Critical review of B-meson anomalies

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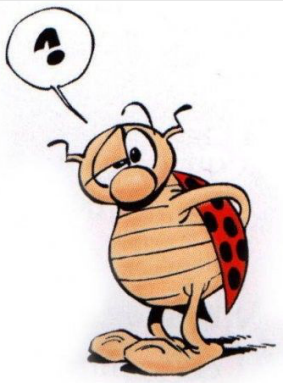
What is happening



Gotlib [1934-2016]

In the last two years three anomalies (wrt Standard Model predictions) in B decay observables have received a lot of attention.

These are:

The lepton universality test ratios $R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)}$ (global combination more than 4σ away from SM).

Various (in particular angular) observables of exclusive $b \to s\mu\mu$ decays, with K, K^* and ϕ in the final state (many SM pull values larger than 2-3σ).

The lepton universality test ratios $R(K^{(*)}) = \frac{\mathcal{B}_{\rm bin}(B \to K^{(*)}\mu\mu)}{\mathcal{B}_{\rm bin}(B \to K^{(*)}ee)}$ (3-4σ away from SM).

In particular the last two sets can be combined in a global analysis that leads to a more than 5σ effect in Wilson coefficient C_9.

Questions

Statistical fluctuations ?

Experimental issues ?

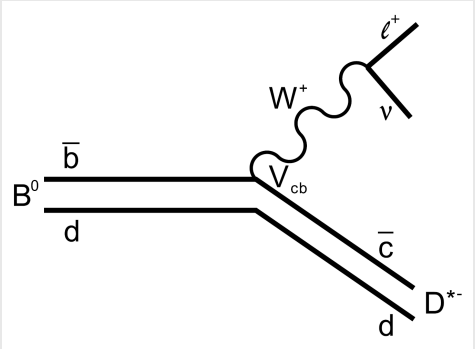
Hadronic and/or perturbative theory issues ?

New Physics ?

I will try to at least kill the first possibility. . .

Semileptonic $B \to D^{(*)}$ decays

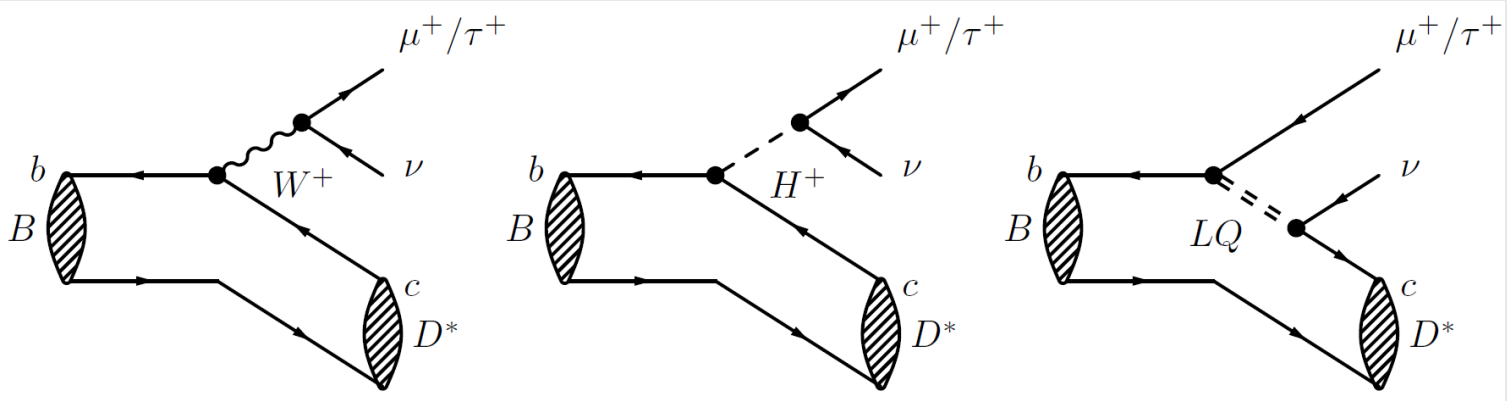
In the SM, semileptonic $B \to D^{(*)}\ell\nu_\ell$ decays are mediated by $V-A$ charged weak current: the only matrix elements that appear are heavy-to-heavy form factors, that are tightly constrained by heavy quark symmetry and can be computed in Lattice QCD. At leading order in the weak interaction, and neglecting QED corrections, no other hadronic quantity plays a rôle.



On the experimental side one benefits from large rates ($|V_{cb}|$ is the main coupling to the b quark) and good efficiency for electron and muon channels. Tauonic modes are significantly more difficult.

Main observables are integrated branching ratios, but there are also measurements of differential observables that are sensitive to D^* and/or τ polarization and thus to the detailed structure of the weak current.

Heavy-to-heavy form factors



Whatever the mediator, the hadronic part is a matrix element of a two quark current

$$\langle D^{(*)}|\bar{c}\Gamma b|B\rangle$$

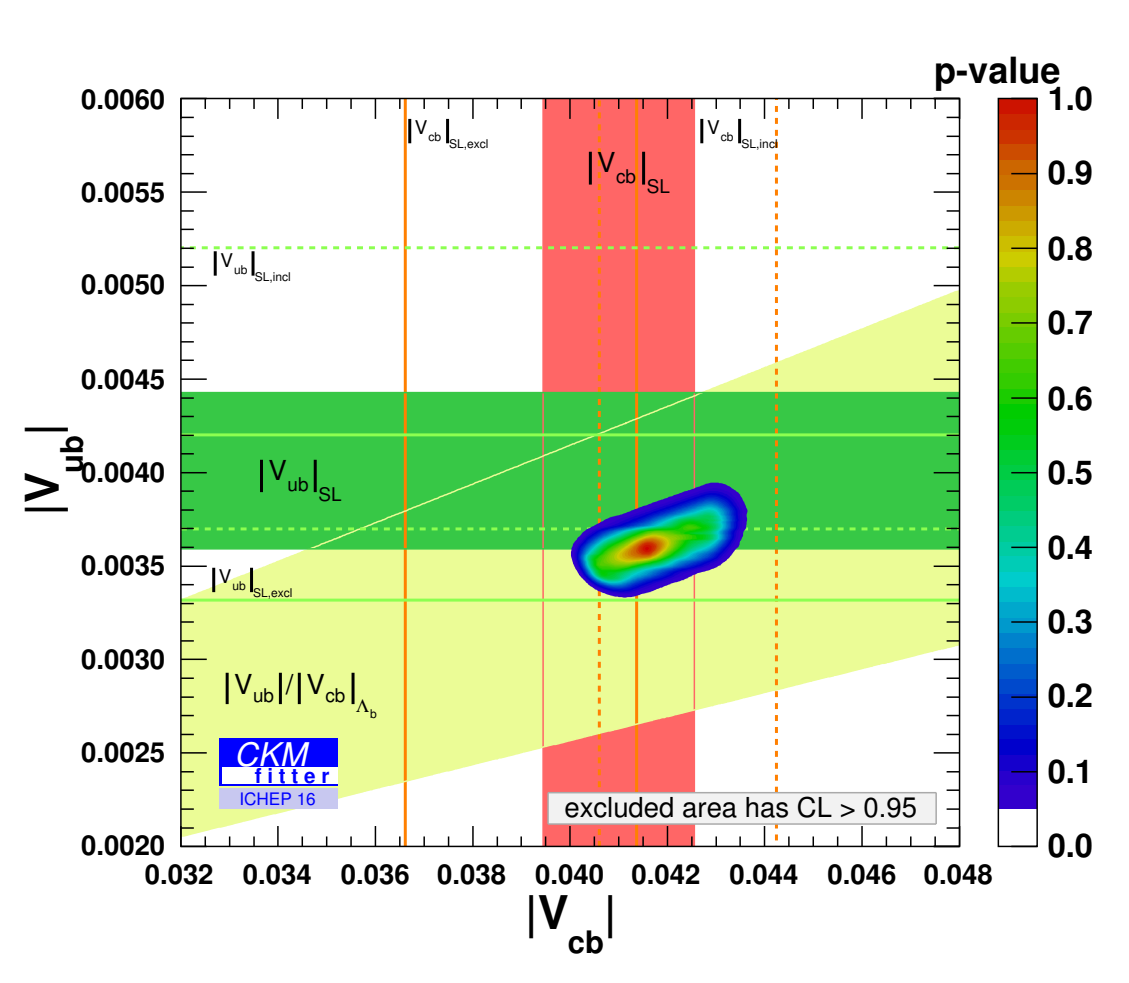
Heavy quark symmetry, in the $m_{b,c} \to \infty$ limit, essentially predicts that D, D^* and B are the same state: hence the matrix element is fully described by a single elastic form factor $\xi(w)$, $w = v_B \cdot v_D$, that is normalized at zero recoil $\xi(1) = 1$ [Isgur and Wise '89,'90] ($w \leftrightarrow q^2$, the lepton invariant mass). Hence in principle in the heavy quark limit $|V_{cb}|$ can be extracted from the measurement of the zero recoil rate without any input from QCD calculations !

The extraction of $|V_{cb}|$

In practice one needs to control the corrections to the heavy mass limit to reach an accuracy of a few %. Form factors are calculated in LQCD, with the help of heavy quark expansion to extrapolate to the physical b mass.
Conformal z-expansion is used to fit LQCD and get access to the full q^2 (or w) range.
However there has been a long standing 3σ discrepancy between the value of $|V_{cb}|$ extracted from the exclusive $D^{(*)}$ channels as above, and the one from the inclusive $b \to c$ decay rate, that relies on completely different techniques (OPE based analytical calculation).
It has been shown recently [Bigi *et al.*. '17, Grinstein & Kobach '17] that two different versions of the z-expansion do not agree: the original one [Boyd *et al.*'95] gives $|V_{cb}| = (41.7^{+2.0}_{-2.1}) \times 10^{-3}$, $(41.9^{+2.0}_{-1.9}) \times 10^{-3}$, in agreement with the inclusive value, while the one that uses in addition HQS constraints [Caprini *et al.*'98] gives $(37.4 \pm 1.3) \times 10^{-3}$.
Possible interpretation: corrections to the heavy mass limit in the CLN approach are underestimated.

$|V_{cb}|$ and CKM matrix

Nevertheless $|V_{cb}|$ is the most precisely known short-distance quantity in the B meson sector



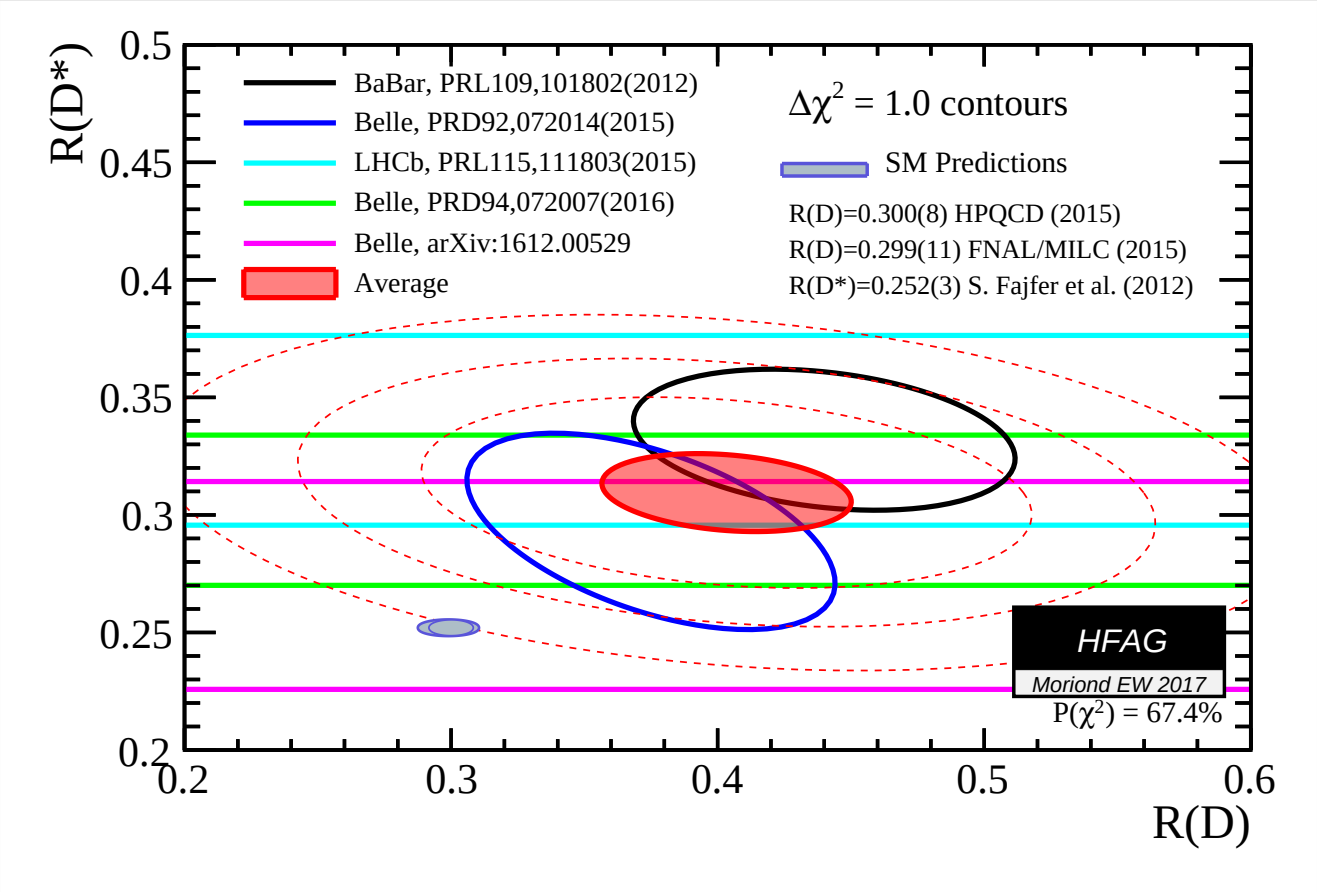
Lepton universality: $R(D)$ and $R(D^*)$

First measurement of

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

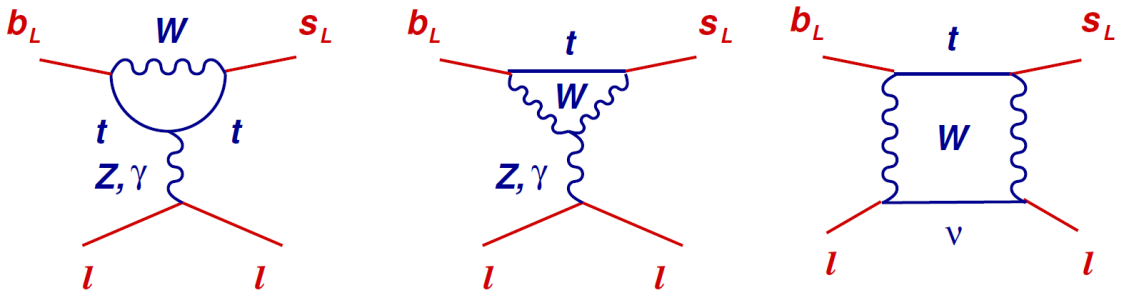
by BaBar in 2012. Dependence to form factors is much reduced in these ratios, which allows a test of the universality of lepton couplings to quarks (a quite accidental prediction of the Standard Model). Note however that $R(D^*)$ has a $\sim 10\%$ dependence on the pseudoscalar form factor F_2 that have not yet been calculated in LQCD (use HQS instead).
On the experimental side the measurement is challenging, because of missing energy in τ decay: excited D states constitute a significant background to the tauonic mode, especially at hadron colliders (LHCb).
On the theoretical side the $|V_{cb}|$ issue (parametrization of z or q^2 dependence) has not been explored; but it is naively expected to play a minor rôle in the R ratios.

World summary of $R(D)$ and $R(D^*)$



Full combination is more than 4σ away from the SM prediction (precise value depends a bit on the treatment of form factors)

Flavor changing neutral currents: $B \to K^{(*)}\ell\ell$



These are significantly more complicated but leading contributions still come from matrix elements of operators with only two quarks

$$\langle K^{(*)}|\bar{s}\Gamma b|B\rangle$$

Subleading contributions come from 4-quark operators where two quarks are contracted together: a long distance matrix element

$$\int d^4x\, e^{-iq\cdot x}\, \langle K^{(*)}|(\bar{s}\Gamma b\bar{q}\Gamma' q)(x)(\bar{q}\gamma_\mu q)(0)|B\rangle$$

Effective Hamiltonian

For $\Lambda_{\rm EW,NP} \gg m_b$: $$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i(\mu) O_i(\mu)$$

$$\begin{aligned} O_7 &= \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu} \\ O_9 &= \frac{\alpha}{4\pi} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell) \\ O_{10} &= \frac{\alpha}{4\pi} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell) \end{aligned}$$

$$\begin{aligned} O_1 &= (\bar{c}\gamma_\mu P_L b)(\bar{s}\gamma^\mu P_L c) \\ O_2 &= (\bar{c}\gamma_\mu P_L T^a b)(\bar{s}\gamma^\mu P_L T^a c) \end{aligned}$$

SM contributions to $C_i(\mu_b)$ have been computed to NNLL [Bobeth *et al.* '99; Misiak *et al.* '04; Gorbahn *et al.*, '04,'05; Czakon *et al.* '06]

$C_{7,\rm eff} = -0.3,\ C_9 = 4.1,\ C_{10} = -4.3,\ C_1 = 1.1,\ C_2 = -0.4$

other operators have Wilson coefficients smaller than 10^{-2} in the SM; primed operators ($P_L \leftrightarrow P_R$) generically appear in NP scenarios.

Heavy-to-light form factors

Heavy quark symmetry alone does not constrain much $B \to K^{(*)}$ matrix elements. However one can perform a combined $m_b \to \infty$ and $E \to \infty$ expansion, where E is the energy of the final meson in the B rest frame,

$$E = v_b \cdot p_K = (m_B/2)(1 - q^2/mB^2)$$

(E large $\Leftrightarrow q^2 \sim \Lambda^2$ or $q^2 \sim m_B\Lambda$): in this limit the 3 (for $B \to K$) +7 (for $B \to K^*$) form factors reduce to three independent ζ, $\zeta_\perp$, $\zeta_\parallel$ 'soft' form factors, that obey well-defined scaling laws in E [JC *et al.*'99].

For example

$$f_0(q^2) \sim (1 - q^2/mB^2) f_+(q^2) \sim (1 - q^2/mB^2)\zeta(E)$$

with $\zeta(E) \sim 1/E^2$.

Effective field theory implementation: Soft-Collinear Effective Theory [Bauer *et al.*. '00,'01]

Heavy-to-light form factors

The SCET limit is best used in the moderate to large recoil region, $q^2 \sim m_B \Lambda$ ($q^2 \sim \Lambda^2$ region is plagued by the contribution of light resonances from 4-quark operators), where LQCD has no access. Residual form factor dependence is computed with Light-Cone Sum Rules, with an irreducible 5-10% model uncertainty.

In the low recoil region $q^2 \sim m_B^2$, SCET does not apply. However in this region the form factors can be computed directly on the lattice. Caveat: K^* resonance is difficult to access in unquenched LQCD.

Contribution from 4-quark operators

Leading contribution from 4-quark operators is purely perturbative: the 'free' quark loop can be absorbed into a redefinition of $C_9 \to C_{9,\mathrm{eff}}$.

Hard gluon corrections can be computed, at leading order in $1/m_b$ by QCD factorization techniques (or equivalently, SCET).

Soft gluon corrections are much more challenging. Using LCSR they can be estimated to a $\sim 10\%$ level contribution to C_9 [Khodjamirian *et al.*'10,'12], with a somewhat uncontrolled uncertainty. This is the most debated issue !

Optimized observables

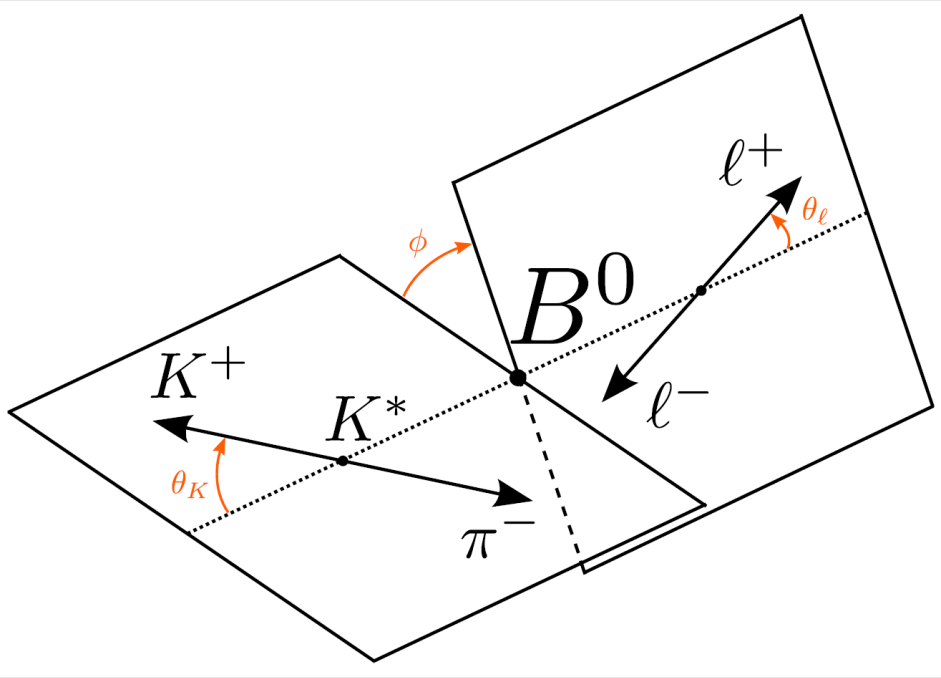
Assuming the contribution of 4-quark operators to be not anomalously large, independent amplitude combinations are related to each other thanks to SCET form factor relations.

This allows the construction of 'optimized' observable ratios, that are asymptotically independent of form factors. First one was the forward-backward asymmetry [Ali *et al.*'00].

This can be made very general, by taking appropriate ratios of angular observables.

$B \to K^{(*)}\ell\ell$ angular observables

Experiments can measure
4-dimensional distribution

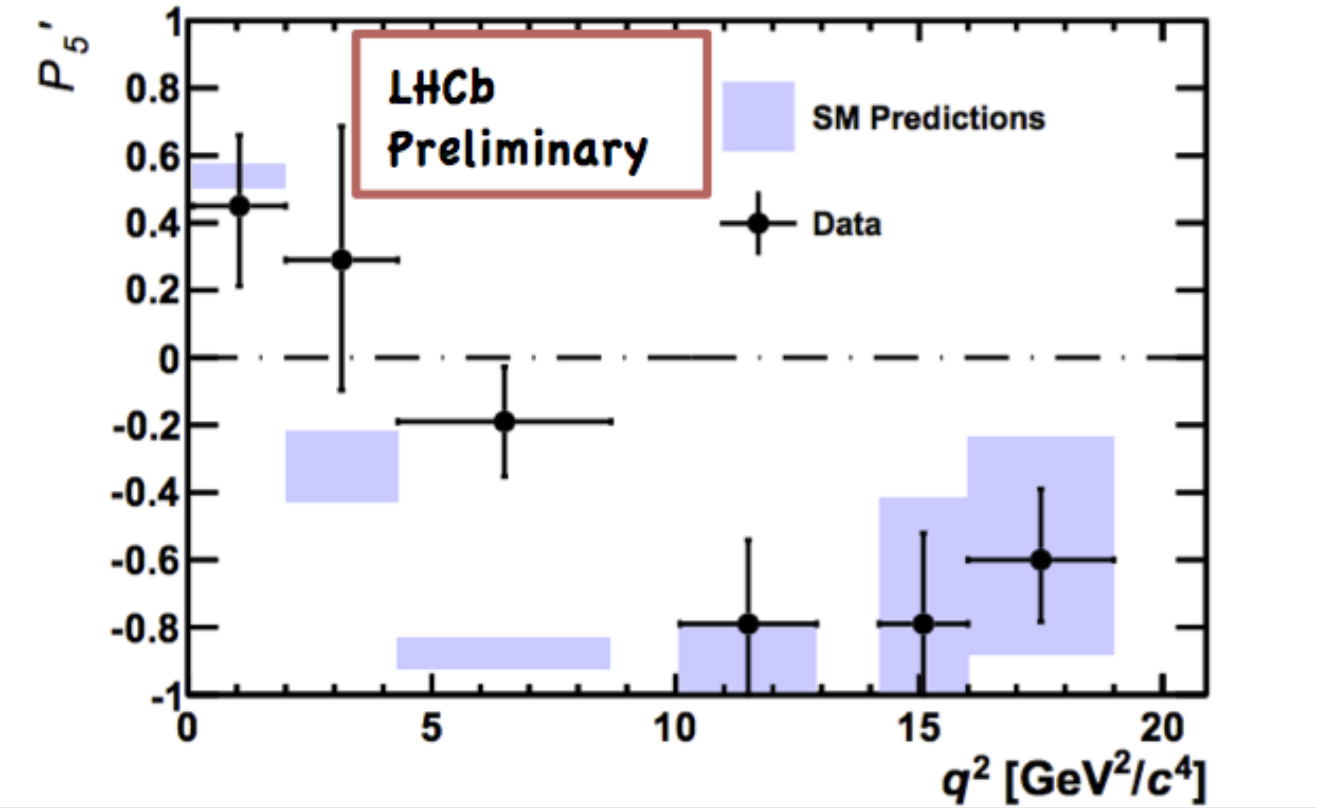


$$\frac{d^4\Gamma}{dq^2 d\cos\theta_{K^*} d\cos\theta_\ell d\phi} \sim \sum_i I_i f_i(\Phi)$$

where the linear coefficients I_i are angular observables that can be expressed in terms of $B \to K^*$ matrix elements.

Products and ratios of $I_i \Rightarrow P_j^{(\prime)}$ 'optimized' observables that are independent of form factors in the SCET limit [Krüger *et al.*'12, Descotes-Genon *et al.*'12].

Experimental results



First significant tension: 2-3σ in third bin of P_5' (LHCb '13)

This was the motivation for more sophisticated global analyses [Altmannshofer *et al.*, Descotes-Genon *et al.*, Bobeth *et al.*, Camalich *et al.*, Hurth *et al.*, Ciuchini *et al.*] and refined measurements (LHCb, Belle, Atlas, CMS).

Global analyses

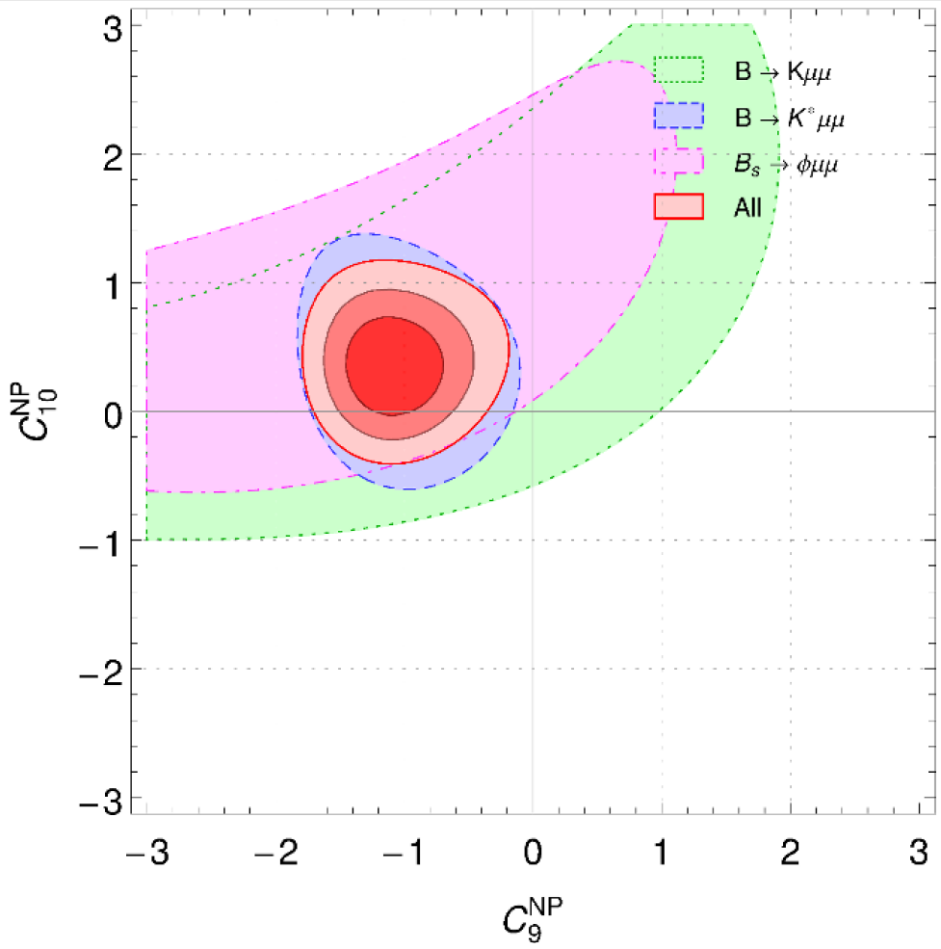
The idea: plug-in as many $b \to s$ observables as possible, and fit for the Wilson coefficients (or their deviation wrt the SM values). There are up to ~ 200 observables ! They are in principle independent, but technicalities induce (known) correlations.

Now it is even possible to fit simultaneously for several Wilson coefficients: the hope is that it would bring insight on possible New Physics contributions, if any.

A common feature of all these analyses: several observables request a negative NP contribution to C_9: $\Delta C_9 \sim -1$ (25% of the SM value). Other Wilson coefficients may be modified too, but the fit is good only if C_9 deviates from its SM value.

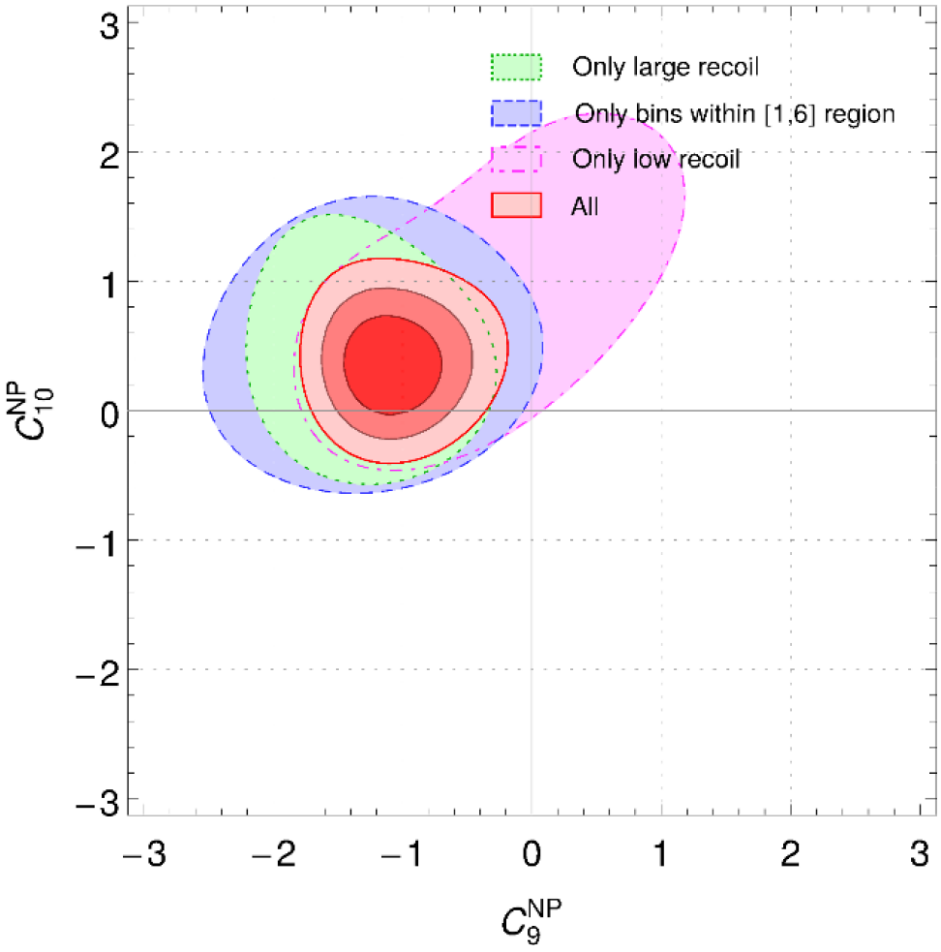
Most complete analysis [Descotes-Genon *et al.*'15]: the statistical pull for the $6D$ hypothesis $C_{7,9,10}^{(\prime)}$ =SM is 5σ. The 1D hypothesis C_9 =SM hypothesis is excluded at the 5.7σ level.

Global analyses: the rôle of different channels



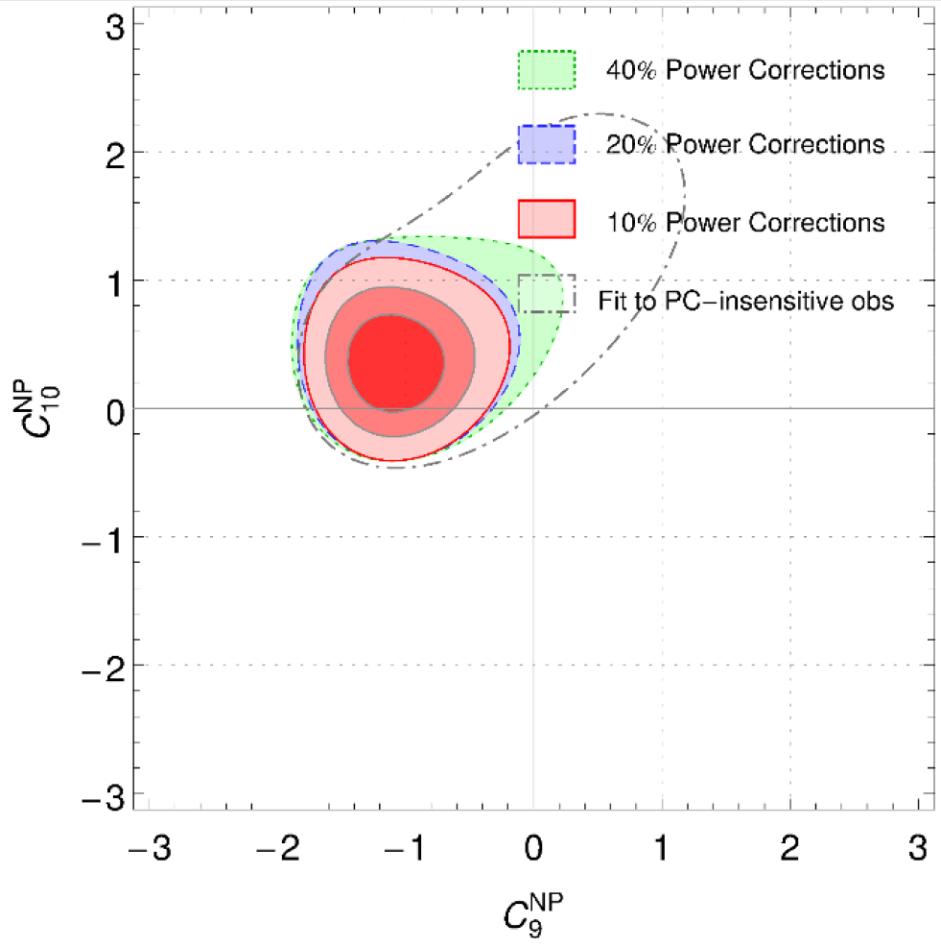
excellent consistency between the different channels

Global analyses: low vs. large recoil



large q^2 regions is less constraining but compatible with low q^2 one

Global analyses: the rôle of power corrections



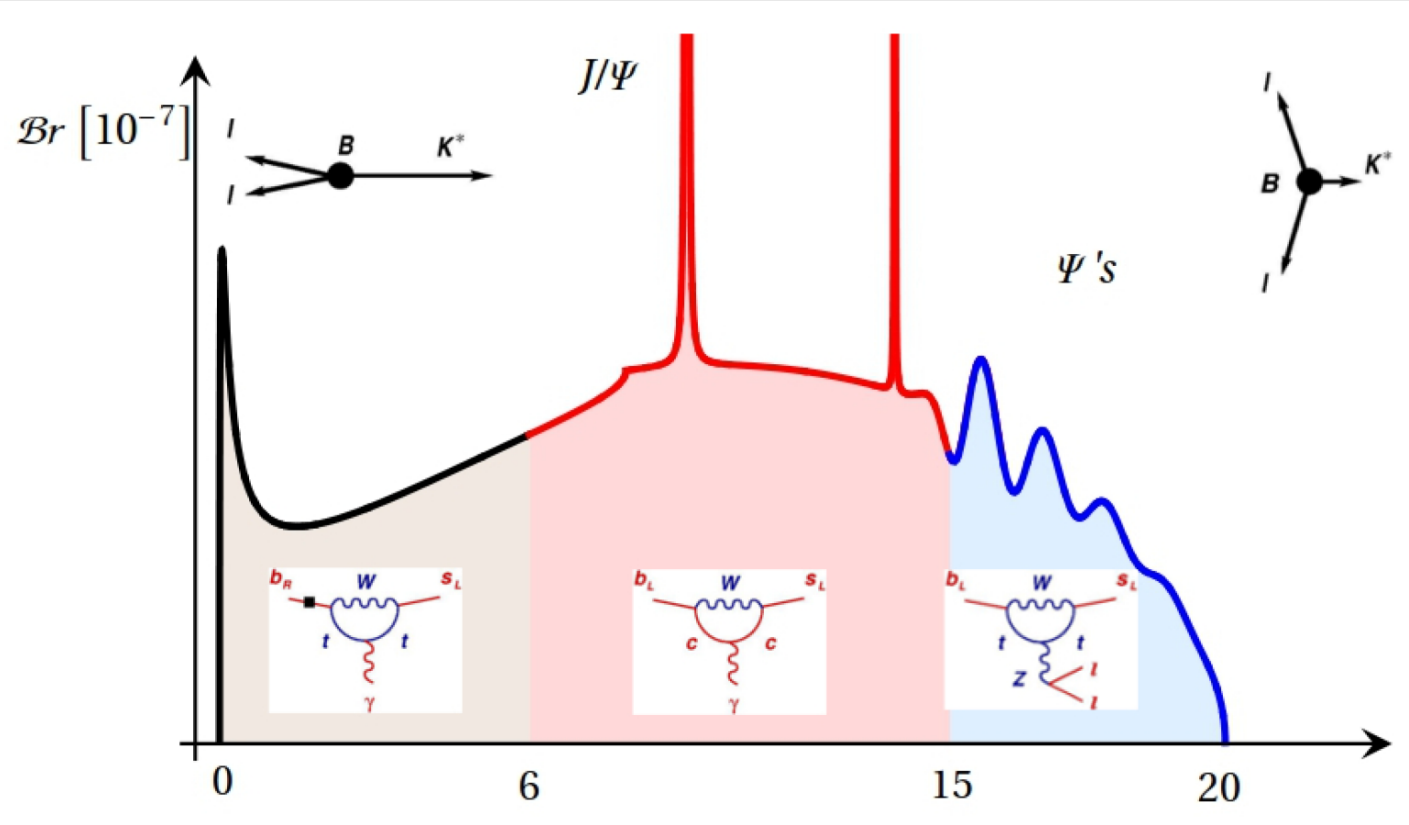
very large power corrections would be needed to fit the data in the SM

Controversies: form factors

In the large recoil region, the form factor dependence of 'optimized' observables disappears in the SCET limit. Power corrections to form factors need to be parametrized and bounded in a 'reasonable' range. It was argued [Camalich & Jäger '13] that 'reasonable' power corrections would fit the data in the SM framework.

However it was realized [Descotes-Genon *et al.*'15] that such a scenario would not agree with LCSR calculation of form factors: one cannot parametrize power corrections arbitrarily, given the knowledge of asymptotic form factor relations and LCSR inputs.
Note: when extrapolated from the large recoil region to the low recoil one, LCSR form factors show excellent consistency with LQCD simulations. This is a non trivial validation of the method, but it might be the only one.

Controversies: 4-quark operators



4-quark operators contribute through a photon emission from the quark loop: hence it mimics a modification of the O_9 (or O_7) matrix element, which is precisely the place where a potential NP contribution is needed to describe the data. If the deviation were instead located in C_{10} this would be an unambiguous sign of New Physics.

Light-Cone Sum Rules and dispersion relations provide a somewhat model-dependent estimate of these effects [Khodjamirian *et al.*'10,'12], that is expected to give the correct order of magnitude at least far away from resonance peaks. In global analysis, take this as a starting point and add a large conservative uncertainty $\sim 100\%$

Complete experimental analysis in the full q^2 range has been performed by LHCb '17 and is in reasonable agreement with theoretical expectations. Message: in principle there is enough information in the data to deconvolute the contribution of intermediate states.

The key point is that hadronic loop effects have a strong q^2 dependence, whereas the anomalies only require a constant contribution to C_9.

'Model independent' parametrization

It has been advocated to take into account all kind of corrections, and in particular charm loop contributions, with an helicity-dependent arbitrary polynom in q^2 [Ciuchini *et al.*'16,'17]:

$$h_\lambda^0 + h_\lambda^1 \left(\frac{q^2}{\Lambda^2}\right) + h_\lambda^2 \left(\frac{q^2}{\Lambda^2}\right)^2$$

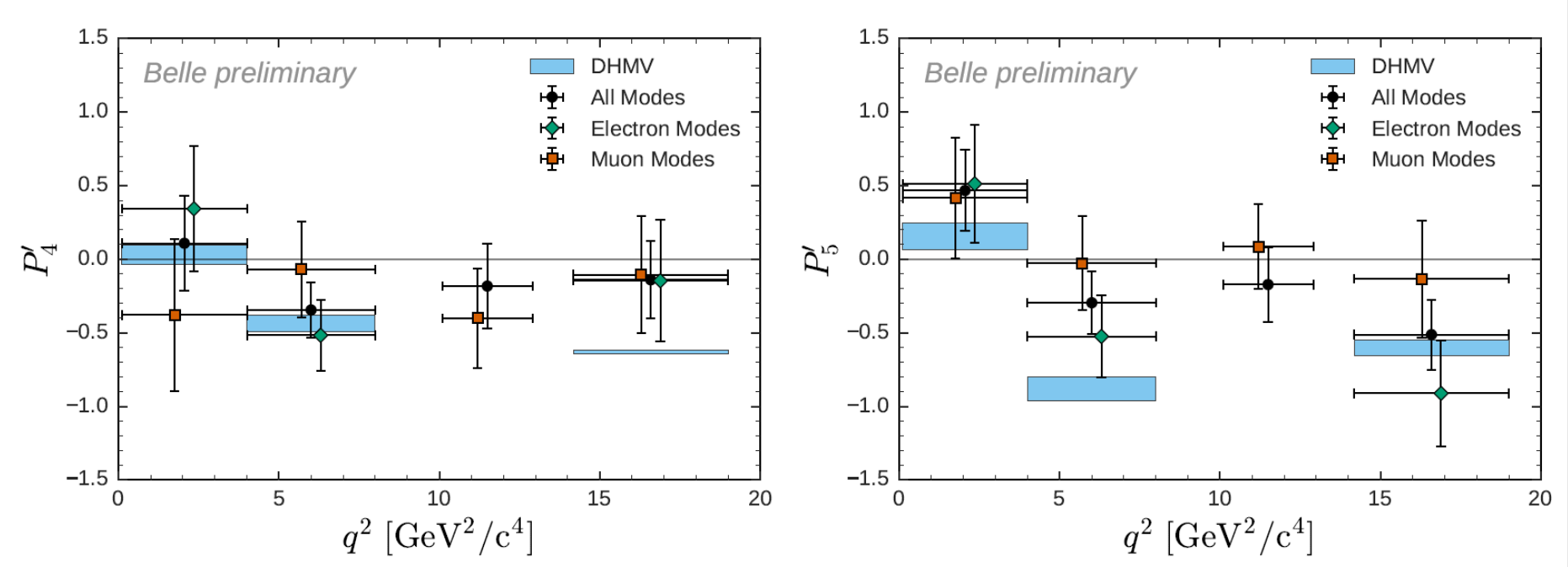
where $\lambda = 0, \pm 1$ and the coefficients are complex numbers to be determined by the fit.

It adds 18 free parameters in the $B \to K^*$ channel ! Without *a priori* knowledge of the coefficients, any data in smooth q^2 intervals (outside resonance peaks) can be fitted, with very little information on short-distance couplings, if any.

Message: the data are sensitive to the q^2 dependence of the amplitudes. One recovers the intriguing conclusion that the fit is dramatically improved by a constant contribution to C_9, while q^2 corrections remain compatible with zero.

Other experimental results

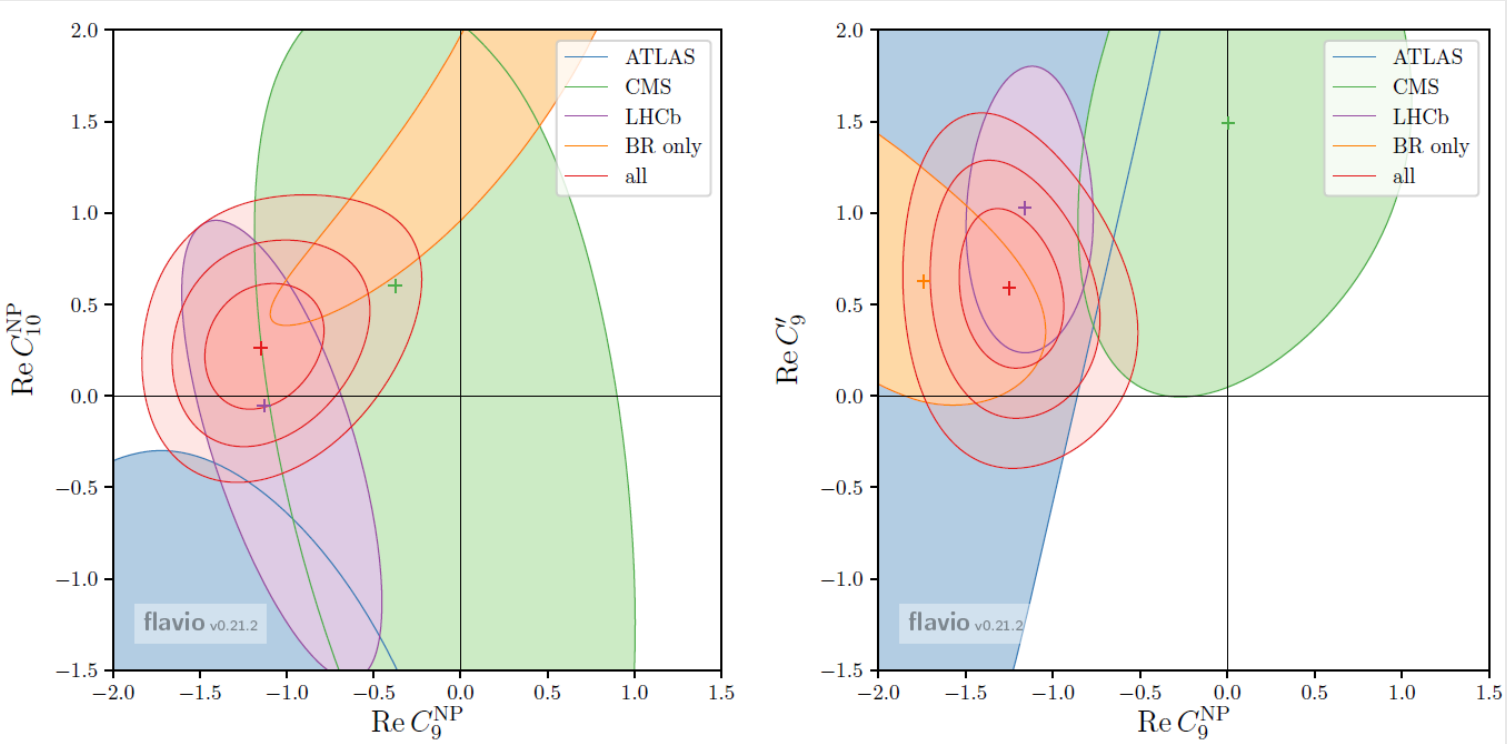
In 2016 Belle has been able to perform an angular analysis separately for muon and electron modes.



The anomaly may be in the muon channel rather than the electron one !

Other experimental results

Very recently ATLAS and CMS also performed an angular analysis of $K^*\mu\mu$ channel



Global analysis shows that ATLAS confirms the tension, while CMS tends to reduce it [Altmannshofer *et al.*'17]. However the CMS analysis is not self-consistent (some quantities are taken from other analyses).

$R(K)$ and $R(K^*)$ ratios

One defines the lepton universality test ratios

$$R(K^{(*)}) = \frac{\mathcal{B}_{\rm bin}(B \to K^{(*)}\mu\mu)}{\mathcal{B}_{\rm bin}(B \to K^{(*)}ee)}$$

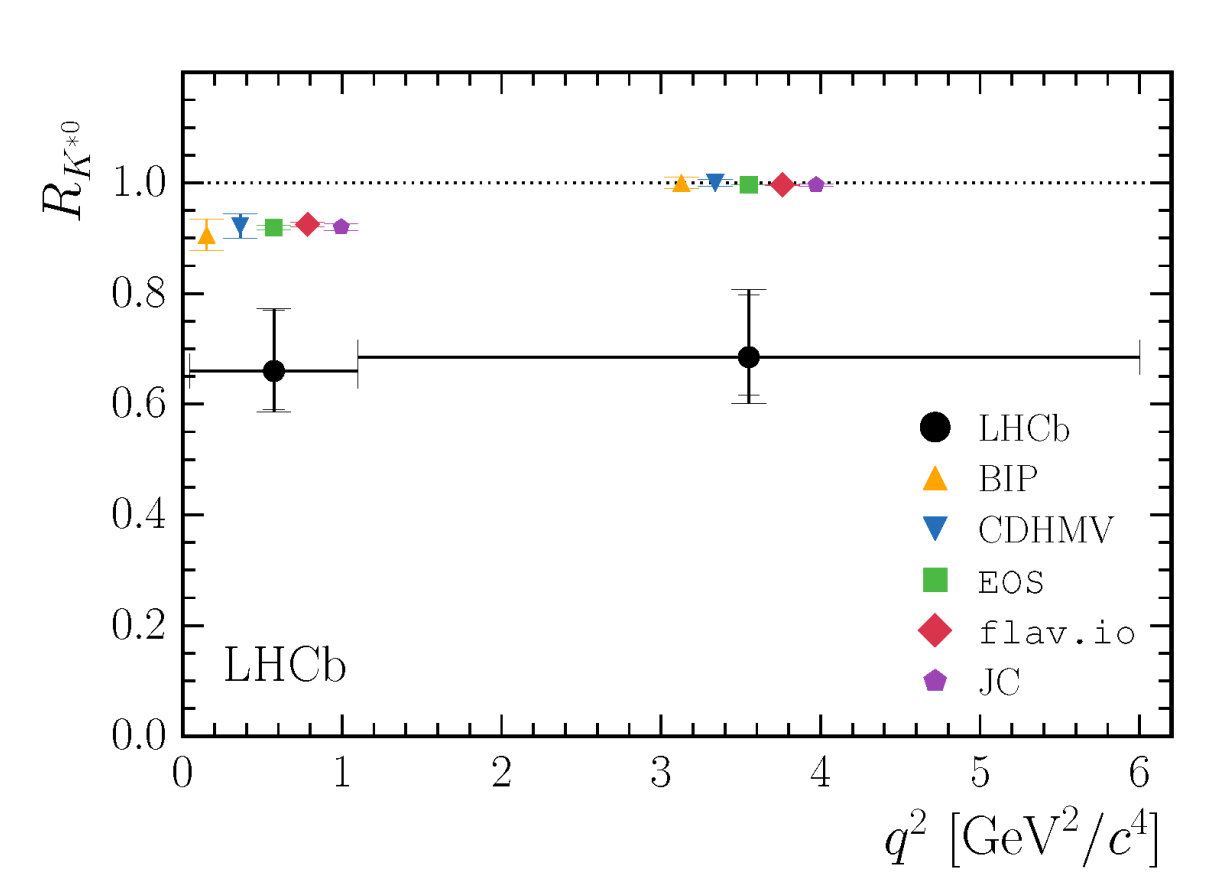
Neglecting QED effects, these ratios are basically independent of hadronic matrix elements, and are predicted to be ~ 1 in the SM with an excellent accuracy $\sim 1\%$.
Also on the experimental side, systematics are completely different from the angular analyses. Main challenge is reconstruction of the electron channel in an hadronic environment (LHCb).

$R(K)$ and $R(K^*)$ ratios

Experimental measurements vs. theoretical predictions

$$R_K^{[1,6]} = 0.745^{+0.097}_{-0.082}\ [2.6\sigma]$$

$$R_{K^*}^{[0.045,1.1]} = 0.66^{+0.113}_{-0.074}\ [2.3\sigma] \quad R_{K^*}^{[1.1,6]} = 0.685^{+0.122}_{-0.083}\ [2.6\sigma]$$



$R(K)$ and $R(K^*)$ in global analyses

It was shown before the measurement of $R(K^*)$ that the R_K anomaly can be well fitted with the same negative contribution to $C_9^{\mu\mu}$ as indicated by $K^*\mu\mu$ angular observables. In this interpretation the ee channel would remain SM-like.

The very recent measurement of $R(K^*)$ provided a consistency check of global analyses.

Charm loop cancels in these ratios, hence the explanation with an hadronic effect is unplausible .

QED radiative corrections

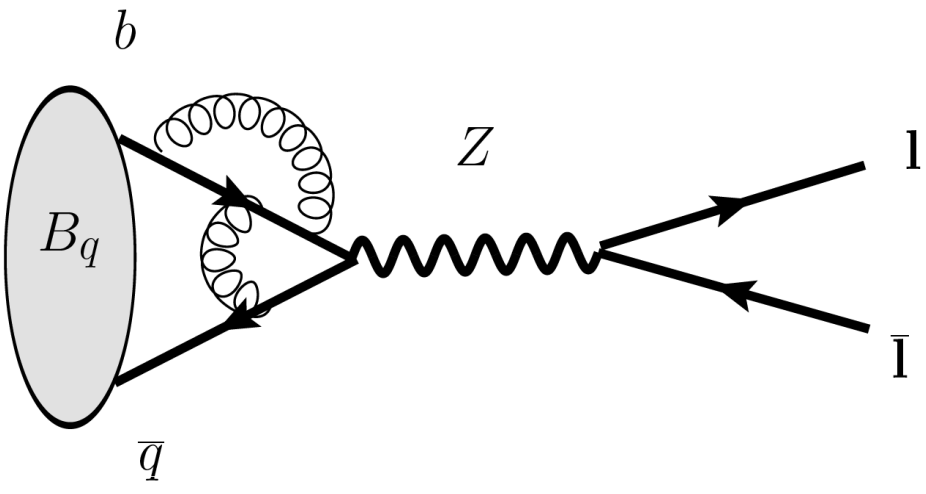
QED corrections to B decays are difficult to compute because they generically induce new hadronic matrix elements. No systematic calculation available so far. One may worry about large logarithms of lepton masses, especially for the ratios $R(D^{(*)})$ and $R(K^{(*)})$.

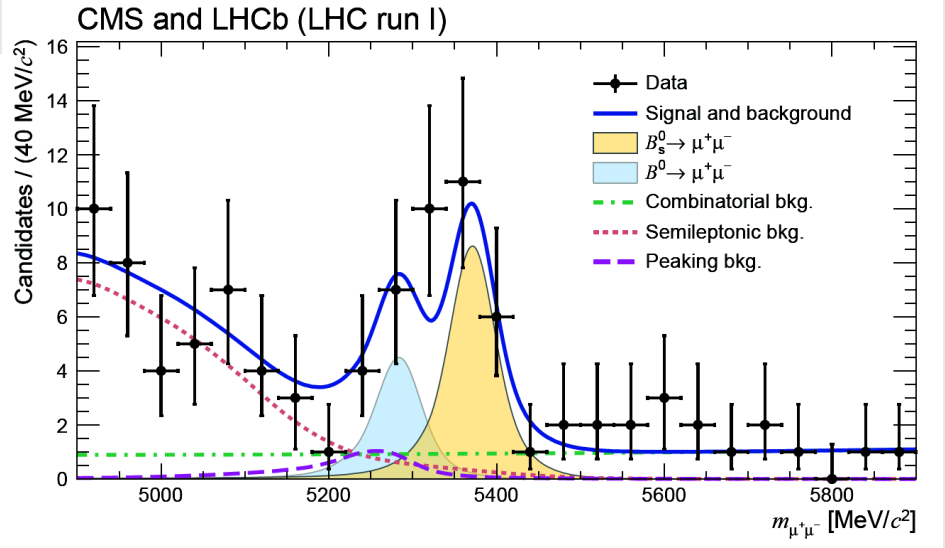
However in the case of $R(K^{(*)})$ QED corrections have been partially estimated at the few % level, and bulk of the effect is already taken at the experimental level with the PHOTOS MC software [Bordone *et al.*'16].
In the case of $K^*\mu\mu$ angular observables, since they are ratios of same final state quantities, QED corrections are expected to be really negligible.

Other rare decays

$B_{d,s} \to \mu\mu$ is both the simplest and cleanest FCNC B decay: it only depends on the decay constant $f_{B_{d,s}}$, plus perturbative corrections that have been calculated.

Both channels are in good agreement with the SM prediction, but they do not depend on C_9 so that there is no contradiction with $K^*\mu\mu$ observables.





They however depend on other Wilson coefficients and put stringent constraints on possible NP scenarios.

Standard Model Interpretation

$R(D^{(*)})$ ($> 4\sigma$): the anomaly is large and unlikely related to statistical fluctuations. Form factor issues are reasonably well controlled. Possible experimental subtleties might come from background discrimination, as both excited D states and τ produce missing energy.

$R(K^{(*)})$ (3-4σ): the anomaly is smaller but there is a systematic trend $R < 1$. QED issues might be more complicated than expected, a complete calculation would be needed.

Global analyses of $b \to s$ ($> 5\sigma$): they are very robust against different experimental and theoretical input scenarios. The anomalies have only increased since 2013. Light and charm quark loops are a serious concern, but there is no known hadronic mechanism that would mimic a large enough constant contribution to C_9, without introducing other inconsistencies.

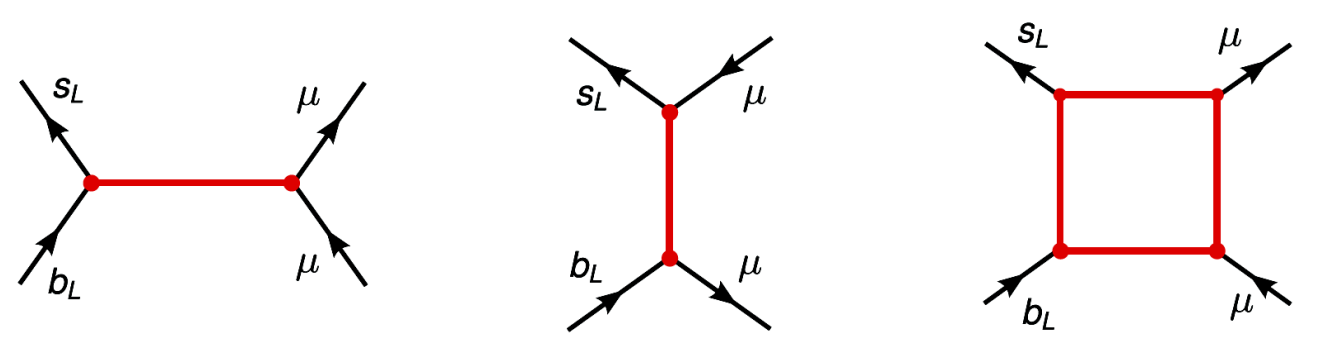
New Physics interpretation in a nutshell

Leptoquarks and Z' scenarios are the favorite NP explanations of the anomalies.

Nevertheless $R(D^{(*)})$ demand a significant contribution to a dominant tree-level coupling, while $b \to s$ anomalies are loop suppressed. Hence it is generically difficult to explain both sets of anomalies at the same time.

A 'one leptoquark' solution has been proposed [Bauer & Neubert '15], but there is some controversy about its compatibility with various constraints [Becirevic *et al.*'16]. Improvements are possible, to the price of having more degrees of freedom.

Typical NP explanations require new particles in the 10-100 TeV range, some of them may be detected in future collider experiments.



Future progress

Many 'R' ratios, testing $e/\mu/\tau$ lepton coupling universality, can be constructed by changing the flavor of the spectator quark (d,s,c), considering Λ_b baryon decays, and playing with both $\ell\nu$ (CC) and $\ell\ell$ (NC) channels. Some of them will be measured soon.

Belle 2 and LHCb upgrade will provide significantly more precise measurements of all these decay, giving access to more observables, more q^2 bins, and opening the possibility to fit for the amplitude contributions that cannot be computed accurately.

Belle 2 will also provide a precise measurement of $b \to s\ell\ell$ inclusive observables, for which present experimental determination is not competitive.

Future progress

In the longer term $b \longrightarrow s$ transitions with τ pairs will provide stringent constraints on short-distance couplings.

On the theoretical side a lot of progress is expected on the understanding of contributions from 4-quark operators, radiative QED corrections, and more accurate measurements of hadronic matrix elements on the Lattice.

For sure in the next five years we will learn fundamental new phenomena !

Conclusion

For sure 'something' is happening: statistical fluctuations only can hardly explain all these anomalies.
There must be one (or several...) systematic effects: subtle experimental issues, hadronic/QED complications, New Physics...

In the $b \to s$ sector the simplest explanation is a negative constant contribution to C_9. Other generic NP scenarios are well possible. On the other hand it does not seem possible to absorb all anomalies with a single and simple hadronic explanation.
The $b \to c$ transitions are more delicate, as many NP scenarios have difficulties to explain $R(D^{(*)})$ while at the same time remaining compatible with stringent SM constraints. One faces the common problem that the SM remains the most compact model that explains (almost) everything !