$K \to \pi \nu \bar{\nu}$ in

the Standard Model and Beyond

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Moriond - Electroweak Interactions and Unified Theories

La Thuile, 14 - 21 March 2015

European Research Council

IAS TUM Institute for Advanced Study

New Physics landscape in the **LHC era**

imagined...

...present day (La Thuile)

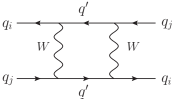
Bounds from direct searches: (talks this week; ATLAS, CMS)

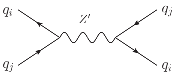
$M_{\tilde{g}},\ M_{\tilde{q}} \gtrsim 1\ \mathrm{TeV}, \quad M_{Z'} \gtrsim 2\text{-}3\ \mathrm{TeV}, \quad \dots$

What if NP scale too high?

Indirect searches with FCNCs (Flavour Changing Neutral Currents)

$\boxed{\Delta F lavour = 2}$ i.e meson mixing

SM : 

e.g. NP : 

Model-independent descr.:

$$\mathcal{H}_{\rm eff}^{\rm NP} \ni \frac{C_{\rm NP}}{\Lambda_{\rm NP}^2} \bar{q}_i \Gamma q_j \, \bar{q}_i \Gamma' q_j$$

$$\Gamma^{(\prime)} = \gamma^\mu P_{L,R},\ P_{L,R}, \dots$$

$$\text{for} \quad |C_{\rm NP}| \sim 1 \quad \Longrightarrow \quad \Lambda_{\rm NP}\Big|_{\text{@end LHC}} \sim \begin{cases} 500 \text{ TeV} & : \quad B_s \\ 2000 \text{ TeV} & : \quad B_d \\ 10^4 - 10^5 \text{ TeV} & : \quad K^0 \end{cases}$$

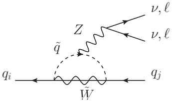
probe **zeptometer** scales ($1/200\,\text{TeV} \simeq 10^{-21}$m),

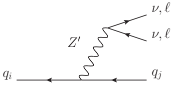
but structure of NP hidden

(CKMFitter; 1309.2293)

(UTFit; 0707.0636)

$\boxed{\Delta F lavour = 1}$ e.g. rare decays



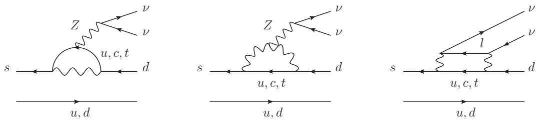


Potential access to $\pm C_{\rm NP}^{L,R} \, \bar{q}_i \Gamma P_{L,R} q_j, \dots$

$\rightarrow$ disentangle NP structure

($B \to K^* \bar{\mu}\mu$ prime example; talks this morning)

$K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$



very strongly suppressed in SM...

FCNCs with tops:

$|V_{td}V_{ts}^*| \simeq 0.0004$

$\ll \ |V_{td}V_{tb}^*| \simeq 0.01$

$< \ |V_{ts}V_{tb}^*| \simeq 0.04$

Hadronic ME : $\langle \pi^{0,+}|\bar{s}\gamma^\mu d|K^{0,+}\rangle \overset{\text{ChPT}}{\longleftrightarrow} \langle \pi^{+,0}|\bar{s}\gamma^\mu d|K^{0,+}\rangle$ from $K \to \pi l \nu$

...and theoretically very clean $\Longrightarrow$ **Golden guns for hunting NP!**

Experimental status:

$\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = \left(17.3^{+11.5}_{-10.5}\right) \times 10^{-11}$ (BNL; 2008), $\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) \leq 2.6 \times 10^{-8}$ (KEK; 2009)

Future expected precision (relative to SM prediction):

- 10% (~2018) - $K^+ \to \pi^+\nu\bar{\nu}$, NA62 at CERN (see talk of S. Dario)
- first observation (2018+) - $K_L \to \pi^0\nu\bar{\nu}$, KOTO at J-PARC
- ~~5% (~5 yrs) - $K^+ \to \pi^+\nu\bar{\nu}$, ORKA at Fermilab~~
- ~~5% - $K_L \to \pi^0\nu\bar{\nu}$, Project X at Fermilab~~

$K \to \pi\nu\bar{\nu}$ in the SM and Beyond

Status and perspectives in SM?

(Buras, Buttazzo, Girrbach-Noe, RK; 1503.02693)

How can their interplay discriminate models of NP?

(review + Buras, Buttazzo, RK; in preparation)

+ what NP scales could ultimately be reached?

(Buras, Buttazzo, Girrbach-Noe, RK; 1408.0728)

In collaboration with:

Andrzej Buras

Dario Butazzo

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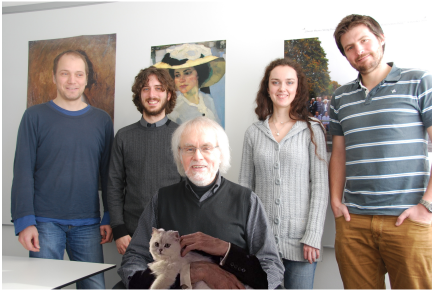
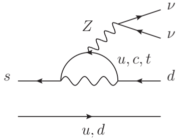


Standard Model prediction



Z-penguin loop function 'X' $\sim \frac{m_q^2}{M_W^2}$ $(\equiv x_q)$

Top dominant, charm relevant: $m_t^2 \; |V_{td} V_{ts}^*| \sim m_c^2 \; |V_{cd} V_{cs}^*|$

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = \tilde{\kappa}_+ \left[\left(\frac{\mathrm{Im}(V_{td} V_{ts}^*)}{\lambda^5} X(x_t) \right)^2 + \left(\frac{\mathrm{Re}(V_{cd} V_{cs}^*)}{\lambda} P_c(X) + \frac{\mathrm{Re}(V_{td} V_{ts}^*)}{\lambda^5} X(x_t) \right)^2 \right]$$

$$\mathrm{BR}(K_\mathrm{L} \to \pi^0 \nu\bar{\nu}) = \kappa_\mathrm{L} \left(\frac{\mathrm{Im}(V_{td} V_{ts}^*)}{\lambda^5} X(x_t) \right)^2 \qquad \leftarrow \text{almost purely CP violating}$$

$\tilde{\kappa}_+$, κ_L $\supset$ hadronic matrix elements $\leftarrow$ semileptonic K decays (Mescia, Smith, 0705.2025)

Charm loops: including NNLO QCD and two-loop EW corrections:
(Buras, Gorbahn, Haisch, Nierste; hep-ph/0508165, hep-ph/0603079), (Brod, Gorbahn; 0805.4119)

$$P_c(X) = 0.404 \pm 0.024 \qquad (\text{updated} - 1503.02693)$$

Top loops: including NLO QCD and two-loop EW corrections:
(Buchalla, Buras; Nucl.Phys.B400 1993), (Misiak, Urban; hep-ph/9901278), (Brod, Gorbahn, Stamou; 1009.0947)

$$X(x_t) = 1.481 \pm 0.005\big|_\mathrm{th} \pm 0.008\big|_\mathrm{exp} \qquad (\text{updated} - 1503.02693)$$

That leaves CKM inputs : $V_{td} V_{ts}^*$ and $V_{cd} V_{cs}^*$

Which CKM inputs? (I)

For New Physics studies tree-level observables desirable:

$$|V_{us}| = \lambda = 0.2252(9), \qquad \gamma = \left(73.2^{+6.3}_{-7.0}\right)^\circ \qquad \text{(CKMFitter)}$$

and $\quad |V_{ub}|_{\rm excl} = (3.72 \pm 0.14) \times 10^{-3}, \qquad |V_{cb}|_{\rm excl} = (39.36 \pm 0.75) \times 10^{-3},$

(Fermi lattice, MILC; 1411.6038), (FLAG; 1310.8555)

or $\quad |V_{ub}|_{\rm incl} = (4.40 \pm 0.25) \times 10^{-3}, \qquad |V_{cb}|_{\rm incl} = (42.21 \pm 0.78) \times 10^{-3},$

(HFAG avg.), (Alberti, Gambino, Healey, Nandi; 1411.6560)

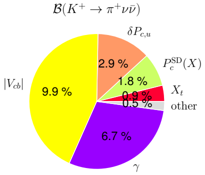
Exclusive/inclusive puzzle unlikely NP? (Crivellin, Pokorski; 1407.1320)

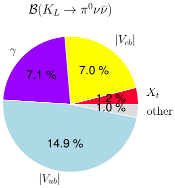
Weighted average (PDG method) gives:

$$\boxed{|V_{ub}|_{\rm avg} = (3.88 \pm 0.29) \times 10^{-3}, \quad |V_{cb}|_{\rm avg} = (40.7 \pm 1.4) \times 10^{-3}}$$

Using weighted averages →

(Buras, Buttazzo, Girrbach-Noe, RK, 1503.02693)





CKM errors dominant

Which CKM inputs? (II)

SM predictions from **tree-level CKM inputs** (weighted avgs):

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) \times 10^{11} = \mathbf{8.4 \pm 1.0} = 8.39 \pm 0.30 \left[\frac{|V_{cb}|}{40.7 \times 10^{-3}}\right]^{2.8} \left[\frac{\gamma}{73.2^\circ}\right]^{0.708}$$

$$\mathrm{BR}(K_\mathrm{L} \to \pi^0 \nu\bar{\nu}) \times 10^{11} = \mathbf{3.4 \pm 0.6} = 3.36 \pm 0.05 \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^{2} \left[\frac{|V_{cb}|}{40.7 \times 10^{-3}}\right]^{2} \left[\frac{\sin\gamma}{\sin(73.2^\circ)}\right]^{2}$$

to very good accuracy (Buras, Buttazzo, Girrbach-Noe, RK, 1503.02693)

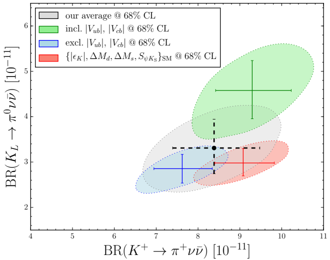
OR. . . predictions from **loop-level CKM inputs**:

$$|\epsilon_K|,\ \Delta M_d,\ \Delta M_s,\ S_{J/\psi K_\mathrm{S}}$$

Using latest lattice QCD results (FLAG; 1310.8555)
and PDG/HFAG inputs:

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) \times 10^{11} = \mathbf{9.1 \pm 0.7}$$

$$\mathrm{BR}(K_\mathrm{L} \to \pi^0 \nu\bar{\nu}) \times 10^{11} = \mathbf{3.0 \pm 0.3}$$



$|V_{cb}|$-less test of SM

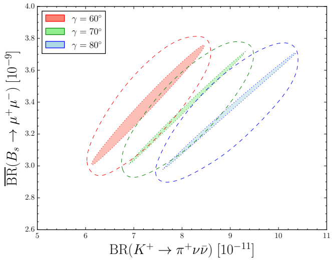
So $\quad \mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) \propto |V_{cb}|^{2.8}\, \gamma^{0.708}$

Similarly (to very good accuracy)

$$\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-) = (3.37 \pm 0.06) \times 10^{-9} \left[\frac{|V_{cb}|}{40.7 \times 10^{-3}}\right]^2 \left[\frac{f_{B_s}}{227\,\mathrm{MeV}}\right]^2$$

Combination gives $|V_{cb}|$ independent SM prediction:

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (65.3 \pm 2.9) \left[\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)\right]^{1.4} \left[\frac{\gamma}{73.2^\circ}\right]^{0.708} \left[\frac{f_{B_s}}{227\,\mathrm{MeV}}\right]^{-2.8}$$



filled region:
$1\,\sigma$ CL from remaining CKM inputs

dashed region:
$1\,\sigma$ CL from all remaining inputs

Beyond the SM: Minimal Flavour Violation

MFV $\equiv$ SM Yukawa couplings **only source** of flavour-changing currents

$$V_{td} V_{ts}^* X(x_t) \quad \to \quad V_{td} V_{ts}^* \underbrace{\left(X(x_t) + X^{\mathrm{NP}}\right)}_{\in \mathcal{R}}$$

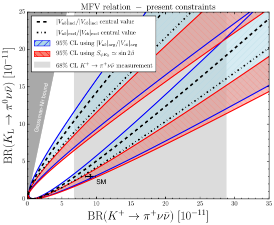
$$\frac{\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})}{\tilde{\kappa}_+} = \frac{\mathrm{BR}(K_\mathrm{L} \to \pi^0 \nu\bar{\nu})}{\kappa_\mathrm{L}} + \left[\underbrace{\frac{\mathrm{Re}(V_{td} V_{ts}^*)}{\mathrm{Im}(V_{td} V_{ts}^*)}}_{\simeq -\cot\beta/\sigma} \sqrt{\frac{\mathrm{BR}(K_\mathrm{L} \to \pi^0 \nu\bar{\nu})}{\kappa_\mathrm{L}}} - \frac{\mathrm{sgn}(X)}{\sqrt{\sigma}} P_c(X) \right]^2$$

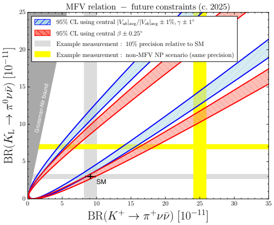
Triple correlation together with $S_{J/\psi K_\mathrm{S}} \simeq \sin 2\beta$ (Buras, Fleischer; hep-ph/0104238)

Or tree-level inputs: $\left|\frac{V_{ub}}{V_{cb}}\right|$ and γ

contrary to $S_{J/\psi K_\mathrm{S}}$

valid for $U(2)^3$ symmetry



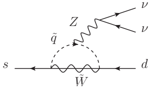


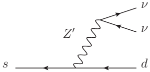
Beyond the SM: correlated constraints (I)

NP in $s \to d\nu\bar{\nu}$:

modified Z couplings (MSSM, RS, Little Higgs, PC . . .)

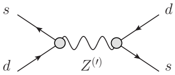
heavy Z'-like bosons (LR-sym., 331, RS . . .)





Leading constraints on $s \to d$ FCNCs:

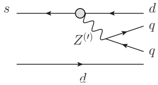
K^0-$\overline{K}^0$ mixing



$|\epsilon_K|_{\mathrm{exp}} = (2.228 \pm 0.011) \times 10^{-3}$

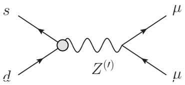
$(\Delta M_{K\,\mathrm{exp}} = 0.5292 \times 10^{-2}\,\mathrm{ps}^{-1})$

$K \to \pi\pi$ direct CPV



$\mathrm{Re}(\epsilon'/\epsilon)_{\mathrm{exp}} = (16.6 \pm 2.3) \times 10^{-4}$

$K_{\mathrm{L}} \to \mu^+\mu^-$



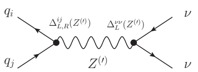
$\mathrm{BR}(K_{\mathrm{L}} \to \mu^+\mu^-)_{\mathrm{SD}} < 2.5 \times 10^{-9}$

(Isidori, Unterdorfer; hep-ph/0311084)

Beyond the SM: correlated constraints (II)

Simplified $Z^{(\prime)}$ with

tree-level FCNC couplings



Z-penguin modified to:

(Buras, De Fazio, Girrbach; 1211.1896)

$$X(x_t) \to X(x_t)_{\rm SM} + \frac{\pi^2}{2M_W^2 G_F^2} \frac{\Delta_L^{\nu\nu}(Z^{(\prime)})}{V_{ts}^* V_{td} M_Z^{(\prime)2}} \left[\Delta_L^{sd}(Z^{(\prime)}) + \Delta_R^{sd}(Z^{(\prime)})\right]$$

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) \propto |X + \ldots|^2, \qquad \mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) \propto (\mathbf{Im}\, X)^2$$

K^0-$\overline{K}^0$ mixing:

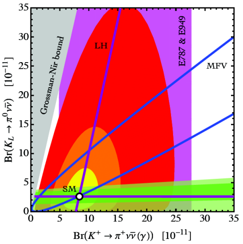
$$|\epsilon_K| \propto \frac{1}{M_Z^{(\prime)2}} \mathbf{Im} \left[(\Delta_L^{sd})^2 + (\Delta_R^{sd})^2 - 240\, \Delta_L^{sd} \Delta_R^{sd}\right] + \ldots$$

$K \to \pi\pi$ direct CPV:

$$\mathbf{Re}\left(\frac{\epsilon'}{\epsilon}\right) \propto -\mathbf{Im}\left(\Delta_L^{sd}\right) - 3\,\mathbf{Im}\left(\Delta_R^{sd}\right) + \ldots \quad [Z \text{ only}]$$

(Buras, De Fazio, Girrbach; 1404.3824)

$$\mathbf{BR}(K_L \to \mu^+\mu^-)_{\rm SD} \propto \left(\frac{1}{M_Z^{(\prime)2}} \mathbf{Re}\left[(\Delta_L^{sd} - \Delta_R^{sd})\Delta_A^{\mu\mu}\right] + \ldots\right)^2$$

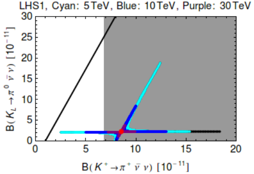


(Al-Binni et al;1306.5009)

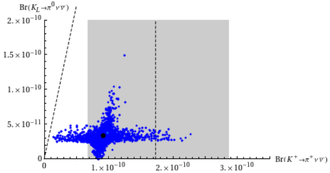
(see also Blanke; 0904.2528)

Beyond the SM: correlated constraints (III)

Z' with LH couplings (Buras et al; 1211.1896)

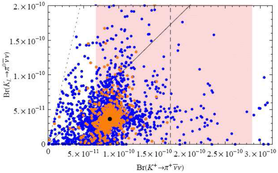


Little Higgs + T-parity (Blanke et al; 0906.5454)



Exclusively LH couplings

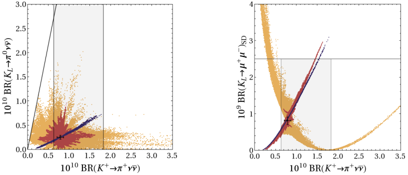
RS + custodial sym. (Blanke et al; 0812.3803)



RH couplings generally dominant;

KK gluons saturate K mixing: no visible correlation

Partial compositeness (Straub; 1302.4651)



orange: triplet model (RH); **red**: doublet model (LH)

Beyond the SM: Minimal Flavour Violation (II)

MFV $\iff$ CKM suppression: NP effects in $K \to \pi\nu\bar{\nu}$ principle small

e.g. MSSM+MFV $\to \mathcal{O}(10\%)$

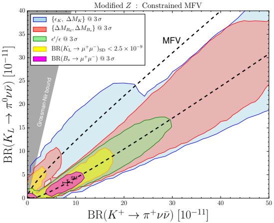
(Isidori, Mescia, Paradisi, Smith, Trine; hep-ph/0604074), (Smith; 1409.6162)

Simplified $Z^{(\prime)}$ with tree-level FCNCs in MFV:

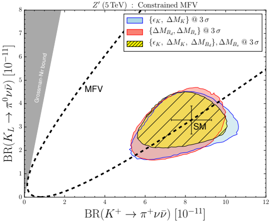
(Buras, Buttazzo, RK; in preparation)

$$\Delta_L^{ij} = V_{ti}^* V_{tj}\, \boldsymbol{C}, \qquad \boldsymbol{C} \in \mathcal{R}$$

Modified Z



Z' (5 TeV)



- $\Delta F = 1$ most constraining
- $\Delta F = 2$ very constraining

MFV models in general already very constrained

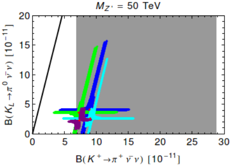
What NP scales could ultimately be reached?

Model-dependent :

use simplified Z' as a **benchmark**

with maximum couplings consistent with

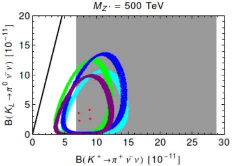
perturbativity and K mixing



LH or RH couplings only:

$\to \mathcal{O}(50\,\mathrm{TeV}) \sim$ 4 zeptometers

(Buras, Buttazzo, Girrbach-Noe, RK; 1408.0728)



LH + RH couplings:

precise $\Delta_L^{sd}/\Delta_R^{sd}$ tuning cancels $\Delta F = 2$

$\to \mathcal{O}(500\,\mathrm{TeV}) \sim$ 0.4 zeptometers

$K \to \pi\nu\bar{\nu}$ decays can reach the **zeptouniverse**

Summary

- $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ **golden modes** for probing NP

- Precise SM predictions (updated); CKM dominant uncertainty:
  loop-level inputs $> |V_{ub}|, |V_{cb}|$ incl./excl. average
- SM triple correlation: $K^+ \to \pi^+\nu\bar{\nu}$ – $B_s \to \mu^+\mu^-$ – γ
  free of dominant $|V_{cb}|$ input

- $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ excellent probes of **MFV**
  though large effects difficult in general
- Correlations with existing constraints complement model discrimination

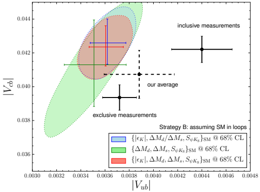
- NA62 and KOTO results coming soon: **exciting future awaits!**

Backup slides

SM predictions with various CKM inputs

CKM inputs	$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) \times 10^{11}$	$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) \times 10^{11}$
$\lvert V_{ub}\rvert, \lvert V_{cb}\rvert$ incl.	9.3 ± 0.9	4.6 ± 0.7
$\lvert V_{ub}\rvert, \lvert V_{cb}\rvert$ excl.	7.6 ± 0.7	2.9 ± 0.3
$\lvert V_{ub}\rvert, \lvert V_{cb}\rvert$ avg.	8.4 ± 1.0	3.4 ± 0.6
$\lvert V_{ub}\rvert, \lvert V_{cb}\rvert$ excl. †	7.6 ± 0.7	2.2 ± 0.4
$\lvert V_{ub}\rvert, \lvert V_{cb}\rvert$ avg. †	8.4 ± 1.0	3.4 ± 1.0
Loop-observables	9.11 ± 0.72	3.00 ± 0.30
CKMFitter	$8.17^{+0.61}_{-0.71}$	2.65 ± 0.29
UTFit	8.64 ± 0.54	2.93 ± 0.25

† using $|V_{ub}|_{\mathrm{excl}} = (3.28 \pm 0.29) \times 10^{-3}$ (HFAG avg. 2014)



(Buras, Buttazzo, Girrbach-Noe, RK, 1503.02693)