Future prospects for K experiments

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Outline

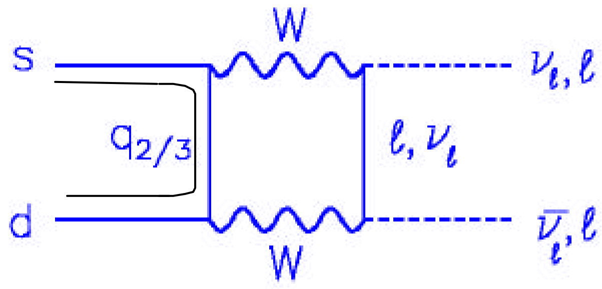
- What is still to be learned from the K system
- Prospects of ongoing programs
  - KLOE @ DAPHNE
  - NA48 @ CERN
  - E949 @ BNL
  - E391a @ KEK
- New projects
  - KOPIO @ BNL
  - ~~KAMI @ FNAL~~ ?
  - CKM @ FNAL

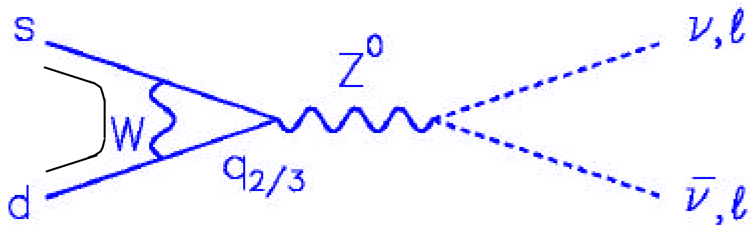
Physics issues

- Overconstrain flavour structure of S.M.
  - FCNC decay channels
    - exploit suppressions (2nd order weak interactions, GIM , CP violation) for enhanced sensitivity to “new physics”
- Simmetry violations
  - CP, T : narrow the gap between experiment and predictions using improved experimental techniques
    - Charge asymmetries , T violating observables
  - CPT: Tighten constraints from Bell-Steinberger sum rule + K_S/K_L semileptonic decays ?
- Sharpen the theoretical tools
  - χPT tests + parameter determination
  - framework for interpretation of more fundamental processes

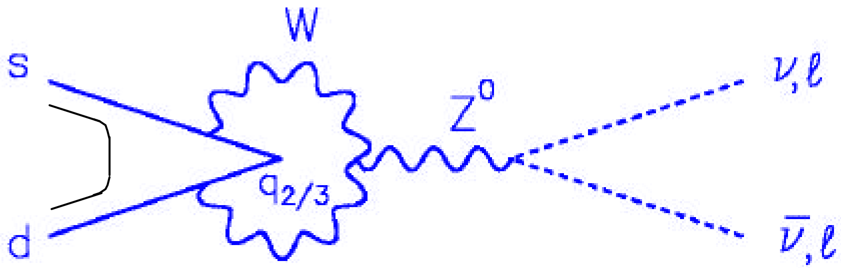
A few loop diagrams ...

$K^0 \rightarrow l\ \bar{l}$





$K \rightarrow \pi\, l\ \bar{l}$

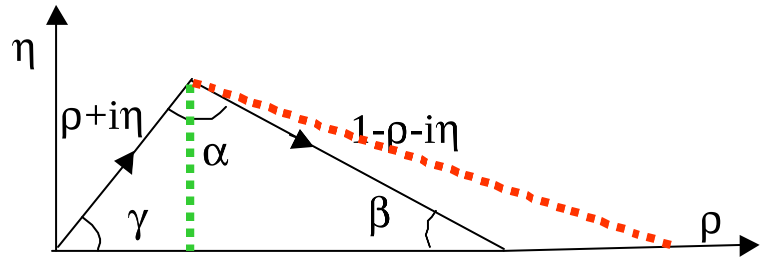


FCNC decays (1)

- $K_L \to \mu\mu$
  - Experimental effort concluded [B.R.=$(7.18 \pm 0.17) \times 10^{-9}$]
  - Information on short range contribution limited by interpretation
    - Dominating absorptive contribution from $\gamma\gamma$: $(7.07 \pm 0.18) \times 10^{-9}$
    - Better experimental information on $K_L \to \mu\mu\gamma, ee\gamma, eeee, ee\mu\mu$ needed to constrain long range dispersive contributions
- $K_L \to \pi^0 e^+ e^-, \pi^0 \mu^+ \mu^-$
  - Direct CP violation component has to be disentangled from
    - Indirect $\not{CP}$
    - 2 γ CP conserving long range contribution
  - Experimental information on $K_S \to \pi^0 e^+ e^-$, $K_L \to \pi^0 \gamma\gamma$ valuable
  - Prohibitive physical background from $\gamma\gamma e^+ e^-$, $\gamma\gamma\mu^+\mu^-$

FCNC decays (2)

- K→ πν $\bar{\nu}$
  - Unique "theoretical cleanliness"
    - no long range contribution
    - matrix elements of quark operators related to Ke3 decays
    - K_L decay dominated by direct CP̸



$$B\left(K_L^0 \to p^0 n\bar{n}\right) = kB\left(K^+ \to p^0 e^+ n\right)\left[\mathrm{Im}\left(V_{ts}^* V_{td}\right) X\left(\frac{m_t^2}{m_W^2}\right)\right]^2 = k' h^2 \approx 3\times 10^{-11}$$

Known to ~ 2% precision

$$B\left(K^+ \to p^+ n\bar{n}\right) = kB\left(K^+ \to p^0 e^+ n\right)\left|V_{cs}^* V_{cd} X\left(\frac{m_c^2}{m_W^2}\right) + V_{ts}^* V_{td} X\left(\frac{m_t^2}{m_W^2}\right)\right|^2 \propto \left[(1.4 - r)^2 + h^2\right] \approx 8\times 10^{-11}$$

Small additional uncertainty from m_C

  - Experiments challenging
    - B.R. ~ 10^{-11} , kinematics underconstrained, background from channels with much larger decay rates

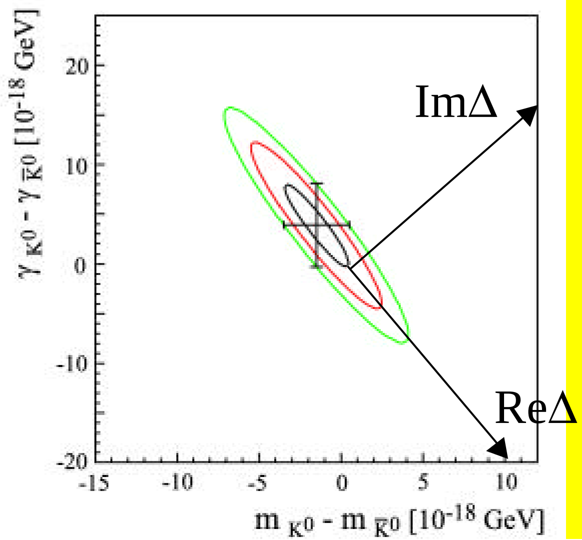
CPT tests

- CPT violation in K^0 mass matrix Λ = M – iΓ/2 characterized by

$$\Delta = \frac{\Lambda_{\overline{K}^0\overline{K}^0} - \Lambda_{K^0K^0}}{2(l_L - l_S)}$$

$$\mathrm{Re}\,\Delta = \left(m_{K^0} - m_{\overline{K}^0}\right)\frac{-2\Delta m}{(\Gamma_S-\Gamma_L)^2+4\Delta m^2} + \left(\Gamma_{K^0} - \Gamma_{\overline{K}^0}\right)\frac{\Gamma_S-\Gamma_L}{(\Gamma_S-\Gamma_L)^2+4\Delta m^2}$$

$$\mathrm{Im}\,\Delta = \left(m_{K^0} - m_{\overline{K}^0}\right)\frac{\Gamma_S-\Gamma_L}{(\Gamma_S-\Gamma_L)^2+4\Delta m^2} + \left(\Gamma_{K^0} - \Gamma_{\overline{K}^0}\right)\frac{2\Delta m}{(\Gamma_S-\Gamma_L)^2+4\Delta m^2}$$



- PDG 2000:
  - from $4\,\mathrm{Re}\,\Delta = \dfrac{P[\overline{K}^0 \to \overline{K}^0(t)] - P[K^0 \to K^0(t)]}{P[\overline{K}^0 \to \overline{K}^0(t)] + P[K^0 \to K^0(t)]}$

    CPLEAR: error ~ 3.3×10^{-4}
  - neglecting ~~CPT~~ in $\pi\pi$ decay amplitude

    $$|h_{+-}|\left(f_{SW} - \frac{2}{3}f_{+-} - \frac{1}{3}f_{00}\right) = \Delta_\perp = \frac{\left(m_{K^0} - m_{\overline{K}^0}\right)}{(\Gamma_S-\Gamma_L)^2+4\Delta m^2}$$

    $\Delta_\perp$ known to precision ~ 2.5×10^{-5}
  - from B.S. sum rule Im Δ to ~ 5×10^{-5}

CPT tests

- Bell-Steinberger sum rule (unitarity)

$$\left(1+i\frac{2\Delta m}{\Gamma_S-\Gamma_L}\right)(\mathrm{Re}\,e-i\,\mathrm{Im}\,\Delta)=$$

$$=\frac{1}{\Gamma_S}\sum_f A^*(K_S\to f)A(K_L\to f)$$

- ◆ ImΔ limited by η_{000} and Re ε

Decay mode	α_f	$10^3\times$ Re(α_f)	$10^3\times$ Im(α_f)
$K_L\to\pi^+\pi^-$	$\alpha_{+-}=\mathcal{B}^{(S)}_{+-}\eta_{+-}$	1.137 ± 0.015	1.079 ± 0.016
$K_L\to\pi^0\pi^0$	$\alpha_{00}=\mathcal{B}^{(S)}_{00}\eta_{00}$	0.519 ± 0.011	0.491 ± 0.011
$K_L\to\pi^+\pi^-\gamma$	$\alpha_{+-\gamma}=\mathcal{B}^{(S)}_{+-\gamma}\eta_{+-\gamma}$	<0.001	<0.001
$K_L\to\pi l\nu$	$\alpha_{l3}=\frac{\tau_S}{\tau_L}[\mathcal{B}^{(L)}_{\pi\mu\nu}+\mathcal{B}^{(L)}_{\pi e\nu}]\times$ $[\delta_l(1+\mathrm{Re}(x))-2i\mathrm{Im}(x)]$	0.004 ± 0.001	0.007 ± 0.059
$K_S\to\pi^+\pi^-\pi^0$	$\alpha_{+-0}=\frac{\tau_S}{\tau_L}\mathcal{B}^{(L)}_{+-0}\eta_{+-0}$	0.000 ± 0.002	0.000 ± 0.002
$K_S\to\pi^0\pi^0\pi^0$	$\alpha_{000}=\frac{\tau_S}{\tau_L}\mathcal{B}^{(L)}_{000}\eta_{000}$	0.062 ± 0.044	0.026 ± 0.055
$(1+i\tan\phi_{SW})\mathrm{Re}(\epsilon)$		1.635 ± 0.060	1.551 ± 0.057
Difference $\sum_f\alpha_f\ -\ (1+i\tan\phi_{SW})\,\mathrm{Re}(\epsilon)$		0.087 ± 0.077	0.052 ± 0.101

- Semileptonic charge asymmetries K_S vs K_L

$$d_{L,S}=\frac{\Gamma(K_{L,S}\to p^-e^+n)-\Gamma(K_{L,S}\to p^+e^-\bar{n})}{\Gamma(K_{L,S}\to p^-e^+n)+\Gamma(K_{L,S}\to p^+e^-\bar{n})}$$

$$d_S-d_L=4\,\mathrm{Re}\,\Delta-4\,\mathrm{Re}\left(\frac{d^*}{a}\right)$$

=0 if no $\Delta S=-\Delta Q$, CPT violating

- ◆ $\delta_L=(32.7\pm1.2)\times10^{-4}$
  - ❖ (1974: ~$5\times10^7 K_{l3}$ decays)
- ◆ δ_S from KLOE ?
  - ❖ error ~10^{-3} with design L

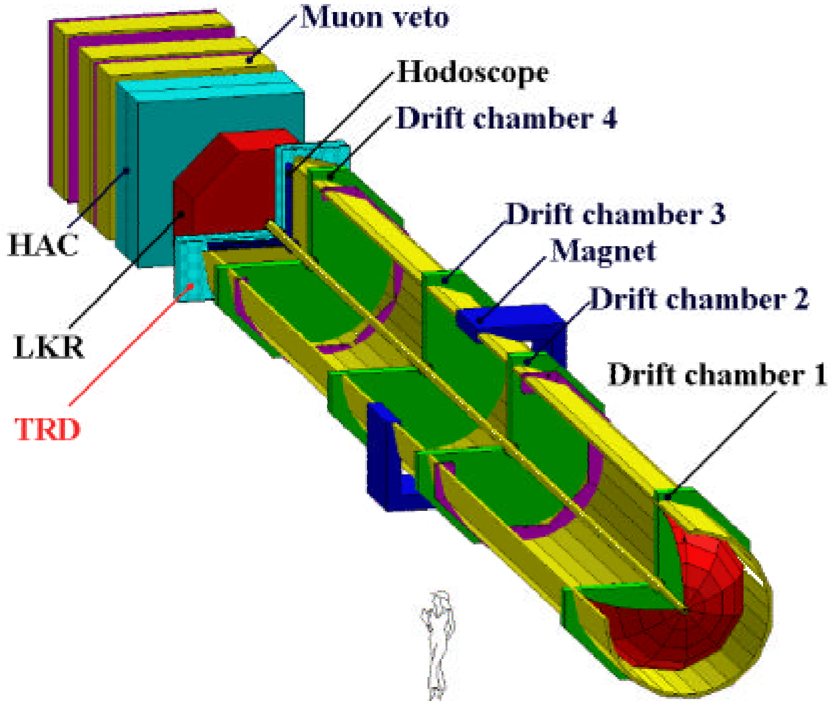
KLOE

- Tagged K_L/K_S decays from $\Phi\rightarrow K_L/K_S$
  - design luminosity: $5\times10^{32}cm^{-2}/s$
  - even before that has interesting program of K_S measurements
    - branching ratio's for dominating decays
    - K_S semileptonic branching ratio's
    - rare K_S decays
- Machine performance improved
  - $2\times10^{31}cm^{-2}/s$ peak L , 1 pb^{-1}/day reached, but large backgr.
  - 35 pb^{-1} logged
    - Performance demonstrated by preliminary data on $K_S\rightarrow\pi e\nu$
      - 283 events in 11.5 pb^{-1} sample
      - ~ 4 × present world statistics (CMD-2: 75 ev.)
  - 200 pb^{-1} goal for 2000 running

data yield for $200 pb^{-1}$

- Ks $2\ 10^8$
  - Tagged Ks (Kl visible Interactions) $0.6\ 10^8$
    - Ks $\pi^+ \pi^-$ — $0.3\ 10^8$ x BR ~ $2\ 10^7$
    - Ks $\pi^0 \pi^0$ — $0.3\ 10^8$ x BR ~ $1\ 10^7$
    - Ks $\pi e \nu$ — $0.9\ 10^7$ x BR ~ 6700
    - Ks $\gamma\gamma$ — $3.3\ 10^7$ x BR ~ 70
    - Ks $\pi^0 e^+ e^-$ Single Event Sens. $0.8\text{-}1.5\ 10^{-7}$
    - Ks $\pi^0 \pi^0 \pi^0$ Single Event Sens. $3\ 10^{-8}$
- Kl $2\ 10^8$
  - Tagged Kl (Ks $\pi^+ \pi^-$) $0.9\ 10^8$
    - Kl Decay in FV (D.C.) $2.5\ 10^7$
    - Kl $\pi^+ \pi^-$ ~ $2.7\ 10^4$
    - Kl $\pi^0 \pi^0$ ~ $1.0\ 10^4$
    - Kl $\gamma \gamma$ ~ $0.5\ 10^4$
- $K^{+/-}$ $3\ 10^8$
  - Tagged K^+ (K^-) $0.7\ 10^8$
    - Reconstructed K^+ (K^-) $5\ 10^7$

CERN NA48



- 2001 ends ε'/ε program
- 2 extensions approved
- NA48/1 (2002)
  - K_S rare decays
- NA48/2 (2003 …)
  - K^+/K^- $\not{CP}$ asymmetries
  - High statistics study of $K^\pm \to e^\pm \pi^+ \pi^- \nu$ [$\pi\pi$ scattering length $\Rightarrow \langle 0 | \bar{q} q | 0 \rangle$]

- Drift chambers rebuilt (operational from 2001)
- TRD will be installed before NA48/2

NA48 K_S rare decays

- ~ 3×10^{10} decays in typical 1 year run

- $K_S \to \pi^0 e^+ e^-$ with a SES ~ 6×10^{-10}
  - $1.5\times10^{-12} < BR_{CPdir}(K_L \to \pi^0 e^+ e^-) < 5\times10^{-12}$
  - $BR_{CPind}(K_L \to \pi^0 e^+ e^-)$?
    - 3×10^{-3} $BR(K_S \to \pi^0 e^+ e^-)$
  - $5\times10^{-10} < BR(K_S \to \pi^0 e^+ e^-) < 5\times10^{-8}$
    - ~7 events with B.R. in the middle of expected range

- Bounds on η_{000} of ~ 10^{-2}
  - 8×10^6 events for $1.2\tau_S < t_0 < 4.7\tau_S$
  - Control of acceptance to $10^{-3}/c\tau_S$
  - Precision of B.S. sum rule to ~2×10^{-2}

- Sizable samples for channels of interest for χPT phenomenology
  - $K_S \to \gamma\gamma$
    - exp BR 2.1×10^{-6}
    - 24000 events
  - $K_S \to \pi^0\gamma\gamma$:
    - exp BR 3.8×10^{-8} ($m_{\gamma\gamma}$>220MeV/c^2)
    - 114 ev.
  - . . .

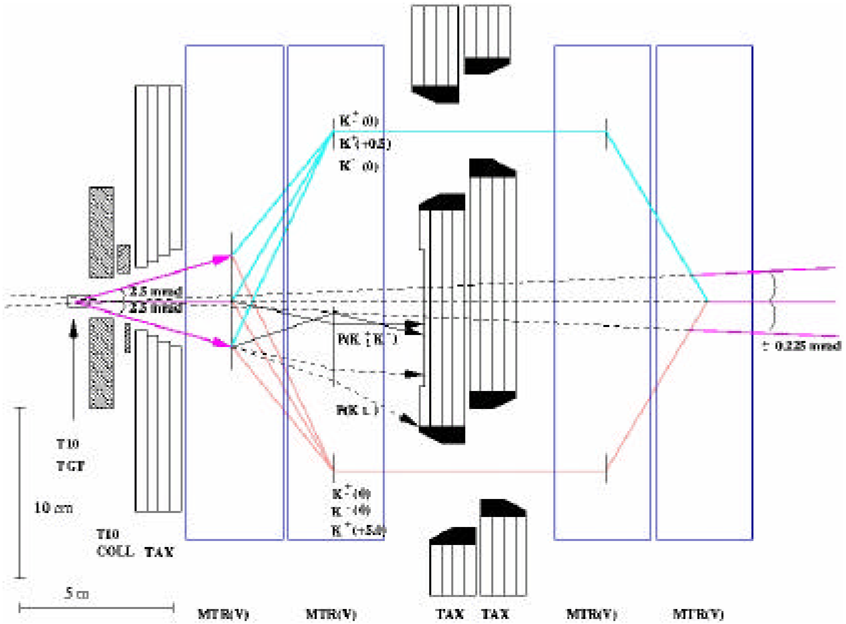
NA48 K± program

- Main goal: $\pi^{\pm}\pi^{+}\pi^{-}$ Dalitz plot slope asymmetry

$$|M(u,v)|^2 \propto 1 + gu + hu^2 + kv^2$$

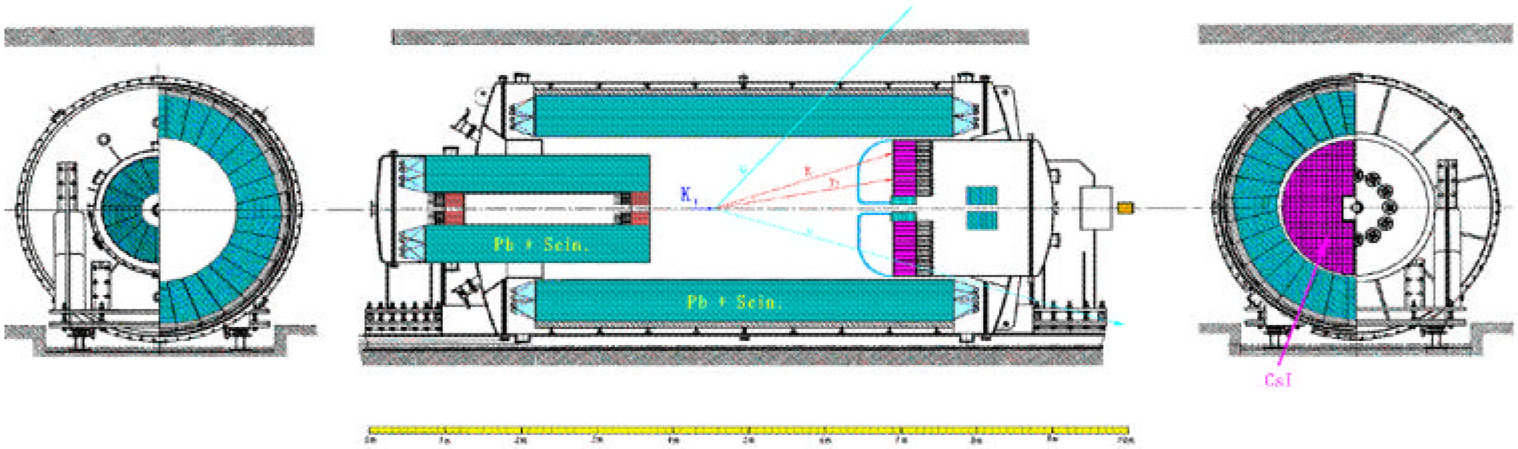
$$u = \frac{2M(M - 3E_p^*)}{3m^2} \qquad A_g = \frac{g^+ - g^-}{g^+ + g^-}$$

  - Present experimental limit: $A_g = (-7 \pm 5) \times 10^{-3}$ [Ford .. 70]
  - HyperCP has $3.9/1.6 \times 10^{8}$ K^+/K^- decays yielding $\Delta A_g \sim 5 \times 10^{-4}$ stat, $> 10^{-3}$ syst
  - S.M. theoretical predictions range from $\sim 10^{-6}$ to $\sim 10^{-4}$
    - no $\Delta I = 1/2$ rule suppression ↑
    - FSI phases ↓



- NA48 aims at $\sim 10^{-4}$ ΔA_g
  - $7.3/4.4 \times 10^{9}$ +/– decays/year
    - $\Delta A_g \sim 0.7 \times 10^{-4}$(stat)
  - Simultaneous $K^{\pm}$ beams + B field reversal to symmetrize efficiencies
    - $\Delta A_g \sim 0.5 \times 10^{-4}$(sys)

KEK E391a



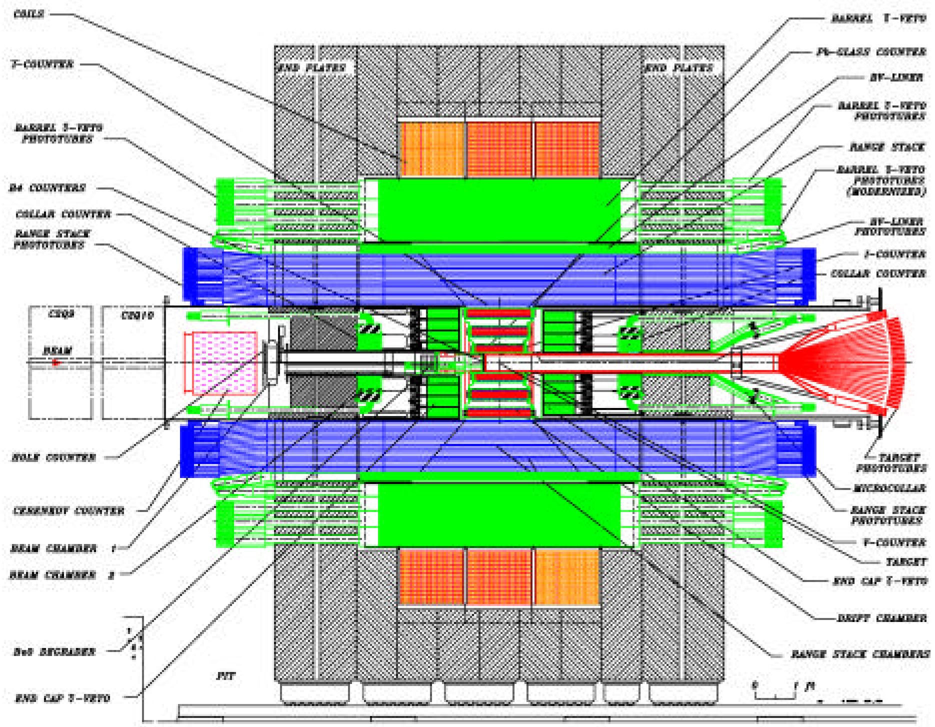
- Ground breaking experiment for $K_L \to \pi^0 \nu \bar{\nu}$
- Approved december 97 . Addressing relevant experimental issues in a systematic way
  - Detector inefficiency measurements (physics limited)
  - Beam survey (Dec. 2000)
- Prospects:
  - Data taking from Oct 2003, aiming at sensitivity ~ 1×10^{-10}
  - Test bed for experiment at JHF aiming at sensitivity ~ 3×10^{-14}

BNL E949

- Upgrade of E787
  - with 1 event in 1995-97

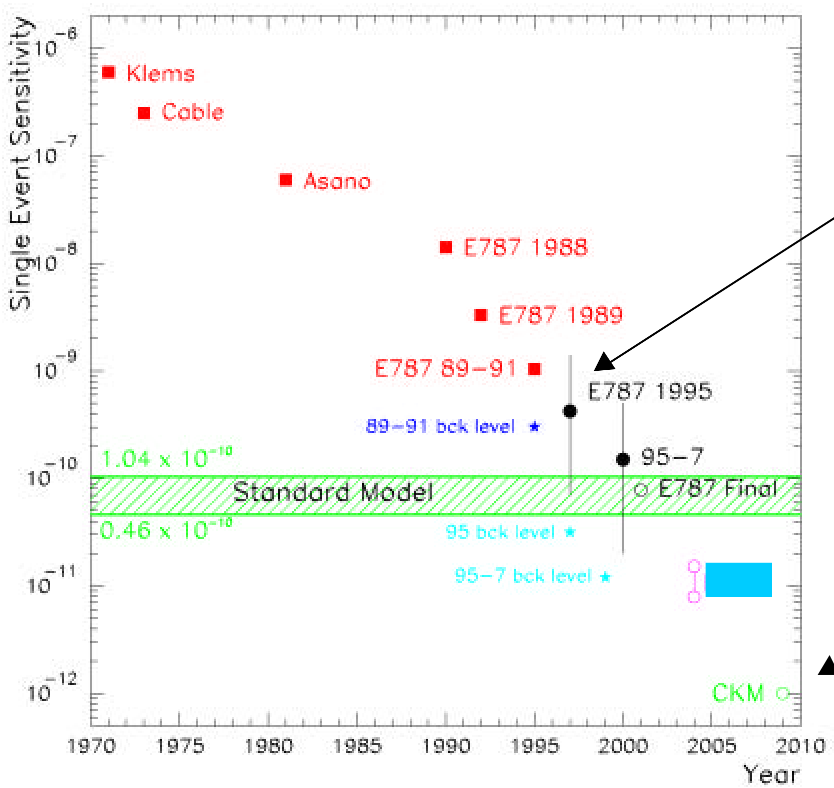
$$B\left(K^+ \to p^+ n\bar{n}\right) = \left(1.5^{+3.4}_{-1.2}\right)\times 10^{-10}$$

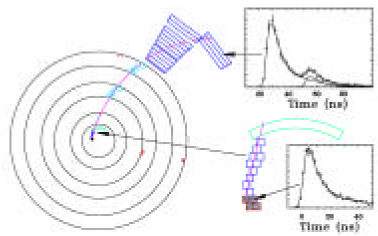
  - 98 data of comparable size
- Key features
  - Redundant kinematic information on π^+
  - hermetic veto coverage
  - looks for π^+ above end point for $K^+ \to \pi^+\pi^0$
- E 949
  - improved sensitivity (14 ×)
  - data for 2 additional years
  - expect to reach 10^{-11}/ evt by 2004 (7 events for S.M. BR prediction)



Increased spill length (×1.56)
Lower momentum (×1.38)
Increased efficiency (trigger, DAQ, analysis) (×3.2)
Acc. below $K\pi2$ + higher rate analysis reopt. (×2)
Total gain - ×14 per hour of data taking

Progress in K^+ ®p^+ n`n

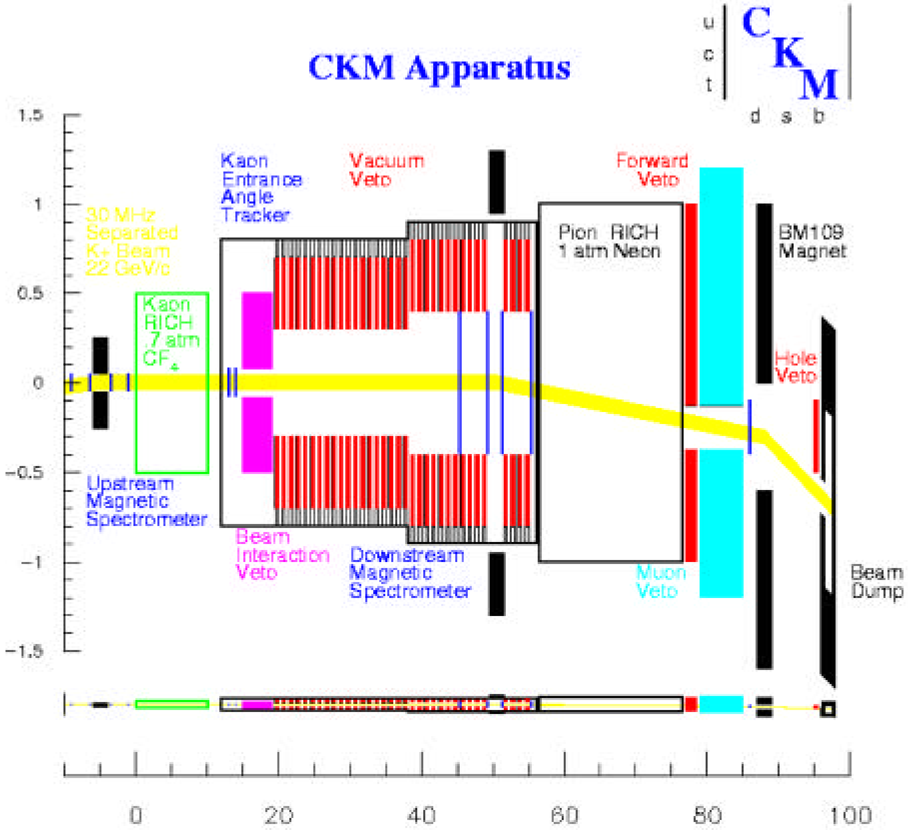




(courtesy of L.Littenberg)

- Dedicated FNAL expt CKM
  - aims at 100 events with S.M. branching ratio
  - approved (end june)
  - TDR in 12-18 months

CKM at FNAL M.I.



- Features
  - First attempt of in-flight measurement of $K^+ \to \pi^+ \nu \bar{\nu}$
  - Superconducting RF separated beam
    - Hadron purity > 70%
    - 33MHz 22GeV/c K^+
  - redundant determination of K^+ and π^+ momentum
    - spectrometer + RICH
  - veto with total inefficiency for π^0 from $\pi^+ \pi^0$ ~10^{-7}
  - expects 100 signal with ~10 background events

KAMI

KAMI DETECTOR LAYOUT

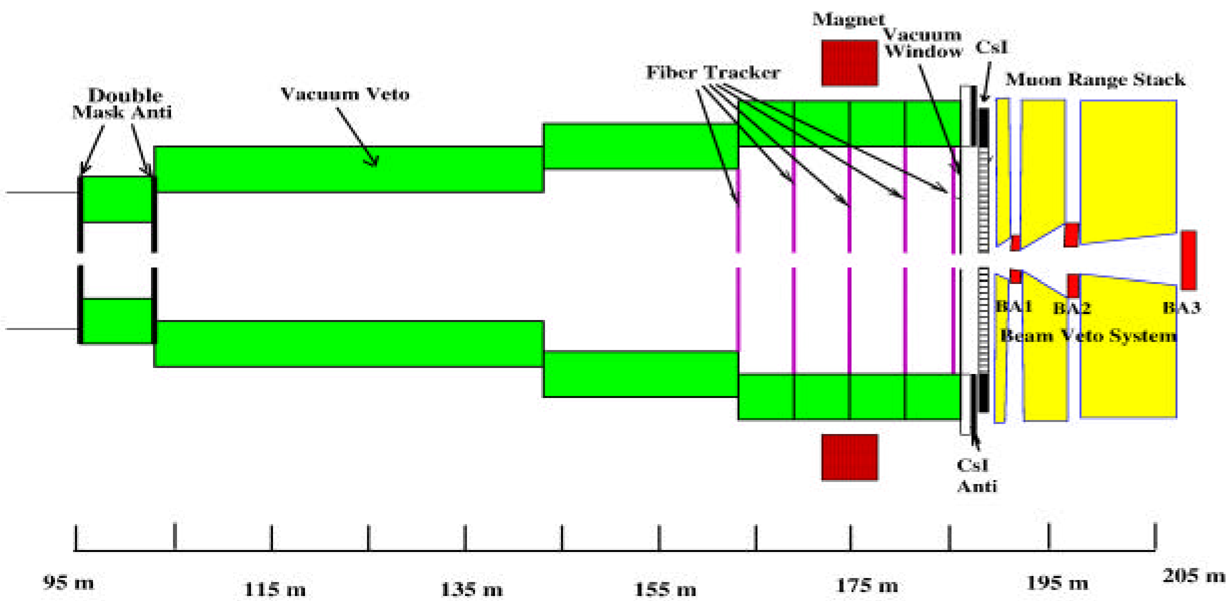
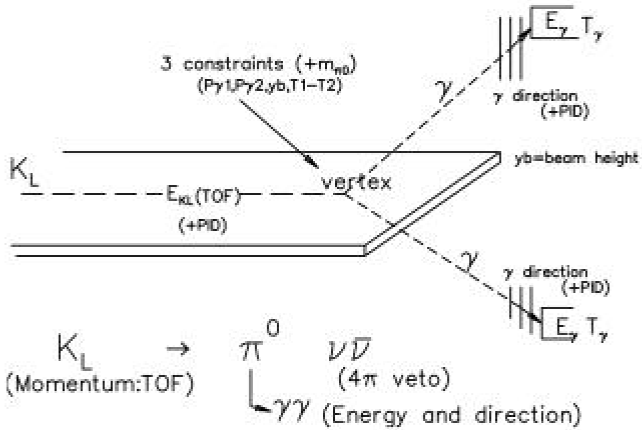


Figure 1: Schematic of the KAMI detector.

- Aiming at ~ 100 $\pi^0 \nu \bar{\nu}$ events with S:B 4:1
- Veto inefficiencies ~ 10^{-6} required
- Recently discussed by FNAL PAC and not recommended

KOPIO: new way to p^{0}n`n

- In addition to veto's as many kinematical constraints as possible
  - photon energy, position and angle
  - K_L momentum via TOF allows transformation to CM system
- RF bunched beam , <p> ~ 0.8GeV/c



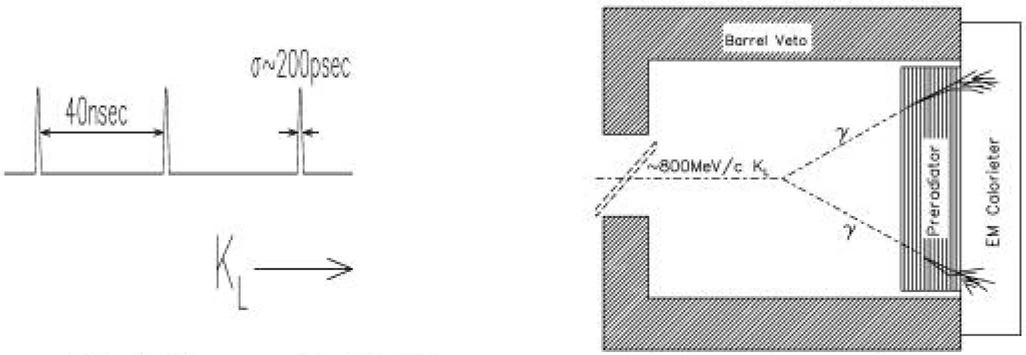
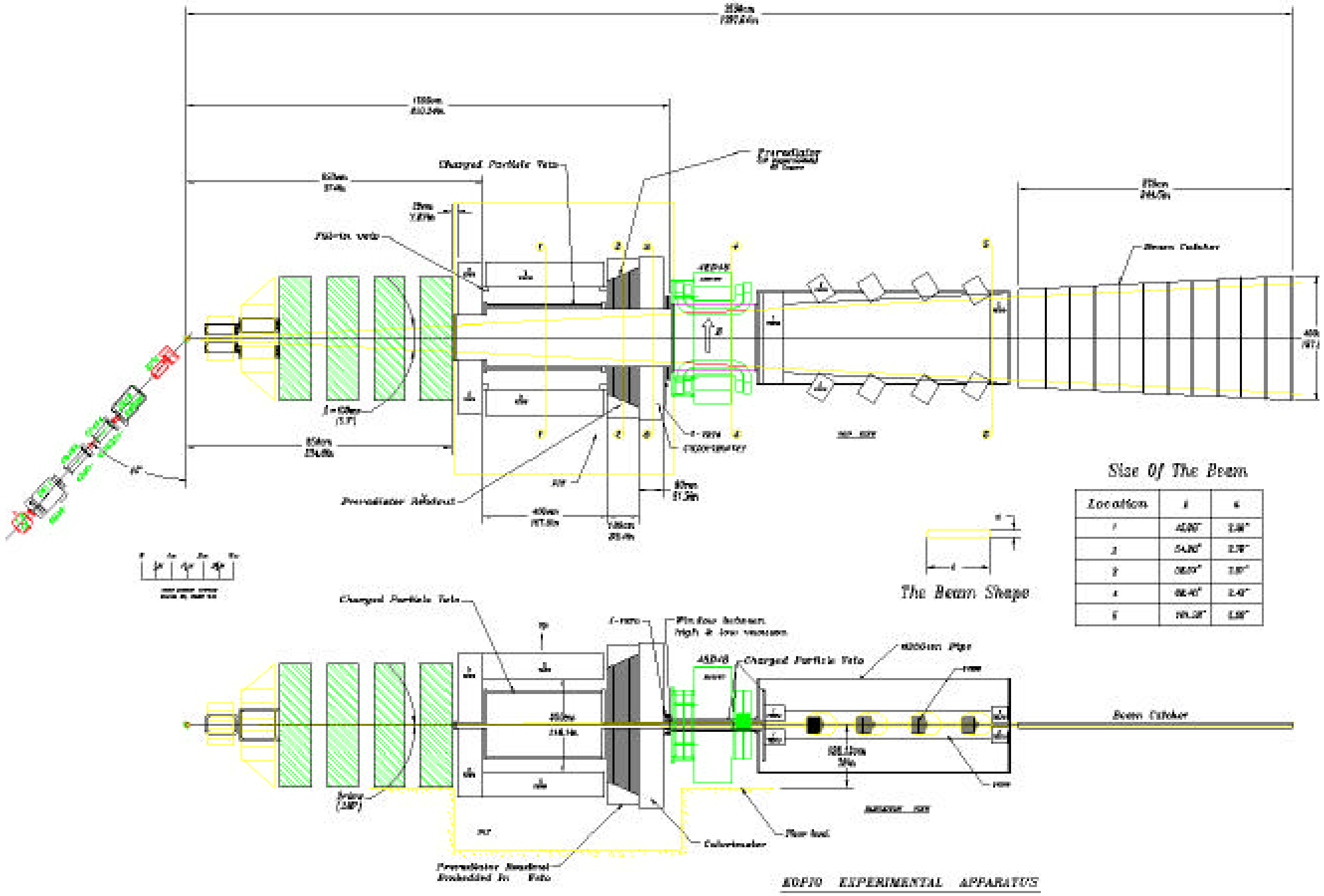


Fig. 4. Elements of the KOPIO concept : a pulsed primary beam produces low energy kaons whose time-of-flight reveals their momentum when the π^0 from $K_L^0 \to \pi^0\nu\bar{\nu}$ decay is reconstructed.

- Tracking preradiator for γ direction measurement
- E measurement combining prerad + Shashlik
- Hermetic veto coverage including beam hole

KOPIO layout



KOPIO: existence proofs

- Many critical parameters established by test measurements
  - Beam bunching: 280 ps achieved with 33MHz, 30 kV cavity
    - final scheme with 25MHz, 150kV + additional harmonic cavity at 100MHz
  - Preradiator angle resolution 25-30 mr for 250 MeV $\gamma\gamma$
  - Energy resolution in Shashlik 6.7% for 250MeV γ
    - In combination with preradiator Monte-Carlo indicates

$$s/E \cong 2.7\% / \sqrt{E(GeV)}$$

  - Veto efficiencies from E787 measurements, only slightly upgraded for better sampling (low E) and larger number of radiation lengths (high E)

KOPIO: kinematics at work

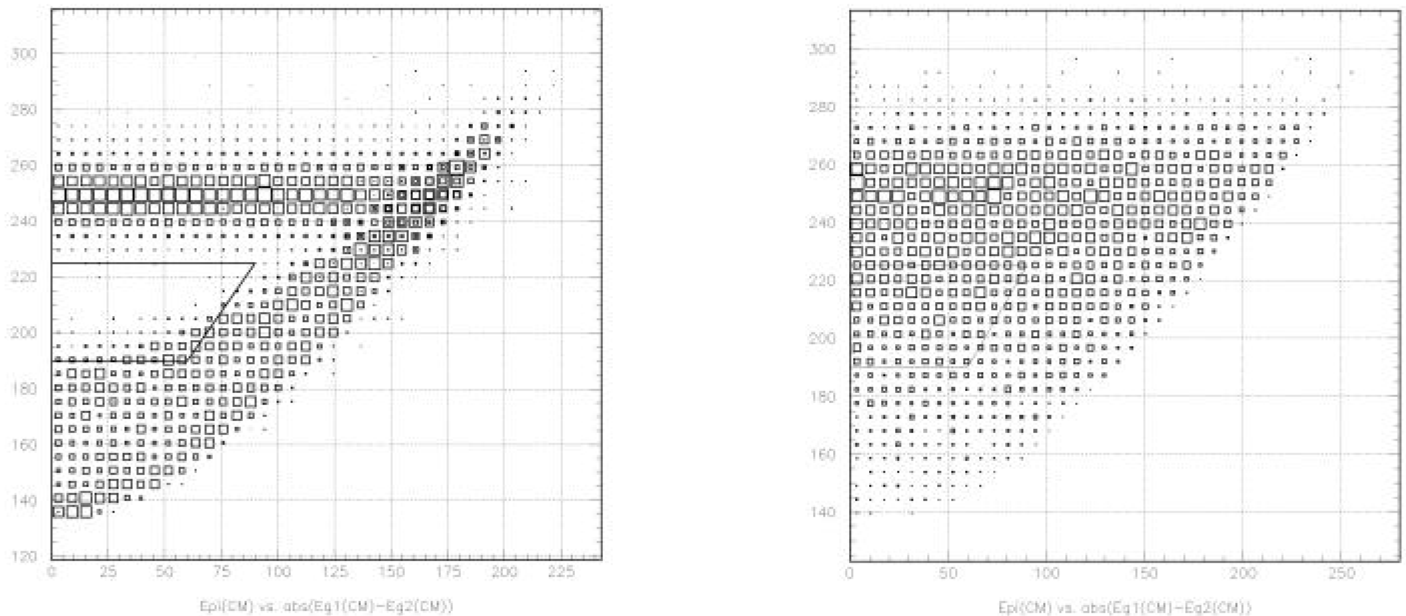
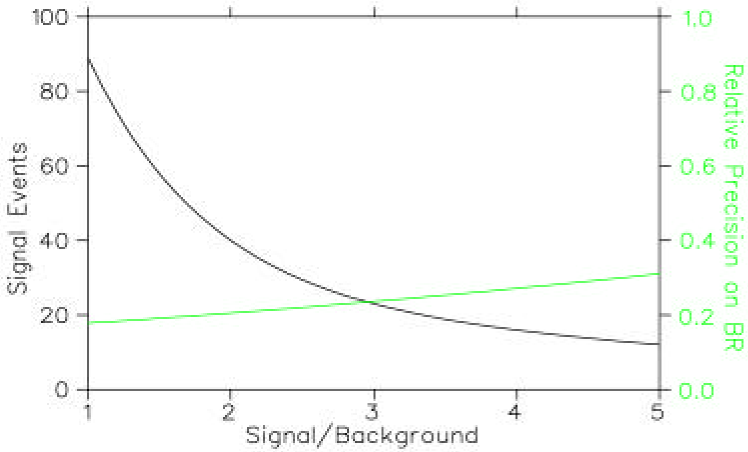


Fig. 9. Distributions of $E^*_{\pi^0}$ vs. $|E^*_{\gamma 1} \quad E^*_{\gamma 2}|$ after π^0 mass requirement for the $K_L \to \pi^0\pi^0$ (left) and for the signal (right). The solid line encloses the signal region.

- Transformation to CM and full γ reconstruction provides region where $2\pi^0$ background negligible
- kinematics complementary to vetos (small E_π* $\to$ higher veto efficiency)

KOPIO: expected results

Process	Modes	Main source	Events
$K_L^0 \to \pi^0 \nu \bar{\nu}$			40
K_L decays $(\bar{\gamma})$	$\pi^0\pi^0$,$\pi^0\pi^0\pi^0$,$\pi^0\gamma\gamma$	$\pi^0\pi^0$	12.4
$K_L \to \pi^+\pi^-\pi^0$			1.7
$K_L \to \gamma\gamma$			0.02
K_L decays $(\overline{charge})$	$\pi^\pm e^\mp \nu$,$\pi^\pm \mu^\mp \nu$,$\pi^+\pi^-$	$\pi^- e^+ \nu$	0.02
K_L decays $(\bar{\gamma}, \overline{charge})$	$\pi^\pm l^\mp \nu\gamma$, $\pi^\pm l^\mp \nu \pi^0$,$\pi^+\pi^-\gamma$	$\pi^- e^+ \nu\gamma$	4.5
Other particle decays	$\Lambda \to \pi^0 n, K^-_{\pi 2}, \Sigma^+ \to \pi^0 p$	$\Lambda \to \pi^0 n$	0.01
Interactions	n, K_L, γ	$n \to \pi^0$	0.2
Accidentals	n, K_L, γ	n, K_L, γ	0.6
Total Background			19.5

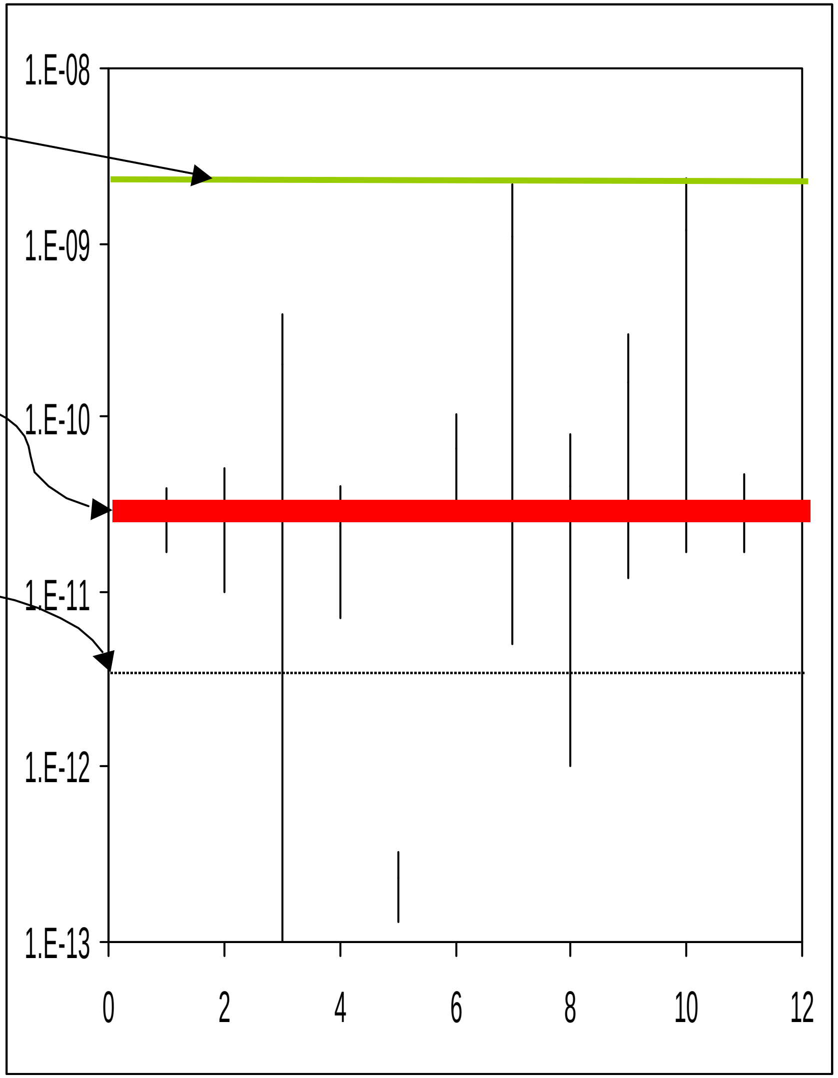


KOPIO "discovery potential"

Expected error band for B.R.=2.2×10^{-9}

Expected error band for B.R.=3×10^{-11}

90% UL for 0 events



	Authors	Model	B.R. limits (10^-11)	
1	Buchalla	Standard model CKM fit	1.7	3.9
2	Plaszczvnski/Schune	Conservative SM fit	1	5
3	Buras et al.	Generic SUSY w/min part. content	0.01	40
4	Buras et al.	MSSM w/o new flavour or CP viol.	0.7	4.02
5	Brhlik et al.	all CP-viol due to SUSY	~0.023	
6	Chanowitz	SU(2)L X SU(2)R Higgs	2.8	10.6
7	Hattori et al.	4th generation	0.5	220
8	Xiao et al.	top-color assisted technicolor	0.1	8
9	Xiao et al.	multiscale walking technicolor	1.2	30
10	Grossman/Nir	Extra "vector-like" quarks	1.7	240
11	Kiyo et al.	seesaw L-R model	1.7	4.68

Conclusions

- K system still has potentialities for exciting physics
- With the ε'/ε saga come to an end, the next few years will see
  - polishing of precision results
  - a more complete phenomenological picture of K decays and CP violation
  - room for surprises
- Great potentialities of two new ambitious projects for studies of the FCNC in the K sector
  - Together with B results, capable to put severe constraints on the flavour structure of the S.M.
  - No technical show stopper
  - It would be a pity if they are missed for lack of funding