Rare K Decays in the Standard Model

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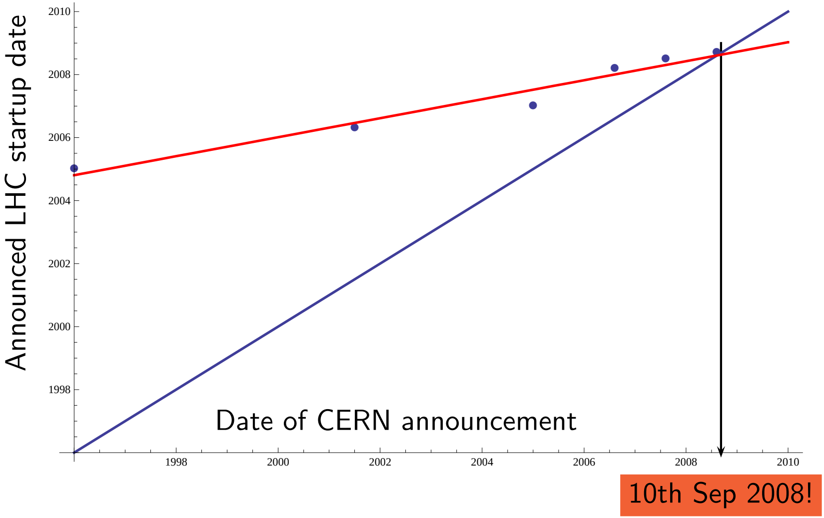
10th September 2008

LHC will start today. . .



Also K Physics is important:

Rare K decays...

- ...test flavour structure of standard model
- ...allow discovery of new particles by precision measurements
- ...allow to distinguish different new physics models $\longrightarrow$ Details in next talk by Christopher Smith

This talk: Overview of the current situation in the Standard Model

Four Rare K Decays

$$K_L \to \pi^0 e^+ e^- \qquad K^+ \to \pi^+ \nu \bar{\nu}$$
$$K_L \to \pi^0 \mu^+ \mu^- \qquad K_L \to \pi^0 \nu \bar{\nu}$$

The Main Points

- FCNC $\Rightarrow$ sensitive to New Physics
- Short distance contributions sizeable
- Experimentally challenging but feasible
- Very precise theoretical predictions possible

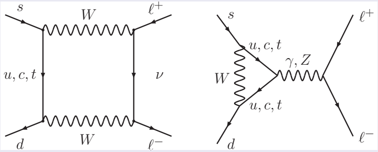
Why are we able to make Precise Predictions?

- Short distance (SD) contributions (Wilson coefficients) can be calculated precisely in perturbation theory
- Semileptonic decays $\Rightarrow$ extract matrix elements via isospin symmetry from $K_{\ell 3}$ decays [Marciano, Parsa '96]
- powerlike GIM suppresses Long Distance (LD) contributions for $K \to \pi\nu\bar{\nu}$
- LD contributions to $K_L \to \pi^0\ell^+\ell^-$ can be extracted from experiment ($K_L \to \pi^0\ell^+\ell^-$ and $K_L \to \pi^0\gamma\gamma$)
- Error mainly parametric – can be reduced in the future

Contents

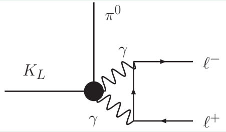
$K_L \to \pi^0\ell^+\ell^-$: Three Contributions

Direct *CP* Violating

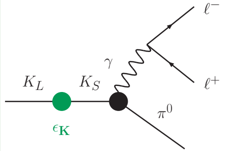


$$Q_{7V} = (\bar{s}_L\gamma_\mu d_L)(\bar{\ell}\gamma^\mu\ell), \quad Q_{7A} = (\bar{s}_L\gamma_\mu d_L)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$

CP Conserving



Indirect *CP* Violating



$K_L \to \pi^0\ell^+\ell^-$: Theoretical Status

Short Distance Q_{7V} and Q_{7A}

- $Q_{7V} \to 1^{--}$
- $Q_{7A} \to 1^{++}, 0^{-+}$
- Wilson coefficients known to NLO QCD (scale dependence $< 1.5\%$) [Buchalla et al. '96]

CP conserving contribution

- From double-photon penguin
- Estimate from $K_L \to \pi^0\gamma\gamma$ [Isidori et al. '04] (New results 2008! [KTEV])

Indirect CP violating contribution

- counterterm $|a_S| = 1.20 \pm 0.20$ from $K_S \to \pi^0\ell^+\ell^-$ [D'Ambrosio et al. '98, Mescia et al. '06]
- $\ell^+\ell^-$ in 1^{--} state $\Rightarrow$ (constructive) interference with Q_{7V} contribution [Buchalla et al. '03, Friot et al. '04; Bruno et al. '93]
- $\to$ Use lepton energy asymmetry [Mescia, Smith, Trine '06]

$K_L \to \pi^0\ell^+\ell^-$: Branching Ratio

$$B(K_L \to \pi^0\ell^+\ell^-) = \left(C^\ell_{\rm dir} \pm C^\ell_{\rm int}|a_S| + C^\ell_{\rm mix}|a_S|^2 + C^\ell_{\gamma\gamma}\right) \times 10^{-12}$$

ℓ	$C^\ell_{\rm dir}$	$C^\ell_{\rm int}$	$C^\ell_{\rm mix}$	$C^\ell_{\gamma\gamma}$
e	$(4.62 \pm 0.24)({y_V}^2 + {y_A}^2)$	$(11.3 \pm 0.3)y_V$	14.5 ± 0.5	≈ 0
μ	$(1.09 \pm 0.05)({y_V}^2 + 2.32{y_A}^2)$	$(2.63 \pm 0.06)y_V$	3.36 ± 0.20	5.2 ± 1.6

[Mescia, Smith, Trine '06]

In the Standard Model,

$$y_A(M_W) = -0.68 \pm 0.03, \qquad y_v(\mu \approx 1\text{GeV}) = 0.73 \pm 0.04$$

[Buchalla, Buras, Lautenbacher '96]

$K_L \to \pi^0 \ell^+ \ell^-$: Branching Ratio

$$B^{\text{theo}}(K_L \to \pi^0 e^+ e^-) = 3.54\,^{+0.98}_{-0.85} \quad (1.56\,^{+0.62}_{-0.49}) \times 10^{-11}$$

$$B^{\text{theo}}(K_L \to \pi^0 \mu^+ \mu^-) = 1.41\,^{+0.28}_{-0.26} \quad (0.95\,^{+0.22}_{-0.21}) \times 10^{-11}$$

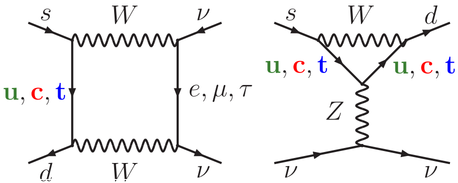
$$B^{\text{exp}}(K_L \to \pi^0 e^+ e^-) < 28 \times 10^{-11}$$ [KTEV '04]

$$B^{\text{exp}}(K_L \to \pi^0 \mu^+ \mu^-) < 38 \times 10^{-11}$$ [KTEV '00]

Theoretical error completely dominated by $K_S \to \pi^0 \ell^+ \ell^-$ measurement!

Contents

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



Dominated by $Q_\nu = (\bar{s}_L \gamma_\mu d_L)(\bar{\nu}_L \gamma^\mu \nu_L)$

$$B\left(K^+ \to \pi^+ \nu \bar{\nu}(\gamma)\right) = \kappa_+ (1 + \Delta_{\mathrm{EM}}) \times \left| \frac{V_{ts}^* V_{td} \, X_t(m_t^2) + \lambda^4 \mathrm{Re} V_{cs}^* V_{cd} \left(P_c(m_c^2) + \delta P_{c,u} \right)}{\lambda^5} \right|^2 .$$

$K^+ \to \pi^+ \nu \bar{\nu}$: Theoretical Status

LD Contributions

- Uncertainty in matrix element reduced by a factor of 7
  [Mescia, Smith '07]
- QED radiative corrections included ($|\Delta_{\text{EM}}| < 1\%$)
  [Mescia, Smith '07]
- $\delta P_{c,u}$ enhances branching ratio by 6%
  [Falk, Lewandowski, Petrov '01; Isidori, Mescia, Smith '05]

Charm Contribution P_c

Scale dependence reduced to $\pm 2.5\%$ (NNLO QCD)

[Buras, Gorbahn, Haisch, Nierste '06]

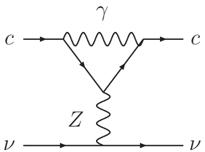
Top Contribution X_t

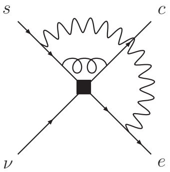
- Scale dependence reduced to $\pm 1\%$ (NLO QCD)
  [Misiak, Urban '99; Buchalla, Buras '99]
- Electroweak corrections to X_t in the large m_t limit $\approx 0.1\%$ ($\approx 2\%$ remaining) [Buchalla, Buras '98]

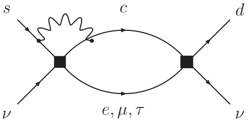
$K^+ \to \pi^+ \nu \bar{\nu}$: Electroweak Corrections to P_c

Why Electroweak Corrections?

- Match precision achieved in matrix elements
- There is a large QED log
- Fix input parameters







Electroweak Corrections to P_c

P_c increases by up to 2% [JB, Gorbahn '08]

$K^+ \to \pi^+ \nu \bar{\nu}$: Branching Ratio

$m_c(m_c) = (1286 \pm 13)\text{MeV}$

[Kühn et al. '07]

$m_c(m_c) = (1224 \pm 57)\text{MeV}$

[Hoang, Manohar '05]

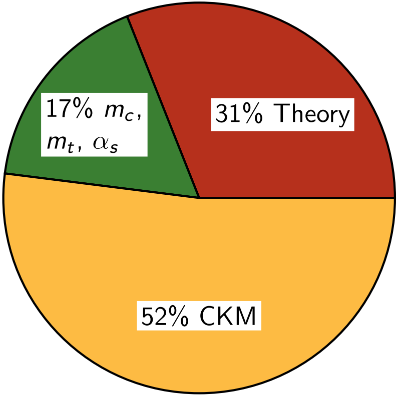
$$B^{\text{theo}}\left(K^+ \to \pi^+ \nu \bar{\nu}(\gamma)\right) = (0.85 \pm 0.07) \times 10^{-10}.$$

$$B^{\text{theo}}\left(K^+ \to \pi^+ \nu \bar{\nu}(\gamma)\right) = (0.80 \pm 0.08) \times 10^{-10}.$$

Compare with current experimental value [E787, E949 '08]

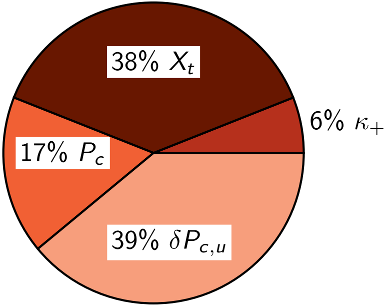
$$B^{\text{exp}}\left(K^+ \to \pi^+ \nu \bar{\nu}(\gamma)\right) = \left(1.73\,^{+1.15}_{-1.05}\right) \times 10^{-10}.$$

$K^+ \to \pi^+ \nu \bar{\nu}$: Error Budget



- Error dominated by CKM elements
- Theory error can still be reduced

$K^+ \to \pi^+ \nu \bar{\nu}$: Theory Error Budget



- Calculate electroweak corrections to X_t [Work in progress]
- Improve on $\delta P_{c,u}$ by a lattice calculation [Isidori et al. '06]
- With better $K_{\ell 3}$ data improve on κ_+ [Mescia, Smith '07]

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

$K_L \to \pi^0 \nu \bar{\nu}$ is now easy to discuss:

Contributions to the branching ratio

$$\text{DCPV} : \text{ICPV} : \text{CPC} = 1 : 10^{-2} : \lesssim 10^{-4}$$ [Buchalla, Isidori '98]

- (Almost) completely SD dominated
- $\longrightarrow$ Only top quark contributes

$$B\left(K_L \to \pi^0 \nu \bar{\nu}\right) = \kappa_L \left[\frac{\text{Im}(V_{ts}^* V_{td})}{\lambda^5} X_t(m_t^2) \right]^2$$

$K_L \to \pi^0\nu\bar{\nu}$: Theoretical Status

LD Contributions

- Uncertainty in matrix element reduced by a factor of 4 [Mescia, Smith '07]
- No further LD contributions

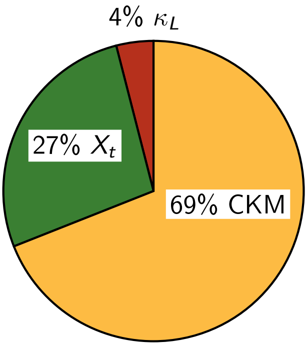
Charm Contribution

No charm contribution

Top Contribution X_t

- Scale dependence reduced to $\pm 1\%$ (NLO QCD) [Misiak, Urban '99; Buchalla, Buras '99]
- Electroweak corrections to X_t in the large m_t limit $\approx 0.1\%$ ($\approx 2\%$ remaining) [Buchalla, Buras '98]

$K_L \to \pi^0 \nu \bar{\nu}$: Error Budget



- Mainly parametric uncertainties
- Electroweak corrections to X_t

$$B^{\text{theo}}\left(K_L \to \pi^0 \nu \bar{\nu}\right) = (2.76 \pm 0.40) \times 10^{-11}$$

$$B^{\text{exp}}\left(K_L \to \pi^0 \nu \bar{\nu}\right) < 6.7 \times 10^{-8}$$ [E391a '08]

$K \to \pi \nu \bar{\nu}$: Experimental Prospect

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

New CERN Experiment NA62 aiming at detecting 80 events, measuring $B(K^+ \to \pi^+ \nu \bar{\nu})$ with 10% error

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

E14 experiment at J-PARC: Measuring $B(K_L \to \pi^0 \nu \bar{\nu})$ with uncertainty $< 10\%$

Conclusion

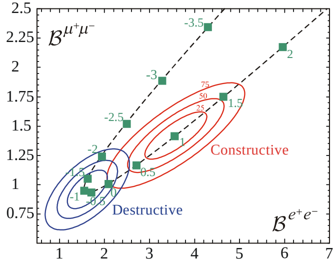
- Rare K decays test high-energy degrees of freedom
- Branching ratios can be predicted with remarkable precision
- Errors are dominated by parametric uncertainties and can be reduced significantly in the future

	Theory	Experiment
$K_L \to \pi^0 e^+ e^-$	$(3.54\,^{+0.98}_{-0.85}) \times 10^{-11}$	$< 28 \times 10^{-11}$ KTEV
$K_L \to \pi^0 \mu^+ \mu^-$	$(1.41\,^{+0.28}_{-0.26}) \times 10^{-11}$	$< 38 \times 10^{-11}$ KTEV
$K_L \to \pi^0 \nu\bar{\nu}$	$(2.76 \pm 0.40) \times 10^{-11}$	$< 6.7 \times 10^{-8}$ E391a
$K^+ \to \pi^+ \nu\bar{\nu}$	$(8.51 \pm 0.70) \times 10^{-11}$	$(1.73\,^{+1.15}_{-1.05}) \times 10^{-10}$ E787 E949

Backup Slides

$K^+ \to \pi^+\nu\bar{\nu}$: Input Parameters

M_W	(80.403 ± 0.029) GeV	[PDG]
M_Z	(91.1876 ± 0.0021) GeV	[PDG]
M_t	(172.6 ± 1.4) GeV	[CDF]
$m_b(m_b)$	(4.164 ± 0.025) GeV	[Kühn et al.]
$m_c(m_c)$	(1.286 ± 0.013) GeV	[Kühn et al.]
M_H	(155 ± 40) GeV	–
m_τ	$(1776.99^{+0.29}_{-0.26})$ MeV	[PDG]
$\bar{\eta}$	0.343 ± 0.016	[CKMfitter]
$\alpha_s(M_Z)$	0.1176 ± 0.0020	[PDG]
$\alpha(M_Z)$	$1/127.9$	[PDG]
$\sin^2\theta_W^{\overline{\mathrm{MS}}}$	0.23122 ± 0.00015	[PDG]
G_F	$1.166\,37 \times 10^{-5}\mathrm{GeV}^{-2}$	[PDG]
λ	0.2255 ± 0.0007	[Antonelli et al.]
$\|V_{cb}\|$	$(4.15 \pm 0.09) \times 10^{-2}$	[CKMfitter]
$\bar{\rho}$	$0.141^{+0.029}_{-0.017}$	[CKMfitter]



$\mathcal{B}^{\mu^+\mu^-}$
$\mathcal{B}^{e^+e^-}$
Constructive
Destructive
-3.5
-3
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
75
50
25
2.5
2.25
2
1.75
1.5
1.25
1
0.75
1
2
3
4
5
6
7