Experimental Status of CP Violation in the Kaon System

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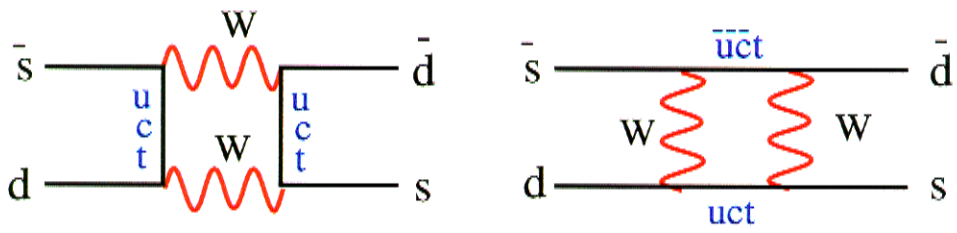
2/24/00

Introduction

- Survey of CP violation topics in the kaon system
- ϵ'/ϵ
- $K_L \to \pi^+\pi^- e^+ e^-$ and CP violating, T-odd asymmetry
- T violation at CPLEAR
- Disclaimer: unfairly weighted (by me) to KTeV and ϵ'/ϵ
- Thanks to
  - A. Ceccuci (CERN/NA48)
  - J. Cogan (Saclay/NA48)
  - S. Ledovskoy (Virginia/KTeV)
  - T. Ruf (CERN/CPLEAR)
  - The entire KTeV ϵ'/ϵ group
  - And lots of others for supplying slides and info

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

- Weak Interactions ($\Delta S = 2$) Mix $K^0, \bar{K}^0$



- CP Eigenstates:

$K_1 = (K^0 + \bar{K}^0)/\sqrt{(2)}$ - CP Even,
$K_2 = (K^0 - \bar{K}^0)/\sqrt{(2)}$ - CP Odd

Note: K_1 can go to $\pi\pi$ (CP Even), much more phase space than K_2

$K^0 - \bar{K}^0$ Mixing and CP Violation

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

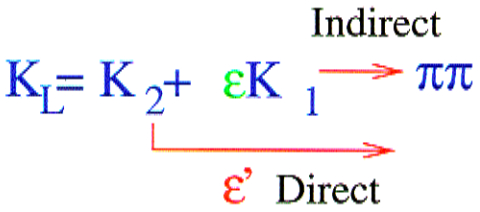
    $K_S \propto K_1 + \epsilon K_2, K_L \propto \epsilon K_1 + K_2$ or,
    $K_S \propto pK^0 + q\bar{K}^0, K_L \propto pK^0 - q\bar{K}^0$ $(p, q \propto 1 \pm \epsilon)$
  - $\epsilon = (2.263 \pm 0.023) \times 10^{-3}$

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

  - In SM, ϵ arises from $\eta \neq 0$

Direct CP Violation

- Direct CP violation also possible



- $\epsilon' \propto Im(A_2/A_0)$
  - A_0 - I=0 $\pi\pi$ amplitude
  - A_2 - I=2 $\pi\pi$ amplitude

  Sum of QCD and EW penguin contributions

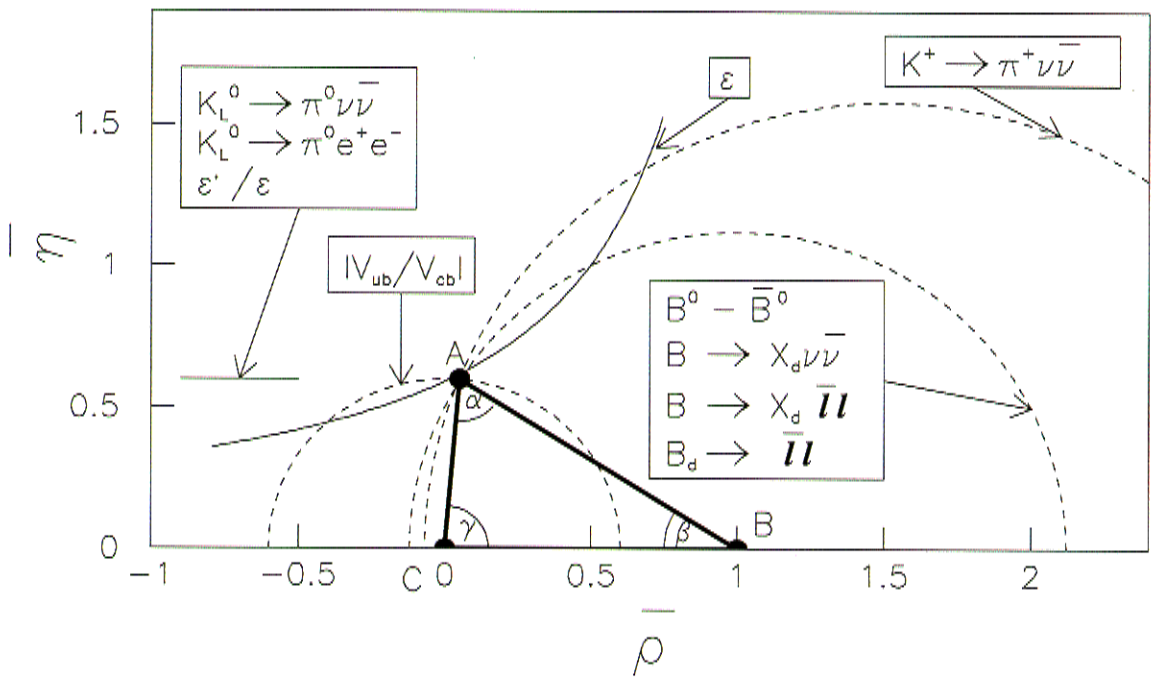
- $\epsilon'/\epsilon = Im\lambda_t \cdot [c_0 + R_s(c_6 B_6^{(1/2)} + c_8 B_8^{(3/2)})]$

  e.g. A. Buras hep-ph/9806471, R. Gupta hep-ph/9801412
  - $Im\lambda_t = ImV_{td}V_{ts}^* = A^2\lambda^5\eta$
  - $B_{6,8}$ - Long distance physics
- B_6 and B_8 are theoretically difficult, and tend to cancel
  - ϵ'/ϵ is hard to predict

Kaons and the Unitarity Triangle

- Same unitary matrix as in B system

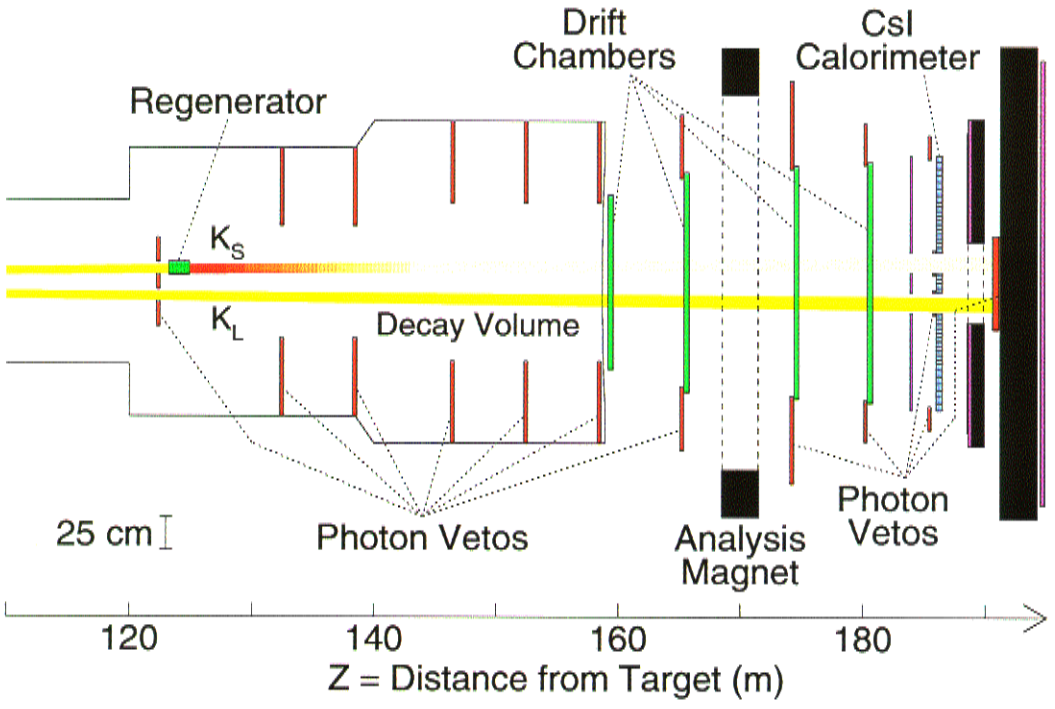
A.J. Buras, hep-ph/9711217, TUM-HEP-299/97



- ϵ and ϵ' have clear trajectories in $\rho - \eta$ plane
  - Problem is... all the other stuff multiplying the effect!
  - Value as check against B system is nevertheless essential
- Ultra-rare $K \to \pi\nu\bar{\nu}$
  - will have more quantative impact

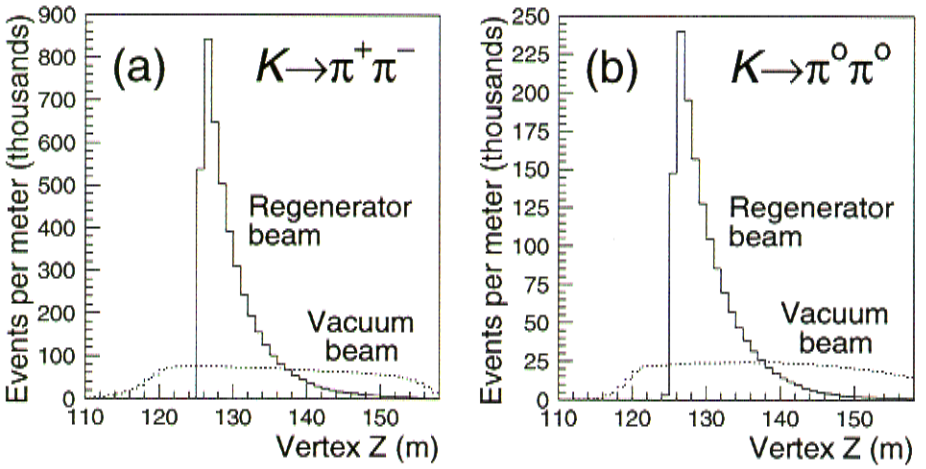
KTeV

- 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



ϵ'/ϵ - KTeV

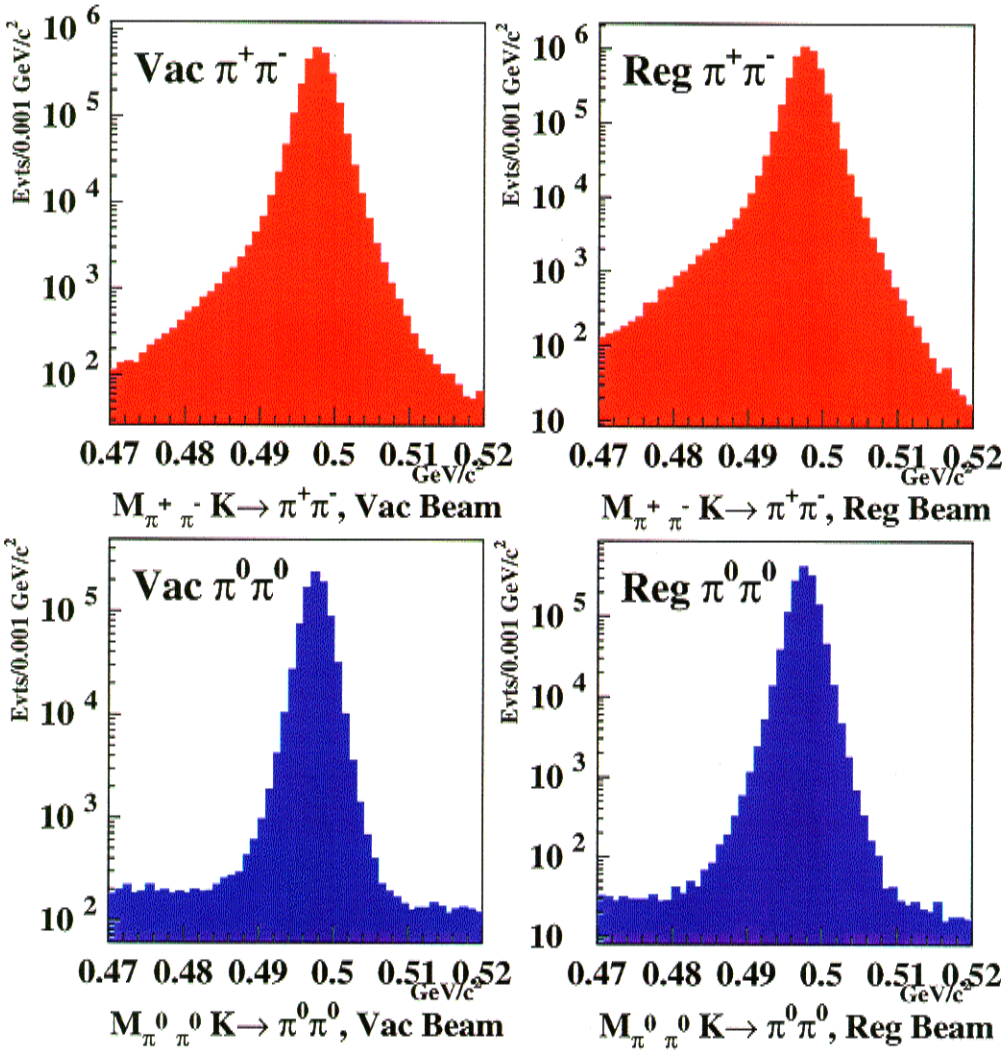
- $\frac{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)} = \frac{|\eta_{\pm}|^2}{|\eta_{oo}|^2} \approx 1 + 6Re(\frac{\epsilon'}{\epsilon})$
- Simultaneous K_L, K_S beams - coherent regeneration
- Background subtraction
- Acceptance correction - large K_S-K_L lifetime difference



- Fit for ϵ'/ϵ

ϵ'/ϵ - KTeV

- $K \to \pi^0\pi^0$ - reconstruct with CsI using π^0 mass constraint
- $K \to \pi^+\pi^-$ - 2 good pion tracks

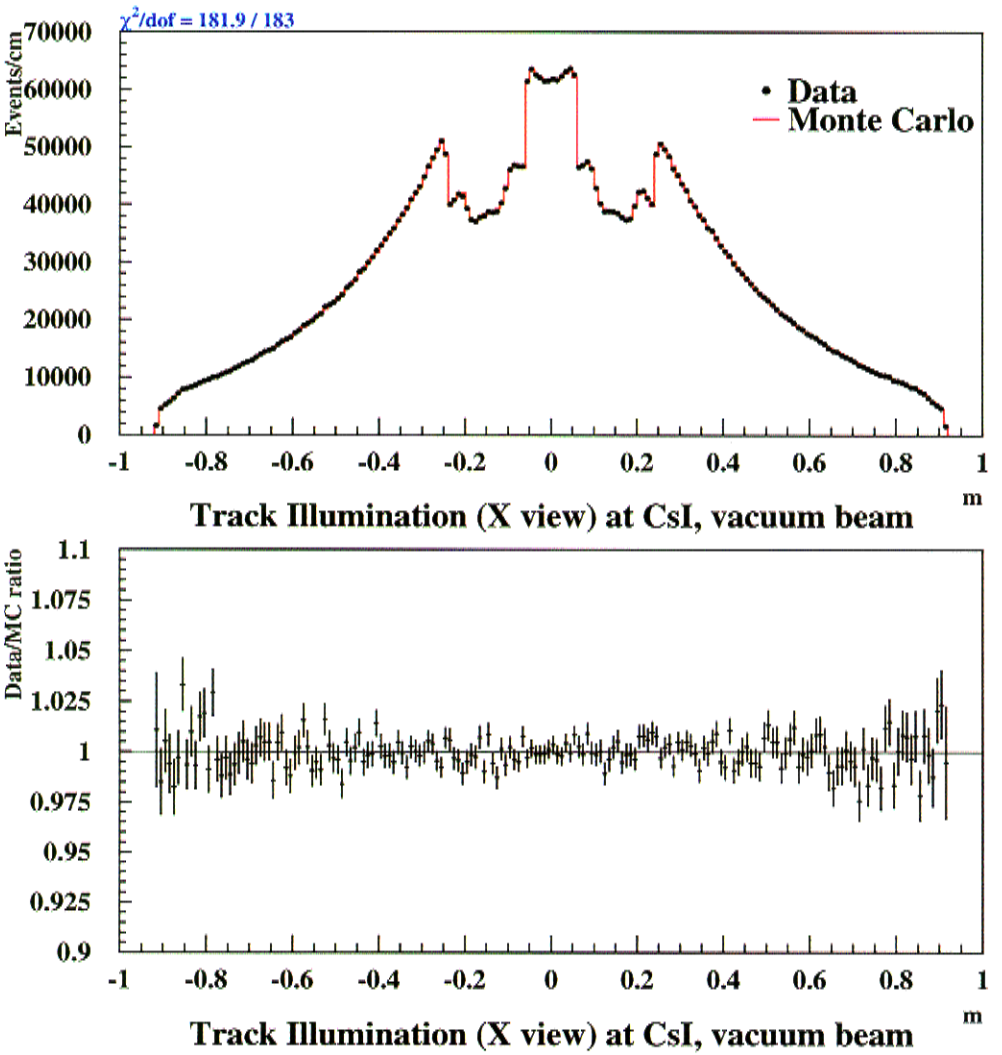


- Backgrounds range from 0.08% to 1.2% for the 4 modes

Acceptance and ϵ'/ϵ in KTeV

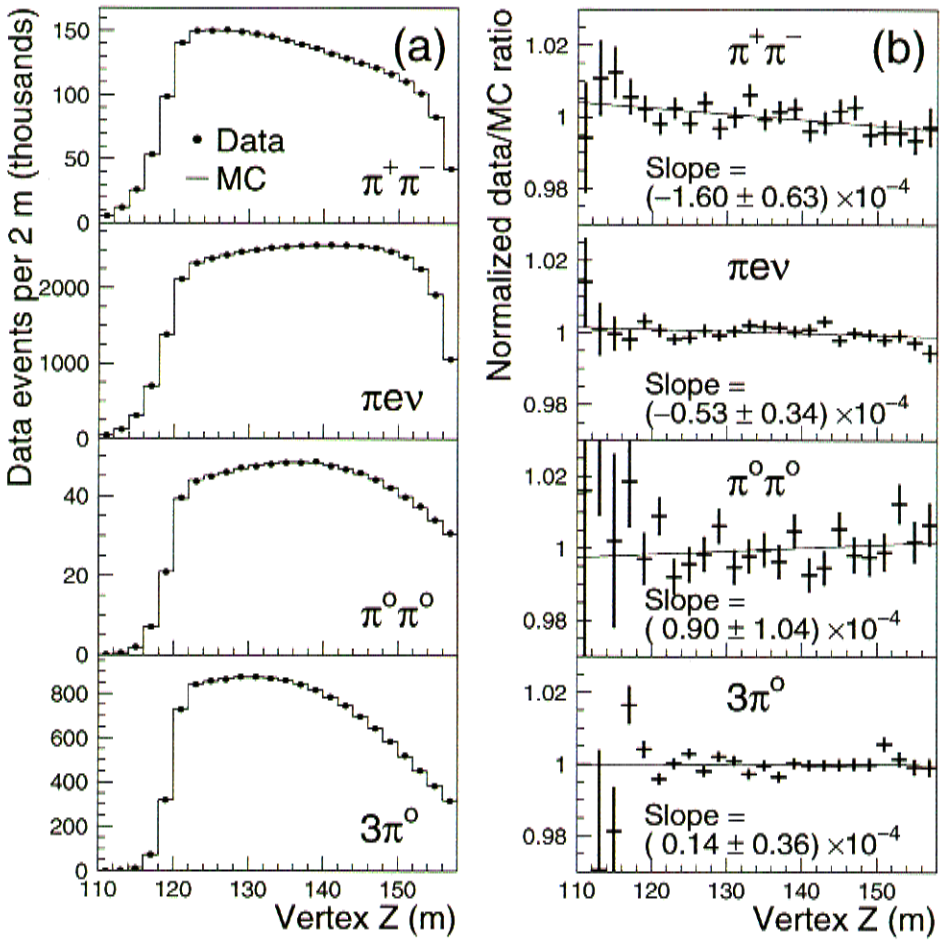
- Use MC to correct K_L and K_S samples for acceptance
  - 10's of millions of $K \to \pi e \nu$, $K \to \pi^0\pi^0\pi^0$ and $K \to \pi^+\pi^-\pi^0$ to study detector response

$K \to \pi^+\pi^-$ track illumination



Acceptance and ϵ'/ϵ in KTeV

- Overlay of Data and MC for K_L decay vertex distributions
  - Slope in overlay $\rightarrow$ misunderstood acceptance?
  - Net relative correction between K_L and K_S



  - $K_L \rightarrow \pi^+\pi^-$ slope gives largest single systematic uncertainty (1.6×10^{-4})

KTeV ϵ'/ϵ Result

- Result is based on 1996 $K \to \pi^0\pi^0$ and fraction of 1997 $K \to \pi^+\pi^-$

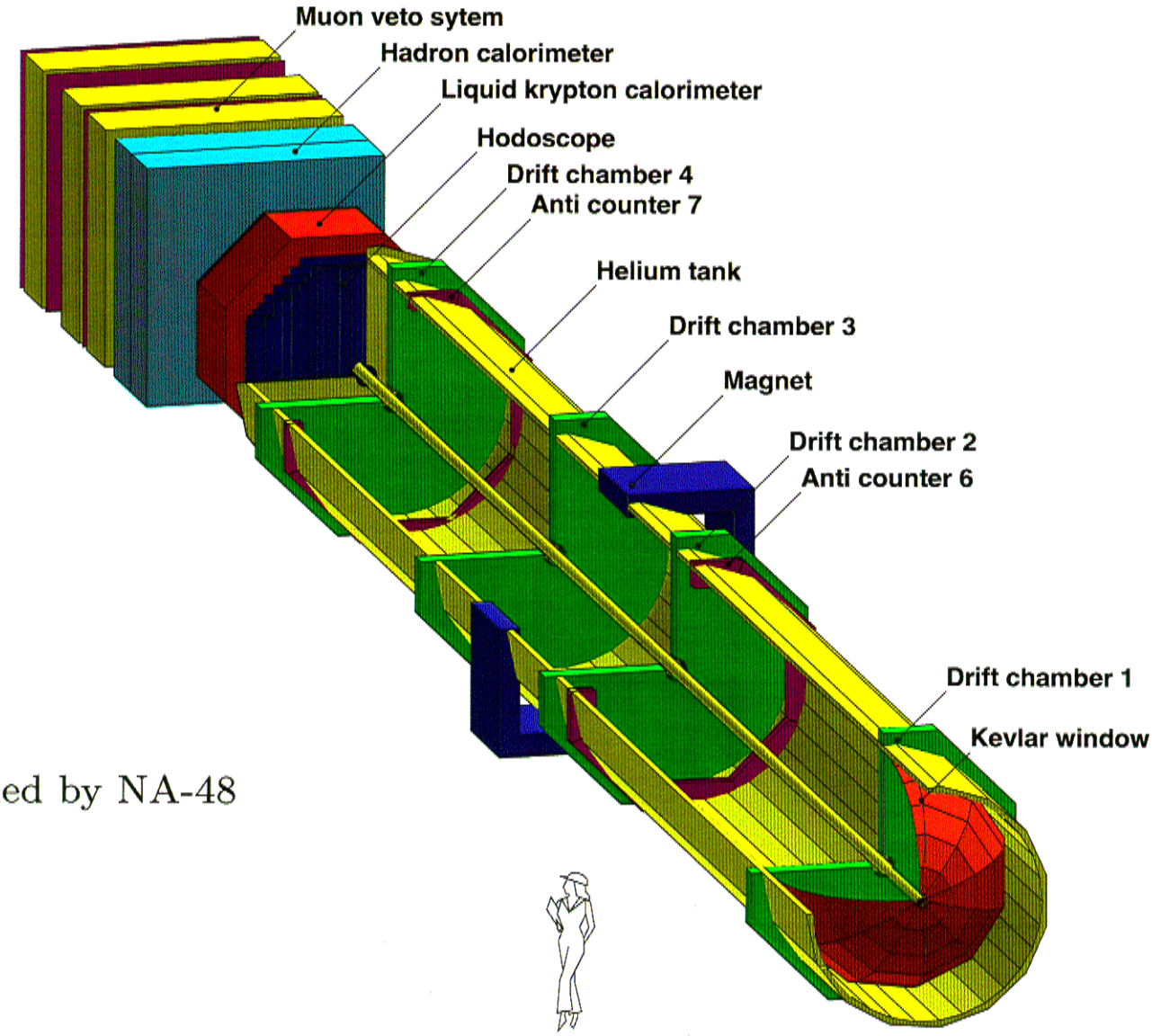
$$Re(\frac{\epsilon'}{\epsilon}) = (28.0 \pm 3.0(stat) \pm 2.8(syst)) \times 10^{-4}$$

A.Alavi-Harati *et al.*, Phys. Rev. Lett. 83, 22 (1999)

- This result taken alone establishes existence of direct CP violation
- Analysis of entire 1997 dataset in progress - 4 times more data
- 1999 Fixed Target Run
  - Doubled dataset
  - Improved detector performance
  - Substantial running at 2 different intensities

NA-48 at CERN

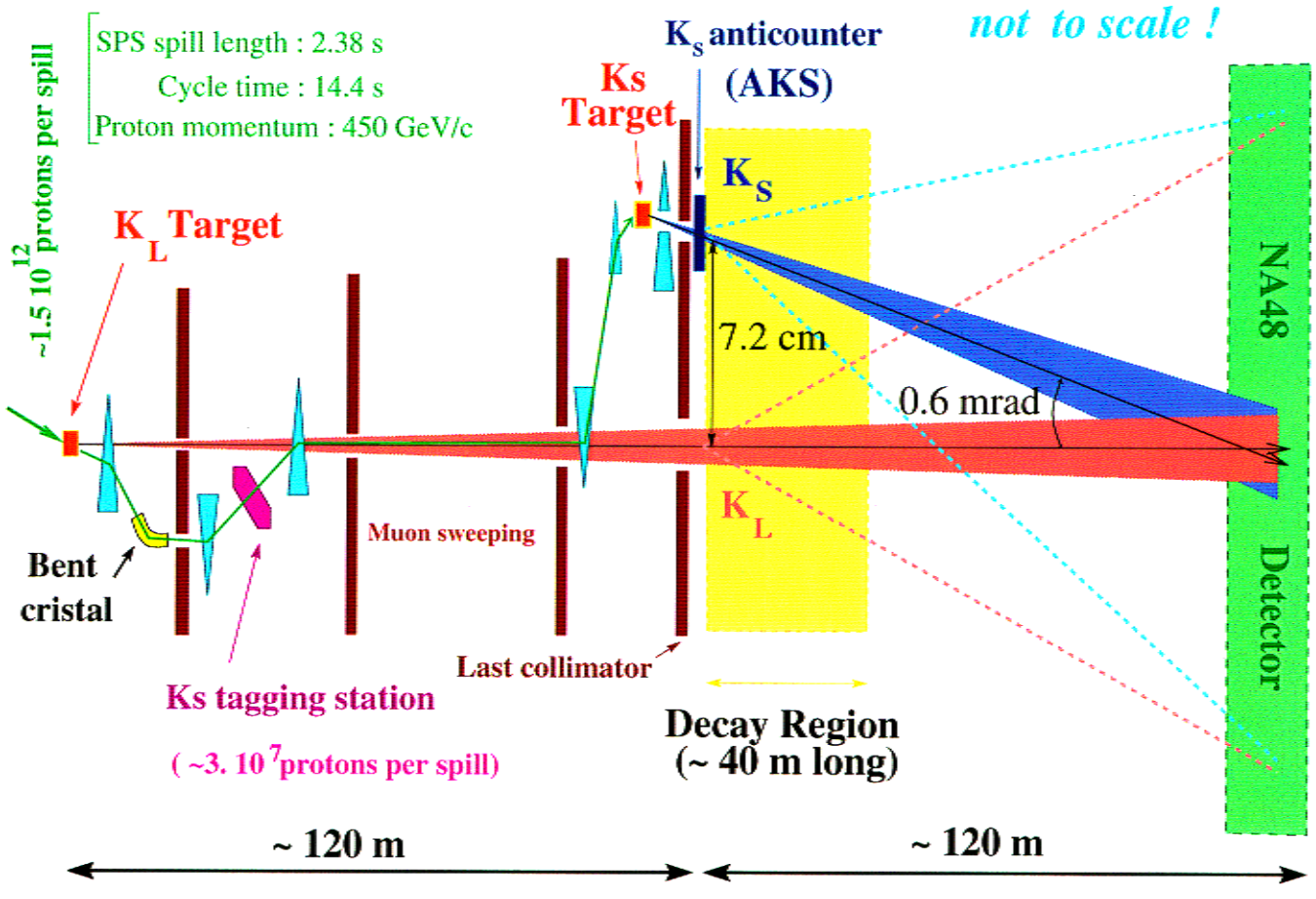
- Similar ϵ'/ϵ objectives to KTeV's
  - ▷ High precision LKr calorimeter
- K_L and K_S production targets (beam proton tagger in K_S line)



Provided by NA-48

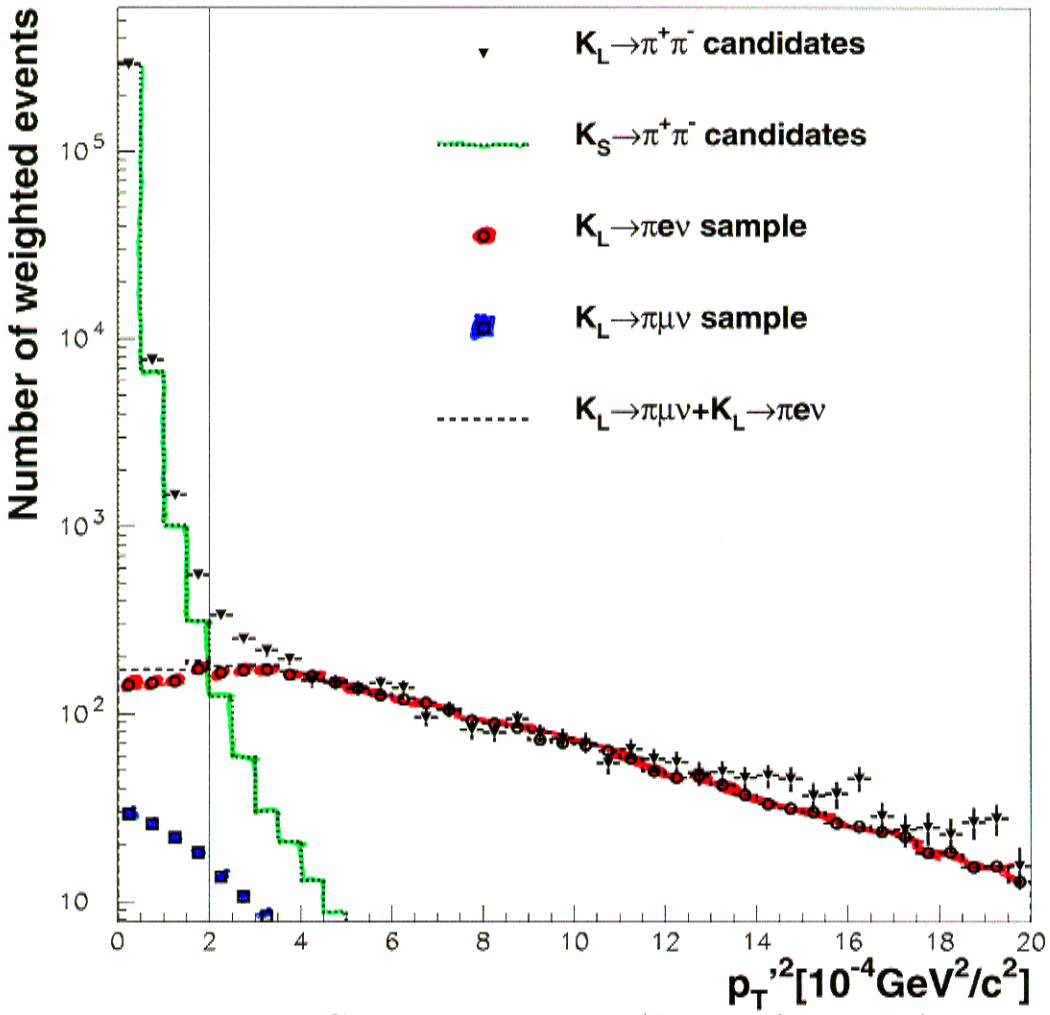
NA-48 K_S vs. K_L

Provided by NA-48



NA-48 $\pi^+\pi^-$ Background

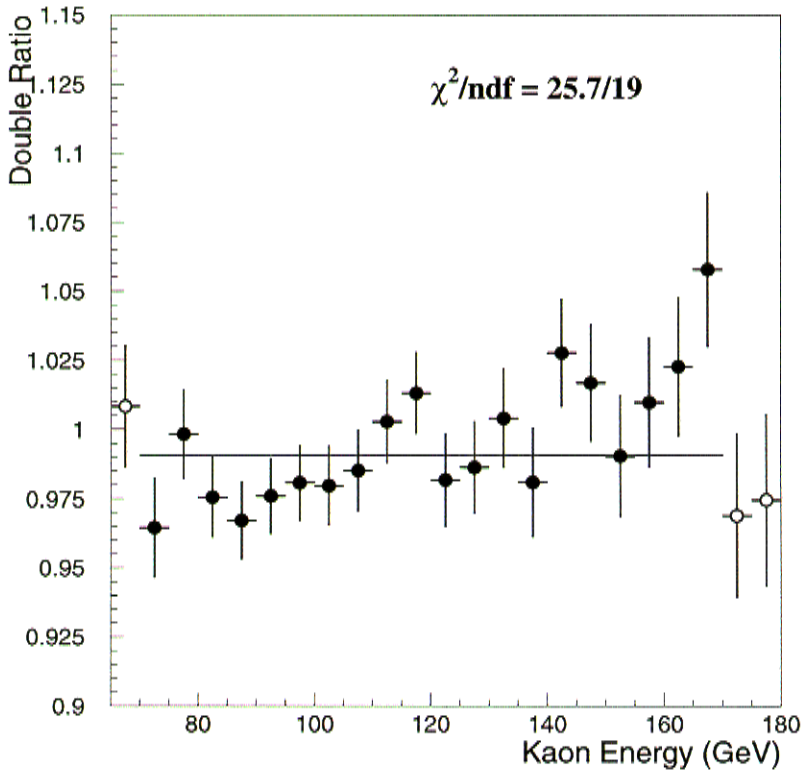
- $K \to \pi l \nu$ important background to $K_L \to \pi^+\pi^-$
  - $P_T'^2$ peaked at 0 for signal
  - Use $K_S \to \pi^+\pi^-$, enhanced $K_L \to \pi l \nu$
  - Background is $(0.23 \pm 0.02(stat) \pm 0.04(syst))\%$ in signal region



CERN-EP-99-114 (*hep-ex/9909022*)

NA-48 ϵ'/ϵ

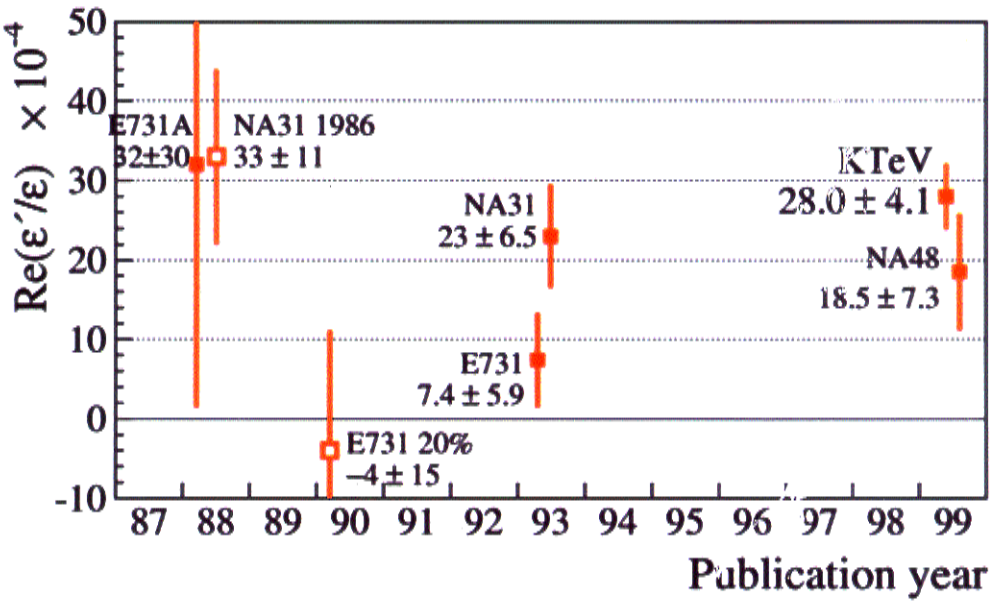
- Double Ratio $R \approx 1 - 6Re(\epsilon'/\epsilon)$
  - Variation of R with E_K? Flat hypothesis $\chi^2 = 26.5$ per 19 DOF
  - Extended range (not included in this result) disfavors a trend in E_K

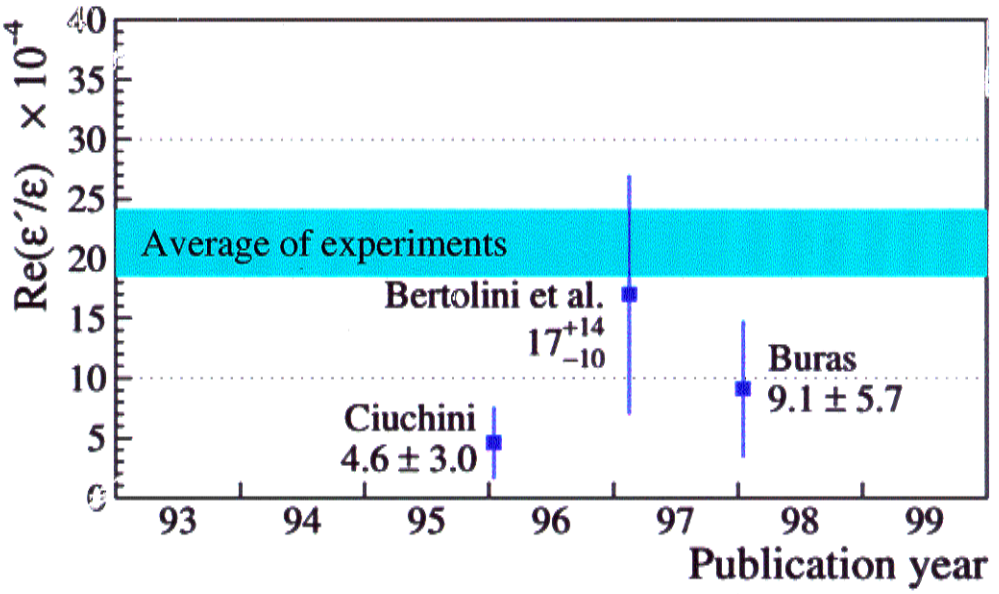


$$Re(\frac{\epsilon'}{\epsilon}) = (18.0 \pm 4.5(stat) \pm 5.8(syst)) \times 10^{-4}$$

CERN-EP-99-114, submitted to Phys. Lett. B

Experiment & Theory Status of $Re(\epsilon'/\epsilon)$



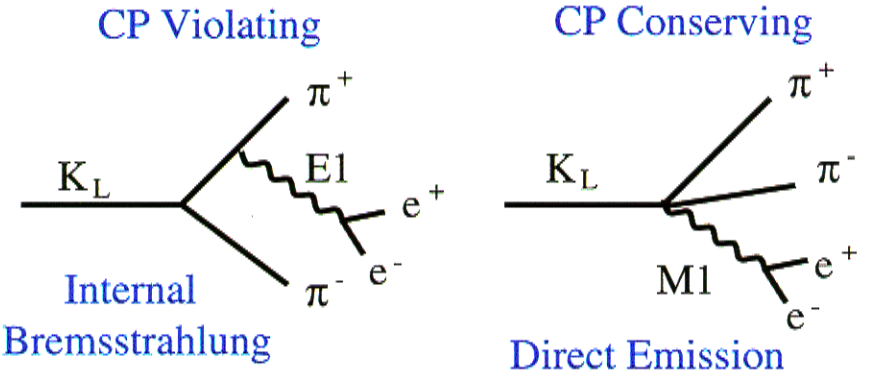


ϵ'/ϵ Status

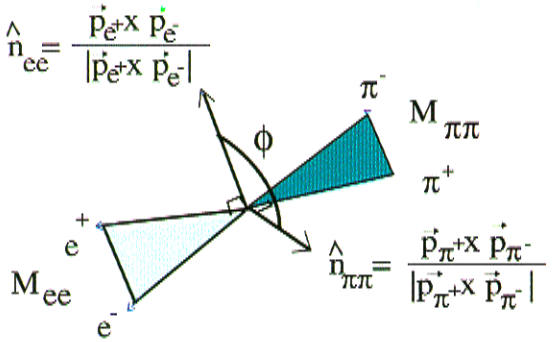
- Agreement between NA-48 and KTeV
- World Average (with scaled error):
  - $Re(\epsilon'/\epsilon) = (21.2 \pm 4.6) \times 10^{-4}$
  - Regardless of long distance haze, η many σ from 0
- KLOE at DAPHNE (Frascati)
  - Very different technique: $e^+e^- \to \phi \to K_L K_S$
  - Completely different systematic effects
  - KLOE will provide a valuable test of NA-48 and KTeV techniques

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

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



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

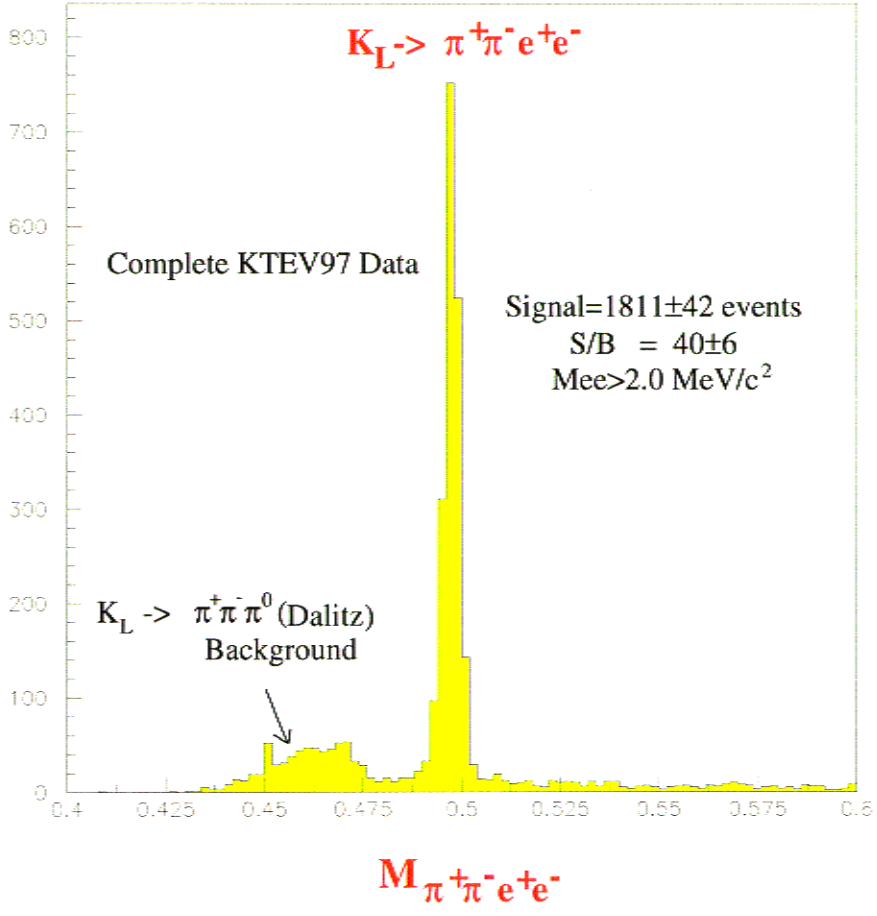
$$\sin\phi\cos\phi = (\hat{n}_{ee} \times \hat{n}_{\pi\pi}) \cdot \hat{z}(\hat{n}_{ee} \cdot \hat{n}_{\pi\pi})$$

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

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

L. M. SEHGAL AND M. WANNINGER
PHYS. REV. D46, 1035 (1992)
ibid D46, 5209(E) (1992)

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

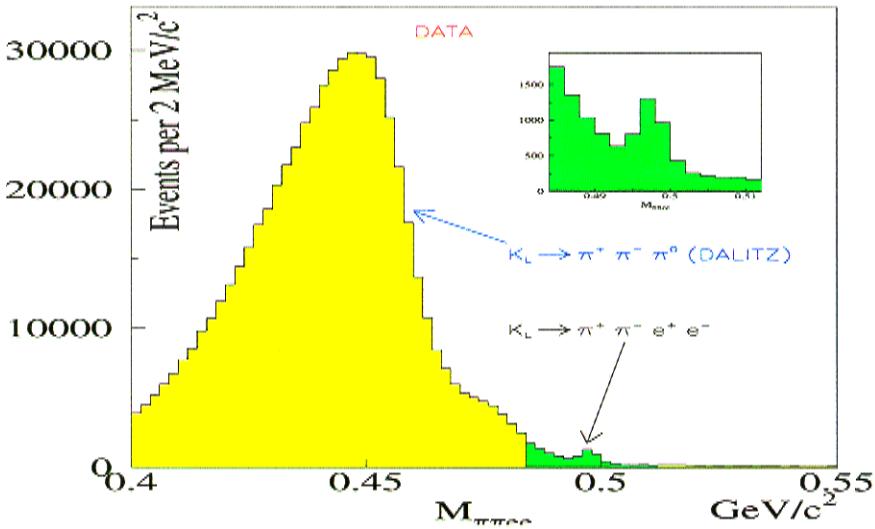


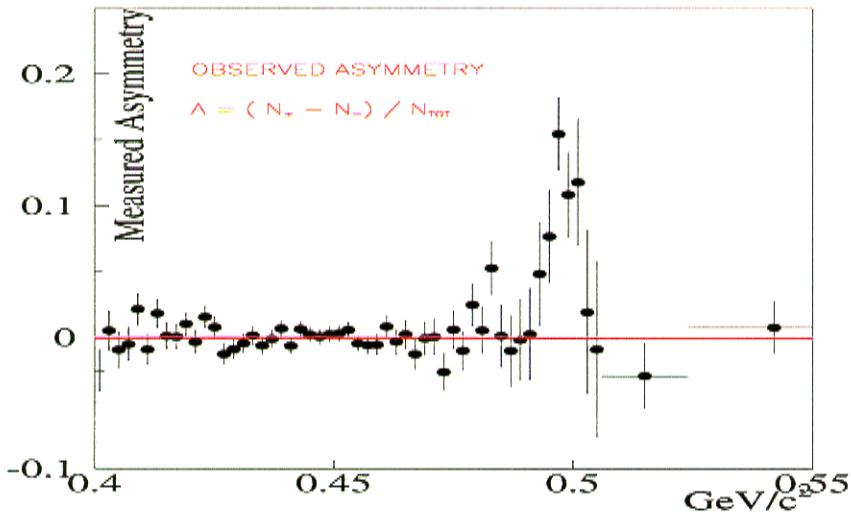
- Main BG: $K_L \to \pi^+\pi^-\pi^0$, $\pi^0 \to e^+e^-\gamma$ with missing γ
- $K_L \to \pi^+\pi^-\pi^0$, $\pi^0 \to e^+e^-\gamma$ normalization
- $BR(K_L \to \pi^+\pi^- e^+ e^-)$ (KTeV)
  - $(3.2 \pm 0.6(\text{stat}) \pm 0.4(\text{syst})) \times 10^{-7}$
    - PRL 80, 4123 (1998) - based on c. 60 events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

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

- $A_\phi = \frac{N_{\sin\phi\cos\phi>0} - N_{\sin\phi\cos\phi<0}}{N_{\sin\phi\cos\phi>0} + N_{\sin\phi\cos\phi<0}}$
  - ▷ Asymmetry varies with $m_{\pi\pi}$ due to relative importance of DE and IB
  - ▷ Acceptance variation with $m_{\pi\pi}$ affects (but doesn't create) A_ϕ
- A_ϕ is only present in signal!

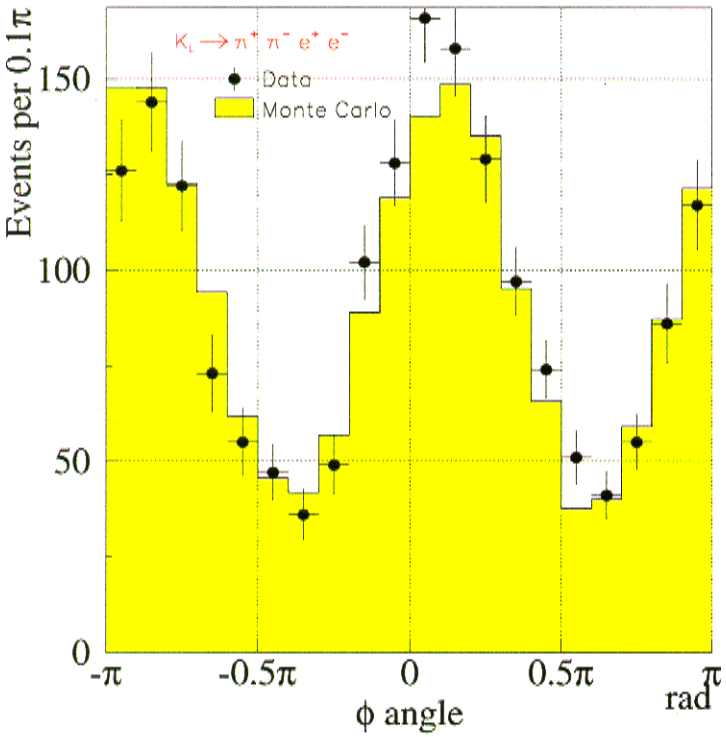
$K_L \to \pi^+\pi^-e^+e^-$ after PID+topological cuts only

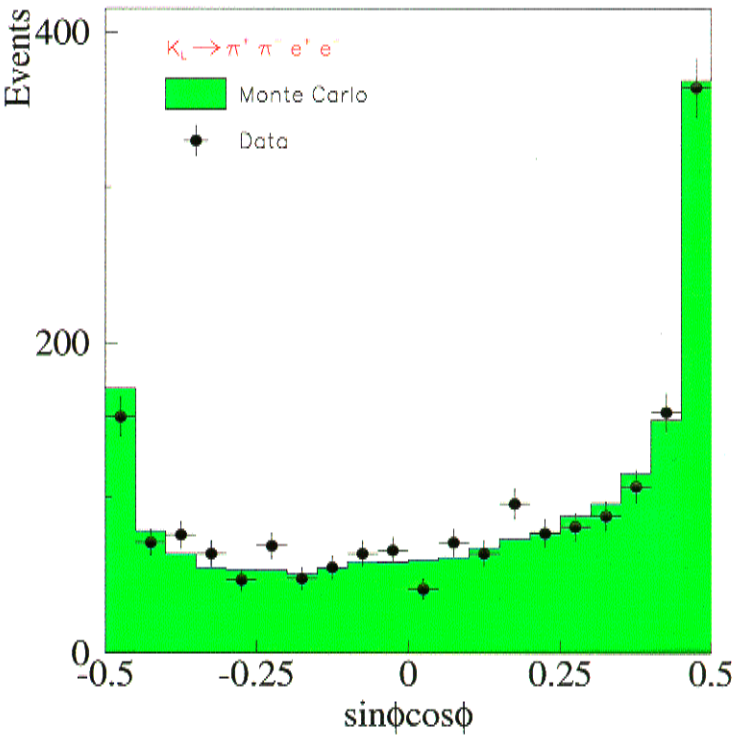




$K_L \to \pi^+\pi^- e^+ e^-$

- Raw asymmetry
  - $A_\phi(raw) = (23.3 \pm 2.3)\%$

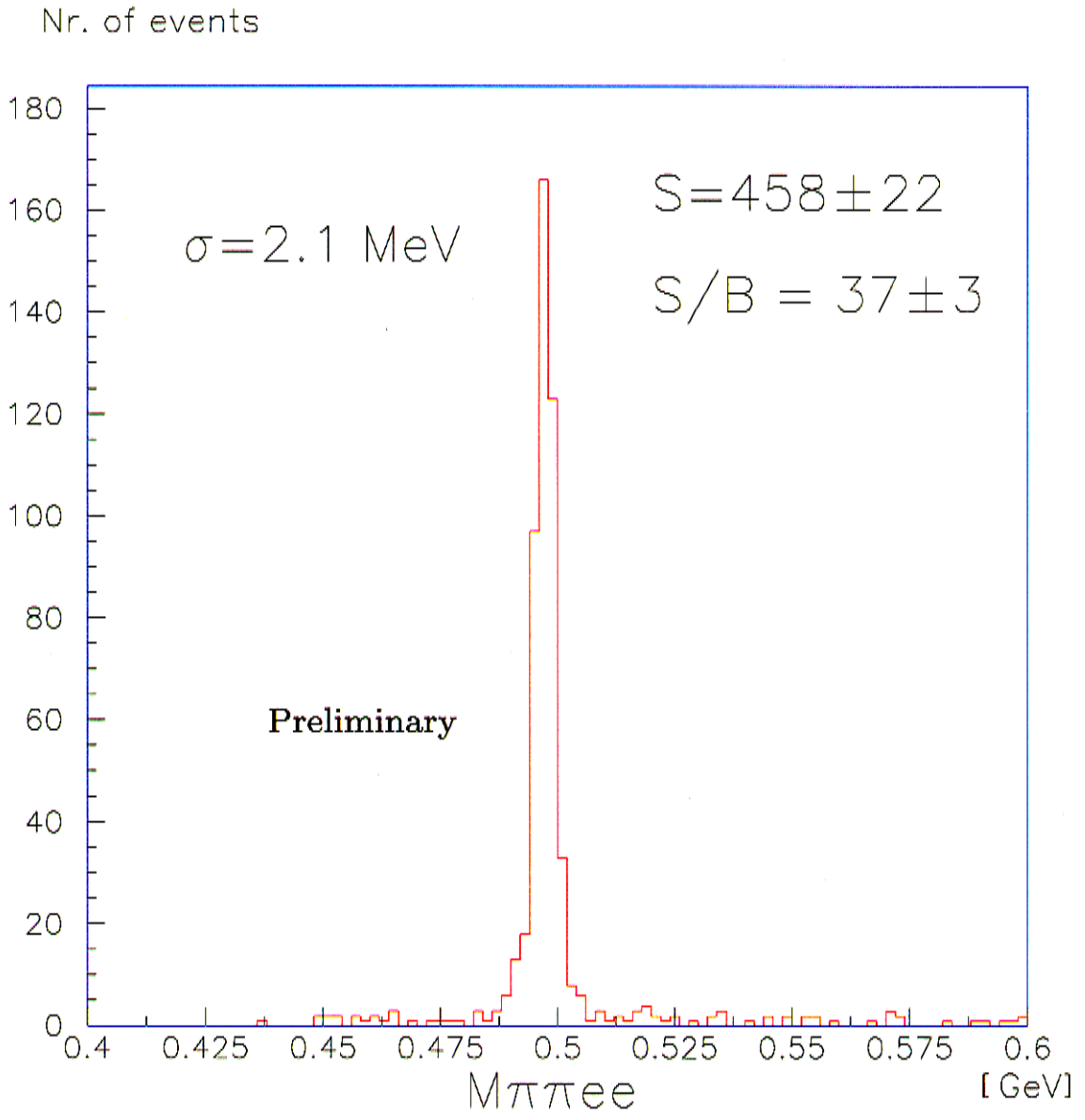




A.Alavi-Harati *et al.*, Phys. Rev. Lett. 84, 408 (2000)

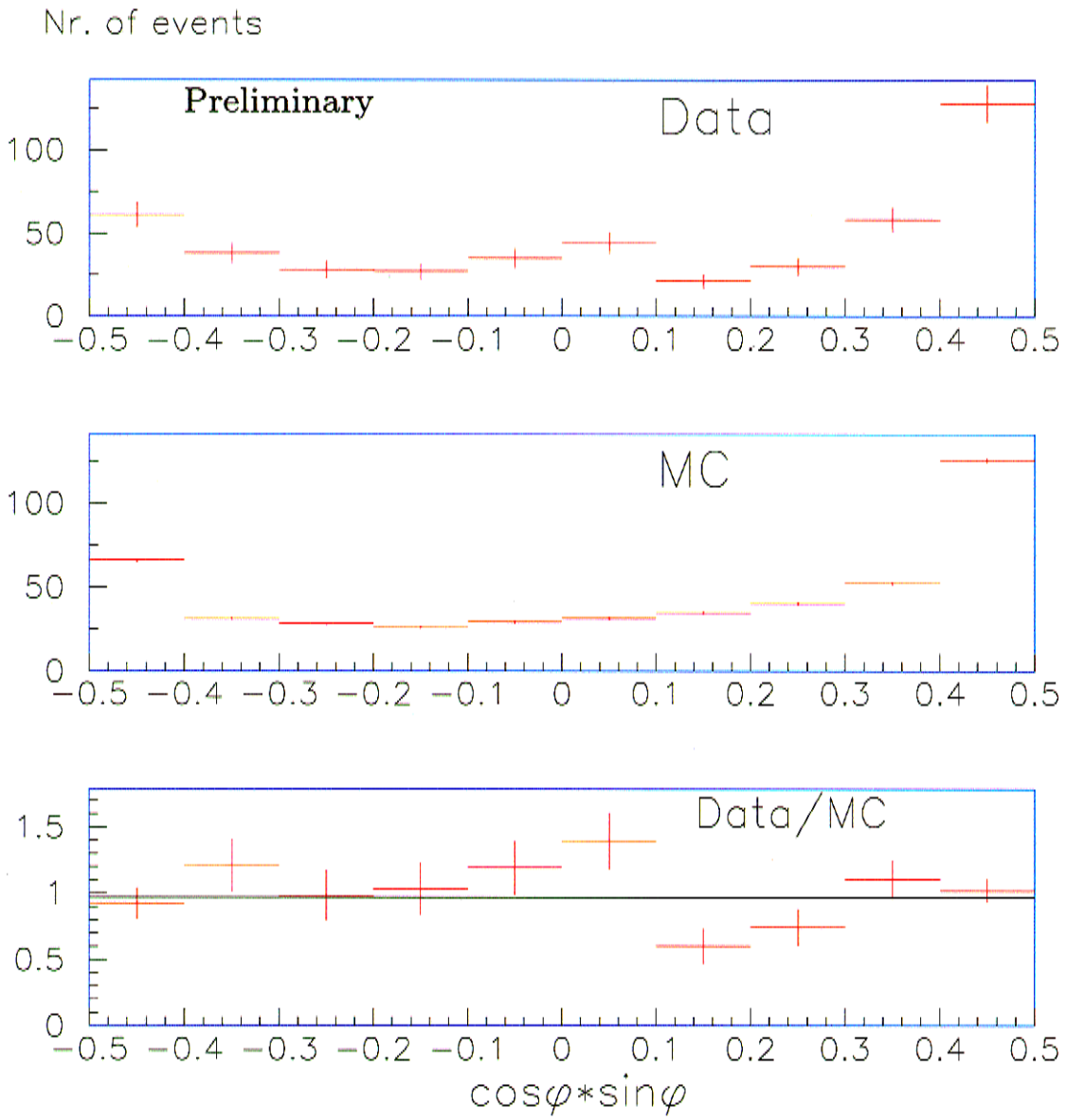
- Acceptance correction based on MC
  - Acceptance studied in millions of $K_L \to \pi^+\pi^- pi_D^0$
  - MC generated with best fit values for DE form factor
  - MC corrected Asymmetry: $A_\phi = (13.6 \pm 2.5(stat) \pm 1.2(syst))\%$
  - Theoretical expectation 14.4%

$K_L \to \pi^+\pi^-e^+e^-$ - NA48



- Preliminary BR based on 1998 data:
  - 458 ± 22 signal events over 37 ± 3 background events
  - $BR(K_L \to \pi^+\pi^-e^+e^-) = (2.90 \pm 0.15) \times 10^{-7}$

NA-48 $K_L \to \pi^+\pi^-e^+e^-$ Asymmetry



- Preliminary Asymmetry based on 1998 data:
  - Asymmetery $A_\phi = (20 \pm 5)\%$
  - MC: Input mean $A_\phi = 14\% \to 20\%$ after all cuts

T-Violation in CPLEAR

- Assuming CPT Conservation, indirect CP violation (ϵ) arises from T-violating $K^0 \to \bar{K}^0$ transistion:

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

- Tagging:

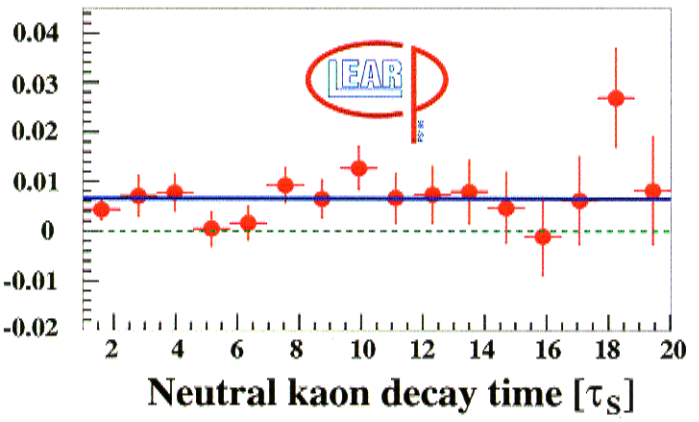
  $\Rightarrow$ $p\bar{p} \to K^+\pi^- K^0$ or $p\bar{p} \to K^-\pi^+\bar{K}^0$ for initial flavor

  $\Rightarrow$ lepton flavor gives flavor tag at decay

- Substantial Corrections:

  $\Rightarrow$ Different initial and final state tagging efficiencies

- $A_T \equiv \frac{R(\bar{K}^0|_{t=0} \to e^+\pi^-\nu|_{t=\tau}) - R(K^0|_{t=0} \to e^-\pi^+\bar{\nu}|_{t=\tau})}{R(\bar{K}^0|_{t=0} \to e^+\pi^-\nu|_{t=\tau}) + R(K^0|_{t=0} \to e^-\pi^+\bar{\nu}|_{t=\tau})} = 4Re(\epsilon)$ (CPT)



A. Anelopoulos, *et al.*, Phys.Lett. B 444, 43 (1998)

- $< A_T^{exp} >= (6.6 \pm 1.3(stat) \pm 1.0(syst)) \times 10^{-3}$

  $\Rightarrow$ Direct Observation of T Violation

  $\Rightarrow$ compare to $4Re(\epsilon) = 6.5 \times 10^{-3}$ from $K_L \to \pi\pi$

$K \to \pi ll$

- $K_L \to \pi^0 \nu\bar{\nu}$
  - Almost pure CP violation
  - Proportional to η
  - Theoretically clean
  - Tough measurement!
- $K^+ \to \pi^+ \nu\bar{\nu}$
  - sensitive to $(1.4-\rho)^2+\eta^2$ (mostly $|V_{td}V_{ts}^*|^2$)
  - 1 event observed in BNL E787 -

    $BR(K^+ \to \pi^+ \nu\bar{\nu}) = (1.5^{+3.4}_{-1.2}) \times 10^{-10}$
  - Peter Cooper's talk
- $K_L \to \pi^0 e^+ e^-$
  - Substantially direct CP violating (+ indirect and CP conserving)
  - Background limited: $K \to e^+ e^- \gamma\gamma$

Conclusions

- Wide Range of Important CP Violation Results in Kaon System
- Direct CP Violation Now Clearly Established
  - η Clearly non-Zero
- Observation of CP Violation in Dynamical Variable
- Direct Observation of T Violation
- Analysis Continuing on Current Experiments
- Direct Measurements of CKM Parameters in Rare K-Decays in Future
  - See P. Cooper's talk next!