Phénoménologie de la physique des saveurs

Sébastien Descotes-Genon

Laboratoire de Physique Théorique
CNRS & Université Paris-Sud 11, 91405 Orsay, France

Journée prospective LAPP (Annecy)
3 Octobre 2013

Why flavour ?

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

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

$$\bar{Q}_L^i Y_D^{ik} d_R^k \phi + \bar{Q}_L^i Y_U^{ik} u_R^k \phi + h.c. + \dots \qquad Q_L = (u_L, d_L)$$

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

$$\bar{d}_L^i M_D^{ik} d_R^k + \bar{u}_L^i M_U^{ik} u_R^k + \dots$$

- Diagonalise the mass matrices to get mass eigenstates

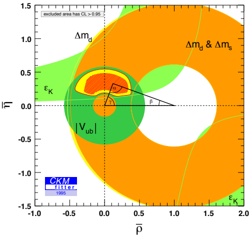
$$m_q = \frac{y_q \langle\phi\rangle}{\sqrt{2}} \quad M_D = \mathrm{diag}(m_d, m_s, m_b) \qquad M_U = \mathrm{diag}(m_u, m_c, m_t)$$

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

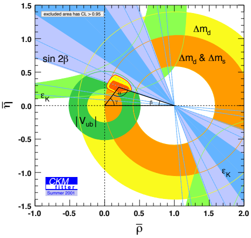
$$J_W^\mu = \bar{u}_L^i \gamma^\mu d_L^i \to \bar{u}_L' V_u^\dagger \gamma^\mu V_d d_L' = \bar{u}_L' V \gamma^\mu d_L'$$

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

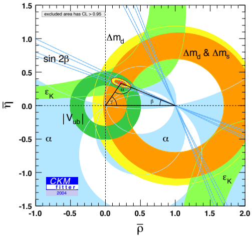
Two decades of CKM



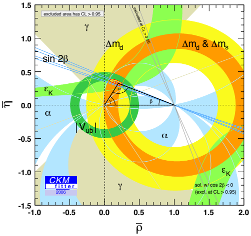
1995



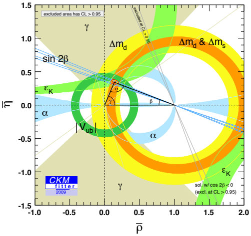
2001



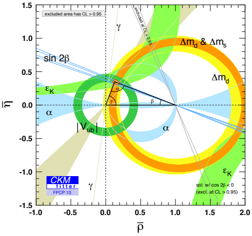
2004



2006

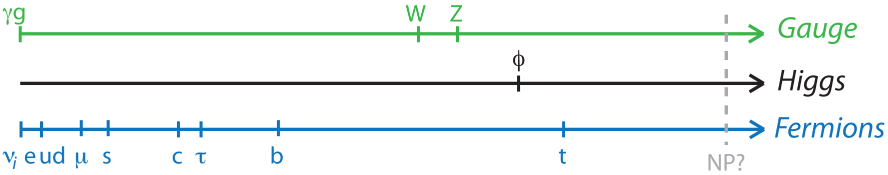


2009



2013

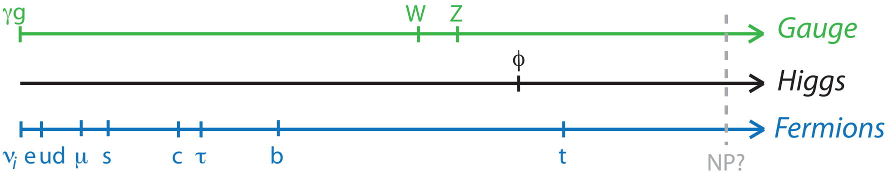
Flavour parameters and SM



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

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

Flavour parameters and SM



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

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

With interesting phenomenological consequences

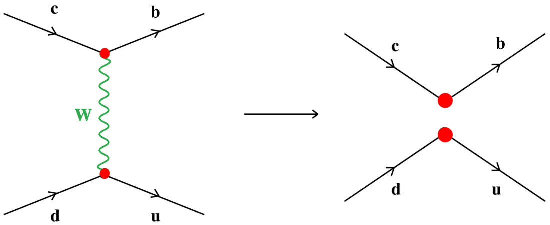
- Hierarchy of CP asymmetries according to generations
- Quantum sensitivity (via loops) to large range of scales
- GIM suppression of Flavour-Changing Neutral Currents

Very significant constraints on any SM extension
and challenge to explain the hierarchy dynamically

From Fermi to SM: an effective approach

Fermi-like approach : separation between different scales

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

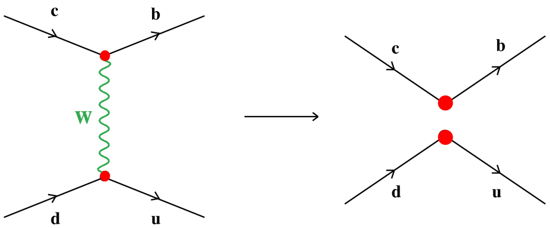


$$V_{ud} V_{cb}^* \frac{G_F}{\sqrt{2}} \frac{m_W^2}{m_W^2 - p_W^2} \bar{u}\gamma_\mu(1-\gamma_5)d\bar{b}\gamma^\mu(1-\gamma_5)c$$

From Fermi to SM: an effective approach

Fermi-like approach : separation between different scales

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



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

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

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

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

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

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

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

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

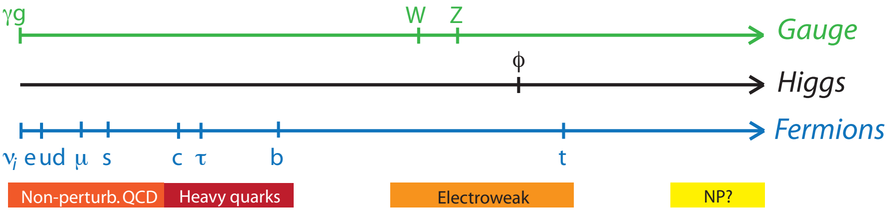
$$\mathcal{L}_{SM+1/\Lambda} = \mathcal{L}_{gauge}(A_a, \Psi_j) + \mathcal{L}_{Higgs}(\phi, A_a, \Psi_j) + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \Psi_j)$$

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

- New d.o.f. and energy scale of NP ?
- Symmetries and structure ?

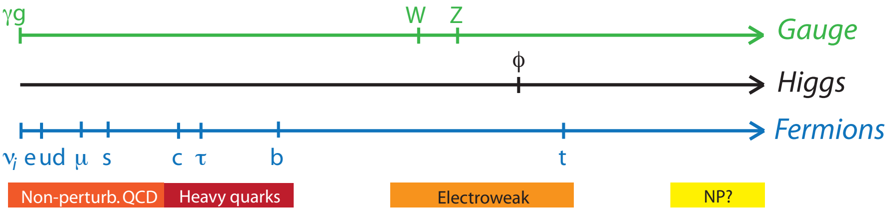
A multi-scale problem



- 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



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

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

- 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

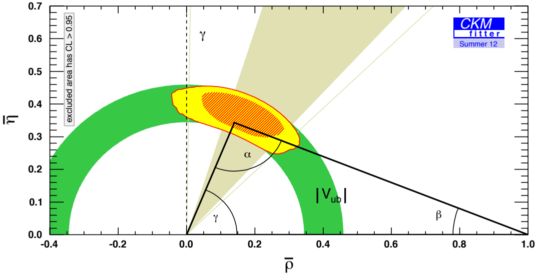
  lattice QCD simulations, effective theories...

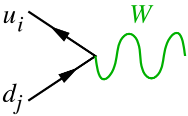
Different processes for different goals

SM expected to be dominant (tree-dominated processes)	SM and NP competing (loop-dominated processes)	SM zero or very small (SM symmetry forbidden proc.)
Metrology of SM	Constraints on NP	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. . .

SM ! Flavour-Changing Charged Currents





Determining flavour SM-parameters accurately even with NP

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

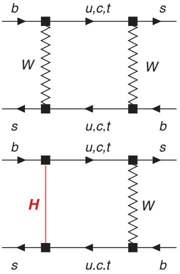
- $|V_{ud}|$, $|V_{us}|$ (rather accurately known from K and nuclear decays)
- γ (not yet at the same level of accuracy as α and β)
- $|V_{ub}|$ and $|V_{cb}|$ from exclusive semileptonic B decays (improvement of hadronic uncertainties from lattice QCD)

Caveat: Babar $B \to D(^*)\tau\nu$ with significant tree-level NP ?

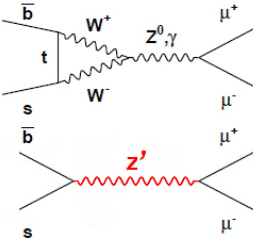
NP ? Flavour-Changing Neutral Currents

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



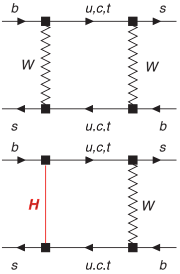
$\Delta F = 1$: $B_s \to \mu\mu$



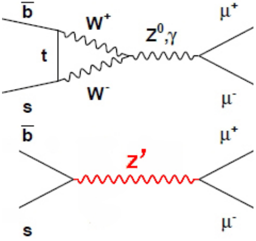
NP ? Flavour-Changing Neutral Currents

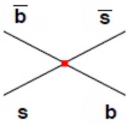
Forbidden in SM at tree level, and suppressed by GIM at one loop
so good place for NP to show up (tree or loops)

$\Delta F = 2$: B_s mixing



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





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

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

Bounding NP: $\Delta F = 2$ 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

Bounding NP: $\Delta F = 2$ constraints

Operator	Bounds on Λ in TeV ($c_n = 1$) Re	Im	Bounds on c_n ($\Lambda = 1$ TeV) Re	Im	Observables
$(\bar{s}_L \gamma^\mu d_L)^2$	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; $\|q/p\|$, 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; $\|q/p\|$, 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:

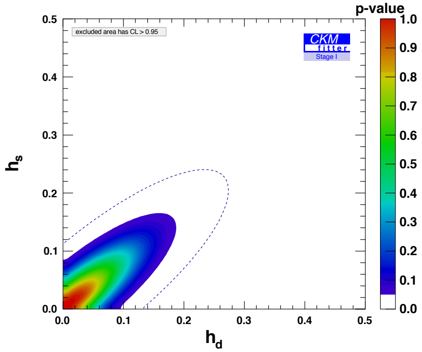
- Significant mass gap
- Couplings with close-to-SM pattern of flavour violation
- Additional selection rules

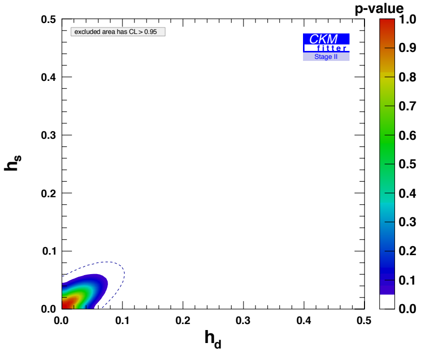
NP flavour problem: BSM models with many flavour violation sources

- Decoupling *[Λ large compard to Λ_{EW}, loop suppression]*
- Universality *[Minimal Flavour Violation: all flavour violation from Y]*
- Alignment *[Loops with NP only, coupling only within a generation]*

Bounding NP: $\Delta F = 2$ constraints in the future

- Stage I: 7 fb^{-1} LHCb data + 5 ab^{-1} Belle II
- Stage II: 50 fb^{-1} LHCb data + 50 ab^{-1} Belle II





NP in B_d and B_s mixings

$$M_{12}^q = (M_{12}^q)_{\rm SM} \times \left(1 + h_q\, e^{2i\sigma_q}\right)$$

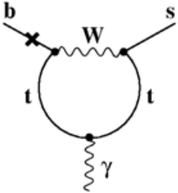
from $C_{ij}/\Lambda^2 \times (\bar{b}_L \gamma^\mu q_L)^2$

[J. Charles et al.]

Couplings	NP loop order	Scales (in TeV) probed by B_d mixing	B_s mixing
$\lvert C_{ij}\rvert = \lvert V_{ti} V_{tj}^*\rvert$ (CKM-like)	tree level	17	19
	one loop	1.4	1.5
$\lvert C_{ij}\rvert = 1$ (no hierarchy)	tree level	2×10^3	5×10^2
	one loop	2×10^2	40

Hunting NP: $\Delta F = 1$ effective approach at $\mu = m_b$

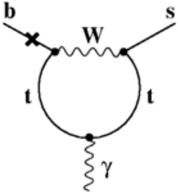
$$b \to s\gamma(^*) : \mathcal{H}^{SM}_{\Delta F=1} \propto \sum_{i=1}^{10} V^*_{ts} V_{tb} C_i Q_i + \ldots$$



- $Q_7 = \frac{e}{g^2} m_b \, \bar{s}\sigma^{\mu\nu}(1+\gamma_5)F_{\mu\nu}\, b$ [real or soft photon]
- $Q_9 = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b \, \bar{\ell}\gamma_\mu \ell$ [$b \to s\mu\mu$ via Z/hard γ]
- $Q_{10} = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b \, \bar{\ell}\gamma_\mu\gamma_5 \ell$ [$b \to s\mu\mu$ via Z]

Hunting NP: $\Delta F = 1$ effective approach at $\mu = m_b$

$$b \to s\gamma(^*) : \mathcal{H}^{SM}_{\Delta F=1} \propto \sum_{i=1}^{10} V^*_{ts} V_{tb} C_i Q_i + \dots$$



- $Q_7 = \frac{e}{g^2} m_b \, \bar{s}\sigma^{\mu\nu}(1+\gamma_5)F_{\mu\nu}\, b$ [real or soft photon]
- $Q_9 = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b \, \bar{\ell}\gamma_\mu\ell$ [$b \to s\mu\mu$ via Z/hard γ]
- $Q_{10} = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b \, \bar{\ell}\gamma_\mu\gamma_5\ell$ [$b \to s\mu\mu$ via Z]

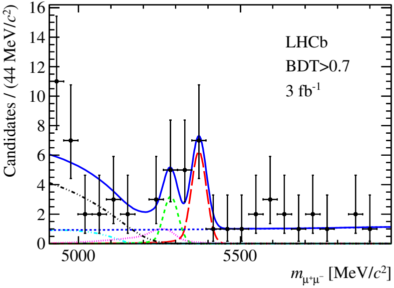
NP changes short-distance C_i and/or add new long-distance ops Q'_i

- Chirally flipped operators ($W \to W_R$)
  $Q_7 \propto \bar{s}\sigma^{\mu\nu}(1+\gamma_5)F_{\mu\nu}\, b \to Q_{7'} \propto \bar{s}\sigma^{\mu\nu}(1-\gamma_5)F_{\mu\nu}\, b$
- Scalar/pseudoscalar operators ($\gamma \to H$)
  $Q_9 \propto \bar{s}\gamma_\mu(1-\gamma_5)b \, \bar{\ell}\gamma_\mu\ell \to Q_S \propto \bar{s}b(1+\gamma_5)\bar{\ell}\ell,\ Q_P \propto \bar{s}b(1+\gamma_5)\bar{\ell}\gamma_5\ell$
- Tensor operators ($\gamma \to T$)
  $Q_9 \propto \bar{s}\gamma_\mu(1-\gamma_5)b \, \bar{\ell}\gamma_\mu\ell \to Q_T \propto \bar{s}\sigma_{\mu\nu}(1-\gamma_5)b \, \bar{\ell}\sigma_{\mu\nu}\ell$

Hunting NP: $b \to s\gamma(^*)$ data

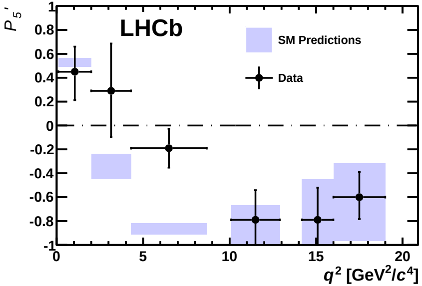
Choose incoming and outgoing states (same quark content, but different spin, parity...) to select some of the operators for $b \to s\gamma(^*)$

$B \to X_s\gamma$, $B \to K^*\gamma$: C_7, good agreement with SM



$B_s \to \mu\mu$: Br

$C_{10(')}, C_{S(')}, C_{P(')}$: OK with SM



$B \to K^*(K\pi)\mu\mu$: ang. analysis

All operators: $C_9 \neq C_9^{SM}$?

$\Longrightarrow$Global fits to data suggest $C_9 \neq C_9^{SM}$, all the rest $\sim$ SM

[SDG, J.Matias, J.Virto; D.Straub, W.Altmanshoffer]

Hunting NP: model building

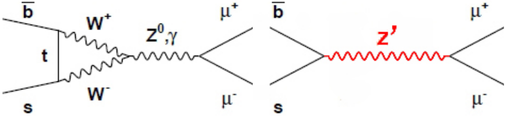
Model-independent approach restricted to $b \to s\gamma$ transitions

- Interpretation in terms of a particular NP model
- Accounting for pattern of results
- And complying with other constraints (in particular $\Delta F = 2$)

Hunting NP: model building

Model-independent approach restricted to $b \to s\gamma$ transitions

- Interpretation in terms of a particular NP model
- Accounting for pattern of results
- And complying with other constraints (in particular $\Delta F = 2$)



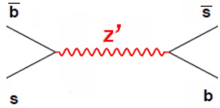
Which model for this pattern ? [from "Fermi" to "EW"]

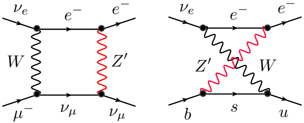
- Contribution to (real) C_9: FCNC coupling b and $s \propto V_{ts}^* V_{tb}$
- No contribution to $C_{S,P}$: vector meson (Z' style)
- No contribution to $C_{9'}$: coupling to left-handed b and s
- No contribution to $C_{10(')}$: vector coupling to muons

$\Longrightarrow$Not easy to account for in other models (susy, compositeness)

[D.Straub, W.Altmanshoffer]

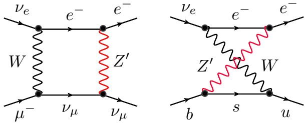
NP hunting: connecting $\Delta F = 1$ and $\Delta F = 2$





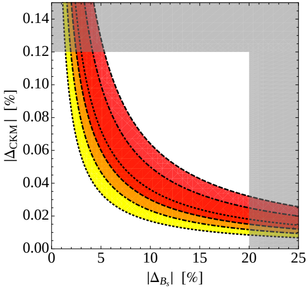
Such a Z' would also affect at least

- $B_s\bar{B}_s$ 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. . .]



Such a Z' would also affect at least

- $B_s\bar{B}_s$ 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 observables (depend on $M_{Z'}$ =1,3,10 TeV) OK with bounds [R. Gauld, F. Goertz, U. Haisch]
- Extended to Z' having FCNC bd and bs to reproduce $\Delta m_s/\Delta m_d$, other lepton couplings. . . $\Longrightarrow$more correls [e.g., $B_{d,s} \to \mu\mu$]

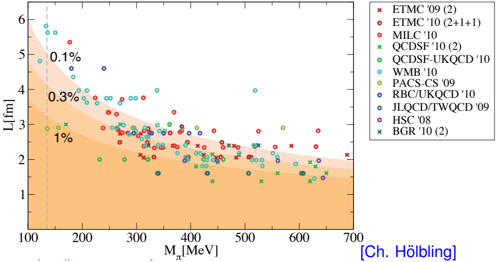
[A. Buras, J. Girrbach]

Prospective: recent improvements 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

Prospective: recent improvements 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

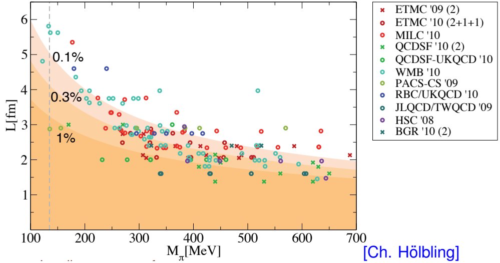


[Ch. Hölbling]

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

Prospective: recent improvements 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



[Ch. Hölbling]

- Most results already dominated by syst
- Saturation likely 1% for many qties (small syst neglected before...)
- 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	soon		

2018 USQCD predictions

Prospective: observables of interest

γ, $B \to \pi(\rho)\ell\nu$	Accurate tree-level SM
$B \to D(^*)\tau\nu$ vs $B \to D(^*)\ell\nu$, $B \to \ell\nu$	Charged Higgs
$B_{s,d} \to \ell\ell$	Higgs mediated FCNC
ϕ_s [CP-violation in B_s mixing]	New CPV mechanisms
$B \to K(^*)\ell\ell, B \to K(^*)\nu\bar{\nu}$ (and $\Lambda \to \Lambda_b$)	Non-standard FCNC
γ polarisation in $b \to s\gamma$	Right-handed currents
$K \to \pi\nu\bar{\nu}$	MFV
CP-violation in charm	Null test of SM in up sector
EDM	CPV in $\Delta F = 0$
Lepton Flav. Viol. ($\mu \to e\gamma$, $\tau \to 3\mu$)	Null test of SM in lepton sector

without mentioning all the neutrino phenomenology...

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

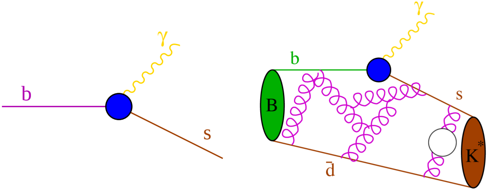
NP analyses in flavour with two successive steps

- Model-independent: focus on class of quark processes to constrain c/Λ^2 and operator structure [already NP flavour problem]
- Model-dependent: design model and connect it with other flavour constraints (and high-p_T if possible)
- Illustration with $\Delta F = 2$ (setting bounds) and $\Delta F = 1$ processes (model building)

Powerful tool to probe and constrain not ontly SM but also NP
if enough data from different sources to extract meaningful patterns

Back-up

Theoretical tools for QCD



$\langle K^*(k,\varepsilon)\bar{s}\gamma_\mu(1-\gamma_5)b|\bar{B}(p)\rangle$
$= \epsilon_{\mu\nu\rho\sigma} \times 2V(q^2)/(m_B+m_{K^*})$
$\quad -i\varepsilon^*_{K^*,\mu}(m_B+m_{K^*})A_1(q^2)+\ldots$

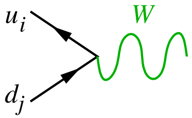
4 form factors
depending on γ virtuality

- lattice QCD (discretised version of the theory)
  - progress in computational power (1% accuracy in view)
  - access to final-state interactions for two meson states, start tackling unstable particles under strong interaction
- heavy-flavour effective theories
  - Expansion in Λ_{QCD}/m_b to exploit heavy-quark symmetry
  - Separation of soft (universal) and hard (process-dependent)
  - Simplification in terms of soft form factors (all $B \to K^*$: $7 \to 2$)
- sum rules
  - Duality between hadron and quark in specific energy range
  - Different energy window from lattice QCD
  - Difficult to assess corrections due to duality violations

Flavour and SM

Misalignment of up-type and down-type Yukawa couplings

$\Longrightarrow$ weak interaction not diagonal in mass eigenstates



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

unitary Cabibbo-Kobayashi-Maskawa matrix

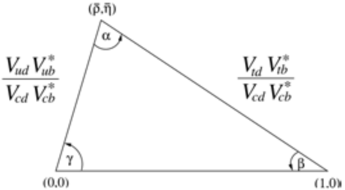
$$V = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \simeq \begin{bmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

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

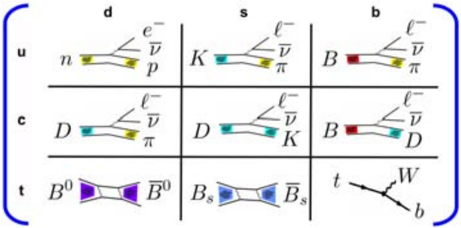
(small but non-squashed)

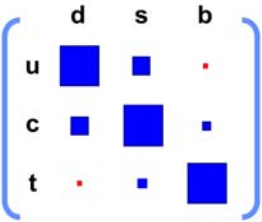
B-meson triangle (bd)

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



SM: Constraining the CKM matrix

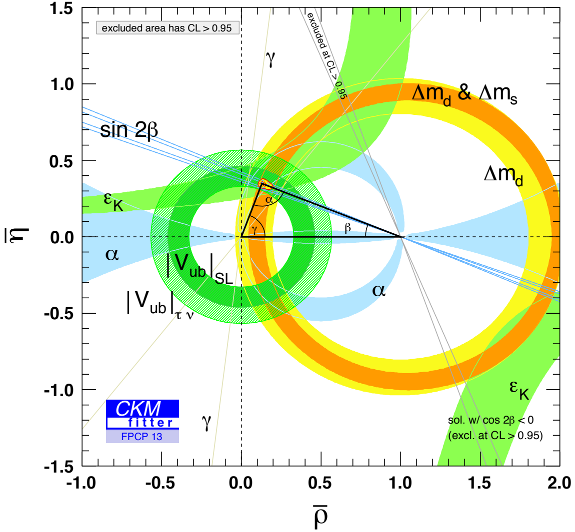
V = 



- CP-invariance of QCD to build hadronic-indep. CP-violating asym. or to determine hadronic inputs from data
- Lattice inputs (mostly) for CP-conserving quantities
- 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)

SM: The current status of CKM



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

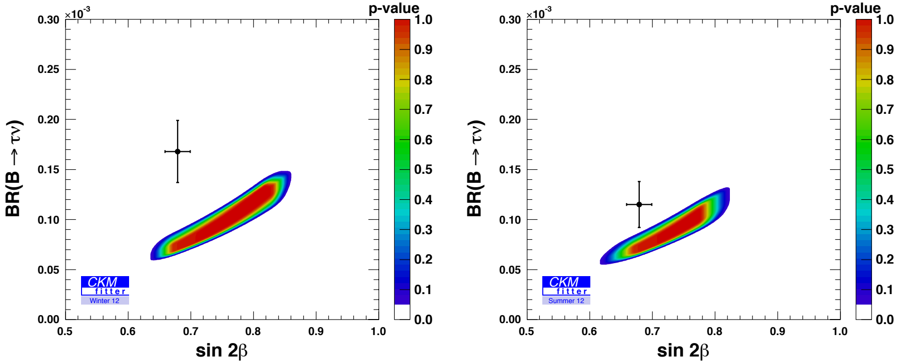
$B \to \tau\nu$

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

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

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

SM: A discrepancy dies away

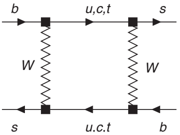


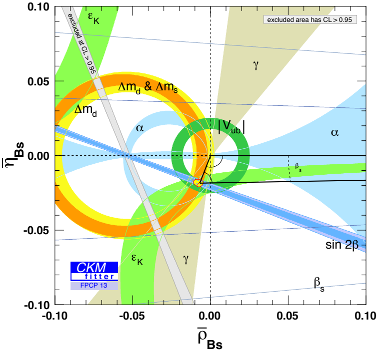
- There *used to be* a significant discrepancy for $B \to \tau\nu$ or $\sin(2\beta)$

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

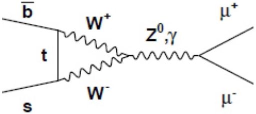
- New Belle result with hadronic tag for $Br(B \to \tau\nu)$ changing WA $(1.68 \pm 0.31) \cdot 10^{-3}$ [Moriond12] $\to$ $(1.15 \pm 0.23) \cdot 10^{-3}$ [ICHEP12]
- Brings pure QCD (no CKM) ratio $d\Gamma(B \to \pi\ell\nu)/dq^2/Br(B \to \tau\nu)$ closer to theoretical estimates (sum rules)

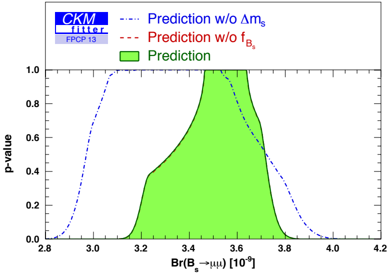
$\Delta F = 2$: B_s mixing





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





$$Br^{exp} = (3.2 \pm 1.0) \cdot 10^{-9}$$

$$Br^{th}_{SM} = (3.55^{+0.18}_{-0.34}) \cdot 10^{-9}$$

Agree well with SM, as probed by LHCb (B_s) and before, by B-factories

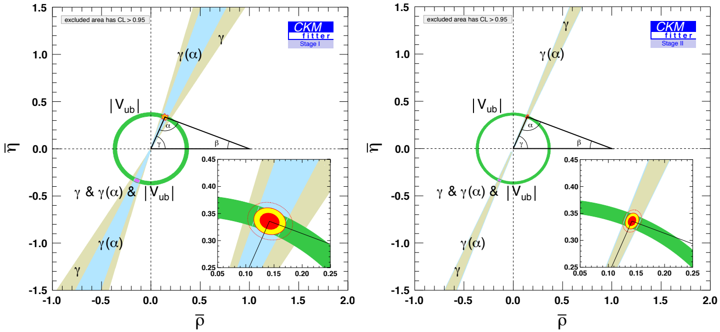
Setting bounds on NP in $\Delta F = 2$: Inputs

	2003	2013	Stage I	Stage II
$\|V_{ud}\|$	0.9738 ± 0.0004	$0.97425 \pm 0 \pm 0.00022$	id	id
$\|V_{us}\|$ $(K_{\ell 3})$	$0.2228 \pm 0.0039 \pm 0.0018$	$0.2258 \pm 0.0008 \pm 0.0010$	0.22494 ± 0.0006	id
$\|\epsilon_K\|$	$(2.282 \pm 0.017) \times 10^{-3}$	$(2.228 \pm 0.011) \times 10^{-3}$	id	id
Δm_d [ps^{-1}]	0.502 ± 0.006	0.507 ± 0.004	id	id
Δm_s [ps^{-1}]	> 14.5 [95% CL]	17.768 ± 0.024	id	id
$\|V_{cb}\| \times 10^3$	$41.6 \pm 0.58 \pm 0.8$	$41.15 \pm 0.33 \pm 0.59$	42.3 ± 0.4	42.3 ± 0.3
$\|V_{ub}\| \times 10^3$	$3.90 \pm 0.08 \pm 0.68$	$3.75 \pm 0.14 \pm 0.26$	3.56 ± 0.10	3.56 ± 0.08
$\sin 2\beta$	0.726 ± 0.037	0.679 ± 0.020	0.679 ± 0.016	0.679 ± 0.008
α (mod π)	—	$(85.4^{+4.0}_{-3.8})^\circ$	$(91.5 \pm 2)^\circ$	$(91.5 \pm 1)^\circ$
γ (mod π)	—	$(68.0^{+8.0}_{-8.5})^\circ$	$(67.1 \pm 4)^\circ$	$(67.1 \pm 1)^\circ$
β_s	—	-0.005 ± 0.035	0.0178 ± 0.012	0.0178 ± 0.004
$\mathcal{B}(B \to \tau\nu) \times 10^4$	—	1.15 ± 0.23	0.83 ± 0.10	0.83 ± 0.05
$\mathcal{B}(B \to \mu\nu) \times 10^7$	—	—	3.7 ± 0.9	3.7 ± 0.2
$A^d_{\mathrm{SL}} \times 10^4$	10 ± 140	23 ± 26	-7 ± 15	-7 ± 10
$A^s_{\mathrm{SL}} \times 10^4$	—	-22 ± 52	0.3 ± 6.0	0.3 ± 2.0
$\bar{m}_c$	$1.2 \pm 0 \pm 0.2$	$1.286 \pm 0.013 \pm 0.040$	1.286 ± 0.020	1.286 ± 0.010
$\bar{m}_t$	167.0 ± 5.0	$165.8 \pm 0.54 \pm 0.72$	id	id
$\alpha_s(m_Z)$	$0.1172 \pm 0 \pm 0.0020$	$0.1184 \pm 0 \pm 0.0007$	id	id
B_K	$0.86 \pm 0.06 \pm 0.14$	$0.7615 \pm 0.0026 \pm 0.0137$	0.774 ± 0.007	0.774 ± 0.004
f_{B_s} [GeV]	$0.217 \pm 0.012 \pm 0.011$	$0.2256 \pm 0.0012 \pm 0.0054$	0.232 ± 0.002	0.232 ± 0.001
B_{B_s}	1.37 ± 0.14	$1.326 \pm 0.016 \pm 0.040$	1.214 ± 0.060	1.214 ± 0.010
f_{B_s}/f_{B_d}	$1.21 \pm 0.05 \pm 0.01$	$1.198 \pm 0.008 \pm 0.025$	1.205 ± 0.010	1.205 ± 0.005
B_{B_s}/B_{B_d}	1.00 ± 0.02	$1.036 \pm 0.013 \pm 0.023$	1.055 ± 0.010	1.055 ± 0.005
$\tilde{B}_{B_s}/\tilde{B}_{B_d}$	—	$1.01 \pm 0 \pm 0.03$	1.03 ± 0.02	id
$\tilde{B}_{B_s}$	—	$0.91 \pm 0.03 \pm 0.12$	0.87 ± 0.06	id

[J. Charles et al.]

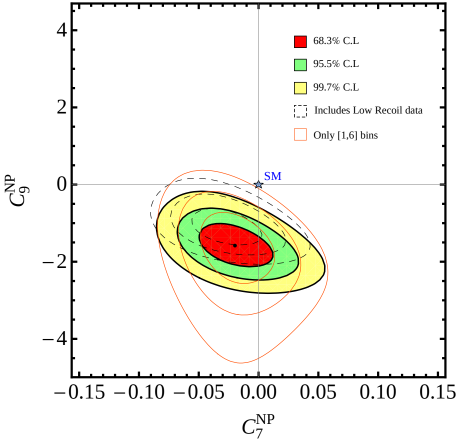
Setting bounds on NP in $\Delta F = 2$: CKM projections

- Stage I: 7 fb^{-1} LHCb data + 5 ab^{-1} Belle II
- Stage II: 50 fb^{-1} LHCb data + 50 ab^{-1} Belle II



[J. Charles et al.]

Hunting for NP in $\Delta F = 1$: Global fit to radiative



- $B \to K^* \mu\mu$: $P_1, P_2, P'_4, P'_5, P'_6, P'_8, A_{FB}, F_L$
- $B \to X_s\gamma$: Br
- $B \to X_s\mu^+\mu^-$: Br
- $B_s \to \mu\mu$: Br
- $B \to K^*\gamma$: A_I and $S_{K^*\gamma}$

with interesting results

- consistent pattern favouring $C_9 \simeq 2 \neq C_9^{SM} \simeq 4.1$
- $C_9^{SM} = 0$ discarded 3.9 σ

[SDG, J.Matias, J.Virto]

Other global fit with different binning and observables agrees with $C_9 \neq C_9^{SM}$ but favours also $C'_9 \neq 0$

[D.Straub, W.Altmanshoffer]