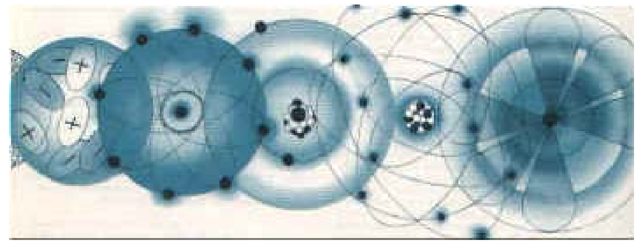


Kaon Physics: Report from the Precision Frontier.

R. Tschirhart

Fermilab

May 19th 2005

LNF School, Frascati

Lecture 1: The Precision Frontier. Hunt for small asymmetries that signal CP, CPT, or Unitarity violation in the kaon system. .

- Needle in a Haystack: Understand the Haystack in excruciating detail, subtract winter from summer and the needle is revealed.

−

= ?

Lecture 2: The Sensitivity Frontier: A Window to New Physics Beyond the Standard Model.

- Needle in a Haystack: Get a really strong magnet to separate the signal from the background.

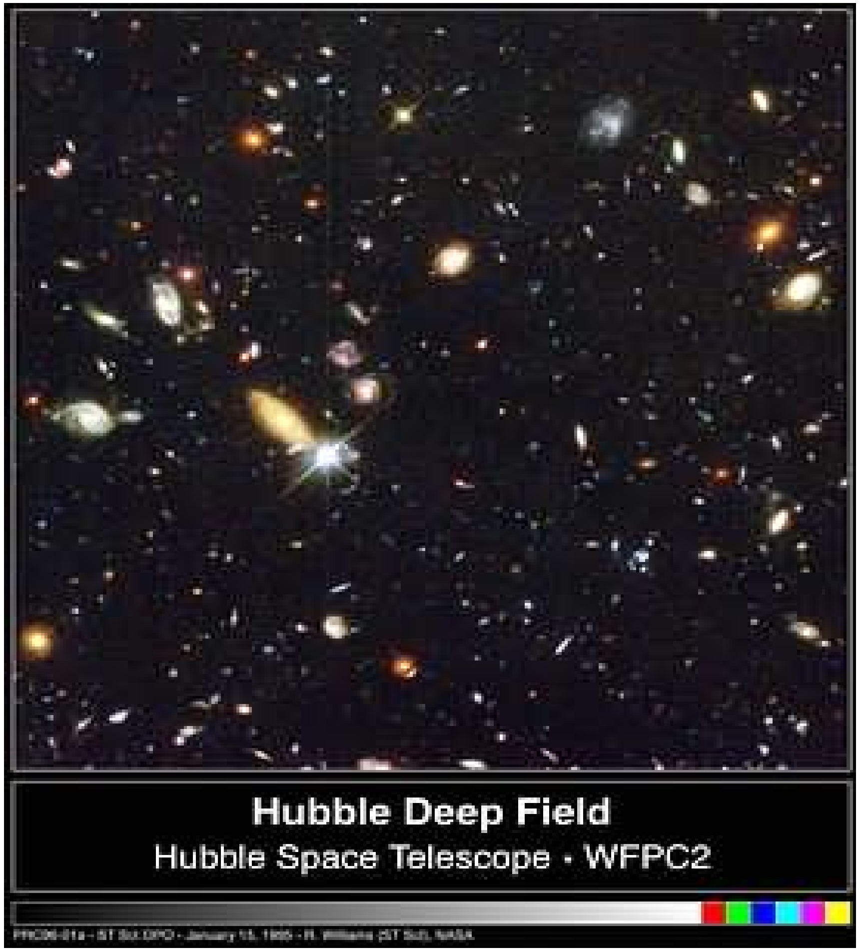
Apologies and Acknowledgements….

- ***Not a complete treatment, not a review.*** Too many experiments, too much phenomenology. Select a few measurements and explore techniques and results as instruction.

- Special thanks to A. Ceccucci, L. Bellantoni, D. Bryman, S. Chen, G. Isidori, R. Kessler, L. Littenberg, Matteo Palutan, M. Sozzi, K. Schubert for excellent slides.

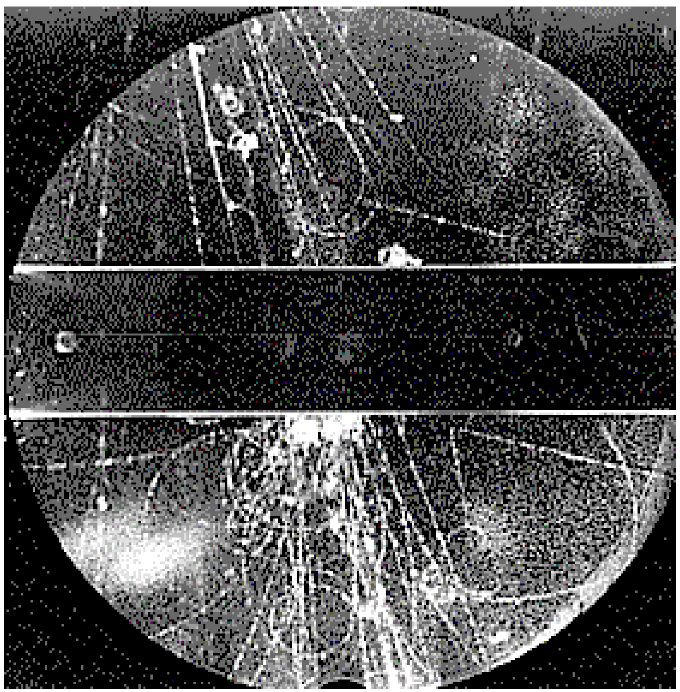
Big Questions of Flavor: Why Flavor?…. How are We Here? Baryogenesis? Leptogenesis?

- Naïve Big bang cosmology has a ***balanced production of matter & antimatter***… but our current universe is dominated by matter.
- **Sakharov's 3 conditions** for matter dominance
  - baryon number non-conservation
  - C and **CP violation**
  - not in thermal equilibrium

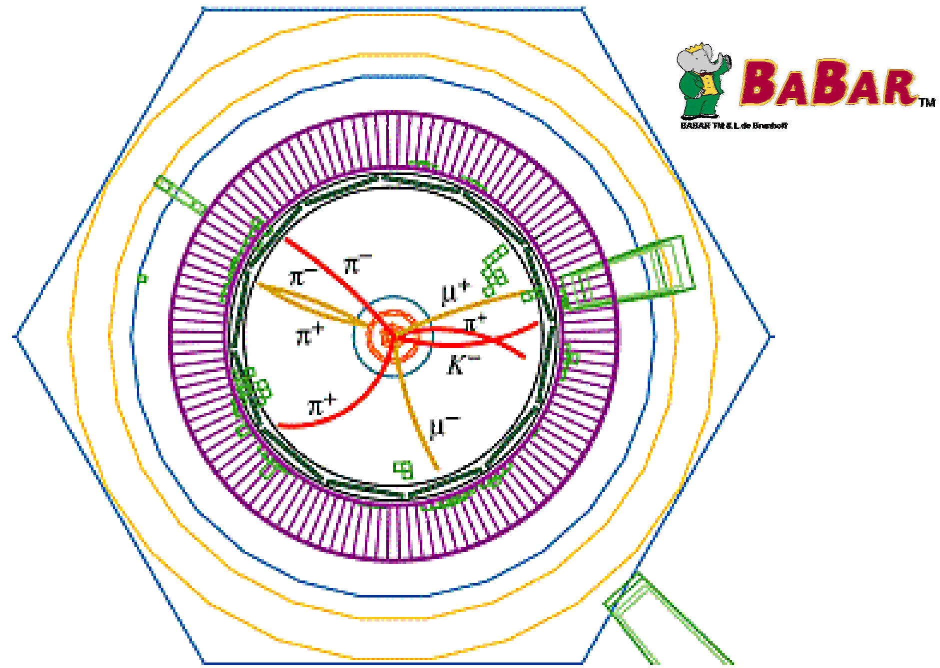


The March of Flavor Physics.

Neutral Kaons discovered in ***Cosmic Rays*** in 1947.

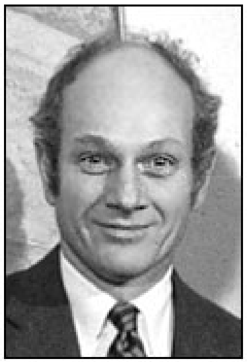


Quantitative Test of Matter-Antimatter Asymmetry of the Standard Model today.

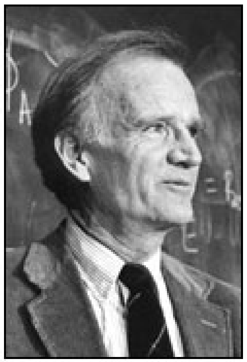


$B^0 \Rightarrow \Psi K_S$ Decays

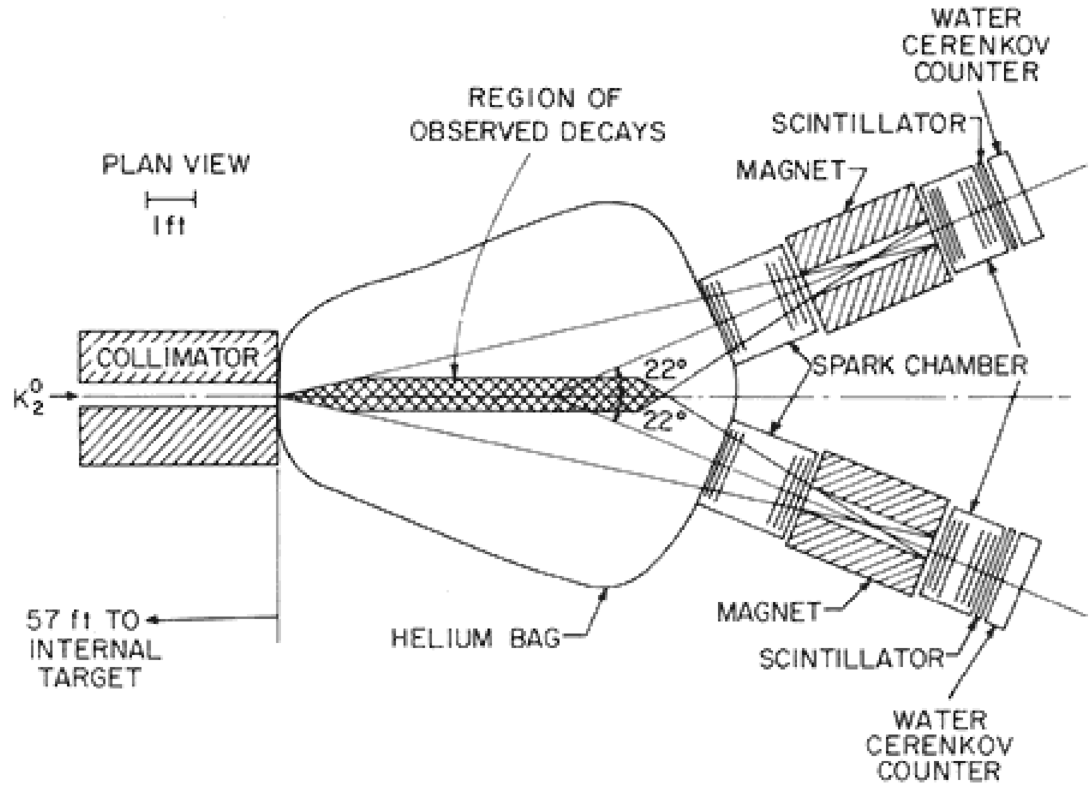
Observation of CP Violation: $K^0_L \rightarrow 2\pi$ in 1964.



James Cronin

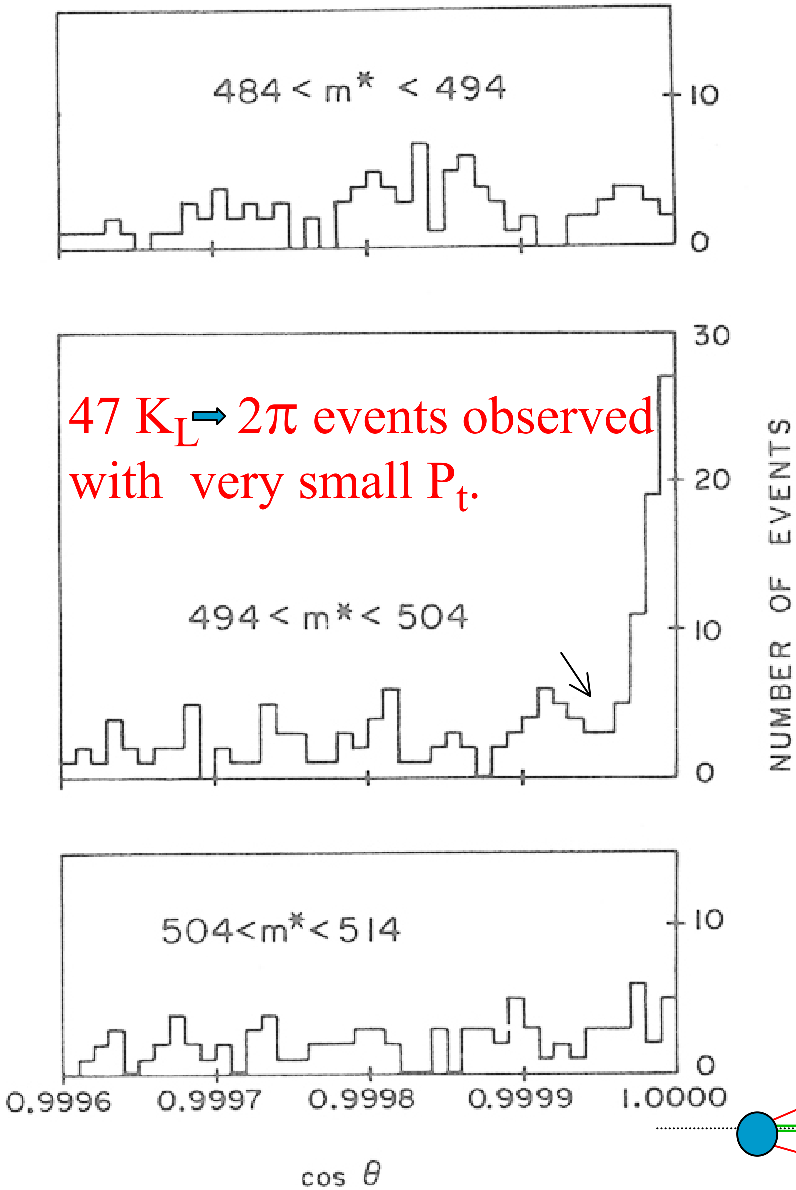


Val Fitch



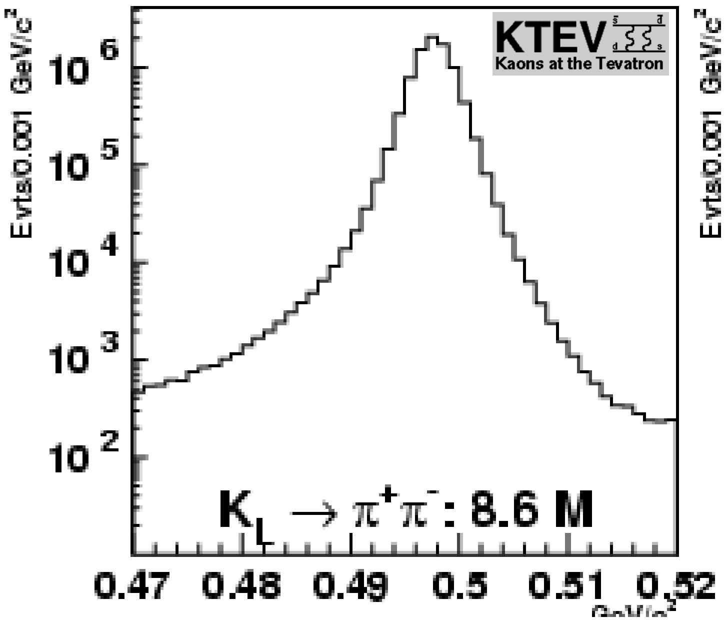
1964

~2004

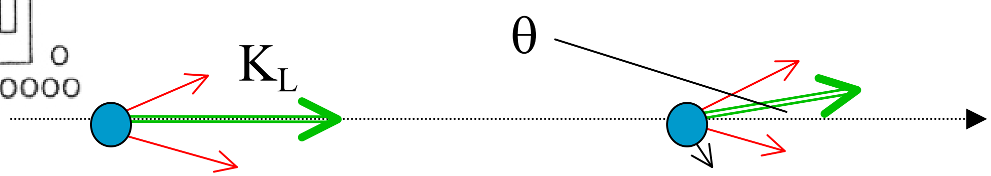


47 $K_L \Rightarrow 2\pi$ events observed with very small P_t.

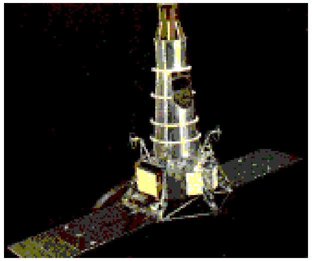
~20 Million CP $K_L \Rightarrow 2\pi$ Observed by the KTeV Experiment.



2π Mass (GeV/c²)

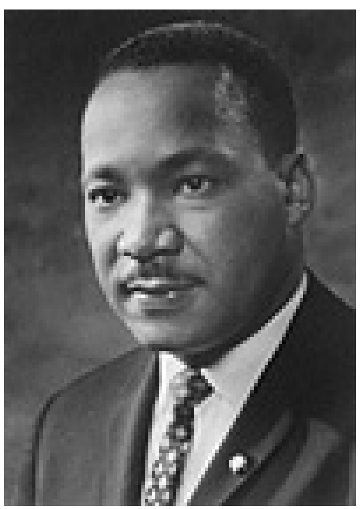


Some Other High Points in 1964….



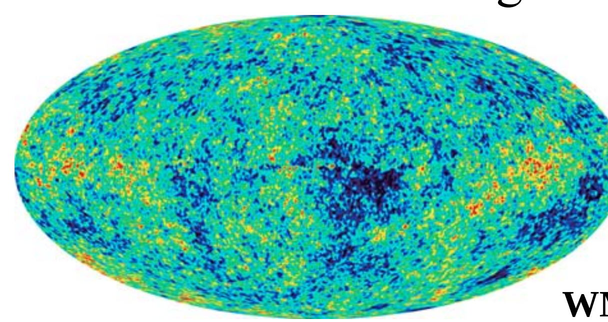
Ranger-7
to Moon.

British Invasion….



Martin Luther King
Nobel Peace Prize.

Penzias & Wilson Discover
Cosmic Microwave Bkg.



WMAP

Weak interactions today: The weak quark eigenstates are related to the strong (or mass) eigenstates through a unitary transformation.

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix} \Rightarrow \begin{pmatrix} u \\ \updownarrow \\ d' \end{pmatrix} \begin{pmatrix} c \\ \updownarrow \\ s' \end{pmatrix} \begin{pmatrix} t \\ \updownarrow \\ b' \end{pmatrix}$$

Cabibbo-Kobayashi-Maskawa (CKM) Matrix

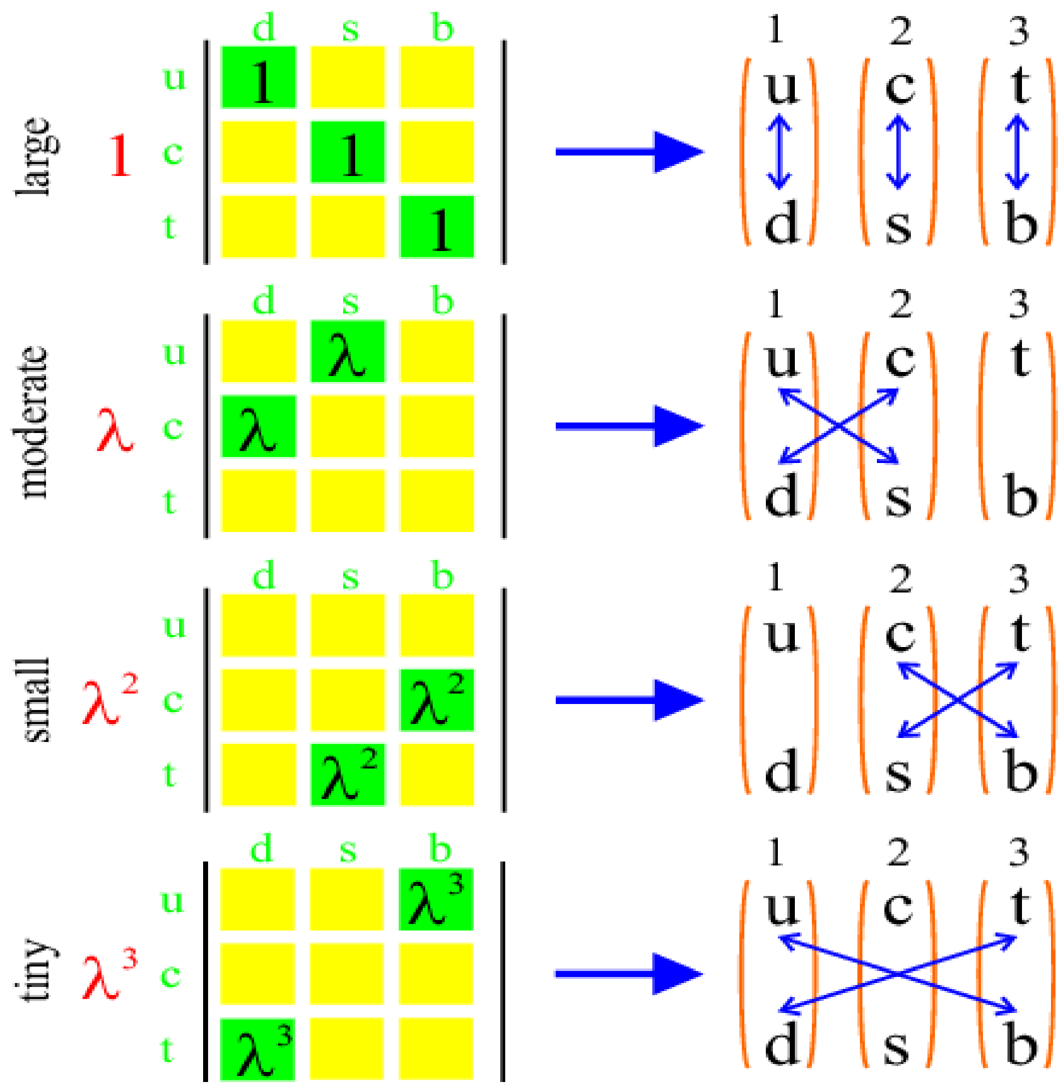
$$\mathcal{L}_{ew} = g u_j V_{ji} \gamma^{\lambda} (1 - \gamma^5) d_i W^{\lambda} + \text{h.c.}$$

Matter-Antimatter Symmetry: $V_{ij} = V_{ij}^{*}$

Parity Violation [(1 - γ^5)] put in by hand…the left hand in fact.

An interesting *observed* hierarchy……..

The CKM Matrix:



CKM Matrix Highly Constrained by Unitarity

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Unitarity implies:

$$V_{\rm CKM} V_{\rm CKM}^\dagger = V_{\rm CKM}^\dagger V_{\rm CKM} = 1$$

- Rows and columns normalized (weak universality):

$$\sum_{i=1}^{3} |V_{ij}|^2 = 1 = \sum_{j=1}^{3} |V_{ij}|^2$$

$$\sum_{i=1}^{3} V_{ji} V_{ki}^\dagger = 0 = \sum_{i=1}^{3} V_{ij} V_{ik}^\dagger$$

$\Rightarrow$ Matrix can be described by only 4 parameters!

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

where: $\lambda \approx 0.220$ and $A \approx \rho \approx \eta \approx 1$.

Important: Imaginary part η violates CP symmetry!

Properties of the CKM Matrix

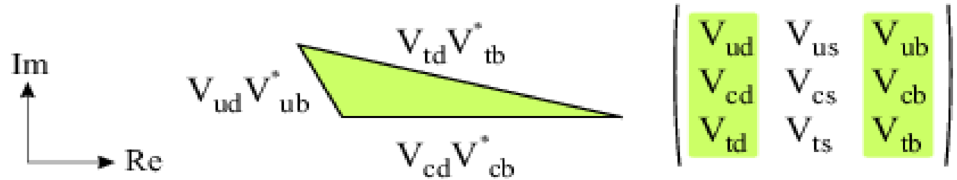
- Things rapidy get more complicated with increasing number of generations:

$$\begin{array}{lll} n_g = 2 & 1 \text{ angle} & 0 \text{ CP phase} \\ n_g = 3 & 3 \text{ angles} & 1 \text{ CP phase} \\ n_g = 4 & 6 \text{ angles} & 3 \text{ CP phases} \end{array}$$

- To have CP violation:

$$m_u \neq m_c \neq m_t \quad \text{and} \quad m_d \neq m_s \neq m_b$$

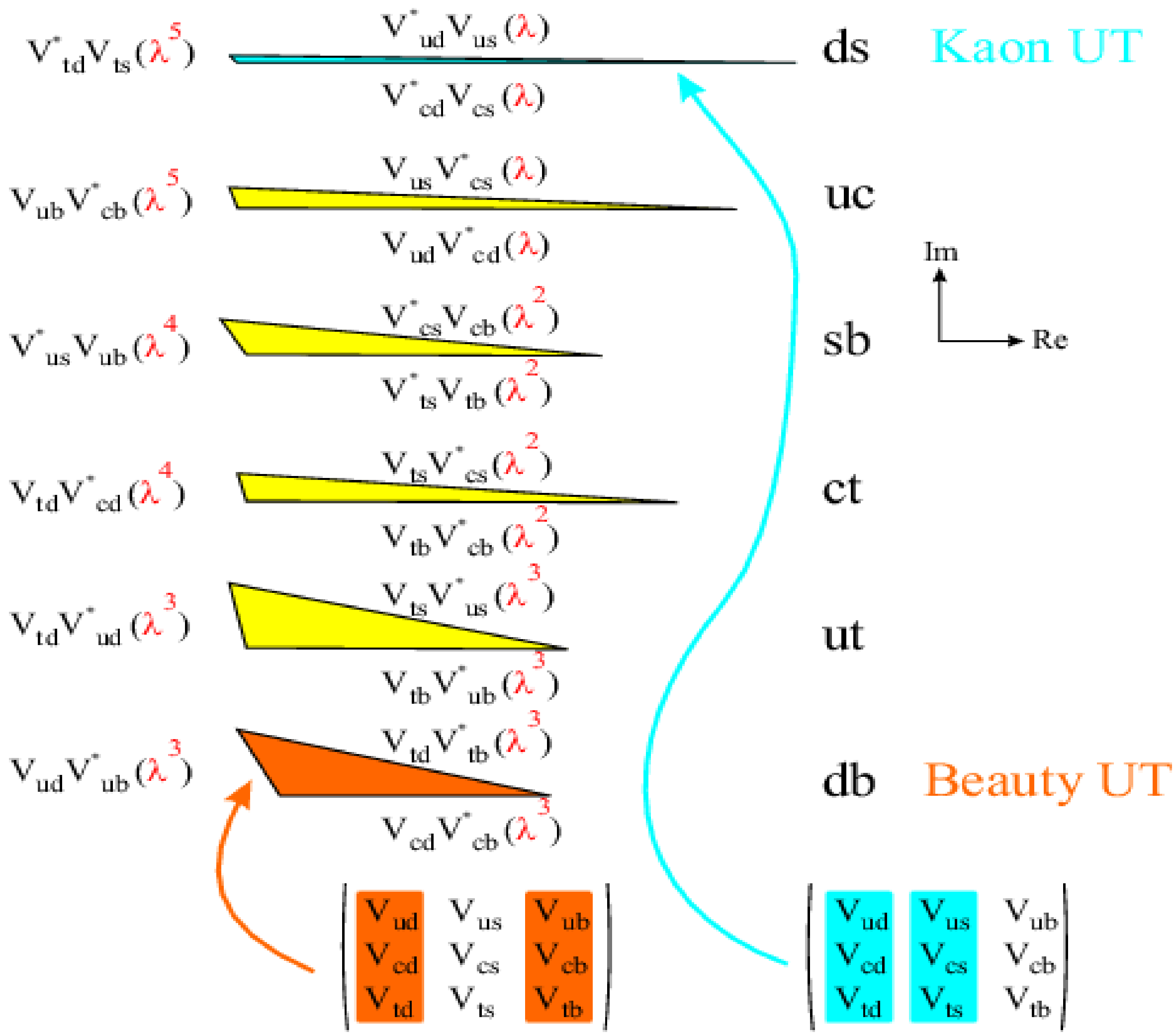
- Can represent 6 unitarity relations in terms triangles in the complex plane.



- Note: area of all triangles is the same: $A^2\lambda^6\eta$
- Length of sides determined by measuring decay rates.
- Size of angles determined by measuring CP asymmetries.

One can measure the CP-violating phase in the CKM matrix without ever measuring a CP asymmetry!

The Unitarity Triangles

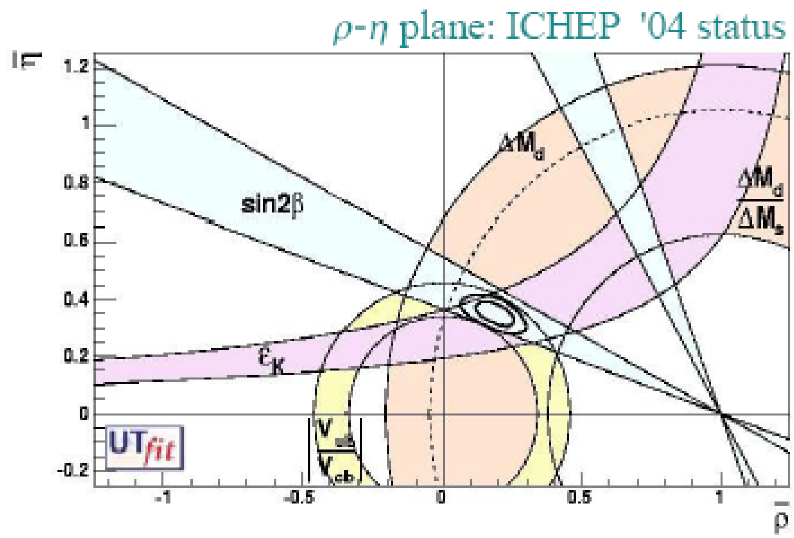


SM works well at the Electroweak Scale

$$L_{SM} = L_{Gauge} + L_{Higgs}(\phi_i, A_i, \psi_i, Y, v)$$

Flavor degeneracy broken by Yukawa couplings
CKM quark mixing matrix:

$$V_{CKM} \approx \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$



Where does CP Violation and T-violation manifest itself in our world today?

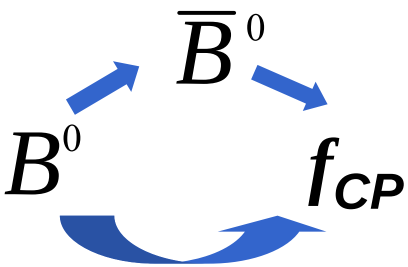
CP Violation:

1) CPV in Mixing; e.g. $Re(\varepsilon_K)$, $Re(\varepsilon_B)$
2) CPV in Mixing-Decay Interference; e.g. Sin2β in neutral B system.
3) CPV in Decays to one final state (Direct); e.g. $Re(\varepsilon'/\varepsilon)$

T Violation and T odd effects:

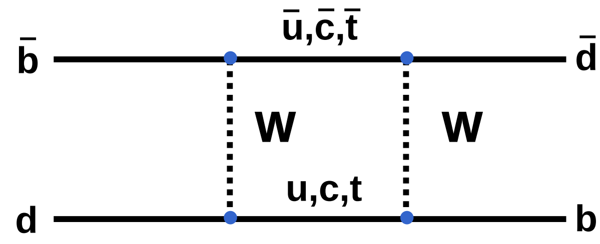
1) Observation of T-Violation in $K^0 \Leftrightarrow \overline{K}^0$.
2) Observation of T-odd decay asymmetries in $K_L \rightarrow \pi^+\pi^-e^+e^-$.

$\bar{B}^0$-B^0 mixing introduces time-dependant CP violation



$$|B_{L,H}\rangle = p|B^0\rangle \pm q|\overline{B}^0\rangle$$

$$\Delta m_d = m_H - m_L$$



top quark box introduces: $V_{tb}\ V_{td}^*$

$$f_- = \Gamma(B^0 \to f_{CP})$$

$$f_+ = \Gamma(\overline{B}^0 \to f_{CP})$$

$$\lambda_f = \frac{q}{p}\frac{A(\overline{B}^0 \to f_{CP})}{A(B^0 \to f_{CP})}$$

$$\frac{q}{p} \sim \frac{V_{td}}{V_{td}^*}$$

$$f_\pm(t) = \frac{e^{-t/\tau}}{4\tau}\left[1 \mp S_f \sin(\Delta m_d t) \pm C_f \cos(\Delta m_d t)\right]$$

$$S_f = \frac{2\,\mathrm{Im}\,\lambda_f}{1+|\lambda_f|^2}$$

Sensitive to overall phase of λ_f even if no Direct CP Violation

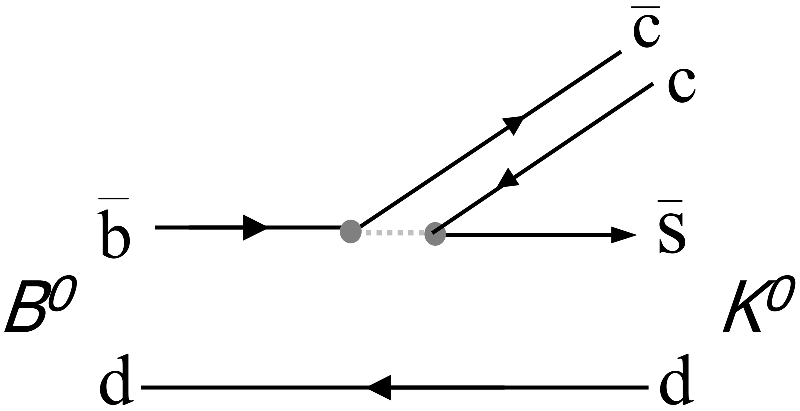
$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$$

Direct CP violation if multiple amplitudes with different phases

CP asymmetry in $\bar{B}^0 \to (cc)K^0$

Theoretically clean:
Tree level dominates
and CP *only* from
B^0-B^0 mixing

Relatively large
branching fractions



$$\lambda_f = \frac{q}{p}\frac{A(\bar{B}^0 \to f_{CP})}{A(B^0 \to f_{CP})}$$

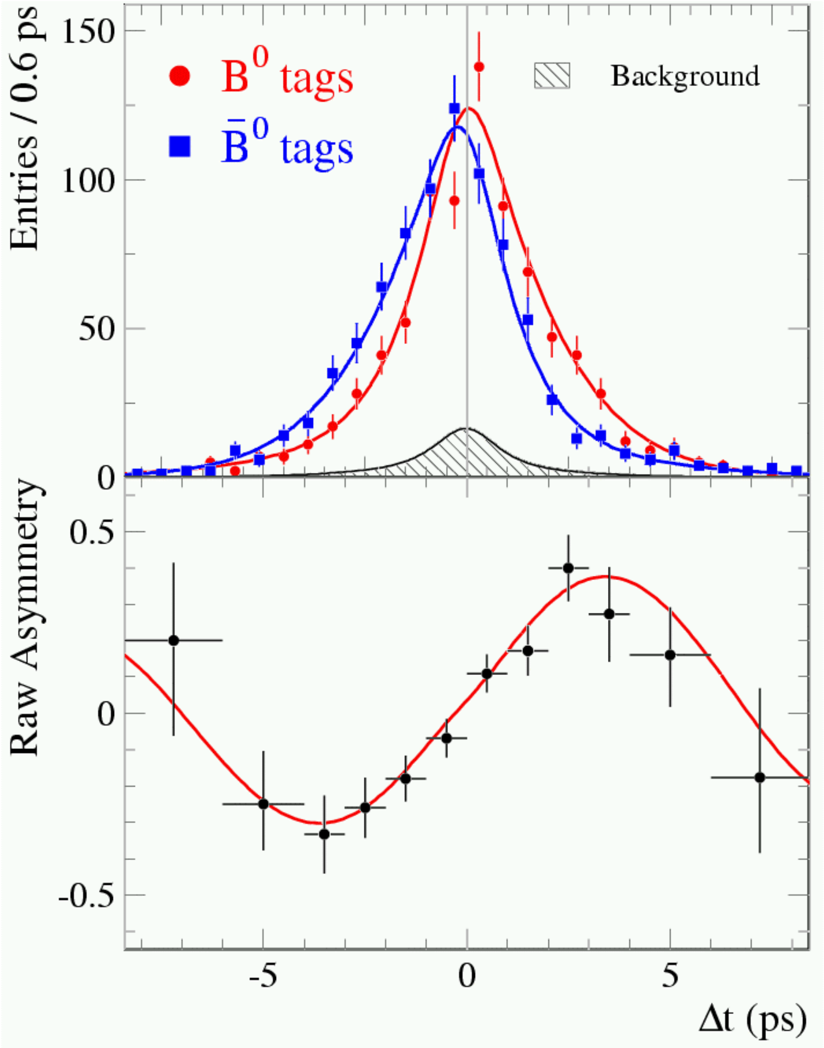
$$\lambda_f = \eta_f e^{-i2\beta}, \quad \eta_f = \pm 1$$

Clear expt
Signatures:

$$A_{CP}(t) = \frac{f_+ - f_-}{f_+ + f_-} = -\eta_f \sin 2\beta \sin(\Delta m_d t)$$

Example for Type-2 CPV: $B^0, \bar{B}^0 \rightarrow c\bar{c}K$

$\sin 2\beta$ = 0.736 ± 0.049 (PDG 2004)



Neutral Kaon Phenomenology Review:

Strangeness eigenstates:

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

CP eigenstates:

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

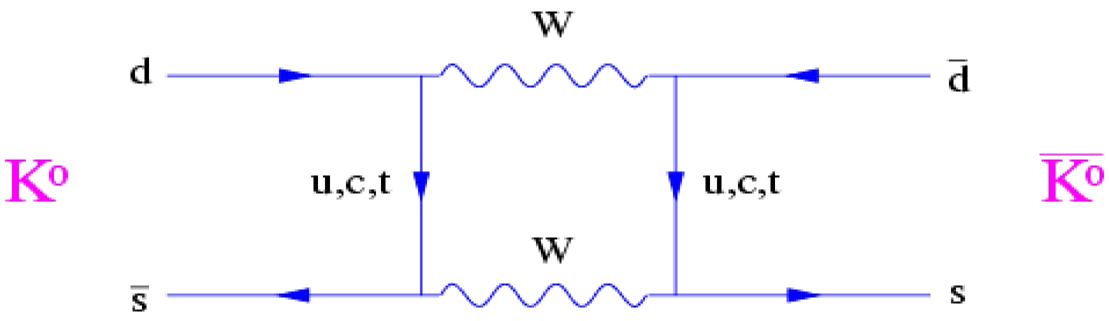
Mass and Lifetime eigenstates:

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

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 %	$\pi^0\pi^0$

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

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



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

$$K_L = K_2^{-1} + \varepsilon\, K_1^{+1} \qquad \pi^+ \pi^-\,,\ \pi^0 \pi^0$$

$CP = +1$

Need interference of two decay amplitudes

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

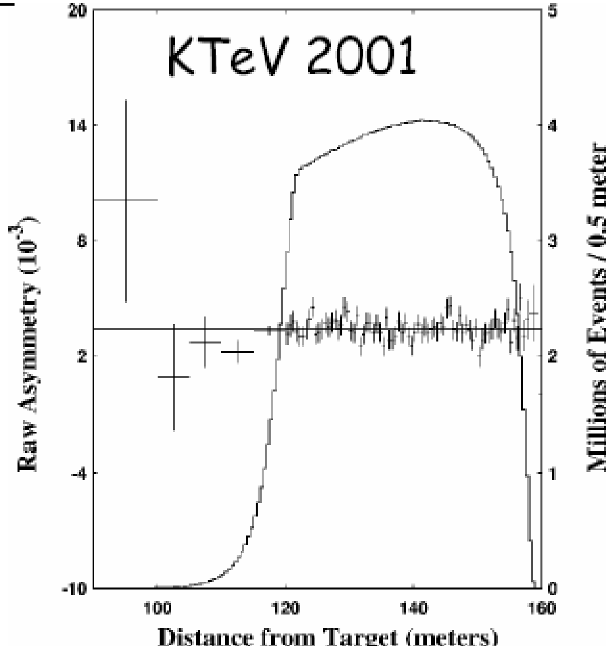
$$A(K^0 \rightarrow \pi\,\pi\,, I) = \quad A_I \exp(i\delta_I)$$

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

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

CP Violating Charge Asymmetry due to mixing is very precisely measured in the K_L system.

$$\delta_L^e = \frac{\Gamma(K_L \to \pi^- e^+ \nu) - \Gamma(K_L \to \pi^+ e^- \bar{\nu})}{\Gamma(K_L \to \pi^- e^+ \nu) + \Gamma(K_L \to \pi^+ e^- \bar{\nu})}$$



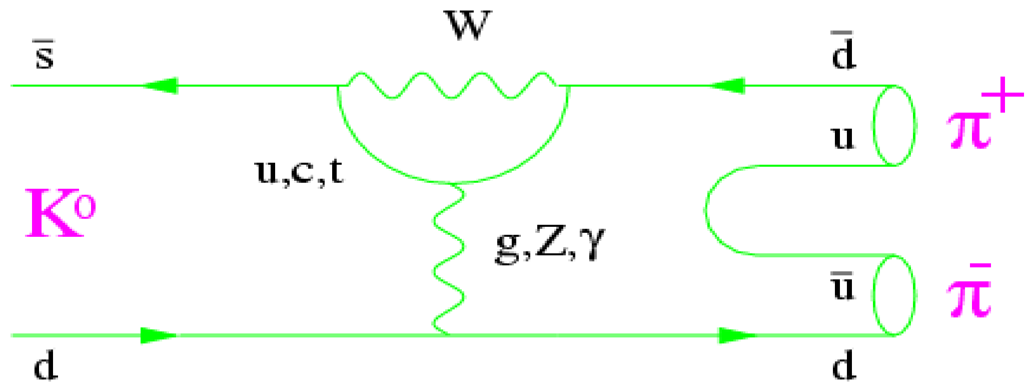
Definitive measurement based on 300M $K_L \to \pi e \nu$ Decays!

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

$$2\,\mathrm{Re}(\varepsilon_m) = \delta_L (3.322 \pm 0.074) \cdot 10^{-3}$$

[PDG 2002]

$\varepsilon' \Rightarrow$ Direct CP violation:



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

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

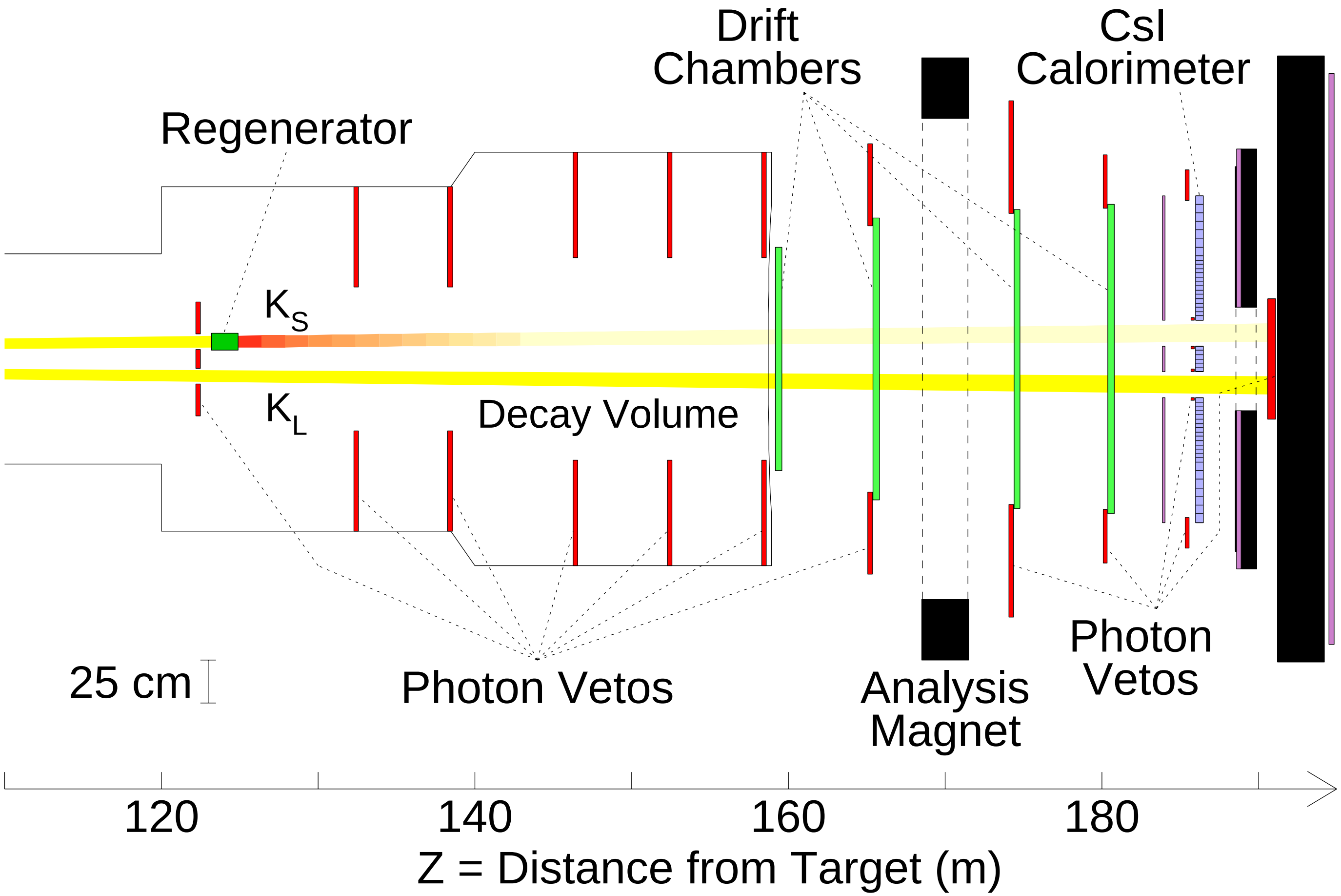
$$R = \frac{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)}{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)} \simeq 1 - 6\ \mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right)$$

IF the 4 modes are taken

- simultaneously
- in the same decay region

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

KTeV Experiment: K_S beam made from an incident K_L beam.



K_L Beam passes through 2m of plastic scintillator, which induces a ~3% *coherent* K_S component in the downstream amplitude.

$$K_{Down} = K_L + \rho K_S$$

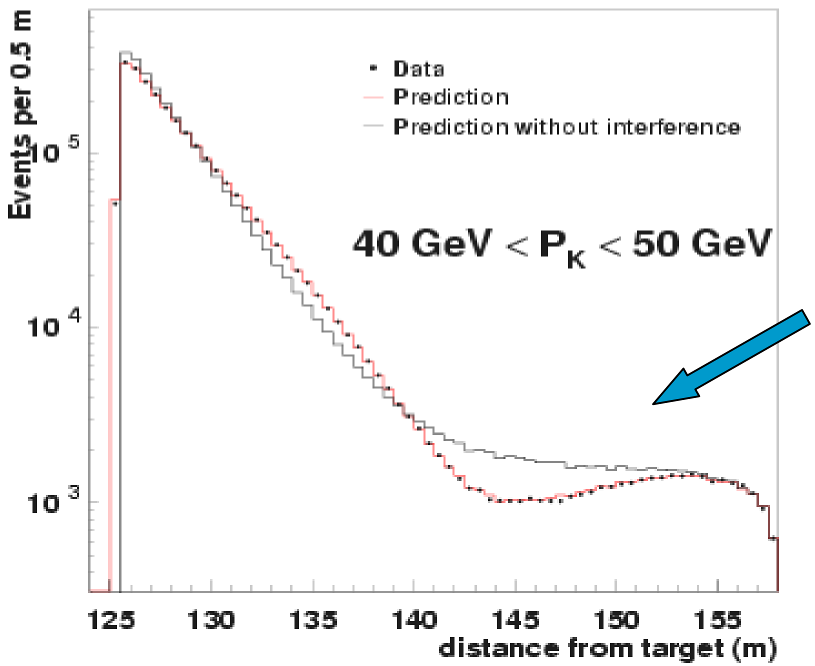
K_L and K_S in the Regenerator Beam.

KTEV
Kaons at the Tevatron

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 $Re(\epsilon'/\epsilon)$.

K_{Reg} shape depends on:

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

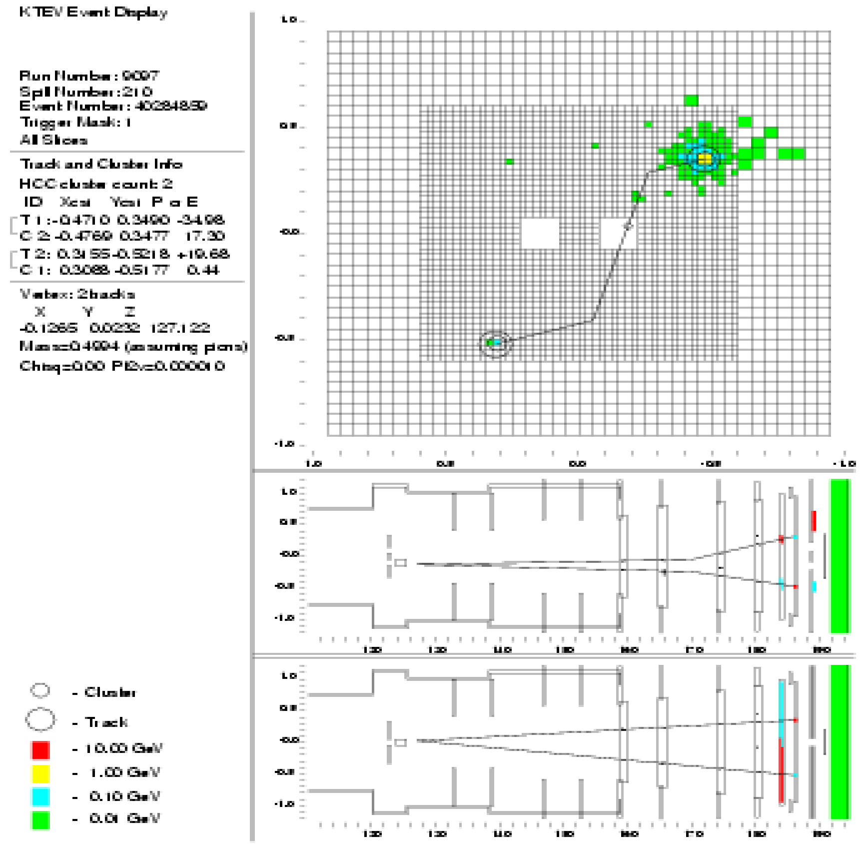


Regenerator Vertex Z distribution

Quantum coherence over 30m!

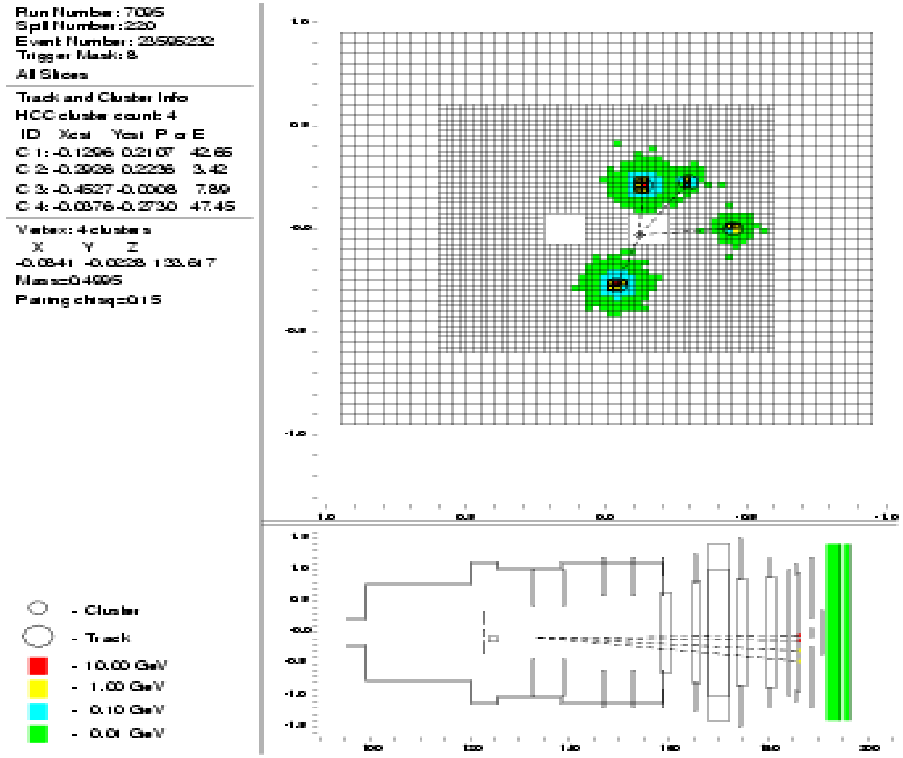
Sample $K \to \pi^+\pi^-$ Event

KTEV Kaons at the Tevatron



- 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

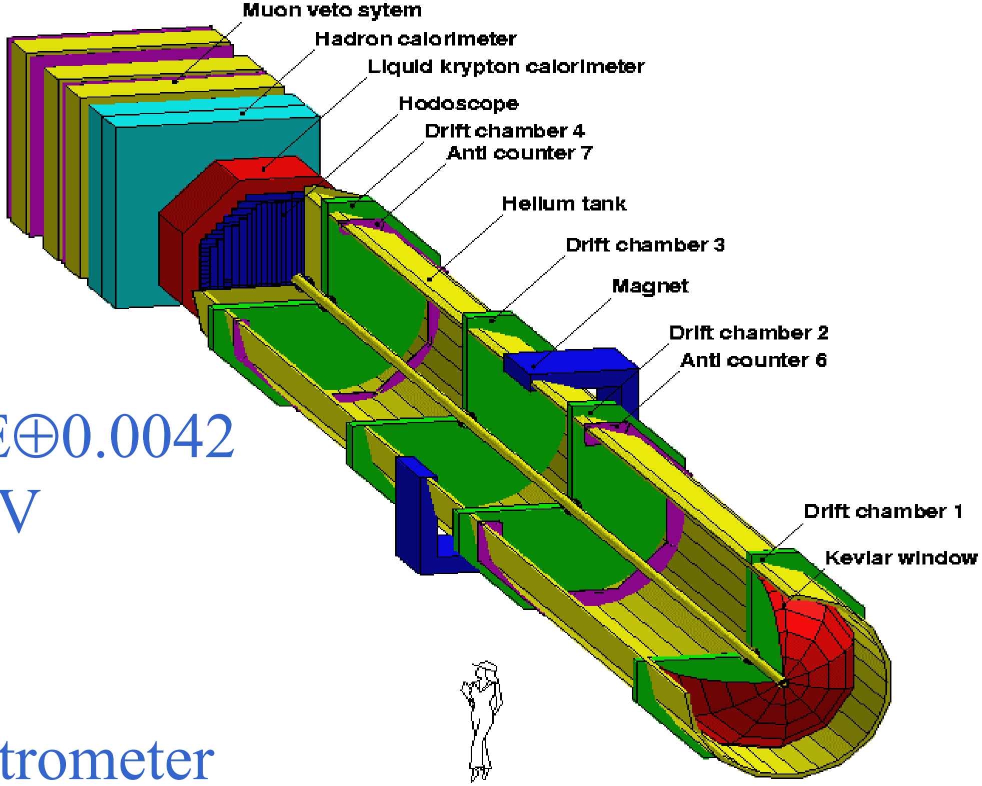


- CsI calorimeter to reconstruct photons energies and positions
- z_v determined as average of

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

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

Sister Experiment to KTeV: CERN-NA48.



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

LKr calorimeter

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

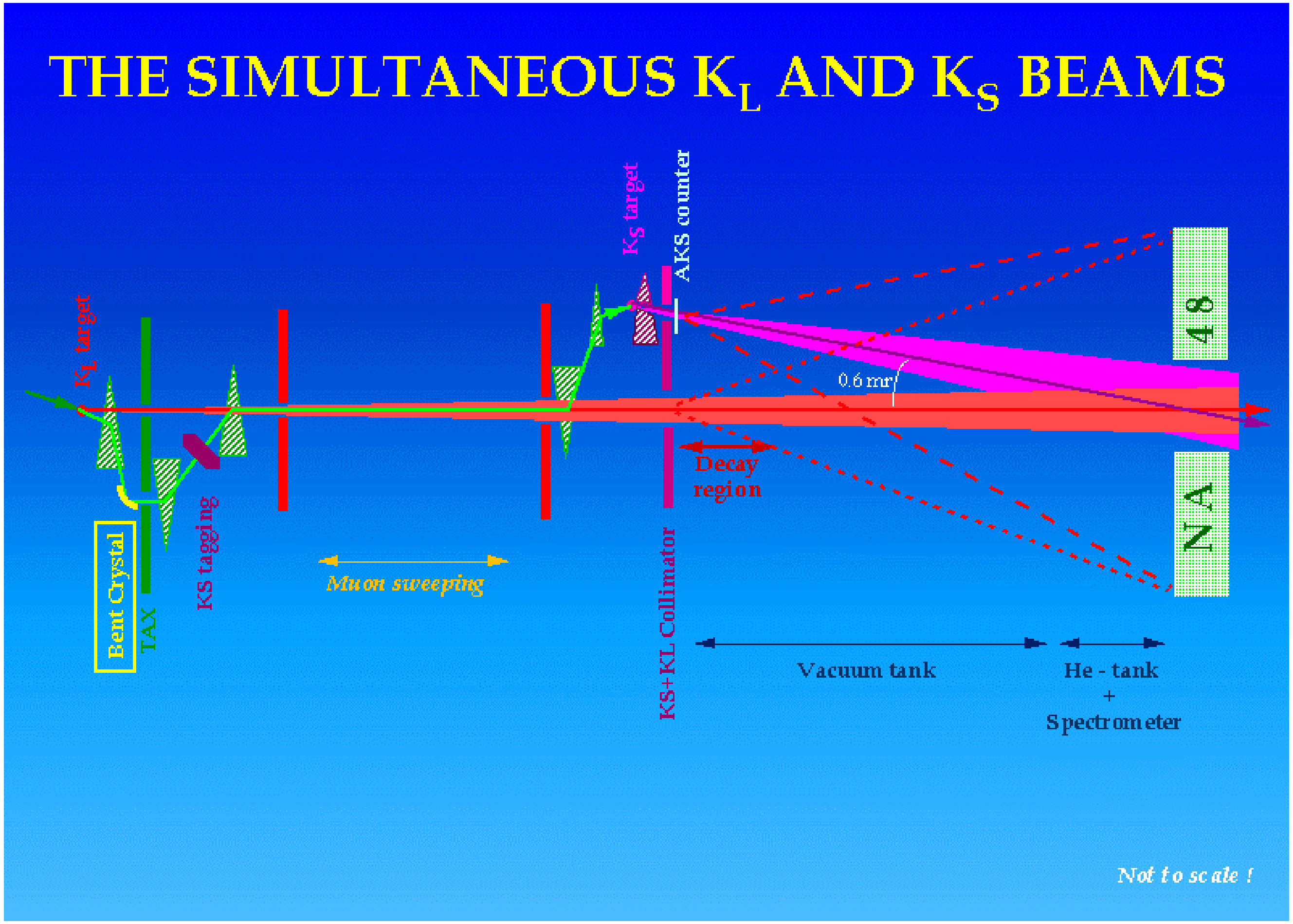
$< 1\%$ for E=25 GeV

$\pi^+\pi^-$ detection

magnetic spectrometer

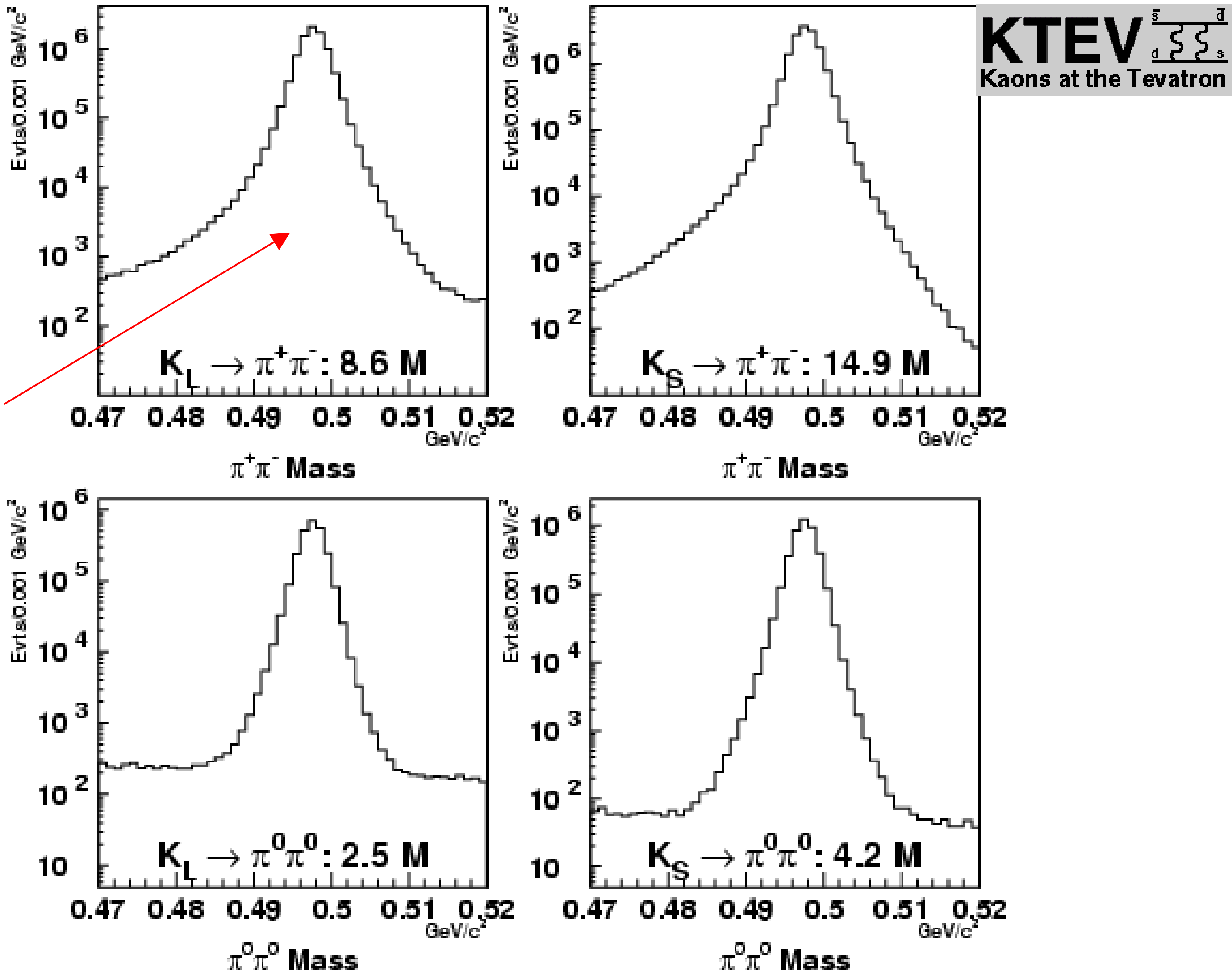
$\sigma(p)/p = 0.5\%\oplus 0.9\%*(p/100\text{ GeV})$

Innovative NA48 CERN Beamline; K_L/K_S tagged event-by-event with time



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

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



Status of Re(ε'/ε)…

Experiment Direct CPV Established!:

NA48, Final Result: $Re(\varepsilon`/\varepsilon_0) = (14.7\pm2.2)\cdot10^{-4}$
KTeV, (1/2 Data): $Re(\varepsilon`/\varepsilon_0) = (20.7\pm2.8)\cdot10^{-4}$

World Average: $Re(\varepsilon`/\varepsilon_0) = (16.6\pm1.6)\cdot10^{-4}$

Theory: (victim of connecting quarks to hadrons)

Typical range has been $5x10^{-4}$ to $40x10^{-4}$, Some hope that Lattice theory and technology can make a precise postdiction someday.

Turning now to T-Violation

- CP Violation is precisely measured in neutral K and B mixing phenomena, and established in in K decay amplitudes.
- CPT symmetry predicts corresponding phenomena in T violation.
- **Let's go look for it in neutral kaons….**

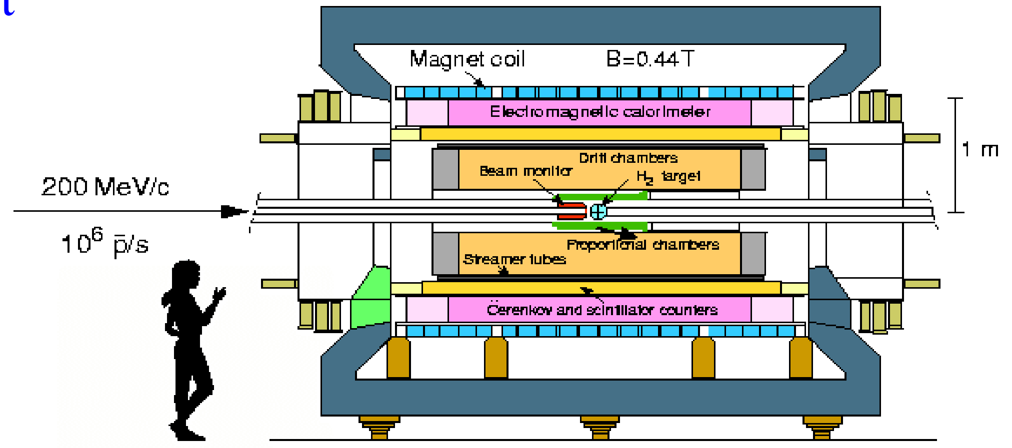
The CPLEAR Detector

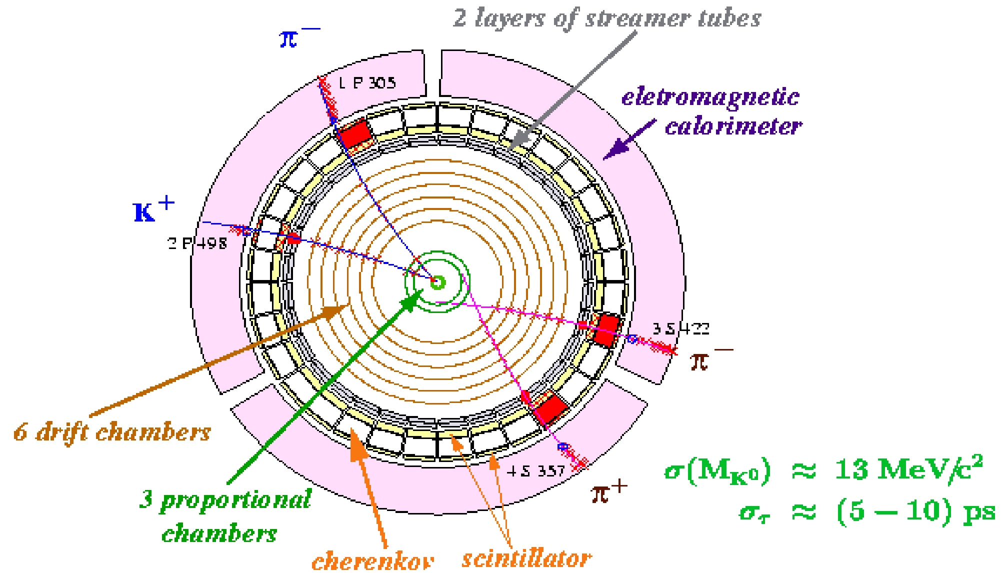
CPLEAR: CP Physics at a Low Energy Antiproton Ring at CERN. Technique is to stop $\bar{p}$'s in H_2, and observe the following reactions:

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

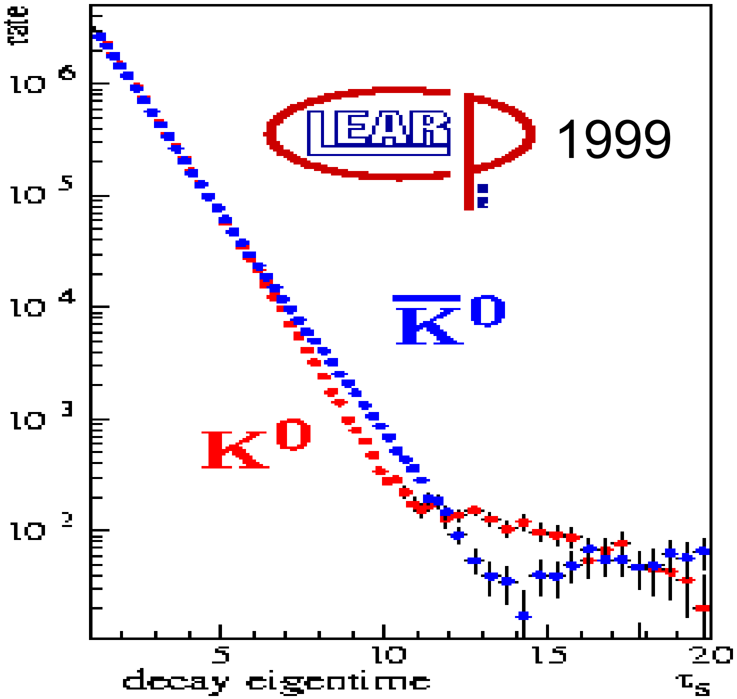
$p\bar{p} \Rightarrow K^-\pi^+K^0$.

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.

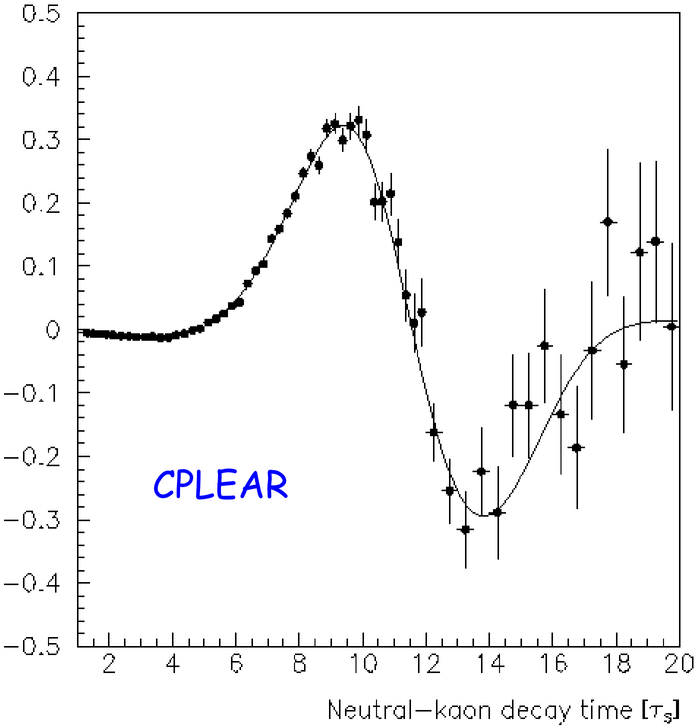




$\pi^+\pi^-$ Results from CPLEAR, CPV in mixing:



a(t)



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

$$\eta_{+-} = (2.27 \pm 0.02)\cdot 10^{-3} \cdot e^{i(43.3\pm 0.5)^0}$$

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

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 $\tau = 6.5\tau_S$

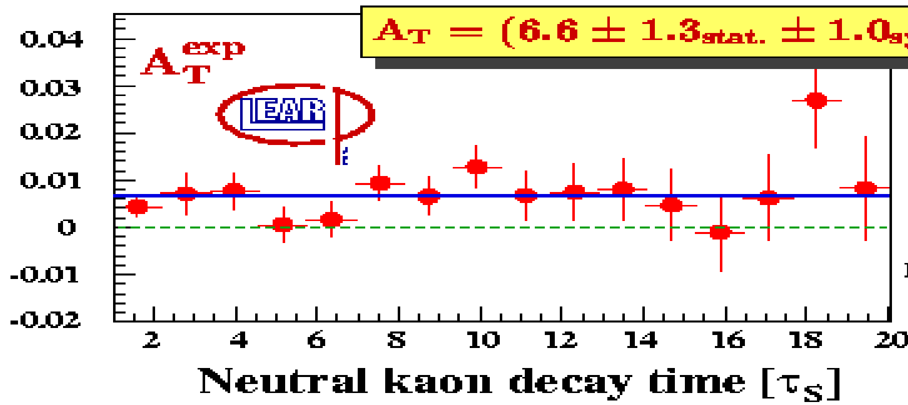
CPLEAR measures:
$N(K^0_{\tau=0} \to e^-\pi^+\bar{\nu})[\tau] = 15050$
$N(\overline{K}^0_{\tau=0} \to e^+\pi^-\nu)[\tau] = 13559$
$A = 0.0521$

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 $\delta_l = 2\Re e\,(\varepsilon_T + \delta) = (0.327 \pm 0.012)\%$
$A = 0.0066$

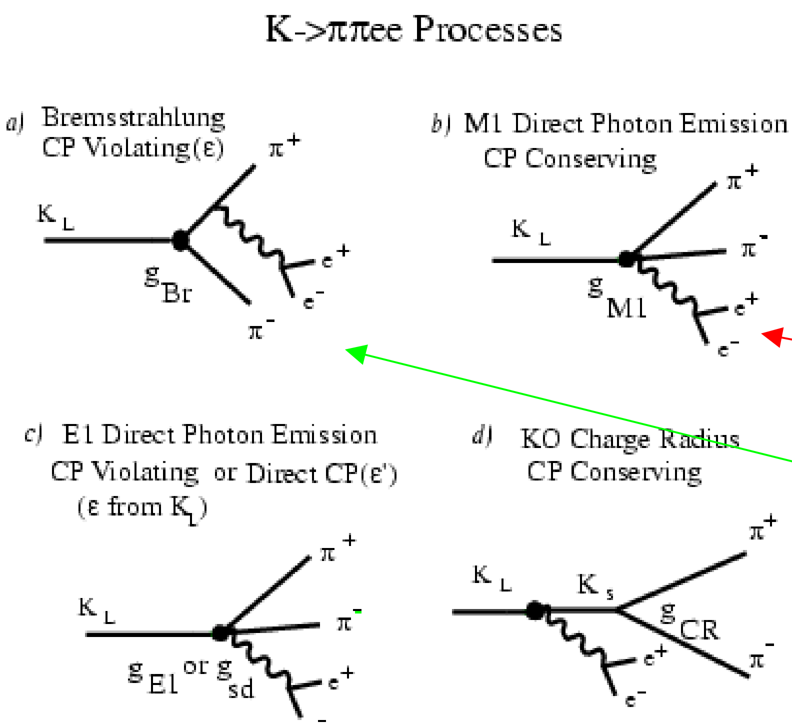
$A_T = (6.6 \pm 1.3_{stat.} \pm 1.0_{syst.}) \times 10^{-3}$



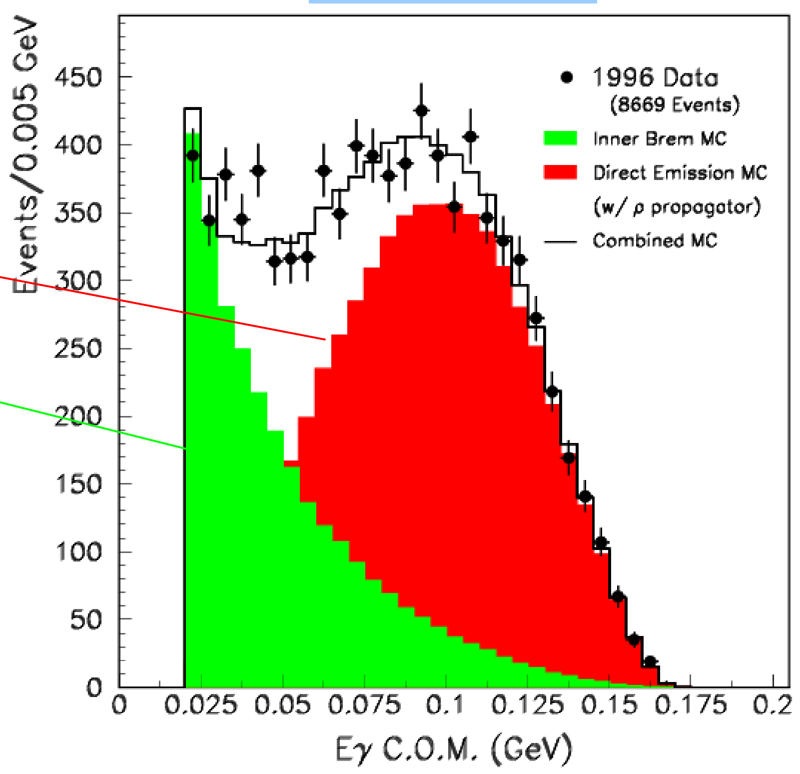
"First direct" measurement of time reversal non-invariance!

Phys.Lett. B444 (1998) 4

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



$K_L \to \pi\pi\gamma$

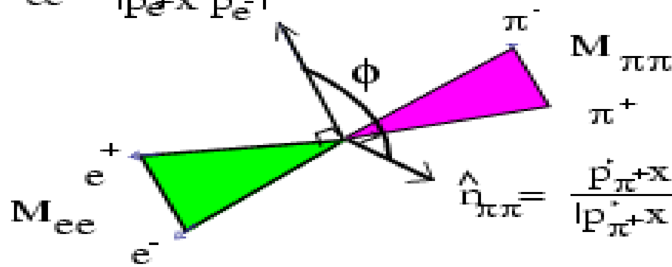


T-odd Observable

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

(K^0_L Center of Mass)

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

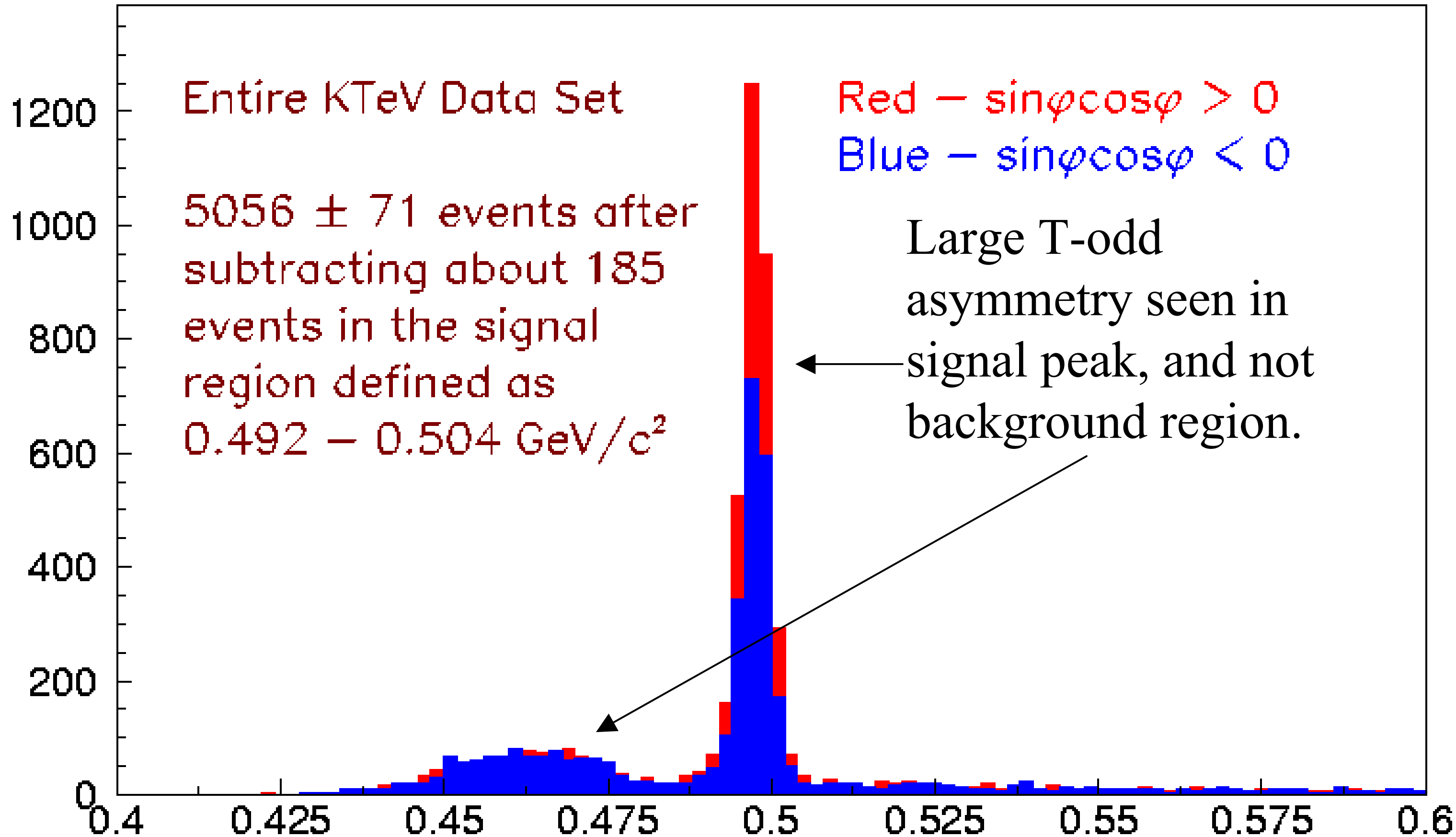


$$\hat{n}_{\pi\pi} = \frac{\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}}{|\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}|}$$

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

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

Observed by KTeV and NA48

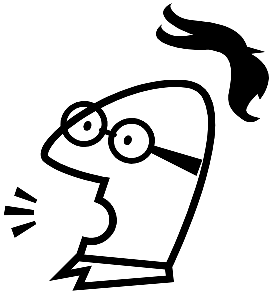


$$BR(K_L \rightarrow \pi^+\pi^-e^+e^-) = 3.6 \times 10^{-7}$$

Does observing a T-odd effect imply T-violation??……..No.

- Final state interactions in ***decays*** can fake a T-odd effect. Consider $K_L \rightarrow \pi^+\pi^-e^+e^-$, where Coulumb interactions and strong phase shifts can bias $\sin\phi\cos\phi$.
- Also, it is in general difficult to untangle T-odd effects from CPT-odd effects…Oh to have that problem!

CPT Violation…



- CPT Violation? That is nuts! Yes, but so was CP violation in 1964 , and P & C violation before then.

- CPT violation is an enormous challenge to field theory…serious problems with Lorentz invariance and Causality….but is this the world at the Plank scale?

- Experimentally well defined: Search for differences in particle-antiparticle masses, lifetimes, total decay rates. One does have to be very careful about expressing results in a form that does not implicitly presume CPT symmetry.

CP & CPT One Page Primer…

CPT symmetry in Particle-Antiparticles:

$$\mathbf{m_K = \overline{m}_K, \quad \tau_K = \overline{\tau}_K, \quad V_{ckm} = V^{\dagger}_{ckm}}\ .$$

Hence the stringent limit on $m_K - \overline{m}_K$ from $\Delta m(K_L - K_S)$ ($\sim 10^{-7}$ eV, 5 GHz RF!):

$\Delta m_{K0}/M_{K0} < 1x10^{-18}$; 95% C.L.

$M_{K0}/M_{Plank} \sim 1x10^{-19}$…..Relevant??

Re(ε'/ε): $K^0 \rightarrow 2\pi \neq \overline{K^0} \rightarrow 2\pi$, $\delta \sim 1x10^{-6}$

This is a violation in *partial rate* (CPV), not the *total rate* (CPT).

Probing CPT Symmetry in Kaons

- In general the most sensitive probe of CPT in mixing and decay amplitudes come from precise comparison of CP violating amplitudes (η) and charge asymmetries (δ).

- As a relatively simple exercise we will study CPT signatures in the balance of K_S and K_L charge asymmetries.

Can we see CPT Violation in Mixing?

- **Sensitivity to CPT violating effects through charge asymmetry:**

$$A_{S,L} = \frac{\Gamma(K_{S,L} \to \pi^- e^+ \nu) - \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})}{\Gamma(K_{S,L} \to \pi^- e^+ \nu) + \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})}$$

$\langle \pi^+ e^- \bar{\upsilon} \vert H_W \vert \bar{K}^0 \rangle = a + b$ $\langle \pi^- e^+ \upsilon \vert H_W \vert K^0 \rangle = a^* - b^*$	b=d=0 if **CPT** holds
$\langle \pi^- e^+ \upsilon \vert H_W \vert \bar{K}^0 \rangle = c + d$ $\langle \pi^+ e^- \bar{\upsilon} \vert H_W \vert K^0 \rangle = c^* - d^*$	c=d=0 by **ΔS=ΔQ** rule

$K \to \pi e \nu$ amplitudes

$$A_S = 2(\mathrm{Re}\,\varepsilon_K \ + \mathrm{Re}\,\delta_K + \mathrm{Re}\,b/a \ - \mathrm{Re}\,d^*/a)$$

$$A_L = 2(\mathrm{Re}\,\varepsilon_K \ - \mathrm{Re}\,\delta_K + \mathrm{Re}\,b/a \ + \mathrm{Re}\,d^*/a)$$

~~CP~~	~~CPT~~ in mixing	~~CPT~~ in decay	$\Delta S \neq \Delta Q$ and ~~CPT~~

$A_S - A_L \neq 0$ implies ~~CPT~~

A_L = (3.322 ± 0.058 ± 0.047) 10^{-3} , KTeV 2002

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Constraining $\Delta S=\Delta Q$:

- **Test of $\Delta S=\Delta Q$ rule: no $\Delta S \neq \Delta Q$ transitions at first order in SM**

$x = (c^*-d^*)/(a+b)$ $\qquad$ $\bar{x} = (c+d)/(a^*-b^*)$

$\Delta S \neq \Delta Q$ in $\overline{K}^0$ decay to e^+ $\qquad$ $\Delta S \neq \Delta Q$ in K^0 decay to e^-

$\Rightarrow$ $\mathbf{x_+ = (x+\bar{x})/2 \sim Re(c^*/a) + i\, Im(d^*/a)}$

Rex_+ describes $\Delta S \neq \Delta Q$ when CPT conserved

$$\mathrm{Re}\; x_+ = \frac{1}{2}\frac{\Gamma_S^{\pi e \nu} - \Gamma_L^{\pi e \nu}}{\Gamma_S^{\pi e \nu} + \Gamma_L^{\pi e \nu}}$$

$|x| \sim 10^{-7}$ SM expect.

$\mathrm{Re}(x_+) = (-0.0018 \pm 0.0041_{stat} \pm 0.0045_{syst})$ CPLEAR 98

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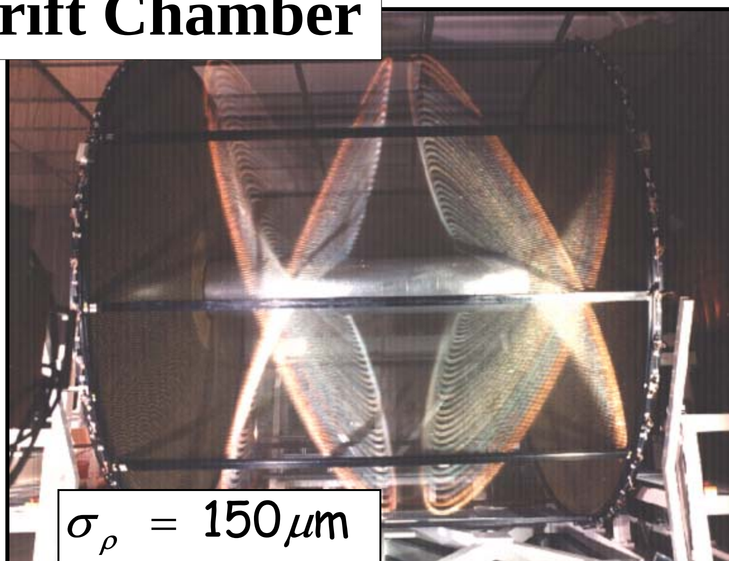
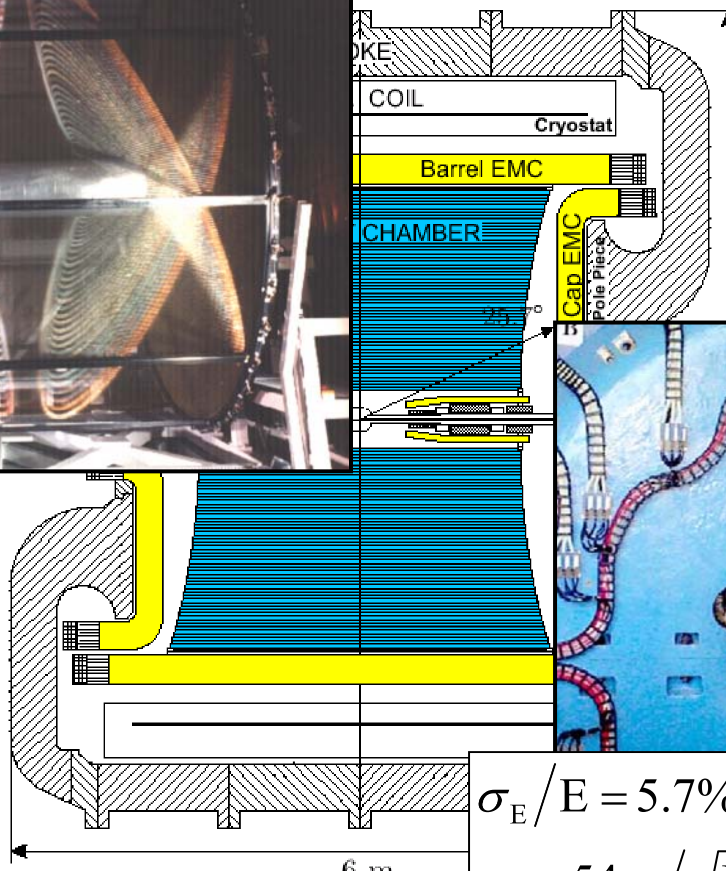
The KLOE detector

- KLOE operates at DAΦNE, the e^+e^- collider known as the "Frascati ϕ-factory"
- Kaons are produced almost back-to-back in the Laboratory

Drift Chamber

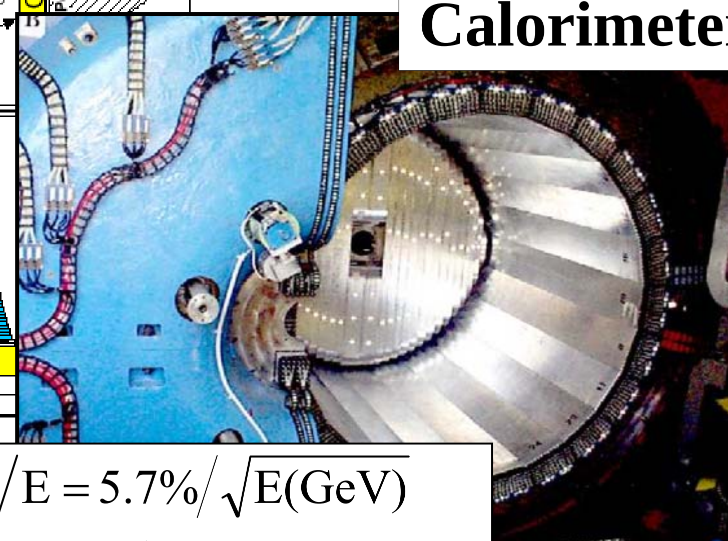


$$\sigma_\rho = 150\mu m$$
$$\sigma_z = 2mm$$
$$\sigma_V = 3mm$$
$$\sigma_p/p = 0.4\%$$



$$\lambda_S = 0.6cm$$
$$\lambda_L = 340cm$$
$$\lambda_\pm = 95cm$$

Calorimeter



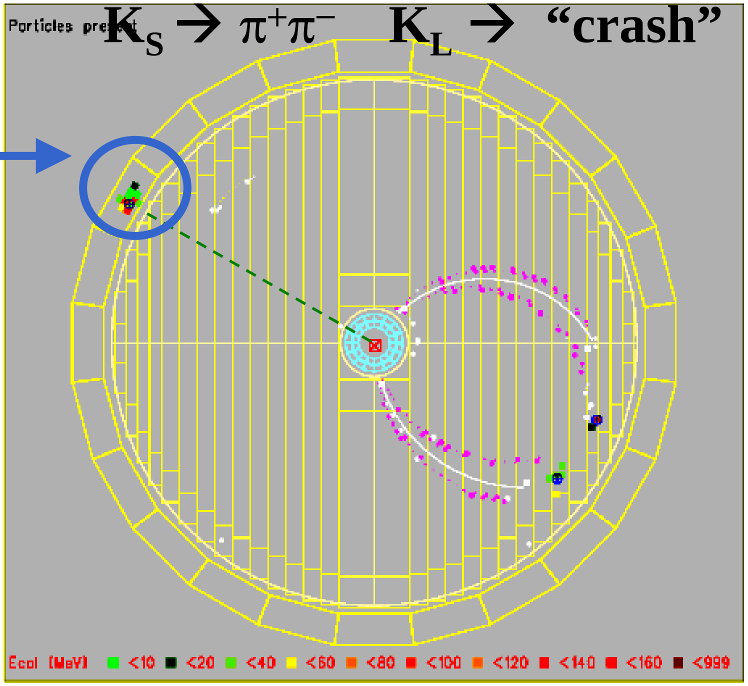
$$\sigma_E/E = 5.7\%/\sqrt{E(GeV)}$$
$$\sigma_t = 54ps/\sqrt{E(GeV)} \oplus 50ps$$

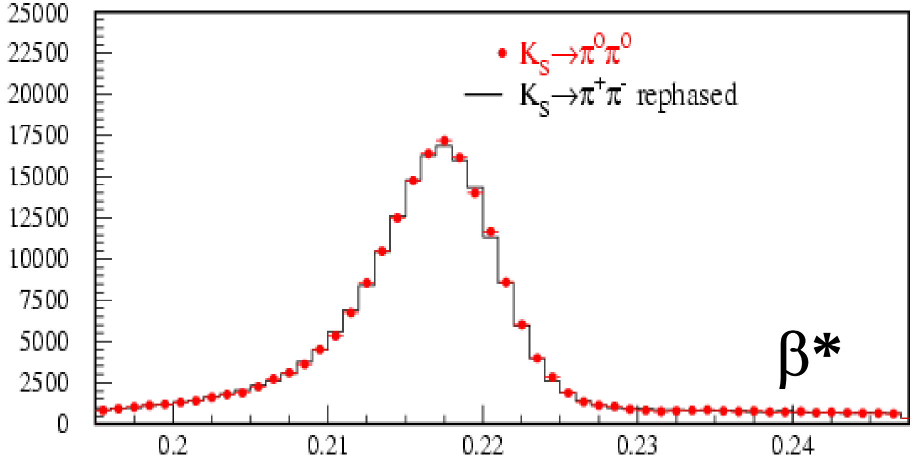
Neutral kaons tagging: K_S "beam"

- Clean $\mathbf{K_S}$ tagging by time-of-flight identification of $\mathbf{K_L}$ interactions in the calorimeter :

  ***tof*(K$_L$) ~30 ns** (*tof* (γ) ~6 ns)

- K_L velocity in the φ rest frame $\beta^* \sim 0.218$
- Tagging efficiency $\varepsilon_{tag,total} \sim 30\% \Rightarrow 1.4\ 10^8$ **tagged K_S**





Kinematic closure of the event
($p_S = p_\phi - p_L$):
K_S angular resolution: ~ 1° (0.3° in φ)
K_S momentum resolution: ~ 1 MeV/c

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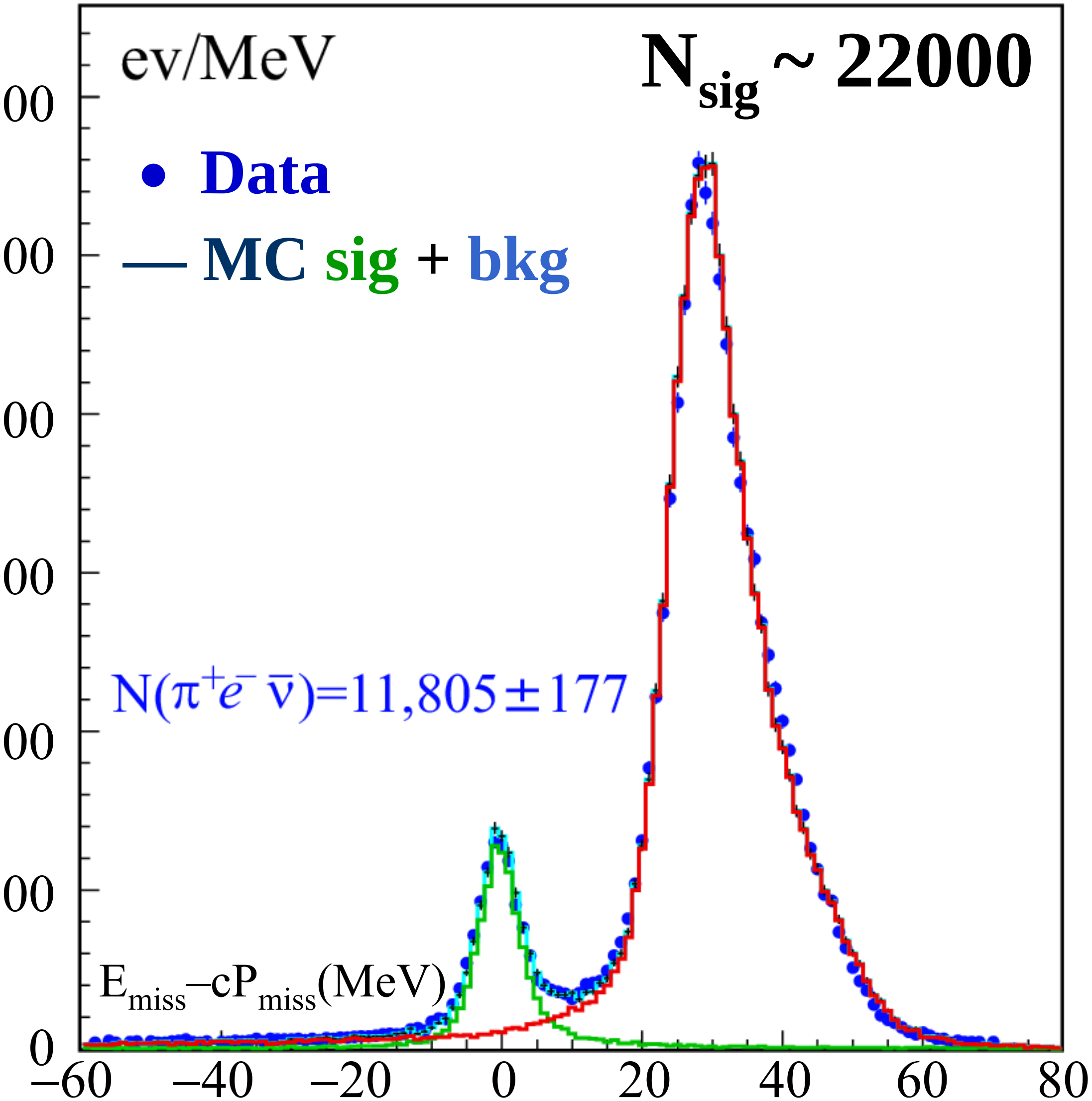
$K_S \to \pi e \nu$ – Events counting

Kinematic closure: use K_L to obtain K_S momentum $\mathbf{P_K}$ and test for presence of neutrino:

$$E_{miss} = \sqrt{M_K^2 + P_K^2} - E_\pi - E_e$$

$$P_{miss} = |\mathbf{P_K} - \mathbf{P_\pi} - \mathbf{P_e}|$$



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$K_S \to \pi e \nu$ – Preliminary BR , A_S , Re(x_+)

Normalize signal counts to $K_S \to \pi\pi(\gamma)$ counts in the same data set ; use KLOE measurement for BR($K_S \to \pi^+\pi^-(\gamma)$)

$$BR(K_S \to \pi e \nu) = (7.09 \pm 0.07_{stat} \pm 0.08_{syst})\ 10^{-4}$$

(Published result: $(6.91 \pm 0.34_{stat} \pm 0.15_{syst})\ 10^{-4}$, KLOE '02)

$A_S = (-2 \pm 9_{stat} \pm 6_{syst})\ 10^{-3}$ **(first measurement)**

$A_L = (\ 3.28 \pm 0.06)\ 10^{-3}$ **(PDG)**

CPT Violation Probed at 1% here.

$Re(x_+) = (\ 0.0136 \pm 0.0031_{stat} \pm 0.0029_{syst})$ with PDG02 BR($K_L \to \pi e \nu$)

$Re(x_+) = (\ 0.0017 \pm 0.0029_{stat} \pm 0.0029_{syst})$ with KTeV BR($K_L \to \pi e \nu$)

$Re(x_+) = (-0.0018 \pm 0.0041_{stat} \pm 0.0045_{syst})$ CPLEAR

Summary of CPT in the kaon system.

- Tightest constraint comes from the **very small value of $\Delta m_{(L,S)}$.** The actual limit on $\Delta m_{(K,\bar{K})}$ comes from an additional factor of ~1/100 from CP violating phase differences. This can in principle be improved by another x10 with next generation precision experiments.

  At Plank scale then?

- Constraints on CPT effects in mixing and rate differences are in the **10^{-2} – 10^{-6} range**. This can improve by x10 with next generation experiments.

Back to Unitarity…How Tightly is CKM Constrained? Are There Hidden Flavors?

Weak eigenstates

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

Mass eigenstates

Uncertainty on $\Sigma_j |V_{ij}|^2$

w/ Particle Data Group '04 Central Values

$$\begin{pmatrix} d_w \\ s_w \\ b_w \end{pmatrix} = \begin{pmatrix} 0.974 & 0.22 & 0.004 \\ 0.22 & 0.97 & 0.04 \\ 0.005 & 0.04 & 0.99 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

<0.2 %

2.7 %

30 %

Unitarity (or lack thereof) of CKM matrix tests existence of further quark generations and possible new physics (eg. Supersymmetry)

Tests of Unitarity, before 2004
V_{us} Revolution:

Precise test of unitarity

SM: $V_{ud}^2+V_{us}^2+V_{ub}^2=1$

$V_{ud}^2=0.9487\pm0.0010$ (nuclear decays)
$V_{us}^2=0.0482\pm0.0010$ (from e.g. $K^+\to\pi^0e^+\nu_e$)
$V_{ub}^2=0.000011\pm0.000003$ (B meson decays)

PDG 2004

Data: $V_{ud}^2+V_{us}^2+V_{ub}^2=0.9970\pm0.0014$
(2.2σ deviation)

First hint: BNL-865 Measurement of $K^+ \rightarrow \pi^0 e^+ \nu_e$

- Key issue is systematic control of the Branching Ratio.
- Detector designed for $\pi^+\mu^-e^+$. not optimized for photons.

Require: $\pi^0 \rightarrow e^+e^-\gamma$ in signal and normalization.

- $BR=(5.13 \pm 0.02_{stat} \pm 0.10_{sys})\%$
- PDG(<2004): $(4.87 \pm 0.06)\%$

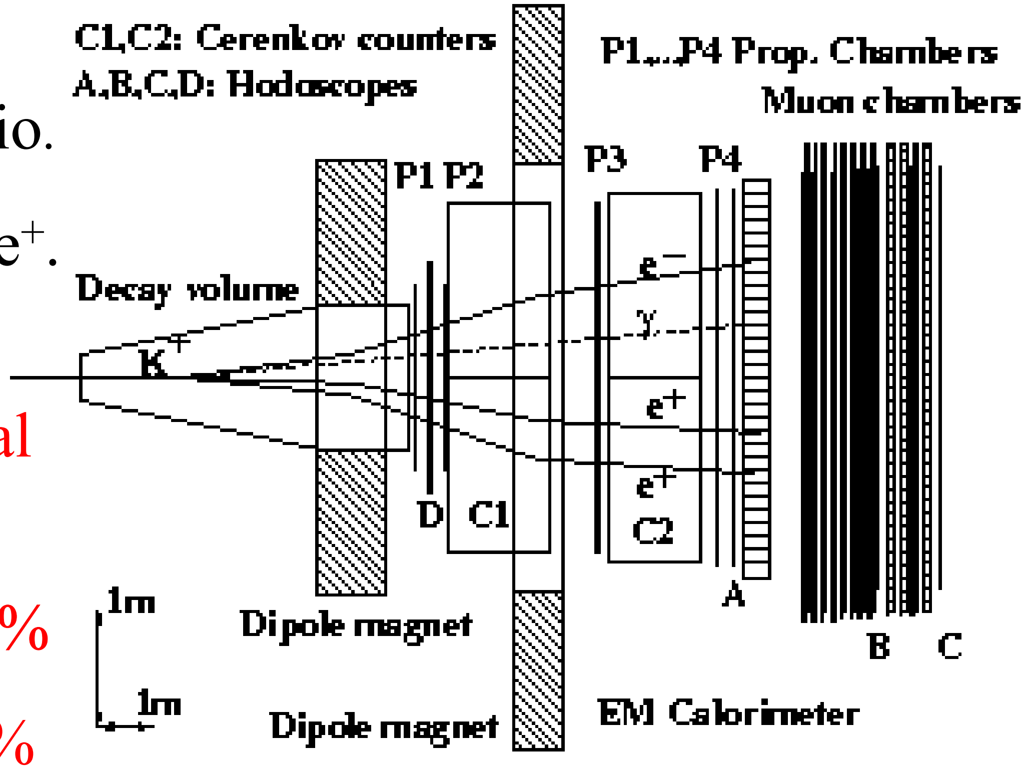


FIG. 1: Plan view of the E865 detector with a simulated $K^+ \rightarrow \pi^0 e^+ \nu$ decay followed by $\pi^0 \rightarrow e^+e^-\gamma$.

Extracting $|V_{us}|$ from K^0_{e3}

Long standing issue: 1st row unitarity $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \neq 1$

BNL E865 (May 2003) found a higher value for $Br(K^+ \to \pi^0 e^+ \nu)$ consistent with unitarity but giving $|V_{us}|$ ~2.7σ above existing $Br(K_L \to \pi^\pm e^\pm \nu)$ value.

@ ~2.2 σ level

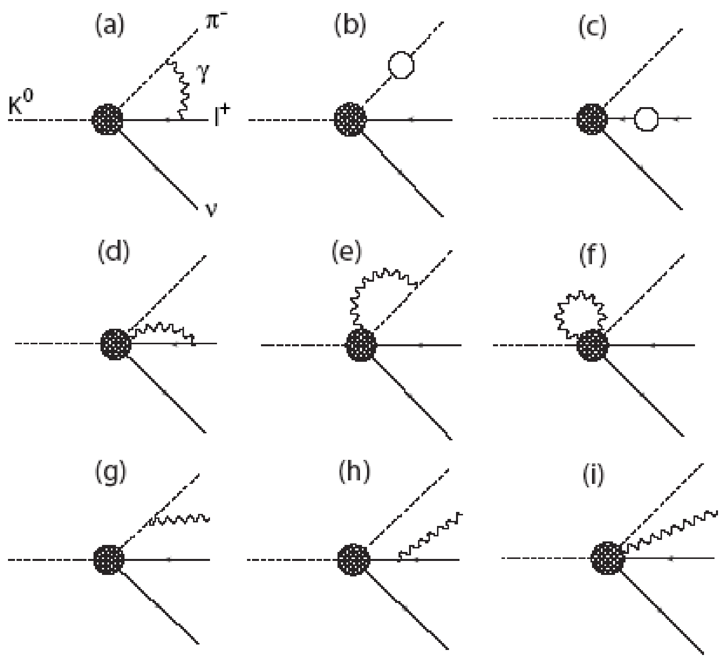
$$\Gamma_{\ell 3} = \frac{Br\left(K_L \to \pi^\pm \ell^\mp \nu\right)}{\tau_L} = \left(\frac{G_F^2\, m_K^5}{384\,\pi^3}\right) S_{EW}\, f_+^2(t=0)\left(1+\delta_\ell\right)|V_{us}|^2 \int \hat{f}^{\,2}$$

S_{EW}	Short range EW & QCD corrections - same for e,μ
$f_+(0)$	Form factor at $t = (P_\ell + P_\nu)^2 = 0$; we use 0.961 ±0.008 [Leutwyler & Roos, 1984]
δ_ℓ	Long range (mode-dependent) radiative corrections
$\int \hat{f}^{\,2}$	Integral over phase space of form factor squared

Step 1: Radiative corrections

$$\Gamma_{\ell 3} = \frac{Br\left(K_L \to \pi^{\pm}\ell^{\mp}\nu\right)}{\tau_L} = \left(\frac{G_F^2\, m_K^5}{384\,\pi^3}\right) S_{EW}\, f_+^2(t=0)\,(1+\delta_\ell)\left|V_{us}\right|^2 \int \hat{f}^{\,2}$$

T.Andre, hep-ph/0406006



Take

$$\left\langle \pi^-(p_\pi)\middle|\bar{s}_L\gamma^\alpha u_L\middle|K^0(p_K)\right\rangle =$$

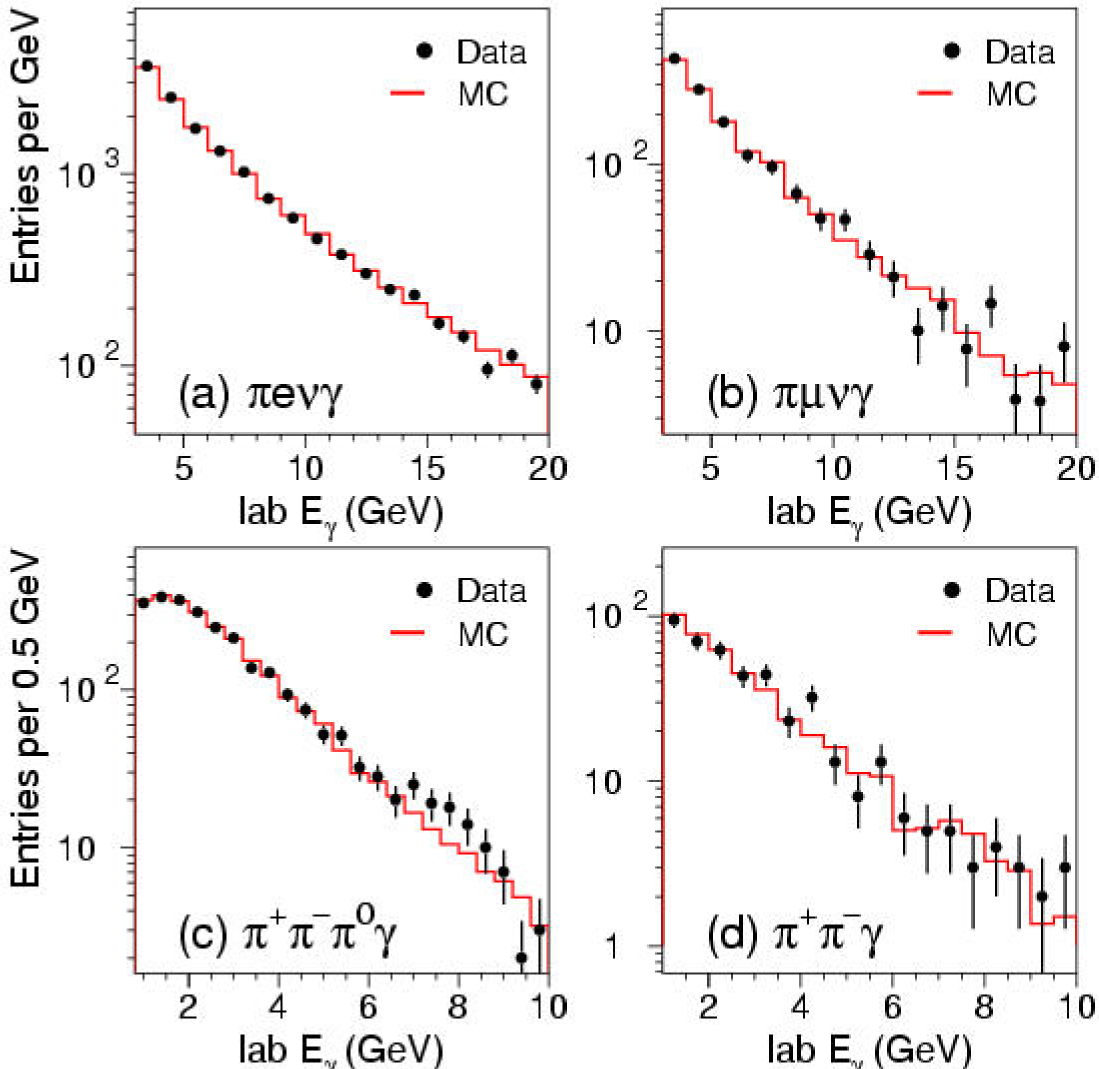
$$f_+(t)[p_K + p_\pi] + f_-(t)[p_K - p_\pi]$$

Evaluate with linear, quadratic and pole model form factors f

Radiative MC Check

KTEV Kaons at the Tevatron

Data-MC comparison of radiated photon energy well modeled for all relevant charged decay modes.



Step 2: Form factors

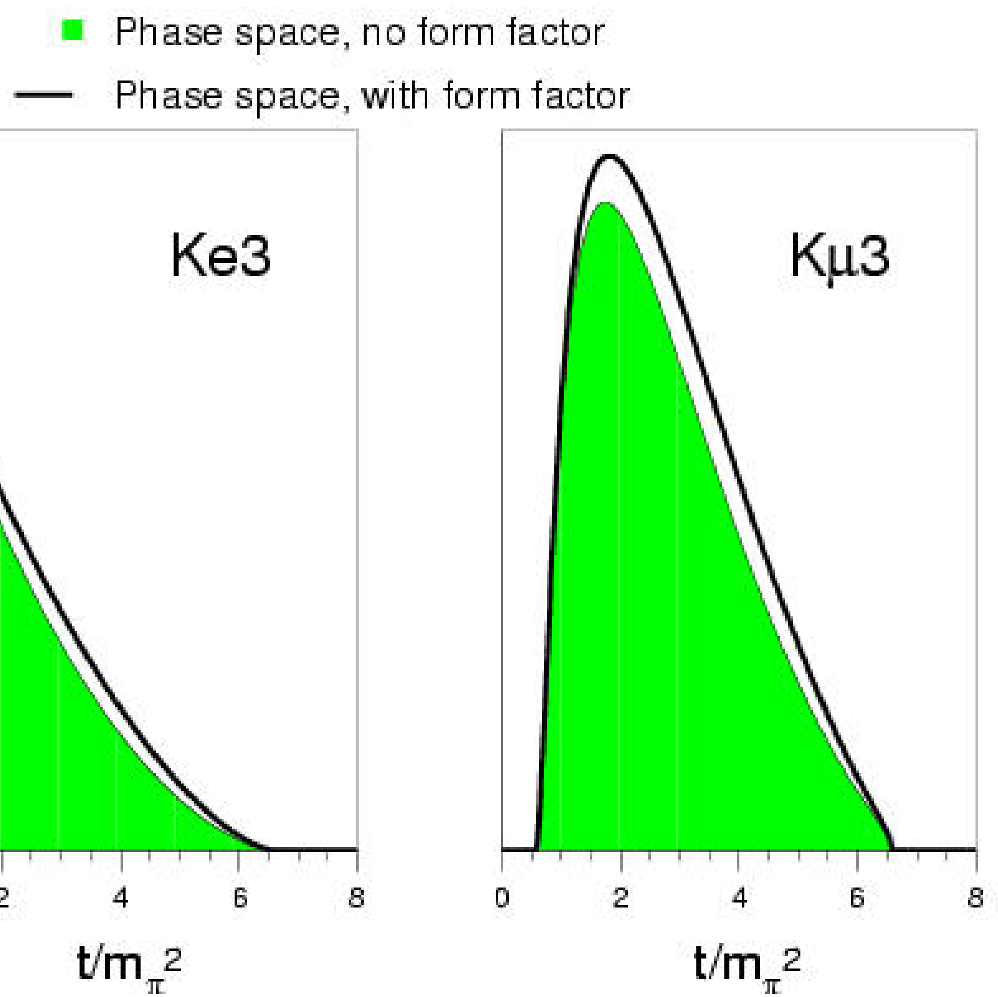
$$\Gamma_{\ell 3} = \frac{Br\left(K_L \to \pi^{\pm}\ell^{\mp}\nu\right)}{\tau_L} = \left(\frac{G_F^2\ m_K^5}{384\,\pi^3}\right) S_{EW}\, f_+^2(t=0)\left(1+\delta_\ell\right)\left|V_{us}\right|^2 \int \hat{f}^2$$

We parameterize with $f_+(t)$ and $f_0(t) = f_+(t) + \frac{t}{m_K^2 - m_\pi^2} f_-(t)$

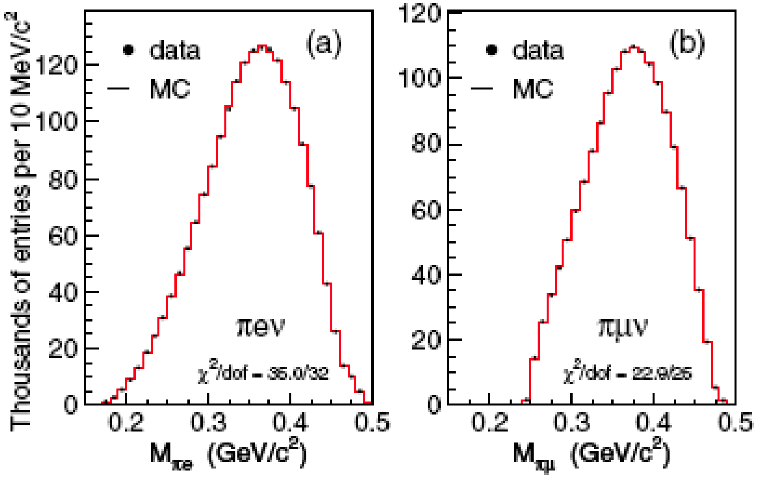
f_i expanded in powers of $t\,/\,m_\pi^2$; coefficients are λ_i

- Since p_K is not known, there is a two-fold reconstruction ambiguity due to unseen ν
- We use $t_\perp^{\ell} = (P'_\ell + P'_\nu)^2$ or $t_\perp^{\pi} = (P'_K - P'_\pi)^2$ -Basically, t evaluated without longitudinal coordinates to momenta. Costs ~15% of statistical power
- Some fits also use $m_{\ell\pi}$

Form Factor modeling, critical for precision extraction of $|V_{us}|$

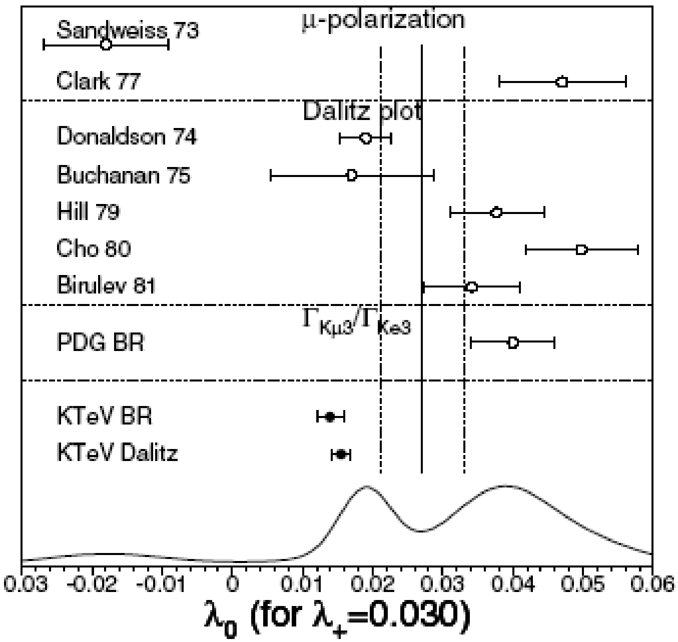


KTEV Kaons at the Tevatron



	K_{e3}	$K_{\mu3}$
	Linear model x10^{-3}	
λ_+	28.32±0.57	27.45±1.08
λ_0	-	16.57±1.25
	Quadratic model x10^{-3}	
λ_+'	21.67±1.99	17.03±3.65
λ_+''	2.87±0.87	4.43±1.49
λ_0	-	12.81±1.83

Pole model fits also reported…



Linear model λ_+ values consistent with PDG values.

Quadratic term significant at 4σ level
Lowers phase space integral by ~1%.

Step 3: Check steps 1&2 with $K_L \to \pi \ell \nu \gamma$

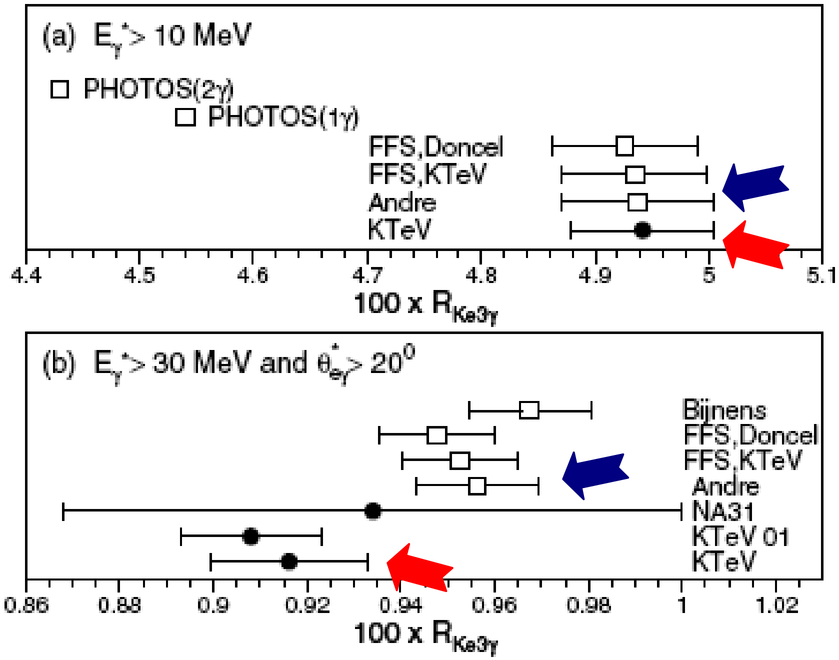
KTEV
Kaons at the Tevatron

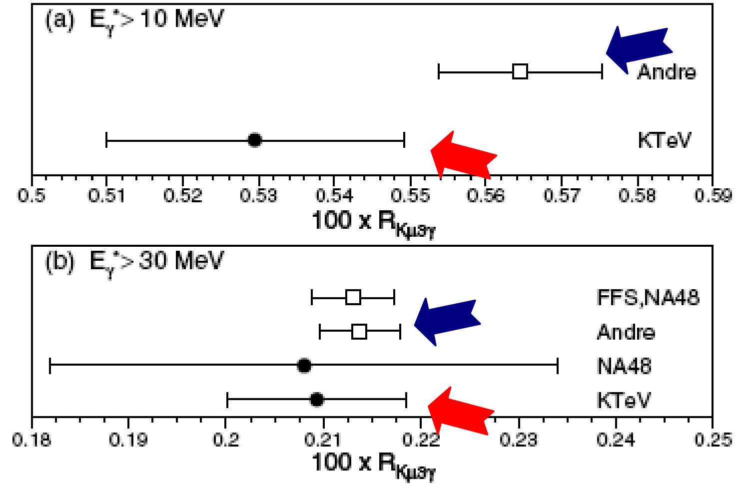
$$R_{K\gamma 3\gamma} \equiv \frac{\Gamma\left(K_L \to \pi^{\pm}\ell^{\mp}\nu\gamma;\ E_{\gamma}^{*} > 10\,MeV\right)}{\Gamma\left(K_L \to \pi^{\pm}\ell^{\mp}\nu + n\gamma\right)}$$

Acceptance corrections for 2^{nd} γ via PHOTOS ~1.8% for K_{e3}

Andre's prediction

KTeV's measurement





Step 4: Get the branching ratio

$$\Gamma_{\ell 3} = \frac{Br\left(K_L \to \pi^{\pm}\ell^{\mp}\nu\right)}{\tau_L} = \left(\frac{G_F^2\ m_K^5}{384\ \pi^3}\right) S_{EW}\, f_+^2(t=0)\left(1+\delta_\ell\right)\left|V_{us}\right|^2 \int \hat{f}^{\,2}$$

Ordinarily, would measure something like $\Gamma\left(K_L \to \pi^{\pm}\ell^{\mp}\nu\right) / \Gamma\left(K_L \to nice\right)$ where the "$nice$" mode has high statistics, a well-known rate, and is similar to $K_{\ell 3}$ in the detector. Sadly, there is no "$nice$" mode.

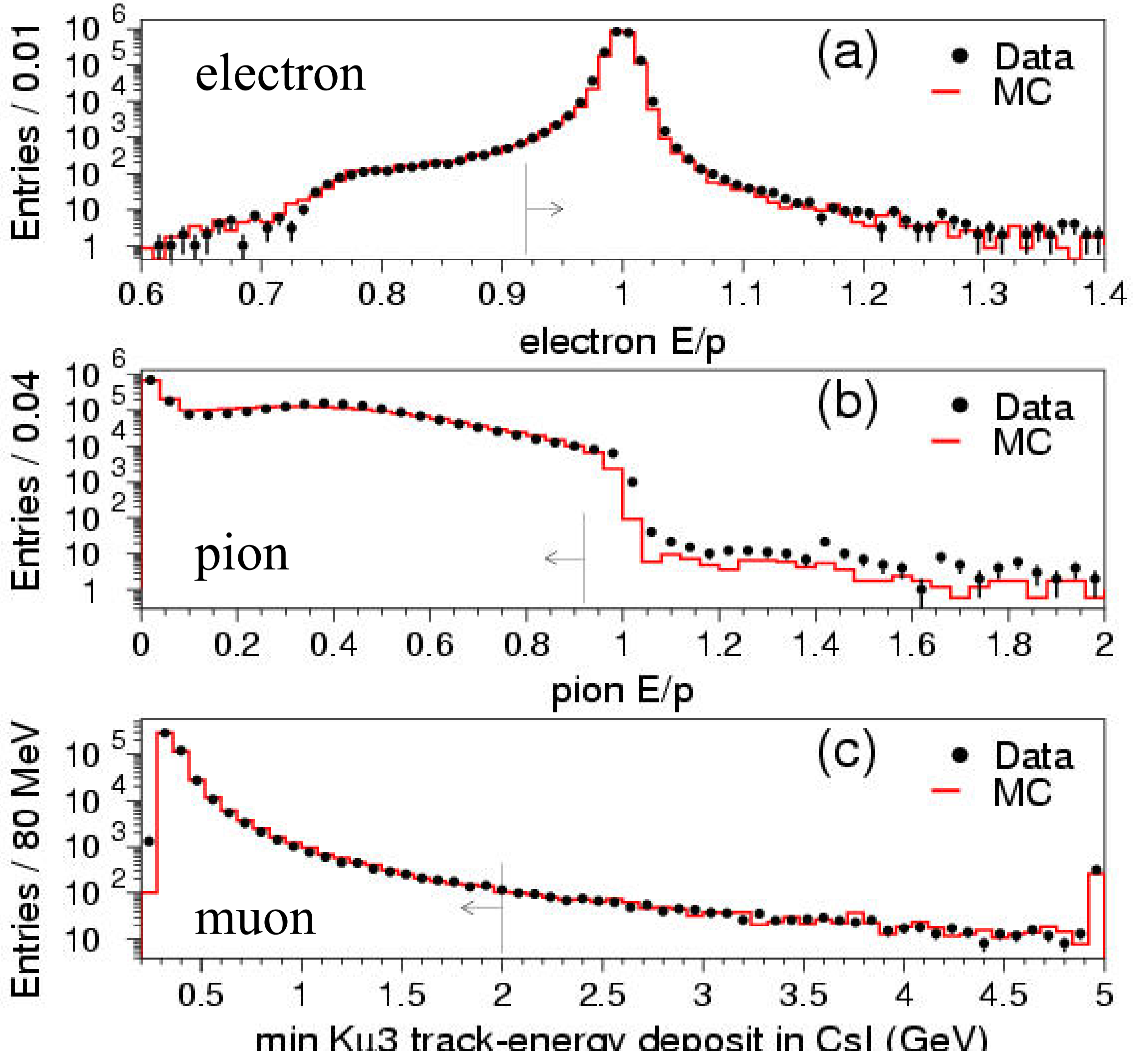
Measure these 5 ratios, use Σ = 1 constraint to get Br

$\Gamma_{K\mu 3} / \Gamma_{Ke3}$ $\quad$ $\Gamma_{+-0} / \Gamma_{Ke3}$ $\quad$ $\Gamma_{000} / \Gamma_{Ke3}$

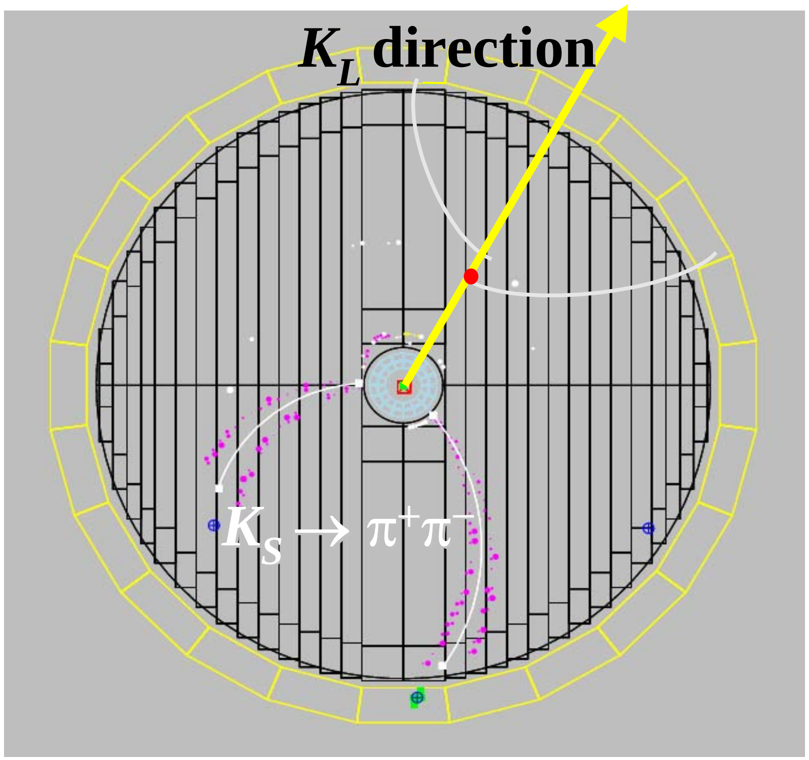
$\Gamma_{+-} / \Gamma_{Ke3}$ $\quad$ $\Gamma_{000} / \Gamma_{00}$

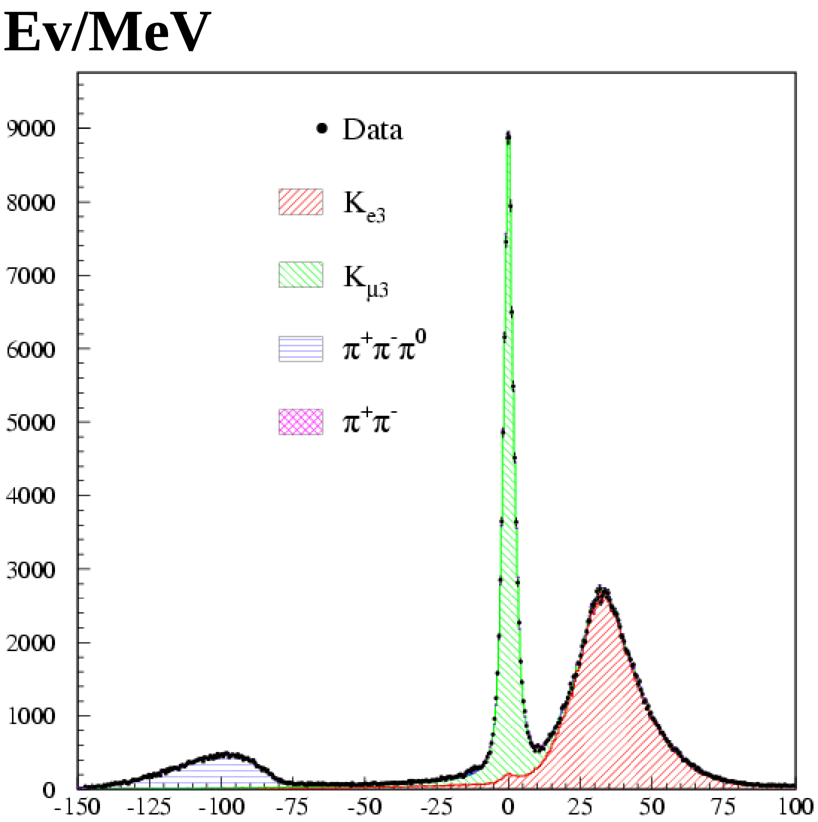
Particle Identification in KTeV

Benefits of High Energy Experiments: Clear separation of electrons, muons, and pions with calorimetry. Detector response is well modeled.



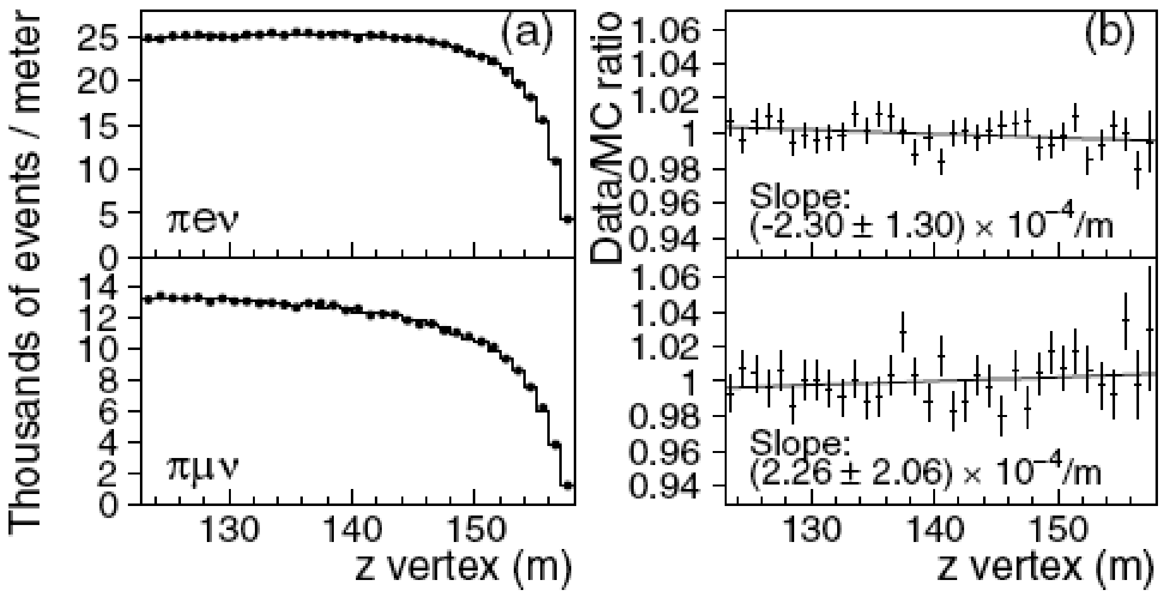
Contrast: KLOE Particle ID in K_L decays: Use Kinematics and timing





Lesser of $\mathbf{P_{miss}} - \mathbf{E_{miss}}$ in $\pi\mu$ or $\mu\pi$ hyp. (MeV)

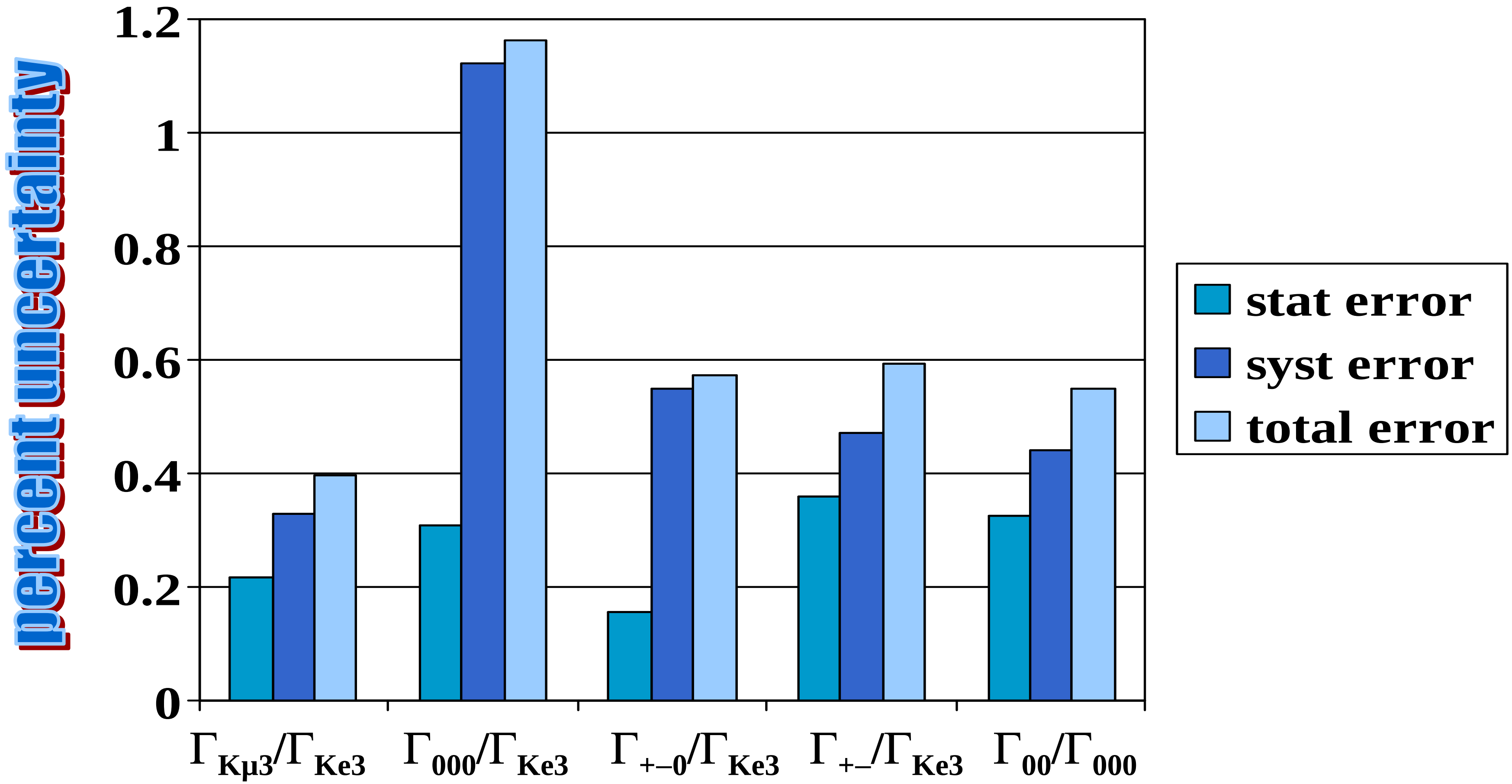
- Except for $\Gamma_{000}/\Gamma_{Ke3}$, all ratios have final similar states
- Except for Γ_{00}/Γ_{000}, all ratios in same trigger; this analysis similar to the ε'/ε neutral mode analysis



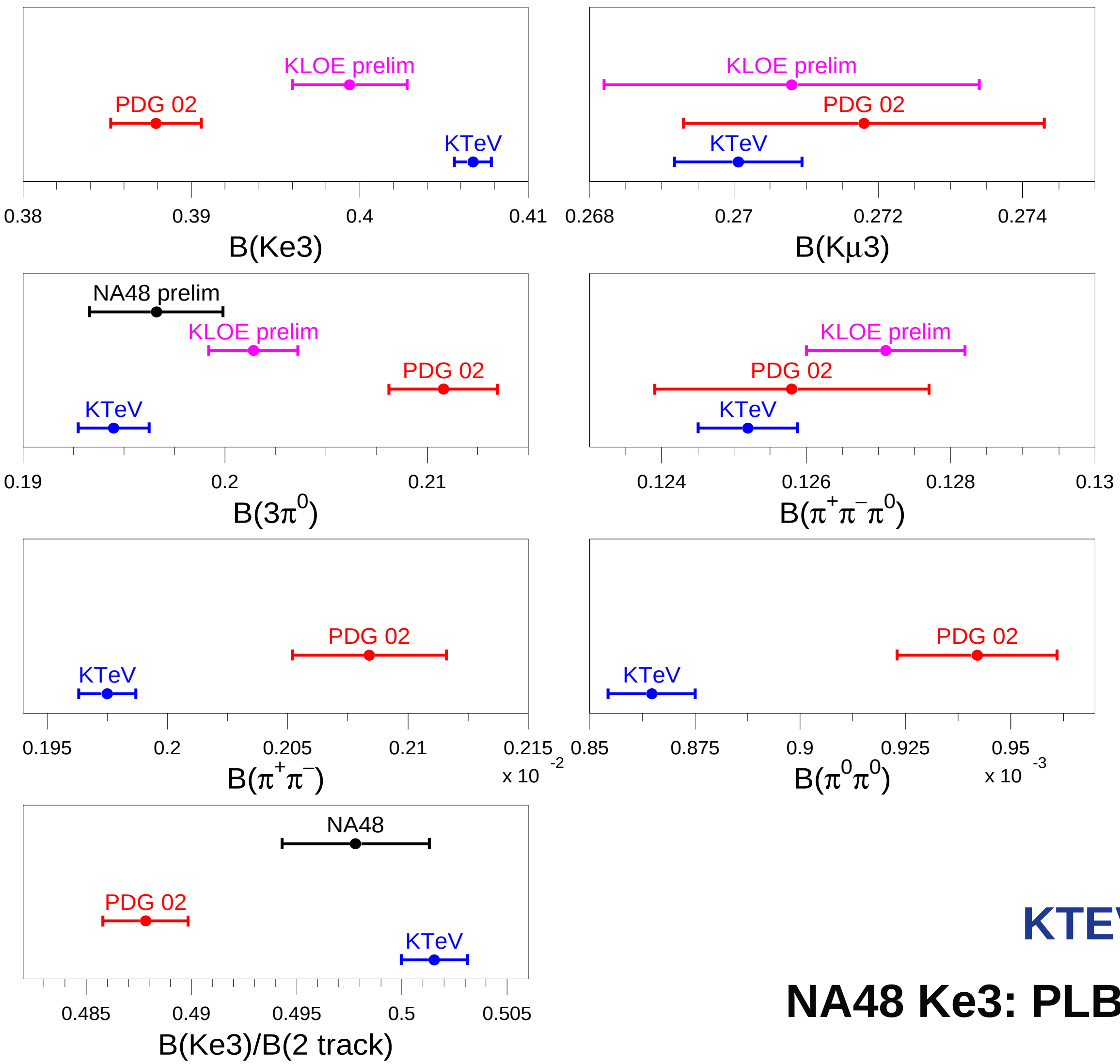
- $K\to\pi\mu\nu$ ratios without/with μ ID agree to $(0.08 \pm 0.02_{stat})\%$
- $K\to\pi^+\pi^-\pi^0$ ratios without/with $\pi^0\to\gamma\gamma$ reconstruction in CsI -factor ~4 change in acceptance- agree to $(0.03 \pm 0.28_{stat})\%$

Uncertainties on Partial Width Ratios

KTEV Kaons at the Tevatron



K_L BR Measurements



NA48 $3\pi^0$: ICHEP04

KLOE: ICHEP04

KTEV: PRD 70, 092006 (2004)

NA48 Ke3: PLB, Volume 602, Nov (2004)

From measured ratios to $|V_{us}|$

KTEV Kaons at the Tevatron

Modes	Partial Width Ratio
$\Gamma_{K\mu3} / \Gamma_{Ke3}$	$0.6640 \pm 0.0014 \pm 0.0022$
$\Gamma_{000} / \Gamma_{Ke3}$	$0.4782 \pm 0.0014 \pm 0.0053$
$\Gamma_{+-0} / \Gamma_{Ke3}$	$0.3078 \pm 0.0005 \pm 0.0017$
$\Gamma_{+-} / \Gamma_{Ke3}$	$(4.856 \pm 0.017 \pm 0.023) \times 10^{-3}$
$\Gamma_{00} / \Gamma_{000}$	$(4.446 \pm 0.016 \pm 0.019) \times 10^{-3}$

$Br(K_{e3})$ = 0.4067 ±0.0011
$Br(K_{\mu3})$ = 0.2701 ±0.0009

Using $\tau_K = 51.5 \pm 0.4\ ns$

$\Gamma(K_{e3}) = (7.897 \pm 0.065) \times 10^6\ s^{-1}$
$\Gamma(K_{\mu3}) = (5.244 \pm 0.044) \times 10^6\ s^{-1}$

K_{e3}: $|V_{us}| = 0.2253 \pm 0.0023$

$K_{\mu3}$: $|V_{us}| = 0.2250 \pm 0.0023$

Average: $|V_{us}| = 0.2252 \pm 0.0008_{KTeV} \pm 0.0021_{ext}$

Γ ratios, form factors

$f_+(0)$, τ_K, rad corrs

Lepton Universality Test with Semileptonic Branching Fractions and Form Factors

Long-distance rad cor ratio from KLOR is 1.0058(10)

KTeV measures 0.6622 +- 0.0018

$$[\Gamma_{K\mu3}/\Gamma_{Ke3}]_{\text{pred}} = \frac{1+\delta_K^\mu}{1+\delta_K^e} \cdot \frac{I_K^\mu}{I_K^e}$$

KTEV Kaons at the Tevatron

$$\frac{[\Gamma_{K\mu3}/\Gamma_{Ke3}]_{\text{KTeV}}}{[\Gamma_{K\mu3}/\Gamma_{Ke3}]_{\text{pred}}} = 0.9969 \pm 0.0048$$

(same test with PDG02 BR and FF: 1.027 ± 0.018)

Theory Corrections

$$\Gamma_{K\ell 3} = \frac{G_F^2 M_K^5}{192\pi^3} S_{EW} (1 + \delta_K^\ell) \, |V_{us}|^2 \, |f_+^2(0)| I_K^\ell$$

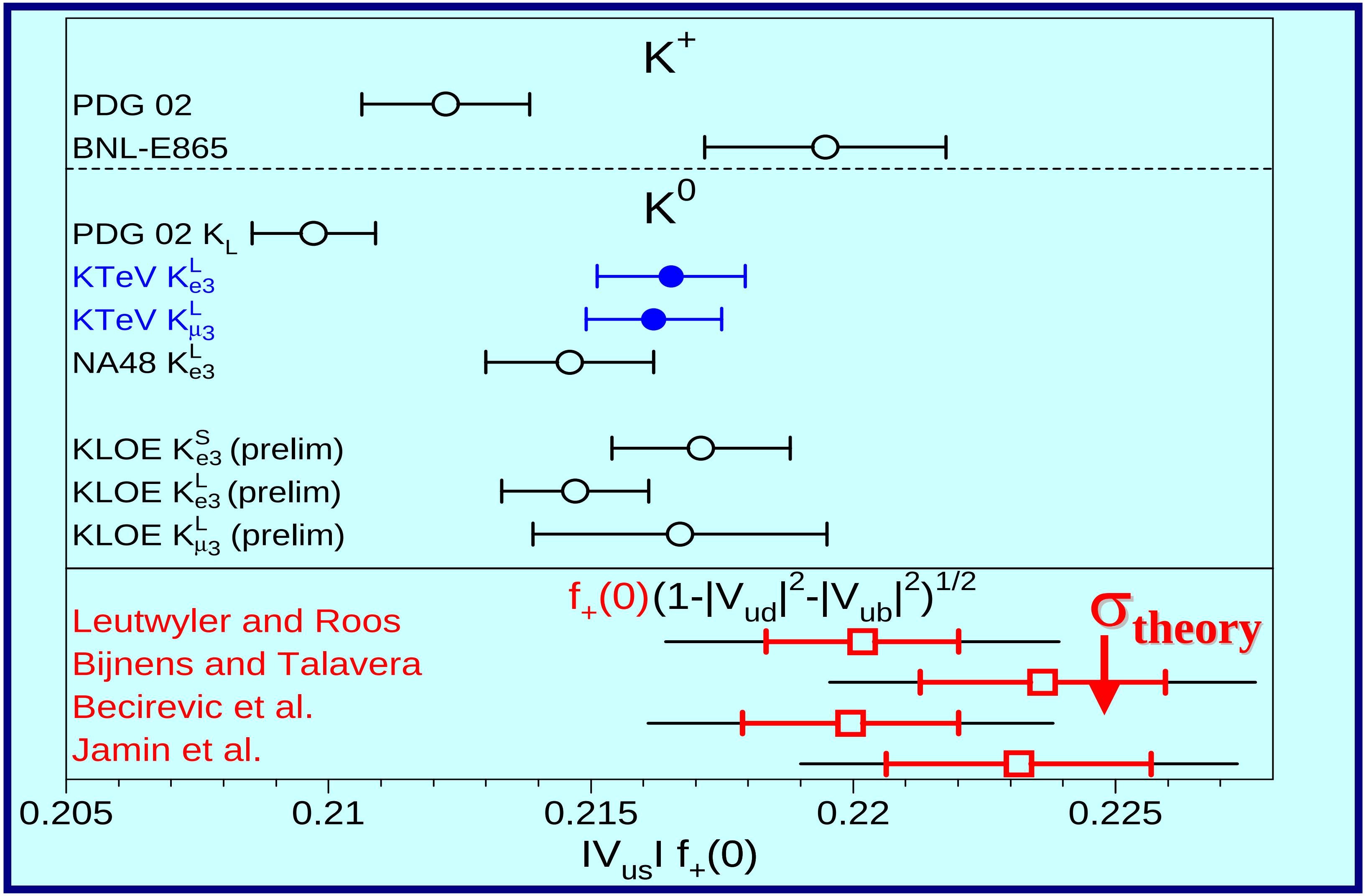
short-distance rad cor: 1.022

long-distance rad cor from KLOR,
$\delta^e = 1.013$
$\delta^\mu = 1.019$

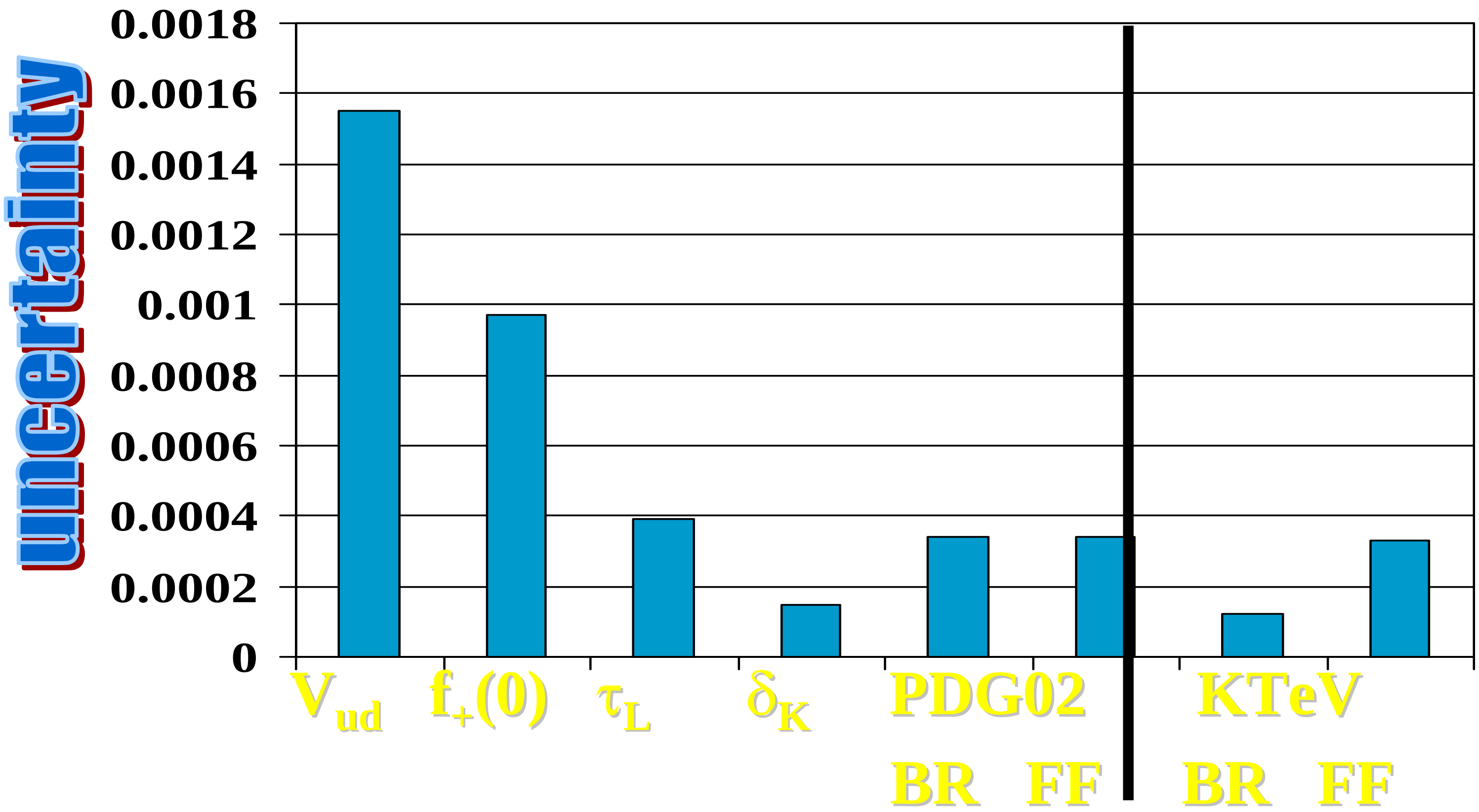
Use Leutwyler-Roos 84:
$f_+(0)=0.961(8)$

Recent works: 0.96-0.98
(no consensus yet ?)

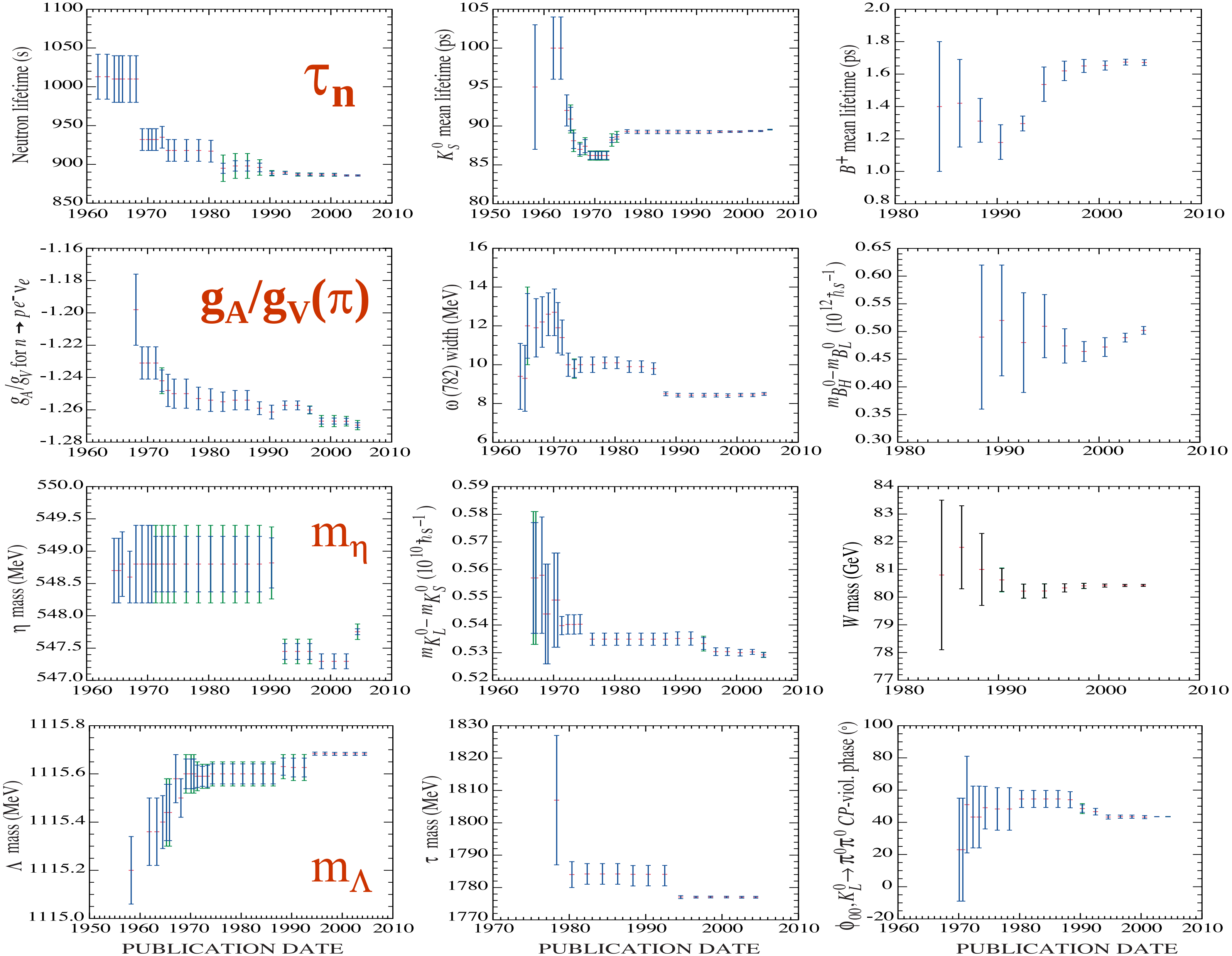
Comparisons with Theory and $|V_{ud}|$



Summary of Uncertainties on $|V_{ud}|^2 + |V_{us}|^2$



PDG Compilation of Selected Measurements….A lesson here!



Unitarity Conclusions

- "Unitarity Crisis" in first row of CKM matrix resolved.
- Radiative corrections are critical.
- Ball is now in theory court to further extract |Vus|
- Analysis of full KLOE statistics will be very welcome.

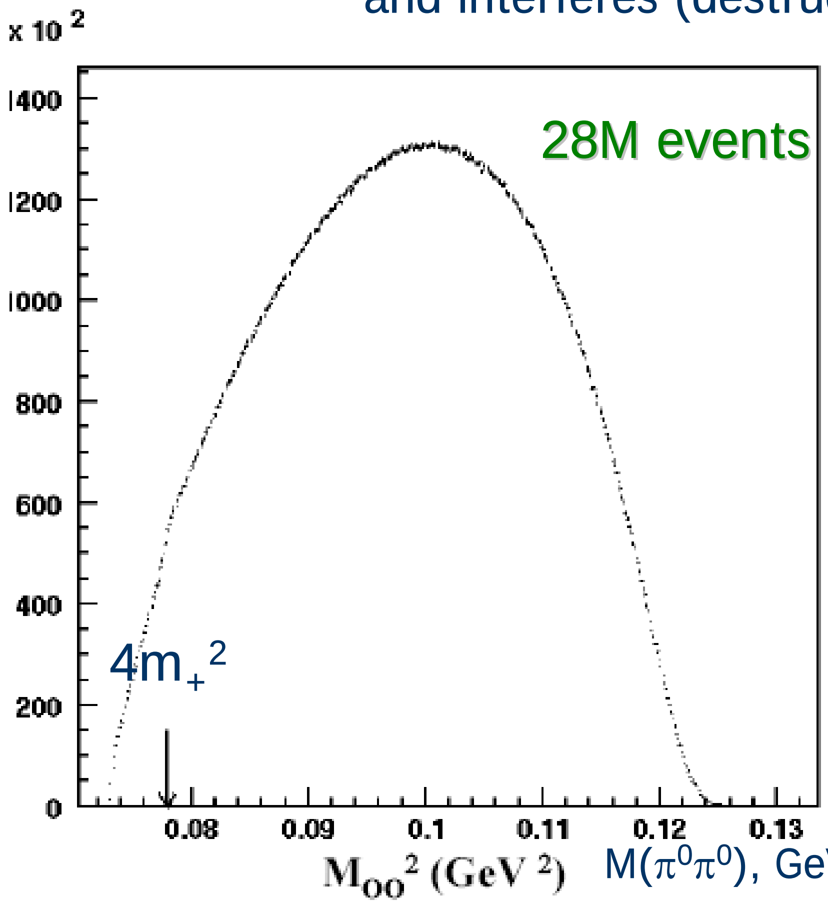
Precise Conclusions.

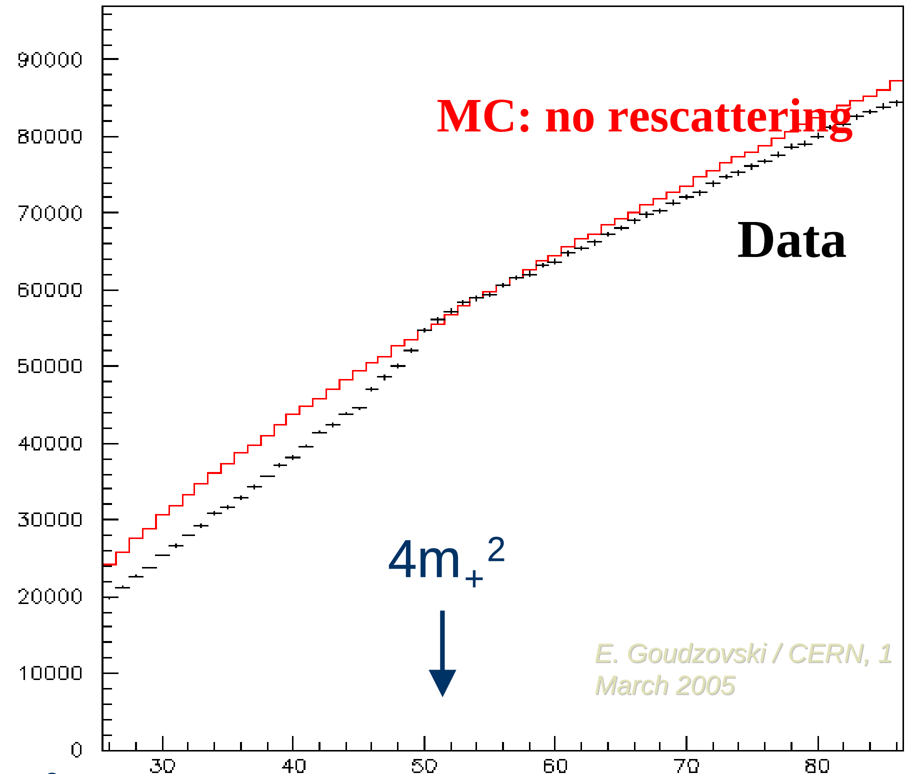
- CP & T violation well established, CPT and CKM unitarity safe for now due to precision measurements in the kaon system.
- Experiment spinoffs: NA48(2): $\pi^{+}\pi^{-}\rightarrow\pi^{0}\pi^{0}$.
- A path to the ultimate energy frontier. Plank scale?

Spares

NA48(2) Observes Fascinating Rescattering effect in $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$

The charge exchange process $\pi^{+}\pi^{-} \to \pi^{0}\pi^{0}$ is not negligible under threshold, and interferes (destructively) with direct emission





$M(\pi^0\pi^0)$, GeV/c^2 1 bin = 0.00015 GeV^2

I_K Uncertainty from Semileptonic Form Factors

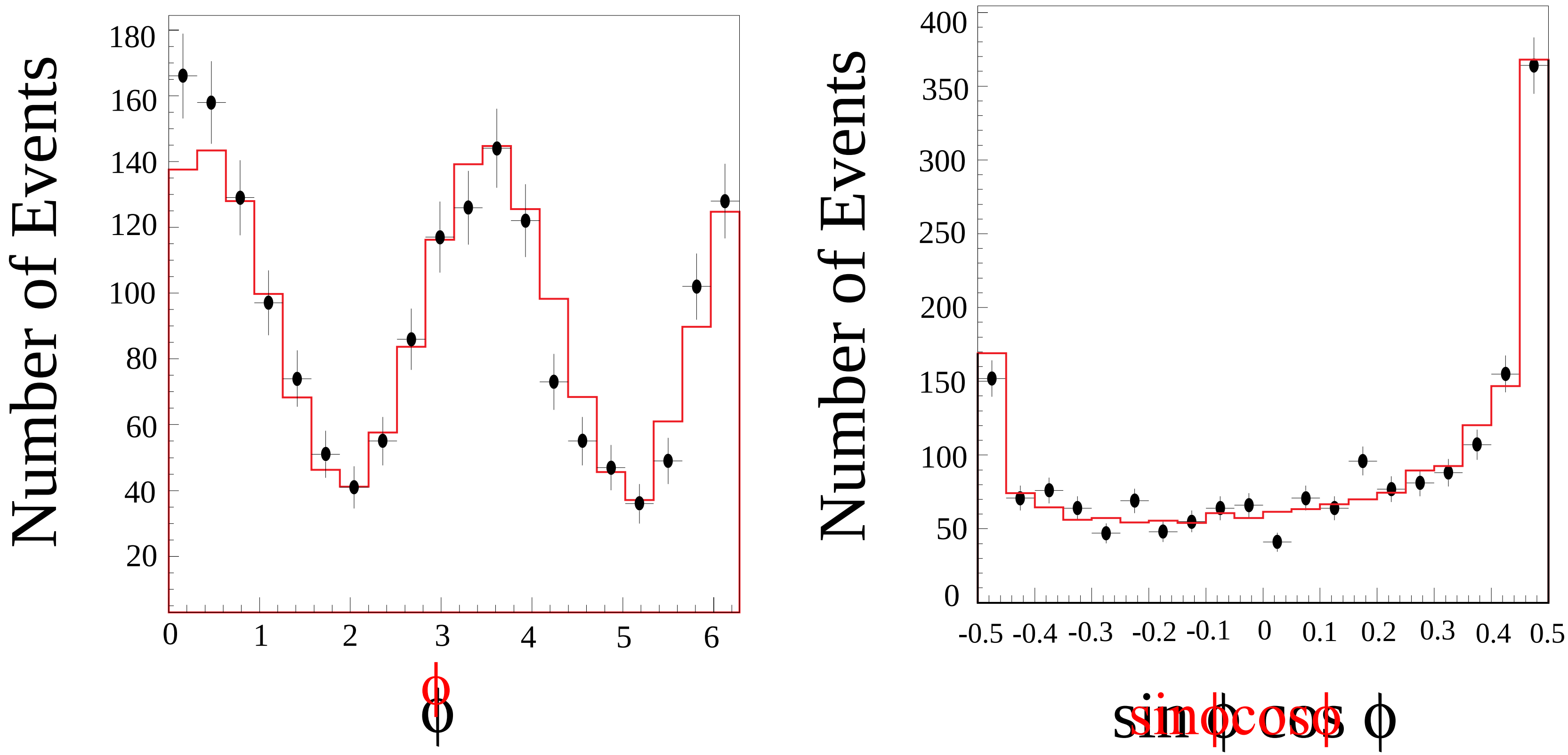
we include 0.7% uncertainty from model dependence (doubles error!).

$$\frac{I_K(\text{quadratic: } \chi^2/\text{dof}=62/64)}{I_K(\text{pole model: } \chi^2/\text{dof}=66/65)} - 1 = 0.7\%$$

Although KTeV form factors are much more precise than PDG, KTeV I_K uncertainty is comparable to PDG uncertainty based on linear FF model.

$I_{K\mu 3} / I_{Ke3}$ ratio is not affected.

Discovered at KTeV, confirmed by CERN-NA48…

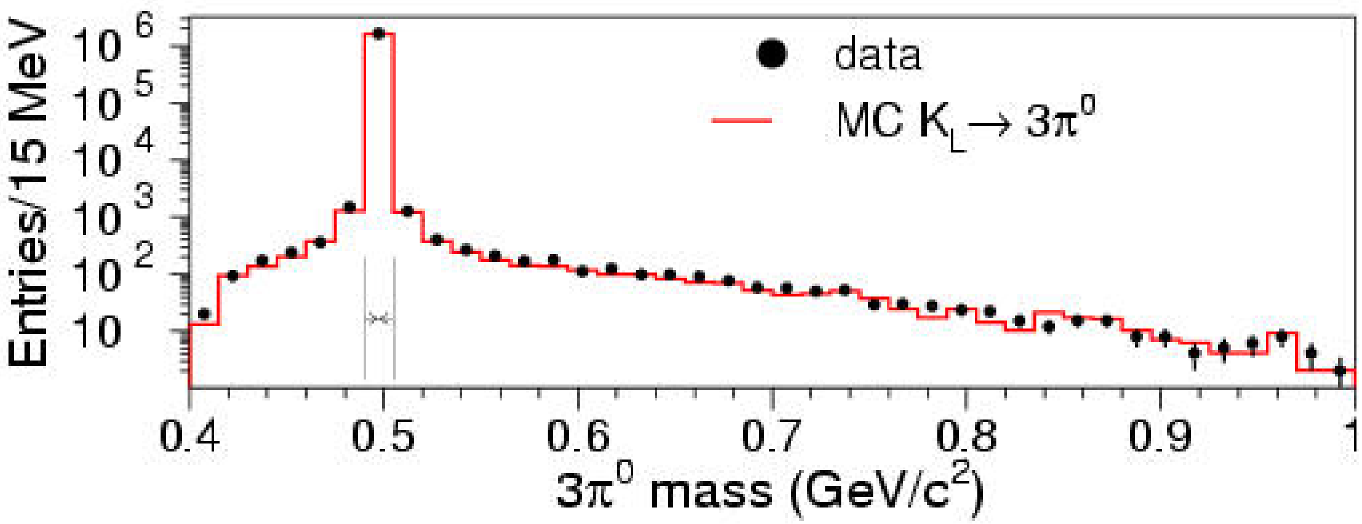


Asymmetry = (13.6 +/- 2.5+/-1.2)%

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

Absolute Efficiency for $3\pi^0$ in $B(3\pi^0)/B(K_{e3})$ ratio

CsI inefficiency (10^{-6}) monitored by laser.
Photon mis-pairings checked in $3\pi^0$ mass;
for events outside signal-mass region, data-MC difference is only 0.14% (included as systematic uncertainty)



Aside: All is not entirely well…CP Violation Parameter $|\eta_{+-}|$ Determined from KTeV Branching Fractions

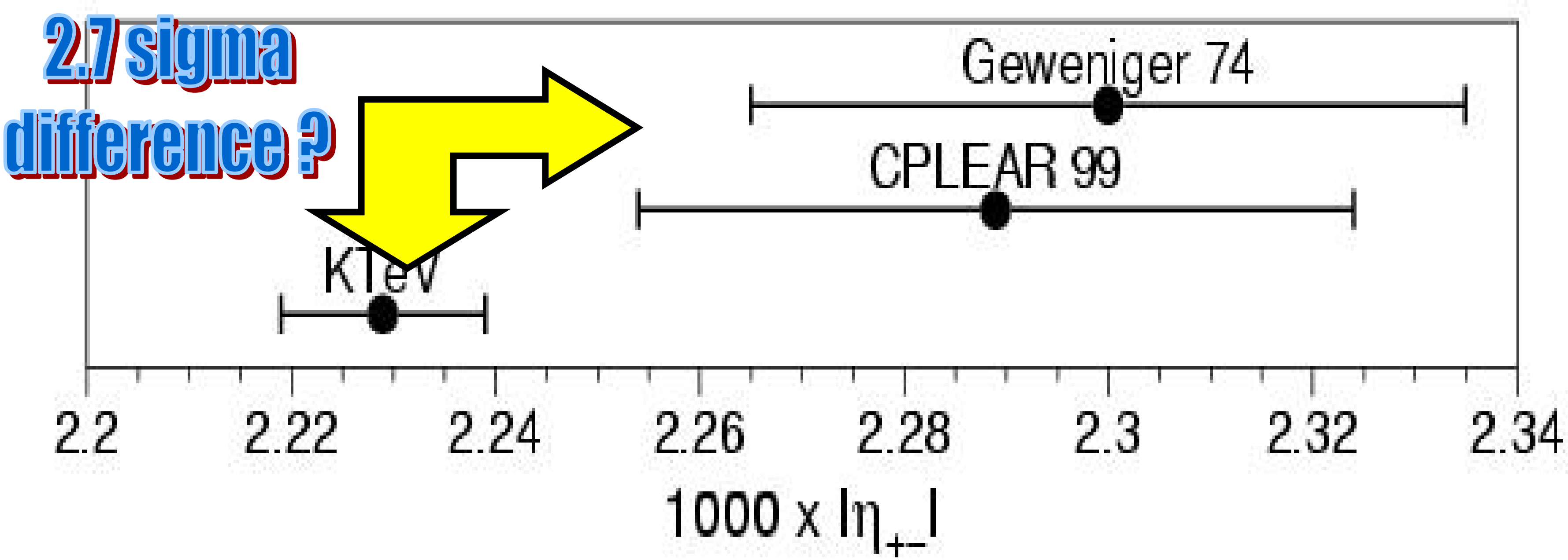
KTeV 2π BRs

$$|\eta_{+-}|^2 = \frac{\Gamma_L}{\Gamma_S}\left\{\frac{B^L_{\pi^+\pi^-} + B^L_{\pi^0\pi^0}[1 + 6Re(\epsilon'/\epsilon)]}{1 - B^S_{\pi\ell\nu}}\right\}$$

K_L and K_S lifetimes

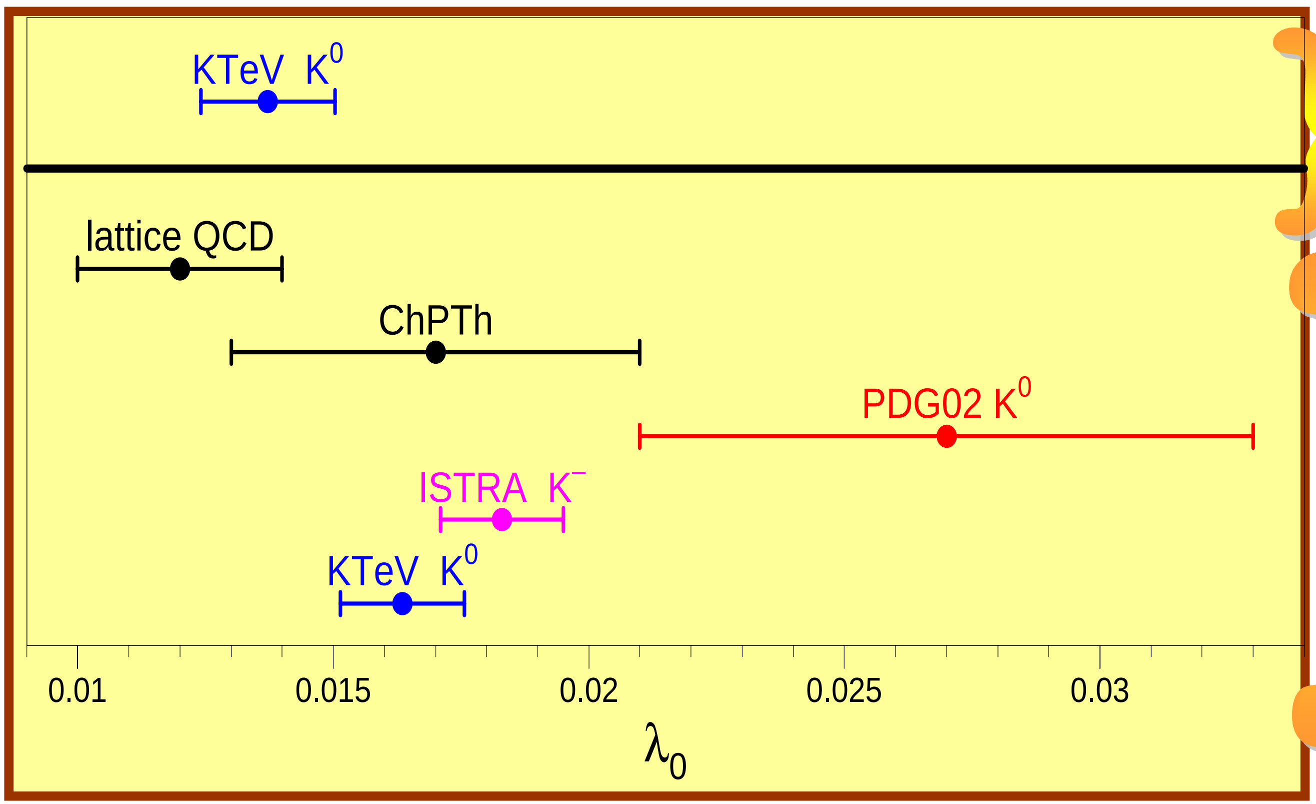
K_S semileptonic BR: 0.12%

Compare KTeV $|\eta_{+-}|$ with previous results using K_L-K_S interference [independent of KTeV-PDG discrepancy in $B(K_L \rightarrow \pi\pi)$]



Recent $f_0(t)$ Comparisons ($K\mu 3$ FF)

Fit with:



quadratic $f_+(t)$

linear $f_+(t)$

Semileptonic Form Factors: λ_+

Ignore 2nd order term in KTeV to compare with other measurements