Flavour Physics and CP Violation

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March 25, 2013

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Plan, or selling flavour physics at the time of LHC

The first question in flavour physics:

Who ordered that?

Flavour physics has built up the SM

[Only quark flavour. Neutrinos are interesting in their own right.]

1. First generation of flavour physics (pre-1970)
   - Strange particles, parity violation, eightfold way, discovery of Ω^-
   - $K^0 - \overline{K}^0$ oscillation, "tiny" CP violation in K decay
   - Cabibbo hypothesis, GIM mechanism
2. Second generation of flavour physics (1970 - 1995)
   - Kobayashi-Maskawa hypothesis
   - J/ψ and Υ production
   - Observation of $B^0 - \overline{B}^0$ oscillation
3. Third generation of flavour physics (1995 - present)
   - e^+e^- B factories, "large" CP violation in B system
   - Top discovery
   - Observation of $B_s - \overline{B_s}$ and $D^0 - \overline{D}^0$ oscillation
   - Rare B decays, Precision flavour physics

Flavour physics has also posed the strongest challenge

Unknown parameters:
12 masses, 6 mixing angles, 2 (possibly) phases (+ Majorana)
Who ordered all that?

Large hierarchy: $m_{\nu_e}/m_t \leq 10^{-14}$

If u and d were not light, we would not have been here!
If top were not heavy, we would not have seen the Higgs by now

Horizontal symmetries?
Fermion localization in warped ED?

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B-factories: past, running, and upcoming

BaBar@SLAC : e^+e^-, 429 fb^{-1}, 4.7×10^8 $B\bar{B}$ pairs

Belle@KEK : e^+e^-, over 1 ab^{-1}, 7.72×10^8 $B\bar{B}$ pairs

LHCb : 1 fb^{-1} at $\sqrt{s} = 7$ TeV, 1.1 fb^{-1} at 8 TeV
7 TeV: $\sigma(pp \to b\bar{b}X) = (89.6 \pm 6.4 \pm 15.5)$ μb, scales linearly with $\sqrt{s}$

Ultimately, 5 fb^{-1}/yr, total $\mathcal{L}_{int} = 50$ fb^{-1},
$\sim$ 200-fold increase over 1 fb^{-1} sample

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Why is flavour physics important ?

- Better understanding of SM for $N_{gen} > 1$
  — **Window to top and triple-gauge dynamics** (e.g. $B^0 - \overline{B}^0$ mixing, $b \to s\gamma$, $Z \to b\overline{b}$, $B_s \to \mu\mu$)
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- Part I: Introduction to basic concepts (for the students only)
- Part II: Survey of New Physics hunting grounds
- Tensions: NP hints?

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Part I : Basic concepts

Part I : Flavour physics in the SM

Charged current weak interaction is of the form

$$\mathcal{L}_{wk} = -\frac{g}{\sqrt{2}}\bar{u}\gamma^\mu P_L d W^+_\mu + \mathrm{h.c.}\,, \quad P_L = \frac{1-\gamma_5}{2}$$

We can generalise it to more than one generations:

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The quarks in this basis are not mass eigenstates — the mass matrix has off-diagonal elements

Suppose the weak and the mass bases are related by

$$u_i = \mathcal{U}_{ij} u'_j \,, \qquad d_i = \mathcal{D}_{ik} d'_k$$

The charged current Lagrangian becomes

$$\begin{aligned} \mathcal{L}_{wk} &= -\frac{g}{\sqrt{2}} \bar{u}'_j (\mathcal{U}^\dagger_{ji} \mathcal{D}_{ik}) \gamma^\mu P_L d'_k W^+_\mu + \mathrm{h.c.} \\ &= -\frac{g}{\sqrt{2}} V_{jk} \bar{u}'_j \gamma^\mu P_L d'_k W^+_\mu + \mathrm{h.c.} \end{aligned}$$

From now on, we will work in the mass basis and drop the prime for brevity.

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$V \equiv \mathcal{U}^\dagger \mathcal{D}$ is the CKM matrix. Note that

- We can measure the elements of V but not the individual elements of $\mathcal{U}$ or $\mathcal{D}$
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Theorem

CPT is a good symmetry of any local Lorentz-invariant axiomatic quantum field theory with a unique vacuum state.

You can never construct a Lorentz-invariant QFT with a hermitian Hamiltonian that violates CPT.

[Lüders, Pauli, Bell, Jost (1954-58)]

Consequences of CPT conservation

- Particle and antiparticle must have same mass and opposite electric charge
- Particle and antiparticle, if unstable, must have same decay width
  Not true if stationary states are particle-antiparticle combinations

$$K_L \approx \frac{1}{\sqrt{2}}(K^0 + \overline{K}^0)\,, K_S \approx \frac{1}{\sqrt{2}}(K^0 - \overline{K}^0)\,,$$

$$M_{K_L} \neq M_{K_S}\,, \quad \Gamma_{K_L} \neq \Gamma_{K_S}$$

- T violation necessarily means CP violation, like EDM

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Unitarity Triangle

$$
V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}
= \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)
$$

$V_{td} = |V_{td}| \exp(-i\beta)$, $V_{ub} = |V_{ub}| \exp(-i\gamma)$

Wolfenstein parametrisation

$$\lambda = 0.22543^{+0.00059}_{-0.00094}, \qquad A = 0.802^{+0.029}_{-0.011},$$

$$\rho(1-\tfrac{1}{2}\lambda^2) = 0.140 \pm 0.027, \qquad \eta(1-\tfrac{1}{2}\lambda^2) = 0.343 \pm 0.015$$

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From $VV^\dagger = V^\dagger V = \mathbf{1}$, one can write

$$\begin{aligned}
V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* &= 0\,,\\
V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* &= 0\,,\\
V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* &= 0\,,\\
V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* &= 0\,,\\
V_{ud}V_{td}^* + V_{us}V_{ts}^* + V_{ub}V_{tb}^* &= 0\,,\\
V_{cd}V_{td}^* + V_{cs}V_{ts}^* + V_{cb}V_{tb}^* &= 0\,.
\end{aligned}$$

Such equations represent triangles in the complex plane. These triangles are known as *unitarity triangles*.

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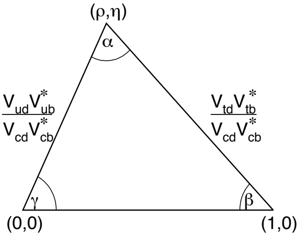
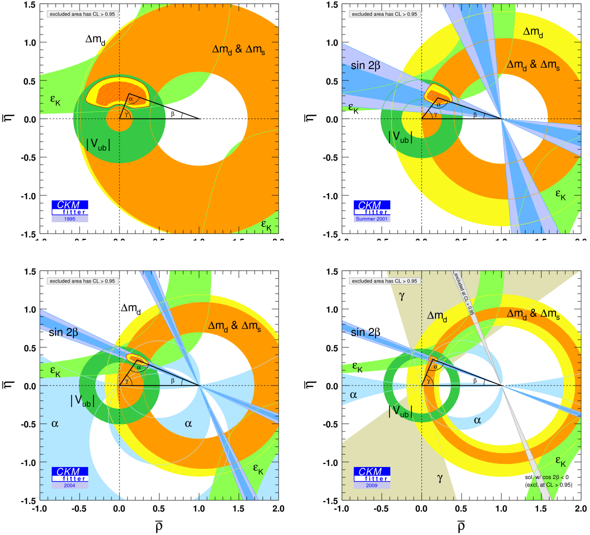


- All UTs have same area. A nonzero area means CP violation
- A good check of the 3-gen CKM paradigm is to see whether $\alpha + \beta + \gamma = \pi$, and whether the sides match

Evolution of the UT



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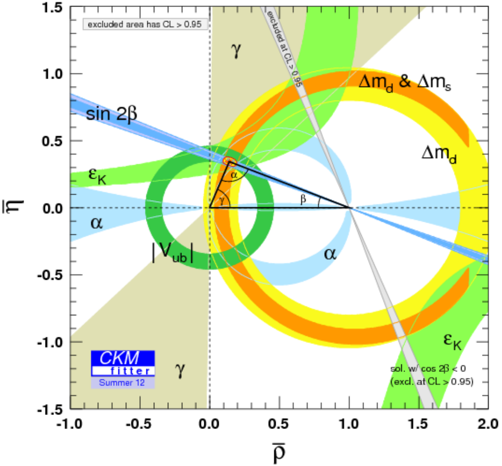

α	$90.5^{+4.3}_{-4.1}$
β direct	$21.38^{+0.79}_{-0.77}$
β indirect	$25.39^{+0.92}_{-2.11}$
β average	$21.73^{+0.78}_{-0.74}$
γ	$67.7^{+4.1}_{-4.3}$

Note the tension in β, caused by the $|V_{ub}|$ band.

CP violation

The CC Lagrangian *must* have a complex coupling — *necessary but not sufficient*

CP is violated if

$$\Gamma(X \to f) \neq \Gamma(\bar{X} \to \bar{f})$$

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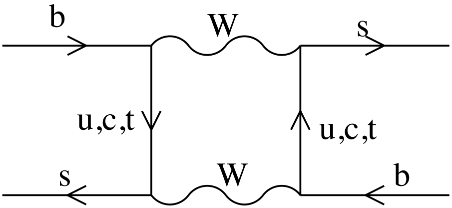
Intro to neutral meson oscillation

Notation: $B_q^0 \equiv \bar{b}q \ (B=+1)\,,\ \overline{B_q}^0 \equiv b\bar{q} \ (B=-1)$

Weak interaction violates B, just like strangeness, and one can have a nonzero mixing amplitude through the diagram



This is our old friend two-level QM (NH_3 molecule, H_2^+, Stark effect, ...)
Only four such systems: $K^0-\overline{K}^0$, $D^0-\overline{D}^0$, $B_d-\overline{B_d}$, $B_s-\overline{B_s}$

$$i\frac{d\psi(t)}{dt} = H\psi(t), \quad |\psi(t)\rangle = \begin{pmatrix} |B_q^0(t)\rangle \\ |\overline{B_q}^0(t)\rangle \end{pmatrix}$$

$$H = \begin{pmatrix} M_q - \frac{i}{2}\Gamma_q & M_q^{12} - \frac{i}{2}\Gamma_q^{12} \\ M_q^{12*} - \frac{i}{2}\Gamma_q^{12*} & M_q - \frac{i}{2}\Gamma_q \end{pmatrix}$$

H is not hermitian, but $H_{11} = H_{22}$ due to CPT

The mass eigenstates are

$$B_{qH(L)} = pB_q^0 + (-)q\overline{B_q}^0$$

Eigenvalues : $\left(M_q \pm \frac{1}{2}\Delta M_q\right) - \frac{i}{2}\left(\Gamma_q \mp \frac{1}{2}\Delta\Gamma_q\right)$ $\Delta M, \Delta\Gamma > 0$ in SM

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$$\Delta M_q = 2|M_q^{12}|, \quad \Delta\Gamma_q = 2|\Gamma_q^{12}|\cos\phi_q, \quad \phi_q = arg\left(-\frac{M_q^{12}}{\Gamma_q^{12}}\right)$$

$$\frac{q}{p} = \exp(2i\phi_M), \quad \phi_M = -\beta \ \text{ for } B_d, \ -\beta_s \ \text{ for } B_s$$

Corollary:
For the $B_s - \overline{B_s}$ system, $\phi_s \approx 0$, so if NP contributes in M_{12} but not in Γ_{12}, $\boxed{|\Delta\Gamma_s| < |\Delta\Gamma_s(SM)|}$ (Grossman, 1996)

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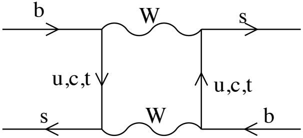

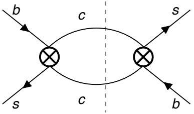

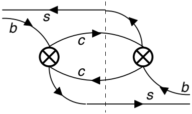

$$M_q^{12}(SM) = (V_{tb}V_{tq}^*)^2 \frac{G_F^2}{12\pi^2} \chi_{B_q} \hat{\eta}_{B_q} M_W^2 S_0(x_t) \, ,$$
$$\Gamma_q^{12}(SM) = -[(V_{cb}V_{cq}^*)^2 \Gamma^{cc} + (V_{ub}V_{uq}^*)^2 \Gamma^{uu} + 2(V_{cb}V_{cq}^* V_{ub}V_{uq}^*)\Gamma^{cu}] \, ,$$

$\chi_{B_q} = M_{B_q} B_{B_q} f_{B_q}^2$, $\hat{\eta}$ contains the short-distance corrections
$S_0(x_t)$ is the Inami-Lim function, $x_t = m_t^2/m_W^2$

Direct CP Violation

$\langle f|T|i\rangle \neq \langle (CP)f|T|(CP)i\rangle$, e.g., $\Gamma(B^+ \to f) \neq \Gamma(B^- \to \bar{f})$
For $B^+ \to f$, the two amplitudes are of the form

$$M_1 \exp(i\theta_1) \exp(i\delta_1) \quad \text{and} \quad M_2 \exp(i\theta_2) \exp(i\delta_2)$$

θs are weak (CKM) phases and δs are strong phases coming from effects like final-state rescattering

$$\Gamma(B^+ \to f) \propto M_1^2 + M_2^2 + 2M_1 M_2 \cos(\theta + \delta)\,, \quad \theta = \theta_1 - \theta_2\,,\ \delta = \delta_1 - \delta_2$$

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For $B^- \to \bar{f}$, $\theta \to -\theta$, everything else same

$$\Gamma(B^- \to \bar{f}) \propto M_1^2 + M_2^2 + 2M_1 M_2 \cos(-\theta + \delta)$$

Necessary and sufficient condition: both θ and $\delta \neq 0$

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θs are weak (CKM) phases and δs are strong phases coming from effects like final-state rescattering

$$\Gamma(B^+ \to f) \propto M_1^2 + M_2^2 + 2M_1M_2\cos(\theta+\delta)\,, \quad \theta = \theta_1 - \theta_2\,,\ \delta = \delta_1 - \delta_2$$

For $B^- \to \bar{f}$, $\theta \to -\theta$, everything else same

$$\Gamma(B^- \to \bar{f}) \propto M_1^2 + M_2^2 + 2M_1M_2\cos(-\theta+\delta)$$

Necessary and sufficient condition: $\boxed{\text{both } \theta \text{ and } \delta \neq 0}$

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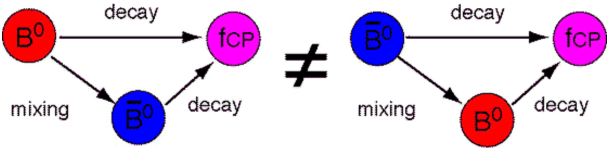
Mixing-induced CP violation

Clean way to extract info, without going into dirty strong phases (not calculable from first principles)
Consider a state f_{CP} which can come from both B and $\bar{B}$, this generates a second amplitude



Part II : Survey of the hunting grounds

Probe of New Physics

If NP is at

- <1 TeV: within direct reach of LHC@8 TeV, almost ruled out
- a few TeV: within reach of LHC@14 TeV
- $>$ a few TeV: beyond LHC

Indirect detection

Flav. structure	<1 TeV	a few TeV	$>$ a few TeV
Anarchy	huge O(1) ✗	O(1) ✗	small ($<$ O(1))
Small misalignment	Sizable O(1) ✗	small (O(0.1))	tiny (O(0.01-0.1))
Alignment (MFV)	small (O(0.1))	tiny (O(0.01))	out of reach $<$ O(0.01)

Probe of New Physics

If NP is at

- $<$ 1 TeV: within direct reach of LHC@8 TeV, almost ruled out
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New Physics in B_d and B_s Mixing?

$$H = \begin{pmatrix} M_q - \frac{i}{2}\Gamma_q & M_q^{12} - \frac{i}{2}\Gamma_q^{12} \\ M_q^{12*} - \frac{i}{2}\Gamma_q^{12*} & M_q - \frac{i}{2}\Gamma_q \end{pmatrix}$$

$$\frac{M_q^{12}}{M_{q,SM}^{12}} \equiv \mathrm{Re}\Delta_q + i\mathrm{Im}\Delta_q = |\Delta_q| \exp(2i\Phi_{q,NP})$$

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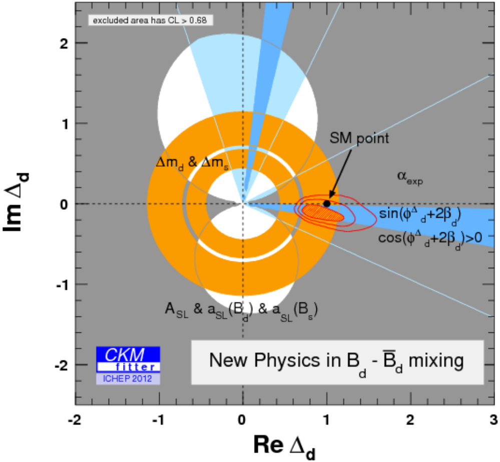
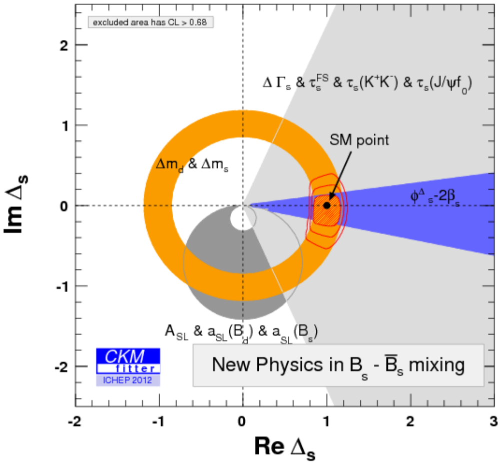
New Physics in B_d and B_s Mixing?



The tension is mostly due to V_{ub} coming from $B^+ \to \tau\nu$, even though new Belle result brings the tension down.

New Physics in B_d and B_s Mixing?



Does not include dimuon results from D0. All other results are consistent with SM. A_{SL} is 3.3σ away.

Some recent results from LHCb

- $\Delta M_s = 17.719 \pm 0.043$ ps^{-1} SM: 17.3 ± 2.6
- $\beta_s = \arg\left(-\frac{V_{cb}V_{cs}^*}{V_{tb}V_{ts}^*}\right)$

  $-2\beta_s = -0.040^{+0.090}_{-0.085}$ (direct), $-0.0363^{+0.0016}_{-0.0015}$ (global fit)

  SM: -0.038 ± 0.002

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Caution !!!

Need a better control over nuisance parameters

- Quark masses and CKM elements
- Form factors, decay constants
  Lattice people doing a commendable job
  uncertainty associated with LCD amplitudes
- Subleading Λ/m corrections
  Also, higher orders in α_s, but they can be summed in most cases
- renormalization scale (μ) dependence

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Hunting grounds for NP

1. $\gamma = \arg(V_{ub}^*)$
   — Can be determined even from tree-level $B \to DK$ decays only
   — $B \to DK$, D to CP eigenstates
   — $B \to DK$, D through DCS
   — $B \to DK$, D through 3-body self-conjugate final
   — $B \to DK$, D through SCS
2. Semileptonic $B \to K^{(*)}\mu^+\mu^-, \phi\mu^+\mu^-, \pi\mu^+\mu^-$
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$b \to s\gamma$

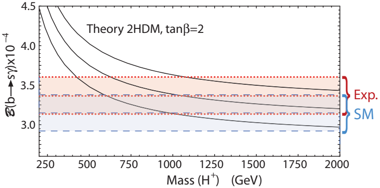
$$\Gamma(\bar{B} \to X_s\gamma) = \Gamma(b \to s\gamma) + O(\Lambda_{QCD}/m_b)$$

$$A_{CP} = \frac{\Gamma(\bar{B} \to X_s\gamma) - \Gamma(B \to X_{\bar{s}}\gamma)}{\Gamma(\bar{B} \to X_s\gamma) + \Gamma(B \to X_{\bar{s}}\gamma)}$$

Measured with cut $E_\gamma > E_0 \sim 2$ GeV: $A_{CP} = -(1.2 \pm 2.8)\%$

$$Br(b \to s\gamma) = (3.37 \pm 0.23) \times 10^4 \ (\mathrm{exp}), (3.15 \pm 0.23) \times 10^{-4} \ (\mathrm{SM})$$

Strong constraint on 2HDM:



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Tensions with SM: NP or mirage?

Cheshire cat tensions

- The $2\beta_s$ discrepancy — now consistent with SM
  — No need to introduce NP in $B_s - \overline{B_s}$ mixing
- $\sin(2\beta)$ tension between $B_d \to J/\psi K_S$ and $B_d \to \phi K_S$
  — *Direct and indirect measurements still inconsistent!*
- $B \to V_1 V_2$ polarization anomaly
  — A case of poorly understood subleading SM effects
- ...

Smiles:

1. Wait and be conservative.
2. Understand the SM dynamics better, even if post-facto.

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$B \to K\pi$ CP asymmetries

$$A_{CP} = [\Gamma(B \to f) - \Gamma(\bar{B} \to \bar{f})] \;/\; [\Gamma(B \to f) + \Gamma(\bar{B} \to \bar{f})]$$

$$A_{CP}(B^+ \to K^+\pi^0) = 0.040 \pm 0.021 \; : \; \overbrace{b \to s\bar{u}u \,,\, b \to s\bar{d}d}^{}$$

Related by SU(2)

$$A_{CP}(B^0 \to K^+\pi^-) = -0.086 \pm 0.007 \;\; : \; b \to s\bar{u}u$$

$$\Delta A_{CP} \equiv A_{CP}(\pi^0 K^-) - A_{CP}(\pi^+ K^-) = (12.6 \pm 2.2)\,\% \,,\, (1.9^{+5.8}_{-4.8})\;\%(SM)$$

Strong penguins are flavour-blind. EW penguins are not but they are suppressed by coupling.

Possible resolution: NP that mimics a large EWP [Nandi and AK '04]

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$B \to \tau\nu$

- Completely analogous to $\pi^+ \to \mu^+\nu_\mu$:

$$\Gamma(B \to \tau\nu_\tau) = \frac{1}{8\pi} G_F^2 |V_{ub}|^2 f_B^2 m_\tau^2 m_B \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2$$

- World average:
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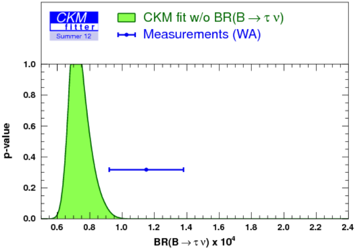
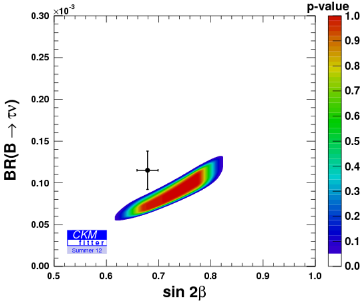

CKM fitter Summer 12
CKM fit w/o BR(B → τ ν)
Measurements (WA)
p-value
BR(B → τ ν) x 10^4


×10^-3
BR(B → τν)
sin 2β
p-value
CKM fitter Summer 12

$B \to \tau\nu$

- an SM-only explanation would require

$$|V_{ub}| = (4.22 \pm 0.51) \times 10^{-3}$$

- Inconsistent with the indirect determination of V_{ub} from the sides of the Unitarity Triangle (UT),

$$|V_{ub}|_{\rm indirect} = (3.49 \pm 0.13) \times 10^{-3}$$

or the average of direct inclusive ($B \to X_u \ell\nu$) and exclusive ($B \to \pi\ell\nu$) measurements,

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How well do we know V_{ub} ?

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or the average of direct inclusive ($B \to X_u \ell\nu$) and exclusive ($B \to \pi\ell\nu$) measurements,

$$|V_{ub}|_{\rm measured} = (3.92 \pm 0.09 \pm 0.45) \times 10^{-3}$$

How well do we know V_{ub} ?

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$B \to D(D^*)\tau\nu$

$$R(D^{(*)}) = \frac{\mathrm{Br}(B \to D^{(*)}\tau\nu)}{\mathrm{Br}(B \to D^{(*)}\ell\nu)}$$

$$\mathrm{SM:}\quad R(D) = 0.297 \pm 0.017\,, \qquad R(D^*) = 0.252 \pm 0.003$$

$$\mathrm{BaBar:}\quad R(D) = 0.440 \pm 0.058 \pm 0.042\,, \qquad R(D^*) = 0.332 \pm 0.024 \pm 0.018\,.$$

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$B \to \tau\nu$ and $B \to D(D^*)\tau\nu$

Possible resolutions:

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  — Type I/II charged Higgs is not enough [Deschamps et al. 2010]
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The dimuon anomaly

$$A_{sl}^{b} = \frac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)}$$

$$D\O\ 9.0\ \mathrm{fb}^{-1}: \quad A_{sl}^{b} = (-7.87 \pm 1.96) \times 10^{-3}$$

Can be expressed as individual flavour-specific (fs) semileptonic asymmetries coming from B_d and B_s:

$$A_{sl}^{b} = (0.595 \pm 0.022)\, a_{fs}^{d} + (0.405 \mp 0.022)\, a_{fs}^{s}$$

$$a_{fs}^{d} = 0.0038 \pm 0.0036\ (\mathrm{HFAG})\,, \quad a_{fs}^{s} = -0.0022 \pm 0.0052\ (\mathrm{LHCb,\ D0})$$

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$$(A^b_{sl})_{SM} = (-2.4 \pm 0.4) \times 10^{-4}$$

3.9σ discrepancy

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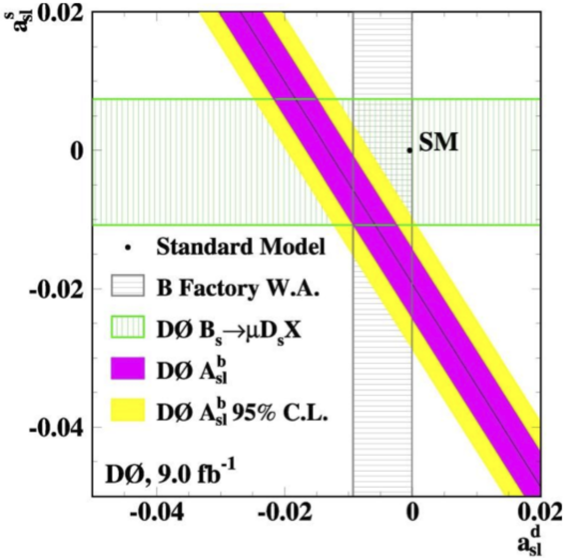

The dimuon anomaly

The only way to resolve the dimuon anomaly is to introduce some operators that give new absorptive parts in $B_s - \overline{B_s}$ mixing.

Possibly, the only option still left is $(\bar{s}\Gamma^A b)(\bar{\tau}\Gamma^A \tau)$
[Dighe, AK, Nandi, PRD 2007, 2010; Bauer and Dunn, PLB 2011]

$B_s \to \tau^+\tau^-$? $B \to X_s\tau^+\tau^-$? Lifetime difference between B_d and B_s?
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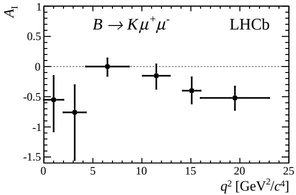
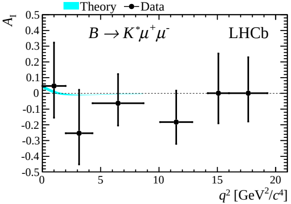
Isospin asymmetry

$$A_I = \frac{Br(B^0 \to K^{0(*)}\mu^+\mu^-) - \frac{\tau_0}{\tau_+} Br(B^+ \to K^{+(*)}\mu^+\mu^-)}{Br(B^0 \to K^{0(*)}\mu^+\mu^-) + \frac{\tau_0}{\tau_+} Br(B^+ \to K^{+(*)}\mu^+\mu^-)}$$

- $A_I = 0$ in naive factorization
- ISR from spectator can contribute up to $\sim 1\%$ unless q^2 is very small
- $B \to K^*\mu\mu$ is consistent with SM
- $B \to K\mu\mu$: 4.4σ away from zero, integrated over all q^2

[LHCb, 1205.3422]





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The resurrection of R_b

$$R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to \text{hadrons})}$$

R_b (SM) has gone down from 0.21576(8) to 0.21474(3) after the computation of full two-loop effects [Freitas and Huang 2012]

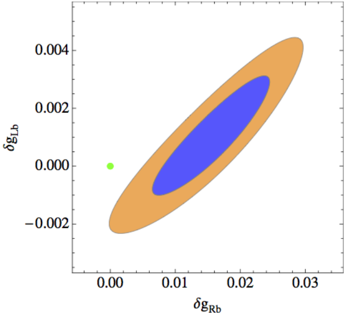
2.4σ discrepancy with R_b (exp) $= 0.21629(66)$.

A_{FB}^b has a discrepancy of 2.5σ

SM: $0.1032^{+0.0004}_{-0.0006}$

exp: 0.0992 ± 0.0016

Possible resolution: slightly increase $Z - b_R - \bar{b}_R$ coupling



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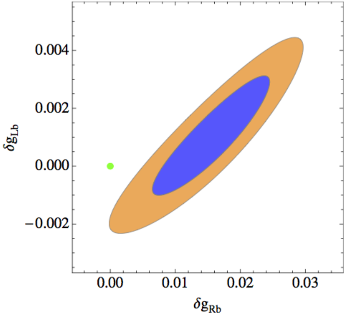

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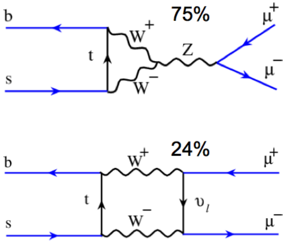
B-physics observables and cMSSM

$B_s \to \mu\mu$



Theoretically clean. LD effects negligible

Sensitive probe to FCNC effects, like new penguins

SM [Buras et al. 1208.0934]:

$$
\begin{aligned}
Br(B_s \to \mu\mu) &= (3.23 \pm 0.27) \times 10^{-9} \\
Br(B_d \to \mu\mu) &= (1.07 \pm 0.10) \times 10^{-10}
\end{aligned}
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Maximum uncertainty from f_{B_s}. This is for $f_{B_s} = 227$ MeV [MILC: 242(10); HPQCD: 225(4); ETMC: 234(6)]

Expert advice: Take HPQCD central values but MILC errors

includes leading NLO EW and full NLO QCD
But $\sim 10\%$ enhancement for nonzero $\Delta\Gamma_s$ [de Bruyn et al. 1204.1735]
Time-averaged SM: $Br(B_s \to \mu\mu) = (3.54 \pm 0.30) \times 10^{-9}$

LHCb (1211.2674)

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Br(B_s \to \mu\mu) &= (3.2^{+1.5}_{-1.2}) \times 10^{-9}, \\
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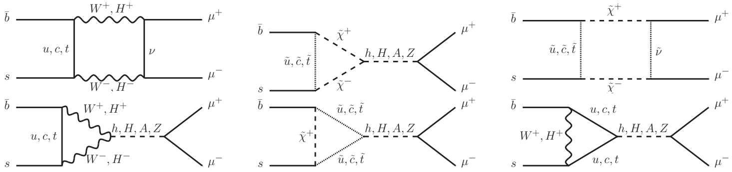
$B_s \to \mu\mu$ in SUSY



$$Br(B_s \to \mu\mu) \approx 3.5 \times 10^{-5} \left(\frac{m_t}{m_A}\right)^4 \left(\frac{\tan\beta}{50}\right)^6 \times \left(\frac{f_{B_s}}{230\ MeV}\right)^2 \left(\frac{V_{ts}}{0.040}\right)^2$$

[Buras et al. NPB 659, 2003]

Observable	Mean value μ	Uncertainties σ (exper.)	τ (theor.)
M_W [GeV]	80.399	0.023	0.015
$\sin^2\theta_{eff}$	0.23153	0.00016	0.00015
$\delta a_\mu^{\mathrm{SUSY}} \times 10^{10}$	28.7	8.0	2.0
$Br(b \to s\gamma) \times 10^4$	3.55	0.26	0.30
$R_{\Delta M_{B_s}}$	1.04	0.11	-
$Br(B \to \tau\nu)$	1.63	0.54	-
$R(D) \times 10^2$	41.6	12.8	3.5
$Br(D_s \to \tau\nu) \times 10^2$	5.38	0.32	0.2
$Br(D_s \to \mu\nu) \times 10^3$	5.81	0.43	0.2
$Br(D \to \mu\nu) \times 10^4$	3.82	0.33	0.2
$\Omega_\chi h^2$	0.1109	0.0056	0.012
m_h [GeV]	125.8	0.6	2.0
$Br(B_s \to \mu\mu)$	3.2×10^{-9}	1.5×10^{-9}	10%
$m_0, m_{1/2}$	ATLAS, 5.8, $\sqrt{s} = 8$ TeV, 2012 limits		
$m_A, \tan\beta$	CMS, 4.7, $\sqrt{s} = 7$ TeV, 2012 limits		
$m_\chi - \sigma^{SI}_{\chi^0-p}$	XENON100 2012 limits (224.6×34 kg days)		

[Strege et al. 1212.2636]

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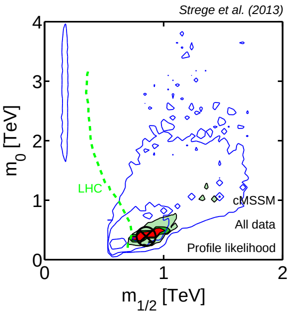
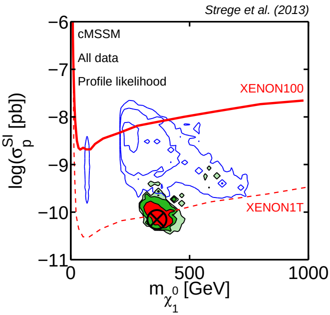
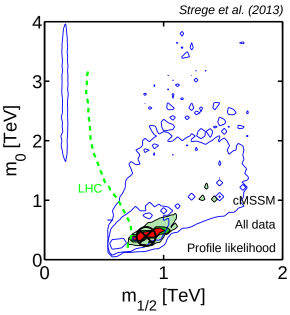
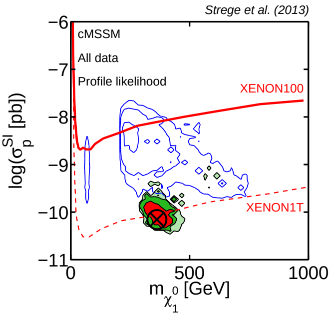




Large fine-tuning needed (0.07% or worse)





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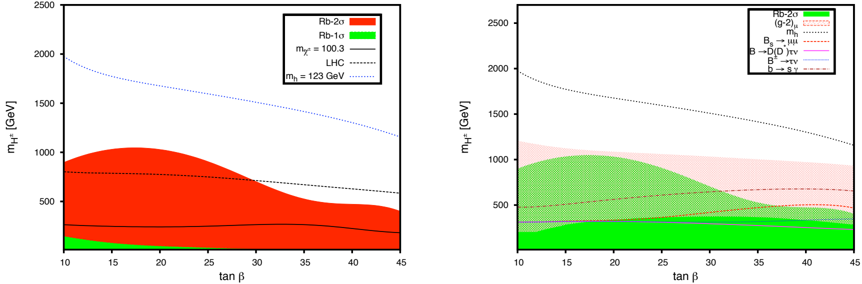
Enter R_b and A_{FB}^b [Bhattacharyya, AK, Ray, 2013]

$$\delta R_b = R_b^{\rm SM}\left(1 - R_b^{\rm SM}\right)\nabla_b$$
$$\nabla_b = \xi\left[\frac{2g_L^b F_L + 2g_R^b F_R}{\left(g_L^b\right)^2 + \left(g_R^b\right)^2}\right],$$
$$\xi \equiv \frac{\alpha}{4\pi\sin^2\theta_W},$$

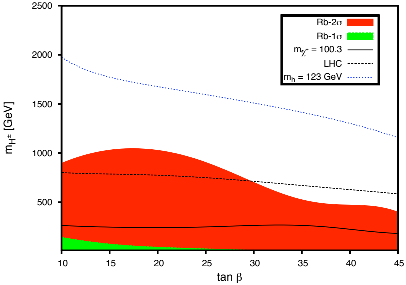
$$\nabla_b = \xi\left[-\frac{60}{13}F_L + \frac{12}{13}F_R\right] \qquad > 0$$
$$\frac{A_{FB}^b}{A_{FB}^b({\rm SM})} - 1 = -\frac{5}{13}\xi\left[F_L + 5F_R\right] \qquad < 0\,.$$

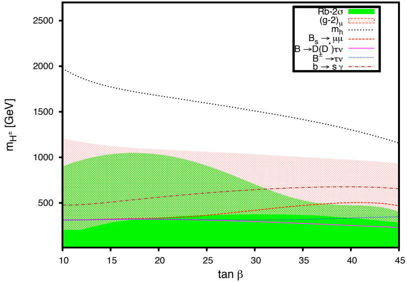
SUSY contribution decouples for heavy chargino and charged Higgs.
$F_L, F_R < 0$ with $|F_L| > |F_R|$.
No solution with both R_b and A_{FB}^b. Take only R_b then ...



$123 < m_h < 127$ GeV; gluino $>$ 1310 GeV for LSP $<$ 650 GeV; stop between 220 and 500 GeV ruled out for LSP $<$ 160 GeV; LEP on chargino

cMSSM is in terribly bad shape, if not dead, when you take *all the low-energy, cosmological, and direct constraints.*





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NP in Charm

Direct CP violation in SCS decays

- D^0-$\overline{D}^0$ mixing established by LHCb at more than 5σ. Taking all experiments, no-mixing ruled out by $> 9\sigma$.
- $\Delta A_{CP} \equiv A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$
  SM prediction: close to zero, at most $O(10^{-3})$.
- Common wisdom: DCPV in charm above 0.1% is a *clear signal for NP*

$$\Delta A_{CP} \sim 0.13\% \times \mathrm{Im}(\Delta R)$$

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Outlook for the future

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Thank you.

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