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Proton Driver Workshop

Charm and bottom physics in 2015 and beyond

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Outline

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1. Flavor physics in the LHC era

Strategies to physics above the electroweak scale of $174\,$GeV:

↙	↘
High energy:	High precision:
direct production of new particles	quantum effects from new particles
LHC	high statistics

Theoretical considerations from the gauge sector predict the onset of new physics at the TeV scale. The LHC will find new particles and will, possibly in conjunction with the International Linear Collider, study their production cross sections and decay patterns.

Why still study charm and bottom decays?

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Why still study charm and bottom decays?

- Flavor-changing neutral current (FCNCs) processes probe scales up to 100 TeV, well beyond the reach of the LHC.
- One wants to determine the parameters of the flavor sector of the new physics scenario found by the LHC.
  In particular in supersymmetric theories the squark flavor sector
  - reveals information on the SUSY breaking sector,
  - can be better probed with K's, D's and B's than with squark decays, because it is difficult to study squark FCNC's with high statistics. There are no analogues of the $\Delta F = 2$ transitions $\mathrm{K}-\overline{\mathrm{K}}$, $\mathrm{D}-\overline{\mathrm{D}}$, $\mathrm{B_d}-\overline{\mathrm{B}}_\mathrm{d}$ and $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixings with superpartners as external states.

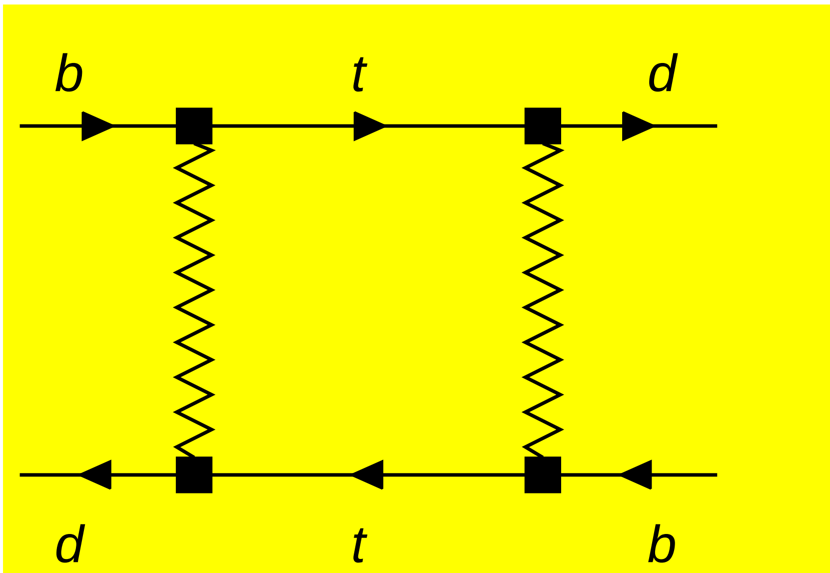
Why do FCNC's probe scales up to $\Lambda \sim 100\,\text{TeV}$?

If new physics is associated with the scale Λ, effects on weak processes (such as weak B decays) are generically suppressed by a factor of order M_W^2/Λ^2 compared to the Standard Model.

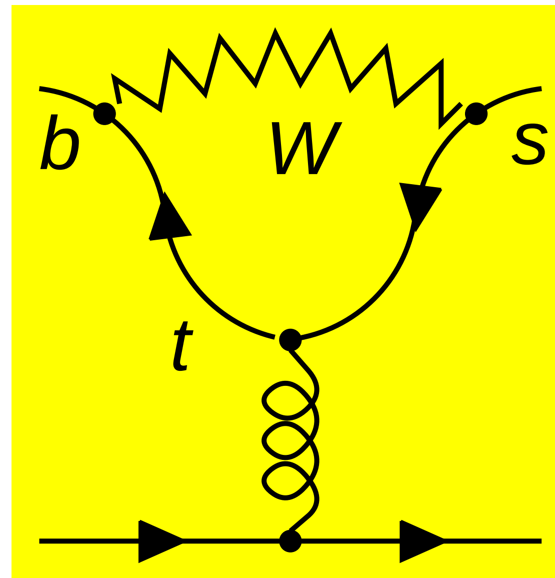
$\Rightarrow$ study processes which are suppressed in the Standard Model.

In the Standard Model predictions for FCNC's several suppression factors can pile up: electroweak loop, small CKM elements, GIM suppression, helicity suppression.

Examples for FCNC processes:



$\mathrm{B_d - \overline{B}_d}$ mixing



penguin diagrams

The suppression of FCNC processes in the Standard Model is not a consequence of the $SU(3) \times SU(2)_L \times U(1)_Y$ symmetry. It results from the particle content of the Standard Model and the accidental smallness of most Yukawa couplings. It is absent in generic extensions of the Standard Model.

Examples:

extra Higgses $\Rightarrow$ Higgs-mediated FCNC's at tree-level ,
helicity suppression possibly absent,

squarks/gluinos $\Rightarrow$ FCNC quark-squark-gluino coupling,
no CKM/GIM suppression,

vector-like quarks $\Rightarrow$ FCNC couplings of an extra Z',

$\mathrm{SU(2)_R}$ gauge bosons $\Rightarrow$ helicity suppression absent

E.g. $\mathrm{B_d}-\overline{\mathrm{B}}_\mathrm{d}$ mixing, $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing and $Br(K \to \pi\nu\overline{\nu})$ are sensitive to scales up to $\Lambda \sim 100\,$TeV.

Proton Driver

A Proton Driver at Fermilab, supplemented with changes to the Tevatron and the antiproton source, may increase the event rates at BTeV by a factor of 3 to 10.

This talk: Sketch which measurements could be interesting in the Proton Driver era.

The natural upper limit for the desirable experimental accuracy of some measurement is roughly the theoretical accuracy of its prediction. Experimental effort in the second half of the next decade will therefore focus on

- theoretically clean observables (with small hadronic uncertainties) and
- very rare processes.

2. Charm

In the Standard Model the interesting short-distance contributions to Charm FCNC's are extremely suppressed from the down-type GIM mechanism. In the Standard Model charm FCNC's are dominated by long-distance QCD effects.

However, short-distance contributions from new physics can well compete with the long-distance QCD effects.
extended Higgs sector, 4th generation, supersymmetry, topcolor, extra dimensions with bulk fermions, ...

Most new physics scenarios are designed for the gauge sector and are not very predictive for the flavor sector, i.e. they involve a lot of new free parameters, just as the values of the CKM elements of the Standard Model are not predicted.

$\Rightarrow$ Theory predictions stretch wide ranges.

$\mathrm{D}-\overline{\mathrm{D}}$ mixing

Mixing parameters:

$$x \equiv \frac{\Delta m_D}{\Gamma_D}, \qquad y = \frac{\Delta\Gamma_D}{2\,\Gamma_D}$$

Standard Model predictions:

$$x \lesssim y \lesssim 10^{-2}$$ Bigi, Uraltsev; Falk et al.

$\Rightarrow$ Precision measurements of x and y far below the percent level are not useful.

Better: Mixing-induced CP asymmetries (in, say, $D^0 \to KK, K\pi, \pi\pi \ldots$):

$$A_{CP} \sim 2(x\cos\delta + y\sin\delta)\,\sin\phi\,\Gamma_D\,t,$$

where δ is a strong rescattering phase. In the Standard Model the $\mathrm{D}-\overline{\mathrm{D}}$ mixing phase ϕ is tiny: $\phi \lesssim 10^{-3}$. In new physics scenarios $-1 \leq \sin\phi \leq 1$.

Rare D decays

Fajfer, Prelovšek, Singer

Rare D decays are long-distance dominated as well.

Consider $D \to M\ell^+\ell^-$ decays, with $D = D^0, D^+, D_s^+, \ldots$,
$M = \pi, \eta, K, \rho, K^* \ldots$ and $\ell = e, \mu$:

$$10^{-8} \lesssim Br(D \to M\ell^+\ell^-) \lesssim 10^{-6}.$$

Enhanced sensitivity to short-distance physics is in the region of high lepton invariant mass in

$D \to \pi\ell^+\ell^-$, Fajfer et al., Burdman et al.

Radiative decays (V is a vector meson):

$$10^{-6} \lesssim Br(D \to V\gamma) \lesssim 10^{-3}.$$

In

$$R = \frac{Br(D^0 \to \rho^0\gamma) - Br(D^0 \to \omega\gamma)}{Br(D^0 \to \omega\gamma)} = 0.06 \pm 0.15$$

most long-distance $c\overline{u} \to d\overline{d}\gamma$ effects cancel, while the long-distance $c \to u\gamma$ piece persists. $Br(D^0 \to \rho^0\gamma, \omega\gamma) = (0.1 - 1) \cdot 10^{-5}$ Fajfer et al.
In models of new physics $|R| = \mathcal{O}(1)$ is possible.

3. Bottom

In 2015 we will have learned a lot from precision B physics at BaBar, BELLE, CDF, D0, BTeV and LHCb.

A higher statistics B physics program will

- focus on observables with small hadronic uncertainties, which then allow to extract fundamental parameters with higher precision.
- address the "near zero" predictions of the Standard Model. These quantities can be dominated by new physics: E.g.: branching ratios and angular distributions of (ultra-) rare decays and certain CP asymmetries.
- not be motivated by "unitarity triangle trigonometry".

Purity Classification:

Rating:	uses:	example:
∗∗∗∗∗	CP or isospin symmetry of QCD	$\gamma - 2\beta_s$ from $B_s \to D_s^{\pm} K^{\mp}$
∗∗∗∗	CP or isospin symmetry of QCD plus $\mathcal{O}(\lambda^2)$-suppressed penguin pollution to tree decay	β from $B \to J/\psi K_S$
∗∗∗	operator product expansion	$\lvert V_{cb} \rvert$ from incl. decays
	HQET without $1/m_b$ term	$\lvert V_{cb} \rvert$ from $B \to D^* \ell \nu_\ell$

Rating:	uses:	example:
**	CP asymmetries in $b \to s$ penguin modes	$a_{CP}(B_d \to \phi K_S)$
	other HQET	$\lvert V_{cb}\rvert$ from $B \to D\ell\nu_\ell$
	four-quark matrix elements	$B-\overline{B}$ mixing
	from unquenched lattice QCD	
*	SU(3)$_F$ symmetry	γ from
		$B_s \to K^+K^-$ and
		$B_d \to \pi^+\pi^-$
	QCD factorization/SCET	$Br(B_d \to \phi K_S)$

CP asymmetries

CP seems to be a perfect symmetry of the strong interaction. It allows to eliminate hadronic matrix elements from those mixing-induced CP asymmetries which are unpolluted by penguins.

$\Rightarrow$ Study time-dependent CP asymmetries in $b \to c\overline{u}s, b \to u\overline{c}s$ decays.

Assuming that $\gamma = \arg[-V_{ub}^* V_{ud}/(V_{cb}^* V_{cd})]$ is known precisely in 2015,

$$\left\{ \begin{array}{c} a_{CP}^{\rm mix}(B_d \to D^0 K_S) \\ a_{CP}^{\rm mix}(B_s \to D^0 \phi) \end{array} \right\} \text{ will determine the } \left\{ \begin{array}{c} \rm B_d - \overline{B}_d \text{ mixing phase} \\ \rm B_s - \overline{B}_s \text{ mixing phase} \end{array} \right\}$$

precisely.

An important example for a "near zero" prediction of the Standard Model is the CP asymmetry in decays $B_s \to f$ which are flavor-specific, i.e.

$$\overline{B}_s \not\to f \text{ and } B_s \not\to \overline{f}.$$

Examples: $B_s \to X\ell^+\nu_\ell$ or $B_s \to D_s^- \pi^+$.

In the Standard Model:

$$a_{\rm fs} = 2 \cdot 10^{-5} \ \propto \ |V_{us}|^2 \frac{m_c^2}{m_b^2}$$

Beneke, Buchalla, Lenz, U.N.

The suppression factor $|V_{us}|^2 m_c^2/m_b^2$ is absent in new physics scenarios with new non-CKM contributions to $\rm B_s\!-\!\overline{B}_s$ mixing.

$\Rightarrow$ An enhancement by a factor of ~ 200 to $a_{\rm fs} \sim 5 \cdot 10^{-3}$ is possible.

Rare decays

Among the rare hadronic decays iso-spin violating $b \to s$ decays are interesting, because

- the tree contribution is doubly Cabibbo-suppressed and
- QCD penguins drop out.

They probe electroweak penguins in the Standard Model and generally iso-spin violating new physics. They are not accessible at $\Upsilon(4S)$ B-factories:

$$B_s \to \phi\pi^0, \qquad B_s \to \phi\rho^0, \qquad \Lambda_b \to \Lambda\phi \ldots$$

Standard Model: $Br(B_s \to \phi\pi^0) \sim 10^{-7}$ Beneke, Neubert

Rare leptonic decays:

A measurement of any of

$$B_d \to \mu^+\mu^-, \qquad B_d \to \tau^+\tau^-,$$
$$B_s \to \mu^+\mu^-, \qquad B_s \to \tau^+\tau^-,$$

will constrain the supersymmetric Higgs sector. For large $\tan\beta$ the neutral Higgs couplings are probed. The simultaneous measurement of several of these leptonic decay modes will quantify the deviation from minimal flavor violation.

Standard Model: $Br(B_s \to \mu^+\mu^-) = (4 \pm 1) \times 10^{-9}$ Buchalla, Buras

Conversely

$$B^+ \to \mu^+\nu_\mu, \qquad B^+ \to \tau^+\nu_\tau,$$

probe the charged Higgs sector of supersymmetric and other multi-Higgs models.

The decay constant f_B drops out from ratios like

$$Br(B_d \to \mu^+\mu^-)/Br(B^+ \to \mu^+\nu_\mu)$$

rendering them theoretically very clean.

4. Summary

- In 2015 and beyond precision B physics will probe the flavor structure of the new particles found by the LHC. If the world is supersymmetric, flavor physics will teach us something about the SUSY breaking mechanism.
- There are quantities with hadronic uncertainties well below 1%, which are suitable for precision determinations of fundamental parameters. These include certain CP asymmetries and ratios of certain branching fractions.
- A further long-term goal of charm and bottom physics are the "near zero" predictions of the Standard Model, where new physics can dominate. These include charm FCNC's, the CP asymmetry in flavor-specific B_s decays and rare decays like $B \to \ell^+\ell^-$.
- The analysis of iso-spin violating new physics can best be performed at hadron colliders through e.g. $B_s \to \phi\pi^0$, $B_s \to \phi\rho^0$, $\Lambda_b \to \phi\Lambda$.
- The opportunities of the proton driver for BTeV should be seriously explored.
- My talk covered only a few examples. There are many more interesting points for the flavor physics agenda in 2015 and beyond.