Rare Kaon Decays

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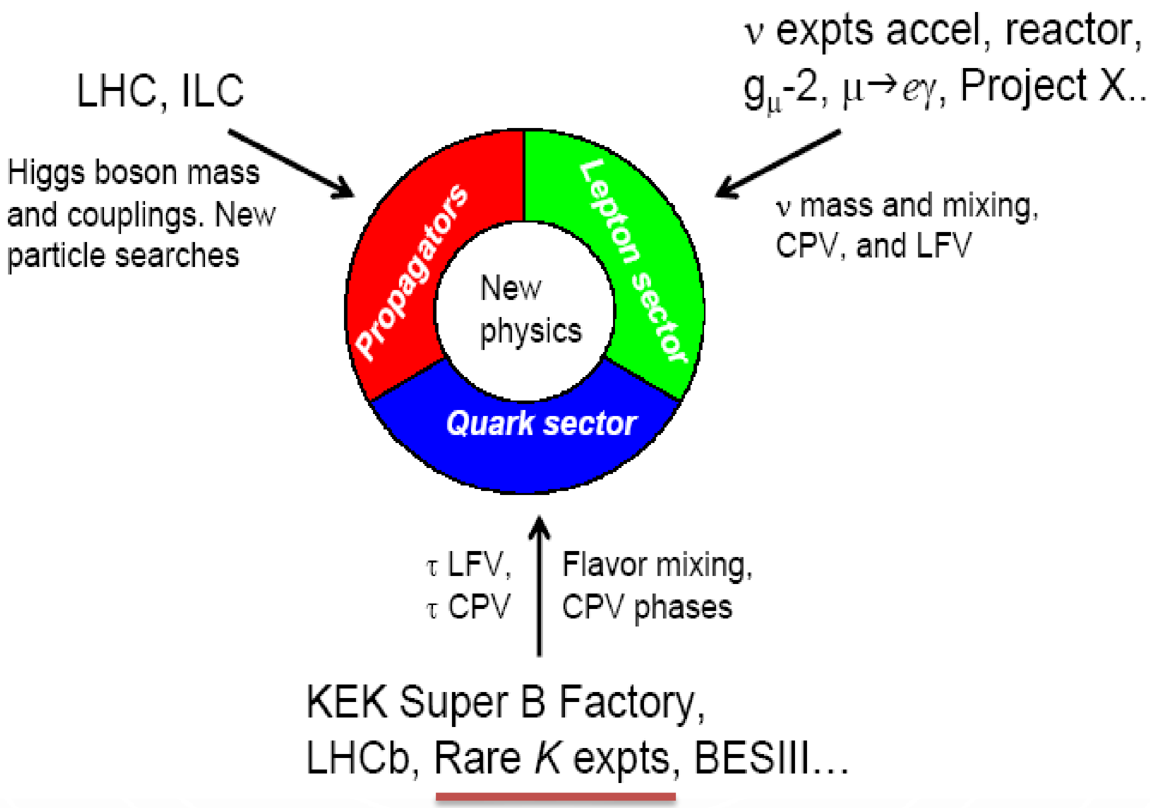
Project X meeting
@
TIFR
A Deemed University
Jan13-14, 2011


LHC, ILC
Higgs boson mass and couplings. New particle searches
ν expts accel, reactor, g_μ-2, μ→eγ, Project X..
ν mass and mixing, CPV, and LFV
Propagators
Lepton sector
Quark sector
New physics
τ LFV, τ CPV
Flavor mixing, CPV phases
KEK Super B Factory, LHCb, Rare *K* expts, BESIII…

Why study Rare Kaon Decays ?

- Search for explicit violation of Standard Model

  Lepton Flavor Violation

- Probe the flavor sector of the Standard Model

  FCNC

- Test fundamental symmetries

  CP, CPT

- Study the strong interactions at low energy

  Chiral Perturbation Theory, K structure

- Exploring lepton mass matrix

  Unique possibility of measuring double beta decay analogue for μ.

Rare decays: K_L decays

$\Delta S = 1$

Mode	Expt. value	
☼ $K_L \to \pi^0 \nu\bar{\nu}$	$< 6.7 \times 10^{-8}$	$= (2.7 \pm 0.4) \times 10^{-11}$
$K_L \to \pi^0\pi^0 \nu\bar{\nu}$	$< 4.7 \times 10^{-5}$	CP
☼ $K_L \to \pi^+\pi^- e^+ e^-$	$< (3.11 \pm 0.19) \times 10^{-7}$	CP
$K_L \to \pi^0\pi^0 e^+ e^-$	$< 6.6 \times 10^{-9}$	CP
$K_L \to \mu^+\mu^-$	$(6.84 \pm 0.11) \times 10^{-9}$	
$K_L \to e^+ e^-$	$(9^{+6}_{-4}) \times 10^{-12}$	
$K_L \to \pi^0 \mu^+\mu^-$	$< 3.8 \times 10^{-10}$	
$K_L \to \pi^0 e^+ e^-$	$< 2.8 \times 10^{-10}$	
$K_L \to e^\pm \mu^\mp$	$< 4.7 \times 10^{-12}$	LF
$K_L \to e^\pm e^\pm \mu^\mp \mu^\mp$	$< 4.12 \times 10^{-11}$	LF
$K_L \to \pi^0 e^\pm \mu^\mp$	$< 7.6 \times 10^{-11}$	LF
$K_L \to \pi^0\pi^0 e^\pm \mu^\mp$	$< 1.7 \times 10^{-10}$	LF

K^+ decays

$\Delta S = 1$

- ☼ $K^+ \to \pi^+ \nu\bar{\nu}$ $(1.7 \pm 1.1) \times 10^{-10}$ $= (8.5 \pm 0.07) \times 10^{-11}$
- $K^+ \to \pi^+ \pi^0 \nu\bar{\nu}$ $< 4.3 \times 10^{-5}$
- $K^+ \to \pi^+ e^+ e^-$ $(3.00 \pm 0.09) \times 10^{-7}$
- $K^+ \to \pi^+ \mu^+ \mu^-$ $(8.1 \pm 1.4) \times 10^{-8}$

- $K^+ \to \mu^- \nu e^+ e^+$ 2.0×10^{-8}
- $K^+ \to \pi^+ \mu^+ e^-$ $< 1.3 \times 10^{-11}$ Lepton Family Number
- $K^+ \to \pi^+ e^+ \mu^-$ $< 5.2 \times 10^{-10}$

- $K^+ \to \pi^- \mu^+ e^+$ $< 5.0 \times 10^{-10}$
- $K^+ \to \pi^- e^+ e^+$ $< 6.4 \times 10^{-10}$ Lepton number
- $K^+ \to \pi^- \mu^+ \mu^+$ $< 3.0 \times 10^{-9}$

- $K^+ \to \pi^+ \gamma$ $< 2.3 \times 10^{-9}$ Angular momentum

$K^+ \to \pi^+ \nu\bar{\nu}$

Theoretically clean mode

Buras: $K^+ \to \pi^+\nu\bar{\nu}$, $K^0 \to \pi^0\nu\bar{\nu}$, ratio x_d/x_s of $B_d^0 - \overline{B_d^0}$ to $B_s^0 - \overline{B_s^0}$ mixing and class of asymmetries in neutral B decays cleanest observables, being essentially free from hadronic uncertainties.

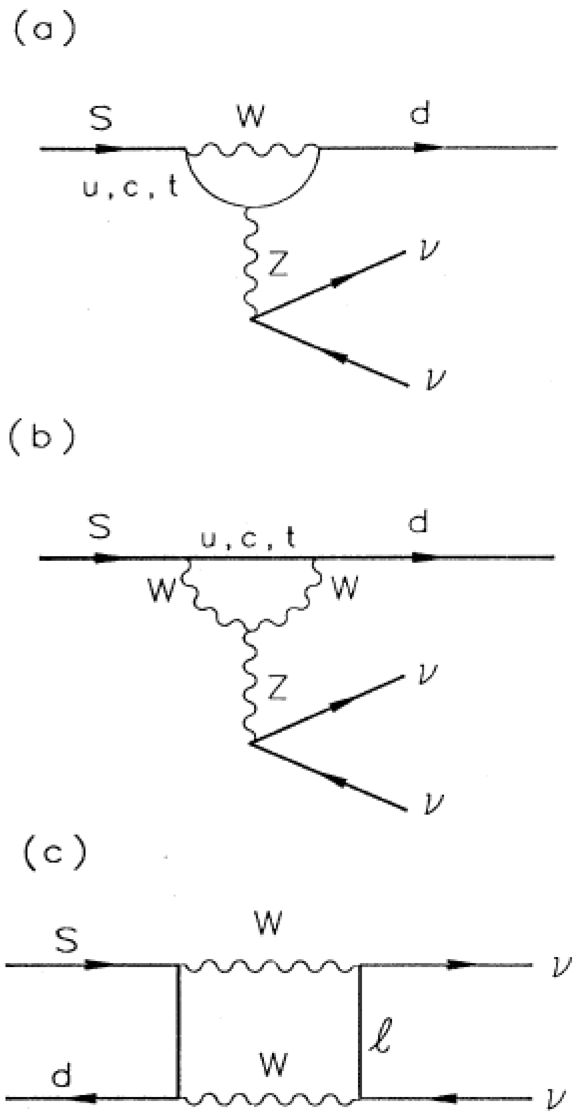
Hadronic matrix element of the operator

$$\bar{s}\gamma_\mu(1-\gamma_5)d \;\bar{\nu}\gamma_\mu(1-\nu_5)\nu$$

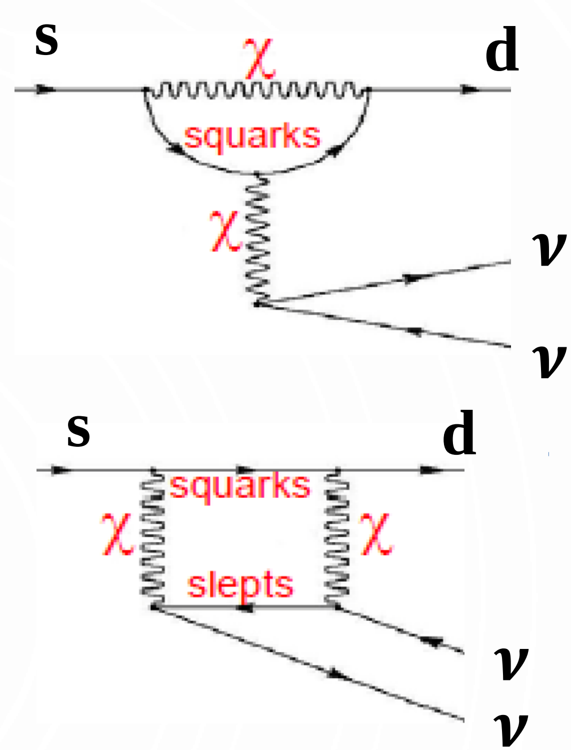
can be measured in the leading decay $K^+ \to \pi^0 e^+ \nu$

$$B_{SD}(K^+ \to \pi^+ \nu\bar{\nu}) = \frac{\kappa_+ \alpha^2 B(K_{e3})}{2\pi^2 \sin^4\theta_W |V_{us}|^2} \sum_l |X_t\lambda_t + X_c\lambda_c|^2 =$$

$$8.9 \times 10^{-11} A^4 \left[(\rho_0 - \bar{\rho})^2 + \bar{\eta}^2\right]$$



SM contribution



SUSY Contribution

Project X sensitive to 1000 SM events.

BSM rates 10x SM rates.

$K_L \to \pi^0 \nu\bar{\nu}$

Buras: $K_L \to \pi^0\nu\bar{\nu}$, $K^+ \to \pi^+\nu\bar{\nu}$, ratio x_d/x_s of $B_d^0 - \overline{B_d^0}$ to $B_s^0 - \overline{B_s^0}$ mixing and class of asymmetries in neutral B decays cleanest observables, being essentially free from hadronic uncertainties.

- *Purely CP-Violating (Littenberg, 1989)*
- *Totally dominated from t-quark*
- *Computed to NLO in QCD (Buchalla, Buras, 1999)*
- *No long distance contribution SM ~3 × 10^{-11}*

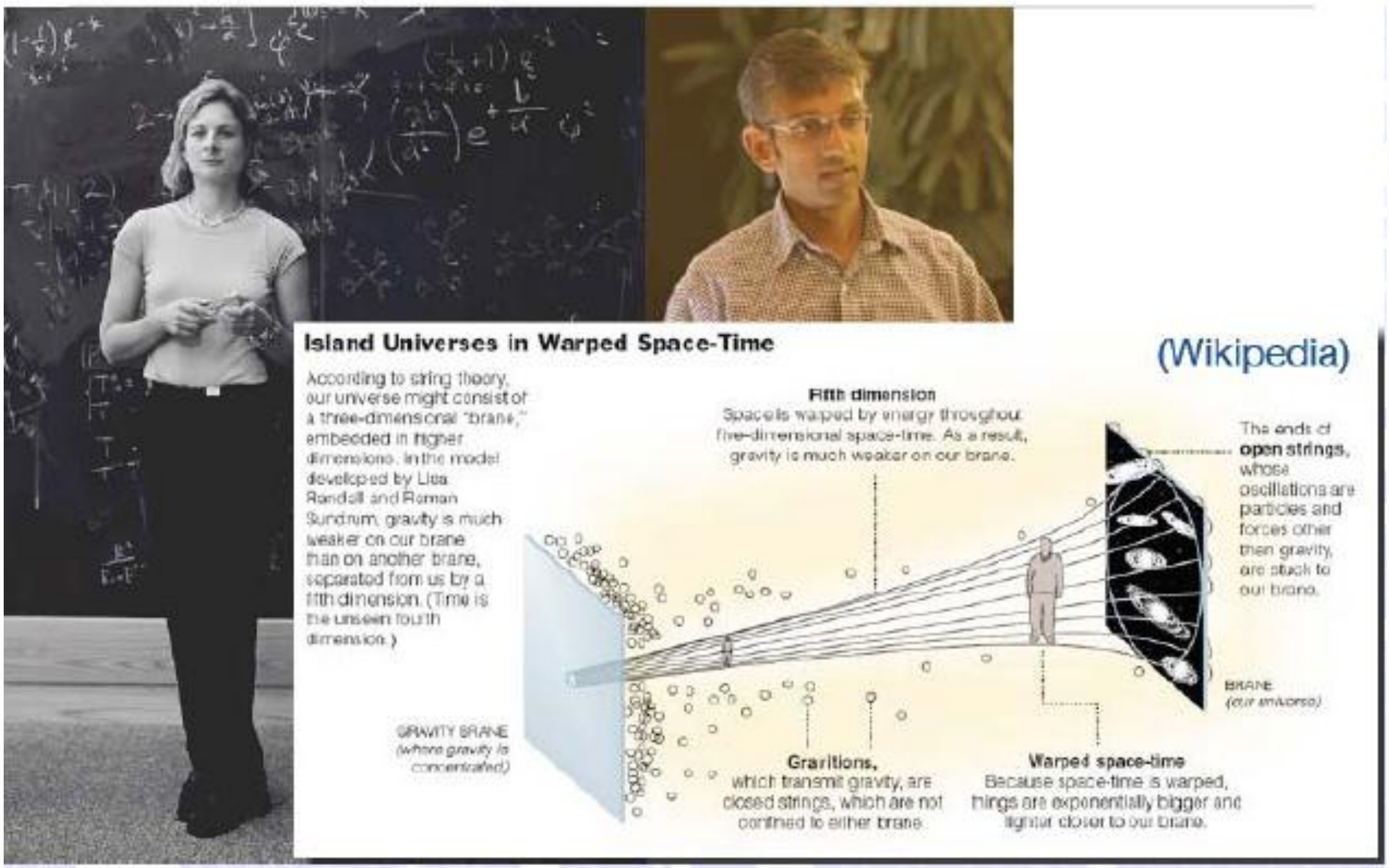
Backgrounds:

$K_L \to 2\pi^0, \pi^0 e^+ e^-, \pi^0\gamma\gamma$

Difficult mode to measure

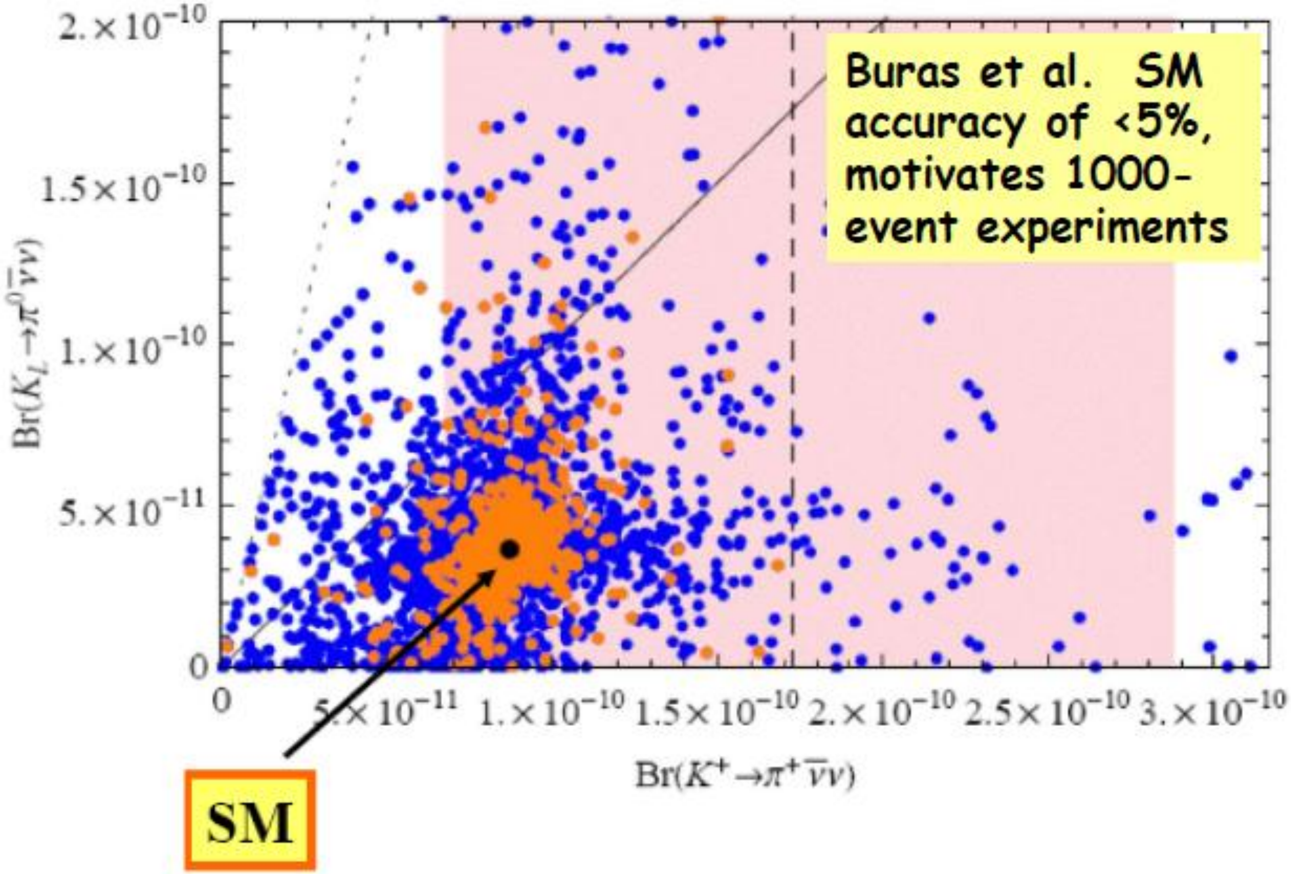
Rates of $K^0 \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$ sensitive to other NP models also

The Randall-Sundrum (RS) idea



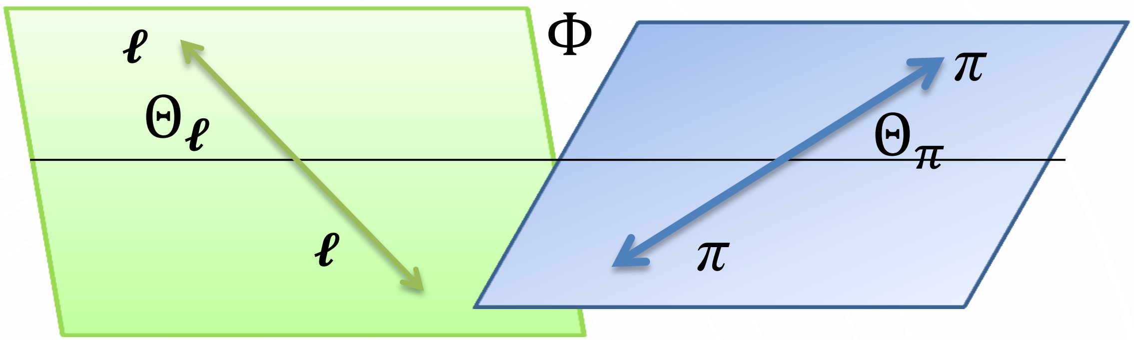
$K_L \to \pi^0 \nu\bar{\nu}$ vs. $K^+ \to \pi^+ \nu\bar{\nu}$ (RS)

(Up to Factor 3 and 2 Enhancements)



Effect of Warped Extra Dimension Models on Branching Fractions

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



$$d\Gamma = \frac{G_F^2}{2^{12}\pi^6 M_K^5} \sin^2\Theta_C X \sigma_\pi \left[1 - \frac{4m_l^2}{s_l}\right]^2 I(s_\pi, s_l, \Theta_\pi, \Theta_l, \Phi) ds_\pi ds_l d\cos\Theta_\pi d\cos\Theta_l d\Phi ,$$

$$\begin{aligned} I = I_1 &+ I_2 \cos 2\Theta_l + I_3 \sin^2\Theta_l \cos 2\Phi \\ &+ I_4 \sin 2\Theta_l \cos\Phi + I_5 \sin\Theta_l \cos\Phi \\ &+ I_6 \cos\Theta_l + I_7 \sin\Theta_l \sin\Phi \\ &+ I_8 \sin 2\Theta_l \sin\Phi + I_9 \sin^2\Theta_l \sin 2\Phi , \end{aligned}$$

$$F_1 = Xf + \sigma_\pi s \cos\Theta_\pi g ,$$

$$F_2 = \sigma_\pi (s_\pi s_l)^{1/2} g ,$$

$$F_3 = \sigma_\pi X (s_\pi s_l)^{1/2} \frac{h}{M_K^2} ,$$

$$\begin{aligned} I_1 &= \tfrac{1}{4}[\{|F_1|^2 + \tfrac{3}{2}(|F_2|^2 + |F_3|^2)\sin^2\Theta_\pi\} \\ &\quad + (F_{1,2,3} \to \tilde{F}_{1,2,3})] , \\ I_2 &= -\tfrac{1}{4}[\{|F_1|^2 - \tfrac{1}{2}(|F_2|^2 + |F_3|^2)\sin^2\Theta_\pi\} \\ &\quad + (F_{1,2,3} \to \tilde{F}_{1,2,3})] , \\ I_3 &= -\tfrac{1}{4}[\{|F_2|^2 - |F_3|^2\} + (F_{1,2,3} \to \tilde{F}_{1,2,3})] , \\ I_4 &= \tfrac{1}{2}\mathrm{Re}(F_1^* F_2)\sin\Theta_\pi + (F_{1,2,3} \to \tilde{F}_{1,2,3}) , \\ I_5 &= -\{\mathrm{Re}(F_1^* F_3)\sin\Theta_\pi - (F_{1,2,3} \to \tilde{F}_{1,2,3})\} , \\ I_6 &= -\{\mathrm{Re}(F_2^* F_3)\sin^2\Theta_\pi - (F_{1,2,3} \to \tilde{F}_{1,2,3})\} , \\ I_7 &= -\{\mathrm{Im}(F_1^* F_2)\sin\Theta_\pi - (F_{1,2,3} \to \tilde{F}_{1,2,3})\} , \\ I_8 &= \tfrac{1}{2}\mathrm{Im}(F_1^* F_3)\sin\Theta_\pi + (F_{1,2,3} \to \tilde{F}_{1,2,3}) , \\ I_9 &= -\tfrac{1}{2}[\mathrm{Im}(F_2^* F_3)\sin^2\Theta_\pi + (F_{1,2,3} \to \tilde{F}_{1,2,3})] . \end{aligned}$$

$$\mathcal{A} = \frac{\int_0^{\pi/2} \frac{d\Gamma}{d\Phi} d\Phi - \int_{\pi/2}^{\pi} \frac{d\Gamma}{d\Phi} d\Phi}{\int_0^{\pi/2} \frac{d\Gamma}{d\Phi} d\Phi + \int_{\pi/2}^{\pi} \frac{d\Gamma}{d\Phi} d\Phi} = 15\% \sin[\Phi_{+-} + \delta_0(m_K^2) - \bar{\delta}_1] \approx 14\% .$$

Strong phase

Weak phase

Heiliger & Sehgal Phys. Rev. D48, 4146 (1993).

$$K_L \to \pi^+(p_+)\pi^-(p_-)\ell^+(k_+)\ell^-(k_-)$$

Under CP:

$$p_\pm \xrightarrow{CP} -p_\mp \quad \cos\Theta_\pi \to -\cos\Theta_\pi \quad \sin\Theta_\pi \to \sin\Theta_\pi$$

$$k_\pm \xrightarrow{CP} -k_\mp \quad \cos\Theta_\ell \to -\cos\Theta_\ell \quad \sin\Theta_\ell \to \sin\Theta_\ell$$

$$\cos\Phi \to \cos\Phi \quad \sin\Phi \to -\sin\Phi$$

Signal of T-reversal violation

Several papers supporting and several other disputing signal is genuine T-violation

CPT is introduced through the Hamiltonian

$$\mathcal{H} = E\begin{pmatrix} \cos\theta & \sin\theta e^{-i\phi} \\ \sin\theta e^{i\phi} & -\cos\theta \end{pmatrix} - iD\mathcal{I}\ .$$ *CPT restored if* $\theta = \frac{\pi}{2}$

A complete calculation without CPT in mixing is underway.

CPT violation should be studied in K since large numbers of K mesons will be produced.

Conclusion

- ***After more than 60 years K meson continues to be produced in lab and is still a valuable source for understanding new physics.***
- ***Will continue to be a studied at least until a 5σ signal is observed in $K_L \rightarrow \pi^0 \nu\bar{\nu}$.***

$$K_1 = (K^0 + \bar{K}^0)/\sqrt{2} \, ,$$

$$K_2 = (K^0 - \bar{K}^0)/\sqrt{2} \, ,$$

$$K_S = (K_1 + \tilde{\varepsilon} K_2)/\sqrt{1 + |\tilde{\varepsilon}|^2} \, ,$$

$$K_L = (K_2 + \tilde{\varepsilon} K_1)/\sqrt{1 + |\tilde{\varepsilon}|^2} \, .$$