CP,T symmetries in K_{e4} $(K^{\pm} \rightarrow \pi^{\pm} e^{\pm} \nu)$

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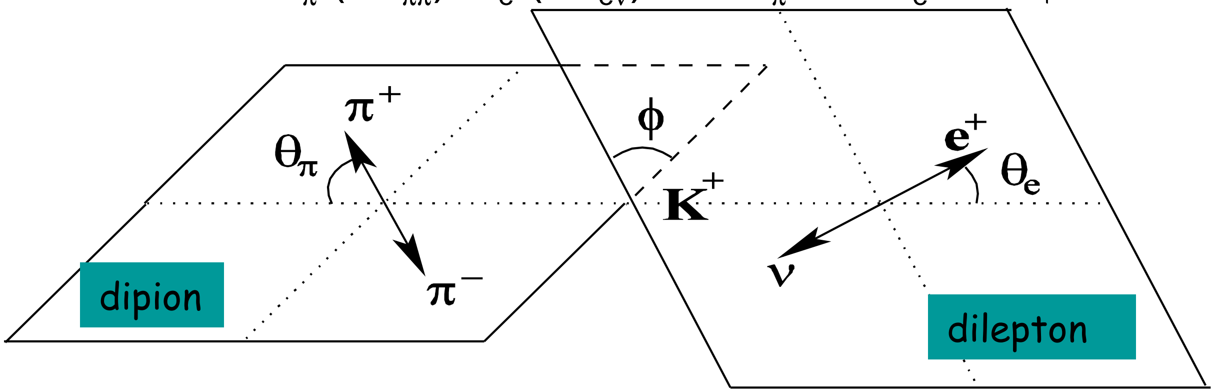
K_{e4} charged decays : formalism

Cabibbo-Maksymowicz define 5 kinematic variables to described Ke4 decay:

s_π ($M^2_{\pi\pi}$), s_e ($M^2_{e\nu}$), $\cos\theta_\pi$, $\cos\theta_e$ and ϕ



The form factors of the decay rate are determined from a fit to the experimental data distribution of the 5 variables.

Several formulations of the form factors appear in the literature:

- Pais and Treiman (Phys.Rev. 168 (1968)) — form factors, $\pi\pi$ phase shift
- Lee and Wu (Ann. Rev. Nucl. Sci. 16 (1966)) — form factors, $\pi\pi$ phase shift, symmetries
- Amoros and Bijnens (J.Phys. G25 (1999)) — form factors, $\pi\pi$ phase shift

Partial rates for $K^{\pm}(p) \to \pi^+\pi^-e^{\pm}\nu_e$

$$d\Gamma_5 = G_F^2|Vus|^2\, N(s\pi,se)\, \mathbf{D}_5(s_\pi,s_e,\theta_\pi,\theta_e,\varphi)\, ds\pi\, dse\, d\cos\theta_\pi\, d\cos\theta_e d\varphi$$

$$\mathbf{D}_5 = I1 + I2\cos 2\theta_e + I3\sin^2\theta_e\cos 2\varphi + I4\sin 2\theta_e\cos\varphi + I5\sin\theta_e\cos\varphi + I6\cos\theta_e + I7\sin\theta_e\sin\varphi + I8\sin 2\theta_e\sin\varphi + I9\sin^2\theta_e\sin 2\varphi$$

intensity functions I1….I9 depend on 3 Form Factors F1, F2 and F3

$I1 = 1/2\{|F1|^2 + 3/2[|F2|^2 + |F3|^2]\sin 2\theta_\pi\}$

$I2 = -1/2\{|F1|^2 - 1/2[|F2|^2 + |F3|^2]\sin 2\theta_\pi\}$

$I3 = -1/2\{|F2|^2 - |F3|^2\}\sin 2\theta_\pi$

$I4 = 2\mathrm{Re}\{F1^* F2\}\sin\theta_\pi$

$I5 = -2\mathrm{Re}\{F1^* F3\}\sin\theta_\pi$

$I6 = -2\mathrm{Re}\{F2^* F3\}\sin 2\theta_\pi$

$I7 = -2\mathrm{Im}\{F1^* F2\}\sin\theta_\pi$

$I8 = \mathrm{Im}\{F1^* F3\}\sin\theta_\pi$

$I9 = -\mathrm{Im}\{F2^* F3\}\sin 2\theta_\pi$ $\rightarrow$ 15 terms

$\tan(\delta) = \frac{1}{2}\langle I7\rangle/\langle I4\rangle = 2\langle I8\rangle/\langle I5\rangle$

$\mathbf{D}_5^{K-} = \mathbf{D}_5^{K+}(s_\pi,s_e,\theta_\pi,\pi-\theta_e,\pi+\varphi)$

kinematic factors: $\alpha = -(PL)\,Q/(M^2\sqrt{s\pi})$, $\beta = Q\sqrt{se}/M^2$ and $\gamma = X/M^2$

take δ_{pg} as phase reference and let $\delta = \delta_{sf} - \delta_{pg}$, $\varepsilon_f = \delta_{pf} - \delta_{pg}$ and $\varepsilon_2 = \delta_{ph} - \delta_{pg}$

On the s- and p-wave hypothesis F1,F2,F3 are expanded in the form

$$F1 = \gamma f_s \exp(i\delta) + \gamma f_p \cos\theta_\pi \exp(i\varepsilon_f) + \alpha\gamma\cos\theta_\pi = g f_s \exp(i\delta) + \alpha\cos\theta\pi\,\{g + \gamma f_p/\alpha\,\exp(i\varepsilon_f)\}$$

and $F2 = \beta g$ and $F3 = \beta g h \exp(i\varepsilon_2)$

fs, fp, g, h and δ = Pais-Treiman parameterization

- amplitudes à la Lee-Wu: $\mathbf{a} = \mathbf{A} \quad l = 0 \quad \mathbf{b}_\sigma = \mathbf{B}_\sigma e^{i(\eta_\sigma - \delta)} \quad l = 1 \quad \sigma = 0, \pm 1$

$$\mathbf{A} = \frac{\sqrt{2}X}{(M_K^2 - s_\pi + s_e)} \mathbf{f_s} \qquad \mathbf{b_0} = \frac{-\sqrt{2}(PL)}{(M_K^2 - s_\pi + s_e)} \frac{\mathrm{Q}}{\sqrt{\mathbf{s}_\pi}} \mathbf{g_p'} e^{i\varepsilon_1}$$

$$\mathbf{b}+ = \frac{\mathrm{Q}}{M_K}\left(\mathbf{g_p} - \frac{X}{M_K^2}\mathbf{h_p} e^{i\varepsilon_2}\right) \qquad \mathbf{b}- = \frac{\mathrm{Q}}{M_K}\left(\mathbf{g_p} + \frac{X}{M_K^2}\mathbf{h_p} e^{i\varepsilon_2}\right)$$

- if CPT holds: $\bar{A} = A$, $\bar{B}_0 = B_0$, $\bar{B}_+ = B_-$, $\bar{B}_- = B_+$

  furthermore $\bar{\eta}_- + \eta_+ = \bar{\eta}_+ + \eta_- = \bar{\eta}_0 + \eta_0 = 2(\delta_p - \delta_s)$

- if CP holds independent of either CPT or T:

  then $\bar{A} = A$, $\bar{B}_0 = B_0$, $\bar{B}_- = B_+$, $\bar{B}_+ = B_-$, $\bar{\eta}_- = \eta_+$, $\bar{\eta}_+ = \eta_-$, $\bar{\eta}_0 = \eta_0$

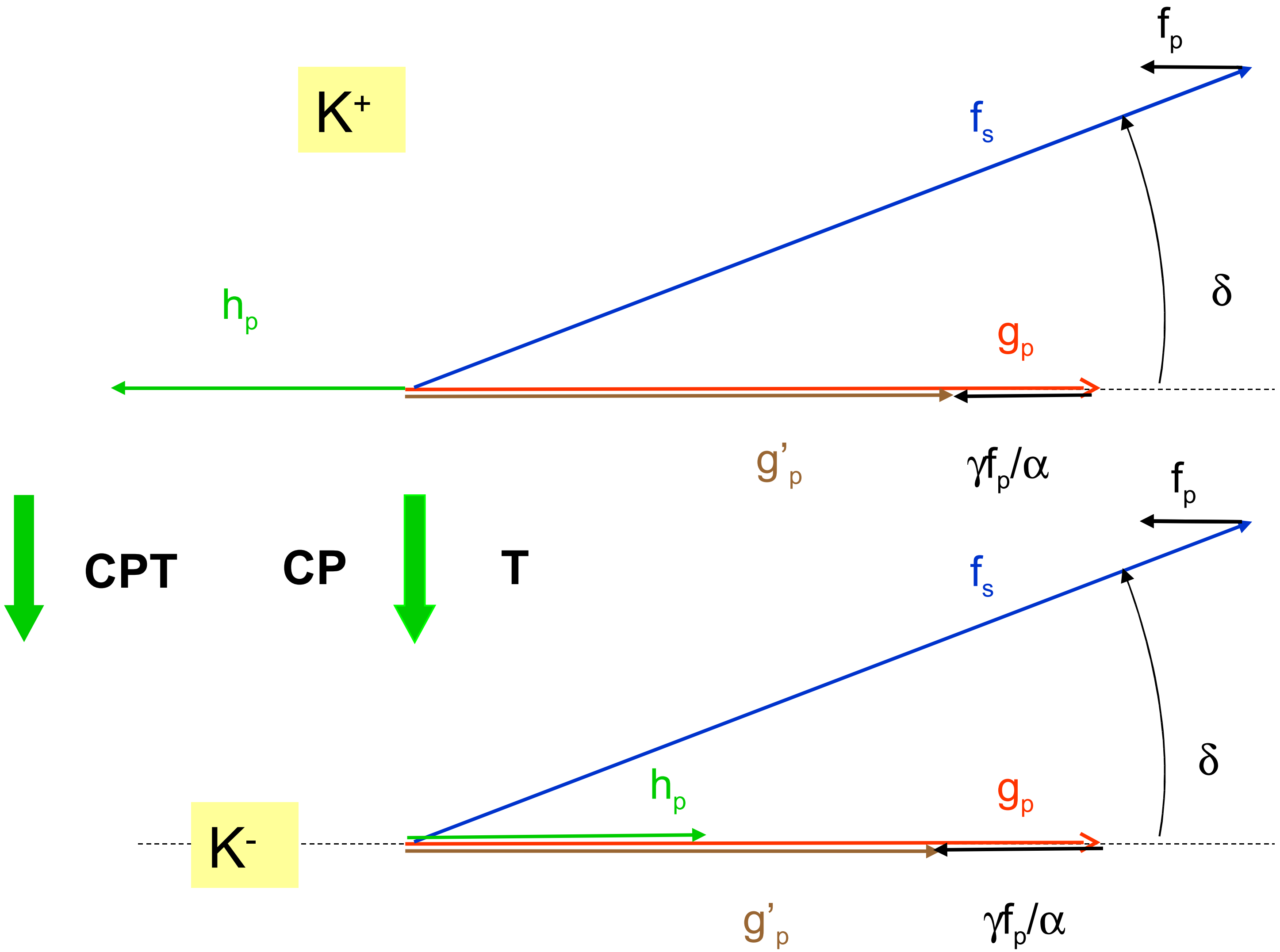
$\rightarrow$ **$\varepsilon_1(K^+) = \varepsilon_1(K^-)$ and $\varepsilon_2(K^+) = \varepsilon_2(K^-)$**

  if CPT $\eta_0 = \eta_+ = \eta_- = \delta_p - \delta_s$

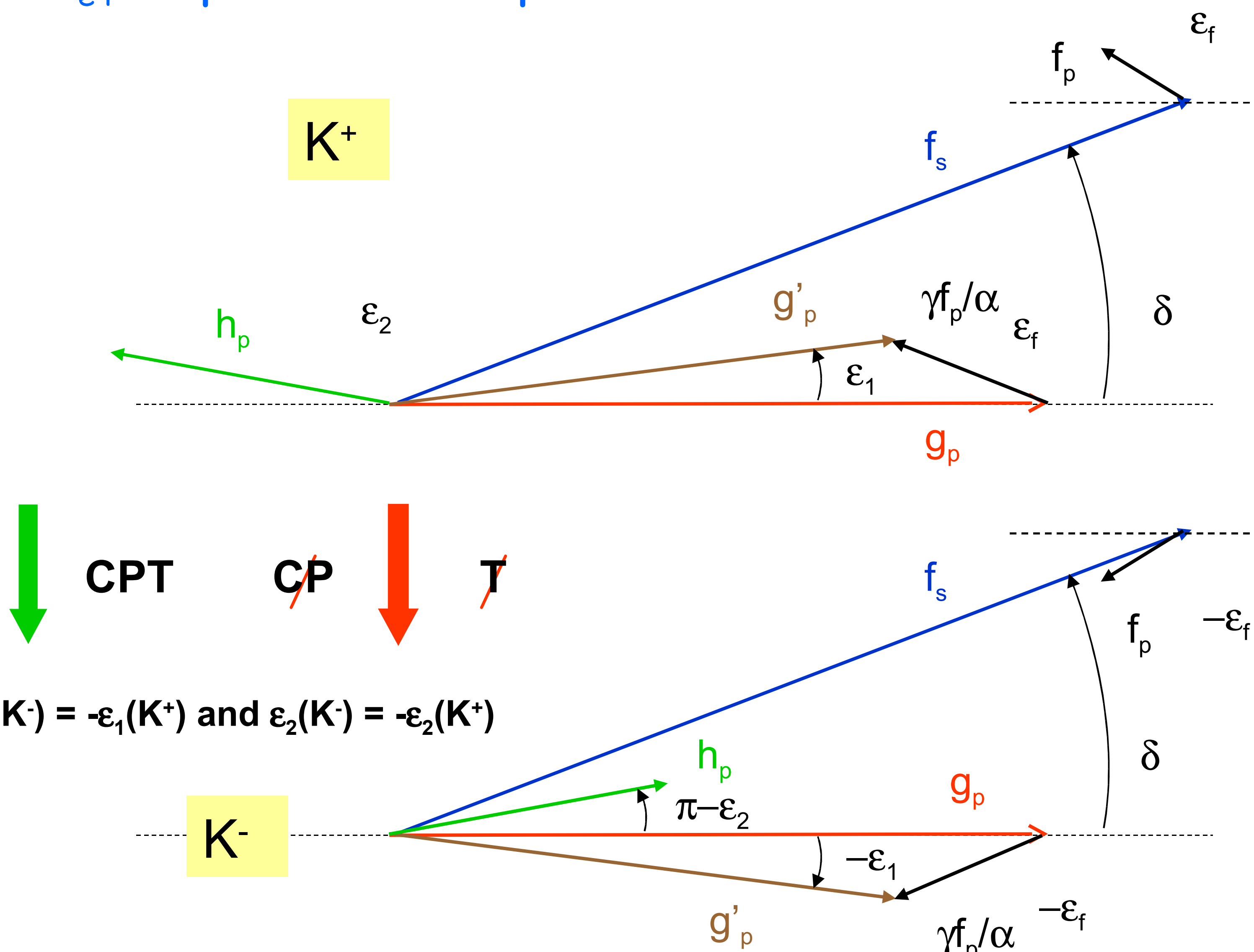
- if T holds independent of either CPT or CP :

  then $\eta_0 = \eta_+ = \eta_- = \delta_p - \delta_s \rightarrow$ **$\varepsilon_1 = \varepsilon_2 = 0$**

K_{e4} amplitudes and phases without T, CP violation



K_{e4} amplitudes and phases with T and CP violation



$\varepsilon_1(K^-) = -\varepsilon_1(K^+)$ and $\varepsilon_2(K^-) = -\varepsilon_2(K^+)$

Standard Ke4 parameters

$g=0.92$, $g'=0.84$, $h=0.37$, $a00=0.25$, $\varepsilon_1=0$, $\varepsilon_2=0$

i	Ji	Bi	typical weight in decay rate
1	f^2	$\gamma^2 \sin^2\theta_e$	1.000
2	g^2	$\beta^2 \sin^2\theta_\pi (1-\sin^2\theta_e \cos^2\phi)$	0.058
3	g'^2	$\alpha^2 \cos^2\theta_\pi \sin^2\theta_e$	0.073
4	h^2	$\beta^2\gamma^2 \sin^2\theta_\pi (1-\sin^2\theta_e \sin^2\phi)$	0.0002
5	$fg'\cos(\delta_0-\varepsilon_1)$	$2\alpha\gamma\cos\theta_\pi \sin^2\theta_e$	0.290
6	$fg\cos\delta_0$	$2\beta\gamma\sin\theta_\pi \sin\theta_e \cos\theta_e \cos\phi$	0.071
7	$fh\cos(\delta_0-\varepsilon_2)$	$-2\beta\gamma^2\sin\theta_\pi \sin\theta_e \cos\phi$	0.013
8	$gg'\cos\varepsilon_1$	$2\alpha\beta\sin\theta_\pi \cos\theta_\pi \sin\theta_e \cos\theta_e \cos\phi$	0.027
9	$g'h\cos(\varepsilon_1-\varepsilon_2)$	$-2\alpha\beta\sin\theta_\pi \cos\theta_\pi \sin\theta_e \cos\phi$	0.0033
10	$gh\cos\varepsilon_2$	$-2\beta^2\gamma\sin^2\theta_\pi \cos\theta_e$	0.0049
11	$fg\sin(\delta_0)$	$2\beta\gamma\sin\theta_\pi \sin\theta_e \sin\phi$	0.031
12	$fh\sin(\delta_0-\varepsilon_2)$	$-2\beta\gamma^2\sin\theta_\pi \sin\theta_e \cos\theta_e \sin\phi$	0.0011
13	$gg'\sin\varepsilon_1$	$2\alpha\beta\sin\theta_\pi \cos\theta_\pi \sin\theta_e \sin\phi$	0.0053 ($\varepsilon 1=0.1$)
14	$g'h\sin(\varepsilon_1-\varepsilon_2)$	$-2\alpha\beta\gamma\sin\theta_\pi \cos\theta_\pi \sin\theta_e \cos\theta_e \sin\phi$	0.0002 ($\varepsilon 1=0.1$)
15	$gh\sin\varepsilon_2$	$-2\beta^2\gamma\sin^2\theta_\pi \sin^2\theta_e \sin\phi \cos\phi$	0.0002 ($\varepsilon 2=0.1$)

Sensitivity to δ

Sensitivity to ε_1

Variation of fit parameters operates on Ji

The 5d shape decay rate is distributed ~ 30000 bins

T violating amplitude $J_{13}B_{13}$ for ε_{fp}=0.2

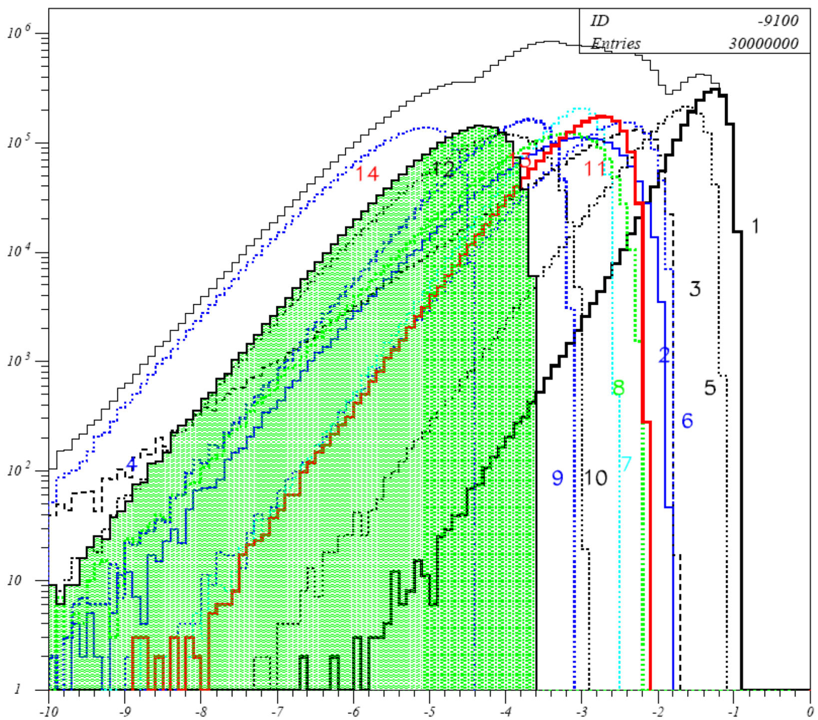
this is a Monte Carlo exercise

Phase of fp

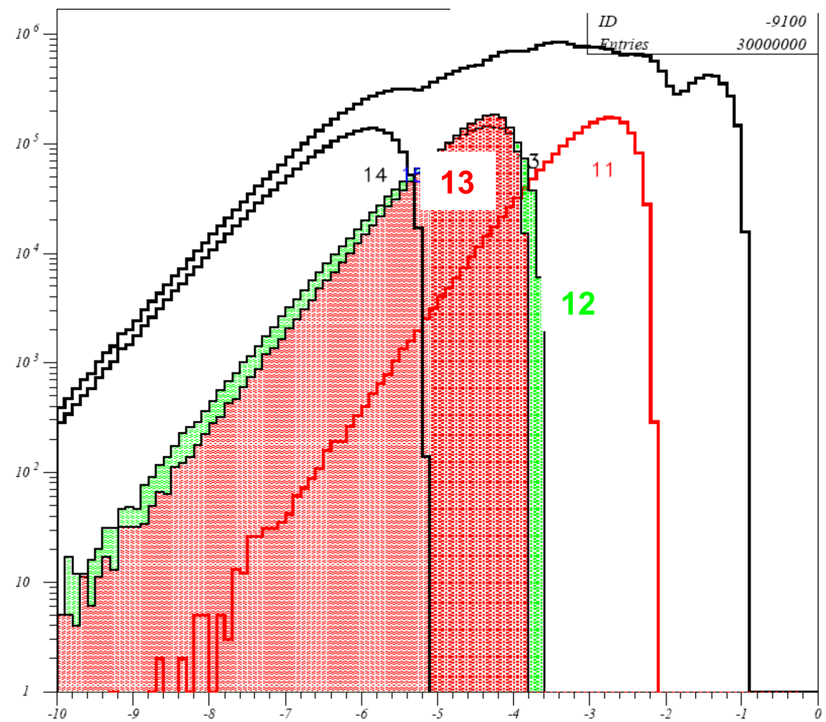
Ke4 matrix elements epscp=0.00 fp=0.05

Ke4 matrix elements epscp=0.200 fp=0.05

$J_{13}B_{13} = O(10^{-3})$



LogJiBi



LogJiBi

Experimental Tests of Discrete Symmetries in the Decays $K^{\pm} \to \pi^{+}\pi^{-}e^{\pm}\nu_e$†

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Tests of the discrete symmetries P, C, CP, and T are obtained through comparison of the rare decays $K^{\pm} \to \pi^{+}\pi^{-}e^{\pm}\nu_e$ (K_{e4} decays). An important outgrowth of the experiment is a direct measurement of the low-energy pion-pion relative scattering phase, $\delta_0 - \delta_1$.

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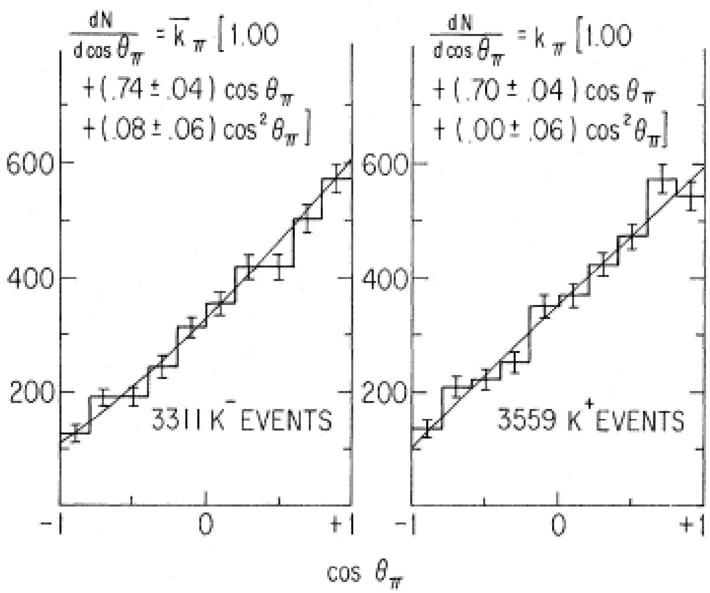

FIG. 2. Distributions in $\cos\theta_\pi$ for K^+ and K^- decays, both corrected for experimental detection efficiency. That correction changes the linear term observed in the raw data by about 16%. The correction is the same for K^+ and K^-.

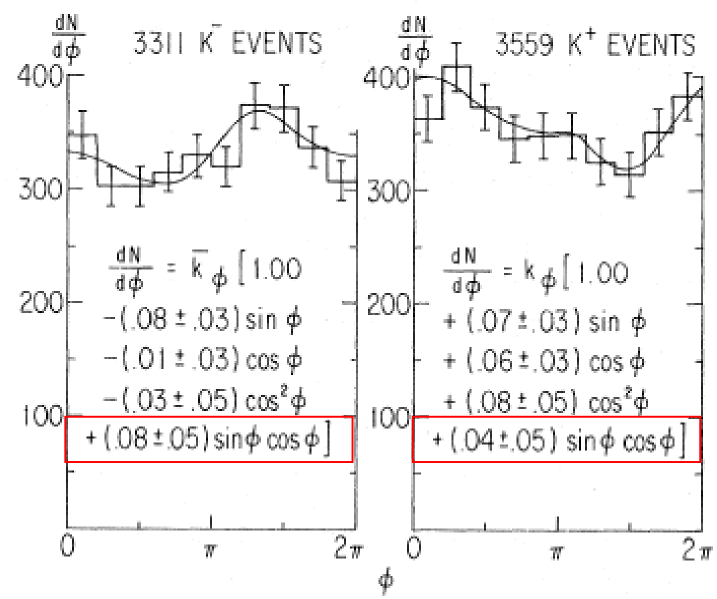

FIG. 3. Distributions in φ for K^+ and K^- decays, both corrected for experimental detection efficiency. The correction is the same for K^+ and K^-. It amounts to $+0.02$ in the coefficient of $\sin\varphi$, -0.06 in the coefficient of $\cos\varphi$, 0.02 in the coefficient of $\cos^2\varphi$, and 0.03 in the coefficient of $\sin\varphi\cos\varphi$.

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How to elucidate the mechanism of *CP* violation

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Several *CP*-violating observables, particularly in semileptonic decays of *K*'s, have the property that they are expected to vanish in the standard model, but are nonzero in alternative models. Thus, they provide very clean ways to test whether the standard model is the (sole) source of *CP* violation and to determine the properties of any other source that may enter. We mainly consider the transverse muon polarization from $K_{\mu 3}$ (which isolates *S* and *P* effective Lagrangians), and the K_{e4} spectrum (which contains a term that isolates *V* and *A* effective Lagrangians). We briefly comment on $W^{\pm}$ production, and heavy-quark and -lepton decays.

TABLE I. This table shows the different ways various mechanisms produce *CP*-violating effects. The entries "yes" and "no" report whether each mechanism is able to produce an observable effect for the experiment in the left-hand column.

Experiment	Mechanism: Standard model	Strong *CP* violation	Non-standard-model *V*, *A* effective Lagrangian	Non-standard-model *S*,*P* effective Lagrangian
ϵ, ϵ'	Yes	No	Yes	Yes
d_n (at level $\gtrsim 10^{-27}$ *e* cm)	No	Yes	Yes	Yes
d_e (at level $\gtrsim 10^{-27}$ *e* cm)	No	No	Yes	Yes
$K_{\mu 3}$ transverse muon polarization	No	No	No	Yes
K_{e4} sin2ϕ term	No	No	Yes	No

Summary

- NA48/2 sensitivity to T violating phases $\varepsilon_{1,2}$ is unique:
  statistics + both K^+ and K^-
- Our K_{e4} samples total ~10^6 K^+ and K^- i.e. x20 larger than those of the last experiment with 3559 K+ and 3311 K-…

E.W. Beier et al. PRL 29, 8(1972)

✂ ⇨ signal of T and CP violation is at reach …

- Question to theorists: ε1(fp) ε2(h) phases within SM and beyond?

Excerpt from Lee Wu paper Ann. Rev. Nucl. Sci. (1966):

… *it seems reasonably certain that some violation of time reversal invariance should be present in these weak decays (Ke4), but the degree of such violation remains unclear.*