

Extremely Rare & Strange

$$K \rightarrow \pi \nu \bar{\nu}$$

Andreas S. Kronfeld



Scientific Challenges for Understanding the
Quantum Universe

and the

Role of Computing at Extreme Scale

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The Old View

- Ten years ago, when discussing neutral and charged $K \rightarrow \pi\nu\bar{\nu}$, it was viewed as a clean constraint on the CKM matrix.
- The tacit underlying assumption was that only SM particles contribute to the loops.
- It was convenient to combine all CKM factors in Wolfenstein ways.

The New View

- Over the next ten years, we expect other, SM tree-level, processes to determine CKM with $\sim 1\%$ precision.
- Over the next ten years, we expect to observe new particles at the LHC.
- We want new and different insights on their dynamics from the loops of $K \rightarrow \pi\nu\bar{\nu}$.

Theory Background

- Even BSM, the only operator is
 $(\bar{s}\gamma_\mu d)(\bar{\nu}_L\gamma^\mu\nu_L)$

as long as neutrinos are left handed.

- Same form factors as $K \rightarrow \pi l\nu$, up to isospin corrections from π^0 - η mixing.

Experiments

- Experiments planned in Japan ($K_L \rightarrow \pi^0 \nu \bar{\nu}$) and at CERN ($K^+ \rightarrow \pi^+ \nu \bar{\nu}$) to observe around 100 events.
- Experiments envisioned at Fermilab (both modes) to observe 1000 events, but given lower priority by P5:
 - 3 % uncertainty target.

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

- Schematically, the (SM) branching ratio is

$$\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \propto r_{K_L} \text{BR}(K^+ \rightarrow \pi^0 e^+ \nu) \times \frac{\alpha^2}{\sin^4 \theta_W} \times \left[\frac{\text{Im} V_{ts}^* V_{td}}{|V_{us}|} \right]^2 \times [X(m_t, \alpha_s)]^2$$

where r_{K_L} describes isospin breaking.

- The largest uncertainty comes from the CKM factor.

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

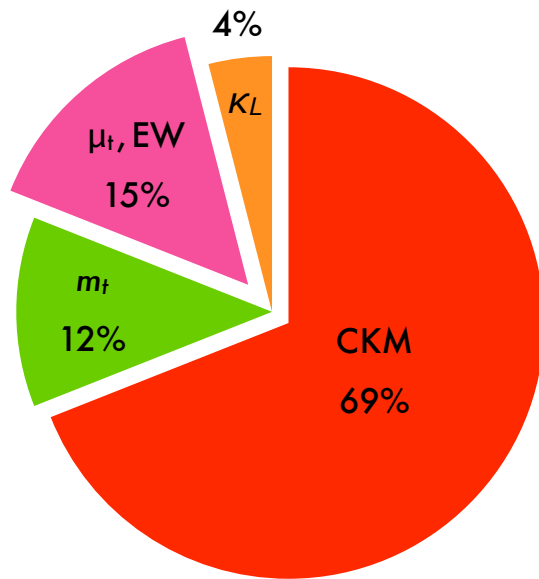
- Schematically, the (SM) branching ratio is

$$\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) \propto r_{K^+} \text{BR}(K^+ \rightarrow \pi^0 e^+ \nu) \times \frac{\alpha^2}{\sin^4 \theta_W} \times \sum_l \left| \frac{V_{ts}^* V_{td}}{V_{us}} X(m_t, \alpha_s) + \frac{V_{cs}^* V_{cd}}{V_{us}} X_{\text{NL}}(m_c, m_l, \alpha_s) \right|^2$$

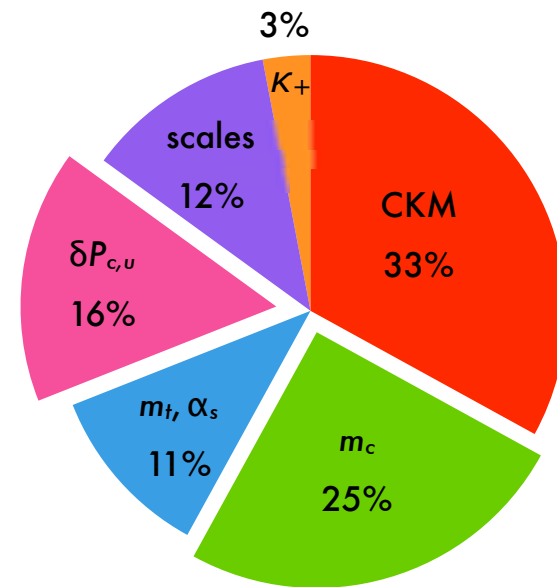
where r_{K^+} describes isospin breaking.

- Same X as before; X_{NL} sums logs.

Error budgets



K_L



K^0

U. Haisch, arXiv:0707.3098v3

m_c

- Flavianet reckons that $m_c = 1.30(5)$ GeV (i.e., 4%) leads to 5% uncertainty in BR^+ .
- HPQCD-Karlsruhe [arXiv:0805.2999]:

$$m_c(m_c) = 1.268(9) \text{ GeV}$$

combining LQCD correlators + α_s^3 PT.

- So 1% m_c uncertainty in BR^+ seems well in hand.

- Using CKM unitarity and dropping $|V_{tb}| - 1$:

$$\frac{\text{Im } V_{ts}^* V_{td}}{|V_{us}|} = - \frac{|V_{cb}| \text{Im } V_{ub}}{|V_{us}|} = \frac{|V_{cb}| |V_{ub}| \sin \delta_{KM}}{|V_{us}|} = \frac{(A\lambda^2)(A\lambda^3\eta)}{\lambda}$$

so we want to forecast the uncertainty of all 4 basic CKM parameters over the next several years.

- Let's look at direct determinations; global analysis could shrink errors further.

$$|V_{us}|, |V_{cb}|, |V_{ub}|$$

- Expect 0.5% on $|V_{us}|$ from K_{l3} and K_{l2} decays “soon.” Could also eliminate this by direct calculation of desired isospin combinations
- Can reach 0.5% on $|V_{cb}|$ before exascale era
- Vera told us that experiment, even with SuperB, could prevent 1% on $|V_{ub}|$.

$\sin \delta_{\text{KM}}$: LHCb

- LHCb forecasts an error on $\gamma = \delta_{\text{KM}}$ of
 - 5° in 2.5 fb^{-1}
 - 2.5° in 10 fb^{-1}
- This corresponds to a 1% (0.6%) error in $\sin \delta_{\text{KM}}$, since $\delta_{\text{KM}} \approx 80^\circ$.
- See <http://lhcb-doc.web.cern.ch/lhcb-doc/presentations/conferencetalks/postscript/2007presentations/MCalviFlavourPhysics.pdf>

Total

$$2 \sqrt{3 \times (0.5)^2 + 2^2} = 4.4\%$$

rate $|V_{cb}|$ $|V_{ub}|$

$|V_{us}|$

$\sin \delta_{KM}$

The 2% for $|V_{ub}|$ may be optimistic.

BSM

- New “beyond the SM” particles change the short-distance dynamics:
 - $\text{CKM} \times X \Rightarrow (\text{new FV}) \times X_{\text{new}}$;
 - if $(\text{new FV}) \propto \text{CKM}$, that’s called MFV
- Solve BR_L for $X(m_t)$, generalize to $X(m_c)$, plug into BR_+ , and see if it agrees with experiment: favor or kill MFV.

- By the time you have 1000-event, the LHC experiments will (we all hope) have seen new particles.
- Models to explain them will be developed.
- Every model will have its own $X(\nu)$, where the $\nu = \{m_t, \alpha_s, \text{new couplings \& masses}\}$.
- Every model can be favored or killed by BR_L and BR^+ .

Isospin Worries

- Relative to $K^+ \rightarrow \pi^0 \bar{l} \nu$
 - $r_{K^+} = 0.9614 \times 0.979 \times 0.9574$
 - $r_{K_L} = 1.0522 \times 0.979 \times 0.9166$

phase	rad.	π^0 - η
space	corr.	mixing
- The last bodes for “excitement” when up and down have different masses.