Flavour physics and indirect searches for new physics

Farvah Nazila MAHMOUDI (IP2I Lyon)

Atelier "Physique Théorique des deux infinis", 7-8 June 2021 (Online)

Flavour physics

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Within the SM, flavour is introduced by a triplication of the quark and lepton spectrum of one family

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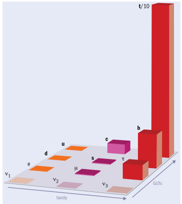
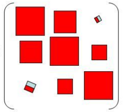
- The Standard Model flavour puzzle
- The New Physics flavour puzzle
- CP violation (new sources of CP violation are needed for baryogenesis)
- Flavour physics is sensitive to new physics at $\Lambda_{\mathrm{NP}} \gg E_{\mathrm{experiments}}$

  Flavour physics can discover new physics or probe it before it is directly observed in experiments



CKM



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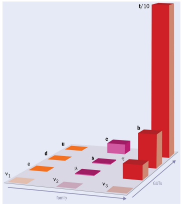

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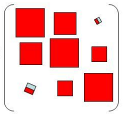

Eratosthenes
discovered the roundness of Earth...

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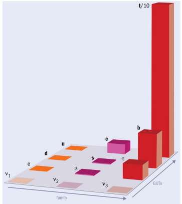

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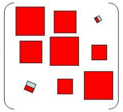

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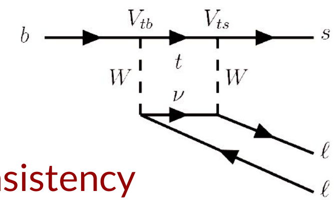
  Flavour physics can discover new physics or probe it before it is directly observed in experiments

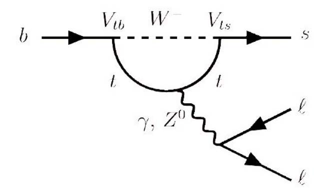
Eratosthenes
discovered the roundness of Earth...

...about 2300 years before its direct observation!

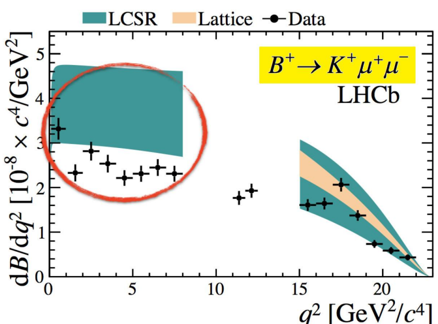
Neutral currents

b → s transitions

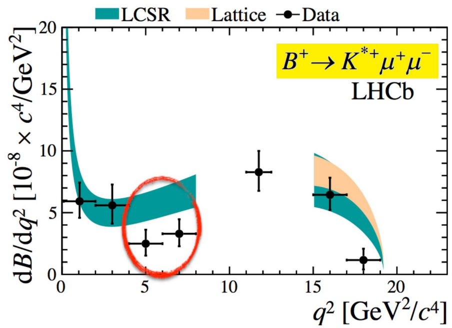




Several deviations from the SM predictions since 2013
growing with time both in statistical significance and in internal consistency



1403.8044



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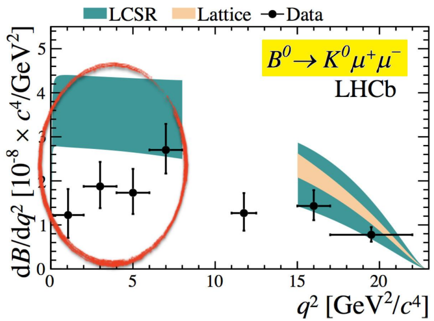

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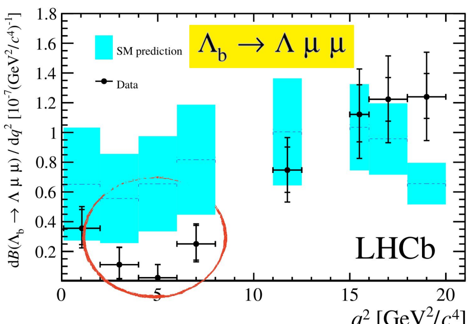

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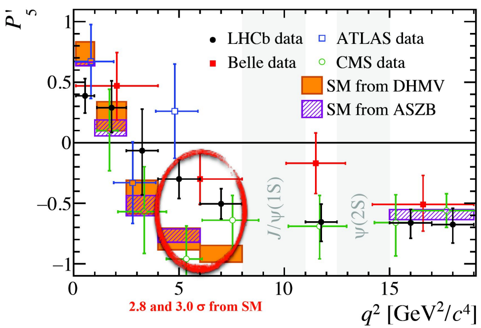
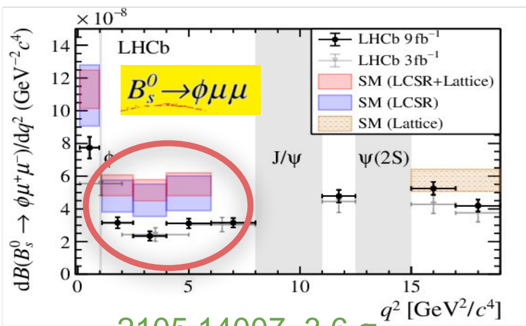


LHCb, JHEP 02 (2016) 104; Belle, PRL 118 (2017);
ATLAS, ATLAS-CONF-2017-023;
CMS, CMS-PAS-BPH-15-008

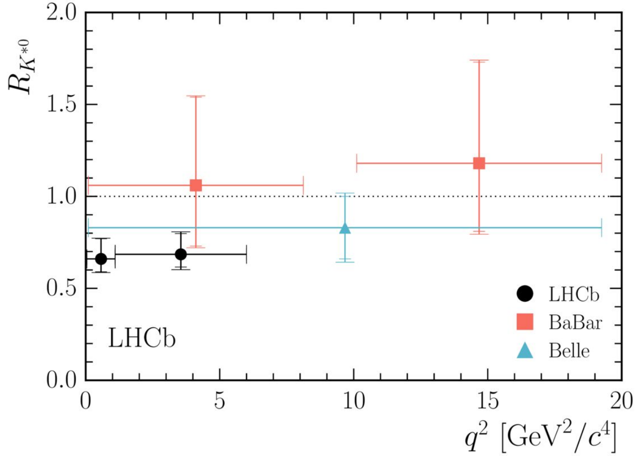


2105.14007, 3.6 σ

Lepton Flavour Universality tests

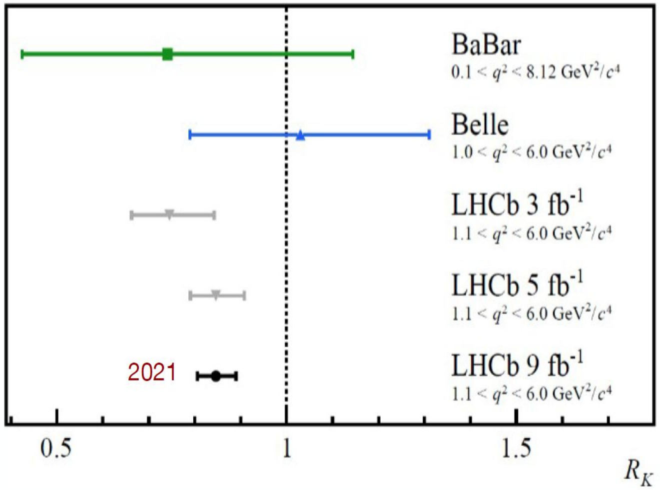
$$R_{K^{(*)}} = \frac{\mathrm{Br}(B \to K^{(*)}\mu\bar{\mu})}{\mathrm{Br}(B \to K^{(*)}e\bar{e})}$$

In the Standard Model, there is a lepton flavour universality, and the ratios are expected to be 1.



1705.05802

Deviations of 2.1 σ and 2.4 σ in the two bins



2103.11769

Evidence (3.1 σ) for
lepton flavour universality violation!

If confirmed this would be an unambiguous sign of new physics
and a groundbreaking discovery!

Theoretical (frame)work

Effective Hamiltonian: $\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i(\mu) \mathcal{O}_i(\mu)$

$C_i(\mu)$ Wilson coefficients, Perturbative, short distance

$\mathcal{O}_i(\mu)$ Operators, Non-perturbative, long distance

$\mathcal{O}_7 \propto (\bar{s}\sigma^{\mu\nu} P_R) F^a_{\mu\nu}$

$\mathcal{O}_9 \propto (\bar{s}\gamma^{\mu} b_L)(\bar{\ell}\gamma_\mu \ell)$

$\mathcal{O}_{10} \propto (\bar{s}\gamma^{\mu} b_L)(\bar{\ell}\gamma_\mu \gamma_5 \ell)$

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- **Theoretical calculations**

- Wilson coefficients ✓
- Non-factorizable QCD corrections, good progress, more work on going
- Lattice, good progress, more work ongoing → see next talk by A. Gérardin

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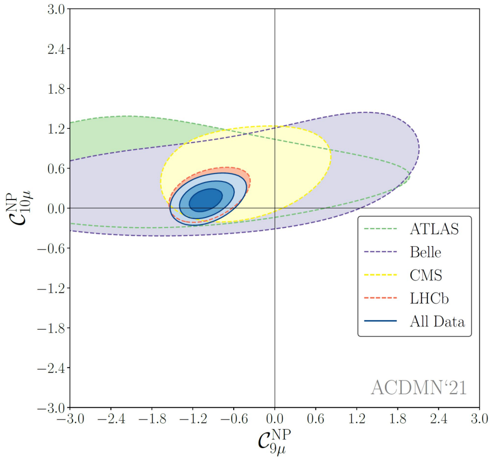
- **Model building**

- Model independent: important to understand the needed model ingredients



M. Algueró, B. Capdevila, S. Descotes-Genon, J. Matias, M. Novoa-Brunet, 2104.08921

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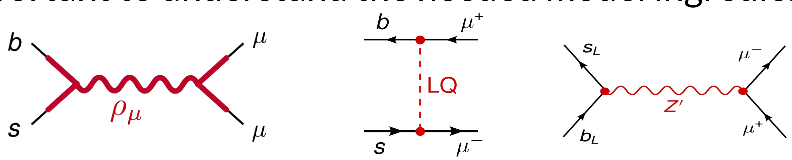

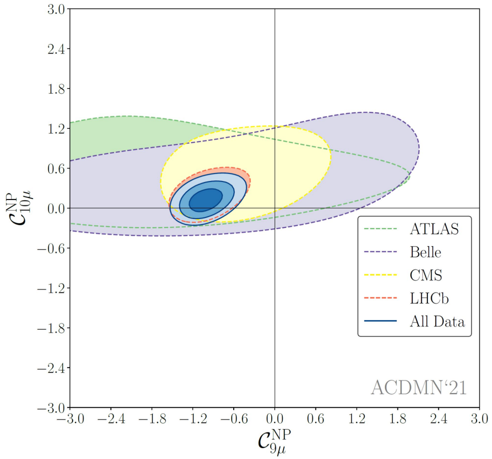

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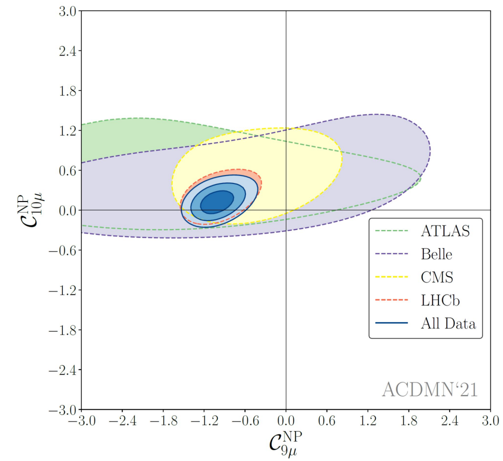

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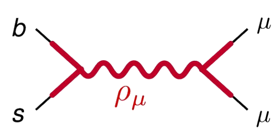
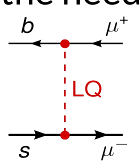
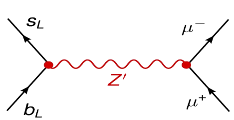




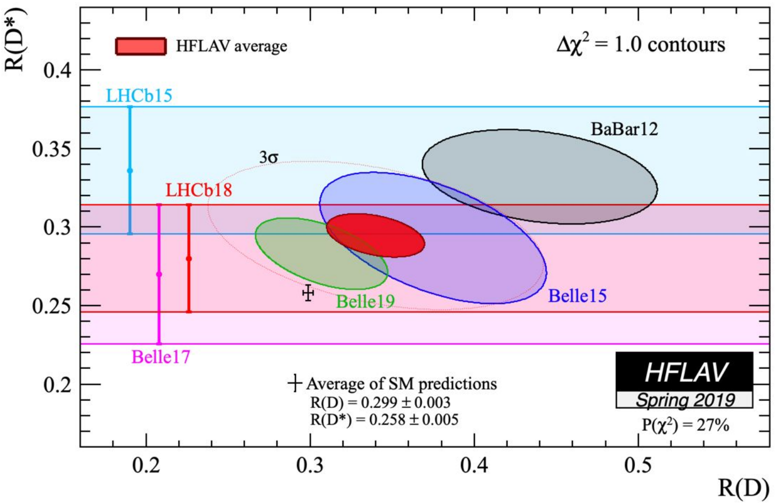


- **Connection with high p_T searches** → see next talk by O. Sumensari

Charged currents

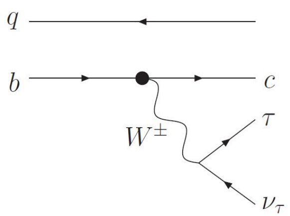
b → c transitions

$$R_{D^{(*)}} = \frac{\mathrm{Br}(B \to D^{(*)}\,\tau\bar{\nu})}{\mathrm{Br}(B \to D^{(*)}\,\ell\bar{\nu})}\Big|_{\ell=e,\mu}$$



Huge 15% discrepancy with the SM prediction

Tree level decay



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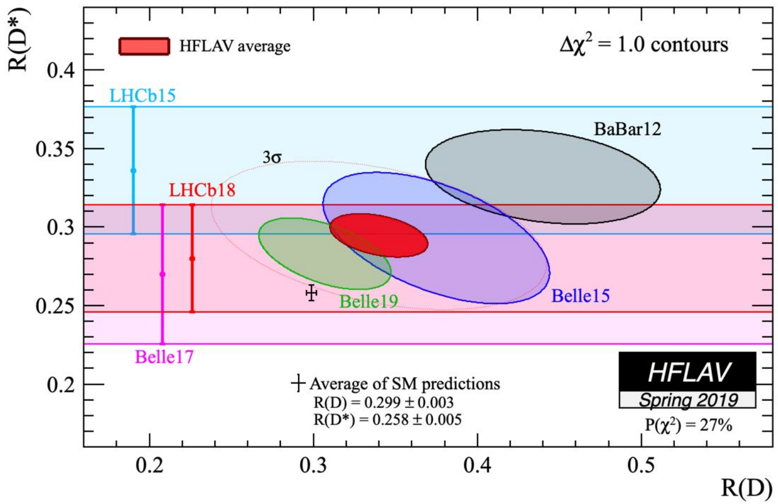

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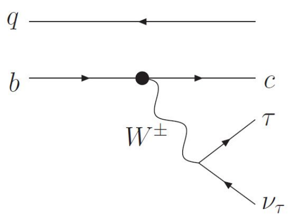
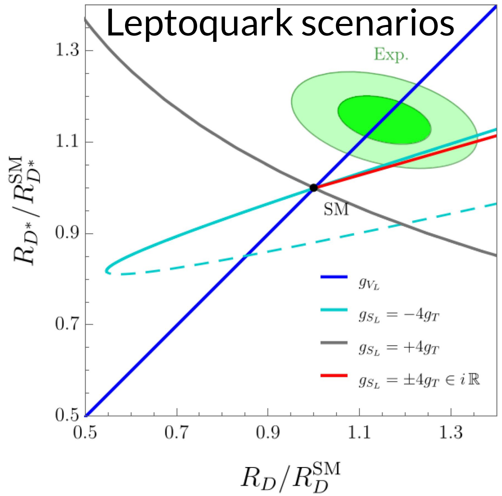


From the theory side:

- Need to be sure about SM prediction, i.e. the form factors
- Build models able to explain such discrepancies



A. Angelescu, D. Becirevic, D. Faroughy, F. Jaffredo, O. Sumensari, arXiv:2103.12504

High precision tests of the CKM mechanism

Future experiments will test the CKM mechanism at the permille level in leading quark flavour transitions through a large set of observables.

In order to reinterpret these measurements within the Standard Model and eventually detect deviations from it, theory predictions must be improved accordingly.

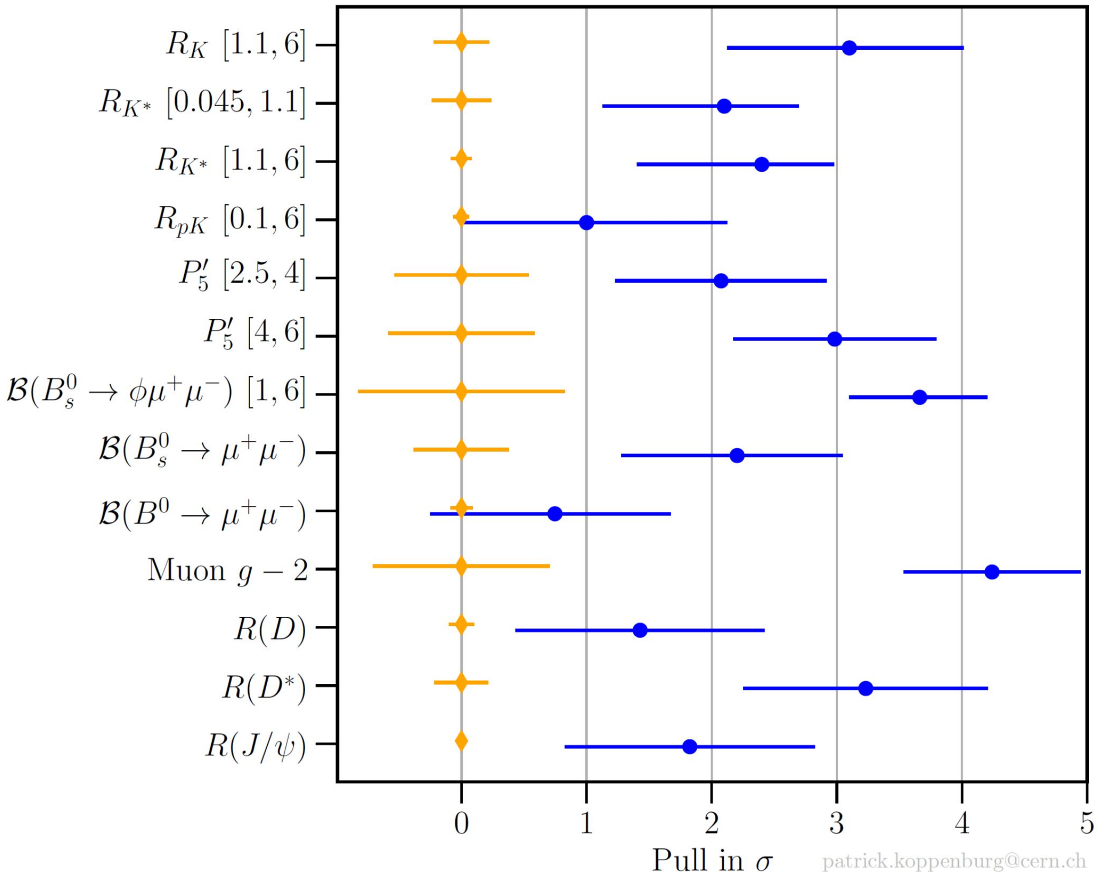
Phase 1: LHCb 23 fb^{-1}, CMS/ATLAS 300 fb^{-1}
Phase 2: LHCb 300 fb^{-1}, CMS/ATLAS 3000 fb^{-1}

CKMfitter Group, hep-ph/0406184
A. Cerri et al., 1812.07638

Prospective example of the determination of the CKM parameters

	Current	Phase I	Phase II
A	0.0120	0.0087	0.0072
λ	0.0007	0.0005	0.0004
$\bar{\rho}$	0.0085	0.0040	0.0019
$\bar{\eta}$	0.0087	0.0036	0.0016
$\|V_{ub}\|$	0.000096	0.000045	0.000031
$\|V_{cb}\|$	0.00070	0.00041	0.00033
$\|V_{td}\|$	0.00014	0.00009	0.00007
$\|V_{ts}\|$	0.00054	0.00040	0.00033
$\sin 2\beta$	0.015	0.006	0.003
α (°)	1.4	0.6	0.3
γ (°)	1.3	0.6	0.3
β_s (rad)	0.00042	0.00020	0.00010

Summary of anomalies



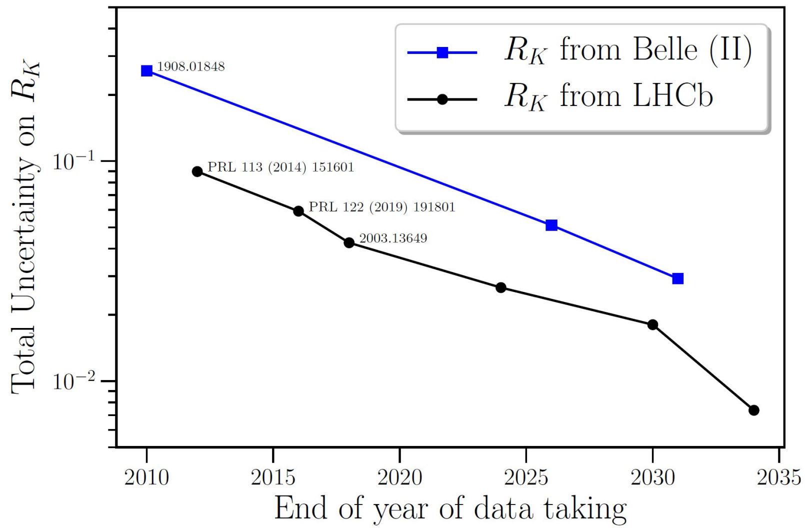
For more details and references

see talk by P. Koppenburg & N. Mahmoudi

@ "Beyond Flavour Anomalies", Durham, April 2021

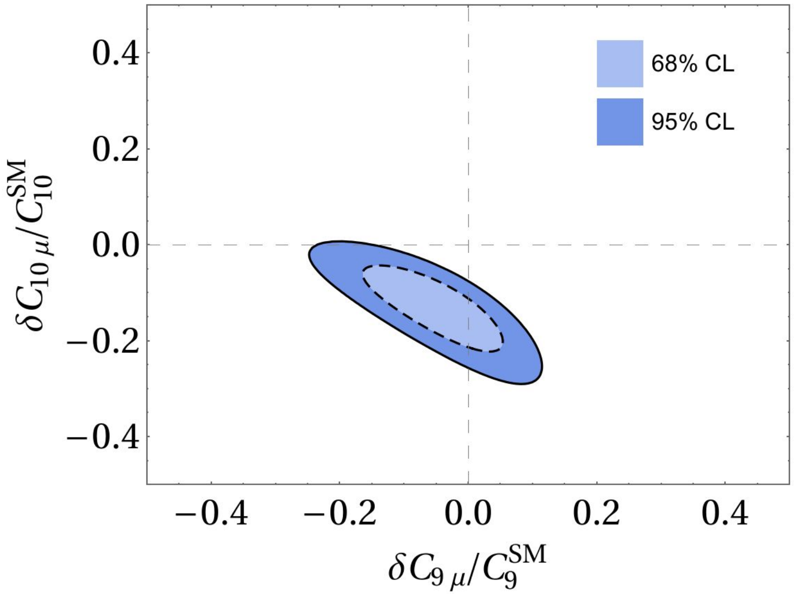
Perspectives

Pull$_{\rm SM}$ with R_K and R_K^* [+ BR($B_s \to \mu^+\mu^-$)] prospects			
LHCb lum.	18 fb^{-1}	50 fb^{-1}	300 fb^{-1}
δC_9^μ	6.5σ [6.5σ]	14.7σ [14.7σ]	21.9σ [21.9σ]
δC_{10}^μ	6.2σ [7.1σ]	16.1σ [16.6σ]	24.6σ [25.1σ]
δC_{LL}^μ	7.2σ [7.5σ]	17.5σ [17.7σ]	26.5σ [26.6σ]



From P. Koppenburg

T. Hurth, F. Mahmoudi, D. Martínez Santos, S. Neshatpour, 2104.10058



Current data

Perspectives

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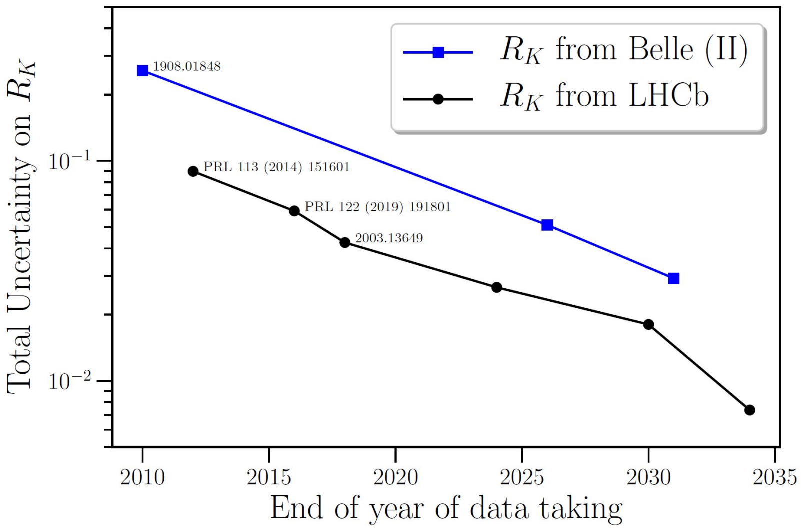

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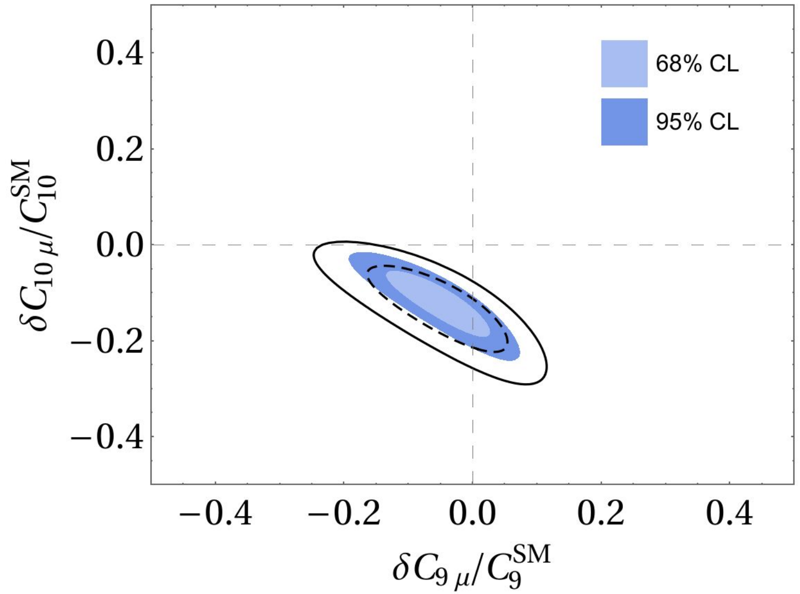

Projection for 18 fb^{-1}

Perspectives

Pull_{SM} with R_K and R_K^* [+ BR($B_s \to \mu^+\mu^-$)] prospects			
LHCb lum.	18 fb^{-1}	50 fb^{-1}	300 fb^{-1}
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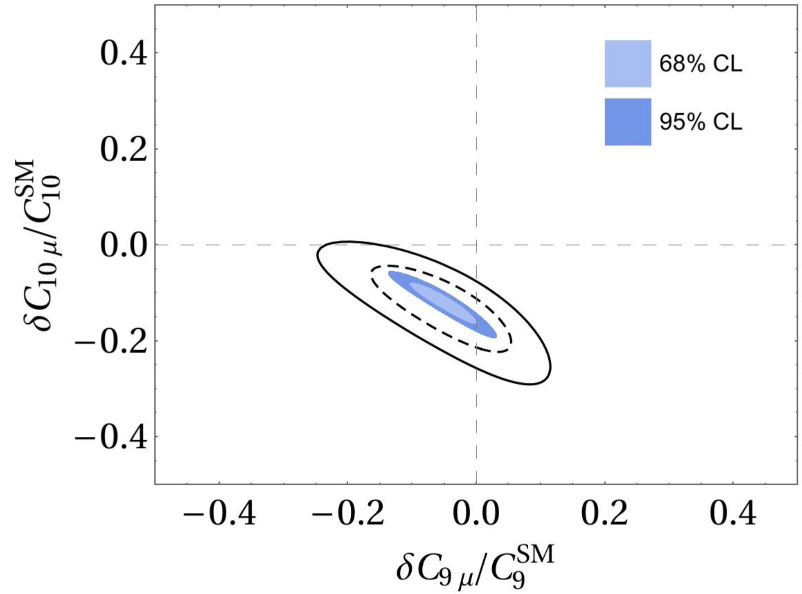

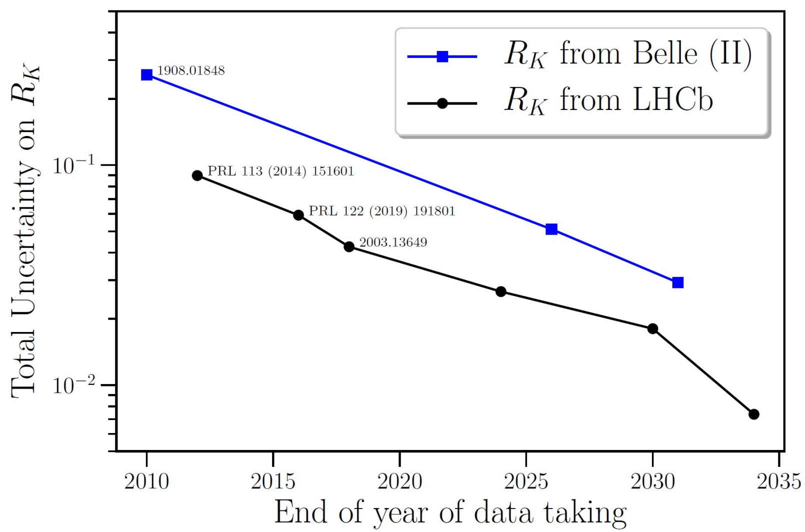

From P. Koppenburg

Projection for 50 fb^{-1}

Perspectives

Pull$_{SM}$ with R_K and R^*_K [+ BR($B_s \to \mu^+\mu^-$)] prospects			
LHCb lum.	18 fb^{-1}	50 fb^{-1}	300 fb^{-1}
δC^μ_9	6.5σ [6.5σ]	14.7σ [14.7σ]	21.9σ [21.9σ]
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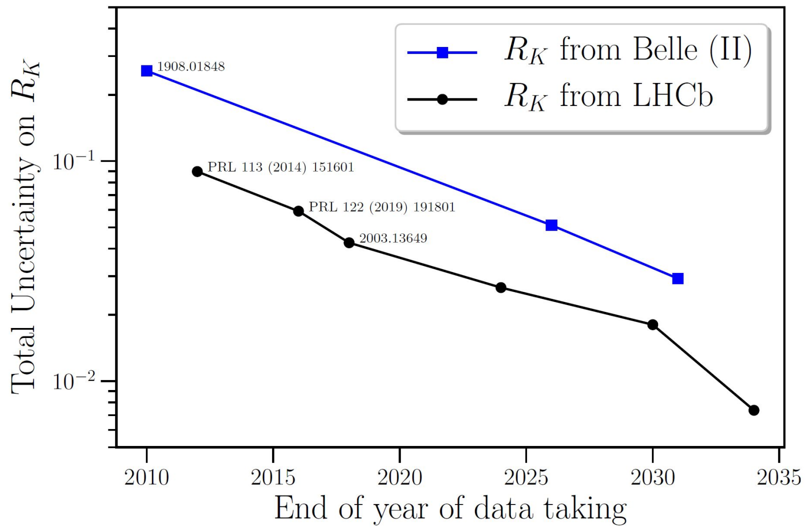

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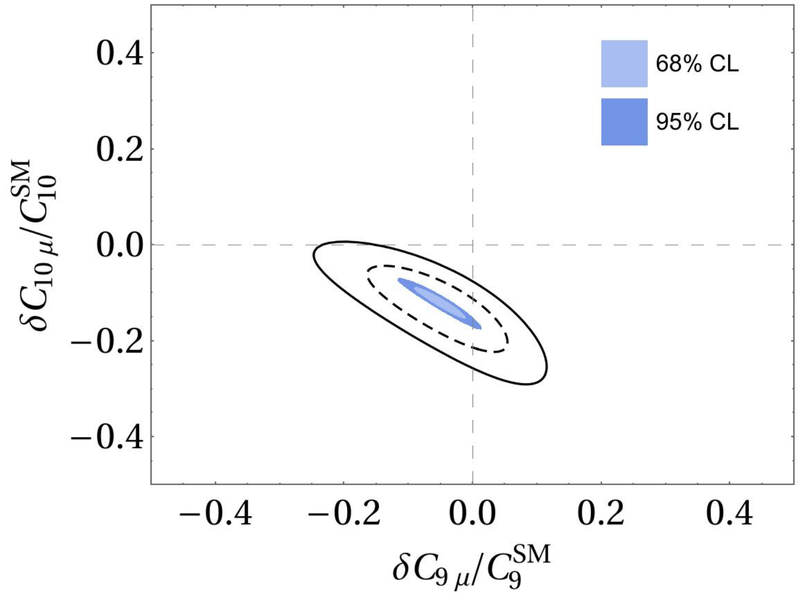
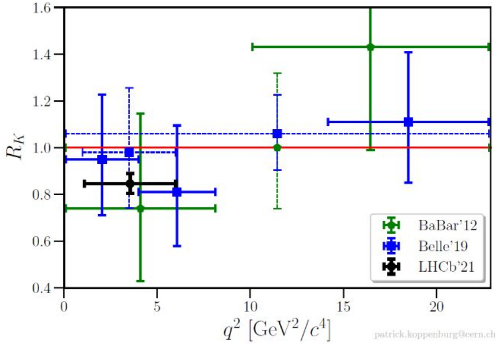
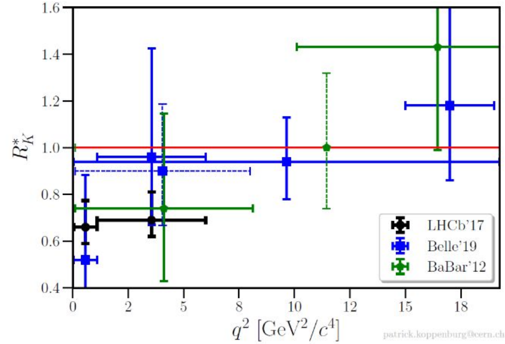


Projection for 300 fb^{-1}

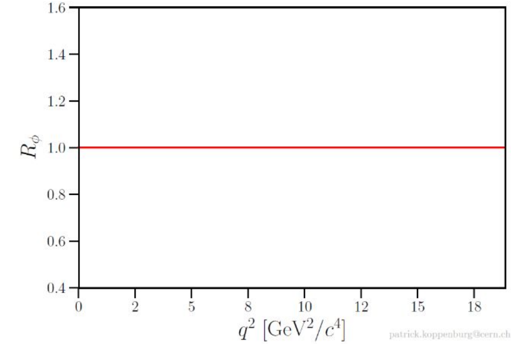
It's just the beginning...



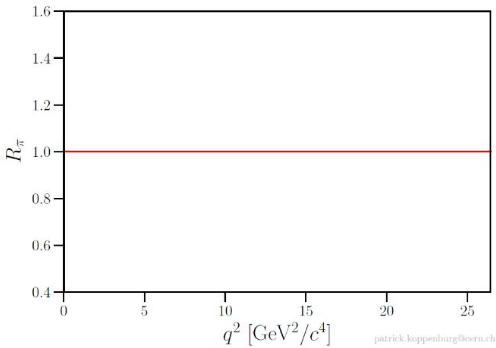
$B \to K\ell^+\ell^-$



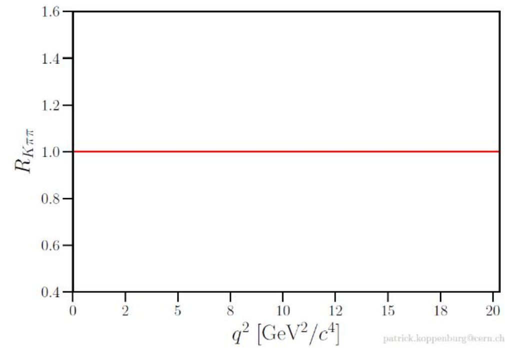
$B \to K^*\ell^+\ell^-$



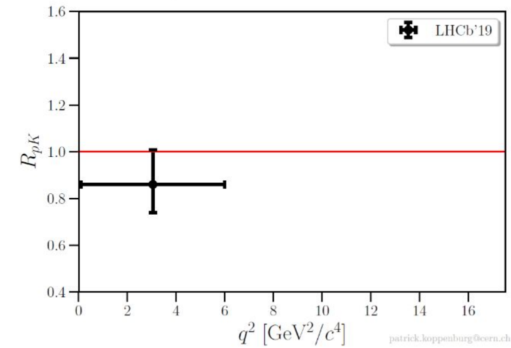
$B_s^0 \to \phi\ell^+\ell^-$



$B \to \pi\ell^+\ell^-$



$B \to K\pi^+\pi^-\ell^+\ell^-$



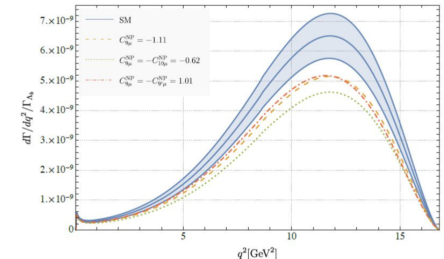
$\Lambda_b^0 \to pK^-\ell^+\ell^-$

Numerous measurements to come, numerous decays to study...

Other sectors

Other flavour physics sectors (baryons, kaons, charm,...) can provide complementary informations

Baryon decays [e.g. $\Lambda_b \to \Lambda(1520)\ell\ell$, see Descotes-Genon, Novoa-Brunet, JHEP06(2019)136]
Charm decays [e.g. $D \to \pi\ell\ell$, see Bharucha, Boito, Méaux, JHEP04(2021)158]
Kaon decays, ...

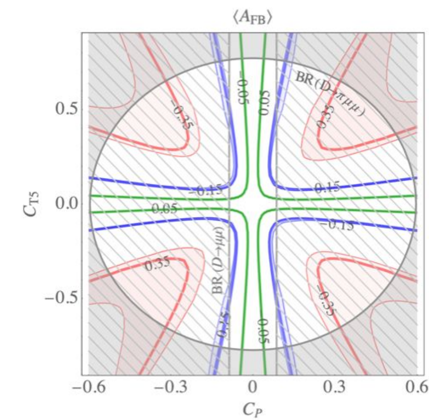


JHEP06(2019)136

Numerous predictions and studies still needed, for example:

- Theory predictions for $B_s \to \gamma\ell\ell$
- Non-factorisable contribution to the radiative $B \to K_{res}\,\gamma$ (K_{res} being the kaonic resonance) to compute charm penguin effects to the photon polarisation measurement
- Improved LCSR results for B to π and B_s to K form factors
- B decays with τ(s) in the final state
- hadronic effects in QCD: calculation of form factors via LCSR or LQCD
- additional non-perturbative effects when factorization breaks down due to hadronic (charmonium) contributions to the quark loop mediating the decay
- Form factors for the non-resonant channels (e.g. $B \to K\pi$) which contribute to the background [Sébastien Descotes-Genon et al., arXiv:1908.02267]
- ...

Sensitivity of observables to Wilson coefficients



JHEP04(2021)158

French groups are playing a leading role in many of the key studies

The coming years will be crucial for new physics searches through flavour physics

And the prospects are very promising!

Thanks to all flavour physics colleagues, in particular those who contributed to the original document for the perspectives!

Flavour physics and indirect searches for new physics (Theory)

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