

Kaon Physics

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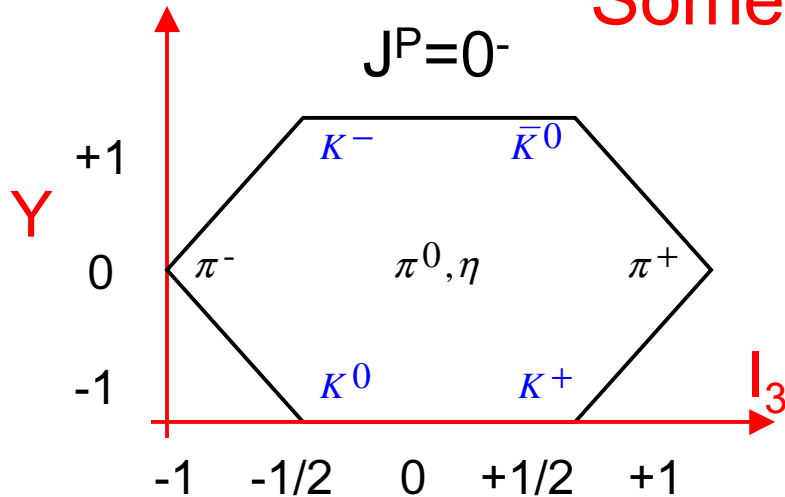
Weak Interactions and Neutrinos 2002

Christchurch (NZ), 21-26 January, 2002

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



Some properties of kaons



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

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

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

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

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

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

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

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

$\tau_L \approx \tau_S \times 579$

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

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

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

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

$\epsilon \approx 2.27 \times 10^{-3} \quad \arg(\epsilon) \approx \tan^{-1} \frac{2\Delta m}{\Delta\Gamma} \approx 43.5^\circ$

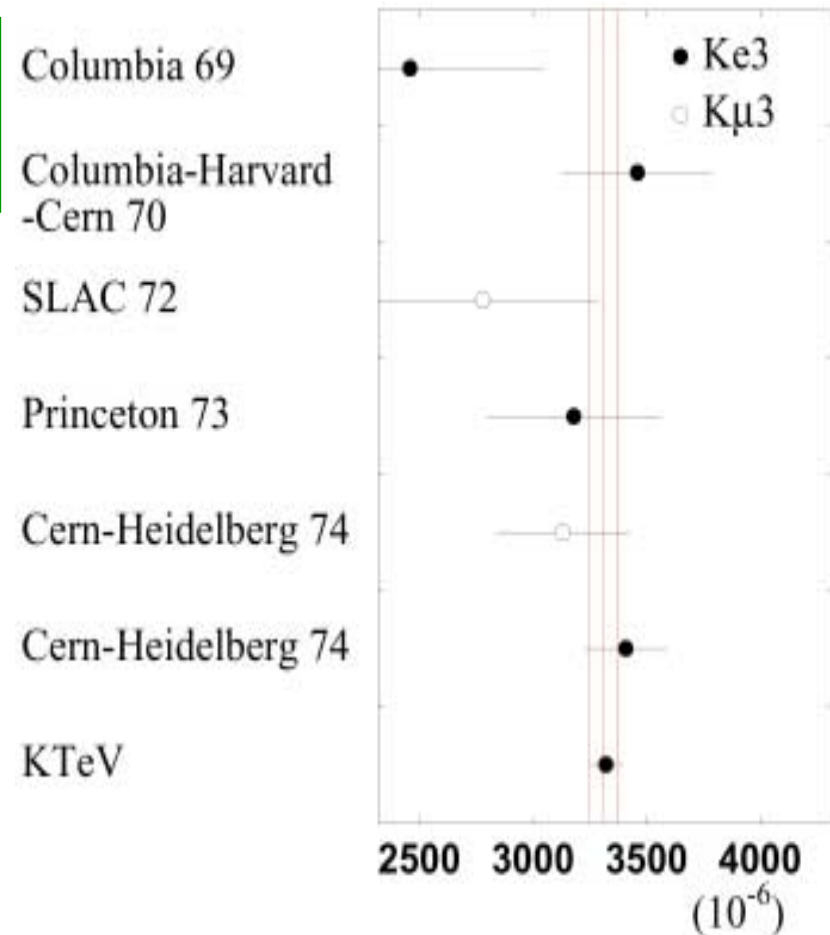
CP-Violation in Semi-leptonic Decays

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

- 298 Million $K_L \rightarrow \pi e \nu$ collected by KTeV-E832 during the 1997 run
- Raw $\delta_L = 3417 \pm 58$ ppm
- Main Correction:
 $\pi^+ \pi^-$ difference in Csl: -156 ± 10 ppm
- Total correction: -95 ± 47 ppm

$$\delta_L = 3322 \pm 58_{\text{sta}} \pm 47_{\text{sys}} \text{ ppm}$$

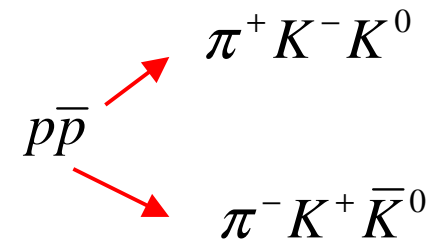
$$3322 \pm 74 \text{ ppm (comb.)}$$



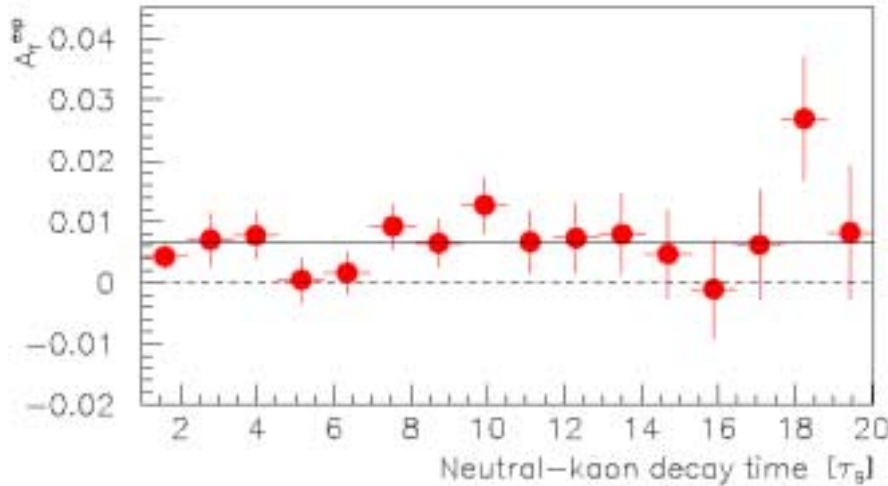
T- Violation in Neutral Kaon mixing

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

CERN-CPLEAR: tagged strangeness at t=0



Assuming CPT conservation in semi-leptonic decays:



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

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

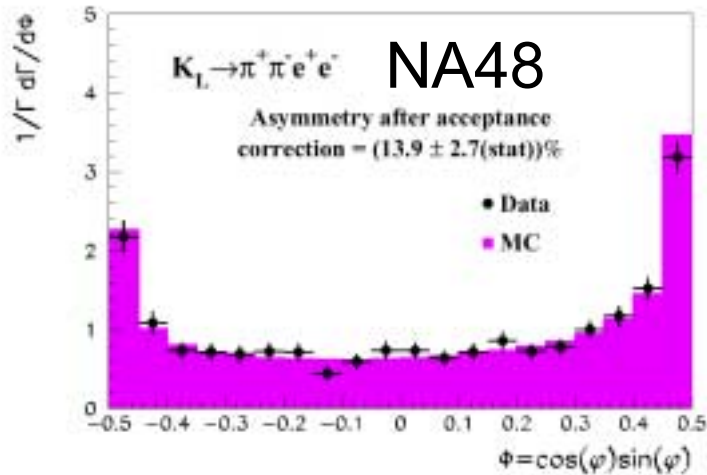
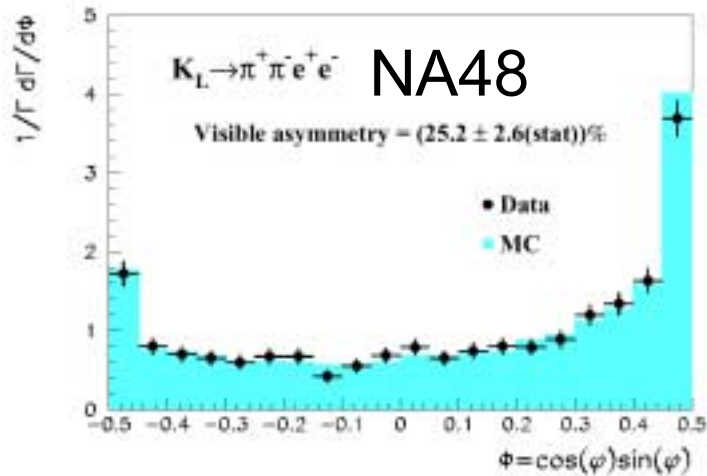
$\text{Im}x_+ = T - \text{violation } \Delta S \neq \Delta Q$

$$4\text{Re}\epsilon = 6.2 \pm 1.4_{sta} \pm 1.0_{sys} \times 10^{-3}$$

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

(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)

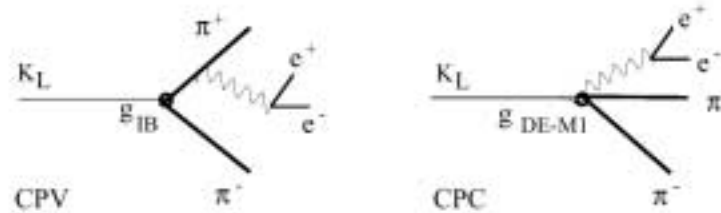
CP-Violation in $K_L \rightarrow \pi^+ \pi^- e^+ e^-$



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:



$$\text{BR} \approx 3 \cdot 10^{-7}$$

Asymmetry measured by KTeV,
then by NA48:

KTEV PRL84 (2000):

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

NA48 (Preliminary):

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

Direct CP Violation in 2π Decays

ε : CP-Violation in the mixing

$\Rightarrow |\Delta S|=2$ Indirect

$$K_L \approx K_2 + \varepsilon K_1 \quad \begin{array}{c} \downarrow \\ \pi\pi \end{array}$$

ε' : CP-Violation in a decay amplitude

$\Rightarrow |\Delta S|=1$ Direct

$$K_L \approx K_2 + \varepsilon K_1 \quad \begin{array}{c} \downarrow \\ \pi\pi \end{array}$$

Theory:

Experiment:

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

$$\eta_+ \approx \varepsilon + \varepsilon'$$

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

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

$$6 \text{Re} \frac{\varepsilon'}{\varepsilon} \approx 1 - \left| \frac{\eta_{00}}{\eta_+} \right|^2$$



CKM description of CP-Violation

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

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \quad \begin{array}{l} N_g=2 \quad N_{phase}=0 \Rightarrow \text{No CP-Violation} \\ N_g=3 \quad N_{phase}=1 \Rightarrow \text{CP-Violation Possible} \end{array}$$

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

For $j \neq k \rightarrow 6$ 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:

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

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

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

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

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

$$\Pi_0 = \frac{1}{\cos \delta_0} \sum_i y_i \operatorname{Re} \langle Q_i \rangle_0 \quad \Pi_2 = \frac{1}{\cos \delta_2} \sum_i y_i \operatorname{Re} \langle Q_i \rangle_2$$

- 1976 Ellis, Gaillard and Nanopoulos: $\varepsilon'/\varepsilon > 0$ is expected in the CKM description
- Gluonic Pinguins can lead to large ε'/ε
- Large top mass \rightarrow 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 they may be reliably calculated in the lattice
- Current Predictions of ε'/ε in SM range from $-4 \div +40 \times 10^{-4}$

\Rightarrow Refer to Fabbrichesi's talk on Kaon theory

ε'/ε Experiments

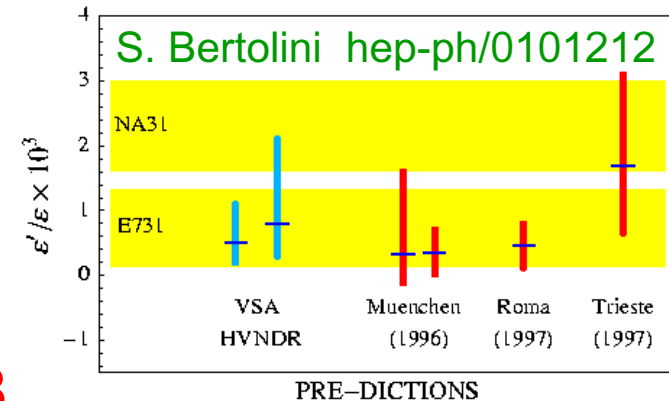
$$R = \frac{\Gamma(K_L \rightarrow \pi^0 \pi^0) \cdot \Gamma(K_S \rightarrow \pi^+ \pi^-)}{\Gamma(K_L \rightarrow \pi^+ \pi^-) \cdot \Gamma(K_S \rightarrow \pi^0 \pi^0)}$$

Two experiment published precise results in 1993

- E731 FNAL $\text{Re } \varepsilon'/\varepsilon = (7.4 \pm 5.9) \times 10^{-4} \Rightarrow$ no effect
- NA31 CERN $\text{Re } \varepsilon'/\varepsilon = (23.0 \pm 6.5) \times 10^{-4} \Rightarrow > 3.5 \sigma$

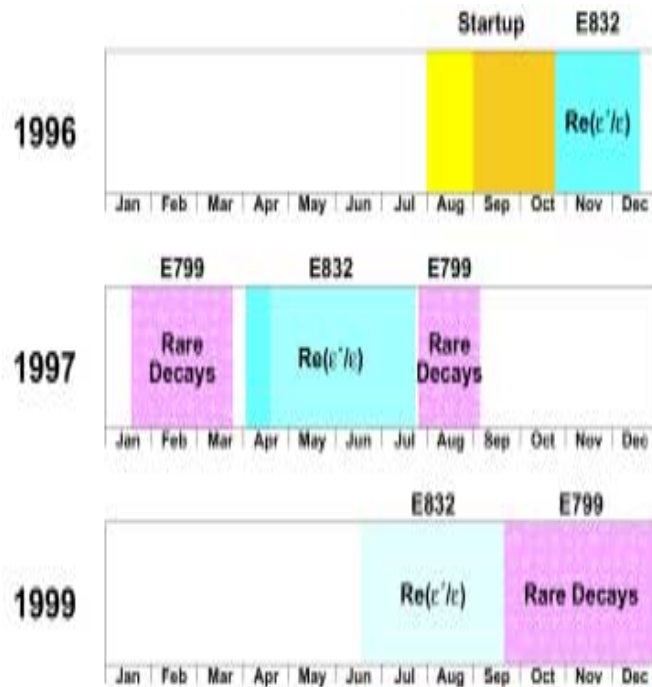
New Round: KTeV and NA48

- Simultaneous collection of the four decay modes \rightarrow Detector inefficiencies drop out
- Precise magnetic spectrometer and EM calorimeter \rightarrow 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

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: $\text{Re } \epsilon'/\epsilon = 18.5 \pm 7.3 \times 10^{-4}$
PLB 465 (1999)

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

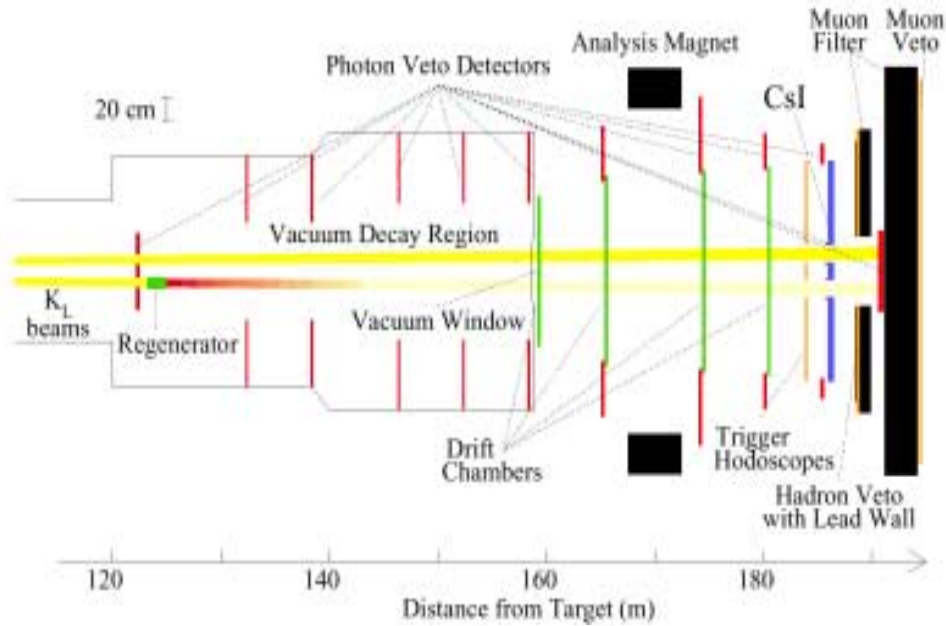
1996+1997 ≈ 2.5 (This talk)

1999 $\approx 1996+1997$

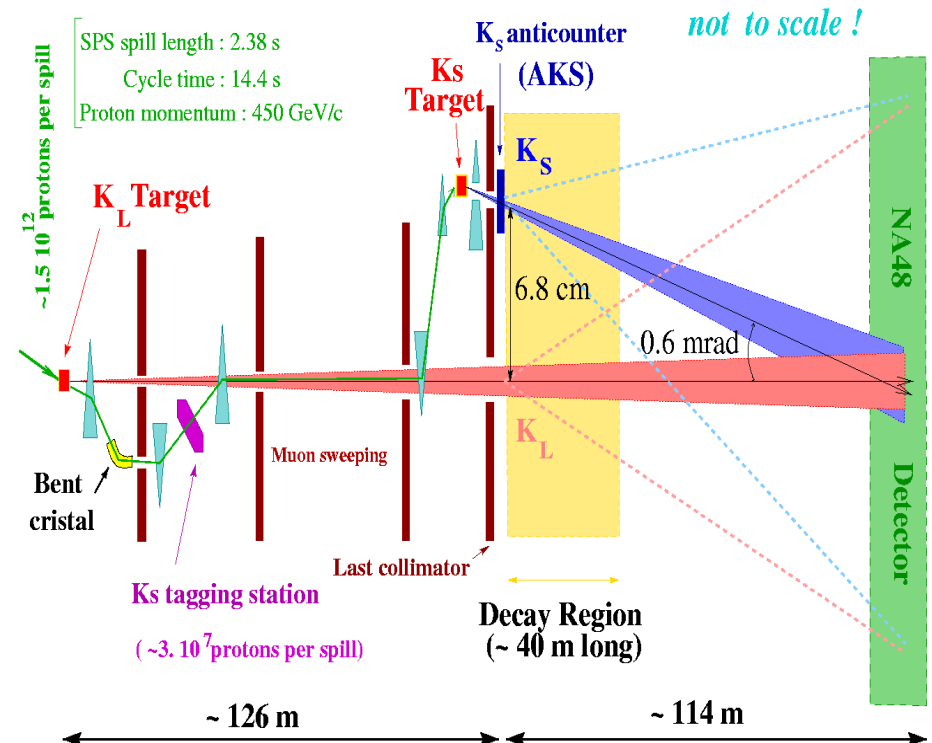
96+97a: $\text{Re } \epsilon'/\epsilon = 28.0 \pm 4.1 \times 10^{-4}$
PRL 83 (1999)

Beams

KTEV

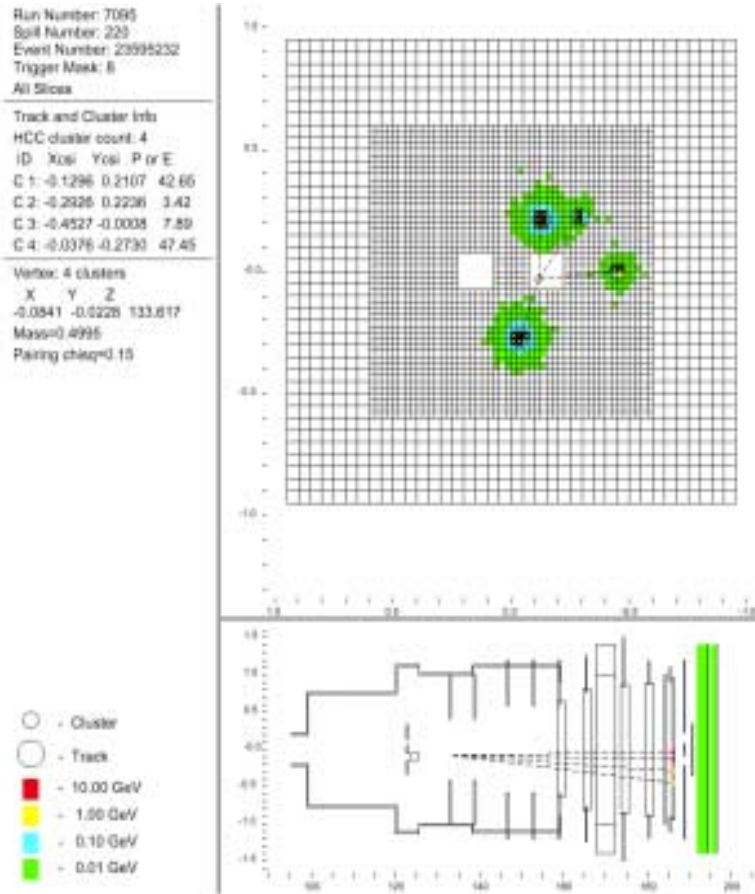


NA48

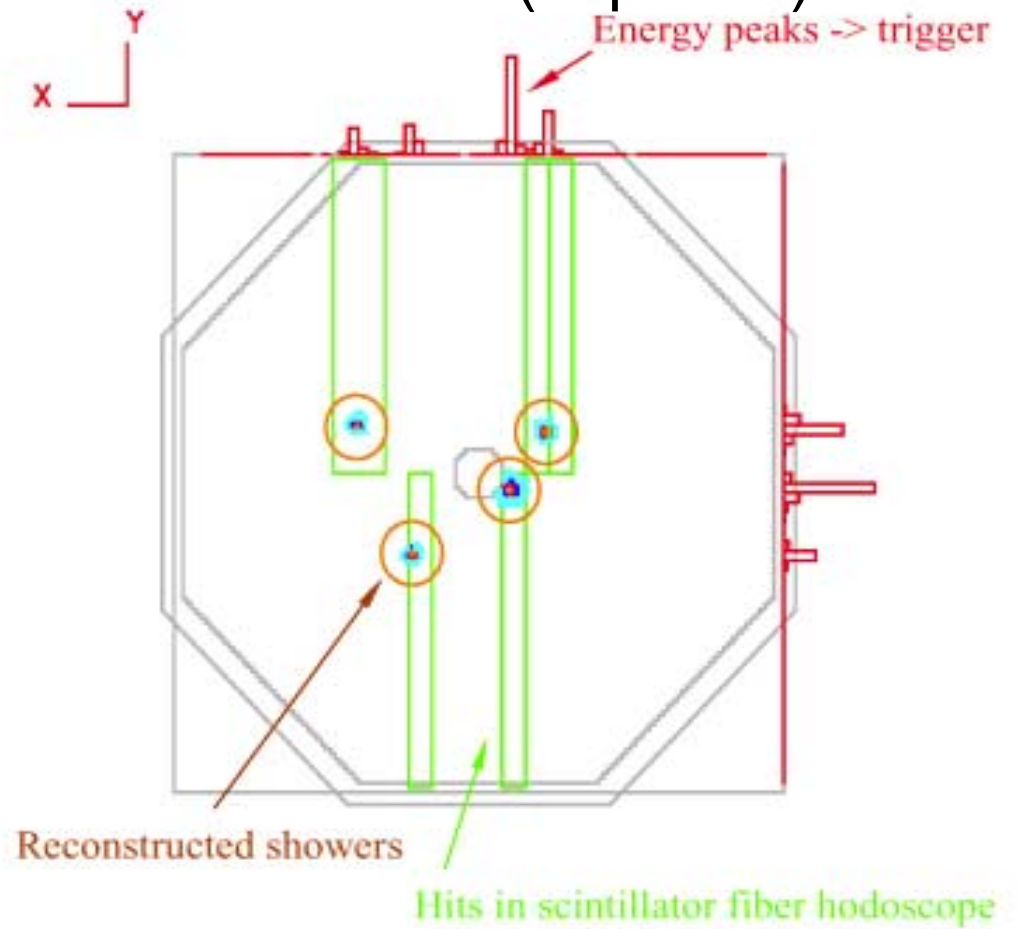


Detectors: $K \rightarrow \pi^0 \pi^0$

KTeV (pure CsI)

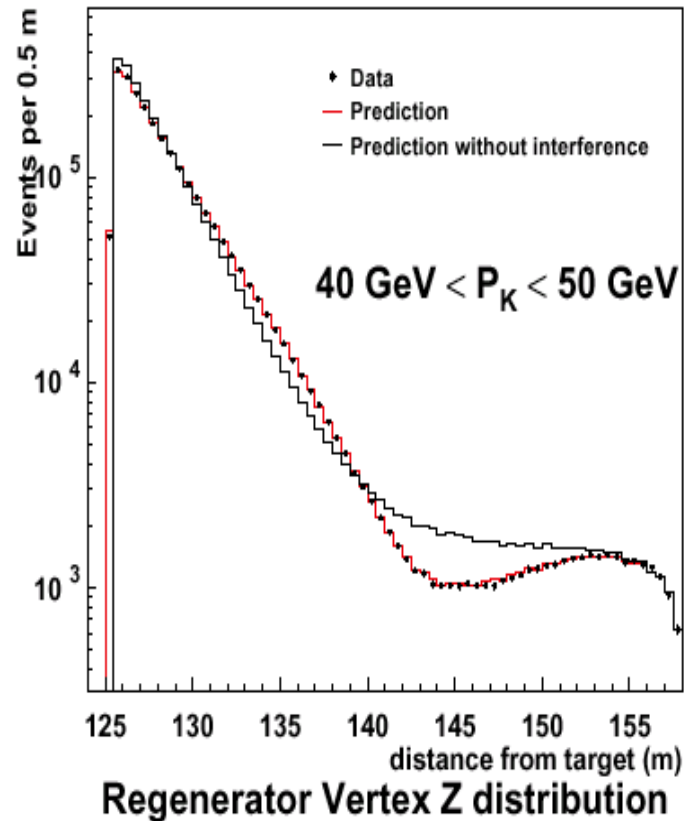


NA48 (Liquid Kr)



Regenerator method (KTeV)

$$K_L + \rho K_S$$



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

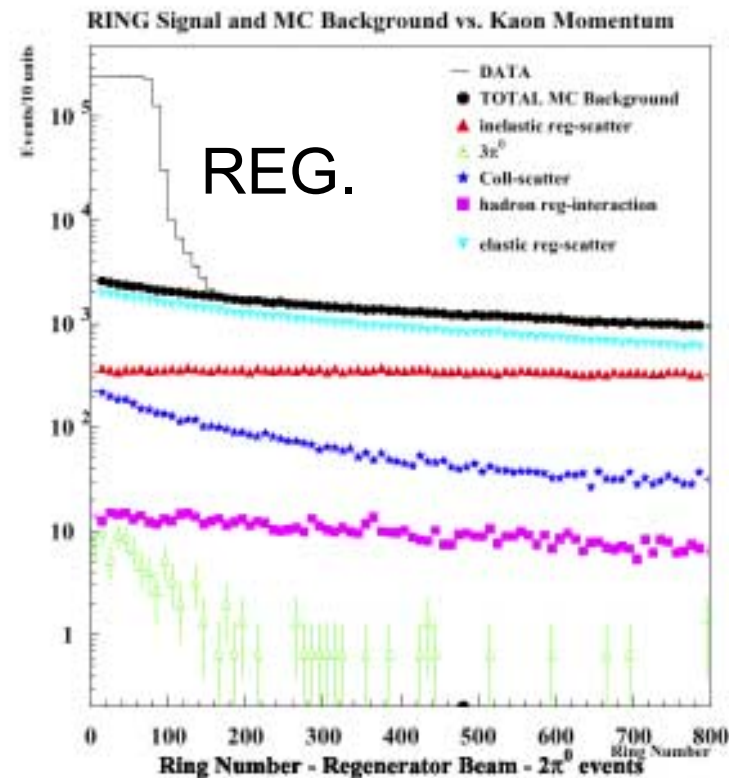
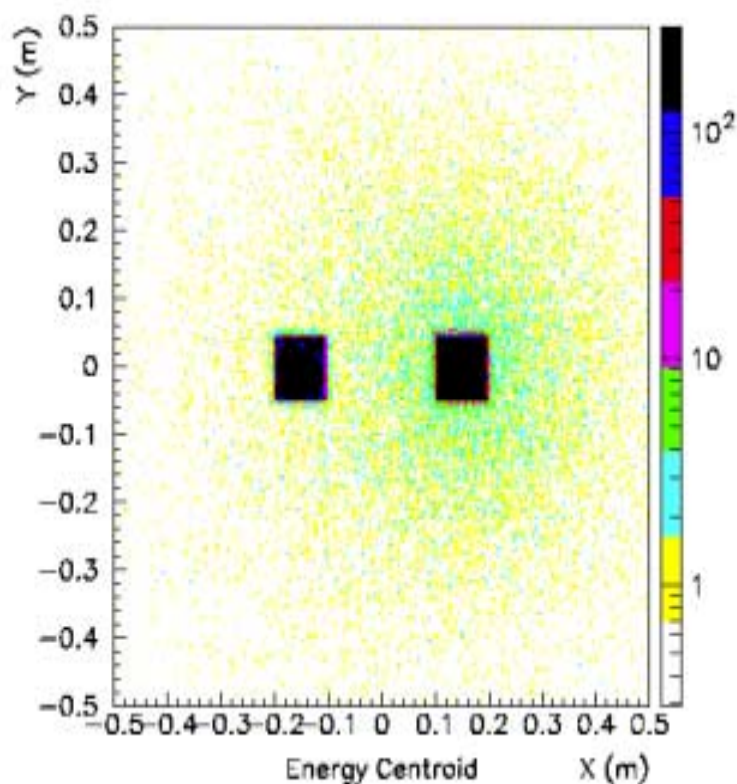
Feature: $\pi\pi$ from K_S - K_L interference

- 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

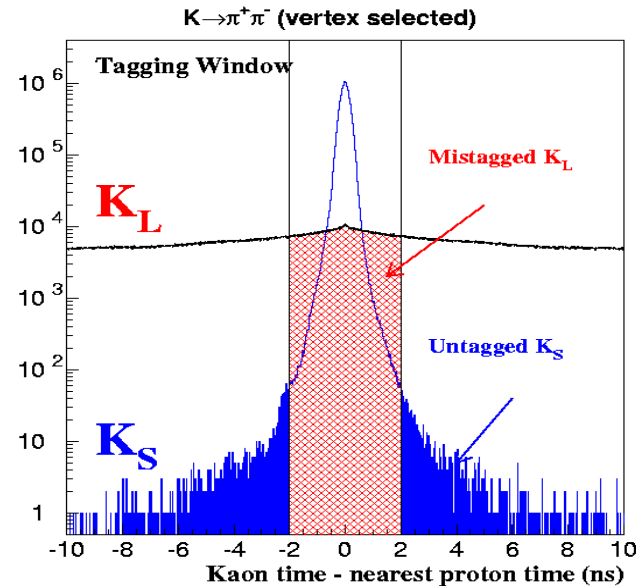
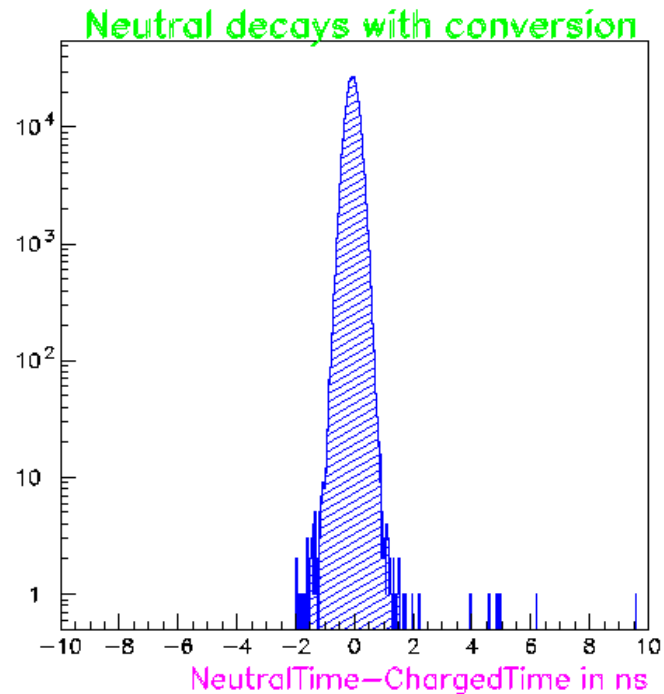
Regenerator Scattering (KTeV)



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}: π⁰π⁰(LKr), π⁺π⁻(hodoscope)



$$\alpha^{\pm}_{SL} = 1.63 \pm 0.03 \times 10^{-4}$$

80% due to tagger counter which is democratic

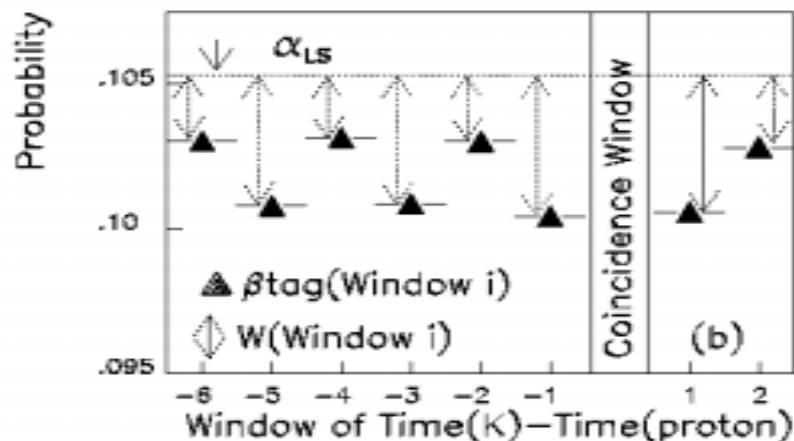
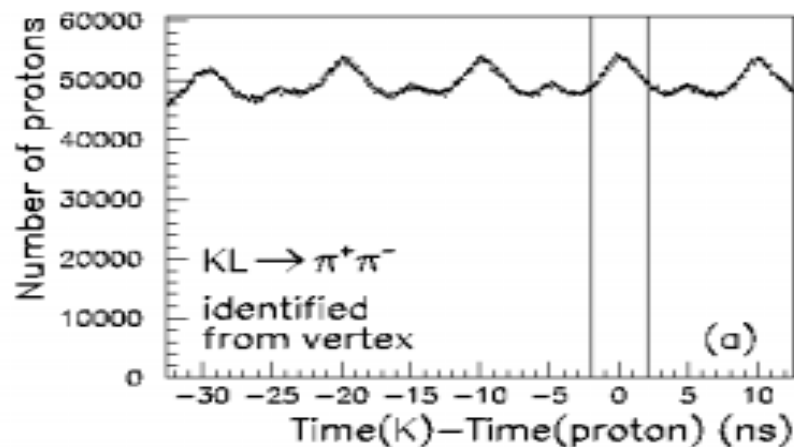
Difference between charged/neutral time:

$$< 2.5 \times 10^{-5}$$

No effect within $\pm 0.5 \times 10^{-4}$



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 $3\pi^0$

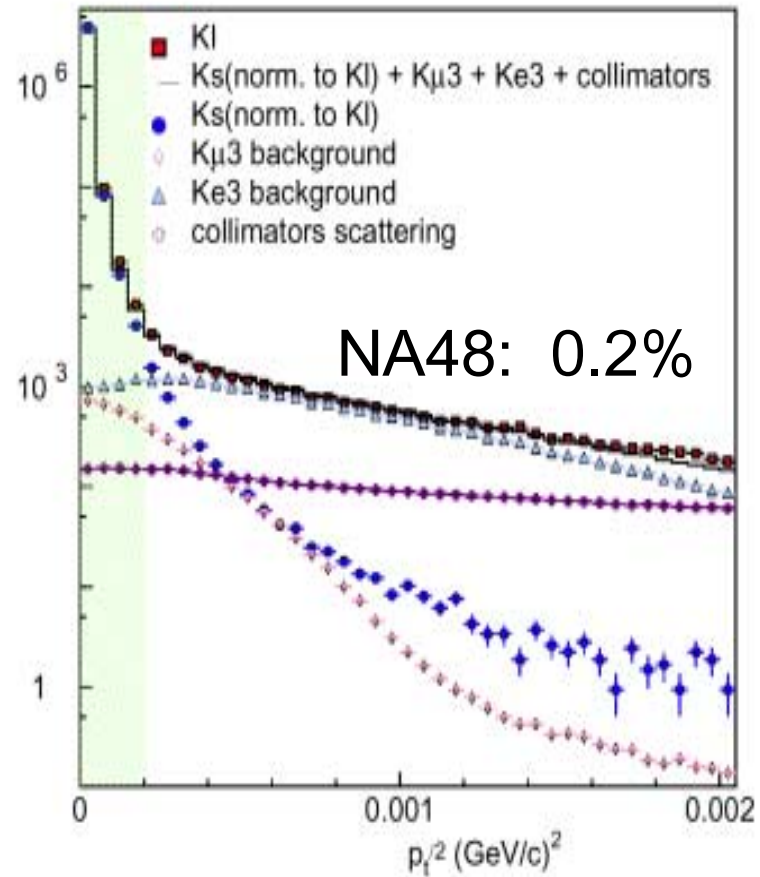
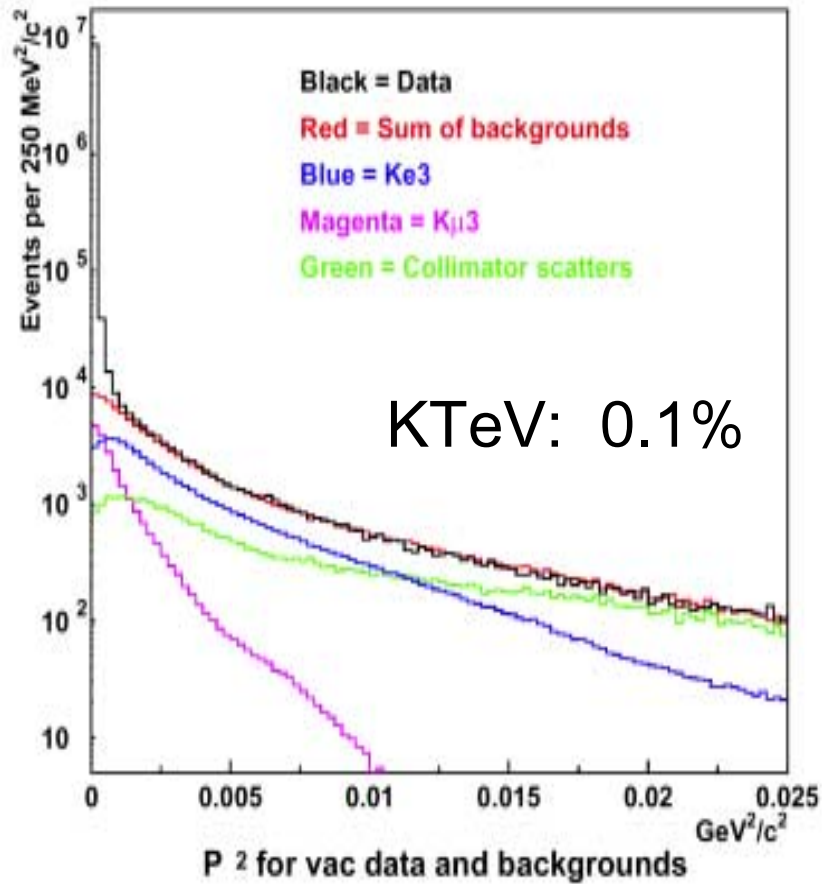
$\Delta\alpha_{LS}$ = difference in accidental tagging between $\pi^+\pi^-$ and $\pi^0\pi^0 = 4.3 \pm 1.8 \times 10^{-4}$

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

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

$$\frac{BR(K_L \rightarrow \pi e \nu)}{BR(K_L \rightarrow \pi^+ \pi^-)} \approx 189$$

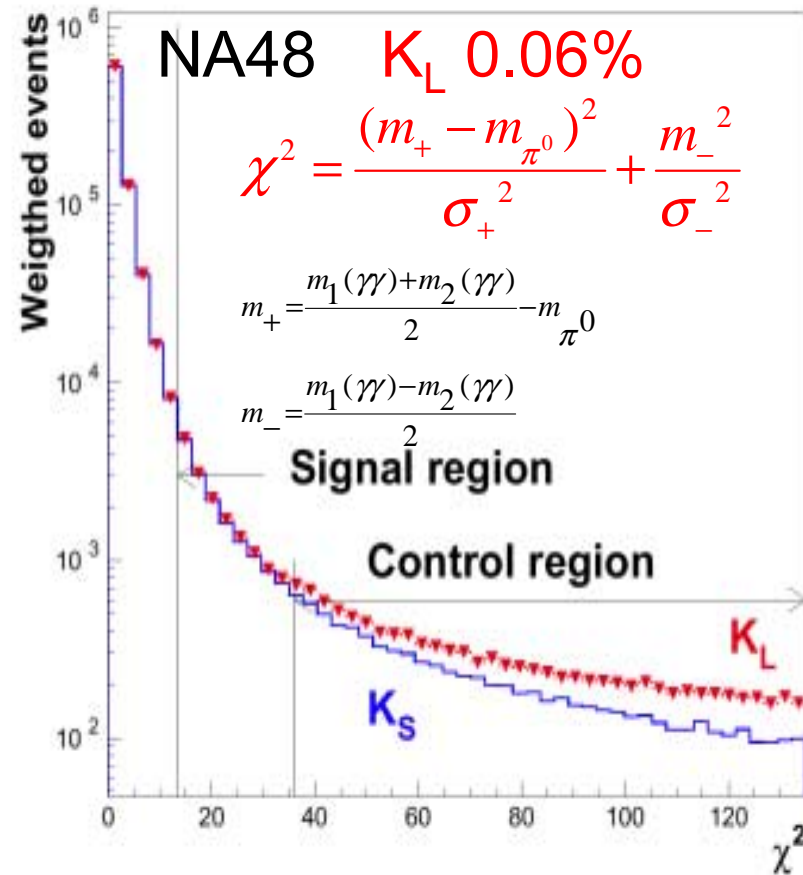
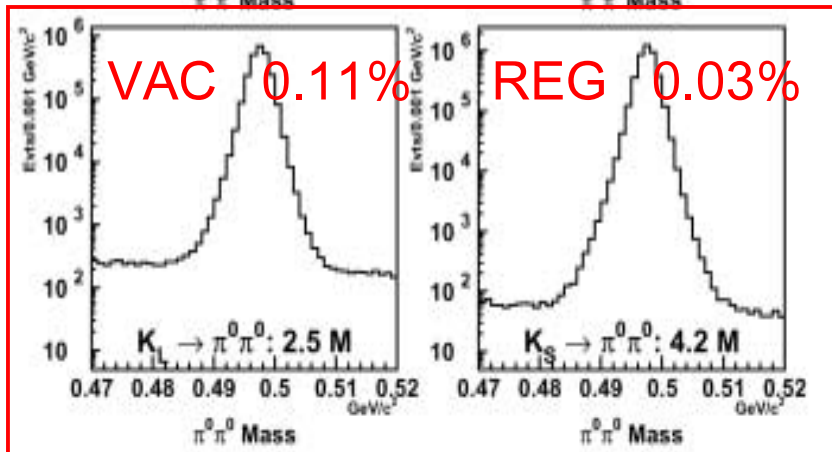
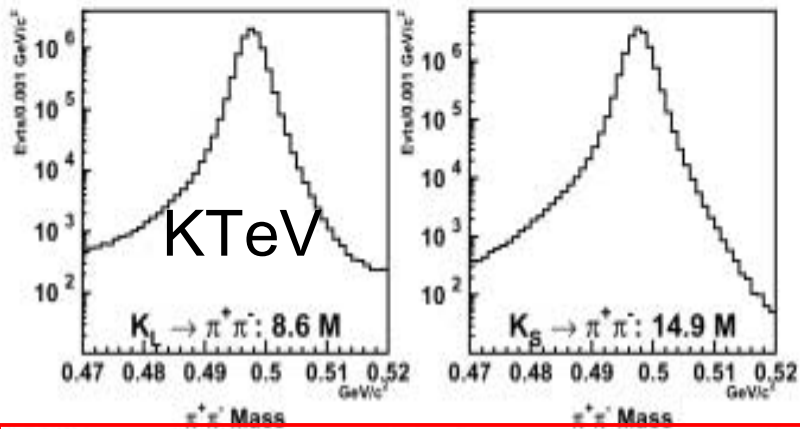
$$\frac{BR(K_L \rightarrow \pi \mu \nu)}{BR(K_L \rightarrow \pi^+ \pi^-)} \approx 132$$



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

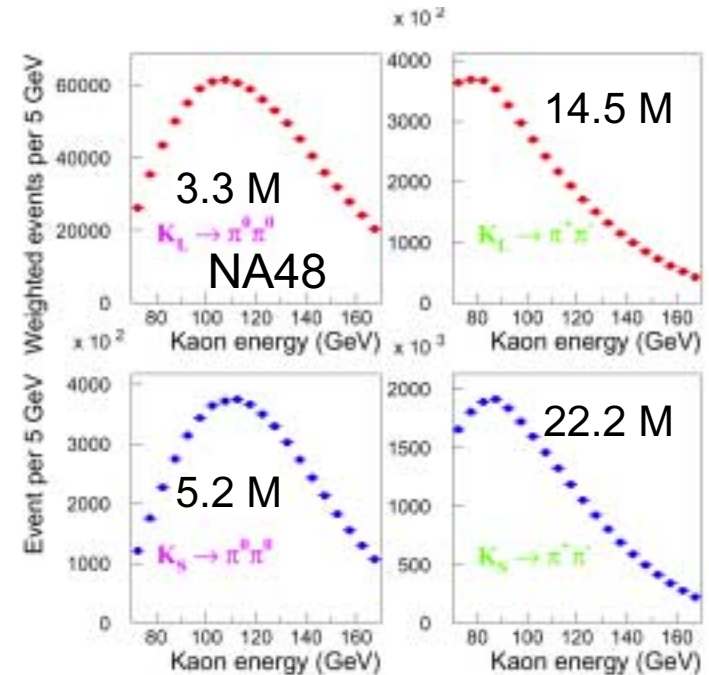
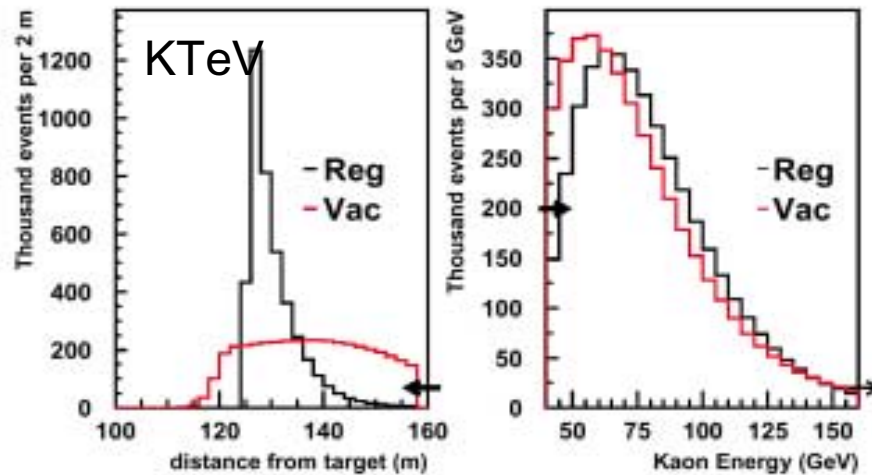
$$\frac{BR(K_L \rightarrow 3\pi^0)}{BR(K_L \rightarrow 2\pi^0)} \approx 228$$

- It can mimic the signal if 2 γ are lost



Definition of the Decay Volume

- Distance scale \leftrightarrow energy scale
- Experiments rely on calibration of EM calorimeters

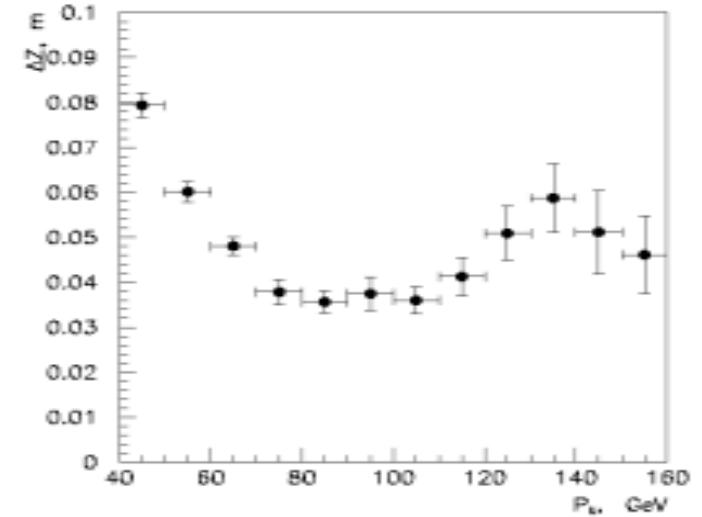
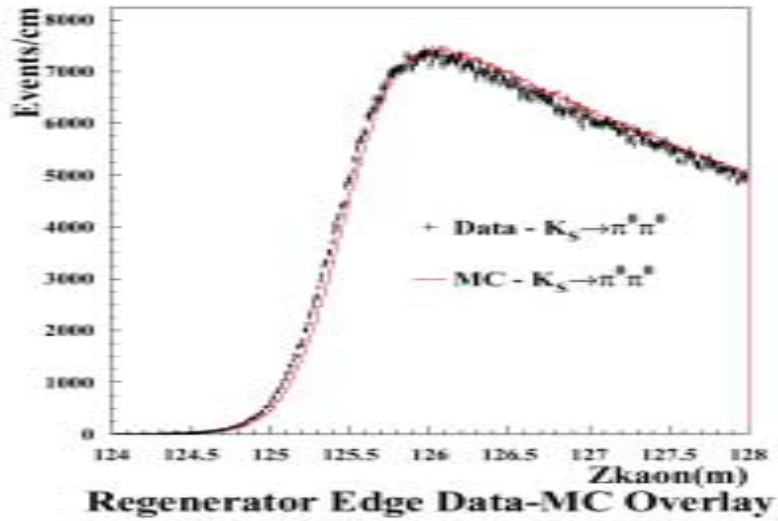


Fiducial cut	KTeV	NA48
K_S Upstream	Anti-counter	Anti-counter
K_L Upstream	mask	t_{rec}/τ_s
K_S Downstream	Z_{rec}	t_{rec}/τ_s
K_L Downstream	Z_{rec}	t_{rec}/τ_s

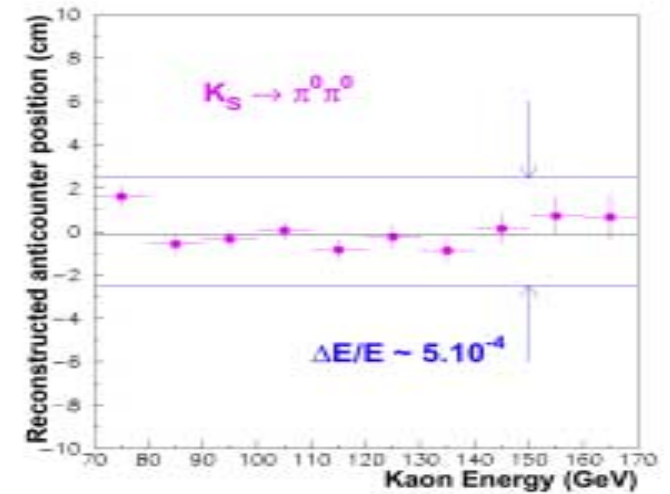
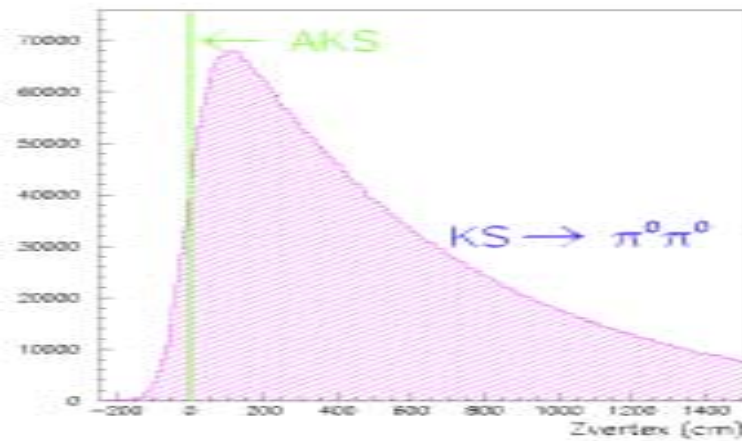
- Sharp anti-counter cut for upstream K_S :
 - Calibration of the distance/energy scale
 - Reduce the error due to energy scale uncertainty

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

KTeV

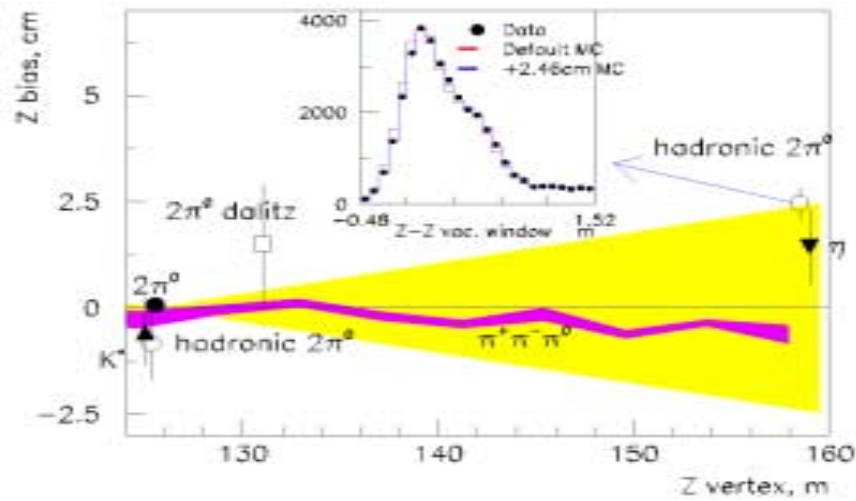


NA48

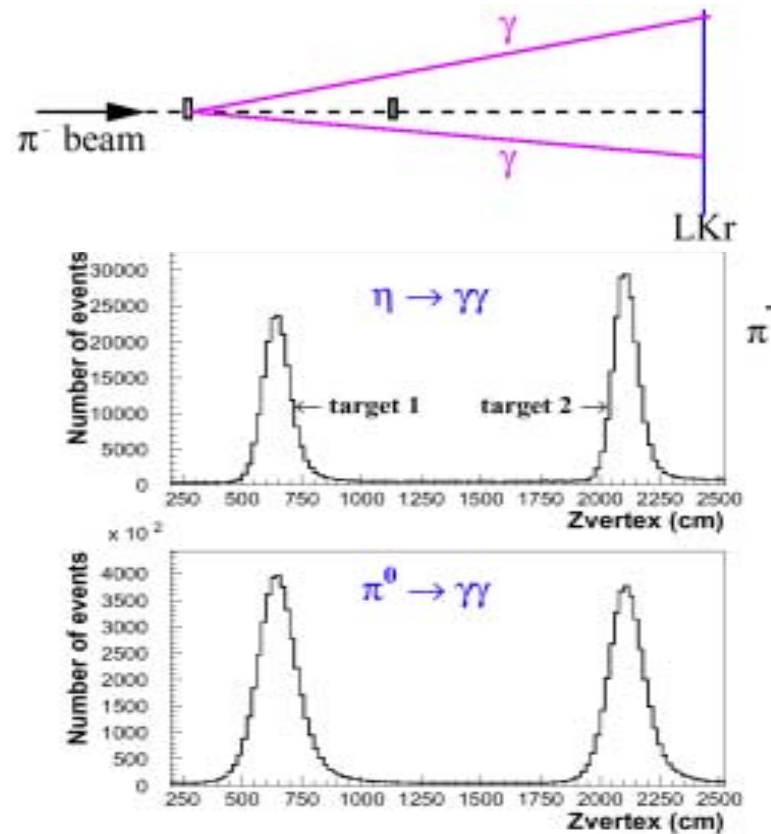


Linearity of the Distance Scale

KTeV



NA48



$< 7 \cdot 10^{-4}$

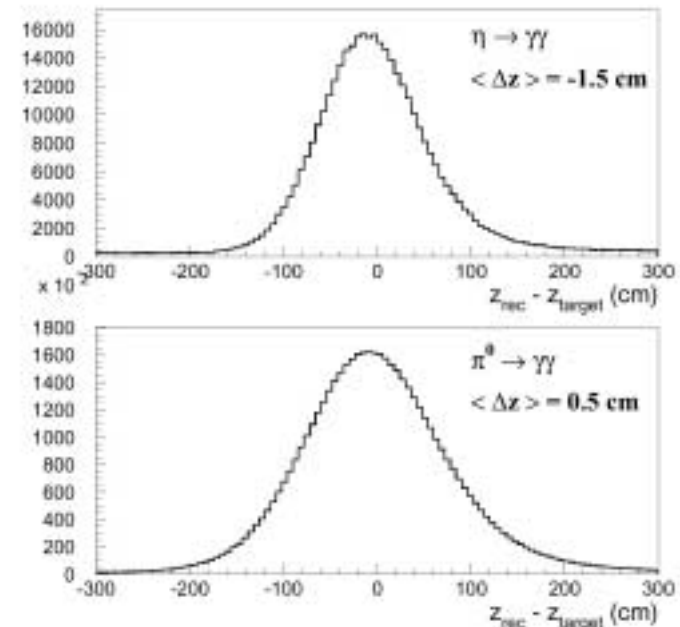
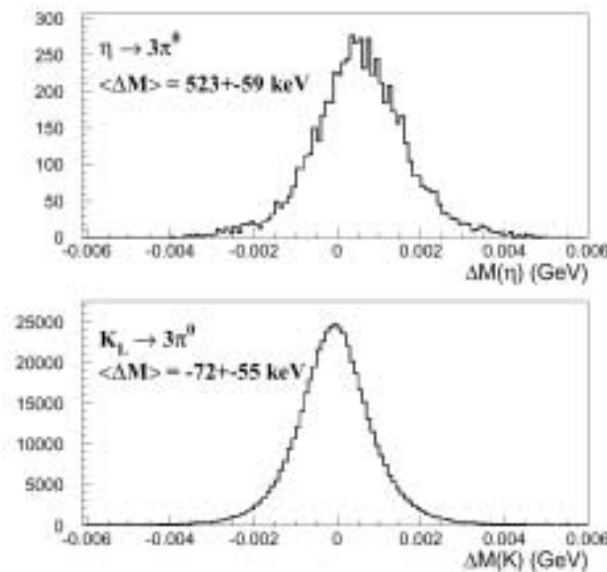
Check of the Energy Scale (NA48)

New preliminary measurement of η mass
 Energy scale independent method:
 measure M_η/M_{π^0}

$$\langle \Delta M \rangle = M_\eta^{\text{NA48}} - M_\eta^{\text{PDG}}$$

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

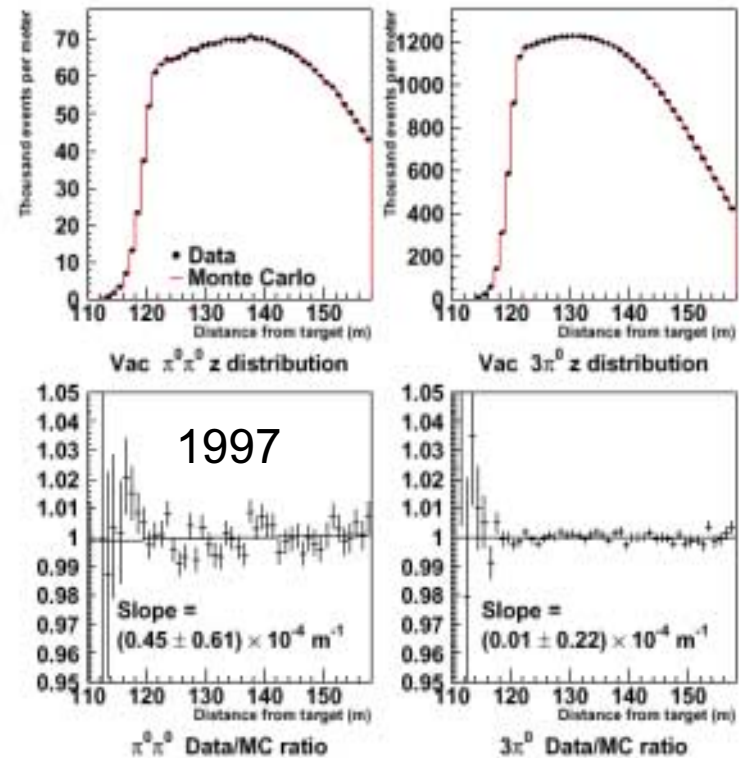
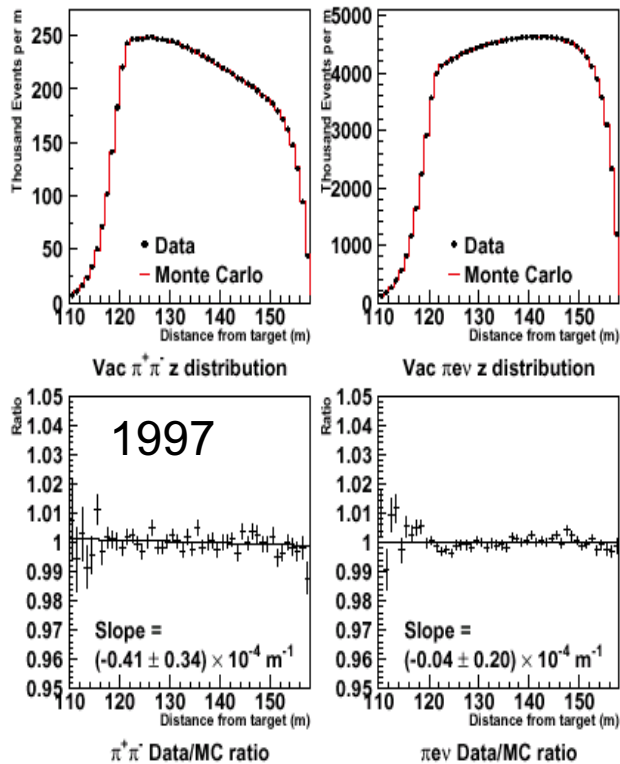
Use new M_η^{NA48} to check energy scale



Good to $\pm 2 \cdot 10^{-4}$
 Allowed syst. on energy scale $\pm 3 \cdot 10^{-4}$

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

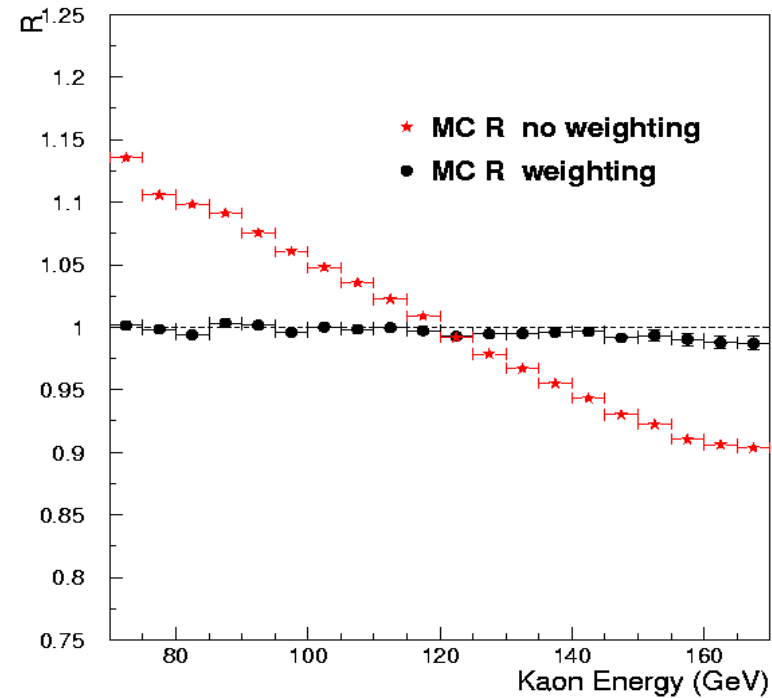
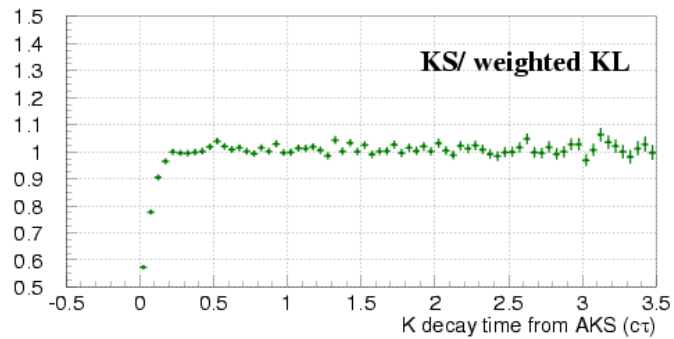
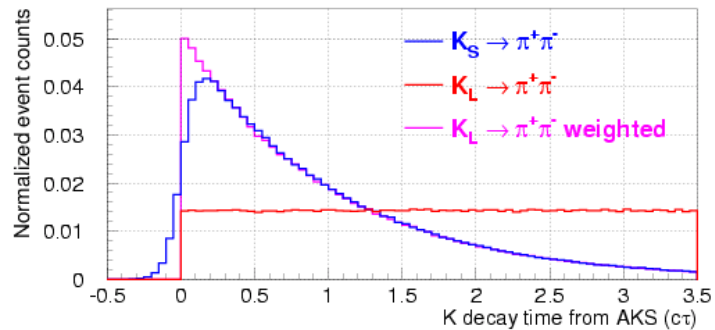


K_L Weighting (NA48)

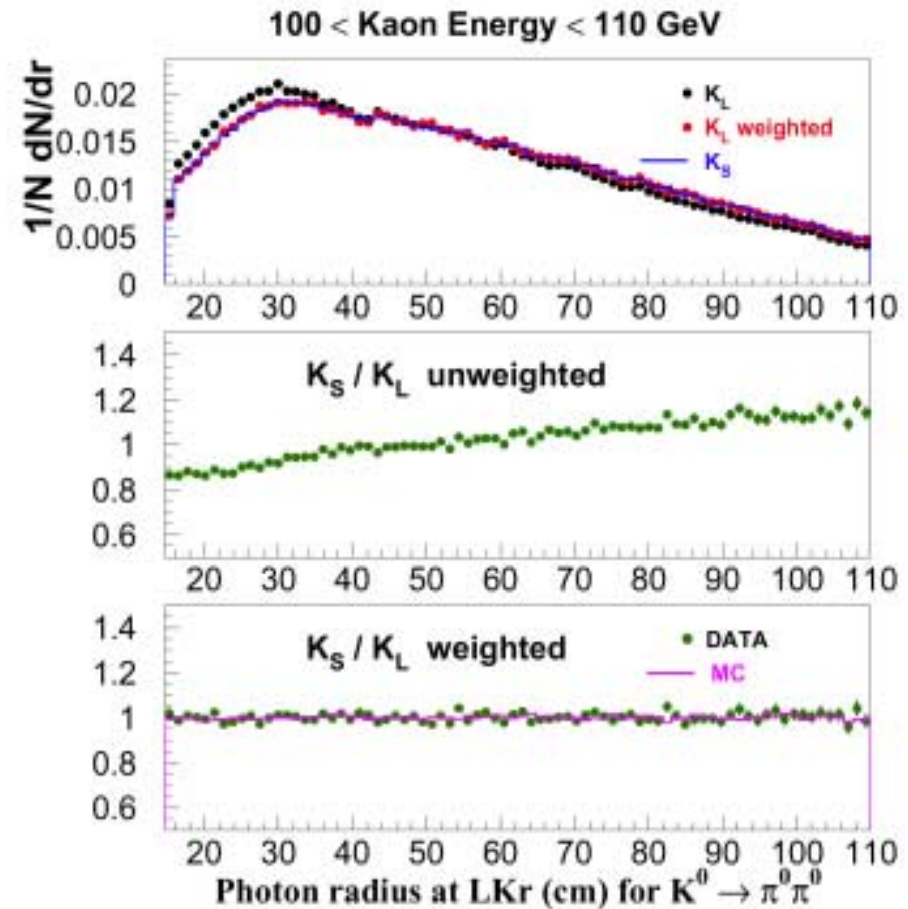
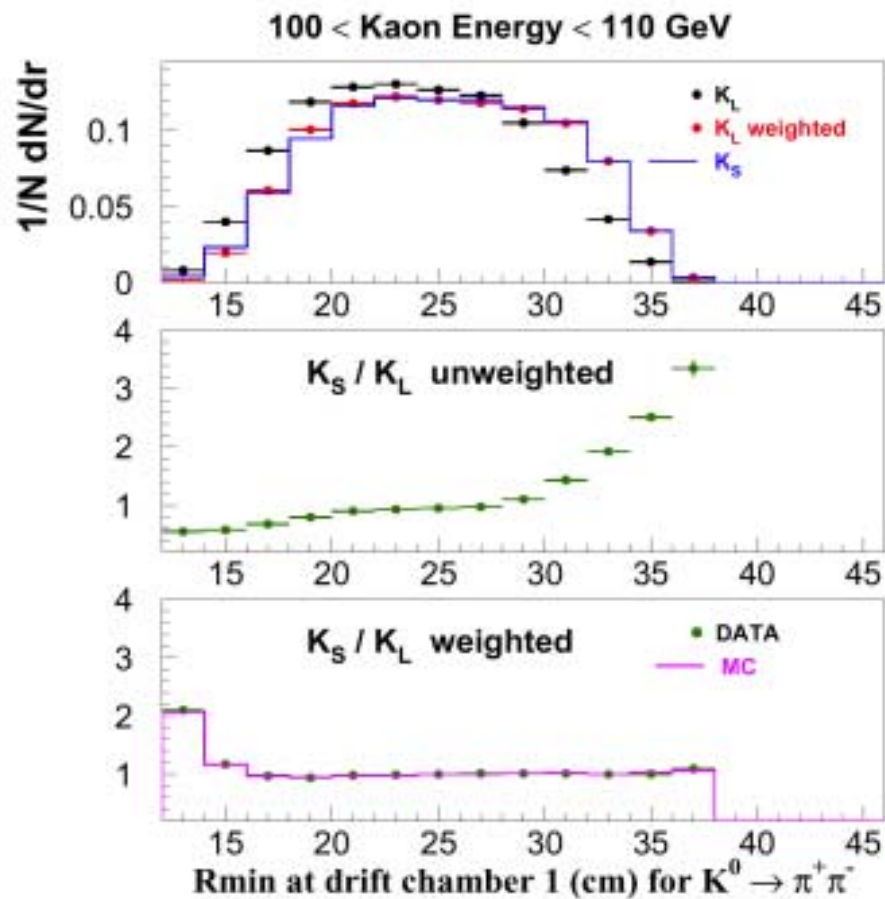
$$W(\tau) = \frac{I_{2\pi}(\tau \text{ from } K_S \text{ target})}{I_{2\pi}(\tau \text{ from } K_L \text{ target})}$$

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

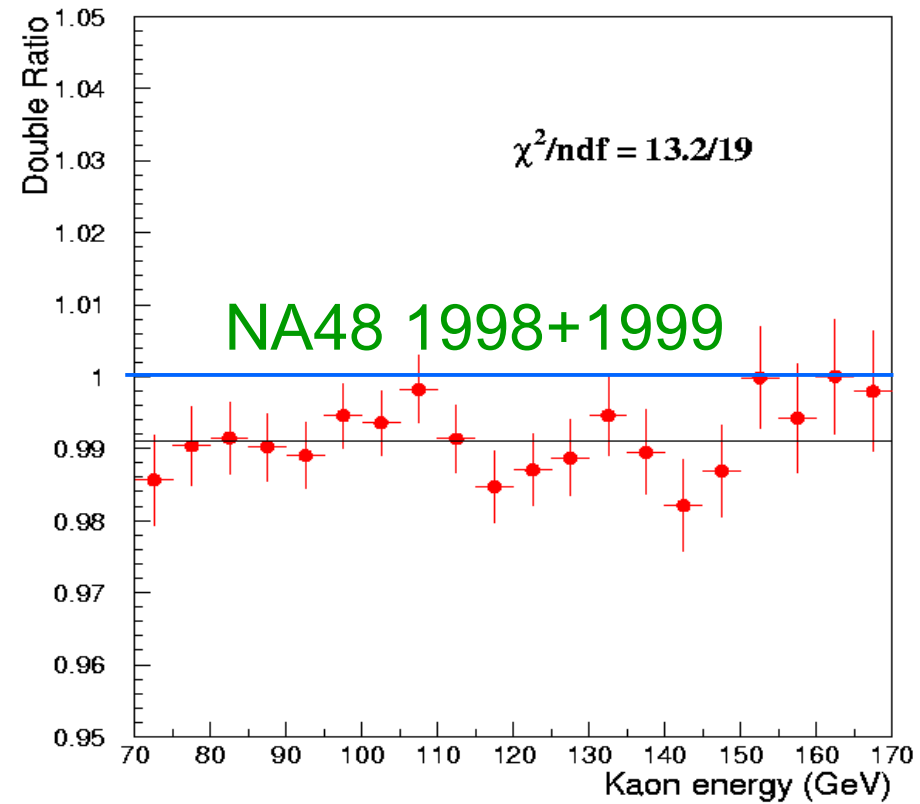
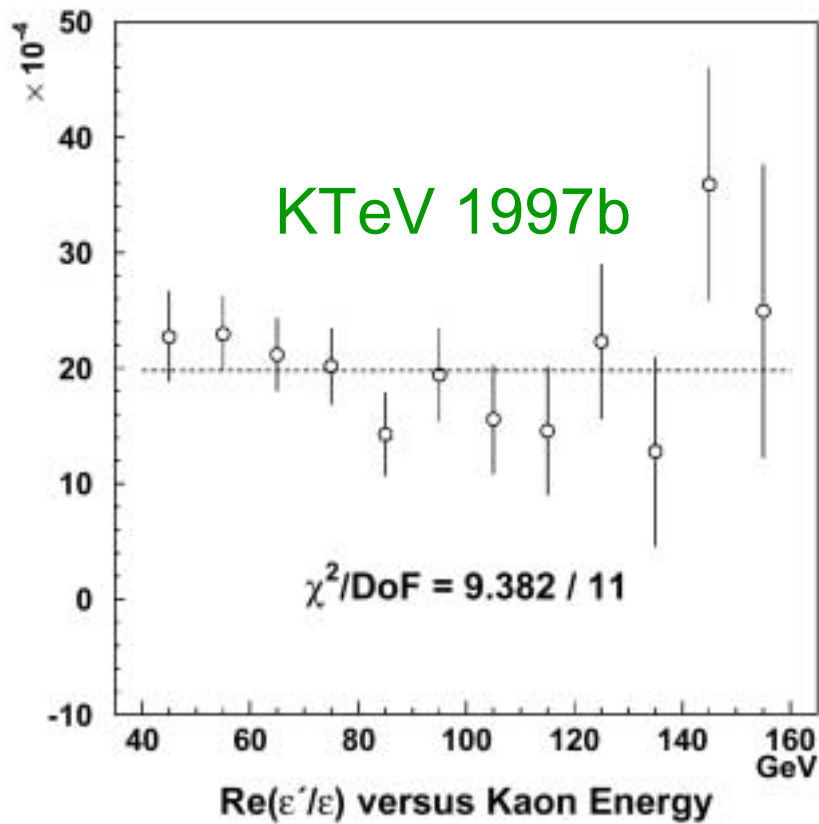
100 < Kaon Energy < 110 GeV



Event weighting (NA48)



Results



Re $\varepsilon'/\varepsilon =$

$$19.8 \pm 1.7_{\text{stat}} \pm 2.3_{\text{syst}} \pm 0.6_{\text{MC}} \times 10^{-4}$$

Re $\varepsilon'/\varepsilon =$

$$15.0 \pm 1.7_{\text{stat}} \pm 2.1_{\text{syst}} \times 10^{-4}$$



Systematics

KTeV 1996+1997 on ε'/ε

NA48 1998+1999 on R

Source of uncertainty	Uncertainty ($\times 10^{-4}$)	
	from $\pi^+\pi^-$	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	
$\Delta m, \tau_S$	0.24	
Reg phase screening	0.31	
TOTAL	2.36	

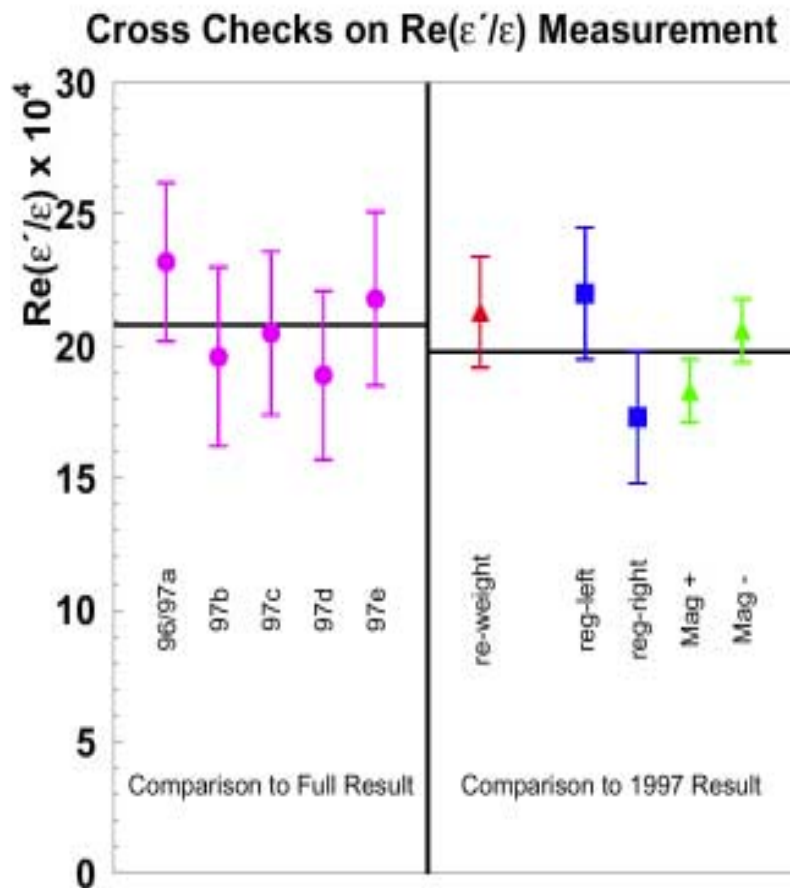
Correction
Uncertainty
($\times 10^{-4}$)

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)

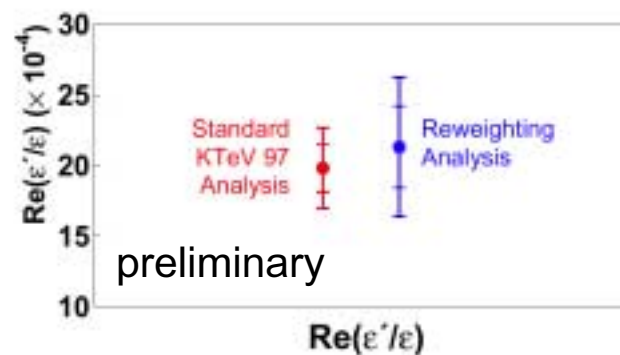


$$\text{Re}(\epsilon'/\epsilon) = (19.8 \pm 1.7 \text{ (stat)} \pm 2.3 \text{ (syst)} \pm 0.6 \text{ (MC stat)}) \times 10^{-4} \quad (1997)$$

Reanalysis of published data:

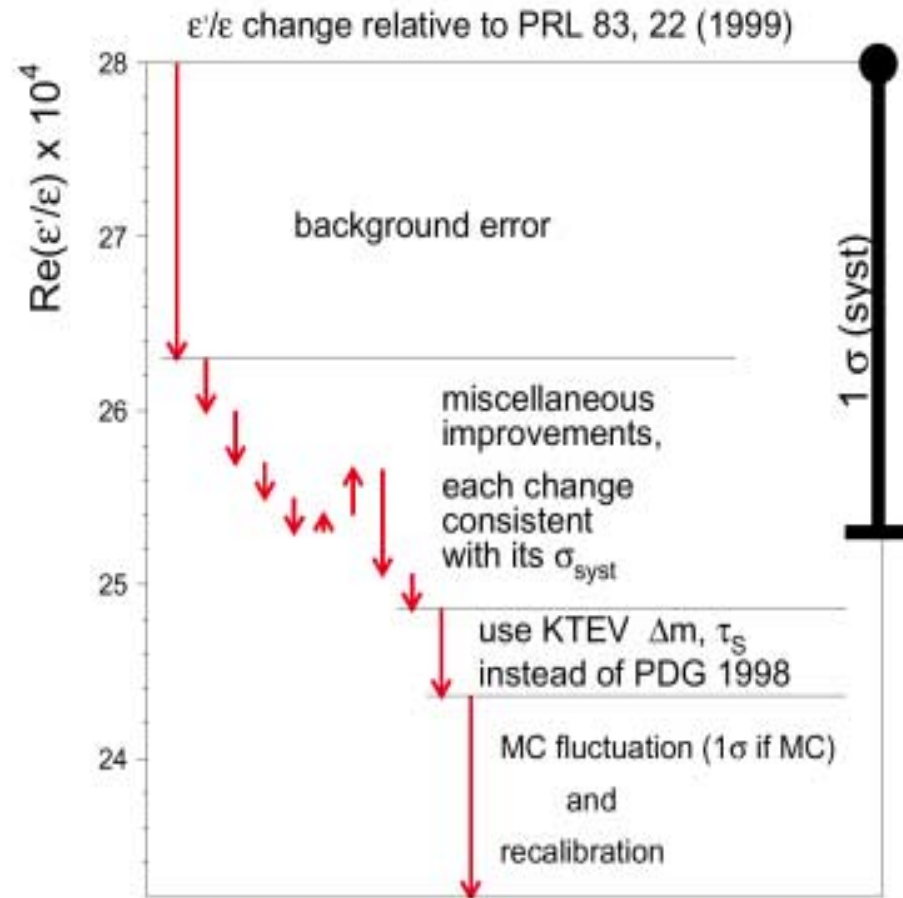
$$\text{Re}(\epsilon'/\epsilon) = (23.2 \pm 3.0 \text{ (stat)} \pm 3.2 \text{ (syst)} \pm 0.7 \text{ (MC stat)}) \times 10^{-4} \quad (\text{PRL})$$

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



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

KTeV reanalysis of PRL data

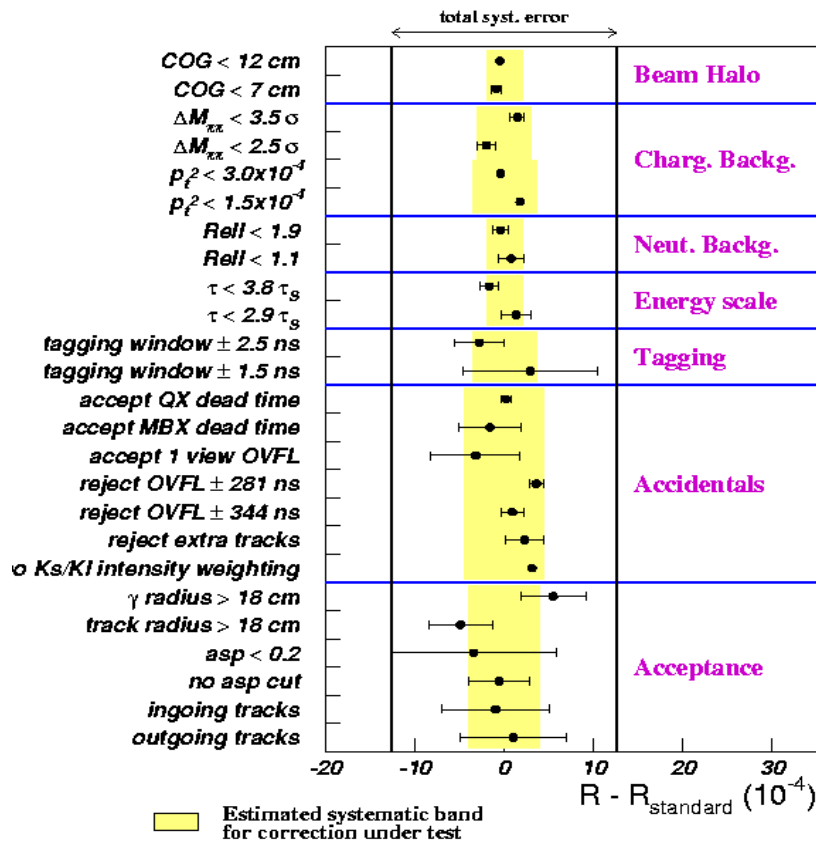


Note: sources of shifts are not correlated

Cross checks and results (NA48)

98+99:
 Eur.Phys.J.C22 (2001)
 hep-ex/0110019

R stability against cut variations

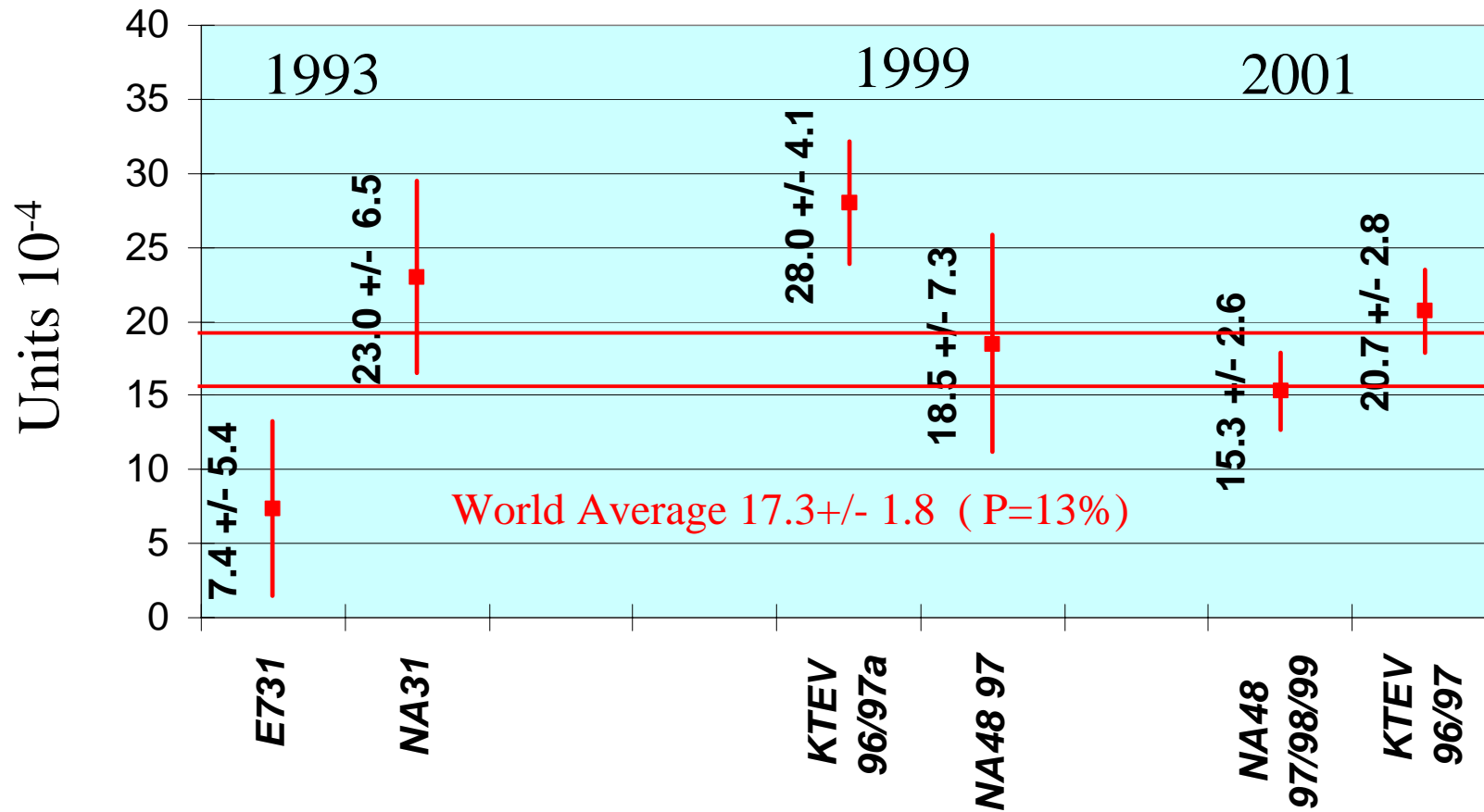


- $Re(\epsilon'/\epsilon) = (15.0 \pm 1.7 \text{ (stat)} \pm 2.1 \text{ (syst)}) 10^{-4}$
- $Re(\epsilon'/\epsilon) = (15.0 \pm 2.7) 10^{-4}$

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

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

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)

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

$$u = (s_3 - s_0) / m_\pi^2 \quad v = (s_1 - s_2) / m_\pi^2$$

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

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

- PDG: $A_g = (-7.0 \pm 5.3) \times 10^{-3}$ W.T. Ford et. al. 1970

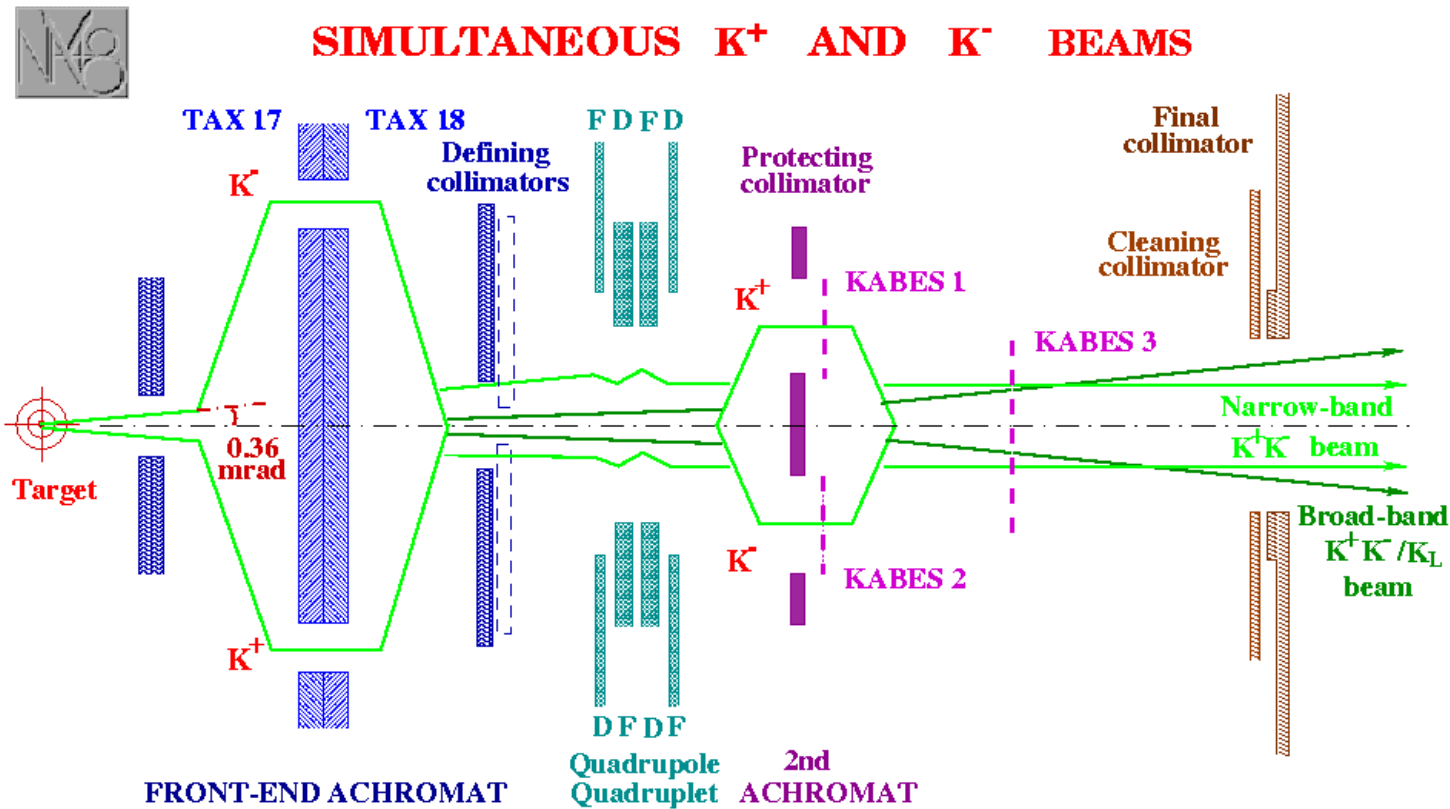
- New data FNAL-HyperCP, 5% -preliminary!-
→ No CP-Violation seen at a few per mill level
FERMILAB-CONF-01-321-E

NA48/2

New technique: **Simultaneous**, unseparated K^+/K^- beams
60 GeV; narrow band ($\Delta P/P \sim 10\%$ 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

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

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

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

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

$$K_L \rightarrow \pi^0 \mu^+ \mu^- \quad \Leftrightarrow \quad \text{Im } \lambda_t$$

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

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

$$K_L \rightarrow \mu^+ \mu^- \quad \Leftrightarrow \quad \text{Re } \lambda_t$$

LFV

One Loop decays

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

- SM prediction: $BR(\text{Direct CPV}) \sim (\text{Im}V_{td})^2 \times 3 \cdot 10^{-4}$
- Mixing contamination:
 - $BR(\text{CP-Violation mixing}) \sim 1/300 BR(K_S \rightarrow \pi^0 e^+ e^-)$
- CP-Conserving Component
 - To be bound by studying $K_L \rightarrow \pi^0 \gamma \gamma$
- Background from $K_L \rightarrow ee\gamma\gamma$ (Greenle, 1990) starts to be seen

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

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

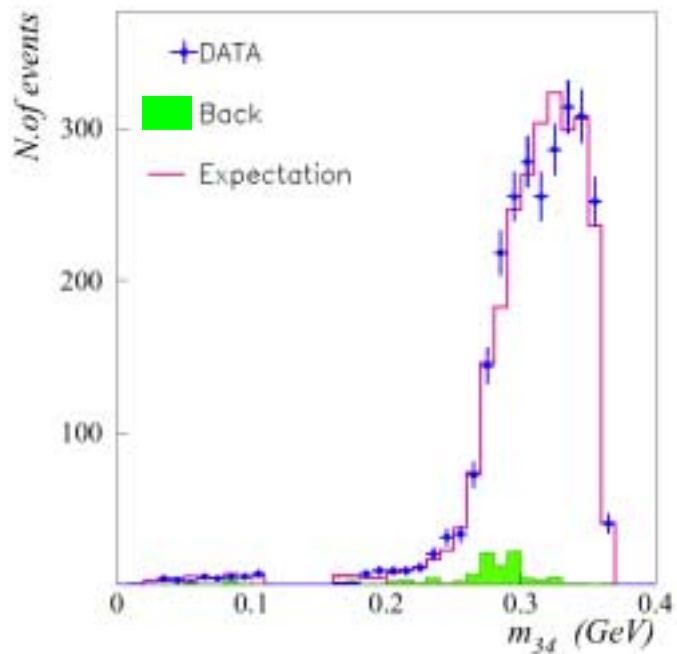
NA48/1: Unique Opportunity for $K_S \rightarrow \pi^0 e^+ e^-$ ($\mu^+ \mu^-$)

- 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
 - $\Rightarrow BR(K_L \rightarrow \pi^0 e^+ e^-)_{\text{mixing}} < 4.2 \times 10^{-10}$ 90% CL
- 2002:
 - Scheduled to run for about 80 days: it aims to reach SES $\sim 3 \cdot 10^{-10}$ 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 $\sim 175 \text{ pb}^{-1}$ in 2001, about $\times 10$ more than Y2K
 - Expect $\sim 500 \text{ pb}^{-1}$ 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):
 - $\text{BR}(K_S \rightarrow \pi e \nu) = (6.8 \pm 0.3) \times 10^{-4}$
 - $\text{BR}(K_S \rightarrow \pi^+ \pi^-) / \text{BR}(K_S \rightarrow \pi^0 \pi^0) = 2.23 \times (1 \pm 0.35 \text{ } 10^{-2}_{\text{sta}} \pm 1.5 \text{ } 10^{-2}_{\text{sys}})$

K_L → π⁰ γγ (NA48)



2588 events with 3.3% background

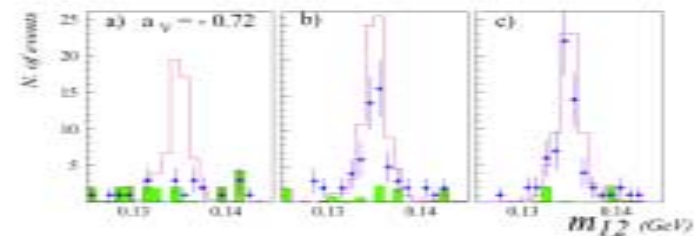
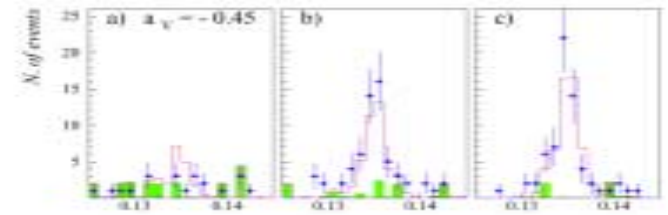
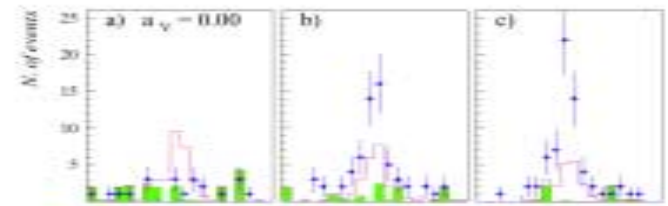
$$\text{BR} = 1.36 \pm 0.03_{\text{sta}} \pm 0.03_{\text{sys}} \pm 0.03_{\text{norm}} \times 10^{-6}$$

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

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

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

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



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

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, $< 5.9 \times 10^{-7}$ 90% CL)

First round of dedicated experiments approved:

- KOPIO AGS (goal: ~10% measurement of $\text{Im}(\lambda_t)$)

- TOF technique to measure E_K

- Plans to measure photon direction

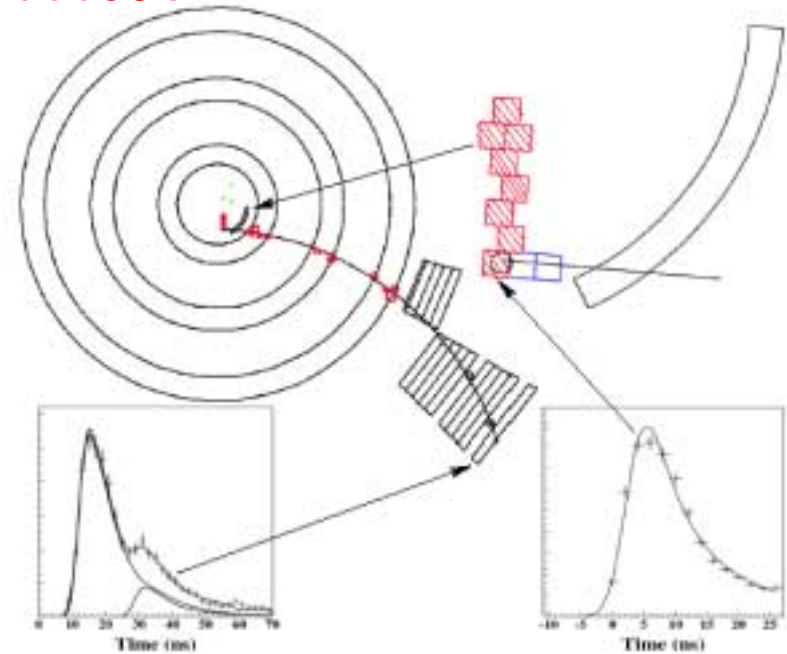
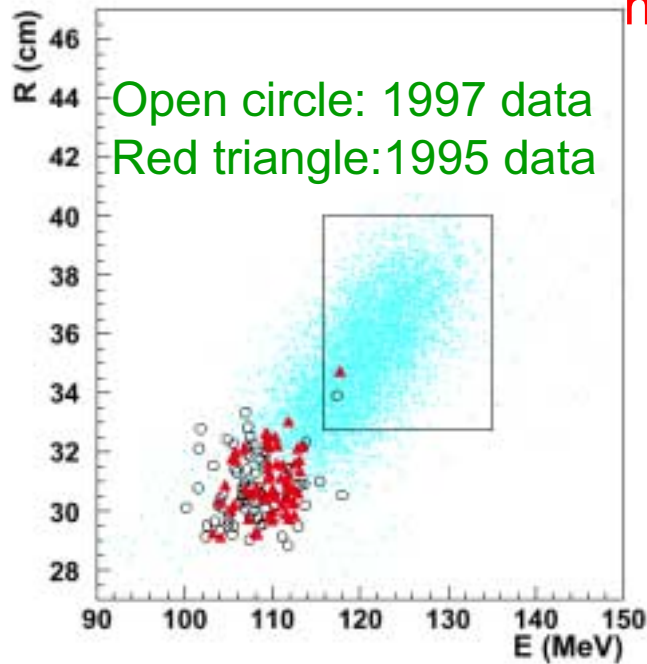
- Found a way to run at 100 Tpp

- 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

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

hep-ex/0111091



Analysis of 1997 just presented:

New candidate found

AGS-E787

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

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

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 $K^+ \rightarrow \pi^+ \nu \nu$ by another order of magnitude employing a super-conducting RF separator and K^+ decays in flight

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

Conclusions

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

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

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