/Frascati)
for the KLOE collaboration

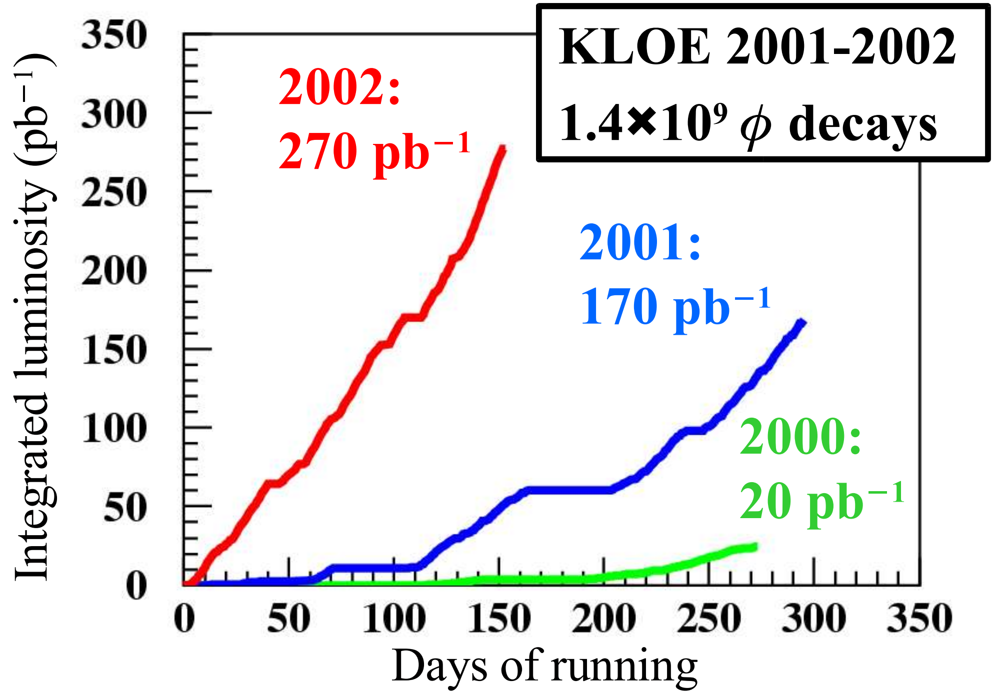
Les Rencontres de Physique de la Vallée d'Aoste 2005

La Thuile, February 27- March 5

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 $\mathcal{L}_{peak}$ **1.2×10^{32} cm^{-2} s^{-1}**

2004 integrated $\mathcal{L}$ **~0.7 fb^{-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^+) ⟵ Φ ⟶ 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 $K_{L,S}$

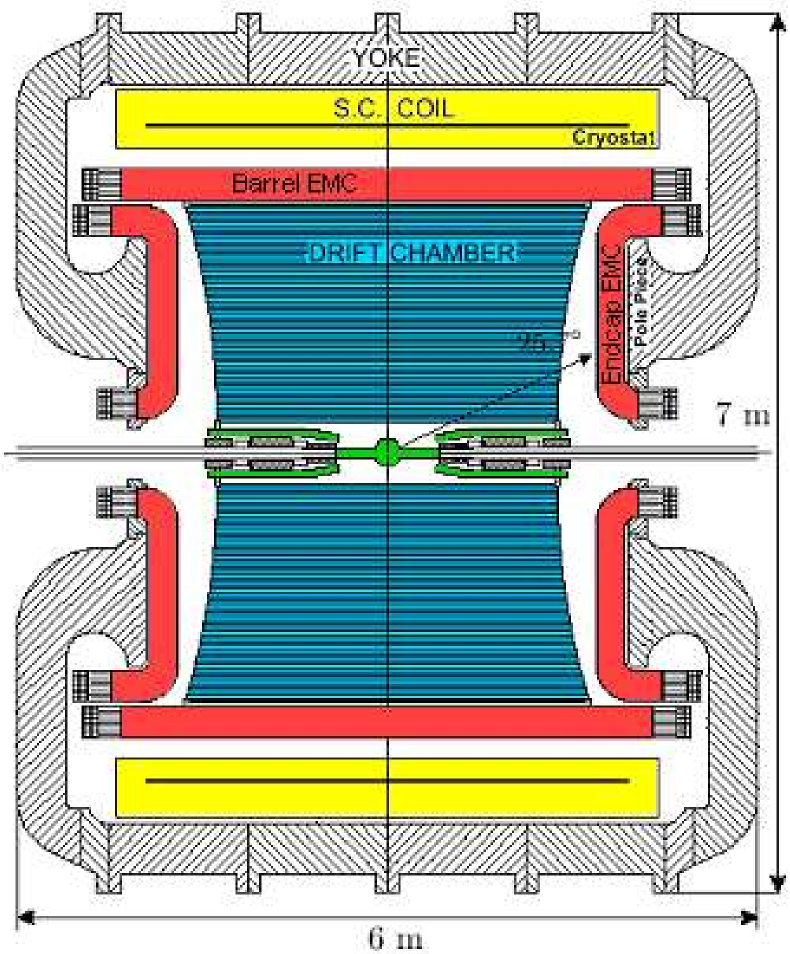
  - precision measurement of absolute BR's

- 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



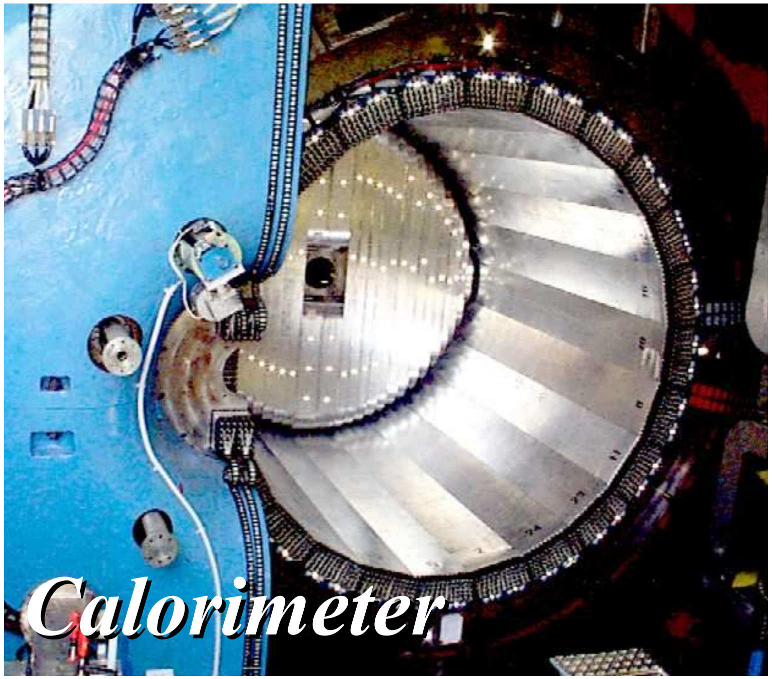
Be beam pipe (0.5 mm thick)
Instrumented permanent magnet quadrupoles (32 PMT's)

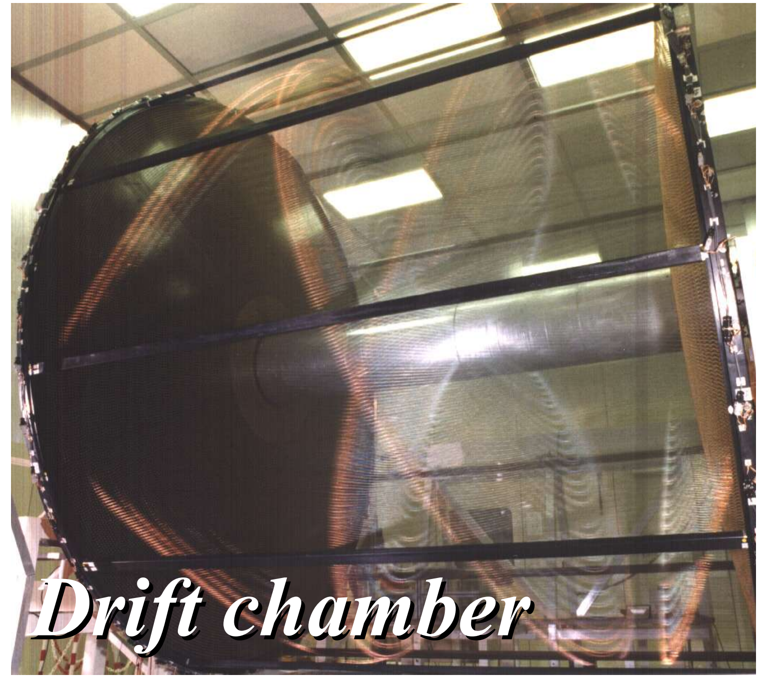
Drift chamber (4 m ∅ × 3.3 m)
90% He + 10% IsoB, CF frame
12582 stereo sense wires

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 performance





σ_E/E **5.7% $/\sqrt{E(\text{GeV})}$**

σ_t **54 ps $/\sqrt{E(\text{GeV})} \oplus$ 50 ps**

(relative time between clusters)

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

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

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

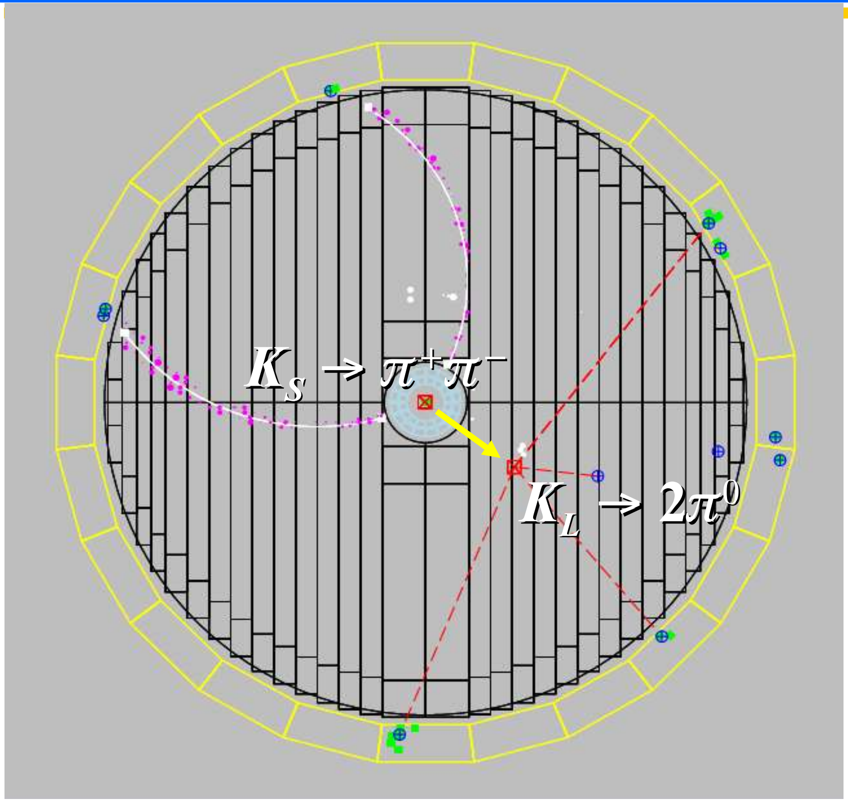
σ_x^{vertex} **~1 mm**

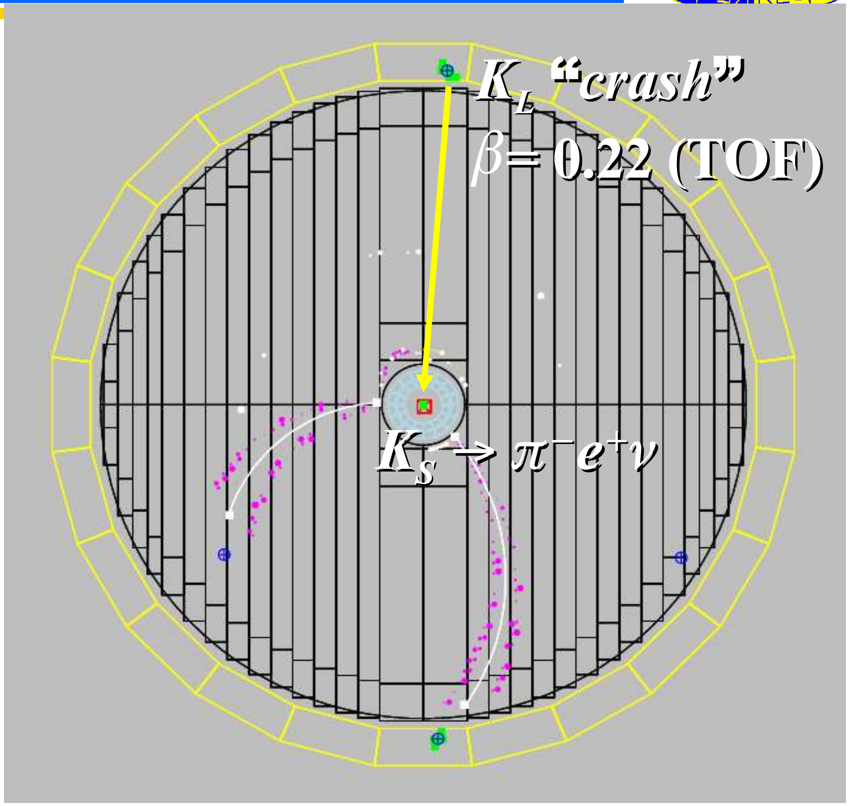
$\sigma(M_{\pi\pi})$ **~1 MeV**

Kaon physics at KLOE

$\Rightarrow$ $K_S \to \pi^0\pi^0\pi^0$	**Final 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
$K_S \to \pi e \nu$ $\Rightarrow$ $K_S \to \pi \mu \nu$	***Phys. Lett.* B535 37 (2002) Preliminary update** **First observation**
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)**
$\Rightarrow$ $K_L \to \pi\mu\nu$, $\pi e\nu$, $\pi^+\pi^-\pi^0$, $3\pi^0$	**Final results**
$\Rightarrow$ **K_L mean life**	**Final results**
$\Rightarrow$ **V_{us} from $K \to \pi \ell \nu$**	**Final results**
CP violation & interference	**In progress**
V_{us} from $K^{+/-}$	**In progress**
$K^+ \to \pi^+\pi^0\pi^0$	***Phys. Lett.* B597 139 (2004)**

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 < 7.4 × 10^{-7} 90% CL NA48 '05

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 $\delta = (2.4 \pm 5.0) \times 10^{-5}$ CPLEAR '99

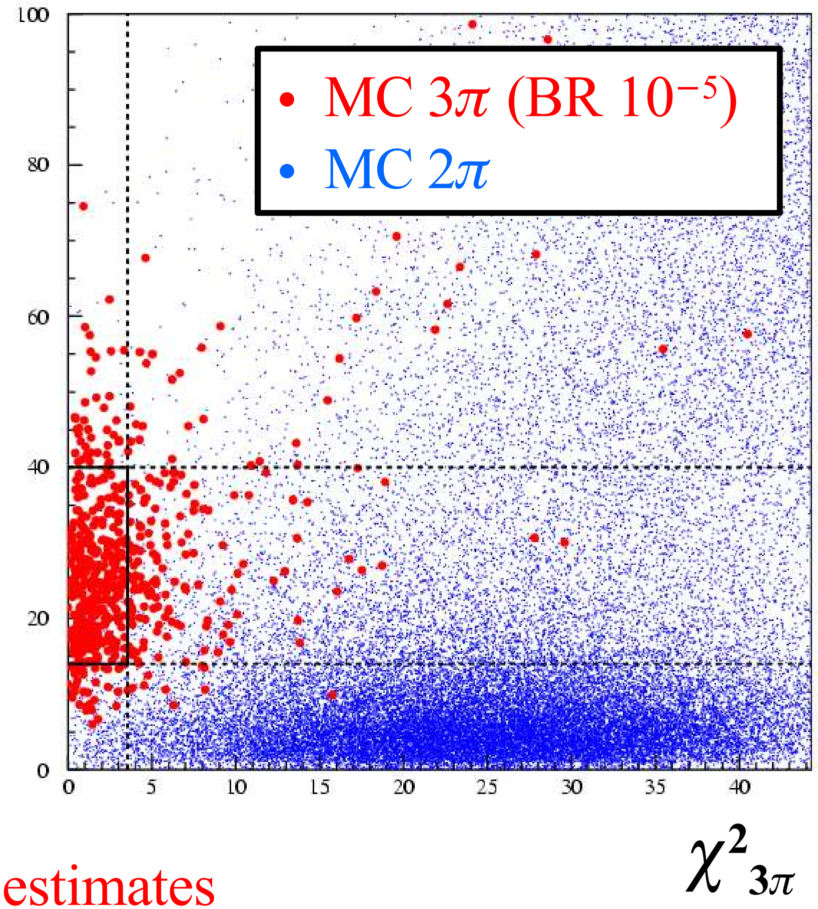
Im $\delta = (-0.2 \pm 2.0) \times 10^{-5}$ NA48 '05

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

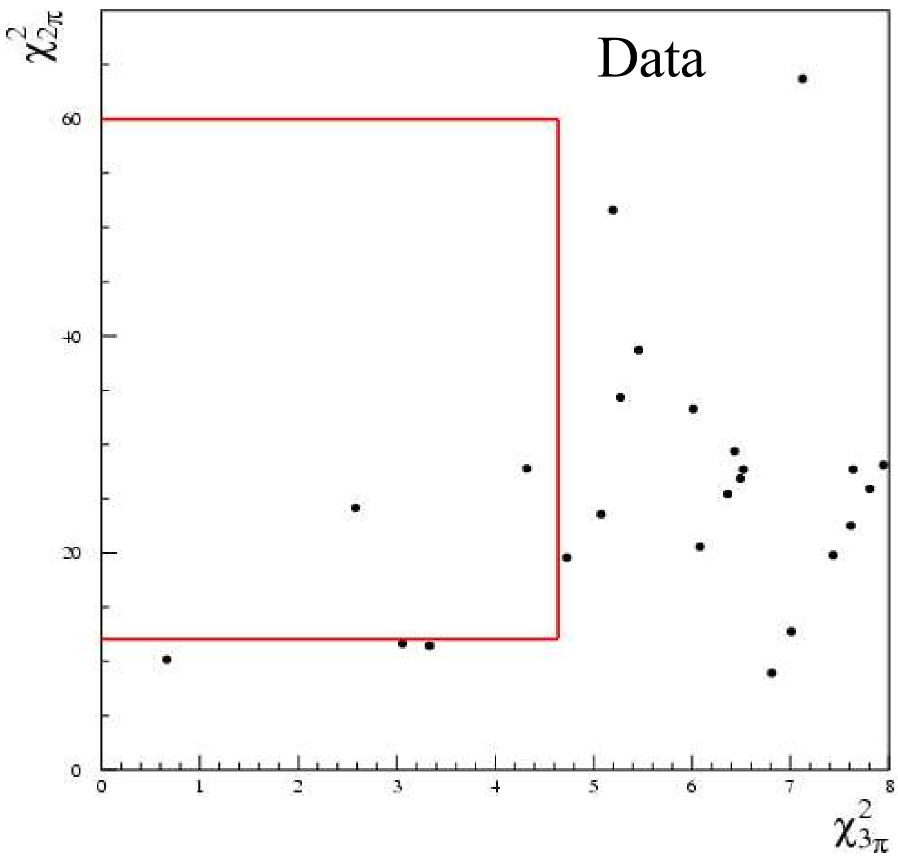
- Define signal box in $\chi^2_{3\pi}$ vs. $\chi^2_{2\pi}$ plane:

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

  $\chi^2_{2\pi}$ pair best 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

$\varepsilon_{3\pi} =$ 24.3%

(events with K_L crash)

N_{bkg}**(MC) = 3.13 ± 0.82 ± 0.37**

N_{obs} **= 2**

KLOE

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

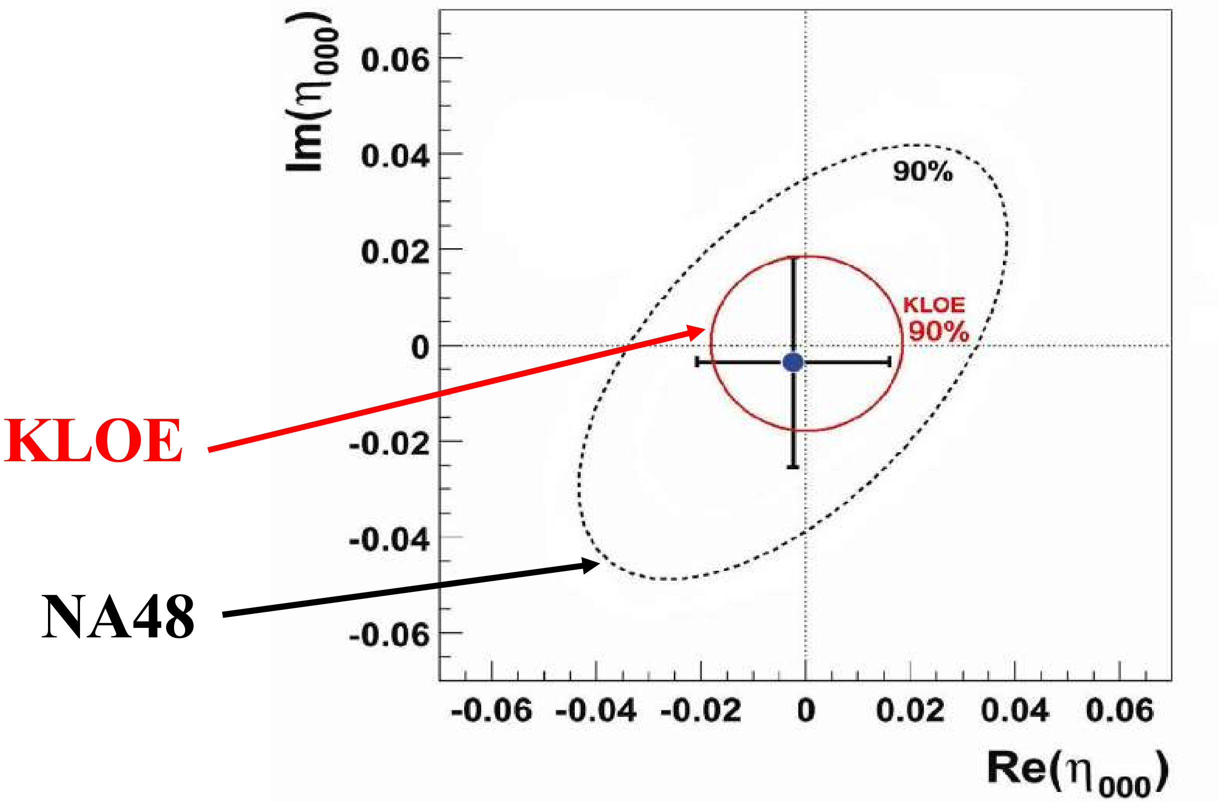
BR($K_S \to \pi^0\pi^0\pi^0$)

$\leq 1.2 \times 10^{-7}$ 90% CL

Constraints for η^{000}

Using the PDG values and our limit we have:

$$|\eta^{000}| = \frac{A(K_S \to 3\pi^0)}{A(K_L \to 3\pi^0)} \sqrt{\frac{\tau_L}{\tau_S} \frac{B(K_S \to 3\pi^0)}{B(K_L \to 3\pi^0)}} < 0.018 \quad 90\ \%\ \mathrm{CL}$$



First observation of $K_S \to \pi\mu\nu$ decay

- Selection a la $K_S \to \pi e \nu$:

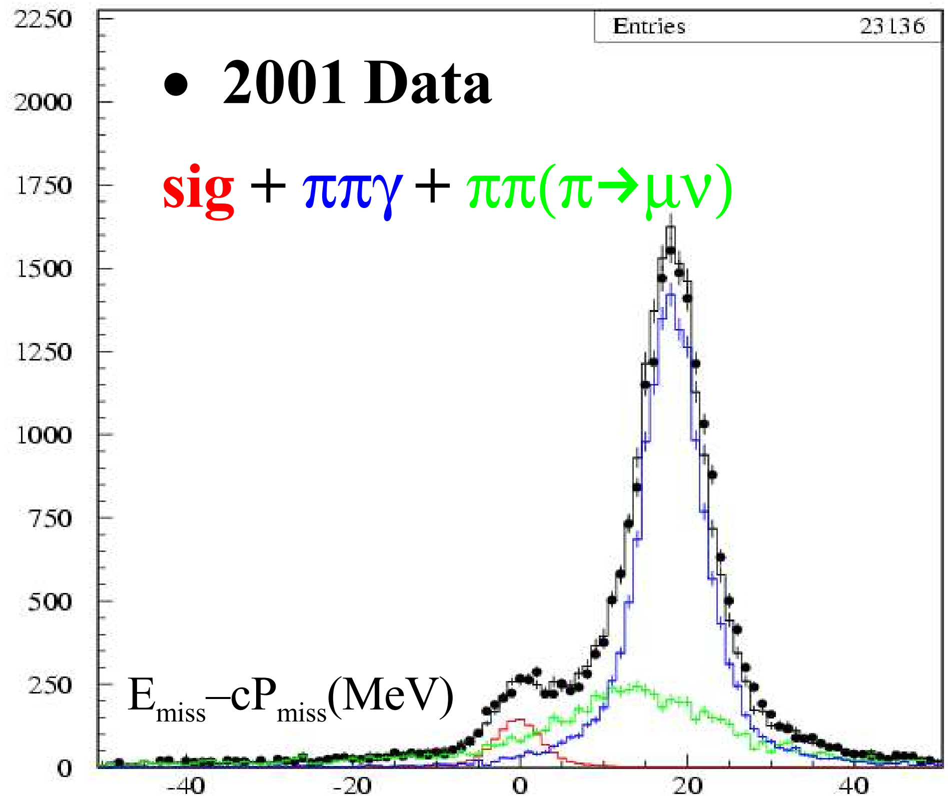
  K_{crash} tag + 2 tracks from IP with $M_{\pi\pi} < 490$ MeV (reject $K_S \to \pi\pi(\gamma)$)

TOF identification: compare π-μ expected flight times, reject ππ,πμ bkg

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

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

$$P_{miss} = |\mathbf{P_K} - \mathbf{P_\pi} - \mathbf{P_\mu}|$$



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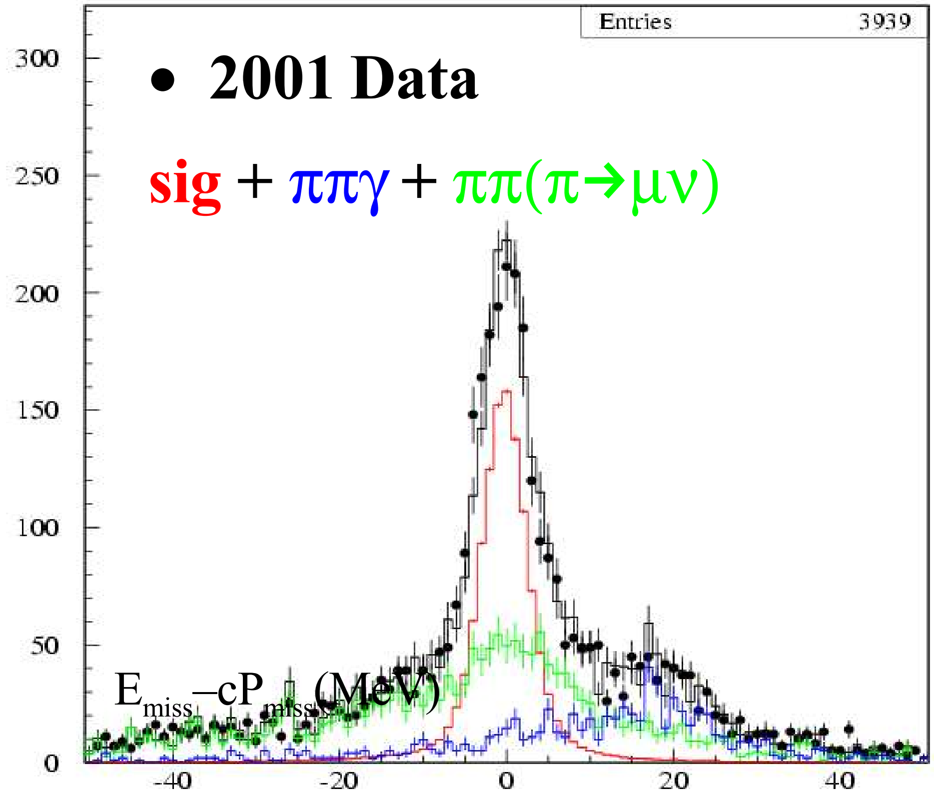
$$E_{miss} = \sqrt{M_K^2 + P_K^2} - E_\pi - E_\mu$$

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

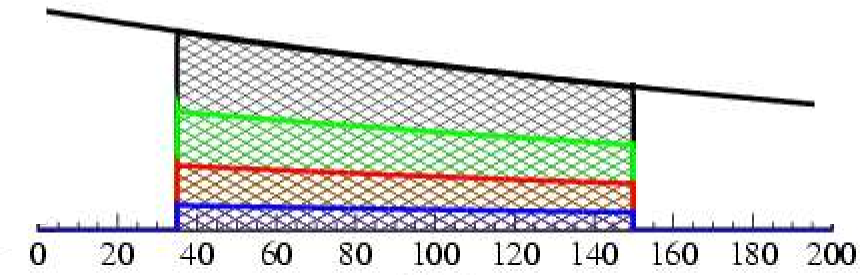
with tighter Kinematic cuts + rad. photon search in ππγ



K_L absolololute branching ratios

Absolute BR K_L:

$$BR(K_L \to i) = \frac{N(i)}{\varepsilon(i)_{tag}/\varepsilon(all)_{tag}\ \varepsilon(i)_{rec}\ N_{tag}\ \varepsilon_{FV}[\tau(K_L)]}$$



N_{tag} from $K_S \to \pi^+\pi^-$ tag

$N(i)$ from: kinematic shape for charged modes, cuts based for neutral mode

$\varepsilon_{FV}[\tau(K_L)]$ from Monte Carlo + corrections from data and $\tau(K_L)$ measurement (~0.26)

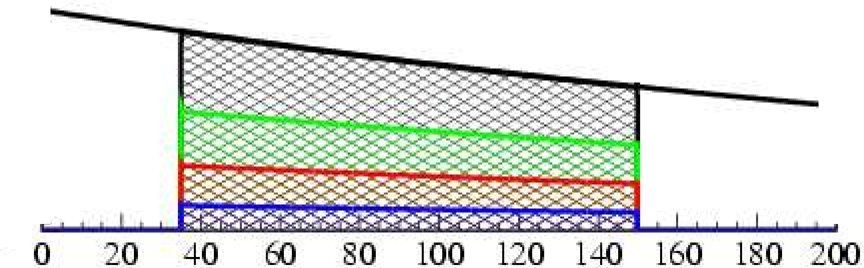
$\varepsilon(i)_{tag}/\varepsilon(all)_{tag}$ from Monte Carlo + corrections from data

$\varepsilon(i)_{rec}$ from Monte Carlo + corrections from data (0.5 for $\mathbf{K}_{\ell 3}$, 0.4 for $\pi^+\pi^-\pi^0$, 1.0 for $3\pi^0$)

Unitarity and K_L lifetime

Absolute BR K_L:

$$BR(K_L \to i) = \frac{N(i)}{\varepsilon(i)_{tag}/\varepsilon(all)_{tag}\ \varepsilon(i)_{rec}\ N_{tag}\ \varepsilon_{FV}[\tau(K_L)]}$$



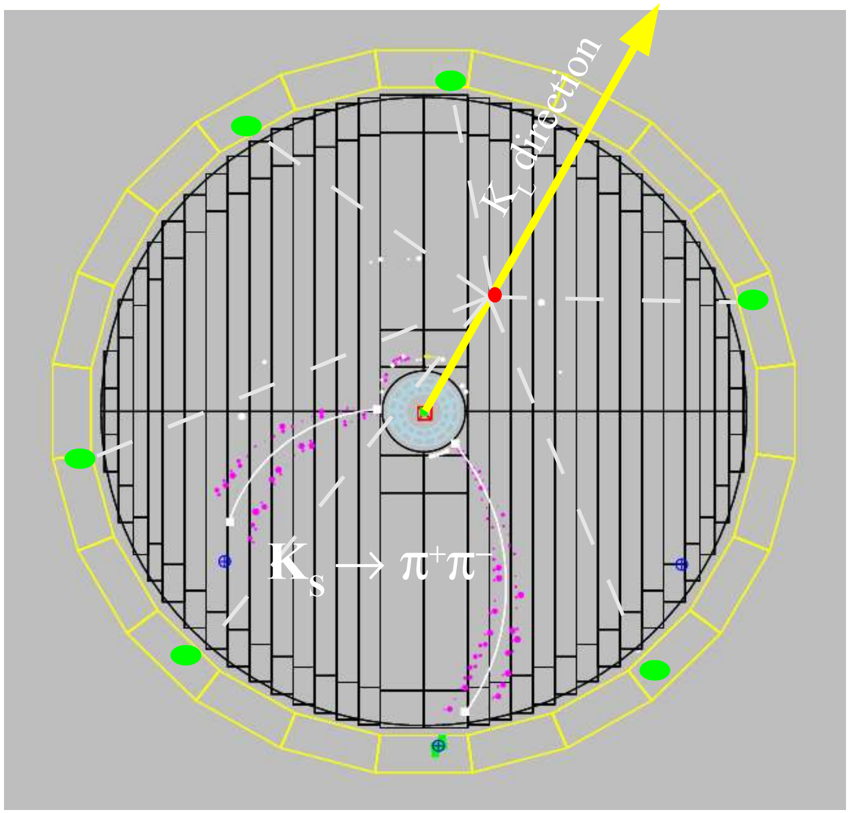
We measure ~99.64% of the K_L decays ($\pi e\nu$, $\pi\mu\nu$, $3\pi^0$, $\pi^+\pi^-\pi^0$):

Unitarity $\sum_i BR(K_L \to i)[\tau(K_L)] + 0.0036 \equiv 1 \quad \to \quad \tau(K_L)$

$$BR(K_L \to i) \quad \to \quad \frac{BR(K_L \to i)}{\sum_i BR(K_L \to i)[\tau(K_L)] + 0.0036}$$

K_L decays: Tag bias

Slightly different Tagging efficieny among K_L topologies

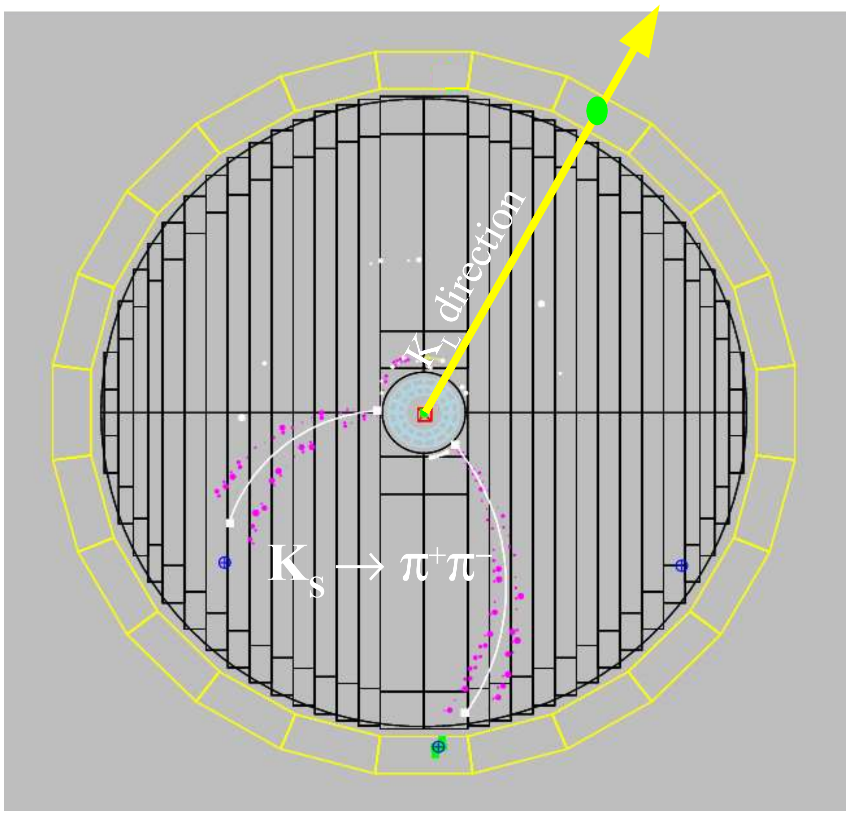


$K_L \rightarrow$ neutrals

- ~ 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

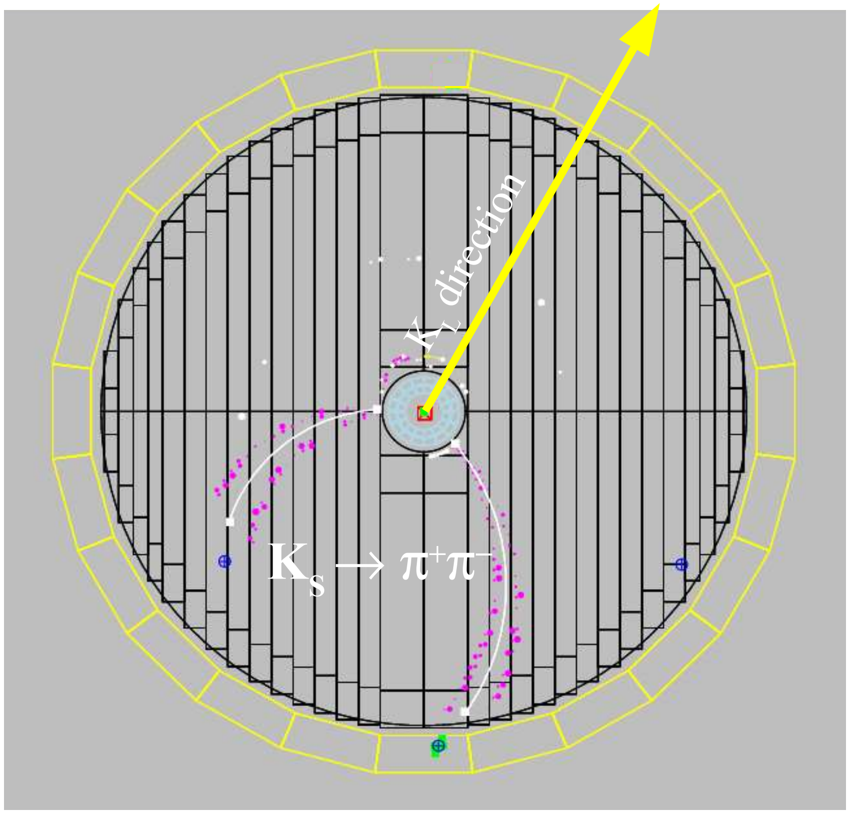
30%

trigger efficiency

90%

K_L decays: Tag bias

Slightly different Tagging efficieny among K_L topologies



$K_L \to$ interaction, punch-trough

	interaction	punch-trough
fraction	30%	17%
trigger efficiency	90%	65%

data/MC agreement at ~ 90%

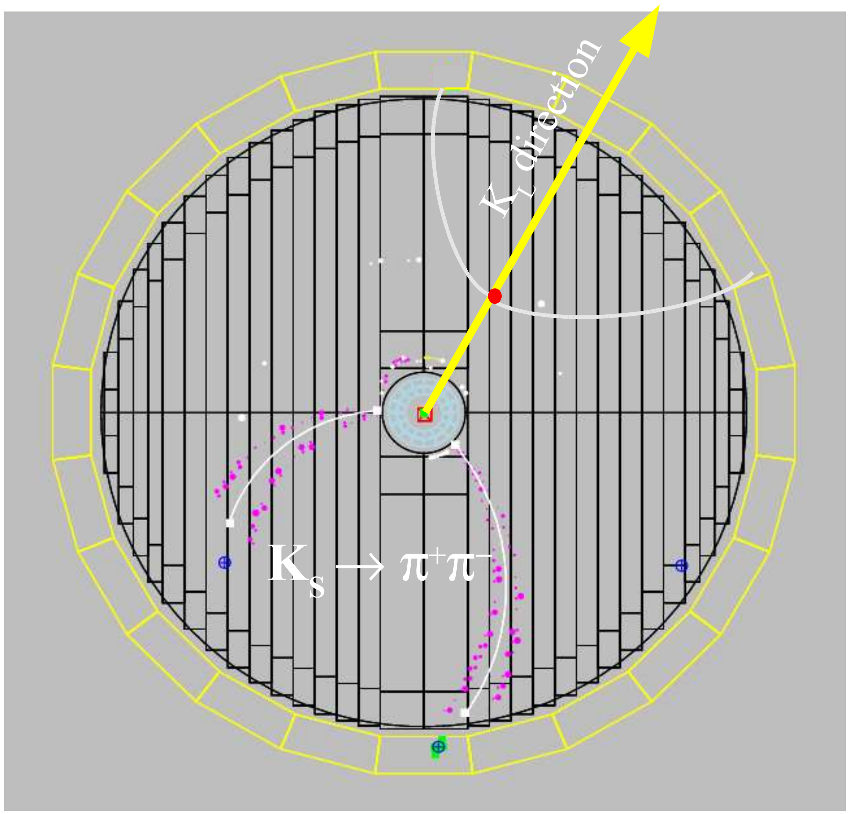
possible source of systematic uncertainty at ~ 1-2%

→

Tagging with K_S autoTrigger $\varepsilon \sim 10\%$

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%

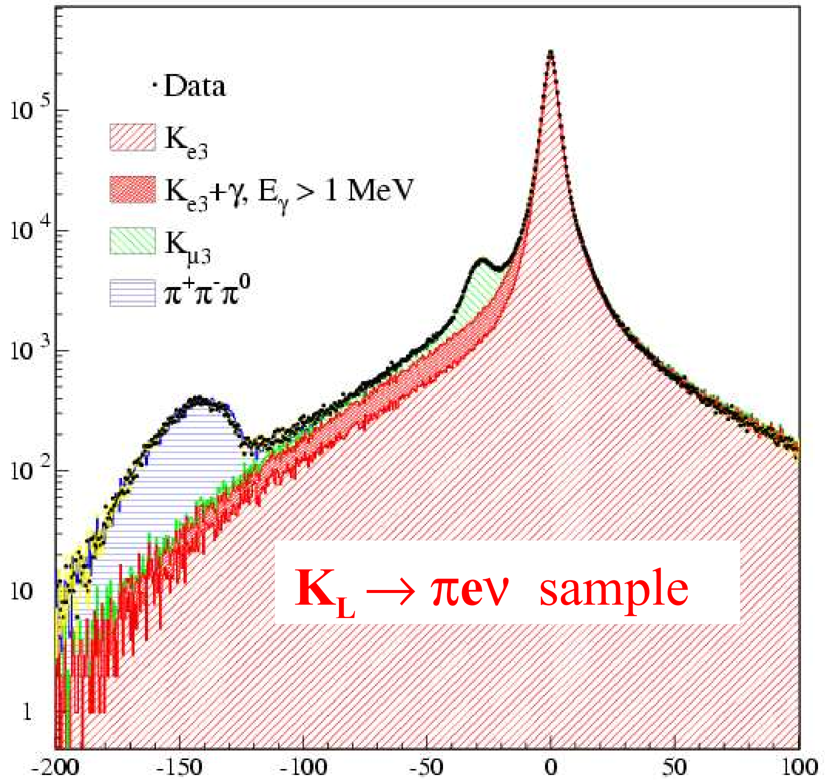
Typical biases for K_S autoTrigger Tag

charged	neutrals
0.98	1.00

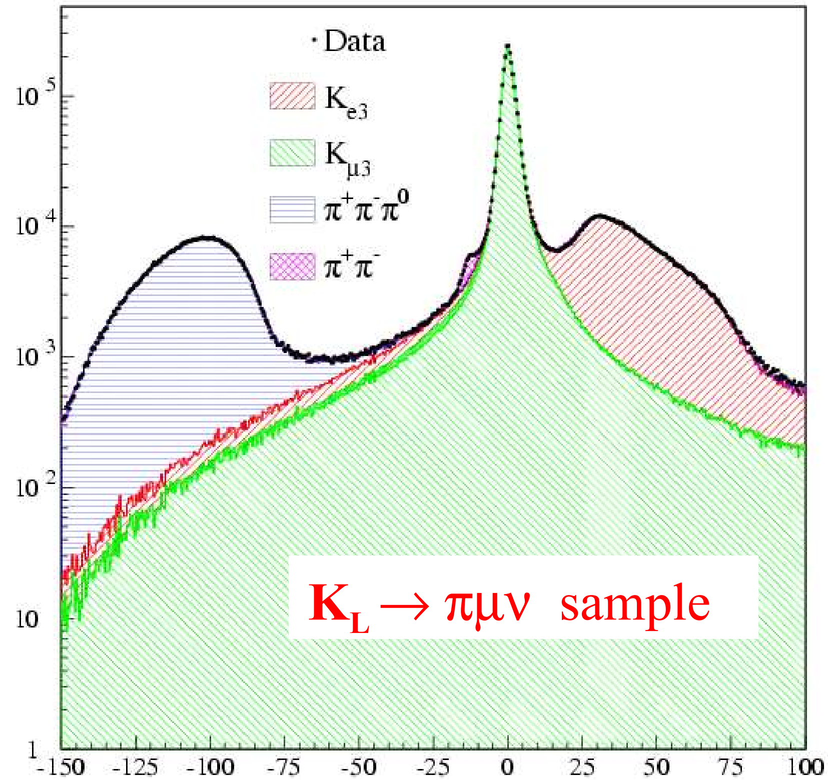
K_L decays: Kinematics

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 eπ hyp. (MeV)



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

K_L decays: Absolute BR's results

- Absolute BR's results ($\tau_{KL} = 51.54 \pm 0.44$ ns):

$BR(K_L \to \pi e \nu) = 0.4049 \pm 0.0010 \pm 0.0031$

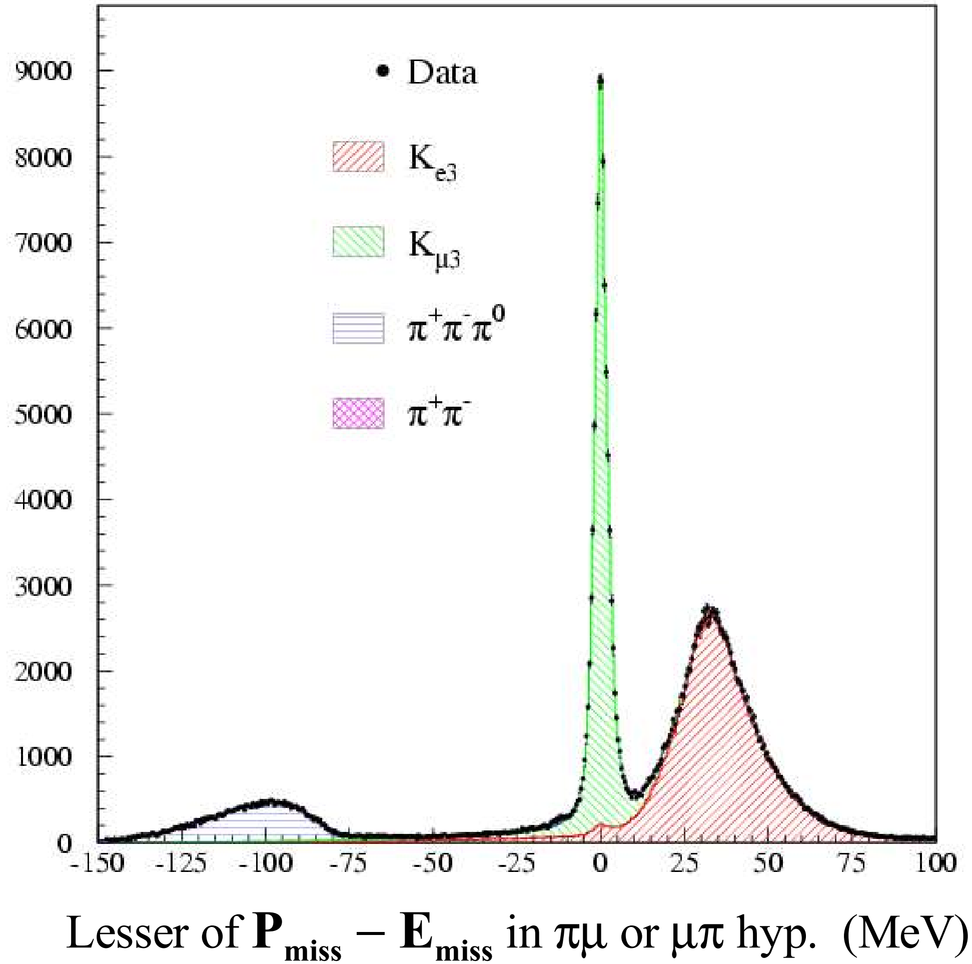
$BR(K_L \to \pi \mu \nu) = 0.2726 \pm 0.0008 \pm 0.0022$

$BR(K_L \to 3\pi^0) = 0.2018 \pm 0.0004 \pm 0.0026$

$BR(K_L \to \pi^+\pi^-\pi^0) = 0.1276 \pm 0.0006 \pm 0.0016$

- Systematics:

	$\pi e \nu$	$\pi \mu \nu$	$\pi^+\pi^-\pi^0$	$3\pi^0$
Selection	0.0011	0.0007	0.0004	0.0020
Shape	0.0006	0.0009	0.0010	-
Tag bias	0.0013	0.0008	0.0007	0.0005
Lifetime	0.0023	0.0017	0.0007	0.0012



K_L decays: lifetime from unitarity

- sum of absolute branching fractions ($\tau_{KL} = 51.54 \pm 0.44$ ns):

$$\sum BR(K_L \to \mathbf{i}) = 1.0104 \pm 0.0018 \pm 0.0074$$ Rare decays from PDG

Upper limit on K_L invisible BR $\quad 7.5 \cdot 10^{-3}$ @90 C.L.

- K_L FV acceptance depends on K_L lifetime

Assuming $\sum BR(K_L \to \mathbf{i}) \equiv 1 \qquad \tau_{KL} = 50.72 \pm 0.14 \pm 0.36$ ns

K_L decays: BR's results with unitarity

- BR's results :

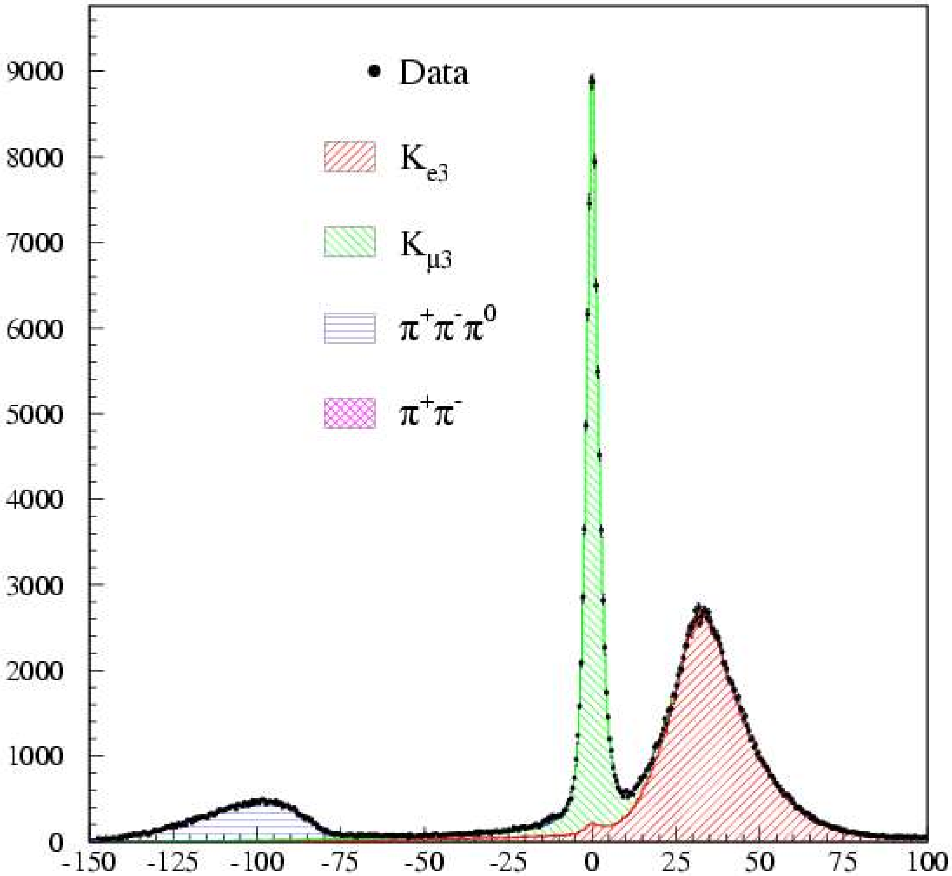
$BR(K_L \to \pi e \nu) = 0.4007 \pm 0.0006 \pm 0.0014$

$BR(K_L \to \pi \mu \nu) = 0.2698 \pm 0.0006 \pm 0.0014$

$BR(K_L \to 3\pi^0) = 0.1997 \pm 0.0005 \pm 0.0019$

$BR(K_L \to \pi^+\pi^-\pi^0) = 0.1263 \pm 0.0005 \pm 0.0011$

- Systematics evaluated including full error matrix from all sources.



Lesser of $\mathbf{P}_{\mathbf{miss}} - \mathbf{E}_{\mathbf{miss}}$ in $\pi\mu$ or $\mu\pi$ hyp. (MeV)

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

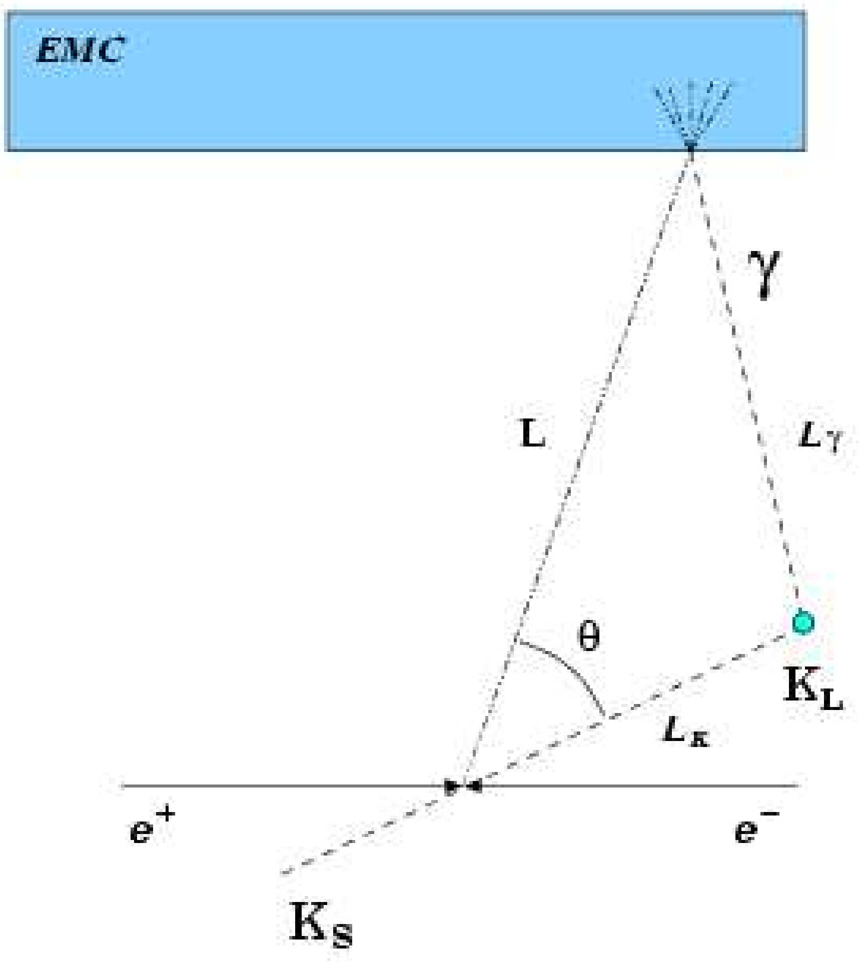
tag with $K_S \to \pi^-\pi^+$

at least 3 neutral clusters in EMC

neutral vertex reconstruction

$3\pi^0$ selection

~99% efficiency ~1% background



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

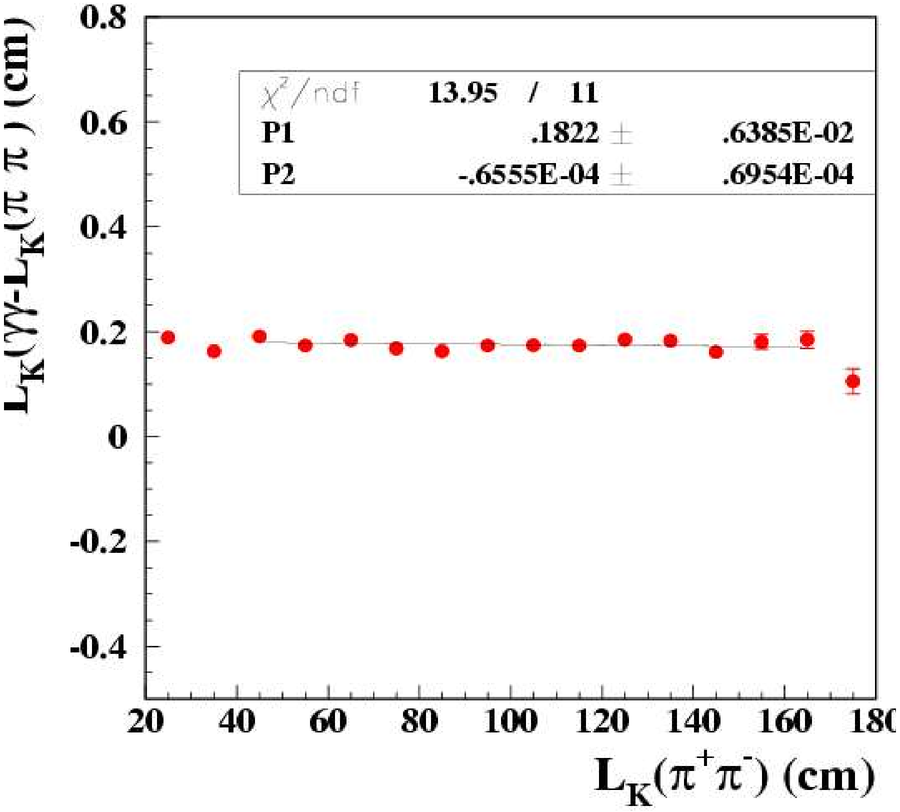
$3\pi^0$ selection

checks with data for:

neutral vertex calibration, resolution

and photon efficiency

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



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

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

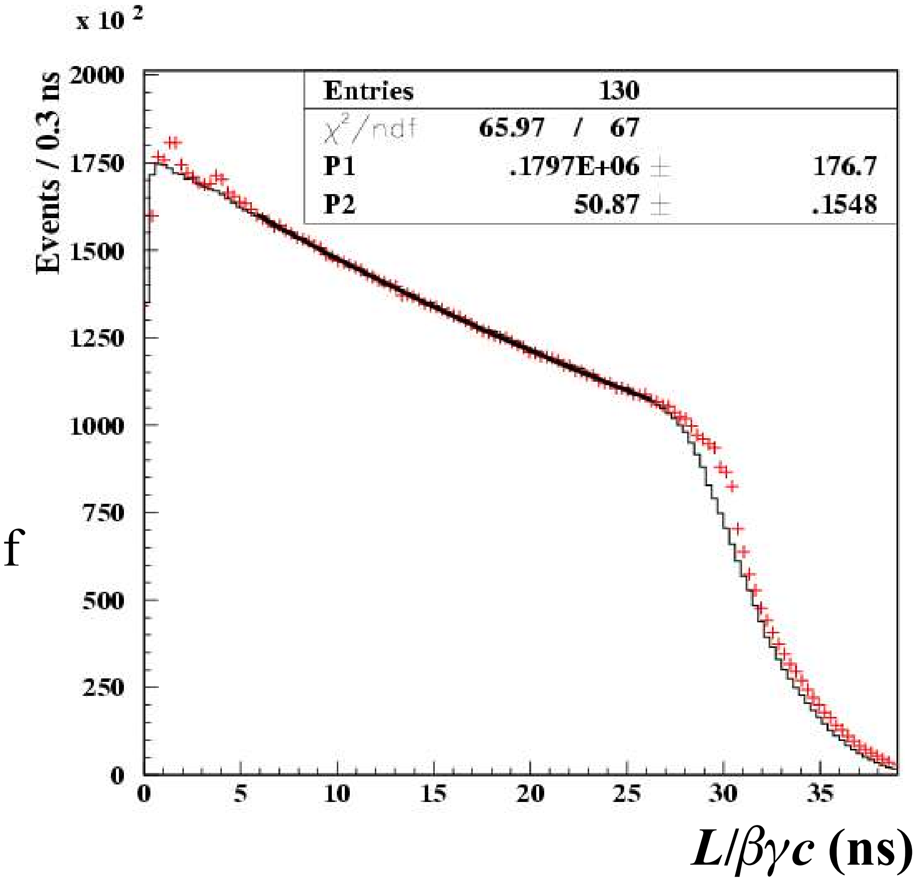
at least 3 neutral clusters in EMC

neutral vertex reconstruction

$3\pi^0$ selection

14.5 Mevents selected

Systematics dominated by knowledge of
photon efficiency and background
evaluated from data ($K_L \to \pi^+\pi^-\pi^0$)
and selection cut variation



τ (PDG) (fit) = (51.8 ± 0.4) ns
τ (Vosburg, 1972) = (51.54 ± 0.44) **ns - 0.4 Mevents**
τ (KLOE) = (50.87 ± 0.16 ± 0.26) ns - 14.5 Mevents – 440 pb^{-1}

Unitarity test of CKM matrix – V_{us}

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

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

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

$2|V_{ud}|dV_{ud} = 0.0015$ 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 $V_{us} f_+^{K\pi}(0)$

Prescription from hep-ph/0411097 (F. Mescia @ICHEP04)

use quadratic parametrization

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

$\lambda_+ = 0.0226 \pm 0.0114$

$\lambda'_+ = 0.0023 \pm 0.0004$

from KTeV & ISTRA+

$\lambda_0 = 0.0154 \pm 0.0008$

average K_L lifetime from KLOE

$\tau_{KL} = 50.81 \pm 0.23$ ns

K_L BR's assuming unitarity

KLOE results:

$|V_{us}|f_+^{K\pi}(0)(K_{Se3}) = 0.2169 \pm 0.0017$

$|V_{us}|f_+^{K\pi}(0)(K_{Le3}) = 0.2164 \pm 0.0007$

$|V_{us}|f_+^{K\pi}(0)(K_{L\mu3}) = 0.2174 \pm 0.0009$

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)**

M. Okamoto et al. (MILC)
(Lattice+CHPT) **0.962(11)**

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:

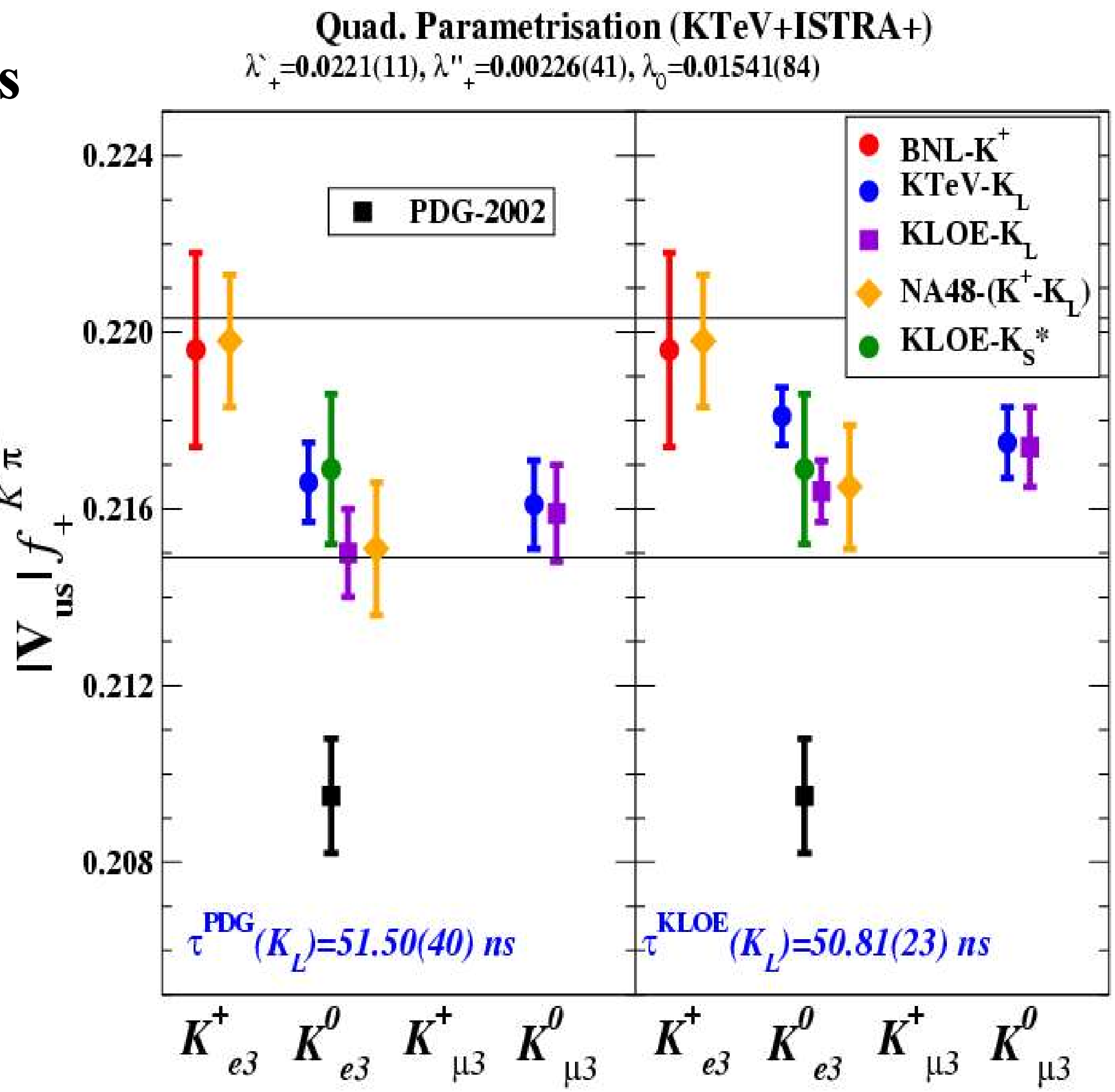
$\Gamma(K^+ \to \pi^0 e^+ \nu)$ from E865

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

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

$\Gamma(K^{+/-} \to \pi e \nu)$ 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 $K_S \to \pi^0\pi^0\pi^0$
- First observation of $K_S \to \pi\mu\nu$

Important contributions to the measurement of V_{us}

- Measurements of dominat K_L BR's with 0.5% accuracy
- Two measurements of K_L lifetime with 0.5% accuracy

Next in line:

- Final result on $K_S \to \pi e\nu$ BR
- Analysis of $K^{\pm}$, BR's, and lifetime
- Analysis of K_L semileptonic form factor slopes

KLOE expects to collect 2 fb^{-1} by the end of 2005

- improved analyses of rare decays and interference studies