Where do we stand and where could we go?
Some General Remarks at the End ...

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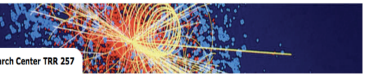


IPPP Workshop "Beyond the Flavour Anomalies", Byteland, April 3rd, 2020

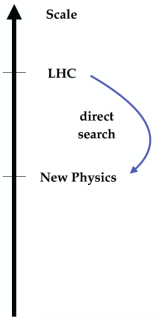
Contents

Introduction

Current state of Particle Physics:

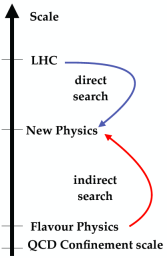
- High Energy Frontier:
  - LHC
  - future colliders
- Precision Frontier
  - Charged Lepton Flavour Physics
  - Neutrinos
  - Quark Flavour Physics

Direct Searches @ LHC

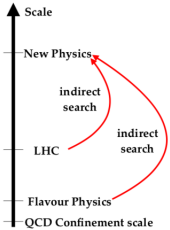


- New particles created on shell
- Identification through decay products
- Search is limited by the collider energy

Indirect searches through precision:



- New particles through virtual effects
- Small deviations from SM predictions
- Sensitive also to large scales



- Effective Theories as common method
- Generic approach in collider and flavour
- Seach is not limited by the collider energy

Currently the indirect methods seem to be our only telescope to BSM phyiscs

The right picture seems to be most likely from current data, however, it could be ...

Thus (Quark) Flavour has attracted renewed attention:

- Various measurements showing “anomalies”
- ... unlike at the high energy frontier
- These anomalies allow for a BSM interpretation (Leptoquarks, Z')
- However, be cautious!! Hadronic traps can be everywhere!

Vast experience with effective theory methods from flavour physics

Landscape of Anomalies (and beyond)

Seven "sets" of anomalies:

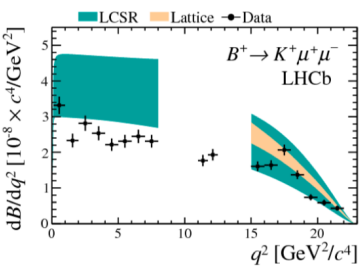
- Branching ratios of $b \to s\,\mu\mu$ processes
- Angular distributions in $b \to s\,\mu\mu$ processes
- Ratios of $b \to s\,ee$ versus $b \to s\,\mu\mu$
- Ratios of exclusive $b \to c\tau\bar{\nu}$ versus $b \to c\ell\bar{\nu}$

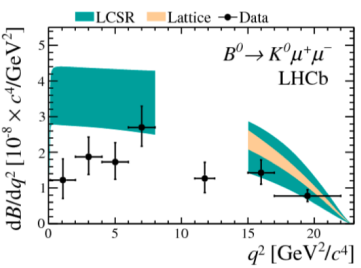
- CP Violation: Δa_{CP} in Charm and Kaon ϵ'/ϵ
- Exclusive versus inclusive V_{xb}
- Anomalous magnetic moment of the muon

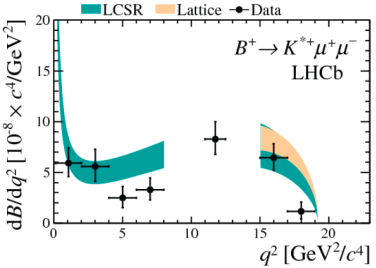
Anomalies

Beyond Anomalies

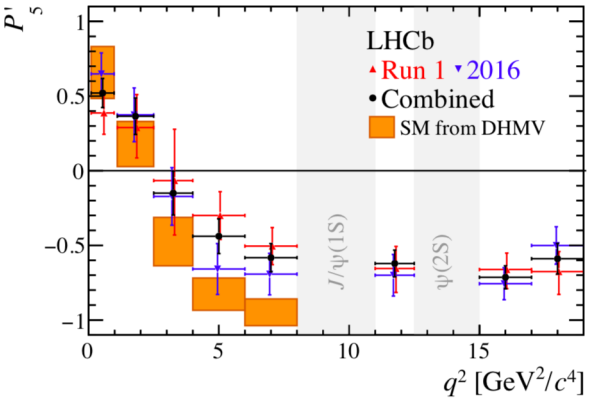
Branching ratios of $b \to s\mu\mu$ processes

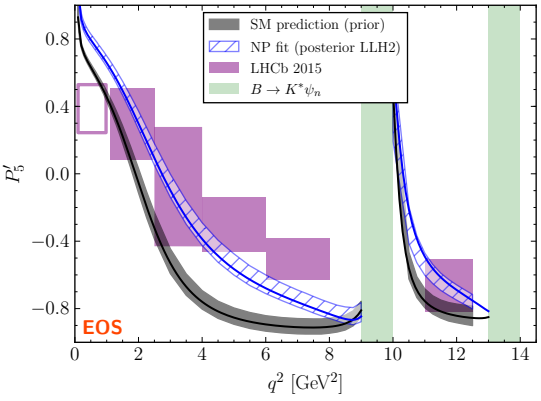




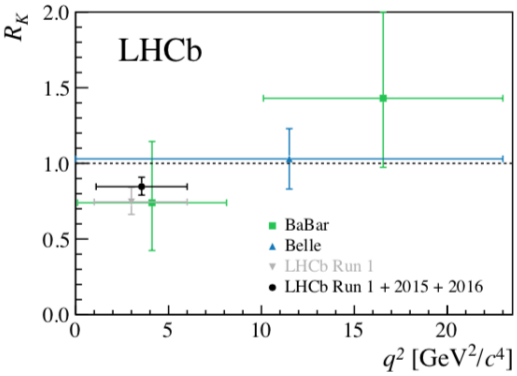


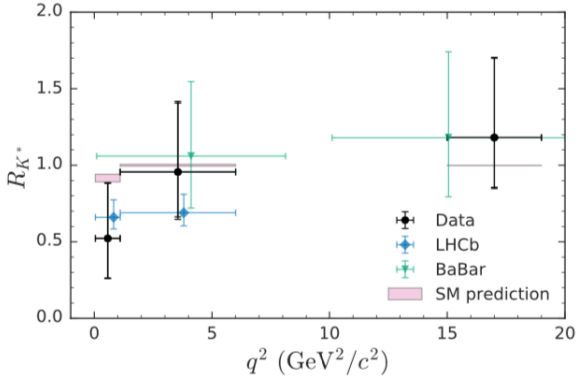
Angular Distributions in $b \to s\mu\mu$ processes



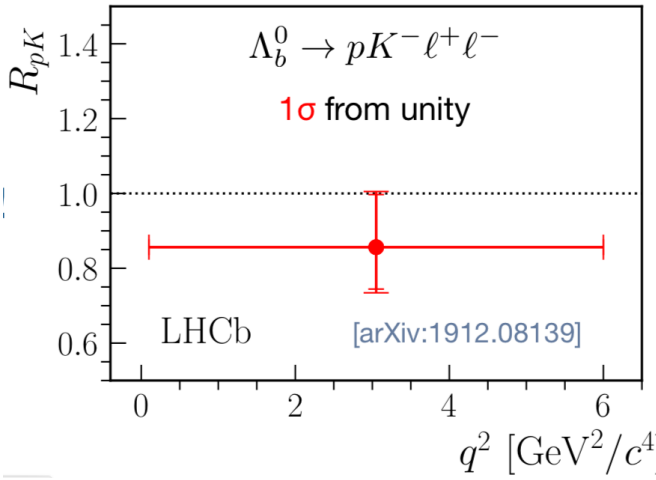


Ratios of $b \to s\, e^+ e^-$ and $b \to s\, \mu^+ \mu^+$ rates

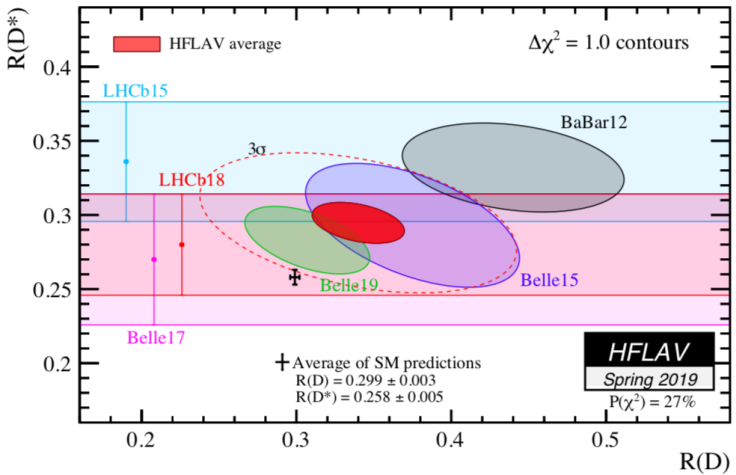




Fairly new and interesting:



Ratios of $b \to c\tau\bar{\nu}$ and $b \to c\ell\bar{\nu}$ rates



Theoretical Interpretation

Proceed in three steps:

- Effective Field Theory Analysis
- Simplified Models
- (UV) Complete Theory

Effective Field Theory Analysis

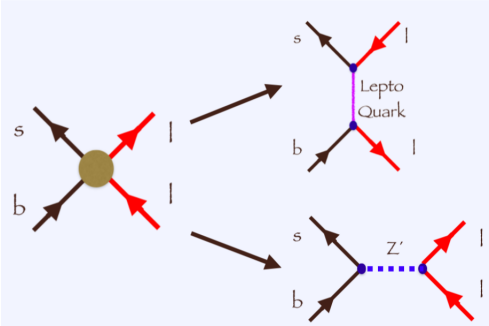
Effective Hamiltonian at the bottom scale:

$$H_{\text{eff}} = \frac{G_F}{\sqrt{2}} \lambda_{\text{CKM}} \sum_i C_i O_i + \frac{1}{\Lambda_{\text{NP}}^2} \sum_i C_i^{\text{NP}} O_i^{\text{NP}}$$

All the current anomalies can be incorporated by a shift in the coefficients $C_{9^{(\prime)}}$ and $C_{10^{(\prime)}}$ for the Muon channel

$$\mathcal{O}_{9\ell} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell), \quad \mathcal{O}_{10\ell} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell),$$
$$\mathcal{O}_{9\ell'} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell), \quad \mathcal{O}_{10\ell'} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell),$$

Interpretation in simplified models

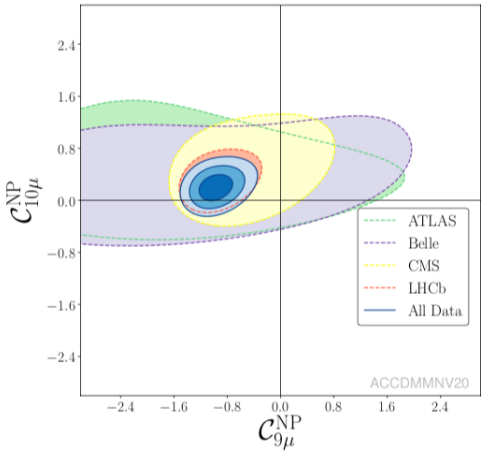


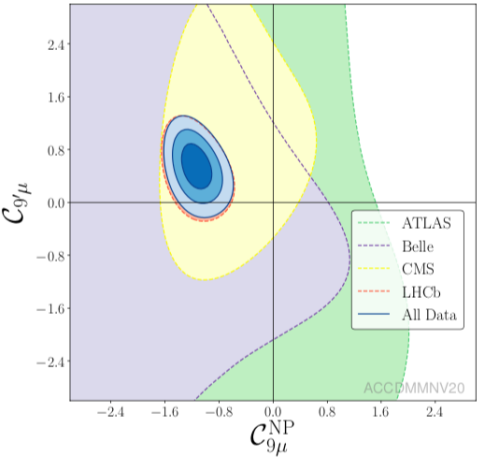
- Introduce a Z'
- Introduce a Leptoquark

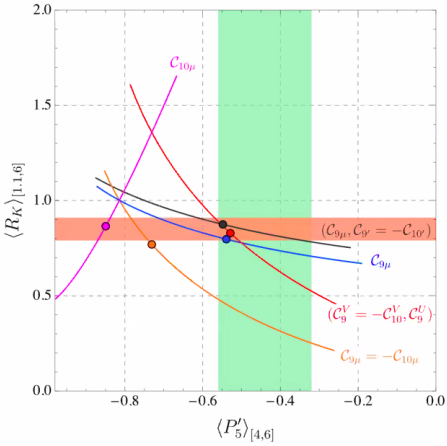
$\rightarrow$ Leptoquark seems to be more promising, but ...

What to conclude as of now?

Effective Field Theory: WET and SMEFT







New $B \to K^* \mu\mu$ data a very reassuring confirmation of the situation in $b \to s\ell\ell$

- Increased consistency between $B \to K^* \mu\mu$ data and the rest of the global fit, in particular between R_K and P'_5
- Increase in the pull_{SM} of the favoured scenarios, no change in hierarchy of scenarios
- Possibility of right-handed currents in several favoured scenarios
- Possibility of LFU contributions, in good agreement with simple EFT interpretations combining $b \to c\ell\nu$ and $b \to s\ell\ell$ anomalies
- Significant decrease of the p-value of the SM

(Descote-Genon, Stangl)

Towards a UV complete theory … (talk by G. Isidori)

- *Toward a UV completion: the* PS^3 *hypothesis*

Starting observation: the gauge theory proposed in the 70's to unify quarks and leptons by Pati & Salam predicts a massive vector LQ with the correct quantum numbers to fit the anomalies:

Pati-Salam group: $SU(4)\times SU(2)_L\times SU(2)_R$

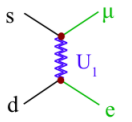
Fermions in SU(4): $\begin{bmatrix} Q_L^{\alpha} \\ Q_L^{\beta} \\ Q_L^{\gamma} \\ L_L \end{bmatrix} \begin{bmatrix} Q_R^{\alpha} \\ Q_R^{\beta} \\ Q_R^{\gamma} \\ L_R \end{bmatrix}$

Main Pati-Salam idea:
Lepton number as "the 4th color"

The massive LQ [U_l] arise from the breaking $SU(4) \rightarrow SU(3)_C\times U(1)_{B-L}$

The problem of the "original PS model" are the strong bounds on the LQ couplings to 1st & 2nd generations [e.g. $M > 200$ TeV from $K_L \rightarrow \mu e$]

Interesting recent attempts to solve this problem adding extra fermions and/or modifying the gauge group [Calibbi, Crivellin, Li, '17; Di Luzio, Greljo, Nardecchia, '17]



- *The PS^3 model*

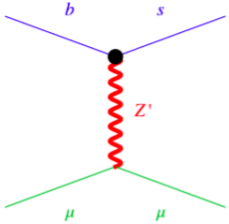
$$[\,PS\,]^3 = [\,SU(4)\times SU(2)_L\times SU(2)_R\,]^3$$

Bordone, Cornella, Fuentes-Martin, GI, '17

- Has the proper Leptoquarks
- Flavour Symmetries
- Phenomenology at high Energies

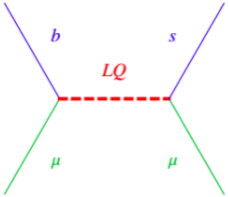
- Simplified models with LQ states seem to be favored. Among them, the U_1 case stands for simplicity & phenomenological success.
  The PS^3 model is an interesting example of (a class of) UV framework(s) which could host it, and could help to shed light on "old" SM problems.

Other Ideas (talk by J. Davighi)



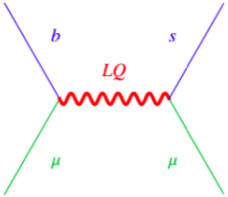
Z'

E.g. spontaneously-broken $U(1)$. Anomaly-free?



S_3

Light scalar - how? Why no proton decay due to $\overline{Q^c} S_3 Q$?



$U_1,\ U_3$

Non-renormalizable; UV completions? E.g. PS-based models, "4321",...

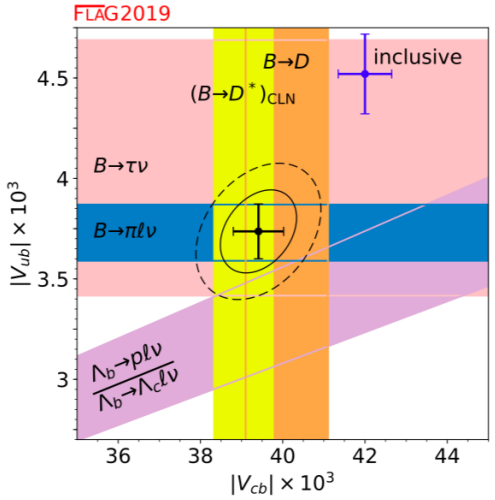
3rd z' models ...

Beyond Anomalies: Old(er) Problems

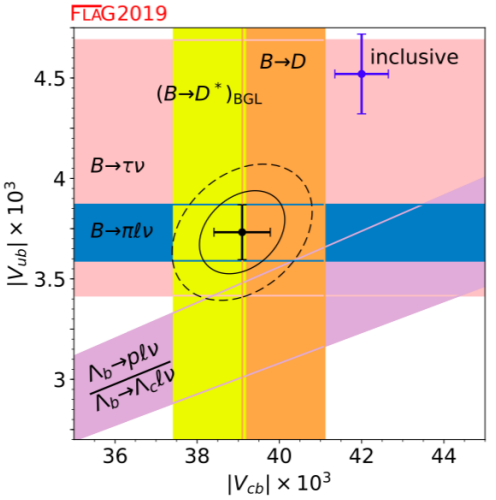
Inclusive versus Exclusive V_{xb}

Charged Current Semileptonics are under scrutiny:

- Tensions between inclusive and exclusive determinations of V_{cb}
- Tensions between inclusive and exclusive determinations of V_{ub}



BGL param.



CLN param.

A lot of theoretical effort:

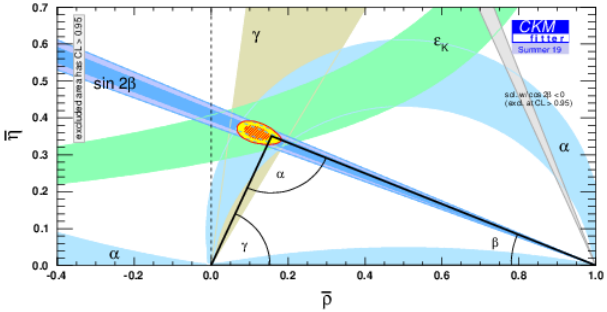
- Exclusive:
  - Detailed analysis of BGL parametrizations for $b \to c$ (Liegti, Bernlochner ...)
  - Theoretical analysis of $b \to c$ form factors to $1/m^2$ (Bordone, Jung, van Dyk)
  - $b \to u$ channels beyond $B \to \pi$ ($B \to \pi\pi$, ...)
  - Baryonic $b \to c$
- Inclusive:
  - Higher orders in α_s and $1/m$ in $b \to c$ (Gambino, Pivovarov, Moreno, ...)
  - Reducing the number of HQE parameters $b \to c$ (Fael, Vos, Korbach ...)
  - Update BLNP for $b \to u$ (Lange, Paz: WIP)

A comment on V_{ub}

- Inclusive V_{ub} is more difficult that Inclusive V_{cb}
- Shape function-dependent methods GGOU and BLNP
- Update for BLNP urgently needed
- Most precise V_{ub} from $B \to \pi \ell \bar{\nu}$
- Method is Lattice QCD $\otimes$ Light Cone sum rules
- Need for V_{ub} extraction from other exclusive channels

CP Violation

- ... in two-body Bottom decays



- ... in multibody Bottom decays
- ... in Charm decays: Δa_{CP} from LHCb
- ... in Kaon Decays: ϵ'/ϵ

CP Violation in Charm Decays (from Khodjamirian, Petrov)

- Experimental results
  - note that while the new result does constitute an observation of CP-violation in the difference...

$$\Delta a_{CP}^{dir} = a_{CP}(K^-K^+) - a_{CP}(\pi^-\pi^+) = (-0.156 \pm 0.029)\% \quad \text{LHCb 2019}$$

  - ... it is not yet so for the individual decay asymmetries

$$\begin{aligned} a_{CP}(K^-K^+) &= (0.04 \pm 0.12\ (\text{stat}) \pm 0.10\ (\text{syst}))\%\,, \\ a_{CP}(\pi^-\pi^+) &= (0.07 \pm 0.14\ (\text{stat}) \pm 0.11\ (\text{syst}))\%\,. \end{aligned} \quad \text{LHCb 2017}$$

- Need confirmation from other experiments (Belle II)

Result from a QCD Sum rule estimate (from Khodjamirian, Petrov)

- The magnitude of direct CPV asymmetry in $D \to \pi^+\pi^-$ and $D \to K^+K^-$ can be predicted from the calculation of the relevant hadronic matrix elements from LCSRs

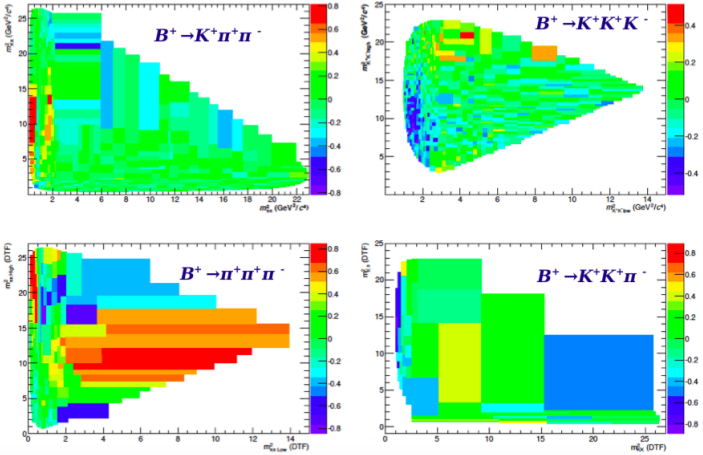
$$\Delta a_{CP}^{dir} = \quad 0.020 \pm 0.003\%$$

- No topological amplitude decomposition was used (note that OPE hierarchy sorts out the leading penguin-type diagrams)
- The strong phase difference is not yet reliably accessible: duality violations are not easily identifiable (e.g. broad scalar resonances influencing hadronic matrix elements)

This remains a real challenge for TH ...

CPV in three-body B decays

Interesting LHCb data:



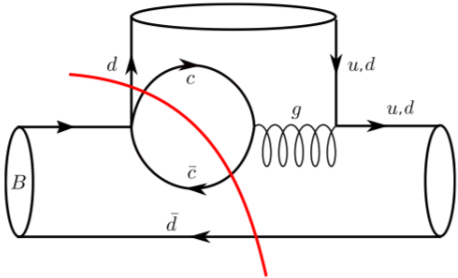
TH Description of the CP distribution is really difficult!

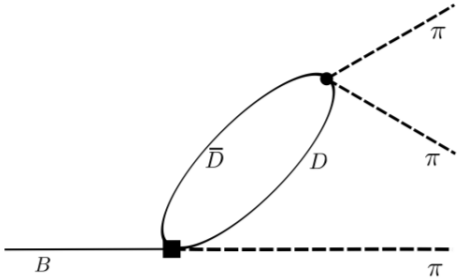
- QCDF can be applied to multibody decays (Kränkl, Virto, ...)
- CPV Distribution is a power suppressed effect (Klein, Virto, Vos ...)
- Must be modelled (I. Bediaga, T. Frederico and P. Magalhaes, K. Olschewsky, K. K. Vos ...)

Teaches us more about QCD aspects than about the CPV mechanism!

Model Ansatz for an amplitude analysis

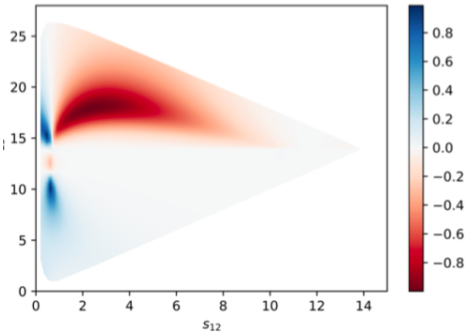
Direct CPV from the interference of A_u and A_c

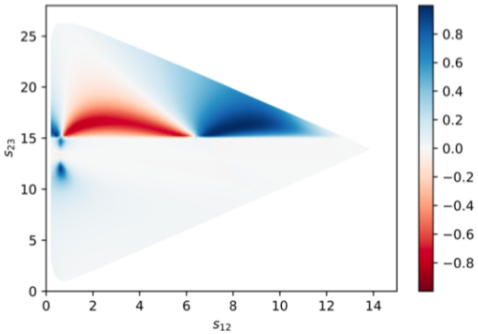




Relevant Effect: Charm thresholds in A_c (I. Bediaga, T. Frederico and P. Magalhaes ... Olschewsky, Vos

Modelling charm theshold effects:





s-wave resonance

p wave resonance

Fits need to be done, separating A_u and A_c ...

Conclusions / Questions

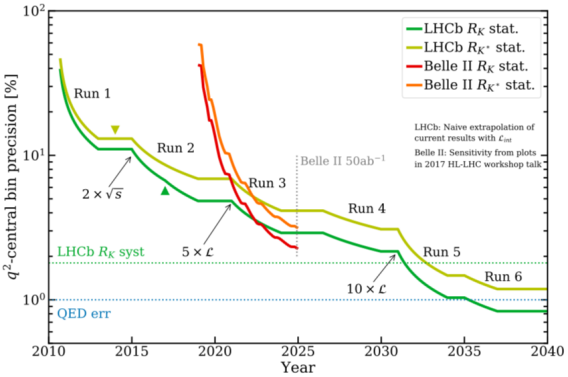
- How will the anomalies evolve in time?
- What is going on in V_{xb}? In particular in V_{ub}
- Scrutinize the methods for inclusive V_{ub} (Update BLNP)
- Is there “new physics” in CP violating observables?
  - Δa_{CP} in Charm
  - ϵ'/ϵ
  - What will the CPV data from multibody decays tell us about hadronic matrix elements?
- Do we understand the hadronic matrix elements well enough?

In any case:

- Quark (and Lepton) Flavour Physics is in good shape
- It is an important tool to analyse BSM effects
- Due to the anomalies, there has been intensified interest

The current situation suggests that the era of direct searches might be over until further notice, we will all need to go the “precision road”, including also LHC at highes reachable energies.
If the anomlies are true, this may also indicate that the solution of the flavour problem may lie not as high as the Planck scale, as it has been often assumed in the past ...

Theory needs Experiment!!



We all look forward to more data from LHCb and Belle II, keep on going strong!

Thanks

.. and stay healthy!!