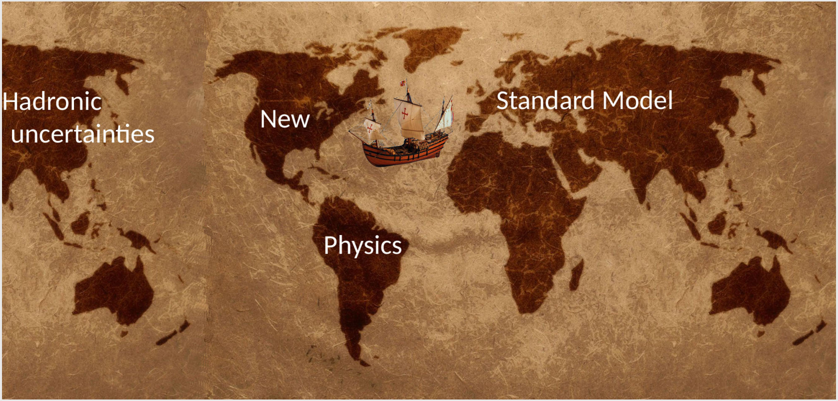
The quark flavor sector: from the Standard Model to New Physics



Jérôme Charles - Centre de Physique Théorique (Marseille)

21st IFT Xmas workshop, Madrid, 9-11 December 2015

In order to find New Physics, *i.e.* new particles and/or new interactions, one can perform *direct* or *indirect* searches.

Direct searches aim at producing new particles in colliders. However we have no clue how they look like (mass, lifetime . . .); and these searches are limited by the amount of available energy.
Indirect searches perform precision tests of SM transitions with SM particles, in order to detect deviations from theoretical predictions. However if a deviation is found there is no guarantee that it can be related to a given NP model. Furthermore *precision* tests mean both *precise* measurements and *precise* predictions.

Quark flavor physics belongs to the second category, with the specific challenge that we are interested in fundamental couplings of quarks, while we only see hadrons.

Hadronic matrix elements

To leading order of the weak interaction, one has

$$\langle f|H_{eff}|i\rangle \sim V_{CKM} \times \langle f|O|i\rangle$$

where the operators O can be further decomposed with the Operator Product Expansion from the weak scale

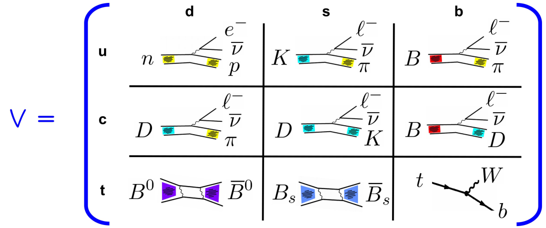
$$O \sim C_i(\mu)Q_i(\mu)$$

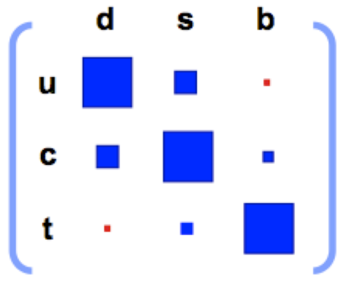
The $C_i(\mu)$ are renormalized Wilson coefficients that can be computed in terms of fundamental couplings in the SM and beyond, and the O_i are (renormalized) quark operators, the matrix elements of them have to be computed in QCD at low energy: they are genuinely non perturbative objects (decay constants, current form factors, non local matrix elements...). Alternatively they can be extracted from the data within a phenomenological analysis that relates different observables.

The Cabibbo-Kobayashi-Maskawa matrix

The CKM matrix parametrizes the quark flavor transitions. Its unitarity implies triangular relations in the complex plane of couplings, where a single phase describes CP violation in weak interactions.

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



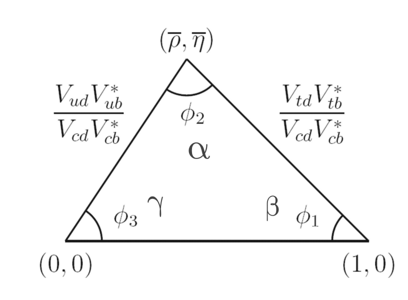


The Cabibbo-Kobayashi-Maskawa matrix

It has become standard to use the four Wolfenstein parameters A, λ and $(\bar{\rho}, \bar{\eta})$ to parametrize the CKM matrix. It happens that λ is small (~ 0.2) while the others can be considered $\mathcal{O}(1)$. The Unitarity Triangle in the B_d systems plays a special rôle because it is not flat (all sides $\sim \lambda^3$) and it can be overconstrained by independent phenomenological analyses.

$$\lambda^2 \equiv \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2} \qquad A^2\lambda^4 \equiv \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2}$$

$$\bar{\rho} + i\,\bar{\eta} \equiv -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$



The CKMfitter project

Perform global analyses within a consistent statistical framework to combine data and assess uncertainties.

Frequentist profile likelihood (χ^2-like) with a specific model for theoretical uncertainties, *R*fit. In this model the central value of a theoretical prediction is moved freely in a given uncertainty range.

Take as input flavor experimental data and associated theoretical predictions, with hadronic parameters taken from Lattice QCD wherever possible.

The 'moulinette' is a strongly optimized computer code, with a user/theorist *Mathematica* interface, and a Fortran kernel for numerical (minimization) calculations.

The people: 4/5 theorists, about 12 experimentalists (BaBar, Belle, LCHb, ATLAS); France, Germany, Switzerland, Japan, Australia.

The tools

CKMfitter has a modular structure:

- (Mathematica) theory packages, that defines 'observables' as a function of fit parameters; can exist in different versions (SM@NLO, SM@NNLO, MFV ...)
- (text) input datacards, that gather experimental and theoretical input values
- (text) analysis datacards, that defines tasks to be done by the fitter

about $\sim$ 25 packages, that cover leptonic and semileptonic decays, meson mixing, rare decays, charmless B decays ...

all results are available on `http://ckmfitter.in2p3.fr`

Coming soon: CKMlive web interface ! will allow users to perform personalized analyses (input/output) within predefined physics scenarios.

The inputs to the standard CKM analysis

V_{ud}	β decays	nuclear matrix elements
V_{us}	semi- and leptonic K decays	form factors
$V_{(u,c)b}$ (excl.)	semi- and leptonic B decays	form factors
$V_{(u,c)b}$ (incl.)	semileptonic $b \to u, c$ decays	matrix elements
$\lvert\varepsilon_K\rvert$	$K \to \pi\pi$, $\pi\pi\pi$	bag parameter
$\Delta m_{d,s}$	$B_{d,s}$ oscillations	decay and bag parameters
α, β, γ	CP asymmetries	-

time-dependent CP asymmetries are independent of hadronic matrix elements if only one CKM coupling appears in the amplitude: exact for some γ modes, excellent approximation for β, good for α assuming isospin symmetry

other inputs (quark masses, electroweak couplings ...) appear; some of them can be fixed

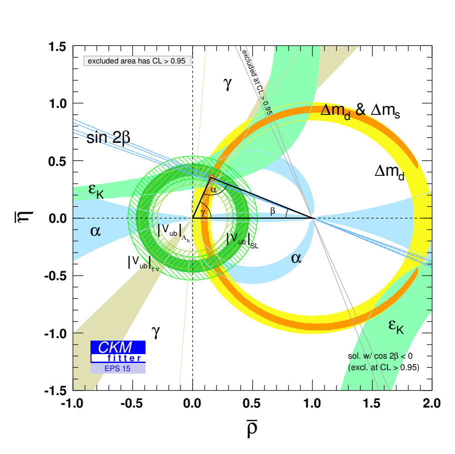
Theoretical uncertainties

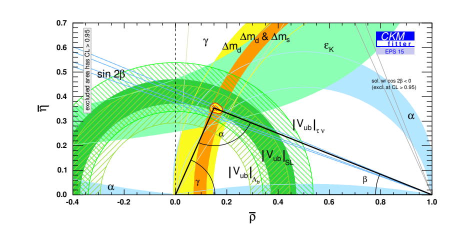
Theoretical uncertainties are unavoidable in global analyses, because almost all extraction of quarks couplings rely on the knowledge of hadronic matrix elements, that must be computed by non perturbative QCD techniques (Lattice QCD, sum rules, effective theories. . .).

CKMfitter uses a conservative model, *R*fit, where each theory uncertainty is modelled by a given bound of the associated parameter. It was set up at the time where all lattice simulations were quenched, and potentially plagued by sizable and out of control systematic effects.

Nowadays most lattice simulations for phenomenology use unquenched configurations, and careful error analyses lead to much better understood theory errors. On the phenomenology side, we are exploring a new technique that defines theory uncertainties as bias (*i.e.* what is left in the difference between the true value and the computed one, when statistics goes to infinity), that is typically more aggressive for metrology (measuring the value of SM parameters), and more conservative for NP searches (interpreting the $N\sigma$ anomalies).

The results





$$A = 0.8227^{+0.0066}_{-0.0136},\ \lambda = 0.22543^{+0.00042}_{-0.00031}$$

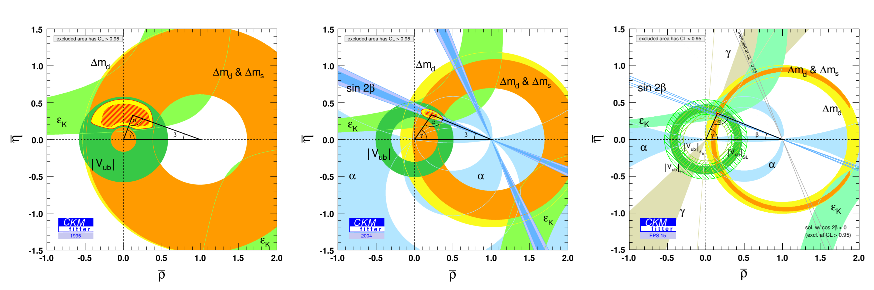
$$\bar\rho = 0.1504^{+0.0121}_{-0.0062},\ \bar\eta = 0.3540^{+0.0069}_{-0.0076}$$

nice agreement, at the few % level

more in Phys. Rev. D 91, 073007 (2015)

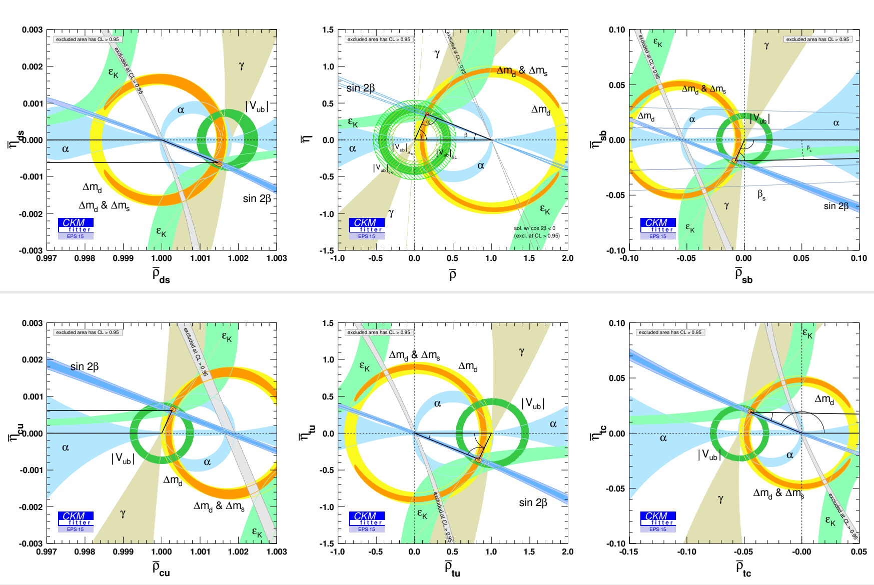
History of CKM analyses

1995, 2004, 2015

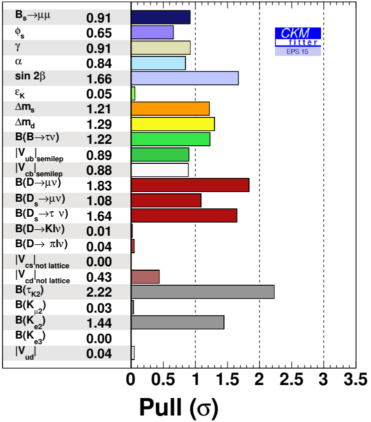


B-factories have consistently established the CKM paradigm as the main source of quark flavor transitions and weak CP violation: Nobel Prize to Kobayashi and Maskawa in 2008 !

Other unitarity triangles



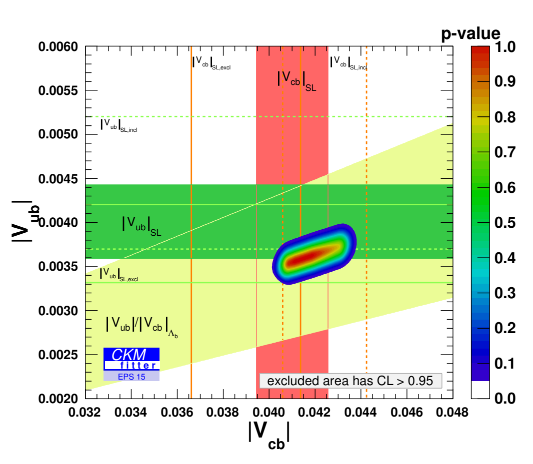
Consistency of the SM: pull values



no significant discrepancy

beware that many pull values are actually correlated

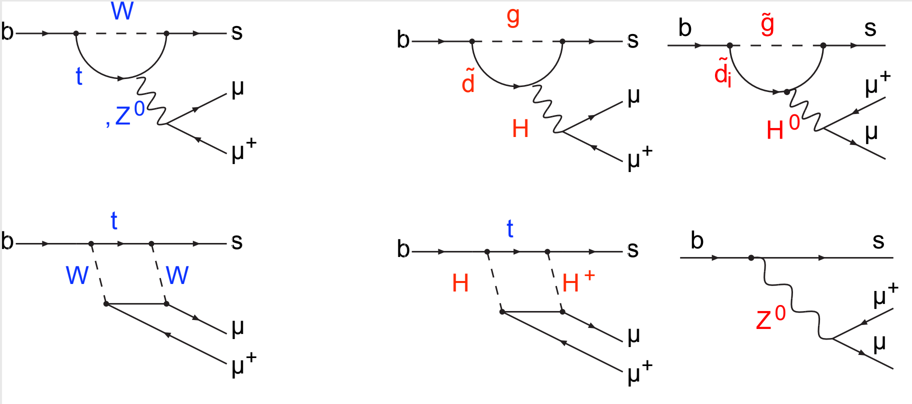
New measurement of $|V_{ub}/V_{cb}|$



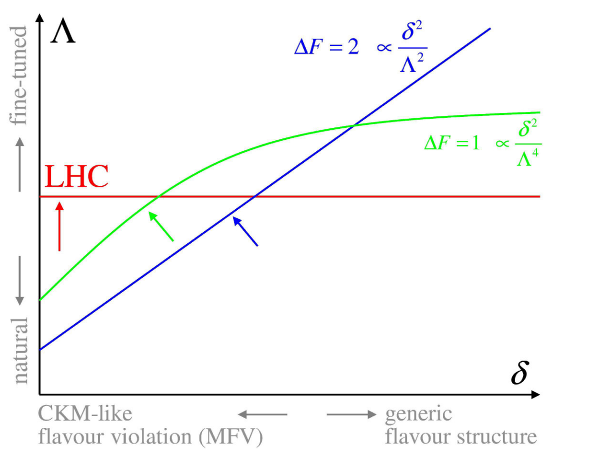
LHCb: $\Gamma(\Lambda_b \to p)/\Gamma(\Lambda_b \to \Lambda_c) = (1.00 \pm 0.04 \pm 0.08) \times 10^{-2}$
using baryonic SL form factors from LQCD, Detmold, Lehner and Meinel, arXiv:1503.01421

Virtual new particles

Of course the metrology of the CKM matrix is not the end of the story. The impressive overall agreement (at better than 10%) does not tell us everything about fundamental flavor structure. In particular an interesting question is whether new particles could contribue virtually to flavor transitions

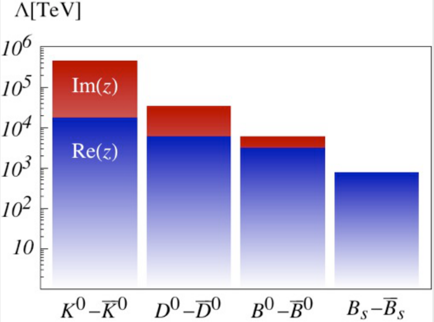


This allows to test New Physics in different directions of couplings δ and scales Λ, and provides a complementary insight with respect to direct searches



[Crivellin]

Because of the strong hierarchy of the CKM matrix ($\propto \lambda^n$), different meson mixing observables test very different NP scales [Kamenik]



The typically very large NP scales in flavor physics, compared to what is requested to solve the EW hierarchy (a few TeV), constitute the *flavor problem*. Two possibilities (that may coexist): either the NP is very far, and one needs to understand the EW fine-tuning, or the NP is at a "low" scale and it must exhibit a specific hierarchy in flavor couplings (as the SM).

In the last few years effort has been made to exploit flavor observables that could shed light on these issues.

Some ‘anomalies’ (w.r.t. to Standard Model expectations) related to these observables have been reported, mostly small ones but still very interesting and encouraging .

The $(\sin 2\beta, \mathcal{B}(B \to \tau\nu))$ correlation

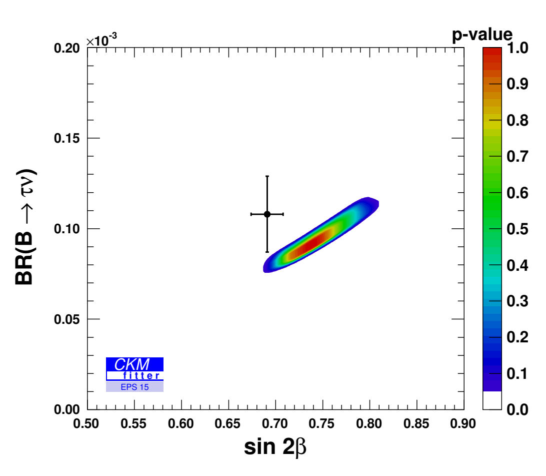
The correlation between these two observables in the global CKM fit allows a clean test of the SM prediction. A deviation larger than 3σ emerged in 2008, but progressively disappeared with new and better data, especially from Belle.

$$\frac{\mathrm{BR}(B \to \tau\nu)}{\Delta m_d} = \frac{3\pi}{4} \frac{m_\tau^2}{m_W^2 S(x_t)} \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 \tau_{B^+} \frac{1}{B_{B_d}} \frac{1}{|V_{ud}|^2} \left(\frac{\sin\beta}{\sin\gamma}\right)^2$$

where $B_{B_d} = 1.1262 \pm 0.083 \pm 0.081$ is the only source of theoretical uncertainty

The $(\sin 2\beta, \mathcal{B}(B \to \tau\nu))$ correlation

The fact that the deviation is mostly statistical and weakly dependent of hadronic matrix elements was successfully predicted by the global analysis.



Semileptonic asymmetries

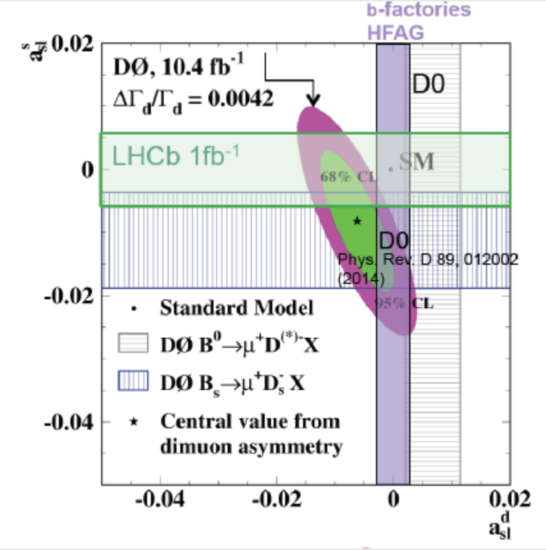
They are defined from the mixing Hamiltonian $H_{12} = M_{12} + i\Gamma_{12}$ with

$$a^q_{SL} = \mathrm{Im}\frac{\Gamma^q_{12}}{M^q_{12}}$$

In the B_d, B_s systems they are analogous to the (50 year old !) ε_K CP asymmetry. SM predicts they are small (Lenz and Nierste).

D0 measures a linear combination of these two observables that deviates by almost 4σ from the SM. However it is a semi-inclusive measurement for which it is still debated whether it is fed only by the semileptonic asymmetries. Flavor-specific measurements of a^q_{SL} by all experiments agree with the SM. Still, NP in $B\bar{B}$ mixing remains allowed at $30-40\%$ at 3σ

Semileptonic asymmetries



New Physics in B-$\overline{B}$ mixing

Independently of the flavor problem, the natural "to start with" choice is to assume that New Physics only contribute to FCNC

Then only a few new parameters are needed to describe neutral meson mixing, and other FCNC observables can be discarded from the inputs

In other words New Physics only enters M_{12} which is the real (dispersive) part of the mixing Hamiltonian

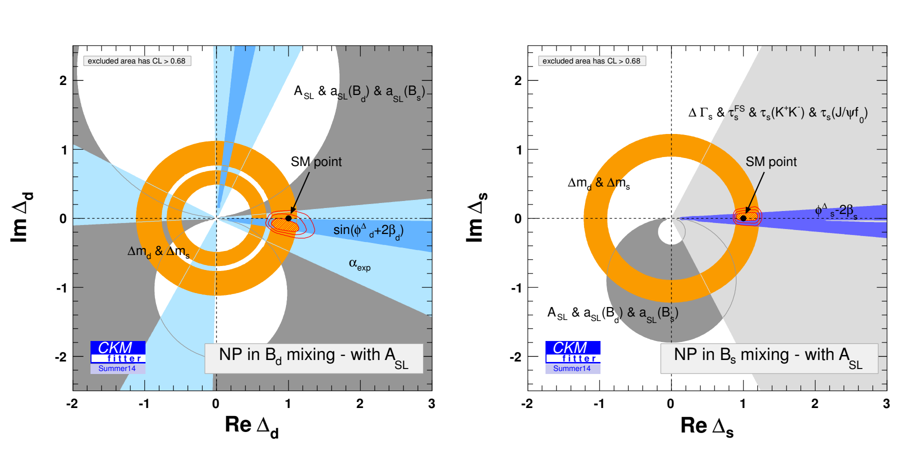
$$\left\langle B_q \left| \mathcal{H}_{\Delta B=2}^{\mathrm{SM+NP}} \right| \bar{B}_q \right\rangle \equiv \langle B_q \,|\, \mathcal{H}_{\Delta B=2}^{\mathrm{SM}} \,|\, \bar{B}_q \rangle \times (\mathrm{Re}(\Delta_q) + i\,\mathrm{Im}(\Delta_q))$$

SM is thus located at $\Delta_d = \Delta_s = 1$;

alternative parametrization $\Delta_q = (1 + h_q e^{2i\sigma_q})$.

Lenz, Nierste, CKMfitter (2010)

Constraints on Δ_d and Δ_s

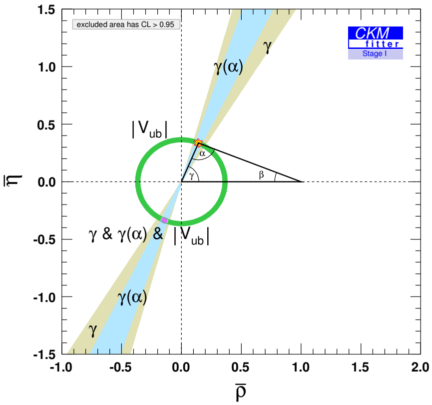


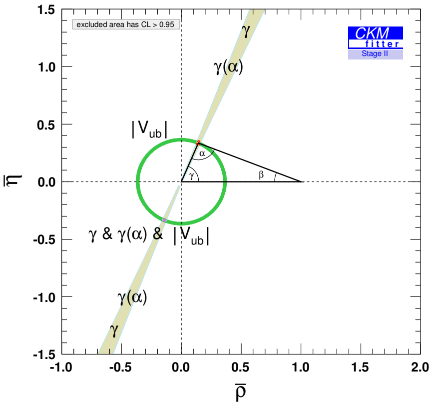
there is still room for New Physics at the 30% level

Prospective for B-$\overline{B}$ mixing: $(\bar{\rho}, \bar{\eta})$ plane

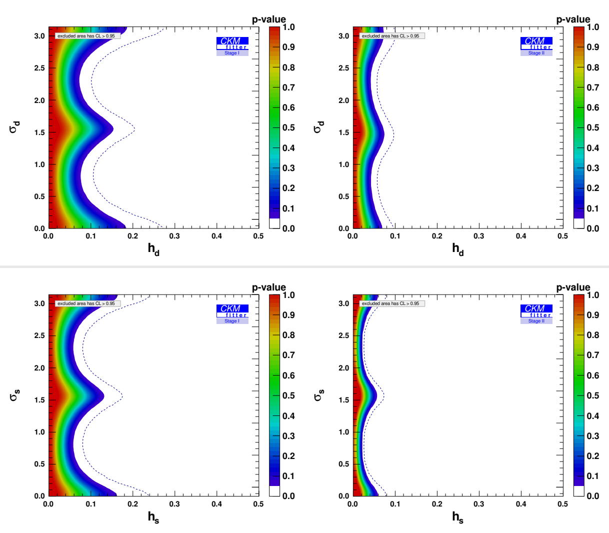
Stage I: 7 fb^{-1} LHCb and 5 ab^{-1} Belle II

Stage II: 50 fb^{-1} LHCb and 50 ab^{-1} Belle II





Prospective for B-$\overline{B}$ mixing: (h_q, σ_q) plane



New Physics exclusion scales

if no discrepancy is found

	NP order	scale (TeV) probed by B_d	B_s
CKM-like NP couplings	tree	17	19
CKM-like NP couplings	loop	1.4	1.5
$\mathcal{O}(1)$ NP couplings	tree	2000	500
$\mathcal{O}(1)$ NP couplings	loop	200	40

Ligeti, Papucci, CKMfitter (2013)

Semileptonic $B \to$ charm

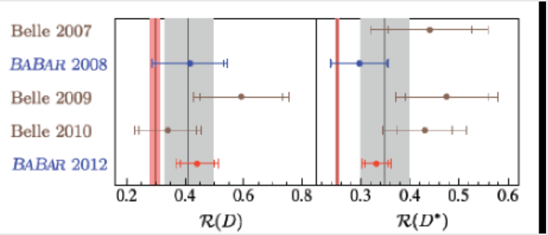
$B \to D^{(*)}\ell\nu$ and their inclusive partner decays are used to extract $|V_{cb}|$. There is a long-standing and unexplained 2-3σ discrepancy between the exclusive and inclusive determinations.

Recently, advanced experimental techniques have allowed to measure the ratios

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

that directly measures lepton universality. Hadronic form factors are computed on the lattice. Both BaBar and Belle measurements, and both D and $D^{(*)}$ modes deviate from the SM prediction; combined discrepancy is larger than 4σ...

Semileptonic $B \to$ charm



This issue has received a lot of attention (Crivellin et al., Buras et al., Becirevic et al., Tanaka et al. ...). Main message is that NP explanation is not easy: simplest models with additional Higgs go into the wrong direction.

There could be an underestimate of open charm background ($D^{(**)}$–like), that also could play a rôle in the $V|_{cb}|$ exclusive vs. inclusive discrepancy.

In any case lepton universality has been little tested in B-decays, and remains an interesting issue (more later).

The very rare $B_s \to \mu^+\mu^-$ decay

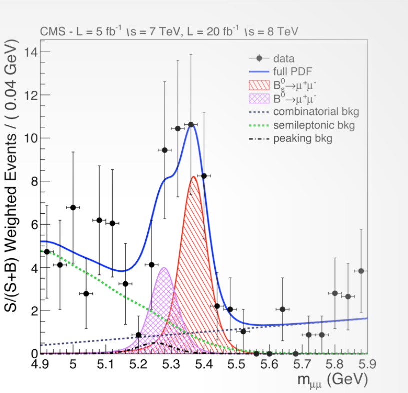
This is the rarest decay that comes with both a non trivial measurement and a non trivial theoretical prediction.

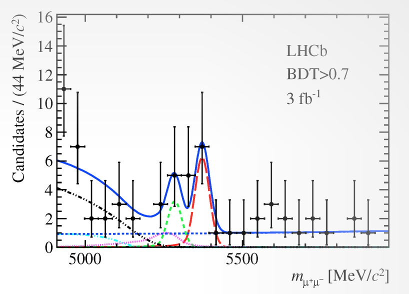
Hadronically, it only depends (even outside SM !) on the f_{B_s} decay constant that is well computed on the lattice. Perturbative contributions have been computed up to NLO-EW and NNLO-QCD (Buchalla *et al.*, Bobeth *et al.*, Hermann *et al.*) with the result

$$\mathcal{B}(B_s \to \mu\mu)_{\mathrm{theo}} = (3.34^{+0.13}_{-0.25}) \times 10^{-9}$$

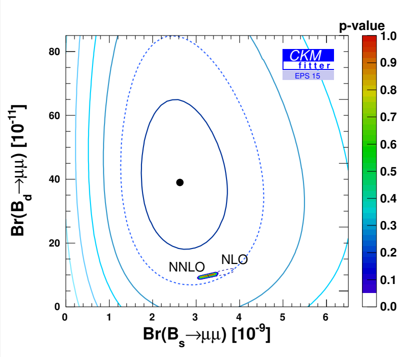
Both LHCb and CMS have found evidence for this decay, with the combined result

$$\mathcal{B}(B_s \to \mu\mu)_{\rm exp} = (2.9 \pm 0.7) \times 10^{-9}$$





Since $\mathcal{B}(B_s \to \mu\mu)_{\text{SUSY}} \sim \tan\beta^6$, the excellent agreement of this measurement with the SM is a true challenge ! Also the ratio to the B_d mode will put very clean and stringent constraints on NP scenarios.



However the parameter space is so big in many NP models that one needs further observables to get more insight.

$B \to K^* \mu\mu$

Being a 3-body decay with non trivial spins, the decay $B \to K^* \mu\mu$ is much richer than $B_s \to \mu\mu$. It is also much more complicated to predict, as the hadronic matrix elements of weak currents involve many form factors that need to be computed on the lattice or extracted from the data.

Furthermore there are also contributions from 4-quark operators that do no reduce to form factors.

Fortunately both in the small recoil (large q^2, Isgur and Wise) and in the large recoil (small q^2, JC *et al.*, Beneke *et al.*) regions, symmetry and scaling relations between form factors emerge. Also the leading power contribution from 4-quarks operators can be computed at small recoil by means of the OPE (Grinstein *et al.*) and at large recoil by means of QCDF/SCET (Beneke *et al.*, Bauer *et al.*). In particular dimensionless observables can be reliably predicted, and experimentally extracted from an angular analysis.

$B \to K^*\mu\mu$

A lot of activity in the last years have been devoted to design optimized observables, by taking specific combinations of the original ones in which the residual dependence to the hadronic form factors is reduced.

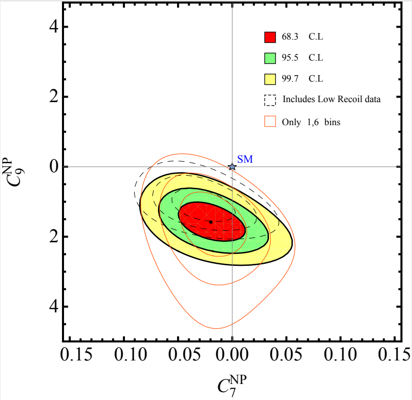
$$\frac{d\Gamma}{dq^2 d\cos\theta^* d\cos\theta_\ell d\phi} \sim J_i(q^2)\Omega_i(\cos\theta^*, \cos\theta_\ell, \phi)$$

$$J_i \to P_i, P_i'$$

The uncertainties that remain to evaluate are: residual form factor dependence, power corrections (part of them are factorizable and calculable), and long distance contributions from $c\bar{c}$ loops.

Global analysis

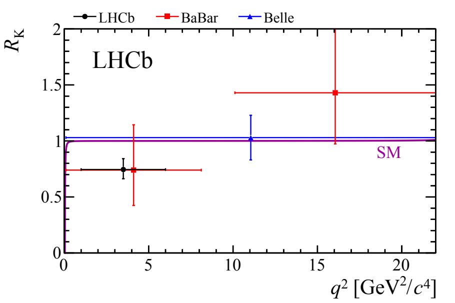
In 2013 a theory vs. data discrepancy emerged for the 'clean' angular observable P_5' (3-4σ) and global analyses showed a consistent picture when New Physics enters into (at least) C_9 Wilson coefficient



[Descotes-Genon *et al.*]

The situation in 2015

better data (LHCb)
updated theory predictions
more robust treatment of uncertainties
new observable: R_K. The ratio $d\Gamma(B \to K\mu\mu)/d\Gamma(B \to Kee)$ is another test of lepton universality (prediction is 1). It has been measured by LHCb and deviates from the prediction by 2.6σ



Updated global analysis

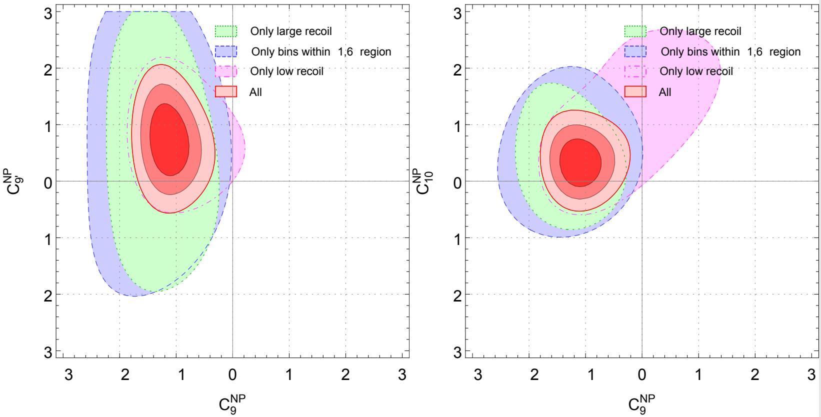
Descotes *et al.* performed an extensive analysis of rare B decays, with a detailed discussion of all issues related to hadronic uncertainties

They find that data ask for a New Physics contribution to $C_9^{\mu\mu}$: adding only the corresponding parameter to the fit improves it by 4.9σ !

One reaches the 5σ value in the $C_9 = -C_9'$, $C_{10} = C_{10}'$ NP scenario

They claim that the simplest explanation is the NP one: all explanations based on hadronic uncertainties need, in addition, a certain amount of data statistical fluctuations

Consistency between different sets of observables



[Descotes-Genon *et al.*]

Discussion

Other groups (Altmannshofer *et al.*, Beaujean *et al.*, Jaeger and Camalich . . .) agree on the main results, but not necessarily on the uncertainties and thus the size of the global anomaly

Since C_9 is the dominant effect, non perturbative $c\bar{c}$ contribution is the natural SM 'pollution', but the only existing estimate (based on light-cone sum rules, Khodjamirian *et al.* 2010) does not have the requested (constant) q^2 dependence, and goes into the wrong direction; in addition this effect cancels in the ratio R_K

Such a large effect emerging from a global fit (the individual pulls for each observable do not exceed $\sim 3\sigma$) is very intriguing: even if it' s not New Physics, it's something we completely missed

Lepton universality/flavor violation

In view of the anomalies in $D^{(*)}\tau\nu$, $K*\mu\mu$ and Kee a lot of activity is ongoing on lepton universality/flavor violation.

A hot issue is whether NP could finally show up in couplings of quarks to leptons, with non trivial lepton-flavor dependent effects; new gauge bosons and leptoquarks are typical examples of such scenarios.

Recent articles use explicit dynamical models (that allow correlations with direct NP searches, typically Z'- or leptoquark-type mediators), or effective theory approaches (that are more general, but less predictive).

Many models/scenarios that are designed to accommodate present anomalies predict sizable (or even huge) effects in rare B decays to final states with τ leptons, especially if the third generation of fermions has specifically large couplings to New Physics.

$B_s \to \tau\tau$ and $B \to K^*\tau\tau$ challenges

τ leptons are notoriously difficult to measure because of at least one neutrino (per τ) escapes detection.

LHCb follows the $\tau \to (3\pi)\nu$ strategy (already used in $D^*\tau\nu$) because the three charged tracks and the decay vertex allow a better discrimination against the background (mainly composed of $D_{(s)}$ decays, that look very similar to the τ) (CPPM/CPT exp/theo collaboration in Marseille).

On the theory side the issues are also very interesting: τ final states are richer than their e/μ counterpart, thanks to the sizable lepton mass and the sensitivity to non trivial lepton-spin correlations among the decay products.

Also $B \to K^*\tau\tau$ is dominated by the low recoil region, in contrast to $\mu\mu/ee$.

Next generation experiments (FCC-ee), together with theory progress, may lead to a genuinely new bunch of B physics observables.

Conclusion

B factories have established flavor physics, and especially B system, as a precision field of the Standard Model tests.

The metrology of the CKM matrix is successful, but first measurements of rare and very rare decays show intriguing anomalies w.r.t. SM predictions, although typically smaller that what was expected (hoped).

This picture is consistent with direct searches that haven't found non standard particles.

If New Physics is far away and/or weakly coupled to SM, flavor physics is an instrumental tool to understand its fundamental structure.

Future: Belle II (almost two orders of magnitude more data), LHCb upgrade ($\times 6$), next generation colliders...; in parallel lattice calculations should reach the $\sim 1\%$ level for many crucial parameters.

Advertisement