Kaon Physics in the New B-era

R. Tschirhart

Fermilab

August 8^{th}-9^{th} 2002

Borrowing some nice material from:

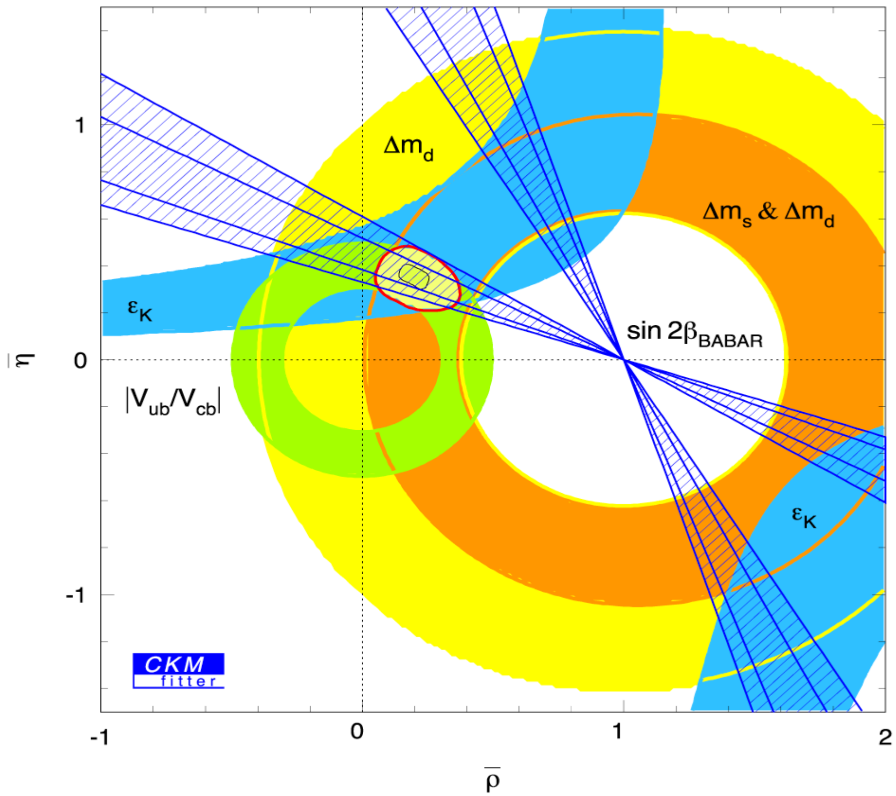
- K. Schubert, Dresden.
- J. Graham, University of Chicago, KTeV.
- Massimo Lenti, INFN Firenze, CERN-NA48.
- The KTeV, CERN-NA48 and CPLEAR collaborations.

Outline of These Two Lectures…

- Relevance: We are entering the era of precision measurements in B-physics….What impact can Kaon physics have??
- Brief review of the CPV and *T-violating* phenomena that have been observed, and some common formalism.
- Review of precision CP, T, and CPT measurements & techniques in the kaon system. (Today)
- Review of rare kaon decay $O(10^{-10} – 10^{-12})$! physics, which can *quantitatively* probe the CP structure of the CKM matrix.

Relevance I: Baryogenesis Dilemma.

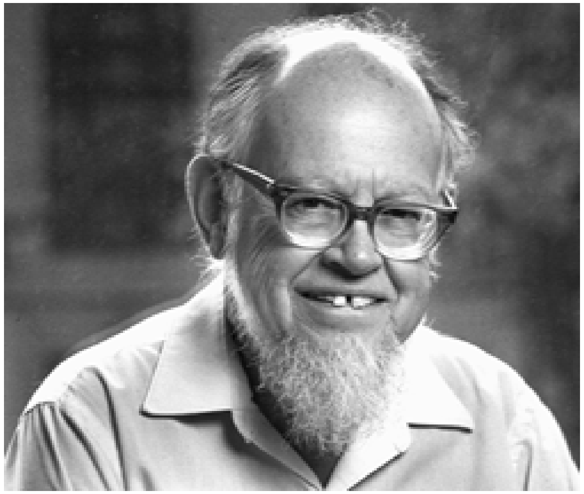
We need more CPV than present in the CKM formalism; But B's and K's so far respect this formalism!



Doug Wright's ICHEP 2002 talk

Relevance II…

``I invented ρ and η and I don't care what there values are so why should you?? The *physics* here is to determine if the breadth of CPV phenomena are really described by this simple description.''



Lincoln Wolfenstein, CMU

The work of Nir, Isidori, Colangelo, Buras and others have shown that theories beyond (e.g. SUSY) the Standard Model typically contain much more CPV, and often very different manifestations between the B and K systems.

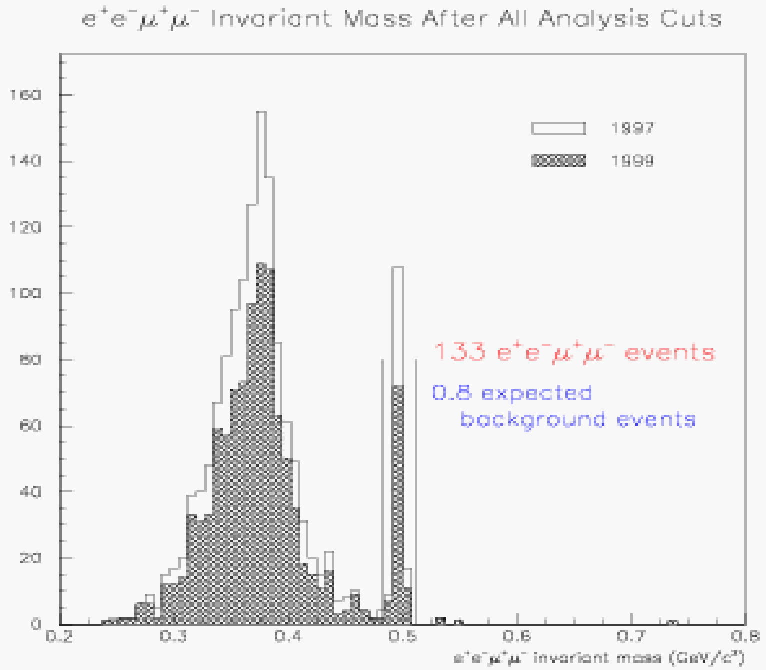
Relevance III…

- Kaon Physics is a mature field…Advances in very intense beams and detector technology have staked out the Precision and Sensitivity Frontiers….

Where the holy grail is the $K \rightarrow \pi\nu\bar{\nu}$ process.

Post Cards From the Frontier...

- Link to the high energy frontier: $B(K_L \to \mu e) < 4.7 \times 10^{-12}(90\%CL)$ BNL-871. Corresponds to Lepton Flavor Violating X-boson: $m_X > 190\ TeV/c^2$.
- Rarest particle decay every seen: $B(K_L \to e^+e^-) = (9^{+6}_{-4}) \times 10^{-12}$, BNL-871.
- The KTeV $K_{\gamma^*\gamma^*}$ laboratory: $K_L \to \mu^+\mu^-e^+e^-$.



Branching Fraction $= (2.61 \pm 0.23(stat) \pm 0.18(syst)) \times 10^{-9}$

(KTeV Preliminary.)

Evolution of the Frontier...

Branching Fraction scale: 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6}, 10^{-7}, 10^{-8}, 10^{-9}, 10^{-10}, 10^{-11}, 10^{-12}, 10^{-13}, 10^{-14}

$K_L \to \pi^+\pi^-$ — 1964, Discovery of CP violation.

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

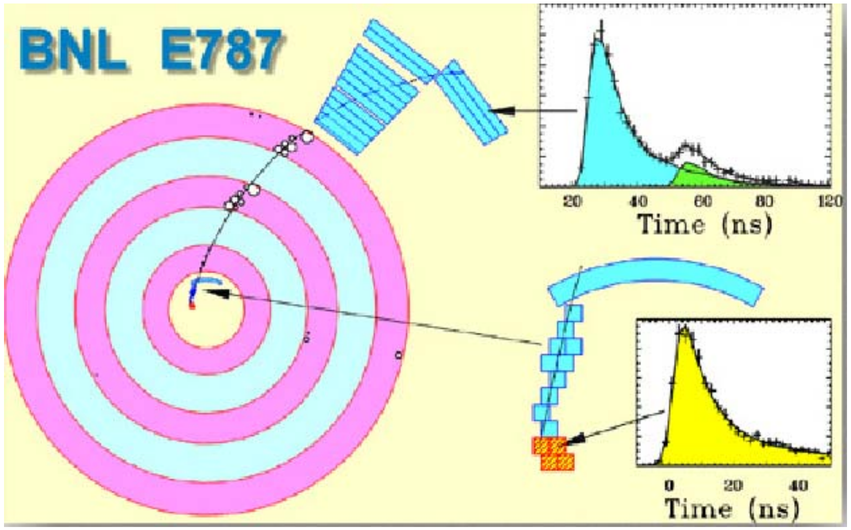
$K_L \to \mu^+\mu^-\gamma$ — 1980, Dalitz Decays.

$K_L \to \mu^+\mu^-$ — 1973, GIM Suppression.

$K^+ \to \pi^+\nu\bar{\nu}$ — 1997, Birth of Quantitative CKM tests.

$K_L \to e^+e^-$ — 1998, Rarest particle decay ever seen.

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



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

Where and how does CPV and T-violation manifest itself in our world?

CP Violation:

1) CPV in Mixing; e.g. Re(ε_K), Re(ε_B)
2) CPV in Mixing-Decay Interference; e.g. Sin2β
3) CPV in Decays to one final state (Direct); e.g. Re(ε'/ε)

T Violation:

1) Observation of T-Violation in $K^0 \Leftrightarrow \overline{K}^0$.
2) Observation of T-odd decay asymmetries in $K_L \rightarrow \pi^+\pi^-e^+e^-$.

Kaon Phenomenology Review:

Strangeness eigenstates:

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

CP eigenstates:

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

Mass and Lifetime eigenstates:

$$K_S \simeq K_1 + \varepsilon K_2 \quad (c\tau_S = 2.67 \text{ cm})$$
$$K_L \simeq K_2 + \varepsilon K_1 \quad (c\tau_L = 15.5 \text{ m})$$

K_S		K_L	
69 %	$\pi^+\pi^-$	21 %	$3\pi^0$
31 %	$\pi^0\pi^0$	13 %	$\pi^+\pi^-\pi^0$
		27 %	$\pi\mu\nu$
		39 %	$\pi e\nu$
		0.2 %	$\pi^+\pi^-$
		0.1 %	$\pi^0\pi^0$

$$\varepsilon = (2.27 \pm 0.02) \times 10^{-3}$$

$\mathrm{Re}(\varepsilon_K)$ can be related to the p/q formalism,
$K_L = pK^0 - q\overline{K}^0$, which leads to:

$$\left|\frac{p}{q}\right| = 1 + \frac{2\,\mathrm{Re}(\varepsilon_K)}{1+|\varepsilon_K|^2} = 1 + 2\,\mathrm{Re}(\varepsilon_K), \quad \mathrm{Re}(\varepsilon_K) << 1.$$

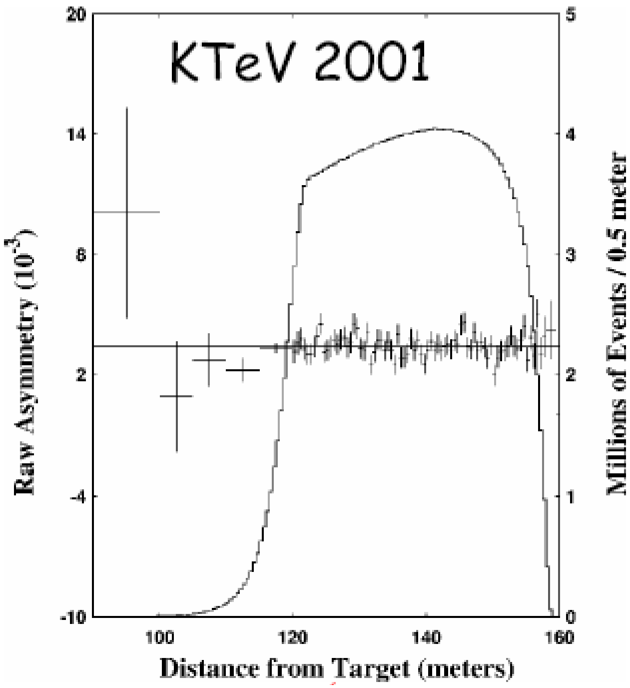
Experimental results:

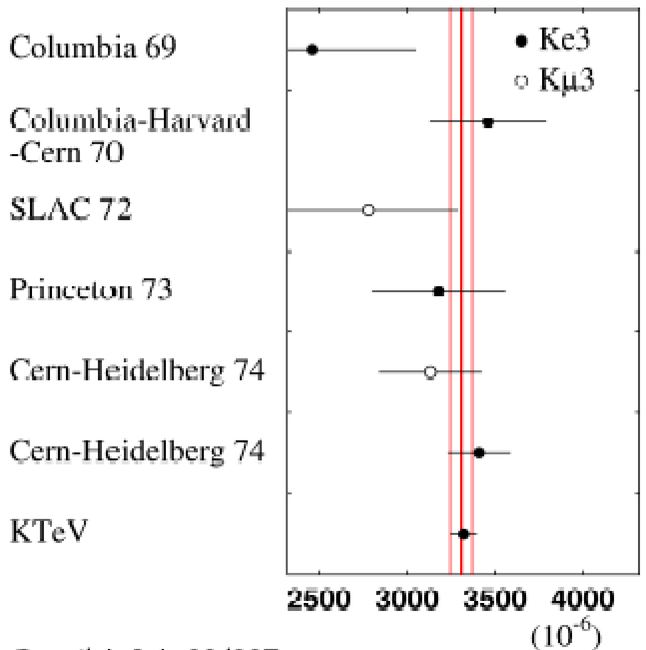
$$\frac{\Gamma(K_L \to \ell^+ \nu \pi) - \Gamma(K_L \to \ell^- \nu \pi)}{\Gamma(K_L \to \ell^+ \nu \pi) + \Gamma(K_L \to \ell^- \nu \pi)} = \frac{|p|^2 - |q|^2}{|p|^2 + |q|^2} = (0.327 \pm 0.012)\%.$$ [PDG 2000]

$$\left| p/q \right| = 1.00327 \pm 0.00012\,, \quad \mathrm{Re}(\varepsilon_K) = (1.64 \pm 0.06)\cdot 10^{-3}$$

For B^0 mesons: $\mathrm{Re}(\varepsilon_B) = (1 \pm 3 \pm 4)\cdot 10^{-3}.$ [BABAR 2001]

300M $K_L \to \pi e \nu$ Decays!





Fermilab-Pub-02/007

$$\mathrm{Re}(\varepsilon_K) = (1.64 \pm 0.06) \cdot 10^{-3}$$ [PDG 2000]

$$\mathrm{Re}(\varepsilon_K) = (1.661 \pm 0.037) \cdot 10^{-3}$$ [KTeV 2001]

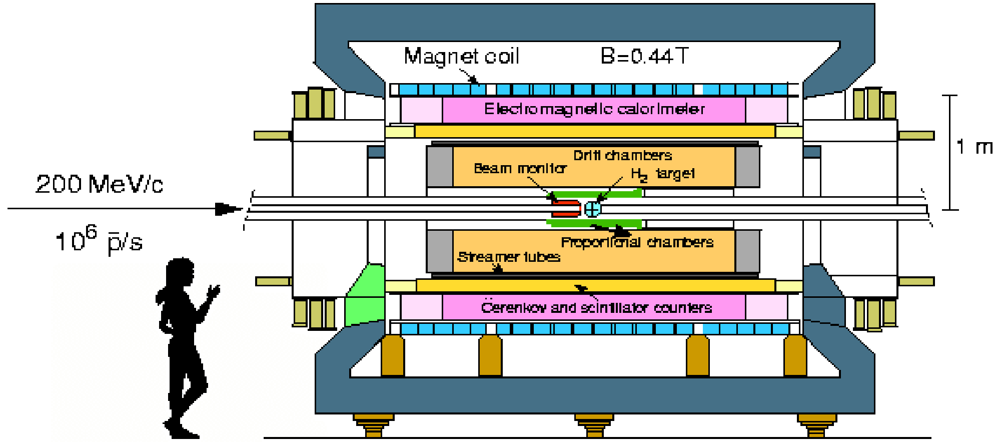
The CPLEAR Detector

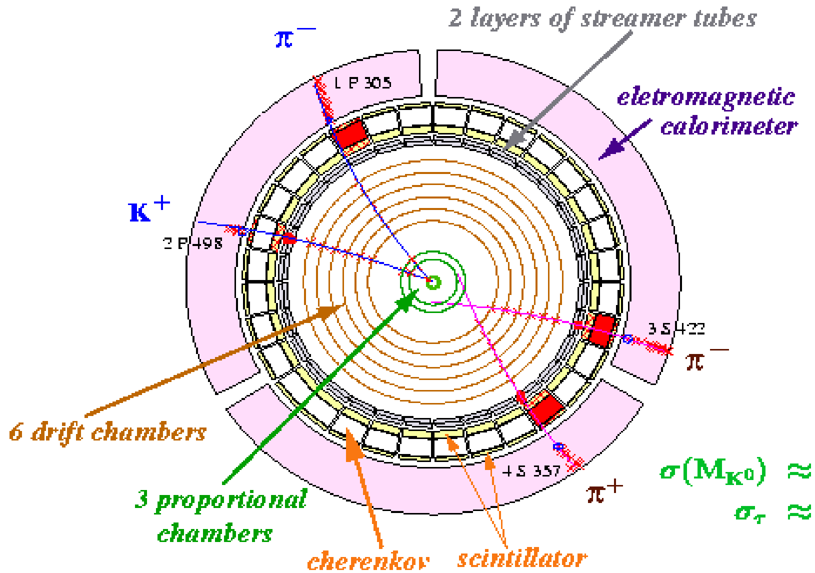
CPLEAR: CP Physics at a Low Energy Antiproton Ring. Technique is to stop $\bar{p}$'s in H_2, and observe the following reactions:

$p\bar{p} \Rightarrow K^+\pi^-\overline{K^0}$, and

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

The $K^0/\overline{K^0}$ is tagged by the away-side $K\pi$. Hence one can study the time evolution of CPV in $K^0 \Leftrightarrow \overline{K^0}$ mixing.

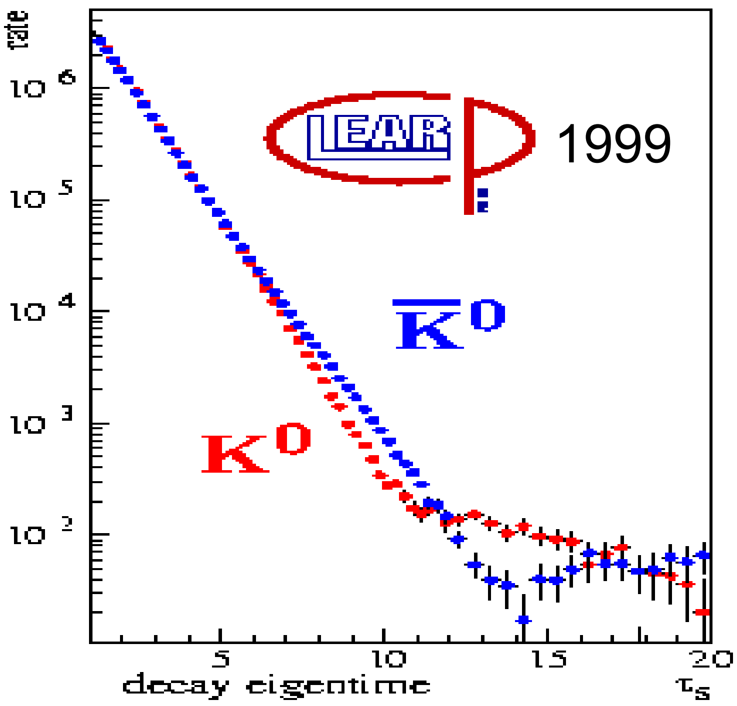




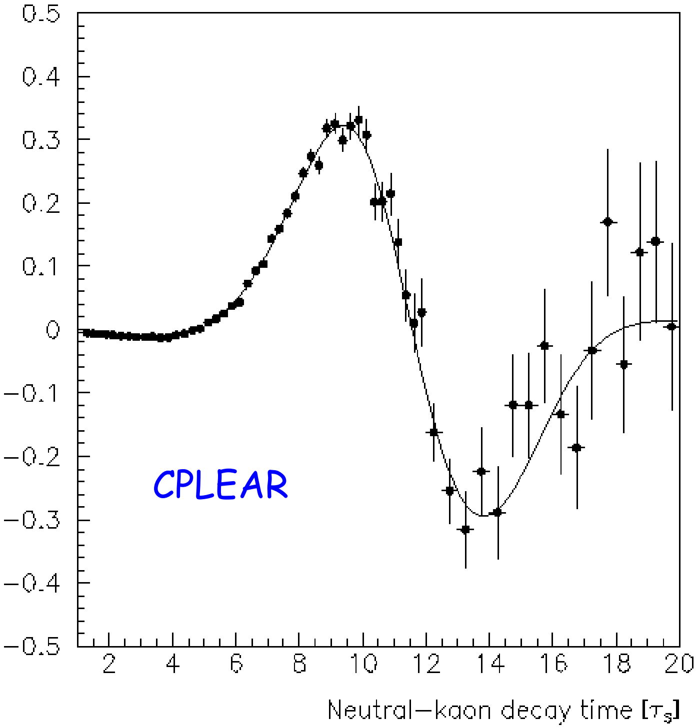
$\sigma(M_{K^0}) \approx 13\ \mathrm{MeV/c^2}$

$\sigma_\tau \approx (5-10)\ \mathrm{ps}$

$\pi^+\pi^-$ Results from CPLEAR, CPV in mixing:



a(t)



$$a(t) = \frac{N(\overline{K}^0 \to \pi^+\pi^-) - N(K^0 \to \pi^+\pi^-)}{N(\overline{K}^0 \to \pi^+\pi^-) + N(K^0 \to \pi^+\pi^-)} = \frac{-2|\eta_{+-}|e^{-(\Gamma_S+\Gamma_L)t/2}\cos(\Delta m \cdot t - \varphi_{+-})}{e^{-\Gamma_S t} + |\eta_{+-}|^2 e^{-\Gamma_L t}}$$

$$\eta_{+-} = (2.27 \pm 0.02)\cdot 10^{-3} \cdot e^{i(43.3\pm0.5)^0}$$

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

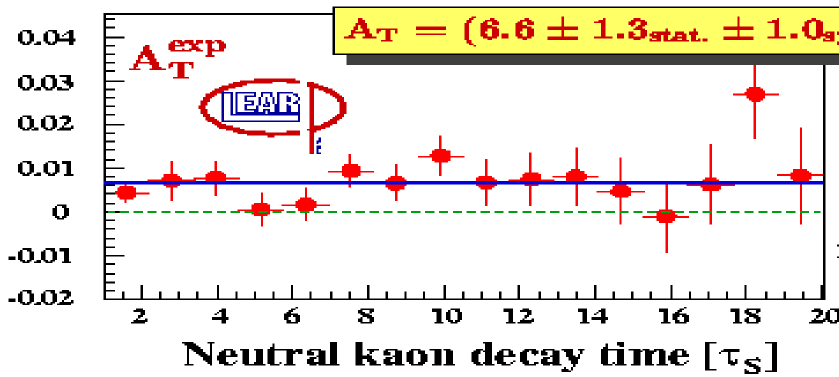
Measurement of $\mathcal{T}$ violation

$$A_T = \frac{R(\overline{K^0} \to K^0) - R(K^0 \to \overline{K^0})}{R(\overline{K^0} \to K^0) + R(K^0 \to \overline{K^0})} = 4\Re e\, \varepsilon_T$$

Example $\tau = 6.5\tau_S$

CPLEAR measures:	$N(K^0{}_{\tau=0} \to e^-\pi^+\bar{\nu})[\tau] = 15050$ $N(\overline{K^0}{}_{\tau=0} \to e^+\pi^-\nu)[\tau] = 13559$	$A = 0.0521$
first correction:	different reconstruction efficiency for $e^+\pi^-$ and $e^-\pi^+$. Obtained from unbiased pure electron and pion samples: $\langle\eta\rangle = 1.014 \pm 0.002$	$A = 0.0610$
second correction:	different reconstruction efficiency for $K^+\pi^-$ and $K^-\pi^+$. Obtained from $\pi\pi$ decays: $\langle\alpha\rangle = 1.12756 \pm 0.00034$ (ratio of $K^+\pi^-/K^-\pi^+$ efficiencies) $\times$ $[1 + 4\Re e\,(\varepsilon_T + \delta)]$	$A = 0.0098$
third correction:	assume CPT conservation in semileptonic decay amplitudes, use $\delta_l = 2\Re e\,(\varepsilon_T + \delta) = (0.327 \pm 0.012)\%$	$A = 0.0066$

$A_T = (6.6 \pm 1.3_{stat.} \pm 1.0_{syst.}) \times 10^{-3}$

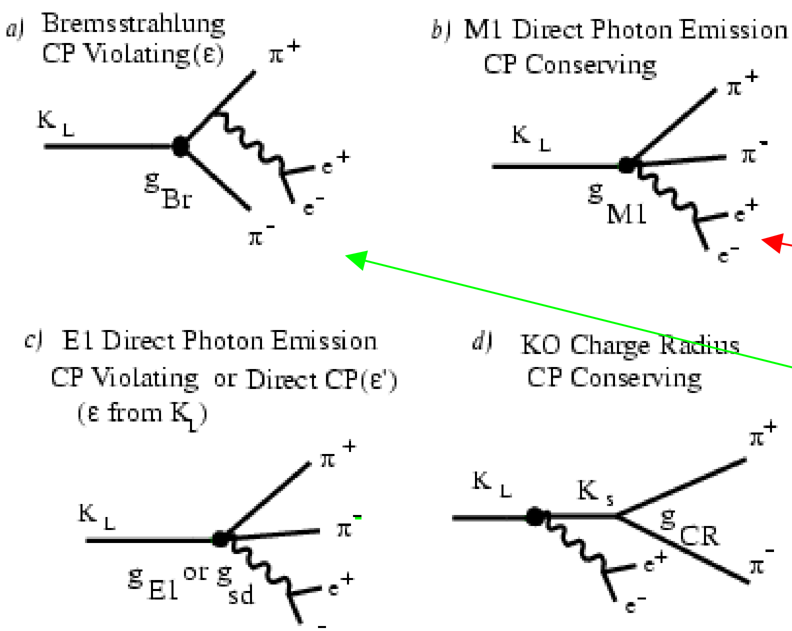


"First direct" measurement of time reversal non-invariance!

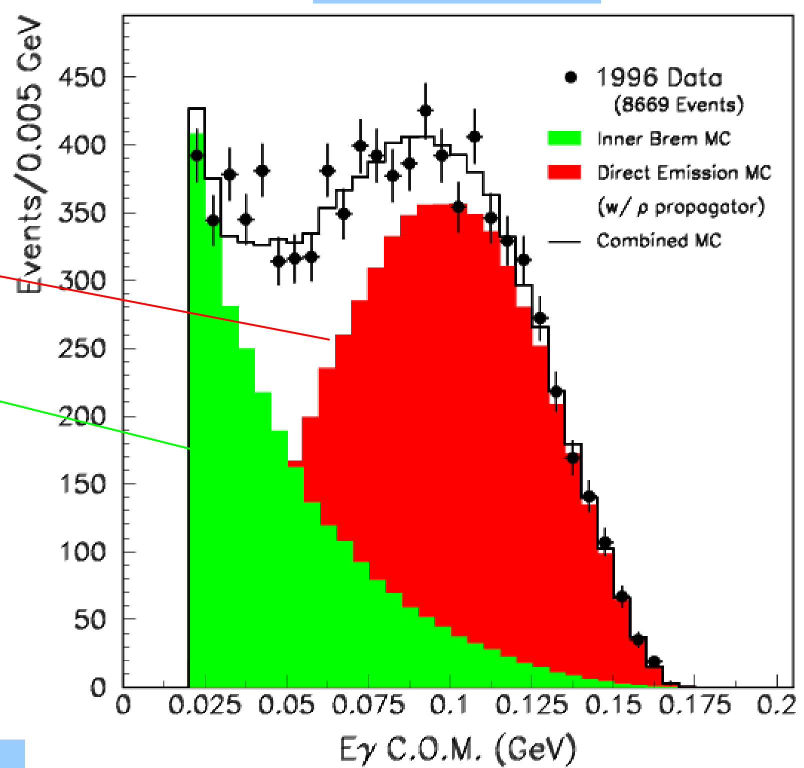
Phys.Lett. B444 (1998) 43

$K_L \rightarrow \pi^+\pi^- e^+ e^-$, Another T-odd laboratory…

K->ππee Processes



$K_L \rightarrow \pi\pi\gamma$



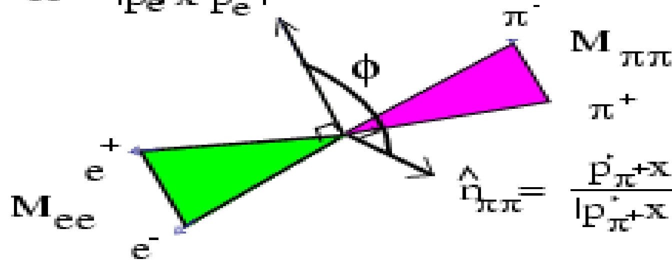
$BR(K_L \rightarrow \pi^+\pi^- e^+ e^-) = 3.6 \times 10^{-7}$

T-odd Observable

$K^0_L \to \pi^+\pi^- e^+ e^-$ ϕ Angle

(K^0_L Center of Mass)

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

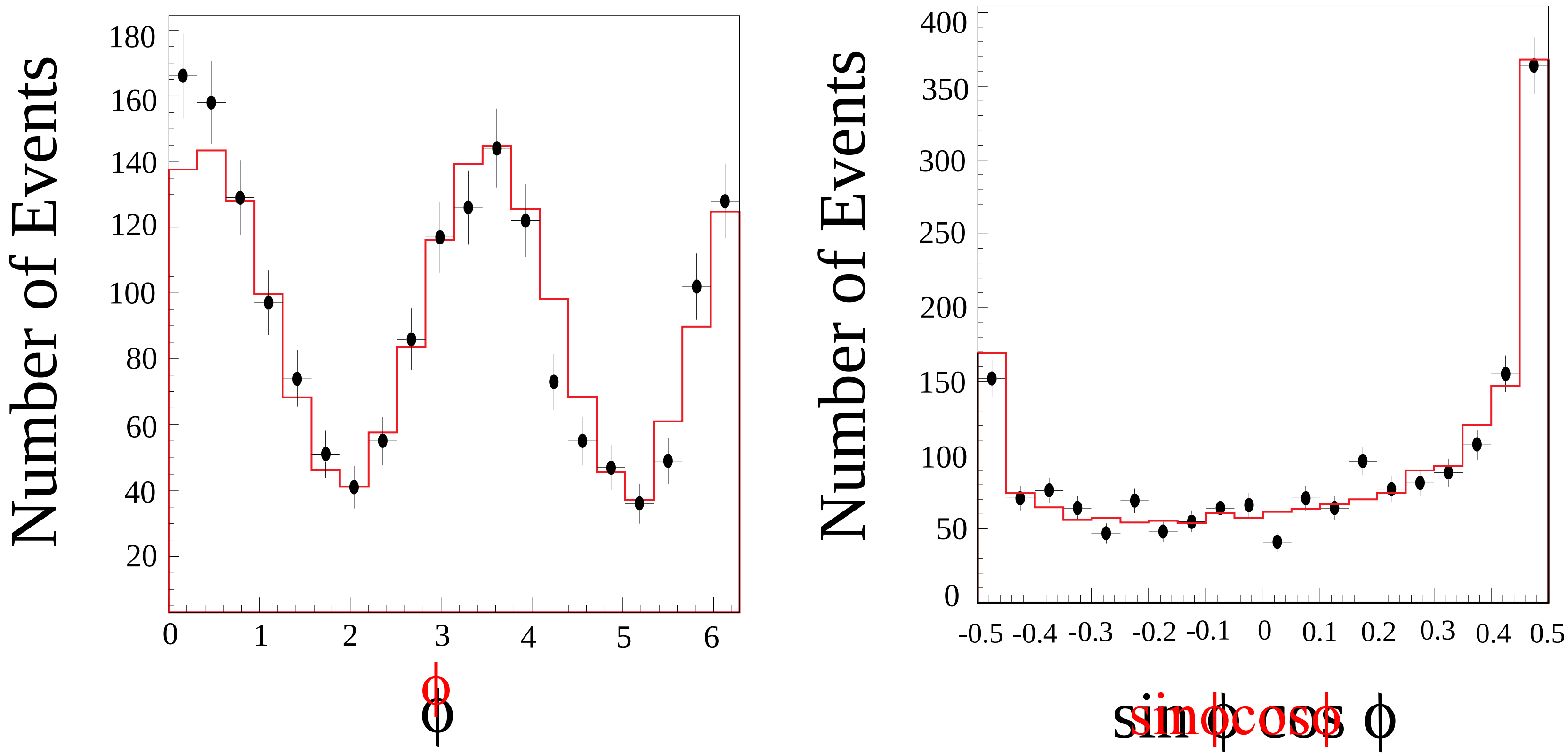


$$\hat{n}_{\pi\pi} = \frac{\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}}{|\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}|}$$

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

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

Discovered at KTeV, confirmed by CERN-NA48…



Asymmetry = (13.6 +/- 2.5+/-1.2)%

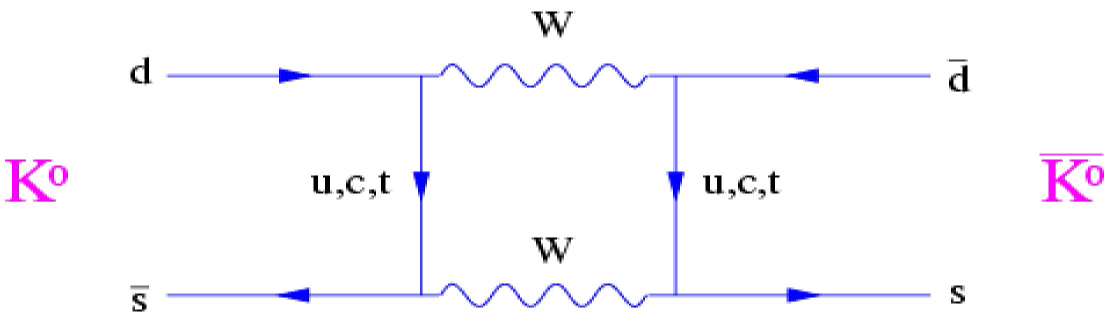
This T-odd effect is due entirely to mixing, no evidence of direct CPV.

Summary of $K^0 \leftrightarrow \overline{K^0}$ CPV

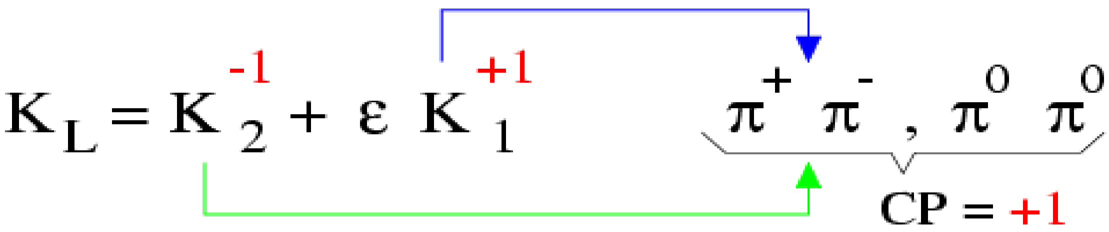
- Precisely measured in both $K^0 \rightarrow \pi\pi$ and and $K^0 \rightarrow \pi e \nu$ decays.

- Recently, T-violation in $K^0 \leftrightarrow \overline{K^0}$ has been directly measured, and agrees with CPV; thereby testing CPT.

$\varepsilon \Rightarrow$ Indirect CP violation via $K^0/\overline{K^0}$ mixing



Is there also a component of CP violation in the decay process?



Need interference of two decay amplitudes

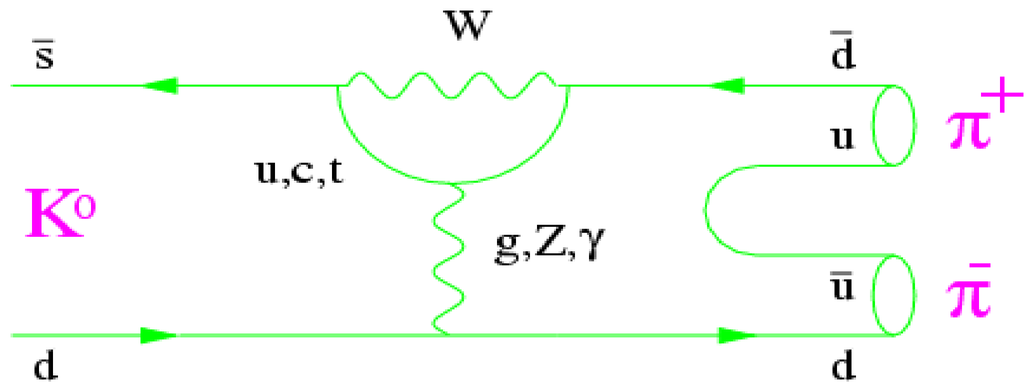
$\pi\pi$ from K^0 can have I=0,2 $\Rightarrow$ amplitudes A_0, A_2

$$A(K^0 \rightarrow \pi\,\pi\,, I) = A_I \exp(i\delta_I)$$

$$A(\overline{K^0} \rightarrow \pi\,\pi\,, I) = A_I^* \exp(i\delta_I)$$

$$\varepsilon' = \frac{i}{\sqrt{2}} \Im\mathrm{m} \frac{A_2}{A_0} \exp(i(\delta_2 - \delta_0))$$

$\varepsilon' \Rightarrow$ Direct CP violation:



$$\eta_{+-} \equiv \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} \simeq \varepsilon + \varepsilon'$$

$$\eta_{00} \equiv \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} \simeq \varepsilon - 2\,\varepsilon'$$

$$R = \frac{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)}{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)} \simeq 1 - 6\ \mathrm{Re}(\frac{\varepsilon'}{\varepsilon})$$

IF the 4 modes are taken

- simultaneously
- in the same decay region

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

Status of Re(ε'/ε)…

Experiment:

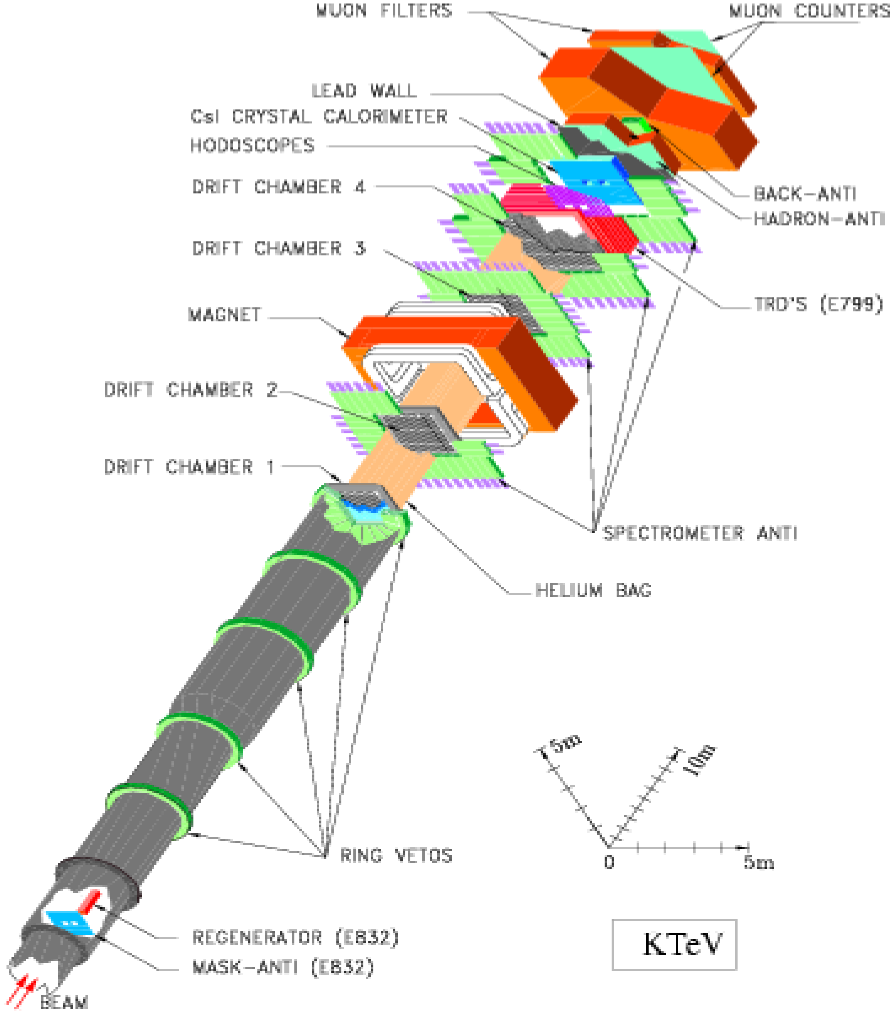
NA48, Final Result @ Blois 2002: $Re(\varepsilon`/\varepsilon_0) = (14.7 \pm 2.2) \cdot 10^{-4}$
KTeV, (1/2 Data) @ Blois 2002: $Re(\varepsilon`/\varepsilon_0) = (20.7 \pm 2.8) \cdot 10^{-4}$

World Average: $Re(\varepsilon`/\varepsilon_0) = (16.6 \pm 1.6) \cdot 10^{-4}$

Theory: (victim of the brown muck)

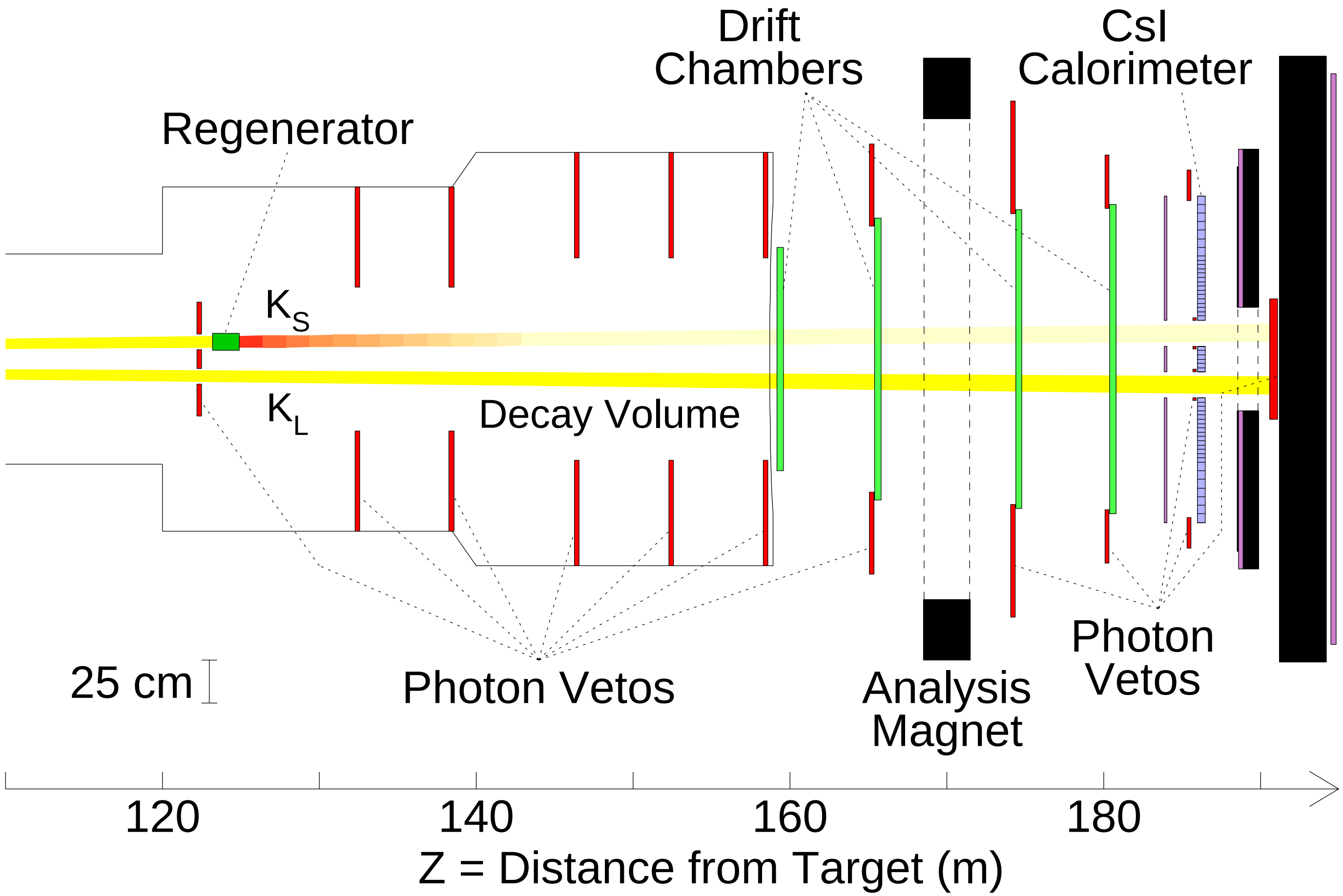
Typical range has been $5x10^{-4}$ to $40x10^{-4}$,
However, latest Lattice calculations are around $-7x10^{-4}$ (!) (CP-PACs, RBC)

The KTeV Detector



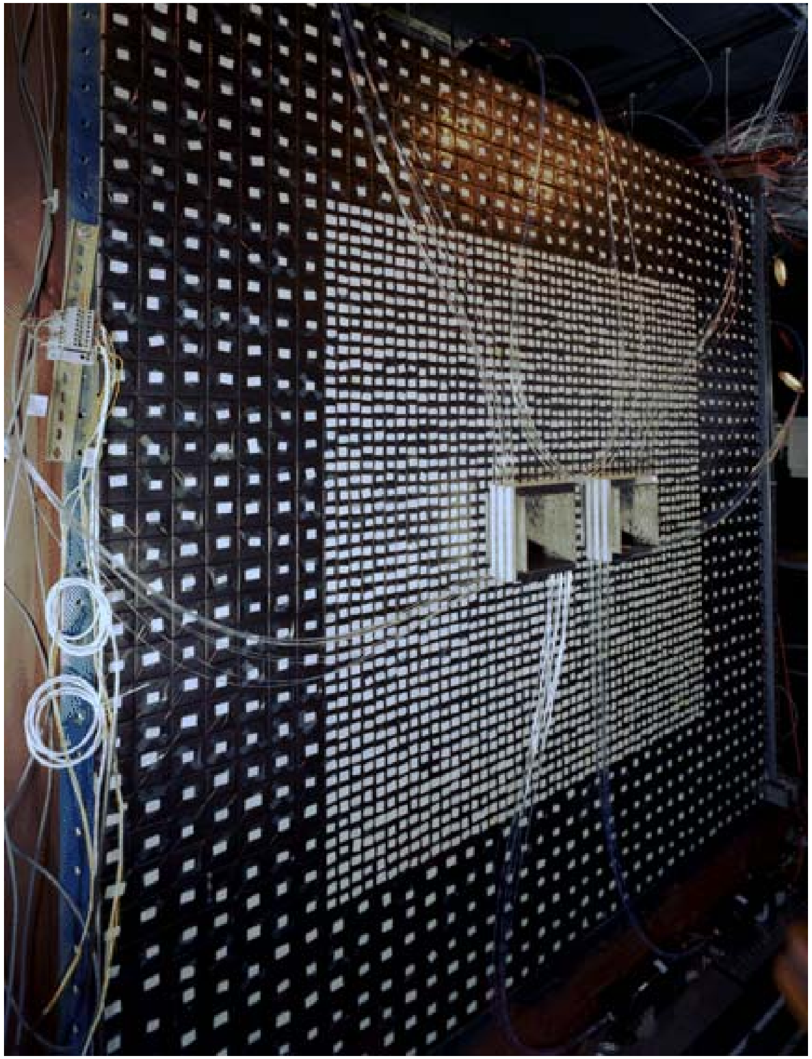
"Vacuum" beam $\rightarrow K_L$ beam

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


Drift
Chambers
CsI
Calorimeter
Regenerator
K S
K L
Decay Volume
25 cm
Photon Vetos
Analysis
Magnet
Photon
Vetos
120
140
160
180
Z = Distance from Target (m)

The KTeV Pure CsI Calorimeter.

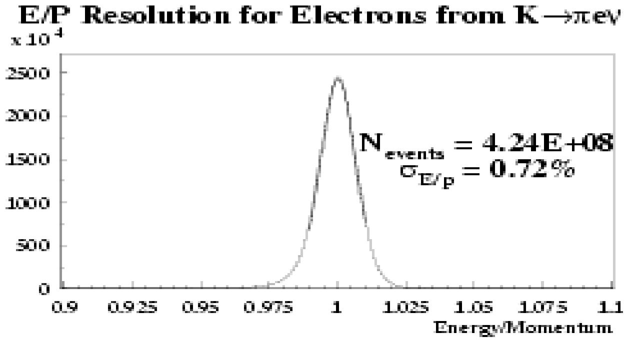
Very fast scintillation light, $\tau \sim 20$ nsec, lower light yield requires PMT readout.

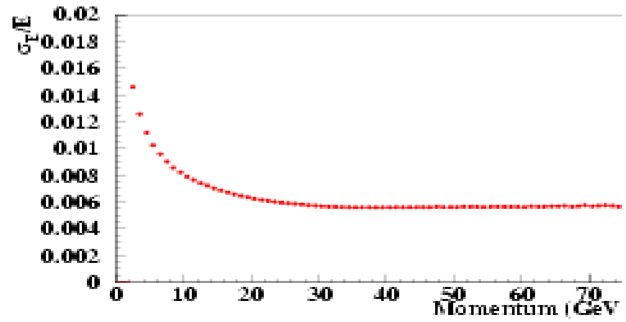


The KTeV Detector Performance

NEUTRAL:

- CsI energy res: 0.7% at 15 GeV (1.3% at 3 GeV)
- CsI position res: $\sim$ 1 mm





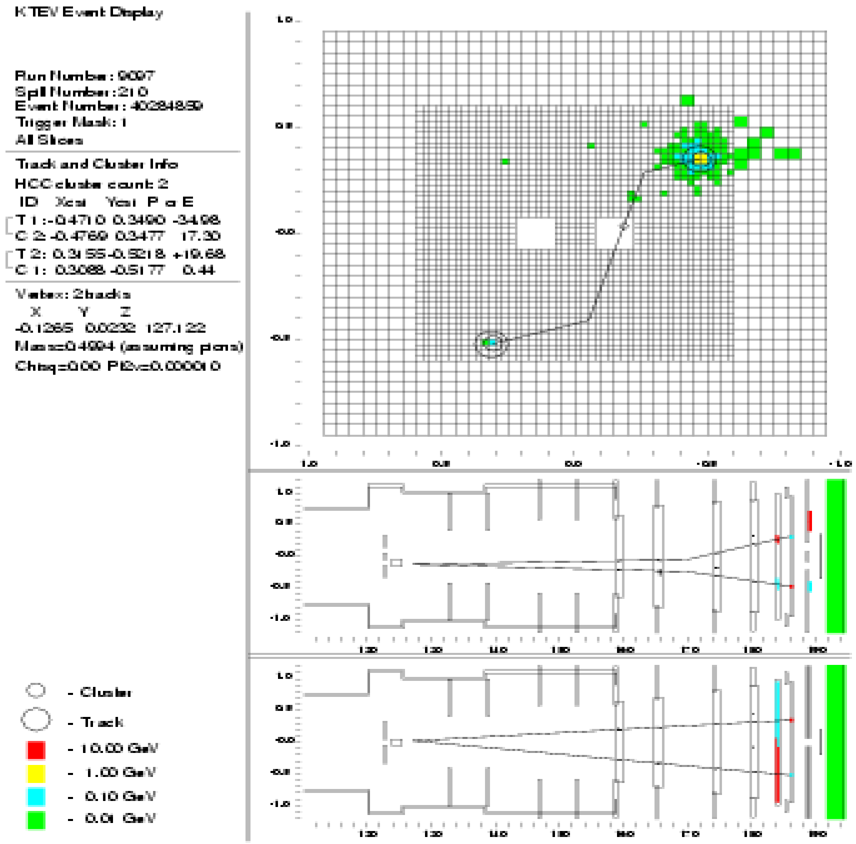
CHARGED:

- Drift Chamber resolution: 100 μm.
- Momentum resolution:

$$\frac{\sigma_p}{p} = 0.17\% \oplus 0.0071\% \cdot p \text{ [GeV]}$$

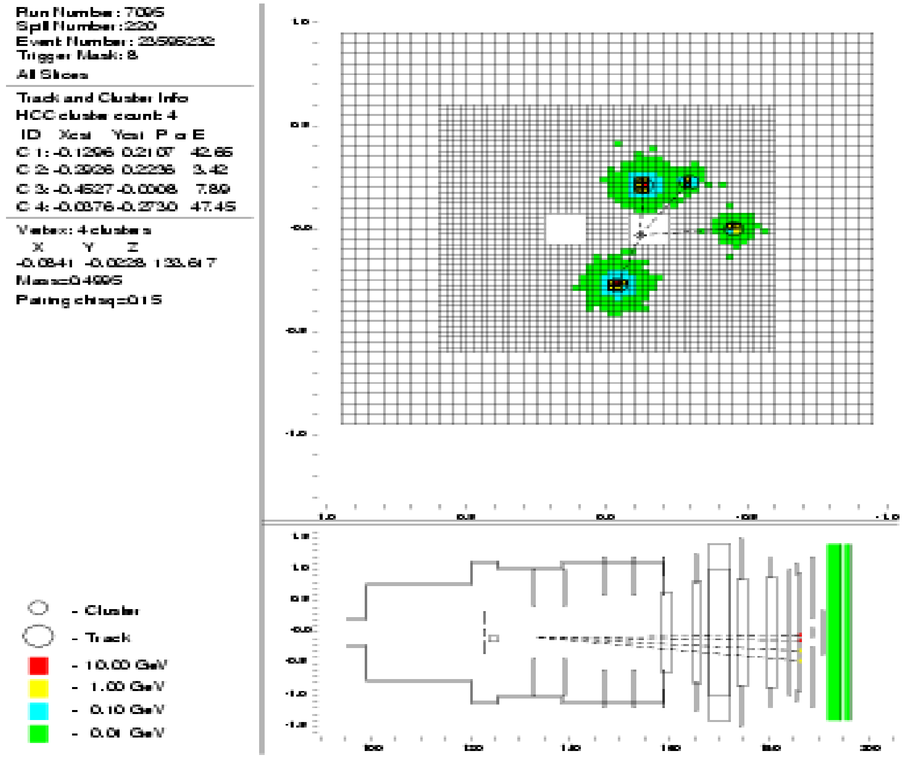
$$\sigma(M_{\pi^+\pi^-}) \sim \sigma(M_{\pi^0\pi^0}) \sim 1.5 \text{ MeV}$$

Sample $K \to \pi^+\pi^-$ Event



- Magnetic spectrometer to reconstruct kinematics.
- Regenerator/Vacuum beam identification using x-vertex position
- Clearance cuts define fiducial volume.

Sample $K \to \pi^0\pi^0$ Event



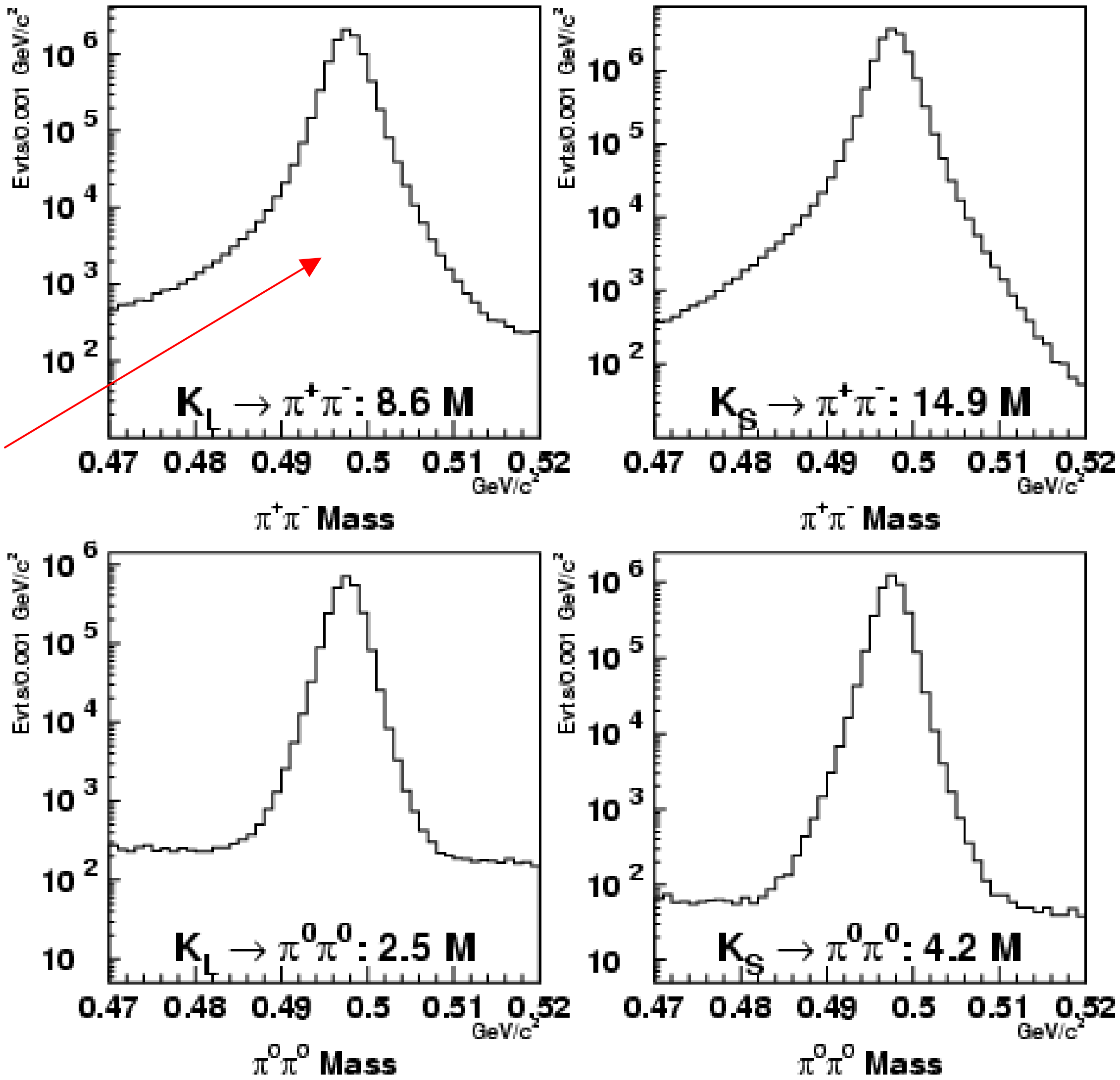
- CsI calorimeter to reconstruct photons energies and positions
- z_v determined as average of

$$z_{\pi^0} = \sqrt{E_1 E_2} R_{12} / m_{\pi^0}$$

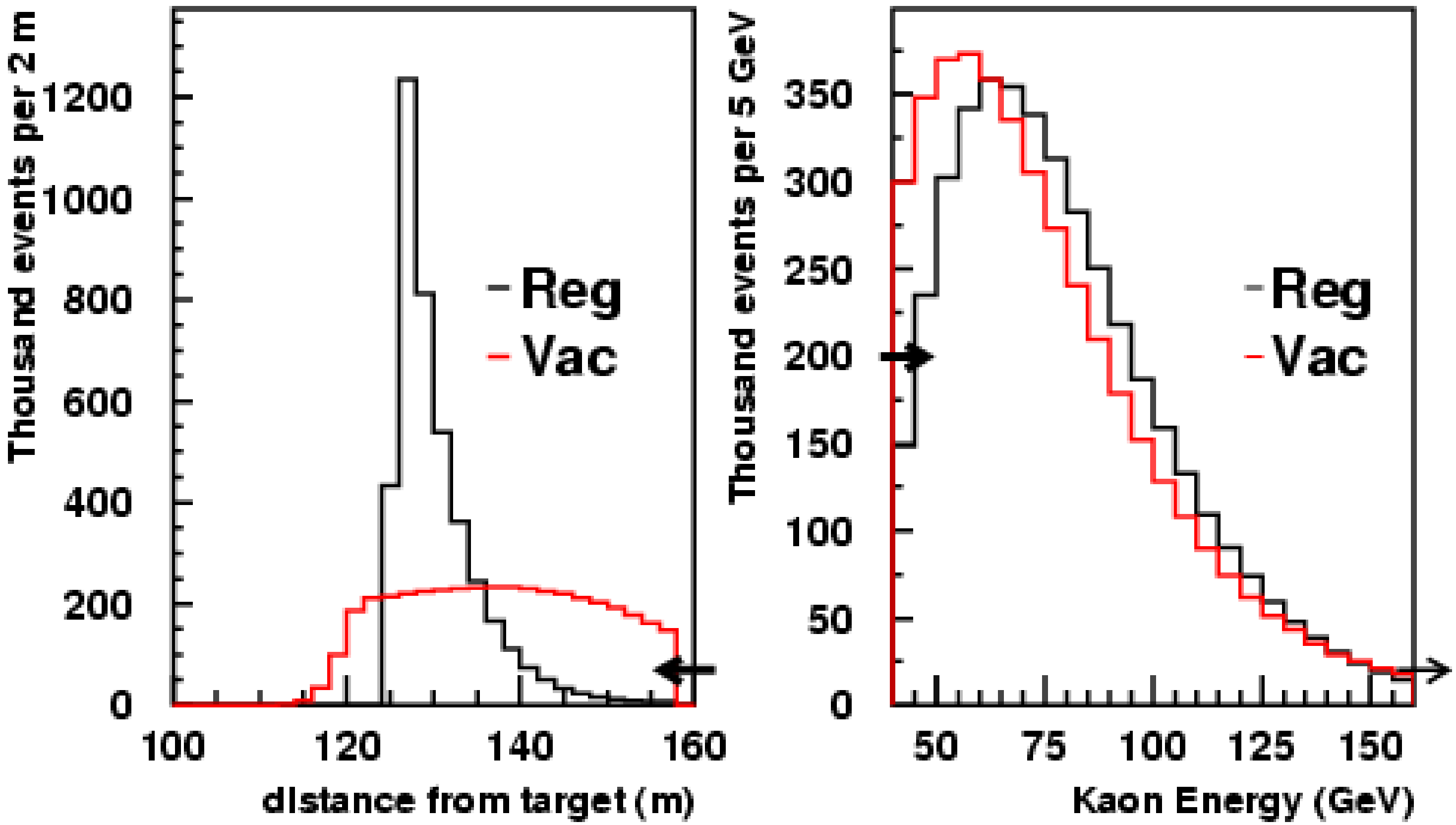
- Regenerator/Vacuum beam identification using x-center of enegy
- Fiducial volume defind by veto detectors & z_v

Raw $K^0 \Rightarrow \pi\pi$ Statistics: $\sigma(\varepsilon'/\varepsilon) = 1.7\times10^{-4}$

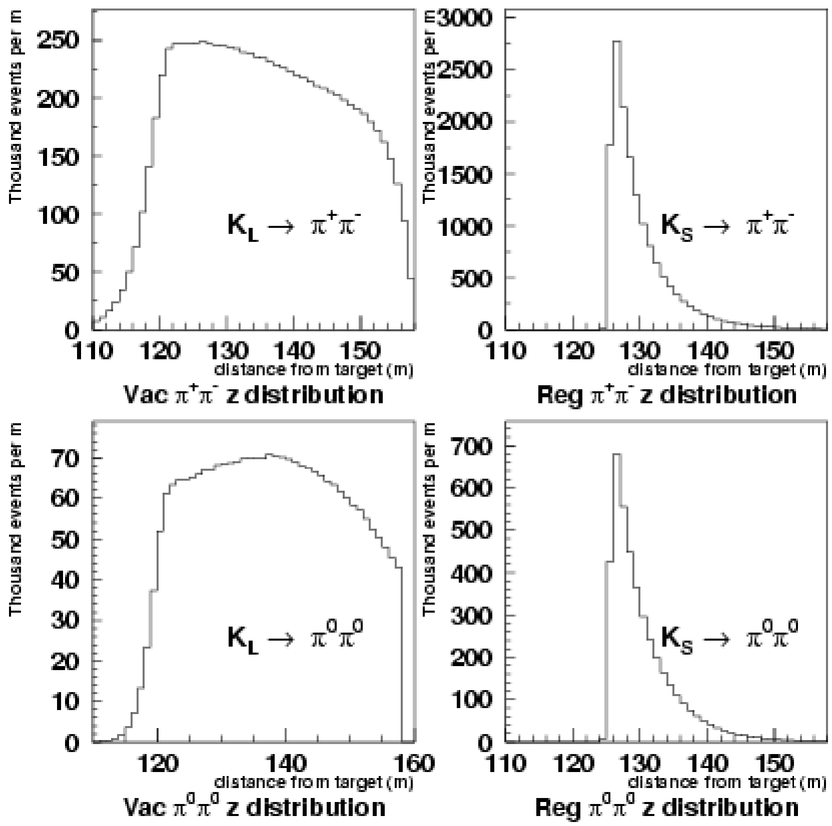
CPV first found with 47 $K_L \rightarrow \pi^+\pi^-$ events!



Position and Energy of $K \to \pi\pi$ decays…



Detector Acceptance Issues.



Due to the different lifetimes ($\tau_L \gg \tau_S$), the K_S beam reconstructs upstream of the K_L beam, and hence has a different *average* acceptance.

Need an analysis technique to put two beams on equal footing.

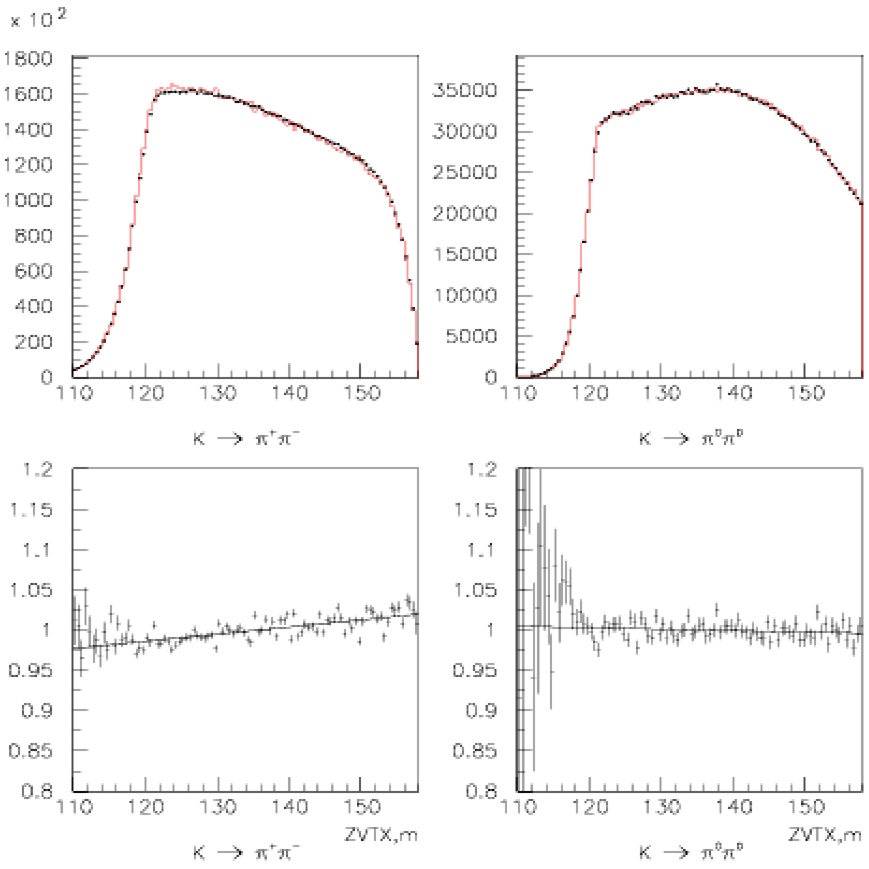
Monte Carlo Acceptance Correction.

We measure the detector geometry and response, and create a detailed MC prediction of the acceptance in each beam.

Correction to $\mathrm{Re}(\epsilon'/\epsilon)$ is large ($\sim 80 \times 10^{-4}$) $\rightarrow$ Systematics under control?

- Most of the correction is due to the geometry of the detector ($\sim 90\%$).
- Remaining effort for detailed understanding of detector response.
- Use large statistics modes (K_{e3}, $K_L \rightarrow 3\pi^0$) to cross-check performance of the Monte Carlo.
- Monte Carlo predicts slight acceptance differences between beams, due to accidental activity.
- Can measure kaon parameters ($\tau_S, \Delta m$)

Geometry-Only Monte Carlo Simulation.



Acceptance correction based on Monte Carlo with ideal detector response: $\Delta\mathrm{Re}(\epsilon'/\epsilon) \approx 12 \times 10^{-4}$, of which $\sim 10 \times 10^{-4}$ is seen as a z-slope.

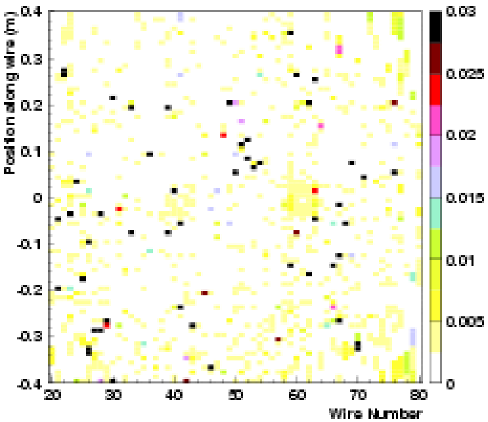
$\rightarrow$ corrections due to detector simulation $\sim 10 \times 10^{-4}$.

The ``Hard Part'' of Detector Simulation.

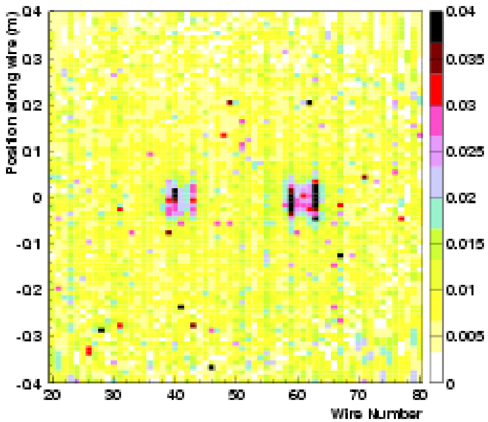
We measure the response of detector:

- Resolutions.
- Inefficiency profiles.
- DC "maps" of response.
- New DC delayed-hit model.
- GEANT showers in CsI.

For example, measure the inefficiency and delayed-hit probabilities across chamber face, use as input to MC.



Missing hit probability in DC1X plane 1



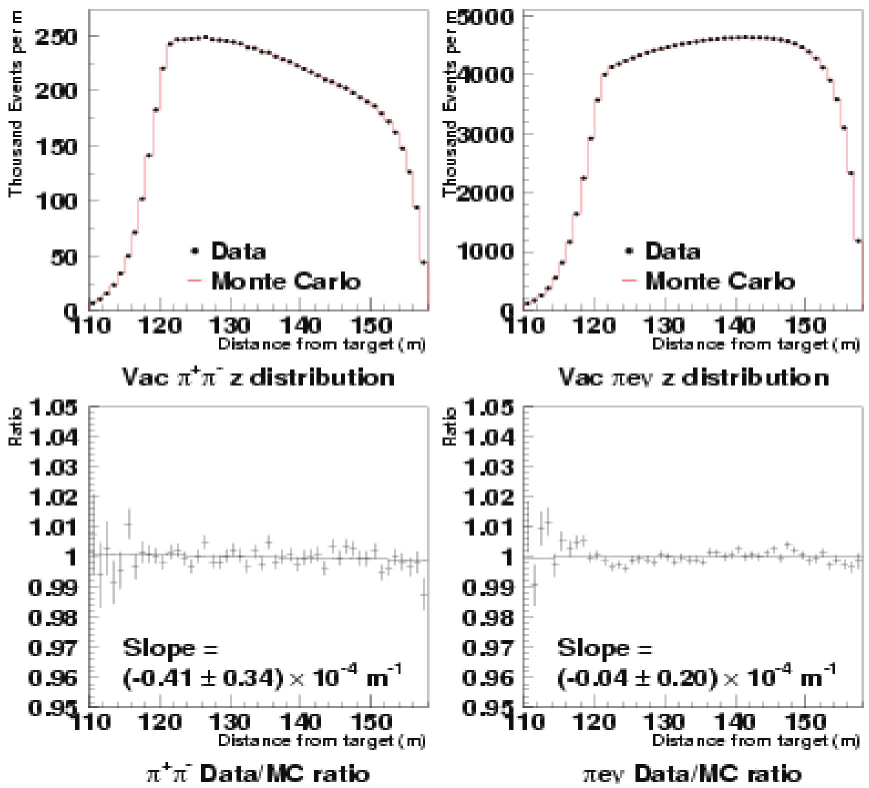
Delayed hit probability in DC1X plane 1

How well is the Acceptance Known?

The final check of the acceptance is the vertex z distribution in the vacuum beam.

Acceptance bias on $\text{Re}(\epsilon'/\epsilon) \leftrightarrow$ slope in plot, due to different vertex z distributions in vac/reg beams.

$\underline{1997\ K \rightarrow \pi^+\pi^-\ \&\ K_{e3}}$



From Counting to Re(ε'/ε)….

Naïvely, could take global acceptance, raw number of events, and calculate $\mathrm{Re}(\epsilon'/\epsilon)$.

$$\mathrm{Re}(\epsilon'/\epsilon) \stackrel{?}{\approx} \frac{1}{6}\left[\frac{\frac{N(\mathrm{Vac}\ \pi^+\pi^-)}{A(\mathrm{Vac}\ \pi^+\pi^-)} \Big/ \frac{N(\mathrm{Reg}\ \pi^+\pi^-)}{A(\mathrm{Reg}\ \pi^+\pi^-)}}{\frac{N(\mathrm{Vac}\ \pi^0\pi^0)}{A(\mathrm{Vac}\ \pi^0\pi^0)} \Big/ \frac{N(\mathrm{Reg}\ \pi^0\pi^0)}{A(\mathrm{Reg}\ \pi^0\pi^0)}} - 1\right]$$

Problems:

- Regenerator beam not pure K_S.

  $K_{\mathrm{reg}} = K_L + \rho K_S$

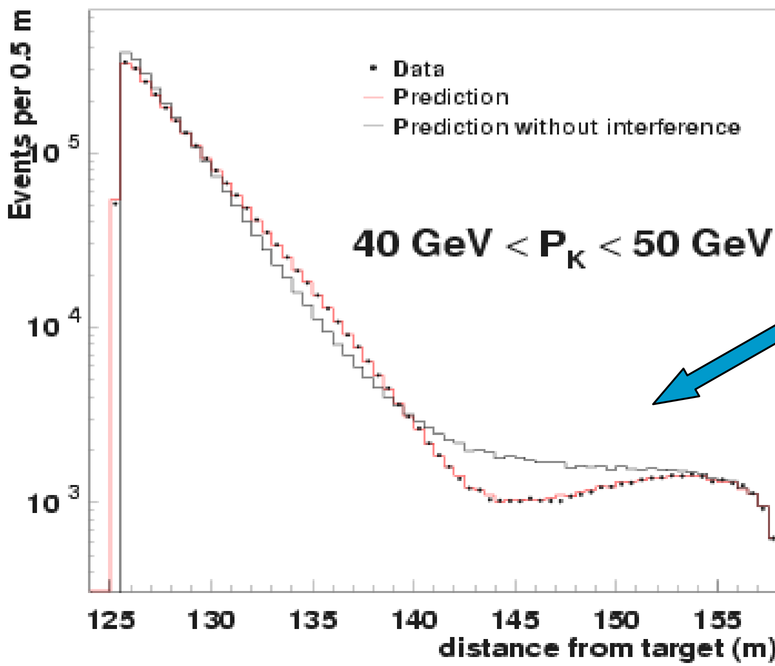
  Interference
- Requires precise determination of *average* acceptance.

K_L and K_S in the Regenerator Beam.

The regenerator beam is a coherent super-position of K_S and K_L. Must account for K_L component to extract correct value of $\mathrm{Re}(\epsilon'/\epsilon)$.

K_{Reg} shape depends on:

- τ_S, Δm, ϕ_η.
- Attenuation in the regenerator.



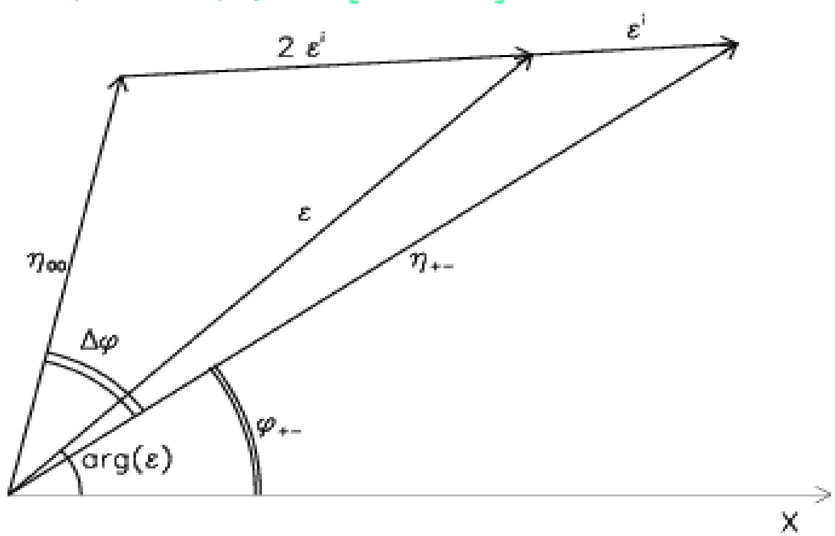
Regenerator Vertex Z distribution

Quantum coherence over 30m!

Fitting for Δm, τ_S, ϕ_{+-}, $\Delta\phi$ ..

With the interference information in the regenerator beam, KTeV can measure the ka sector parameters:

- $\Delta m = m_{K_L} - m_{K_S}$
- τ_S
- ϕ_{+-}, phase of η_{+-}
- $\Delta\phi = \phi_{00} - \phi_{+-}$ [$\not{CPT}$]

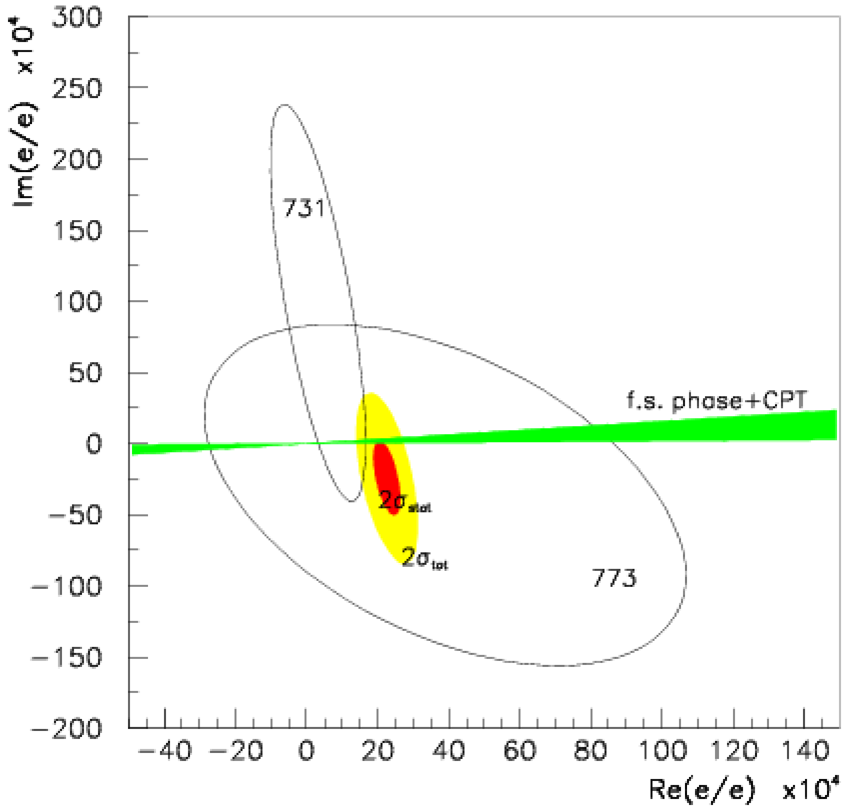


$$\mathrm{Im}(\epsilon'/\epsilon) = -\frac{1}{3}\Delta\phi \quad [\not{CPT}]$$

Have made new measurements of the above.

Summary of KTeV $K^0 \rightarrow \pi\pi$ Measurements.

FNAL experiments can measure both $\mathrm{Re}(\epsilon'/\epsilon)$ and $\mathrm{Im}(\epsilon'/\epsilon)$ (with less precision).



$\mathrm{Re}(\varepsilon'/\varepsilon) =$

$20.7 \pm 1.5(\mathrm{stat}) \pm 2.4(\mathrm{sys}) \times 10^{-4}$

$\Delta\phi =$

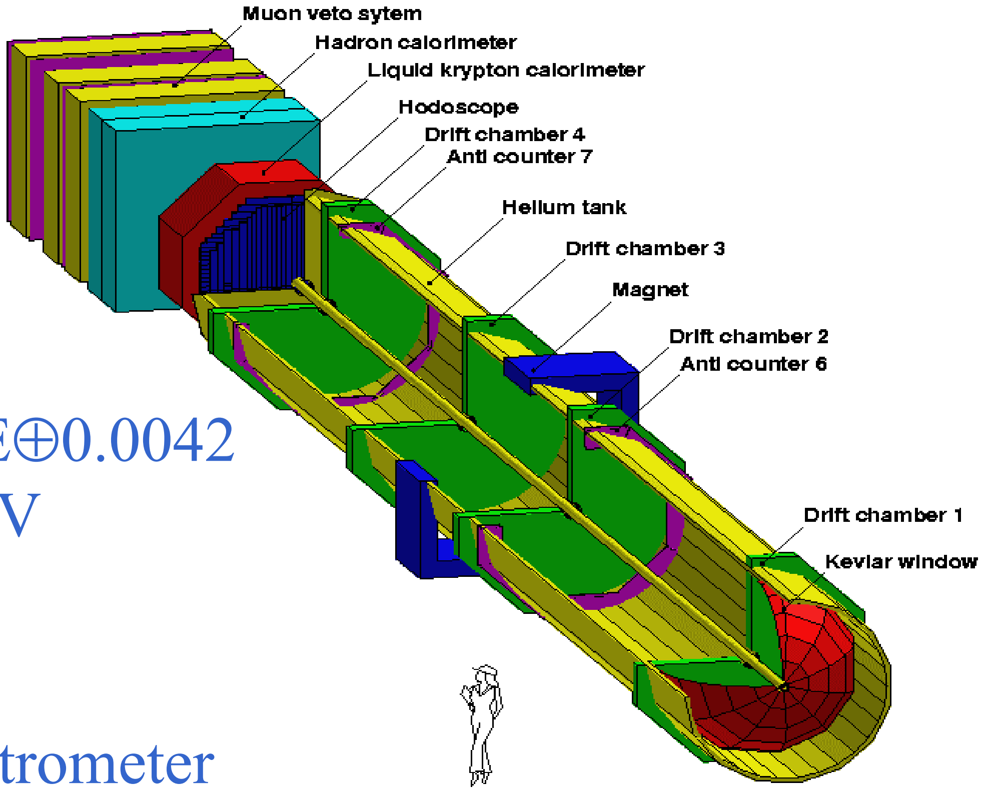
$0.41^{o} \pm 0.22^{o}(\mathrm{stat}) \pm 0.48^{o}(\mathrm{sys})$

(CPT test)

$\phi_{+-} =$

$44.11^{o} \pm 0.72^{o}(\mathrm{stat}) \pm 1.1^{o}(\mathrm{sys})$

Sister Experiment to KTeV: CERN-NA48.



$\pi^0\pi^0$ detection ($\rightarrow 4\ \gamma$)

LKr calorimeter

$\sigma(E)/E = 0.032/\sqrt{E} \oplus 0.09/E \oplus 0.0042$

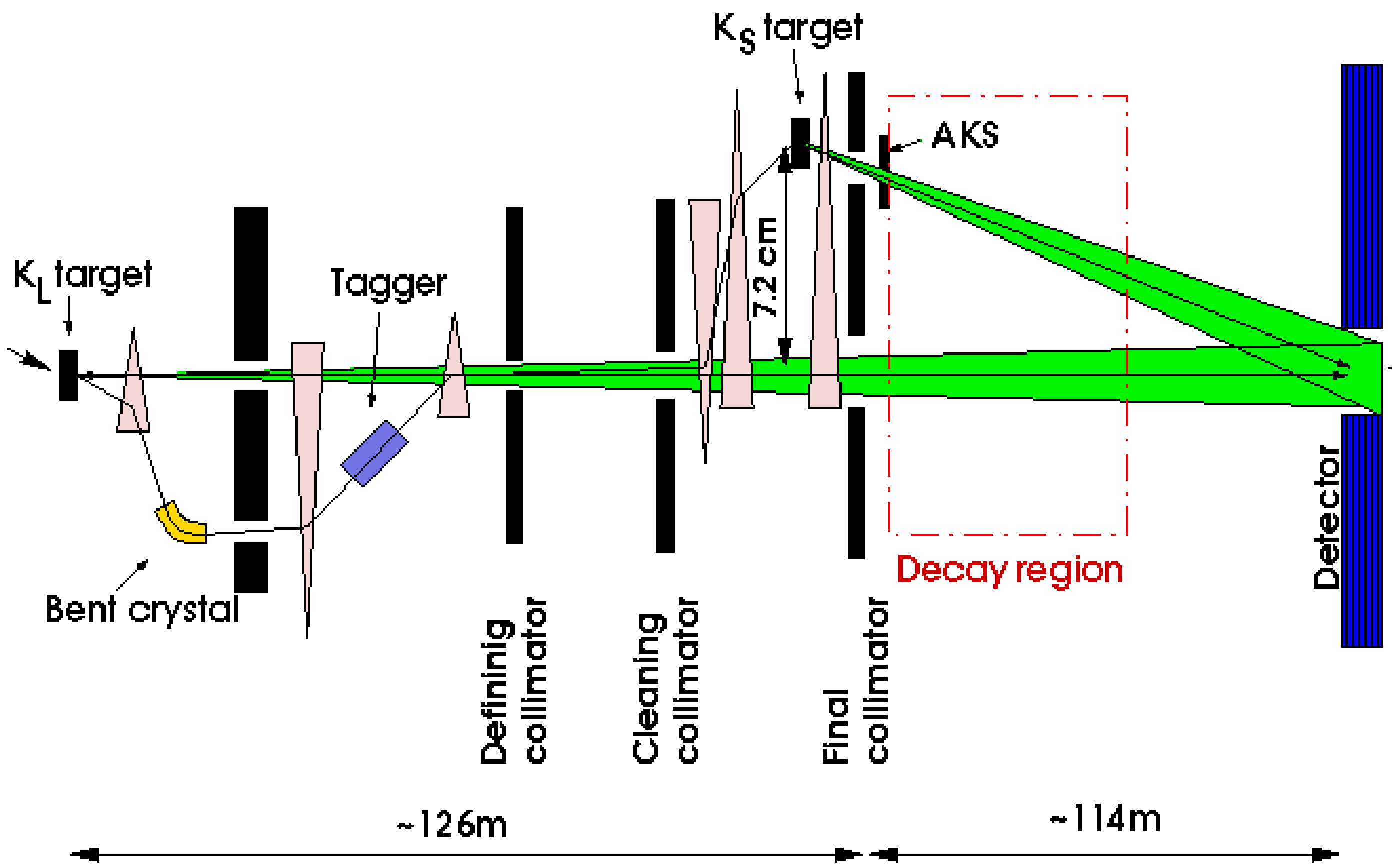
$< 1\%$ for E=25 GeV

$\pi^+\pi^-$ detection

magnetic spectrometer

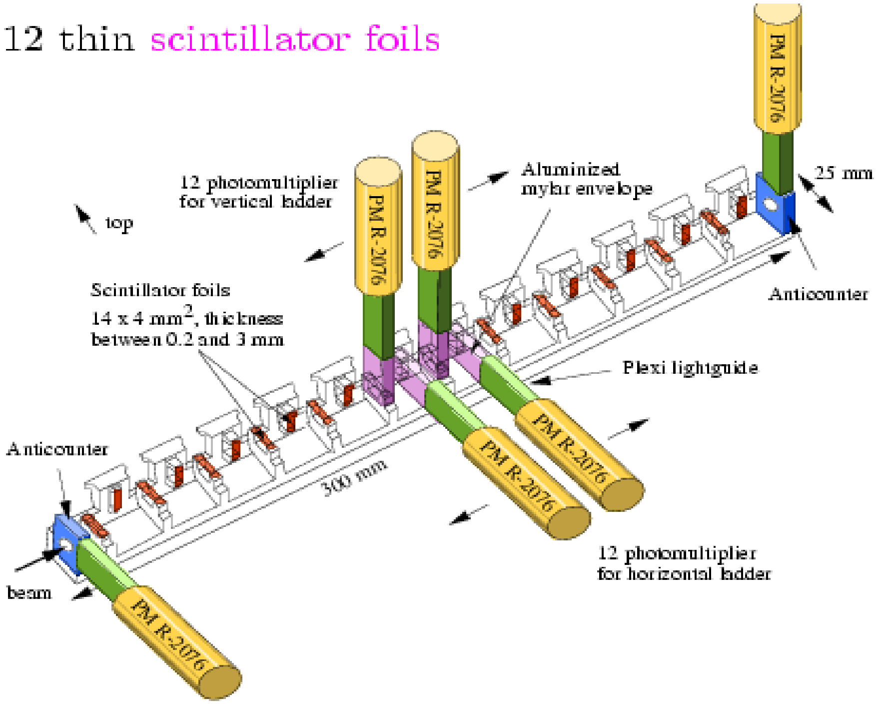
$\sigma(p)/p = 0.5\% \oplus 0.9\% * (p/100\ \text{GeV})$

The CERN NA48 Technique: Separate K_L and K_S decays in *time*, and analyze K_L and K_S with the same effective proper time ➡ Relative K_L/K_S acceptance cancels!



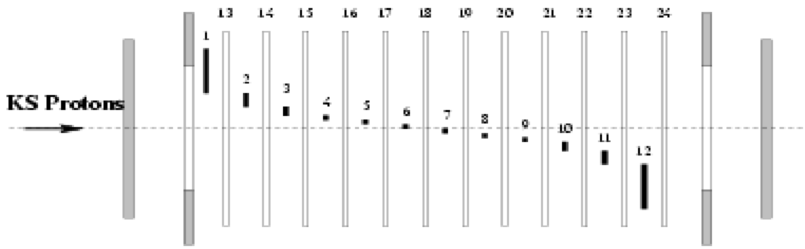
NA48
K_S tagger:

2×12 thin scintillator foils

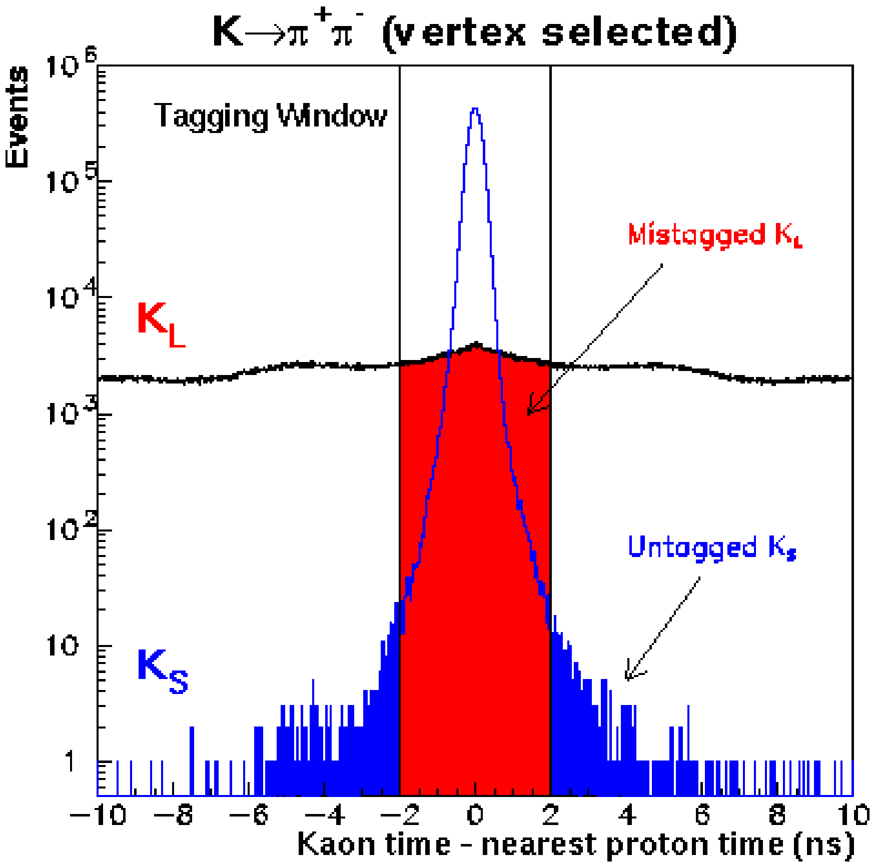


Proton rate: ≈ 30 MHz
$\longrightarrow$ split the intensity between foils

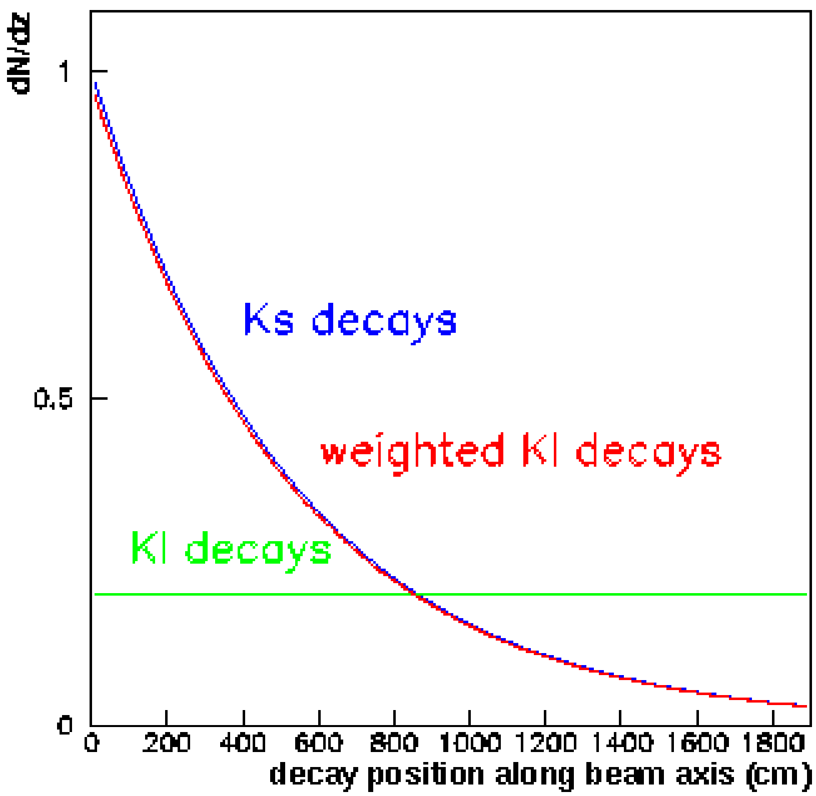
readout by Flash-ADC 8 bits at 960 MHz
$\Rightarrow$ Time resolution: 140 ps
$\Rightarrow$ Double pulse separation: 4 ns



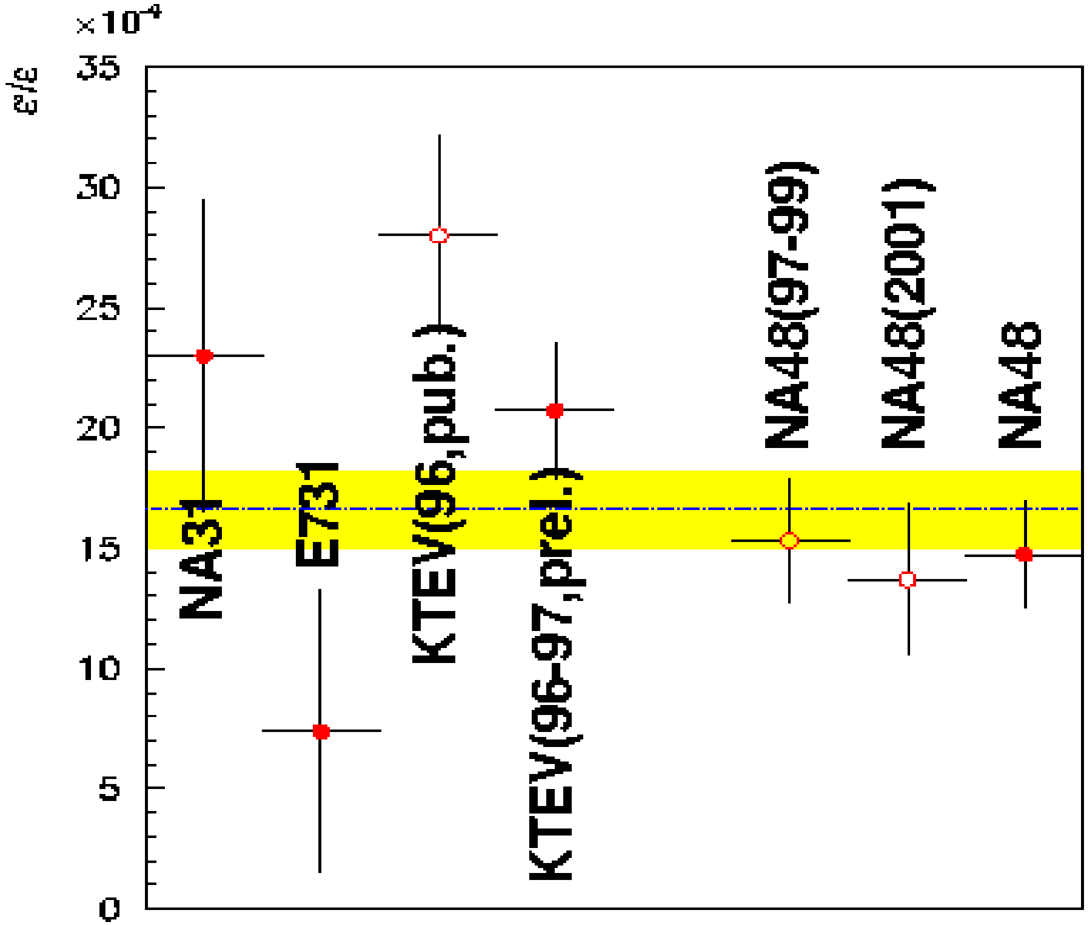
K_L/K_S Identification:



Equalize Acceptance…



Comparison of experimental results



NA31: $(23.0 \pm 6.5) 10^{-4}$

E731: $(7.4 \pm 5.9) 10^{-4}$

KTeV: $(20.7 \pm 2.8) 10^{-4}$
(preliminary)

NA48: $(14.7 \pm 2.2) 10^{-4}$

World average **$\varepsilon'/\varepsilon = (16.6 \pm 1.6) 10^{-4}$** $\chi^2 = 6.2/3$ (prob=10%)

Summary of Re(ε'/ε) Measurements.

- Direct CPV into one final state has been clearly established, ($K_L \Rightarrow \pi\pi$).

- This validates a clear prediction of the Standard Model, although the prediction comes with a poor level of precision due to difficulty of the calculation.

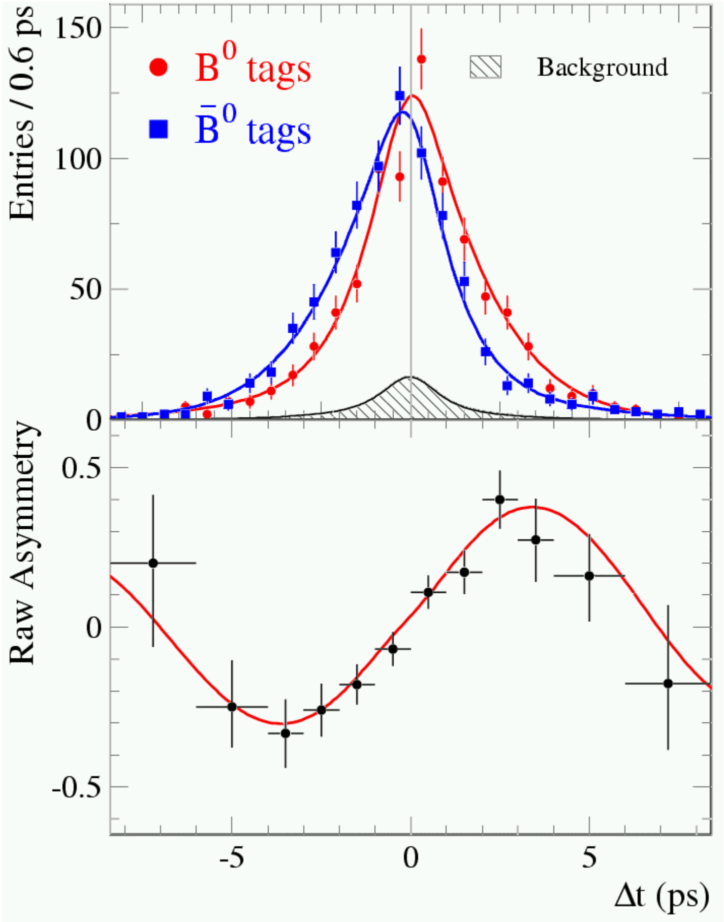
- Re(ε'/ε) will stand for quite some time as the most precise measurement of Direct CPV. Lattice based calculation techniques are promising, and could provide a precision test in the future.

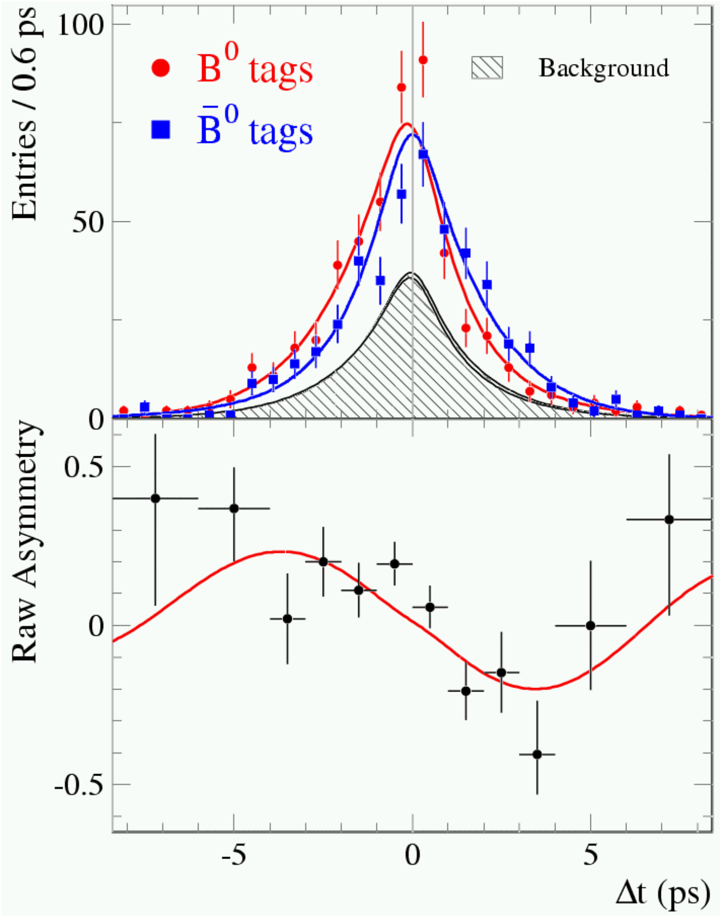
Preview for Friday….

- Tommorow our discussion will turn to rare kaon decays, where we can leave the brown muck behind and quantitatively challenge the Standard Model.

Spare Slides

Second example for Type-II CPV: $B^0,\bar{B}^0 \to c\bar{c}K$





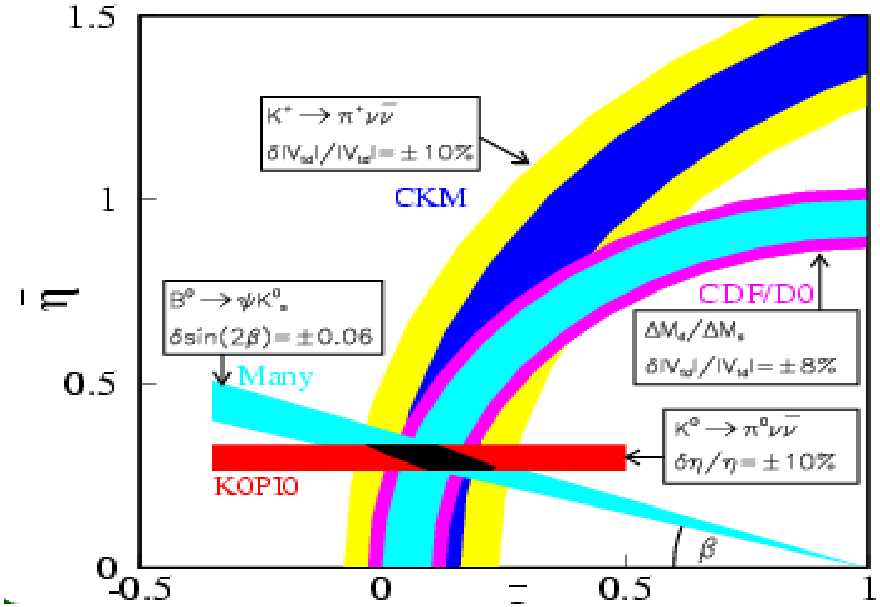
$\sin 2\beta = 0.755 \pm 0.074$ $\sin 2\beta = 0.723 \pm 0.158$

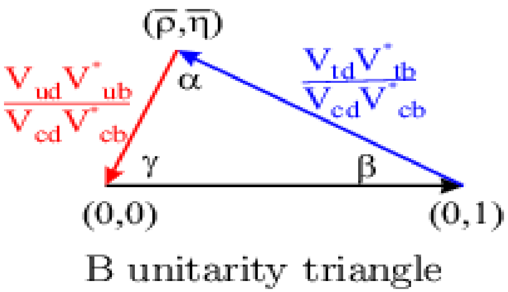
$\sin 2\beta = 0.741 \pm 0.067$ (stat) ± 0.033 (sys)
(BaBar, ICHEP 2002)

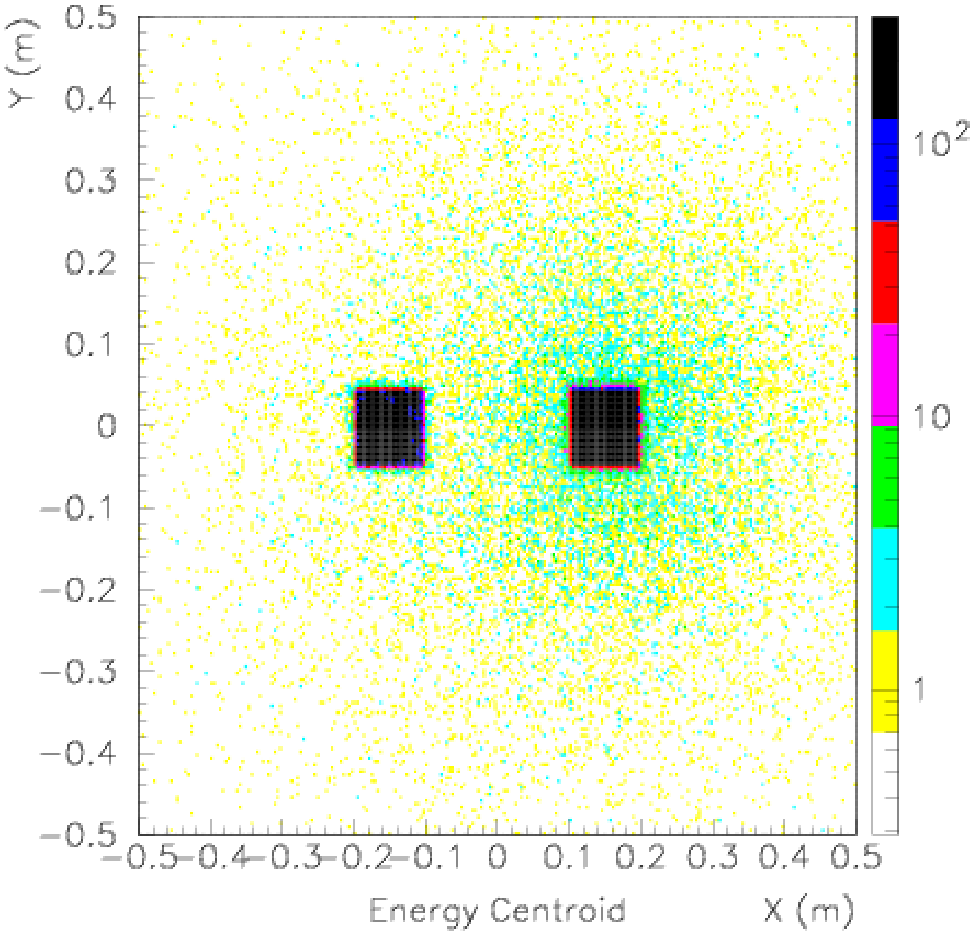
The Physics Context

- It is *vital* that ρ and η of the CKM matrix be precisely measured.
- The *critical question* is not what ρ and η are, but whether all CP phenomena can be described with such a compact formalism.
- Four Gold-Plated accessible measurements have sufficient theoretical robustness that a contradiction could call the Standard Model into question:

$K^+ \rightarrow \pi^+ \nu\bar{\nu}$	:	BNL787/949, CKM
$K^\circ \rightarrow \pi^\circ \nu\bar{\nu}$	:	KOPIO, KEK-e391a/JHF
$B_d \rightarrow J/\psi K_S$	:	Babar, Belle, CDF, D0, LHCb, Atlas, CMS, BTeV
$\Delta M_d/\Delta M_s$	:	CDF, D0, LHCb, Atlas, CMS, BTeV



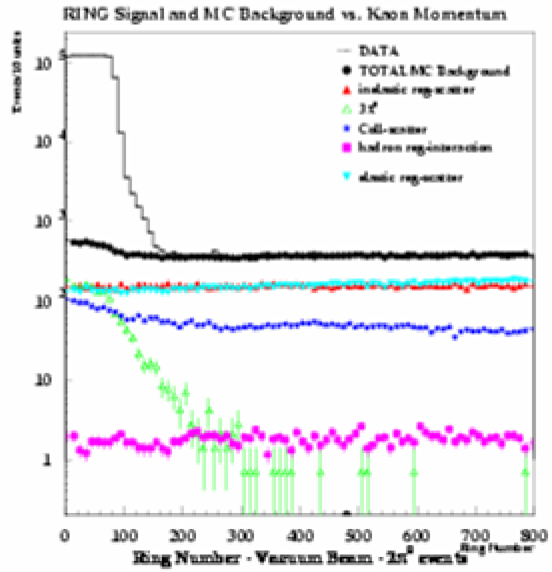




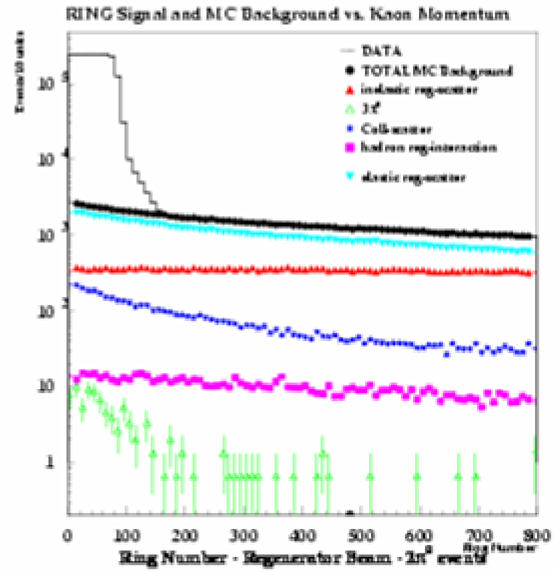
The two KTeV beams are shown: Vacuum on left, Regenerator on right.

Neutral-Mode Backgrounds

"Ring Number" is a scaled Center of Energy. Cut at $R = 110$ is the edge of the beam. Scattered events appear outside beam, $R > 110$. $K_L \to 3\pi^0$ events are inside beam, but identifiable from mass sidebands.



Back/Sign(Vac) ≈ 0.5%



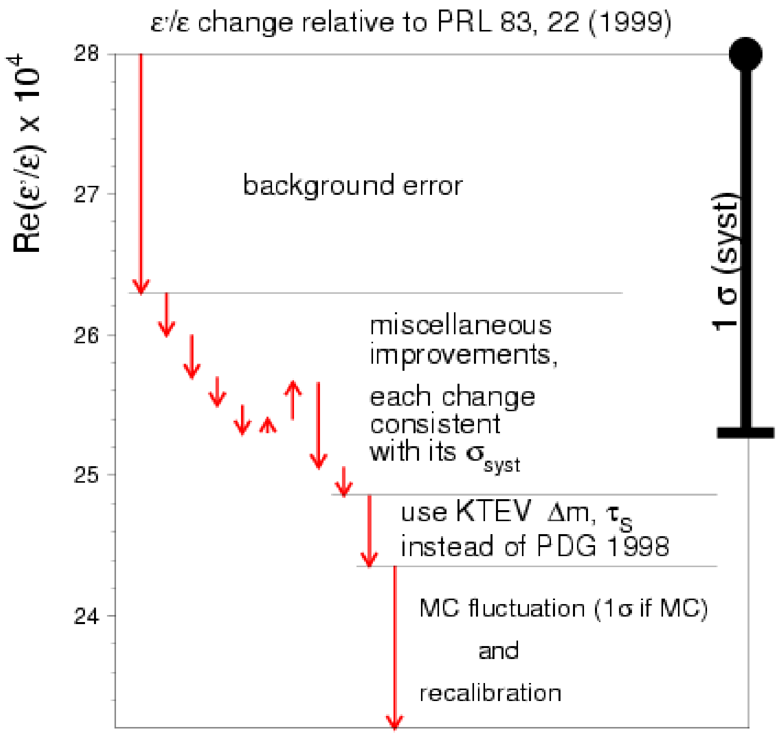
Back/Sign(Reg) ≈ 1.2 %

Systematic Uncertainties for 1997

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	**0.62**	**0.16**
Class 2: Event reconstruction, selection, backgrounds		
Energy/Resolution scale	**0.16**	**1.37**
Calorimeter nonlinearity	—	**0.66**
Detector calib, aligned	**0.28**	**0.38**
Analysis cut variations, Reconstruction	**0.25**	**0.37**
Background subtraction	**0.20**	**1.06**
Class 3: Detector acceptance		
Limiting apertures	**0.33**	**0.48**
Detector resolution	**0.15**	**0.08**
Drift chamber simulation	**0.37**	—
z dependence	**0.53**	**0.26**
Class 4: Kaon flux and physics parameters		
Reg-beam attenuation	**0.19**	
Δm, τ_S	**0.24**	
Reg phase screening	**0.31**	
TOTAL	**2.32**	

Update of Published Result with Improved Techniques (cont)

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



Note: sources of shifts are not correlated