

What's New with KTeV.

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Representing the KTeV Collaboration.

February 15th, 2001

- Status of $Re(\epsilon'/\epsilon)$.
- Appetizer for the $K_L \rightarrow \pi^\pm \pi^\mp \nu$ charge asymmetry result to be presented at BCP4.
- The richness of the $K_L \rightarrow \pi \pi e^+ e^-$ system.
- Employing $K_L \rightarrow \gamma^* \gamma^*$ decays to extract $|V_{td}|$ from $K_L \rightarrow \mu^+ \mu^-$: What are the prospects?

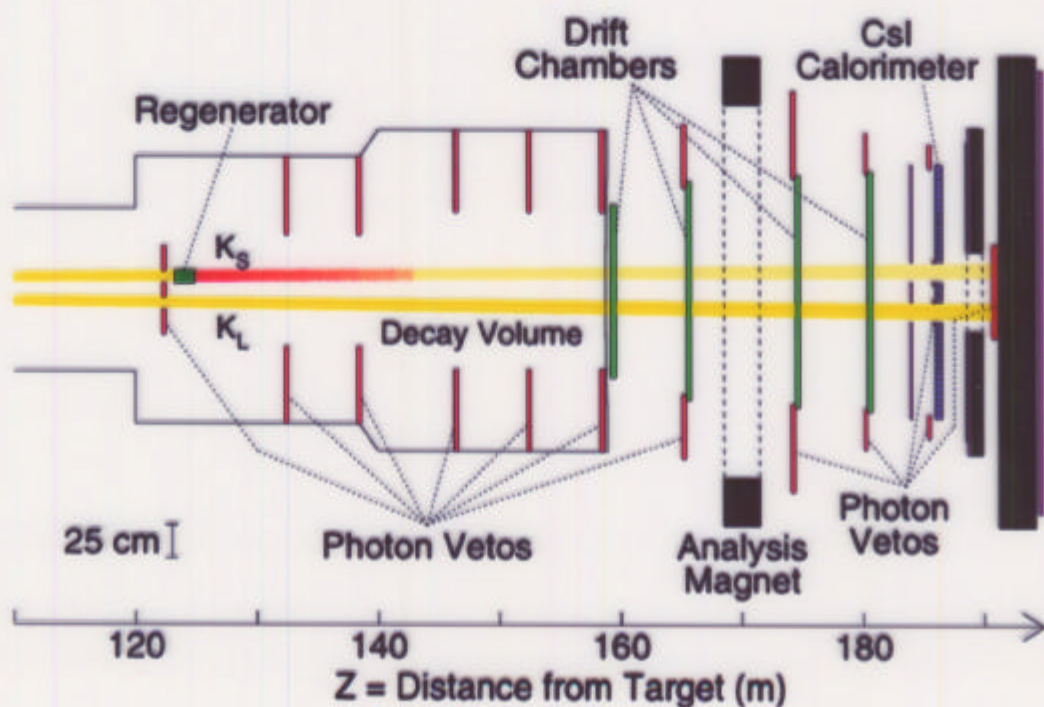
KTeV Collaboration

University of Arizona
University of California, Los Angeles
University of California, San Diego
University of Chicago
University of Colorado
Elmhurst College
Fermilab
Osaka University
Rice University
Rutgers University
University of Virginia
University of Wisconsin

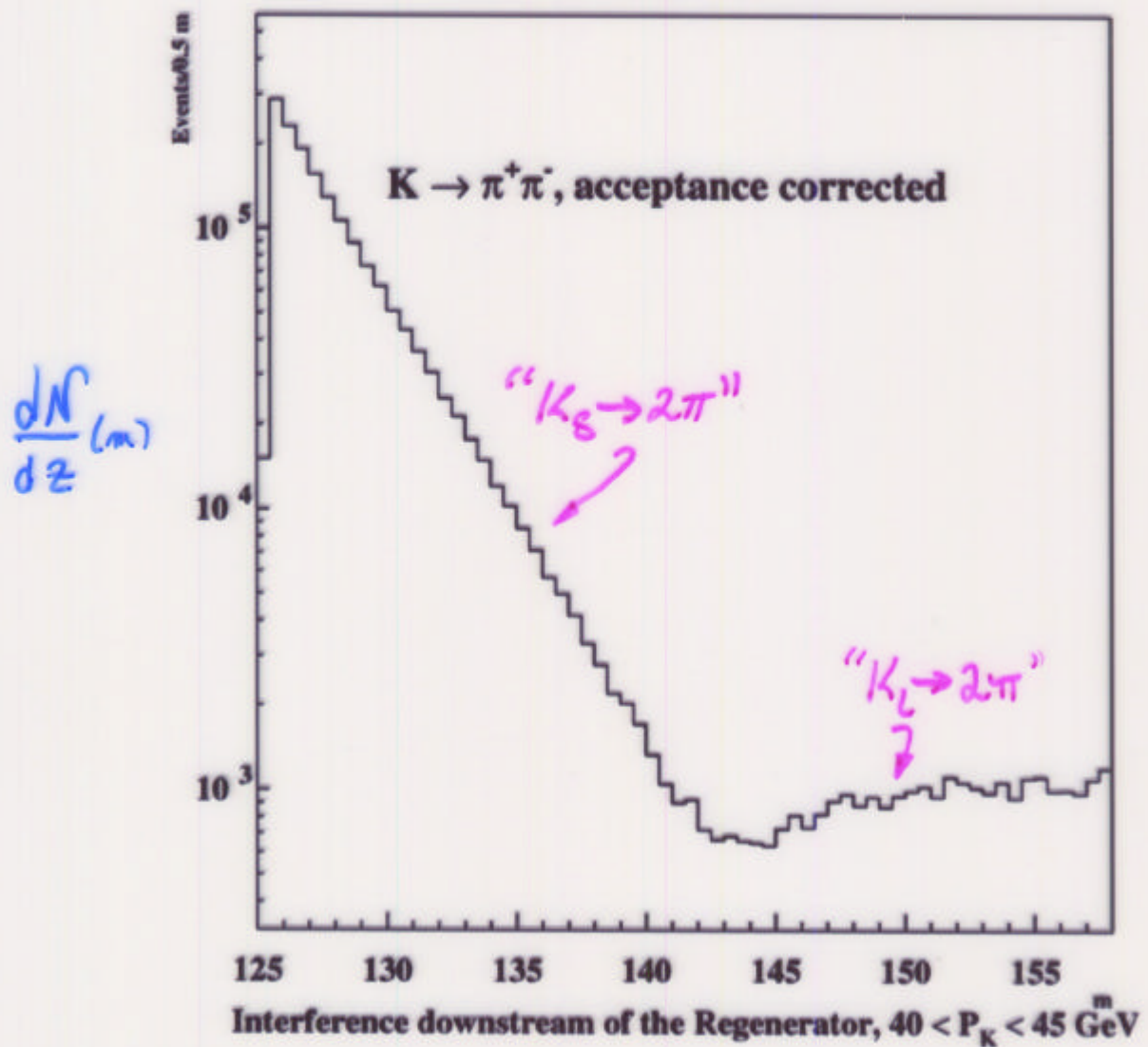
Universidade Estadual de Campinas (1999)
Universidade de Sao Paulo (1999)

KTeV

- E832 (ϵ'/ϵ) - E799 (Rare Decays)
 - ▶ 2 K_L beams (1 K_S beam for E832)
 - ▶ High precision CsI calorimeter
 - ▶ Low mass spectrometer
 - ▶ Excellent photon veto system
 - ▶ TRD package for E799



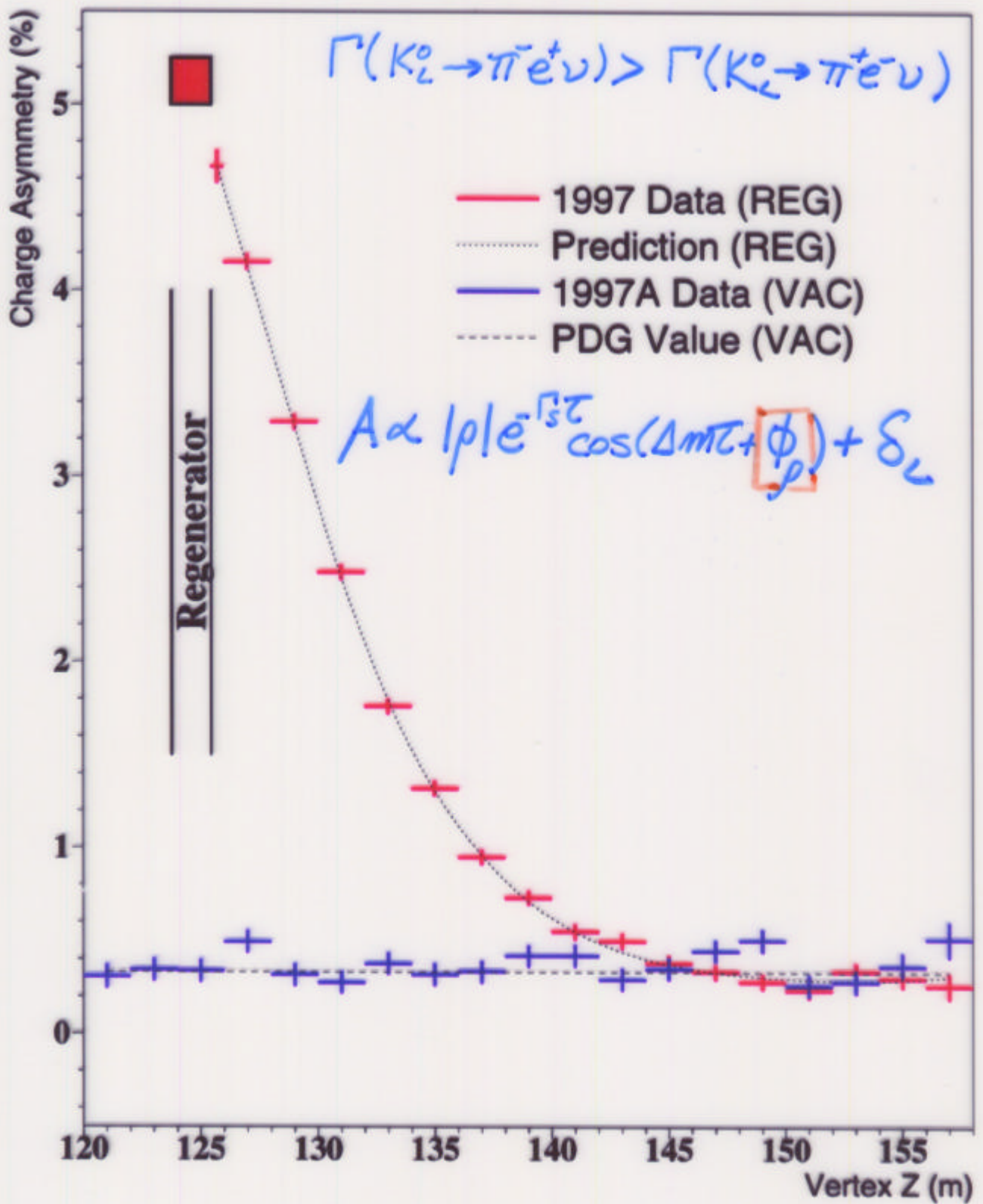
Interference of K_S and K_L



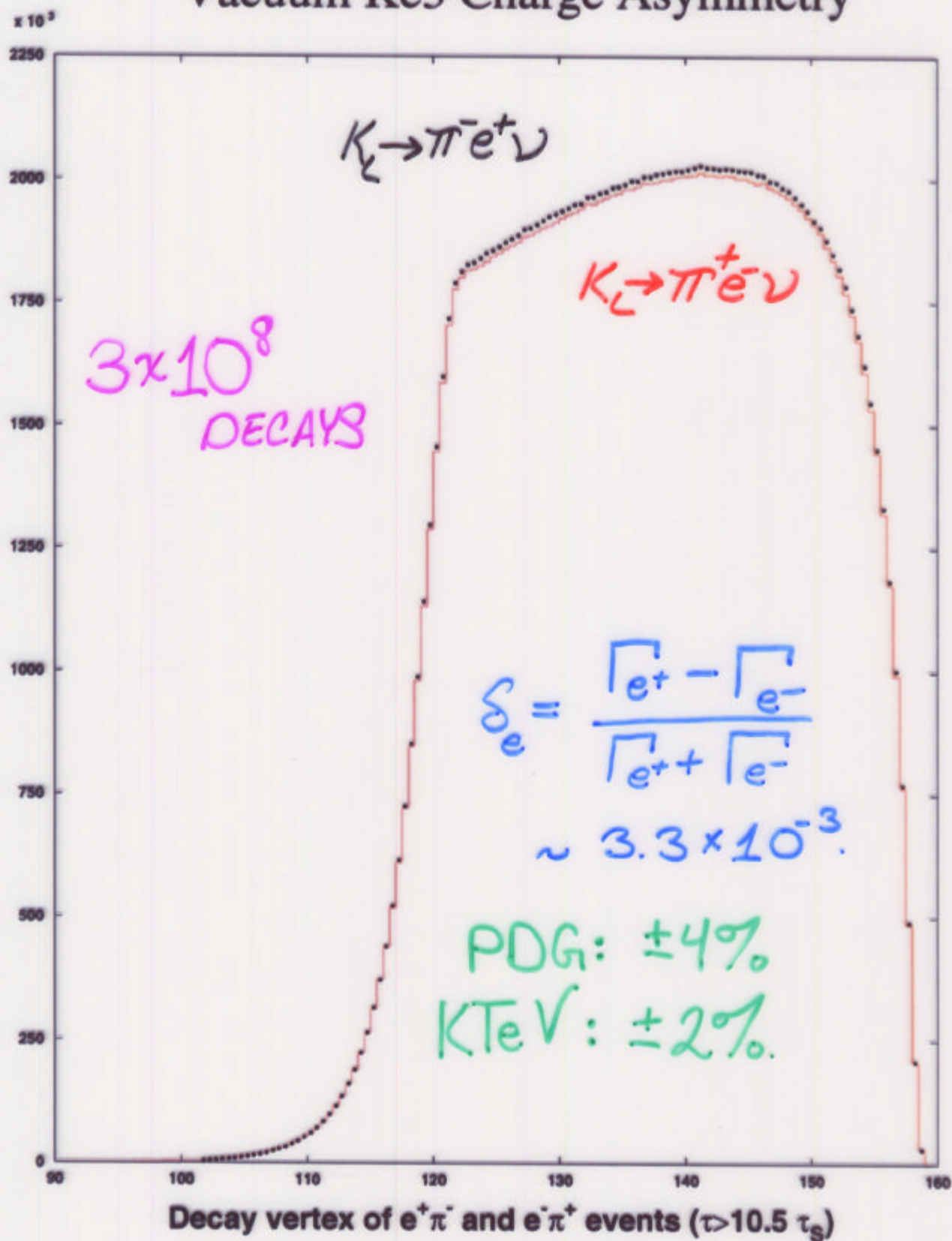
$\frac{dN}{dz} (m)$

$$\frac{dN}{dz} \propto \frac{\rho}{\eta} e^{-\Gamma_S \tau} + 2 \frac{\rho}{\eta} e^{-\Gamma_S/2 \tau} \cos(\Delta m \tau + \phi_m) + 1$$

Semileptonic Charge Asymmetry ($K \rightarrow \pi e \nu$)



Vacuum Ke3 Charge Asymmetry



KTeV PRELIMINARY.

WILL BE PRESENTED @ BCP

- CP Violation:

- ▷ K_L observed to go to $\pi\pi$ (Christenson, Cronin, Fitch, Turlay (1964))
- ▷ Bulk of effect comes from $A(K^0 \rightarrow \bar{K}^0) \neq A(\bar{K}^0 \rightarrow K^0)$

- ▷ Mass eigenstates are not CP eigenstates

$$K_S \propto K_1 + \epsilon K_2, K_L \propto \epsilon K_1 + K_2$$

- ▷ $\epsilon = (2.263 \pm 0.023) \times 10^{-3}$



$$\delta_\epsilon = 2 \operatorname{Re}(\epsilon)$$

- Standard Model explains CP violation via quark flavor mixing matrix

- ▷ ϵ arises from non-trivial complex phase: $\eta \neq 0$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- ▷ Unitarity \rightarrow 4 independent parameters for all quark mixing effects
- ▷ ρ and η measurements in different quark transitions will test this

Calculating ϵ'/ϵ

- $\epsilon'/\epsilon = A^2 \lambda^5 \cdot \eta \cdot [c_0 + R_s(c_6 B_6^{(1/2)} + c_8 B_8^{(3/2)})]$

e.g. A. Buras hep-ph/9806471, R. Gupta hep-ph/9801412

▷ $B_{6,8}$ - low energy (not perturbative) QCD

- B_6 and B_8 are theoretically difficult, and tend to cancel

▷ ϵ'/ϵ is hard to predict

- Variation in predictions from $Re(\epsilon'/\epsilon)$:

$(4.6 \pm 3.0 \pm 0.4) \times 10^{-4}$ (Ciuchini, et al., Jan 97)

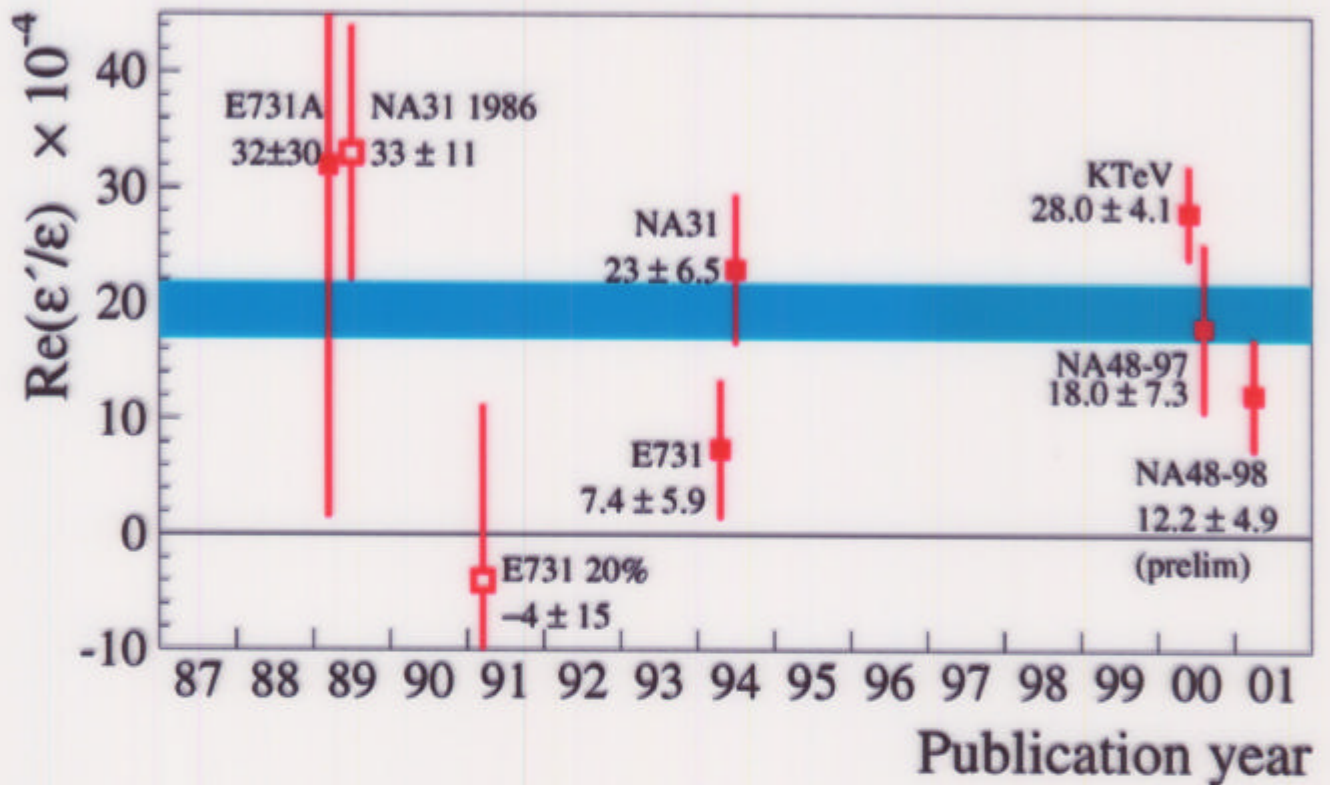
$(5.7 \pm 3.6) \times 10^{-4}$ ($m_s = 130 \pm 20$ MeV) (Buras, et al., Jan 99)

$(9.1 \pm 5.7) \times 10^{-4}$ ($m_s = 110 \pm 20$ MeV) (" " ")

$(17_{-10}^{+14}) \times 10^{-4}$ (Bertolini, et al., Feb 98)

This is just a sample....

Current Experimental Status of ϵ'/ϵ



- World Average: $Re(\epsilon'/\epsilon) = (19.3 \pm 2.4) \times 10^{-4}$

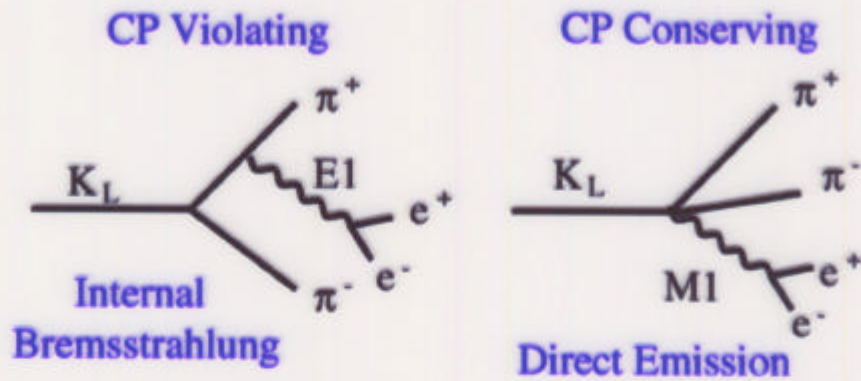
$$\chi^2/ndf = 11.1/5, CL=5\%$$

- ϵ'/ϵ is clearly non-zero.
 η is therefore also clearly non-zero, despite theoretical uncertainties

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

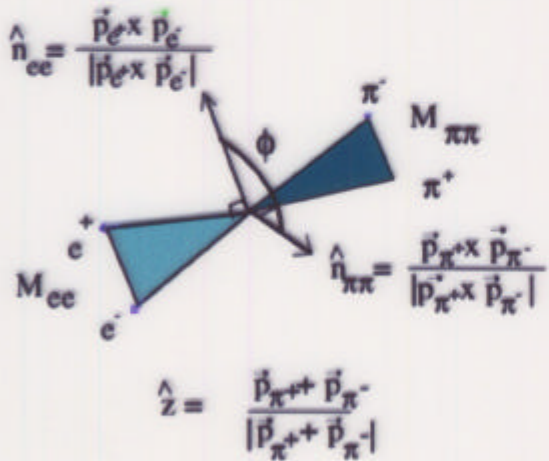
- Closely Related to $K_L \rightarrow \pi^+ \pi^- \gamma$

▶ CP Conserving and CP Violating components:



- Interference $\Rightarrow \gamma^*$ polarization

- ▶ asymmetry in angle ϕ between $\pi^+ \pi^-$ and $e^+ e^-$ planes
- ▶ T-Odd and CP-Violating asymmetry



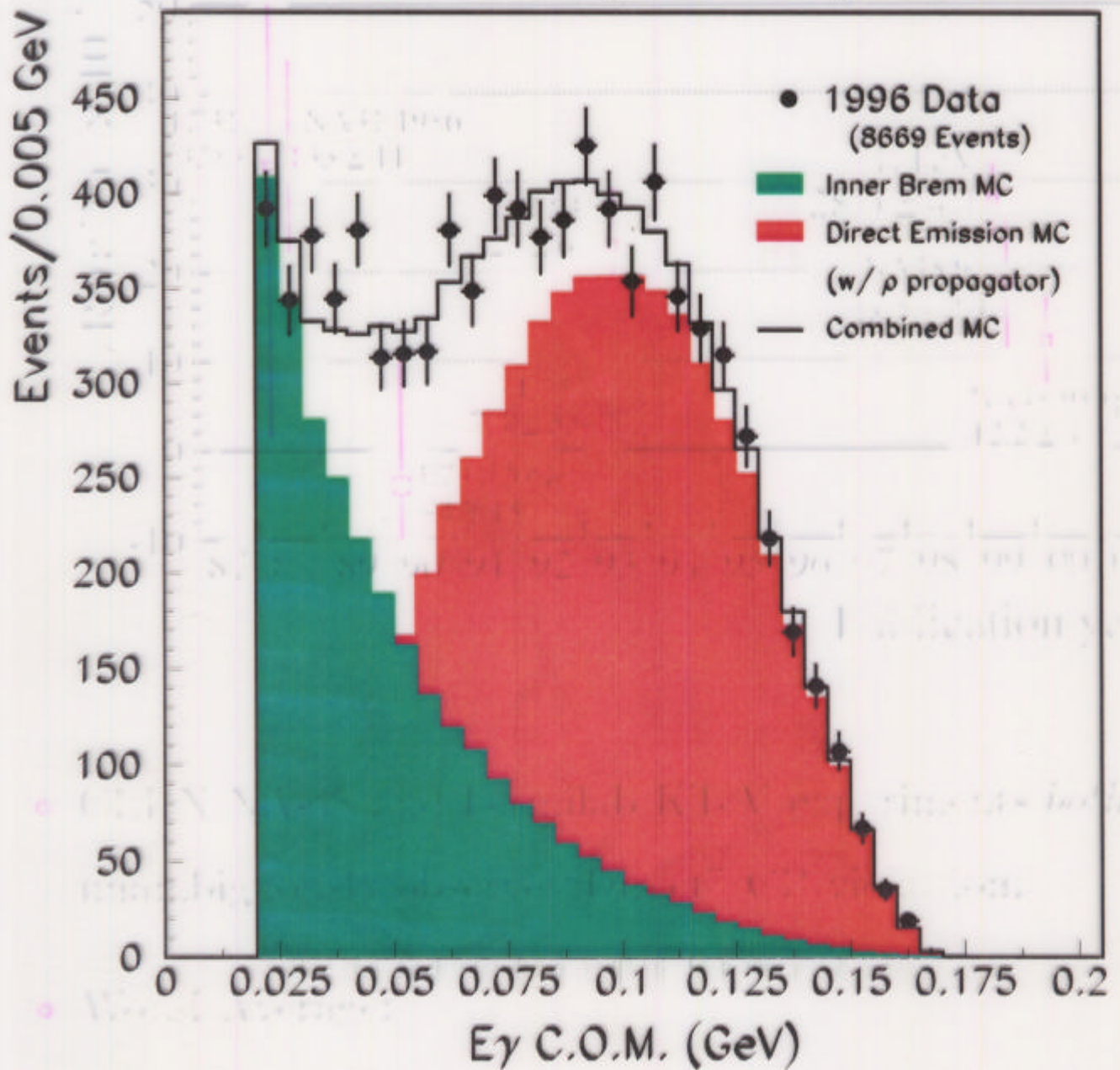
$$\frac{d\Gamma}{d\phi} = \Gamma_1 \cos^2 \phi + \Gamma_2 \sin^2 \phi + \Gamma_3 \sin \phi \cos \phi$$

$$A_\phi \equiv \frac{N_{\sin \phi \cos \phi > 0} - N_{\sin \phi \cos \phi < 0}}{N_{\sin \phi \cos \phi > 0} + N_{\sin \phi \cos \phi < 0}}$$

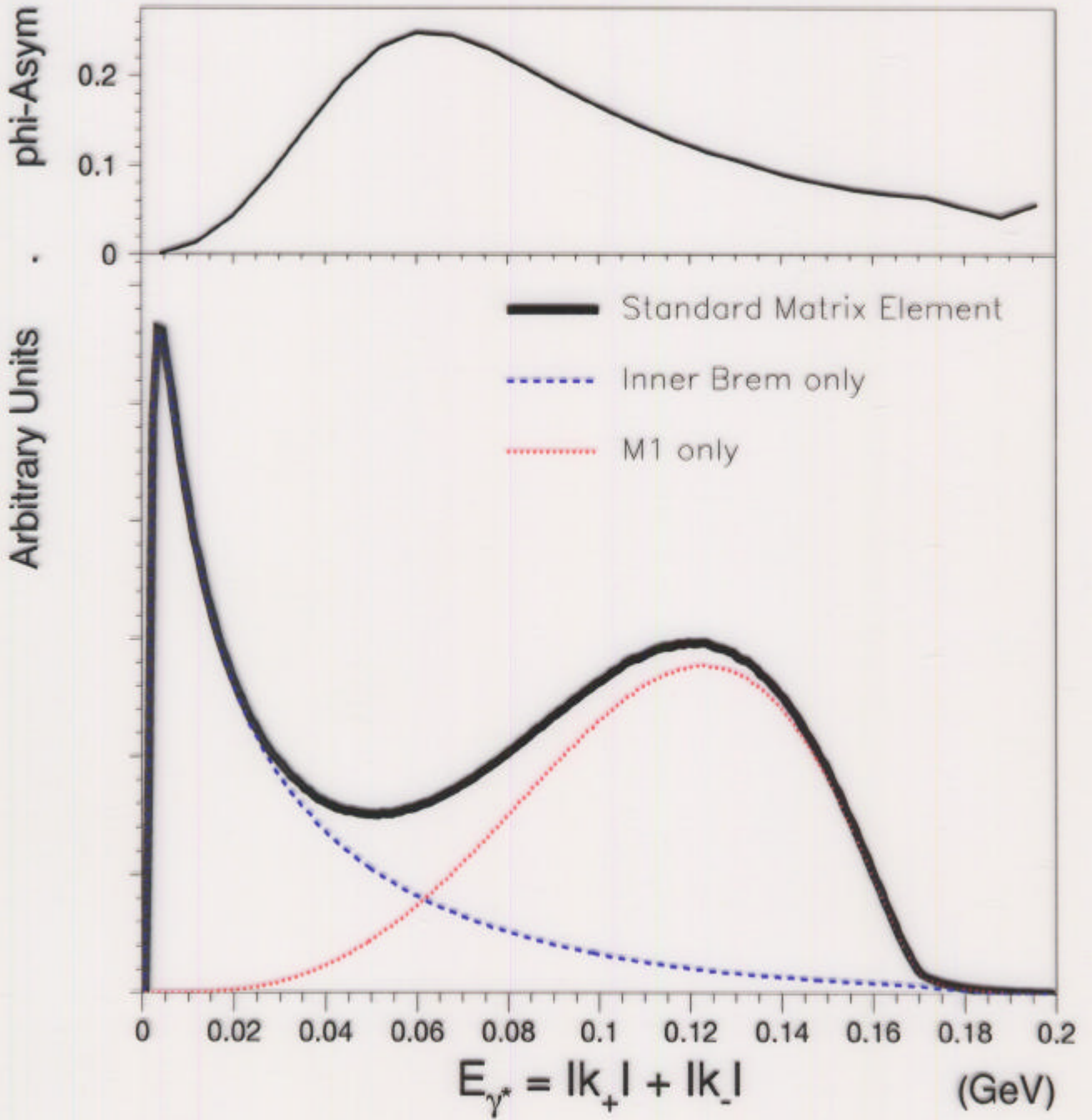
$$\sin \phi \cos \phi = (\hat{n}_{ee} \times \hat{n}_{\pi\pi}) \cdot \hat{z} (\hat{n}_{ee} \cdot \hat{n}_{\pi\pi})$$

ρ/π Status

KTeV 1996 $K_L \rightarrow \pi^+\pi^-\gamma$

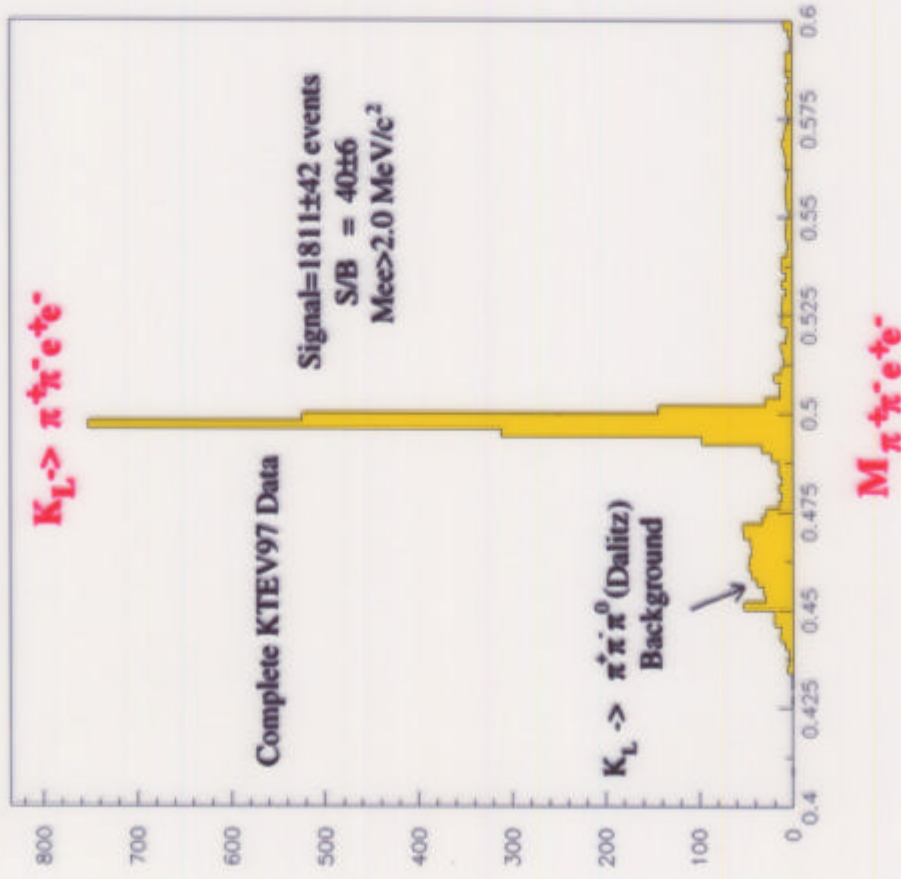


$K_L \rightarrow \pi^+ \pi^- e^+ e^-$ Monte Carlo



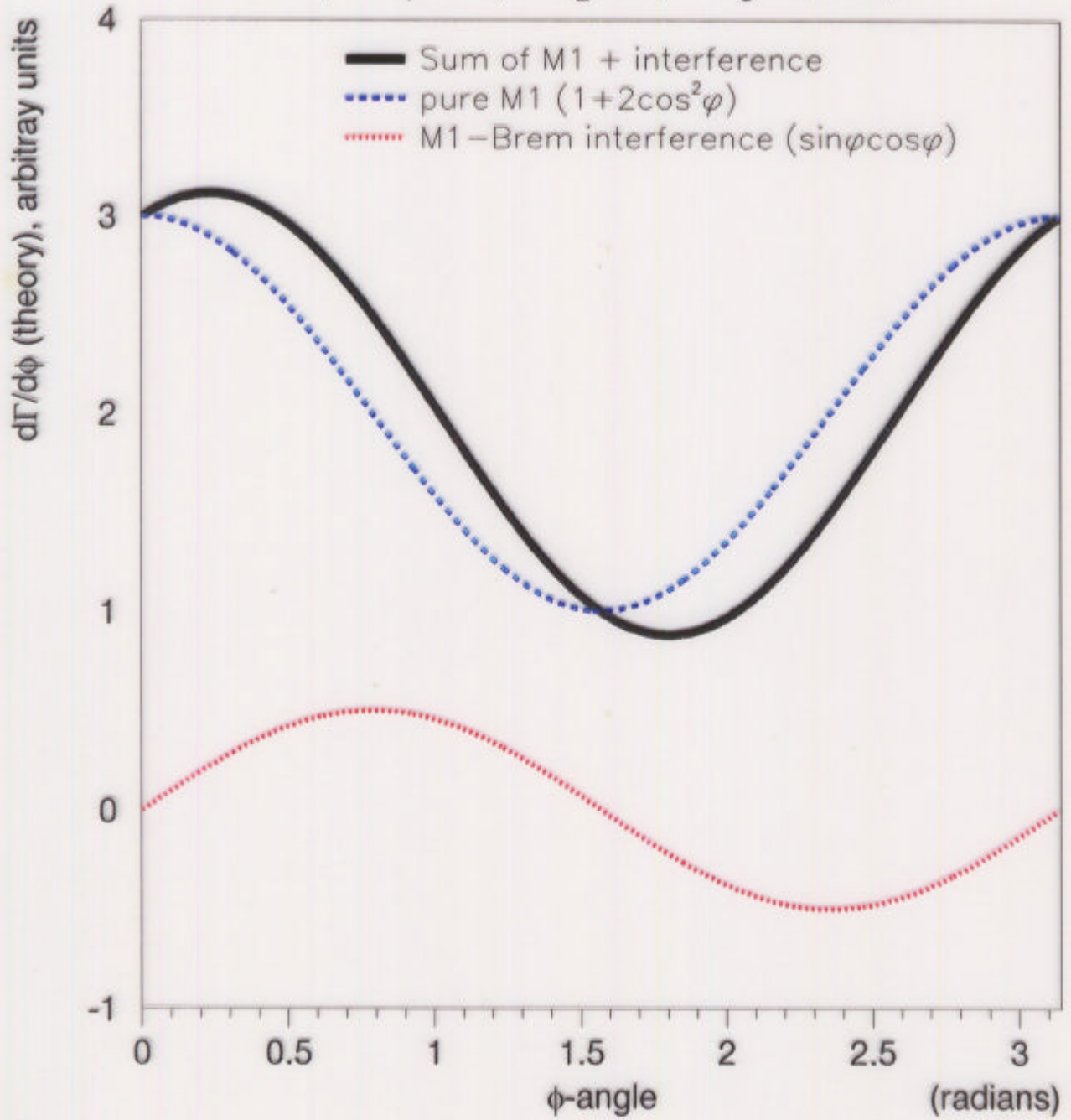


$K_L \rightarrow \pi^+ \pi^- e^+ e^-$



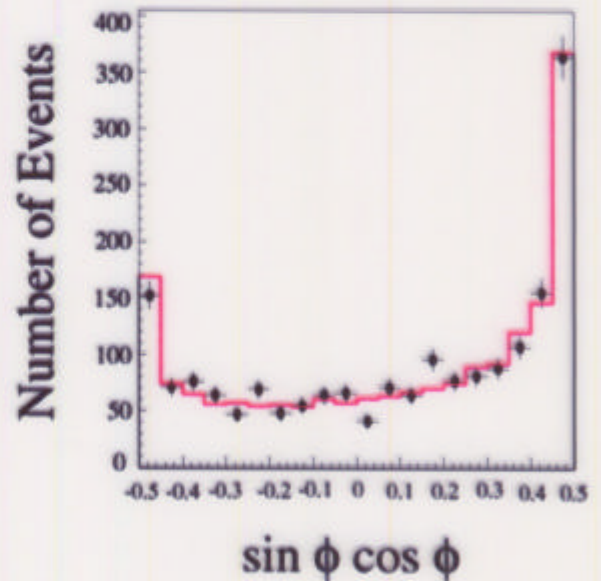
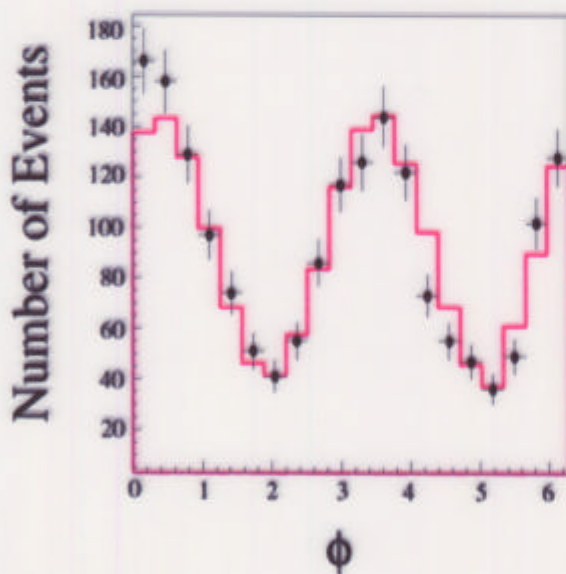
- Main BG: $K_L \rightarrow \pi^+ \pi^- \pi^0, \pi^0 \rightarrow e^+ e^- \gamma$ with missing γ
- $K_L \rightarrow \pi^+ \pi^- \pi^0, \pi^0 \rightarrow e^+ e^- \gamma$ normalization
- $BR(K_L \rightarrow \pi^+ \pi^- e^+ e^-)$ (KTeV)
 - ▶ $(3.2 \pm 0.6(\text{stat}) \pm 0.4(\text{syst})) \times 10^{-7}$
 - PRL 80, 4123 (1998) - based on c. 60 events
 - ▶ $(3.32 \pm 0.14(\text{stat}) \pm 0.28(\text{syst})) \times 10^{-7}$
 - Preliminary based on entire 1997 dataset

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



T-Odd Asymmetry Distributions

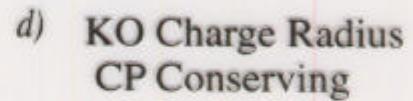
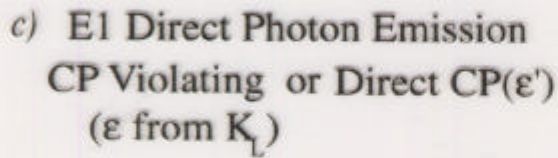
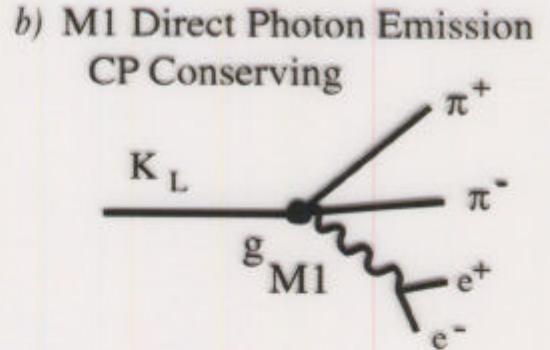
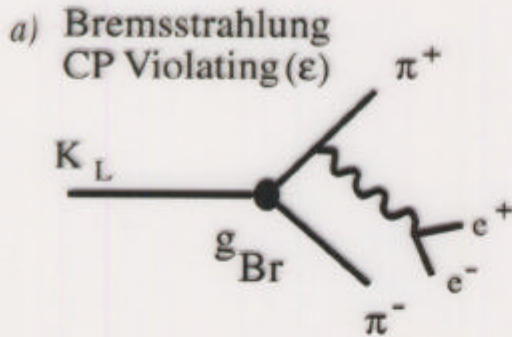
The **T-Odd** asymmetry (A) is defined as the normalized integral difference between the $\sin\phi\cos\phi \leq 0$ and $\sin\phi\cos\phi \geq 0$ data, and is manifest as a phase shift in the the ϕ distribution. The measured asymmetry is $13.6 \pm 2.5 \pm 1.2\%$.



The data are shown as dots, the theoretical expectation as a histogram.

Theoretical Model (Sehgal and Wanninger)

$K \rightarrow \pi\pi e e$ Processes



CAN FIT FOR THIS AMPLITUDE.

PARTICULAR SIGNATURE IS RELATIVELY LARGE m_{ee} MASS.

5 DIMENSIONAL FIT: $M_{\pi\pi}, M_{ee}, \phi, \cos\Theta_{e^+}, \cos\Theta_{e^-}$

CLASSICAL PICTURE...

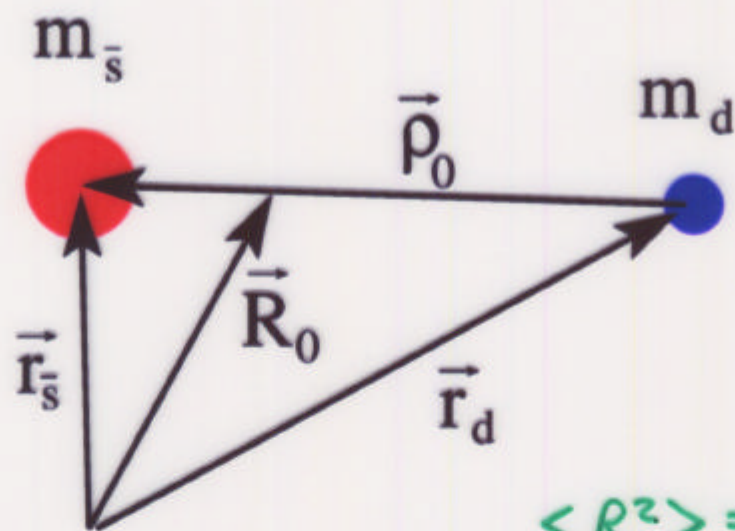


Figure 1.1:

$$\langle R^2 \rangle = -\frac{1}{3} \frac{m_s - m_d}{3m_s + m_d}$$

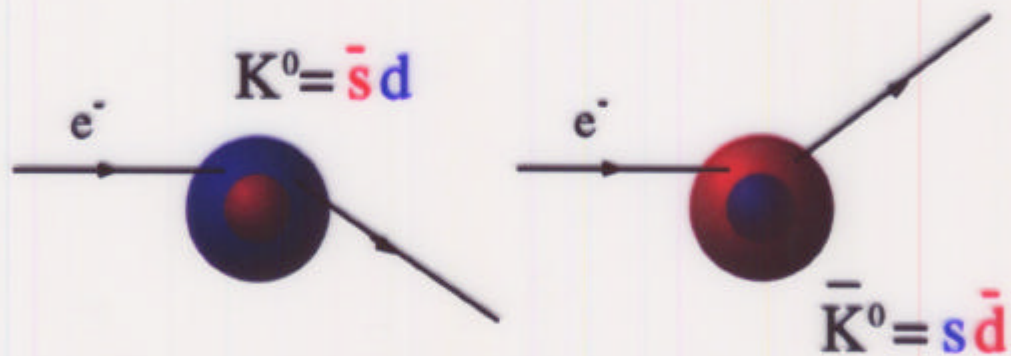
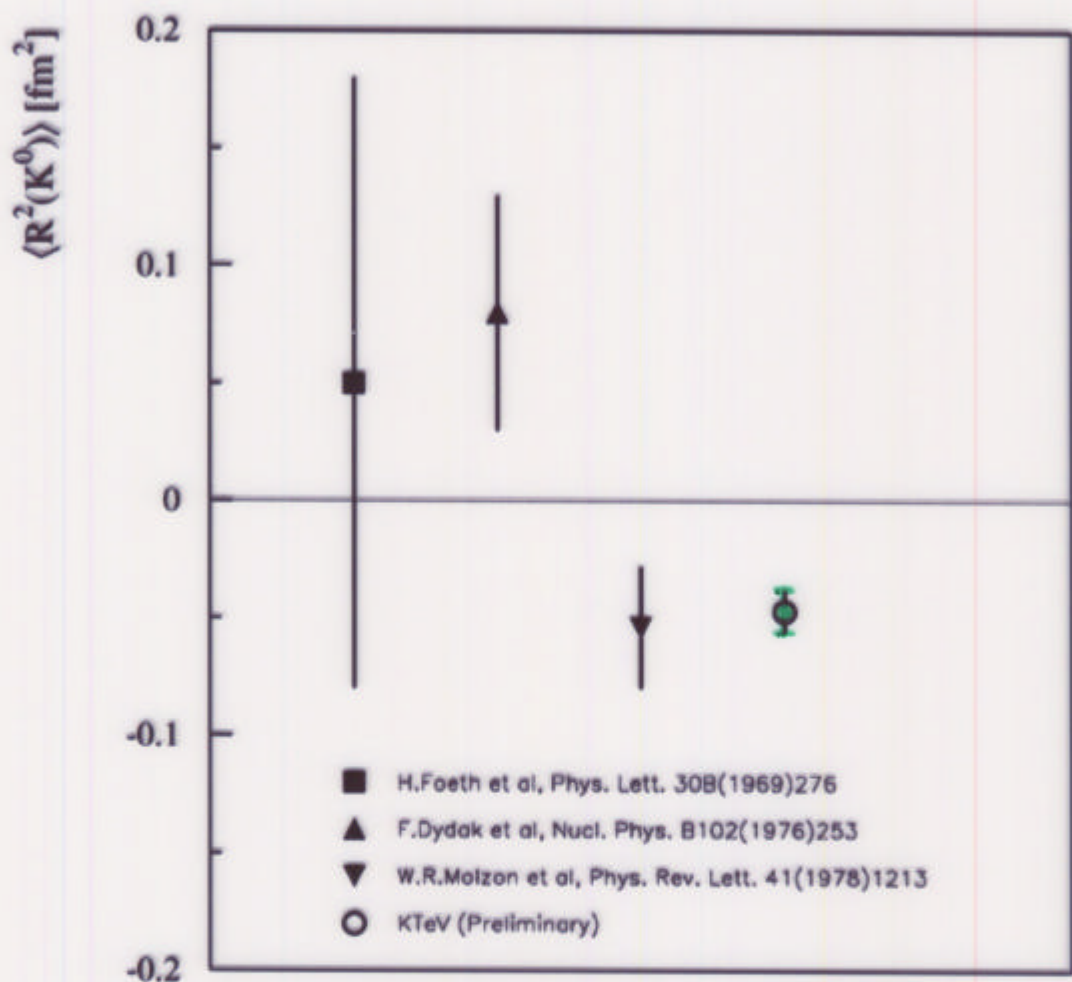


Figure 1.2: Electron scattering on K^0 and \bar{K}^0

3

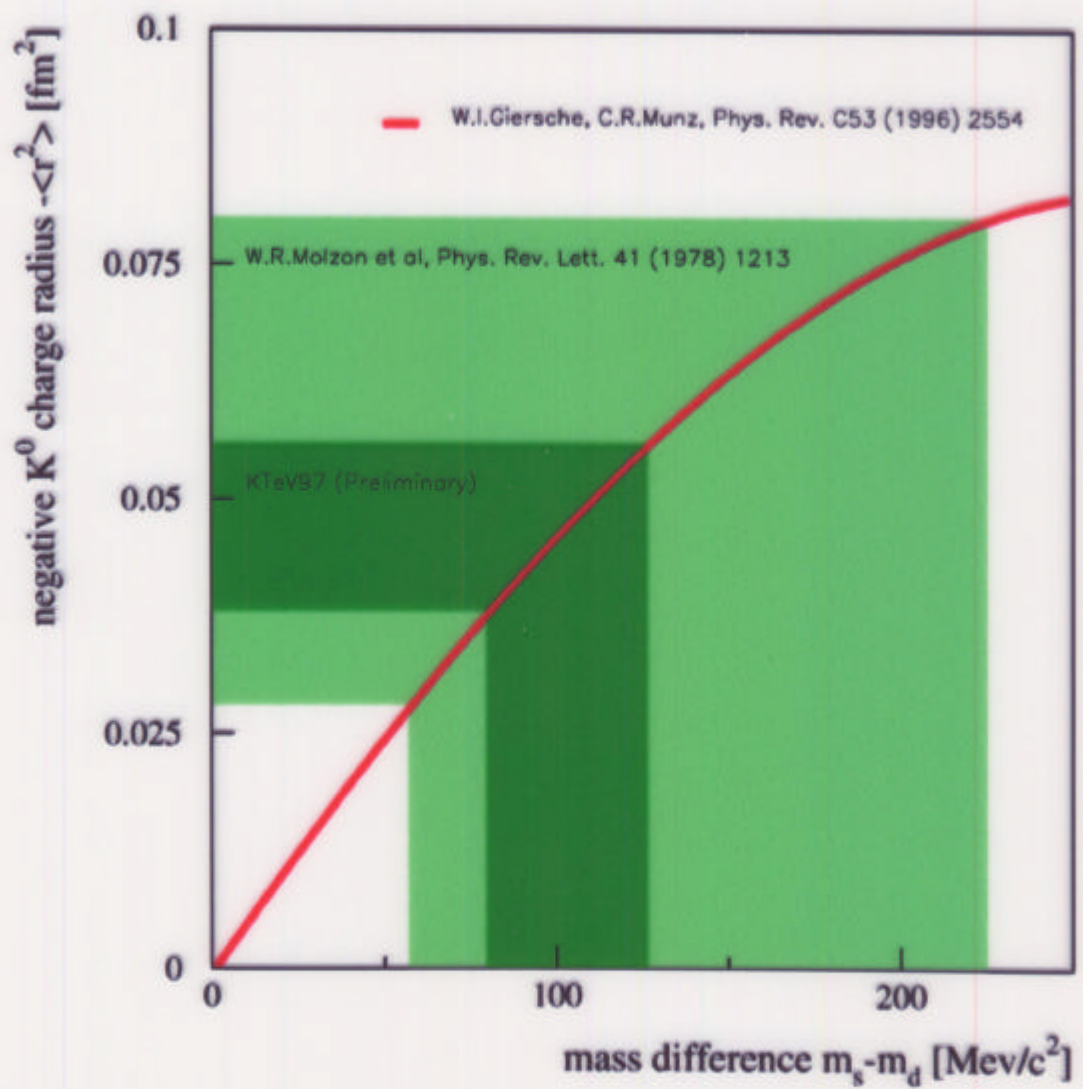
→ "ELECTRONIC" REGENERATION CAN PROBE K_L CHARGE RADIUS. $f^e = -\bar{f}^e$

[Ya. B. Zel'dovich, Sov. Phys. JTEP 23, 1040 (1967)]



CAVEAT: THIS IS REALLY A MEASURE OF
 THE S-WAVE COMPONENT OF $\pi\pi^+$

OTHER S-WAVE COMPONENTS ARE
 EXPECTED TO BE SMALL AND ARE
 UNDER STUDY.



MODEL THAT SUGGESTS A RELATIVELY LOW STRANGE QUARK MASS.

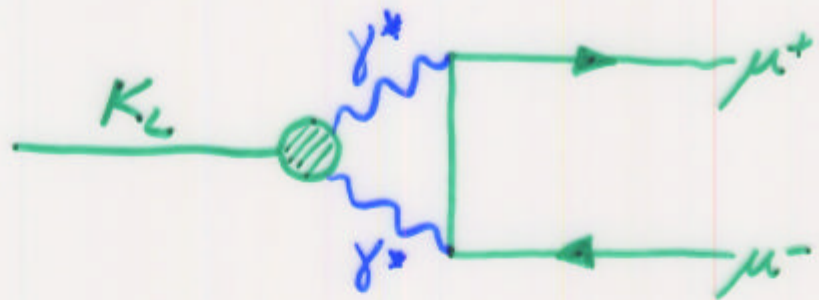
$$K_L \rightarrow \pi\pi e^+e^-$$

OUTLOOK.



- DETAILED STUDIES OF EXTRACTING CHARGE RADIUS ARE UNDERWAY.
- SEARCH FOR $K_L \rightarrow \pi^0\pi^0 e^+e^-$ WILL BE PRESENTED AT BCP4.
- TOTAL DATA SET IS X3 PUBLISHED TO DATE.

UNITARITY BOUND:



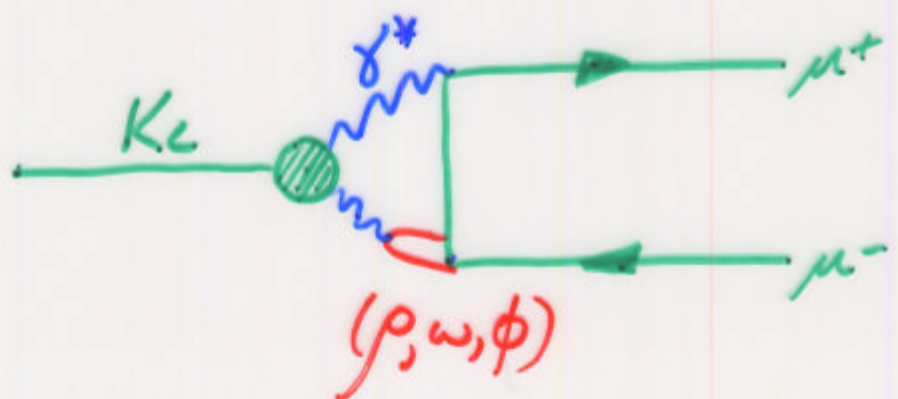
QED (SEHGAL, 1969):

$$\frac{\Gamma(K_L \rightarrow \mu^+ \mu^-)}{\Gamma(K_L \rightarrow \gamma\gamma)} = 1.195 \times 10^{-5}$$

PDG: $B(K_L \rightarrow \gamma\gamma) = (5.92 \pm 0.15) \times 10^{-4}$

$\rightarrow B(K_L \rightarrow \mu^+ \mu^-) > (7.07 \pm 0.18) \times 10^{-5}$

DOES NOT INCLUDE "DISPERSIVE" TERMS



PDG: $B(K_L \rightarrow \mu\mu)_{\text{exp}} = (7.18 \pm 0.17) \times 10^{-9}$

$$B(K_L \rightarrow \mu\mu)_{\gamma\gamma} = (7.07 \pm 0.18) \times 10^{-9}$$

$$\delta \Delta \sim 3$$

WHAT IS ACTUALLY MEASURED?

Exp: BNL-E871:

$$\frac{B(K_L \rightarrow \mu^+ \mu^-)}{B(K_L \rightarrow \pi^+ \pi^-)} = (3.474 \pm 0.054) \times 10^{-2}$$

Exp: CERN NA31:

$$\frac{B(K_L \rightarrow \gamma\gamma)}{B(K_L \rightarrow 2\pi^0)} = 0.632 \pm 0.009$$

PHYSICS EXTRACTED FROM:

$$\frac{\Gamma_{\mu\mu}}{\Gamma_{\gamma\gamma}} = \left(\frac{\Gamma_{\mu\mu}}{\Gamma_{+-}} \right) \left(\frac{\Gamma_{00}}{\Gamma_{\gamma\gamma}} \right) \left(\frac{\Gamma_{+-}}{\Gamma_{00}} \right)$$

Recall:

$$\Gamma_{00}/\Gamma_{00}^S / \Gamma_{+-}/\Gamma_{+-}^S \approx 1 - 6 \operatorname{Re}(\epsilon'/\epsilon)$$

→

$$\frac{\Gamma_{\mu\mu}}{\Gamma_{\gamma\gamma}} = \frac{\Gamma_{\mu\mu}}{\Gamma_{+-}} \left/ \left[\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\pi^0\pi^0}} \frac{\Gamma_{00}^S}{\Gamma_{+-}^S} \left(1 - 6 \operatorname{Re} \frac{\epsilon'}{\epsilon} \right) \right. \right.$$

↓
BNL-871

↓
NA31

↓
PDG

(KT0V/NA4)

(1.6%) (1.4%) (1.0%) (0.2%)

(0.9% sts) (1.2% sts) ??

$$\rightarrow \frac{\Gamma_{\mu\mu}^{\text{EXP}}}{\Gamma_{\gamma\gamma}^{\text{EXP}}} = (1.213 \pm 0.030) \times$$

$$\text{c.f. QED} = (1.195 \pm 0.000) \times$$

$$\Delta = {}^+0.6\%$$

$$\Delta = 2.5\%$$

TO REDUCE Δ :

KAMI?

$$K_L \rightarrow \mu\mu / \pi^+\pi^-$$

$$\Delta = 1.6\%$$

NA48 \neq

KTeV \neq

DAPHNE

$$K_L \rightarrow \gamma\gamma / \pi^0\pi^0$$

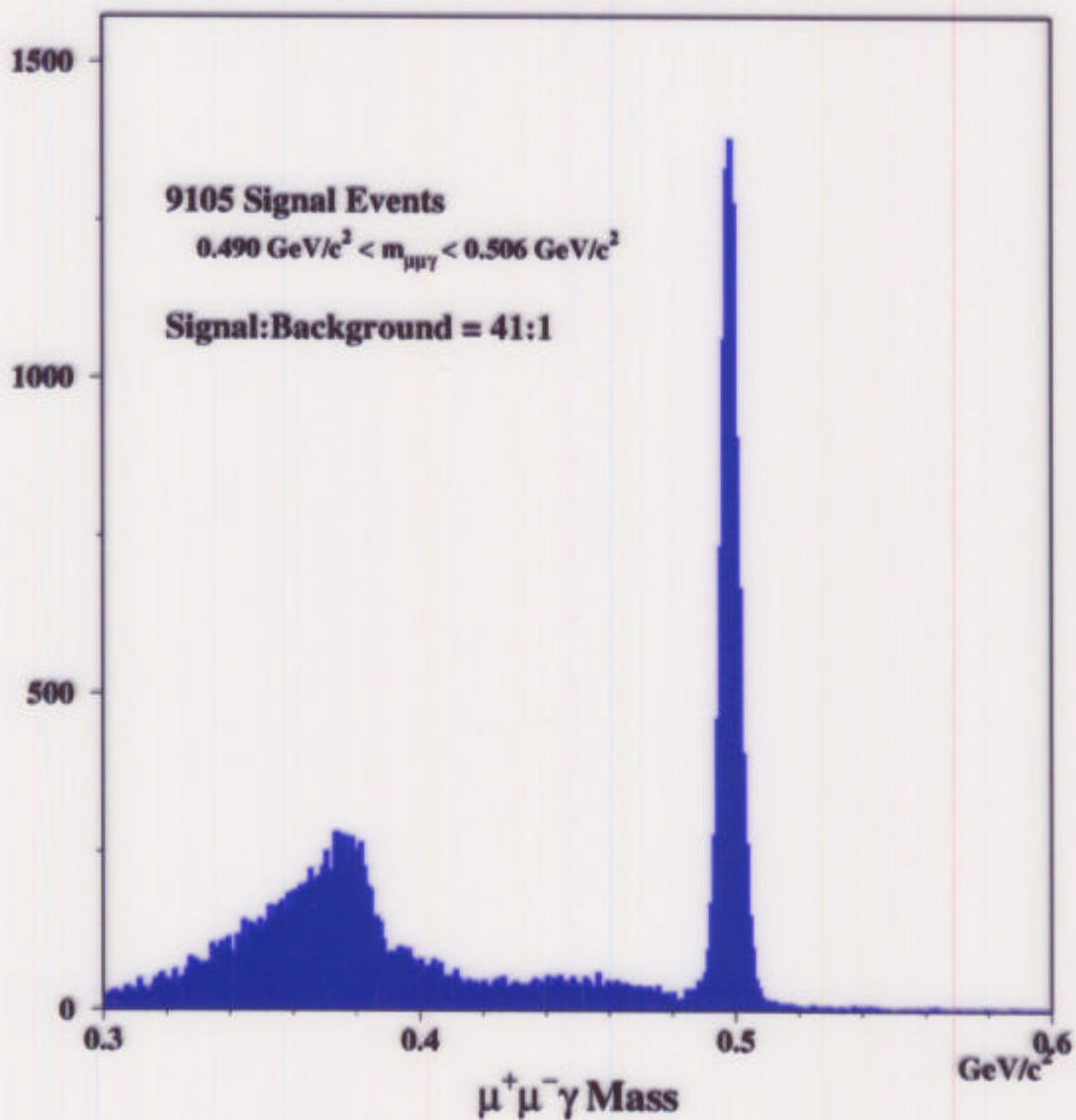
$$\Delta = 1.4\%$$

$$K_S \rightarrow \pi^0\pi^0 / \pi^+\pi^-$$

$$\Delta = 1.0\%$$

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

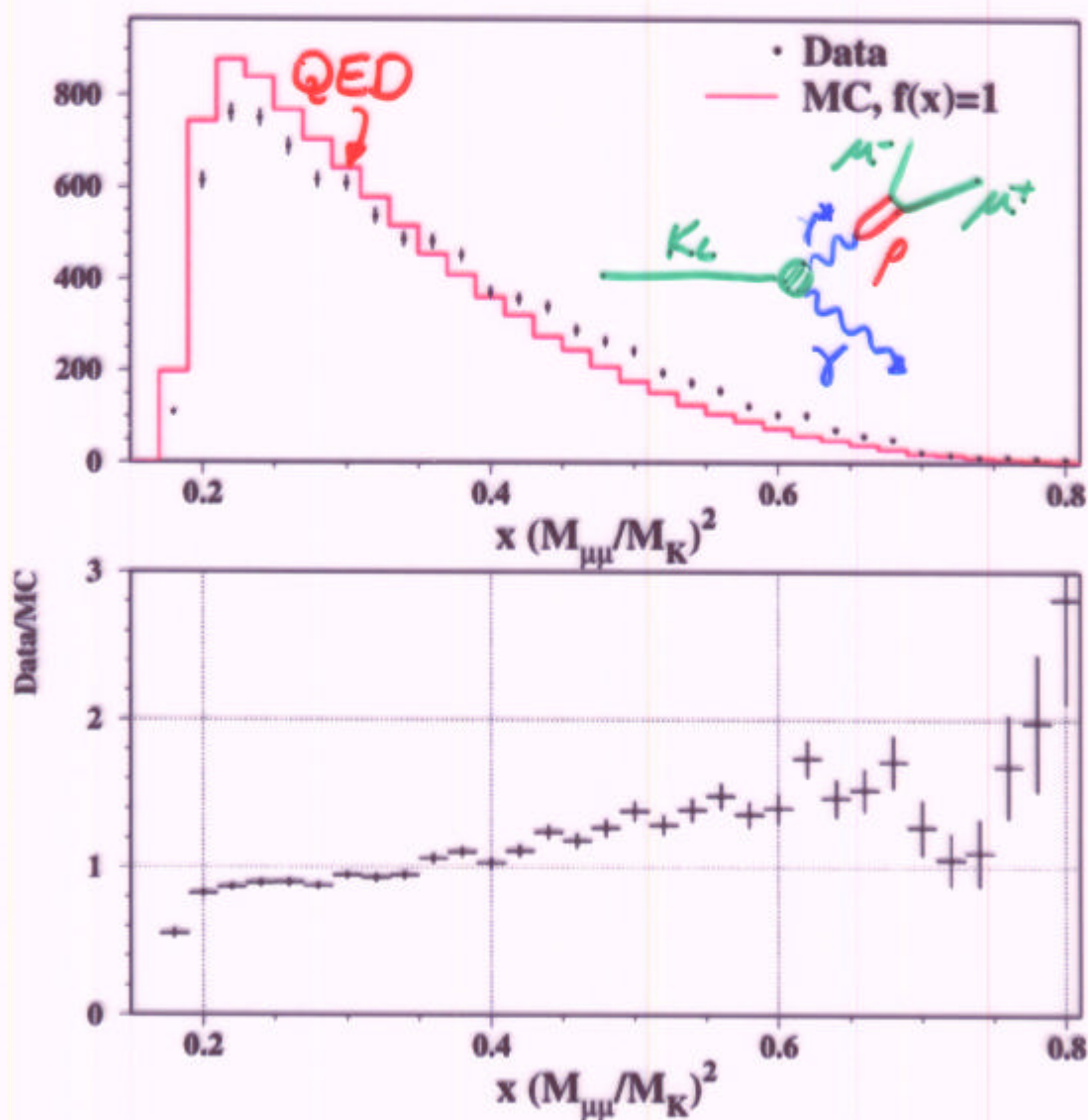
Branching Ratio Measurement



$$BR(K_L \rightarrow \mu^+ \mu^- \gamma) = (3.66 \pm 0.04_{stat} \pm 0.07_{sys}) \times 10^{-7}$$

Dimuon Mass Distribution

- The Data/MC ratio is the measured value of the form factor, $|f(x)|^2$
- Completely model-independent



SUMMARY

KTeV PRECISION MEASUREMENTS

- $\text{Re}(\frac{\epsilon'}{\epsilon})$: AIMING FOR WINTER CONF.
- S_e : BCP4
- $K_L \rightarrow \pi\pi e e$: CHARGE RADIUS EXTRACTION IN PROGRESS.
- EXTRACTING ρ FROM $K_L \rightarrow \mu^+ \mu^-$
 - LONG ROAD
 - EXPERIMENTAL INPUTS POSSIBLE.
 - CAN THEORY ERROR BE CONTROLLED?



016-7207