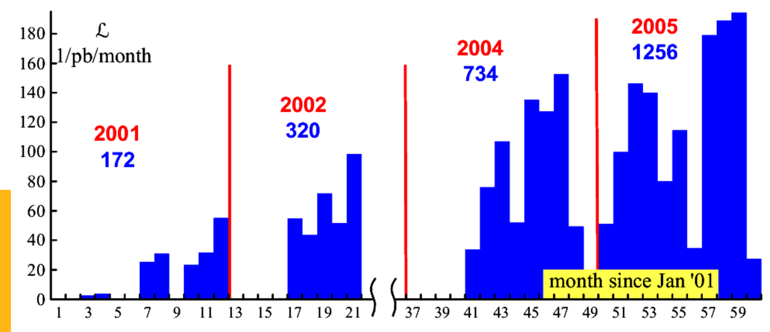
Precision Kaon Physics with KLOE

The KLOE collaboration

The DAΦNE ϕ-factory

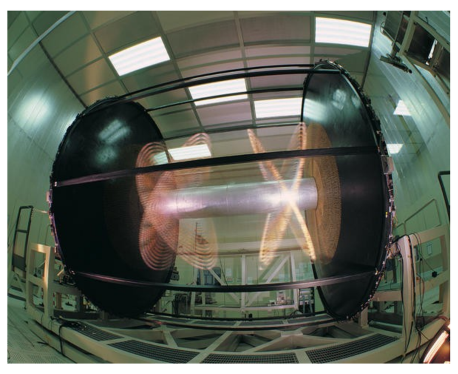
- e^+e^- collider @ $\sqrt{s} = M_\phi = 1019.4$ MeV
- $\sigma_{peak} \sim 3000$ nb
- Separate e+e– rings to reduce beam-beam interaction
- 2 interaction regions
- Beams crossing angle $\pi - 25$ mrad
- Peak luminosity 1.5×10^{32} cm^{-2}s^{-1}

March 2006 end of data taking.
Integrated luminosity: ~2.5 fb^{-1} @ ϕ-peak and ~250 pb^{-1} off-peak.



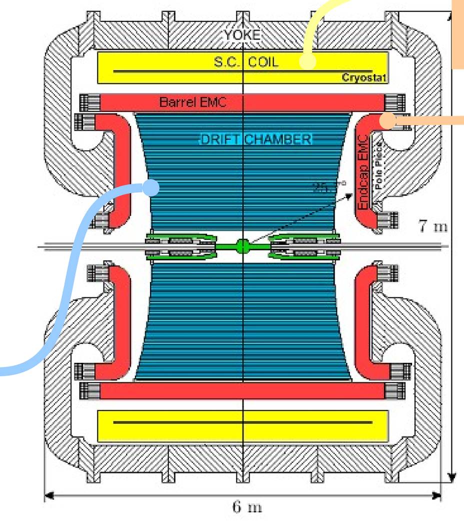
A ϕ-factory offers the possibility to select pure kaon beams: neutral kaons from $\phi \to K_S K_L$ are in fact produced in pairs and the detection of a K_S (K_L) tags the presence of a K_L (K_S), the same holds for charged kaons.

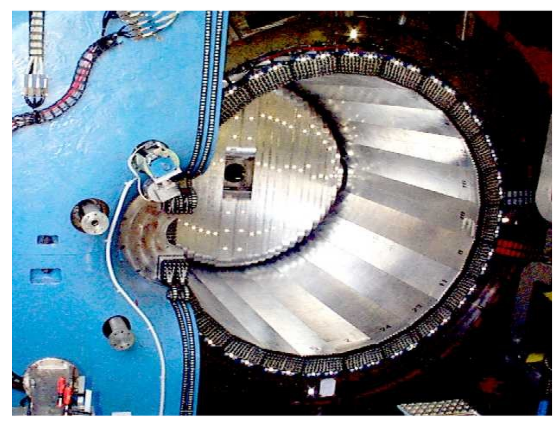
The KLOE detector



Superconducting coil:
- $\langle B \rangle = 0.52$ T

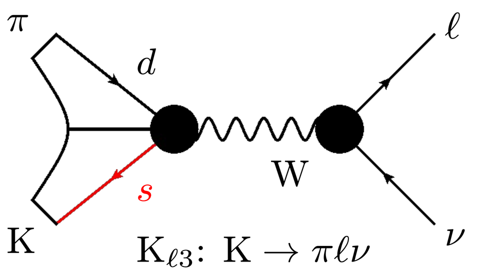
Lead/scintillating-fiber calorimeter:
- $\sigma_E/E = 5.7\% / \sqrt{E(\text{GeV})}$
- $\sigma_t = 54$ ps $/ \sqrt{E(\text{GeV})} \oplus 100$ ps





Large cylindrical drift chamber:
- 4 m diameter – 3.7 m length, carbon-fiber, gas: 90% He – 10% IsoC$_4$H$_{10}$
- $\sigma_p/p = 0.4$ % (track with $\theta > 45°$)
- $\sigma_{xy}^{hit} = 150$ μm, $\sigma_z^{hit} = 2$ mm
- $\sigma_{vtx} \sim 3$ mm

CKM unitarity and lepton-flavor violation



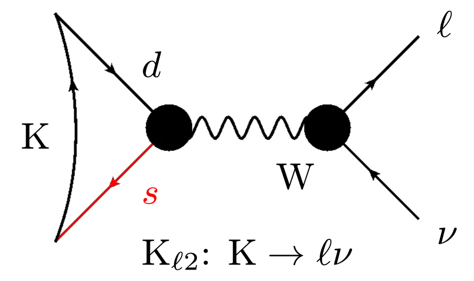
Vector transition: only 2nd order SU(3) breaking [Ademollo-Gatto]

Precise determination of V$_{us}$
Test of lepton universality Ke3 vs Kμ3
Most precise **test of CKM unitarity**

$|V_{ud}|^2 + |V_{us}|^2 = 1$; $|V_{ub}|^2$ negligible

$G_F^2 = G_{CKM}^2 = (|V_{ud}|^2 + |V_{us}|^2)\, G_F^2$

Lepton-Quark universality of weak interaction.



Helicity suppressed:
Sensitivity to NP enhanced

Precise determination of **V$_{us}$/V$_{ud}$**
Test of Physics beyond the SM:
right-handed contributions to charged weak currents
charged Higgs exchange (2 Higgs doublet scenarios)
Lepton Flavor Violation test with R$_K$=Γ(Ke2)/Γ(Kμ2)

Γ(Kμ2)/Γ(πμ2)

Ingredients for V$_{us}$ determination

$$BR(K \to \pi \ell \nu(\gamma)) \over \tau = \frac{G^2 m_K^5}{768\pi^3} C_K^2 |V_{us}|^2 |f_+^{K\pi}(0)|^2 I_K^\ell S_{ew} [1 + \delta_{SU(2)} + \delta_{em}]$$

1) 2) 1) 3) 4)

Inputs from theory
1) Universal short distance EW correction (1.0232)
2) Hadronic matrix element at zero momentum transfer (t=0)
3) Form factor correction for strong SU(2) breaking
4) Long distace EM effects

Inputs from experiment
1) **Branching ratios** with well determined treatment of radiative decays; **lifetimes**
2) Phase space integral: λ's parametrize form factor dependence on t:
Ke3: only λ$_+$ (or λ$_+$' λ$_+$'')
Kμ3: need λ$_+$ and λ$_0$

KLOE has measured all relevant Inputs for charged and neutral kaons:
BR's, lifetimes (K$_{L}$,K$^{\pm}$), form factors (FFs)

PLB 632 (2006)
BR(K$_{Le3}$) = 0.4008(15)
BR(K$_{Lμ3}$) = 0.2699(14)

PLB 626 (2005)
τ$_L$ = 50.92(30) ns

PLB 636 (2006)
BR(K$_{Se3}$) = 7.046(91)×10^{-4}

PLB 636 (2006)
λ$_+$' = (25.5±1.8) × 10^3
λ$_+$'' = (1.4±0.8) × 10^3

JHEP04 (2008) 059

PLB 632 (2006)
BR(K$^{\pm} \to \mu^{\pm}\nu$) = 0.6366(17)

JHEP01 (2008)
τ$^{\pm}$ = 12.347(30) ns

JHEP02 (2008)
BR(K$^{\pm} \to \pi^0 e^{\pm}\nu$) = 0.04965(53)
BR(K$^{\pm} \to \pi^0 \mu^{\pm}\nu$) = 0.03233(39)

PLB 666 (2008)
BR(K$^{\pm} \to \pi^{\pm}\pi^0(\gamma)$) = 0.2065(9)

KLOE average $|V_{us}| f_+(0) = 0.2157(6)$ χ^2/ndf=7/4 (13%)
$|V_{us}| = 0.2237(13)$

f$_+$(0)=0.964(5)

PRL 100 (2008)

V$_{us}$, V$_{ud}$, and V$_{us}$/V$_{ud}$

$|V_{us}/V_{ud}|$= 0.2323(15)
BR(K$^{\pm} \to \mu^{\pm}\nu$) = 0.6366(17)
f_K/f_π = 1.189(7)
PRL 100 (2008)

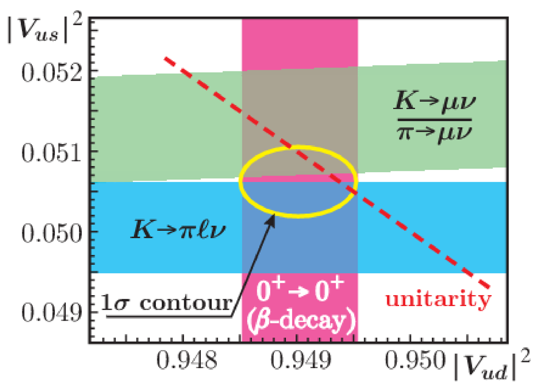
$|V_{us}|$ = 0.2237(13) from Kℓ3 decays
$|V_{ud}|$ = 0.97418(26) PRC 77 (2008)

•Fit to $|V_{ud}|^2$, $|V_{us}|^2$ and $|V_{us}/V_{ud}|^2$

$|V_{ud}|^2$ = 0.9490(5)
$|V_{us}|^2$ = 0.0506(4)
χ^2 = 2.3/1 (13%)

JHEP 04 (2008)

• Agreement with unitarity
1-V$_{ud}^2$-V$_{us}^2$ = 4(7)×10^{-4} @ 0.6 σ
G$_F$ = 1.166371(6) x10^{-5} GeV^{-2}
G$_{CKM}$ = 1.16604(40) x10^{-5} GeV^{-2}
G$_{ew}$ = 1.1655(12) x10^{-5} GeV^{-2} from EW precision tests



R$_K$ precision measurement

- RK=Γ(Ke2(γ IB))/Γ(Kμ2(γ IB)) inclusive of IB only
- DE (or SD)≈ IB presently known with 15% accuracy

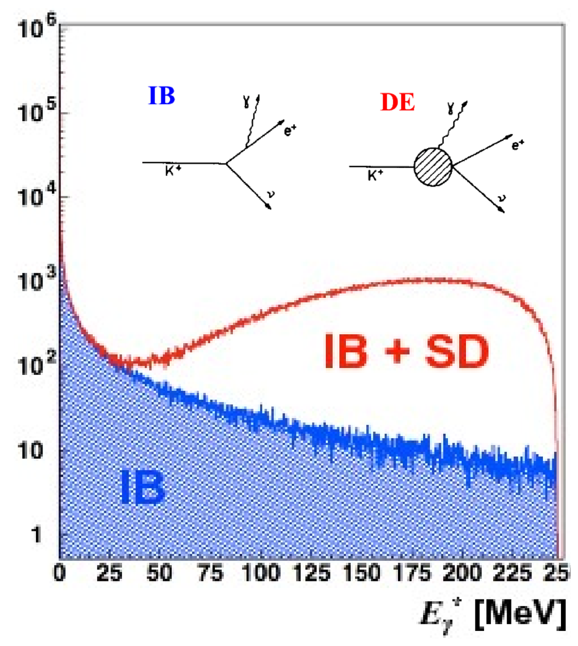
To achieve ~1% accuracy on R$_K$ improve knowledge of DE.

- In the SM R$_K$ has been calculated at 0.04% (no hadronic uncertainties)
- Lepton Flavor Violation in the MSSM would enhance R$_K$ up to 1% LFV appears at 1-loop level via an effective H$^+\ell\nu_\tau$, Yukawa interaction dominated by $e\nu_\tau$.

$$R_K^{LFV} \approx R_K^{SM}\left[1 + \left(\frac{m_K^4}{M_{H\pm}^4}\right)\left(\frac{m_\tau^2}{m_e^2}\right)|\Delta_{13}|^2 \tan^6\beta\right]$$

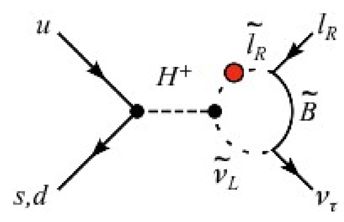
Δ_{13} Lepton flavor violating coupling

[Masiero-Paradisi-Petronzio PRD74 (2006) 011701]



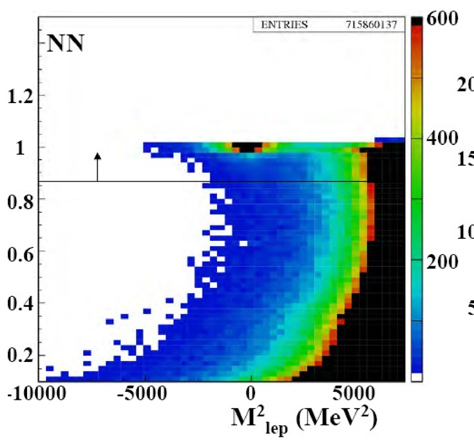
ANALYSIS STRATEGY

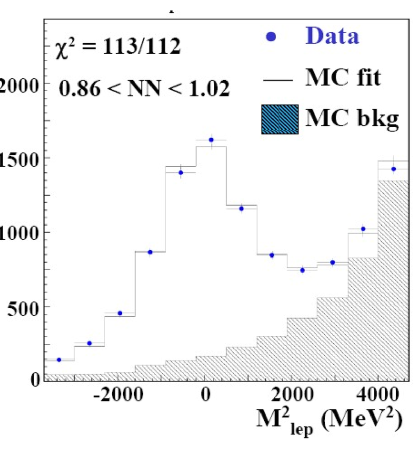
- Perform Direct search for Ke2 and Kμ2, no tag: gain ×4 of statistics
- Select 1-prong kinks in DC, K track from IP & secondary P > 180 MeV
  Signal events with E$_\gamma$<10 MeV (no explicit photon detection)
- Exploit tracking of K and secondary: assuming $m_\nu = 0$ get M$^2_{lep}$ (S/B ~1/10)
- Particle Identification by Neural Network based on EMC information.



Signal count from fit in NN- M$^2_{lep}$

Free parameters:
normalization factors for Kμ2 and Ke2(γ) including only IB with E$_\gamma$<10 MeV (to O(α_{em}) and resummation of leading logs)
Fixed parameter:
f$_{DE}$= 10.2% (Ke2 contamination from Ke2(γ) with E$_\gamma$>10 MeV)
But 0.5% systematics on R$_K$ from f$_{DE}$ (δ(DE)/DE=15%)
⇒ dedicated measurement of Ke2(γ) with E$_\gamma$>10 MeV





- 1-prong selection – NN > 0.98 – 1 photon cluster with E$_\gamma$>20 MeV in time with K
- Cluster times for photon and electron must be compatible
With this selction we measure Ke2γ with:
E$_\gamma^*$ >10 MeV
cos$\theta_{e\gamma}^*$ > 0.9
p$_e^*$ > 200 MeV
The result obtained is:

$$\frac{\Gamma_{SD}(K_{e2\gamma})}{\Gamma(K_{\mu2(\gamma)})} = 1.484(66)_{st}(16)_{sy} \times 10^{-5}$$

In agreement with ChPT O(p^4) prediction, 1.447×10^{-5} [Bijinens, Eker, Gasser '93]
Systematic error on RK from SD = 0.2%.

Using the complete KLOE data set (2.2 fb^{-1}) we obtain:

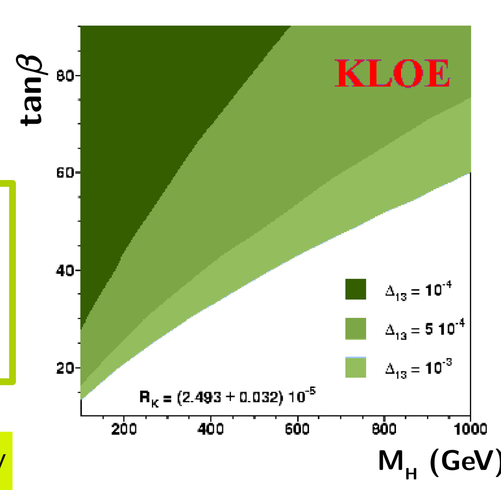
$R_K = (2.493 \pm 0.025_{stat} \pm 0.019_{syst}) \times 10^{-5}$

$R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$

Systematic errors %	stat	syst
Reconstruction	0.4	0.4
Trigger efficiency	0.4	-
Background sub	-	0.3
Ke2(DE) comp.	0.2	-
Clustering	0.2	-
Total	0.6	0.5

Sensitivity shown as 95%-CL excluded regions in the tanβ- M$_H$ plane, for fixed values of the 1-3 slepton-mass matrix element, Δ_{13} = 10^{-3},0.5×10^{-3},10^{-4}

Main contribution to systematic uncertainty from control-sample statistics (0.6%)



K$_L$ lifetime measurement

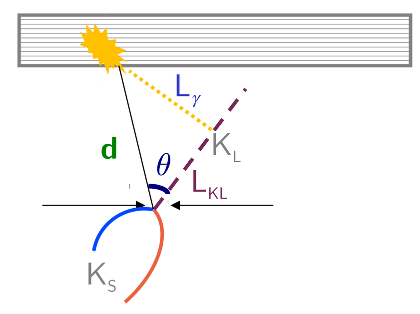
The error on τ_L is the main limiting factor on V$_{US}$ accuracy from K$_L$ decays

$$\frac{\delta(V_{us}f_+(0))}{(V_{us}f_+(0))} = 0.1\% \oplus 0.2\% \oplus 0.1\% \oplus 0.1\%$$

BR τ$_L$ phase space integral radiative corr.

τ$_L$ measurement can be improved (stat.+syst.) with whole KLOE data sample

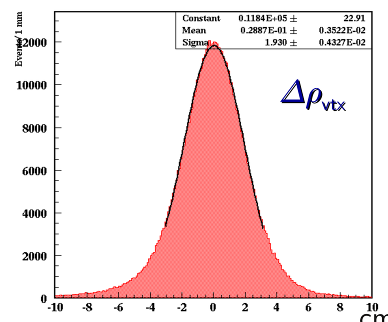
- K$_L$ tagged with K$_S$ → π$^+$π$^-$ vertex at IP
- K$_L$ direction and momentum from DC measurements
- Unique to the KLOE calorimeter: L$_{KL}$ and L$_\gamma$ by time measurements t$_\gamma$

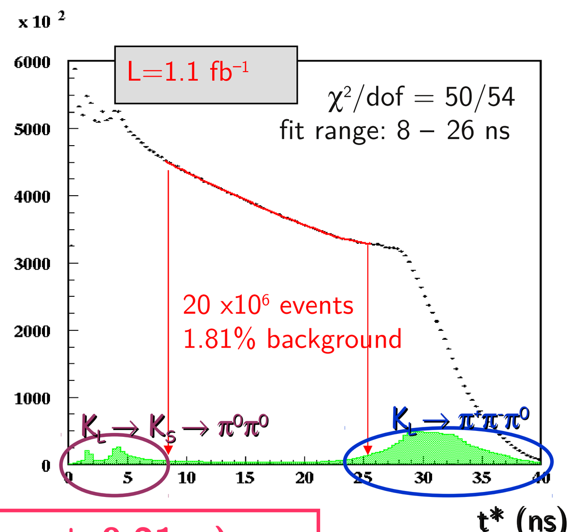


$L_\gamma^2 = d^2 + L_{KL}^2 - 2dL_{KL}\cos\theta$

$ct_\gamma = L_{KL}/\beta_L + L_\gamma$

- K$_L$ "photon" vertex, built with at least 3 γ's from π^{0}π^{0}π^0 decay
- Time scale, neutral vertex resolution, γ reconstruction efficiency survived with K$_L$→π$^+$π$^-$π^0 events





$\tau_L = (50.56 \pm 0.14_{stat} \pm 0.21_{syst})$ ns

KLOE
τ$_L$ = 50.92(30) ns PLB 626 (2005)
τ$_L$ = 50.72(36) ns PLB 632 (2006)

Whole data sample: $\sigma_{stat} \to 0.11$ ns
Work in progress to reduce systematics

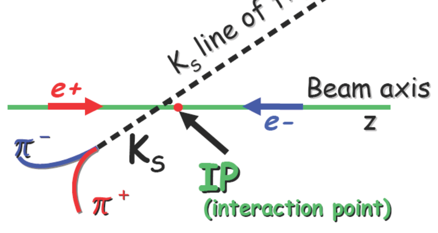
K$_S$ lifetime measurement

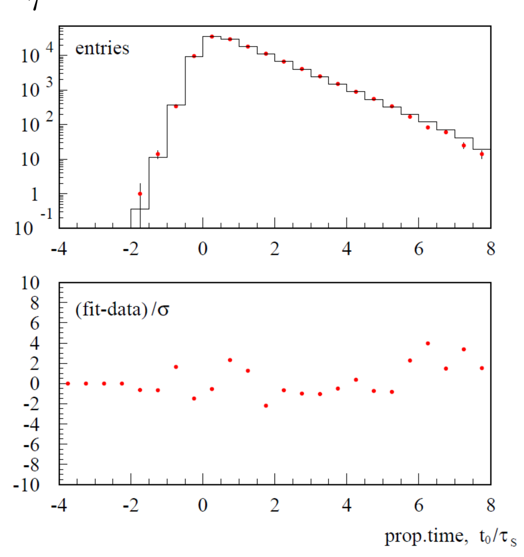
- Lifetime from fit to proper time t* distribution of K$_S$ → π$^+$π$^-$ decays (18 million from '04 data)
- Event-by-event φ-meson decay point (PCA of K$_L$ flight direction to beam line)
- Improve time resolution with kinematic fit (free x$_{KS}$ and L$_{KS}$, K direction fixed)

- First measurement with pure K$_S$ beam and with an event by event knowledge of K$_S$ momentum KLOE
- is well suited to perform τ$_S$ measurement as a function of sidereal time which is interesting to test QM, CPT and Lorentz invariance
- V$_{us}$ from K$_S$ with KLOE data (we measured BR(Kse3) at 1.3%, we can reach 0.5% on the whole data set)

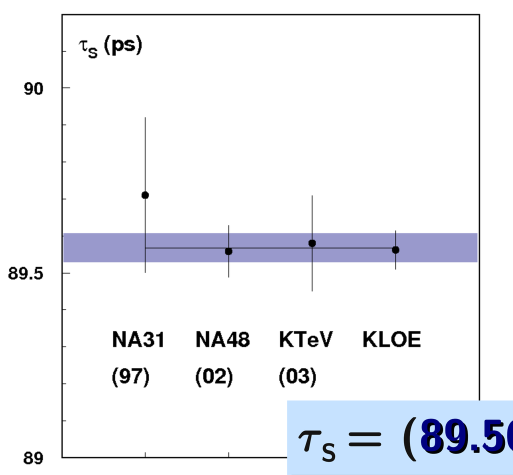
$$f(t) = A\int_{-\infty}^{+\infty} \theta(x)\frac{1}{\tau}\exp(x/\tau)\epsilon(x)g(t+\delta-x)dx$$

•Fiducial volume: 18x10 [ϕ_K, cosθ_K] bins
-0.5< cosθ_K< +0.5
- Fit range: 15 bins from -1 to +6.5 in t*/τ$_S$(MC)
- Fit function used in [ϕ_K, cosθ_K] bin





Systematics	Value (ps)
Fit range	0.012
Selection cuts	0.024
p$_K$ calibration	0.033
Kaon mass	0.004
Efficiency(L$_K$)	0.005
Total	**0.043**



$\tau_S = (89.562 \pm 0.029_{stat} \pm 0.043_{syst})$ ps