Experimental Progress in Kaon Physics

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Frascati, 20 may 2003

Outline of the lecture

- Introduction: landmark results, physics issues, present impact and context of Kaon Physics
- Same formalism and review of experiments and measurements of simmetry violation effects with Kaons
- Prospects in Kaon physics: quantitative test of theoretical techniques and review of high precision rare decays measurements and experiments

Kaon Physics: landmark results

- Concept of strangeness $\rightarrow$ quark model $\rightarrow$ basis of QCD
- First hint of Parity Violation $\rightarrow$ chiral nature of weak gauge forces
- Absence of FCNC $\rightarrow$ charm quark and GIM structure of flavour dynamics
- Discovery of CP Violation $\rightarrow$ matter-antimatter asymmetry $\rightarrow$ 3-generation structure of nature and KM description

Kaon Physics Issues

Motivations for Kaon Experiments:

- Simmetry violation measurements
- Overconstrain flavour structure of Standard Model
- Sharpen theoretical tools

CP Violation: charge asimmetry, T violating observables

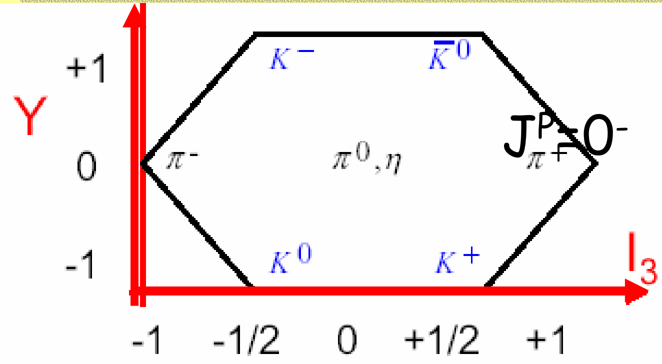
CPT test: tigher contraints from Bell-Steinberger rule, K_S/K_L semileptonic decays

Rare decays suppressed (due to 2nd order weak interactions, GIM, CP Violation) or not allowed by SM
→ fundamental SM parameters
→ sensitivity to new physics BSM

Low energy hadron dynamics: χPT tests and parameter determination
→ framework for interpretation of more fundamental processes

Some properties of Kaons

Kaons: pseudoscalar mesons
Production: S.I. - Decay: W.I.



$$\tau_L = (5.17 \pm 0.04)\times 10^{-8}\,\mathrm{s}$$
$$\tau_S = (8.927 \pm 0.009)\times 10^{-10}\,\mathrm{s}$$
$$\tau_L \approx \tau_S \times 579$$
$$m_{K^0} = 497.672 \pm 0.031\ \mathrm{MeV}$$
$$\Delta m = m_L - m_S = (5.304 \pm 0.014)\times 10^{9}\,\mathrm{s}^{-1}$$
$$\tau_{K^+} = (1.2385 \pm 0.0024)\times 10^{-8}\,\mathrm{s}$$
$$m_{K^+} = 493.677 \pm 0.016\ \mathrm{MeV}$$

NEUTRAL KAON SYSTEM

Strangeness eigenstates

$$K^0\ (\bar{s}d) \qquad (S=+1)$$
$$\bar{K}^0\ (s\bar{d}) \qquad (S=-1)$$

CP eigenstates

$$K_1 = (K^0 + \bar{K}^0)/\sqrt{2} \quad (CP=+1)$$
$$K_2 = (K^0 - \bar{K}^0)/\sqrt{2} \quad (CP=-1)$$

Mass eigenstates

$$K_S \cong K_1 + \varepsilon K_2 \quad (c\tau = 2.67\ \mathrm{cm})$$
$$K_L \cong K_2 + \varepsilon K_1 \quad (c\tau = 15.51\ \mathrm{m})$$

$\varepsilon \sim 2.28 \times 10^{-3}$
$\mathrm{Arg}(\varepsilon) \sim \tan^{-1}(2\Delta m/\Delta\Gamma) \sim 43.5°$

The physics context: CKM matrix

CKM: Unitarity matrix connecting weak with mass quark eigenstates

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Wolfenstein Parametrization:

- expansion in power of $\lambda = |V_{us}|$
- 4 parameters: λ, $A=V_{cb}/\lambda^2$, ρ, $i\eta$
- 3 real parameters, 1 phase

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda^2 & A\lambda^3(\rho-i\eta) \\ -\lambda^2 & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

where $\lambda=\sin(\theta_{Cabibbo}) \sim 0.220$ $A \sim \rho \sim \eta \sim 1$

and the imaginary part η violates CP

Unitarity implies

$V_{CKM}V^{\dagger}_{CKM}=V^{\dagger}_{CKM}V_{CKM}=1$

i.e. rows and columns verify:

$$\sum_{i=1,3} V_{ij}^2 = \sum_{j=1,3} V_{ji}^2 = 1$$

$$\sum_{i=1,3} V_{ji}V_{ki}^{\dagger} = \sum_{j=1,3} V_{ij}V_{ik}^{\dagger} = 0$$

6 triangles in the complex plane (ρ, η)

with same area $A^2\lambda^6\eta$, lenght of sides obtained by measuring decay rates, angles obtained by measuring CP asymmetries.

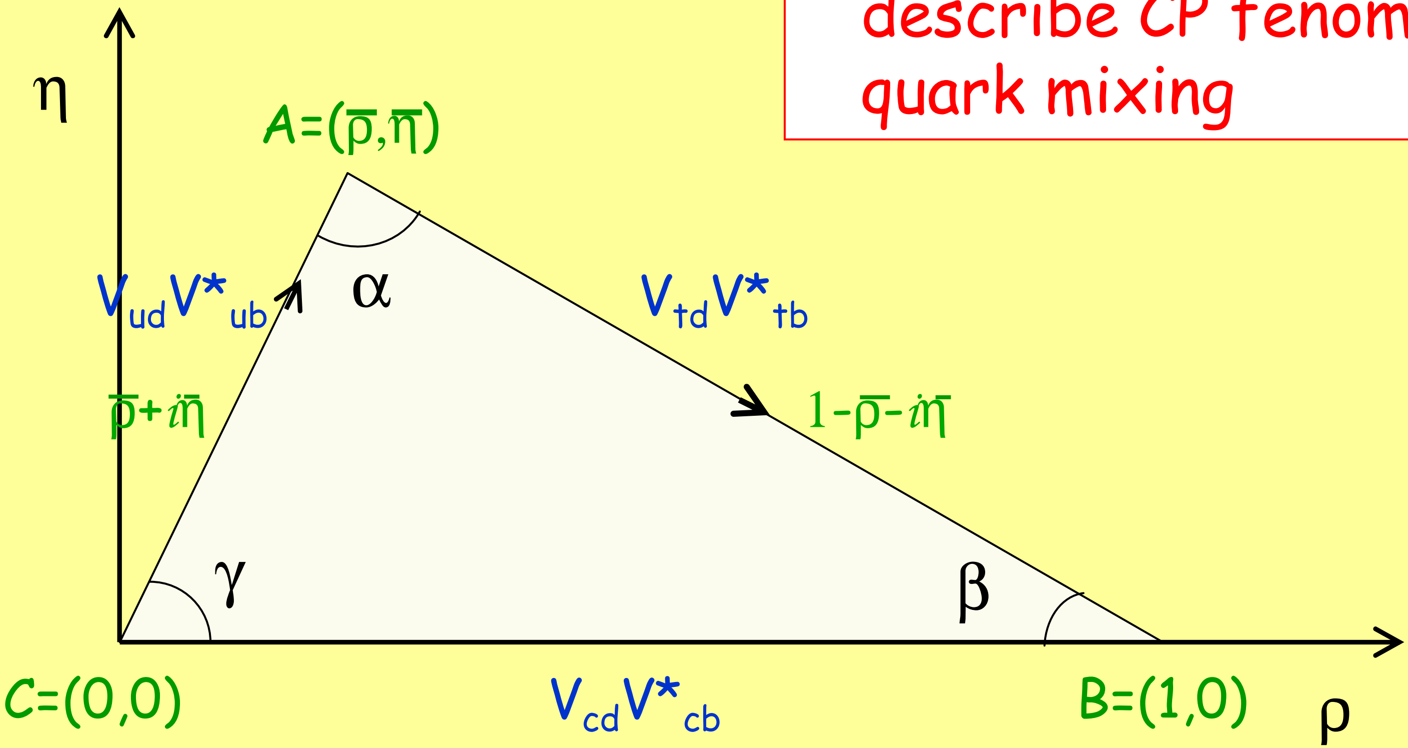
Unitarity Triangle

$V_{ud} V^*_{ub} + V_{cd} V^*_{cb} + V_{td} V^*_{tb} = 0$

$\bar{\rho} = \rho\,(1-\lambda^2/2)$

$\bar{\eta} = \eta\,(1-\lambda^2/2)$

- $\boldsymbol{\rho}$ and $\boldsymbol{\eta}$ precise measurements are very important to confirm the CMK formalism used to describe CP fenomena and quark mixing

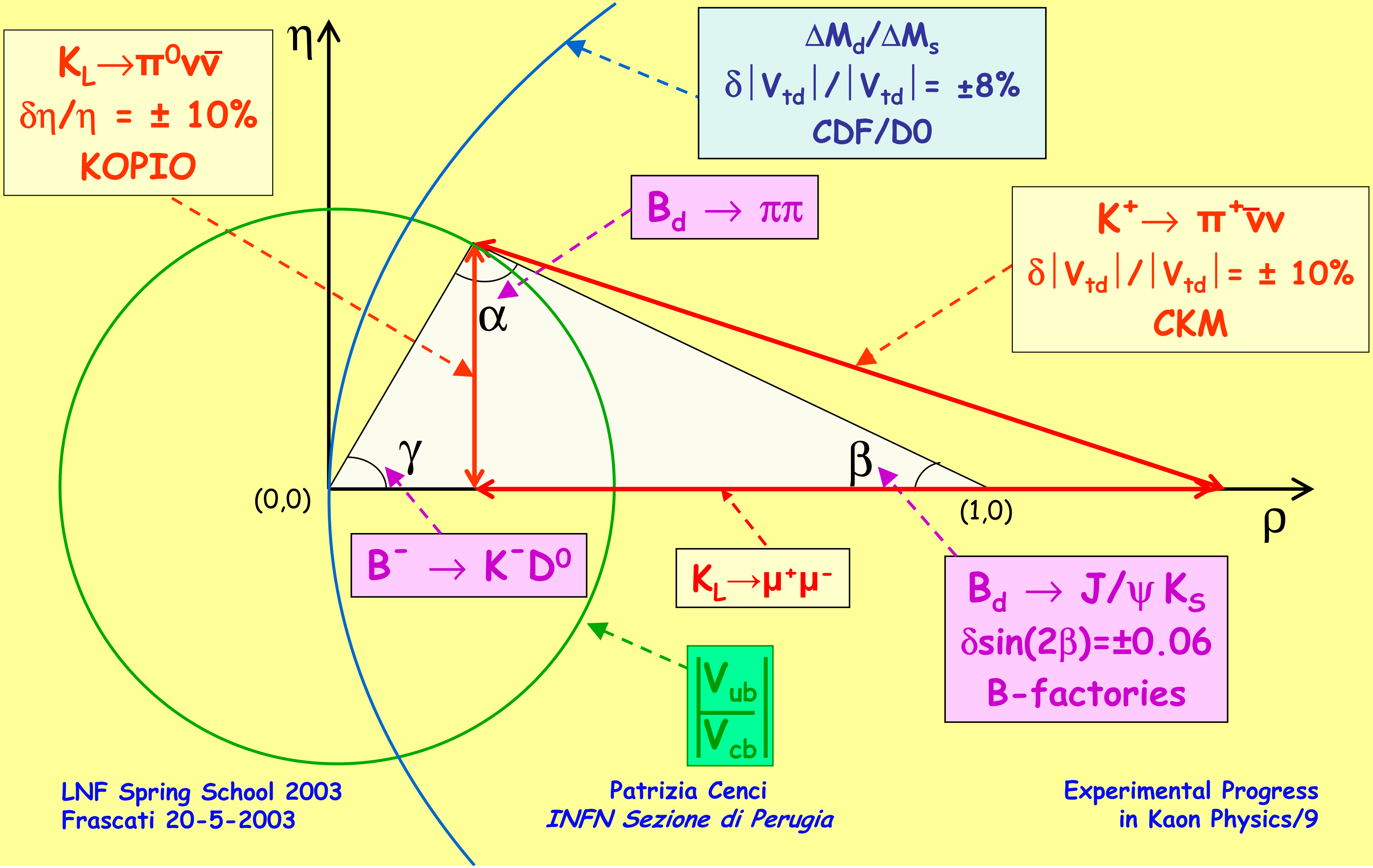


Test CP structure of CKM matrix

K and B provide 4 super-clean mode measurements to test CP violation and quark mixing formalism with sufficient theoretical robustness

$K^+ \to \pi^+ \nu\bar{\nu}$	$\lvert V^*_{ts} V_{td} \rvert$	E787/E949 (BNL) CKM (FNAL)
$K^0_L \to \pi^0 \nu\bar{\nu}$	$Im\,(V^*_{ts} V_{td}) \propto \eta$	KOPIO (BNL) E391a/JHF (KEK)
$B_d \to \Psi K_s$	$\sin 2\beta$	BABAR, BELLE, CDF D0, LHCB, BTeV
$\frac{x_s}{x_d} = \frac{B_s - \bar{B}_s}{B_d - \bar{B}_d}$	$\lvert V_{ts} / V_{td} \rvert$	CDF, D0 LHCB, BTeV

Constraints from K and B contributions



Simmetry Violation Tests with Kaons

- Brief review of $Re(\varepsilon'/\varepsilon)$ measurement results and experiments
- T violation in neutral Kaon Mixing
- CPV in $K_L \rightarrow \pi^+\pi^-e^+e^-$ (T-odd asymmetry)
- CPV in semileptonic K^0 decays CPV in $K_S \rightarrow 3\pi^0$ (CPT test)
- CPV in charged kaon decays

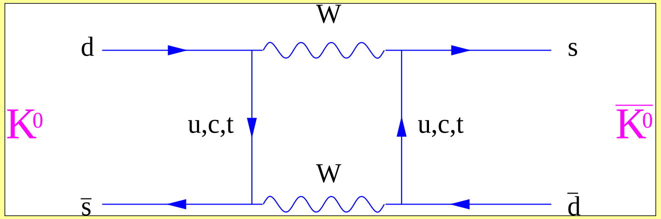
CP Violation in $K^0 \to \pi\pi$

CP Violation: naturally included in the SM due to an irriducible complex phase in the quark mixing matrix with three families

Indirect CPV: ε

K^0-$\bar{K}^0$ mixing

Box diagram $\Delta S=2$



$|A(K^0 \to \pi\pi)| \neq |A(\bar{K}^0 \to \pi\pi)|$

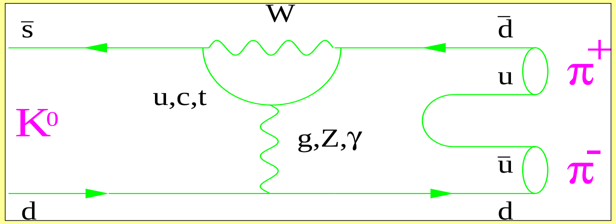
$$|\varepsilon| = (2.282 \pm 0.017) \times 10^{-3}$$

(PDG2002)

Direct CPV: ε′

Interference of I=0,2 amplitudes

Penguin diagram $\Delta S=1$



$A(K_L \to \pi^+\pi^-) / A(K_S \to \pi^+\pi^-) = \eta^{+-} = \varepsilon + \varepsilon'$

$A(K_L \to \pi^0\pi^0) / A(K_S \to \pi^0\pi^0) = \eta^{00} = \varepsilon - 2\varepsilon'$

$$\varepsilon' = i\, e^{i(d_2 - d_0)}\, \mathrm{Im}(A_2/A_0)/\sqrt{2}$$

The Re(ε′/ε) measurement

Re(ε′/ε) is connected to the "Double Ratio" R of the four observable decay rates $K^0 \to \pi\pi$:

$$R = \frac{|\eta^{00}|^2}{|\eta^{+-}|^2} = \frac{\Gamma(K_L \to \pi^0\pi^0) \times \Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^0\pi^0) \times \Gamma(K_L \to \pi^+\pi^-)} \cong 1 - 6\,\mathrm{Re}(\varepsilon'/\varepsilon)$$

The measurement of Double Ratio: count number of events

$$R = \frac{N(K_L \to \pi^0\pi^0) \times N(K_S \to \pi^+\pi^-)}{N(K_S \to \pi^0\pi^0) \times N(K_L \to \pi^+\pi^-)}$$

If the 4 modes are taken:

⇨ Simultaneously

⇨ In the same decay region

Theoretical predictions: Re(ε′/ε) in the range $5\text{-}40 \times 10^{-4}$

Review of Re(ε′/ε) experiments

- Pioneer experiment: (1972, BNL) Princeton experiment:

  $Re(\varepsilon'/\varepsilon) = -0.008 \pm 0.02$

- First generation experiments: CERN NA31 (1981) and FNAL E731 (1983)
- Last generation experiments: CERN NA48, FNAL KTeV, KLOE at DAΦNE (LNF)

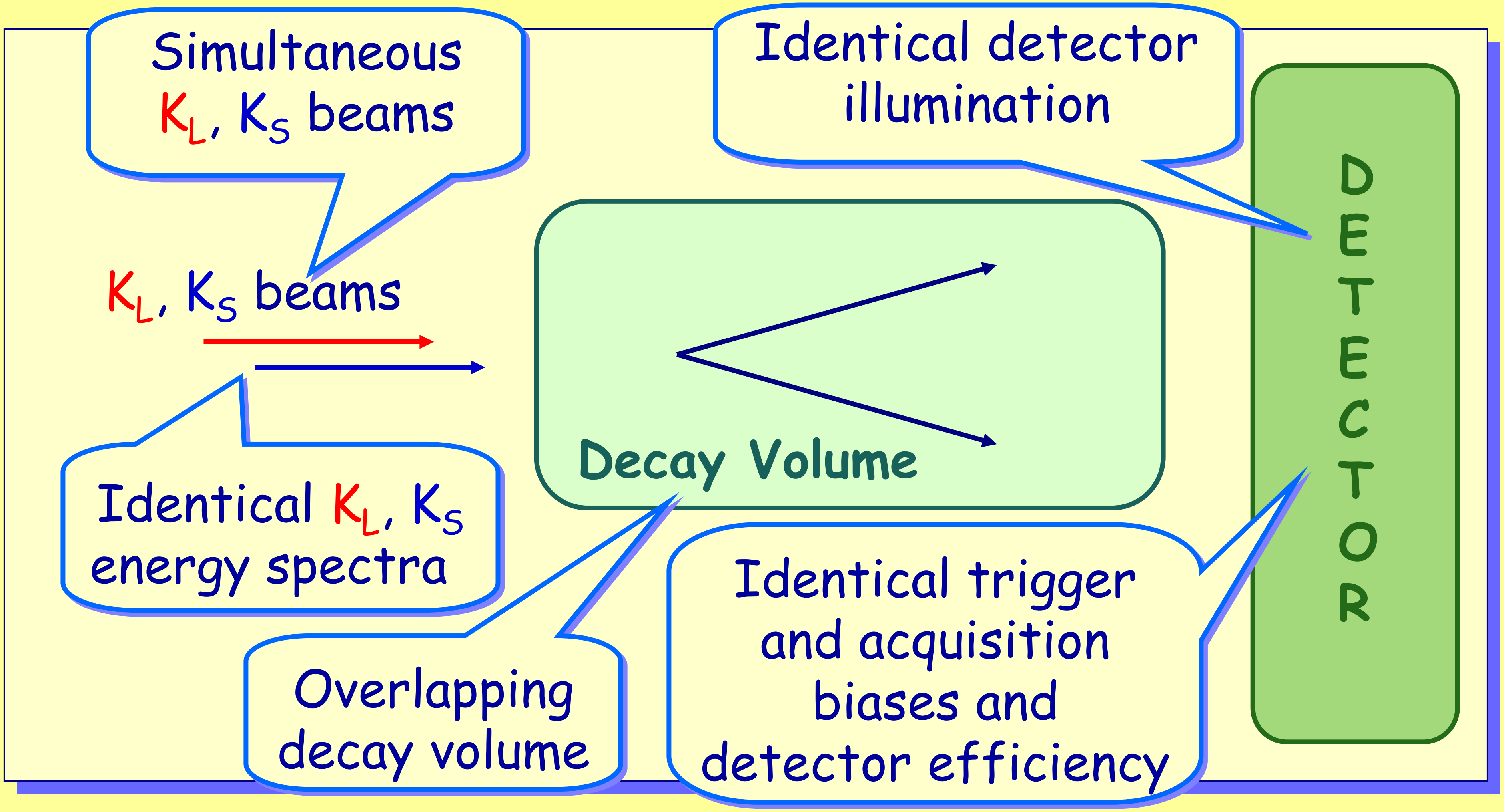
K_L + regenerated K_S beam, the 4 ππ modes collected in different periods, decay ratios corrected for beam fluxes:

$$\frac{|\eta^{00}|^2}{|\eta^{+-}|^2} = 1.05 \pm 0.14$$

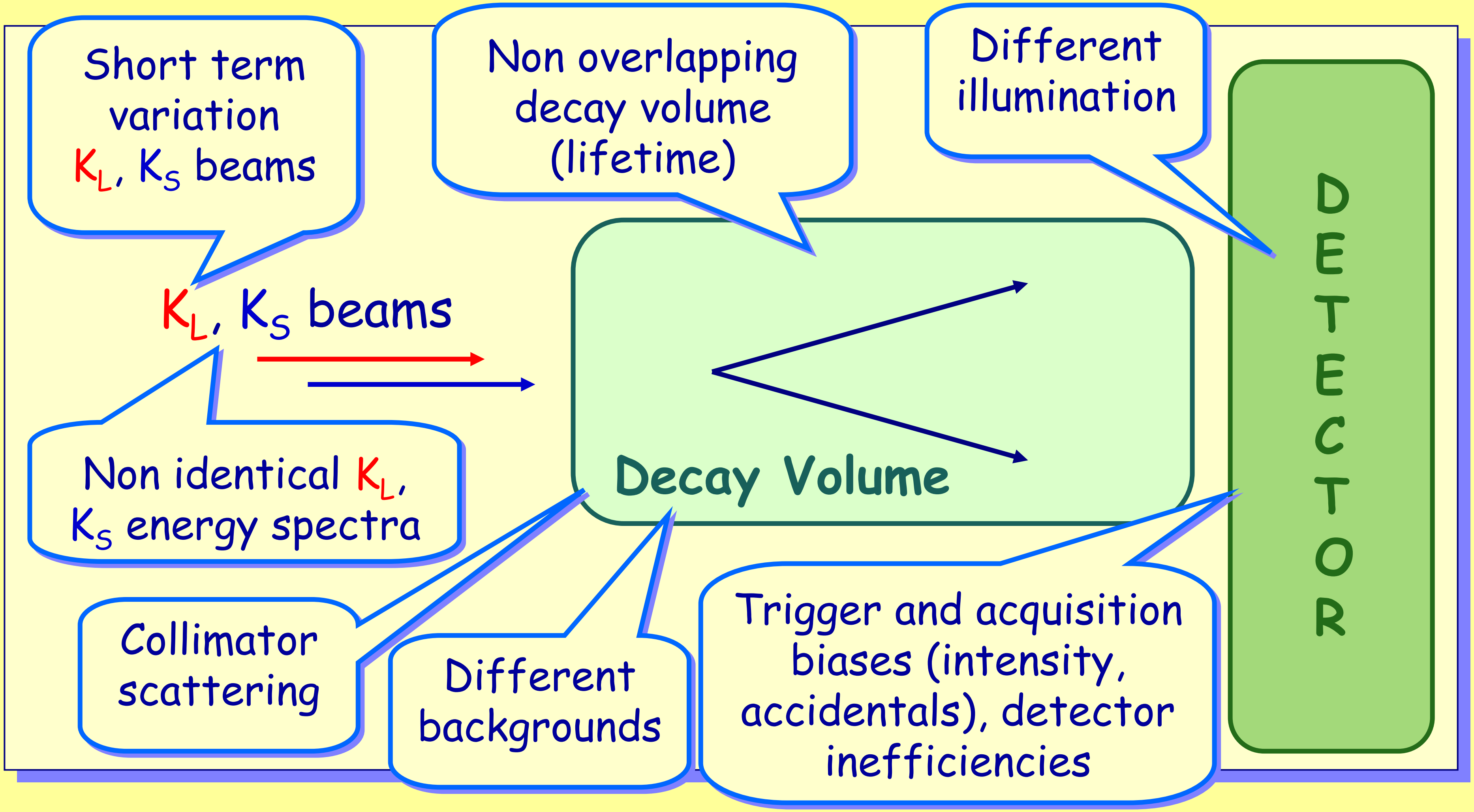
New precision experiment design, error down to 10^{-3}: *intense beams, Double Ratio technique, systematics reduced with simultaneous mode collection (NA31) or simultaneous beams (E831)*

Error down to 10^{-4}: *high intensity simultaneous K_L and K_S beams and concurrent modes collection*

The ideal $Re(\varepsilon'/\varepsilon)$ experiment



...and the real case



Re(ε′/ε) in KTeV and NA48

- Last generation experiments for Re(ε′/ε) measurement
- High intensity simultaneous K_L and K_S beams
- Simultaneous collection of the four decay modes
  → detector inefficiencies drop out
- Precise magnetic spectrometer and EM calorimeter
  → small backgrounds from other K decays and good control of the decay volume

	KTEV-FNAL	NA48-CERN
Proton beam	Tevatron (800 GeV)	SPS (450 GeV)
K_S Production	Regenerator	2nd target
K_S Identification	Center of Gravity of K	Proton tagging
$K_{S,L}$ decay vertex dist.	MC (KL weighting as check)	K_L weighting

Re(ε′/ε) measurement results

NA31: $(23.0 \pm 6.5) \times 10^{-4}$
E731: $(7.4 \pm 5.9) \times 10^{-4}$

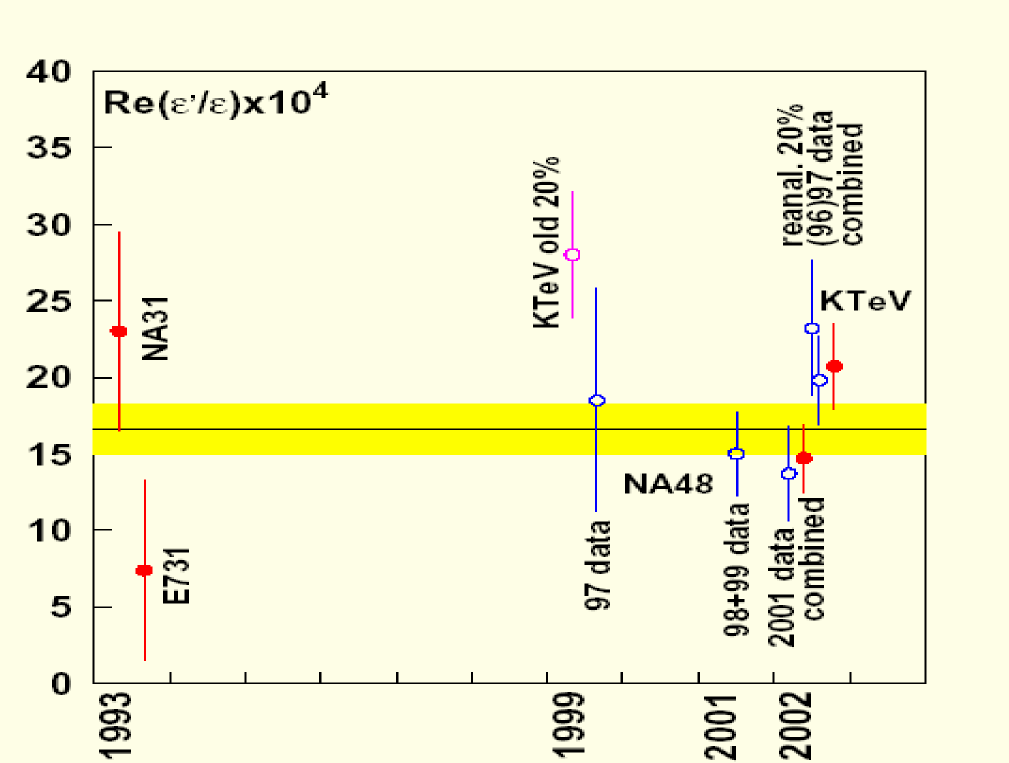
NA48: $(14.7 \pm 2.2) \times 10^{-4}$
PL B544 97 (2002) (final result)

NA48 Total Event Statistics:

$K_L \to \pi^0\pi^0$: 4.8×10^6 $K_S \to \pi^0\pi^0$: 7.4×10^6
$K_L \to \pi^+\pi^-$: 21.6×10^6 $K_S \to \pi^+\pi^-$: 31.8×10^6

KTeV: $(20.7 \pm 2.8) \times 10^{-4}$
PRD 67 012005 (2003) ('96-'97 data)
In progress analysis of 1999 data

	Vacuum beam (K_L)		Reg. Beam ("K_S")		$\sigma(\varepsilon'/\varepsilon)_{stat}$
	$\pi^+\pi^-$ ($\times 10^6$)	$\pi^0\pi^0$ ($\times 10^6$)	$\pi^+\pi^-$ ($\times 10^6$)	$\pi^0\pi^0$ ($\times 10^6$)	($\times 10^{-4}$)
96+97	11.2	3.4	19.4	5.6	1.5
1999	14.9	3.7	25.8	6.1	1.4
96-99	26.1	7.1	45.2	11.7	1.0



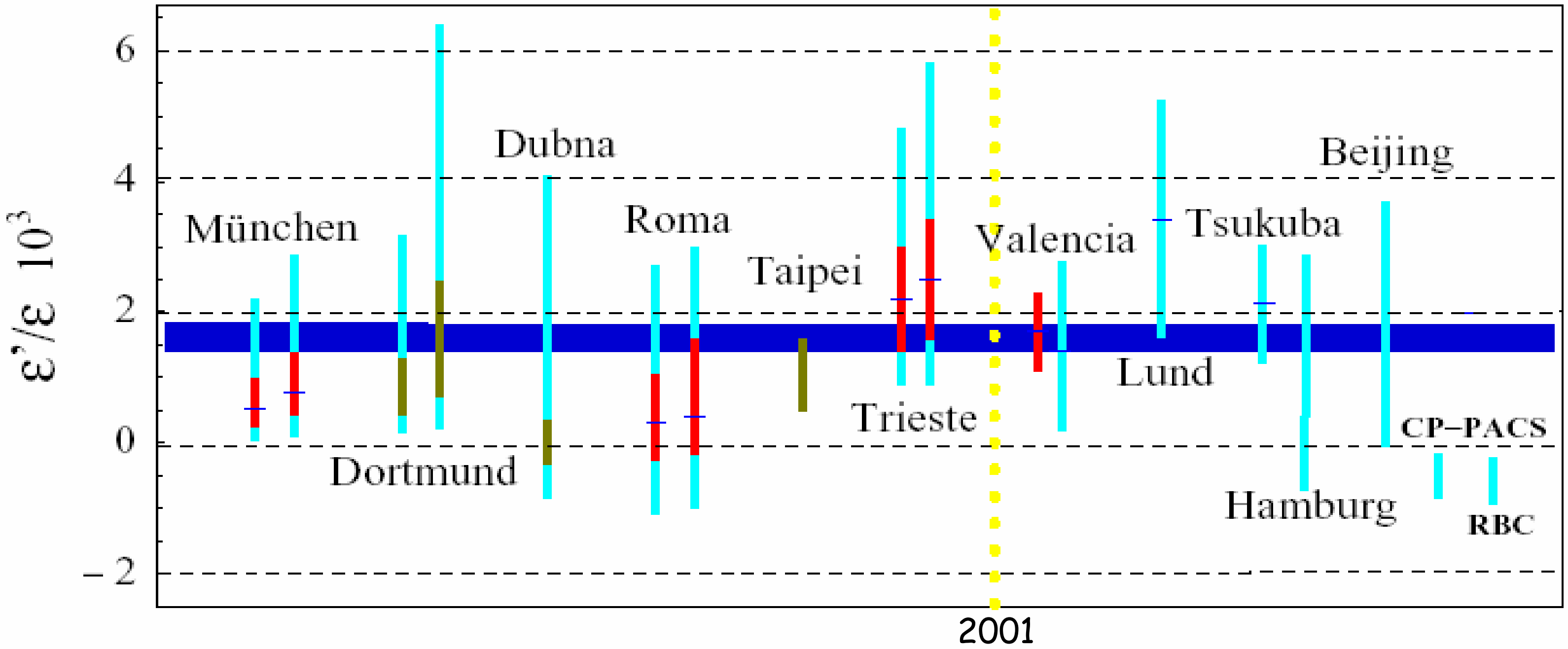
New world average:

$\mathrm{Re}\,(\varepsilon'/\varepsilon) = (16.6 \pm 1.6) \times 10^{-4}$

$\chi^2/\mathrm{ndf} = 6.3/3$ (10% prob.)

Comparison of theoretical predictions

SM can strech to accomodate experimental value

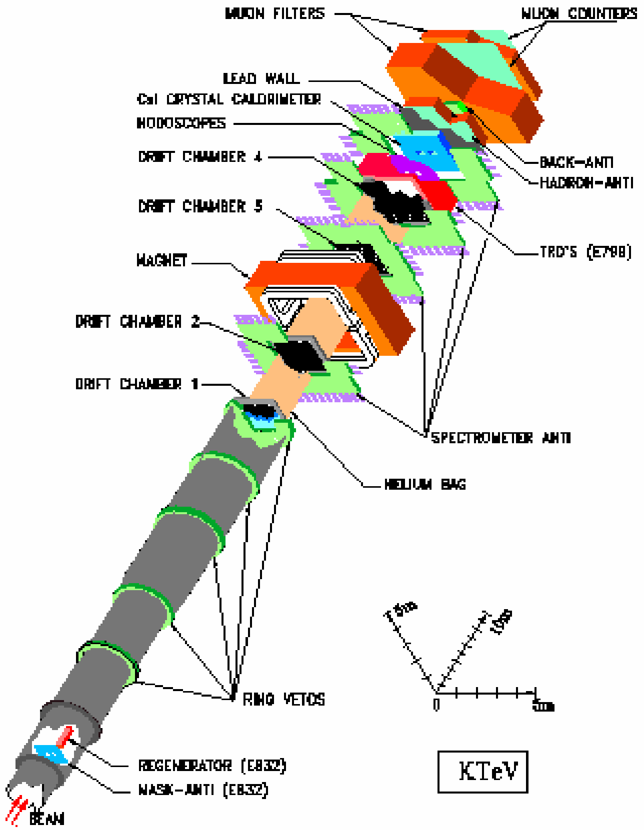


Theoretical predictions: Re(ε'/ε) in the range 5-40 x 10^{-4}
(but also recent negative values)

Lessons from ε′/ε

- Direct CPV clearly established in $K^0 \to \pi\pi$ by NA48 and KTeV: waiting for KLOE results
- No third generation experiments
- Result consistent with SM predictions
- Alternative to CKM mechanism excluded (superweak models and approximate-CP)
- Large hadronic uncertainties → no useful CKM contraint
- New physics may contribute significantly as a correction to SM predictions

FNAL KTeV Experiment



"Vacuum" beam $\rightarrow K_L$ beam

"Regenerator" beam $\rightarrow K_L + \rho K_S$ beam

- Parallel K beams: 2 high intensity proton lines (~ 10^{12} ppp), K_S from K_L on Regenerator (scintillator plates), K_S identification via x-y position, switches beam line once per cycle
- $\pi^+\pi^-$: Magnetic Spectrometer
- $\pi^0\pi^0$: CsI calorimeter
- Photon veto and muon veto

CsI Calorimeter Resolution:

$\sigma(E)/E \cong 2.0\%/\sqrt{E} \oplus 0.45\%$

(E in GeV) (0.7% for 15 GeV photons)

Spectrometer: (p_T kick ~ 400 MeV/c):

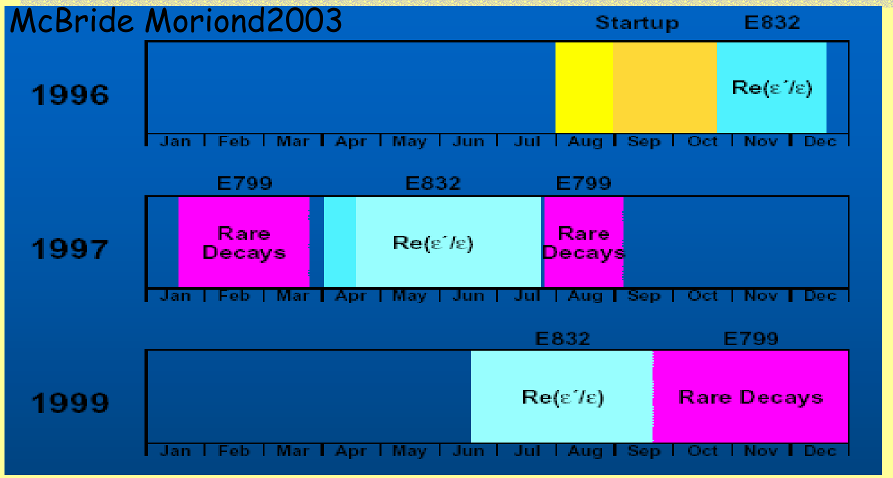
$\sigma(p)/p \cong 0.17\% \oplus 0.007\ p[GeV/c]\%$

$\sigma_M(\pi^0\pi^0) \sim \sigma_M(\pi^+\pi^-) \sim 1.5$ MeV

KTeV Experimental Program

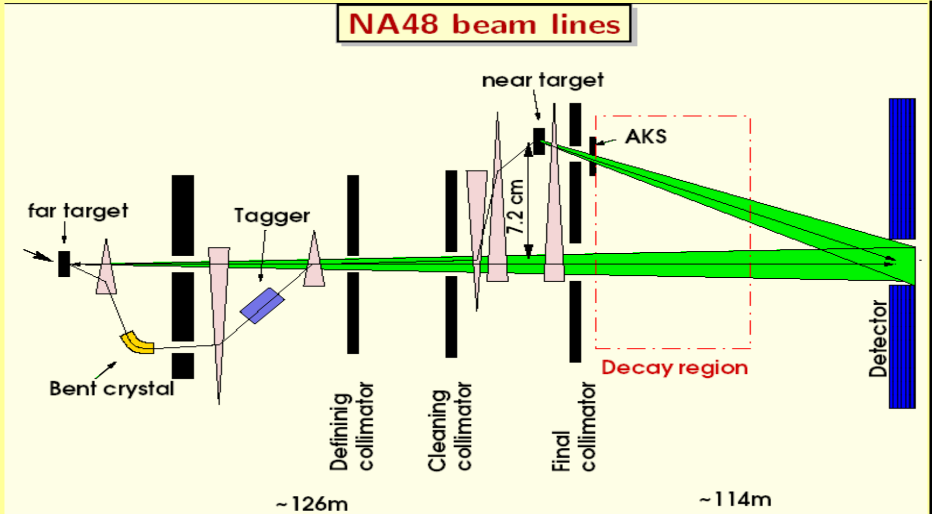
Two KTeV goal, different experimental setup:

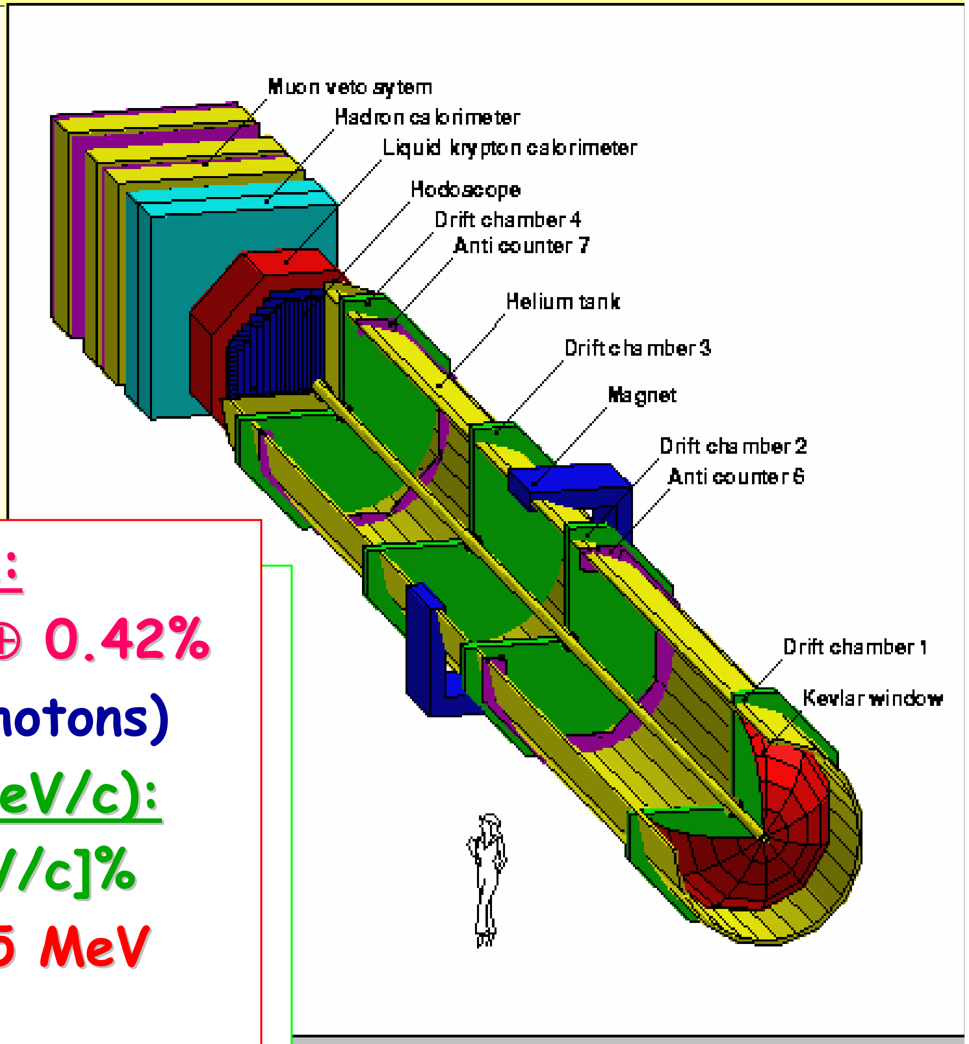
- **E832:** Re(ε′/ε) measurement with K_S and K_L beams
- **E799:** no regenerator, higher beam intensity, TRD for particle identification to investigate rare K decays



Decay Mode	Publ.	# Events	BR
Direct CP Violation			
$K_L \to \pi^0 e^+ e^-$	x 97	2	$< 5.1 \times 10^{-10}$
$K_L \to \pi^0 e^+ e^-$	97+99	3	$< 2.8 \times 10^{-10}$
$K_L \to \pi^0 \mu^+ \mu^-$	x	2	$< 3.8 \times 10^{-10}$
$K_L \to \pi^0 \nu\nu$	x	0	$< 5.9 \times 10^{-7}$
Indirect CP Violation			
$K_L \to \pi^+ \pi^+ \gamma$	x	8,669	$(2.08 \pm 0.03) \times 10^{-2}$ $\times B(K_L \to \pi^+ \pi^+)$
$K_L \to \pi^+ \pi^- e^+ e^-$		1,558	$(3.63 \pm 0.11 \pm 0.14) \times 10^{-7}$
χPT and VMD			
$K_L \to \pi^0 \gamma\gamma$	x	884	$(1.68 \pm 0.07 \pm 0.08) \times 10^{-6}$
$K_L \to \pi^0 e^+ e^- \gamma$	x	48	$(2.34 \pm 0.35 \pm 0.13) \times 10^{-8}$
$K_L \to \pi^0 \pi^0 e^+ e^-$	x	1	$< 5.4 \times 10^{-9}$
Kγγ* Vertex			
$K_L \to e^+ e^- \gamma$		93.4k	$(10.13 \pm 0.04 \pm 0.06 \pm 0.29) \times 10^{-6}$
$K_L \to \mu^+ \mu^{+-} \gamma$	x	9,327	$(3.62 \pm 0.04 \pm 0.08) \times 10^{-7}$
$K_L \to e^+ e^- \gamma\gamma$	x	1,543	$(5.84 \pm 0.15 \pm 0.32) \times 10^{-7}$
$K_L \to \mu^+ \mu^- \gamma\gamma$	x	4	$(1.04^{+0.75}_{-0.59} \pm 0.07) \times 10^{-8}$
Kγ*γ* Vertex			
$K_L \to e^+ e^- e^+ e^-$	x 97	441	$(3.72 \pm 0.18 \pm 0.23) \times 10^{-8}$
$K_L \to e^+ e^- e^+ e^-$	97+99	1056	$(4.07 \pm 0.12 \pm 0.11 \pm 0.16) \times 10^{-8}$
$K_L \to e^+ e^- \mu^+ \mu^-$	x 97+99	132	$(2.69 \pm 0.24 \pm 0.12) \times 10^{-9}$
Lepton Flavor Violation			
$K_L \to e^{\pm} e^{\pm} \mu^{7} \mu^{7}$	x 97+99	0	$< 4.12 \times 10^{-11}$
$K_L \to \pi^0 \mu^{\pm} e$		2	$< 4.4 \times 10^{-10}$

CERN NA48 Experiment





LKr Calorimeter resolution:

$\sigma(E)/E \cong 3.2\%/\sqrt{E} \oplus 100MeV/E \oplus 0.42\%$

(E in GeV) (< 1% for 25 GeV photons)

Spectrometer (p_T kick ~ 250 MeV/c):

$\sigma(P)/P \cong 0.48\% \oplus 0.009\ P[GeV/c]\%$

$\sigma M(\pi 0 \pi 0) \sim \sigma M(\pi + \pi -) \sim 2.5$ MeV

NA48 Experimental Program

- **Main physics program:** Re(ε′/ε) measurement
- In parallel with Re(ε′/ε): many rare K_L, K_S and neutral hyperons decays studies
- **Two addenda to NA48 proposal approved in 2000:**

NA48/1: investigation of K_S and Hyperon decays with a high intensity K_S beam

NA48/2: precision measurement of $K^{\pm}$ decay parameters with simultaneous K^+/K^- beams

1997 ε′/ε K_L+K_S

1998 ε′/ε K_L+K_S

1999 ε′/ε K_L+K_S

K_L only run

K_S HI test

2000 ε′/ε checks K_L only, η run

K_S HI NA48/1 phase 1

No spectrometer

2001 ε′/ε K_L+K_S

2002 NA48/1 phase 2 K_S High Intensity

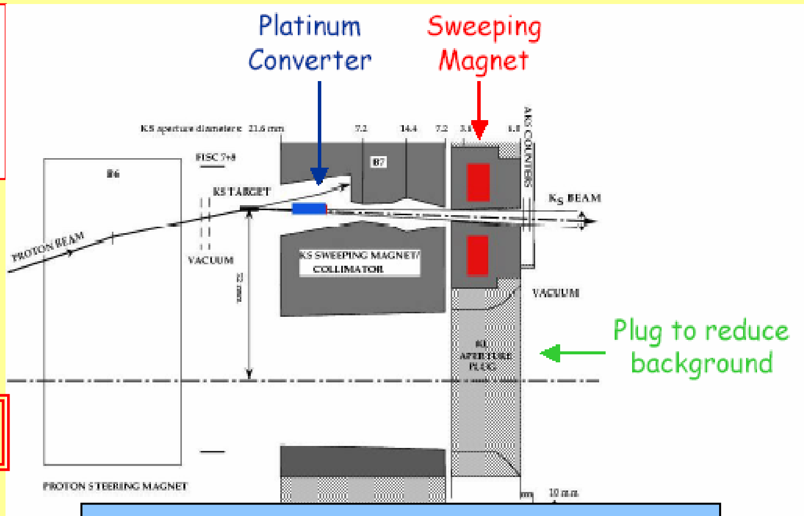
2003 NA48/2 $K^+ + K^-$

NA48/1: K_S Program

A high sensitivity investigation of K_S and neutral hyperon decays

NA48/1: K_S Physics

K_S Decay Mode	PDG 2002	Theory	NA48/1 expected (stat err) Measured
Constraint the Indirect CP-Violation in K_L Rare decays			
BR($K_S \to \pi^0 e^+ e^-$)x10^{10}	<1400 NA48/1 test	1-100	~4 (SES)
BR($K_S \to \pi^0 \mu^+ \mu^-$)x$10^{10}$	-	1-100	~ 2 (SES)
CP Violation, Test of CPT			
$3\pi^0$, Im(η_{000})x10^2	-5 ± 12	~0	± 1 (Y2K)
Im $\delta \times 10^5$	-2.4 ± 5.0	~0	± 3 (Y2K)
$\pi^+\pi^-\pi^0$, Im $\eta_{+-0} \times 10^3$	-2 ± 9	~0	± 5
CPC Re $\lambda \times 10^3$, Im $\lambda \times 10^3$	28 ± 9, -10 ± 8	-	± 4, ± 4
Ke3, BR $\times 10^4$	7.2 ± 1.4	-	± 0.1
Re $\delta \times 10^4$	~3	0	-
$\pi^+\pi^-e^+e^-$ BR $\times 10^5$ asym.(%)	4.5 ± 0.8 NA48	-,~0	± 0.04, 0.2
Chiral Perturbation theory			
BR($K_S \to \gamma\gamma$)x10^6	2.5 ± 0.4NA48/1 test	2.1 O(p4)	2.78 ± 0.07(Y2K)
BR($K_S \to ee\gamma$)x10^8	-	3.4	± 0.2
BR($K_S \to \pi^0\gamma\gamma$)x$10^8$	-	3.8	± 2 (Y2K)
BR($K_S \to \pi^0\pi^0\gamma\gamma$)x$10^9$	-	5.0	1 (SES)



Beam modifications: K_S target

- **No K_L beam, high intensity modified K_S beam, improved readout and daq capabilities**
- **Data records:**

Phase I (2000): ≈10^{10} K_S

Phase II (2002): ≈4.4×10^{10} K_S

SES(5% acceptance) ≈ 4.5×10^{-10}

NA48/1: Main Physics Cases

NA48 ('99 data): BR($K_S \to \pi^0 e^+ e^-$) <1.4 x 10^{-7} (90% CL)
NEW RESULT (all data): CERN Seminar in June

$K_S \to \pi^0 e^+ e^-$:

- **bound $BR_{CPdir}(K_L \to \pi^0 e^+ e^-)$:**

$BR_{CPind}(K_L) = |\varepsilon|^2 \tau_L/\tau_S$ BR(K_S) ≈~ 3×10^{-3} BR(K_S)

- **test chiral structure of $K \to \pi\gamma^*$ vertex:**

BR($K_S \to \pi^0 e^+ e^-$) ~ $5.2\times10^{-9}\, |a_S|^2$

(a_S ~ O(1) according to χPT)

- Expected ≈~ 7 events with SES ≈~ 6 $\times10^{-10}$
- Main background: $K_S \to \pi^0 \pi^0_D$ < 0.3 ev. (MC)

$K_S \to \pi^0\pi^0\pi^0$: CPV decay, parametrized with η_{000}:

- Re(η_{000}) = Re(ε) ⇨ indirect CPV measurement
- Im(η_{000}) sensitive to direct CPV
- Aim: ~ 1% error on Re(η_{000}) and Im(η_{000})

(K_S-K_L interference near production target)

- Precision of B.S. sum rule to ~ 2×10^{-2} (CPT test)

Sizeable samples of **radiative K decays** of interest for χPT phenomenology:

$K_S \to \gamma\gamma$:

collected O(10^4) events

$BR_{\chi PT}$ ≈ 2.1×10^{-6}

with 10% error

$K_S \to \pi^0\gamma\gamma$:

collected 114 events,

BR_{ChPT} ≈ 3.8×10^{-8}

($m_{\gamma\gamma}$>220MeV/c^2)

NA48/2: $K^{\pm}$ Program

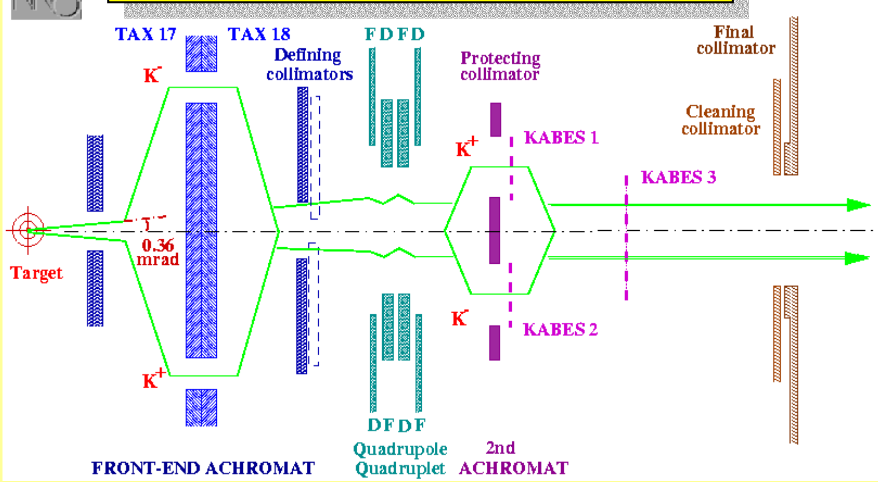
- **Main goal:** $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$
  Dalitz Plot slope asymmetry: direct CPV measurement
  Present experimental limit:
  $A_g=(-7\pm5)\times10^{-3}$ (1970)
- **HyperCP** ~3.9/1.6×10⁸ K^+/K^-
  $A_g=(2.2\pm1.5_{stat}\pm3.7_{syst})\times10^{-3}$
- **KLOE** ~ 6x10⁵ $K^{\pm}$ tag/pb⁻¹
- SM predictions ~10^{-6} to 10^{-4}
- Data taking in 2003
- Also: asymmetry in $\pi^{\pm}\pi^{0}\pi^{0}$ and $\pi^{\pm}\pi^{0}\gamma$ and $K^{\pm}$ rare decays

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

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

Slope Parameter

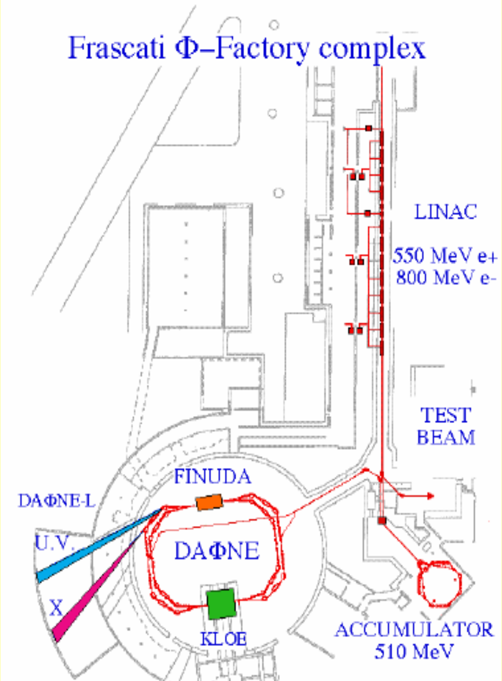
Simultaneous K^+ and K^- beams



NA48 aims at ~10^{-4} δA_g

- 7.3/4.4×10⁹ K^+/K^- decays/year
  - $\delta A_g \sim 0.7\times10^{-4}$(stat)
- Simultaneous $K^{\pm}$ beams + B field reversal to symmetrize efficiencies
  - $\delta A_g \sim 0.5\times10^{-4}$(sys)

The KLOE Experiment at DaΦne



e+e-@√s=1020 MeV

Summary of DAΦNE Operations

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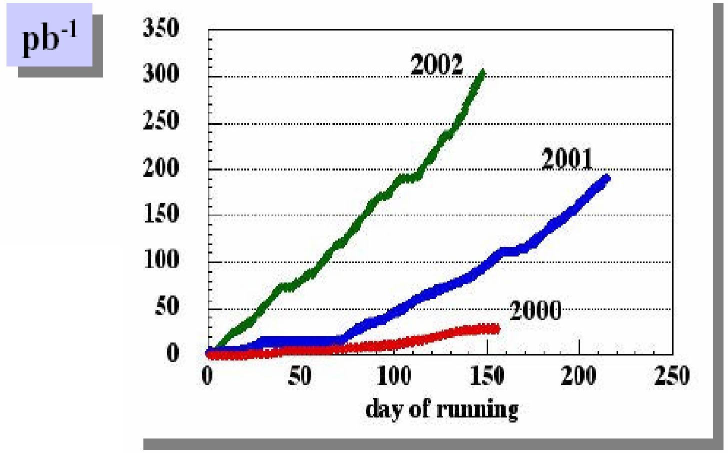


	Design	2002
♦ Max number of bunches	120	51
♦ Lifetime (min)	120	40
♦ Bunch current (mA)	40	20
♦ Single Bunch lum. (10^{30} cm^{-2}s^{-1})	4.4	1.5
♦ Peak Luminosity (10^{32} cm^{-2}s^{-1})	5.3	0.75
♦ ϕ per year (10^9)	15	0.9

March 1st 1998:
First collisions

1999 run: **2.5 pb^{-1}**
detector calibration

2000 run: **25 pb^{-1}**
7.5 x 10^7 ϕ
first published results

2001 run: **190 pb^{-1}**
5.7 x 10^8 ϕ
analysis in progress

2002 run: **300 pb^{-1}**
9.0 x 10^8 ϕ
analysis in progress

next run (2003): 1 fb^{-1}

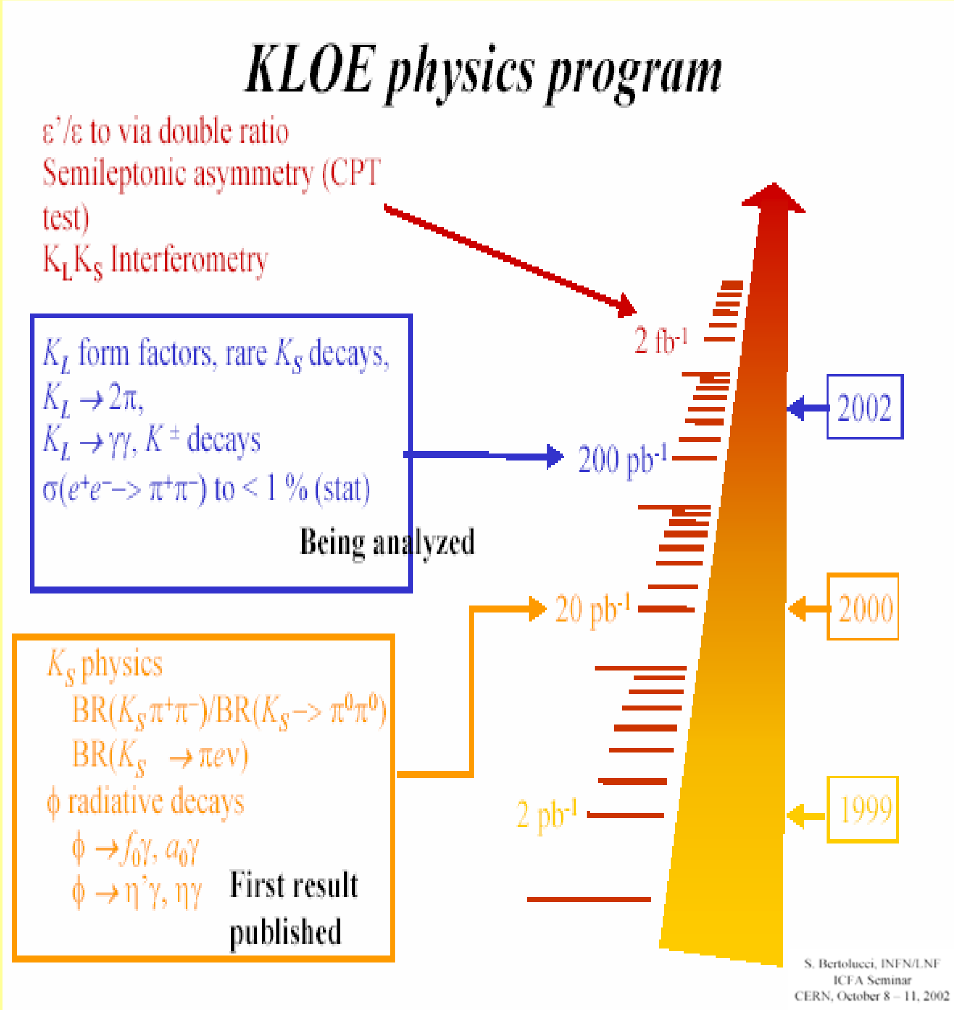
The KLOE Physics Program

Φ Factory: tagged K decays from $\Phi \rightarrow K\bar{K}$:
→ pure K beams

- complimentary Re(ε′/ε) measurement
- clean investigation of rare K decays and precision measurement

φ Decays	
K^+K^-	49.1%
K_LK_S	34.3%
ρπ	15.4%
ηγ	1.3%

Available data set:
≈ 500 pb^{-1}
Including efficiencies this correspons to:



The KLOE detector

Drift Chamber (DC)

- Cylindrical structure, (4 m ∅×3.3 m)
- 12582/52140 sense/total wires
- All stereo geometry
- Helium (90 %) + Isobutan (10 %)

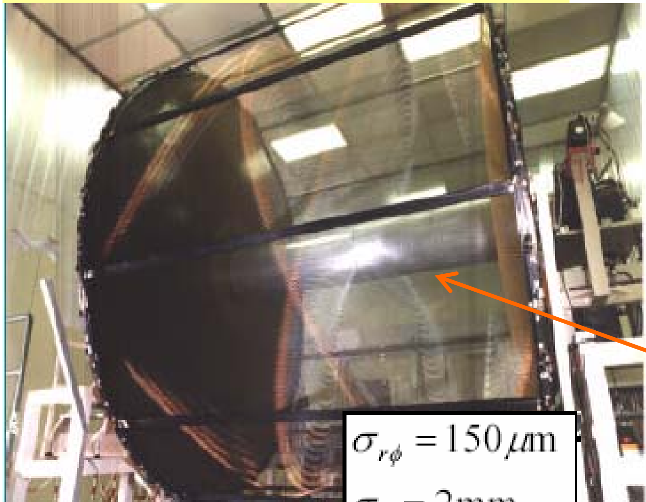
$\lambda_S = 0.6\text{cm}$

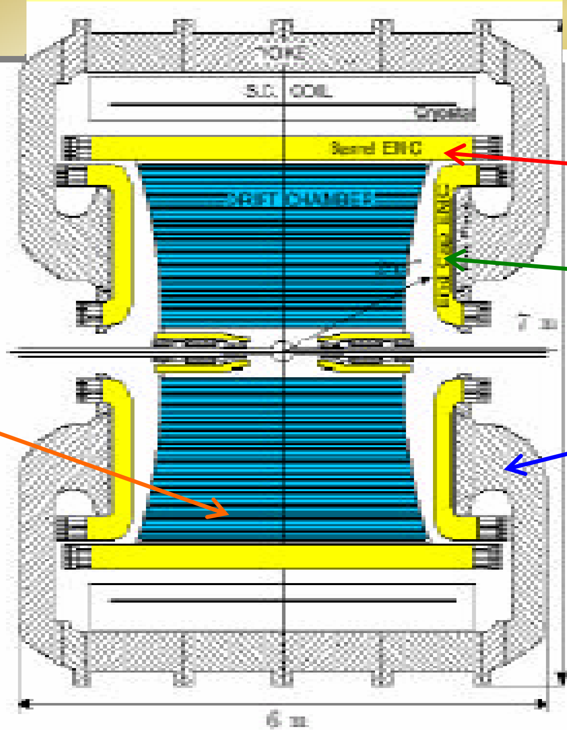
$\lambda_L = 340\text{cm}$

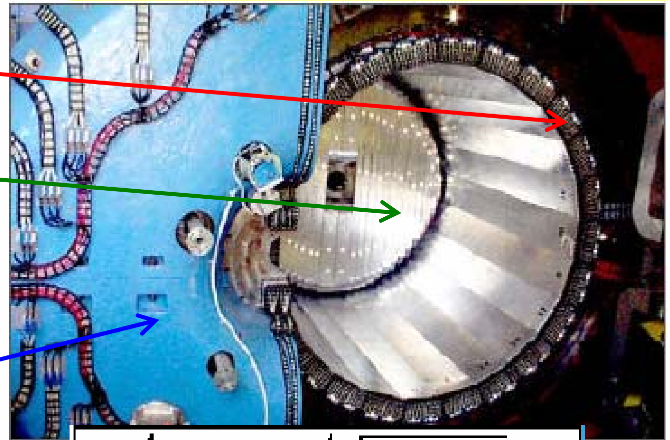
$\lambda_\pm = 95\text{cm}$

Electromagnetic Calorimeter (EMC)

- Lead/Scintillating - Fiber calorimeter
- 24 Barrel Modules
- 64 End-Cap Modules
- 4880 channels







$\sigma_{r\phi} = 150\,\mu\text{m}$

$\sigma_z = 2\text{mm}$

$\sigma_V = 3\text{mm}$

$\sigma_p / p = 0.4\%$

$\sigma_E / E = 5.7\% / \sqrt{E(\text{GeV})}$

$\sigma_t = 54\text{ps} / \sqrt{E(\text{GeV})} \oplus 50\text{ps}$

$\sigma_{r\phi} = 1\text{cm}$

KLOE: prospects for Re(ε′/ε)

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

K_L

Statistical error : ≈ 1%

Contributions to the systematic error :

Presently at about 2% level, improving by work on:

- **Residual effects in tracking (gravitational sags)**
- **Separation of overlapping clusters**
- **Regeneration**

Need at least x10 data to reach the 10^{-4} *régime*

K_S

Statistical error : **already negligible**

Contributions to the systematic error

Source	Error, %
Tagging	0.55
γ-counting	0.20
trigger and t_0	0.23
tracking	0.26

Now ~0.1% (Tagging)

Total error 0.68 %

Should scale down to 0.1% on full data set

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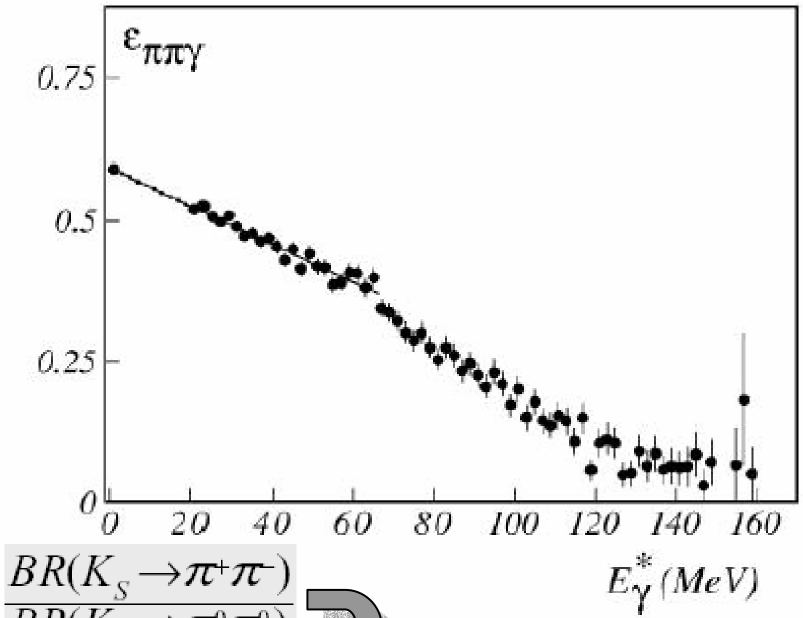
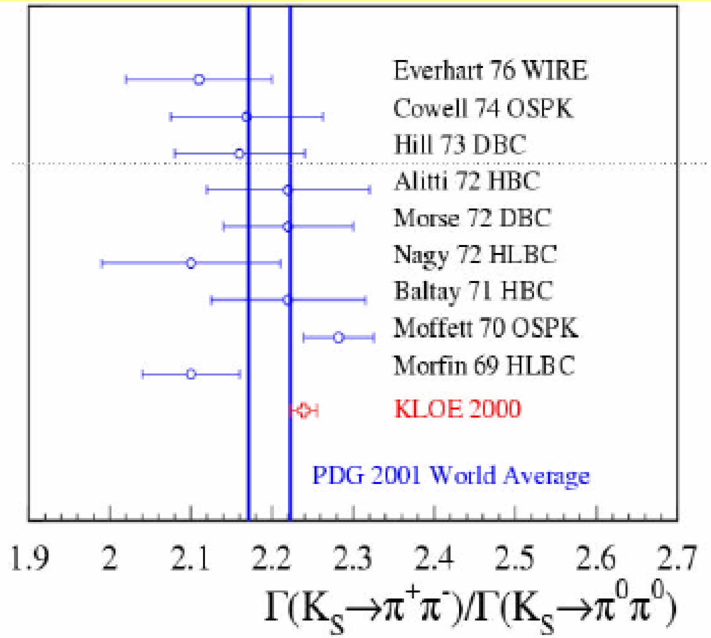
KLOE: $K_S \to \pi^+\pi^-(\gamma)/K_S \to \pi^0\pi^0$

Motivations: first part of double ratio in $Re(\varepsilon'/\varepsilon)$ measurement
extractions of Isospin amplitudes A_0, A_2 and phases δ_0 and δ_2



$$\frac{BR(K_S \to \pi^+\pi^-)}{BR(K_S \to \pi^0\pi^0)}$$



KLOE 2000 data	$2.239 \pm 0.003_{(stat)} \pm 0.015_{(sys)}$
PDG 2002	2.197 ± 0.026

Phys. Lett. **B 538** (2002), 21

- Measurement done on Y2K 17 pb^{-1}

$N(K_S \to \pi^+\pi^-) = 1.098 \times 10^6$

$N(K_S \to \pi^0\pi^0) = 0.788 \times 10^6$

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KLOE: Isospin Analysis

$$\frac{BR(K_S \to \pi^+\pi^+)}{BR(K_S \to \pi^0\pi^0)} \cong \sqrt{\frac{m_K^2 - 4m_{\pi^\pm}^2}{m_K^2 - 4m_{\pi^0}^2}}\left[2 + 6\sqrt{2}\frac{A_2}{A_0}\cos(\delta_2 - \delta_0)\right]$$

Neglecting ΔI=5/2 EM contributions:

$$(A_0/A_2)^2 \cong \frac{3}{4}\frac{\tau_S}{\tau_+}\frac{1}{BR(K^\pm \to \pi^+\pi^0)} - 1 = (22.2 \pm 0.07)^2$$

Using PDG values for the $K^0 \to \pi^+\pi^-/\pi^0\pi^0$ BRs:

$$\delta_0 - \delta_2 \cong (56.7 \pm 3.8)^\circ$$

This value is in disagreement with:

- the prediction from $O(p^2)$ χpT [Gasser *et al.* '91] $\delta_0 - \delta_2 \cong (45 \pm 6)^\circ$
- the value from $\pi\pi$ scattering [Gasser *et al.* '01] $\delta_0 - \delta_2 \cong (45.2 \pm 1.3 \pm {}^{4.5}_{1.6})^\circ$

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While with the KLOE measurement

$$\delta_0 - \delta_2 \cong (48 \pm 3)^\circ$$

CPV in $K_S \to \pi^0\pi^0\pi^0$

PHYSICS INTEREST

$|K_S> \simeq |K_1> + \epsilon_S |K_2>$

$CP(|K_1>) = +1 \quad CP(|K_2>) = -1 \quad CP(\pi^0\pi^0\pi^0) = -1$

$\Longrightarrow$ parametrized by $\eta_{000} = \frac{A(K_S \to \pi^0\pi^0\pi^0)}{A(K_L \to \pi^0\pi^0\pi^0)}$

If CPT conserved:
$\Re e\,\eta_{000}$ - CP violation in mixing
$\Im m\,\eta_{000}$ - Sensitive to direct CP violation

MEASUREMENT IN NA48

Time evolution of $K_{L,S} \to 3\pi^0$:

$$I_{3\pi^0}(t) \propto \overbrace{e^{-\Gamma_L t}}^{K_L \text{ decay}} + \overbrace{|\eta_{000}|^2 e^{-\Gamma_S t}}^{K_S \text{ decay}}$$

$$\underbrace{+\,2\,D(p)\,\left(\mathrm{Re}(\eta_{000})\cos\Delta m\,t - \mathrm{Im}(\eta_{000})\sin\Delta m\,t\right)\,e^{-\frac{1}{2}(\Gamma_S+\Gamma_L)\,t}}_{K_L\text{-}K_S \text{ interference}}$$

Dilution $D(p) = \frac{N(K^0) - N(\overline{K^0})}{N(K^0) + N(\overline{K^0})} \approx 0.35$ momentum dependent.

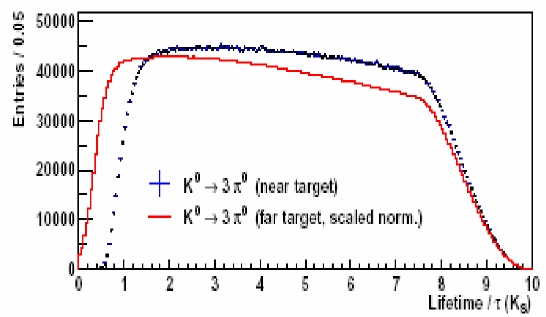
- NA48 Sensitivity to η_{000} : from K_S-K_L interference superimposed on a huge flat $K_L \to \pi^0\pi^0\pi^0$ component
- Aim: O(1%) error on $\mathrm{Re}(\eta_{000})$ and $\mathrm{Im}(\eta_{000})$
- Method: measure K_S-K_L interference near the production target

NA48: Search for $K_S \to \pi^0\pi^0\pi^0$

METHOD and DATA SAMPLE

Method:

- Use $3\pi^0$ events from near-target run for η_{000}.
- Normalize to $K_L \to 3\pi^0$ from far-target run.
- Use Monte Carlo to correct for residual acceptance difference and Dalitz decays.



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Data samples:

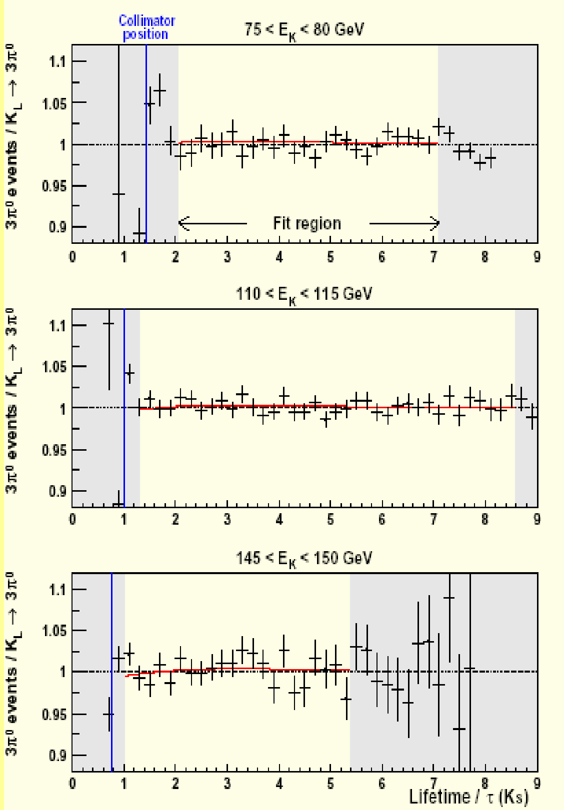
Near-target run:	Events:
$3\pi^0$ data:	6.5×10^6
$K_L \to 3\pi^0$ MC:	66×10^6
Far-target run:	
$K_L \to 3\pi^0$ data:	154.7×10^6
$K_L \to 3\pi^0$ MC:	66×10^6

Fit Method: Fit double ratio

$$\frac{3\pi^0\ \text{(Data, } K_S \text{ run)}}{K_L \to 3\pi^0\ \text{(Data, } K_L \text{ run)}} \Big/ \frac{K_L \to 3\pi^0\ \text{(MC, } K_S \text{ run)}}{K_L \to 3\pi^0\ \text{(MC, } K_L \text{ run)}}$$

Simultaneous fit in energy bins

⟹ Free parameters:
$\mathrm{Re}(\eta_{000})$, $\mathrm{Im}(\eta_{000})$, normalizations



NA48: η_{000} measurement

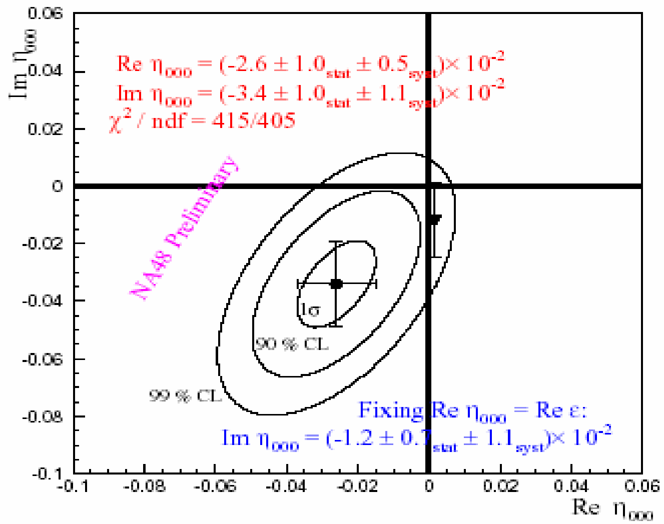
PRELIMINARY NA48 RESULTS

***Preliminary* NA48 result:**

$$\mathrm{Re}(\eta_{000}) = -0.026 \pm 0.010_{\mathrm{stat}} \pm 0.005_{\mathrm{sys}}$$

$$\mathrm{Im}(\eta_{000}) = -0.034 \pm 0.010_{\mathrm{stat}} \pm 0.011_{\mathrm{sys}}$$

(CPLEAR: $\mathrm{Re}(\eta_{000}) = 0.18 \pm 0.14 \pm 0.06$
$\mathrm{Im}(\eta_{000}) = 0.15 \pm 0.20 \pm 0.03$)



If $\mathrm{Re}(\eta_{000}) = \mathrm{Re}(\epsilon)$ (CPT):

$$\mathrm{Im}(\eta_{000}) = -0.012 \pm 0.007_{\mathrm{stat}} \pm 0.011_{\mathrm{sys}}$$

Branching fraction: *(preliminary)*

$$\mathrm{Br}(K_S \to 3\pi^0) < 1.4 \times 10^{-6} \quad 90\%\ \mathrm{CL}$$

With $\mathrm{Re}(\eta_{000}) = \mathrm{Re}(\eta_\epsilon)$ (CPT):

$$\mathrm{Br}(K_S \to 3\pi^0) < 3.0 \times 10^{-7} \quad 90\%\ \mathrm{CL}$$

(SND: $\mathrm{Br}(K_S \to 3\pi^0) < 1.4 \times 10^{-5}$)

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NA48: CPT test from $K_S \rightarrow \pi^0\pi^0\pi^0$

CPT TEST RESULTS

- **Bell-Steinberger relation:**

Connects CPT violating phase δ with η parameters via unitarity:

$$(1 + i \tan\phi_{SW})[\mathrm{Re}(\epsilon) - i\,\mathrm{Im}(\delta)] = \sum_{\text{final states } f} \alpha_f \qquad (\phi_{SW} = \arctan \frac{2\,\Delta m}{\Gamma_L - \Gamma_S})$$

- Largest contributions:

α_f		$10^3 \times \mathrm{Re}(\alpha_f)$	$10^3 \times \mathrm{Im}(\alpha_f)$
α_{+-}	$= \eta_{+-}\,\mathrm{Br}(K_S \to \pi^+\pi^-)$	1.139 ± 0.017	1.078 ± 0.017
α_{00}	$= \eta_{00}\,\mathrm{Br}(K_S \to \pi^0\pi^0)$	0.520 ± 0.010	0.488 ± 0.010
$\alpha_{+-\gamma}$	$= \eta_{+-\gamma}\,\mathrm{Br}(K_L \to \pi^+\pi^-\gamma)$	0.004 ± 0.000	0.004 ± 0.000
α_{l3}		0.004 ± 0.000	0.003 ± 0.005
α_{+-0}	$= \frac{\tau_S}{\tau_L}\,\eta^{\star}_{+-0}\,\mathrm{Br}(K_L \to \pi^+\pi^-\pi^0)$	0.000 ± 0.002	0.000 ± 0.002
α_{000}	$= \frac{\tau_S}{\tau_L}\,\eta^{\star}_{000}\,\mathrm{Br}(K_L \to 3\,\pi^0)$	0.029 ± 0.040	-0.026 ± 0.058

- **NA48:** $\alpha_{000} = (\,-0.009 \pm 0.004\,) + i\,(0.012 \pm 0.005\,) \times 10^{-3}$

$\Longrightarrow \mathrm{Im}(\delta) = (-1.2 \pm 3.0) \times 10^{-5}$ (was $(2.4 \pm 5.0) \times 10^{-5}$)

$\Longrightarrow m_{K^0} - m_{\overline{K^0}} = (-1.7 \pm 4.2) \times 10^{-19}$ GeV

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T Violation Measurement

Kabir Test:
first direct measurement of time reversal non-invariance

$$A_T = \frac{\Gamma(\bar{K}^0 \to K^0) - \Gamma(K^0 \to \bar{K}^0)}{\Gamma(\bar{K}^0 \to K^0) + \Gamma(K^0 \to \bar{K}^0)}$$

A.Ceccucci WIN02

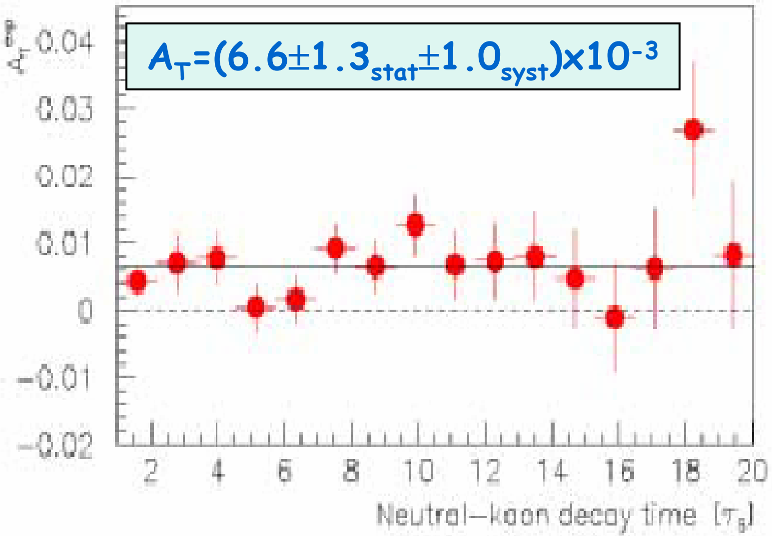
CERN-CPLEAR: tagged strangeness at t=0

$$p\bar{p} \to \pi^+ K^- K^0$$

$$p\bar{p} \to \pi^- K^+ \bar{K}^0$$

K^0-$\bar{K}^0$ s-tag with $K^\pm$ charge

Assuming CPT conservation in semi-leptonic decays:



$$A_T(\tau) = \frac{\Gamma(\bar{K}^0_{t=0} \to \pi^- e^+ \nu_{t=\tau}) - \Gamma(K^0_{t=0} \to \pi^+ e^- \bar{\nu}_{t=\tau})}{\Gamma(\bar{K}^0_{t=0} \to \pi^- e^+ \nu_{t=\tau}) + \Gamma(K^0_{t=0} \to \pi^+ e^- \bar{\nu}_{t=\tau})}$$

$$= 4\mathrm{Re}\,\varepsilon + \frac{2\,\mathrm{Im}\,x_+ \sin(\Delta m \tau)}{\cosh(\frac{1}{2}\Delta\Gamma\tau) - \cos(\Delta m \tau)}$$

$$\mathrm{Im}\,x_+ = T - \text{violation} \quad \Delta S \neq \Delta Q$$

$$4\mathrm{Re}\,\varepsilon = 6.2 \pm 1.4_{sta} \pm 1.0_{sys} \times 10^{-3}$$

$$\mathrm{Im}\,x_+ = 1.2 \pm 1.9_{sta} \pm 0.9_{sys} \times 10^{-3}$$

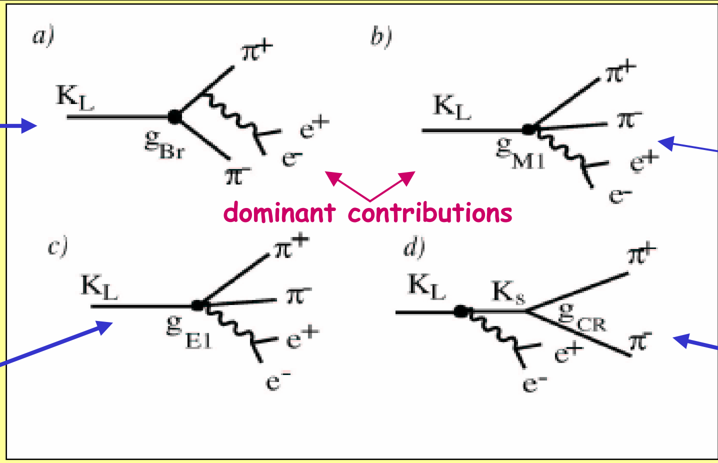
cfr. review of T and CPT tests with semileptonic K decays in CPLEAR in Eur. Phys. J. C22 (2001)

T Violation in $K_L \to \pi^+\pi^- e^+e^-$

$K_L \to \pi^+\pi^- e^+e^-$ process: matrix elements from Heiliger, Sehgal (1993)

Inner Bremsstrahlung
CP Violating (g_{Br})

E1 Direct Photon Emission
CP Violating (g_{E1})
(both direct and indirect CPV: indirect contribution dominant)



M1 Direct Photon Emission
CP Conserving (g_{M1})

$$F = \tilde{g}_{M1}\left[1 + \frac{a_1/a_2}{(M_\rho^2 - M_K^2) + 2M_K(E_{e^+} + E_{e^-})}\right]$$

K^0 charge radius
CP Conserving (g_{CR})

✓The interference between IB and M1 DE leads to an observable CP-violating polarization of γ^* →

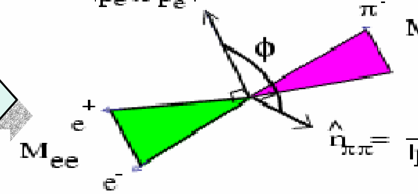
$$d\Gamma/d\varphi = \Gamma_1 \cos^2\varphi + \Gamma_2 \sin^2\varphi + \Gamma_3 \sin\varphi\cos\varphi$$

Expected: $|A(\varphi)| \approx 14\%$

CP-violation asymmetry:

$$A_\varphi = \frac{N_{\sin\varphi\cos\varphi>0} - N_{\sin\varphi\cos\varphi<0}}{N_{\sin\varphi\cos\varphi>0} + N_{\sin\varphi\cos\varphi<0}}$$

T-odd observable:
function of the angle φ between $\pi^+\pi^-$ and e^+e^- planes in K_L C.M.



$$\hat{n}_{ee} = \frac{\vec{p}_{e^+} \times \vec{p}_{e^-}}{|\vec{p}_{e^+} \times \vec{p}_{e^-}|} \qquad \hat{n}_{\pi\pi} = \frac{\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}}{|\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}|}$$

$$\hat{z} = \frac{\vec{p}_{\pi^+} + \vec{p}_{\pi^-}}{|\vec{p}_{\pi^+} + \vec{p}_{\pi^-}|}$$

$$\sin\phi\cos\phi = (\hat{n}_{ee} \times \hat{n}_{\pi\pi}) \cdot \hat{z}(\hat{n}_{ee} \cdot \hat{n}_{\pi\pi})$$

$K_L \rightarrow \pi^+\pi^-e^+e^-$ experimental results

Measurements in KTeV

(Phys.Rev.Lett 84, 408 (2000), 1st evidence)

and NA48

$K_L \rightarrow \pi^+\pi^-e^+e^-$ in NA48:

Data sample: 1998-99 data

Signature: 4 tracks

K_L events: 1162

Background: $(3.2 \pm 0.5)\%$

Normalized to $K_L \rightarrow \pi^+\pi^-\pi^0_{Dalitz}$

Couplings measurement (NA48)

- ✓ Couplings are extracted by max likelihood fitting of data to MC

$$a_1/a_2 = \left(-0.81^{+0.07}_{-0.13\,stat} \pm 0.02_{syst}\right) GeV^2$$

$$\tilde{g}_{M1} = 0.99^{+0.28}_{-0.27\,stat} \pm 0.07_{syst}$$

$$g_{CR} = 0.19 \pm 0.04_{stat} \pm 0.02_{syst}$$

- ✓ In agreement with KTeV results

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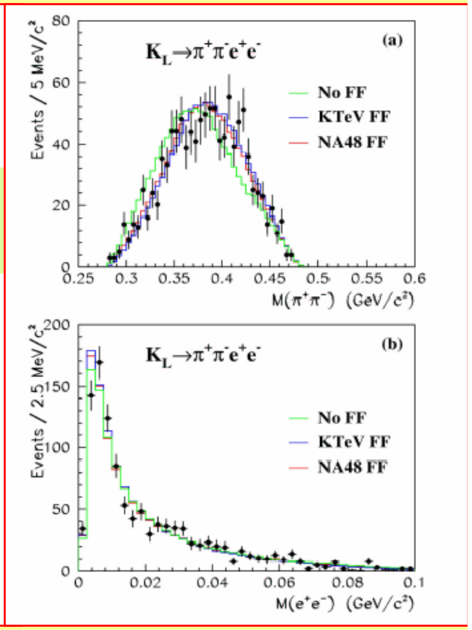


Branching Ratio measurement

NA48

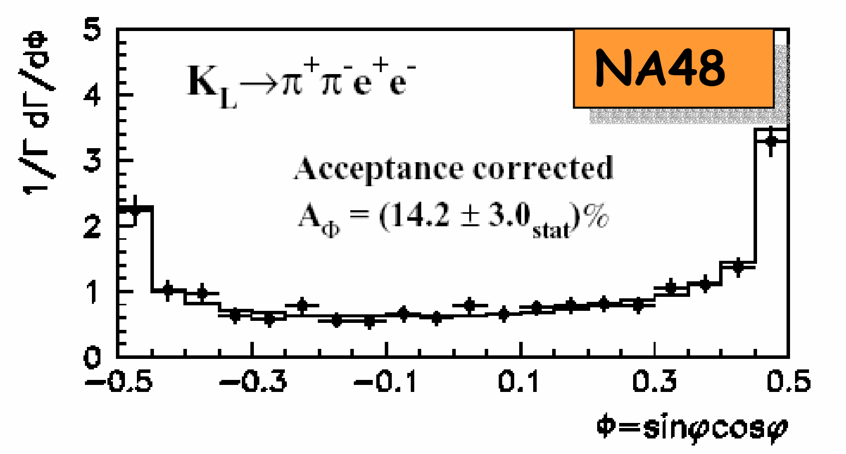
$BR = (3.08 \pm 0.09_{stat} \pm 0.15_{syst} \pm 0.10_{norm}) \times 10^{-7}$

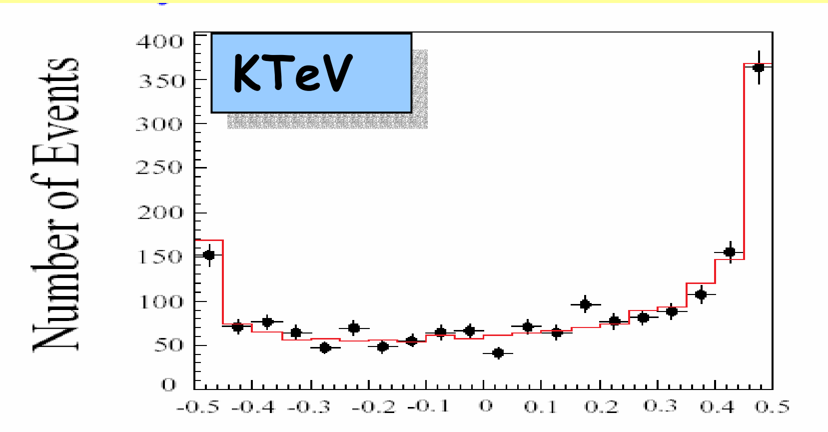
KTeV

$BR = (3.63 \pm 0.11_{stat} \pm 0.14_{syst}) \times 10^{-7}$

$K_L \to \pi^+\pi^-e^+e^-$ -experimental results - II

$K_L \to \pi^+\pi^-e^+e^-$ analysis results: Asymmetry measurement





$A(\varphi) = (14.2 \pm 3.0_{stat} \pm 1.9_{syst})\%$

$A(\varphi) = (13.6 \pm 2.5_{stat} \pm 1.2_{syst})\%$

Experimental data in agreement with theory predictions:
clear signature of indirect CPV effects, T-odd effect
due entirely to mixing, no evidence of direct CPV

CP Violation in semileptonic K decays

Motivations: check semileptonic K^0 Asymmetries in Standard Model

$$\langle e^+\pi^-\nu \mid H_{WK} \mid K^0\rangle = a + b$$
$$\langle e^-\pi^+\bar{\nu} \mid H_{WK} \mid \bar{K}^0\rangle = a^* - b^*$$
$$\langle e^-\pi^+\bar{\nu} \mid H_{WK} \mid K^0\rangle = c + d$$
$$\langle e^+\pi^-\nu \mid H_{WK} \mid \bar{K}^0\rangle = c^* - d^*$$

T	$Im\ a = Im\ b = Im\ c = Im\ d = 0$
CP	$Im\ a = Re\ b = Im\ c = Re\ d = 0$
CPT	$b = d = 0$
$\Delta S{=}\Delta Q$	$c = d = 0$

$$A_{S,L} = \frac{\Gamma^+_{S,L} - \Gamma^-_{S,L}}{\Gamma^+_{S,L} + \Gamma^-_{S,L}}$$

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

~~CP~~ | ~~CPT~~ in mixing | ~~CPT~~ in decay | $\Delta S \neq \Delta Q$ and ~~CPT~~

$A_S - A_L \neq 0$ implies ~~CPT~~

$$\frac{\Gamma_S^{semi}}{\Gamma_L^{semi}} = 1 + 4\Re(x_+) \approx 1 + 4\Re(c^*/a)$$

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Present situation:

- A_L: recent measurements (K_{e3}): NA48 (new result) and KTeV
- A_S: never measured before (now→ KLOE)

CP Violation in K^0_{e3} decays

- Charge asymmetry in K^0_{l3} decays due to K^0-$\bar{K}^0$ mixing (CPV)
- If CPT conserved and $\Delta S=\Delta Q$:

$$\delta_L = \frac{\Gamma(K_L \to e^+\pi^-\nu) - \Gamma(K_L \to e^-\pi^+\bar{\nu})}{\Gamma(K_L \to e^+\pi^-\nu) + \Gamma(K_L \to e^-\pi^+\bar{\nu})} = 2\,\mathrm{Re}\,\varepsilon$$

- Results in NA48 and KTeV
- K_{e3} analysis in NA48:

Data sample: 2001 data

Selection: E(LKr)/p to distinguish N(π+e-) from N(π-e+)

K_{e3} sample: 2.1×10^8 ($\sim10^8$ per mode)

Statistical error: 7×10^{-5}

Systematics: asymmetry of particle interactions (correction for trigger inefficiency and π identification)

Measurement Results

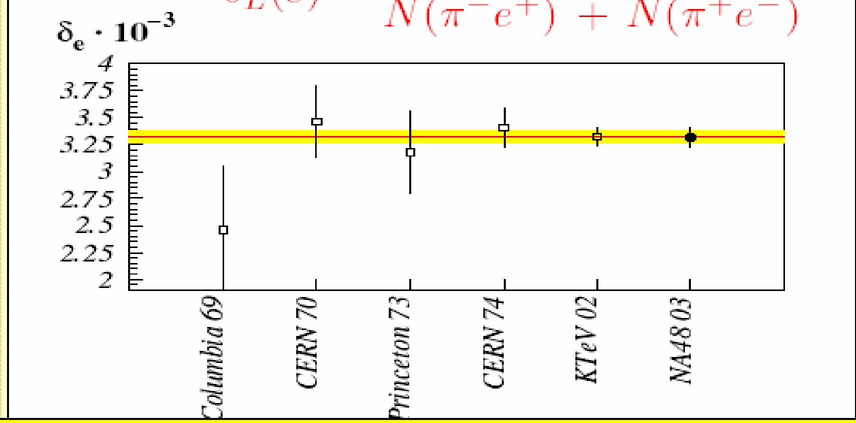
NA48: (new result, preliminary)

$(3.319 \pm 0.070_{stat} \pm 0.068_{syst})\times10^{-3}$

KTeV: (Phys. Rev. Lett 88, 181601 (2002))

$(3.322 \pm 0.058_{stat} \pm 0.047_{syst})\times10^{-3}$

$$\delta_L(e) = \frac{N(\pi^-e^+) - N(\pi^+e^-)}{N(\pi^-e^+) + N(\pi^+e^-)}$$

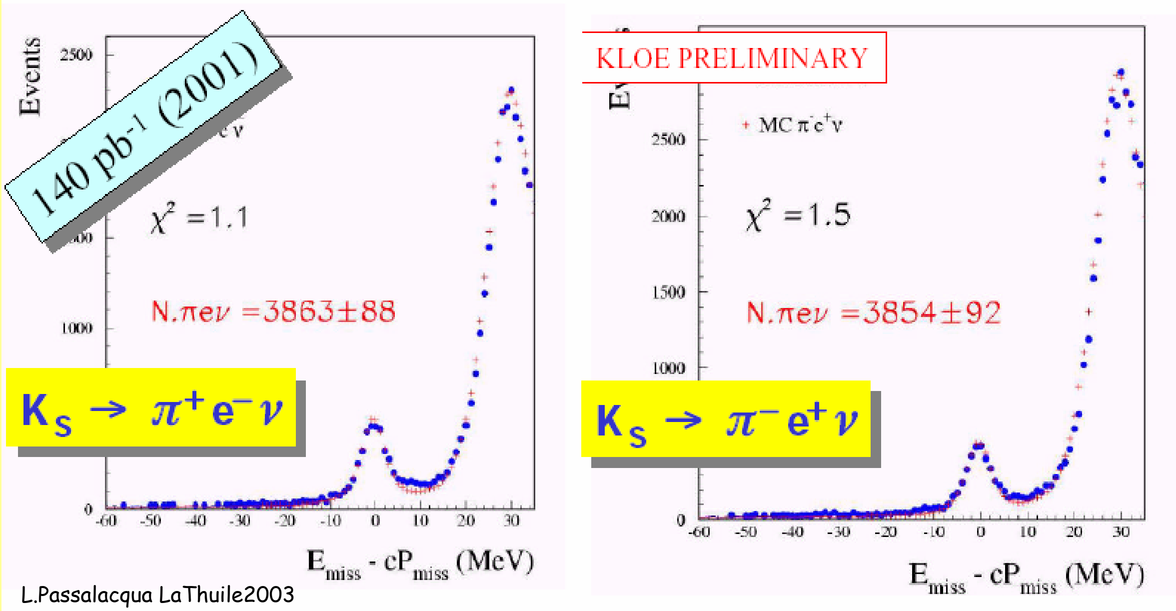


World average: $\delta_e = (3.323 \pm 0.055)\times10^{-3}$

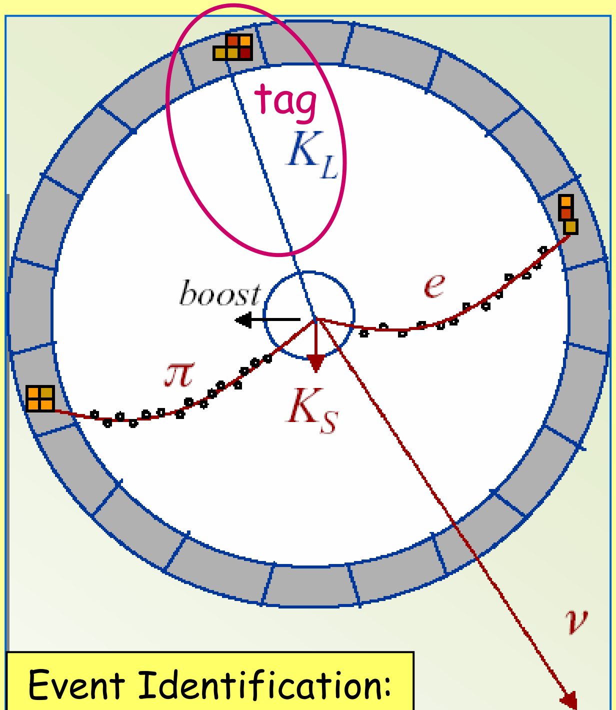
KLOE: Semileptonic K_S decays

KLOE: first results on Semileptonic K_S decays

$K_S \rightarrow \pi^+ e^- \nu \, / \, \pi^- e^+ \nu$



Semileptonic K_S decays data samples



Event Identification:

- Events tagged by a 'K_{crash}' cluster
- 2 tracks and 1 vertex close to the IP
- Reject events with invariant mass $M_{\pi\pi}$ close to the K^0 mass
- Use time information from calorimeter clusters to perform PID for charged tracks

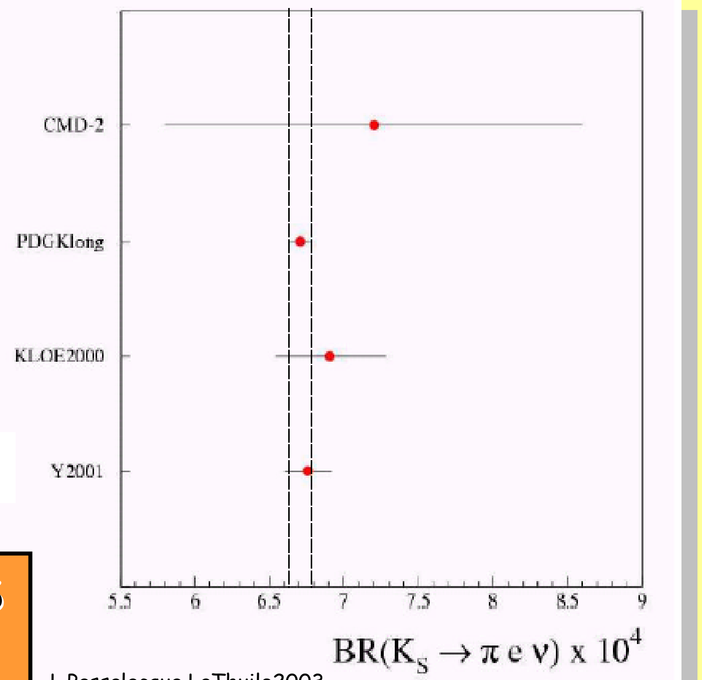
KLOE: Semileptonic K_S decays - II

K_S BRANCHING RATIO PRELIMINARY RESULTS

$$BR(\pi^- e^+ \nu) = (3.44 \pm 0.09_{stat} \pm 0.06_{syst})\ 10^{-4}$$
$$BR(\pi^- e^+ \nu) = (3.31 \pm 0.08_{stat} \pm 0.05_{syst})\ 10^{-4}$$
$$BR(\pi^\pm e^\mp \nu) = (6.76 \pm 0.12_{stat} \pm 0.10_{syst})\ 10^{-4}$$

KLOE PRELIMINARY

PDG2002: BR(πeν)=(7.2±1.4)x10^{-4} (CMD-2@VEPP-2M, 1999)



L.Passalacqua LaThuile2003

ASYMMETRIES PRELIMINARY RESULTS and comparisons

KLOE PRELIMINARY

kTEV $A(K_L)=(3332\pm58\pm47)\ 10^{-6}$

KLOE $A(K_S)=(1.9\pm1.7\pm0.6)\ 10^{-2}$

CPLEAR $\Re(x_+)=(-1.8\pm4.1\pm4.5)10^{-3}$

KLOE $\Re(x_+)=(+2.2\pm5.3\pm3.5)10^{-3}$

FIRST EVER DONE MEASUREMENT

ΔS=ΔQ TEST

KLOE: Prospects in Charged Kaons

Tagging via $K^{\pm}\to\pi^{\pm}\pi^{0}$ and $K^{\pm}\to\mu^{\pm}\nu$ ID in DCH (BR~85%): 6×10^{5} tag/pb^{-1}

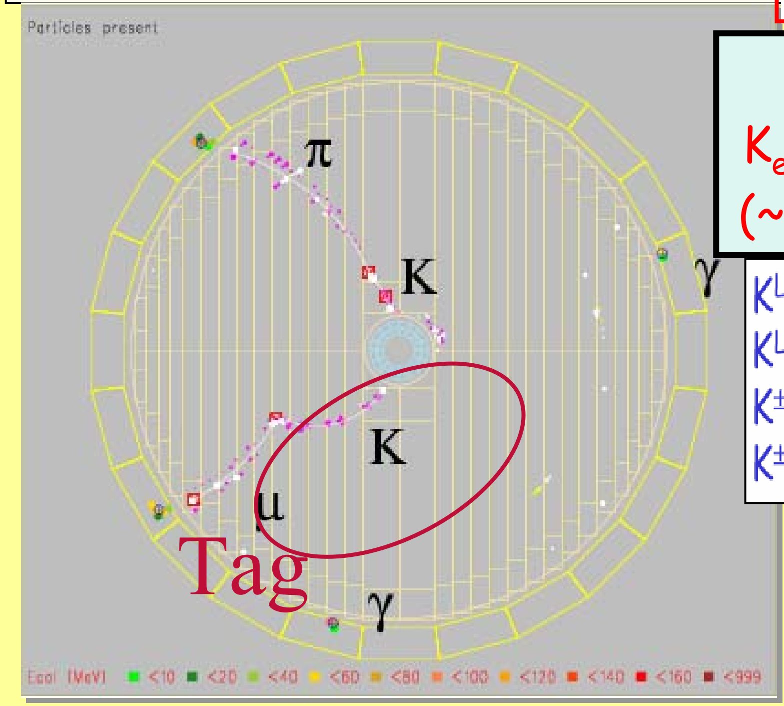
(data reprocessing under way
to improve reconstruction)

V_{us} measurement expectations:

$$\frac{\Delta|V_{us}|}{|V_{us}|}=0.5\left(\frac{\Delta BR_{K_{e3}}}{BR_{K_{e3}}}+\frac{\Delta\tau}{\tau}\right)+0.05\frac{\Delta\lambda_{+}}{\lambda_{+}}+\frac{\Delta f_{+}(0)}{f_{+}(0)}$$

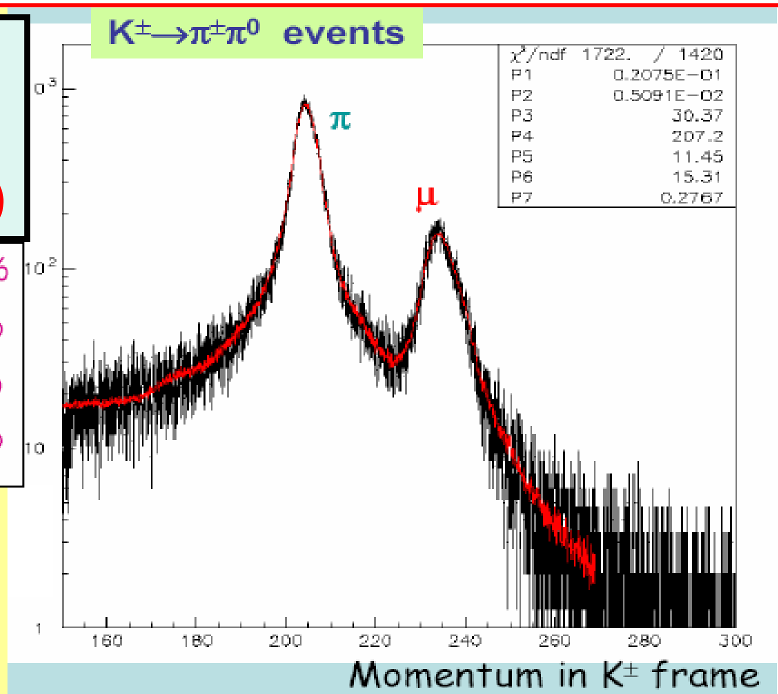
$K^{\pm}_{e3}$	0.59%	0.22%	0.86%

BRs essentially from [Chiang et al., '72].,



KLOE K_{e3} samples (~ 400 pb^{-1})

- K^{L}_{e3} : 2.8×10^{6}
- $K^{L}_{\mu3}$: 1.9×10^{6}
- $K^{\pm}_{e3}$: 1.8×10^{6}
- $K^{\pm}_{\mu3}$: 1.2×10^{6}



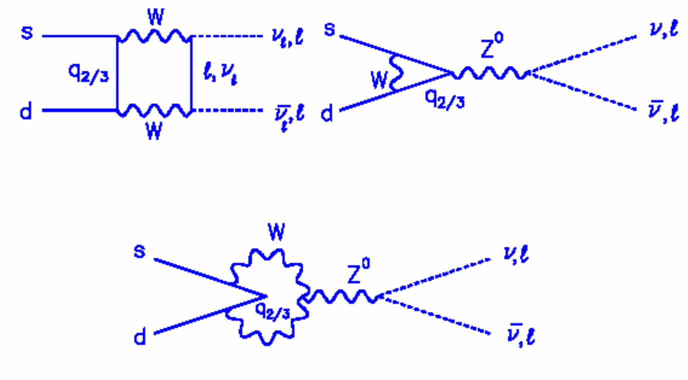
Prospects in Kaon physics

- Quantitative tests of CKM mechanism are possible with rare Kaon decay mesurements
- High level of precision is attainable
- Constraints to CKM variables and further test of CPV from FCNC processes:
  - $K_L \rightarrow \pi^0 e^+ e^-$ decays
  - $K \rightarrow \pi\nu\nu$ decays

$K_L \rightarrow \pi l \bar{l}$ decays

$K_L \rightarrow \pi l \bar{l}$:

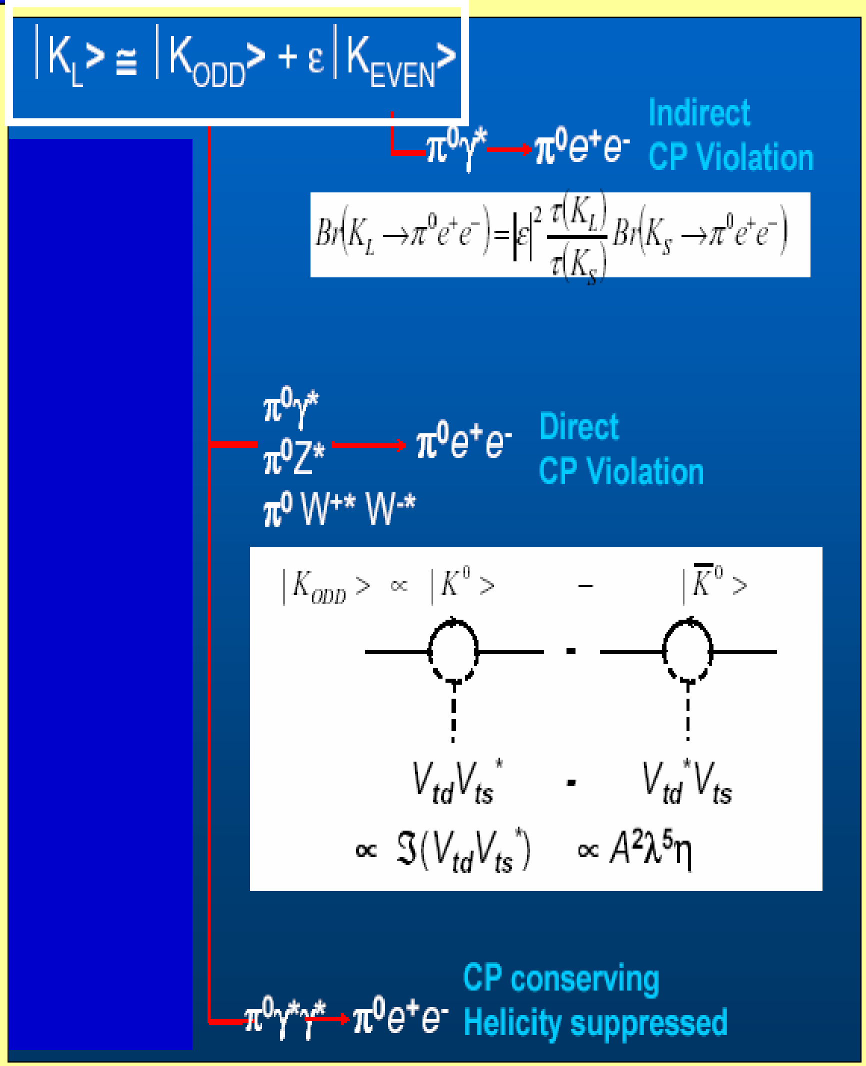
- FCNC processes, no tree level, proceed via loop diagrams
- access to quark level physics with small theoretical uncertanties:
  - dominant short distance contributions
  - long distance only for charged lepton modes
  - matrix elements of quark operators related to K_{e3} decays
  - CPV K_L decays
- charged leptons final states easier to measure but high levels of radiative background
- Best change: $K \rightarrow \pi \nu \bar{\nu}$ decays:
  - no long distance contributions
  - clean theoretical predictions
  - no radiative background
  - K_L decay dominated by direct CPV



$K_L \rightarrow \pi e^+ e^-$ decays

$K_L \rightarrow \pi^0 e^+ e^-$

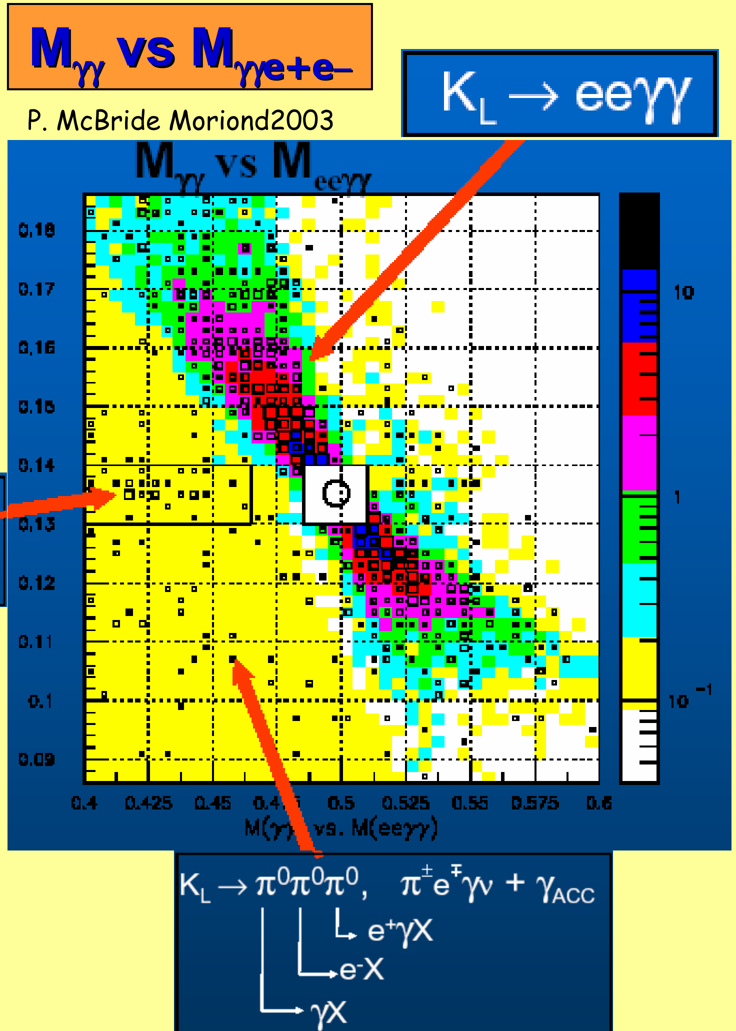
- SM prediction: BR = 3-10 x 10^{-12}
- 3 components contribute to the decay:
  - Large direct CPV component through electroweak penguins and W boxes with top quark
  - Indirect CPV component, due to the decay of K_1 component in the K_L : study of $K_S \rightarrow \pi^0 e^+ e^-$
  - 2γ CP conserving long range contribution proceedings through $\pi^0 \gamma^* \gamma^*$ states: study of $K_L \rightarrow \pi^0 \gamma\gamma$
- Prohibitive physical background from $\gamma\gamma e^+ e^-$ ("Greenlee", BR ≈ 6×10^{-7})



KTeV: search for $K_L \to \pi^0 e^+ e^-$

KTeV: measurement of upper limit in BR

- Published result: 1997 data
- New measurement: 1999 data
- $K_L \to \gamma\gamma e^+ e^-$ (main) background reduction → kinematic cuts on foton direction and angles
- Other background: $\pi^0\pi^0\pi^0_{Dalitz}$
- Normalization to $K_L \to \pi^0\pi^0_{Dalitz}$
- Signal and control regions in $M_{\gamma\gamma}(=M_{\pi 0})$ vs $M_{\gamma\gamma e+e-}$ $(=M_K)$

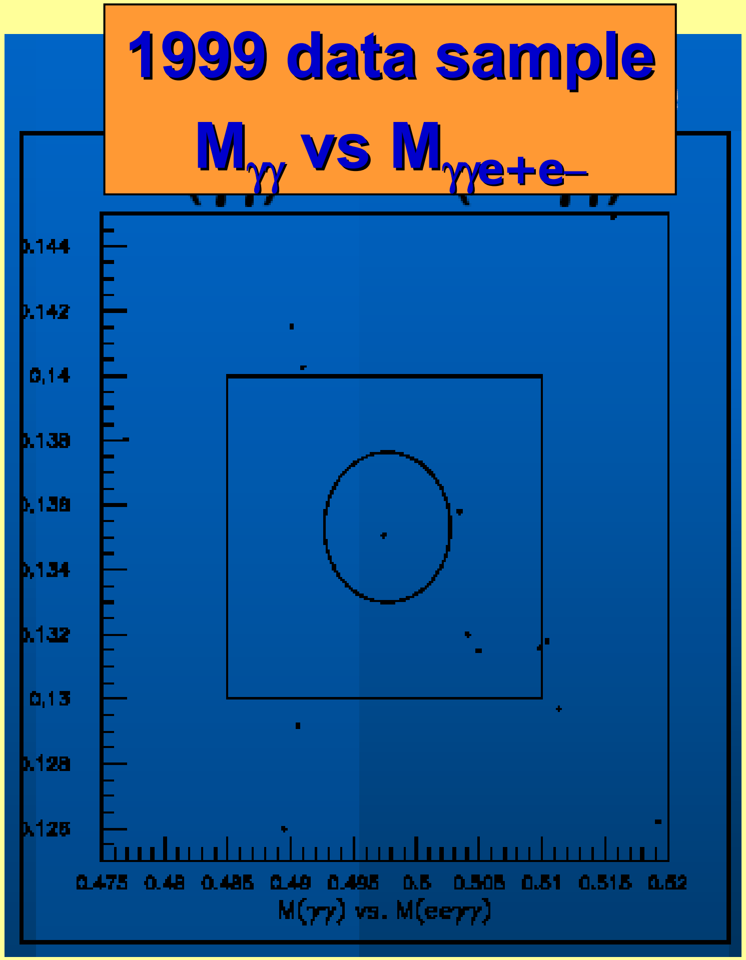


KTeV: $K_L \to \pi^0 e^+ e^-$ experimental results

- **1997 data:** 2 events observed, with background = 1.06±0.41 : (90% CL)
  $BR(K_L \to \pi^0 e^+ e^-) < 5.1 \times 10^{-10}$

- **New result (preliminary) from 1999 data:** 1 event observed, with background= 0.99 ± 0.35 : (90% CL)
  $BR(K_L \to \pi^0 e^+ e^-) < 3.5 \times 10^{-10}$

- **Combined result from whole data sample (preliminary):**
  $BR(K_L \to \pi^0 e^+ e^-) < 2.8 \times 10^{-10}$



Prospects for $K_L \to \pi^0 e^+ e^-$

- Huge Greenlee background
- Difficult to disentangle contributions:
  - CPV components contribution (interference):

$$B.R.\left(K_L^0 \to \pi^0 e^+ e^-\right)_{CPV} \approx 10^{-12}\left[15.3 a_S^2 - 6.8 a_S \frac{\Im\left(V_{ts}^* V_{td}\right)}{10^{-4}} + 2.8\left(\frac{\Im\left(V_{ts}^* V_{td}\right)}{10^{-4}}\right)^2\right] \approx 7\times 10^{-12} + ??$$

  - $K_S \to \pi^0 e^+ e^-$: needed better BR measurement (if $a_S \approx \pm 0.5$ then indirect/direct ~ 1)

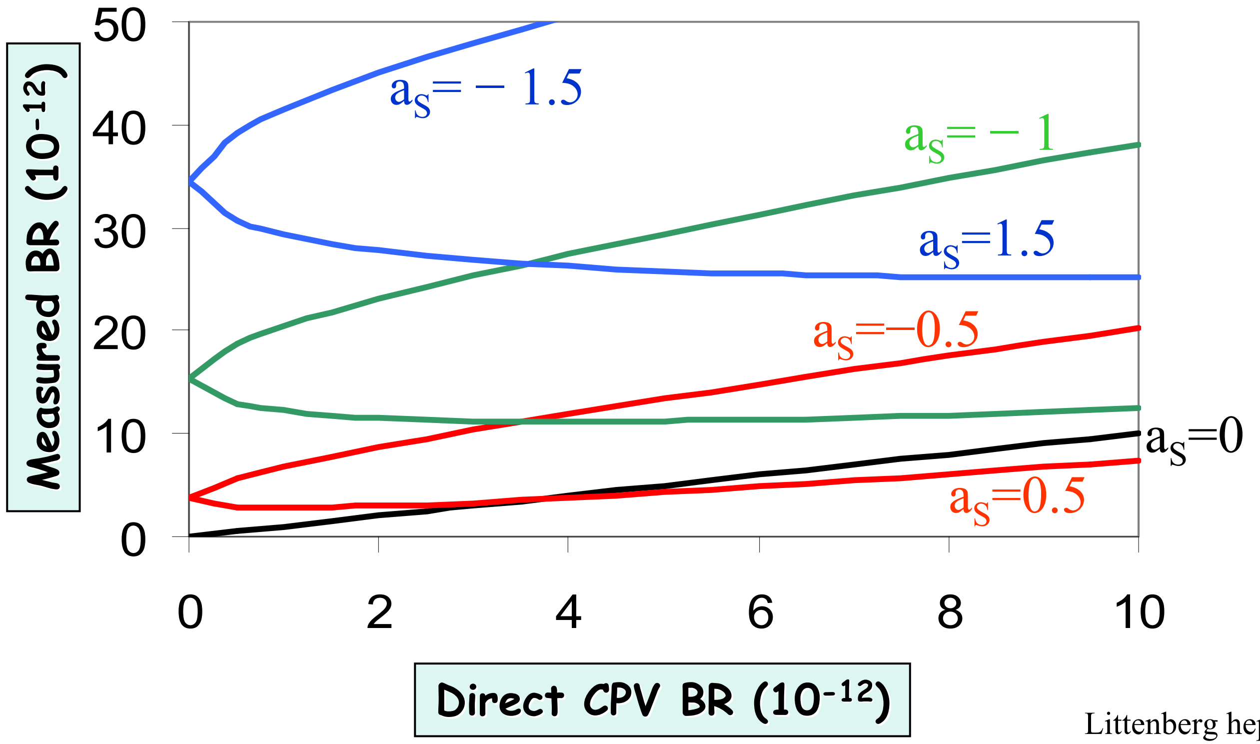
$$B.R.\left(K_S^0 \to \pi^0 e^+ e^-\right)_{CPV} \approx 5.2 a_S^2 \times 10^{-9}$$

NA48 limit: (90% CL)
$BR(K_S \to \pi^0 e^+ e^-) < 1.4 \times 10^{-7}$

  - CP conserving
    - NA48 $K_L \to \pi^0 \gamma\gamma$ data gives $BR_{CPC} < 10^{-12}$

Prospects for $K_L \to \pi^0 e^+ e^-$ - II

$K_L \to \pi^0 e^+ e^-$: direct vs indirect CPV contributions



Littenberg hep-ex/0212005

CPC contribution to $K_L \to \pi^0 e^+ e^-$

- The CP Conserving contribution to $K_L \to \pi^0 e^+ e^-$ proceed through $K_L \to \pi^0 \gamma^* \gamma^*$ intermediate states and can be derived from the measurement of $K_L \to \pi^0 \gamma\gamma$ decay rate and $m_{\gamma\gamma}$ distribution
  - important to know BR($K_L \to \pi^0 \gamma\gamma$) and the angular momentum state J of the 2 photons
  - predictions from χPT (effective theory of SM at low energy in the hadronic sector) can be parametrized as:

$$\frac{d^2\Gamma}{dydz} \propto z^2 |A+B|^2 + \left(y^2 - y_{\max}^2\right)^2 B \text{ con } z = \left(\frac{m_{\gamma\gamma}}{m_K}\right)^2, y = \frac{\left|p_K\left(k_{\gamma 1} - k_{\gamma 2}\right)\right|}{m_k^2}$$

where amplitudes A and B refers, respectively, to the photon angular states J=0 J=2, and B is sensitive to the low mass $m_{\gamma\gamma}$ region and to the CPC component of $K_L \to \pi^0 e^+ e^-$

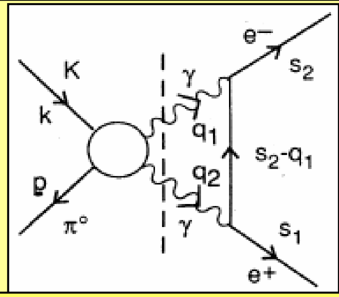
  - J=O gives no contributions to $\pi^0 e^+ e^-$ (helicity conservation)

$K_L \rightarrow \pi^0\gamma\gamma$: experimental results

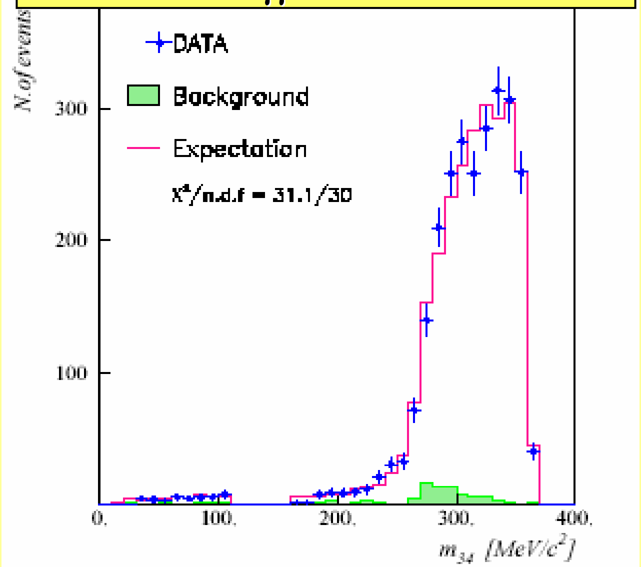
- **Measurements in KTeV and NA48**
  - NA48 find small B (J=2) contribution to CPC in $K_L \rightarrow \pi^0 e^+e^-$
  - KTEV data in disagreement with NA48: predict bigger contributions to CPC in $K_L \rightarrow \pi^0 e^+e^-$
- The contribution to $\pi^0 e^+e$ depends on fit function to $m_{\gamma\gamma}$ distribution

NA48	Fit $m_{\gamma\gamma}$ distribution :VMD	$0.47^{+0.22}_{-0.17} \times 10^{-12}$
Gabbiani-Valencia	Fit distribution and rate: VMD	$13.8^{+0.09}_{-0.21} \times 10^{-12}$
Gabbiani-Valencia	Fit distribution and rate:3 parameters à la $O(p^6)$ χPT	$0.46^{+0.22}_{-0.17} \times 10^{-12}$

$K_L \rightarrow \pi^0 \gamma^*\gamma^* \rightarrow \pi^0 e^+e^-$



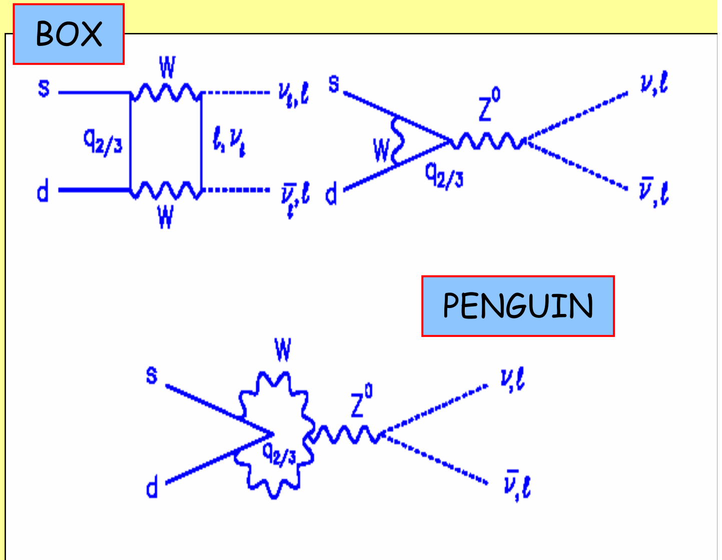
NA48: $m_{\gamma\gamma}$ distribution



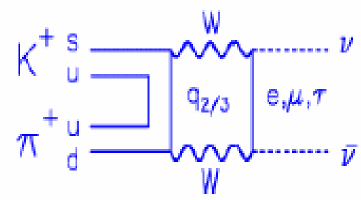
$K \rightarrow \pi\nu\bar{\nu}$ decays

$K \rightarrow \pi\nu\bar{\nu}$:

- FCNC processes sensitive to physics at the scale of m_W, m_Z and m_T
- leading loop diagrams
- unique "theoretical cleanliness"
  - ❖no long range contribution
  - ❖matrix elements of quark operators related to K_{e3} decays
  - ❖K_L decay dominated by direct CP
- direct sensitivity to V_{td} and BSM physics
- **K_L decay:** direct CPV, negligible hadronic uncertainties (top quark dominant)
- **K^+ decay:** CP conserved, hadronic contributions from top and charm quarks



Dressing up into hadrons:



$K \to \pi\nu\bar{\nu}$ in the SM

CKM structure of $K \to \pi\nu\bar{\nu}$ processes

K_L: direct CPV

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

K^+: CP conserving

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

Known to ~ 2% precision

Small additional uncertainty from m_c

Theoretically clean extraction of $\lambda_t = V^*_{ts} V_{td}$

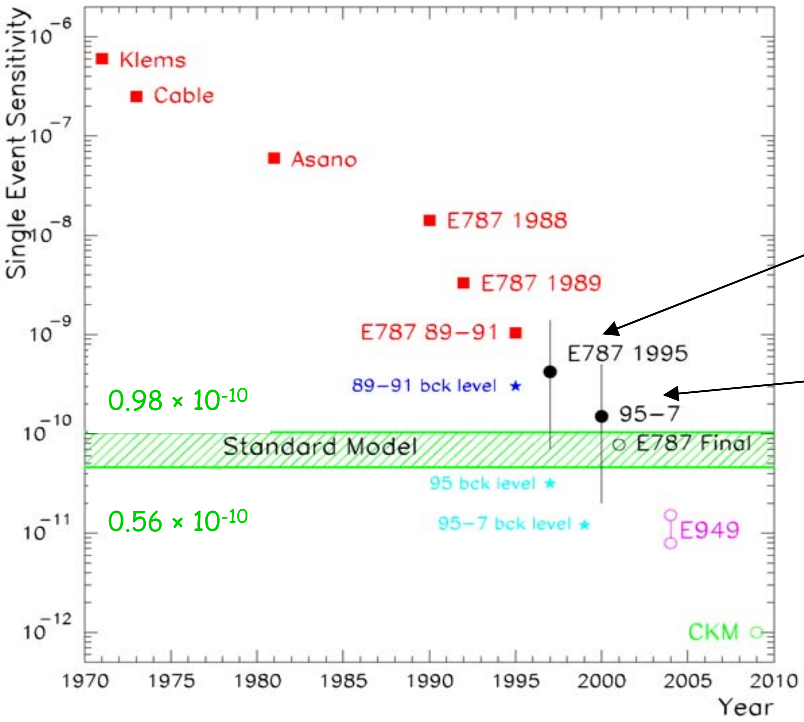
Constraints on η, ρ

- Huge experimental challenge
  - BR ~ 10^{-10} - 10^{-11}, kinematics underconstrained (ν)
  - background from channels with much larger decay rates

The $K^+ \to \pi^+ \nu \bar{\nu}$ experimental program

- **BNL E787** completed, analyzed 5.9×10^{12} stopped K^+: 2 candidates, measured background 0.15 ± 0.05 events
    - **$BR = (1.57^{+1.75}_{-0.82}) \times 10^{-10}$**
- **BNL E949** running (upgrade of E787):
    - expected 40×10^{12} stopped K^+ corresponding to 5-10 SM events
- **Fermilab CKM** (Charged Kaons at the Main injector) approved in 2001:
    - decay in-flight technique
    - 100 SM events over 10 background
    - will match expected theory uncertainty
    - results before 2010

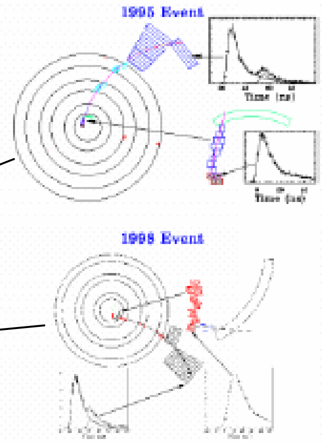
Progress in $K^+ \to \pi^+ \nu\bar{\nu}$

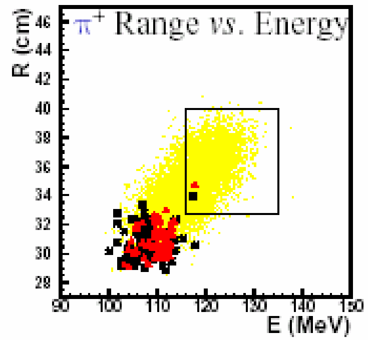


(courtesy of L.Littenberg)

E787 2002:
hep-ex/0111091

Two $K^+ \to \pi^+ \nu\bar{\nu}$ Candidates





Event	P (MeV/c)	R (cm)	E (MeV)	S/N
1995	218.2	34.8	117.8	35
1998	213.8	33.9	117.1	3.6

$N_{K^+} = 5.9 \; x \; 10^{12}$ Efficiency $\varepsilon = 2 \; x \; 10^{-3}$

Estimated Background: 0.15±0.05 events

Branching Ratio

$$B(K^+ \to \pi^+ \nu\bar{\nu}) = 1.57 \pm^{1.75}_{0.82} \; x \; 10^{-10}$$

SM: BR = $(0.72 \pm 0.21) \times 10^{-10}$

Status of $K^+ \to \pi^+ \nu\bar{\nu}$

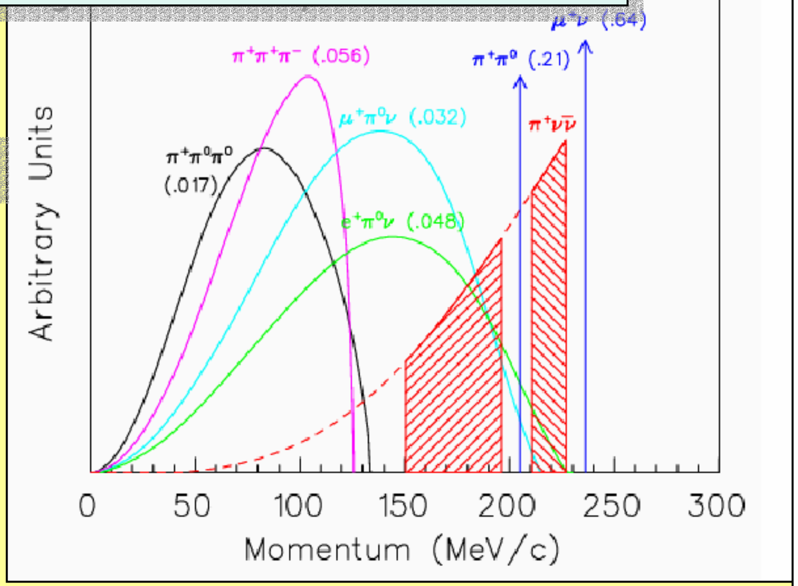
Experimental features:

- 3 body decay (BR~10^{-10}) with 2 missing particles → weakly contrained kinematics
- Huge amount of background: signal at the 10^{-10} level → need background measurement at 10^{-11} level
- Tool for background reduction: kinematic suppression, γ-veto and particle ID

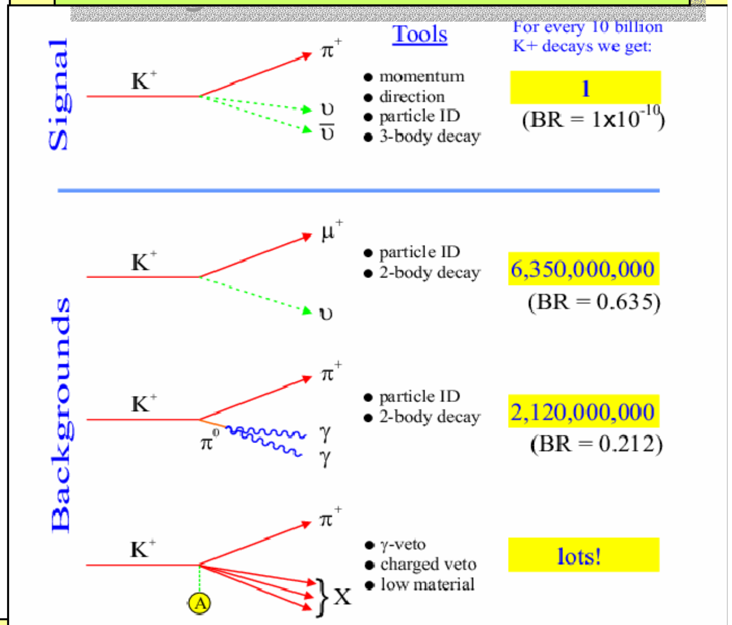
Signal and background kinematics: above 205 MeV/c no π^+ from other significant decay mode than πνν

Background sources

decay mode	BR [%]
$K^+ \to \pi^+\pi^0$	0.21
$K^+ \to \mu^+\nu$	0.63
$K^+ \to \mu^+\nu\gamma$	$5 \cdot 10^{-3}$
$K^+ \to \pi^0\mu^+\nu$	0.032
$K^+ \to \pi^0 e^+\nu$	0.048
$K^+ \to \pi^+\pi^-\pi^+$	0.056



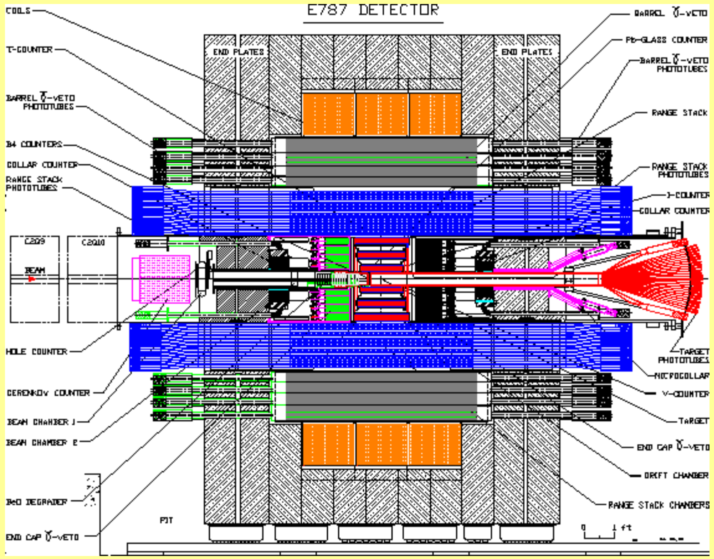
Background reduction tools

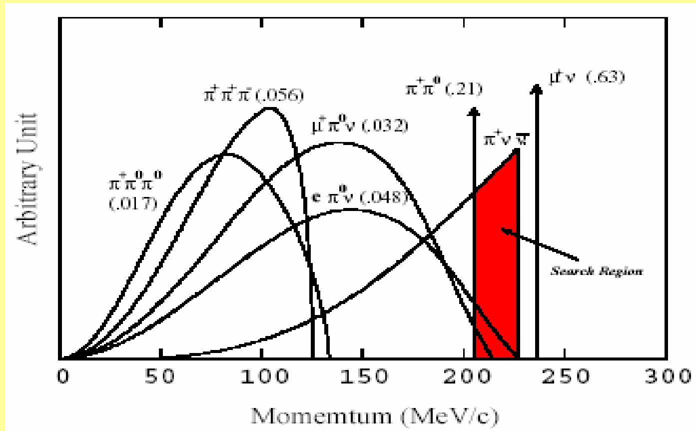


BNL E787 Experiment

Key features:

- stopped K^+ in active degrader and target → access to K^+ center of mass, help vetoing
- hermetic veto coverage
- redundant kinematic information on π^+: comparison of momentum, energy and range to identify low energy particles; π^+ identification through $\pi \to \mu \to e$ decay chain
- misidentification π/μ rate $O(10^{-8})$
- look for π^+ above end point for $K^+ \to \pi^+ \pi^0$: $p_{\pi+} > 205$ MeV/c

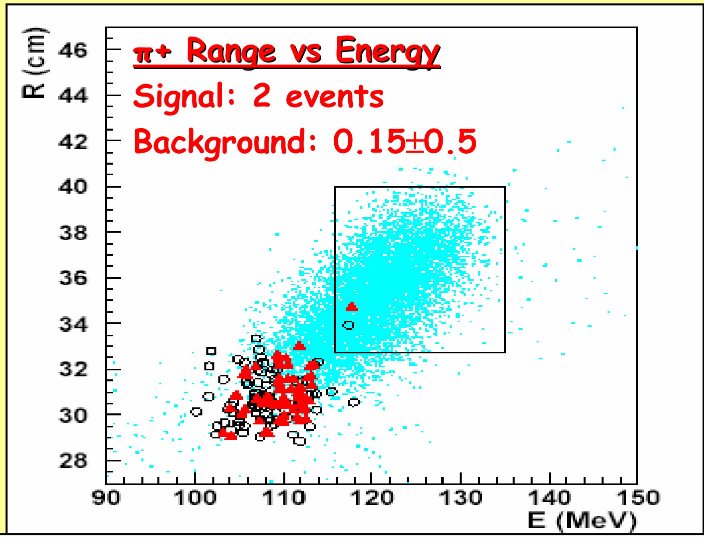




BNL E787 Experiment Results

To establish a signal at the 10^{-10} level, measure background at 10^{-11}

- A priori identification of background sources, directly from data, independent cuts for each source
- Correlations accounted after studies with looser cuts
- Acceptance measurement based mainly on data
- Blind analysis, likelihood method for assessing candidate events
- 5.9×10^{12} K^+ with $\varepsilon = 2 \times 10^{-3}$



Branching Ratio

$$B(K^+ \to \pi^+ \nu \bar{\nu}) = 1.57 \pm^{1.75}_{0.82} \ x\ 10^{-10}$$

Consistent with SM: $(0.72\pm0.21)x10^{-10}$

Estimated probability of being due to background only : 0.02%

Limits on $\lambda_t \equiv V_{ts}^* V_{td}$ (Independent of B system, $\varepsilon_K, \varepsilon'$)

$2.9\ x\ 10^{-4} < |\lambda_t| < 1.2\ x\ 10^{-4}$ (68% C.L.)

$-0.88\ x\ 10^{-3} < Re(\lambda_t) < 1.2\ x\ 10^{-3}$ (68% C.L.)

$Im(\lambda_t) < 1.1\ x\ 10^{-3}$ (90% C.L.)

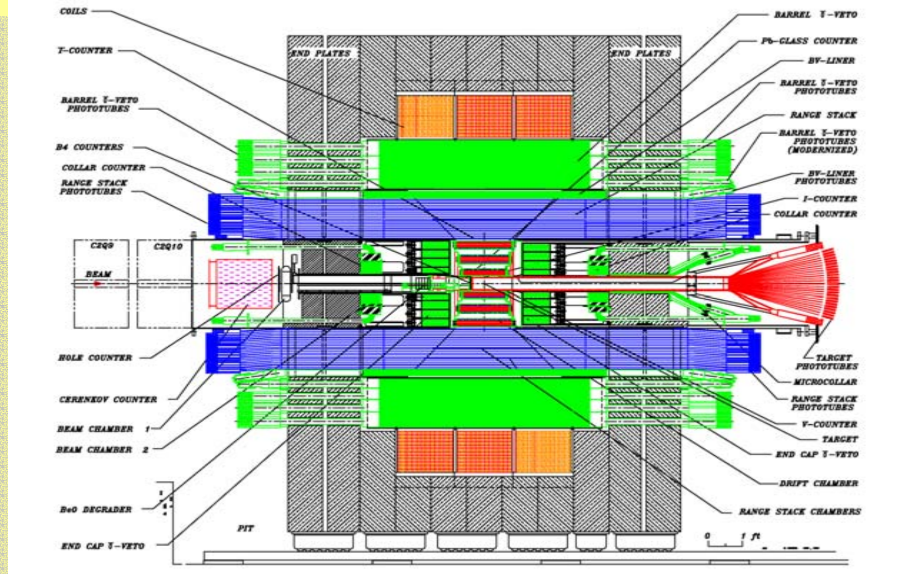
BNL E949 Experiment

E 949: upgrade of E787 experiment

- Run with RHIC, get entire AGS proton production
- improve sensitivity (x 14)
- extend kinematical region in 140 < $p_{\pi+}$ < 190 MeV/c (s/b ~ 1)
- data for 2 additional years
- expect sensitivity ~10^{-11}/evt by 2004 (7 events for SM BR prediction)

Detector improvements:

- veto coverage
- beam instrumentation
- higher DAQ capability
- more efficient trigger counters
- upgraded chamber electronics



Upgrade of BNL AGS 787

Sensitivity improvement with respect to E787 (1995):

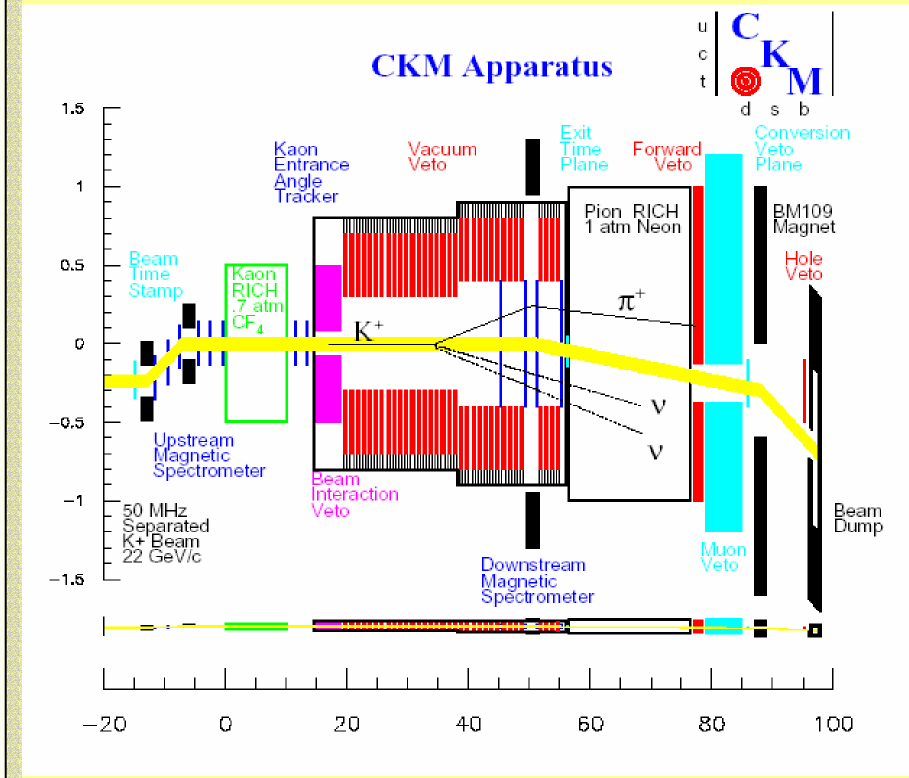
- Increased spill length (×1.56)
- Lower momentum (×1.38)
- Increased efficiency (trigger, DAQ, analysis) (×3.2)
- Acc. below $K\pi2$ + higher rate analysis reopt. (×2)
- Total gain - ×14 per hour of data taking

Expect to reach ~ 10^{-11}/evt by 2004

The CKM Experiment

- First attempt of in-flight measurement of $K^+ \to \pi^+ \nu\nu$
- Superconducting RF separated beam: hadron purity >70% , 33MHz 22GeV/c K^+
- redundant determination of K^+ and π^+ momenta: magnetic spectrometer + RICH
- veto with total inefficiency for π^0 from $\pi^+ \pi^0$ ~10^{-7}
- expects 100 signal with ~10 background events (BR ~10^{-10})
- 5% statistical precision on $|V_{td}|$ determination

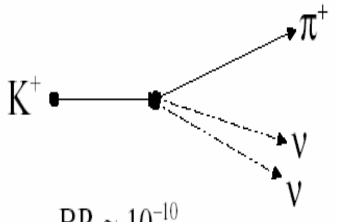
CKM experiment at Fermilab Main Injector



CKM Experiment Requirements

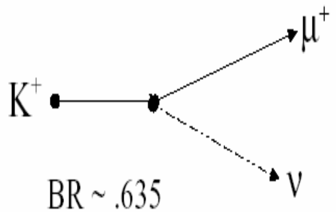
Searching for $K^+ \to \pi^+ \nu\nu$

Signal

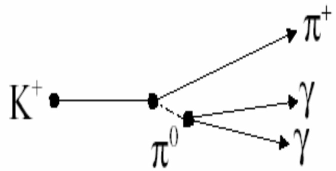


BR ~ 10^{-10}

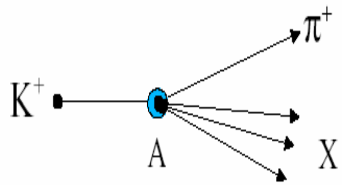
Background



BR ~ .635



BR ~ .212



Requirements for 100 $K^+ \to \pi^+ \nu\nu$ and 10 bkg

- A clean, debunched, 33 Mhz, 22 GeV K^+ beam
- $O(10^5)$ kinematic rejection of the 2−body background
- Robust / redundant particle ID
- Veto system to achieve $O(10^7)$ rejection of the multi−particle background

ICHCBH 2002 H.Nguyen

Number of Kaons Needed

$BR(K^+ \to \pi^+ \nu\nu) \approx 10^{-10}$

Acceptance = $2.86 \bullet 10^{-3}$

3.65×10^{14} K^+ needed for 100 events

Assuming:

- 2 year run
- 39 weeks/year, 120 hr/week, 3600 s/hr
- 1 second long spill every 3 seconds

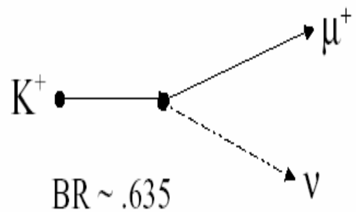
We will have 1.12×10^7 seconds of beam

$\Rightarrow$ 32.5 MHz K^+ beam needed

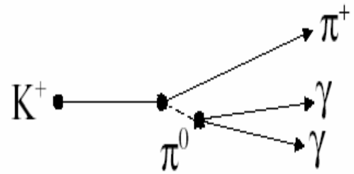
Implications:

– Unbunched and enriched K^+ beam

$O(10^{12})$ Background Rejection Needed



BR ~ .635



BR ~ .212

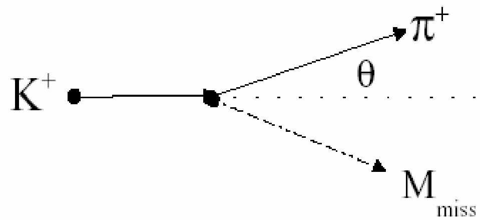
Kinematic Rejection: $O(10^5)$

Veto Rejection: $O(10^7)$

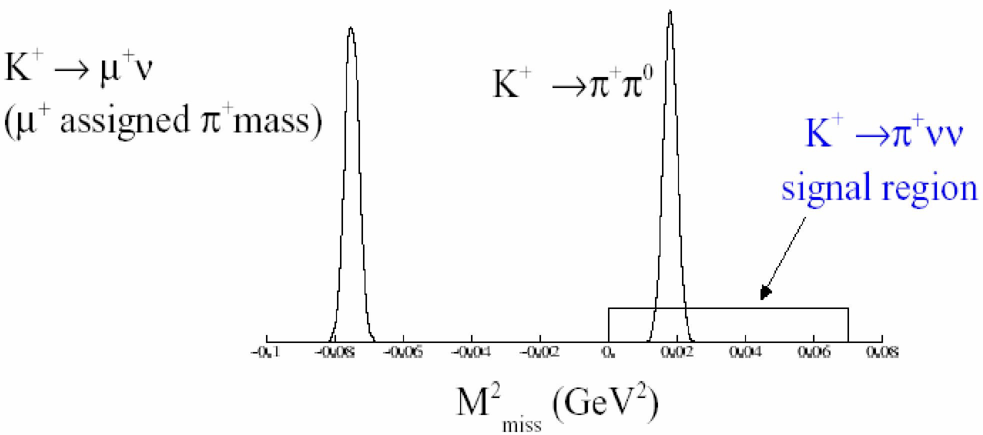
CKM Experiment Technique

Kinematic Rejection of Background

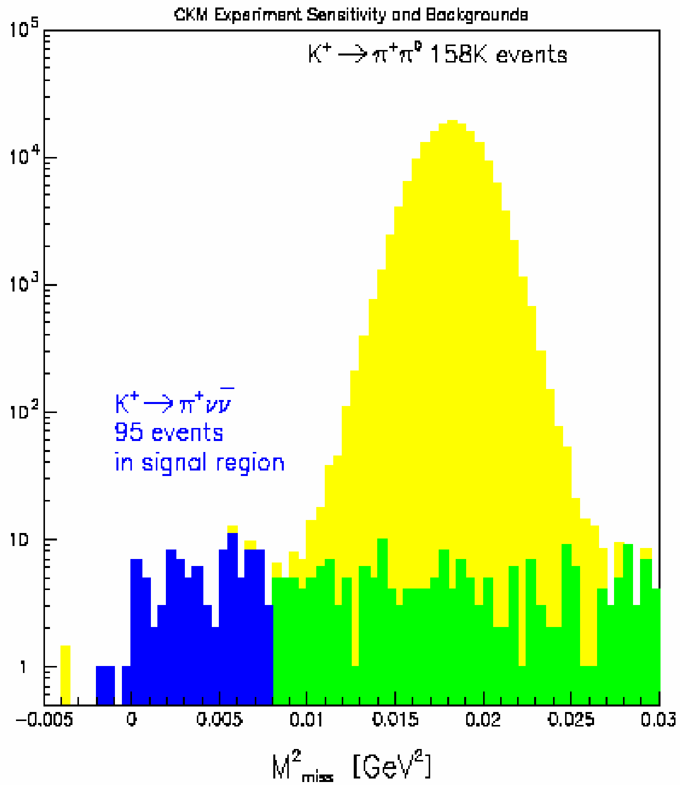
The dominant $K^+ \to \pi^+\pi^0$ and $K^+ \to \mu^+\nu$ backgrounds have well defined missing mass (M_{miss})



$$M^2_{miss} = M^2_K(1-p_\pi/p_K) + M^2_\pi(1-p_K/p_\pi) - p_\pi p_K \vartheta^2$$



CKM experiment sensitivity and background after 2 years running



Lessons from $K^+ \to \pi^+ \nu\bar{\nu}$

- $BR(K^+ \to \pi^+ \nu\bar{\nu})$ consistent with SM expectations:

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (1.57^{+1.75}_{-0.82}) \times 10^{-10}$$

$$\text{SM:} \quad BR = (0.72 \pm 0.21) \times 10^{-10}$$

- It provides a model-independent upper bound on $K_L \to \pi^0 \nu\nu$ decay

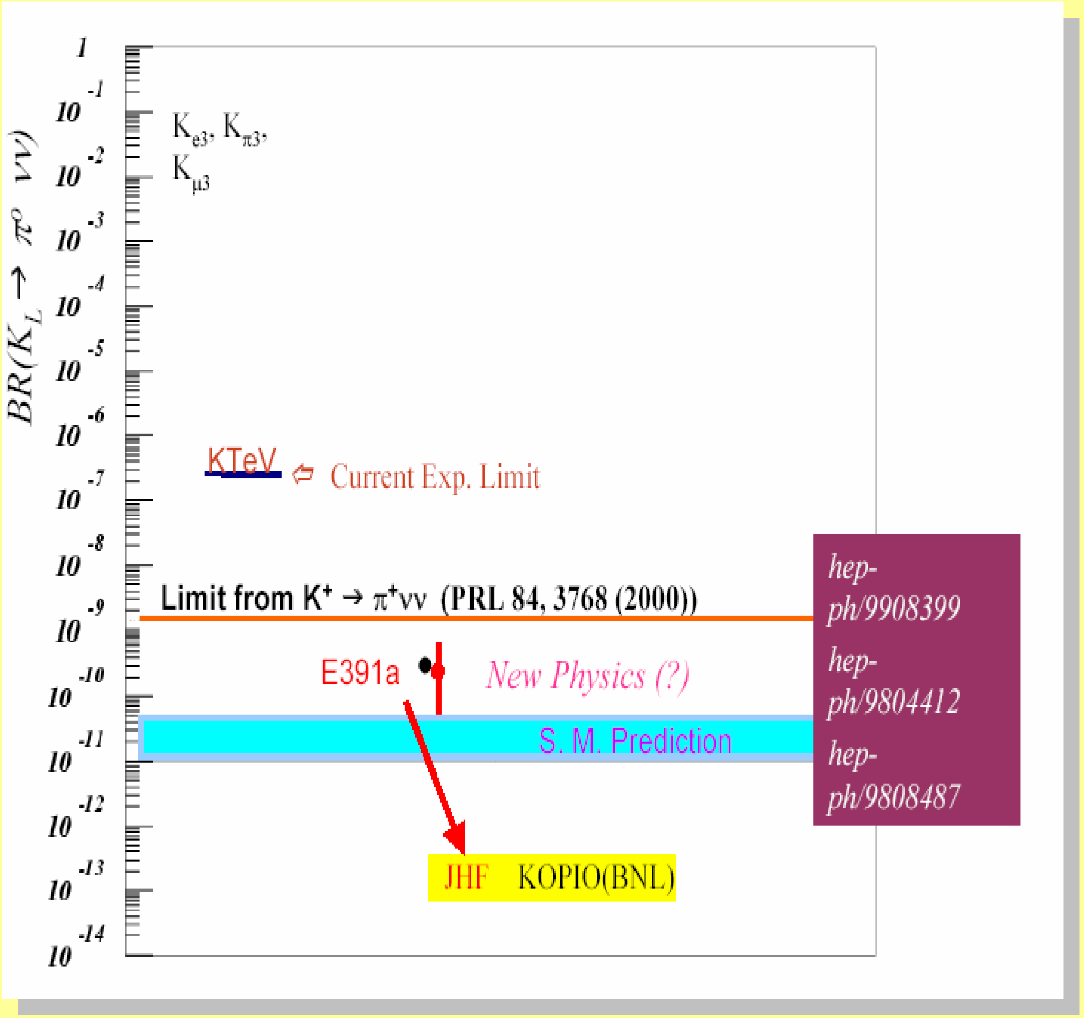
$$BR(K_L \to \pi^0 \nu\bar{\nu}) < 1.7 \times 10^{-9}$$

- A more precise measurement would be extremely interesting both as a CKM constraint and as a probe of new physics

The $K_L \to \pi^0 \nu\bar{\nu}$ experimental program

- **KTEV:** measured U.L. of 5.9×10^{-7} (90%CL) using $\pi^0 \to ee\,\gamma$
- **KEK-E391a:** pilot experiment, exploits full hermetic veto coverage. Accurate design of "pencil" beam. After detailed studies of physics limitations to detection of γ, e and π: expect sensitivity $\sim10^{-10}$ (x30 above SM level). Proposed continuation (JPARC) > 2008
- **KOPIO at BNL:** new technique to measure K momentum and γ direction. Expected sensitivity of ~ 40 Standard Model events (~ 20 background events)
  - Veto power complemented by kinematic rejection of dominating background
  - K^0 momentum by TOF using beam microbunching
  - full measurement of π^0, including γ direction by tracking preradiator

Prospects in $K_L \to \pi^0 \nu\bar{\nu}$



$K_L \rightarrow \pi^0 \nu \bar{\nu}$ Upper Limits in KTeV

A. ALAVI-HARATI *et al.* PHYSICAL REVIEW D **61** 072006

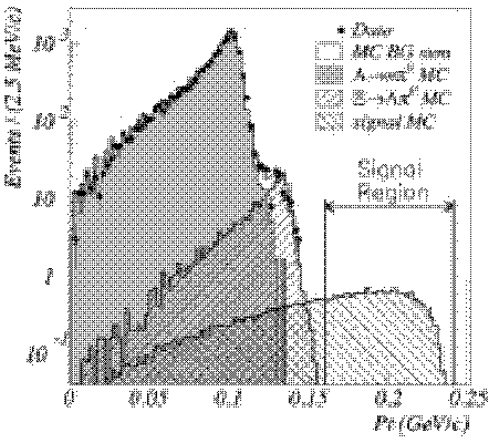


FIG. 3. Final p_t distribution. The dots represent data, and open histogram is for MC expectation. Two main background contributions are overlaid. Also shown is the signal distribution predicted from the MC simulation whose normalization is arbitrary.

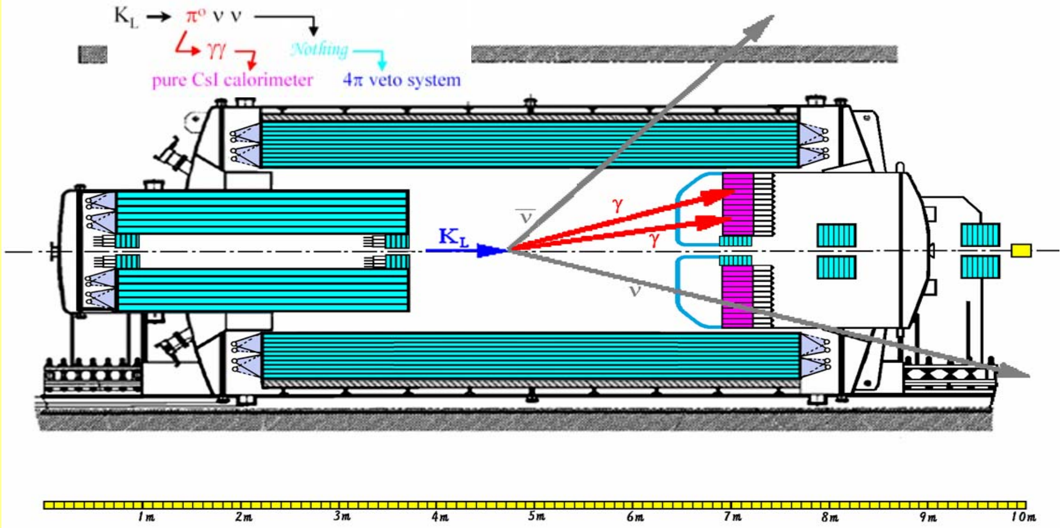
TABLE I. Summary of expected background contribution in the final signal region.

Decay mode	Expected number of events
$K_L \rightarrow \pi e \nu + \gamma$	0.02 ± 0.02
$K_L \rightarrow \pi^+ \pi^- \pi^0_D$	< 0.01
$\Lambda \rightarrow n \pi^0_D$	< 0.04
$\Xi^0 \rightarrow \Lambda^0 (\rightarrow p \pi^-) \pi^0_D$	$0.01^{+0.006}_{-0.004}$
$\Xi^0 \rightarrow \Lambda^0 (\rightarrow n \pi^0) \pi^0_D$	$0.01^{+0.006}_{-0.004}$
$\Xi^0 \rightarrow \Lambda^0 (\rightarrow n \pi^0_D) \pi^0$	0.01 ± 0.01
$K_L \rightarrow \pi^0 \pi^0 \pi^0_D$	0.03 ± 0.03
$K_L \rightarrow \pi^0 \pi^0_D$	< 0.01
$n + X \rightarrow \pi^0 X'$	$0.04^{+0.04}_{-0.01}$
Total	$0.12^{+0.05}_{-0.04}$

B.R. < 5.9×10^{-7} (95% CL)

- Flux of 0.33×10^{12} K decays analyzed, required $\pi^0 \rightarrow \gamma e^+ e^-$:
  - Constraints on π^0 mass (vertex unknown in π^0)
  - Better p_T measurement resolution (no pencil beam)
  - Disadvantage: BR($\pi^0 \rightarrow \gamma e^+ e^-$)=1.2%

KEK E391a Experiment

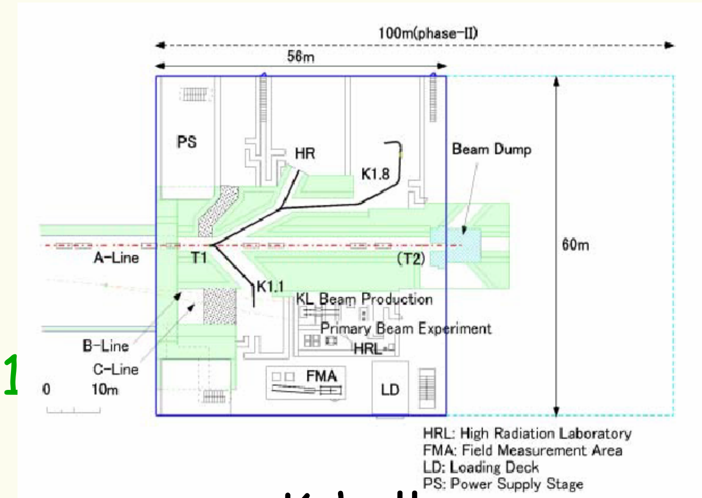


- $\langle p \rangle_K \sim$ 2 GeV/c
- pencil beam
- compact detector
- apparatus in vacuum
- CsI photon calorimeter
- Very high performance veto

- First dedicated experiment for $K_L \to \pi^0 \nu \bar{\nu}$
- Approved in december 1997. Addressing relevant experimental issues in a systematic way:
  - Detector inefficiency and physics limits measurements
  - Beam survey (Dec. 2000)
- Data taking in 2004, aiming at SES ~ 3×10^{-10}
- Test bed for experiment at JHF aiming at sensitivity $\sim 3 \times 10^{-14}$

JPARC

- New proton accelerator in Japan
  - final parameters : E=50 GeV i=15μA
  - phase 1: E 30 o 40 GeV
  - experimental hall with 2 beam lines in addition to Kamioka neutrino beam
  - one beam line instrumented in phase 1
  - start in 2008



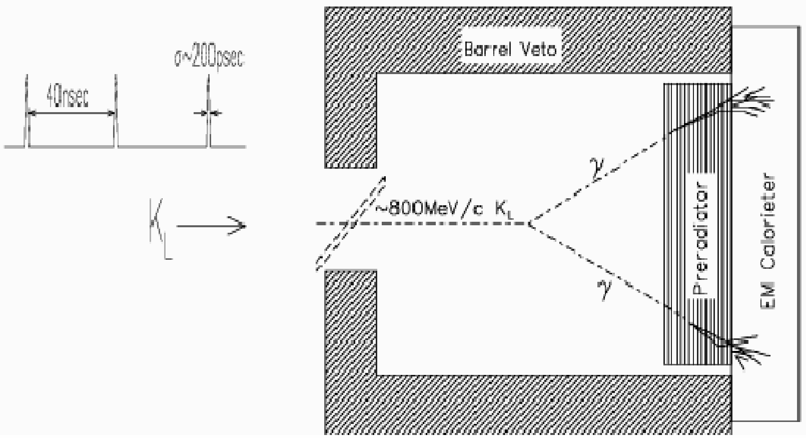
K-hall

- Call per LOI (dicembre 2002)
- Many letters of intent for K physics:
  - $K_L \to \pi^0 \nu \bar{\nu}$ (E391a upgrade)
  - $K^+ \to \pi^+ \nu \bar{\nu}$ (stopped K^+ à la BNL E787)
  - T violating P_T in $K^+ \to \mu^+ \pi^0 \nu$ at 10^{-4} level
  - $K^+ \to e^+ \pi^0 \nu$ for V_{us} measurement

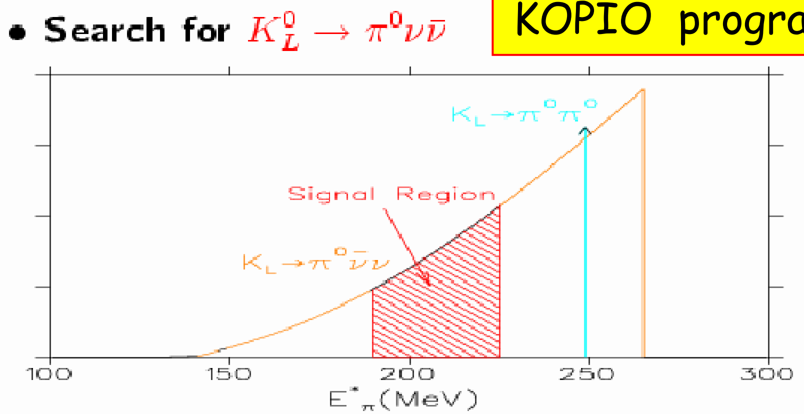
KOPIO: a proposal for $K_L \rightarrow \pi^0 \nu \bar{\nu}$

Lessons from BNL E787 experiment

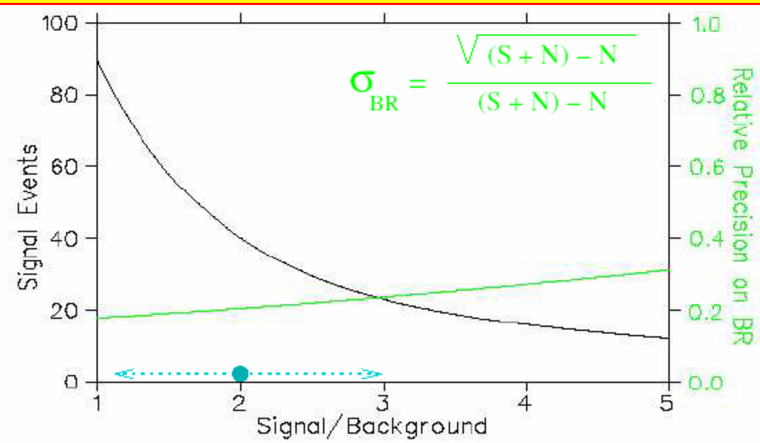
- Measure as much as possible:
  Energy, position and *ANGLE* of each photon.
- Work in the C.M. system :
  Use TOF to get the K_L^0 momentum.
- Photon Veto limited by photonuclear interactions at low energies.



KOPIO program



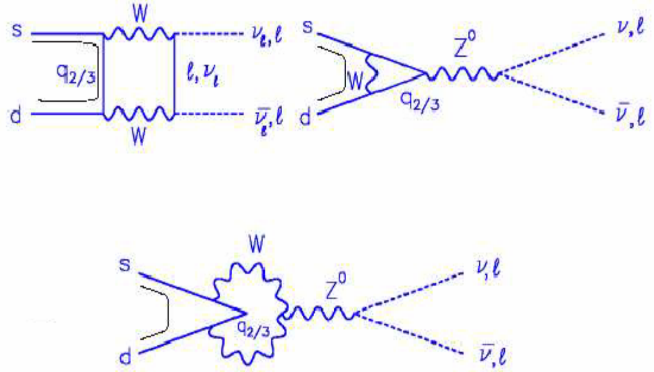
Measure BR to 20% → δη/η ~ 10%



Expected ~ 40 SM events, S/B ~ 2

$K_L \to \pi^0 \nu\bar{\nu}$ theoretical predictions

$K_L \to \pi^0 \nu\nu$ in Standard Model

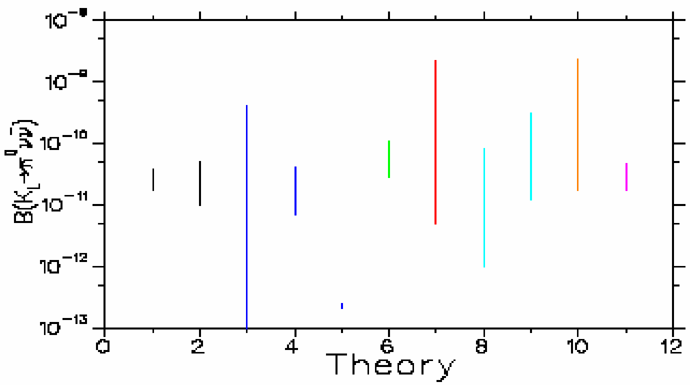


$$BR(K_L \to \pi^0 \nu\bar{\nu}) \simeq (3.1 \pm 1.3) \cdot 10^{-11}$$

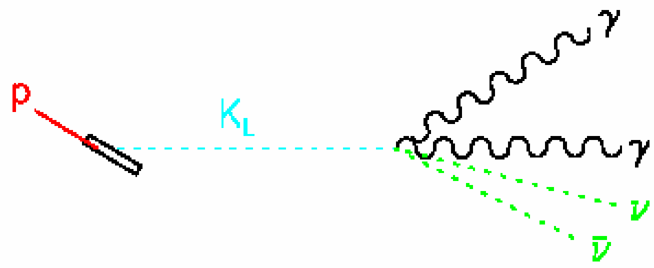
$K_L \to \pi^0 \nu\nu$ beyond SM

	Who	What	$10^{11} B(K_L \to \pi^0 \nu\bar{\nu})$
1	Buchalla	Standard Model CKM fit	2.8 ± 1.1
2	Plaszczynski/Schune	Conservative SM fit	$1 - 5$
3	Buras, et al.	Generic SUSY w/min. part. content	$0 - 40$
4	Buras, et al.	MSSM w/o new flavor or CP viol.	$(0.41 - 1.03) \times$ SM
5	Brhlik, et al.	all CP-viol. due to SUSY	$\sim .023$
6	Chanowitz	$SU(2)_L \times SU(2)_R$ Higgs	$2.8 - 10.6$
7	Hattori, et al.	4th generation	$0.5 - 260$
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	$1.7 - 260$
11	Kiyo, et al.	seesaw L-R model†	$(1 - 1.2) \times$ SM

† predicts spectrum will be altered.



$K_L \to \pi^0\nu\bar{\nu}$ experimental issues



All neutral initial & final state, γ's make π^0

Expected branching ratio 3×10^{-11}
- need high flux of K_L

Largest background $K_L \to \pi^0\pi^0$, BR $\sim 10^{-3}$
- need excellent vetoing, other handles if possible

Background from neutron-produced π^0's, η's
- requires vacuum of 10^{-7}
- need to make sure decay vertex was in beam

Potential backgrounds from hyperon decay π^0's
- could use a clever way of getting rid of them

Only 2 photons seen, a priori unknown decay vertex and K energy

Background from K_L decays:

Process	Modes	Main source	Events
$K_L^0 \to \pi^0\nu\bar{\nu}$			41
K_L^0 decays ($\bar{\gamma}$)	$\pi^0\pi^0, \pi^0\pi^0\pi^0, \pi^0\gamma\gamma$	$\pi^0\pi^0$	12.8
$K_L^0 \to \pi^+\pi^-\pi^0$			0.65
$K_L^0 \to \gamma\gamma$			0.02
K_L^0 decays ($\overline{charge}$)	$\pi^\pm e^\mp\nu, \pi^\pm\mu^\mp\nu, \pi^+\pi^-$	$\pi^-e^+\nu$	0.02
K_L^0 decays ($\bar{\gamma}, \overline{charge}$)	$\pi^\pm l^\mp\nu\gamma, \pi^\pm l^\mp\nu\pi^0, \pi^+\pi^-\gamma$	$\pi^-e^+\nu\gamma$	4.4
Other particle decays	$\Lambda \to \pi^0 n, K^- \to \pi^-\pi^0, \Sigma^+ \to \pi^0 p$	$\Lambda \to \pi^0 n$	0.01
Interactions	n, K_L^0, γ	$n \to \pi^0$	0.2
Accidentals	n, K_L^0, γ	n, K_L^0, γ	0.8
Total Background			18.9

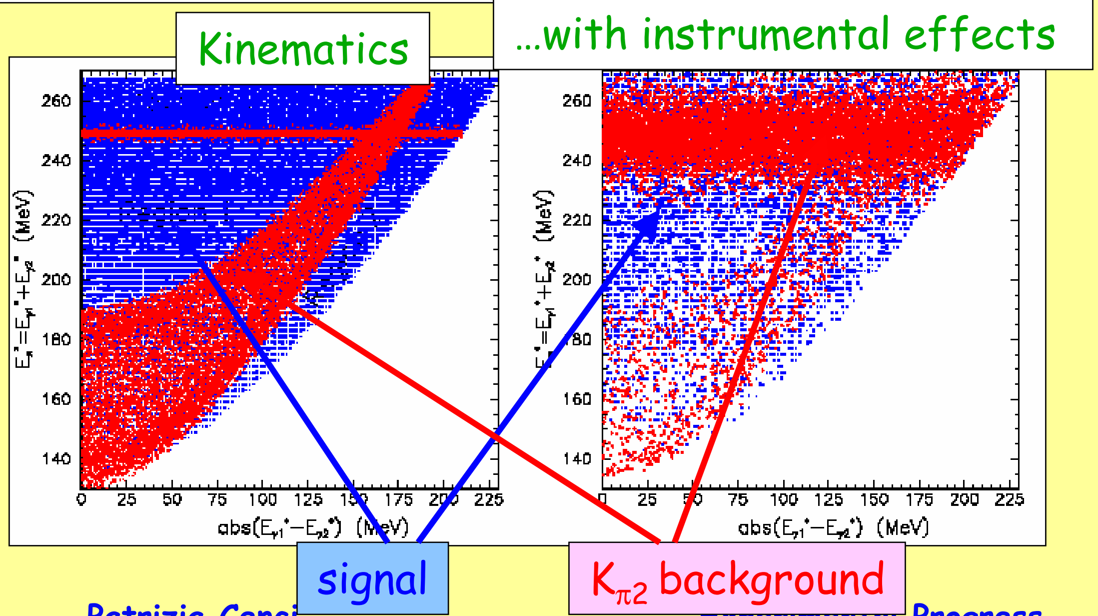
$K_L \to \pi^0 \pi^0$ background

Reduction of $K_L \to \pi^0 \pi^0$ background:

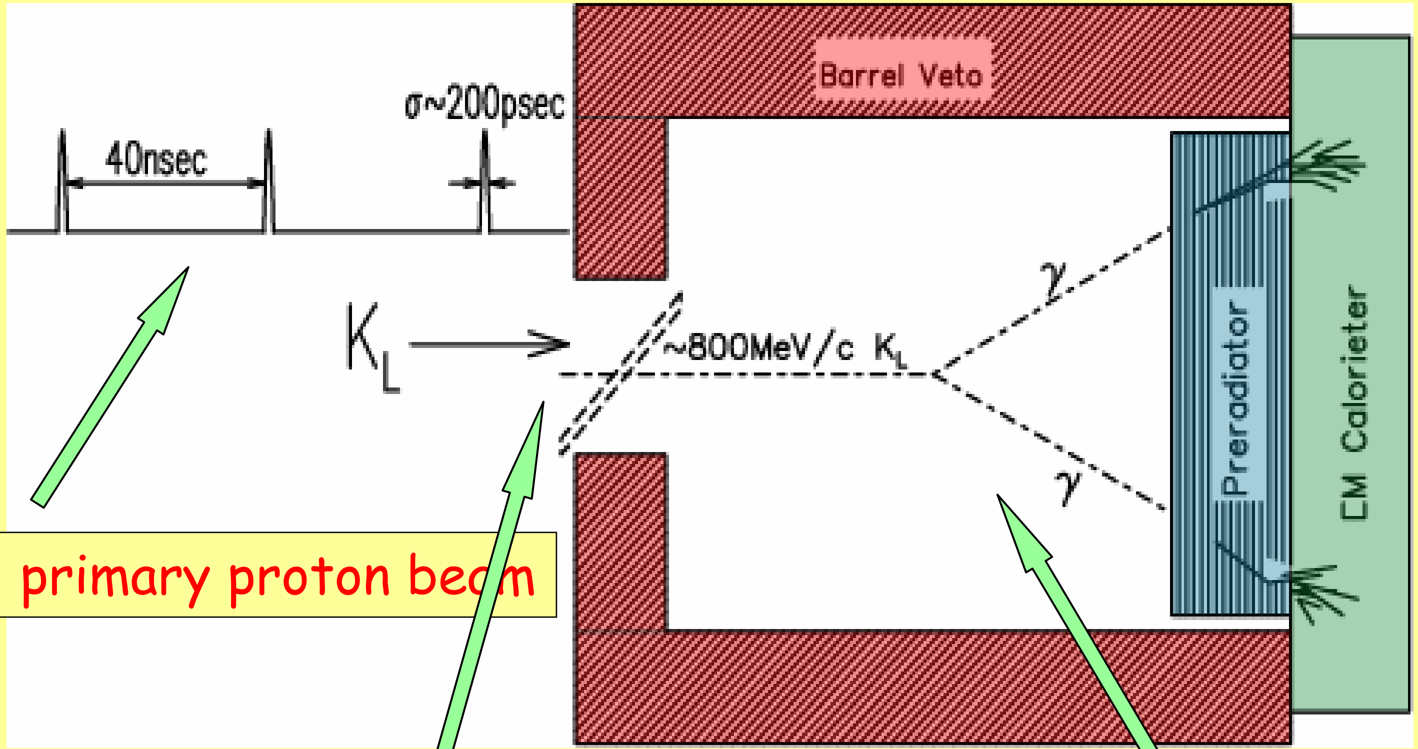
- require 4 recostructed photons
- require kinematics: in K center of mass the two π^0 have $E^*_\pi = m_K/2$
  - Combine photon energies: photons in $m_{\gamma\gamma} = m_{\pi 0}$ could come from:
    - same π^0 (EVEN pair) $E^*_\pi = m_K/2$
    - different π^0 (ODD pair) bigger E^*_π

$E^*(\gamma_1+\gamma_2)$ vs $E^*(\gamma_1-\gamma_2)$

Method of π^0 kinematic reconstruction in K_L c.m.:
found region with negligible $K_L \to \pi^0 \pi^0$ background



KOPIO experiment concept

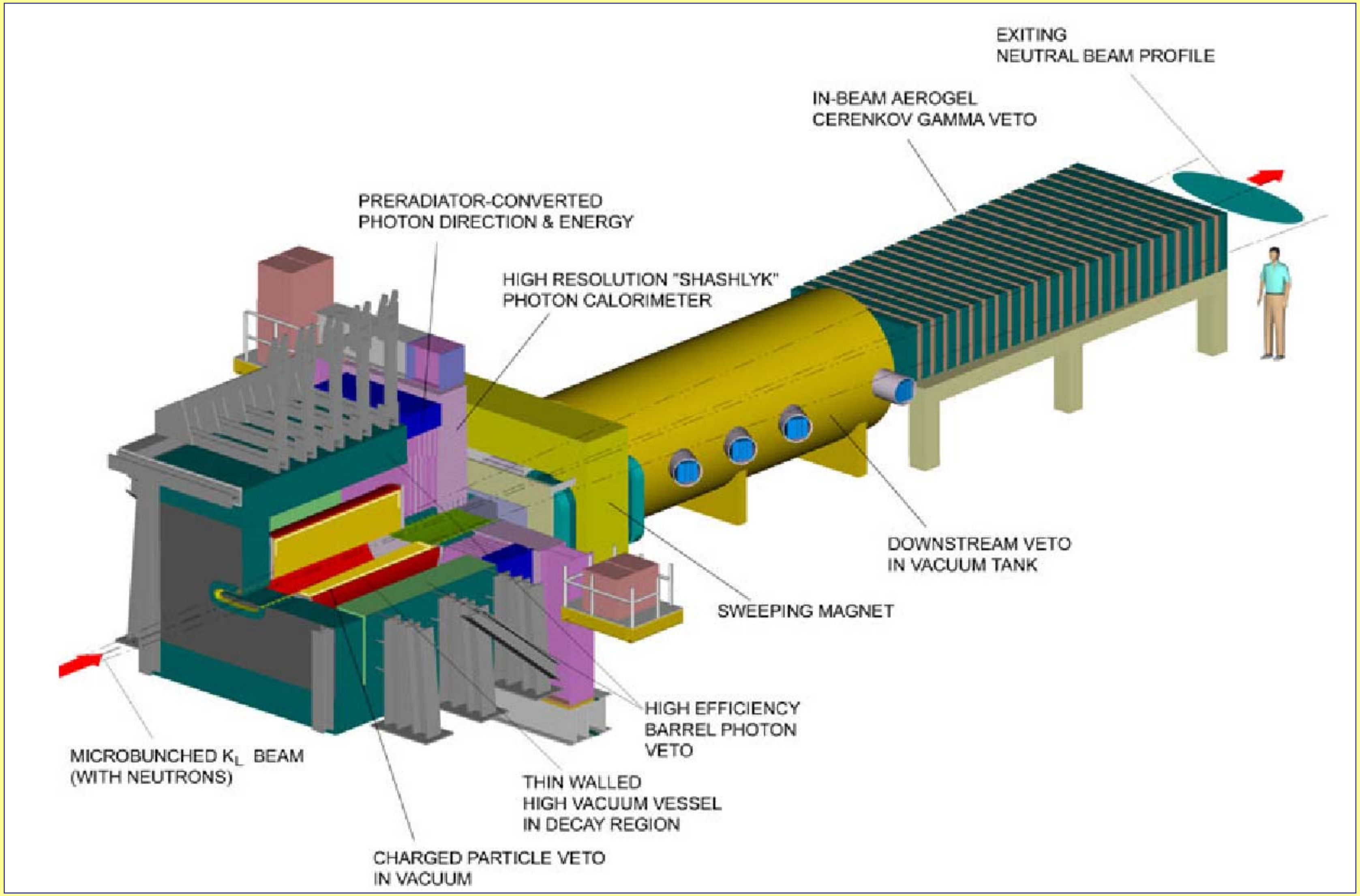


pulsed primary proton beam

TOF technique for K_L momentum

reconstructed π^0 from $K_L \rightarrow \pi^0 \nu \bar{\nu}$

KOPIO Detector



KOPIO detector requirements

Obtained with prototype test

	Parameter	Minimal Requirement	Expected Performance
PR+CAL	E_γ resolution	$3.5\%/\sqrt{E}$	$2.7\%/\sqrt{E}$
PR	θ_γ resolution (250MeV)	$(25-30)$ mr	23 mr
PR+CAL	t_γ resolution	$100ps/\sqrt{E}$	$50ps/\sqrt{E}$
PR	x_γ, y_γ resolution(250MeV)	10mm	<1mm
AGS	μ-bunch width	$300ps$	$200ps$
	γ-veto inefficiency	$\bar{\epsilon}_{E787}$	$0.3\bar{\epsilon}_{E787}$

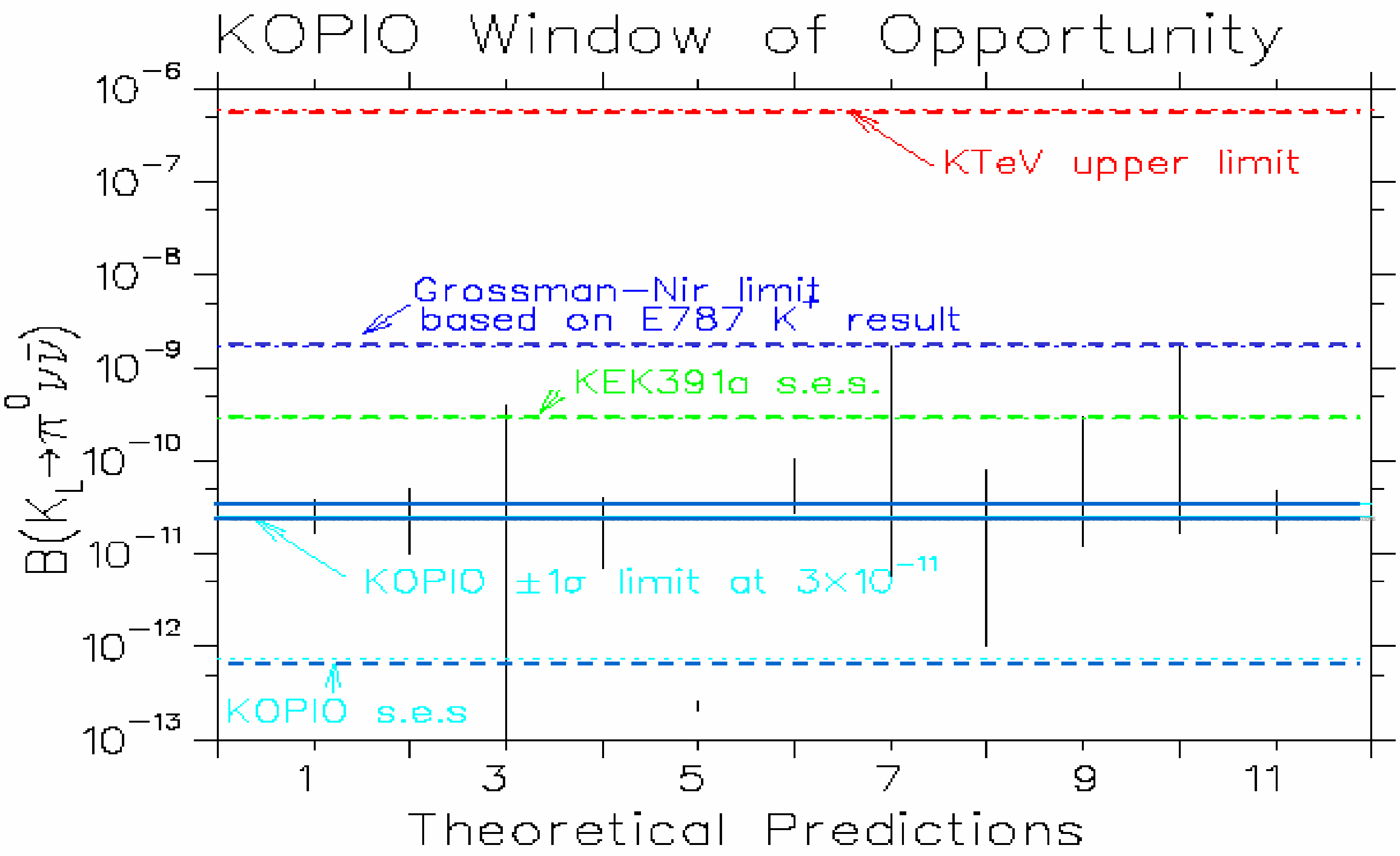
KOPIO: existence proofs

- 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

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

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

Possible KOPIO outcomes



Sensitivity frontier

Branching fractions

10^{-2}

$K_L \to \pi^+\pi^-$ 1964: discovery of CP violation

10^{-3}

10^{-4}

10^{-5}

$K_L \to e^+e^-\gamma$

1980: Dalitz Decays

10^{-6}

$K_L \to \mu^+\mu^-\gamma$

10^{-7}

10^{-8}

$K_L \to \mu^+\mu^-$ 1973: GIM suppression

10^{-9}

$K^+ \to \pi^+\nu\bar{\nu}$ 1997: birth of quantitative CKM tests

10^{-10}

10^{-11}

$K_L \to e^+e^-$ 1998: rarest decay ever seen → BNL E871: $Br = (8.7^{+5.7}_{-4.1}) \times 10^{-12}$

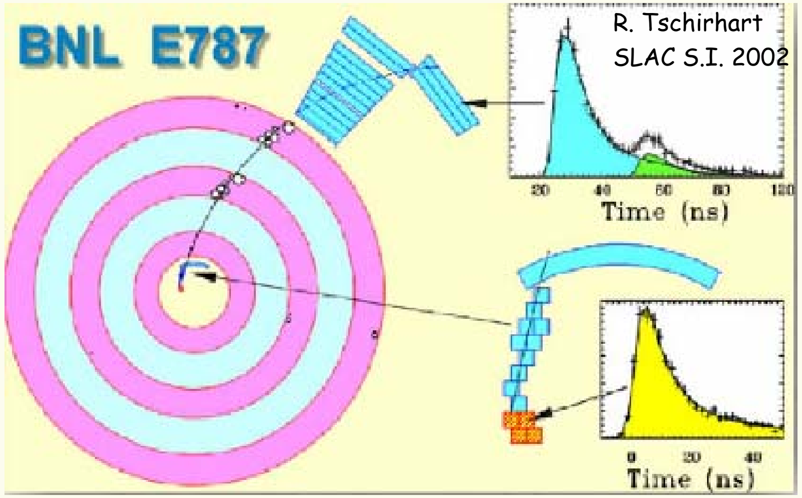
10^{-12}

The frontier: $K_L \to \mu^+e^- < 4.7 \times 10^{-12}$ (90% CL) (2002)

10^{-13}

→ BNL E871: corresponds to LFV X-boson $m_X > 170$ TeV

10^{-14}

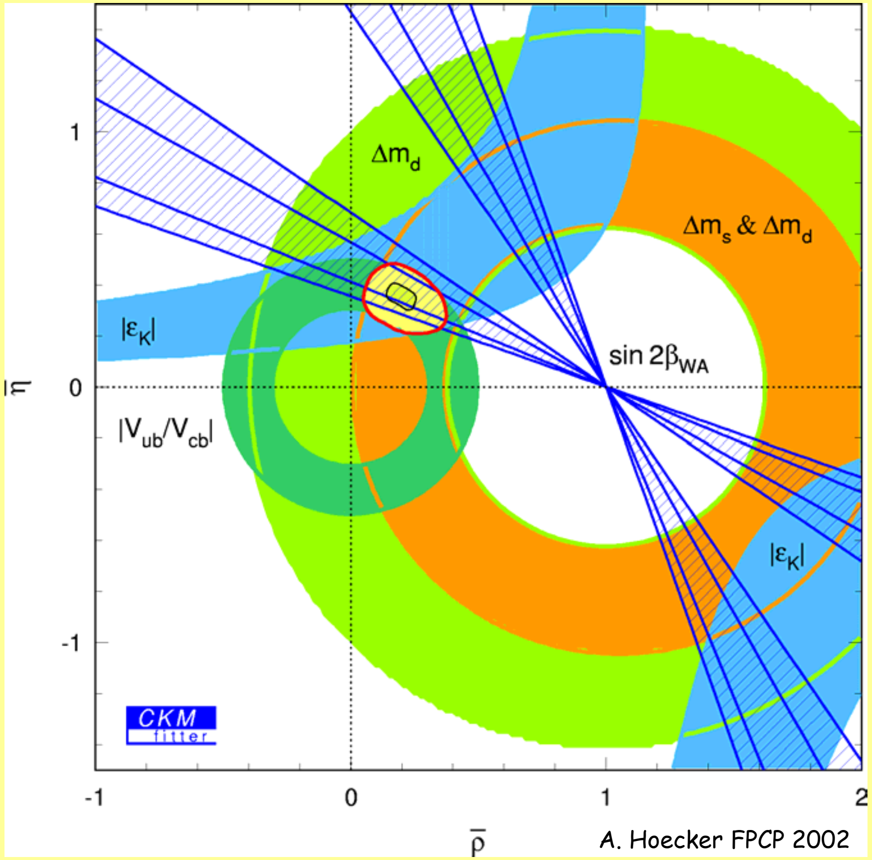


$Br(K^+ \to \pi^+\nu\bar{\nu}) = (1.57^{+1.75}_{-0.82}) \times 10^{-10}$

Conclusions

- K and B respect so far the CMK formalism, even if more CPV than expected is needed (baryogenesis dilemma)
- CKM mechanism is very likely the dominant source of CPV at EW scale, however:
  - consistency could be accidental → needed many new CP Violation measurements and SM test by direct mesurements of U.T. parameters with rare K decays, B decays and study of CPV in leptonic sector
  - still room for new physics → corrections to CKM (rather than alternatives to CKM)

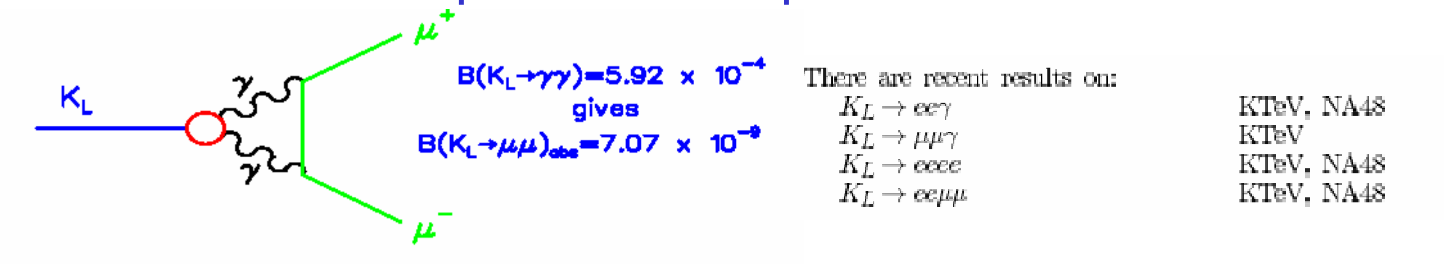
CKM mechanism: fit with standard contraints ($\sin(2\beta)$ non included)



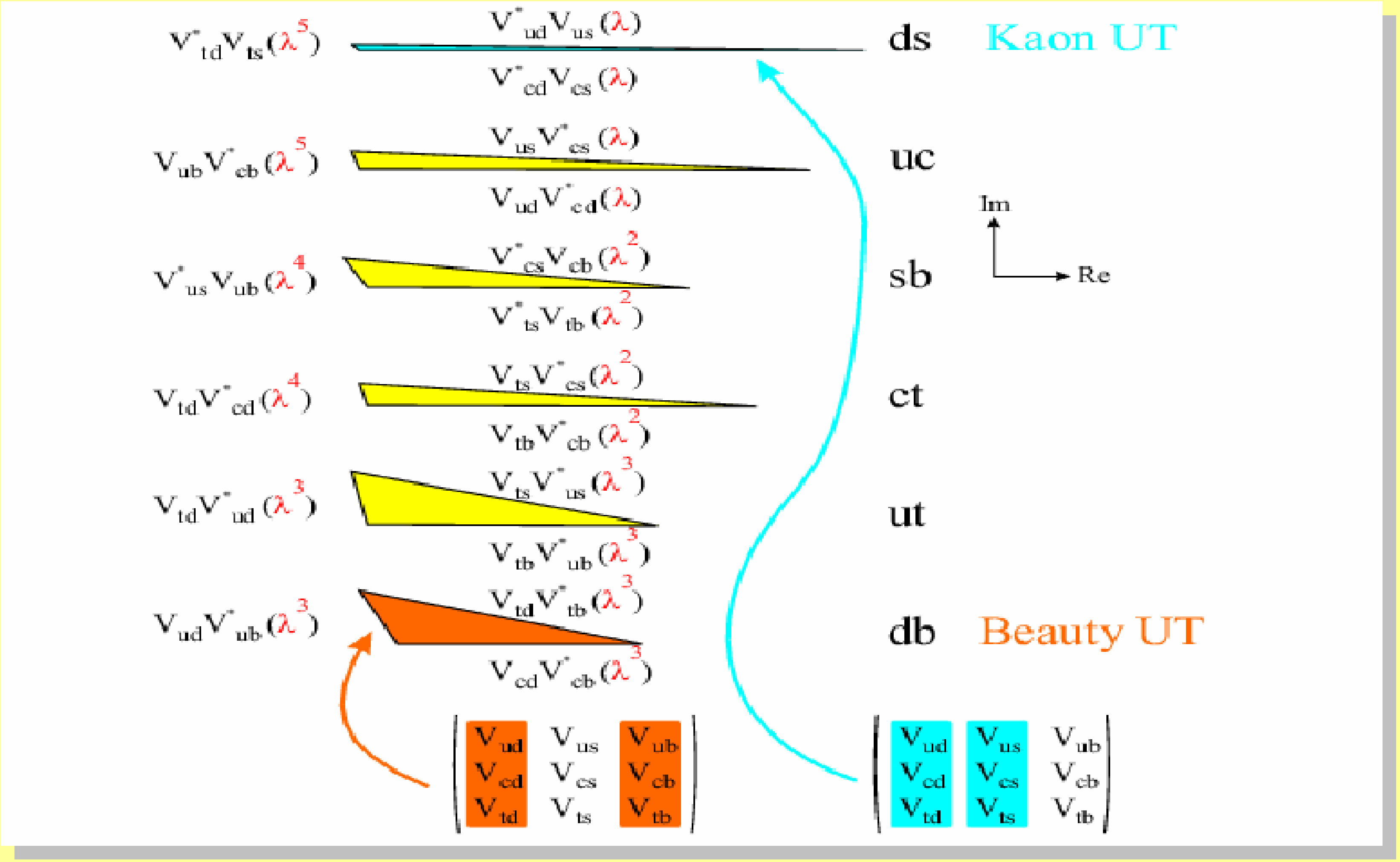
Spare slides

FCNC decays: $K_L \to \mu^+\mu^-$

- **$K_L \to \mu^+\mu^-$**
  - ◆Experimental effort concluded with 2.4% precision:
    BR=(7.18±0.17)×10^{-9} E871 (BNL AGS) (~6000 events)
  - ◆Short range contribution reliably calculated in SM but comparison with measurement limited by interpretation:
    - ❖Dominating absorptive contribution from intermediate $\gamma\gamma$:
      $BR_{abs} = (7.07 \pm 0.18) \times 10^{-9}$
    - ❖Better experimental information on $K_L \to \mu\mu\gamma, ee\gamma, eeee, ee\mu\mu$ needed to constrain long range dispersive contributions: additional effort required both experimental and theoretical



The Unitarity Triangles



CKM Matrix Elements measurement

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

	Element	Value	Error	Method
1	$\vert V_{ud}\vert$	0.9735 ± 0.0008	0.08%	nuclear β-decay neutron β-decay
2	$\vert V_{us}\vert$	0.2196 ± 0.0023	1.1%	K_{e3} decays hyperon β-decays
3	$\vert V_{cb}\vert$	0.0402 ± 0.0019	4.7%	$B \to \overline{D}^* l^+ \nu_l$ inclusive B decays
4	$\vert V_{cd}\vert$	0.224 ± 0.016	7.1%	$\nu \overline{\nu}$ charm production
5	$\vert V_{cs}\vert$	1.04 ± 0.16	15%	D_{e3} decays charm-tagged W decays
6	$\vert V_{tb}^* V_{td}\vert$	0.0083 ± 0.0016	19%	ΔM_{B_d}
7	$\vert V_{ub}/V_{cb}\vert$	0.090 ± 0.025	28%	$b \to u l^+ \nu_l$

Comparison of K and B contributions

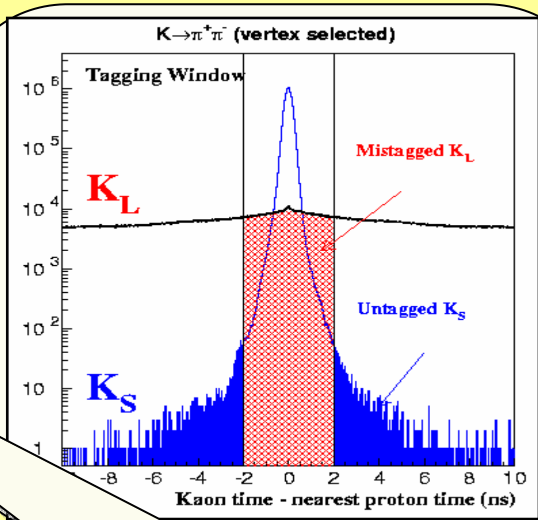
Buras 1999 comparison:

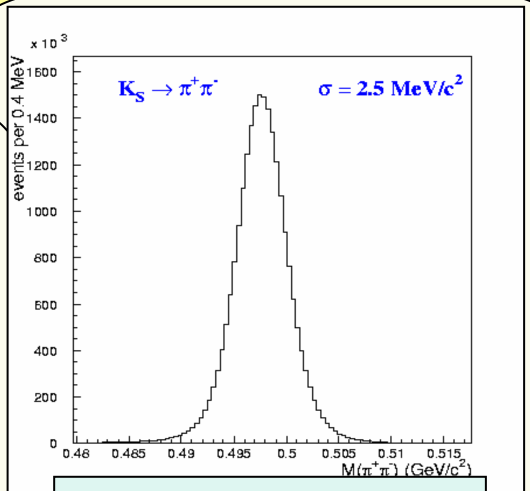
$\sigma(|V_{cb}|) = \pm 0.002(0.001)$

	$K \to \pi \nu \bar{\nu}$	**B-Factory Era**	**LHCB/BTEV**
$\sigma(\|V_{td}\|)$	$\pm 10\%(9\%)$	$\pm 5.5\%(3.5\%)$	$\pm 5\%(2.5\%)$
$\sigma(\bar{\rho})$	$\pm 0.16(0.12)$	± 0.03	± 0.01
$\sigma(\bar{\eta})$	$\pm 0.04(0.03)$	± 0.04	± 0.01
$\sigma(\sin 2\beta)$	± 0.05	± 0.06	± 0.02
$\sigma(\mathrm{Im}\,\lambda_t)$	$\pm 5\%$	$\pm 14\%(11\%)$	$\pm 10\%(6\%)$

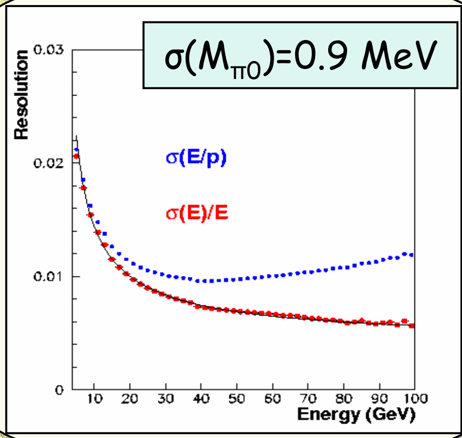
NA48 experimental technique

- K_S-K_L identification: proton tagger to identify K_S (T.O.F. technique)
- $\pi^+\pi^-$ identification: magnetic spectrometer
  $\sigma(p)/p = 0.5\% \oplus 0.009\ p[GeV/c]\%$
- $\pi^0\pi^0$ identification: LKr calorimeter
  $\sigma(E)/E \cong 3.2\%/\sqrt{E} \oplus 90MeV/E \oplus 0.42\%$
  (E in GeV) (< 1% for 25 GeV photons)
- Lifetime weighting to equalize acceptance

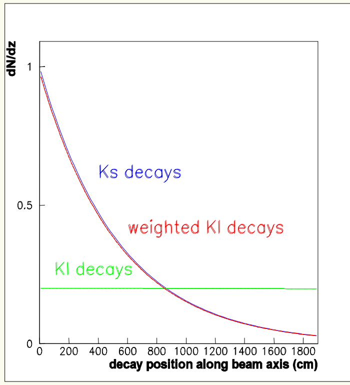


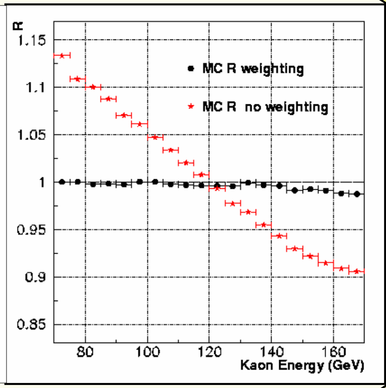


$\sigma(M_{\pi+\pi-}) = 2.5\ MeV/c^2$



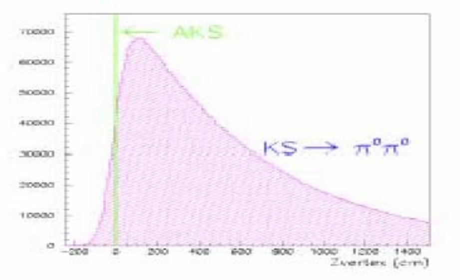
$\sigma(M_{\pi0}) = 0.9$ MeV

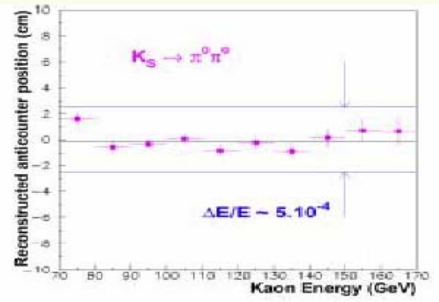


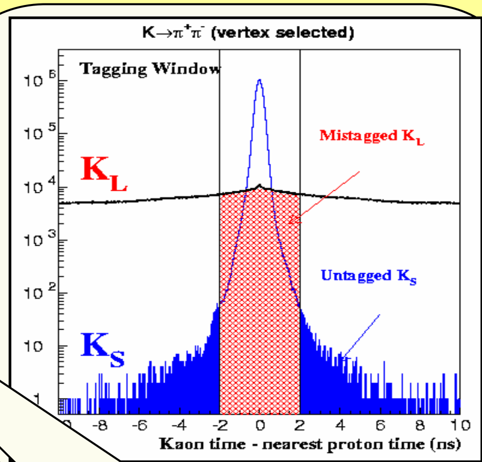


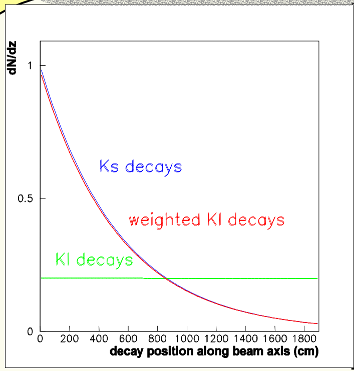
NA48 experimental technique

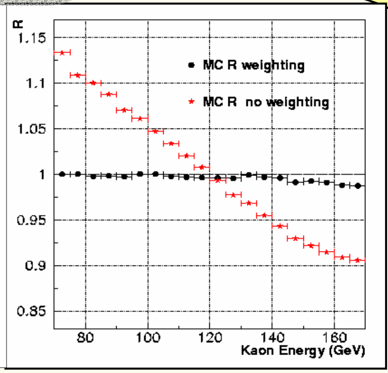
- K_S-K_L identification: proton tagger to identify K_S
- Background to $\pi^+\pi^-$ (K_{e3} $K_{\mu3}$):
- Background to $\pi^0\pi^0$ ($K_{3\pi0}$):
- Energy Scale: and calibration ($\pi^0\pi$
- Lifetime weighting to equal e acceptances

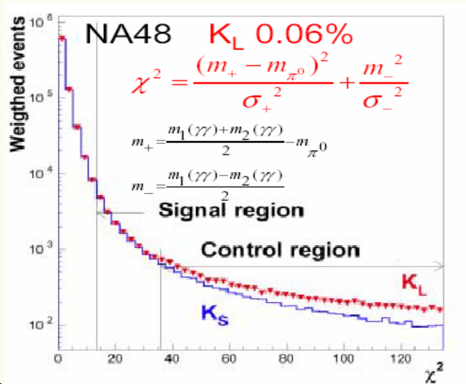


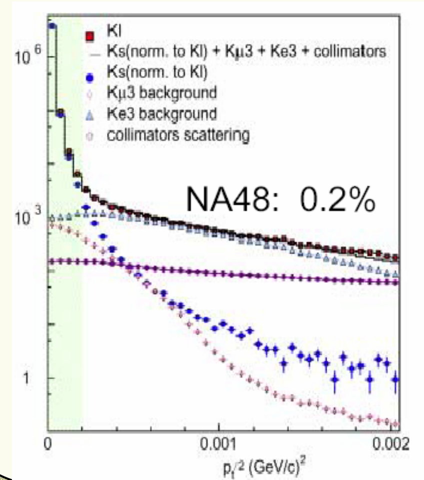




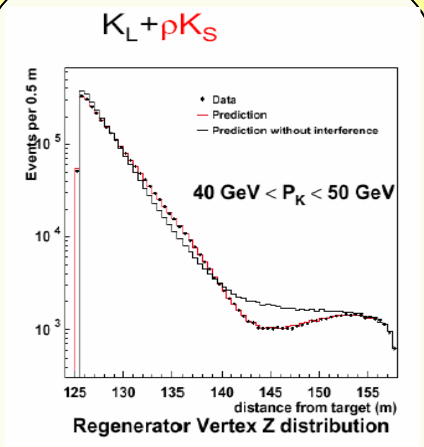








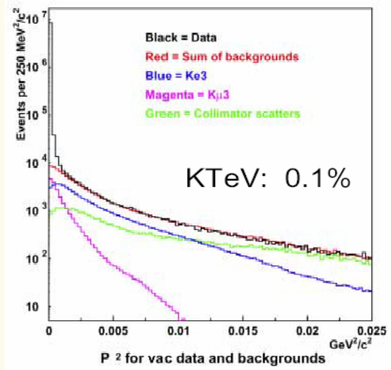
KTeV experimental technique

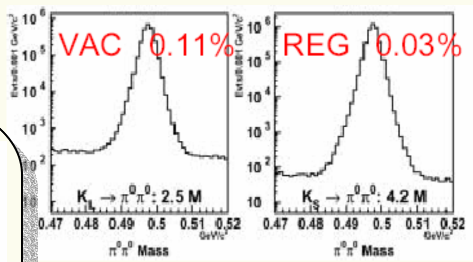


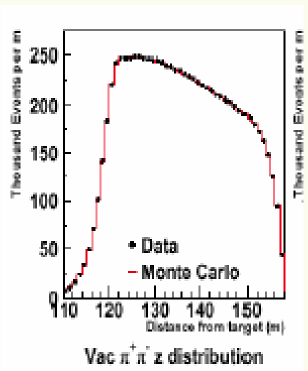
- K_S-K_L identification:

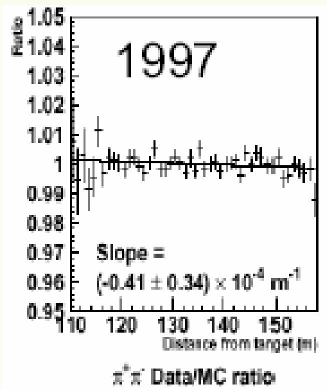
K_S from K_L on regenerator

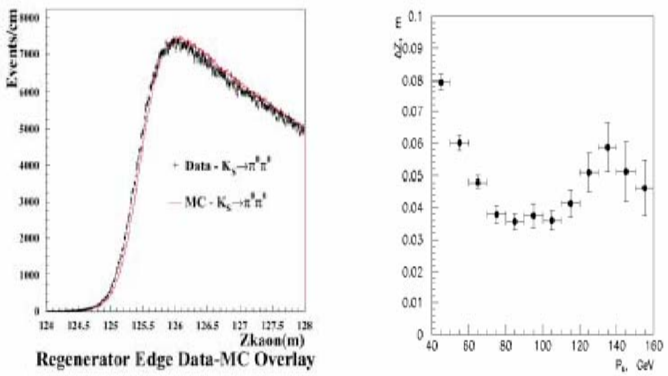
- Background to $\pi^+\pi^-$ (K_{e3} $K_{\mu3}$)
- Background to $\pi^0\pi^0$ ($K_{3\pi^0}$)
- Energy scale and calibration (π
- MC correction to equalize acceptances





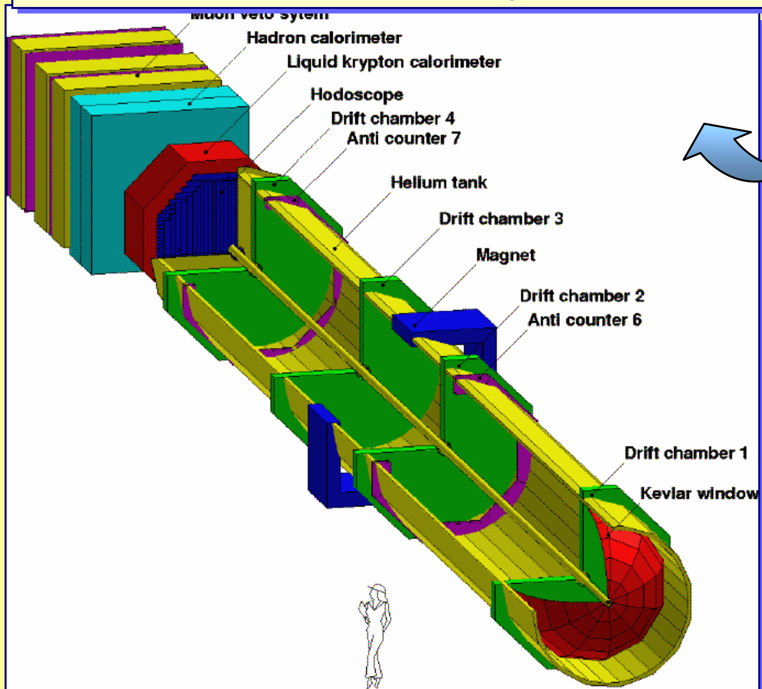






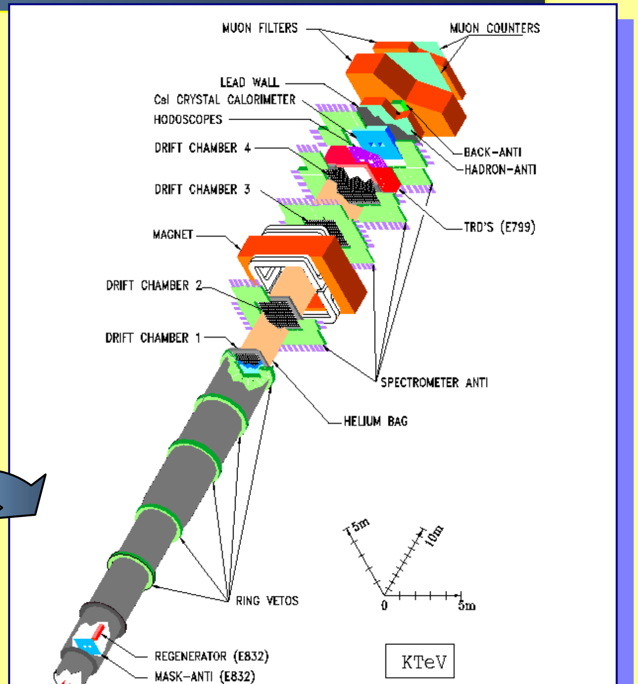
KTeV and NA48: the Detectors

LKr Calorimeter:
$\sigma(E)/E \cong 3.2\%/\sqrt{E} \oplus 100\text{MeV}/E \oplus 0.42\%$
Spectrometer (p_T kick ~250 MeV/c):
$\sigma(P)/P \cong 0.48\% \oplus 0.009\ P[\text{GeV/c}]\%$
$\sigma_M(\pi^0\pi^0) \sim \sigma_M(\pi^+\pi^-) \sim$ 2.5 MeV
Convergent Beams: K_S from protons on target, K_S ID via proton tagging



NA48

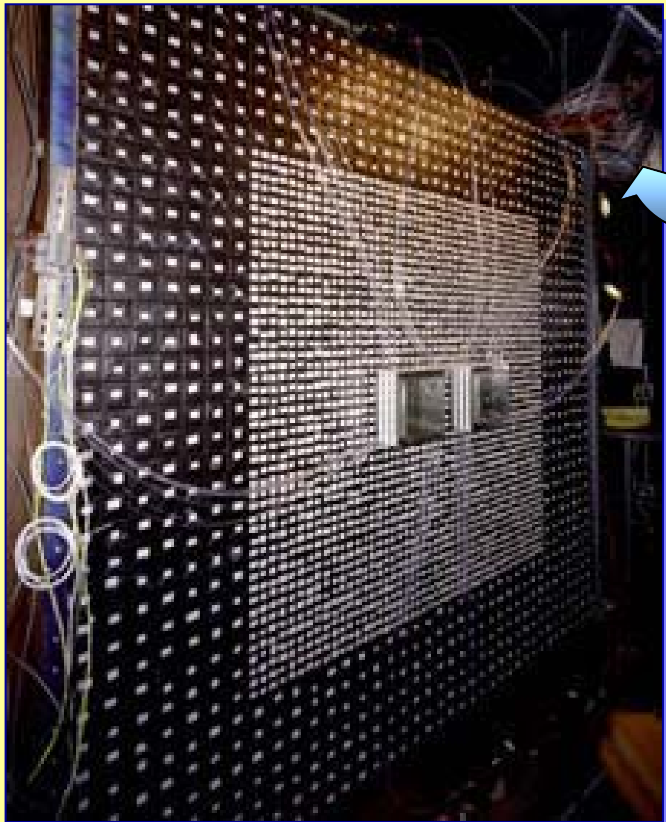
KTeV



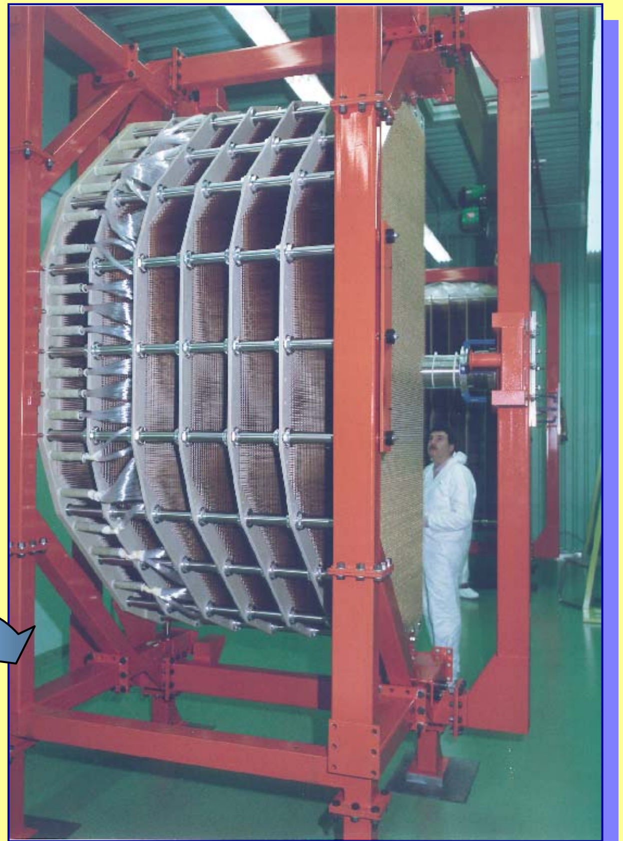
CsI Calorimeter:
$\sigma(E)/E \cong 2.0\%/\sqrt{E} \oplus 0.45\%$
Spectrometer (p_T kick ~400 MeV/c):
$\sigma(P)/P \cong 0.17\% \oplus 0.007\ P[\text{GeV/c}]\%$
$\sigma_M(\pi^0\pi^0) \sim \sigma_M(\pi^+\pi^-) \sim$ 1.5 MeV
Parallel Beams: K_S from K_L on regenerator, K_S ID via x-y position

KTeV & NA48: the Art of Calorimetry

- 3100 CsI crystals
- 0,5 m depth (~27 X_0)
- 0.7% resolution for 19 GeV γ



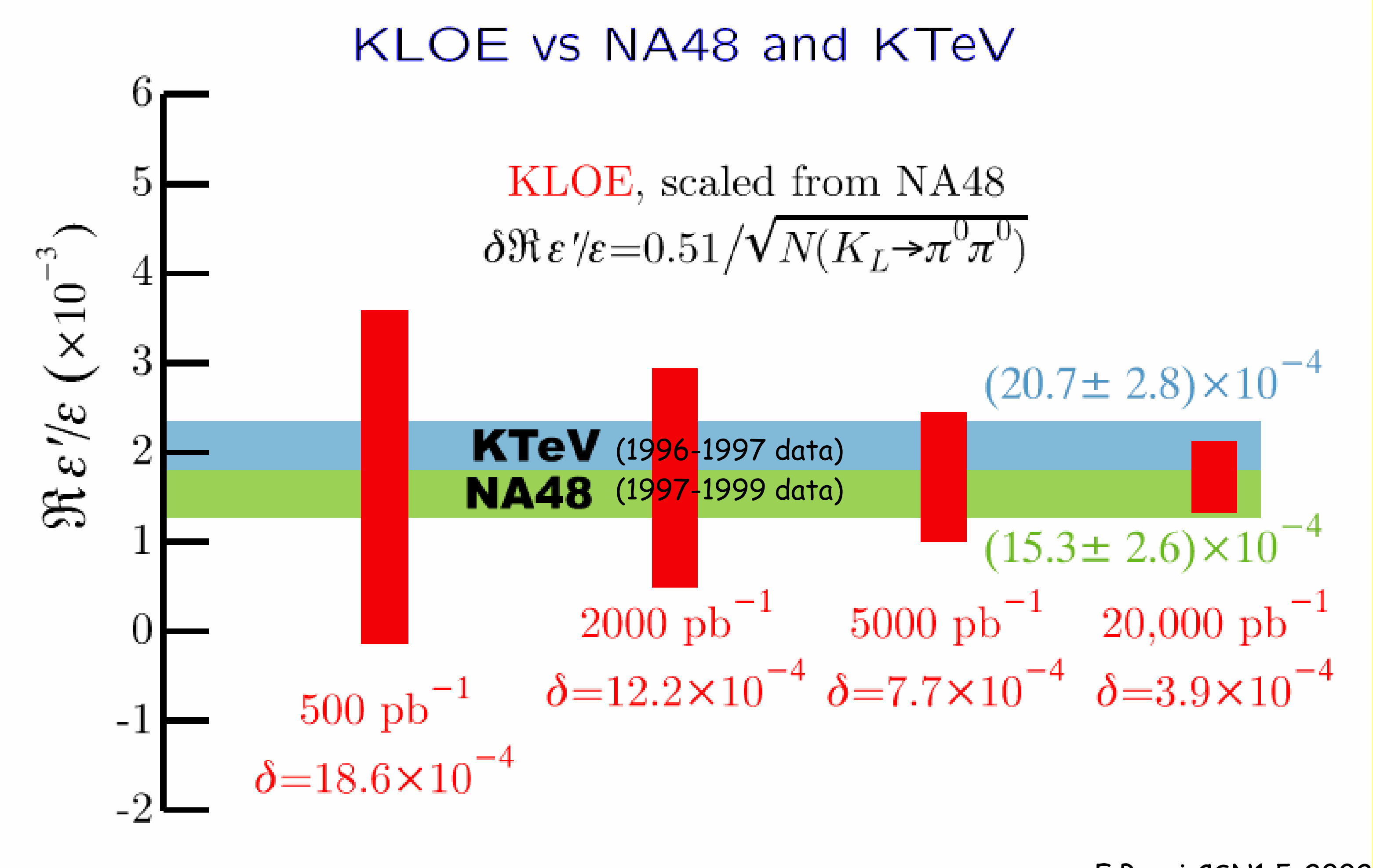
KTeV



NA48

- 10 m^3 of LKr (13212 cells)
- 1.25 m depth (~27 X_0)
- 1% resolution for 25 GeV γ

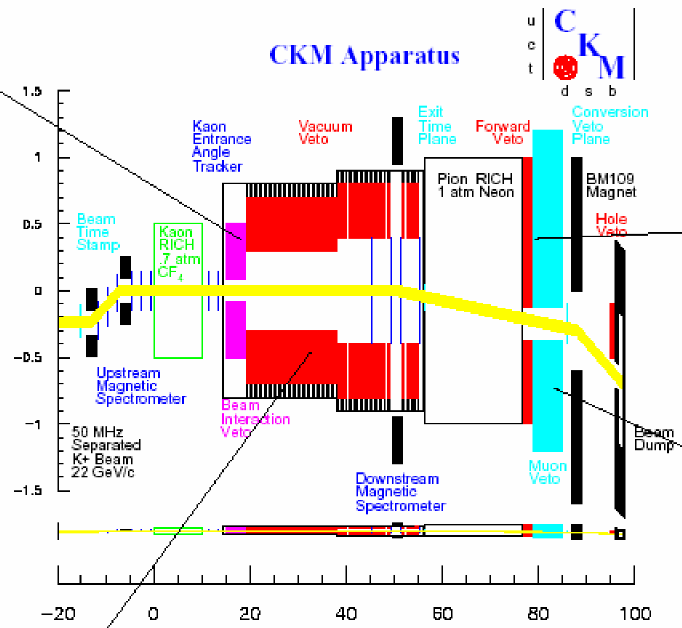
KLOE vs NA48 and KTeV



F.Bossi CSN1 5-2002

CKM Experiment Veto System

Beam Interaction Veto: rejects inelastics in the KRICH gas and windows



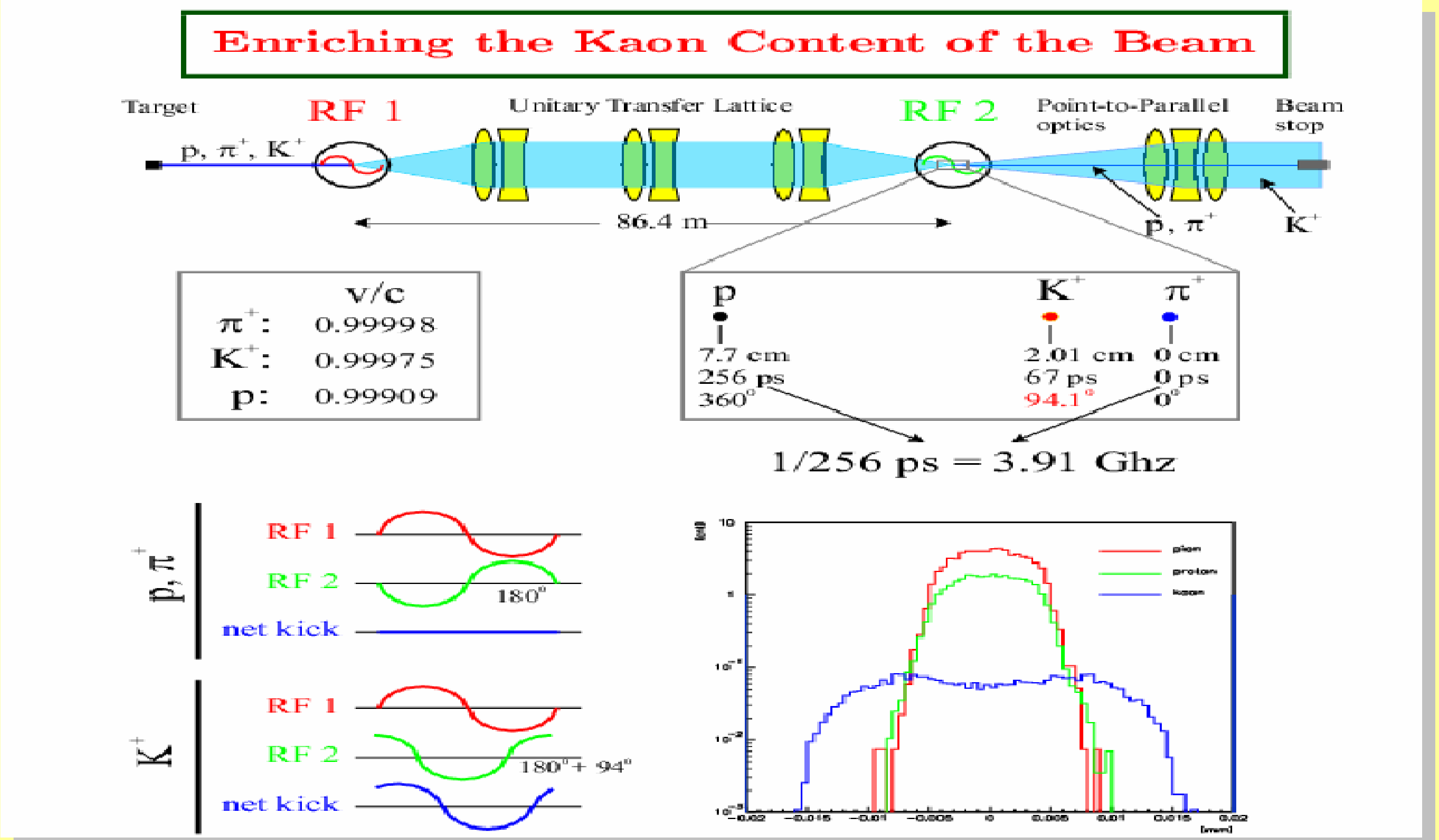
Forward γ veto to reject forward π^0

Muon Veto to reject $K^+ \to \mu^+ \nu$ (redundant with π RICH)

Vacuum Photon Veto

- Handles most of the π^0 rejection
- 25 tons of plastic scintillator
- Must not spoil the 1 μTorr Vacuum

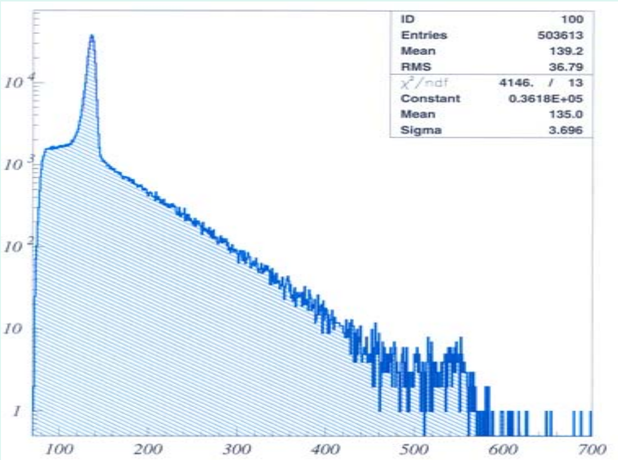
The CMK Beam



Patrizia Cenci
INFN Sezione di Perugia

E391a status

- Under completion: data taking in 2004
- engineering run falling 2002 with CsI detector



Two γ invariant mass (MeV/c²)

- DAQ using self-trigger of CsI
  - Same scheme of real run
    - Tuning / feed-back
- CsI calibration
  - Cosmic test in vacuum chamber
  - Cosmic test during stacking
  - Punch-through muon
  - Two gammas from single π^0
  - Multi-gamma decay (Kpi2, Kpi3)
- KL decay data – same format of real run
  - Develop on-line/off-line software

New sources of CPV

ICHCBH 2002 H.Nguyen

New Sources of CP Violation

CKM CP Violation is too small to explain baryon asymmetry in the universe. Lots of possible new sources:

- Multi–Higgs–doublet and supersymmetry models
- Spontaneous CP violation
- Left–right symmetric models
- Strong CP violation
- Leptonic sector

"We are willing to stake our reputation on the prediction that dedicated and comprehensive studies of CP violation will reveal the presence of New Physics"

– Bigi and Sanda, *CP Violation*