Heavy flavours

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Why flavour ?

Particle physics

Central question of QFT-based particle physics

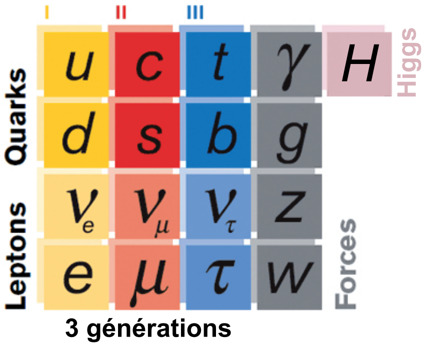
$$\mathcal{L} = ?$$

Particle physics

Central question of QFT-based particle physics

$$\mathcal{L} = ?$$

i.e. which degrees of freedom, symmetries, scales ?



SM best answer up to now, but

- neutrino masses
- dark matter
- dark energy
- baryon asymmetry of the universe
- hierarchy problem

Flavour in the SM

$$\mathcal{L}_{SM} = \mathcal{L}_{gauge}(A_a, \Psi_j) + \mathcal{L}_{Higgs}(\phi, A_a, \Psi_j)$$

Gauge part $\mathcal{L}_{gauge}(A_a, \Psi_j)$

- Highly symmetric (gauge symmetry, flavour symmetry)
- Well-tested experimentally (electroweak precision tests)
- Stable with respect to quantum corrections

Higgs part $\mathcal{L}_{Higgs}(\phi, A_a, \Psi_j)$

- Ad hoc potential
- Dynamics not fully tested
- Not stable w.r.t quantum corrections
- Origin of flavour structure of the Standard Model

From BEH to CKM

- In $\mathcal{L}_{Higgs}$, general Yukawa interaction between Higgs and quarks

$$\bar{Q}^i_L Y^{ik}_D d^k_R \phi + \bar{Q}^i_L Y^{ik}_U u^k_R \phi + h.c. + \ldots \qquad Q_L = (u_L, d_L)$$

- Vacuum expectation value for Higgs $\langle\phi\rangle \neq 0$ yields mass matrices

$$\bar{d}^i_L M^{ik}_D d^k_R + \bar{u}^i_L M^{ik}_U u^k_R + \ldots$$

- Diagonalise the mass matrices to get mass eigenstates

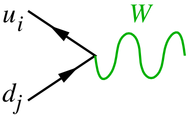
$$m_q = \frac{y_q\langle\phi\rangle}{\sqrt{2}} \quad M_D = \mathrm{diag}(m_d, m_s, m_b) \qquad M_U = \mathrm{diag}(m_u, m_c, m_t)$$

- Misalignment between rotation matrices for M_u and M_d
  charged currents in mass eigenstates involve CKM matrix V

$$J^\mu_W = \bar{u}^i_L \gamma^\mu d^i_L \to \bar{u}'_L V^\dagger_u \gamma^\mu V_d d'_L = \bar{u}'_L V \gamma^\mu d'_L$$

Flavour physics (CKM and masses) deeply connected with
the Yukawa interactions of Higgs and fermions

Structure of CKM matrix



$$\frac{g}{\sqrt{2}}\,\bar{u}_{Li} V_{ij} \gamma^\mu d_{Lj}\, W^+_\mu + \mathrm{h.c.}$$

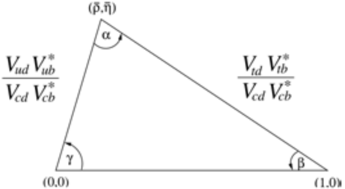
unitary Cabibbo-Kobayashi-Maskawa matrix

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

1 complex phase (for $\eta \neq 0$) source of CP-violation in the quark sector

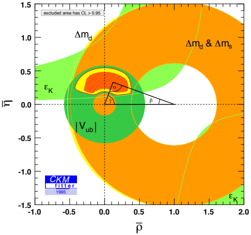
Representation of (ρ,η) through rescaled (small but non-squashed) B-meson triangle (bd)

$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$$

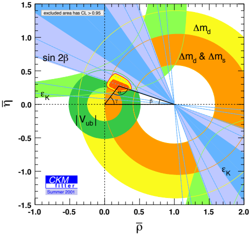


Two decades of CKM

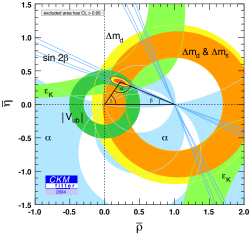
[LEP, KTeV, NA48, Babar, Belle, CDF, DØ, LHCb, CMS. . .]



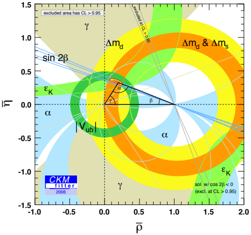
1995



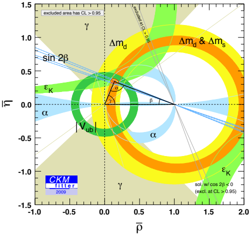
2001



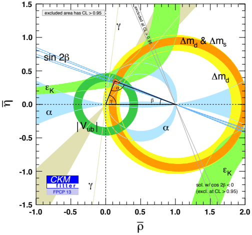
2004



2006

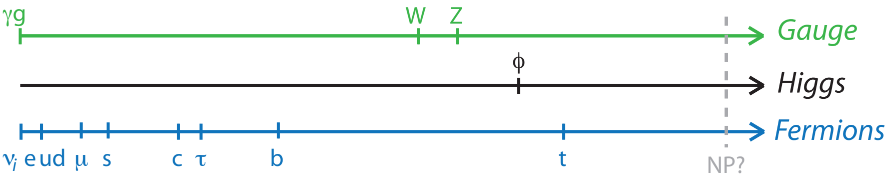


2009



2013

Quark flavour parameters and SM



Important, unexplained hierarchy among 10 of 19 params of $SM_{m_\nu=0}$

- Mass (6 params, a lot of small ratios of scales)
- CP violation (4 params, strong hierarchy between generations)

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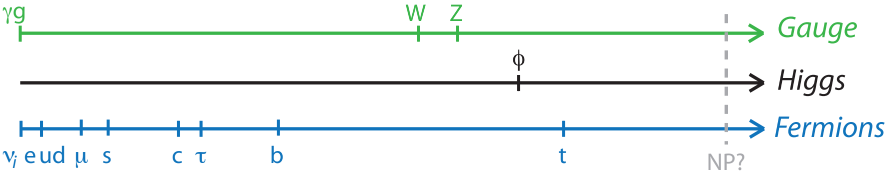

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With interesting phenomenological consequences

- Hierarchy of CP asymmetries according to generations
- Quantum sensitivity (via loops) to large range of scales
- Suppression of Flavour-Changing Neutral Currents

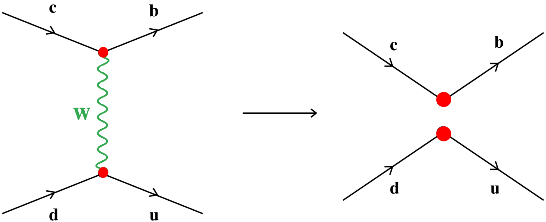
Very significant constraints on any NP extension

Good track record: charm (no $K_L \to \mu\mu$), 3rd family (ϵ_K), m_c (Δm_K), m_t (Δm_B)

From Fermi to SM: an effective approach

Fermi-like approach : separation between different scales

- Short distances : numerical coefficients
- Long distances : local operator



$$V_{ud} V_{cb}^* \, \frac{G_F}{\sqrt{2}} \frac{m_W^2}{m_W^2 - p_W^2} \; \bar{u}\gamma_\mu(1-\gamma_5) d \bar{b} \gamma^\mu (1-\gamma_5) c$$

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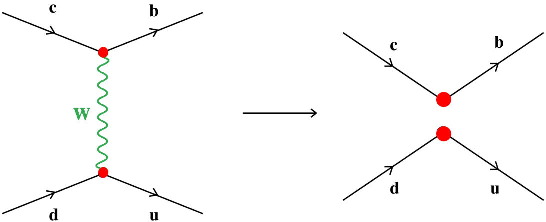

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Before/below SM, Fermi theory carried info on yesterday's NP (=EW)

- G_F: scale of NP physics
- $\mathcal{O}_i$: interaction with left-handed fermions, through charged spin 1
- Obviously not all info (gauge structure, Z^0 ...), but a good start, especially if you cannot excite the NP degrees of freedom directly

From SM to NP: an effective approach

SM = effective low-energy theory from
an underlying, more fundamental and yet unknown, theory

At low energies, below the scale Λ of new particles

$$\mathcal{L}_{SM+1/\Lambda} = \mathcal{L}_{gauge}(A_a, \Psi_j) + \mathcal{L}_{Higgs}(\phi, A_a, \Psi_j) + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \Psi_j)$$

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New operators O_n, suppressed by powers of Λ

- Describe impact of New Physics on "low-energy" physics
- Made of SM fields, compatible with its symmetries,
  e.g., dim. 5 effective neutrino mass term $(g^{ij}/\Lambda)\psi_L^i \psi_L^{Tj} \phi\phi^T$
- Split high energies c_n and low energies O_n, separated by scale Λ

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- New d.o.f. and energy scale of NP ? — High-energy expts
- Symmetries and structure ? — High-precision expts

Different processes for different goals

SM expected to be dominant (tree dominated) [semi/leptonic dec.]
Metrology of SM

SM and NP competing (loop dominated) [rare processes]
Constraints on NP

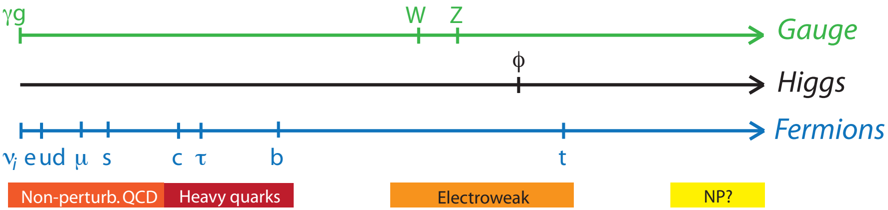
SM very small ("forbidden" by SM symmetry) [ultrarare processes]
Smoking guns of NP

Separation between the last two categories hinge on theorists' beliefs concerning the size of NP, theoretical accuracy of SM prediction and experimental measurements. . .

Facing data

… …

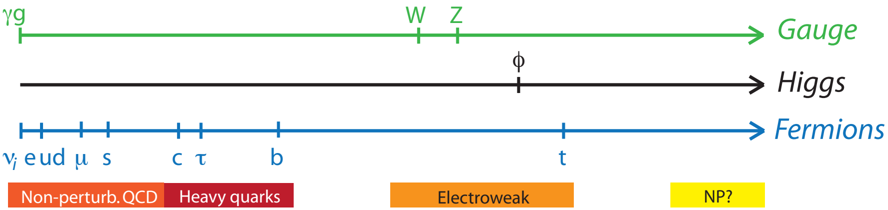
A multi-scale problem



- Tough multi-scale challenge with 3 interactions intertwined
- Several steps to separate/factorise scales

$$\text{BSM} \to \text{SM}+1/\Lambda\ (\Lambda_{EW}/\Lambda) \to \mathcal{H}_{eff}\ (m_b/\Lambda_{EW}) \to \textit{eff. th.}\ (\Lambda_{QCD}/m_b)$$

A multi-scale problem



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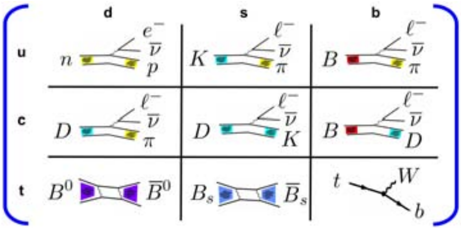
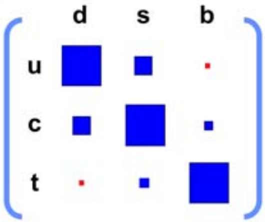
  BSM $\to$ SM+$1/\Lambda$ (Λ_{EW}/Λ) $\to$ $\mathcal{H}_{eff}$ (m_b/Λ_{EW}) $\to$ *eff. th.* (Λ_{QCD}/m_b)
- Main theo problem from hadronisation of quarks into hadrons:
  description/parametrisation in terms of QCD quantities
  decay constants, form factors, bag parameters...
- Long-distance non-perturbative QCD: source of uncertainties
  lattice QCD simulations, effective theories...

The illustration of the SM case

V =

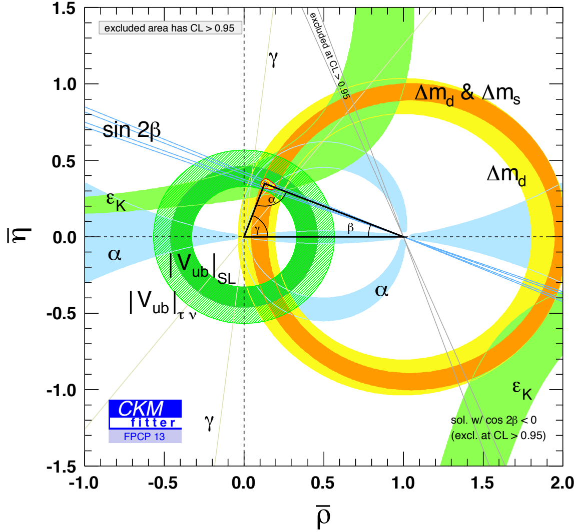




- CP-invariance of QCD to build hadronic-indep. CP-violating asym.
  or to determine hadronic inputs from data
- Statistical framework to combine data and assess uncertainites

	Exp. uncert.		Theoretical uncertainties	
Tree	$B \to DK$	γ	$B(b) \to D(c)\ell\nu$	$\lvert V_{cb}\rvert$ vs form factor (OPE)
			$B(b) \to \pi(u)\ell\nu$	$\lvert V_{ub}\rvert$ vs form factor (OPE)
			$M \to \ell\nu$	$\lvert V_{UD}\rvert$ vs f_M (decay cst)
Loop	$B \to J/\Psi K_s$	β	ϵ_K (K mixing)	$(\bar\rho, \bar\eta)$ vs B_K (bag parameter)
	$B \to \pi\pi, \rho\rho$	α	$\Delta m_d, \Delta m_s$ (B_d, B_s mixings)	$\lvert V_{tb}V_{tq}\rvert$ vs $f_B^2 B_B$ (bag param)

The current status of CKM



$|V_{ud}|, |V_{us}|, |V_{cb}|, |V_{ub}|_{SL}$

$B \to \tau\nu$

$\Delta m_d, \Delta m_s, \epsilon_K$

$\alpha, \sin 2\beta, \gamma$

$$A = 0.823^{+0.012}_{-0.033}$$
$$\lambda = 0.2246^{+0.0019}_{-0.0001}$$
$$\bar{\rho} = 0.129^{+0.018}_{-0.009}$$
$$\bar{\eta} = 0.348^{+0.012}_{-0.012}$$
(68% CL)

Progress in lattice QCD

- chiral extrapolation in quark masses — physical quark masses
- isopin limit — strong and electromag isospin breaking
- u, d, s only in the sea — effect of dynamical charm
- 0 or 1-body (ground) state — 2-body final states, resonances
- SM operators — general BSM operators

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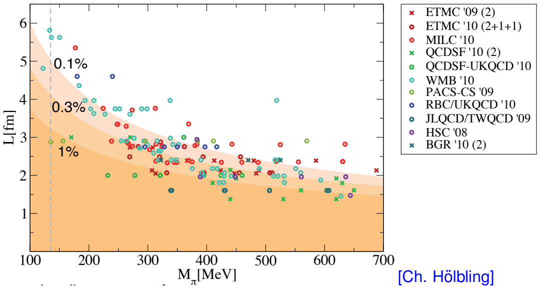

[Ch. Hölbling]

- Most results already dominated by syst
- Saturation $\sim$ 1% for many qties (small syst neglected before…)
- Little about systematics correl. between observ.

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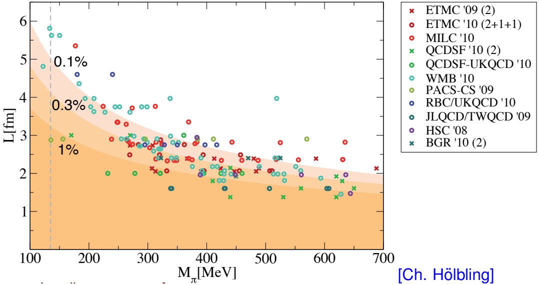

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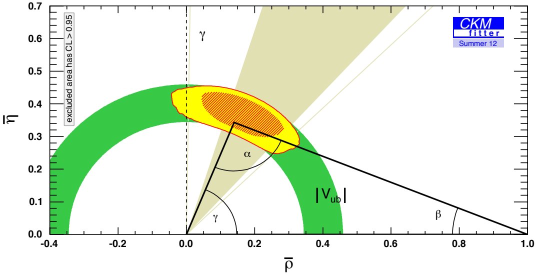
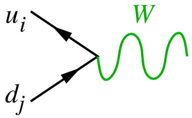
- Little about systematics correl. between observ.

$f_D, f_{D_s}, f_B, \xi, B_K$	$< 1\%$	$D \to \pi\ell\nu, B \to \pi\ell\nu$	2%
$D \to K\ell\nu, B \to D^*\ell\nu$	1%	Δm_s	5%
$B \to K\ell\ell, K \to \pi\ell\ell$, BSM mixings	prelim		

[2018 USQCD predictions]

Flavour-Changing Charged Currents





Determining flavour SM-parameters accurately even in presence of NP

$\Longrightarrow$only SM-dominated processes, i.e. tree-level FCCC

- $|V_{ud}|$, $|V_{us}|$ (rather accurately known from K and nuclear decays)
- γ (not yet at the same level of accuracy as α and β)
- $|V_{ub}|$ and $|V_{cb}|$ from semileptonic B decays

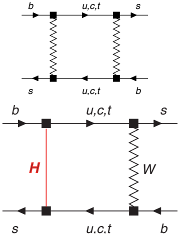
  (improvement of hadronic uncertainties from lattice QCD)

Once CKM constrained, look for other processes to constrain NP

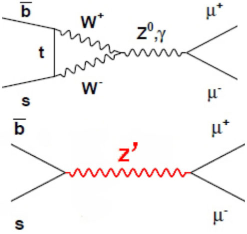
Flavour-Changing Neutral Currents

Forbidden in SM at tree level, and suppressed by GIM at one loop
so good place for NP to show up (tree or loops)

$\Delta F = 2$: B_s mixing



$\Delta F = 1$: $B_s \to \mu\mu$



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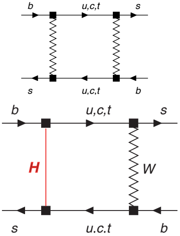

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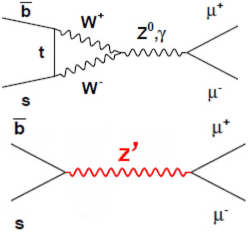

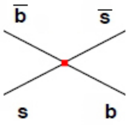

$$A_{\Delta F=2} \sim \frac{(y_t^2 V_{tb}^* V_{ts})^2}{16\pi^2} \frac{1}{m_t^2} \langle \bar{B}_s | (\bar{b}_L \gamma_\mu s_L)^2 | B_s \rangle + \frac{c_i}{\Lambda^2} \langle \bar{B}_s | O_i | B_s \rangle$$

O_i = SM-like or with other structure (scalar, $V + A \ldots$)
in $\mathcal{H}_{eff}$ linked to new particle features (H^+, $W_R \ldots$)

$\Delta F = 2$ FCNC constraints

Operator	Bounds on Λ in TeV ($c_n = 1$)		Bounds on c_n ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p \rvert$, ϕ_D
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p \rvert$, ϕ_D
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

[Isidori, Nir, Perez 2010]

Neutral meson mixing ($\Delta F = 2$) SM-like, and c_i/Λ^2 must be small:

- Significant mass gap
- Couplings with close-to-SM pattern of flavour violation
- Additional selection rules

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$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p \rvert$, ϕ_D
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$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

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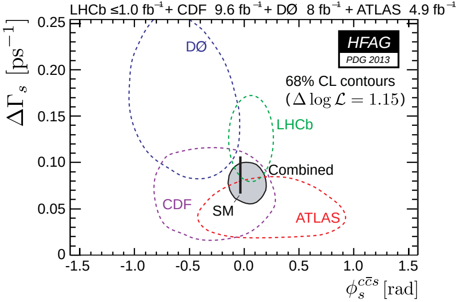
NP flavour problem: BSM models with many flavour violation sources

- Decoupling *[Λ large compard to Λ_{EW}, loop suppression]*
- Universality *[Minimal Flavour Violation: all flavour viol. from Yukawa]*
- Alignment *[Loops with NP only, diagonal in flavour basis]*

$\Delta F = 2$ FCNC: B_s mixing parameters

Confirmation from recent measurement of B_s mixing parameters

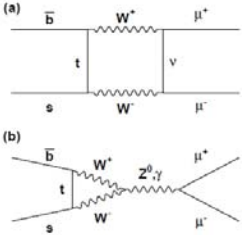
- two mass eigenstates B_{sH}, B_{sL} in terms of CP-states $B_s, \bar{B}_s$
- $\Delta\Gamma_s$ difference of widths
  [quark-hadron duality + $1/m_b$ and α_s expansions] [Lenz, Nierste…]
- ϕ_s mixing phase describing B_{sH}, B_{sL} in terms of $B_s, \bar{B}_s$
  [In SM, $\phi_{Bs} = 2\arg(V_{cs}V^*_{cb}/V_{ts}V^*_{tb}) = -2.1° \pm 0.1°$]

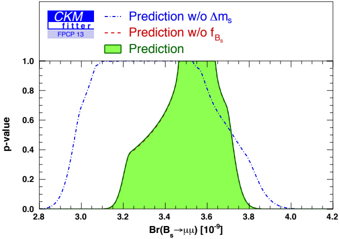


After some confusion, B_s mixing parameters are very SM-like

$\Delta F = 1$ FCNC: $B_s \to \mu\mu$ and $B \to X_s\gamma$

Complementary to B_s mixing for $V_{tb}V_{ts}^*$ in SM, may have $\neq$ NP contribs





- LHCb+CMS: $Br(B_s \to \mu\mu) = (2.9 \pm 0.7) \cdot 10^{-9}$ $(> 5\sigma)$
- NLO pred from SM global fit: $Br(B_s \to \mu\mu) = (3.99^{+0.23}_{-0.37}) \cdot 10^{-9}$
- SM prediction with NNLO strong and NLO weak corrections: $Br(B_s \to \mu\mu) = (3.65 \pm 0.23)10^{-9}$ [Bobeth,Gorbahn,Hermann,Misiak,Stamou,Steinhauser]

- Exp aver: $Br(B \to X_s\gamma)_{E_\gamma > 1.6\ \mathrm{GeV}} = (3.43 \pm 0.21 \pm 0.07) \times 10^{-4}$
- NNLO SM prediction: $Br = (3.13 \pm 0.22) \times 10^{-4}$ [Misiak,Steinhauser]

No sign of significant discrepancy with SM in these modes

Expect the unexpected

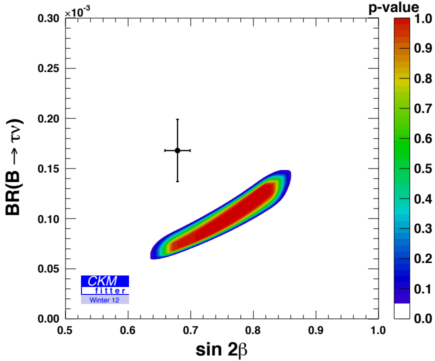
NP hints

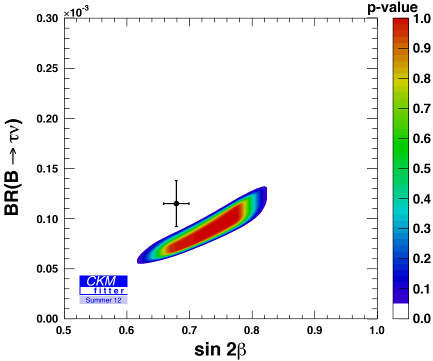
- Several departures from SM expectations
- Some of them unexpected and worrying ($b \to c\ell\nu$)
- Others hoped for and intriguing ($b \to s\ell\ell$)
- But similar to the stock market: many ups and downs !

	Up	Stable	Down
$\Delta F = 1$ FCCC (SM tree)		$B \to D(^*)\tau\nu$	$B \to \tau\nu$ $A_{CP}(D \to PP)$
$\Delta F = 1$ FCNC (SM loop)	$B \to K^*\ell\ell$	$A_I(B \to K\ell\ell)$	
$\Delta F = 2$ FCNC (SM loop)			A_{SL} in $B_{d,s}$ mixing

In each case, one can try to come up with SM or NP solutions

Down: $B \to \tau\nu$





- *Used to* have significant discrepancy in SM for $B \to \tau\nu$ vs $\sin(2\beta)$

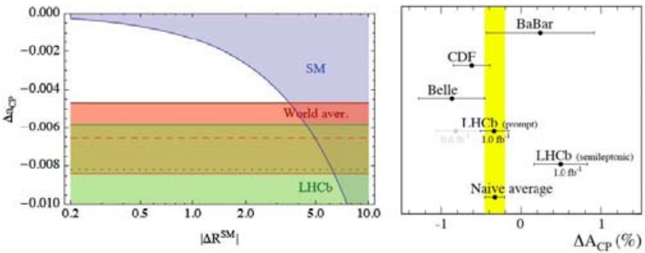
  2.8σ [Moriond 12] $\to$ 1.6σ [ICHEP 12]

- 2012 Belle result changed WA $Br(B \to \tau\nu)$

  $(1.68 \pm 0.31) \cdot 10^{-3}$ [Moriond12] $\to$ $(1.15 \pm 0.23) \cdot 10^{-3}$ [ICHEP12]

- Brings CKM-independent $d\Gamma(B \to \pi\ell\nu)/dq^2/Br(B \to \tau\nu)$ closer to non-perturbative estimates (sum rules, lattice) [A. Khodjamirian et al.]

Down: CP-violation in D decays



$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-0.68 \pm 0.15)\%$$

dominated by $A_{CP}^{dir} = \frac{\Gamma(D\to PP)-\Gamma(\bar{D}\to PP)}{\Gamma(D\to PP)+\Gamma(\bar{D}\to PP)}$

$\Delta A_{CP} \simeq (0.13\%)\mathrm{Im}(\Delta R)$ $\quad \mathrm{Im}(\Delta R)$ matrix elements ratio [Isidori et al.]

- $\mathrm{Im}(\Delta R) < 1$ assuming $m_c \gg \Lambda_{QCD}$
- but $= O(1)$ in decent fits on $D \to PP$ (if large U-spin breaking)
- SM: charm like strange ($\Delta I = 1/2$ rule) with penguins enhanced
- NP: CP-viol. in chromomagnetic dipole operator ($D \to V\gamma, V\ell\ell$)

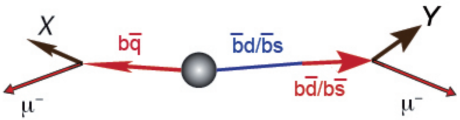
[Hiller et al., Gronau et al., Brod et al., Feldmann et al., Giudice et al...]

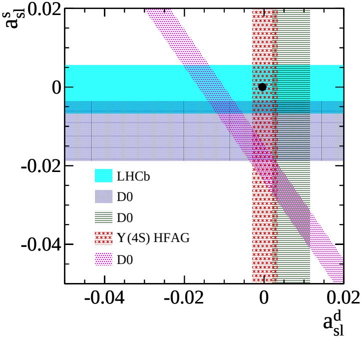
2013 LHCb update: $\quad \Delta A_{CP} = (-0.68 \pm 0.15)\% \to (-0.33 \pm 0.12)\%$

Down: Dimuon asymmetry (1)

CP-violation in mixing through comparison of wrong-sign decays $(\ell^- \leftarrow \bar{B}(b\bar{q}) \leftrightarrow B(\bar{b}q) \rightarrow \ell^+)$

$$a^q_{SL} = \frac{\Gamma(\bar{B}_q(t)\to\ell^+\nu X)-\Gamma(B_q(t)\to\ell^-\nu X)}{\Gamma(\bar{B}_q(t)\to\ell^+\nu X)+\Gamma(B_q(t)\to\ell^-\nu X)}$$

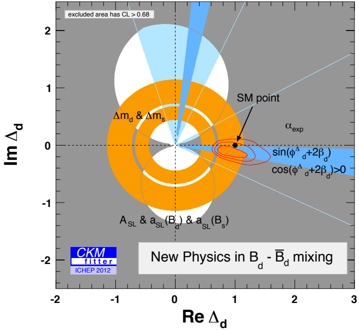


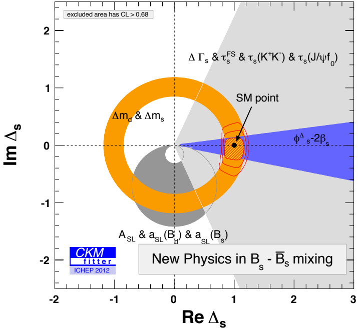


- Same-sign dimuon charge asym. $A_{SL} = (-0.85 \pm 0.28)\%$ [CDF, DØ] linear combination of a^d_{SL} and a^s_{SL}, disagrees with SM at 3 σ
  $A^{SM}_{SL} = -(0.020 \pm 0.003)\%$ [Lenz,Nierste]
- Individual semileptonic asyms. from $B_q \to D_q \mu X$ OK with SM
  $a^d_{SL} = (0.38 \pm 0.36)\%$ [B-factories, Tevatron]
  $a^s_{SL} = (-0.22 \pm 0.52)\%$ [DØ, LHCb]

Down: Dimuon asymmetry (2)

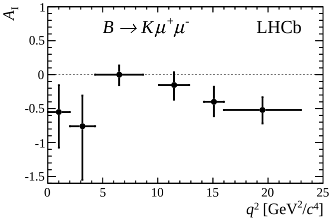
- Hard to accomodate non-SM A_{SL} with SM $\Delta m_{d,s}$, $\Delta\Gamma_s$
- In simple models of NP in $\Delta F = 2$ boxes only, 3.3 σ pull for A_{SL}

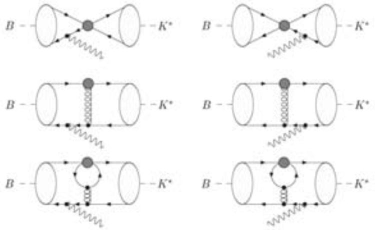




- NP: contribution from $\tau\bar{\tau}$ intermediate states [Haisch, Bobeth]
- NP: CP-viol. in muonic semilept. b or c decays [Gronau et al.; SDG, Kamenik]
- SM: CP-viol. in interference for $B_d \to c\bar{c}d\bar{d}$, absent from DØ analysis, could explain 2/3 of the effect on A_{SL} [Borissov, Hoeneisen]

Stable: Isospin asymmetry in $B \to K\ell^+\ell^-$

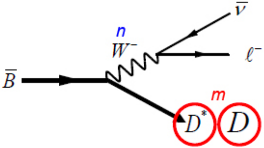


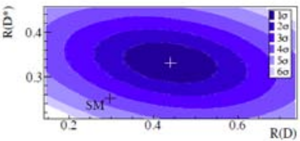


- Integrated over q^2: 4.4 σ from 0 (but nothing for $B \to K^*\mu^+\mu^-$)
- Purely spectator quark effect
- Requires calculation of $1/m_b$-suppressed corrections in QCD factorisation (weak annihilation, quark-loop spectator scattering)
- SM: small non-local effects/soft-gluon diagrams, with a prediction below 1.5% (but with large uncertainties)
- NP: No clue... Hard to break isospin for K and not K^* !

[Kagan, Neubert, Feldmann, Matias, Khodjamiran, Mannel, Yang, Lyon, Zwicky...]

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





$$\frac{d\Gamma(B\to D^*\tau\nu)}{dq^2} \propto \left[\left(|H_{++}|^2+|H_{--}|^2+|H_{00}|^2\right)\left(1+\frac{m_\tau^2}{2q^2}\right)+\frac{3}{2}\frac{m_\tau^2}{q^2}|H_{0t}|^2\right]$$

with H_{mn} helicity amplitude for (D^*, W) [for D, only H_{00} and H_{0t}]

$$\frac{\Gamma(\bar B\to D\tau\nu)}{\Gamma(\bar B\to D\ell\nu)} = 0.440\pm0.058\pm0.042 \text{ [Babar]},\quad 0.430\pm0.091 \text{ [Belle]},\quad 0.297\pm0.017 \text{ [SM]}$$

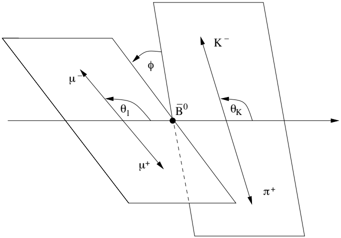
$$\frac{\Gamma(\bar B\to D^*\tau\nu)}{\Gamma(\bar B\to D^*\ell\nu)} = 0.332\pm0.024\pm0.018 \text{ [Babar]}\quad 0.405\pm0.047 \text{ [Belle]},\quad 0.252\pm0.003 \text{ [SM]}$$

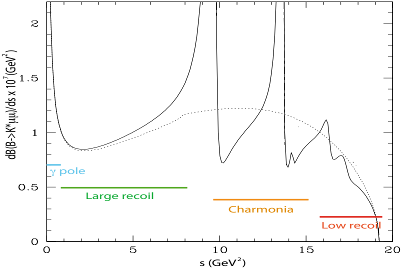
[Fajfer, Kamenik, Nizandzic]

- based on $B \to D(^*)$ form factors (4 for $B \to D^*$, 2 for $B \to D$)
- constrained by HQE, lattice ($B \to D$) and experiment ($B \to D^*$)
- NP: scalar contribution, seen only in helicity-suppressed $O(m_\tau^2)$ (but not 2HDM of type II) and look for further angular observables
- SM: lattice-inspired $B \to D\tau\nu$ FFs: $0.297 \pm 0.017 \to 0.31 \pm 0.02$

[Becirevic, Kosnik, Tayduganov; HPQCD collab]

Up: $B \to K^*\ell\ell$ (1)





- Analysis of $b \to s\ell\ell$ via effective Hamiltonian $\mathcal{H} = V_{tb}V_{ts}^* C_i Q_i$
  - $Q_7 = \bar{s}\sigma^{\mu\nu}(1+\gamma_5)F_{\mu\nu}\, b$ [real or soft photon]
  - $Q_9 = \bar{s}\gamma_\mu(1-\gamma_5)b\ \bar{\ell}\gamma_\mu\ell$ [$b \to s\mu\mu$ via Z/hard γ]
  - $Q_{10} = \bar{s}\gamma_\mu(1-\gamma_5)b\ \bar{\ell}\gamma_\mu\gamma_5\ell$ [$b \to s\mu\mu$ via Z]
  - and potentially other, non SM, operators (chirally flipped, scalar. . .)
- Angular analysis yields $\mathrm{Re}[AB^*]$, $\mathrm{Im}[AB^*]$ between 8 amplitudes A

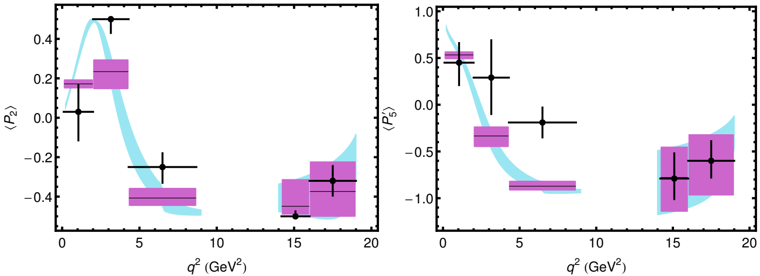
$$A = V_{tb}V_{ts}^* \sum C_i \times \text{ form factors } \times \text{ kinematic factors}$$

  - $B \to K^* V^*(\to \ell\ell)$ with given helicities for K^* and V^*, chirality of $\ell\ell$
  - depending on $q^2 = s$ invariant mass of the lepton pair

- Theoretical control on the 7 $B \to K^*$ form factors
  - Light-cone sum rules and lattice QCD estimates
  - Effective theories: at low and large K^* recoil

$$\text{FF} = \text{soft form factors} + O(\alpha_s) + O(\Lambda_{QCD}/m_B)$$

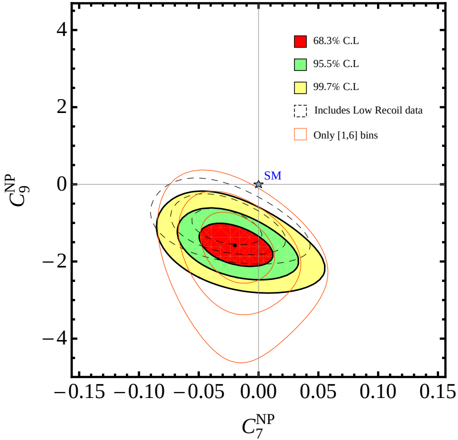
  with only 2 or 3 soft form factors and $O(\alpha_s)$ computable
- Observables with limited sensitivity to form factor uncertainties thanks to effective field theory relations (at large K^* recoil, 6 P_i)



LHCb at EPS13 : 2.9 σ discrepancy in P_2, 4.0 σ in P_5' !

[blue: SM unbinned, purple: SM binned, crosses: LHCb]

Fit of C_i to $B \to K^*\mu\mu$: $P_1, P_2, P_4', P_5', P_6', P_8', A_{FB}$, together with



$$C_i(\mu_{ref}) = C_i^{SM} + C_i^{NP}$$

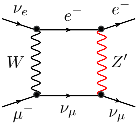
[SDG, Matias, Virto]

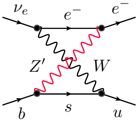
- $B \to X_s\gamma$: Br
- $B \to X_s\mu^+\mu^-$: Br
- $B_s \to \mu\mu$: Br
- $B \to K^*\gamma$: A_I and $S_{K^*\gamma}$

- negative shifts from SM in C_7 (small) and C_9 (large) enough to describe all data well
- no clear need of others ($C_{9'}$?)

- SM: $c\bar{c}$ loops or soft gluons ? not enough, wrong direction
- NP: Z'-boson (compositeness or susy do not work)

Up: $B \to K^* \ell\ell$ (4)

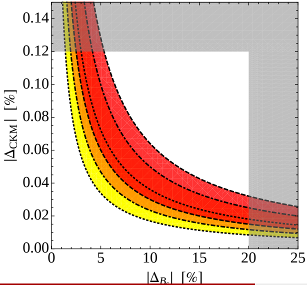




A FCNC Z' boson would manifest itself at least in

- $B_s \bar{B}_s$ mixing $[\Delta_{B_s} = \Delta M_{B_s}/\Delta M_{B_s}^{SM} - 1]$
- unitarity violation in 1st row V_{CKM} $[\Delta_{CKM} = 1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2]$
- $b \to s\nu\bar{\nu}$ [still to be observed...]

Correlation between deviations (depend on $M_{Z'}$ =1,3,10 TeV) OK



[Gauld, Goertz, Haisch]

- $SU_C(3) \otimes SU_L(3) \otimes U_Y(1)$ Z' model still OK but $M_{Z'} = O(7$ TeV$)$

[Gauld, Goertz, Haisch]

- If MFV, more constraints for FCNC bd and bs to reproduce $\Delta m_s/\Delta m_d$ $\Longrightarrow$more correls [e.g., $B_{d,s} \to \mu\mu$]

[Buras, Girrbach; Altmanshoffer, Straub]

Outlook

Flavour physics

- Low-energy window on electroweak scale and beyond
- Using SM symmetries to look for tell-tale signs of NP
- Exploiting different scales through a series of effective theories
- Long distances: non-perturbative QCD source of uncertainties

Two approaches to analyse flavour physics observables

- Model-independent: focus on class of quark processes to constrain c/Λ^2 and operator structure
- Model-dependent: design model and connect it with other flavour constraints (and high-p_T if possible)

Powerful tool to probe and constrain not only SM but also NP
if enough data from different sources to extract meaningful patterns
(more expected from LHCb, but also CMS, ATLAS and NA62 !)