Selected hot topics in quark flavor physics

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Introduction

All Standard Model particles have been found as expected !

However a lot of deep problems remains:

- too many free parameters in the SM
- huge hierarchy of mass scales
- a fundamental scalar particle
- unknown neutrino masses and nature
- CP violation and matter-antimatter asymmetry
- unseen strong CP violation
- dark matter and dark energy
- no established theory of quantum gravity

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

One has typically

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

where the operators O can be further decomposed with the OPE 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: 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

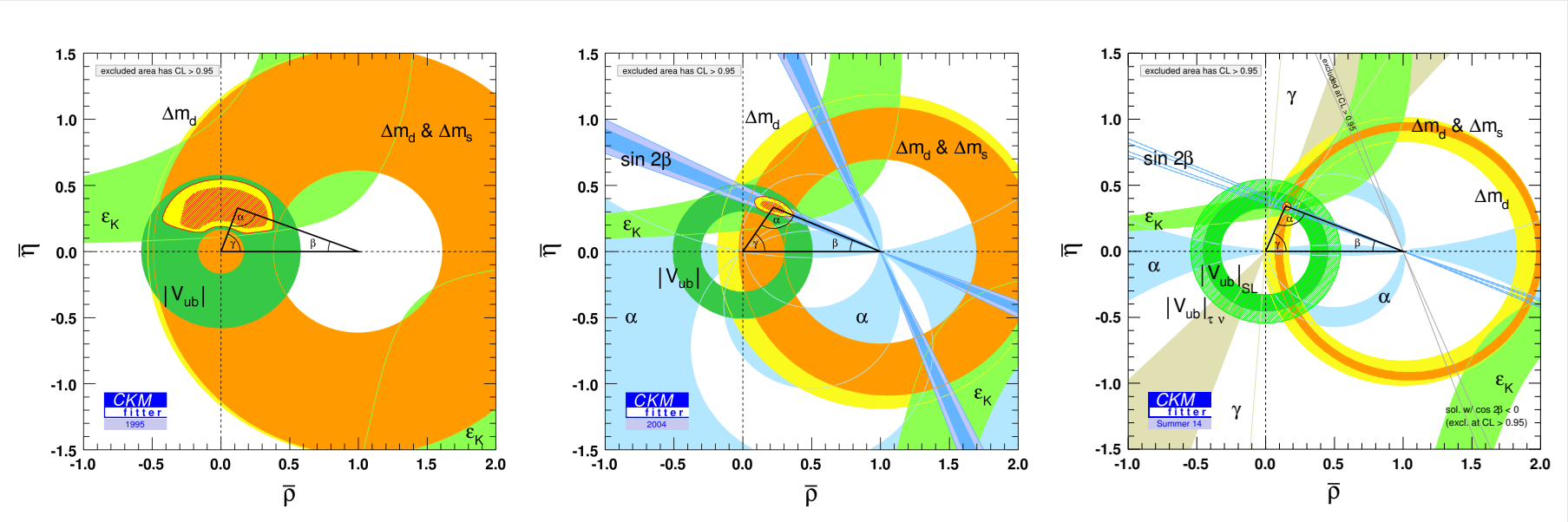
The CKM matrix parametrizes the quark flavor transitions. Its unitarity implies triangular relations in the complex plane of couplings, where a single phase describes CP violation in weak interactions.
It has become standard to use the four Wolfenstein parameters A, λ and $(\bar{\rho}, \bar{\eta})$. 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.

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

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

History of CKM analyses

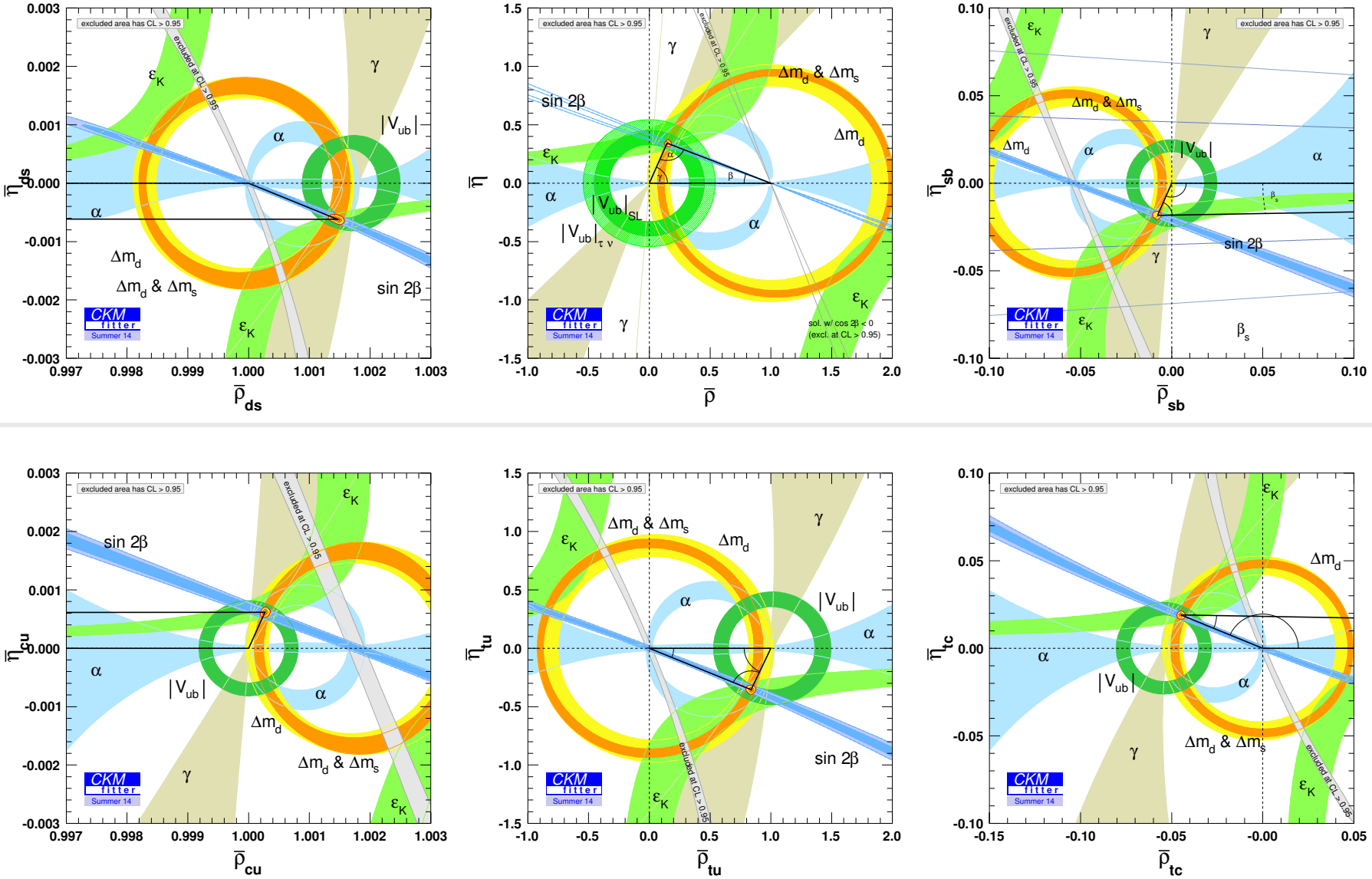
1995, 2004, 2014



[CKMfitter group]

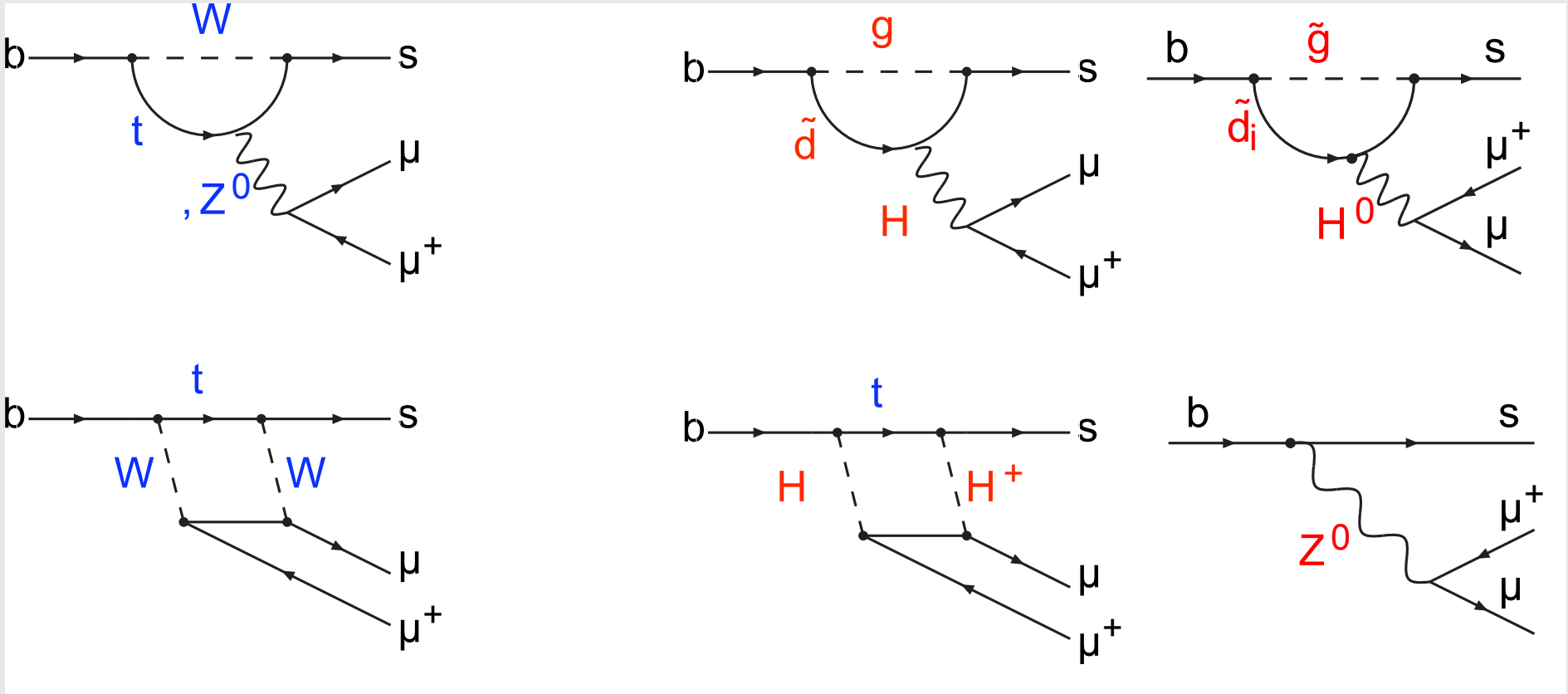
B-factories have consistently established the CKM paradigm as the main source of quark flavor transitions and weak CP violation: Nobel Prize to Kobayashi and Maskawa in 2008 !

Other unitarity triangles

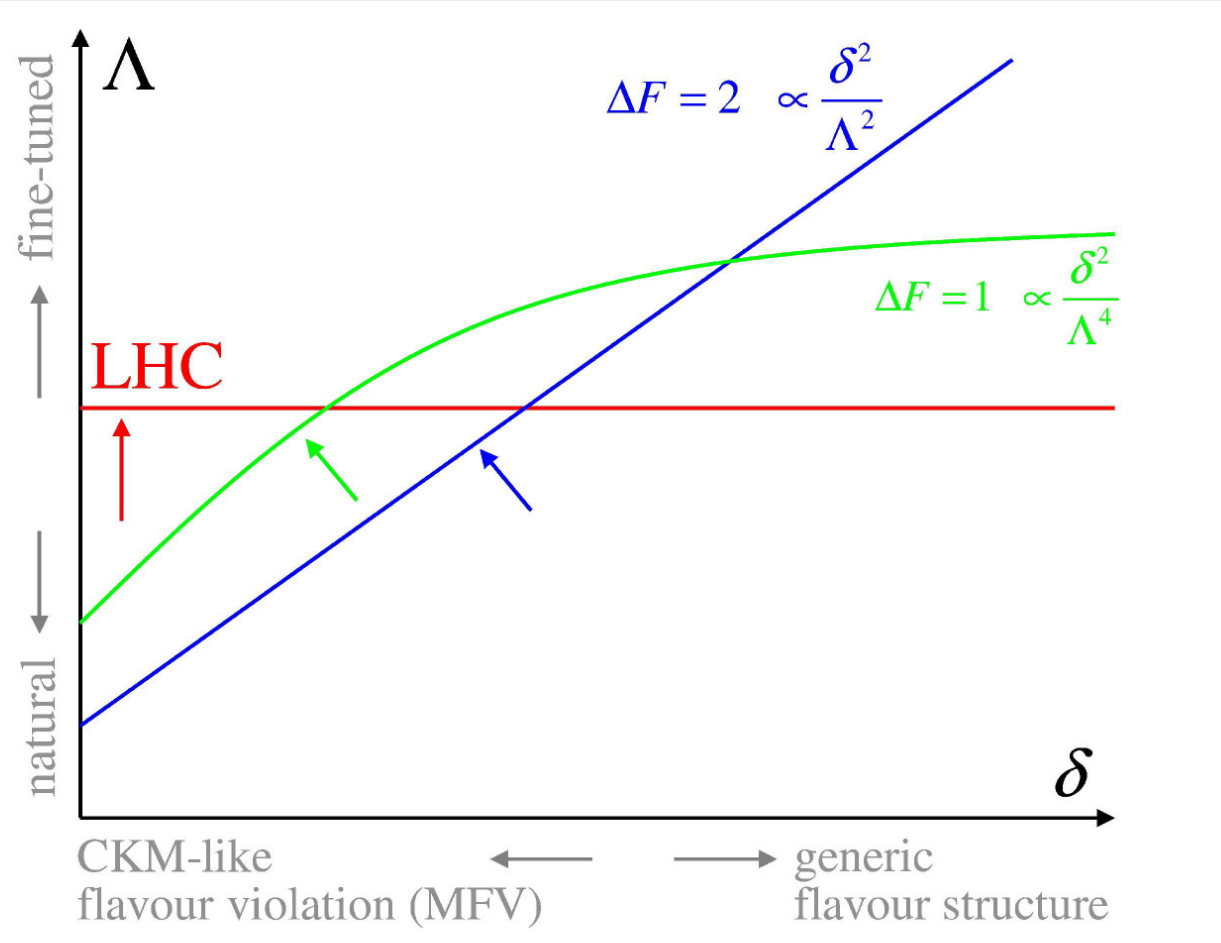


Virtual new particles

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

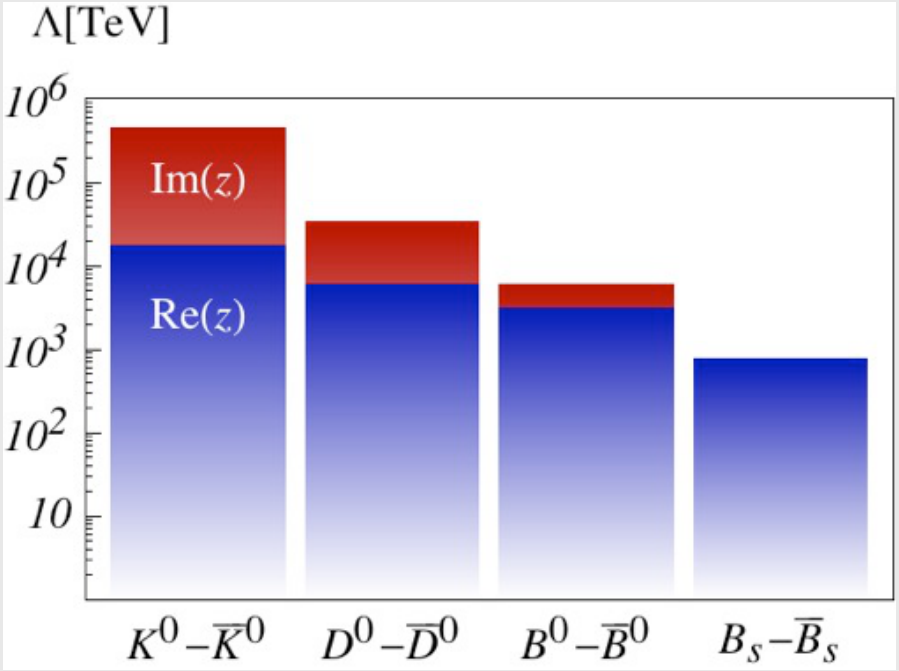


This allows to test New Physics in different directions of couplings δ and scales Λ, and provides a complementary insight with respect to direct searches



[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 electroweak 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 electroweak fine-tuning, or the NP is at a "low" scale and it must exhibit a specific hierarchy in flavor couplings

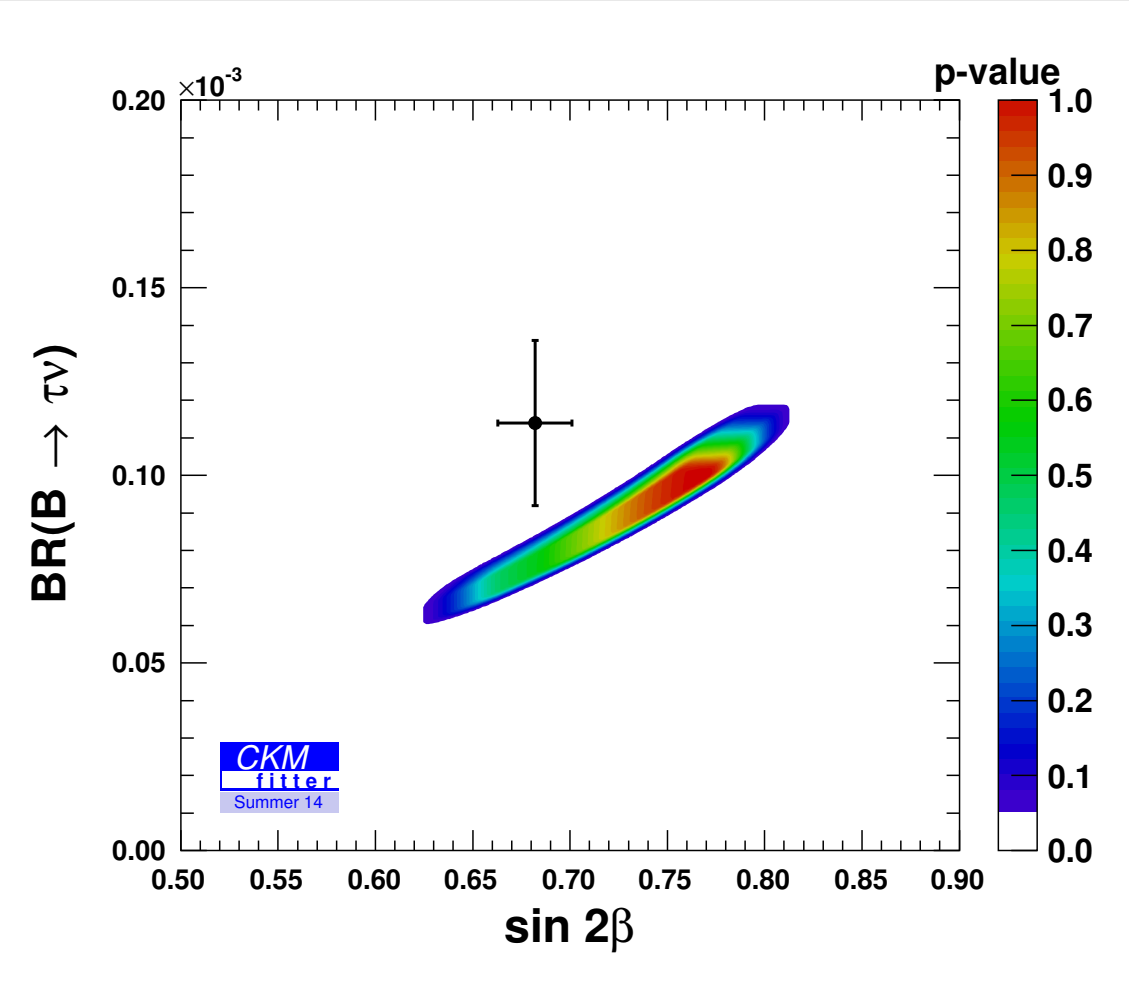
In the last few years effort has been made to exploit flavor observables that could shed light on these issues. Some "anomalies" (w.r.t. to SM expectations) related to these observables have been reported, mostly small ones but still very interesting and encouraging

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.

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.



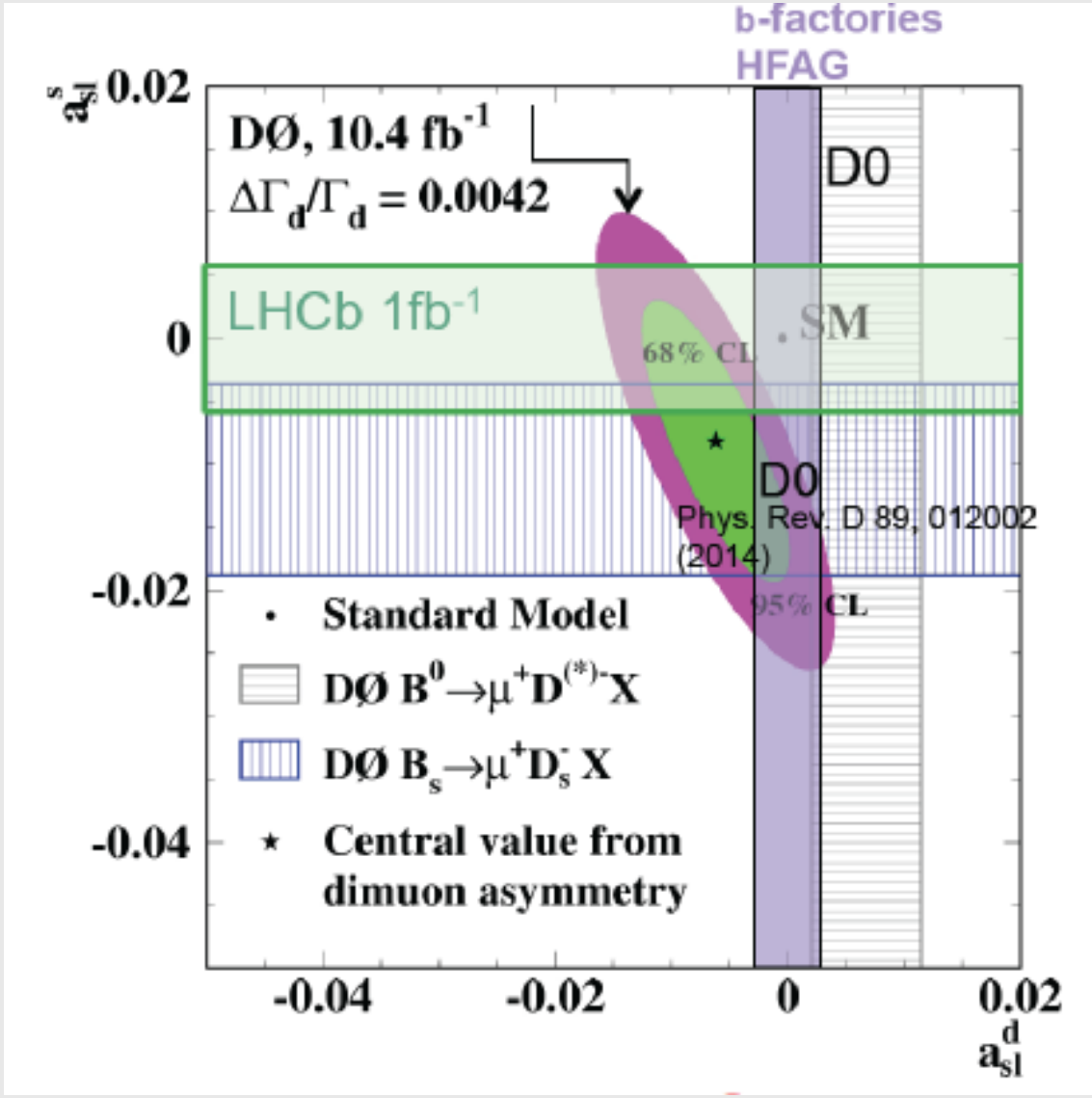
Semileptonic asymmetries

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 !) εK 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



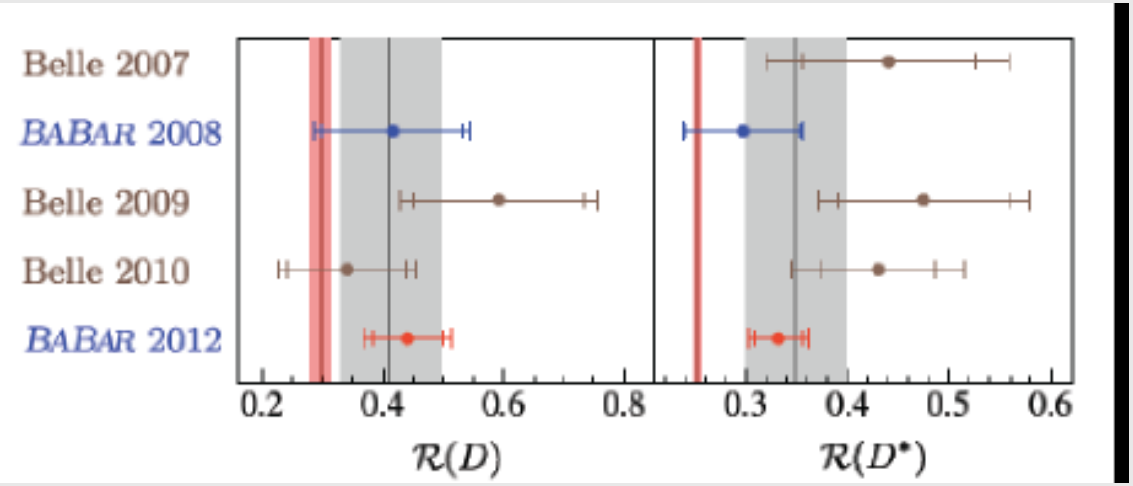
Semileptonic $B \to$ charm

$B \to D^{(*)}\ell\nu$ and their inclusive partner decays are used to extract $|V_{cb}|$. There is a long-standing, persistent and unexplained $2-3-$ *sigma* 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 $4\sigma\ldots$

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).

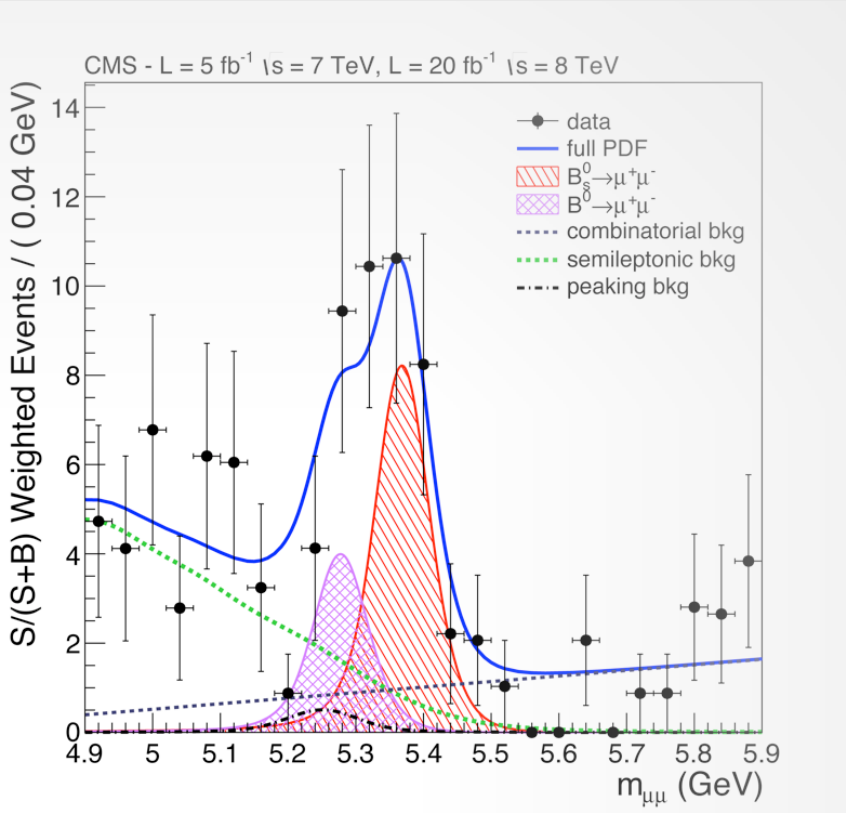
The very rare $B_s \to \mu^+\mu^-$ decay

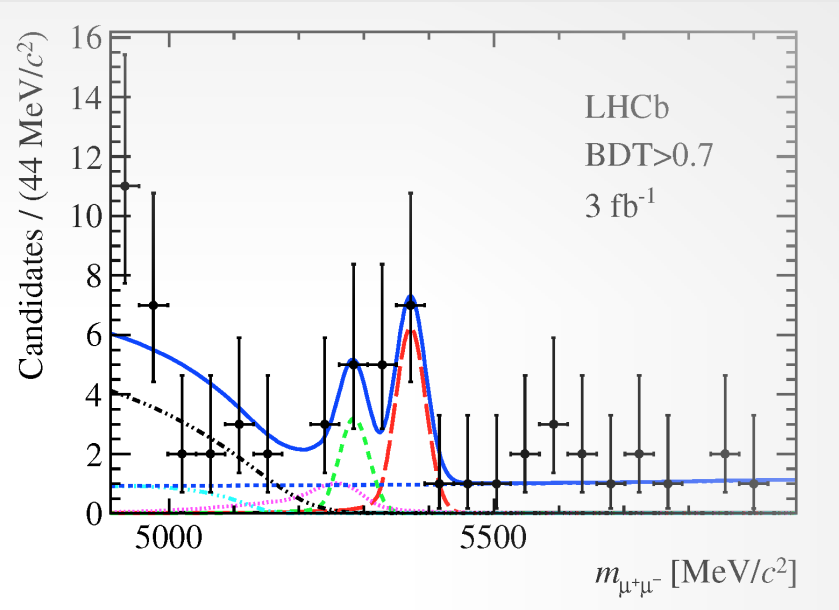
This is the rarest decay that comes with both a non trivial measurement and a non trivial theoretical prediction.
Hadronically, it only depends (even outside SM !) on the f_{B_s} decay constant that is well computed on the lattice. Perturbative contributions have been computed up to NLO-EW and NNLO-QCD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

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

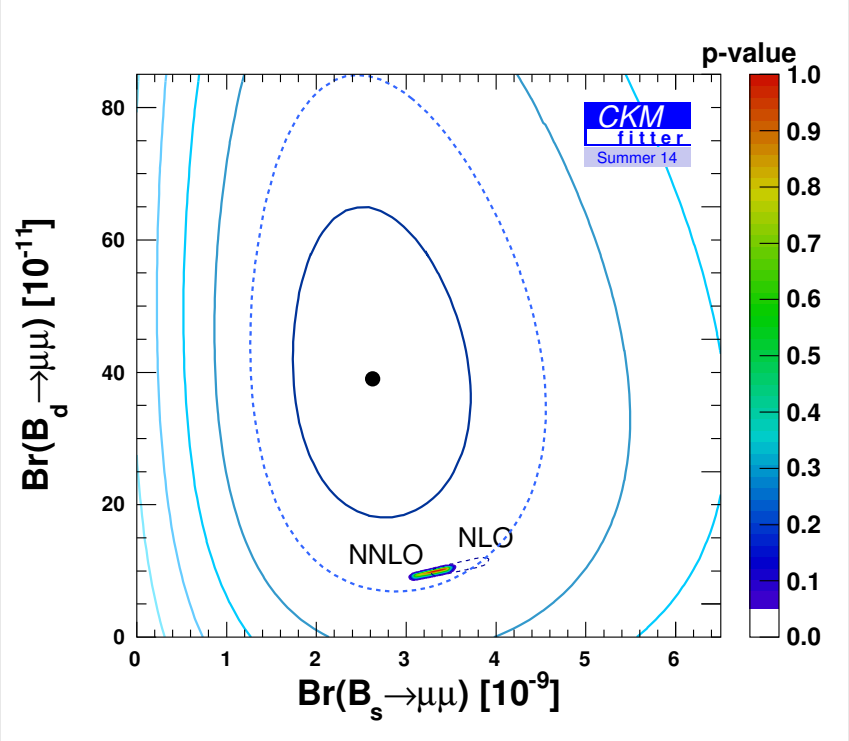
Both LHCb and CMS have found evidence for this decay, with the combined result

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





Since $\mathcal{B}(B_s \to \mu\mu)_{\rm SUSY} \sim \tan\beta^6$, 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.

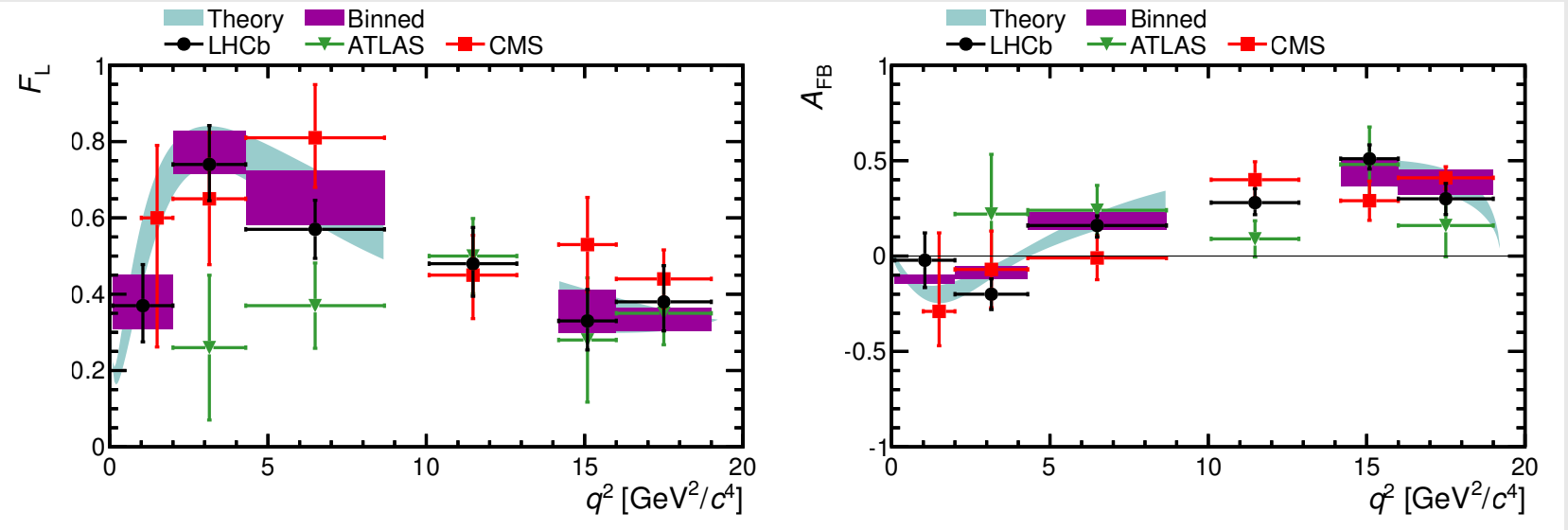


However the parameter space is so big in many NP models that one needs further observables to get more insight.

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

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.

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


Theory
Binned
LHCb
ATLAS
CMS
F_L
q^2 [GeV^2/c^4]

Theory
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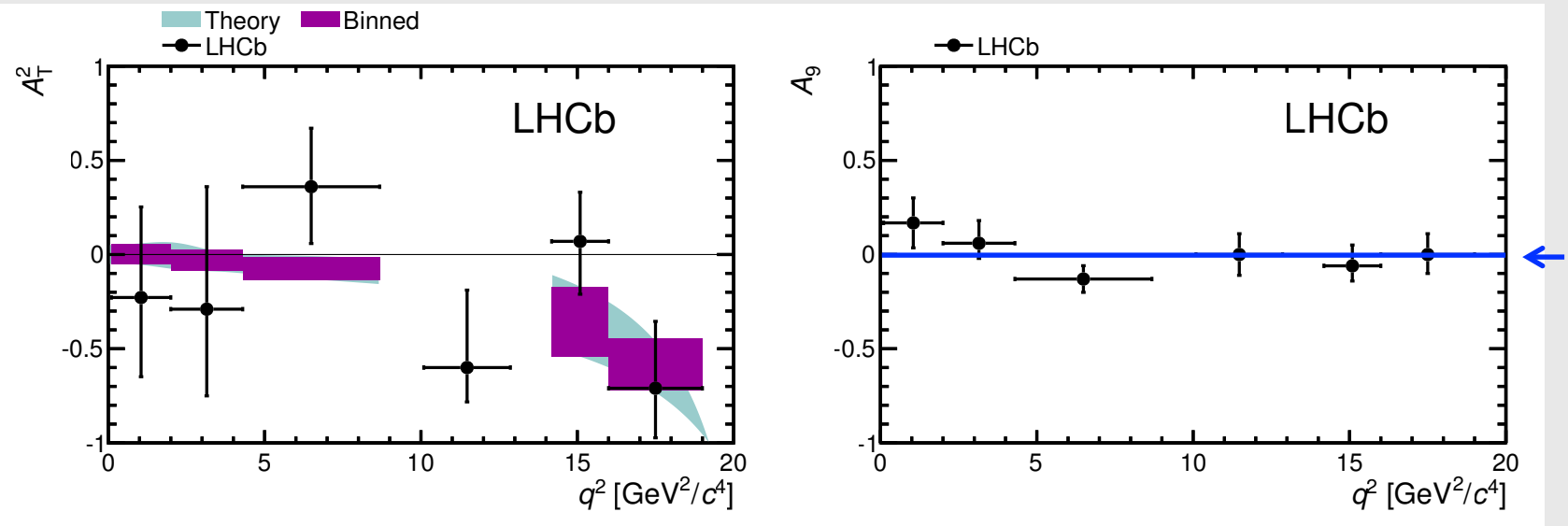

Theory
Binned
LHCb
LHCb
A_T^2
q^2 [GeV^2/c^4]

LHCb
LHCb
A_9
q^2 [GeV^2/c^4]

← SM

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

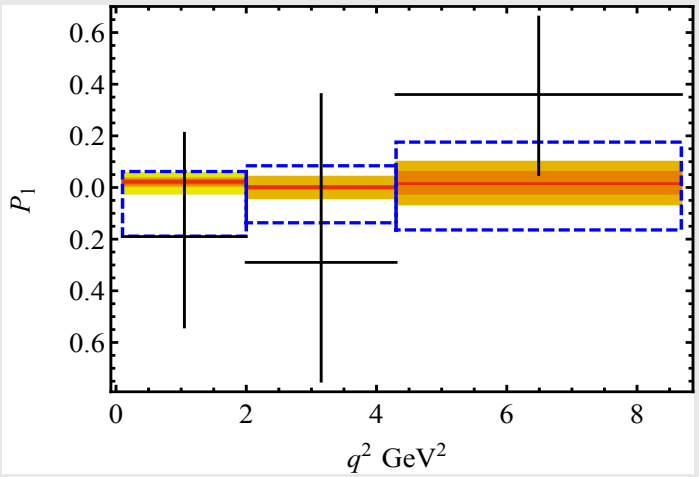
A lot of activity in the last years have been devoted to design optimized observables, by taking specific combinations of the original ones in which the residual dependence to the hadronic form factors is reduced.

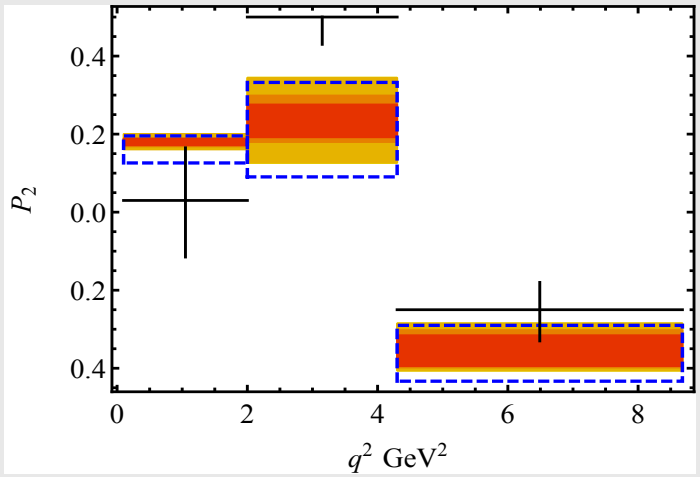
$$\frac{d\Gamma}{dq^2 d\cos\theta^* d\cos\theta_\ell d\phi} \sim J_i(q^2)\Omega_i(\cos\theta^*, \cos\theta_\ell, \phi)$$

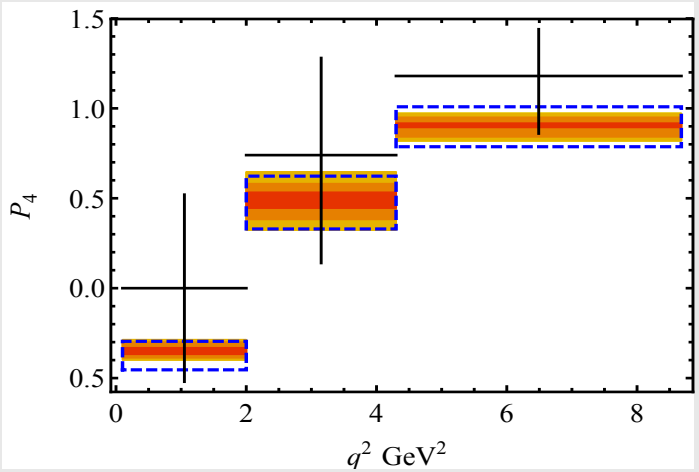
$$J_i \to P_i, P_i'$$

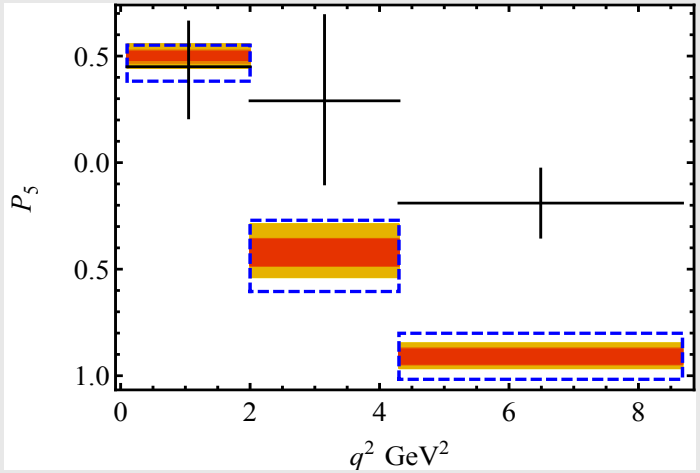
The uncertainties that remain to evaluate are: residual form factor dependence, power corrections (part of them are factorizable and calculable), and long distance contributions from $c\bar{c}$ loops

Comparison with data



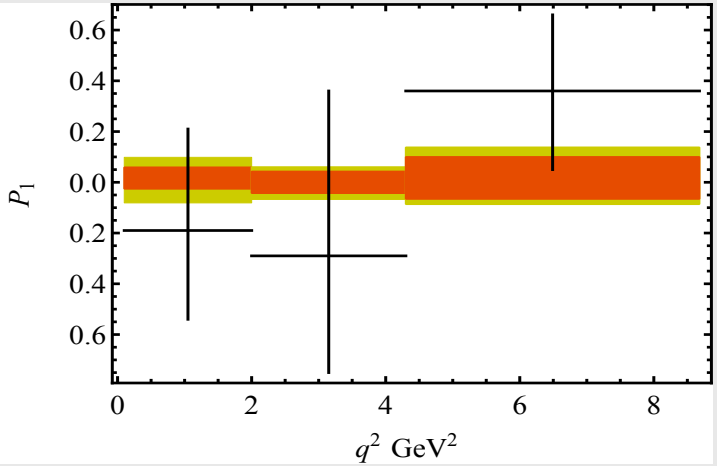


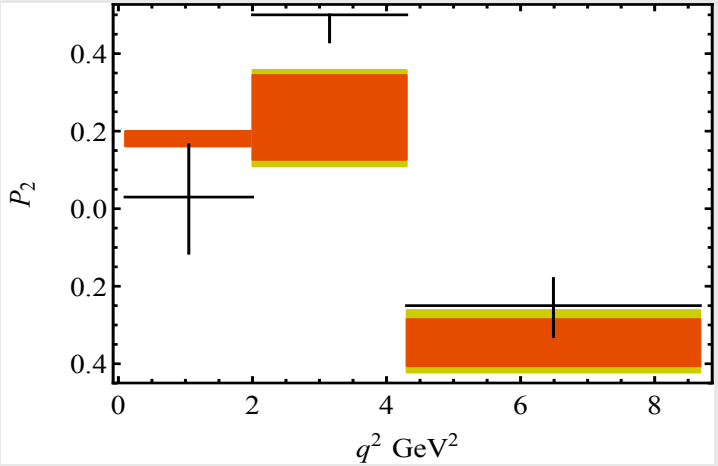


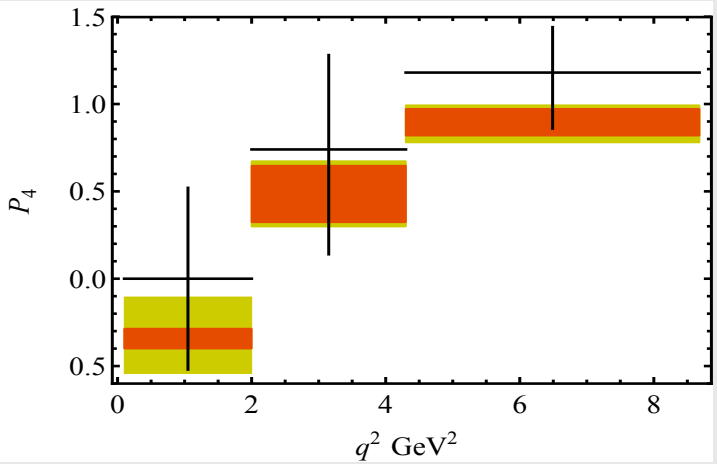


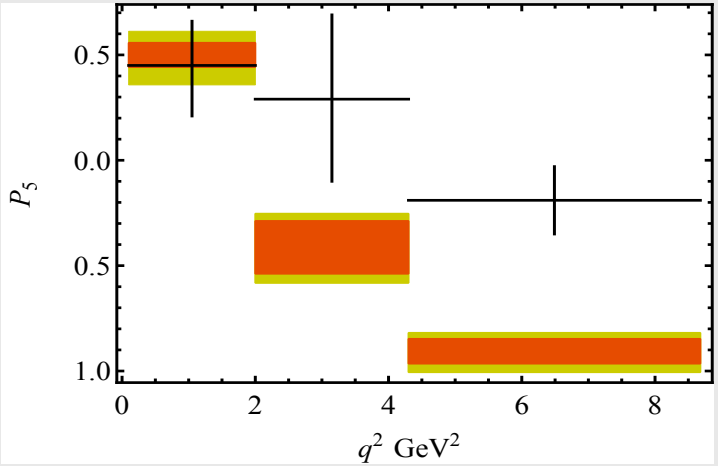
[Descotes-Genon *et al.*]

Comparison with data







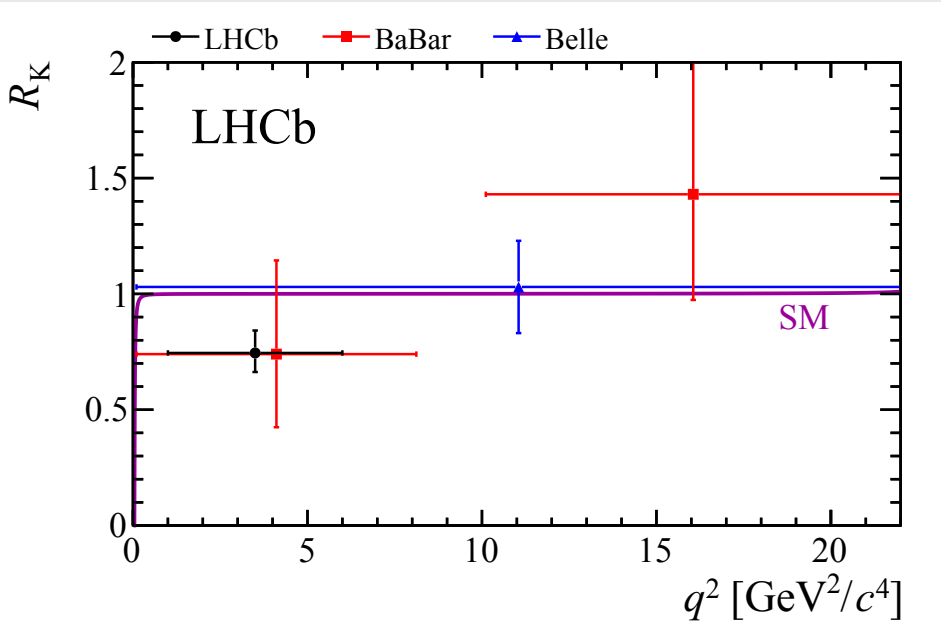


[Descotes-Genon *et al.*]

As for $P_5^{'}$ observable, the deviation w.r.t. SM reaches 3.7σ. Other groups (Altmannshofer *et al.*, Beaujean *et al.*) find similar, albeit smaller, effects. This anomaly is also consistent with the q^2 distribution, for which data systematically lie below theoretical prediction.
It is still under discussion whether it could be a hint for NP (the most natural explanation would be a $Z^{'}$), an underestimate of theoretical uncertainties or a statistical fluctuation. More data are coming, and are likely to help a lot.

$B \to K\mu\mu$ vs. $B \to Kee$

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



However yesterday (!) first measurement of angular observables in $B \to K^*ee$ was made public, and shown to agree with the SM predictions.

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, and first measurements of rare and very rare decays show only small anomalies w.r.t. SM predictions, 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.

Thank you !

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