WTF is a B physics?

A talk for string theorists.

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Durham University IPPP and Cornell University

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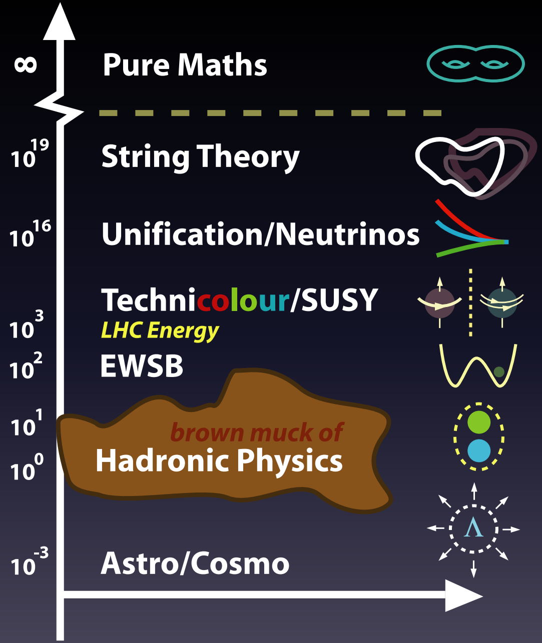
B physics... for *string theorists*?

Outline

- Low-Energy Physics... why?
- Flavour physics and CP
- Searching for new physics in penguins
- Example: $B \to \mu^+\mu^-$

Goal: Understand why B physics is relevant to model-builders.

Caveat: In the interest of actually learning something interesting, I'll go slowly and focus on review. I've cut some 'fancy' topics (e.g. HQET, details of calculations, etc.) and will instead focus on broad introductory ideas.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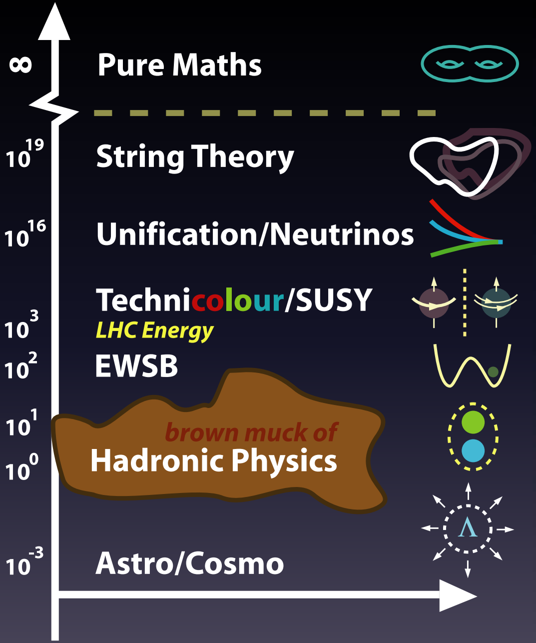
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High energy vs. low energy

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- Unification
- Hierarchies
- Direct production of NP

High energy vs. low energy

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We understand why it's useful to go to high energies. But why is it worthwhile to wade through the hadronic brown muck of low energy?

What we can learn other than: "Non-perturbative QCD is hard" ?

High energy vs. low energy

High Energy

- Unification
- Hierarchies
- Direct production of NP

Low Energy

- Scale of new physics
- Flavour structure
- Matter vs. Antimatter

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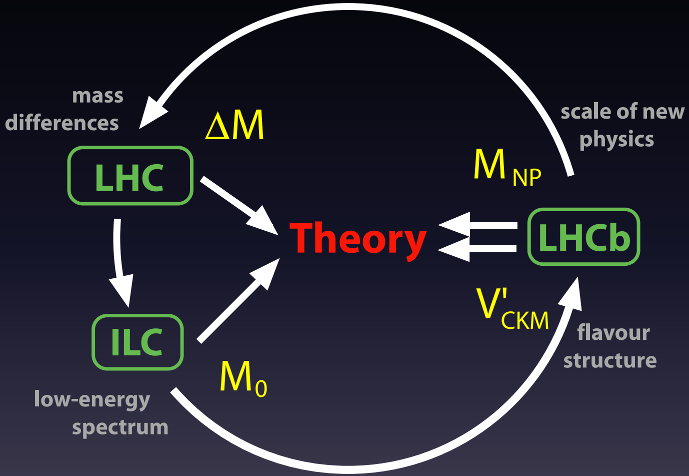
What we can learn other than: "Non-perturbative QCD is hard" ?

Answer: Low-energy (meson-scale) physics provides **complementary** information about new physics!

Complementarity



Reminder: Flavour in the Standard Model

We start with the most general Lagrangian satisfying our $SU(3) \times SU(2) \times U(1)$ gauge symmetry and chiral symmetry.

$$\mathcal{L} = -\frac{1}{2}\bar{\psi}_f \not{D} \psi_f - |D_\mu \phi|^2 - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + y_{ij} \phi^b \bar{\psi}^b_i \psi_j + \text{h.c.}$$

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Upon electroweak symmetry breaking, the Higgs gets a vev and the Yukawa couplings y_{ij} generate new fermion mass terms.

$$\phi = \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \to \begin{pmatrix} v + h \\ 0 \end{pmatrix}$$

$$\mathcal{L}_{EWSB} = -\frac{1}{2}\bar{\psi}_i (\not{D} + m_{ij}) \psi_j + \cdots$$

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But this isn't diagonal. Physical (propagating) fermions are eigenstates of the Hamiltonian.

Reminder: The CKM Matrix

We have the freedom to rotate our fields in flavour space. So it *should* be trivial to diagonalise the masses:

$$\psi_u^L \longrightarrow U_u^L \psi_u^L \qquad \psi_u^R \longrightarrow U_u^R \psi_u^T$$
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But this is **wrong**! Recall that the left-handed fields are part of an $SU(2)$ doublet, Q. They cannot be rotated independently! Instead, $Q \to U^L Q$:

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As a result, we can only diagonalise either the u or the d quarks, but not both. We must have flavour mixing! By the way, there's an analogous mixing matrix for neutrinos.

Reminder: The CKM Matrix

By convention, diagonalise the up-type quarks:

$$\mathcal{L}_{EWSB} = \bar{\psi}_u^L \left(U_u^\dagger \hat{M}_u U_u \right) \psi_u^R + \bar{\psi}_d^L \left(U_d^\dagger \hat{M}_d U_d \right) \psi_d^R$$

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We define the **CKM Matrix** $V_{CKM} \equiv U_u^\dagger U_d$. This is a 3×3 unitary matrix that encodes the difference between the mass and flavour eigenbases.

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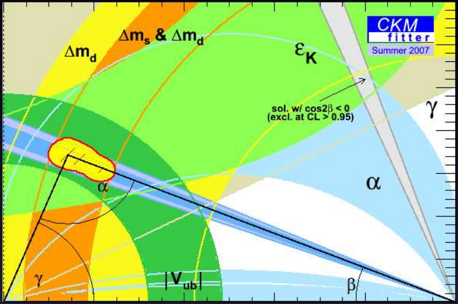
Flavour Basis: Interactions diagonal, propagators get m_{ij}.
Mass Basis: Propagators are diagonal, interactions get V_{CKM}.

Mass basis preferred: resummation of mass insertions.

Goniometry: Measurement of angles

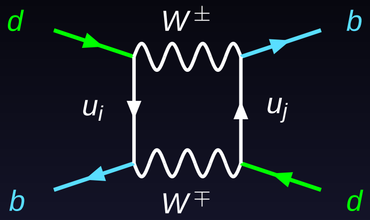


$$
\begin{aligned}
0 &= \left(V^\dagger V\right)_{bd} \\
&= V^\dagger_{bu} V_{ud} + V^\dagger_{bc} V_{cd} + V^\dagger_{bs} V_{sd} \\
&= 1 + \frac{V^*_{cb} V_{cd}}{V^*_{ub} V_{ud}} + \frac{V^*_{sb} V_{sd}}{V^*_{ub} V_{ud}}
\end{aligned}
$$

Null sum of three $\mathbb{C}$ numbers. Can plot each number on the $\mathbb{C}$ plane to form a unitarity triangle.

If this were a 'B-physics for phenomenologists' talk, I would have to explain how these angles are measured. I guess I dodged the bullet on that one, eh?

Bonus: the GIM mechanism



Consider $B - \bar{B}$ mixing.
Note that unitarity implies
$\sum_i V_{bi}^\dagger V_{id} = 0$.

This seems to imply that this
flavour-changing neutral current
is prohibited, as it is at tree level.

But this isn't the case. Let's estimate the amplitude.

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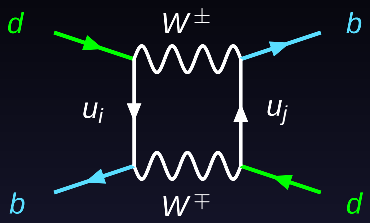

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$$g^4$$

Each vertex gives a weak coupling constant.

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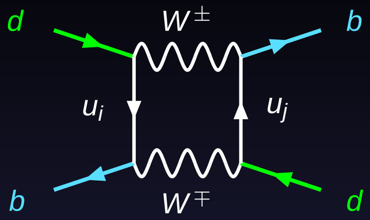

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$$g^4 \frac{1}{4\pi^2}$$

Loop factor

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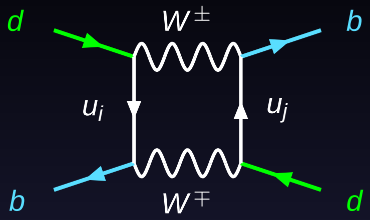

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$$g^4 \, \frac{1}{4\pi^2} \, \frac{1}{M_W^2}$$

Dimensional analysis, characteristic loop momentum

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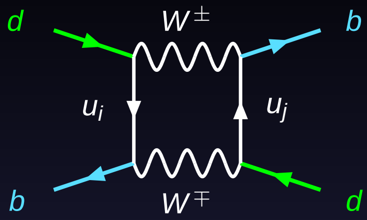

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CKM matrix factors from each vertex

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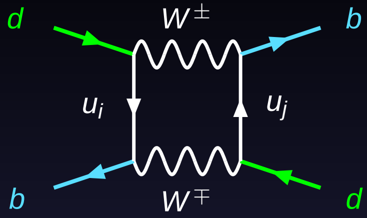

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Taylor expanding in $m_i \ll M_W$

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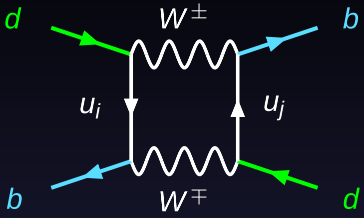

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Removing common mass scale

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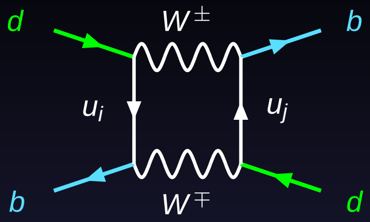

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The lesson: FCNC at one loop are suppressed by the smallness of the quark mass degeneracies.

$\mathbb{C}$ phases of the CKM Matrix with N flavours

Unitary: has $N^2 - \frac{1}{2}N(N-1) = \frac{1}{2}N(N+1)$ $\mathbb{C}$ degrees of freedom.

This is just (total unitary dof) - (orthogonal dof)

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- $2N$ quark species, each can absorb a phase
- But the overall phase of *all* quarks is a symmetry
- $\Longrightarrow$ can absorb $2N-1$ phases

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Physical phases in V_{CKM}:

$$\frac{1}{2}N(N+1) - (2N-1) = \frac{1}{2}(N-1)(N-2)$$

In particular, for $N=3$, we have a single complex phase.

So what? The CKM Matrix and $\mathcal{CP}$ Violation

Under charge-parity ($\mathcal{CP}$) conjugation, matter $\leftrightarrow$ antimatter.

Consider the W^-_μ flavour-changing term and its $\mathcal{CP}$ conjugate:

$$\begin{aligned}
\mathcal{L} &\supset W^+_\mu \bar{u}_i V_{ij} \gamma^\mu P_L d_j + W^-_\mu \bar{d}_i V^\dagger_{ij} \gamma^\mu P_L u_j \\
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Observe: If V_{ij} were purely real, then $(\mathcal{CP})\mathcal{L}(\mathcal{CP})^* = \mathcal{L}$ and the Standard Model would be $\mathcal{CP}$-invariant. The complex phase of the CKM matrix leads to matter-antimatter asymmetry!

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Hint for new physics: We know that this phase is too small to account for the $\mathcal{CP}$ asymmetry of the observed universe. There has to be more.

What we've learned so far

- Non-diagonal masses generate flavour structure
- $\mathbb{C}$ phases from this structure generates $\mathcal{CP}$ asymmetry

Theory: We generically get new mass matrices from, e.g., SUSY.
Experiment: We *need* new sources of $\mathcal{CP}$ asymmetry!

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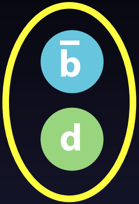
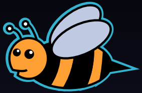
Caveat emptor: Honesty compels me to mention...

- **Leptogenesis:** $\mathcal{CP}$ phase in the neutrino sector is transferred into a baryon asymmetry via topological effects (sphaelerons)
- **Minimal Flavour Violation:** Perhaps, by some perverse coincidence, all new flavour structure is identical to the Standard Model.

B-mesons

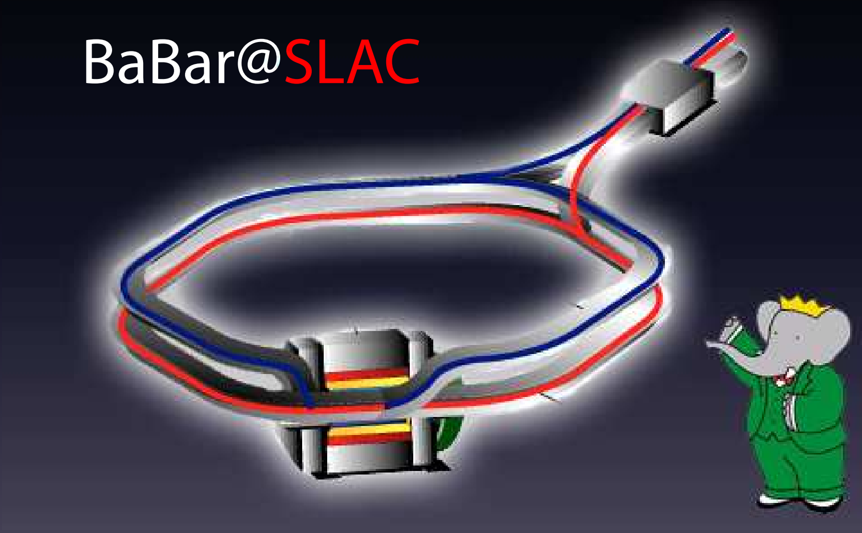




Meson	Mass	Mean lifetime
B_d^0	5.28 GeV	1.53×10^{-12}s
B_s^0	5.37 GeV	1.44×10^{-12}s

B-mesons are the state-of-the-art laboratory for flavour physics. This is the *low* energy frontier. Instead of on-shell production of new particles, look for their *virtual effects*.

Bonus: Asymmetric *B*-factories



Hunting for physics beyond the standard model

This audience mainly cares about *new physics*. How does physics beyond the standard model manifest itself in a B system with $M_B \ll M_{new}$?

Instead of direct production, look for quantum effects. i.e. new particles appear in (virtual) loop effects! ($\Delta E \Delta t \leq \hbar$)

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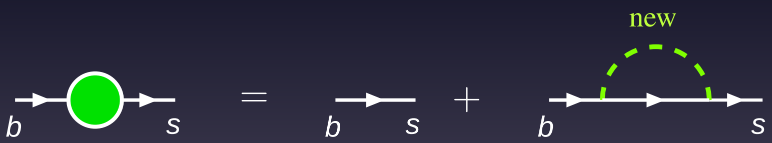
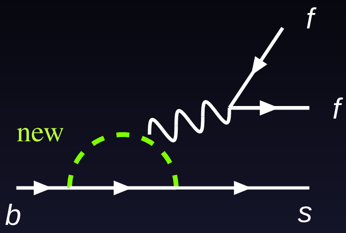
Naively:



But: for large mass differences, this is suppressed by momentum conservation.

Hunting for physics beyond the standard model



Trick: Radiate away the extra momenta. Now the process can occur on-shell, and we can measure the effect of new physics on the branching ratio.

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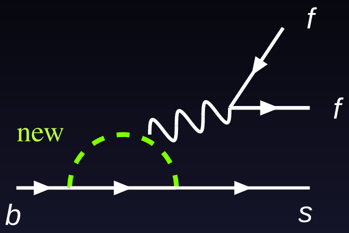

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These types of diagrams are called **penguin diagrams** because of a cheeky Englishman (John Ellis). If you stare really hard you can make it look like a penguin.

The point is that penguin processes help us to see the effect of off-shell new physics in loops.

LoL-Penguin: I can has a $\mathcal{CP}$ violation?

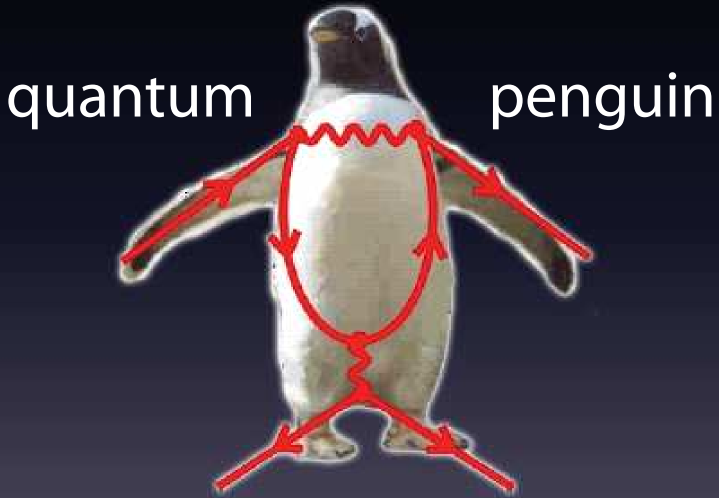

Image source: Google 'Penguin Diagram,' original author unknown.

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A few things to remember about the MSSM

- Many UV theories, unique low-energy theory: MSSM
- SUSY-breaking introduces new flavour structure
- Two Higgs doublets, each gets a vev. $\tan\beta \equiv v_u/v_d$

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The name of the game is to find signatures of new physics in loop diagrams through differences from the Standard Model branching ratio.

Question: Where does one look for penguins?

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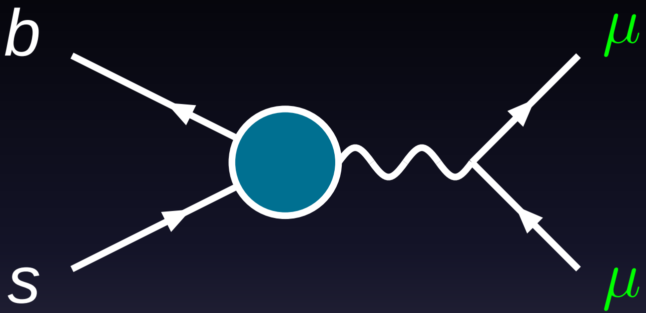
Antarctica: very little background, penguin is dominant.

Where does one look for penguins?



$B \to \mu^+\mu^-$: very little background, penguin is dominant.

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Standard Model suppressed by....

- **Loop**: no tree-level contribution
- **FCNC**: $|V^*V|_{bs}$
- **Helicity**: Angular momentum $\Rightarrow \quad \mathcal{M} \propto m_\mu$

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Experimentally clean: final state is very easy to tag in a detector.

Theoretically clean: the only hadronic uncertainties come from f_B. Wait a second... what's f_B?

Bonus: Lepton/Hadron Factorisation

$$\langle \ell, \ell' | \mathcal{H}_{eff} | B(p) \rangle = \sum_{i=ops} \langle \ell, \ell' | \mathcal{O}^i_L | 0 \rangle \langle 0 | \mathcal{O}^i_Q | B(p) \rangle$$

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Definition of the **decay constant**, f_B

$$\begin{aligned} \langle 0 | \bar{b} \gamma_\mu P_{L,R} s | B(p) \rangle &= \mp \frac{i}{2} p_\mu f_B \\ \Rightarrow \langle 0 | \bar{b} P_{L,R} s | B(p) \rangle &= \pm \frac{i}{2} \frac{M_B f_B}{m_b + m_s} \end{aligned}$$

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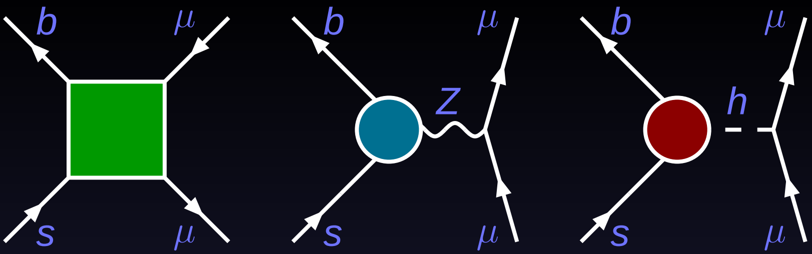
Note that there are no tensor ($\bar{b}\sigma^{\mu\nu}s$) operators by antisymmetry.
f_B contains all the hadronic brown muck! Lattice QCD people give us numbers.

Leptonic decay: don't have to worry about jets, inclusive decays, etc.

Current experimental bounds and SM expectations

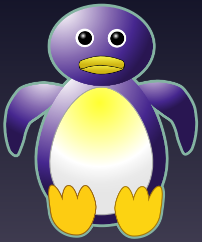
Channel	Expt.	Bound (90% CL)	SM Prediction
$B_s^0 \to \mu^+\mu^-$	CDF II	$< 4.7 \times 10^{-8}$	$(4.817 \pm 0.017) \times 10^{-9}$
$B_d^0 \to \mu^+\mu^-$	CDF II	$< 1.5 \times 10^{-8}$	$(1.903 \pm 0.006) \times 10^{-10}$
$B_s^0 \to \mu^+ e^-$	CDF	$< 6.1 \times 10^{-6}$	≈ 0
$B_d^0 \to \mu^+ e^-$	BABAR	$< 9.2 \times 10^{-8}$	≈ 0

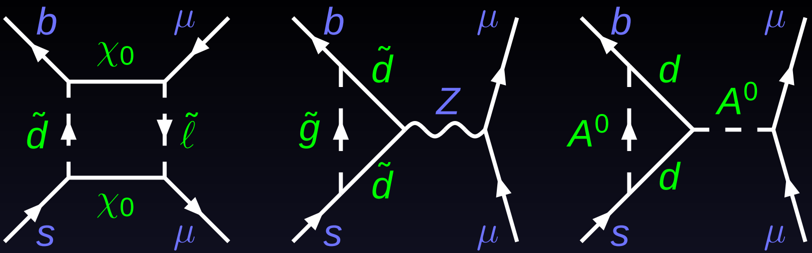
Sources:
arXiv:0712.1708
Phys. Rev. Lett. 81
5742 (1998), arXiv:0712.1516



We have box, Z-penguin, and h-penguin diagrams.

- All blobs are one-loop.
- No photon penguin due to Ward identity.



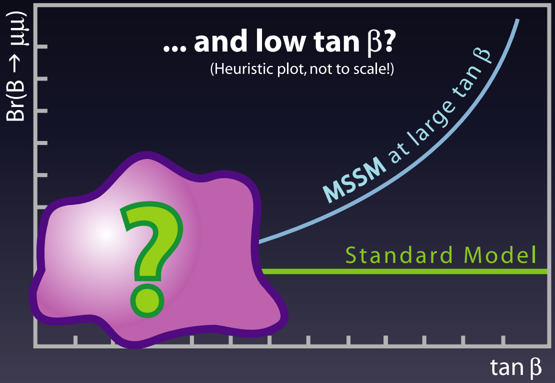


In particular, the **Super** symmetric Higgs **penguin** is enhanced by $\tan^3\beta$.

$$\text{Br} \approx 5 \times 10^{-7} \left(\frac{\tan\beta}{50}\right)^6 \left(\frac{300\text{GeV}}{M_{A_0}}\right)^4$$

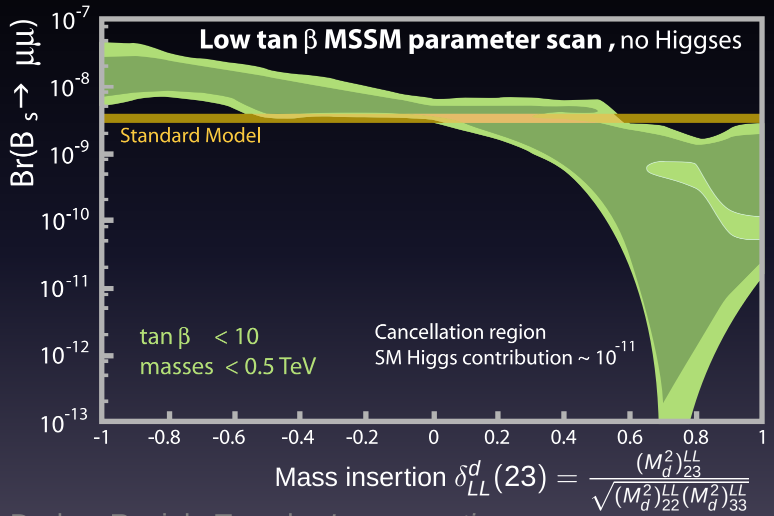
The large tan β regime has been throroughly investigated[1].
On the eve of the LHC(b), we must consider **low** tan β.

Here we expect interference when the box and Z-penguin diagrams are of the same order as the tan β-enhanced h-penguin diagrams.

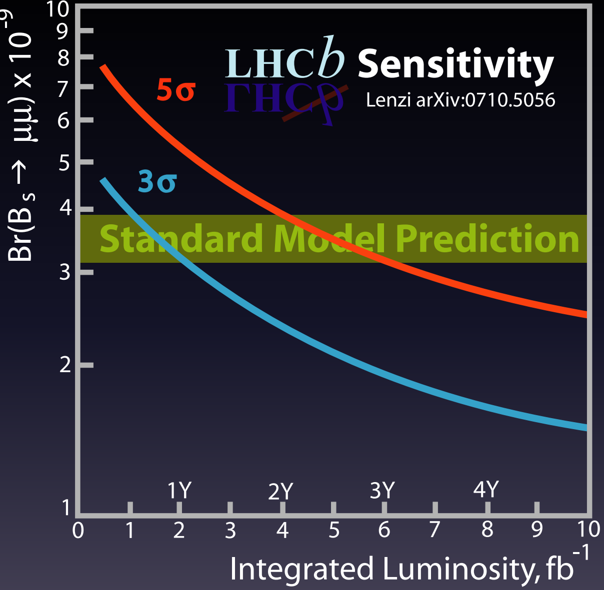


[1] Buras/Buchalla '93, Chankowski/Slawianowska '01, Dedes/Pilaftsis '02, Buras/Chankowski/Rosiek/Slawianowska '03., Babu/Kolda '99, ...

Preliminary scans



Dedes, Rosiek, Tanedo. *In preparation.*

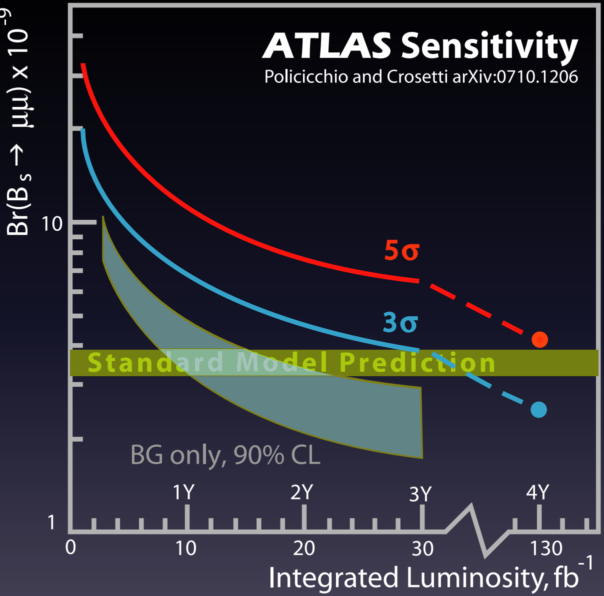


Potential...

'Signal' in 1Y

'Discovery' in 3Y

Implications on **LHCb** upgrade? (B_s or B_d?)



GPDs will also be able to reach SM limit. (More diffi cult to tag, requires higher luminosity than LHCb.)

Summary

- Flavour physics addresses important questions relevant to model-builders
- Current experiments will constrain new physics
- $B_s \to \mu^+\mu^-$ might be the first signal of new physics at the LHC

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Thanks to the organisers (Olga)!

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