Rare Processes at Project X

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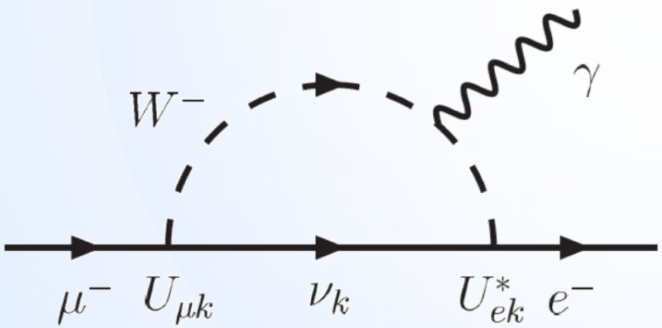
μ decays – Why Muons?

- *Low-energy μ processes in certain cases constitute a powerful unique probe of new physics around the electroweak scale. Similar sensitivity to new physics energy scale as achievable at high-energy colliders.*
- *Constraint from g-2 of μ among the most stringent tests of the Standard Model.*
- *μ decay is the cleanest weak decay process. It provides measurement of G_F , which is used as input for computing other electroweak observables. Polarized μ decay are still very sensitive to New Physics.*

- *Flavor Changing Neutral Current processes observed in the quark sector* ($K^0 - \overline{K^0}$, $b \to s\gamma$, ...)
- *Charged Lepton Flavor Violation (CLFV) not yet observed.*

  Rates depend significantly on physics that gives mass to neutrinos

$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W} \right|^2 < 10^{-54}$$



In SM GIM suppression seems to far more severe for lepton sector than quark sector

- *Measurements that are small in SM are good places to look for NP*

$\mu \to e\gamma$, $\mu^- Z \to e^- Z$

- *Current upper bound* $Br(\mu \to e\gamma) < 1.2 \times 10^{-11}$
- *MEG aims sensitivity to* $Br(\mu \to e\gamma) \leq 10^{-13}$
- *Mu2e and COMET expect* $Br(\mu \to e\gamma) \leq 10^{-17}$

Rely on stopping μ^- on target and observing e^- with energy equivalent to muon plus its binding energy. Require good electron energy resolution.

- ***Interesting measurement at Project X for both scenarios.***
- ***If CLFV observed before Project X would allow precision studies with ~100 μ − e conversion events.***
- ***If not Project X can achieve sensitivity of*** $Br(\mu \to e\gamma) \leq 10^{-19}$

$\mu \to e\gamma$ and $\mu^+ \to e^+e^+e^-$ are limited at Project X due to accidental backgrounds but doable.

Project X can however measure τ_μ (Muon life time) with better precession.

Project X could produce intense beam of muonium. Conversion of muonium to anti-muonium in vacuum corresponds to $\Delta L = 2$

A permanent electric dipole moment of μ in SM $d_\mu \sim 10^{-35}$ e-cm. Current bound is $d_\mu \sim 1.8 \times 10^{-19}$ e-cm. Project X can achieve sensitivities of $d_\mu \sim 10^{-24}$ e-cm.

Also, improvement in magnetic moment of μ, $a_\mu = \frac{g-2}{2}$ achieveable.

K decays

Why study Rare Kaon Decays ?

- Probe the flavor sector of the Standard Model

  FCNC

- Test fundamental symmetries

  CP, T, 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

- Search for explicit violation of Standard Model

  Lepton Flavor Violation.

Rare decays: K_L decays

$\Delta S = 1$

Mode	Expt. value		
• ☼ $K_L \to \pi^0 \nu\bar{\nu}$	$< 6.7 \times 10^{-8}$	$= (2.7 \pm 0.4) \times 10^{-11}$	CP
• $K_L \to \pi^0 \pi^0 \nu\bar{\nu}$	$< 4.7 \times 10^{-5}$		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}
- $K^+ \to \pi^+ \mu^+ e^-$ $< 1.3 \times 10^{-11}$
- $K^+ \to \pi^+ e^+ \mu^-$ $< 5.2 \times 10^{-10}$

Lepton Family Number

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

Lepton number

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

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 $K^+ \to \pi^0 e^+ \nu$

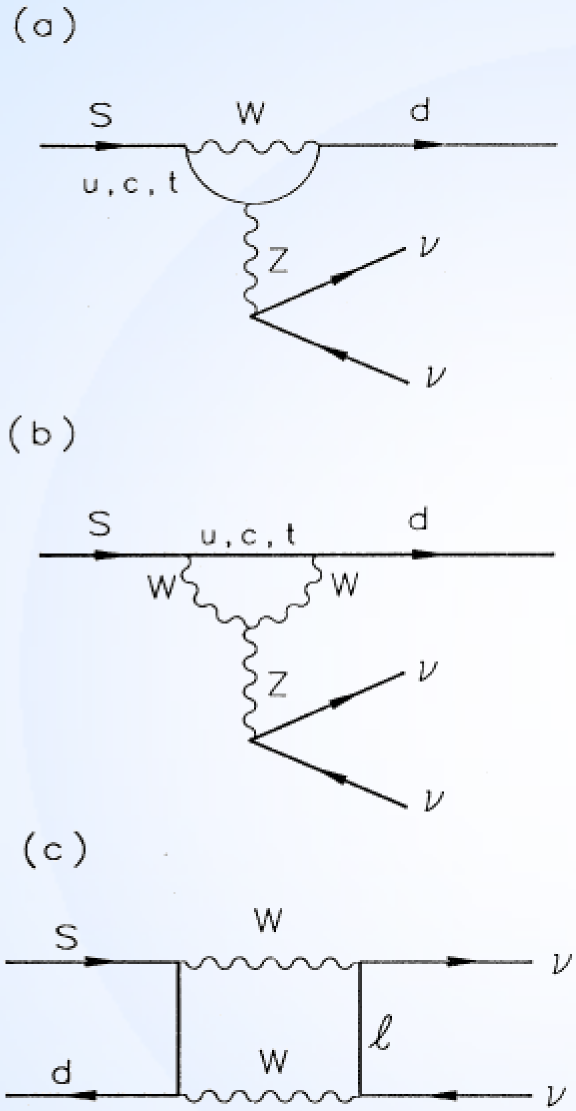
$$B_{SD}(K^+ \to \pi^+\nu\bar{\nu}) = \frac{\kappa_+ \alpha^2 B(K_{e3})}{2\pi^2 \sin^4\theta_W |V_{us}|^2} \sum_l |X_t\lambda_t + X_c\lambda_c|^2 =$$

$$8.9 \times 10^{-11} A^4 \left[(\rho_0 - \bar{\rho})^2 + \bar{\eta}^2\right] = (8.22 \pm 0.84) \times 10^{-11}$$

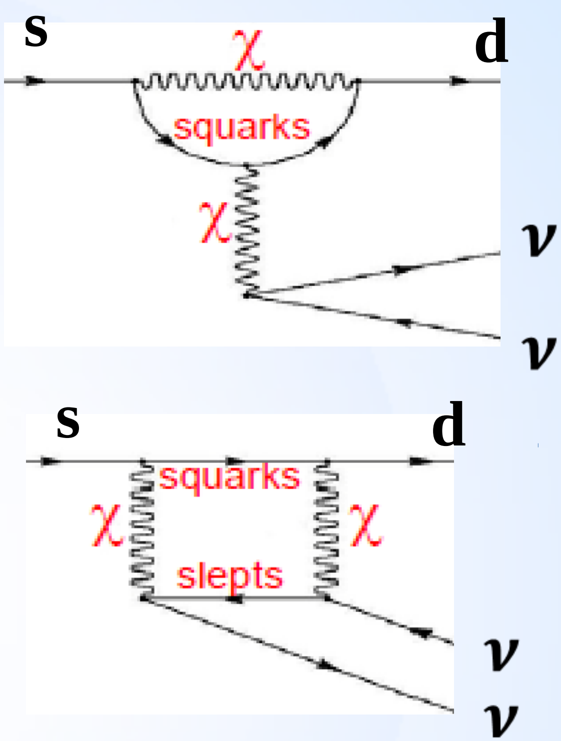
$$= (1.7 \pm 1.1) \times 10^{-10}$$

SM

Exp



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}*

$$B(K_L \to \pi^0\nu\bar{\nu})_{SM} = (2.76 \pm 0.4) \times 10^{-11}$$

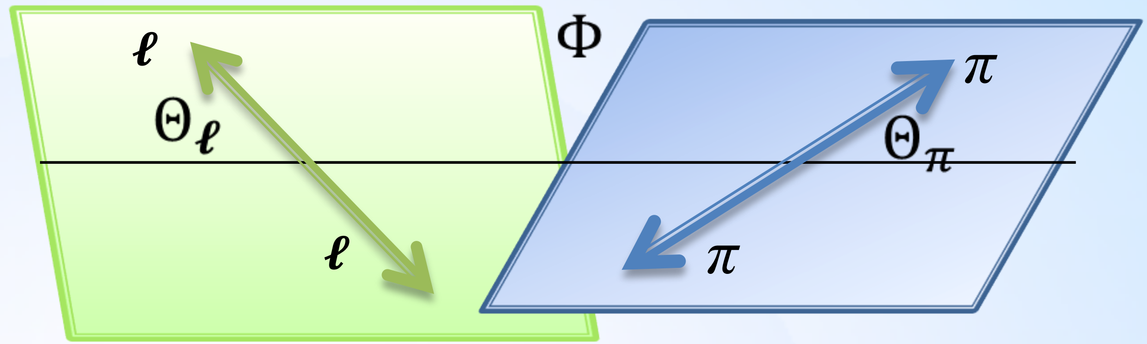
$$B(K_L \to \pi^0\nu\bar{\nu})_{Exp} < 10^{-8}$$

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 NP models

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



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

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

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

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

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

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

$$\mathcal{A} = \frac{\int_0^{\pi/2} \frac{d\Gamma}{d\Phi} d\Phi - \int_{\pi/2}^{\pi} \frac{d\Gamma}{d\Phi} d\Phi}{\int_0^{\pi/2} \frac{d\Gamma}{d\Phi} d\Phi + \int_{\pi/2}^{\pi} \frac{d\Gamma}{d\Phi} d\Phi}$$

$$= 15\% \sin[\Phi_{+-} + \delta_0(m_K^2) - \bar{\delta}_1]$$

$$\approx 14\% \ .$$

Strong phase

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

Weak phase

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

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. Unlikely that CPT violation observed before Project X

An interacting theory that violates CPT invariance necessarily violates Lorentz invariance. On the other hand, CPT invariance is not sufficient for out-of-cone Lorentz invariance. Theories that violate CPT by having different particle and antiparticle mass must be nonlocal.

Greenberg Phys. Rev. Lett. 89, 31602 (2002)
Lot of work by A. Kosteleckỳ

Conclusion

- *Lepon flavour violation is yet to be established. One should be prepared for surprises.*
- *Improvements in G_F are critical in precision tests of NP.*

- *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 $K_L \to \pi^0 \nu\bar{\nu}$.*
- *T and CPT studies need to be done. Large statistics will provide unique opportunity to do so.*