Kaon Physics

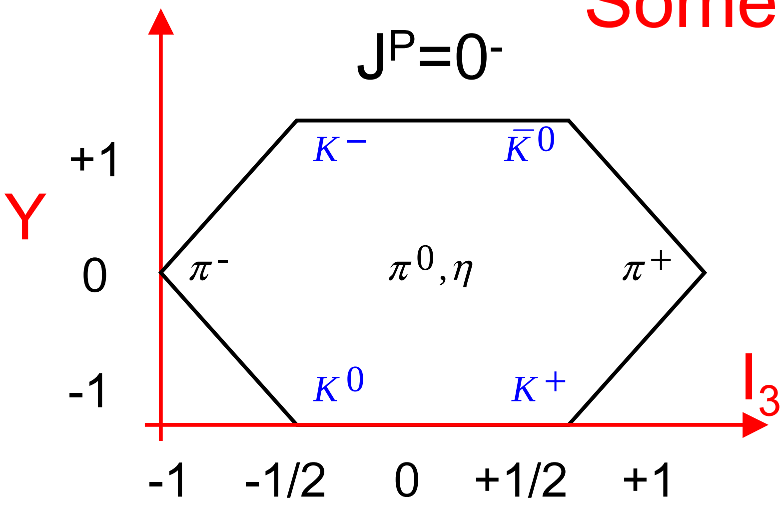
Augusto Ceccucci/CERN

Weak Interactions and Neutrinos 2002

Christchurch (NZ), 21-26 January, 2002

- Kaons have strongly influenced the construction of the Standard Model (e.g.):
  - The θ-τ puzzle → stimulus for the Lee-Yang Parity Violation Conjecture → V-A structure of weak interactions
  - Associated production → Strangeness → Quark Model
  - Absence of FCNC → GIM mechanism and charm quark
  - Discovery of CP violation → KM description → third family
- All of the above was New Physics at the time

Some properties of kaons



$$\tau_L = (5.17 \pm 0.04) \times 10^{-8}\,\mathrm{s}$$

$$\tau_S = (8.927 \pm 0.009) \times 10^{-10}\,\mathrm{s}$$

$$\boxed{\tau_L \approx \tau_S \times 579}$$

$$m_{K^0} = 497.672 \pm 0.031\ \mathrm{MeV}$$

$$\Delta m = m_L - m_S = (5.304 \pm 0.014) \times 10^{9}\,\mathrm{s}^{-1}$$

$$\tau_{K^+} = (1.2385 \pm 0.0024) \times 10^{-8}\,\mathrm{s}$$

$$m_{K^+} = 493.677 \pm 0.016\ \mathrm{MeV}$$

Neutral kaons: Production $K^0 \quad \bar{K}^0$

Decay $K_S \quad K_L$

$K_L \to \pi^+\pi^-$ CP-Violation (1964)

$$K_1 = (K^0 + \bar{K}^0)/\sqrt{2} \qquad \mathrm{CP\ even} \to \pi\pi$$

$$K_2 = (K^0 - \bar{K}^0)/\sqrt{2} \qquad \mathrm{CP\ odd} \to \pi\pi\pi$$

$$K_S = (K_1 + \varepsilon K_2)/\sqrt{1+\varepsilon^2}$$

$$K_L = (K_2 + \varepsilon K_1)/\sqrt{1+\varepsilon^2}$$

$$\varepsilon \simeq 2.27 \times 10^{-3} \qquad \arg(\varepsilon) \simeq \tan^{-1}\frac{2\Delta m}{\Delta\Gamma} \simeq 43.5^\circ$$

CP-Violation in Semi-leptonic Decays

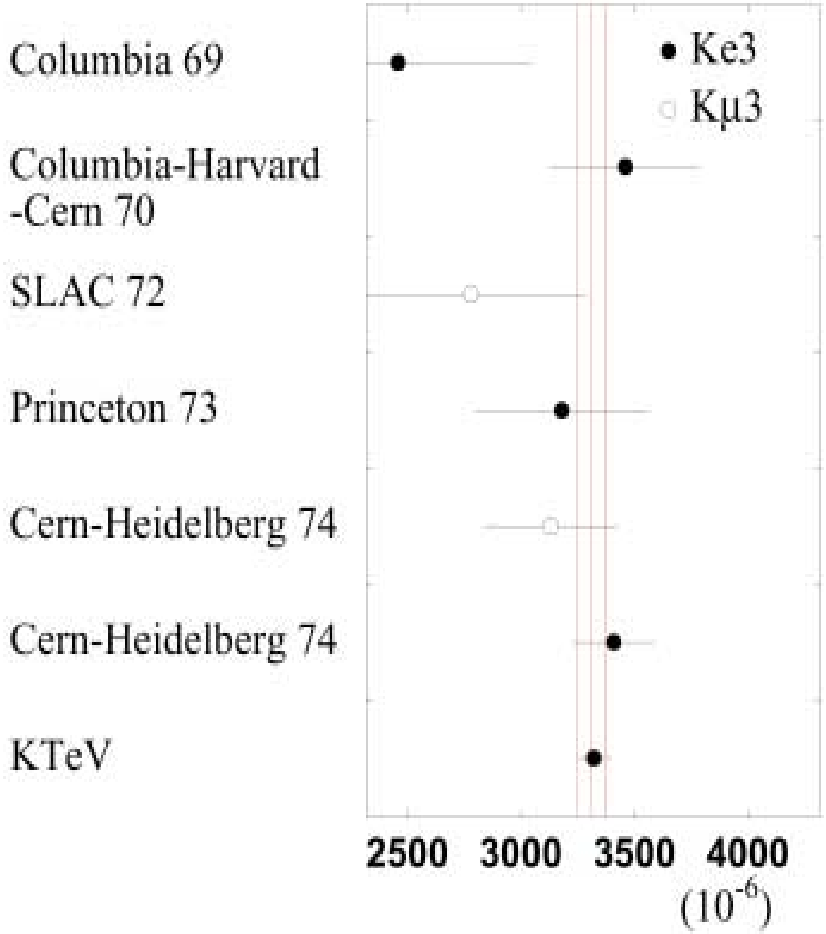
$$\delta_L = \frac{\Gamma(K_L \to e^+\pi^-\nu) - \Gamma(K_L \to e^-\pi^+\bar{\nu})}{\Gamma(K_L \to e^+\pi^-\nu) + \Gamma(K_L \to e^-\pi^+\bar{\nu})} = 2\,\mathrm{Re}\,\varepsilon$$

- 298 Million $K_L \to \pi e \nu$ collected by KTeV-E832 during the 1997 run
- Raw δ_L = 3417± 58 ppm
- Main Correction:

$\pi^+\pi^-$ difference in CsI: -156 ±10 ppm

- Total correction: -95 ± 47 ppm

δ_L= 3322 ± 58_{sta} ± 47_{sys} ppm
3322 ±74 ppm (comb.)



T- Violation in Neutral Kaon mixing

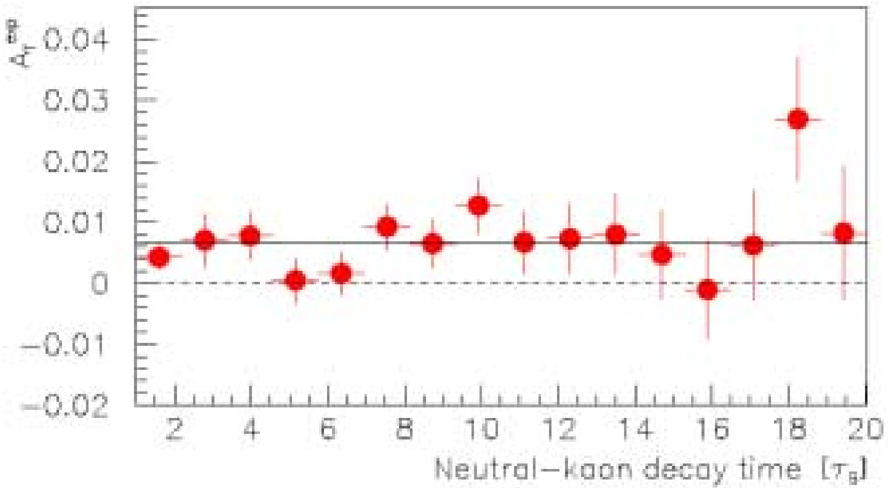
$$A_T = \frac{\Gamma(\overline{K}^0 \to K^0) - \Gamma(K^0 \to \overline{K}^0)}{\Gamma(\overline{K}^0 \to K^0) + \Gamma(K^0 \to \overline{K}^0)}$$

CERN-CPLEAR: tagged strangeness at t=0

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

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

Assuming CPT conservation in semi-leptonic decays:



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

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

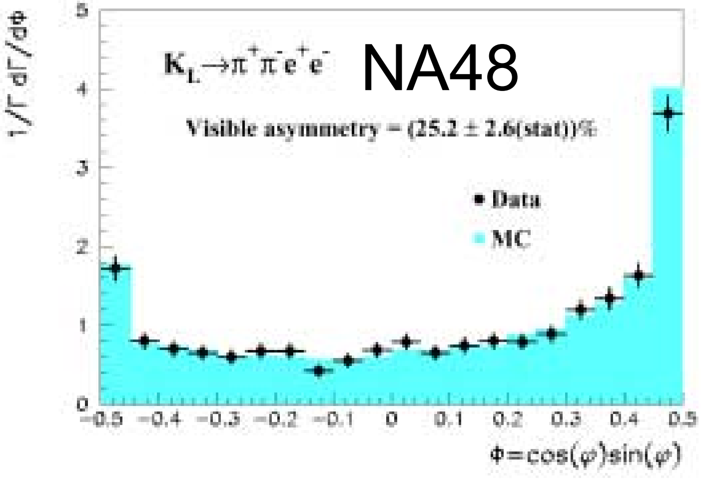
$\mathrm{Im}\,x_+ = T-\text{violation} \quad \Delta S \neq \Delta Q$

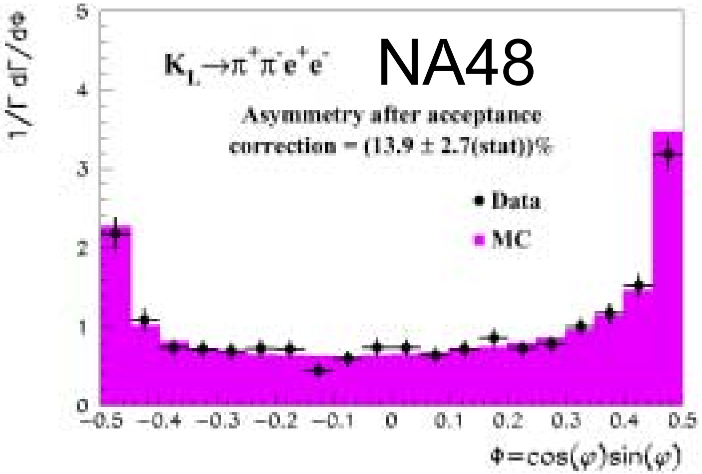
$4\,\mathrm{Re}\,\varepsilon = 6.2 \pm 1.4_{sta} \pm 1.0_{sys} \times 10^{-3}$

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

(refer to Eur. Phys. J. C 22 (2001) for detailed description of T-Violation and CPT-Conservation CPLAR tests in semi-leptonic neutral kaon decays by CPLEAR)

CP-Violation in $K_L \rightarrow \pi^+\pi^-e^+e^-$



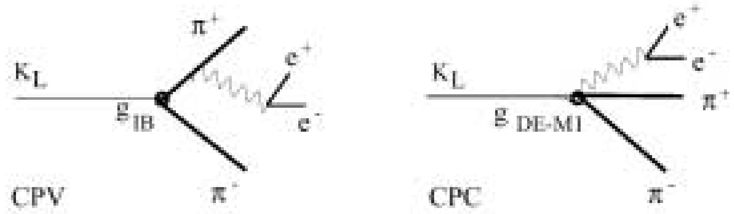


Prediction Heiliger and Sehgal 1992

Large CP asymmetry in the angle ϕ between the $\pi^+\pi^-$ and e^+e^- planes:

$|A(\phi)| \approx 14\%$

- $K_L \rightarrow \pi^+\pi^-e^+e^-$ main contributions:



BR≈3 10^{-7}

Asymmetry measured by KTeV, then by NA48:

KTEV PRL84 (2000):

$A(\phi)=13.6 \pm 2.5_{sta} \pm 1.2_{sys}$ %

NA48 (Preliminary):

$A(\phi)=13.9 \pm 2.7_{sta} \pm 2.0_{sys}$ %

Direct CP Violation in 2π Decays

ε: CP-Violation in the mixing — $K_L \approx K_2 + \varepsilon K_1$ → ππ

⇒ |ΔS|=2 Indirect

ε': CP-Violation in a decay amplitude — $K_L \approx K_2 + \varepsilon K_1$, K_2 → ππ

⇒ |ΔS|=1 Direct

Theory:

$$A(K^0 \to \pi\pi, I) = A_I e^{i\delta_I} \qquad I=0,2$$

$$\varepsilon' \approx i e^{i(\delta_2 - \delta_0)} \frac{\mathrm{Im}(A_2 A_0^*)}{\sqrt{2}|A_0|^2}$$

Experiment:

$$\eta_{+-} \simeq \varepsilon + \varepsilon'$$

$$\eta_{00} \simeq \varepsilon - 2\varepsilon'$$

$$6\,\mathrm{Re}\frac{\varepsilon'}{\varepsilon} \simeq 1 - \left|\frac{\eta_{00}}{\eta_{+-}}\right|^2$$

CKM description of CP-Violation

Need a complex factor in the quark-quark current $J_\mu = \bar{U}\gamma_\mu(1-\gamma_5)D$

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

$N_g=2$ $N_{phase}=0$ $\Rightarrow$ No CP-Violation

$N_g=3$ $N_{phase}=1$ $\Rightarrow$ CP-Violation Possible

Unitarity Conditions: $\sum_{i=u,c,t} V_{ij}V_{ik}^* = \sum_{i=u,c,t} V_{ji}^* V_{ki} = \delta_{jk}$

For $j \neq k$ → 6 triangles all with the same area

$J_{CP}=2\times(\text{Triangle Area})$ Is the unique CP Violation measure in SM

In Kaon Physics is convenient to write:

$$J_{CP}=Im(V_{ud}^*V_{us}V_{ts}^*V_{td})=Im(\lambda_u^*\lambda_t)\approx \sin\theta_c\cos\theta_c Im(\lambda_t)$$

With θ_c = Cabibbo angle and $\lambda_\alpha = V_{\alpha s}^* V_{\alpha d}$

Master Formula for ε'/ε in SM (Trieste group)

$$\frac{\varepsilon'}{\varepsilon} = e^{i\phi} \frac{G_F \omega}{2|\varepsilon| \operatorname{Re} A_0} \operatorname{Im} \lambda_t \left[\Pi_0 (1 - \Omega_{IB}) - \frac{1}{\omega} \Pi_2 \right]$$

$$\omega = \frac{A(K_S \to \pi\pi, I=2)}{A(K_S \to \pi\pi, I=0)} \approx 0.045 \qquad \phi = \frac{\pi}{2} + \delta_2 - \delta_0 \approx 0^\circ$$

$$\Pi_0 = \frac{1}{\cos \delta_0} \sum_i y_i \operatorname{Re} \langle Q_i \rangle_0 \qquad \Pi_2 = \frac{1}{\cos \delta_2} \sum_i y_i \operatorname{Re} \langle Q_i \rangle 2$$

- 1976 Ellis, Gaillard and Nanopoulos: ε'/ε > 0 is expected in the CKM description
- Gluonic Pinguins can lead to large ε'/ε
- Large top mass → contribution of EW Pinguins leads to cancellations
- Short distance physics is in the Wilson Coefficients y_i computed to NLO (Buras et al., Martinelli et al.)
- Low energy physics in the hadronic matrix elements Q_i: eventually the may be reliably calculated in the lattice
- Current Predictions of ε'/ε in SM range from $-4 \div +40 \times 10^{-4}$

⇒Refer to Fabbrichesi's talk on Kaon theory

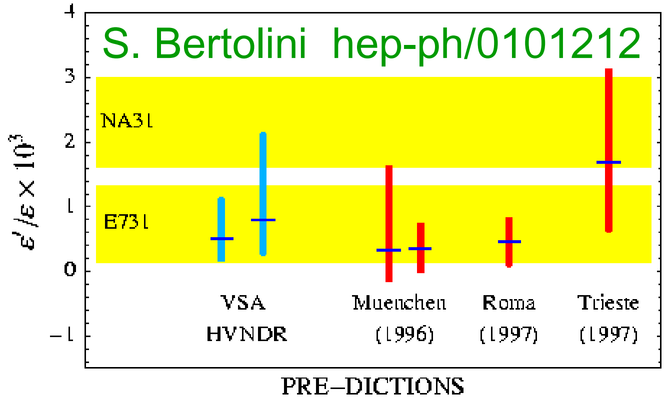
ε'/ε Experiments

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

Two experiment published precise results in 1993

•E731 FNAL Re ε'/ε=$(7.4\pm5.9)\times10^{-4}$ ⇒ no effect

•NA31 CERN Re ε'/ε=$(23.0\pm6.5)\times10^{-4}$ ⇒ >3.5 σ



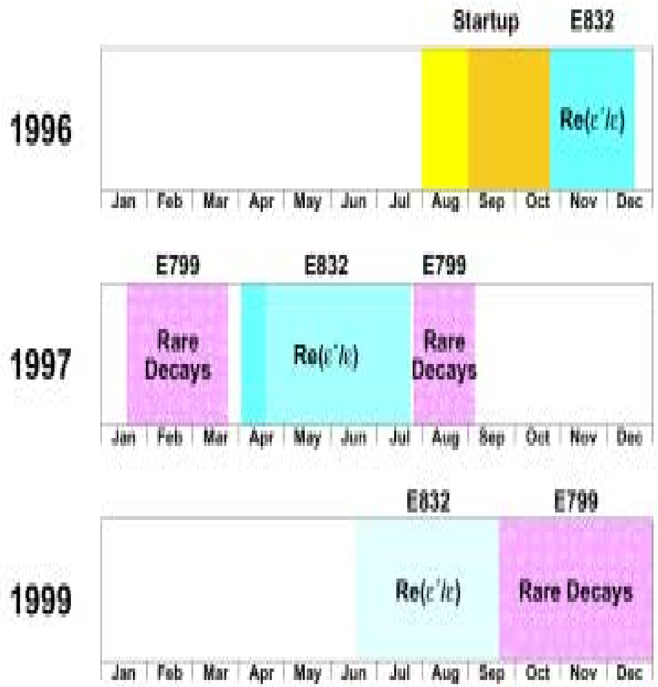
New Round: KTeV and NA48

•Simultaneous collection of the four decay modes → Detector inefficiencies drop out

•Precise magnetic spectrometer and EM calorimeter → small backgrounds from other kaon decays and good control of the decay volume

	KTEV-FNAL	NA48-CERN
Proton beam	Tevatron (800 GeV)	SPS (450 GeV)
K_S Production	Regenerator	2^{nd} 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

Data Taking



KTeV

KTeV ε'/ε statistics ($\times 10^6$ $K_L \rightarrow 2\pi^0$):
1996+1997 ≈ 2.5 (This talk)
1999 ≈ 1996+1997

96+97a: Re ε'/ε=28.0±4.1× 10^{-4}
PRL 83 (1999)

NA48

- 1997-1999: ~240 days
- 2000: neutral checks
- 2001: 80 days
- ε'/ε and rare decays collected simultaneously

NA48 ε'/ε statistics ($\times 10^6$ $K_L \rightarrow 2\pi^0$):

1997 ≈ 0.5

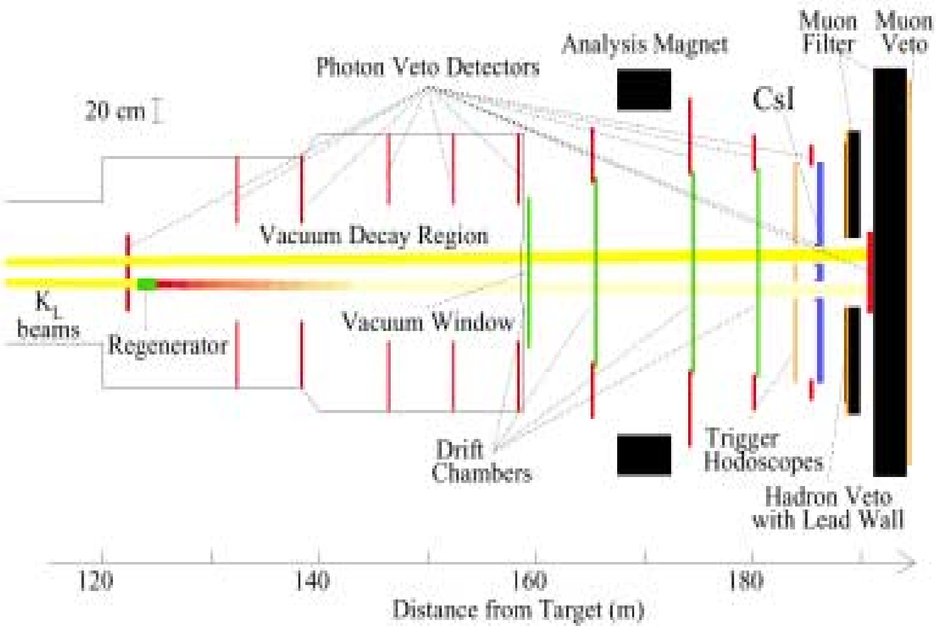
1998+1999 ≈ 3.3 (This talk)

2001 ≈1.4

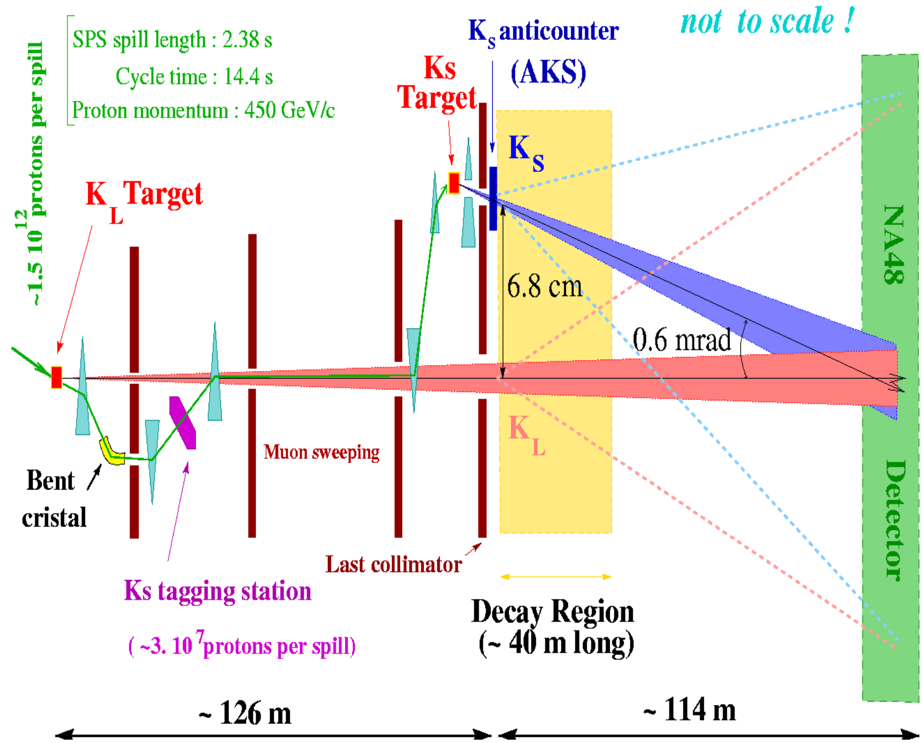
1997: Re ε'/ε= 18.5±7.3× 10^{-4}
PLB 465 (1999)

Beams

KTEV

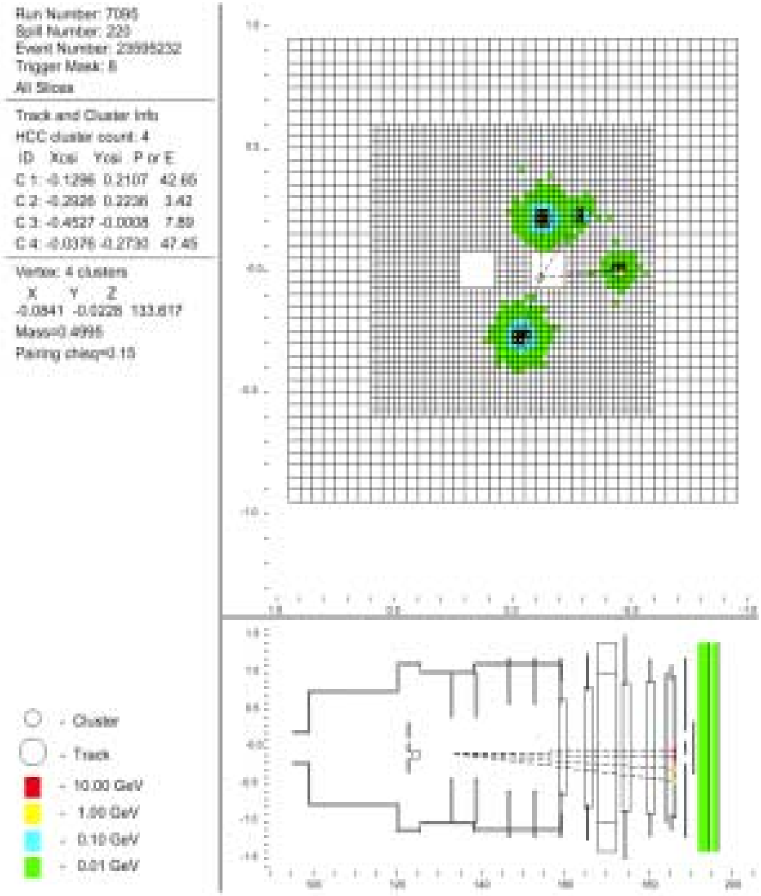


NA48

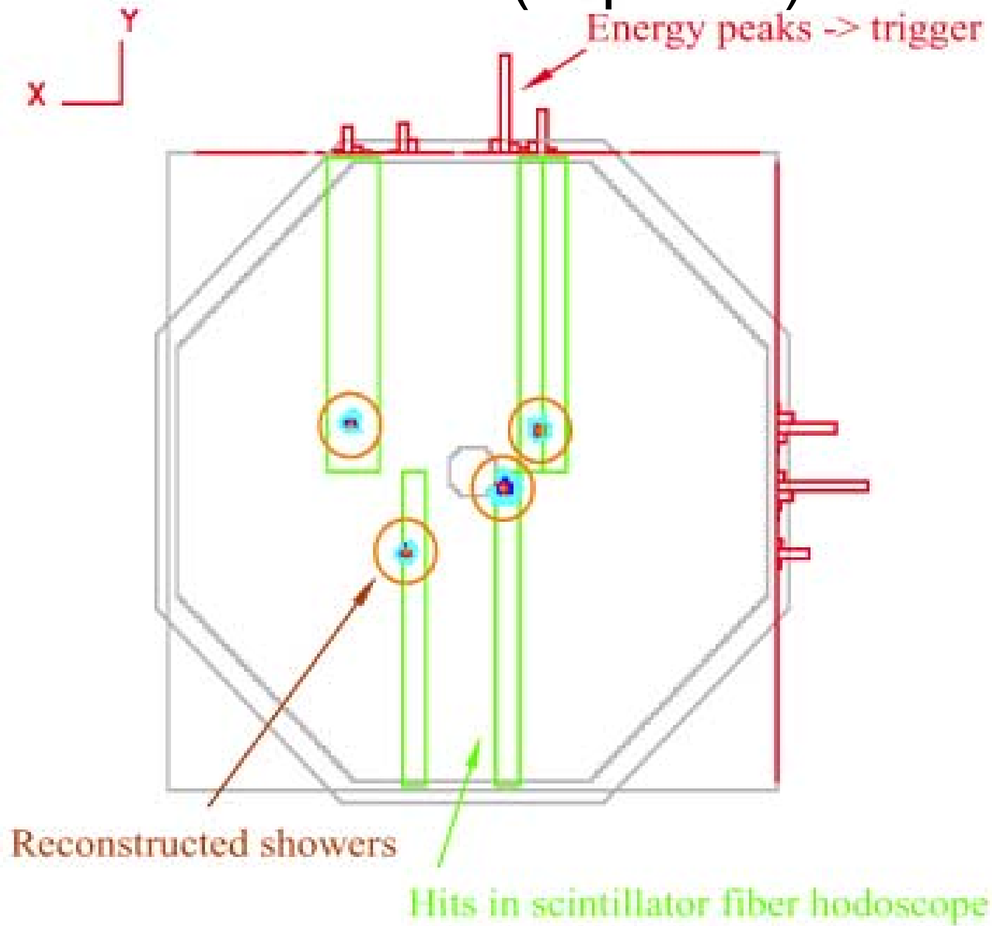


Detectors: K→$\pi^0\pi^0$

KTeV (pure CsI)

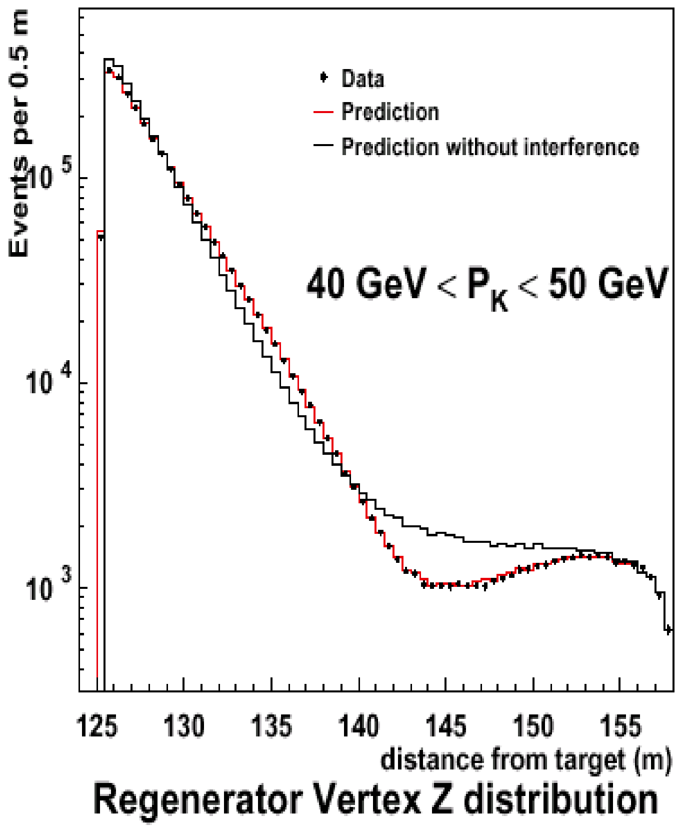


NA48 (Liquid Kr)



Regenerator method (KTeV)

$K_L + \rho K_S$



Advantage: The ratio of regenerated and vacuum decays is fixed by construction

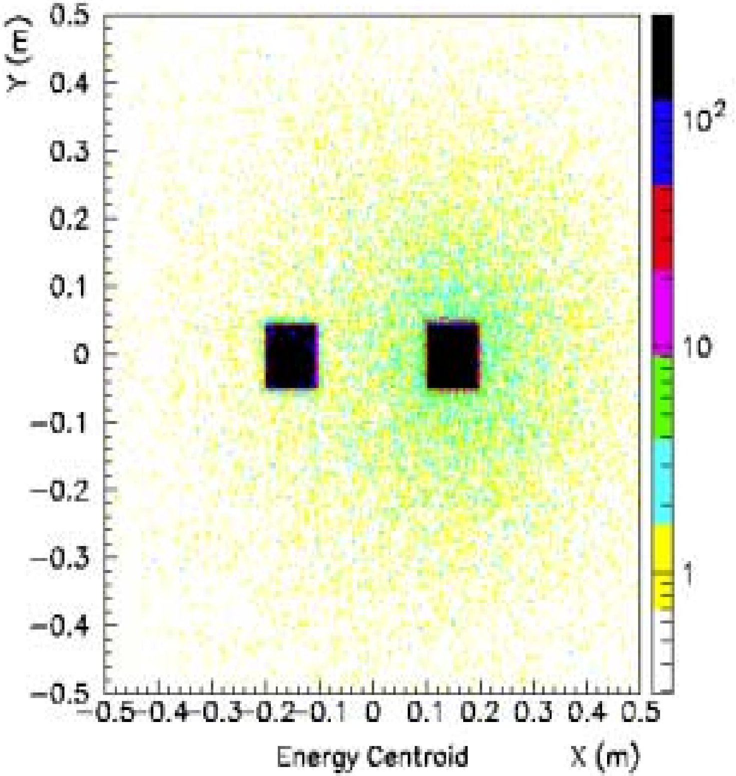
Feature: $\pi\pi$ from K_S-K_L interference

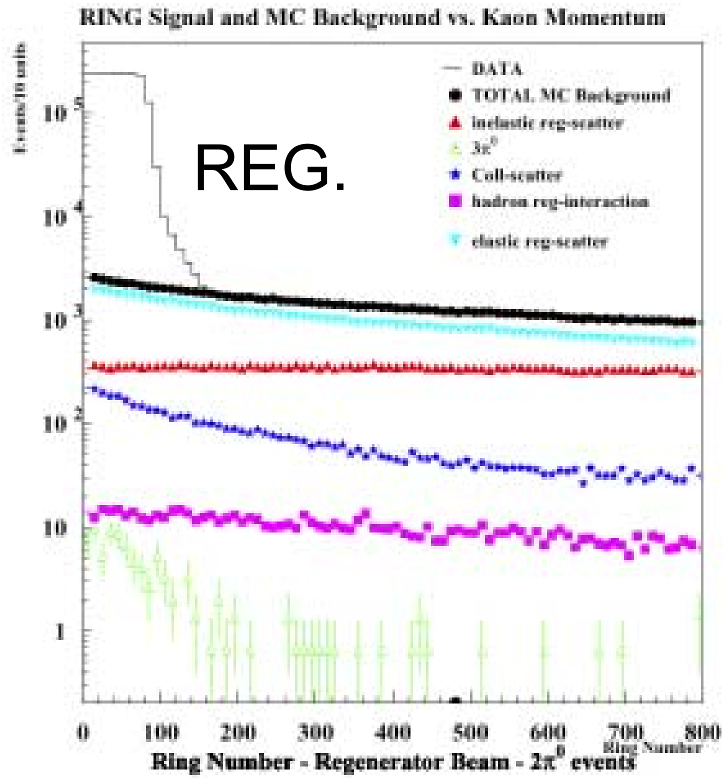
- It complicates the fitting
- It allows to measure $\Delta m, \phi_{+-}, \phi_{00}$

$\pi^+\pi^-$ decays from reg. (KTeV) or 2nd target (NA48) (for illustration only)

	K_s	Int.	K_L
KTeV	1	1/17	1/300
NA48	1	1/500	1/100000

Regenerator Scattering (KTeV)





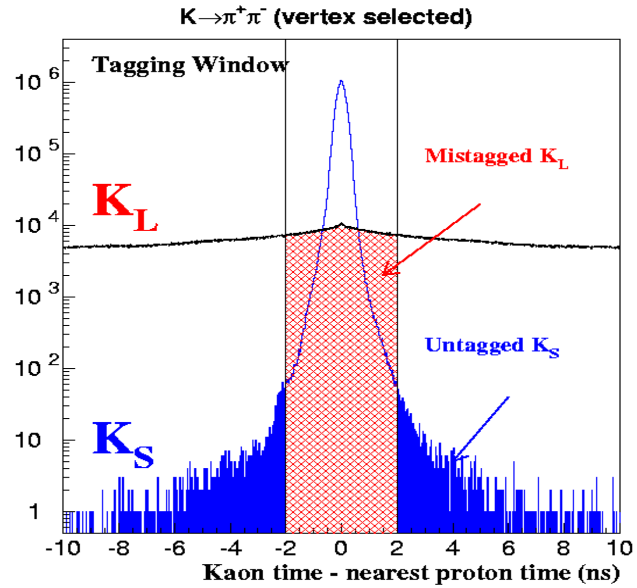
Background to $\pi^0\pi^0$ Regenerated beam: 1.1%

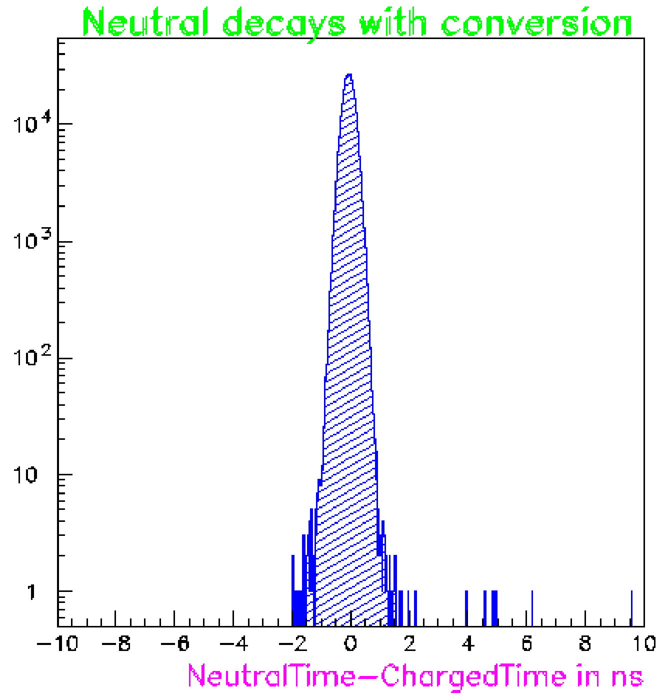
Vacuum beam: 0.25 %

K_S Tagging method (NA48)

TOF between T_{proton} and T_{kaon}

- T_{proton}: scint. counters on p beam
- T_{kaon}: $\pi^0\pi^0$(LKr),$\pi^+\pi^-$(hodoscope)





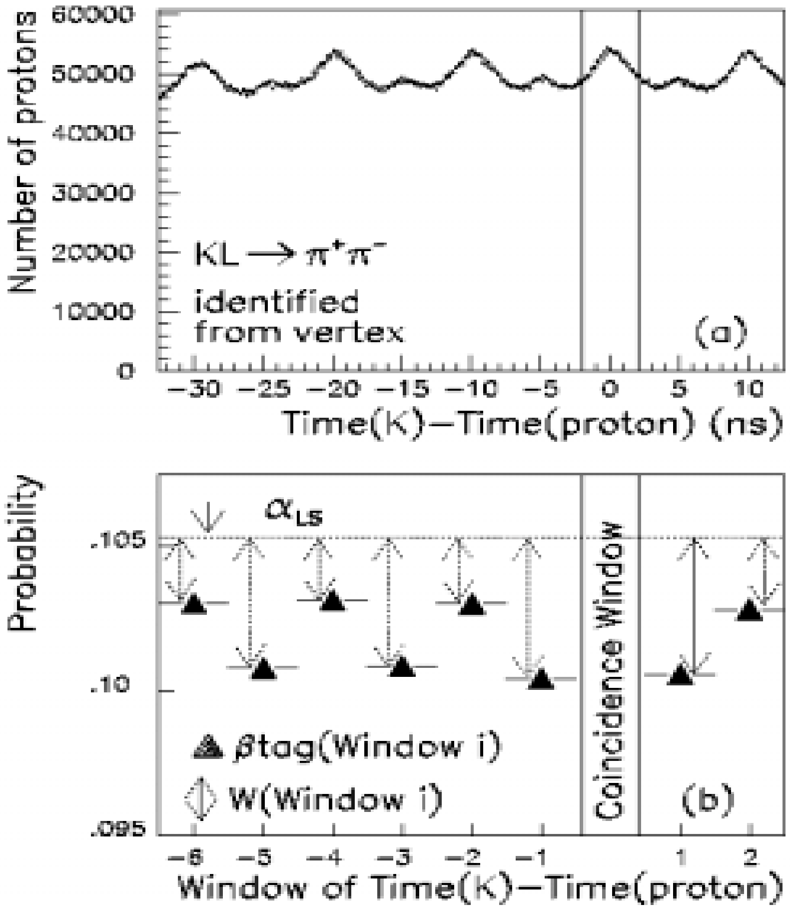
$\alpha^{\pm}_{SL}=1.63\pm0.03 \times 10^{-4}$

80% due to tagger counter which is democratic

Difference between charged/neutral time: $<2.5 \times 10^{-5}$

No effect within $\pm0.5 \times 10^{-4}$

NA48 Accidental Tagging ($K_L \rightarrow K_S$)



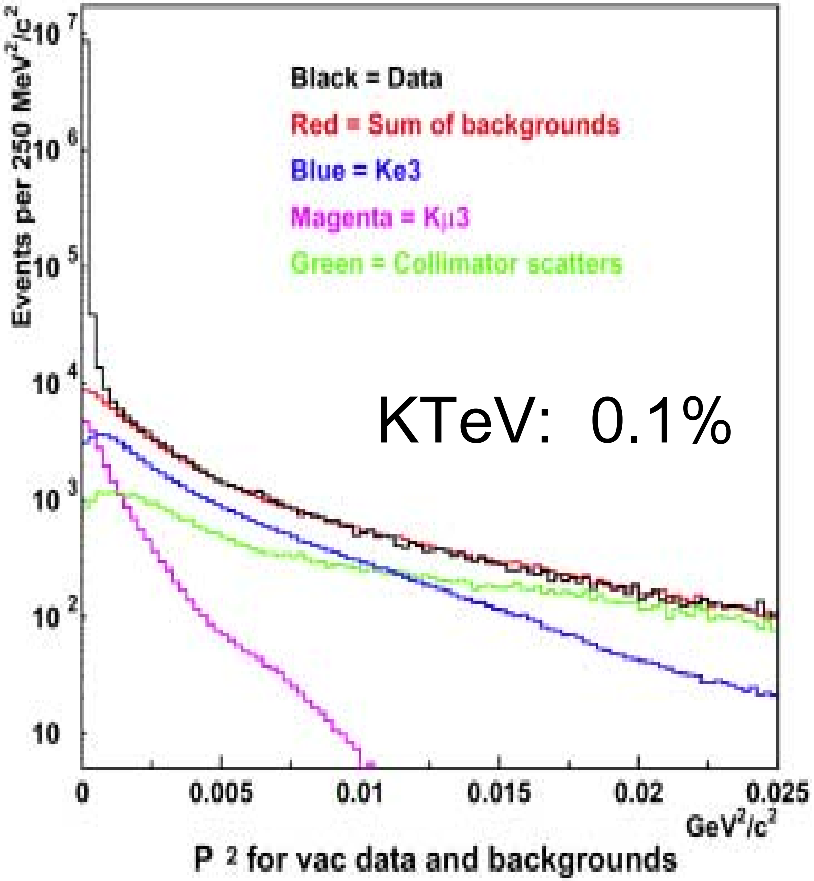
- Accidental protons falling in the tagging window: $K_L \rightarrow K_S$
- Measure $\pi^+\pi^-$/ $\pi^0\pi^0$ accidental tagging in side bands
- Extrapolate to tagging window using vertex ($\pi^+\pi^-$) or $3\pi^0$

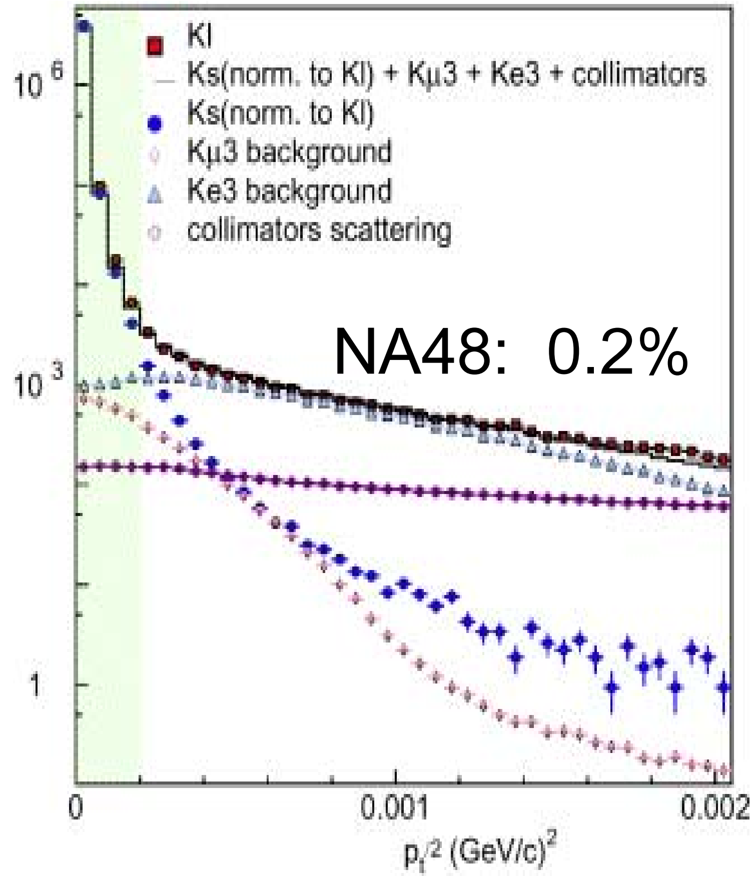
$\Delta\alpha_{LS}$ = difference in accidental tagging between $\pi^+\pi^-$ and $\pi^0\pi^0$ = $4.3 \pm 1.8 \times 10^{-4}$

The difference is consistent with the higher sensitivity of the charged trigger and reconstruction to accidental activity

Backgrounds to $K_L \rightarrow \pi^+\pi^-$

$$\frac{BR(K_L \to \pi e \nu)}{BR(K_L \to \pi^+\pi^-)} \approx 189 \qquad \frac{BR(K_L \to \pi \mu \nu)}{BR(K_L \to \pi^+\pi^-)} \approx 132$$

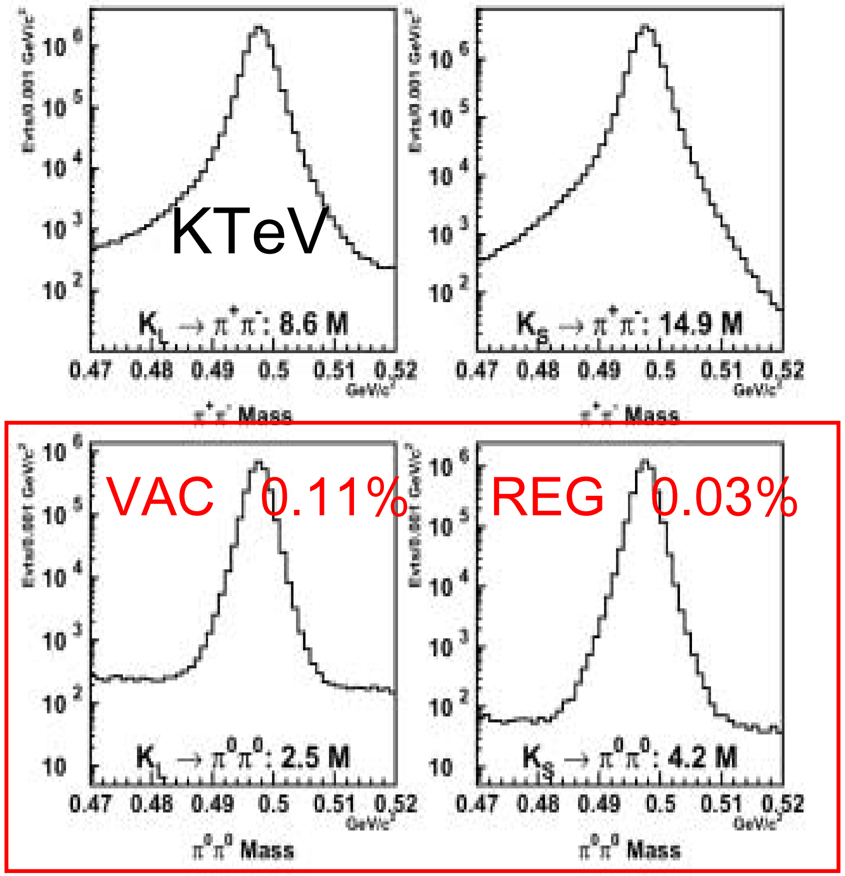


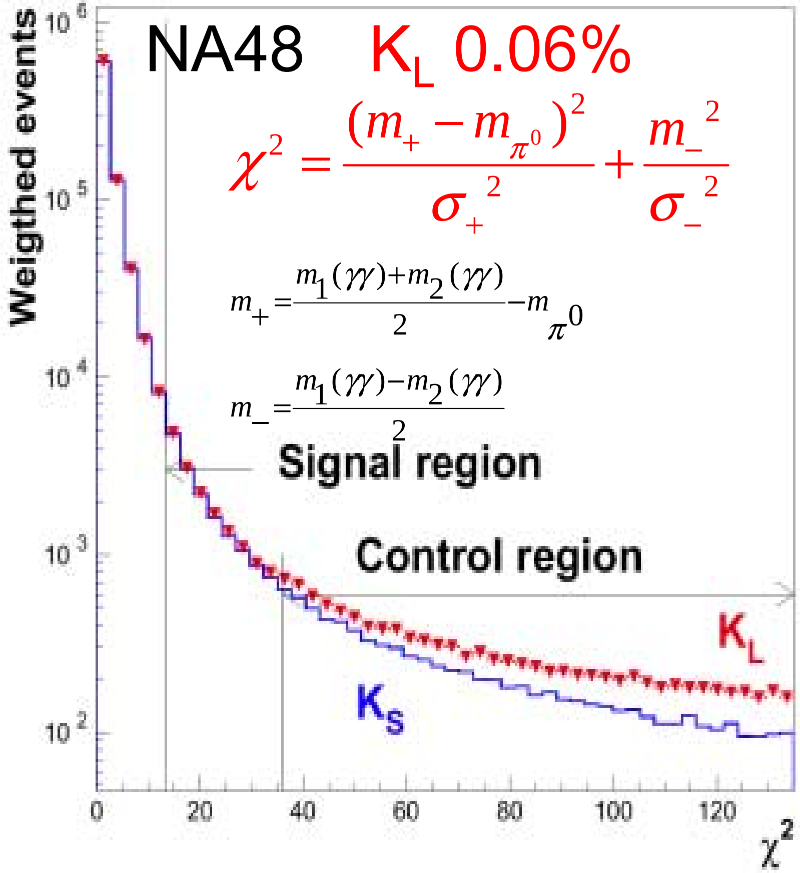


Backgrounds from $K_L \rightarrow 3\pi^0$

$$\frac{BR(K_L \to 3\pi^0)}{BR(K_L \to 2\pi^0)} \approx 228$$

- It can mimic the signal if 2γ are lost





$$\chi^2 = \frac{(m_+ - m_{\pi^0})^2}{\sigma_+^2} + \frac{m_-^2}{\sigma_-^2}$$

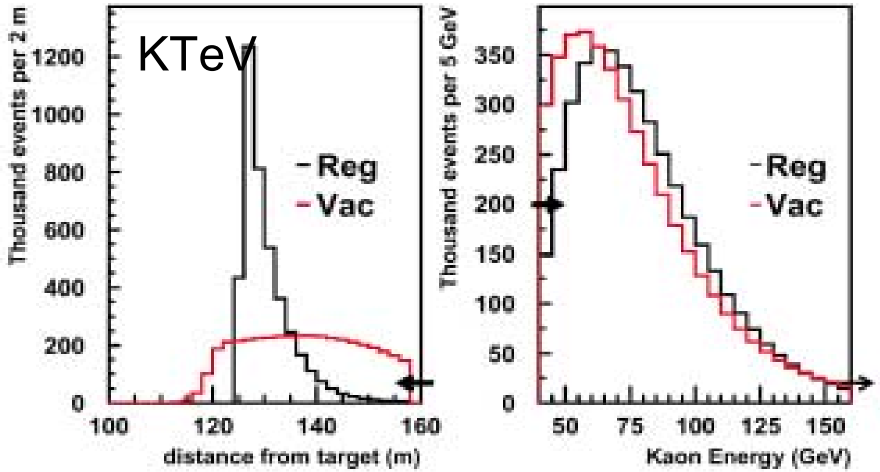
$$m_+ = \frac{m_1(\gamma\gamma) + m_2(\gamma\gamma)}{2} - m_{\pi^0}$$

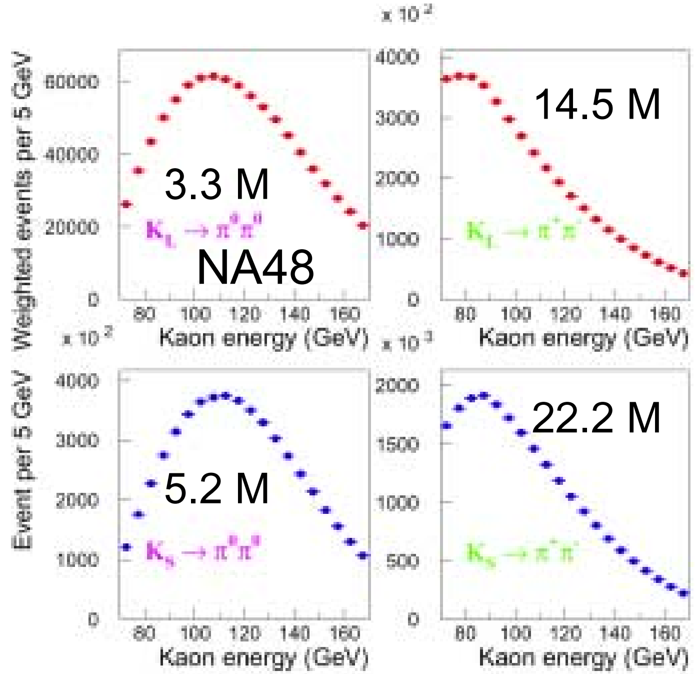
$$m_- = \frac{m_1(\gamma\gamma) - m_2(\gamma\gamma)}{2}$$

Definition of the Decay Volume

•Distance scale ⇔ energy scale

→Experiments rely on calibration of EM calorimeters





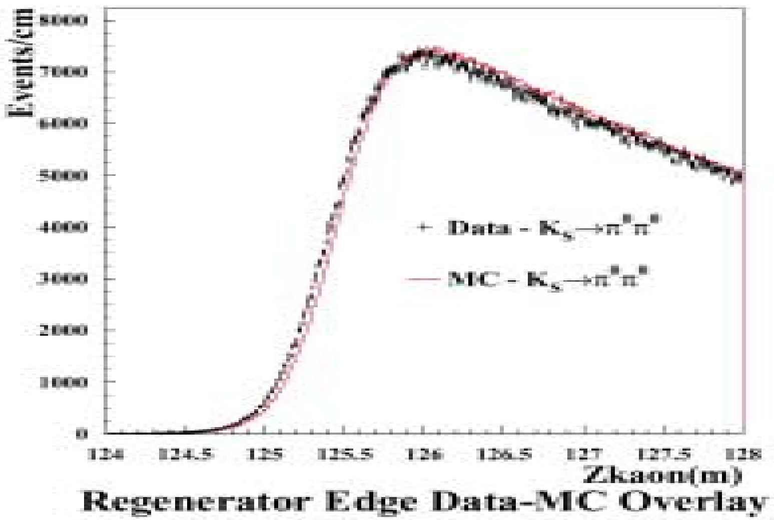
Fiducial cut	KTeV	NA48
K_S Upstream	Anti-counter	Anti-counter
K_L Upstream	mask	t_{rec}/τ_S
K_S Downstream	Z_{rec}	t_{rec}/τ_S
K_L Downstream	Z_{rec}	t_{rec}/τ_S

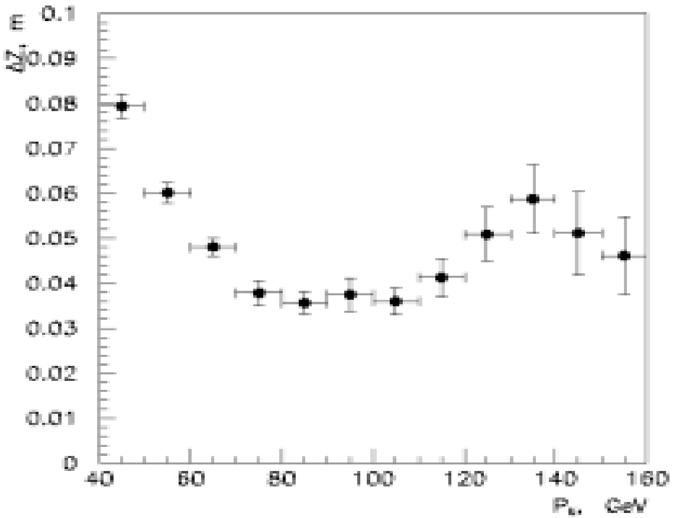
•Sharp anti-counter cut for upstream K_S:

- •Calibration of the distance/energy scale
- •Reduce the error due to energy scale uncertainty

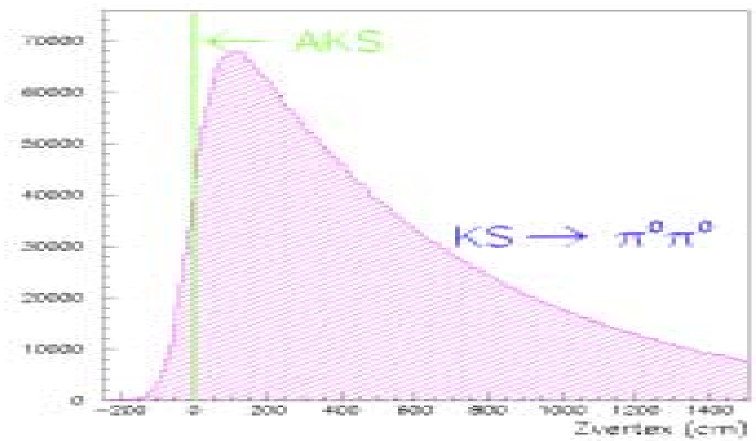
Energy Calibration $K_S \rightarrow \pi^0\pi^0$

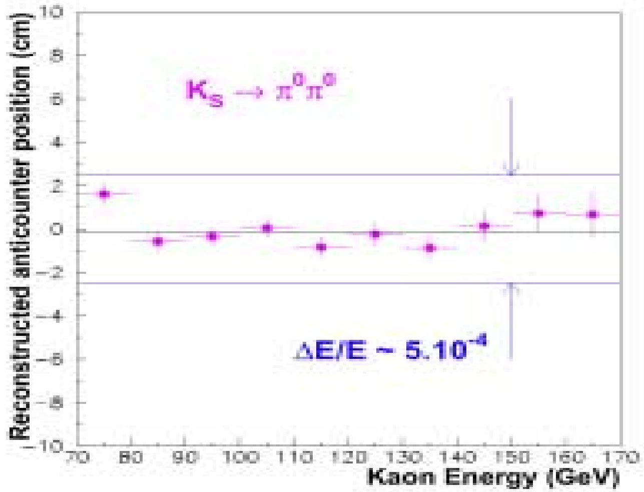
KTeV





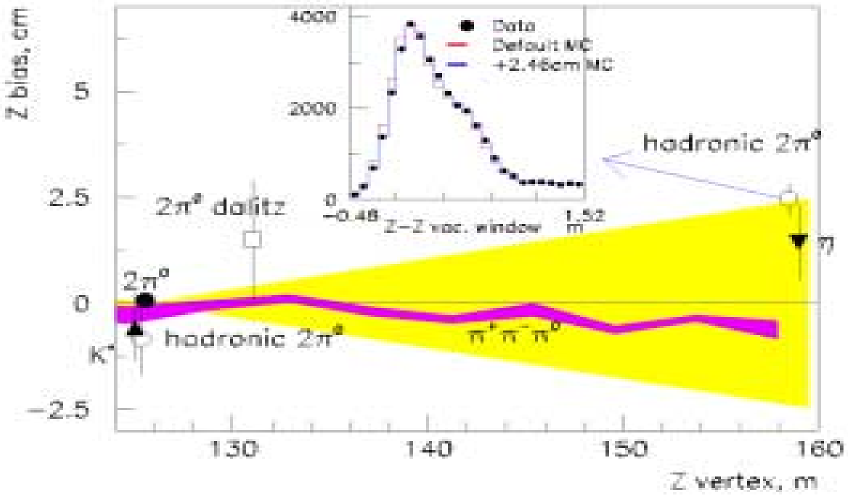
NA48



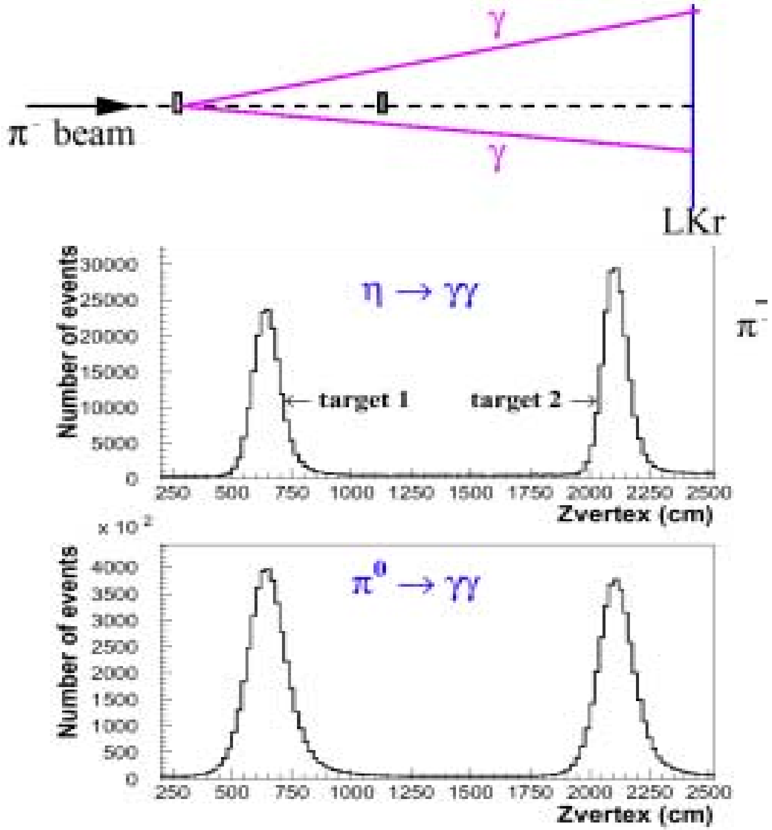


Linearity of the Distance Scale

KTeV



NA48



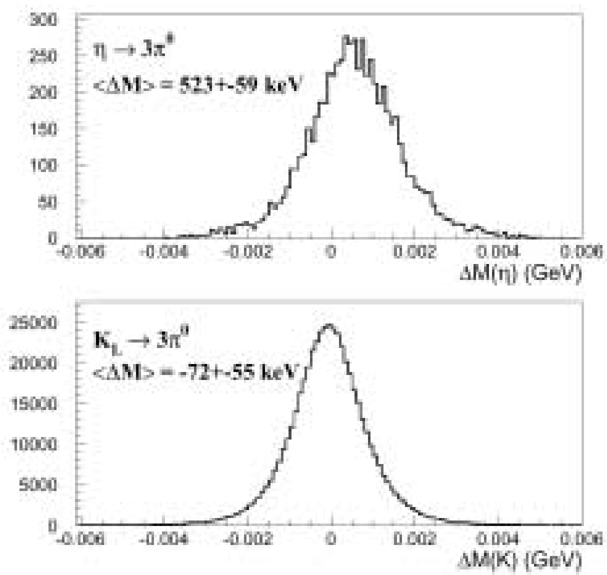
$<7\ 10^{-4}$

Check of the Energy Scale (NA48)

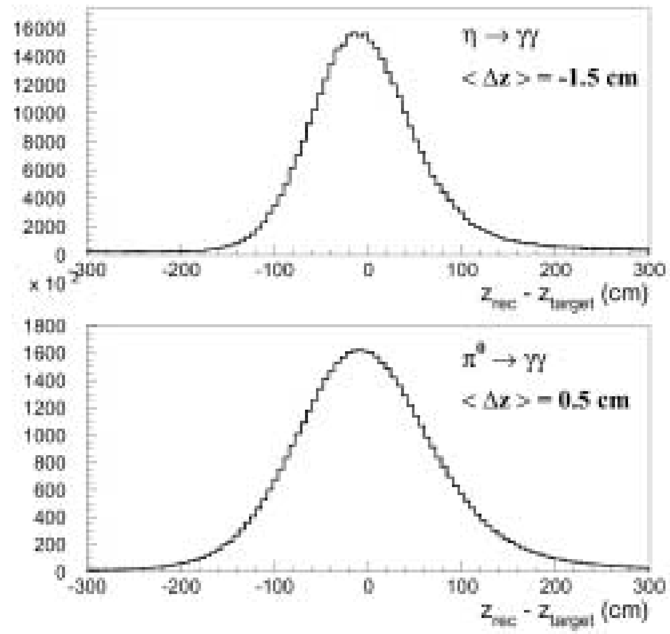
New preliminary measurement of η mass
Energy scale independent method:
measure $M_\eta/M_{\pi 0}$

$<\Delta M>=M_\eta^{NA48} - M_\eta^{PDG}$

$M_\eta^{NA48}=547.823 \pm 0.020_{stat} \pm 0.055_{syst}$ MeV



Use new M_η^{NA48} to check energy scale

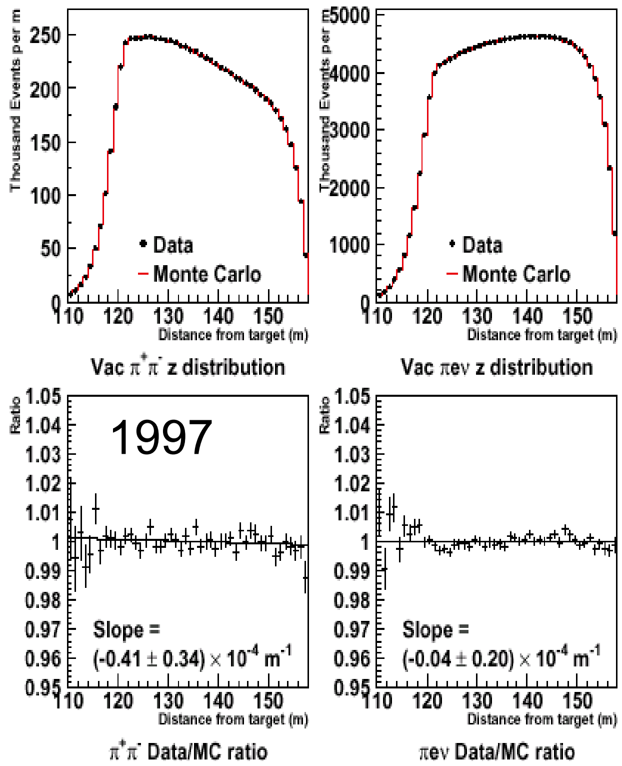


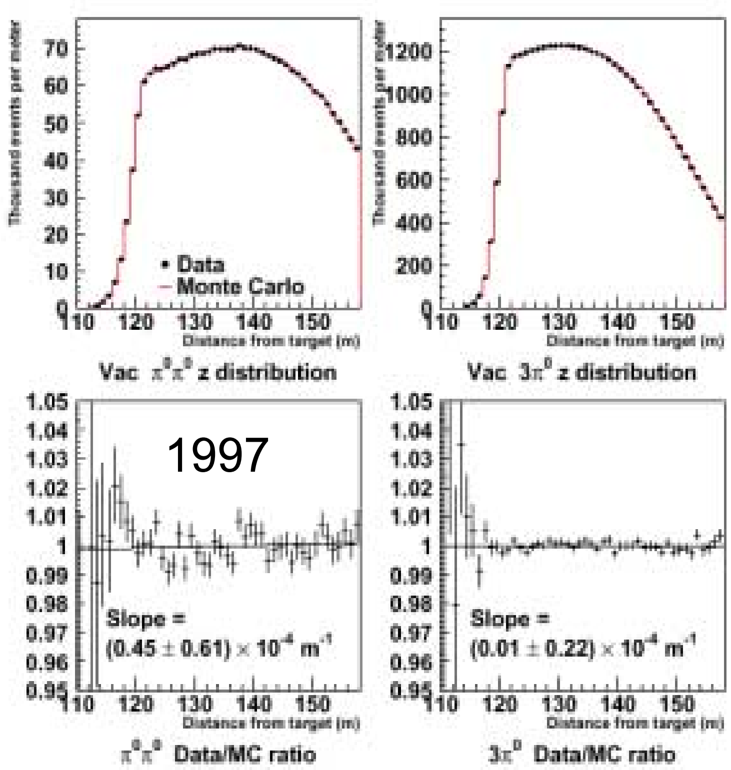
Good to ±2 10^{-4}

Allowed syst. on energy scale ±3 10^{-4}

Final test of MC/acceptance (KTeV)

- Vacuum beam: use $K_L \rightarrow \pi e \nu$ and $K_L \rightarrow 3\pi^0$ to adjust simulation

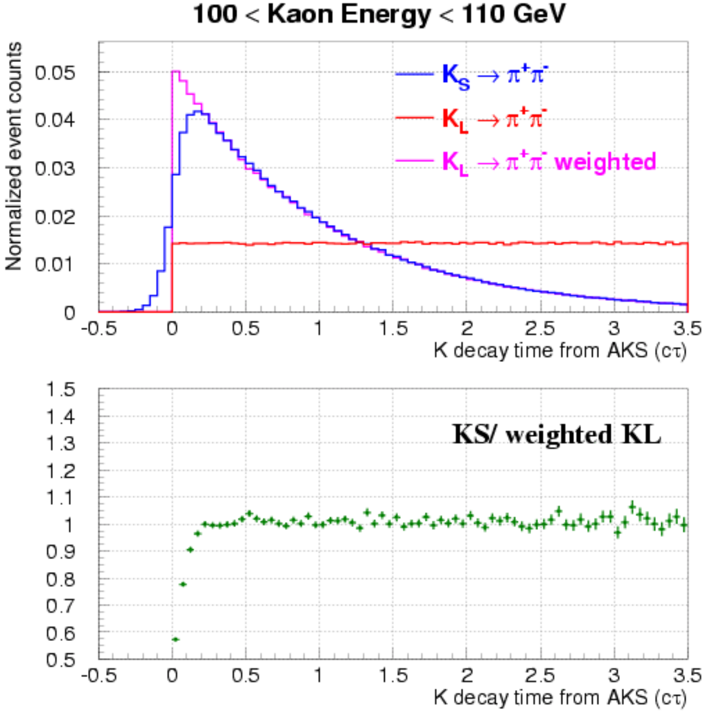


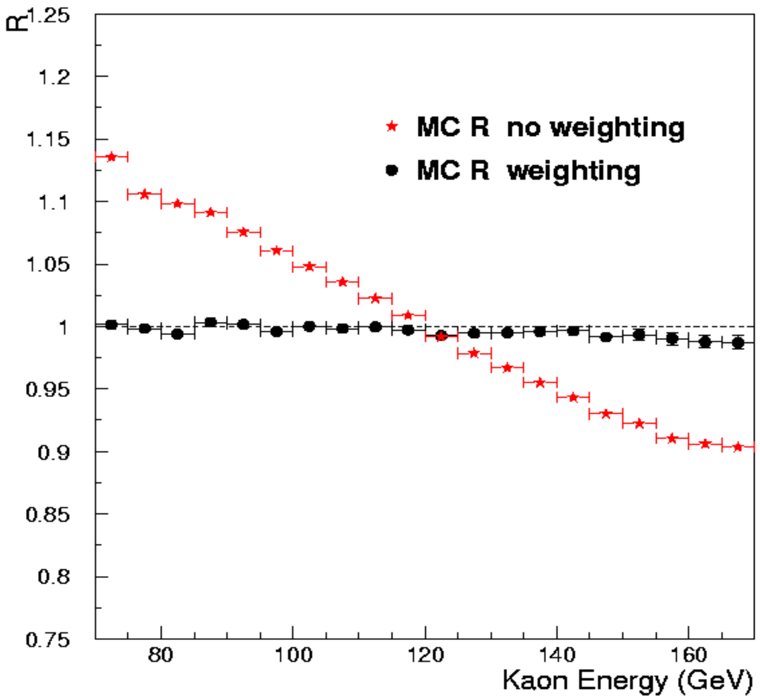


K_L Weighting (NA48)

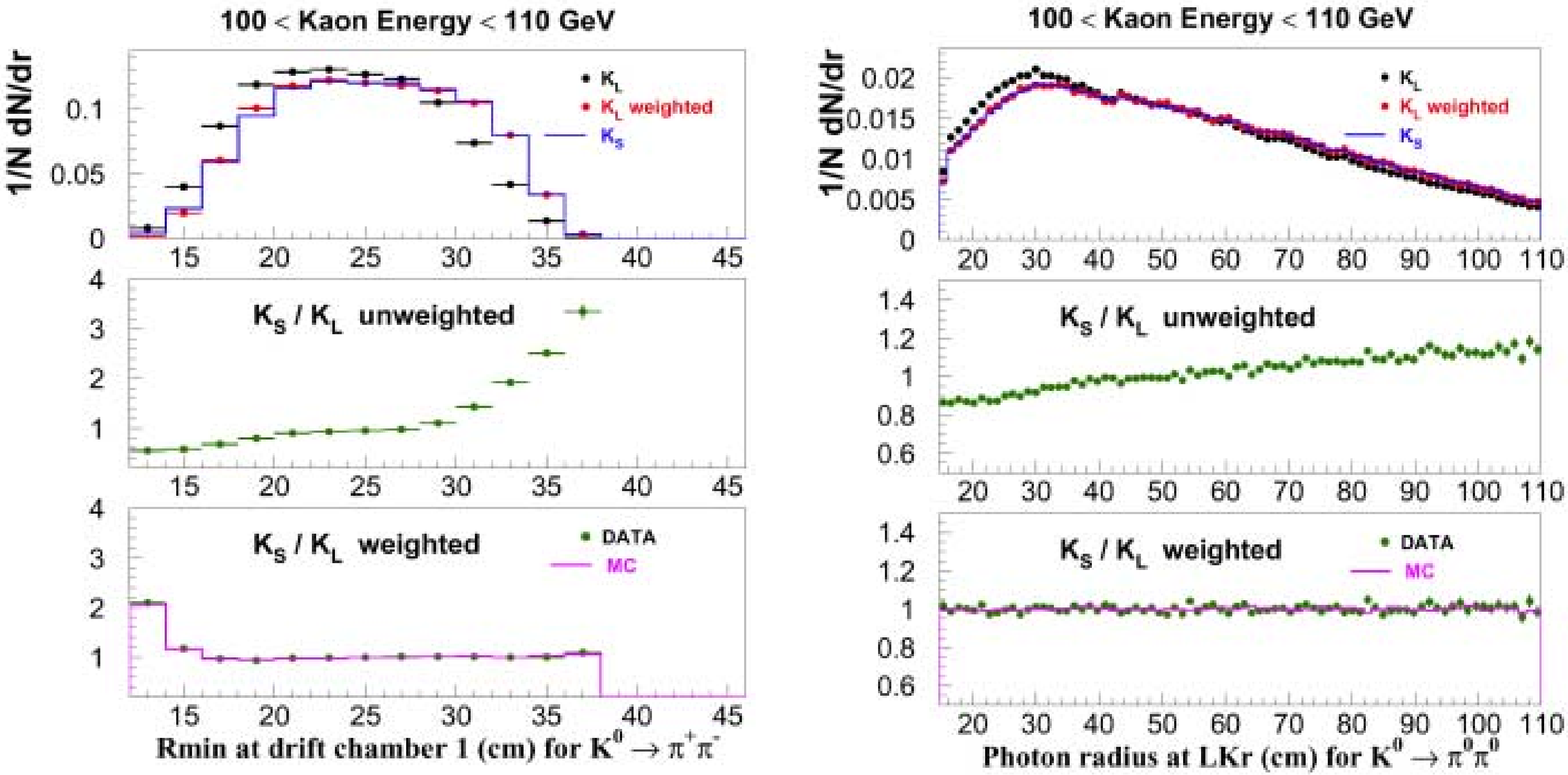
$$W(\tau) = \frac{I_{2\pi}(\tau \text{ from } K_S \text{target})}{I_{2\pi}(\tau \text{ from } K_L \text{target})}$$

$$I_{2\pi}(\tau) = e^{-\frac{\tau}{\tau_S}} + |\eta|^2 e^{-\frac{\tau}{\tau_L}} + 2D_P e^{-\frac{1}{2}\tau(\frac{1}{\tau_S}+\frac{1}{\tau_L})} \cos(\Delta m\tau - \phi)$$

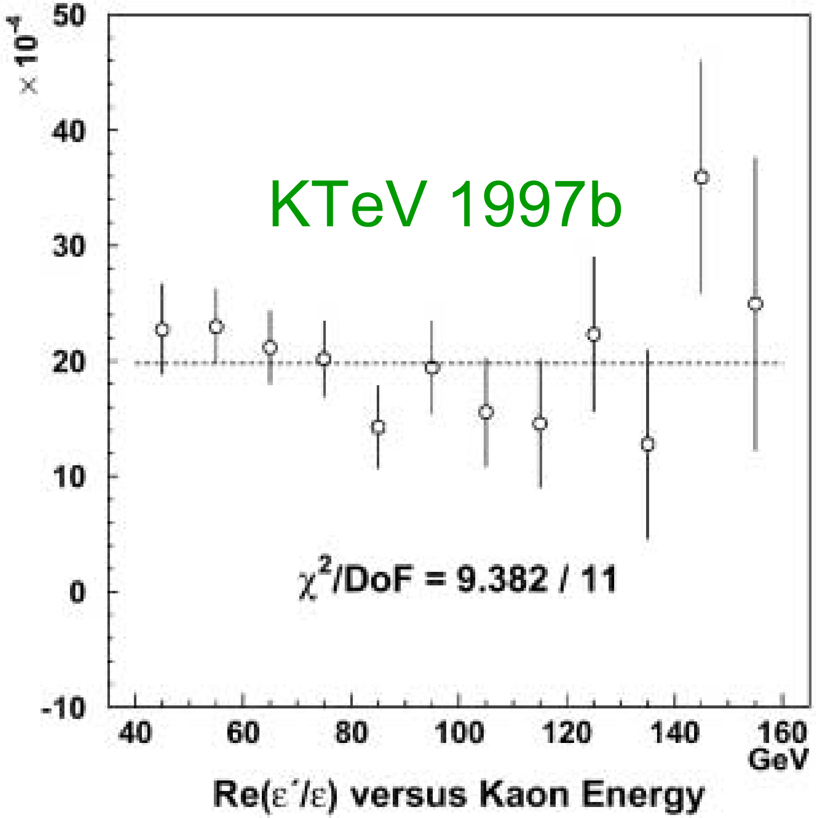


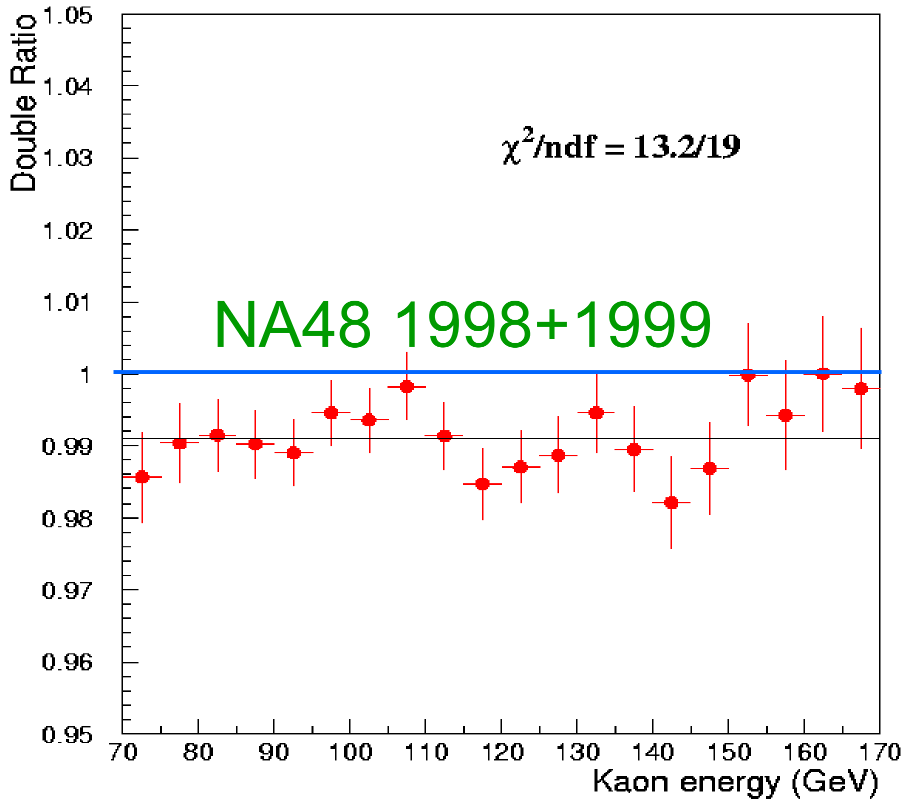


Event weighting (NA48)



Results





Re ε'/ε =
$19.8 \pm 1.7_{stat} \pm 2.3_{syst} \pm 0.6_{MC}\ 10^{-4}$

Re ε'/ε =
$15.0 \pm 1.7_{stat} \pm 2.1_{syst} \times 10^{-4}$

Systematics

KTeV 1996+1997 on ε'/ε

Source of uncertainty	Uncertainty ($\times 10^{-4}$) from $\pi^+\pi^-$	Uncertainty ($\times 10^{-4}$) from $\pi^0\pi^0$
Class 1: Data collection		
Trigger and level 3 filter	0.56	0.18
Class 2: Event reconstruction, selection, backgrounds		
Energy/Resolution scale	0.16	1.27
Calorimeter nonlinearity	—	0.66
Detector calib, align	0.28	0.38
Analysis cut variations	0.23	0.37
Background subtraction	0.20	1.07
Class 3: Detector acceptance		
Limiting apertures	0.30	0.48
Detector resolution	0.15	0.08
Drift chamber simulation	0.37	—
z dependence	0.89	0.32
Class 4: Kaon flux and physics parameters		
Reg-beam attenuation	0.19	
Δm, τ_S	0.24	
Reg phase screening	0.31	
TOTAL	2.36	

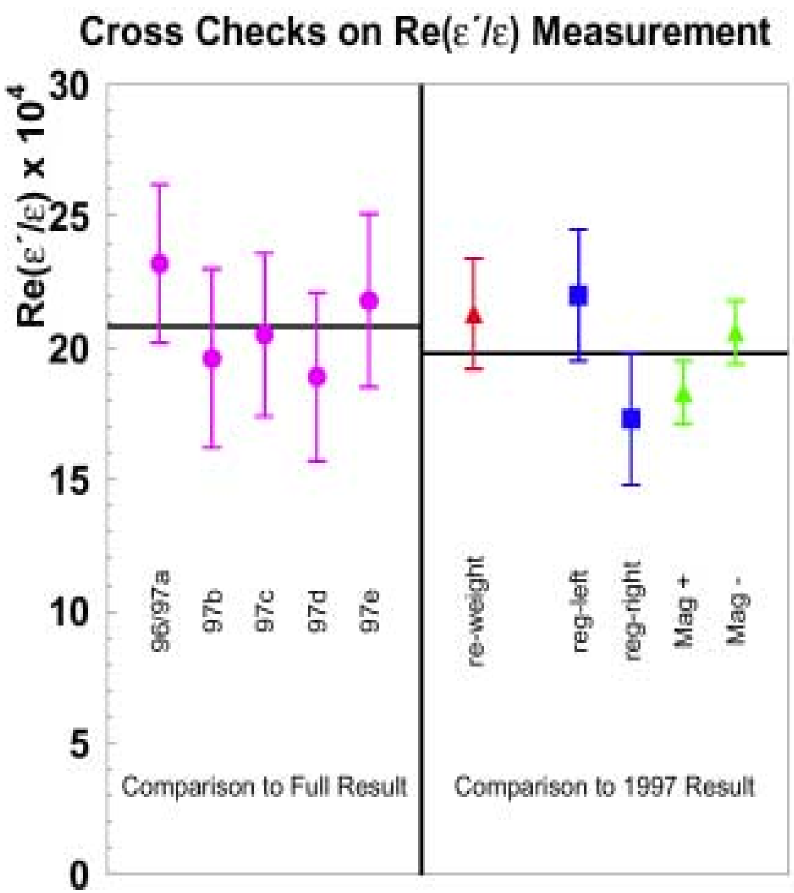
NA48 1998+1999 on R

	Correction ($\times 10^{-4}$)	Uncertainty
Reconstruction of $\pi^0\pi^0$	--	+/- 5.8
$\pi^+\pi^-$ trigger inefficiency	-3.6	+/- 5.2
Accidental Activity	--	+/- 4.4
Acceptance (stat)	+26.7	+/- 4.1
Acceptance (syst)		+/- 4.0
Accidental Tagging	+8.3	+/- 3.4
Background to $\pi^+\pi^-$	+16.9	+/- 3.0
Tagging Inefficiency	--	+/- 3.0
Adding other smaller	Corr.	& Unc.
TOTAL	+ 35.9	+/- 12.6

Comparison

	Uncertainties in 10^{-4}	units on Double Ratio
	KTeV 1996-1997	NA48 1998-1999
Statistics	± 9.0	± 10.1
Trigger Inefficiency	± 3.5	± 5.2
Reconstruction of $\pi^0\pi^0$	± 9.2	± 5.8
Reconstruction of $\pi^+\pi^-$	± 2.4	± 2.8
Background to $\pi^0\pi^0$	± 6.4	± 2.8
Background to $\pi^+\pi^-$	± 1.2	± 3.0
Tagging	--	± 4.5
Acceptance (stat.)	± 3.0	± 4.1
Acceptance (syst.)	± 7.1	± 4.0
Accidental Activity	--	± 4.6
External systematics	± 2.6	--
Total systematics	± 14.5	± 12.6

Cross Checks and Results (KTeV)

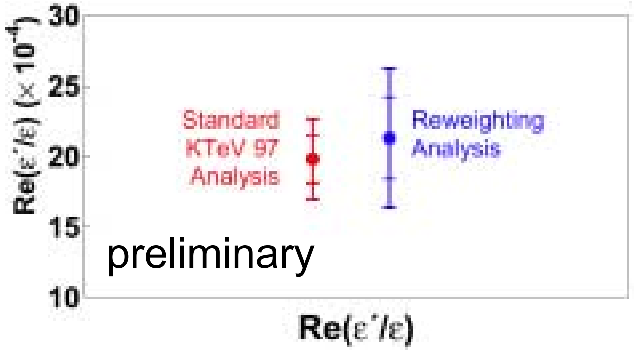


$$\begin{array}{lcl} \mathrm{Re}(\epsilon'/\epsilon) & = & (\mathbf{19.8} \pm \mathbf{1.7}\ (\mathrm{stat}) \pm \mathbf{2.3}\ (\mathrm{syst}) \\ (1997) & & \pm \mathbf{0.6}\ (\mathrm{MC\ stat})) \quad \times \mathbf{10^{-4}} \end{array}$$

Reanalysis of published data:

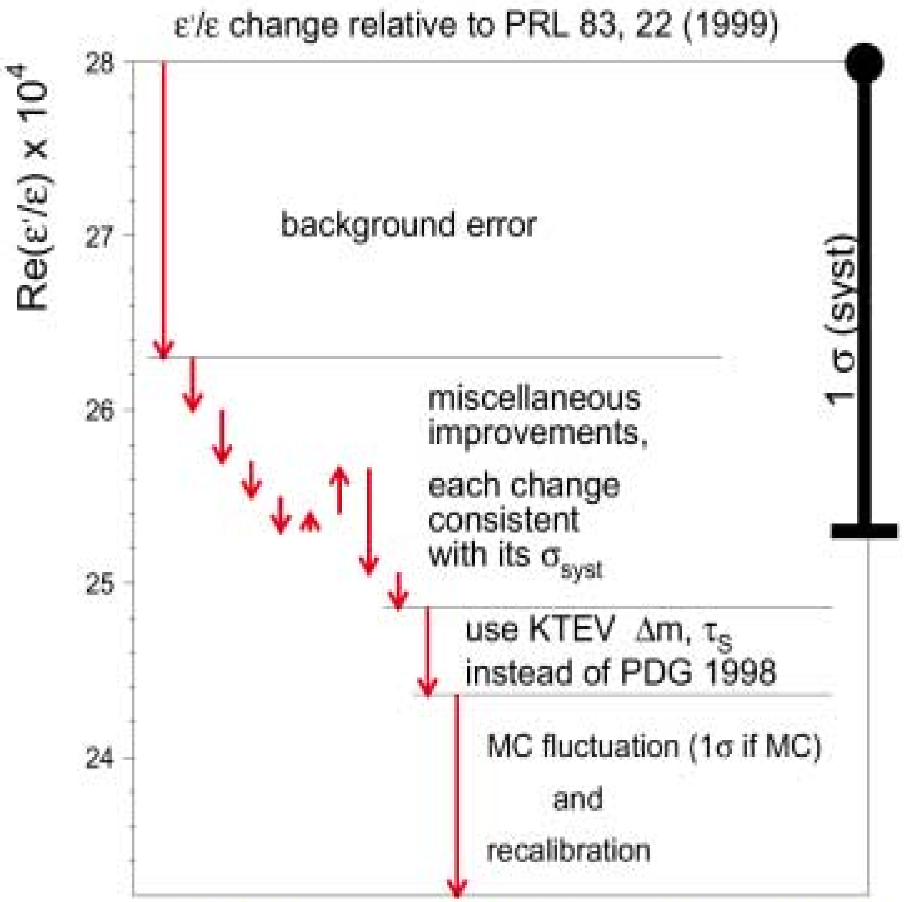
$$\begin{array}{lcl} \mathrm{Re}(\epsilon'/\epsilon) & = & (\mathbf{23.2} \pm \mathbf{3.0}\ (\mathrm{stat}) \pm \mathbf{3.2}\ (\mathrm{syst}) \\ (\mathrm{PRL}) & & \pm \mathbf{0.7}\ (\mathrm{MC\ stat})) \quad \times \mathbf{10^{-4}} \end{array}$$

$$\begin{array}{lcl} \mathrm{Re}(\epsilon'/\epsilon) & = & (\mathbf{20.7} \pm \mathbf{1.5}\ (\mathrm{stat}) \pm \mathbf{2.4}\ (\mathrm{syst}) \\ (96+97) & & \pm \mathbf{0.5}\ (\mathrm{MC\ stat})) \quad \times \mathbf{10^{-4}} \\ & = & (\mathbf{20.7} \pm \mathbf{2.8}) \times \mathbf{10^{-4}} \end{array}$$



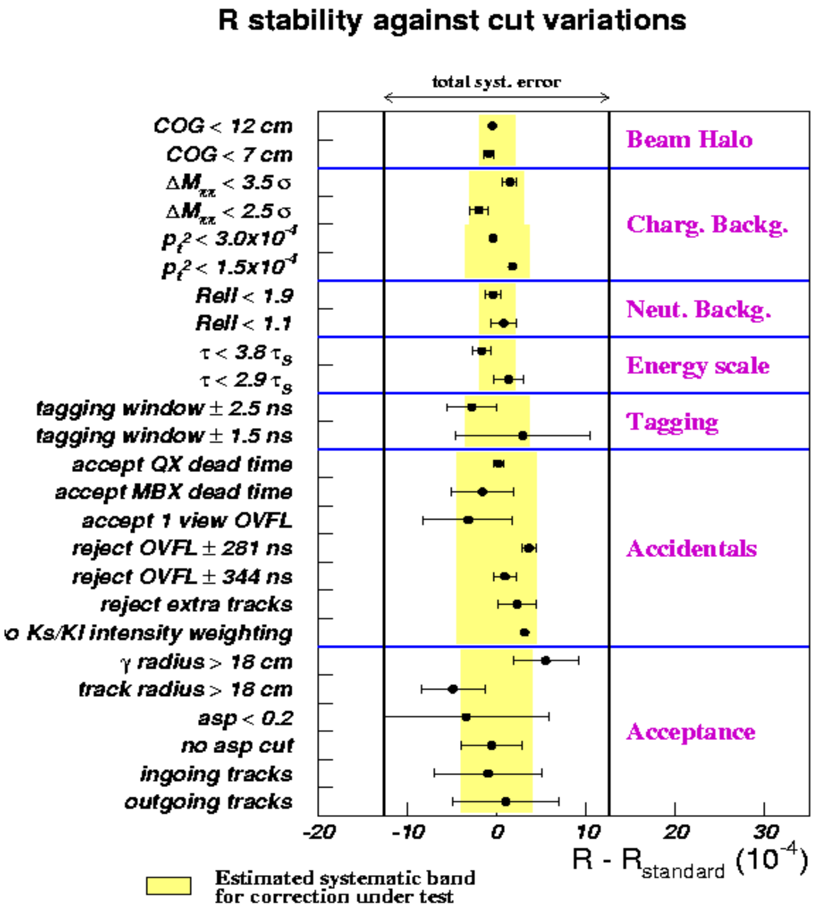
$$\Delta\mathrm{Re}(\epsilon'/\epsilon) = 1.5 \pm 2.1\ (\mathrm{stat}) \pm 3\ (\mathrm{syst}) \times 10^{-4}$$

KTeV reanalysis of PRL data



Note: sources of shifts are not correlated

Cross checks and results (NA48)



98+99:

Eur.Phys.J.C22 (2001)

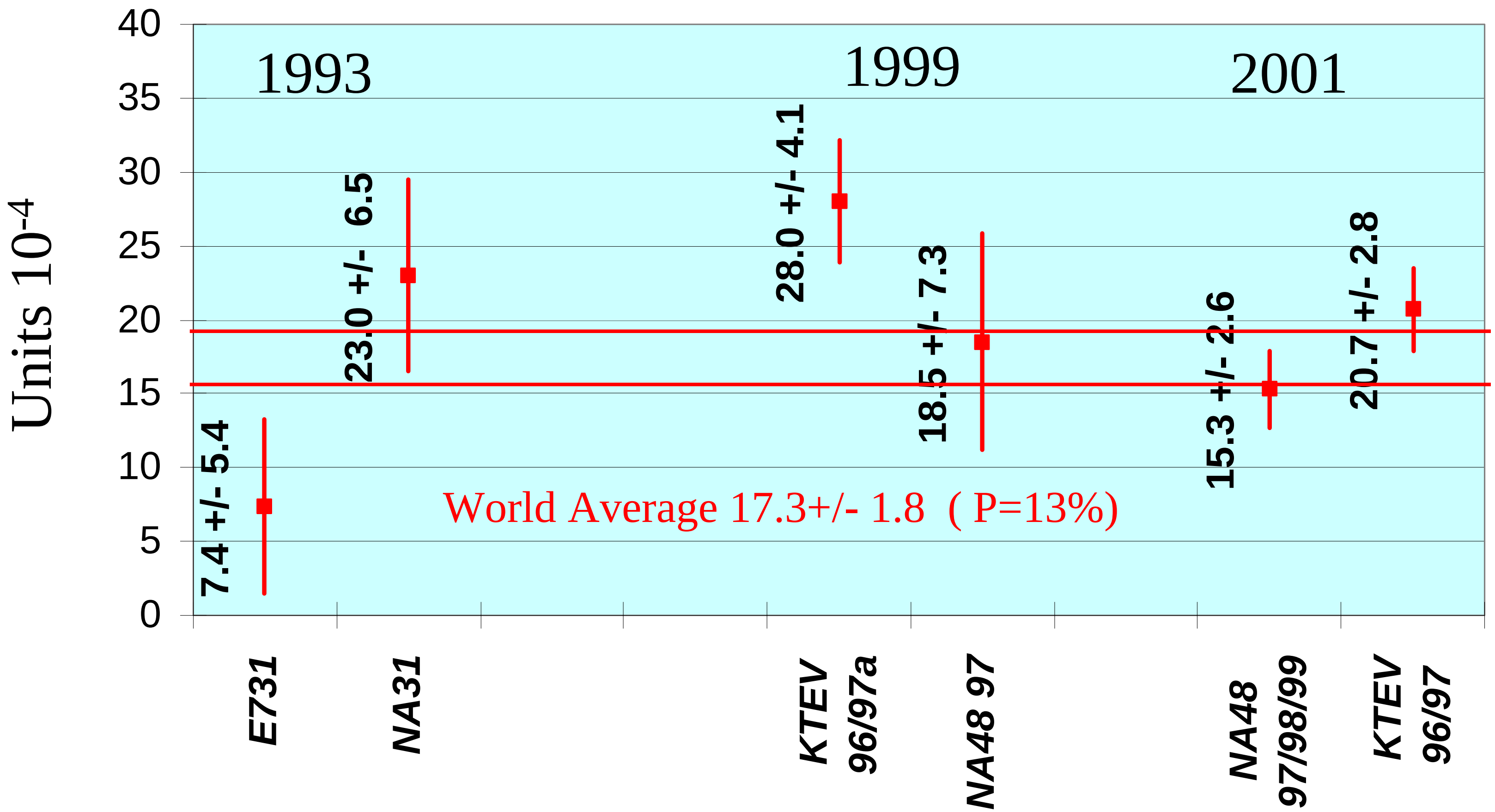
hep-ex/0110019

- $Re(\varepsilon'/\varepsilon)=(15.0 \pm 1.7\ (stat) \pm 2.1\ (syst))10^{-4}$
- $Re(\varepsilon'/\varepsilon)=(15.0 \pm 2.7)10^{-4}$

Combining this result with the previously published NA48 data (1997) yields:

$Re(\varepsilon'/\varepsilon) = (15.3 \pm 2.6)10^{-4}$

Epsilon'/Epsilon as a function of time…



Direct CP Violation in $K^{\pm} \rightarrow \pi^{\pm} \pi^{+} \pi^{-}$

- Important to gather other $|\Delta S|=1$ CP violating effects
- Effects are predicted to be small: SM ($O \sim 10^{-5}$), SUSY ($O \sim 10^{-4}$)

D'Ambrosio, Isidori, Martinelli, PLB480(2000)

$$|M(u,v)|^2 \propto 1 + gu + hu^2 + kv^2 + \ldots \qquad u = (s_3 - s_0)/m_\pi^2 \qquad v = (s_1 - s_2)/m_\pi^2$$

$$S_0 = \frac{1}{3}(s_1 + s_2 + s_3) \qquad S_i = (P_K - P_i)^2 \qquad P_K, P_i = \text{momenta of kaon and pions (i=3 odd pion)}$$

$$A_g = \frac{(g_+ - g_-)}{(g_+ + g_-)}$$

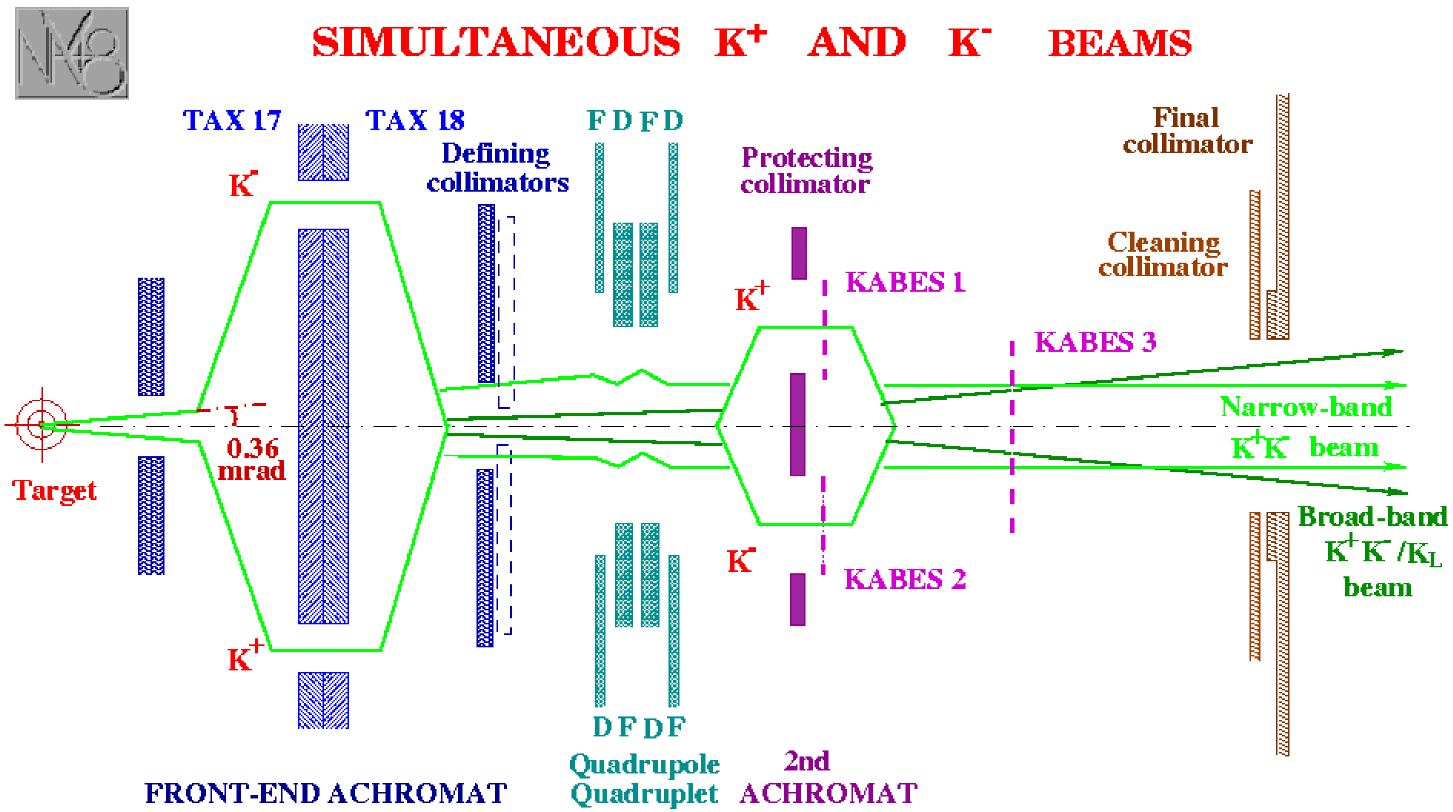
- PDG: $A_g = (-7.0 \pm 5.3) \times 10^{-3}$ W.T. Ford et. al. 1970
- New data FNAL-HyperCP, 5% -preliminary!-

→No CP-Violation seen at a few per mill level

FERMILAB-CONF-01-321-E

NA48/2

New technique: Simultaneous, unseparated K^+/K^- beams
60 GeV; narrow band ($\Delta P/P$ ~ 10% R.M.S.)
5.5 (3.1) 10^{10} $K^+(K^-)$ decays/year (foreseen 2003)
$\Rightarrow$Push the measurement of A_g to 10^{-4}



Rare Kaon Decays and the Standard Model

$BR(K_L \to \mu e) < 4.7 \times 10^{-12}$ AGS-871

$BR(K^+ \to \pi^+ \mu^+ e^-) < 2.8 \times 10^{-11}$ AGS-865

$BR(K_L \to \pi^0 \mu\ e\ ) < 4.4 \times 10^{-10}$ KTeV

LFV

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

$K_L \to \pi^0 \mu^+ \mu^- \quad \Leftrightarrow \quad \mathrm{Im}\ \lambda_t$

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

$K^+ \to \pi^+ \nu\bar{\nu} \quad \Leftrightarrow \quad |\lambda_t|$

$K_L \to \mu^+ \mu^- \quad \Leftrightarrow \quad \mathrm{Re}\ \lambda_t$

One Loop decays

$K_L \to \pi^0 e^+e^-$ and $K_L \to \pi^0\mu^+\mu^-$

•SM prediction: BR(Direct CPV)~$(\mathrm{Im}V_{td})^2 \times 3\ 10^{-4}$

•Mixing contamination:

- BR(CP-Violation mixing)~1/300 BR($K_S \to \pi^0 e^+e^-$)

•CP-Conserving Component

- To be bound by studying $K_L \to \pi^0\gamma\gamma$

• Background from $K_L \to ee\gamma\gamma$ (Greenle, 1990) starts to be seen

Mode	Upper Limit (90% CL)	Exp.	Ref.
$BR(K_L \to \pi^0 e^+ e^-)$	<5.1 10^{-10}	KTeV	PRL86 (2001)
$BR(K_L \to \pi^0 \mu^+ \mu^-)$	<3.8 10^{-10}	KTeV	PRL84 (2000)

New approach: measure muon polarization in $K_L \to \pi^0\mu^+\mu^-$ (Diwan, Ma, Trueman, hep-ex/0112350). Very large asymmetries are expected

NA48/1: Unique Opportunity for $K_S \rightarrow \pi^0 e^+ e^-$ $(\mu^+ \mu^-)$

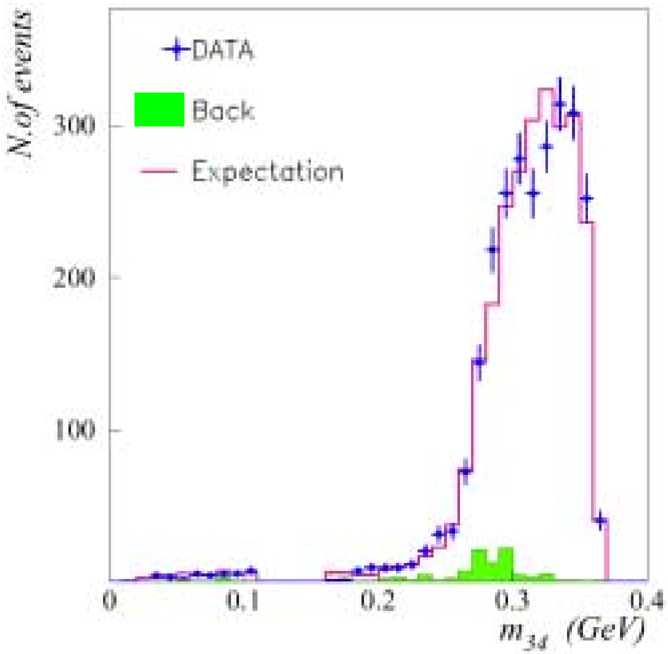
- Use NA48 Detectors and beam-line
  - Exploits the NA48 collimator technique and 400 GeV SPS p beam
  - Intensity can be increased several hundred times wrt to double beam
- $K_S \rightarrow \pi^0 l^+ l^-$, $l = e, \mu$
- Search for CPV in K_S decays $K_S \rightarrow 3\pi^0$, $K_S \rightarrow \pi^+ \pi^- \pi^0$
- 1999: 40h test run
    - $BR(K_S \rightarrow \gamma\gamma) = (2.6 \pm 0.4 \pm 0.2)\, 10^{-6}$ PL B493 (2000) 29
    - $BR(K_S \rightarrow \pi^0 e^+ e^-) < 1.4 \times 10^{-7}$ 90% CL PL B514 (2001) 253

  $\Rightarrow BR(K_L \rightarrow \pi^0 e^+ e^-)_{mixing} < 4.2 \times 10^{-10}$ 90% CL
- 2002:
  - Scheduled to run for about 80 days: it aims to reach SES ~3 10^{-10} for $K_S \rightarrow \pi^0 ee$ (Cut of beam time by 25% due to CERN budget crisis)

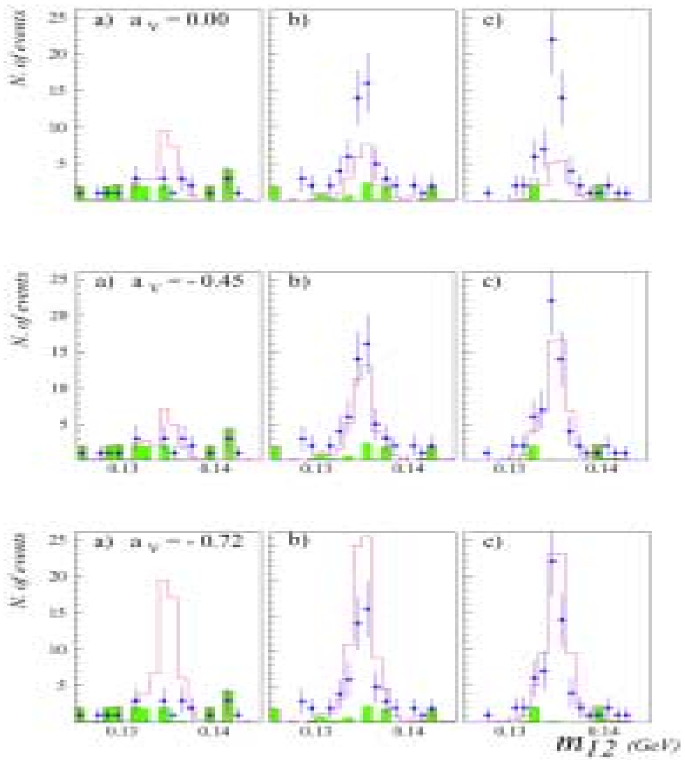
K_S physics: KLOE

- Designed to measure ε'/ε at the Frascati Φ factory
  - Collected ~175 pb^{-1} in 2001, about $\times$10 more than Y2K
  - Expect ~500 pb^{-1} in 2002: enough to measure systematics for a 10^{-3} accuracy on ε'/ε using the interference method
- Competitive tagged K_S program
- Results from 2000 data (hep-ex/010702):
  - $BR(K_S \rightarrow \pi e \nu) = (6.8 \pm 0.3) \times 10^{-4}$
  - $BR(K_S \rightarrow \pi^+\pi^-)/BR(K_S \rightarrow \pi^0\pi^0) = 2.23 \times (1 \pm 0.35\ 10^{-2}{}_{sta} \pm 1.5\ 10^{-2}{}_{sys})$

$K_L \to \pi^0 \gamma\gamma$ (NA48)



a) $160 < m_{34} < 240$ MeV
b) $240 < m_{34} < 260$ MeV
c) $30 < m_{34} < 110$ MeV



2588 events with 3.3% background

$BR = 1.36 \pm 0.03_{sta} \pm 0.03_{sys} \pm 0.03_{norm} \times 10^{-6}$

$a_V = -0.46 \pm 0.03_{sta} \pm 0.03_{sys} \pm 0.02_{theory}$

KTeV: $BR = 1.68 \pm 0.07_{sta} \pm 0.08_{sys} \times 10^{-6}$

$a_V = -0.72 \pm 0.05_{sta} \pm 0.06_{sys}$ (PRL 83 1999)

$K_L \rightarrow \pi^0 \nu\bar{\nu}$

Dominated by Direct CP Violation (Littenberg, 1989)

Very special case: SM prediction is very clean;no pollution

BR = $3.1 \pm 1.3 \times 10^{-11}$ (Buchalla and Buras, 1999)

•Intrinsic theoretical error very small (~%)

•Cleanest way to measure J_{CP} and to compare to B physics:

However: Current Experimental limits are 4 order of magnitude above the SM (KTeV, <5.9 10^{-7} 90% CL)

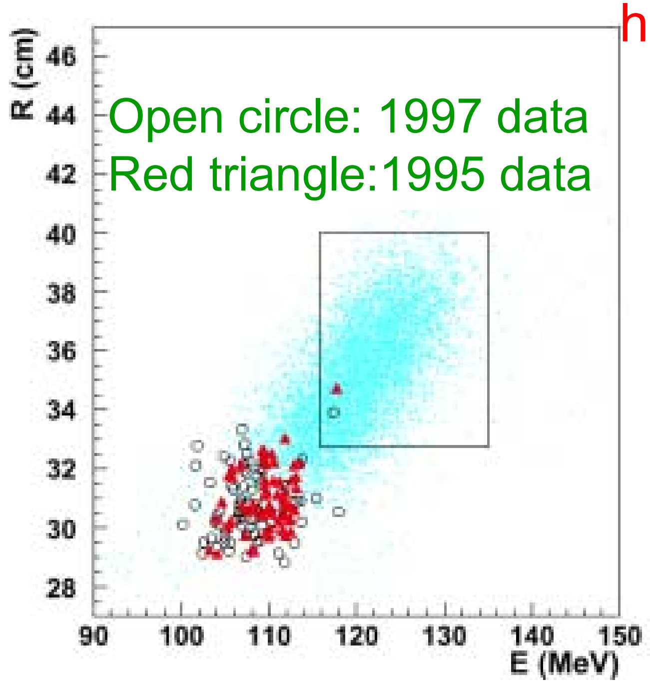
First round of dedicated experiments approved:

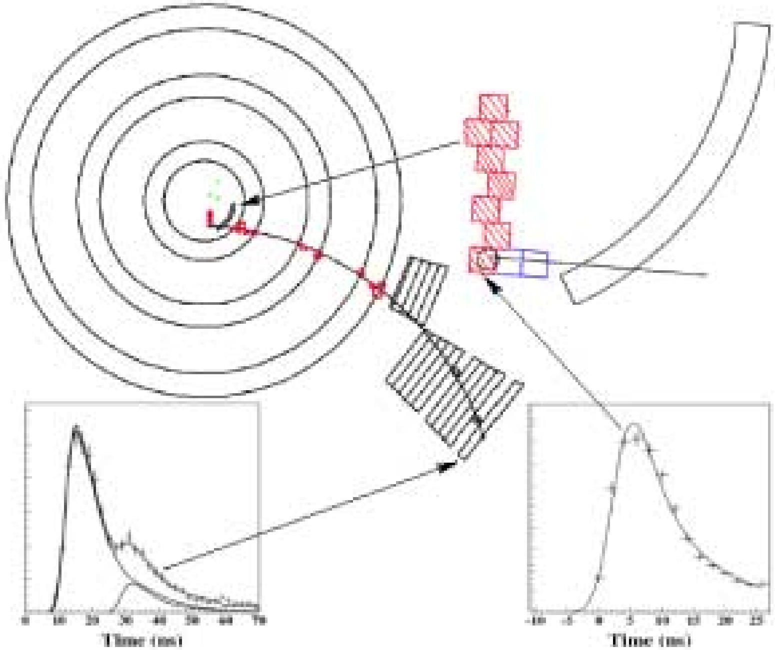
•KOPIO AGS (goal: ~10% measurement of $Im(\lambda_t)$)
   - •TOF technique to measure E_K
   - •Plans to measure photon direction
   - •Found a way to run at 100 Tpp

•E391A KEK (expects 1/10 SM events , start data taking 2003)
   - •Important to demonstrate whether $K_L \rightarrow \pi^0\pi^0$ background with 2 lost γ can be handled with photon vetoes and beam collimation only

$K^+ \to \pi^+ \nu \bar{\nu}$ AGS-787

hep-ex/0111091





Analysis of 1997 just presented:

New candidate found

AGS-E787

- Background expected 0.15±0.05 events
- $BR(K^+ \to \pi^+ \nu\nu) = 1.57^{+1.75}_{-0.82} \times 10^{-10}$ 68%CL
- SM prediction: BR=0.79±0.21 x 10^{-10} D'ambrosio and Isidori (hep-ph/0112135)
- Limits on $|\lambda_t|$can be obtained maximizing the quark c contribution:

$$2.9 \times 10^{-4} < |\lambda_t| < 1.2 \times 10^{-3} \quad 68\%\ CL$$

AGS-E949: to start data taking first week of February. Designed to reach a sensitivity of 10^{-11}/event

FNAL-CKM: Extend the study of $K^+ \to \pi^+ \nu\nu$ by another order of magnitude employing a super-conducting RF separator and K^+ decays in flight

Refer to Peter Cooper's talk for $K \to \pi\ \nu\nu$ present and future

Conclusions

- Kaon physics still provides remarkable results:
  - Direct CP-Violation exists and it is precisely measured:

$$\mathrm{Re}\frac{\varepsilon'}{\varepsilon} = 17.3 \pm 1.8 \times 10^{-4}$$

- Rare Kaon Decays promise quantitative tests of SM highly complementary to B physics