Flavour physics from present to future colliders

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New Physics, where are you?

Despite convincing motivations for NP at the TeV scale,
we are still lacking a discovery!

Where is everyone?

too heavy to be probed by direct searches, EWPT & Higgs physics

too weakly coupled to leave a visible imprint on these observables

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Needed: indirect probes of new particles and interactions that are sensitive even to very small NP effects

➢ **flavour physics!**

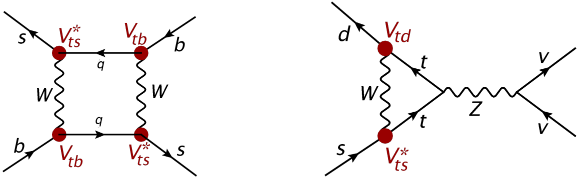
also $(g-2)$, EDMs...

Flavour changing neutral current processes

FCNCs are strongly suppressed in the SM

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

➢ **unique sensitivity to NP** contributions – probing scales far beyond the TeV range



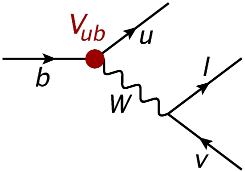
Crucial:

high precision in ➢ measurements of flavour violating decays

➢ predictions of the SM contribution

Precision determination of CKM elements

Tree level decays: flavour changing charged current interactions



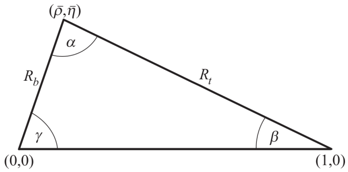
➢ $$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- direct sensitivity to relevant CKM element
- small impact of NP contributions expected
- four independent measurements needed to fully determine CKM matrix

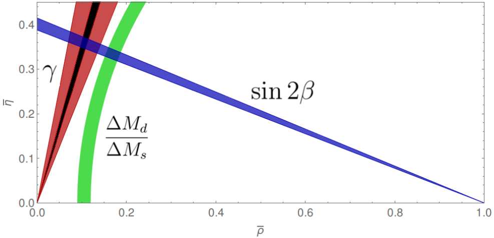
➢ **model-independent** determination of CKM matrix as a **standard candle** of the SM

Implications for the CKM Unitarity Triangle

- ideally determined solely through tree-level measurements: $|V_{us}|$, $|V_{cb}|$, $|V_{ub}|$, γ
  ➢ $R_b \sim |V_{ub}|/|V_{cb}|$ not well known due to persisting $|V_{ub}|$ problem
- currently: need to rely on B meson mixing data $(\sin 2\beta)$
- 2σ tension in R_t determined from tree-level γ vs. $\Delta M_d/\Delta M_s$ which hints for flavour non-universal NP contributions to $B_{d,s} - \bar{B}_{d,s}$ mixing
  ➢ will become **significant with $1°$ precision aimed for at LHCb and Belle II**



➢



MB, Buras (2018); see also MB, Buras (2016); Fermilab/MILC (2016)

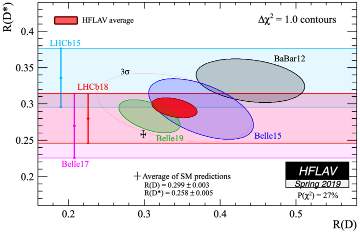
Recent anomalies in LFU-violating B decays

1. 3.1σ anomaly in semi-tauonic B decays, exhibiting lepton flavour universality violation
2. various *consistent* $2 - 3\sigma$ deviations in $b \to s\ell^+\ell^-$ transitions leading to a $\sim 6\sigma$ pull in the global fits

The $\mathcal{R}(D^{(*)})$ anomaly

Test of lepton flavour universality in semi-tauonic B decays

$$\mathcal{R}(D^{(*)}) = \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)} \qquad (\ell = e, \mu)$$



- theoretically clean, as hadronic uncertainties largely cancel in ratio
- measurements by BaBar, Belle, LHCb (so far $\mathcal{R}(D^*)$ only)
- recent Belle result (semi-leptonic tag) in good agreement with SM prediction

➢ **3.1σ discrepancy with SM** HFLAV (2019)

Model-independent prediction for $\Lambda_b \to \Lambda_c\tau\nu$ ➢ experimental consistency check

$$\mathcal{R}(\Lambda_c) = \mathcal{R}_{\mathrm{SM}}(\Lambda_c)(1.15 \pm 0.04) = 0.38 \pm 0.01 \pm 0.01$$

MB, Crivellin, de Boer, Kitahara, Moscati, Nierste, Nišandžić (2018), (2019)

Effective Hamiltonian for $b \to c\tau\nu$

New Physics above B meson scale described model-independently by

$$\mathcal{H}_{\text{eff}}^{\text{NP}} = 2\sqrt{2}G_F V_{cb}\Big[(1 + C_V^L)O_V^L + C_S^R O_S^R + C_S^L O_S^L + C_T O_T\Big]$$

with

$$O_V^L = (\bar{c}\gamma^\mu P_L b)\,(\bar{\tau}\gamma_\mu P_L \nu_\tau) \qquad O_S^R = (\bar{c}P_R b)\,(\bar{\tau}P_L\nu_\tau)$$

$$O_T = (\bar{c}\sigma^{\mu\nu}P_L b)\,(\bar{\tau}\sigma_{\mu\nu}P_L\nu_\tau) \qquad O_S^L = (\bar{c}P_L b)\,(\bar{\tau}P_L\nu_\tau)$$

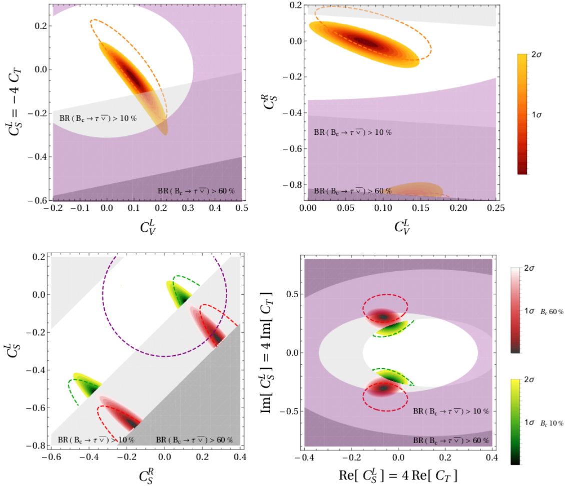
Popular BSM scenarios:

- charged Higgs contributions ➢ $C_S^{L,R} \neq 0$ — Kalinowski (1990); Hou (1993); Crivellin, Kokulu, Greub (2013)...
- charged vector boson W' ➢ $C_V^L \neq 0$ — He, Valencia (2012); Greljo, Isidori, Marzocca (2015)...
- (scalar or vector) leptoquark ➢ various $C_j \neq 0$ (depending on model)

see e. g. Tanaka, Watanabe (2012); Deshpande, Menon (2012); Kosnik (2012); Freytsis et al (2015)
Alonso et al (2015); Calibbi et al (2015); Fajfer, Kosnik (2015); Becirevic et al (2016),(2018)

Single particle scenarios

MB, Crivellin, Kitahara, Moscati, Nierste, Nišandžić (2019)
see also Murgui et al (2019); Shi et al (2019)



Main results

- W' solution disfavoured by LHC direct searches Faroughy, Greljo, Kamenik (2016)
- significant improvement possible with various leptoquark scenarios
- charged Higgs scenario predicts very large $\mathrm{BR}(B_c \to \tau\nu) \simeq 50\%$
  see Alonso, Grinstein, Martin Camalich (2016)
  Akeroyd, Chen (2017); MB et al (2018)
- constraints from LHC mono-τ constraints
  Greljo, Martin Camalich, Ruiz-Alvarez (2018)

More flavour observables to test NP in $\mathcal{R}(D^{(*)})$

Direct probes of NP structure

- $B \to D^{(*)}\tau\nu$ differential distributions, angular and polarisation observables

Nierste et al (2008); Celis et al (2016); Becirevic et al (2016)
Iguro et al (2018); MB, Crivellin et al (2018); Alonso et al (2018; Becirevic et al (2019)

Additionally: implied by $SU(2)_L$ symmetry

- large impact on $B \to K^{(*)}\nu\bar{\nu}$, $B_s \to \tau^+\tau^-$, $B \to K^{(*)}\tau^+\tau^-$ Crivellin, Müller, Ota (2017)
- contributions to $\Upsilon \to \tau^+\tau^-$ and $\psi \to \tau^+\tau^-$ Aloni et al. (2017)

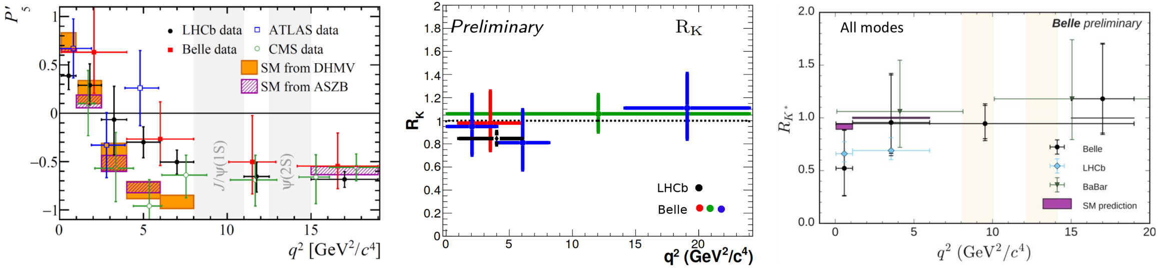
Complementary probes in high-p_T searches

- strong constraints from $b\bar{b} \to \tau\bar{\tau}$ and mono-τ at ATLAS and CMS

Faroughy, Greljo, Kamenik (2016); Altmannshofer, Dev, Soni (2017)
Greljo, Martin Camalich, Ruiz-Alvarez (2018)

➢ **NP explanations can unambiguously be tested**
in both high-p_T and flavour observables

Anomalies in $b \to s\ell^+\ell^-$ transitions



deviations from SM predictions seen in

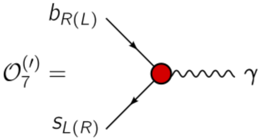
- angular distribution of $B \to K^*\mu^+\mu^-$ (mainly P_5')
- lepton flavour universality ratios $\mathcal{R}_{K^{(*)}} = \frac{\text{BR}(B\to K^{(*)}\mu^+\mu^-)}{\text{BR}(B\to K^{(*)}e^+e^-)}$
- less significant tensions in other observables, e. g. BR$(B_s \to \phi\mu^+\mu^-)$, BR$(B_s \to \mu^+\mu^-)$

New Physics in $b \to s\ell^+\ell^-$

Effective $b \to s\ell^+\ell^-$ Hamiltonian:

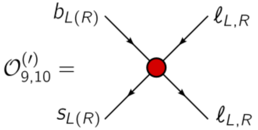
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}^* V_{ts} \frac{e^2}{16\pi^2} \sum_i (C_i \mathcal{O}_i + C_i' \mathcal{O}_i') + h.c.$$

with the operators most sensitive to New Physics



electromagnetic dipole operators $O_7^{(\prime)}$

- govern inclusive and exclusive $b \to s\gamma$ transitions
- enhanced contribution to $B \to K^*\ell^+\ell^-$ in low q^2 region

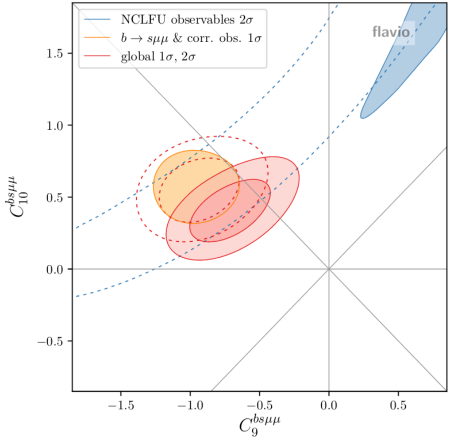


semileptonic four-fermion operators $O_9^{(\prime)}, O_{10}^{(\prime)}$

- loop-suppressed in the SM, but potentially tree level in the presence of NP

Status of global fits

Aebischer, Altmannshofer, Guadagnoli, Reboud, Stangl, Straub (2019)
see also Alguero et al (2019); Arbey et al (2019); Kowalska et al (2019)



Main results

- best 1D fit solutions ($\sim 6\sigma$ pulls):
  - $C_9^{bs\mu\mu} \simeq -0.97$
  - $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu} \simeq -0.53$
- non-zero $C_{10}^{bs\mu\mu}$ preferred by deviation in BR$(B_s \to \mu^+\mu^-)$
- some tension between $b \to s\mu^+\mu^-$ data and LFU observables
  - ➢ small flavour-universal contribution to C_9 possibly generated by RGE effects

see also Crivellin et al (2018)

Popular NP models

Variety of NP models on the market

- tree-level flavour changing Z' — Altmannshofer, Straub (2013); Gauld et al (2013) Altmannshofer et al (2014); Crivellin et al (2015)...
- loop-induced NP — Belanger et al (2015); Gripaios et al (2015); Arnan et al (2016) Kamenik et al (2017)
- leptoquarks — Hiller, Schmaltz (2014); Alonso et al (2015); Crivellin et al (2015) Fajfer, Kosnik (2015); Becirevic et al (2016)...

Most popular (subject to personal taste): $SU(2)_L$-singlet vector leptoquark U_1

- least constrained by complementary data (e. g. B_s mixing, direct searches)
- potential common origin of $b \to s\mu\mu$ and $b \to c\tau\nu$ anomalies
- naturally contained in the Pati-Salam gauge group $SU(4) \times SU(2)_L \times SU(2)_R$

➢ **plenty of model-building effort for UV-complete model**

Barbieri, Murphy, Senia (2016); Di Luzio, Greljo, Nardecchia (2017); Calibbi, Crivellin, Li (2017) Bordone, Cornella, Fuentes-Martin, Isidori (2017); MB, Crivellin (2018) Greljo, Stefanek (2018); Balaji, Foot, Schmidt (2018)...

Complementary tests

B decay observables

- LFU violating angular observables $Q_i = P_{i,\mu}^{(\prime)} - P_{i,e}^{(\prime)}$ — Capdevila et al (2016)
- $B \to K^{(*)}\nu\bar{\nu}$, $B \to K^{(*)}\tau^+\tau^-$, $B_s \to \tau^+\tau^-$ — Crivellin, Müller, Ota (2017)
- LFV meson decays like $B \to K^{(*)}\tau^\pm\mu^\mp$, $B_s \to \tau^\pm\mu^\mp$ — Bordone et al (2018)

Lepton flavour violating decays

Crivellin et al (2017); MB, Crivellin (2018); Bordone et al (2018); Barbieri, Ziegler (2019)...

- $\tau \to \mu\gamma$, $\tau \to \mu\phi$, $\tau \to 3\mu$
- $\mu \to e\gamma$, $\mu \to 3e$, $\mu - e$ conversion

High-p_T tests

- direct production of mediating leptoquark or partner states — Baker et al (2019)
- non-SM effects in tails of di-muon distributions — Greljo, MArzocca (2017)

Beyond B physics

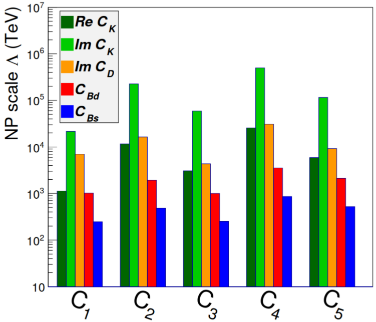
NP sensitivity of flavour observables governed by

- experimental & theoretical precision
- suppression of SM contribution

➢ **rare & CP-violating kaon decays** are unique probe of very high NP scales $> 100\,\text{TeV}$
e. g. $K \to \pi\nu\bar{\nu}$, $(K_L \to \pi^0\ell^+\ell^-)$, ε_K, ε'/ε...

➢ also **CP-violating effects in the charm sector** provide important tests of NP
(only meson system testing up-quark FCNCs!)
e. g. $|q/p|$, $A_{\text{CP}}(KK, \pi\pi)$, 3-body decays...

UTFIT (2018)



Flavour physics from the top

- **FCNC top decays** extremely suppressed in the SM
- new flavour-violating interactions involving third generation may have observable impact on decays like $t \to (c,u)H$, $t \to (c,u)\gamma$, $t \to (c,u)Z$
- HL-LHC and in particular FCC-hh will have **greatly increased sensitivity**
  - ➢ start to test parameter space of motivated NP models

FCC Study Group (2018)

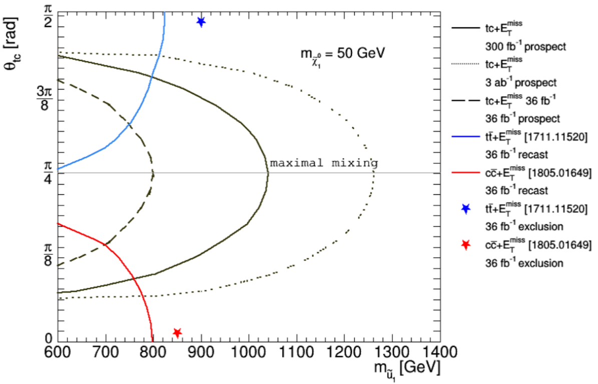
Detector	$\mathcal{B}(t \to u\gamma)$	$\mathcal{B}(t \to c\gamma)$
CMS (19.8 fb^{-1}, 8 TeV)	13×10^{-5}	170×10^{-5}
CMS Phase-2 (300 fb^{-1}, 14 TeV)	2.1×10^{-5}	15×10^{-5}
CMS Phase-2 (3 ab^{-1}, 14 TeV)	0.9×10^{-5}	7.4×10^{-5}
FCC-hh (3 ab^{-1}, 100 TeV)	9.8×10^{-7}	12.9×10^{-7}
FCC-hh (30 ab^{-1}, 100 TeV)	1.8×10^{-7}	2.4×10^{-7}
Detector	$\mathcal{B}(t \to uH)$	$\mathcal{B}(t \to cH)$
CMS (36.1 fb^{-1}, 13 TeV)	4.7×10^{-3}	4.7×10^{-3}
ATLAS (36.1 fb^{-1}, 13 TeV)	1.9×10^{-3}	1.6×10^{-3}
FCC-hh (3 ab^{-1}, 100 TeV)	8.4×10^{-5}	7.7×10^{-5}
FCC-hh (30 ab^{-1}, 100 TeV)	4.8×10^{-5}	4.3×10^{-5}

Flavour violating top partner decays

Many NP models predict the presence of top partners around the TeV scale
e. g. SUSY, composite Higgs, Little Higgs. . .

➢ couplings generally **flavour-violating**
➢ impact on **high-p_T pheno**

Chakraborty et al (2018)
see also MB, Giudice, Paradisi, Perez, Zupan (2013)



ex. SUSY: stop-scharm mixing

- bounds from $t\bar{t} + \not{E}_T$ and $c\bar{c} + \not{E}_T$ significantly affected by flavour mixing
- large mixing scenario $\theta_{tc} \sim \pi/4$ best covered by **dedicated $tc + \not{E}_T$ search**

Summary & outlook

In the absence of direct evidence for New Physics flavour violating decays remain one of our best bets for observing physics beyond the SM:

- interesting hints for NP contributions in B decays ("anomalies")
- sensitivity to very high scales in K decays
- high-p_T potential for flavour physics (rare top decays, flavour-violating NP interactions) yet to be explored

Summary & outlook

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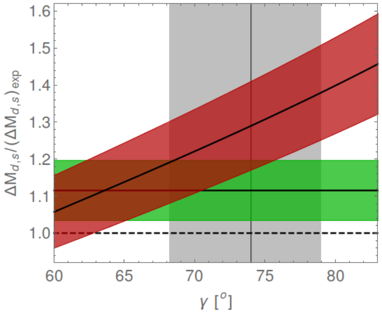
A priori not clear which route leads to a discovery!

Backup slides

A closer look at ΔM_d and ΔM_s



using FLAG2019 averages MB, Buras (2018)

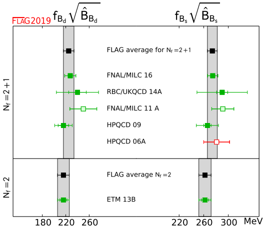
- $(\Delta M_d)_{\mathrm{SM}} > (\Delta M_d)_{\mathrm{exp}}$ due to large γ and $|V_{cb}|_{\mathrm{incl}}$ $(+\mathcal{O}(30\%)!)$
- smaller enhancement in ΔM_s (independent of γ)
- smaller $|V_{cb}|$ cannot cure $\Delta M_d/\Delta M_s$ & introduces tension in ϵ_K see also MB, Buras (2016); Bailey et al (2018)

➢ **emerging anomaly in $b \to d$ transitions?**

➢ **required NP pattern:**

- flavour non-universal NP contribution: $|\Delta S_d| > |\Delta S_s|$
- destructive interference with SM contribution ➢ new source of CP-violation?

A word on $\Delta B = 2$ hadronic matrix elements



FLAG 2019 averages

- based on 2+1 dynamical flavours
- dominated by Fermilab/MILC (2016)

➢ implying a 2σ tension in ΔM_d

Recent 2+1+1 flavour lattice result HPQCD (2019)

- different extraction to continuum limit (bag parameters vs. matrix elements)
- obtained matrix elements lower by $\sim 10\%$

➢ no tension in individual mass differences $\Delta M_{d,s}$

However, **2σ tension between γ and $\Delta M_d/\Delta M_s$** consistently implied by lattice data Fermilab/MILC (2016), HPQCD (2019), RBC/UKQCD (2018) & QCD sum rules King, Lenz, Rauh (2019)

ε'/ε – an opportunity worth the challenge

Measure of direct CP violation in $K \to \pi\pi$ NA48, KTeV (2002)

$$(\varepsilon'/\varepsilon)_{\text{exp}} = (16.6 \pm 2.3) \cdot 10^{-4}$$

- reliable SM prediction difficult due to large cancellation between QCD and EW penguin contributions
- recent progress by lattice QCD (update coming soon!) RBC/UKQCD (2015)
  ➢ current **SM prediction** $(\varepsilon'/\varepsilon)_{\text{SM}} = (1.9 \pm 4.5) \cdot 10^{-4}$ in apparent **tension with data**
  Buras, Gorbahn, Jäger, Jamin (2015); Kitahara, Nierste, Tremper (2016)
- anomaly claim supported by dual QCD calculations Buras, Gérard (2015ff)
  but not seen by chiral perturbation theory methods Gisbert, Pich (2017)

➢ **future more precise lattice QCD results will be able to clarify the situation**

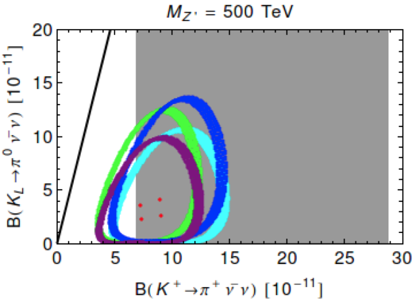
$K \to \pi\nu\bar{\nu}$ decays – a glimpse at the zeptouniverse

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

- complementary probe of NP in ε'/ε

  see e. g. Buras, Buttazzo, Knegjens (2015)
  MB et al (2015); Kitahara et al (2016)

- theoretically extremely clean and very rare
- sensitive to NP contributions from scales well beyond 100 TeV Buras et al. (2014)



Bright future

- NA62 ($K^+ \to \pi^+\nu\bar{\nu}$) and KOTO ($K_L \to \pi^0\nu\bar{\nu}$) to release new results soon
- KLEVER: new proposed experiment to measure $K_L \to \pi^0\nu\bar{\nu}$ with 20% precision