KLOE results on rare K^0 decays

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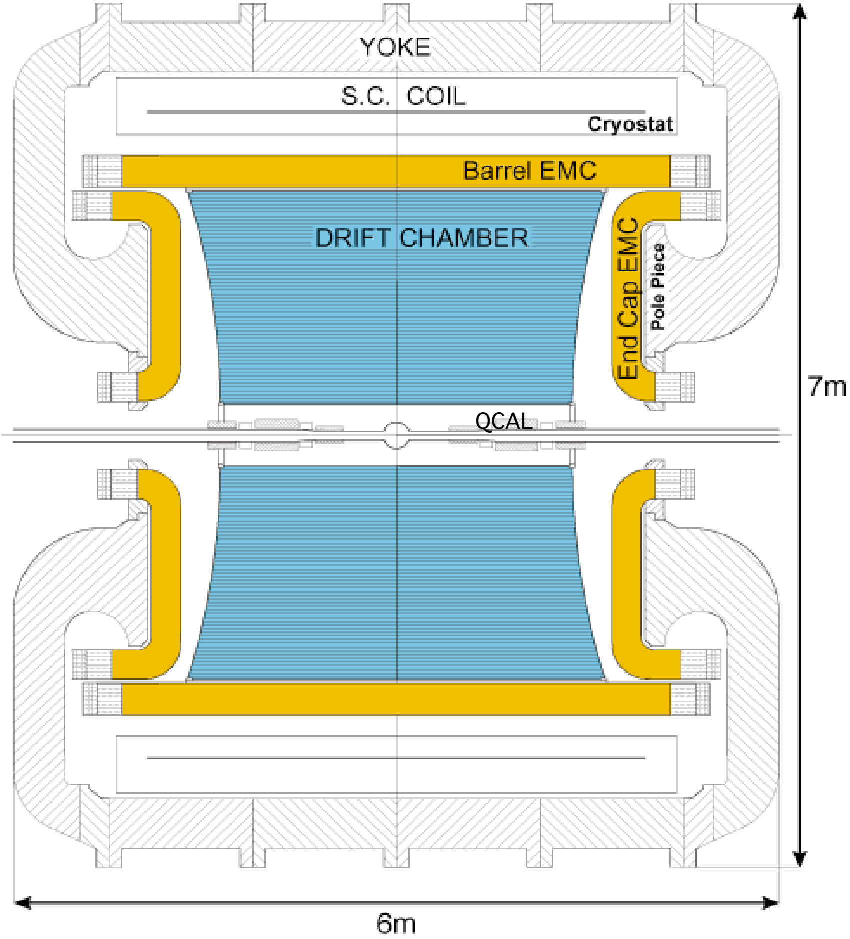
on behalf of the
KLOE Collaboration



Workshop on e^+e^- in the 1-2 GeV Range: Physics and Accelerator Prospects

10-13 September 2003, Alghero (SS), ITALY

Outline

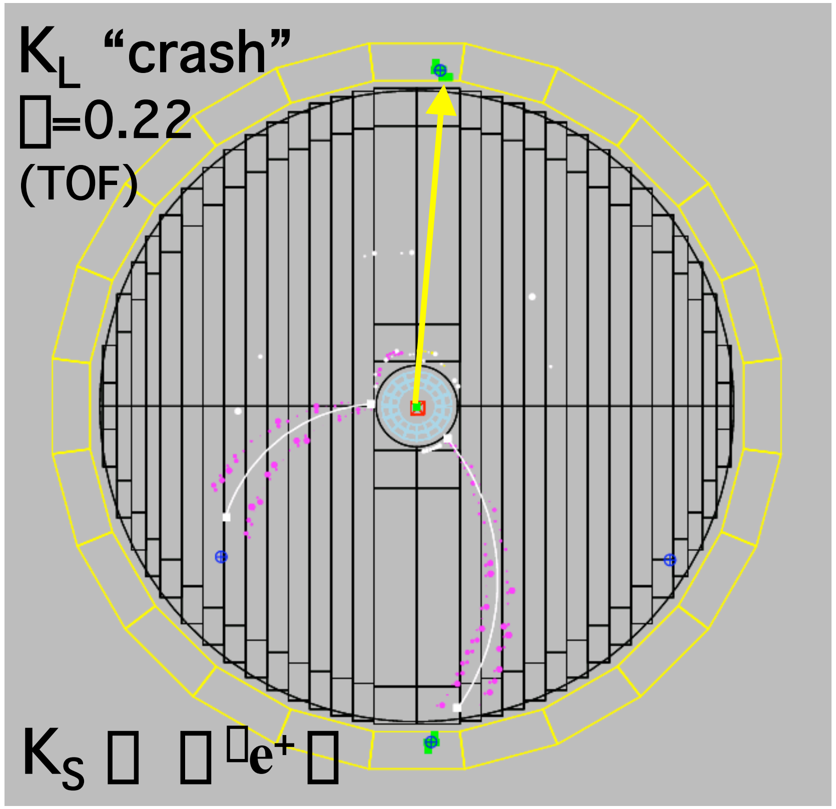
- K^0 data set
- Benchmark K^0 measurements
- BR(K_L□ □□)
- BR(K_S□ □e□)
- Conclusions

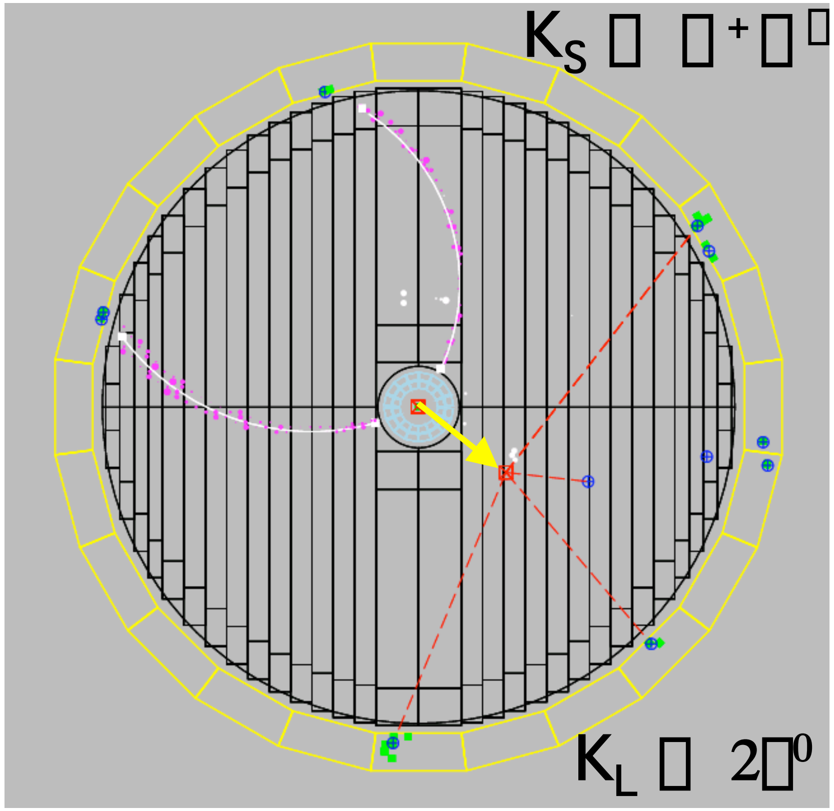
Neutral Kaons at KLOE

$\sigma(e^+e^- \to \phi) \approx 3\ \mu b$, $BR(\phi \to K_S K_L) \sim 34\%$

$p = 110$ MeV, $\beta = 0.22$, $\lambda_S = 6$ mm ($R_{BPIPE} \sim 16\lambda_S$), $\lambda_L = 3.4$ m ($R_{DriftCh} \sim 0.5\lambda_L$)

$J^{PC}(K_S K_L) = 1^{--} \Rightarrow$ TAGGING





K_S tagged by K_L interaction in EmC
Efficiency ~ 30% (largely geometrical)
K_S: δ(angle) ~ 1°, δ(p) ~ 2 MeV

K_L tagged by $K_S \to \pi^+\pi^-$ vertex in BP
Efficiency ~ 70% (mainly geometrical)
K_L: δ(angle) ~ 1.5°, δ(p) ~ 2 MeV

Measured detector performances

1 Kton detector (600 ton yoke)

SC solenoid (B=0.52 T)

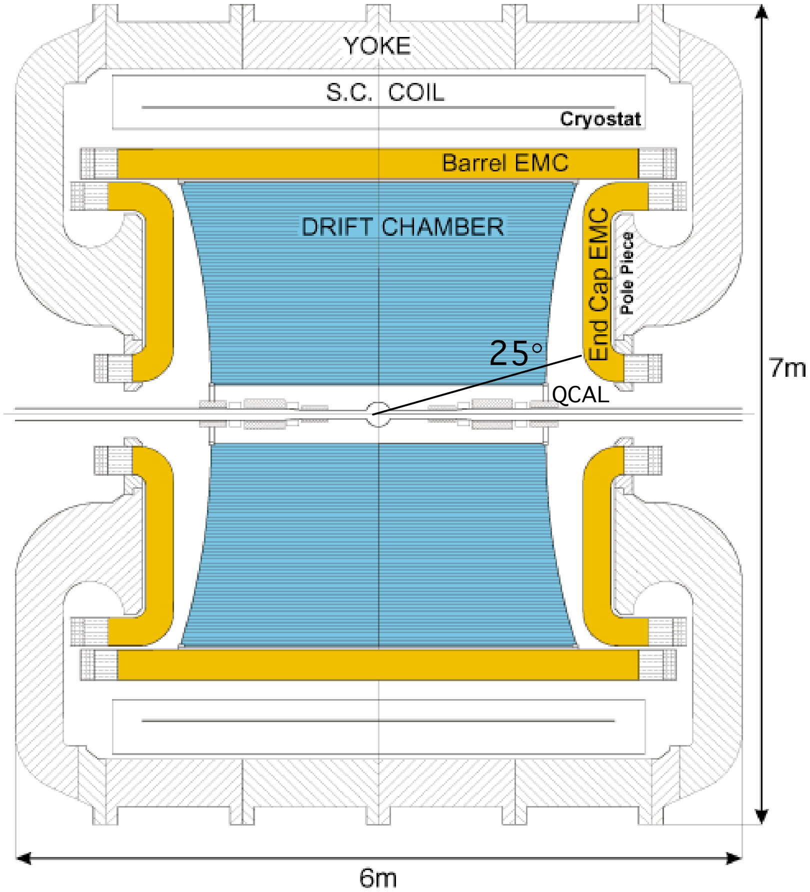
Lead-SciFi EMC (5000 PMs)

Drift Chamber (90% He -10% Isob,

4 m ∅ □ 3.3 m, 12K sense wires)

□ DA□NE quadrupoles inside DC

□ EMC around quads (32 PMs)



EMC

$\square_E/E \sim 5.7\%/\sqrt{E(GeV)}$

$\square_t \sim 54\ ps/\sqrt{E(GeV)} \oplus 50\ ps$

(relative time between clusters)

$\square_{\square\square}^{HIT} \sim 1 cm/\sqrt{E(GeV)}$, $\square_{\square}^{HIT} \sim 1 cm$

$\square^{VTX}(\square\square) \sim 1.5\text{-}2. cm$ (K_L □ $\square^+\square^-\square^0$, □□)

DC

$\square_{p\square}/p_{\square} \sim 0.4\%$ (45° < □ < 135°)

$\square^{HIT}$ ~150 □m (xy), 2 mm(z)

$\square^{VTX}$ ~ 1-3 mm (K_L, K_S □ $\square^+\square^-$)

K^0 data set

- 2000 run: 25 pb^{-1}

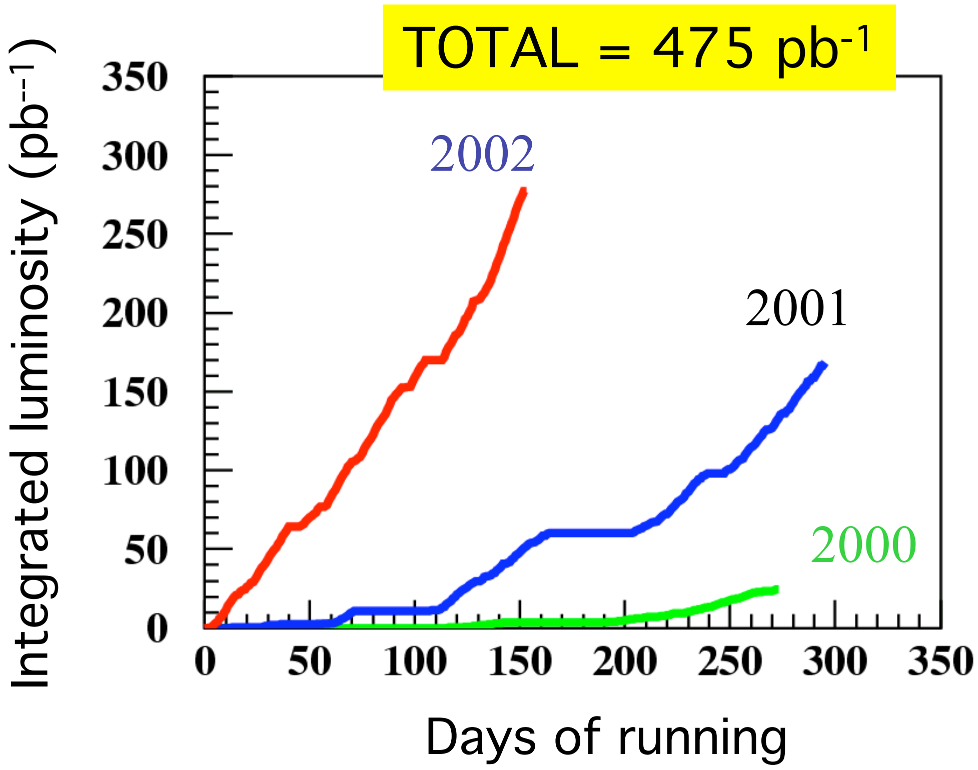
  $27\cdot10^6$ produced K_LK_S

- 2001 run: 170 pb^{-1}

  $180\cdot10^6$ produced K_LK_S

- 2002 run: 280 pb^{-1}

  $296\cdot10^6$ produced K_LK_S



2002: best lum. ≈ $8\cdot10^{31}$ $cm^{-2}s^{-1}$, best daily $\int L\,dt = 4.5$ pb^{-1}

Results shown today cover 17 to 362 pb^{-1}

Benchmark K^0 measurements

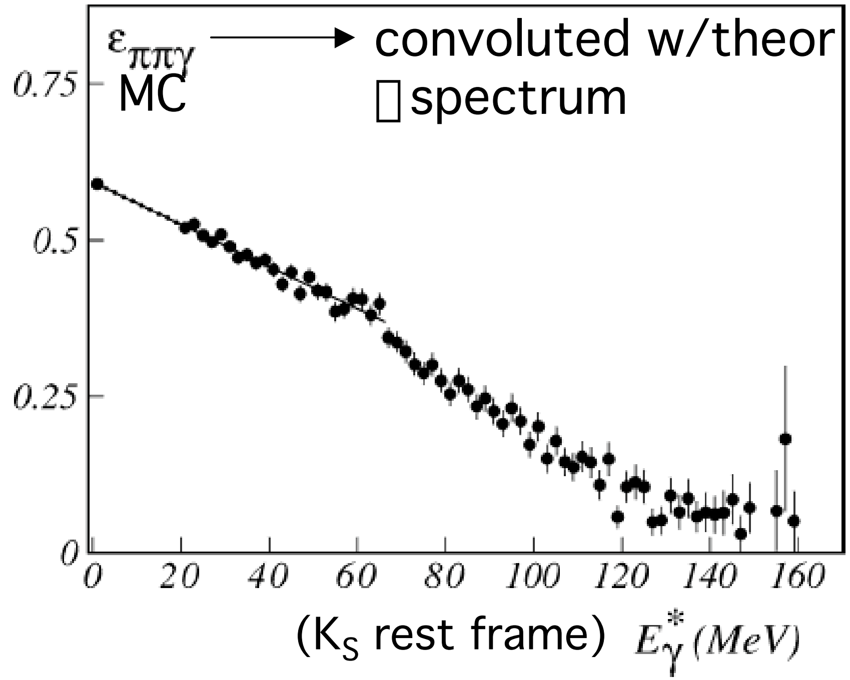
- BR, M, □ which firmly established KLOE capabilities
- Features common to most analysis
  - request a K_L or K_S tag

    $□_{TAG}$ from data (expect 0.1% accuracy w/0.5 fb^{-1})
  - $□_{TRIGGER}$ mainly from data
  - CMS energy, IP measured online w/Bhabha's (0.1pb^{-1} run):

    □√S ~ 40 KeV, □($x_□$,$y_□$) ~ (30,30) □m, □$p_□$ ~ 30 KeV
  - Event time, $T_□$, after offline reconstruction (□$T_□$~50ps)
  - Monte Carlo mainly for acceptance and geometry corrections
    - MC track and photon $□_{RECONSTR}$ scaled according to data

□(K_S□ □$^+$□$^□$(□))/□(K_S□ □^{0}□^{0})

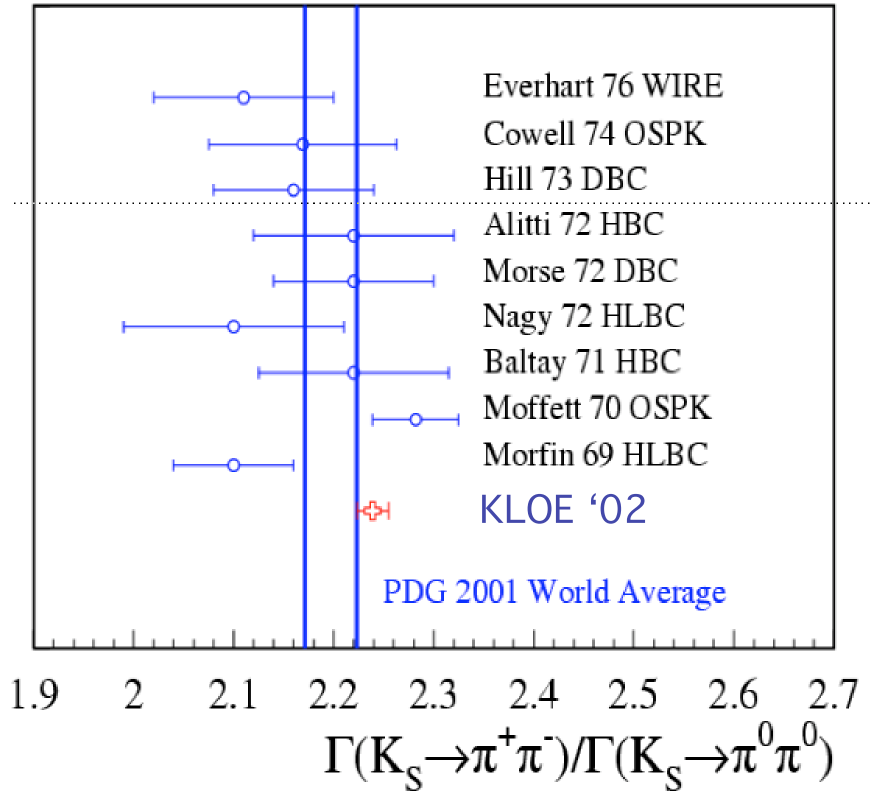
- Benchmark for □/□
- Gives info on EM isospin breaking and on strong phase shifts □$_0$-□$_2$
- Stat. accuracy ~ 0.1% and fully inclusive of □$^+$□$^□$□
- Limited by systematic uncertainty (estimated primarily from data)



Data: 17 pb^{-1} '00,
1.1·10^6 K_S □ □$^+$□$^□$
0.8·10^6 K_S □ □^{0}□^{0}

KLOE: 2.236 ± 0.003 ± 0.015

PL B538 2002



Measurement of K_S mass

http://www.lnf.infn.it/kloe/pub/knote/kn181.ps

Data: 2001 ϕ-peak scan: 29 pts, 0.5 pb^{-1}

W = CMS energy-scale calibrated to CMD-2 '01

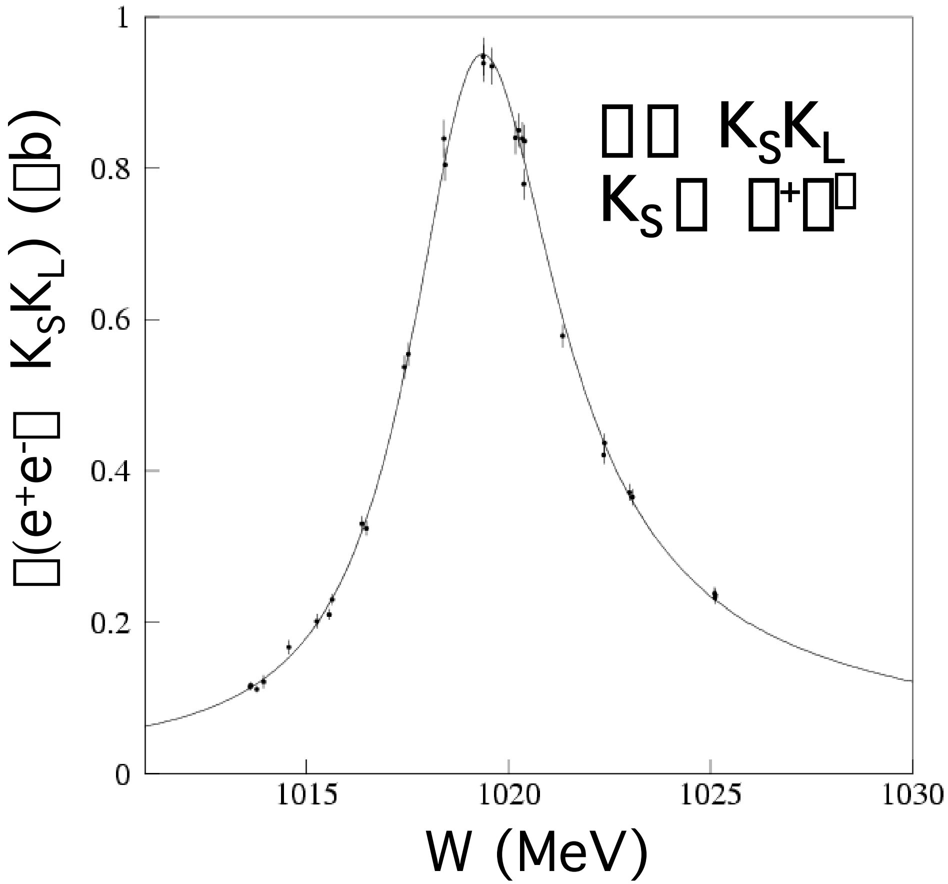
$m(\phi) = 1019.483 \pm 0.011 \pm 0.025$ MeV

$W = M(e^+e^-)$

$P = p(\pi^+) + p(\pi^-)$

$m(K_S) = W^2/4 - P^2$

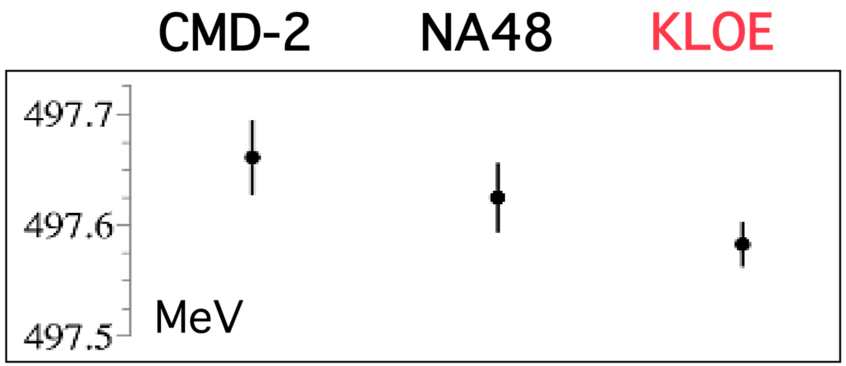
$\delta m/m \approx 0.05(\delta P/P)$



m(K_S) KLOE preliminary

$497.583 \pm 0.005 \pm 0.020$ MeV

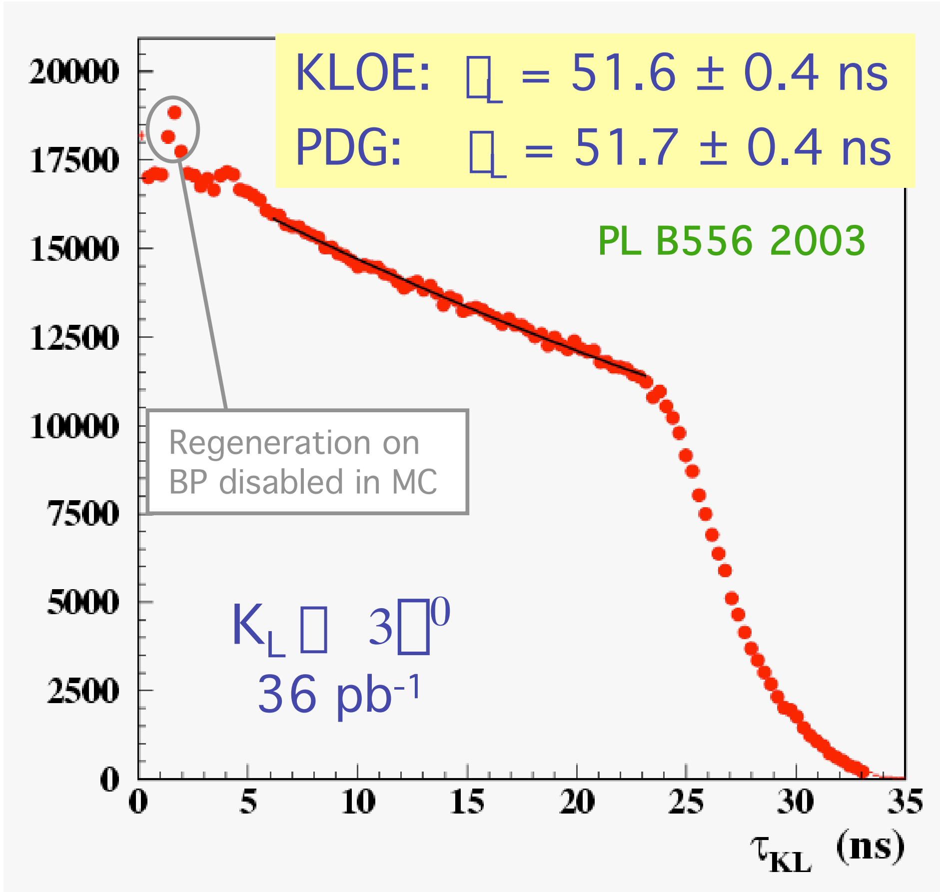
W-calib ISR

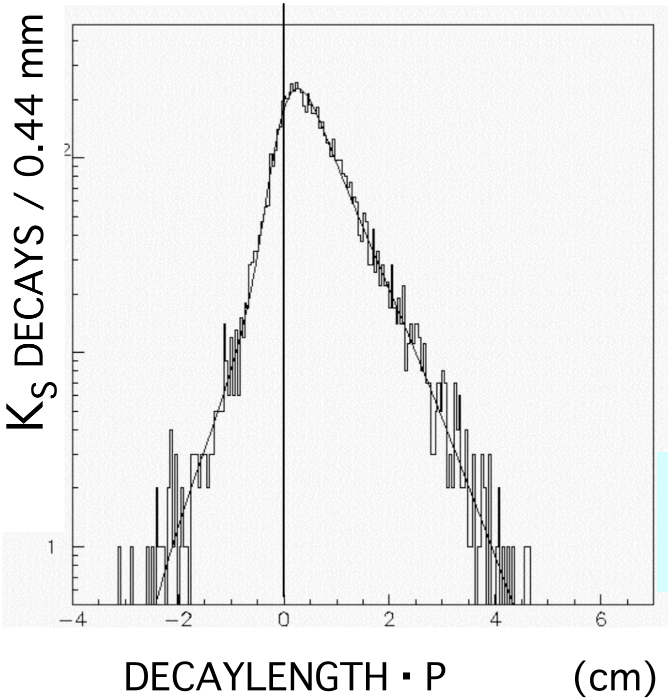


Lifetimes

$\tau(K_L \to 3\pi^0)$ exploits performance of EMC for photon vertex

<u>Statistical uncertainty only</u>





Check that $\lambda(K_S \to \pi^+\pi^-)$ ~ 6 mm

NIM A488 2002

BR($K_L \to \gamma\gamma$)

Large long-distance contribution via (π^0, η, η'). Can be calculated in χPT and is sensitive to θ_P. Dominates long-distance contribution to $K_L \to \mu^+\mu^-$

- N(tagged K_L) = $1.6 \cdot 10^8$ from 362 pb^{-1}
- $K_L \to 3\pi^0$ bkg suppressed by 2-body kinematics

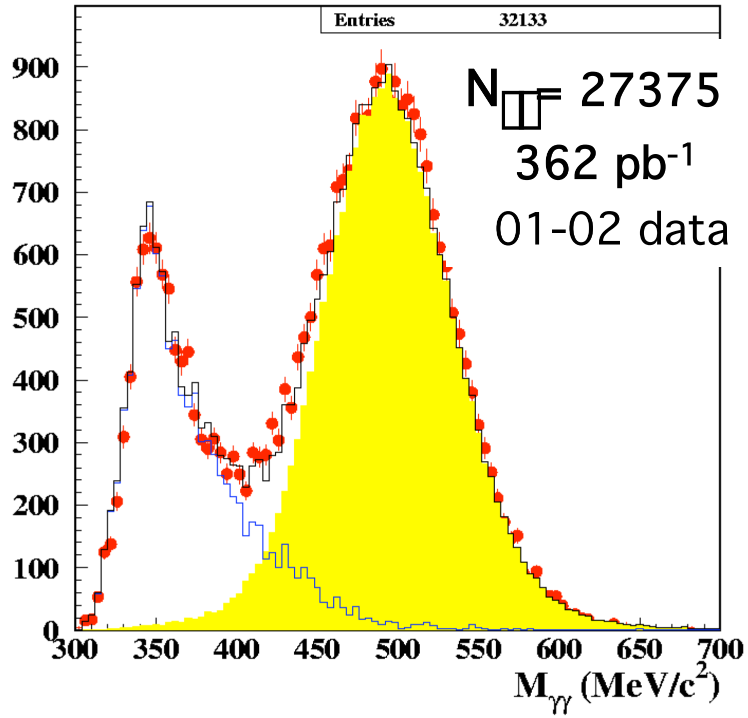
KLOE PL B556 2003

$\Gamma(K_L \to \gamma\gamma)/\Gamma(K_L \to 3\pi^0) = (2.79 \pm 0.02 \pm 0.02) \cdot 10^{-3}$

uncertainty dominated by error on $N_{\gamma\gamma}$

Compare to NA48 PL B551 2003

$\Gamma(K_L \to \gamma\gamma)/\Gamma(K_L \to 3\pi^0) = (2.81 \pm 0.01 \pm 0.02) \cdot 10^{-3}$



Using PDG BR($K_L \to 3\pi^0$) and KLOE $\Gamma(K_L \to \gamma\gamma)/\Gamma(K_L \to 3\pi^0)$:

$BR(K_L \to \gamma\gamma) = (5.89 \pm 0.07_{stat \oplus syst} \pm 0.08_{BR(KL \to 3\pi 0)}) \cdot 10^{-4}$

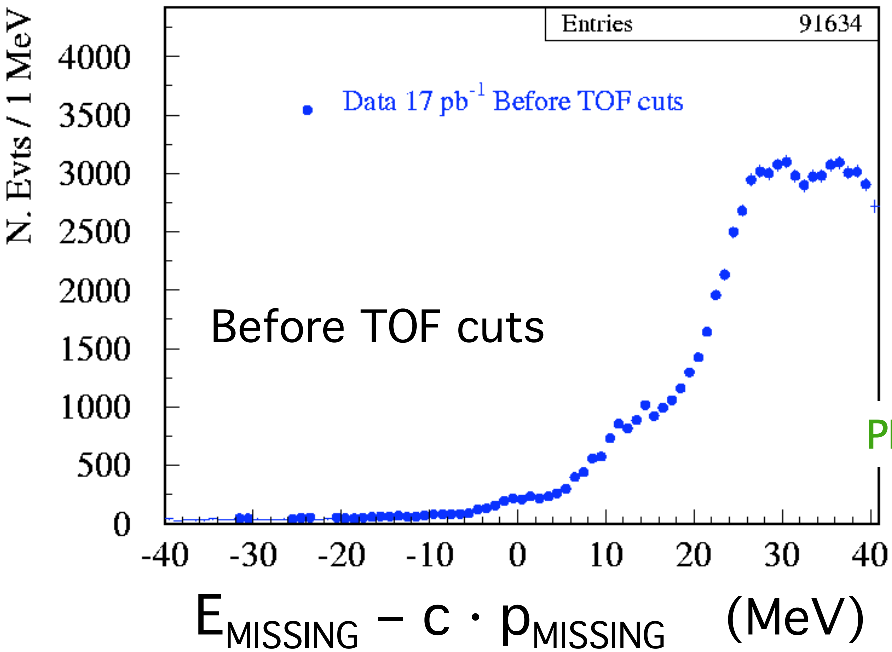
in agreement w/ χPT if θ_P close to KLOE measurement $\theta_P = (-12.9^{+1.9}_{-1.6})°$

PL B541 2002

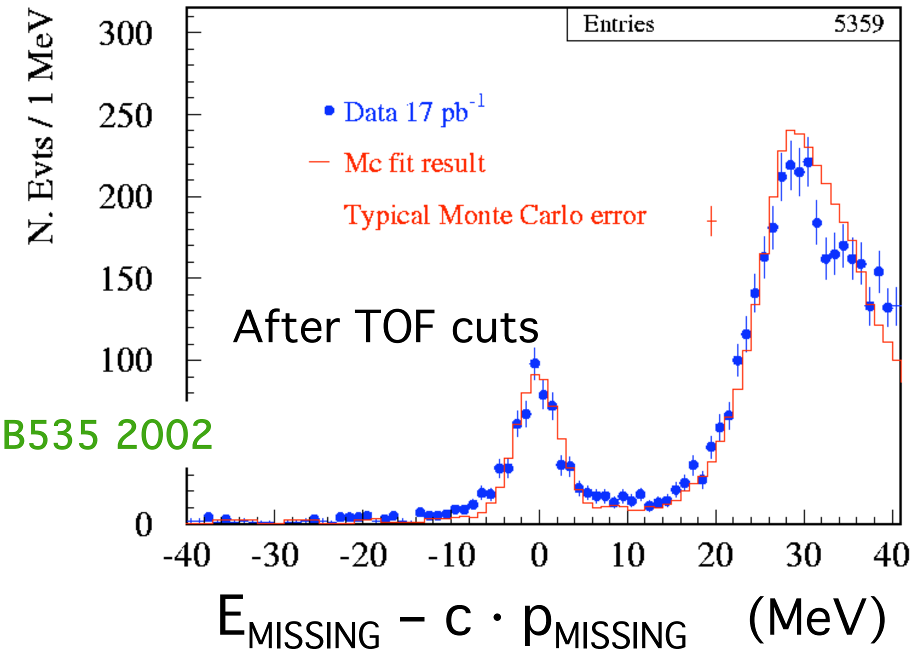
$K_S \to \pi^{\mp} e^{\pm} \nu(\bar{\nu})$

- K_S tagged by K_L-crash in EMC
- $K_S \to \pi^+\pi^-$ background (x10^3) suppressed by
  - 2-track mass, e/π discrimination by TOF
  - remaining bkg: $K_S \to \pi^+\pi^-$ with $\pi \to \mu$ before Drift C.
- Fit data to signal+background (MC) and normalize to BR($K_S \to \pi^+\pi^-$) to get BR($K_S \to \pi e \nu$)

~5 ·10^6 K_S tags
17 pb^{-1} 00 data

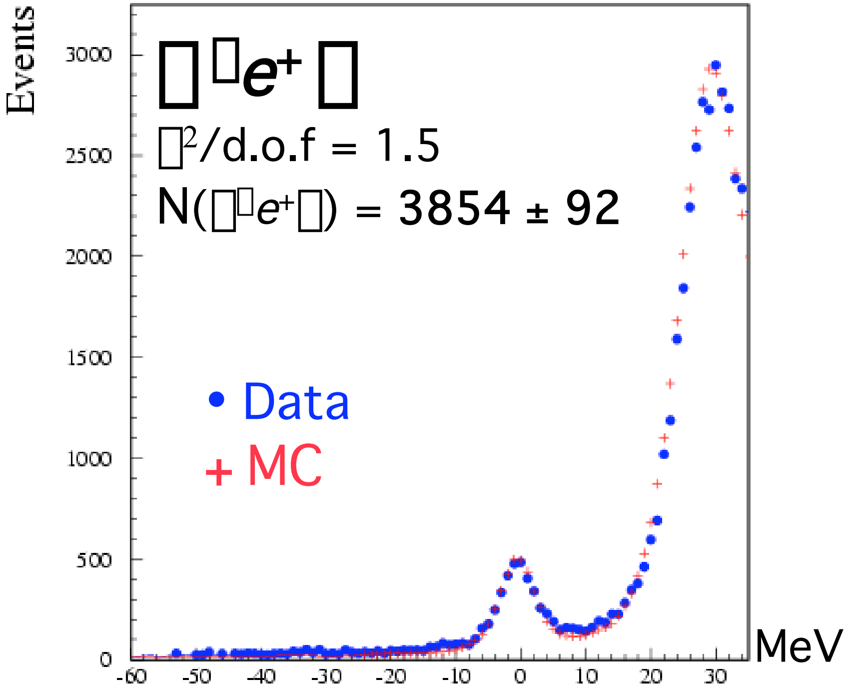


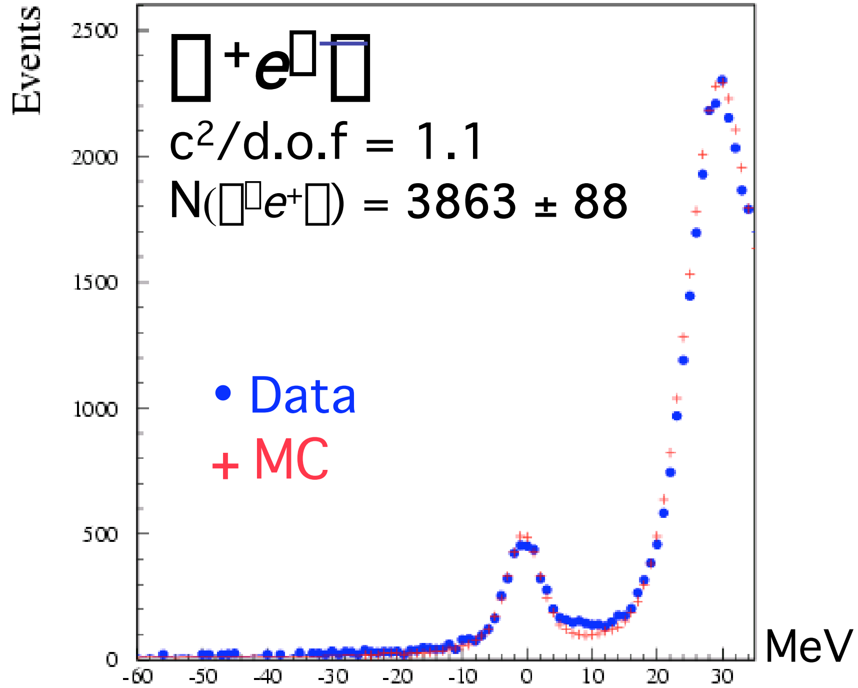
PL B535 2002



BR($K_S \to \pi e \nu$)

KLOE '03 preliminary result w/170 pb^{-1} 2001 data



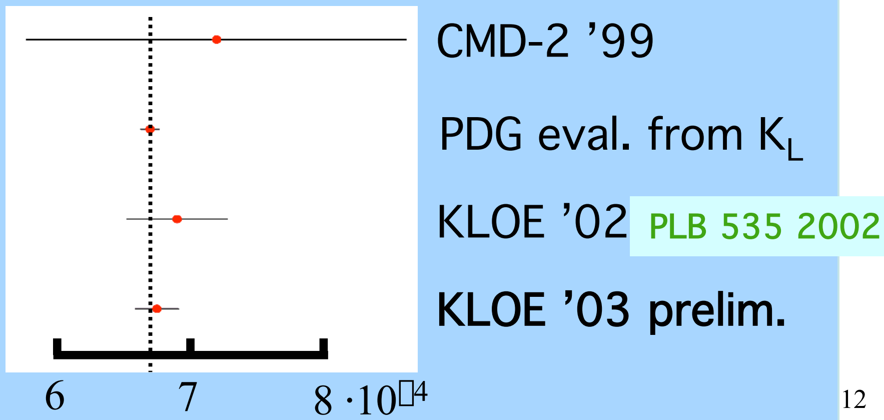


$E_{missing} - c \cdot p_{missing}$

BR($\pi^- e^+ \nu$) = (3.46 ± 0.09 ± 0.06) · 10^{-4}

BR($\pi^+ e^- \bar{\nu}$) = (3.33 ± 0.08 ± 0.05) · 10^{-4}

BR($\pi^{\mp} e^{\pm} \nu$) = (6.81 ± 0.12 ± 0.10) · 10^{-4}



BR($K_S \to \pi e \nu$): charge asymmetry

Matrix elements of semil. decays

$$\langle \pi^- e^+ \nu | H_W | K^0 \rangle = a + b$$
$$\langle \pi^+ e^- \bar{\nu} | H_W | \bar{K}^0 \rangle = a^* - b^*$$

$$\langle \pi^+ e^- \bar{\nu} | H_W | K^0 \rangle = c + d$$
$$\langle \pi^- e^+ \nu | H_W | \bar{K}^0 \rangle = c^* - d^*$$

Symmetry	Constraints
T	*Im a = Im b = Im c = Im d = 0*
CP	*Im a = Re b = Im c = Re d = 0*
CPT	*b = d = 0*
$\Delta S = \Delta Q$	*c = d = 0*

Charge asymmetry

$$A \equiv \frac{\Gamma(\pi^- e^+ \nu) - \Gamma(\pi^+ e^- \bar{\nu})}{\Gamma(\pi^- e^+ \nu) + \Gamma(\pi^+ e^- \bar{\nu})}$$

$$A_S = 2(\mathrm{Re}\,\varepsilon_K + \mathrm{Re}\,\delta_K + \mathrm{Re}\,b/a - \mathrm{Re}\,d^*/a)$$
$$A_L = 2(\mathrm{Re}\,\varepsilon_K - \mathrm{Re}\,\delta_K + \mathrm{Re}\,b/a + \mathrm{Re}\,d^*/a)$$

$\not{CP}$ | $\not{CPT}$ *in mixing* | $\not{CPT}$ *in decay* | $\Delta S \neq \Delta Q$ *and* $\not{CPT}$

$A_S - A_L = 4\mathrm{Re}\,\delta_K - 4\mathrm{Re}\,d^*/a \neq 0$
implies CPT violation

KLOE preliminary

$A_S = (19 \pm 17 \pm 6) \cdot 10^{-3}$

First measurement of A_S!

Compare to A_L w.a.

$A_L = (3.322 \pm 0.055) \cdot 10^{-3}$

$A_L = A_S = 2\,\mathrm{Re}\,\varepsilon_K$ if CPT conserved

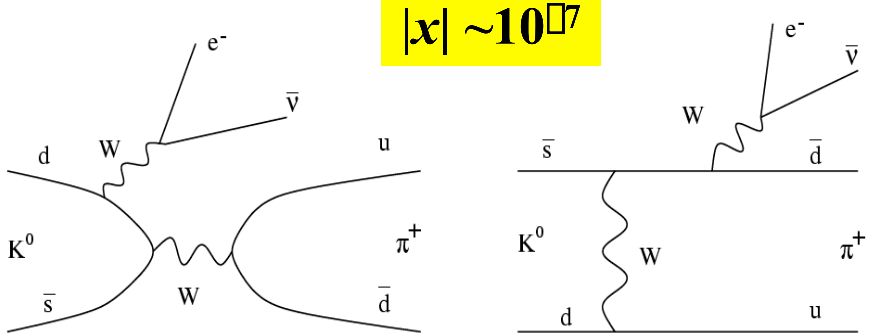
CPLEAR PL B444 1998 **Re δ_K** = (2.9 ± 2.7) 10^{-4}

$K^0 \to \pi e \nu$: test of $\Delta S = \Delta Q$

SM: no $\Delta S \neq \Delta Q$ transitions at lowest order

$\Delta S \neq \Delta Q$ in these higher order transitions:

$|x| \sim 10^{-7}$



$x = (c^* - d^*)/(a + b)$

$\Delta S \neq \Delta Q$ in $\bar{K}^0$ decay to e^+

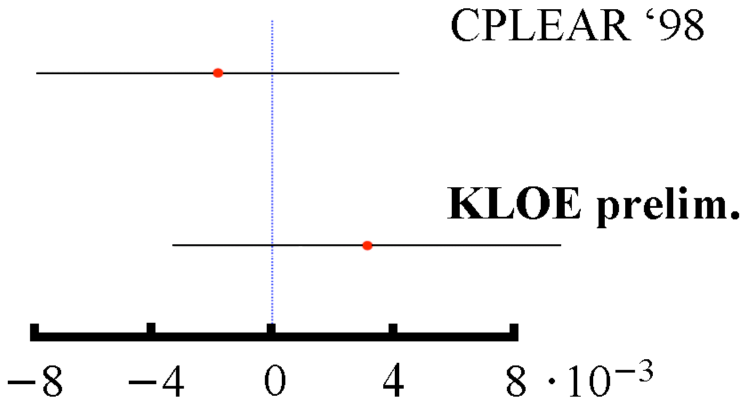
$\bar{x} = (c + d)/(a^* - b^*)$

$\Delta S \neq \Delta Q$ in K^0 decay to e^-

$x_+ = (x + \bar{x})/2 \approx c^*/a$

$\Delta S \neq \Delta Q$ if CPT conserved

$$\mathrm{Re}\, x_+ = \frac{1}{2}\,\frac{\mathrm{BR_S}(\pi e \nu)/\tau_S - \mathrm{BR_L}(\pi e \nu)/\tau_L}{\mathrm{BR_S}(\pi e \nu)/\tau_S + \mathrm{BR_L}(\pi e \nu)/\tau_L}$$



KLOE preliminary

Re $x_+ = (3.3 \pm 5.2 \pm 3.5) \cdot 10^{-3}$

Compare to CPLEAR '98

Re $x_+ = (-1.8 \pm 4.1 \pm 4.5) \cdot 10^{-3}$

280 pb^{-1} from '02 running + KLOE measurements of τ_L, BR($K_L \to \pi e \nu$) on the way

V_{us} from $K_S \to \pi e \nu$

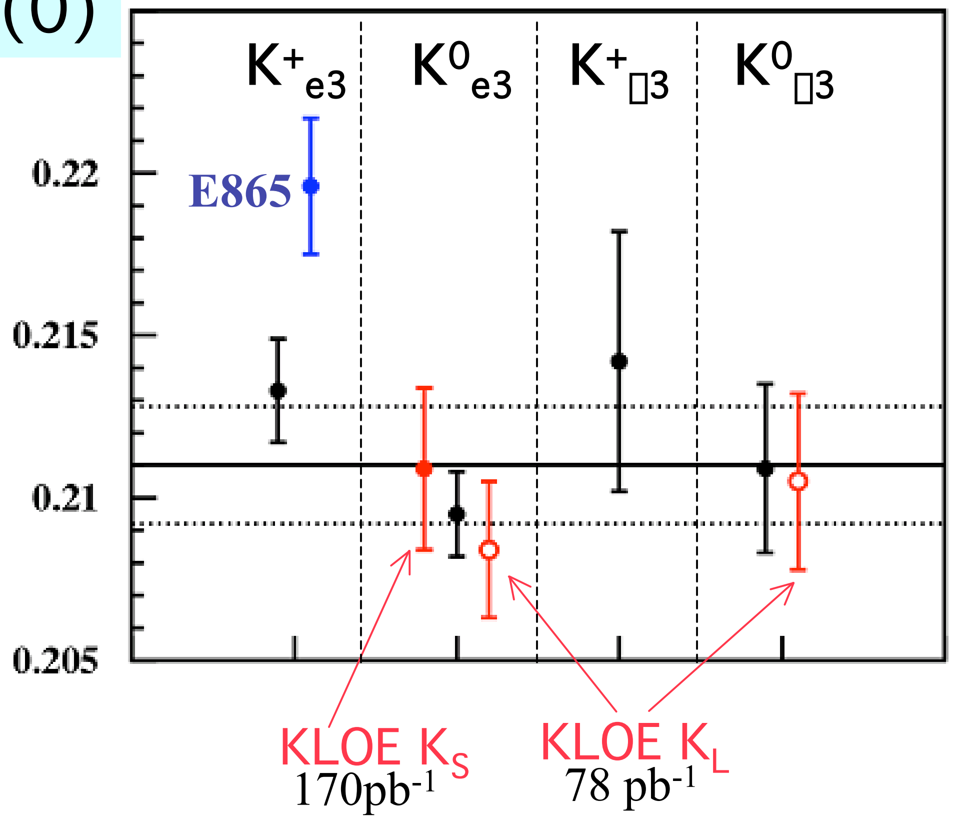
For K_{e3} modes:

$$\frac{\delta |V_{us}|}{|V_{us}|} = \underbrace{\frac{1}{2}\left(\frac{\delta BR}{BR}\right) \oplus \frac{1}{2}\left(\frac{\delta \tau}{\tau}\right) \oplus \frac{1}{20}\left(\frac{\delta \lambda_+}{\lambda_+}\right)}_{\text{exper. measurements}} \oplus \underbrace{\frac{\delta f_+(0)}{f_+(0)}}_{\text{theor. input}}$$

LP2003
(E865 + old)

$|V_{us}| = 0.2220 \pm 0.0019_{EXP} \pm 0.0018_{TH}$

$|V_{us}| \cdot f^+(0)$



KLOE preliminary BR's confirm old (black) values for K^0_{e3}, $K^0_{\mu3}$

KLOE will: have BR(K^+_{e3}) soon, measure BR's to <<1%. KLOE can also significantly improve λ_+, λ_0, τ_L

Conclusions

- K^0 physics program driven significantly by statistics (0.5 fb^{-1}) and, to a lesser extent, by beam background (which has been constantly improving !)
- Major progress on Monte Carlo
  - bkg events from data (ee□ □□) are injected into MC vs run #. Just produced 0.1 fb^{-1} of □□ all, now producing 0.4 fb^{-1} of $K_L K_S$□ all. This matches well what we have in the data
  - Detector/trigger response, materials, geometry and generators for physics processes significantly improved
- K_L□ □□, K_s□ □e□ show that KLOE can measure rarer decays
- The new MC is a prerequisite to tackle the next K_S rare decays with current 0.5 fb^{-1}: K_S□ □□(~150events), K_S□ □$^+$□$^□$□^{0} (~10events), and set a limit on K_S□ 3□^{0} (@ ~ 10^{-7})
- Need major luminosity increase, some detector upgrade

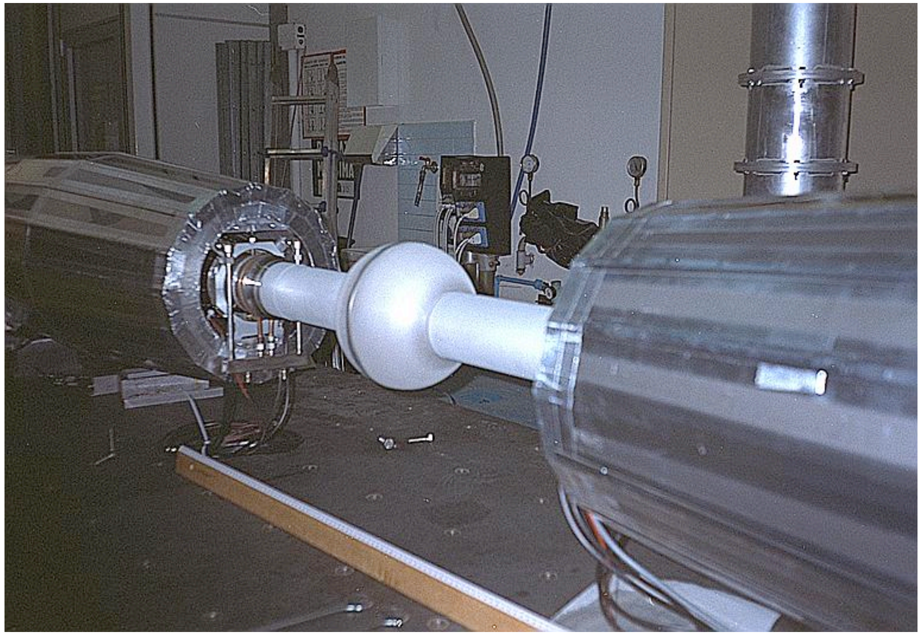
Conclusions: detector upgrades @D2

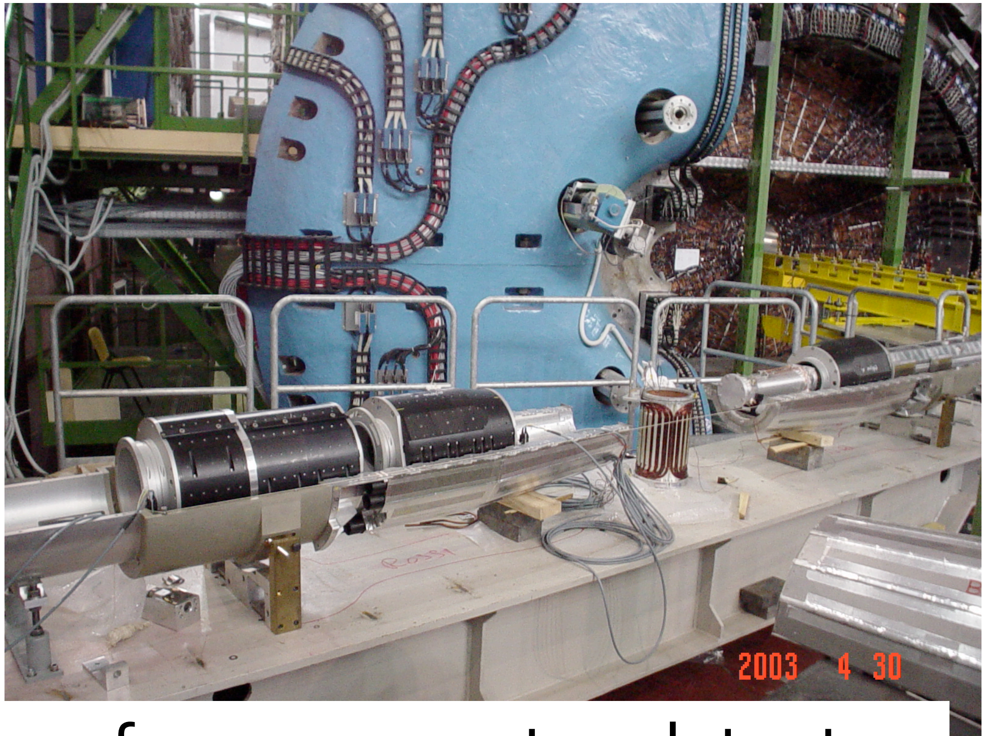
- Just an exercise for future discussion/work
- If IR-D2 smaller, we can consider a compact inner vertex detector inside the Drift Chamber (r=10-25cm)
  - add z measurement !!! Helps pattern recognition
  - improves vertexing at IP and interferometry for all-track events like $K_L K_S$□ □+□□ □+□□ and $K_L K_S$ □ □e□ □+□□
  - helps ID Kaon interactions (esp. Q-exch.) in the inner DC wall
  - if beam pipe were pure Be: big bonus for reconstruction
  - if pure Be sphere difficult □ make a cylinder w/same radius
  - QCAL experience will be useful; can make new QCAL smaller
- Calorimeter: increasing readout granularity would improve clustering and enhance PID
- Current drift chamber upgrade w/new ADCs (enhances e/□ but also) helps □/□ separation in K^0 decays

KLOE interaction region(s)

IR-03
- decrease □$_x$ and coupling
- inner q. removed, outer extended
- much improved quad. rotations
- allow optimal B value for KLOE (for □/□ ID and best map available)

IR-99: 3 permanent quadrupoles/side





If IR-D2 will be smaller □ room for a new vertex detector at low radius (10-25 cm), capable of measuring z

Extraction of □$_0$ − □$_2$

Conventional extraction of strong phase shifts from K_S, K^+ □ □□ decays:

$$\mathcal{A}_{+\square} = \sqrt{2/3}\,\mathcal{A}_0 e^{i\square_0} + \sqrt{1/3}\,\mathcal{A}_2 e^{i\square_2}$$

$$\mathcal{A}_{00} = \square\sqrt{1/3}\,\mathcal{A}_0 e^{i\square_0} + \sqrt{2/3}\,\mathcal{A}_2 e^{i\square_2}$$

$$\mathcal{A}_{+0} = \sqrt{3/4}\,\mathcal{A}_2 e^{i\square_2}$$

- Extraction of K □ □□ amplitudes from measured widths must take into account effective cutoff for processes with □ in final state
- **Including isospin-breaking EM effects:**

  $$\mathcal{A}_I e^{i\square_I} \;\square\; (\mathcal{A}_I + \square\mathcal{A}_I)\, e^{i\square_I}$$

  $$\square_I \equiv \square_I + \square_I \qquad \square = \text{EM phase shift}$$

  K □ □□ decays actually measure □$_0$ – □$_2$

  For □$_0$ – □$_2$, need theoretical input (□$_0$ – □$_2$)

□$_0$ − □$_2$	
PDG widths Cirigliano et al. ’01	(56±8)°
KLOE ’02 value for □(□$^+$□$^□$)/□(□^{0}□^{0})	(48±3)°

□$_0$ − □$_2$	
(45±6)°	□PT estimate Gasser,Meissner 91
(47.7±1.5)°	□□ scattering Colangelo et al. ’01

Prospects for ε'/ε

$$1 - 6\,\mathrm{Re}\,\varepsilon'/\varepsilon = \frac{BR(K_S \to \pi^+\pi^-)}{BR(K_S \to \pi^0\pi^0)} \cdot \frac{BR(K_L \to \pi^0\pi^0)}{BR(K_L \to \pi^+\pi^-)}$$

K_S

Statistical error: ***negligible***

Systematic error:

Source	**Error (%)**
Tagging	0.55 ('00 data) → ~0.1 ('01-02 data)
γ counting	0.20
Trigger/t_0	0.23
Tracking	0.26

Total error: 0.7% → 0.4%
Should scale down to 0.1% on full data set (~400 pb^{-1})

K_L

Statistical error: ~1.5%

Systematic error: ~2%

Work in progress on:

- Momentum reconstruction/resolution, including DC occupancy effects
- Effect of $K\ell3$ decays on background determination
- Separation of overlapping clusters
- Regeneration

Need at least 10× more data to reach the 10^{-4} regime