Flavour physics: status, problems, outlook

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BCTP workshop

LHC Run1 Aftermath – Where Theory meets Experiment

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Rare particle decay delivers blow to supersymmetry

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By Lucie Bradley
Cosmos Online

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SYDNEY: The popular physics theory of supersymmetry has been called into question by new results from CERN.

Physicists working at CERN's Large Hadron Collider (LHC) near Geneva, Switzerland, have announced the discovery of an extremely rare type of particle decay.

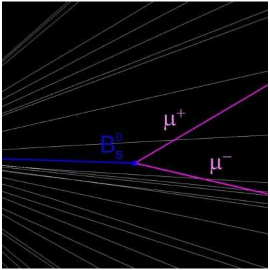
While discoveries are usually accompanied by excitement there is also a tinge of uncertainty surrounding this latest finding from CERN. It has dealt a hefty blow to the popular physics theory of supersymmetry.

The results were presented at the Hadron Collider Physics Symposium in Kyoto, Japan, and will also be submitted to the journal *Physical Review Papers*.

A three in one billion chance

Scientists have been searching for this type of particle decay for the last decade and so the results from CERN have "generated a lot of excitement now that it has been found," according to physicist Mark Kruse, from Duke University, North Carolina, USA. "And it hasn't ruled out supersymmetry – just some of the more favoured variants of it."

The traditional theory of subatomic physics is known as the Standard Model, but it is unable to explain everything observed in the world around us, including gravity and dark matter. Supplementary theories exist to help explain these inconsistencies. Of these theories, supersymmetry, which proposes that 'superparticles' exist – massive versions of those particles that are already known – is arguably the most popular.



A typical decay of the Bs (B sub s) meson into two muons. The two muons traversed the whole LHCb detector, which originated from the B0s decay point 14 mm from the proton-proton collision. Credit: LHCb

COSMOS Magazine

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SUSY

Rare decays

Summary

Basics

Flavour physics

studies transitions between fermions of different generations.

flavour $=$ fermion species

$$\begin{pmatrix} u_L, u_L, u_L \\ d_L, d_L, d_L \end{pmatrix} \quad \begin{pmatrix} c_L, c_L, c_L \\ s_L, s_L, s_L \end{pmatrix} \quad \begin{pmatrix} t_L, t_L, t_L \\ b_L, b_L, b_L \end{pmatrix}$$

$$\begin{matrix} u_R, u_R, u_R \\ d_R, d_R, d_R \end{matrix} \quad \begin{matrix} c_R, c_R, c_R \\ s_R, s_R, s_R \end{matrix} \quad \begin{matrix} t_R, t_R, t_R \\ b_R, b_R, b_R \end{matrix}$$

$$\begin{pmatrix} \nu_{e,L} \\ e_L \end{pmatrix} \quad \begin{pmatrix} \nu_{\mu,L} \\ \mu_L \end{pmatrix} \quad \begin{pmatrix} \nu_{\tau,L} \\ \tau_L \end{pmatrix}$$

$$e_R \quad \mu_R \quad \tau_R$$

Some flavoured mesons

charged:

$$K^+ \sim \bar{s}u, \quad D^+ \sim c\bar{d}, \quad D_s^+ \sim c\bar{s}, \quad B^+ \sim \bar{b}u, \quad B_c^+ \sim \bar{b}c,$$
$$K^- \sim s\bar{u}, \quad D^- \sim \bar{c}d, \quad D_s^- \sim \bar{c}s, \quad B^- \sim b\bar{u}, \quad B_c^- \sim b\bar{c},$$

neutral:

$$K \sim \bar{s}d, \quad D \sim c\bar{u}, \quad B_d \sim \bar{b}d, \quad B_s \sim \bar{b}s,$$
$$\overline{K} \sim s\bar{d}, \quad \overline{D} \sim \bar{c}u, \quad \overline{B}_d \sim b\bar{d}, \quad \overline{B}_s \sim b\bar{s},$$

The neutral K, D, B_d and B_s mesons mix with their antiparticles, $\overline{K}$, $\overline{D}$, $\overline{B}_d$ and $\overline{B}_s$ thanks to the weak interaction (quantum-mechanical two-state systems).

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$\Rightarrow$ gold mine for fundamental parameters

Elektroweak interaction

Gauge group:

$SU(2) \times U(1)_Y$

doublets: $Q_L^j = \begin{pmatrix} u_L^j \\ d_L^j \end{pmatrix}$ und $L^j = \begin{pmatrix} \nu_L^j \\ \ell_L^j \end{pmatrix}$

$j = 1, 2, 3$ labels the generation.

Examples: $Q_L^3 = \begin{pmatrix} t_L \\ b_L \end{pmatrix}$, $L^1 = \begin{pmatrix} \nu^{eL} \\ e_L \end{pmatrix}$

singlets: u_R^j, d_R^j and e_R^j.

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Important: Only left-handed fields couple to the W boson.

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- three gauge interactions
- Yukawa interaction of Higgs with quarks and leptons
- Higgs self-interaction

Yukawa interaction

Higgs doublet $H = \begin{pmatrix} G^+ \\ v + \frac{h^0 + iG^0}{\sqrt{2}} \end{pmatrix}$ with $v = 174\,\mathrm{GeV}$.

Charge-conjugate doublet: $\widetilde{H} = \begin{pmatrix} v + \frac{h^0 - iG^0}{\sqrt{2}} \\ -G^- \end{pmatrix}$

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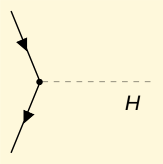

Yukawa lagrangian:

$$-L_Y = Y^d_{jk}\, \overline{Q}^j_L\, H\, d^k_R \;+\; Y^u_{jk}\, \overline{Q}^j_L\, \widetilde{H}\, u^k_R \;+\; Y^l_{jk}\, \overline{L}^j_L\, H\, e^k_R \;+\; \text{h.c.}$$

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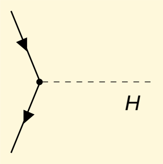

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Here neutrinos are (still) massless.
The Yukawa matrices Y^f are arbitrary complex 3×3 matrices.
The mass matrices $M^f = Y^f v$ are not diagonal!

$\Rightarrow$ $u^j_{L,R}, d^j_{L,R}$ do not describe physical quarks!
We must find a basis in which Y^f is diagonal!

Any matrix can be diagonalised by a bi-unitary transformation. Start with

$$\widehat{Y}^u = S_Q^\dagger Y^u S_u \quad \text{with } \widehat{Y}^u = \begin{pmatrix} y_u & 0 & 0 \\ 0 & y_c & 0 \\ 0 & 0 & y_t \end{pmatrix} \quad \text{and } y_{u,c,t} \geq 0$$

This can be achieved via

$$Q_L^j = S_{jk}^Q Q_L^{k\prime}, \qquad u_R^j = S_{jk}^u u_R^{k\prime}$$

with unitary 3×3 matrices S^Q, S^u.
This transformation leaves L_{gauge} invariant (“flavour-blindness of the gauge interactions”)!

Next diagonalise Y^d:

$$\widehat{Y}^d = V^\dagger S_Q^\dagger Y^d S_d \quad \text{with } \widehat{Y}^d = \begin{pmatrix} y_d & 0 & 0 \\ 0 & y_s & 0 \\ 0 & 0 & y_b \end{pmatrix} \quad \text{and } y_{d,s,b} \geq 0$$

with unitary 3×3 matrices V, S^d.
Via $d_R^j = S_{jk}^d d_R^{k\prime}$ we leave L_{gauge} unchanged, while

$$-L_Y^{\text{quark}} = \overline{Q}_L V \widehat{Y}^d H\, d_R \;+\; \overline{Q}_L \widehat{Y}^u \widetilde{H}\, u_R \;+\; \text{h.c.}$$

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To diagonalise $M^d = V \widehat{Y}^d v$ transform

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$$d_L^j = V_{jk} d_L^{k\prime}$$

This breaks up the $SU(2)$ doublet Q_L. $\Rightarrow$ L_{gauge} changes!

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The transformation $d_L^j = V_{jk} d_L^{k\prime}$ changes the W-boson couplings in L_{gauge}:

$$L_W = \frac{g_2}{\sqrt{2}} \left[\overline{u}_L V \gamma^\mu d_L W_\mu^+ + \overline{d}_L V^\dagger \gamma^\mu u_L W_\mu^- \right]$$

The Z-boson couplings stay flavour-diagonal because of $V^\dagger V = 1$.

V is the Cabibbo-Kobayashi-Maskawa (CKM) matrix.

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

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Leptons: Only one Yukawa matrix Y^l; the mass matrix $M^l = Y^l v$ of the charged leptons is diagonalised with

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$\Rightarrow$ Add a ν_R to the SM to mimick the quark sector or add a Majorana mass term $Y^M \dfrac{\bar{L}HH^T L^c}{M}$.

The lepton mixing matrix is the
Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix.

CKM metrology

The Cabibbo-Kobayashi-Maskawa (CKM) matrix

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

involves 4 parameters: 3 angles and the KM phase δ_{KM}.
Best way to parametrise V: Wolfenstein expansion

Expand the CKM matrix V in $V_{us} \simeq \lambda = 0.2246$:

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3\left(1+\frac{\lambda^2}{2}\right)(\overline{\rho}-i\overline{\eta}) \\ -\lambda - iA^2\lambda^5\overline{\eta} & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\overline{\rho}-i\overline{\eta}) & -A\lambda^2 - iA\lambda^4\overline{\eta} & 1 \end{pmatrix}$$

with the Wolfenstein parameters λ, A, $\overline{\rho}$, $\overline{\eta}$

CP violation $\Leftrightarrow \overline{\eta} \neq 0$

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with the Wolfenstein parameters λ, A, $\overline{\rho}$, $\overline{\eta}$

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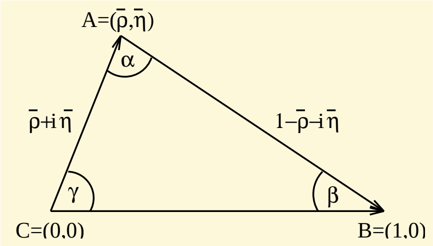
Unitarity triangle:

Exact definition:

$$\overline{\rho} + i\overline{\eta} = -\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}} = \left|\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right| e^{i\gamma}$$



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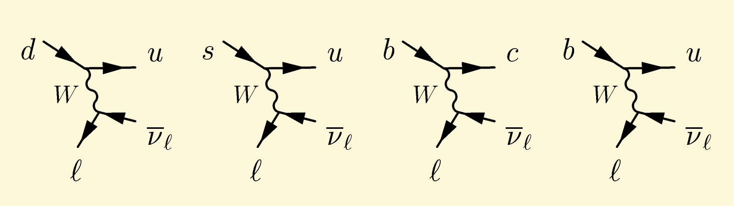
Semileptonic decays:



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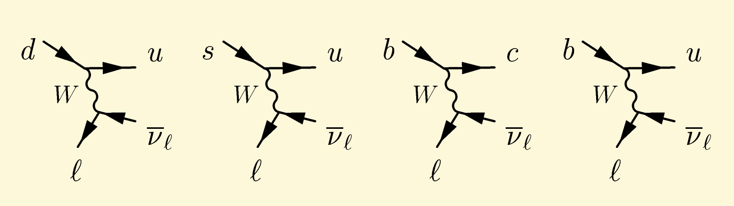

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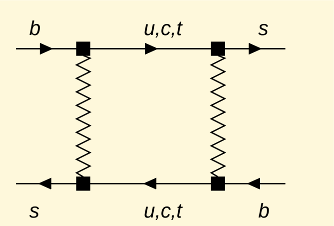
Not an LHC topic!

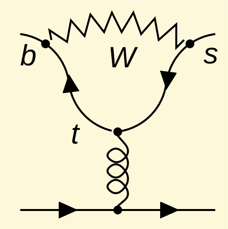
Progress from better lattice calculations and Belle-II.

Flavour-changing neutral current (FCNC) processes

Examples:



$B_s - \overline{B}_s$ mixing



penguin diagram

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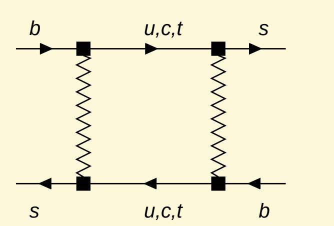

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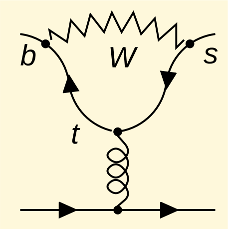

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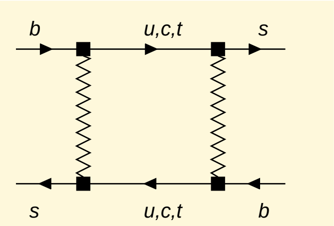

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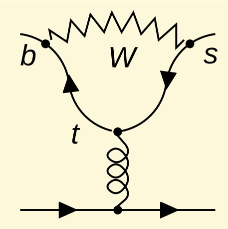

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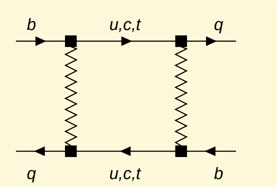
In principle can determine all parameters λ, A, $\overline{\rho}$, $\overline{\eta}$ from tree-level processes.

$\Rightarrow$ View FCNC processes as new physics analysers rather than ways to measure V_{td} and V_{ts}.

$B - \overline{B}$ mixing basics

Consider $B_q - \overline{B}_q$ mixing with $q = d$ or $q = s$:

A meson identified ("tagged") as a B_q at time $t = 0$ is described by $|B_q(t)\rangle$.



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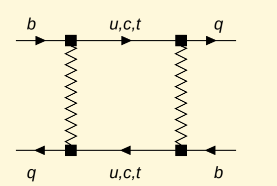

For $t>0$:

$$|B_q(t)\rangle = \langle B_q|B_q(t)\rangle |B_q\rangle + \langle \overline{B}_q|B_q(t)\rangle|\overline{B}_q\rangle + \ldots,$$

with "..." denoting the states into which $B_q(t)$ can decay.

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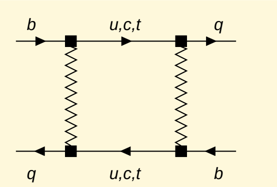

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with "$\ldots$" denoting the states into which $B_q(t)$ can decay.

Analogously: $|\overline{B}_q(t)\rangle$ is the ket of a meson tagged as a $\overline{B}_q$ at time $t=0$.

Schrödinger equation:

$$i\frac{d}{dt}\begin{pmatrix}\langle B_q|B_q(t)\rangle\\ \langle \overline{B}_q|B_q(t)\rangle\end{pmatrix} = \left(M^q - i\,\frac{\Gamma^q}{2}\right)\begin{pmatrix}\langle B_q|B_q(t)\rangle\\ \langle \overline{B}_q|B_q(t)\rangle\end{pmatrix}$$

with the 2×2 mass and decay matrices $M^q = M^{q\dagger}$ and $\Gamma^q = \Gamma^{q\dagger}$.

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$\begin{pmatrix}\langle B_q|\overline{B}_q(t)\rangle\\ \langle\overline{B}_q|\overline{B}_q(t)\rangle\end{pmatrix}$ obeys the same Schrödinger equation.

3 physical quantities in $\mathrm{B_q}-\overline{\mathrm{B}}_\mathrm{q}$ mixing:

$$\left|M_{12}^q\right|,\quad \left|\Gamma_{12}^q\right|,\quad \phi_q \equiv \arg\left(-\frac{M_{12}^q}{\Gamma_{12}^q}\right)$$

Diagonalise $M^q - i\,\frac{\Gamma^q}{2}$ to find the two mass eigenstates:

$$\begin{aligned} \text{Lighter eigenstate:} \quad |B_L\rangle &= p|B_q\rangle + q|\overline{B}_q\rangle. \\ \text{Heavier eigenstate:} \quad |B_H\rangle &= p|B_q\rangle - q|\overline{B}_q\rangle \end{aligned}$$

with masses $M^q_{L,H}$ and widths $\Gamma^q_{L,H}$.
Further $|p|^2 + |q|^2 = 1$.

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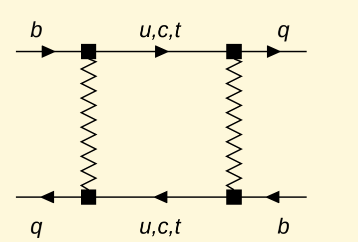
Relation of Δm_q and $\Delta\Gamma_q$ to $|M^q_{12}|$, $|\Gamma^q_{12}|$ and ϕ_q:

$$\begin{aligned} \Delta m_q &= M_H - M_L \simeq 2|M^q_{12}|, \\ \Delta\Gamma_q &= \Gamma_L - \Gamma_H \simeq 2|\Gamma^q_{12}|\cos\phi_q \end{aligned}$$

M_{12}^q stems from the dispersive (real) part of the box diagram, internal t.
Γ_{12}^q stems from the absorpive (imaginary) part of the box diagram, internal c, u.



Effective hamiltonians

Concept: Remove ("integrate out") heavy particles:

$$\langle f | \mathbf{T} e^{-i \int d^4x H_{\rm int}^{\rm SM}(x)} | i \rangle = \langle f | \mathbf{T} e^{-i \int d^4x H^{\rm eff}(x)} | i \rangle \left[1 + \mathcal{O}\left(\frac{m_{\rm light}}{m_{\rm heavy}} \right)^n \right]$$

with n integer.

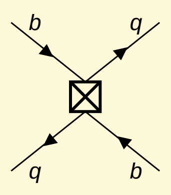
In the weak processes (meson-antimeson mixing, weak hadron decays) considered in these lectures $m_{\rm heavy}$ represents M_W and m_t. Furthermore n is even and the lowest order $n = 2$ is sufficient: $m_b^2/M_W^2 = 3 \cdot 10^{-3}$.

Effective $\Delta B = 2$ hamiltonian $H^{|\Delta B|=2}$:

$$H^{|\Delta B|=2} = \frac{G_F^2}{4\pi^2} (V_{tb} V_{tq}^*)^2 \, C^{|\Delta B|=2}(m_t, M_W, \mu) \, Q(\mu) + h.c.$$

with the four-quark operator

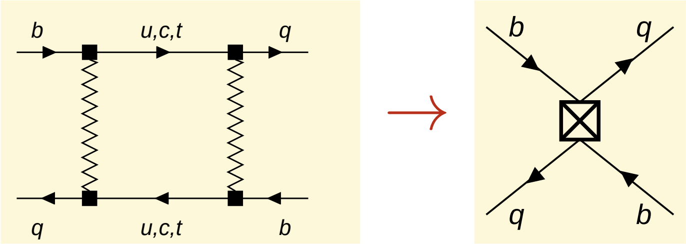
$$Q \quad = \quad \overline{q}_L \gamma_\nu b_L \, \overline{q}_L \gamma^\nu b_L \qquad \text{with } q = d \text{ or } s.$$



All short-distance information resides in the Wilson coefficient $C^{|\Delta B|=2}$. (G_F is the Fermi constant.)
μ is the renormalisation scale, ideally $H^{|\Delta B|=2}$ does not depend on μ. When calculating $C^{|\Delta B|=2}$ in perturbation theory, the dependence on μ diminishes order-by-order in α_s.

The operator Q describes a point-like interactions of four quarks which changes the beauty quantum number B by two units ($\Delta B = 2$).

Graphically: Shrink the box diagram to a point:



The Wilson coefficient $C^{|\Delta B|=2}$ is the effective coupling constant of this four-quark interaction. $C^{|\Delta B|=2}$ is calculated in perturbation theory.

For the desired prediction of the $\mathrm{B_q}-\overline{\mathrm{B}}_\mathrm{q}$ mixing amplitude we need a non-perturbative calculation of $\langle B_q|Q|\bar{B}_q\rangle$. Useful parametrisation:

$$\langle B_q|Q|\bar{B}_q\rangle = \frac{2}{3} m_{B_q}^2 \, f_{B_q}^2 \, B_{B_q}(\mu)$$

Here f_{B_q} is the B-meson decay constant and B_{B_q} is sometimes called "bag parameter".

Lattice gauge theory: $f_{B_s}\sqrt{B_{B_s}(m_b)} = (211 \pm 9)\,\mathrm{MeV}$
$f_{B_d}\sqrt{B_{B_d}(m_b)} = (176 \pm 8)\,\mathrm{MeV}$.

Wilson coefficient:

$$C^{|\Delta B|=2}(m_t, M_W, \mu) = M_W^2\, S\left(\frac{m_t^2}{M_W^2}\right)\eta_B$$

with

$$S(x) = x\left[\frac{1}{4} + \frac{9}{4}\frac{1}{1-x} - \frac{3}{2}\frac{1}{(1-x)^2}\right] - \frac{3}{2}\left[\frac{x}{1-x}\right]^3 \ln x$$

The QCD corrections are contained in $\eta_B(\mu = m_b) = 0.84$.

Putting everything together:

$$\Delta m_q = 2|M_{12}^q| = \frac{|\langle B_q|H^{|\Delta B|=2}|\overline{B}_q\rangle|}{m_{B_q}}$$

$$= \frac{G_F^2}{6\pi^2}\,\eta_B\, m_{B_q}\, f_{B_q}^2\, B_{B_q} M_W^2\, S\left(\frac{m_t^2}{M_W^2}\right)\left|V_{tb}V_{tq}^*\right|^2 .$$

Δm_d determines $|V_{td}|$.

$|V_{ts}|$ entering Δm_{B_s} is fixed by CKM unitarity to $|V_{ts}| \simeq |V_{cb}|$.
Test the SM:

$\Delta m_s = (17.3 \pm 1.5)\,\mathrm{ps}^{-1}$ vs. $\Delta m_s^{\mathrm{exp}} = (17.731 \pm 0.045)\,\mathrm{ps}^{-1}$

The phase of the $\mathrm{B_q} - \overline{\mathrm{B}}_\mathrm{q}$ mixing amplitude can be simply read off from $H^{|\Delta B|=2}$:

$$\arg M_{12}^q = \arg(\langle B_q | H^{|\Delta B|=2} | \overline{B}_q \rangle) = \arg(V_{tb} V_{tq}^*)^2$$

$\arg M_{12}^q$ enters mixing-induced CP asymmetries:

$$\begin{array}{ccc} B & \xrightarrow{q/p} & \overline{B} \\ A_f \searrow & & \swarrow \overline{A}_f \\ & f & \end{array}$$

Effective hamiltonian for decays

To describe meson decays we need effective $\Delta F = 1$ hamiltonians, e.g. $H^{|\Delta B|=1}$ for B decays.

$$H^{|\Delta B|=1} = \frac{G_F}{\sqrt{2}} \left[\sum_{i=1}^{2} C_i \left(V_{CKM} Q_i^u + V'_{CKM} Q_i^c \right) + V''_{CKM} \sum_{i \geq 3} C_i Q_i \right]$$

The Wilson coefficients are determied such that the SM amplitudes are reproduced up to corrections of order $(m_b/M_W)^2$.

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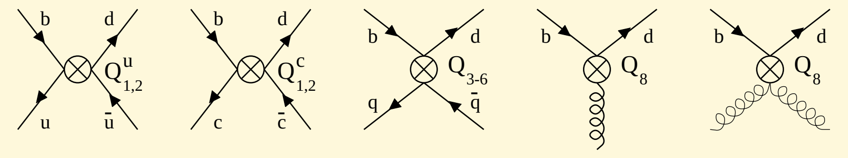
Q_i: effective $|\Delta B| = 1$ operators, e.g.
$Q_2^c = \overline{c}\gamma_\mu(1-\gamma_5)b\;\overline{d}\gamma^\mu(1-\gamma_5)c$

C_i: Wilson coefficients = effective couplings, contain short distance structure, perturbative QCD corrections, depend on m_t/M_W.

$V^{('')}_{CKM}$: product of CKM elements



CP asymmetries

CP eigenstate: $CP|f_{\rm CP}\rangle = \pm|f_{\rm CP}\rangle$
Mixing-induced CP asymmetries in decays $B_q(t) \to f_{\rm CP}$ measure the relative phase between M_{12}^q and the decay amplitude $B_q \to f_{\rm CP}$.

Key quantity:
$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f} \simeq -\frac{M_{12}^{q*}}{|M_{12}^q|}\frac{\overline{A}_f}{A_f}$$

with

$$\begin{aligned} A_f &= \langle f|B_q\rangle = \langle f|H^{|\Delta F|=1}|B_q\rangle\,, \\ \overline{A}_f &= \langle f|\overline{B}_q\rangle = \langle f|H^{|\Delta F|=1}|\overline{B}_q\rangle. \end{aligned}$$

Golden mode: B decay into a CP eigenstate $f_{\rm CP}$ which only involves a single CKM factor ($\Rightarrow |A_{f_{\rm CP}}| = |\overline{A}_{f_{\rm CP}}|$).

$$CP|f_{\rm CP}\rangle = \eta_{f_{\rm CP}} |f_{\rm CP}\rangle \qquad \text{with } \eta_{f_{\rm CP}} = \pm 1.$$

Time-dependent CP asymmetry:

$$a_{f_{\rm CP}}(t) = -\frac{{\rm Im}\,\lambda_{f_{\rm CP}} \sin(\Delta m t)}{\cosh(\Delta\Gamma t/2) - {\rm Re}\,\lambda_{f_{\rm CP}} \sinh(\Delta\Gamma t/2)},$$

${\rm Im}\,\lambda_f$ quantifies the CP violation in the interference between mixing and decay:

$$\begin{array}{ccc} B & \xrightarrow{q/p} & \bar{B} \\ A_f \searrow & & \swarrow \overline{A}_f \\ & f & \end{array}$$

Example 1: $B_d \to J/\psi K_S \quad \Rightarrow \quad |\overline{f}\rangle = -|f\rangle$ (CP-odd eigenstate)

$\Delta\Gamma_d$ is negligibly small: $a_{J/\psi K_S}(t) = -\mathrm{Im}\,\lambda_{f_{\mathrm{CP}}} \sin(\Delta m_d t)$.

Mixing: $\frac{q}{p} = -\frac{M_{12}^{d*}}{|M_{12}^{d}|} = -\frac{(V_{tb}^* V_{td})^2}{|V_{tb} V_{td}^*|^2} = -\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}$

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Now $K_S = \frac{K^0 - \overline{K}^0}{\sqrt{2}}$ and $\bar{B}_d$ decays into $J/\psi \overline{K}^0$ while B_d decays into $J/\psi K^0$. The K_S is detected through $K_s \to \pi^+\pi^-$ and $K^0 \to \pi^+\pi^-$ contributes an extra factor of $V_{us}^* V_{ud}$ while $\overline{K}^0 \to \pi^+\pi^-$ involves $V_{us} V_{ud}^*$ instead:

$$\lambda_{J/\psi K_S} = \frac{q}{p} \frac{\bar{A}_{J/\psi K_S}}{A_{J/\psi K_S}} = -\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}} \frac{V_{us} V_{ud}^*}{V_{us}^* V_{ud}} \simeq -e^{-2i\beta}$$

$$\Rightarrow \qquad \mathrm{Im}\,\lambda_{J/\psi K_S} = \sin(2\beta) \approx 0.68$$

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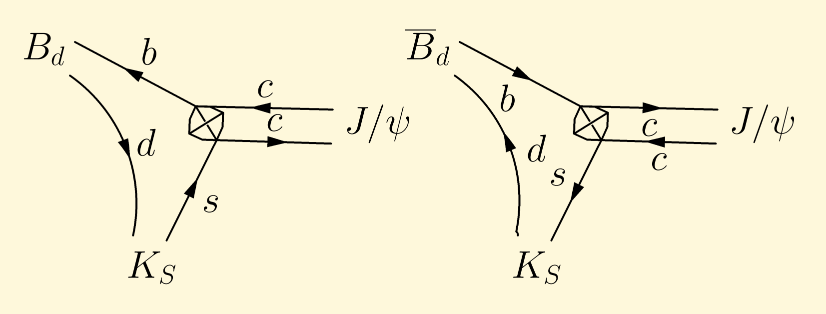


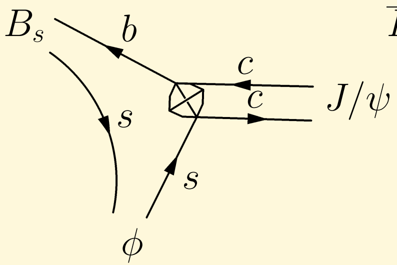
$$a_{J/\psi K_S}(t) \simeq -\sin(2\beta)\sin(\Delta m_d t),$$

where

$$\beta = \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

Example 2:

$B_s \to (J/\psi\phi)_{L=0} \quad \Rightarrow \quad |\bar{f}\rangle = |f\rangle$ (CP-even eigenstate)



$$a_{(J/\psi\phi)_{L=0}}(t) = -\frac{\sin(2\beta_s)\sin(\Delta m_s t)}{\cosh(\Delta\Gamma_s t/2) - \cos(2\beta_s)\sinh(\Delta\Gamma_s t/2)},$$

where
$$\beta_s = \arg\left[-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right] \simeq \lambda^2\overline{\eta}$$

Metrology of the unitarity triangle

The Wolfenstein parameters λ and A are well determined from the semileptonic decays $K \to \pi \ell^+ \nu_\ell$ and $B \to X_c \ell^+ \nu_\ell$, $\ell = e, \mu$.

Metrology of the unitarity triangle:
The apex $(\overline{\rho},\overline{\eta})$ is currently constrained from the following experimental input:

- $|V_{ub}| \propto \sqrt{\overline{\rho}^2 + \overline{\eta}^2}$ measured in $B \to \pi \ell \nu_\ell$, $B \to X_u \ell \nu_\ell$ and $B^+ \to \tau^+ \nu_\tau$.

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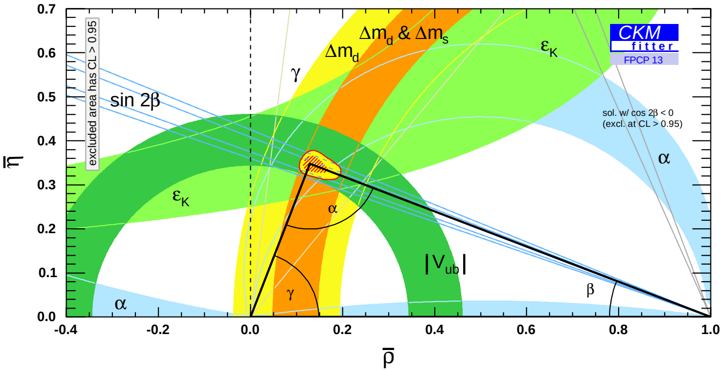
- ϵ_K (the measure of CP violation in $\mathrm{K}-\overline{\mathrm{K}}$ mixing), which defines a hyperbola in the $(\overline{\rho},\overline{\eta})$ plane.

Status

Global fit in the SM from CKMfitter:

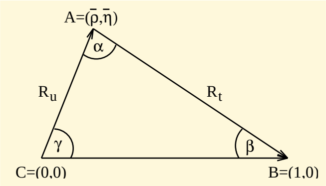


Statistical method: Rfit, a Frequentist approach.

Status

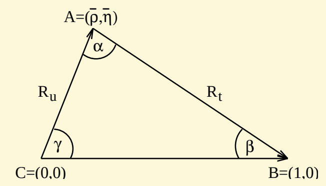
Today: Most precise information on UT from the FCNC processes determining β and α, if one assumes the SM to be correct.

Note: New physics in $B_d - \overline{B}_d$ mixing affects β and α, but drops out in the sum $\beta + \alpha = \pi - \gamma$



Goal for the LHC era: Precise determination of the UT from tree processes. Need

- a better $|V_{ub}|$ for $R_u \Rightarrow$ no LHC topic,
- a better γ from $B^\pm \to \overset{(-)}{D} K^\pm$. July 2013 LHCb value: $\gamma \in [42.6^\circ, 99.6^\circ]$ @95%CL.



LHCb can also improve $\beta = 21.4^\circ \pm 0.6^\circ$ and may contribute pieces to $\alpha = 85.4^{\circ}{}^{+4.0^\circ}_{-3.8^\circ}$, which is determined from $B \to \pi\pi$, $B \to \pi\rho$, and $B \to \rho\rho$. E.g. LHCb can study $B^0 \to \rho^0\rho^0$, $B^+ \to \rho^0\pi^+$, $B^0 \to \pi^-\pi^+$.

New physics

In the LHC era CKM metrology is less important and constraints on physics beyond the SM is the main focus of flavour physics.

In the flavour-changing neutral current (FCNC) processes of the Standard Model several suppression factors pile up:

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Spectacular: In FCNC transitions of charged leptons the GIM suppression factor is even m_ν^2/M_W^2!

$\Rightarrow$ The SM predictions for charged-lepton FCNCs are essentially zero!

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.

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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,
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$B_d - \overline{B}_d$ mixing and $B_s - \overline{B}_s$ mixing are sensitive to scales up to $\Lambda \sim 100\,\text{TeV}$.

Win-win situation

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Flavour physics will explore their couplings to quarks.

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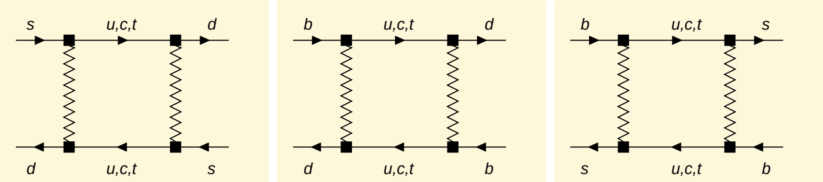
Flavour physics will explore their couplings to quarks.

If ATLAS and CMS find no further new particles:

Flavour physics probes scales of new physics exceeding 100 TeV.

New-physics analysers:

- Global fit to UT: overconstrain $(\bar{\rho}, \bar{\eta})$,
  probes FCNC processes $\mathrm{K}-\overline{\mathrm{K}}$, $\mathrm{B_d}-\overline{\mathrm{B}}_\mathrm{d}$ and $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing.



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- Global fit to $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing: mass difference Δm_s, width difference $\Delta\Gamma_s$, CP asymmetries in $B_s \to J/\psi\phi$ and $\overset{(-)}{B}_s \to X\ell\nu_\ell$.

New-physics analysers:

- Global fit to UT: overconstrain $(\bar\rho, \bar\eta)$, probes FCNC processes $\mathrm{K}-\overline{\mathrm{K}}$, $\mathrm{B_d}-\overline{\mathrm{B}}_\mathrm{d}$ and $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing.
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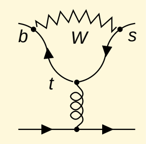
- Penguin decays: $B \to X_s\gamma$, $B \to X_s\ell^+\ell^-$, $B \to K\pi$, $B_d \to \phi K_{\mathrm{short}}$, $B_s \to \mu^+\mu^-$, $K \to \pi\nu\bar\nu$, $B_s \to \phi\rho^0 \ldots$



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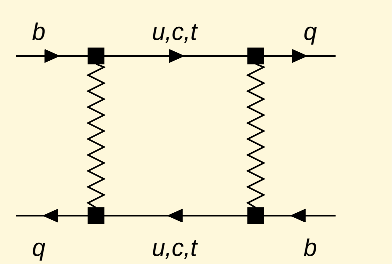
- CKM-suppressed or helicity-suppressed tree-level decays: $B^+ \to \tau^+\nu$, $B \to \pi\ell\nu$, $B \to D\tau\nu$, probe charged Higgses and right-handed W-couplings.

$B-\overline{B}$ mixing and new physics

$B_q - \overline{B}_q$ mixing with $q = d$ or $q = s$:



New physics can barely affect Γ_{12}^q, which stems from tree-level decays.
M_{12}^q is very sensitive to virtual effects of new heavy particles.

Generic new physics

The phase $\phi_s = \arg(-M_{12}^s/\Gamma_{12}^s)$ is negligibly small in the Standard Model:

$$\phi_s^{\rm SM} = 0.2^\circ.$$

Define the complex parameter Δ_s through

$$M_{12}^s \equiv M_{12}^{\rm SM,s} \cdot \Delta_s \, , \qquad \Delta_s \equiv |\Delta_s| e^{i\phi_s^\Delta}.$$

In the Standard Model $\Delta_s = 1$. Use $\phi_s = \phi_s^{\rm SM} + \phi_s^\Delta \simeq \phi_s^\Delta$.

Confront the LHCb-CDF average

$$\Delta m_s = (17.719 \pm 0.043)\ \text{ps}^{-1}$$

with the SM prediction:

$$\Delta m_s = \left(18.8 \pm 0.6_{V_{cb}} \pm 0.3_{m_t} \pm 0.1_{\alpha_s} \right) \text{ps}^{-1} \frac{f_{B_s}^2 B_{B_s}}{(220\,\text{MeV})^2}$$

Here $f_{B_s}^2 B_{B_s}$ parametrises a hadronic matrix element $\langle B_s | Q | \bar{B}_s \rangle$.

Largest source of uncertainty: $f_{B_s}^2 B_{B_s}$ from lattice QCD.

With

$$f_{B_s} = (229 \pm 2 \pm 6)\,\text{MeV}, \qquad B_{B_s} = 0.85 \pm 0.02 \pm 0.02$$

find $\Delta m_s^{\rm SM} = (17.3 \pm 1.5)\,\text{ps}^{-1}$ entailing

$$|\Delta_s| = 1.02^{+0.10}_{-0.08}.$$

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Too good to be true: prediction is based on many calculations of f_{B_s} and the prejudice $B_{B_s} = 0.85 \pm 0.02 \pm 0.02$.

Flavour-specific decay: $B_s \to f$ is allowed, while $\bar{B}_s \to f$ is forbidden

CP asymmetry in flavour-specific decays (semileptonic CP asymmetry):

$$a_{\rm fs}^s = \frac{\Gamma(\bar{B}_s(t) \to f) - \Gamma(B_s(t) \to \bar{f})}{\Gamma(\bar{B}_s(t) \to f) + \Gamma(B_s(t) \to \bar{f})}$$

with e.g. $f = X \ell^+ \nu_\ell$ and $\bar{f} = \overline{X} \ell^- \overline{\nu}_\ell$. Untagged rate:

$$a_{\rm fs,unt}^s \equiv \frac{\int_0^\infty dt \left[\Gamma(\overset{(-)}{B_s} \to \mu^+ X) - \Gamma(\overset{(-)}{B_s} \to \mu^- X)\right]}{\int_0^\infty dt \left[\Gamma(\overset{(-)}{B_s} \to \mu^+ X) + \Gamma(\overset{(-)}{B_s} \to \mu^- X)\right]} \simeq \frac{a_{\rm fs}^s}{2}$$

Relation to M_{12}^s:

$$a_{\text{fs}}^s = \frac{|\Gamma_{12}^s|}{|M_{12}^s|} \sin\phi_s = \frac{|\Gamma_{12}^s|}{|M_{12}^{\text{SM,s}}|} \cdot \frac{\sin\phi_s}{|\Delta_s|} = (4.4 \pm 1.2) \cdot 10^{-3} \cdot \frac{\sin\phi_s}{|\Delta_s|}$$

A. Lenz, UN, 2006,2011,2012

Dilepton events:

Compare the number N_{++} of decays $(B_s(t), \bar{B}_s(t)) \to (f, f)$ with the number N_{--} of decays to $(\bar{f}, \bar{f})$.

Then $a_{\rm fs}^s = \dfrac{N_{++} - N_{--}}{N_{++} + N_{--}}$.

At the Tevatron all b-flavoured hadrons are produced. Still only those events contribute to $(N_{++} - N_{--})/(N_{++} + N_{--})$, in which one of the b hadronises as a B_d or B_s and undergoes mixing.

New physics

M_{12}^s is highly sensitive to new physics, unlike the tree-level decay $b \to c\bar{c}s$ responsible for $B_s \to J/\psi\phi$ and Γ_{12}^s.

It is plausible to consider a generic scenario, in which the M_{12} elements in $\mathrm{B_s - \overline{B}_s}$, $\mathrm{B_d - \overline{B}_d}$, and $\mathrm{K - \overline{K}}$ mixing are affected by new-physics, while all other quantities entering the global fit to the UT are as in the Standard-Model.

Recall: In the Standard Model

$$\phi_s = 0.22^\circ \pm 0.06^\circ \quad \text{and} \quad \phi_d = -4.3^\circ \pm 1.4^\circ.$$

A new-physics contribution to $\arg M_{12}^q$ may enhance

$$|a_{\mathrm{fs}}^q| \propto \sin\phi_q$$

to a level observable at current experiments.

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to a level observable at current experiments.

But: Precise data on CP violation in $B_d \to J/\psi K_S$ and $B_s \to J/\psi \phi$ preclude large NP contributions to $\arg \phi_d$ and $\arg \phi_s$.

New physics

Trouble maker:

$$A_{\rm SL} = (0.532 \pm 0.039) a_{\rm fs}^d + (0.468 \pm 0.039) a_{\rm fs}^s$$
$$= (-7.87 \pm 1.72 \pm 0.93) \cdot 10^{-3} \qquad \text{DØ 2011}$$

This is 3.9σ away from $a_{\rm fs}^{\rm SM} = (-0.24 \pm 0.03) \cdot 10^{-3}$.

A. Lenz, UN 2006,2011

Global analysis of $B_s - \overline{B}_s$ mixing and $B_d - \overline{B}_d$ mixing with A. Lenz and the CKMfitter Group (J. Charles, S. Descotes-Genon, A. Jantsch, C. Kaufhold, H. Lacker, S. Monteil, V. Niess) arXiv:1008.1593, 1203.0238

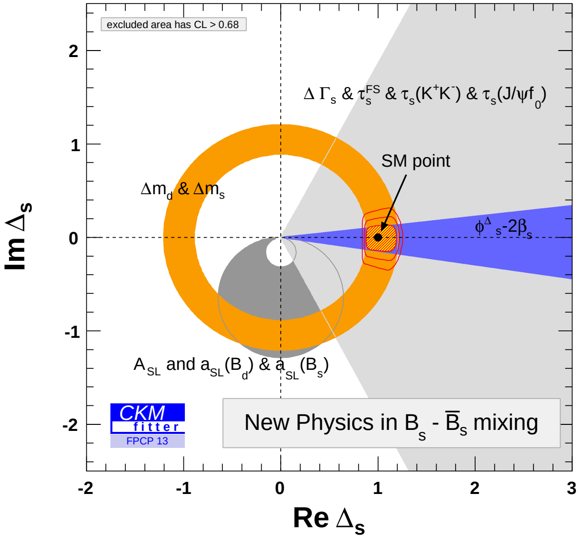
Rfit method: No statistical meaning is assigned to systematic errors and theoretical uncertainties.

We have performed a simultaneous fit to the Wolfenstein parameters and to the new physics parameters Δ_s and Δ_d,

$$\Delta_q \equiv \frac{M_{12}^q}{M_{12}^{q,\mathrm{SM}}}, \qquad \Delta_q \equiv |\Delta_q| e^{i\phi_q^\Delta},$$

and further permitted NP in $K - \overline{K}$ mixing as well.

CKMfitter August 2013 update of 1203.0238:



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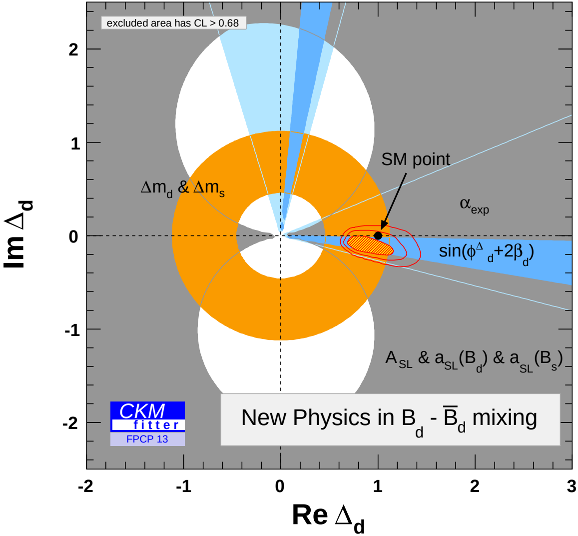

$A_{\rm SL}$ and WA for $B(B \to \tau\nu)$ prefer small $\phi_d^\Delta < 0$.

Pull value for A_{SL}: 3.4σ

$\Rightarrow$ Scenario with NP in M_{12}^{q} only cannot accomodate the DØ measurement of A_{SL}.

The Standard Model point $\Delta_s = \Delta_d = 1$ is disfavoured by 1σ, down from the 2010 value of 3.6σ.

Pull value for $A_{\rm SL}$: 3.4σ

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This is an important LHCb result: The measured $A_{\rm CP}^{\rm mix}(B_s \to J/\psi\phi)$ precludes an easy accomodation of the DØ result for $A_{\rm SL}$ in terms of new physics in M_{12}^s.
Still: Data permit $\mathcal{O}(20\%)$ new physics in both M_{12}^s and M_{12}^d!

Supersymmetry

Motivation for sub-TeV supersymmetry: stabilisation of the electroweak scale. Consider MSSM:

Tree: $M_Z^2 \simeq -2|\mu|^2 - 2m_{H_u}^2$

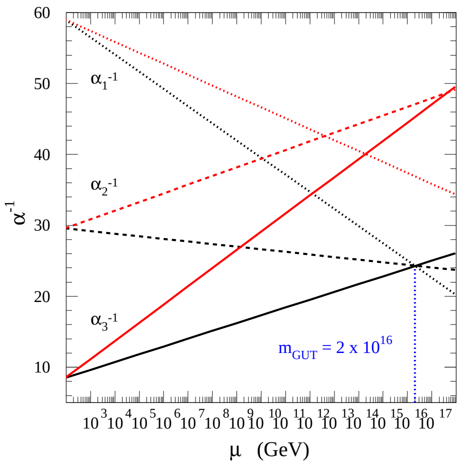
↗ higgsino mass parameter ↖ Higgs mass parameter, $m_{H_u}^2 < 0$

Loop: $$\delta m_{H_u}^2 \simeq \left[-\frac{3}{8\pi^2} y_t^2 m_{\tilde{t}}^2 \left(\ln \frac{m_{\tilde{t}}^2}{Q^2} - 1 \right) \right] - \left[\tilde{t} \to t \right]$$

for degenerate top squarks, $m_{\tilde{t}} = m_{\tilde{t}_{1,2}}$ and $Q = \mathcal{O}(m_{\tilde{t}})$.
$y_t \sim 1$ is the top Yukawa coupling.

With the lower bounds on sparticle masses set by the LHC, supersymmetry is not the full story to protect M_Z from large radiative corrections.

Gauge coupling unification:



Only logarithmic dependence on M_{SUSY}. Works with $\mathcal{O}(10\,\text{TeV})$ sparticle masses as well as with lighter sparticles.

Supersymmetry

The MSSM has many new sources of flavour violation, all in the supersymmetry-breaking sector.

No problem to get big effects in a given FCNC amplitude, but rather to suppress the big effects elsewhere.

Squark mass matrix

Diagonalise the Yukawa matrices Y^u_{jk} and Y^d_{jk}

$\Rightarrow$ quark mass matrices are diagonal, super-CKM basis

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E.g. Down-squark mass matrix:

$$M^2_{\tilde{d}} = \begin{pmatrix} \left(M^{\tilde{d}}_{1L}\right)^2 & \Delta^{\tilde{d}\,LL}_{12} & \Delta^{\tilde{d}\,LL}_{13} & \Delta^{\tilde{d}\,LR}_{11} & \Delta^{\tilde{d}\,LR}_{12} & \Delta^{\tilde{d}\,LR}_{13} \\ {\Delta^{\tilde{d}\,LL}_{12}}^* & \left(M^{\tilde{d}}_{2L}\right)^2 & \Delta^{\tilde{d}\,LL}_{23} & {\Delta^{\tilde{d}\,RL}_{12}}^* & \Delta^{\tilde{d}\,LR}_{22} & \Delta^{\tilde{d}\,LR}_{23} \\ {\Delta^{\tilde{d}\,LL}_{13}}^* & {\Delta^{\tilde{d}\,LL}_{23}}^* & \left(M^{\tilde{d}}_{3L}\right)^2 & {\Delta^{\tilde{d}RL}_{13}}^* & \Delta^{\tilde{d}\,RL*}_{23} & \Delta^{\tilde{d}\,LR}_{33} \\ {\Delta^{\tilde{d}\,LR}_{11}}^* & \Delta^{\tilde{d}RL}_{12} & \Delta^{\tilde{d}RL}_{13} & \left(M^{\tilde{d}}_{1R}\right)^2 & \Delta^{\tilde{d}\,RR}_{12} & \Delta^{\tilde{d}\,RR}_{13} \\ {\Delta^{\tilde{d}\,LR}_{12}}^* & \Delta^{\tilde{d}\,LR*}_{22} & \Delta^{\tilde{d}RL}_{23} & {\Delta^{\tilde{d}\,RR}_{12}}^* & \left(M^{\tilde{d}}_{2R}\right)^2 & \Delta^{\tilde{d}\,RR}_{23} \\ {\Delta^{\tilde{d}\,LR}_{13}}^* & {\Delta^{\tilde{d}\,LR}_{23}}^* & {\Delta^{\tilde{d}\,LR}_{33}}^* & {\Delta^{\tilde{d}\,RR}_{13}}^* & {\Delta^{\tilde{d}\,RR}_{23}}^* & \left(M^{\tilde{d}}_{3R}\right)^2 \end{pmatrix}$$

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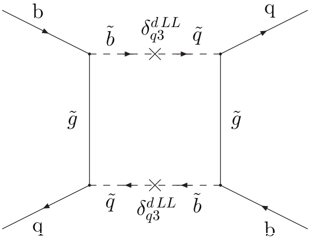
Not diagonal! $\Rightarrow$ new FCNC transitions.


b
q
$\tilde{b}$
$\delta^{d\,LL}_{q3}$
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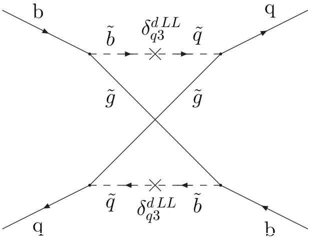
$\delta^{d\,LL}_{q3}$
$\tilde{b}$
q
b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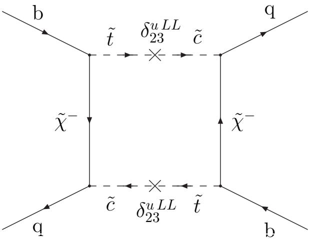
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$\tilde{t}$
q
b

Model-independent analyses constrain

$$\delta_{ij}^{q\,XY} = \frac{\Delta_{ij}^{\tilde{q}\,XY}}{\frac{1}{6}\sum_{s}\left[M_{\tilde{q}}^{2}\right]_{ss}} \qquad \text{with } XY = LL, LR, RR \text{ and } q = u, d$$

using data on FCNC (and also charged-current) processes.

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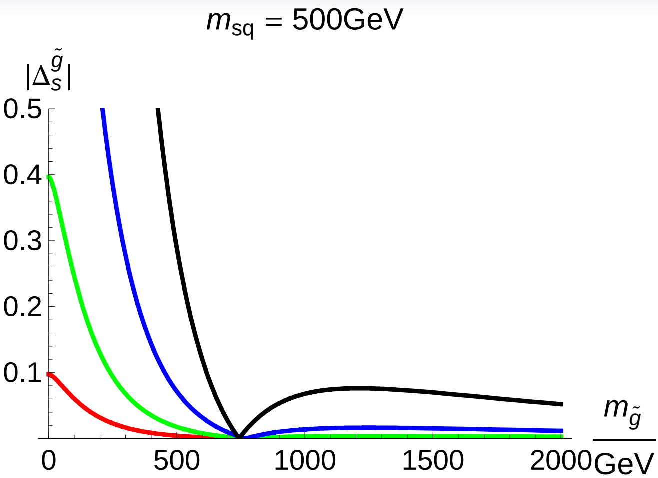
Remarks:

- For $M_{\tilde{g}} \gtrsim 1.5 M_{\tilde{q}}$ the gluino contribution is small for $AB = LL, RR$, so that chargino/neutralino contributions are important.
- To derive meaningful bounds on $\delta_{ij}^{q\,LR}$ chirally enhanced higher-order contributions must be taken into account.

A. Crivellin, UN, 2009



The gluino contribution vanishes for $M_{\tilde{g}} \approx 1.5 M_{\tilde{q}}$, independently of the size of $\Delta_{23}^{d\,LL}$ (curves correspond to 4 different values).

Minimal Flavour Violation

MFV for SUSY-breaking terms with symmetry-based definition (D'Ambrosio et al., hep-ph/0207036):
Yukawa matrices are the only spurions breaking the flavour symmetry of the gauge interaction. This entails an expansion of $M^{\tilde{Q}\,2} = M_L^{\tilde{d}\,2} = M_L^{\tilde{u}\,2}, M_R^{\tilde{u}\,2}, \ldots$ in terms of products of Yukawa matrices:

$$M^{\tilde{Q}\,2} = \widetilde{m}^2 (a_1 \mathbb{1} + b_1 Y^u Y^{u\dagger} + b_2 Y^d Y^{d\dagger} + \ldots)$$

$$M_R^{\tilde{u}\,2} = \widetilde{m}^2 (a_2 \mathbb{1} + b_5 Y^{u\dagger} Y^u + \ldots)$$

Similarly for the trilinear terms, e.g.

$$A^d = A(a_b \mathbb{1} + b_8 Y^u Y^{u\dagger}) Y^d$$

ATLAS and CMS tell us that $\sqrt{|a_i|}\widetilde{m} \gtrsim 1\,\mathrm{TeV}$.

Standard way to implement MFV: Postulate universal i.e. flavour-blind soft SUSY-breaking terms, meaning that $M^{\tilde{Q}\,2}$, $M_R^{\tilde{u}\,2}$, $M_R^{\tilde{d}\,2}$ are proportional to the unit matrix in flavour space, and the trilinear terms satisfy $A^{u,d} \propto Y^{u,d}$.
If implemented at a high scale (as in the CMSSM), the coefficients $b_1, b_2 \ldots$ are rendered non-zero by renormalisation-group effects.

Post-Run-I era: split squark spectrum with $m_{\tilde{t}_{L,R}} < m_{\tilde{u}_{L,R}} \simeq m_{\tilde{c}_{L,R}}$

Can't do that in an ad-hoc way: Recall the rotation from weak to mass basis of quarks, achieving $\widehat{Y}^u = S_Q^\dagger Y^u S_u$. The rotation of the superfields wreaks havoc on the soft terms, e.g.

$$M^{\tilde{Q}\,2} \to S_Q^\dagger M^{\tilde{Q}\,2} S_Q, \qquad M_R^{\tilde{u}\,2} \to S_u^\dagger M_R^{\tilde{u}\,2} S_u$$

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with flavour-changing off-diagonal elements all over the place.

But: MFV ansatz $M^{\tilde{u}\,2} = \widetilde{m}^2(a_2\mathbb{I} + b_5 Y^{u\dagger} Y^u + \ldots)$ permits $m_{\tilde{t}_R} < m_{\tilde{u}_R}$ while $M_R^{\tilde{u}\,2}$ is diagonal in the basis with $Y^u = \widehat{Y}^u$.
Same true for $M^{\tilde{Q}\,2}$ and $m_{\tilde{t}_L}$. Just choose $-b_1$, $-b_5$ sufficiently large.
One gets FCNC squark-gluino loops from $b_j \neq 0$, but they involve CKM elements.

GUT

In a grand unified theory (GUT) one may postulate universal soft SUSY breaking terms at some high scale near the Planck scale. The RG evolution will naturally split the third generation squark masses from those of the first and second one.

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In a grand unified theory (GUT) one may postulate universal soft SUSY breaking terms at some high scale near the Planck scale. The RG evolution will naturally split the third generation squark masses from those of the first and second one.

But: In a GUT right-handed (s)quark fields are tied to the left-handed ones and furthermore (s)quarks are linked to (s)leptons.

- $\Rightarrow$ less flavour symmetries
- $\Rightarrow$ more terms allowed by MFV expansion and possibly generated by renormalization group evolution

Example: The Chang-Masiero-Murayama model is a GUT based on the symmetry-breaking chain $SO(10) \to SU(5) \to SU(3) \times SU(2) \times U(1)$ with universal SUSY breaking terms. In this model y_t destroys the degeneracy of the right-handed down-squark mass matrix. Moreover:

$$M_R^{\tilde{u}\,2} = U_{\text{PMNS}}^\dagger \begin{pmatrix} m_{\tilde{d}_1}^2 & 0 & 0 \\ 0 & m_{\tilde{d}_1}^2 & 0 \\ 0 & 0 & m_{\tilde{d}_3}^2 \end{pmatrix} U_{\text{PMNS}}$$

with the lepton mixing matrix U_{PMNS} (Pontecorvo-Maki-Nakagawa-Sakata matrix).

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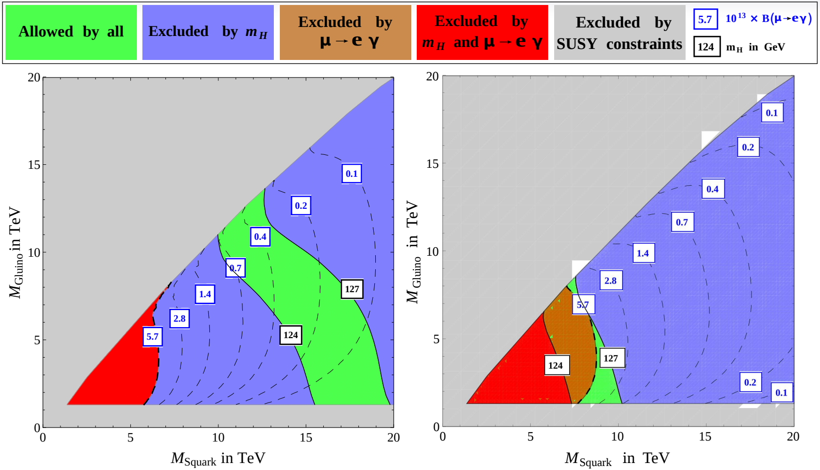
The discovery of $\theta_{13} \neq 0$ has completely changed the phenomenology of the CMM model, because

$$M_{R\,12}^{\tilde{u}\,2} = -\sin\theta_{13}\cos\theta_{13}\sin\theta_{23}(m^2_{\tilde{d}_1} - m^2_{\tilde{d}_3})$$

$\Rightarrow$ Constraints from $B(\mu \to e\gamma)$ and $\mathrm{K}-\overline{\mathrm{K}}$ mixing become dominant.



$\theta_{13} \approx 9^\circ \Rightarrow$ The CMM model becomes a realisation of split SUSY.

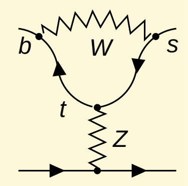
J. Stöckel, UN

Rare decays

FCNC decays of B mesons give very different information on new physics than $\mathrm{B}-\overline{\mathrm{B}}$ mixing.
While we can parametrise new physics in $\mathrm{B_d}-\overline{\mathrm{B}}_\mathrm{d}$ and $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing with one complex parameter $\Delta_{d,s}$ each, e.g. the decay $b \to s\bar{q}q$ involves 84 different Wilson coefficients.

$\Rightarrow$ $B \to K\pi$, $B \to K^*\pi$, $B \to K\rho \ldots$ all probe different new-physics parameters.

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



LHCb 2013:

$$B(B_s \to \mu^+\mu^-) = \left(3.2^{+1.5}_{-1.2}\right) \cdot 10^{-9}$$

$$B(B_d \to \mu^+\mu^-) < 9.4 \cdot 10^{-10} \quad @95\%\ \mathrm{CL}$$

Theory:

$$B\left(B_s \to \mu^+\mu^-\right) = (3.52 \pm 0.08) \cdot 10^{-9} \quad \times$$

$$\frac{\tau_{B_s}}{1.519\,\mathrm{ps}} \left[\frac{|V_{ts}|}{0.040}\right]^2 \left[\frac{f_{B_s}}{230\ \mathrm{MeV}}\right]^2$$

Supersymmetry

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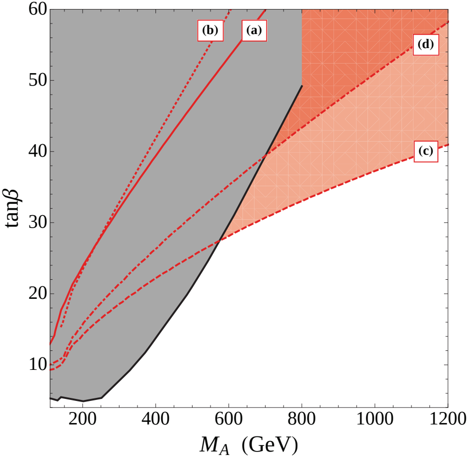
M_A: mass of the pseudoscalar Higgs boson A^0
$\tan\beta$: ratio of the two Higgs-VeVs of the MSSM:

$$B(B_s \to \mu^+\mu^-) \propto \frac{\tan^6\beta}{M_A^4}$$

$\Rightarrow$ $B_s \to \mu^+\mu^-$ places lower bounds on M_A for large values of $\tan\beta$, similarly to searches for $A^0 \to \tau^+\tau^-$ at ATLAS and CMS.

MSSM



$M_3 = 3M_2 = 6M_1 = 1.5$ TeV
$m_{\tilde{f}} = 2$ TeV
$A_b = A_t = A_\tau$,
so dass
$m_h = 125$ GeV.

a) $\mu = 1$ TeV, $A_t > 0$,
b) $\mu = 4$ TeV, $A_t > 0$,
c) $\mu = -1.5$ TeV, $A_t > 0$,
d) $\mu = 1$ TeV, $A_t < 0$,

Ausschlussflächen:
Grau: $A^0, H^0 \to \tau^+\tau^-$
Rot: $B_s \to \mu^+\mu^-$

Altmannshofer et al., 1211.1976

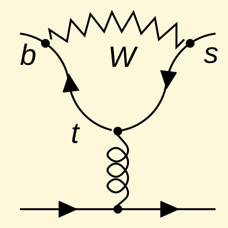
$B_s \to \phi\pi^0, \phi\rho^0$

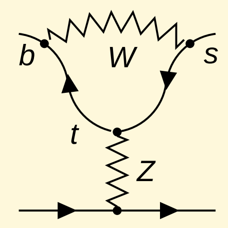
QCD penguins do not contribute to $B_s \to \phi\pi^0$ and $B_s \to \phi\rho^0$, which are therefore ideal testing grounds for Z penguins.

New physics can enhance the branching ratios by a factor of 5 over the SM values

$$\begin{aligned} B(B_s \to \phi\pi^0) &= \left(1.6^{+1.1}_{-0.3}\right) \cdot 10^{-7}, \\ B(B_s \to \phi\rho^0) &= \left(4.4^{+2.7}_{-0.7}\right) \cdot 10^{-7}. \end{aligned}$$

Hofer et al., 1011.6319, 1212.4785





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  - γ through $\pi - \alpha - \beta$ is a joint LHCb and Belle-II topic.

- The $\mathrm{B_s - \overline{B}_s}$ mixing complex probes new physics directly, essentially uncorrelated with the determination of $(\overline{\rho},\overline{\eta})$. Important LHCb topics are CP studies of $B_s \to J/\psi\phi$ and $B_s \to D_s^{\pm}K^{\mp}$.

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- In supersymmetry the rare decay $B_s \to \mu^+\mu^-$ constrains $\tan^6 \beta / M_A^4$.
- Target for LHCb: $B_s \to \phi\rho^0$, a gate to isospin-breaking physics (“Z penguins”).

Penguins: Wake-up call for new physics?