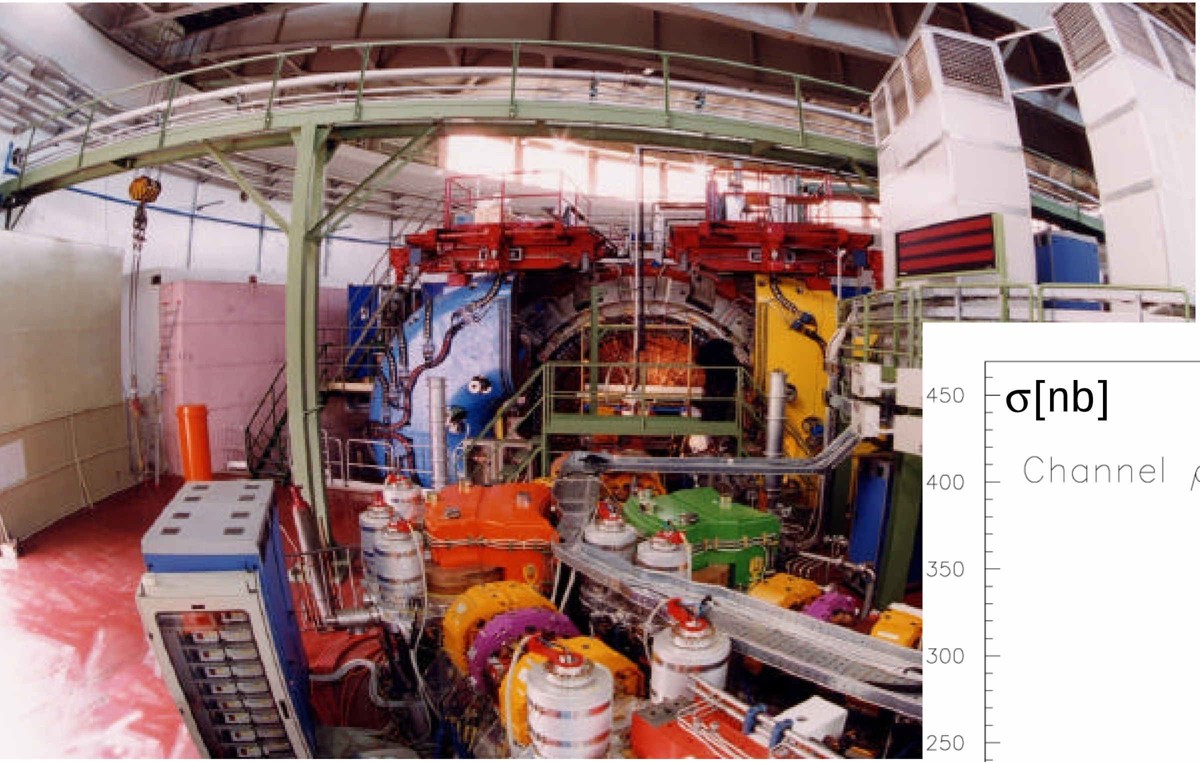
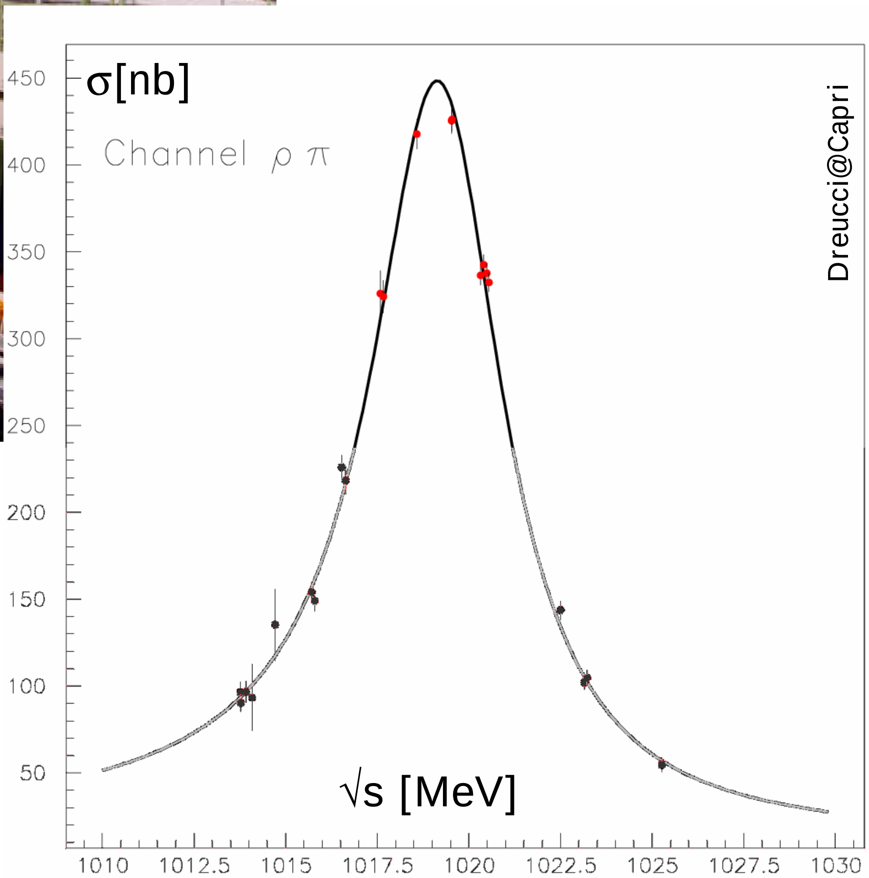




Kaon physics at KLOE

E. De Lucia INFN LNF

for the KLOE Collaboration

Physics at the *f* resonance (I)

✧ Unique facility running at the ϕ peak (DAΦNE) s_f **~ 3.1** m**b**

✧ Extensively study all the possible decay channels with a multipurpose detector

Kaon physics

BR(f ®K $^+$K $^-$) = 49.2%

BR(f ®K$^0\overline{K^0}$) = 33.8%

- K_SK_L and K^+K^- pairs are produced in a pure quantum state ($J^{PC}=1^{--}$) :

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

#*unique feature is the production of pure and quasi monochromatic K_S, K_L, K^+ and K^- beams*

- detection of a K_S (K_L) guarantees the presence of a K_L(K_S) with known momentum and direction (the same for K^+K^-)

precision measurement of absolute BR's

#*interference measurements in K_S K_L system*

Physics at the *f* resonance (II)

Non-kaon physics

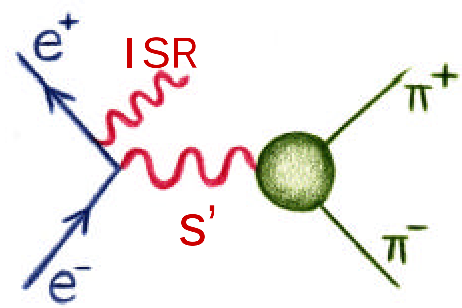
- Radiative ϕ decays ($\phi = |s\bar{s}\rangle$)
  $\phi \rightarrow M\gamma$ to probe the quark structure of the meson M

$\left.\begin{matrix}\eta \\ \eta'\end{matrix}\right\}$ mixing angle $\qquad \left.\begin{matrix}a_0 \\ f_0\end{matrix}\right\}$ $q\bar{q}$ vs $q\bar{q}q\bar{q}$

- η factory $N_\eta \sim 2\text{x}10^7$ / fb-1 (BR($\phi \rightarrow \eta\gamma$) = 1.3%)

- Hadronic cross-section measurement using the Initial State Radiation to vary the energy: $e^+ e^- \rightarrow \pi^+ \pi^- + \gamma$

For the theoretical estimate of the hadronic contribution (a_μ^{hadr}) to the anomalous magnetic moment of the muon (a_μ) ***down to the threshold energy for pp production***



DAfNE

- e+e- collider @ √s = 1019.4 MeV
- 2 IP (KLOE – DEAR/Finuda)
- Separate e+, e- rings to minimize beam-beam interactions
- Crossing angle: 12.5 mrad
- Residual lab. momentum of ϕ: p_ϕ ~ 13 MeV/c
- Injection during data-taking

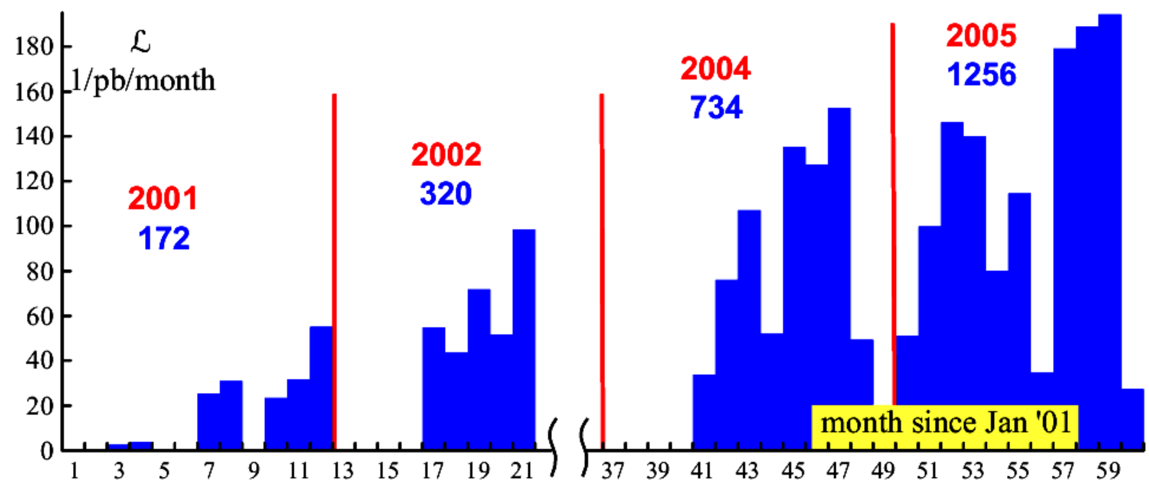
Results presented in this talk from 2001/2 data:

ò*L* = 450 pb^{-1}

Grand total (2001/5):

ò*L* = 2.5 fb^{-1}.

L_{peak}= 1.3×10^{32} cm^{-2}s^{-1}



The KLOE detector

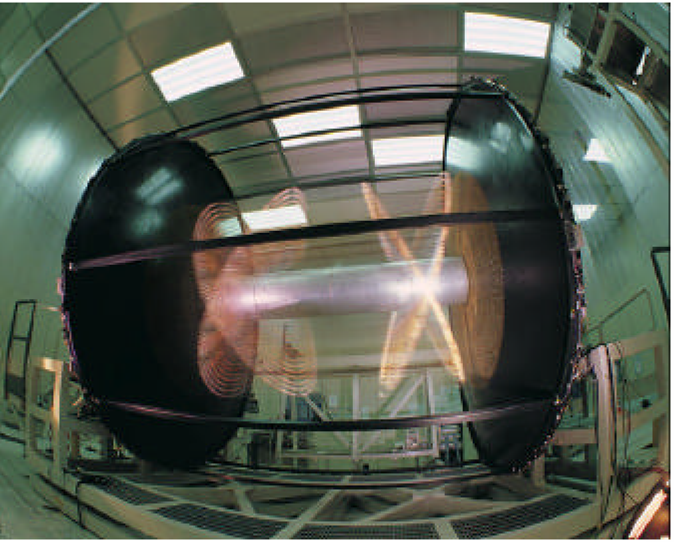
Drift Chamber

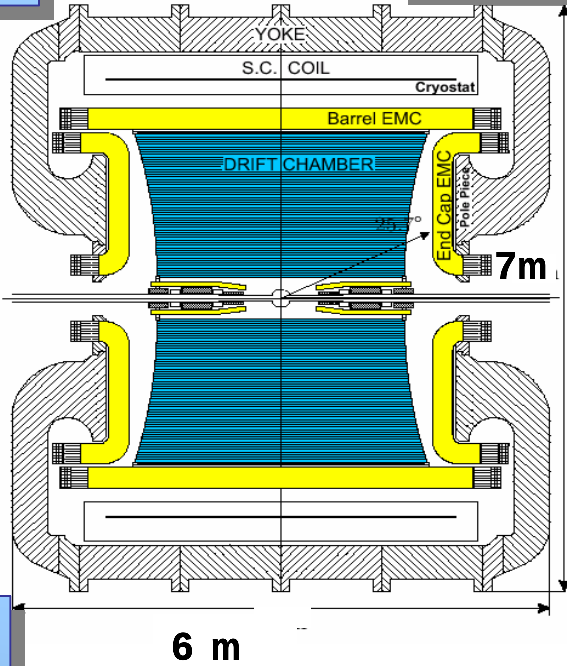
- 4 m diameter × 3.3 m length
- 90% helium, 10% isobutane
- 12582/52140 sense/tot wires
- All-stereo geometry

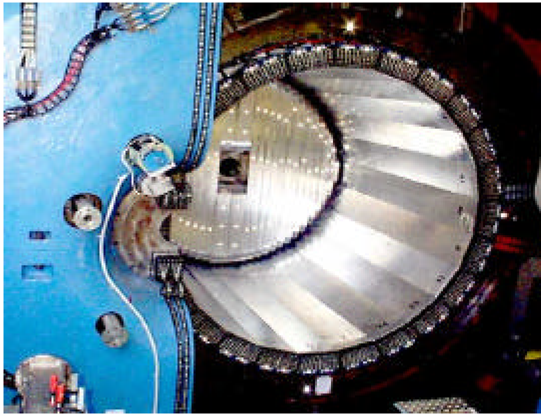
l_S = 0.6 cm
l_L = 340 cm
$l_{\pm}$ = 95 cm

Electromagnetic Calorimeter

- Lead/scintillating fiber
- 98% coverage of solid angle
- 88 modules (barrel + end-caps)
- 4880 PMTs (two side read-out)







s_{rf} = 150 mm s_z = 2 mm
s_V = 3 mm s_p/p = 0.4 %

$s_E/E = 5.4\%/\sqrt{E(GeV)}$

$s_t = 54\ ps/\sqrt{E(GeV)} \oplus 50\ ps(cal)$

Unitarity test of CKM matrix – V_{us} & V_{us} / V_{ud}

- **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 D **= 0 at 10^{-3} level:**

from super-allowed nuclear β-decays: $2|V_{ud}|\delta V_{ud} = 0.0005$

from semileptonic kaon decays: $2|V_{us}|\delta V_{us} = 0.0009$

- **Extract $|V_{us}|$ from K_{l3} decays. EM effects must be included:**

$$\Gamma(K \to \pi l \nu(\gamma)) \propto |V_{us}\, f_+^{K0\pi-}(0)|^2\, I(\lambda_t)\, S_{EW}(1 + \delta_{EM} + \delta_{SU(2)})$$

Relative uncertainty:

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

- **Extract $|V_{us}|/|V_{ud}|$ from $\Gamma(K^\pm \to \mu\nu(\gamma))/\Gamma(\pi^\pm \to \mu\nu(\gamma))$ ratio. Dominated by the theoretical uncertainity on the f_K/f_π evaluation from lattice QCD**

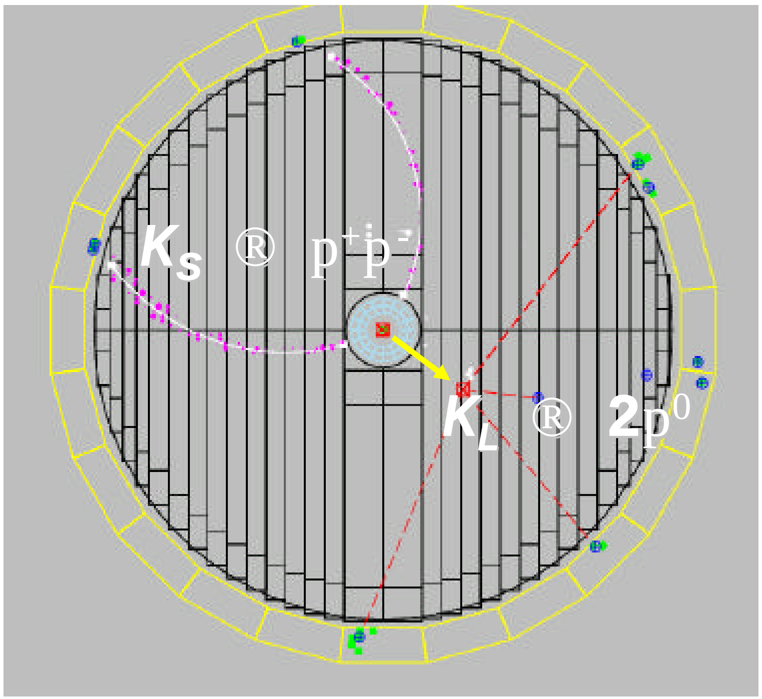
- **KLOE can measure all experimental inputs for neutral and charged kaons: branching ratios, lifetimes, and form factors.**

Neutral Kaons

- K_S semileptonic decays
- K_L dominant BR's
- K_L lifetime
- K_{Le3} form factor slopes

Tagging of K_S K_L beams

K_L tagged
by K_S ® p^+p^- vertex at IP

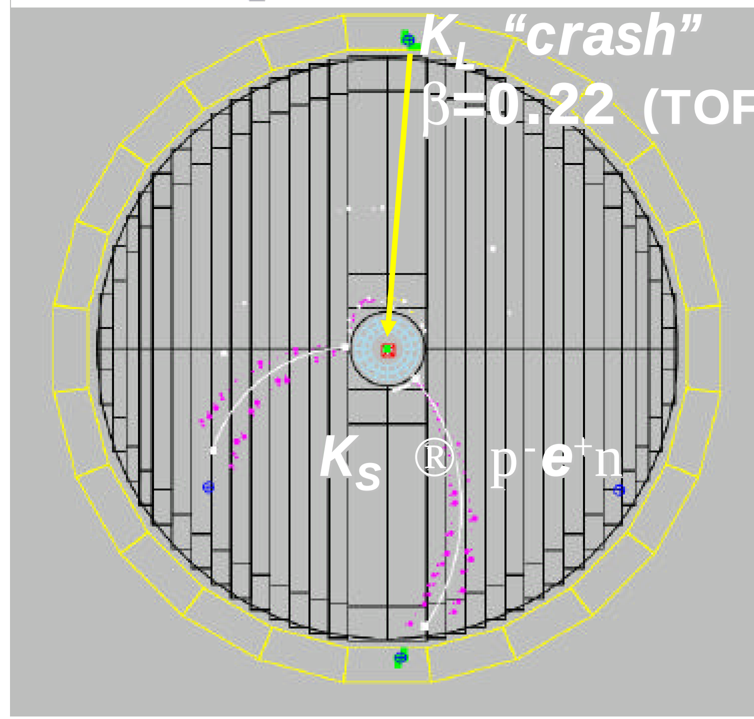


e ~ **70%** (mainly geometrical)

K_L angular resolution: ~ 1°

K_L momentum resolution: ~ 1 MeV

K_S tagged
by K_L interaction in EmC



e ~ **30%** (largely geometrical)

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

K_S momentum resolution: ~ 1 MeV

Analysis of K_S ? *pen* decays

Event selection (410 pb^{-1})

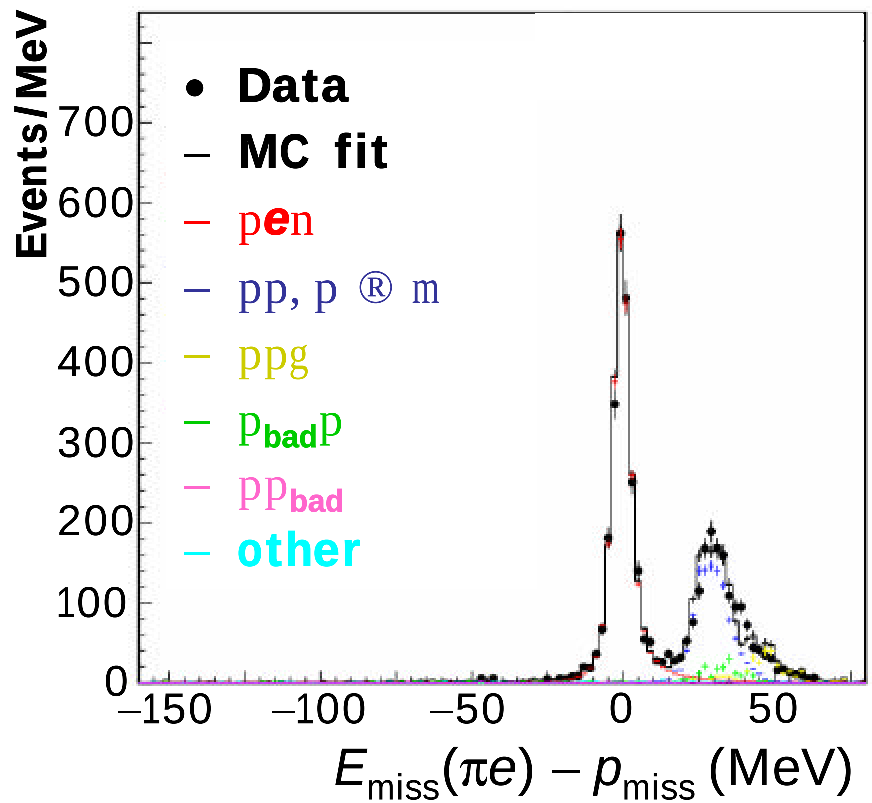
- K_S tagged by K_L crash
- Two tracks from IP to EmC
- Kinematic cuts to reject background from $K_S \to \pi\pi$
- Track-cluster association required

e/π ID from TOF

Identifies charge of final state

Fit distributions of 5 variables in data with various MC sources

including $\pi e \nu \gamma$ and $\pi\pi\gamma$ processes



Obtain number of signal events from a constrained likelihood fit of multiple data distributions

Normalize using $K_S \to \pi^+\pi^-(\gamma)$ events in same data set

K_S ® pen decay – Results

Accepted by PLB

BR($K_S \to \pi^- e^+ \nu$) = $(3.529 \pm 0.057 \pm 0.027) \times 10^{-4}$

BR($K_S \to \pi^+ e^- \nu$) = $(3.518 \pm 0.051 \pm 0.029) \times 10^{-4}$

BR(K_S ® pen) = $(7.048 \pm 0.076 \pm 0.050)$´$10^{-4}$

BR($\pi e \nu$) [KLOE '02, *Phys.Lett.B535*, 17 pb^{-1}]:$(6.91 \pm 0.34_{stat} \pm 0.15_{syst})$ 10^{-4}

Charge asymmetry

- **$A_S = A_L$** if CPT and $\Delta S = \Delta Q$
- $A_S \neq A_L$ signals ~~CPT~~ in mixing and/or decay with $\Delta S \neq \Delta Q$
- **$A_S - A_L = 4Re(d)$** if CPT holds in decays with $\Delta S \neq \Delta Q$

$A_S^e = (1.5 \pm 9.6 \pm 2.9)$´$10^{-3}$

With 2.5 fb^{-1}: $\delta A_S \sim 3 \times 10^{-3} \sim 2$ Re ε

Linear form factor slope l$_+ = (33.8 \pm 4.1)$´ 10^{-3}

In good agreement with linear fit from K_L semileptonic form factor [$(28.6 \pm 0.6) \times 10^{-3}$]

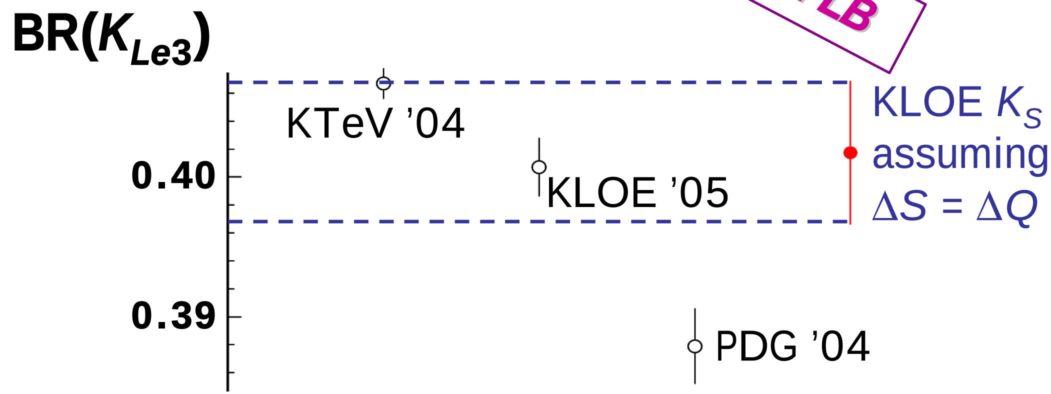
K_S ? *pen* : results

Accepted by PLB

Test of DS = DQ rule

$\tau(K_S)$ = 89.58 ± 0.06 ps
PDG

$\tau(K_L)$ = 51.01 ± 0.20 ns
PDG + KLOE '05 (avg.)



Test of DS = DQ rule, CPT ok

$\hat{A}(x_+) = (\ 0.4 \pm 3.1 \pm 1.8) \times 10^{-3}$

Factor 2 improvement w.r.t. current most precise measurement
(CPLEAR, $\sigma = 6.1\times 10^{-3}$)

$\tau(K_S)$	PDG
$\tau(K_L)$	PDG + KLOE '05 (avg.)
BR(K_L ? *pen*)	KLOE

Test of ~~CPT~~ and DS ¹ DQ:

$\hat{A}(x_-) = (\ -0.2 \pm 2.4 \pm 0.7) \times 10^{-3}$

Factor 5 improvement w.r.t. current most precise measurement
(CPLEAR, $\sigma = 1.3\times 10^{-2}$)

A_L	KTeV
$\Re(\delta)$	CPLEAR

K_S ® *pmn*: first observation

- **Measurement never done before**

- More difficult than K_{Se3}:

  1) Lower BR: expect 4×10^{-4}

  2) Background events from $K_S \to \pi\pi$, $\pi \to \mu\nu$:

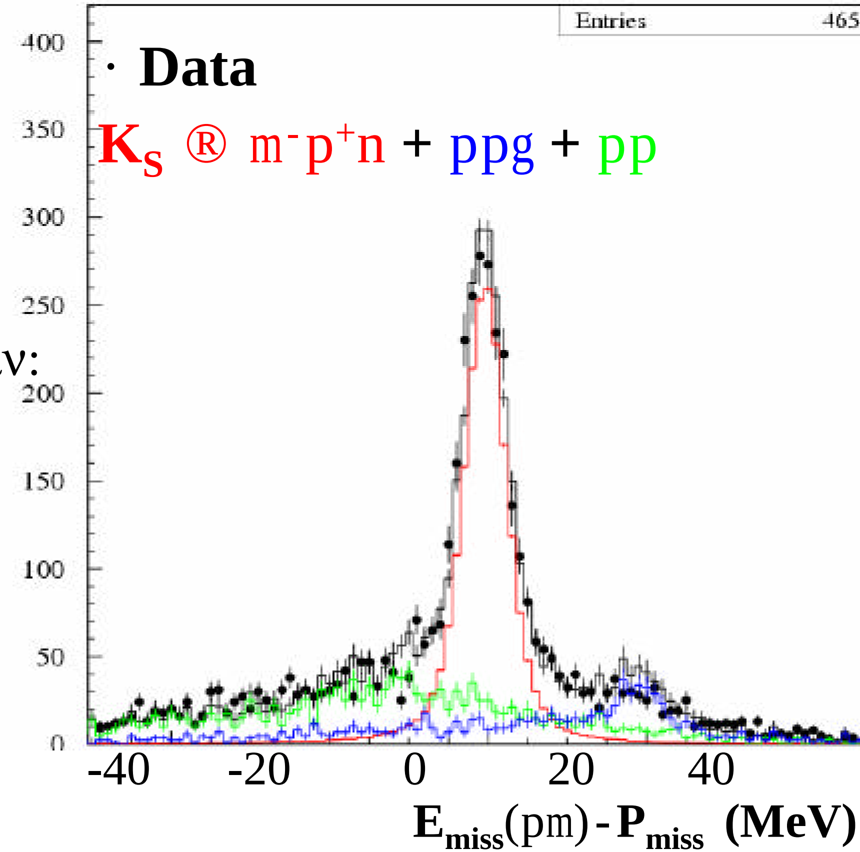
     same PIDs of the signal

- Event counting from the fit to $E_{miss}(\pi\mu) - P_{miss}$ distribution:

  ~ 3% stat error

- Efficiency estimate from $K_{L\mu3}$ early decays and from MC + data control samples.

Coming soon



Dominant K_L branching ratios

Absolute BR measurements to 0.5-1%
from 328 pb^{-1} data sample

K_L* tagged by *K_S ® p^+p^- :

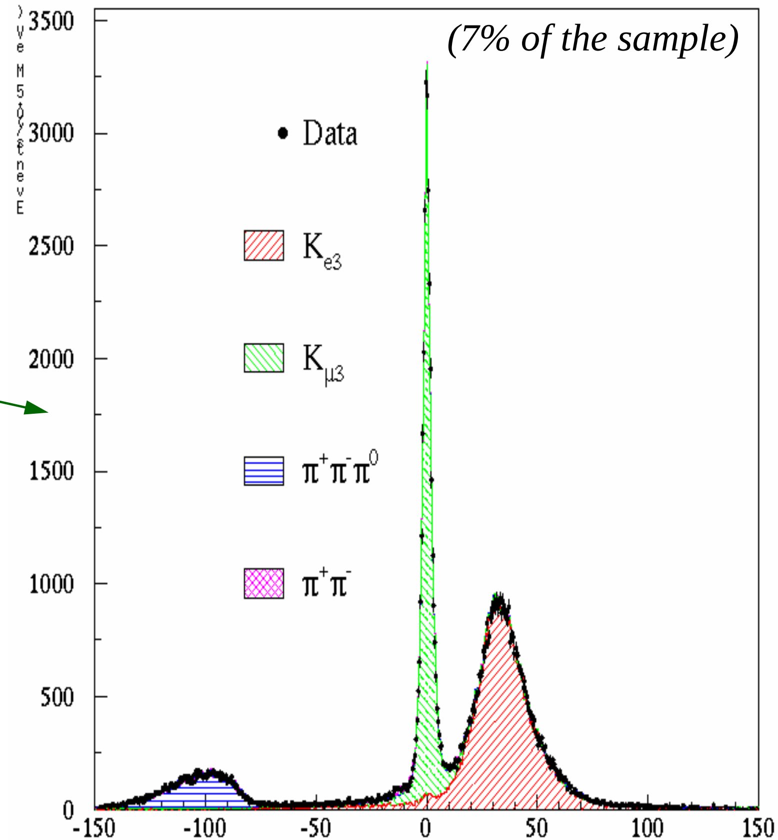
- 13×10^6 for the measurement
- 4×10^6 used to evaluate efficiencies

BR's to pen, pmn, **and** $p^+p^-p^0$:

- K_L vertex reconstructed in DC
- PID using decay kinematics
- Fit with MC spectra including radiative processes and optimized EmC response to $\mu/\pi/K_L$

BR to $p^0p^0p^0$:

- Photon vertex reconstructed by TOF using EmC (3 clusters)
- ε_{rec} = 99%, background < 1%



Lesser of *p_{miss}* - *E_{miss}* in pm **or** mp **hyp. (MeV)**

Dominant K_L BR's and K_L lifetime

Using the constraint $\sum BR(K_L) = 1$ we get:

BR(K_L ® pen(g)) = $0.4007 \pm 0.0006_{stat} \pm 0.0014_{syst}$
BR(K_L ® pmn(g)) = $0.2698 \pm 0.0006_{stat} \pm 0.0014_{syst}$
BR(K_L ® 3p^0) = $0.1997 \pm 0.0005_{stat} \pm 0.0019_{syst}$
BR(K_L ® $p^+p^-p^0$(g)) = $0.1263 \pm 0.0005_{stat} \pm 0.0011_{syst}$

[PLB 632 (2006)]

Lifetime measurement:

$t_L = 50.72 \pm 0.17 \pm 0.33$ ns

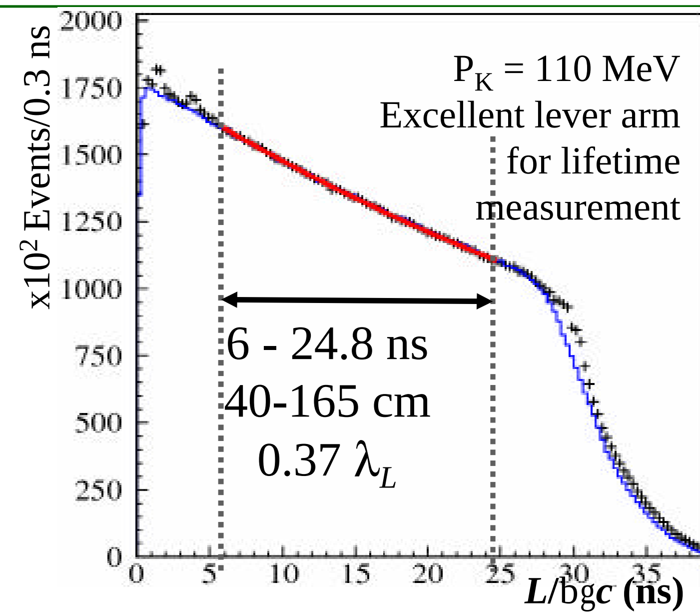
t_L measurement from $K_L \to \pi^0\pi^0\pi^0$, 400 pb^{-1}, f(t)

- Require ≥ 3 γ's
- $\varepsilon(L_K)$ ~ 99%, uniform in L
- $\sigma_L(\gamma\gamma)$ ~ 2.5 cm
- Background ~ 1.3%

Use $K_L \to p^+p^-p^0$ for:
- EmC time scale
- Photon vertex efficiency

Lifetime measurement [PLB 626 (2005)] **:**

$t_L = 50.92 \pm 0.17 \pm 0.25$ ns



K_L lifetime, KLOE average : $t_L = 50.84 \pm 0.23$ ns

Vosburg, '72: $\tau_L = 51.54 \pm 0.44$ ns

K_{Le3} form factor slopes

Accepted by PLB

- **328 pb^{-1}, 2 ´ 10^6 K_{e3}** decays
- Kinematic cuts + TOF PID to reduce background (~ 0.7% final contamination)
- Separate measurement for each charge state ($e^+\pi^-$, π^+e^-) to check systematics
- t **measured** from π and K_L momenta: σ_t/m_π^2 ~0.3

Linear fit

	$\lambda_+ \times 10^3$	χ^2/dof
$e^+\pi^-$	28.7 ± 0.7	156/181
π^+e^-	28.5 ± 0.6	174/181
All	28.6 ± 0.5	330/363

l$_+$ = (28.6 ± 0.5 ± 0.4) ´ 10^{-3}

Quadratic fit

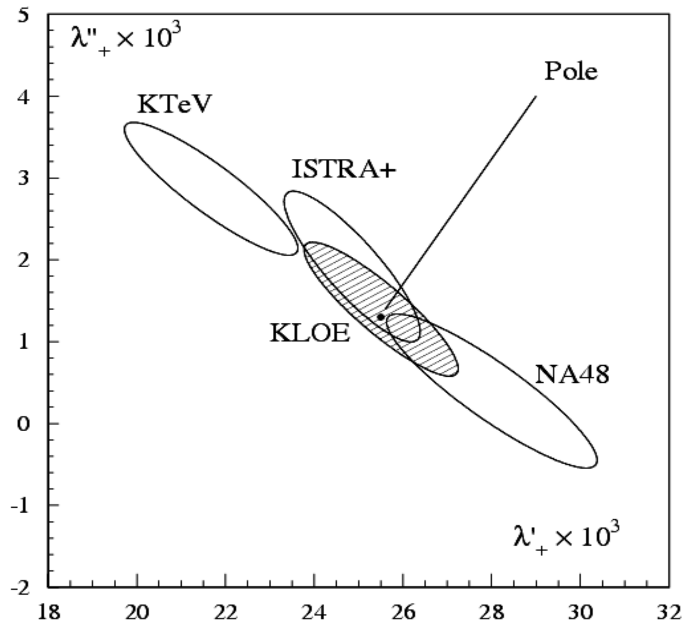
	$\lambda'_+ \times 10^3$	$\lambda''_+ \times 10^3$	χ^2/dof
$e^+\pi^-$	24.6 ± 2.1	1.9 ± 1.0	152/180
π^+e^-	26.4 ± 2.1	1.0 ± 1.0	173/180
All	25.5 ± 1.5	1.4 ± 0.7	325/362

l¢$_+$ = (25.5 ± 1.5 ± 1.0) ´ 10^{-3}

l¢¢$_+$ = (1.4 ± 0.7 ± 0.4) ´ 10^{-3}

Correlation: $\rho(\lambda'_+, \lambda''_+) = -0.95$

Pole model M_V = 870(7) MeV



(*) ISTRA+ $m_{\pi\pm}/m_{\pi 0}$ correction

Phase space integral

Pole model versus **Quadratic parameterization**:

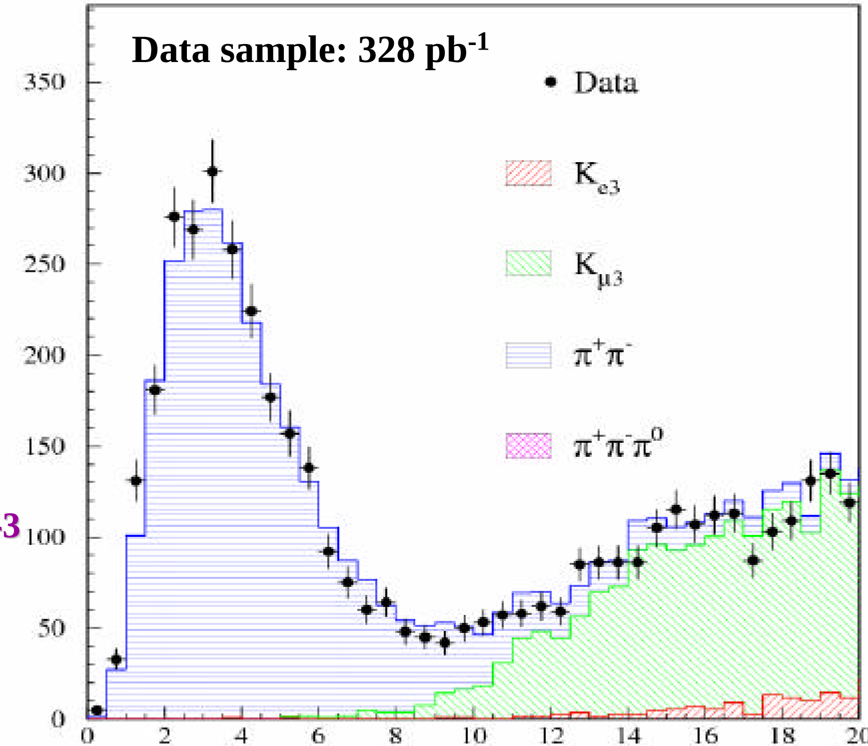
- KLOE: 0.5 per mil difference
- KTeV: 6 per mil difference.

K_L ® p^+p^-

Signal selection:

- K_L beam tagged by K_S ? p^+p^-
- K_L vertex reconstructed in DC
- PID using decay kinematics
- Fit with MC spectra

Normalization using K_L ® πμν events in the same data set



KLOE preliminary result:

BR(K_L ® p^+p^-)= (1.963 ±0.012 ±0.017) ´ 10^{-3}

♦ Agreement with KTeV [PRD70(2004),092006]

BR(K_L ® p^+p^-)= (1.975 ±0.012) ´ 10^{-3}

♦ Confirms the discrepancy with PDG04 = $(2.080 \pm 0.025) \times 10^{-3}$

Using BR($K_S \rightarrow \pi\pi$) and τ_L from KLOE and τ_S from PDG04:

|e| = (2.216 ± 0.013) ´ 10^{-3}

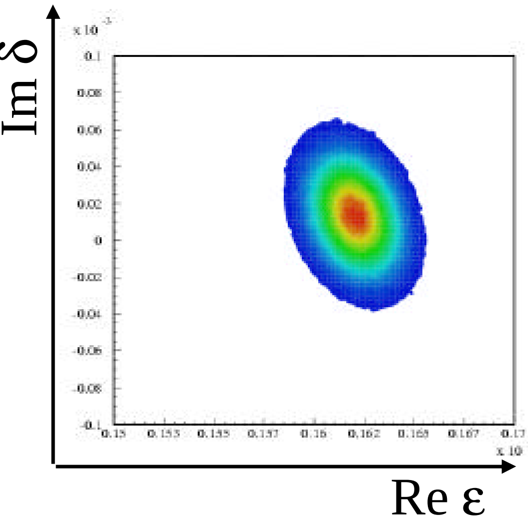
PDG04 $|\varepsilon| = (2.280 \pm 0.013) \times 10^{-3}$

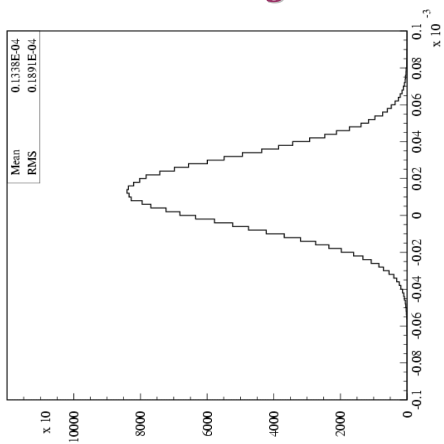
1.6 σ agreement with prediction from Unitarity Triangle

CPT test: the Bell-Steinberger relation

K_S K_L observables can be used for the CPT test from unitarity :

$$(1 + i \tan f_{SW})\,[\mathrm{Re}\,e - i\,\mathrm{Im}\,d] = \frac{1}{G_S} S_f\, A^*(K_S ® f)\, A(K_L ® f) = S_f\, a_f$$



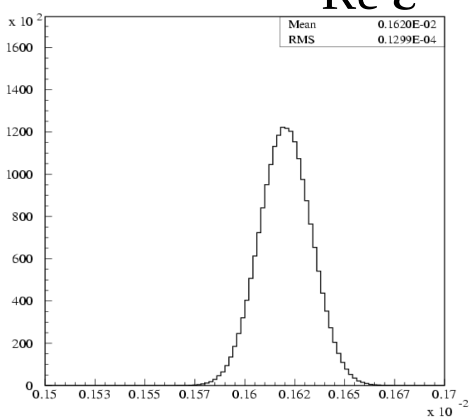


With

BR(K_S ® 3p^0) < 1.2×10^{-7} @ 90% C.L.

[KLOE, PLB 619 (2005)]

the main contribution to the uncertainty now comes from η_{+-}



KLOE preliminary:

Re e = (160.2 ± 1.3) ´10^{-5}
Im d =(1.2 ± 1.9) ´ 10^{-5}

CPLEAR:

Re ε = (164.9 ± 2.5) 10^{-5}

Im δ =(2.4 ± 5.0) 10^{-5}

Charged Kaons

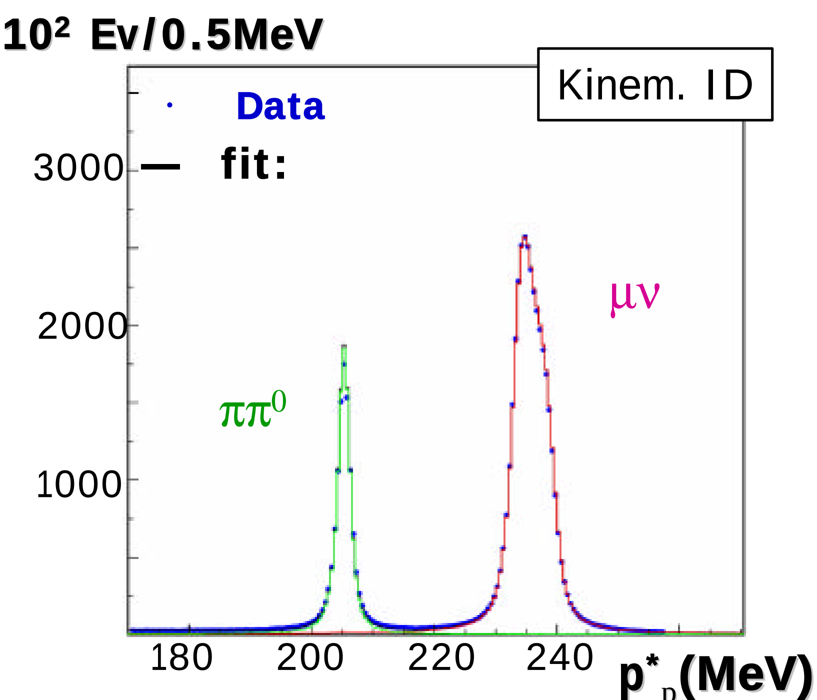
- $K^{\pm}$ lifetime
- $BR(K^{+}_{m2})$
- $K^{\pm}$ semileptonic decays

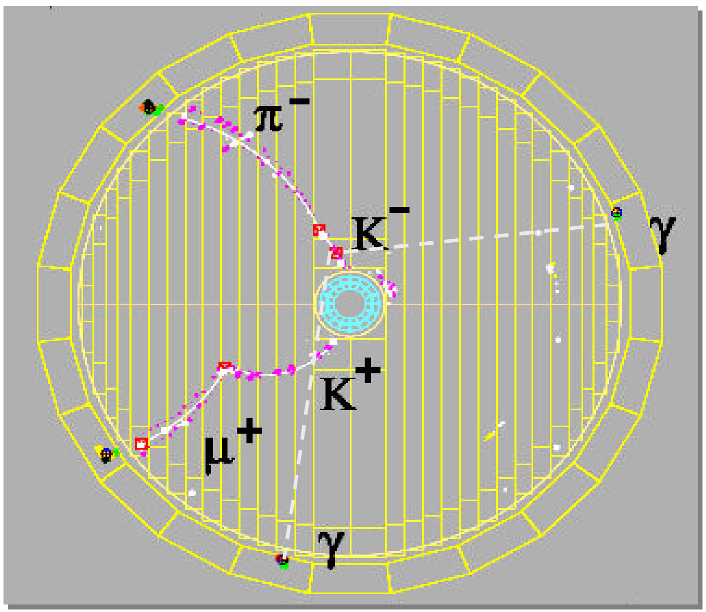
Tagging K+ K-

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: **$6x10^5$ tags/pb^{-1}**

❖ Given the tag a dedicated reconstruction of $K^\pm$ tracks is performed, correcting for dE/dx losses of charged kaons in the DC





$K^+ ® m^+ n_m$ $K^- ® p^- p^0$

Measurement of the $K^{\pm}$ lifetime

• Two different methods to measure $\tau_{\pm}$ allow cross checks on the systematic error.

• Common to both methods:

- Tag events with $K\mu2$ decay
- Kaon decay vertex in the fiducial volume

1st method: $\tau_{\pm}$ from the K decay length

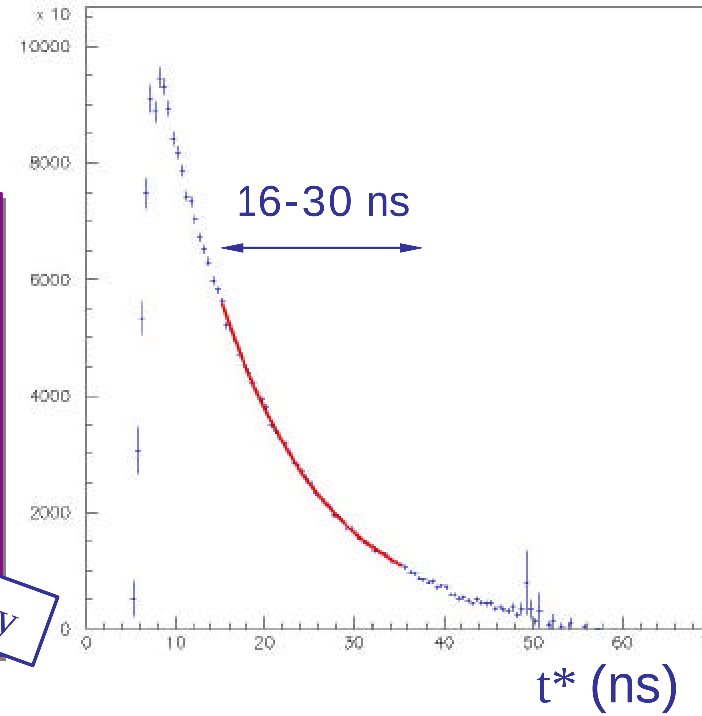
Measure the kaon decay length taking into account the energy loss: $t^* = \sum_i L_i/(\beta_i\gamma_i c)$

• Tracking efficiency and resolution functions measured on data by means of neutral vertex identification.

• Fit of the t* distribution.

KLOE preliminary

$$t_{\pm} = 12.367 \pm 0.044_{Stat} \pm 0.065_{Syst} \text{ ns}$$



2nd method: $\tau_{\pm}$ from the K decay time

• Use only $K\pi2$ decays

• Use tag information to estimate the T_0 i.e. the $\phi \to K^+K^-$ time.

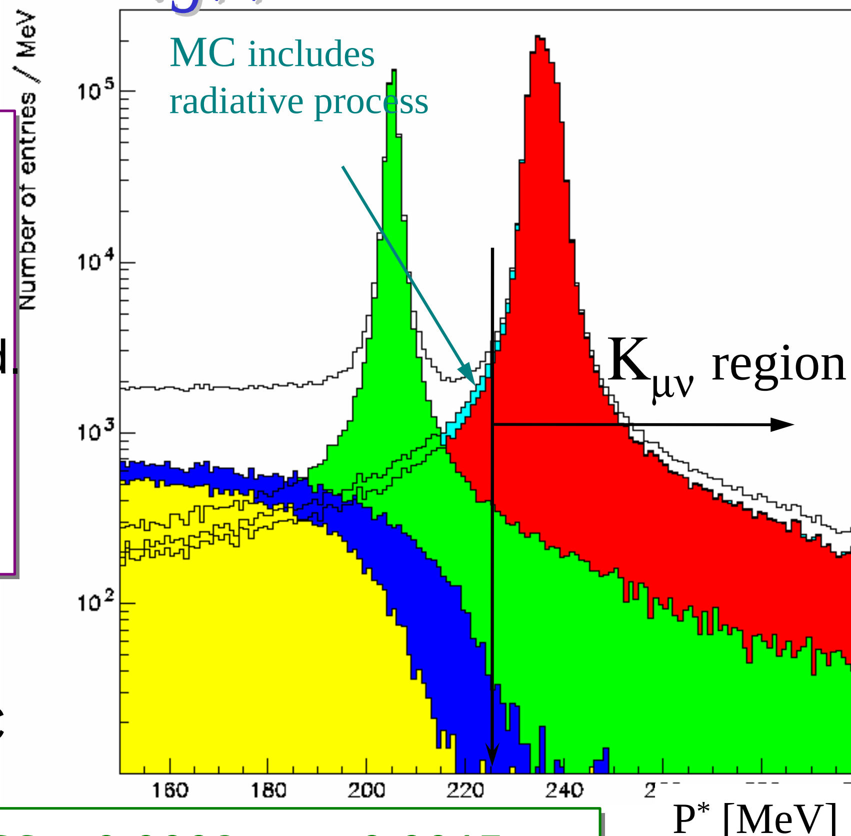
• Measure the kaon decay time: $t^* = (t_\gamma - R_\gamma/c - T_0)g_K$, using the π^0 clusters

• Lorentz factor g_K: slowly changing along the kaon path

Measurement of BR(K$^+$ ® m$^+$n(g))

Signal selection

- Tag from $K^- \to \mu^- \nu$.
- 175 pb^{-1}: 1/3 used for signal selection, 2/3 used as efficiency sample
- Subtraction of π^0 identified background.
- Count events in (225,400) MeV window of the momentum distribution in K rest frame (π hypothesis)



- Selection efficiency measured on data
- Radiated γ acceptance computed by MC

BR(K$^+$ ® m$^+$n(g)) [PLB 632 (2006)]**= 0.6366 ± 0.0009$_{stat.}$ ± 0.0015$_{syst.}$**

- G(**K**®mn(g))/G(p®mn(g)) µ |V$_{us}$|^2/|V$_{ud}$|^2$f_K{}^2$/$f_p{}^2$
- From lattice calculations: f_K / f_p =1.198(3)($^{+16}_{-5}$)

(MILC Coll. PoS (LAT 2005) 025,2005)

|V$_{us}$| / |V$_{ud}$| =0.2294 ± 0.0026

Measurement of BR($K^{\pm}l3$)

- ✧ **4 independent-tag samples: $K^{+}\mu 2$, $K^{+}\pi 2$, $K^{-}\mu 2$, and $K^{-}\pi 2$**
  keep under control the systematic effects due to the tag selection
- ✧ Kinematical cuts to reject non-semileptonic decays,
  residual background is about 1.5% of the selected $K^{\pm}l3$ sample
- ✧ **Constrained likelihood fit of m^2** data distributions from **ToF** measurements
  count the number of signal events
- ✧ Selection efficiency from MC and correct for Data/MC differences.

Perform the **BR measurement on each tag sample,** separately normalizing to tag counts in the same data set, and average accounting for correlations:

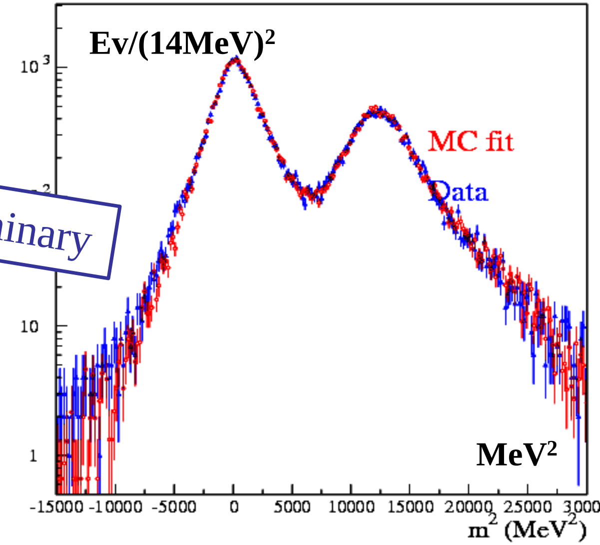
KLOE preliminary

BR($K^{\pm}_{e3}$) =

$$(5.047 \pm 0.019_{Stat} \pm 0.039_{Syst\text{-}Stat} \pm 0.004_{SysTag}) \times 10^{-2}$$

BR($K^{\pm}_{\mu 3}$) =

$$(3.310 \pm 0.016_{Stat} \pm 0.045_{Syst\text{-}Stat} \pm 0.003_{SysTag}) \times 10^{-2}$$



- Fractional accuracy of 0.9% for Ke3, 1.2% for Kμ3.
- The error is dominated by the error on Data/MC efficiency correction and the systematics due to the signal selection efficiency is under evaluation.

V_{us} from KLOE results (BR's and τ_L)

	$K_L\,e3$	$K_L\,\mu3$	$K_S\,e3$	$K^{\pm}e3$	$K^{\pm}\mu3$
BR	0.4007(15)	0.2698(15)	7.046(91)×10^{-4}	0.05047(46)	0.03310(40)
τ	50.84(23) ns		89.58(6) ps	12.384(24) ns	

Slopes

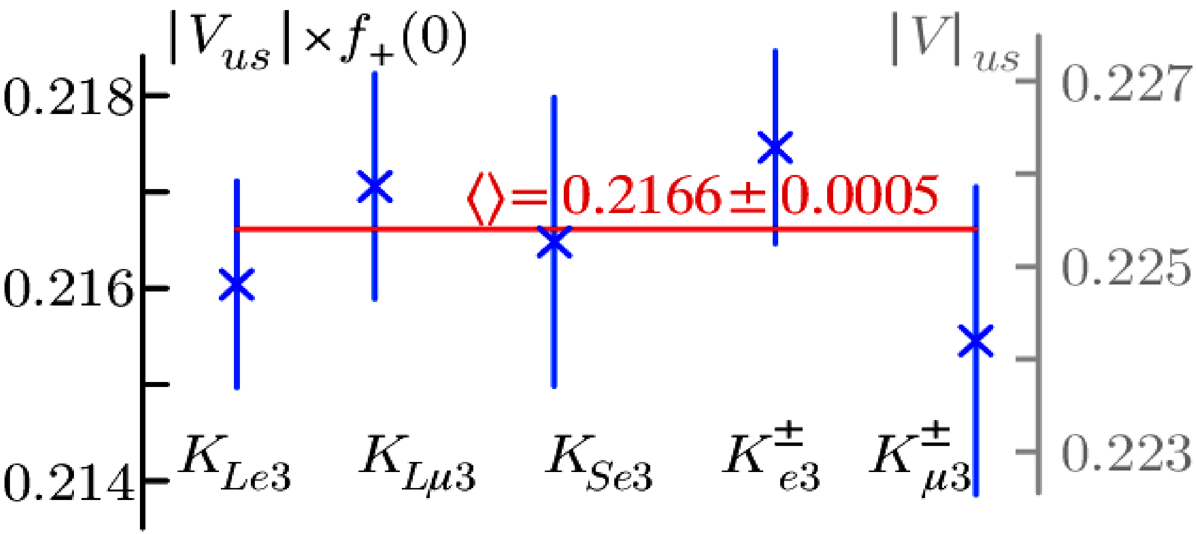
$l¢_+$ = 0.02534(30)

$l¢¢_+$ = 0.00128(3)

(Pole model: KLOE, KTeV, and NA48 ave.)

l_0 = 0.01587(95)

(KTeV and Istra+ ave.)



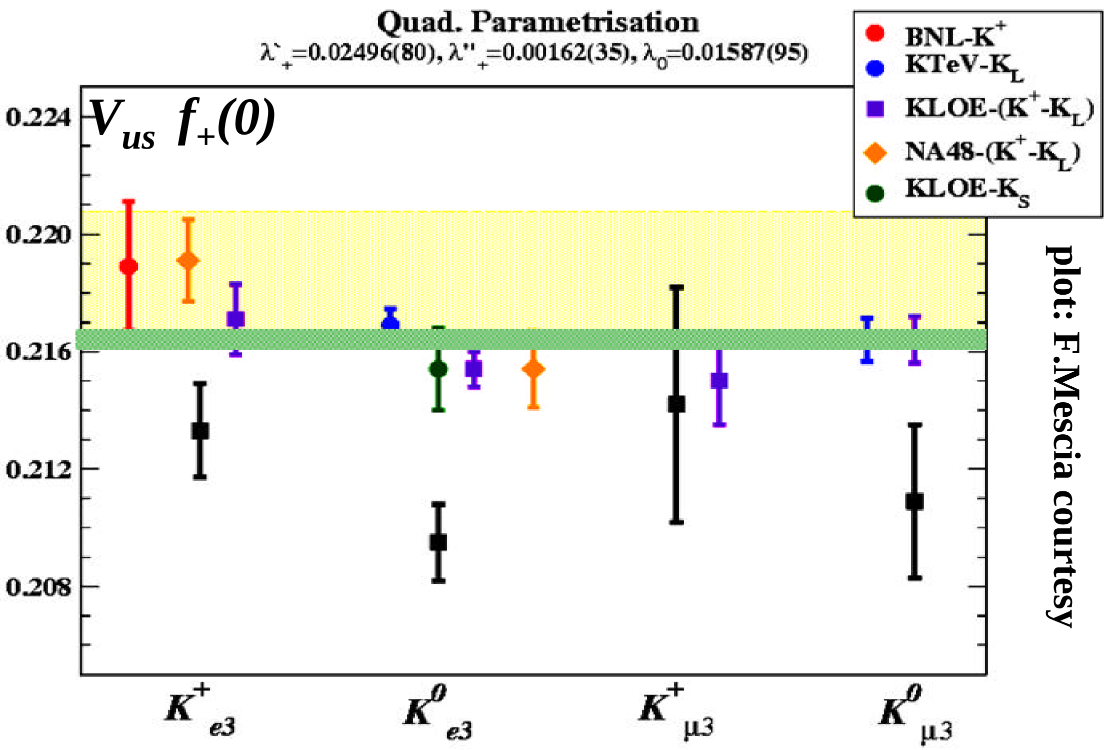
c²/dof = 1.9/4

From unitarity

- $f_+(0)$=0.961(8)
  Leutwyler and Roos Z.
  [Phys. **C25**, 91, 1984]
- V_{ud}=0.97377(27)
  Marciano and Sirlin
  [Phys.Rev.Lett.96 032002,2006]

$V_{us}\times f_+(0)$ = 0.2187(22)

V_{us} and Unitarity



plot: F.Mescia courtesy

- t_L **= 50.99(20) ns,** average KLOE-PDG
- Including all new measurements for semileptonic kaon decays (KTeV, NA48, E865, and KLOE)

$\langle V_{us} \times f_+(0) \rangle_{\text{WORLD AV.}} = 0.2164(4)$

From unitarity

- $f_+(0)=0.961(8)$
  Leutwyler and Roos Z. [Phys. **C25**, 91, 1984]
- $V_{ud}=0.97377(27)$
  Marciano and Sirlin [Phys.Rev.Lett.96 032002,2006]

$V_{us} \times f_+(0) = 0.2187(22)$

The V_{us} - V_{ud} plane

Inputs:

V_{us} = 0.2254 ± 0.0020

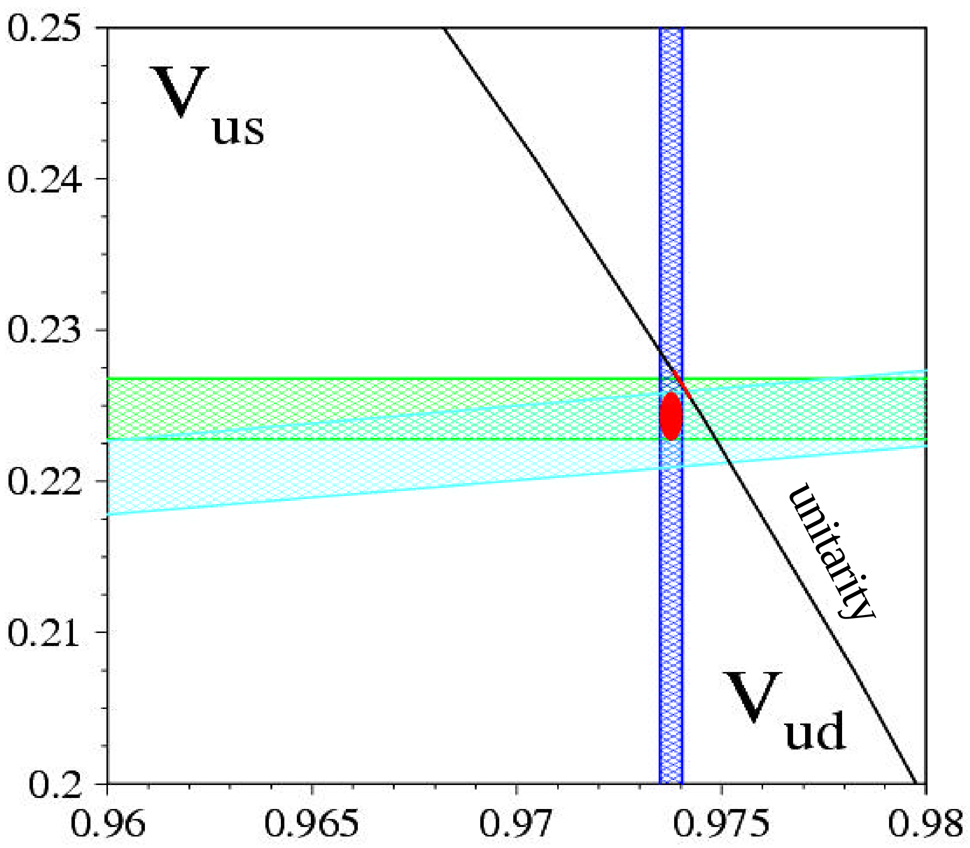
K_{l3} KLOE, using $f_+(0)$=0.961(8)

V_{ud} = 0.97377 ± 0.00027

Marciano and Sirlin
Phys.Rev.Lett.96 032002,2006

V_{us}/V_{ud} = 0.2294 ± 0.0026

$K_{\mu2}$ KLOE
$\Gamma(K\to\mu\nu(\gamma))/\Gamma(\pi\to\mu\nu(\gamma)) \propto |V_{us}|^2/|V_{ud}|^2 f_K^2/f_\pi^2$



Fit results, $P(\chi^2)$ = 0.66:

V_{us} = 0.2246 ± 0.0016
V_{ud} = 0.97377 ± 0.00027

Fit result assuming unitarity, $P(\chi^2)$ = 0.23:
V_{us} = 0.2264 ± 0.0009

Kaon Physics at KLOE – Conclusions (I)

- Completely inclusive measurements of kaon semileptonic BR's with fractional accuracies from ~0.4% to ~1.3%;
- First direct measurement of BR($K_S \to \pi\mu\nu$) coming soon with a statistical accuracy of ~3%.
- Two independent measurements of τ_L: 0.5% fractional accuracy.
- $K_L e3$ form factors: pole model.

Significant contribution to determination of V_{us} $f_+(0)$ to 0.2%

- 0.3% fractional accuracy on BR($K\mu 2(\gamma)$) measurement

Independent determination of V_{us} at 1% level

- Preliminary result on $K^{\pm}$ lifetime.
- Preliminary result on $K_L \to \pi^+\pi^-$

Kaon Physics at KLOE – Conclusions (II)

Perspectives with 2.5 fb^{-1} of collected data:

- Fractional accuracy of < 1% on the BR for $K_S \rightarrow \pi e \nu$ and for $K^{\pm}l\,3$
- More and better measurements of form-factor slopes (K_{e3} and $K_{\mu 3}$).
- Measurement of BR($K_S \rightarrow \pi \mu \nu$), accuracy < 2%

- Improve by a factor 10 the limit **BR(K_S ® 3p^0) < $1.2{\times}10^{-7}$ @** 90% C.L. obtained from a direct search on 450 pb^{-1} [PLB 619 (2005)]
- First measurement of BR($K_S \rightarrow \pi^+\pi^-\pi^0$) from a direct search, with 60% accuracy
- Measure the ratio BR($K \rightarrow e\nu$)/BR($K \rightarrow \mu\nu$) to probe e-μ universality (about $6{\times}10^4$ Ke2 events produced)

SPARES

K_S ® pen decay – Strategy

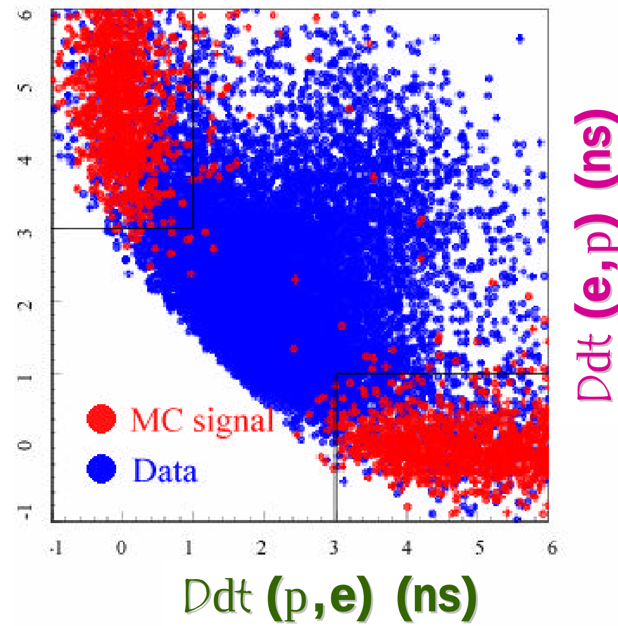
- K_{crash} tag
- 2 tracks from IP with associated EmC clusters and with $M_{\pi\pi} < 490$ MeV (reject $K_S \to \pi\pi(\gamma)$)
- π/e **identification using TOF:**
  - two possible mass hypothesis

$$(e,\pi)\begin{cases} m_- = m_e \\ m_+ = m_p \end{cases} \qquad (\pi,e)\begin{cases} m_- = m_p \\ m_+ = m_e \end{cases}$$

  - two differences between expected flight times

$$\text{Ddt}\,(e,p) = [t_-^{CLU} - t_+^{CLU}] - [L_1\ /c\ \beta(e) - L_2\ /c\ \beta(\pi)]$$

$$\text{Ddt}\,(p,e) = [t_-^{CLU} - t_+^{CLU}] - [L_1\ /c\ \beta(\pi) - L_2\ /c\ \beta(e)]$$



  - comparing Ddt **(e,p)** with Ddt **(p,e)** we can:
    - identify π, e and determine the sign of the charge $\Rightarrow$ A_S accessible
    - reject the background from $\pi\pi$ and $\pi\mu$

Semileptonic decay amplitudes: definitions

$$\langle p^- \ell^+ n | K^0 \rangle = a + b \qquad \langle p^+ \ell^- \bar{n} | K^0 \rangle = c + d$$

$$\langle p^+ \ell^- \bar{n} | \bar{K}^0 \rangle = a^* - b^* \qquad \langle p^- \ell^+ n | \bar{K}^0 \rangle = c^* - d^*$$

	CP	T	CPT	ΔS=ΔQ
a	$\Im$=0	$\Im$=0		
b	$\Re$=0	$\Im$=0	=0	
c	$\Im$=0	$\Im$=0		=0
d	$\Re$=0	$\Im$=0	=0	=0

CPT violation: $y = -\frac{b}{a}$

DS=DQ violation: $x_+ = \frac{c^*}{a}$

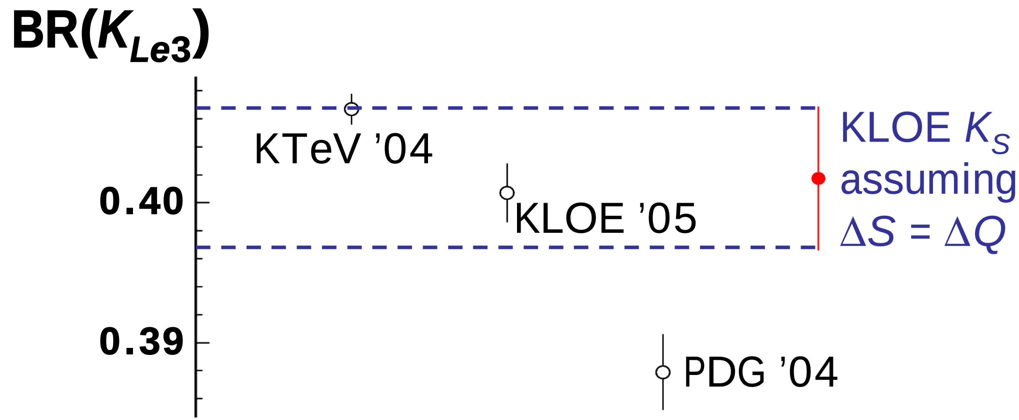
CPT violation & DS=DQ violation : $x_- = -\frac{d^*}{a}$

K_S ® *pen* : test of DS=DQ rule

Test of DS = DQ rule:

$\tau(K_S)$ = 89.58 ± 0.06 ps
PDG fit

$\tau(K_L)$ = 51.01 ± 0.20 ns
PDG + KLOE '05 (avg.)



$$\Re x_+ = \frac{1}{4}\left(\frac{BR(K_S \to pen)}{BR(K_L \to pen)}\frac{t_L}{t_S} - 1\right)$$

ratio of $\Delta S = \Delta Q$ violating and conserving amplitudes (CPT cons.) SM pred. $O(10^{-7})$

Âx₊ = (-0.5 ± 3.1 ± 1.8) ´ 10^{-3}

$\tau(K_S)$	PDG
$\tau(K_L)$	KLOE '05 (avg.)
BR($K_L \to pen$)	KLOE

Factor 2 improvement w.r.t. current most precise measurement (CPLEAR, $\sigma = 6.1 \times 10^{-3}$)

K_S® pen : test of CPT

- Âx_- : CPT viol., DS = DQ viol.

$$A_S - A_L = 4\ (\Re x\_ + \Re d\ )$$

A_L	KTeV	$\sigma=0.75\times10^{-4}$
$\Re\delta$	CPLEAR	$\sigma= 3.4\times 10^{-4}$

Âx_- = (-0.8 ± 2.4 ± 0.7) ´ 10^{-3}

Factor 5 improvement w.r.t. current most precise measurement (CPLEAR, $\sigma= 1.3\times 10^{-2}$)

- Ây : CPT viol., DS = DQ cons.

$$A_S+A_L = 4\ (\Re e-\Re y)$$

$\Re e$ from PDG not assuming CPT

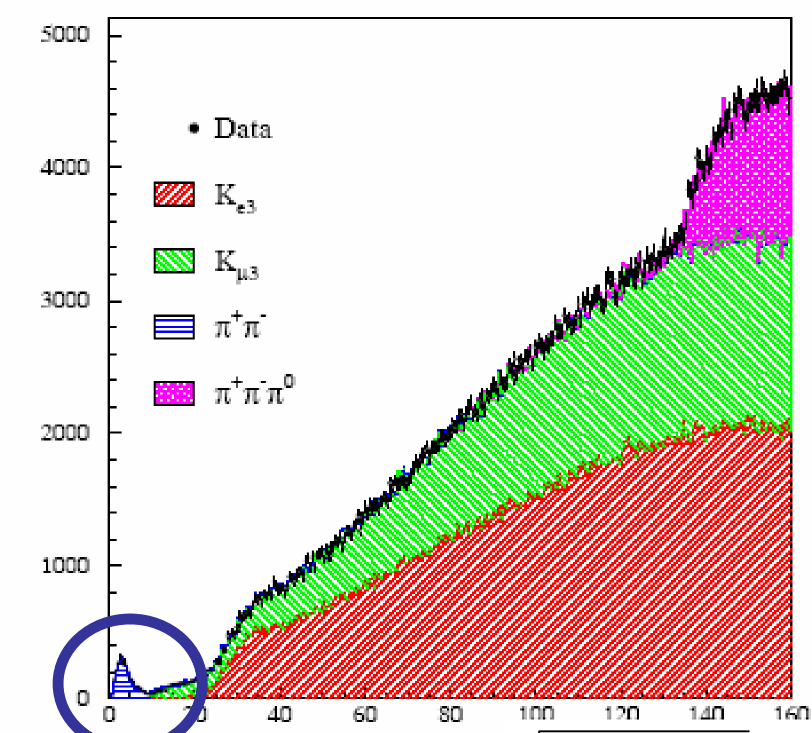
Ây = (0.4 ± 2.4 ± 0.7) ´ 10^{-3}

Comparable with best result (CPLEAR from unitarity, $\sigma= 3.1\times 10^{-3}$)

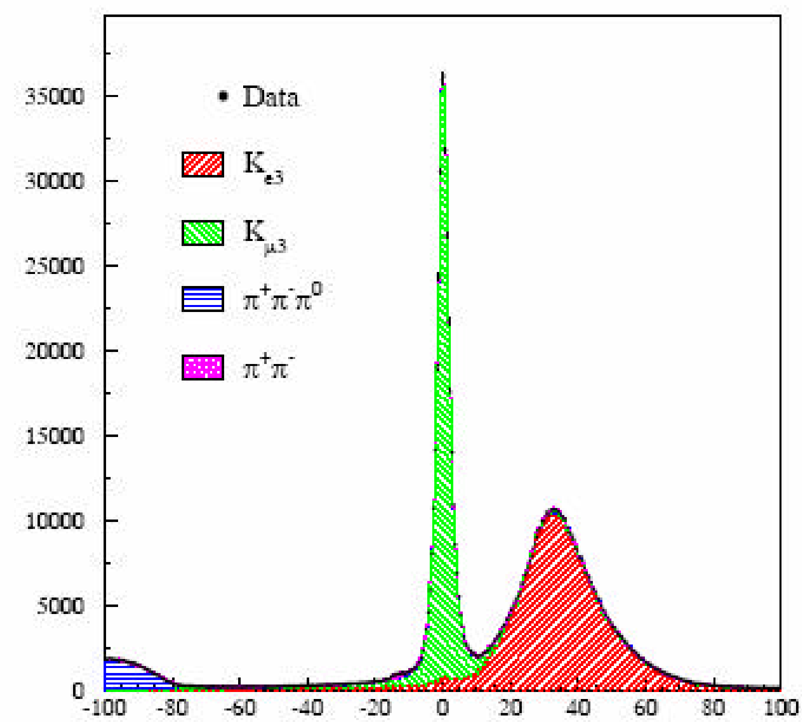
K_L ® p^+p^- : CP violation

Number of $K_L \to \pi^+\pi^-$ from fit of $\sqrt{E^2_{miss}(pp) + p^2_{miss}}$

Number di $K_L \to \pi\mu\nu$ from fit of $p_{miss} - E_{miss}(pmn$ hyp.)



$\sqrt{E^2_{miss} + p^2_{miss}}$ (MeV)



$p_{miss} - E_{miss}$ (MeV)

CPT test: the Bell-Steinberger relation

Measurements of K_S K_L observables can be used for the CPT test from unitarity :

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

$$\alpha_{+-} = \eta_{+-} B(K_S \to \pi^+\pi^-)$$

$$\alpha_{00} = \eta_{00} B(K_S \to \pi^0\pi^0)$$

$$\alpha_{+-\gamma} = \eta_{+-} B(K_S \to \pi^+\pi^-\gamma)$$

$$\alpha_{+-0} = \tau_S/\tau_L\, \eta_{+-0}^* B(K_L \to \pi^+\pi^-\pi^0)$$

$$\alpha_{000} = \tau_S/\tau_L\, \eta_{000}^* B(K_L \to \pi^0\pi^0\pi^0)$$

$$\alpha_{kl3} = 2\tau_S/\tau_L B(K_L l3) [\mathrm{Re}\, \varepsilon - \mathrm{Re}\, y - i(\mathrm{Im}\, \delta + \mathrm{Im}\, x_+)]$$

$$= 2\tau_S/\tau_L B(K_L l3) [(A_S + A_L)/4 - i(\mathrm{Im}\, \delta + \mathrm{Im}\, x_+)]$$

CPT test: inputs to the Bell-Steinberger relation

$B(K_S\to\pi^+\pi^-)/B(K_S\to\pi^0\pi^0)=2.2549\pm0.0059$
$B(K_S\to\pi^+\pi^-\gamma)<9\times10^{-5}$
$B(K_L\to\pi^+\pi^-\gamma)=(29\pm1)\times10^{-6}$
$B(K_L\to\pi l\nu)=0.6705\pm0.0022$
$B(K_S\to\pi^+\pi^-\pi^0)=(3.2\pm1.2)\times10^{-7}$
$B(K_L\to\pi^+\pi^-\pi^0)=0.1263\pm0.0012$
$B(K_S\to\pi^0\pi^0\pi^0)<1.2\times10^{-7}$
$\phi^{SW}=(0.759\pm0.001)$
$\phi^{000}=\phi^{+-0}=\phi^{+-\gamma}=[0,2\pi]$

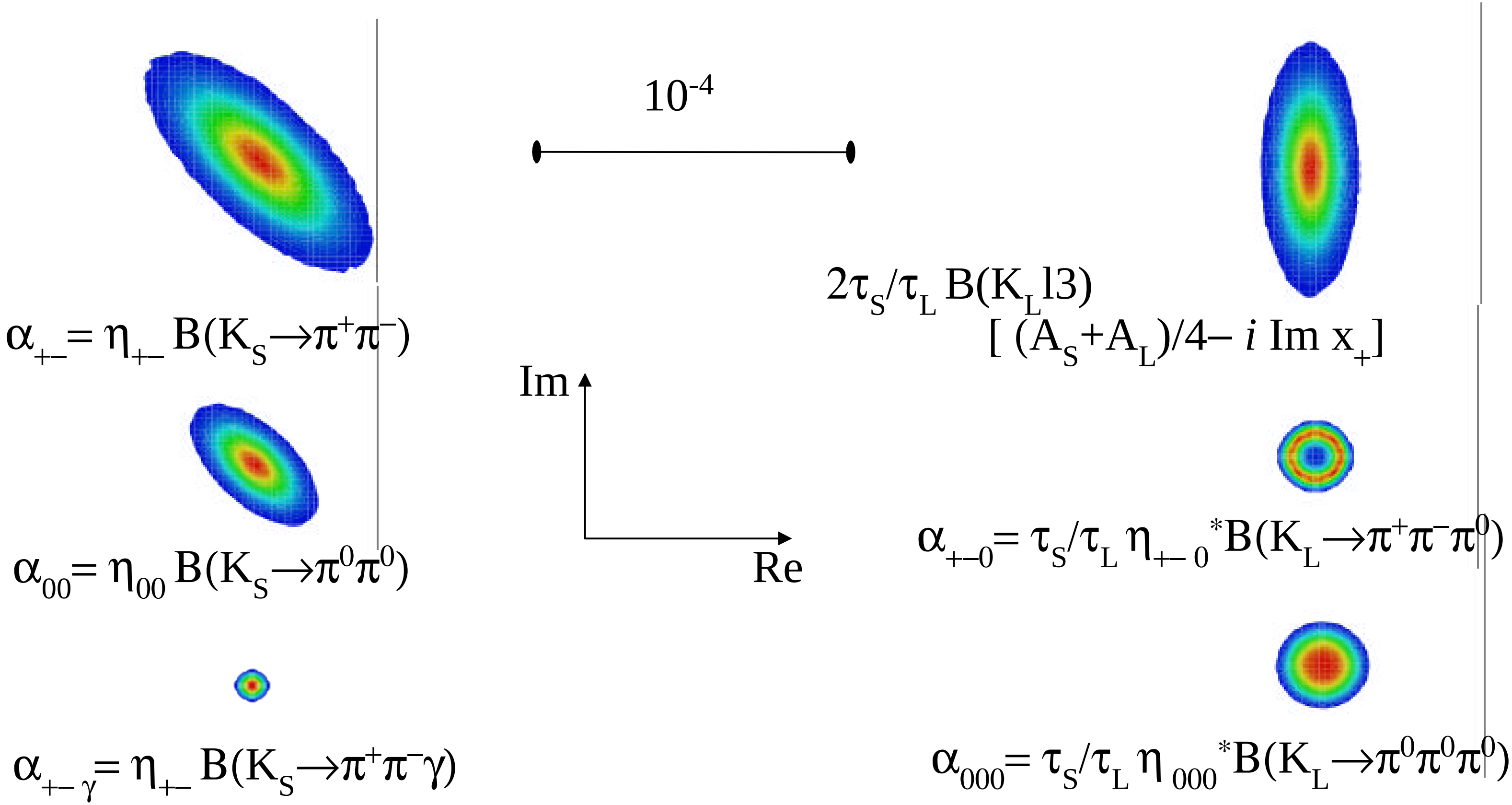
$\tau_S= 0.08958\pm0.00006$ ns
$\tau_L= 50.84\pm0.23$ns
$A_L=(3.32\pm0.06)\times10^{-3}$
$A_S=(1.5\pm10.0)\times10^{-3}$
$B(K_L\to\pi^+\pi^-)=(1.963\pm0.021)\times10^{-3}$
$B(K_L\to\pi^0\pi^0)=(8.65\pm0.10)\times10^{-4}$
$\phi^{+-}=0.757\pm0.012$
$\phi^{00}=0.763\pm0.014$
$\mathrm{Im}\,x_+=(0.8\pm0.7)\times10^{-2}$

KLOE measurements

Im x_+ from a combined fit of KLOE + CPLEAR data

CPT test: accuracy on α_i

We get the following results on each term of the sum



$K_S \rightarrow \pi^0\pi^0\pi^0$: search for a CP violating decay

Observation of K_S ® $3p^0$ signals CP violation in mixing and/or in decay:

SM prediction: $\Gamma_S = \Gamma_L\, |e + e'_{000}|^2$, => $BR(K_S \rightarrow 3\pi^0) \sim 2\times10^{-9}$

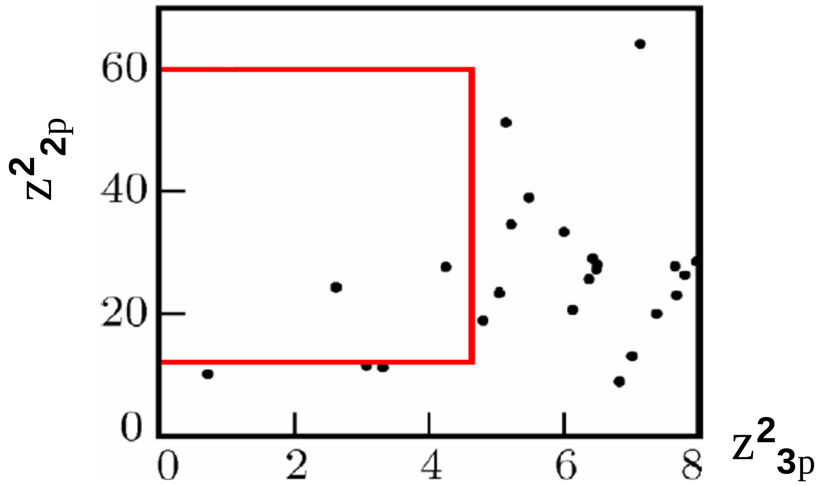
Present published results: $BR(K_S \rightarrow 3\pi^0) < 1.4\times10^{-5}$ (direct search, SND, '99)

$BR(K_S \rightarrow 3\pi^0) < 7.4\times10^{-7}$ (interferometry, NA48, '04)

$BR(K_S$ ® $3p^0) < 1.2\times10^{-7}$ (direct search, KLOE, '05)

90% C.L.

- Data sample: 450 pb^{-1}
  ~ 4 x 10^7 K_L-crash tag + $K_S \rightarrow$neutrals
- Require 6 prompt photons:
  large background ~40K events
- Analysis based on γ counting and kinematic fit in the $2\pi^0$ and $3\pi^0$ hypothesis
- After all analysis cuts ($\varepsilon_{3\pi}$ = 24.4%)
  - 2 candidate events found
  - $3.13\pm0.82_{stat}\pm0.37_{syst}$ expected bckg

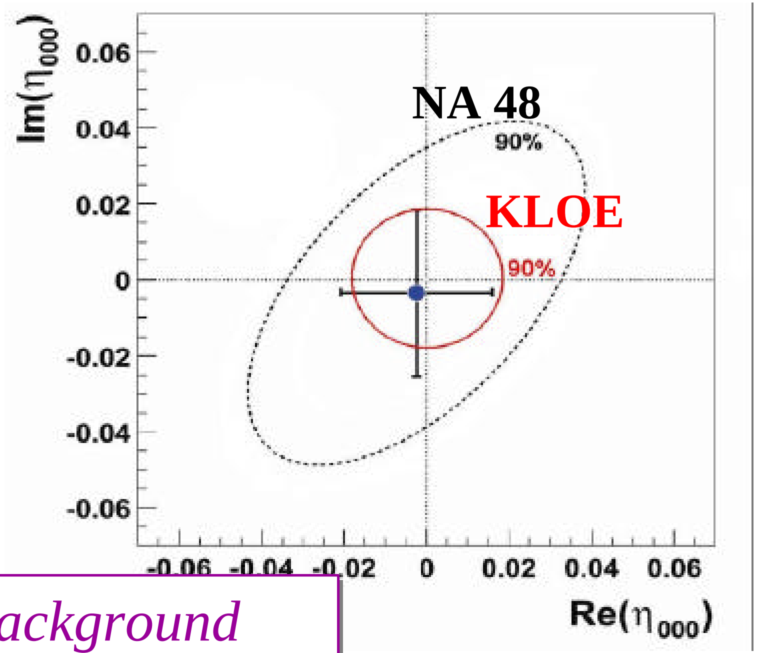


K_S® p^{O}p^{O}p^O : test of CPT

A limit on BR($K_S \to 3\pi^0$) translates into a limit on $|h_{000}|$

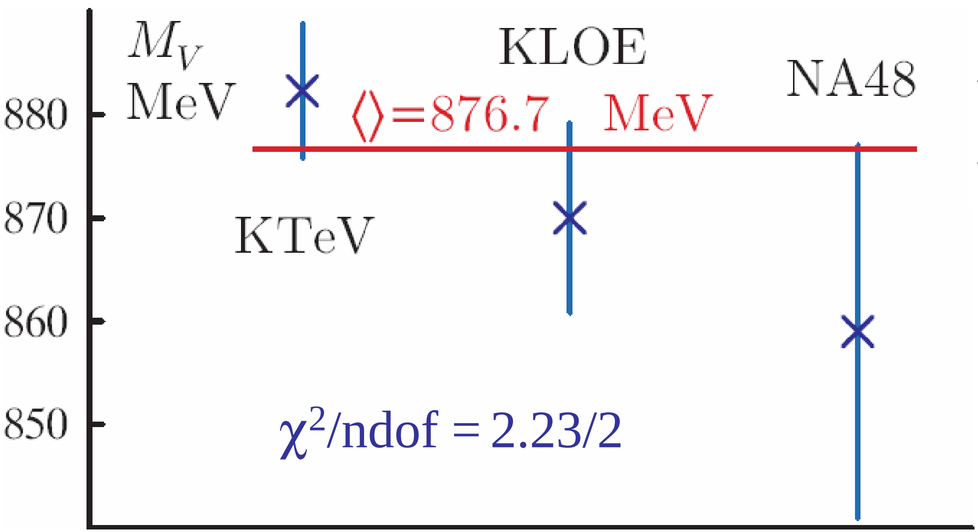
$$|\eta_{000}| = \left|\frac{A(K_S \to 3\pi^0)}{A(K_L \to 3\pi^0)}\right| = \sqrt{\frac{\tau_L}{\tau_S}\frac{BR(K_S \to 3\pi^0)}{BR(K_L \to 3\pi^0)}} < \mathbf{0.018} \quad \text{at 90\% C.L.}$$

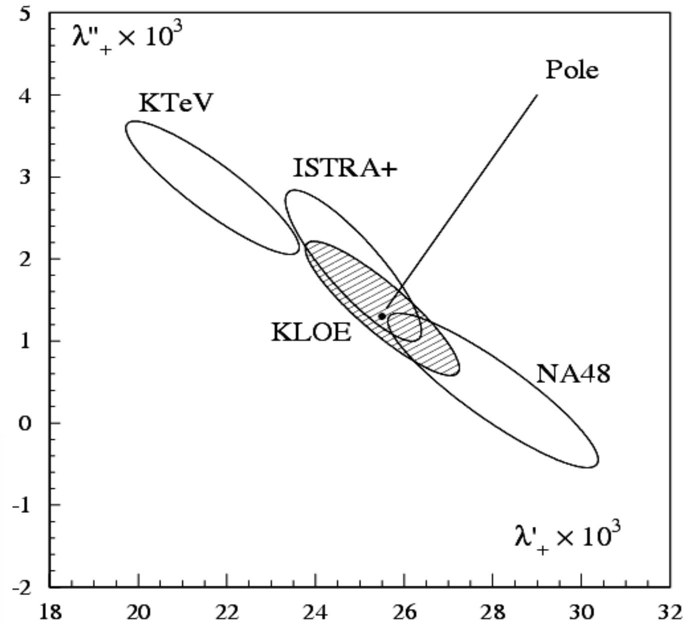
The CPT test from unitarity was limited by the knowledge of $|h_{000}|$ at the 10^{-5} level; now it is limited by uncertainties on other factors,
e.g. h_{+-}



with full statistics of 2.5 fb^{-1} + improved background rejection: => BR limit improved by a factor 10

K_{Le3} form factor slopes: Pole Model Results





(*) ISTRA+ $m_{\pi\pm}/m_{\pi0}$ correction

Search for K_S® $p^0p^+p^-$

Decay mainly *CP*-conserving ($\Delta I = 3/2$)
BR useful to constrain $K \to 3\pi$ amplitudes from χ^{pt}
PDG ’04: BR = $(3.2^{+1.2}_{-1.0}) \to 10^{-7}$
   Based on interference measurements
   [CPLEAR, E621] New NA48 preliminary

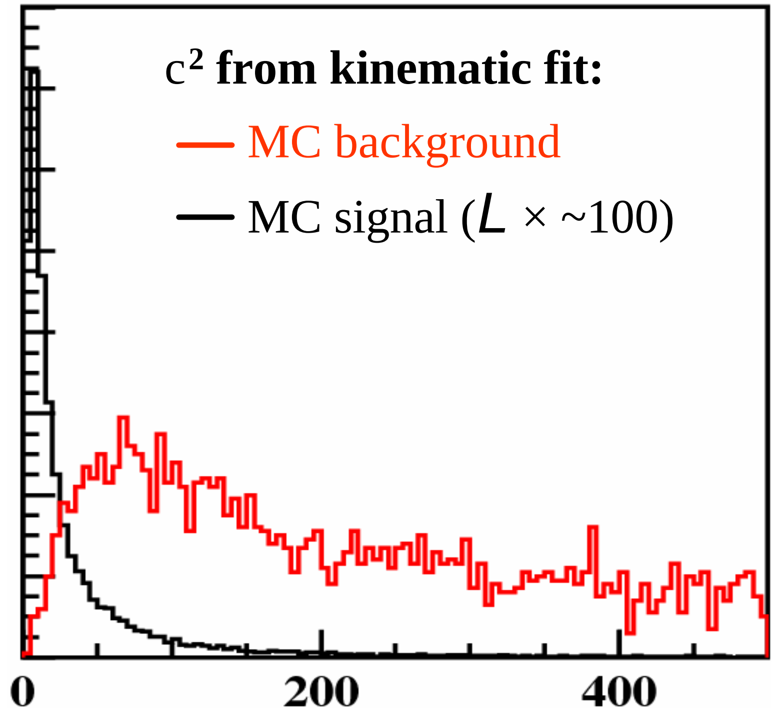
Never observed directly

Preselection criteria (e = 7%)

- K_L crash + vertex + 2 γ clusters

Kinematic fit rejects > 99% of bkg

- 6 constraints + $m(\pi^0)$ + $m(K_S)$



Remaining backgrounds:

- f ? K^+K^- — Cut on momentum of secondaries at ends of π tracks
- K_S ? $p^0{}_D p^0{}_{(D)}$ — Associate tracks to clusters, get *e*/π ID from TOF
- **Both types** — Veto on extraneous prompt clusters

Search for K_S® $p^0p^+p^-$

Preliminary results with 740 pb^{-1} '01 + '02 + '04 data:

- Signal efficiency: **~ 1.5%** (including K_L-crash eff)
- Candidates: **6 events**
- Background (sidebands): **~ 3.5 events**
- Number of events observed consistent with expectation
- Statistical error: ~ 100%
- Evaluation of systematic error in progress

Scaling these values to 2 fb^{-1} we expect:

- Measurement of BR($K_S \rightarrow \pi^+\pi^-\pi^0$) with 60% error

  About the same precision as interference-based measurements
- First measurement of BR from a direct search