Kaon Physics in non-Supersymmetric Models

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Physics Beyond the Standard Model?

Many good reasons for BSM physics

- origin of EW symmetry breaking & naturalness
- origin of flavour (hierarchies)
- dark matter & dark energy
- baryon asymmetry of the universe
- ...

... but no discovery yet!

- data in impressive agreement with SM prediction
- however some hints for deviations

Theoretical paths beyond the SM

1. **effective field theory:** most agnostic approach
2. **simplified models:** minimalistic renormalizable models, popular for collider physics, but also dark matter and flavour physics
3. **"complete" models:** address (some of) the problems of the SM
    - SUSY
    - composite models

➢ **nicely complement each other**

What if. . .

LHC run 2 finds new physics

- 
- understand its structure
- more data and complementary information needed

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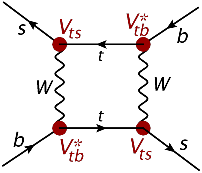
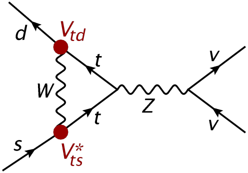
BSM flavour physics

Flavour Changing Neutral Current Processes

strongly suppressed in the SM ➢ high **sensitivity to BSM** contributions

- loop factor
- CKM hierarchy
- chiral structure
- GIM mechanism (CKM unitarity)





CKM hierarchy predicts specific pattern of effects in the SM

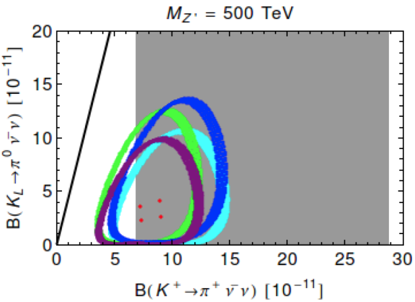
$$\underbrace{V_{ts}^* V_{td}}_{K \text{ system}} \sim 5 \cdot 10^{-4} \ll \underbrace{V_{tb}^* V_{td}}_{B_d \text{ system}} \sim 10^{-2} < \underbrace{V_{tb}^* V_{ts}}_{B_s \text{ system}} \sim 4 \cdot 10^{-2}$$

➢ K decays in general most sensitive to BSM physics

A Glimpse at the Zeptouniverse

recent analysis of tree level flavour changing Z': Buras et al. (2014)

- $K \to \pi\nu\bar{\nu}$ decays sensitive to scales up to 2000 TeV if left- and right-handed FV couplings are present
- (fine-tuned) cancellation of effects in $K^0 - \bar{K}^0$ mixing required
- new physics reach of B decays lower by an order of magnitude (~ 100 TeV!)



➢ **high precision** in rare K and B decays is **crucial**!

WANTED: Precision, Precision, Precision!

high precision in rare K and B decays is **crucial**!

experiment

- precise measurements of rare K and B decays

  e. g. $K \to \pi\nu\bar{\nu}$, $B_{s,d} \to \mu^+\mu^-$, $B \to K^*\mu^+\mu^-$, $K_L \to \pi^0\ell^+\ell^- \ldots$
- precise measurements of $\Delta F = 2$ observables
- precise determination of CKM elements

theory

- precise SM prediction
  - ➢ non-perturbative effects (lattice, sum rules etc.)
  - ➢ perturbative effects
- detailed understanding of BSM effects and their correlations
- new observables & strategies?

Dechiphering BSM Physics in Flavour Observables

Goal: understand the origin of BSM flavour violation

- ➢ measure as many observables as possible
- ➢ identify pattern of correlations

correlations within given meson system give information on BSM operator structure

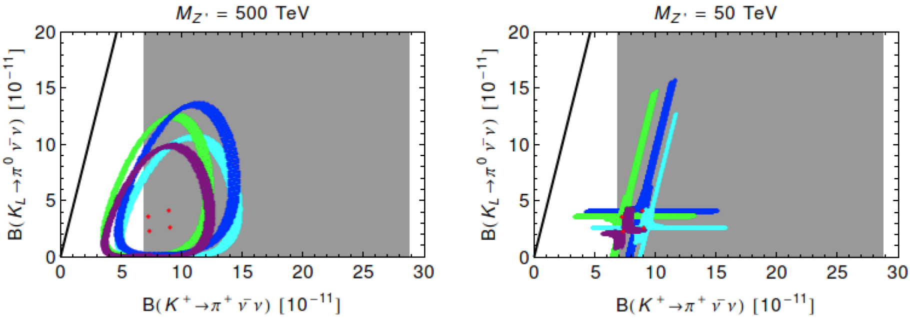
(chirality, vector vs. scalar etc.)

correlations between different meson systems allow to draw conclusions on underlying flavour symmetry

(MFV, NMFV, $U(2)^3$ etc.)

$K \to \pi\nu\bar{\nu}$ – as Clean as it Gets

back to the tree level flavour changing Z' Buras et al. (2014)



- NP reach beyond 1000 TeV in the presence of L and R couplings
- smaller reach for chiral theory (only L oder R couplings)
  distinctive correlation (2 branches) see also Blanke (2009)
- strong dependence on CKM input (plot colours)

In a nutshell

Simplified models, like the Z'

- are more specified that the EFT and get along with less parameters
- help to assess the new physics reach of various observables
- allow to study correlations in a clean manner

Ultimately our main goal is to solve the puzzles of the SM
➢ study complete models!

The Most Famous “Complete” Models

Motivated by EW naturalness:

1. **SUSY** ➢ see Sebastian’s talk
2. **composite Higgs**
   - partial compositeness – Randall-Sundrum scenarios
   - Little Higgs models

. . .

The Littlest Higgs Model with T-Parity

Littlest Higgs model

- global $SU(5)$ broken spontaneously to $SO(5)$ at scale $f \sim 1\,\text{TeV}$
- gauged subgroup $[SU(2) \times U(1)]^2 \longrightarrow SU(2)_L \times U(1)_Y$
- new heavy gauge bosons $W_H^\pm$, Z_H, A_H and heavy scalar triplet Φ
- top quadratic divergence cancelled by new heavy quark T

T-parity: discrete symmetry, under which new particles are odd

➢ analogous to R-parity in SUSY

➢ no tree level contributions to EW precision observables

➢ lightest T-odd particle (A_H) stable: dark matter candidate

Arkani-Hamed, Cohen, Katz, Nelson (2002)
Cheng, Low (2003,2004)

Fermions in the LHT Model

- **T-even quark sector**:

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L \quad \begin{matrix} u_R \\ d_R \end{matrix} \quad \begin{matrix} c_R \\ s_R \end{matrix} \quad \begin{matrix} t_R \\ b_R \end{matrix} \quad T_+$$

  ➢ standard CKM mixing + mixing of T_+ with t

- **T-odd mirror quark sector**: Low, hep-ph/0409025

$$\begin{pmatrix} u_H \\ d_H \end{pmatrix} \quad \begin{pmatrix} c_H \\ s_H \end{pmatrix} \quad \begin{pmatrix} t_H \\ b_H \end{pmatrix} \quad T_-$$

  ➢ new CKM-like mixing matrices V_{Hu}, V_{Hd} parameterising mirror quark interactions with SM quarks

- **Lepton sector**:
  SM leptons + mirror leptons, analogous to quark sector

Recent news on LHT quark flavour

MB, Buras, Recksiegel (2015)

Questions:

1. What is the size and pattern of LHT flavour effects consistent with the LHC run 1 data? (scenario A) see Reuter, Tonini, de Vries (2013)
2. What will be left if no LHT particles are found at the LHC in the coming years? (scenario B)

Strategy for our updated flavour analysis

1. fix non-flavour parameters in accordance with constraints
   Scenario A: $f = 1\,$TeV, $x_L = 0.5$ ("the present")
   Scenario B: $f = 3\,$TeV, $x_L = 0.5$ ("the future")
2. use CKM input from tree level determinations (incl./excl. averages) and latest lattice averages
3. scan over mirror quark masses and mixing parameters
   Scenario A: $1.6\,$TeV $< m^i_{Hq} < 4.5\,$TeV ("the present")
   Scenario B: $4\,$TeV $< m^i_{Hq} < 8\,$TeV ("the future")
   V_{Hd} parameters in physical range
4. impose $\Delta F = 2$ constraints at 1σ level
5. study possible effects in $\Delta F = 1$ observables and their correlations

LHT Flavour Violation

$$\mathcal{A}_{\text{LHT}} = \sum_i B_i^{\text{SM}} \eta_i^{\text{QCD}} \Big[\overbrace{\lambda^i_{\text{CKM}} \underbrace{F_i(m_i, m_{T_+}, \dots)}}^{\text{T-even sector}} + \overbrace{\xi^i_{V_{Hd}} \underbrace{G_i(m^i_H, M_{W_H})}}^{\text{T-odd sector}} \Big]$$

real & flavour universal loop functions

- **T-even sector:** contributions of T_+ (CMFV)
  - small effects ($\lesssim 20\%$)
  - flavour-universal enhancements of $\Delta F = 2^*$ and $\Delta F = 1$ amplitudes

MB, Buras (2006)

- **T-odd sector:** heavy gauge bosons & mirror fermions
  - contribution at the loop level (T-parity)
  - new sources of flavour and CP-violation (V_{Hd})
  - but no new operators (only LH couplings)

➢ potentially large effects & specific correlations

MB, Buras, Poschenrieder, Tarantino, Uhlig, Weiler (2006)
MB, Buras, Poschenrieder, Recksiegel, Tarantino, Uhlig, Weiler (2006)

Naïve Expectations for K and B Physics

MB, Buras, Poschenrieder, Recksiegel, Tarantino, Uhlig, Weiler (2006)

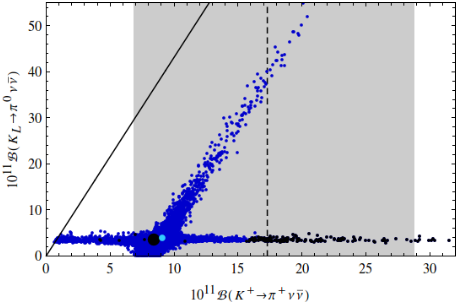
relative size of LHT effects: $\propto \frac{1}{\lambda^i_{\text{CKM}}} \xi^i_{V_{Hd}}$

$$\frac{1}{\lambda_t^{(K)}} \simeq 2500 \quad \gg \quad \frac{1}{\lambda_t^{(d)}} \simeq 100 \quad > \quad \frac{1}{\lambda_t^{(s)}} \simeq 25$$

- largest effects in K physics observables
- moderate effects in $B_{d,s}$ physics observables
- but may be reversed by specific hierarchies in $\xi^i_{V_{Hd}}$

The $K \to \pi\nu\bar{\nu}$ system (scenario A)

MB, Buras, Recksiegel (2015)



two branches: consequence of LHT operator structure — Blanke (2009)

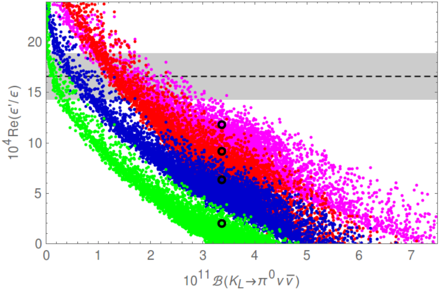
- **horizontal branch:** large enhancements of $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$, but values above $1.6 \cdot 10^{-10}$ excluded by $K_L \to \mu^+\mu^-$
- **sloped branch:** order of magnitude effect in $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$ and enhanced $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$

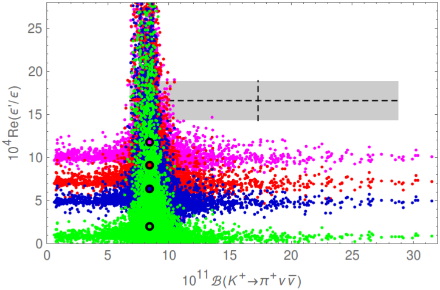
The return of ε'/ε

- recent progress on hadronic $K \to \pi\pi$ matrix elements from lattice QCD and large N theory RBC-UKQCD (2015); Buras, Gérard (2015)
- some tension between SM prediction and data

Buras, Gorbahn, Jäger, Jamin (2015)

- correlation with $K \to \pi\nu\bar{\nu}$



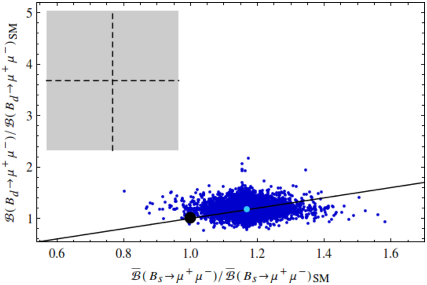


$$(B_6^{(1/2)}, B_8^{(3/2)}) = (1.0, 1.0), (0.76, 0.76), (0.57, 0.76), (1.0, 0.76)$$

MB, Buras, Recksiegel (2015)

$B_{s,d} \to \mu^+\mu^-$

MB, Buras, Recksiegel (2015)



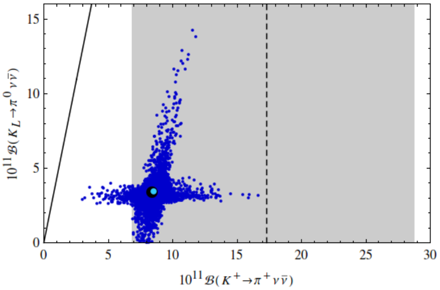
- effects in B decays much smaller than in K decays, yet still sizeable
  - enhancement of $B_s \to \mu^+\mu^-$ favored, not supported by data
  - factor 2 enhancement of $B_d \to \mu^+\mu^-$ possible
- $B_{s,d} \to \mu^+\mu^-$ can deviate from MFV predictions

LHT flavour at the multi-TeV scale

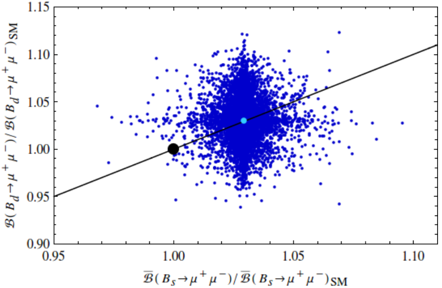
assume that no LHT particle is discovered in the coming years
➢ LHT scales will be pushed to several TeV (scenario B)

MB, Buras, Recksiegel (2015)

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



$B_{s,d} \to \mu^+\mu^-$

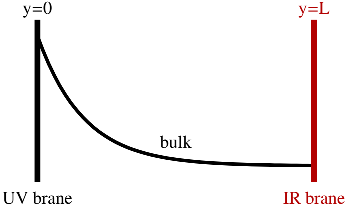


- large effects still possible in rare K decays
- high precision required to distinguish LHT from SM in B physics

The Randall-Sundrum framework

5D space-time with **warped** metric: Randall, Sundrum (1999)

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2\,, \qquad 0 \le y \le L$$



- fermions and gauge bosons propagate in the **5D bulk**
- Higgs localised on IR brane

Chang et al. (1999)
Grossman, Neubert (1999)
Gherghetta, Pomarol (2000)

energy scales suppressed by **warp factor**:

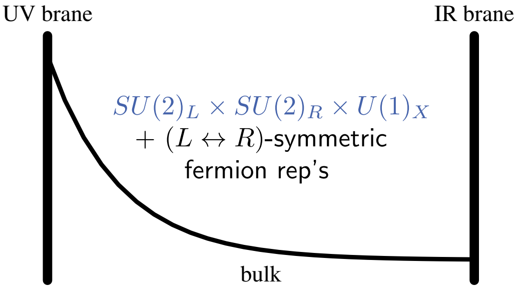
$$\Lambda_{\text{eff}}(y) = e^{-ky}\Lambda_{\text{fund.}}$$

➢ for $kL \sim 35$: natural explanation of gauge hierarchy

The custodially protected model

Agashe et al. (2003,2006); Csaki et al. (2003)

Extended electroweak symmetry structure:



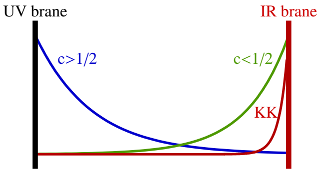
$SU(2)_R \times U(1)_X \to U(1)_Y$
by boundary conditions

$SU(2)_L \times SU(2)_R \to SU(2)_V$
by Higgs VEV

- in agreement with EWP data for $M_{KK} \gtrsim 3$ TeV
- consistent with LHC run 1 data

Flavour hierarchies & FCNC interactions

SM fermion profile depends strongly on bulk mass parameter c:



$c > \frac{1}{2}$: localisation around UV brane
$c < \frac{1}{2}$: localisation around IR brane

effective 4D Yukawa couplings:

$$(Y_{u,d})_{ij} = (\lambda_{u,d})_{ij}\, f_i^Q\, f_j^{u,d}$$

- observed hierarchical structure can be naturally generated by exponential suppression of $f^{Q,u,d}$ (fermion profile on IR brane)
- tree level FCNC interactions with KK gauge bosons and Z exhibit the same hierarchical suppression (➢ *RS-GIM mechanism*)

Grossman, Neubert (1999)
Arkani-Hamed, Grossman, Schmaltz (1999)
Agashe, Perez, Soni (2004)

Pattern of tree level FCNCs in RSc

see e. g. Agashe et al. (2004), Csaki et al. (2008), Blanke et al. (2008)

- KK gluons: $\Delta F = 2$, non-leptonic decays ➢ new operators
- KK weak gauge bosons $(Z_H, Z', A^{(1)})$:
  subdominant in $K - \bar{K}$ and $\Delta F = 1$, but competitive in $B - \bar{B}$
- Z boson: dominant in rare decays
  left-handed FCNC coupling suppressed by protection of $Zb_L\bar{b}_L$
- Higgs: subdominant

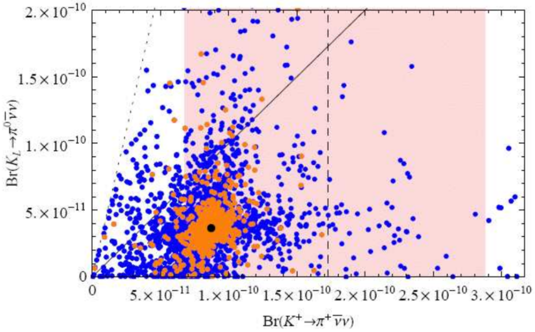
flavour hierarchy weaker in right-handed down sector

- large effects in rare K decays
- small effects in rare B decays

in addition: new sources of CP-violation

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

MB, Buras, Duling, Gemmler, Gori (2008)

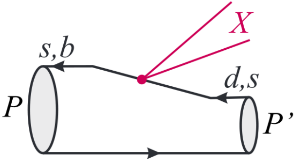


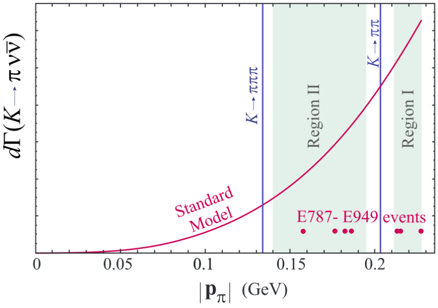
- large enhancements of $K \to \pi\nu\bar{\nu}$ possible
- no visible correlation

$K \to \pi + X$

Kamenik, Smith (2012)
Fuyuto, Hou, Kohda (2014)

- new light invisible states X possibly produced in rare meson decays
- contribute to the measurement of $K \to \pi\nu\bar{\nu}$





- different differential distribution
- resonance(s)?
- no correlaton with ε'/ε

Summary

1. K decays offer unique sensitivity to flavor violation beyond the SM
2. $K \to \pi\nu\bar{\nu}$ are theoretically cleanest and can still differ significantly from their SM predictions
3. correlations allow to distinguish between different models
4. recent theory progress has turned ε'/ε into an important player
5. $K \to \pi\nu\bar{\nu}$ decays also sensitive to light invisible states via $K \to \pi X$