Keynote talk, Implications of LHCb measurements and future prospects, CERN, 2016

Flavour Physics: Outlook

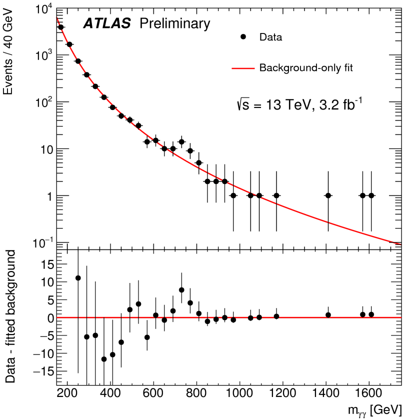
David M. Straub Universe Cluster/TUM, Munich

Disclaimer

- Not a summary of the workshop
- Not a fair representation of all interesting topics

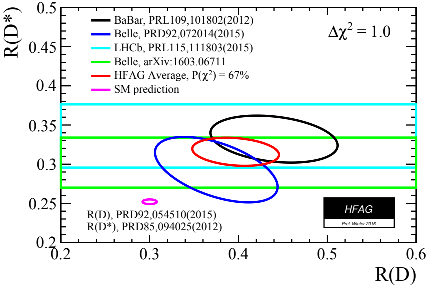
Some lessons learned

Even beloved anomalies can go away



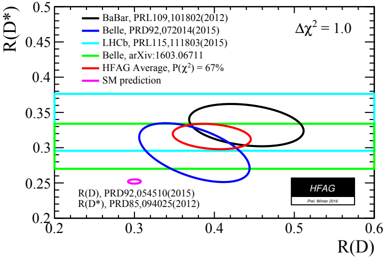
No signal in direct searches: underlines importance of indirect searches (but is depressing nevertheless!)

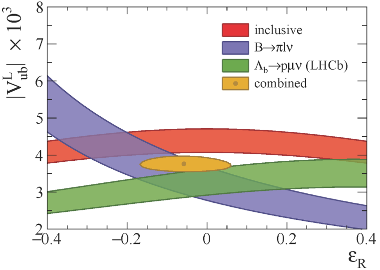
NP could show up in unexpected places



In lack of a clear hint of new physics, crucial to keep an open mind!

LHCb always good for a surprise





Keep suprising us!

Exploiting the apparent mass gap

If new physics is heavy, can use SM gauge symmetry to restrict form of NP, e.g.

- Relation between scalar & pseudoscalar operators in $b \to s$ transitions Alonso et al. 1407.7044
- Right-handed W coupling does not violate LFU Talk by J. Martin Camalich
- Indirect electroweak precision tests using flavour Brod et al. 1408.0792, Bobeth and Haisch 1503.04829
- Charged lepton flavour violation (without hadrons) from LFU violation Feruglio et al. 1606.00524
- ...

Is it worth going for 300 fb^{-1}?

Yes

Why?

- No signal in direct searches $\to$ leave no stone unturned
- $O(1)$ effects in many modes excluded $\to$ precision, precision, precision
- Plethora of (quasi-) null tests or clean observables
  - γ_{CKM} Talk by D. Johnson
  - $B_{s,d}$ mixing phases
  - T-odd CP asymmetries in $B \to V\mu^+\mu^-$ Talk by K. Petridis
  - Rare D decays Talk by S. de Boer
  - ...
- Impressive progress from LQCD Talk by M. Hansen, R. Van de Water
- Complementarity to Belle-II (Λ_b, B_s, ...)
- ...

Status of $b \to s\mu^+\mu^-$ anomalies

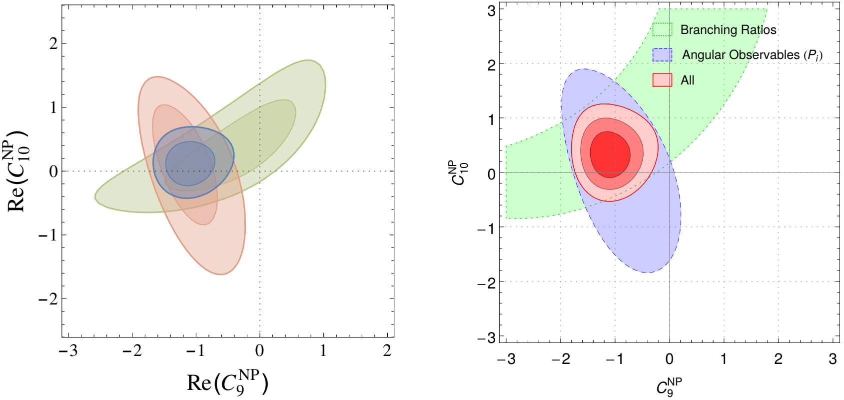
Current tensions in $b \to s\mu^+\mu^-$ transitions

Mode	Observable	Bin	Pull
$B^0 \to K^*\mu^+\mu^-$	P_5'	4–6	$-\mathbf{2.6\sigma}$
$B_s \to \varphi\mu^+\mu^-$	BR	1–6	$-\mathbf{3.3\sigma}$
$B^+ \to K^+\mu^+\mu^-$	BR	1–6	$-\mathbf{2.0\sigma}$
$B^+ \to K^+\mu^+\mu^-$	BR	15–22	$-\mathbf{2.6\sigma}$

Suspects: New physics? Form factors? Charm loop?

(flavio v0.13.1 using combined LCSR+LQCD FFs for $B \to V$ FFs Bharucha et al. 1503.05534 and FNAL/MILC $B \to K$ FFs Bailey 1509.06235; hadronic unc. estimated as in Altmannshofer and Straub 1411.3161)

Global constraints on C_9 & C_{10}



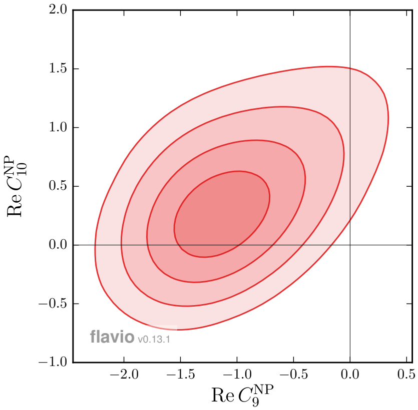
Altmannshofer and Straub 1411.3161, Descotes-Genon et al. 1510.04239

see also Hurth et al. 1603.00865

Update 2016

- including 3 fb^{-1} LHCb measurements of $\text{BR}(B^0 \to K^* \mu^+\mu^-)$ (2016) and $B_s \to \varphi\mu^+\mu^-$ (2015)
- Updated $B \to V$ FFs from v2 of Bharucha et al. 1503.05534
- Best fit point: **4.5σ pull** from SM

What does it mean?



Update 2016

Reproduce this plot
with flavio

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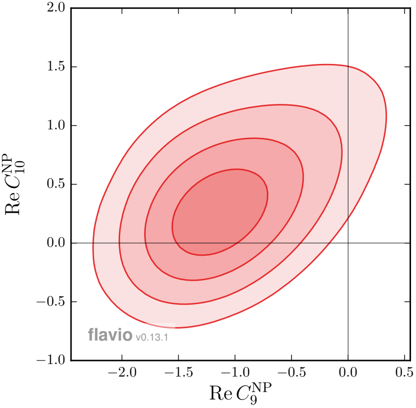
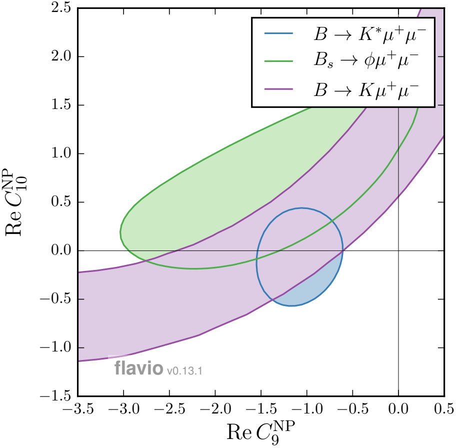


A closer look

Pulls for individual modes:

- $B \to K^* \mu^+ \mu^-$: **2.7σ**
  - famous P_5' anomaly
- $B_s \to \varphi \mu^+ \mu^-$: **3.4σ**
  - BR @ low & high q^2
    cf. Bharucha et al. 1503.05534, Ronald R. Horgan et al. 1310.3887
- $B \to K \mu^+ \mu^-$: **2.6σ**
  - BR @ low q^2 $\to R_K$!
  - First pointed out in: Khodjamirian et al. 1211.0234



Facts

1. Clearly, a significant tension between measurements and (these) predictions
2. All tensions solved simultaneously by a minimal new physics (EFT) assumption

$B \to K^*$: form factors?

- Complementary LCSR & LQCD results show good agreement
  Bharucha et al. 1503.05534, R. R. Horgan et al. 1501.00367
- Agreement of full FFs vs. heavy quark limit "soft" FFs using "optimised" observables Descotes-Genon et al. 1510.04239
  - Eventually, some arbitrariness in how to quantify power corrections without using info from LCSR or LQCD
    cf. Sebastian Jäger and Jorge Martin Camalich 1412.3183
    vs. Descotes-Genon et al. 1407.8526

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  - Comment 1: when contemplating large corrections to low-q^2 form factors use high q^2 info (data, LQCD) to check consistency
  - Comment 2: several open source codes now at disposal to compare different approaches on a common basis

But,

- Branching ratios more problematic than angular observables
- Significance in angular observables *does* depend on form factors
- $B \to K^*$ and $B_s \to \varphi$ more difficult than $B \to K$ Talk by T. Mannel

Future:

- LCSR systematically limited
- Crucial to treat the unstable K^* on the lattice Agadjanov et al. 1605.03386, Talk by M. Hansen

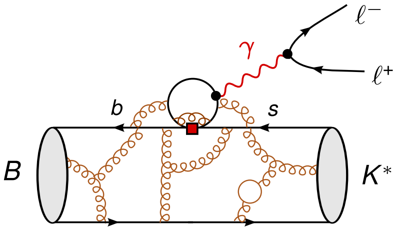
Charm loops in $B \to K^* \mu^+ \mu^-$

- Culprit: matrix element of $O_{1,2}$

$$\langle \bar{K}^* | T\{j^\mu_{\rm em}(x) C_{1,2} O_{1,2}(0)\} | \bar{B} \rangle$$

- Since $O_9 \propto \bar{\ell}\gamma^\mu \ell$, h_λ could mimic a new phyiscs effect in C_9
- can be parametrised as complex-valued (CP-even) functions of q^2: $h_{+,-,0}(q^2)$ for the 3 helicity amplitudes

$$O_2 = (\bar{s}_L \gamma_\mu c_L)(\bar{c}_L \gamma^\mu b_L)$$



How can we disentangle h_λ from C_9?

Anatomy of h_λ

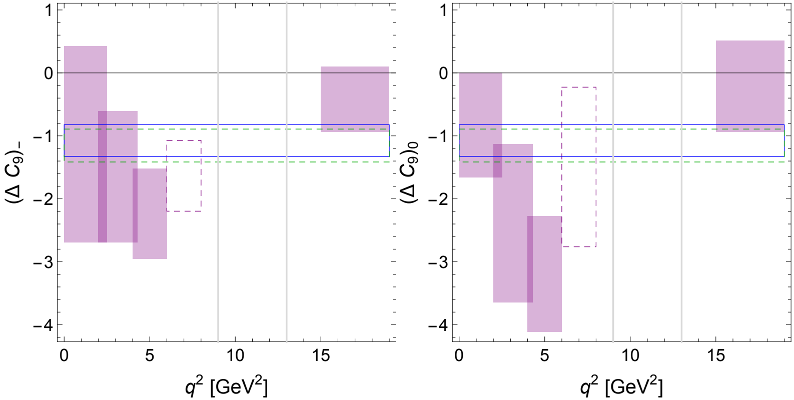
- Without loss of generality, absorb h_λ in a q^2 and helicity dependent shift of C_9:

$$C_9^{\mathrm{SM}} + \Delta C_9^{+,-,0}(q^2)$$

- h_- is expected to be helicity-suppressed
  S. Jäger and J. Martin Camalich 1212.2263
  - This can be tested by looking at S_3, P_2 $\to$ ignore for now
- imaginary parts hardly relevent $\to$ ignore for now

What is the q^2 and helicity dependence of the apparent shift in C_9?

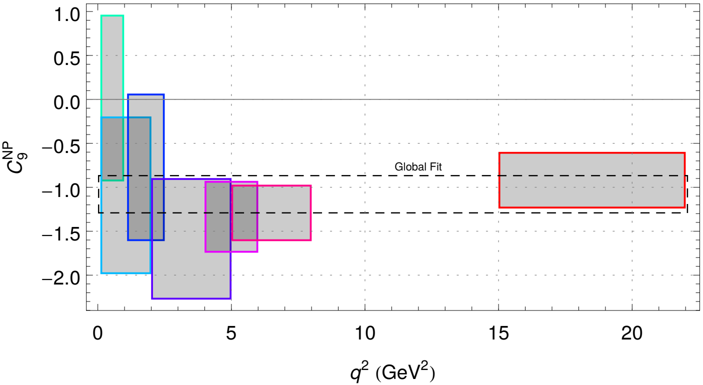
q^2 dependence of ΔC_9^λ



DS @ Moriond EW 2015; Altmannshofer and Straub 1503.06199

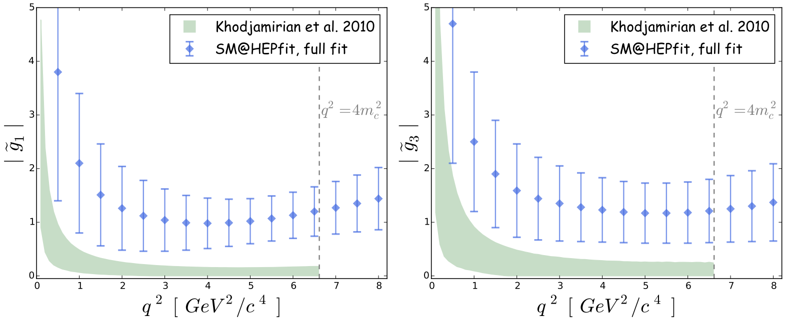
(1σ boxes)

q^2 dependence of ΔC_9^λ



Descotes-Genon et al. 1510.04239

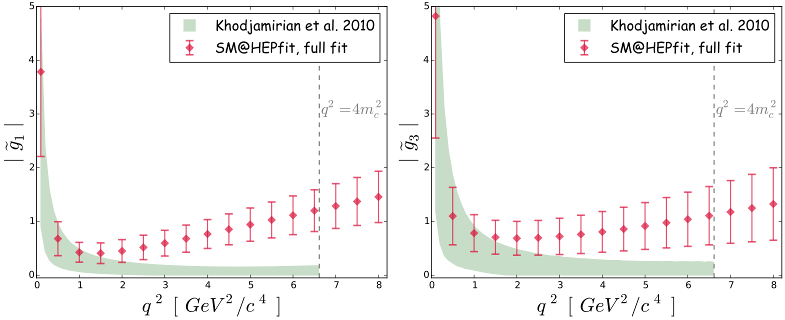
q^2 dependence of ΔC_9^λ



Ciuchini et al. 1512.07157

- Bayesian fit assuming a polynomial form for h_λ
- roughly: $\tilde{g}_1 \propto \Delta C_9^-$, $\tilde{g}_3 \propto \Delta C_9^0$

q^2 dependence of ΔC_9^λ



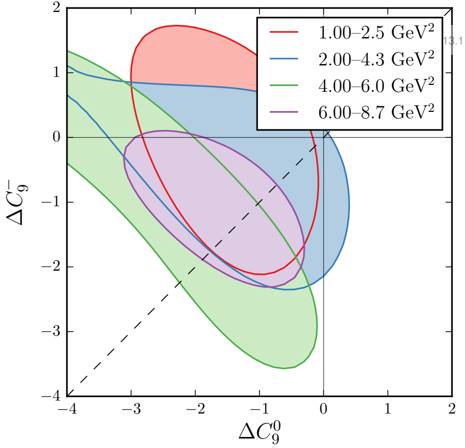
Ciuchini et al. 1512.07157

- Bayesian fit assuming a polynomial form for h_λ
- roughly: $\tilde{g}_1 \propto \Delta C_9^-$, $\tilde{g}_3 \propto \Delta C_9^0$
- **assuming** small ΔC_9^λ for small q^2 (expected for SM, but not NP!)

q^2 dependence of ΔC_9^λ

- Bin-by-bin fit of ΔC_9^0 vs. ΔC_9^-
- New physics: expect $\Delta C_9^0 = \Delta C_9^-$ equal for all bins

Current data **not precise enough** to exclude new physics hypothesis!



Plot based on discussion with C. Bobeth

Current situation

1. Data shows singificant preference for sizable effect around 4–6 GeV^2
2. q^2 dependence is compatible both with new physics and with charm hypothesis Talk by N. Mahmoudi

We can do better!

- Charm contribution obeys a dispersion relation
  Khodjamirian et al. 1006.4945 Talk by T. Mannel

Schematically:

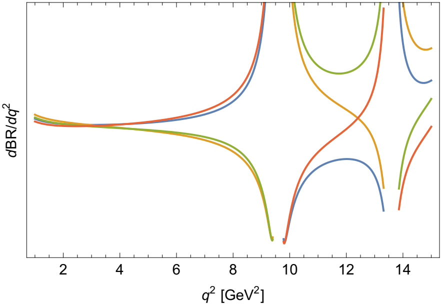
$$h_-(q^2) = h_-(0) + q^2 h'_-(0) + q^4 \left[\underbrace{\mathrm{BW}_{J/\psi} + \mathrm{BW}_{\psi(2S)}}_{\substack{\text{Measured from } B \to \psi K^* \\ \text{up to overall phase}}} + \underbrace{h_-^{\text{higher}}(q^2)}_{\substack{\text{small impact} \\ \text{below } m^2_{J/\psi} (?)}} \right]$$

- Need to fulfill this constraint in fits to data!

Charmonium interference

The q^2 dependence of the differential rate between the J/ψ and $\psi(2S)$ resonances can be used to infer the sign of the interference

Khodjamirian et al. 1006.4945



* this is only a cartoon – not actual numerics

Would be extremely helpful if LHCb could measure this Talk by K. Petridis

Homework: $b \to s\mu^+\mu^-$ anomalies

THEORY

- Improved lattice form factors
  - $B \to K$, $B \to K^*$ (finite lifetime!), $B_s \to \varphi$, $\Lambda_b \to \Lambda$
- Exploit dispersion relation to get better handle on charm
- Non-factorisable corrections to baryon decays

EXPERIMENT

- Measure charm resonances, including relative phases between short-distance and charmonium
- finer q^2 binning
- More precise measurements of related modes: $\Lambda_b \to \Lambda\mu^+\mu^-$, ...

A comment on fits & codes

Open source codes allow to make flavour pheno results accessible to experimentalists & model builders

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BUT please keep in mind that theories (both new physics and hadronic uncertainties) can change. Make sure data is published as independently of that as possible.

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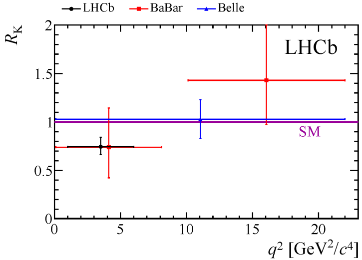
(i.e., Wilson coefficient fits fine “in addition”, but not “instead”.)

Violation of LFU: status of new physics explanations

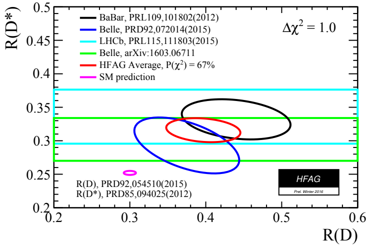
Violation of lepton flavour universality?

$B^+ \to K^+ee$ vs. $B^+ \to K^+\mu\mu$



- 2.6σ
- seen in single experiment
- theoretically very clean Talk by M. Bordone

$B \to D^{(*)}\tau\nu$ vs. $B \to D^{(*)}(e,\mu)\nu$



- 4.0σ combined
- 3 experiments
- dependent on form factors (D: LQCD, D^*: HQET)

Unified new physics explanations

Models with a single (heavy*) new particle/multiplet:

Spin	$SU(3)_c$	$SU(2)_L$	Name	Suggested
1	1	3	W', Z'	Greljo et al. 1506.01705
0	3	1	S_1	Bauer and Neubert 1511.01900
0	3	3	S_3	Medeiros Varzielas and Hiller 1503.01084
1	3	1	U_1	Barbieri et al. 1512.01560
1	3	3	U_3	Fajfer and Košnik 1511.06024

... and many more studies in the last 2 years Talk by A. Crivellin

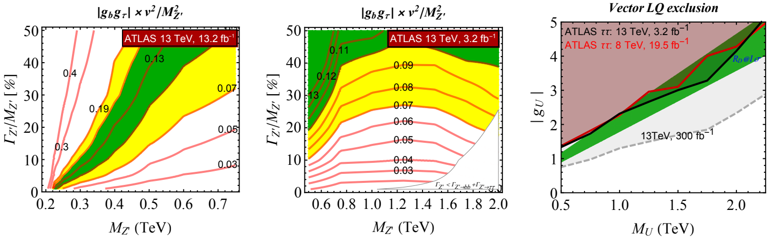
* See Bečirević et al. 1608.08501 for a LQ model with RH neutrinos

Indirect constraints

- U_3, S_3: strong constraint from $B \to K\nu_\tau\bar{\nu}_\mu$ cf. Buras et al. 1409.4557
- S_1:
  - $b \to s\mu^+\mu^-$ generated at 1-loop level Bauer and Neubert 1511.01900
  - Once all constraints (including K and D decays) taken into account, no simultaneous solution of anomalies Bečirević et al. 1608.07583
- All models generate $B \to K\tau\mu$ and $B_s \to \tau\mu$, but too small to be observed at Belle-II or LHCb Bhattacharya et al. 1609.09078
- RG effects lead to purely leptonic LFV Feruglio et al. 1606.00524

Direct constraints

- Strong constraints from $b\bar{b} \to \tau^+\tau^-$ searches at ATLAS/CMS
  Greljo et al. 1506.01705, Faroughy et al. 1609.07138
  - both Z' (s-channel) and LQ (t-channel)



- U_1 LQ on the verge of being excluded
- W'/Z' only allowed if light ($M < 500$ GeV) or broad ($\Gamma/M > 30\%$)

Summary of new physics explanations

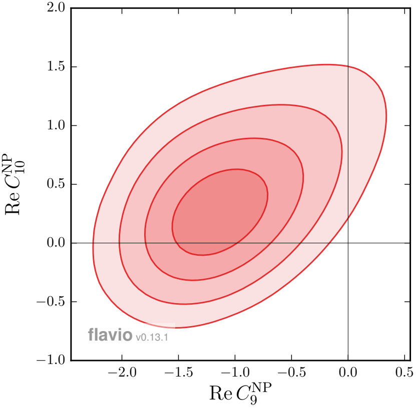
Single-particle explanations of all B decay anomalies are increasingly challenged by a **fruitful interplay** between

- model building
- B factory constraints ($B \to K\nu\bar{\nu}$!)
- LHCb constraints
- Charged lepton flavour violation
- Direct constraints from ATLAS/CMS

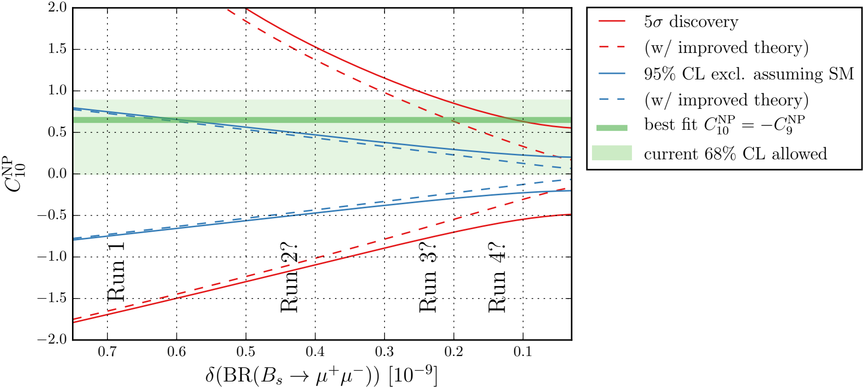
… of course, more eloborate constructions possible!

The crucial role of $B_s \to \mu^+\mu^-$

- All single-particle explanations of all anomalies predict $C_9^{NP} = -C_{10}^{NP}$
- C_{10} affects $B_s \to \mu^+\mu^-$ – free from photon-mediated effects!



Future constraints on C_{10} from $B_s \to \mu^+\mu^-$



Homework: violation of LFU

EXPERIMENT

- R_{K^*}, R_φ, and all that Talk by B. Capdevila
- $\Lambda_b \to \Lambda_c \tau \nu$ etc. Talk by G. Ciezarek

Homework: violation of LFU

EXPERIMENT

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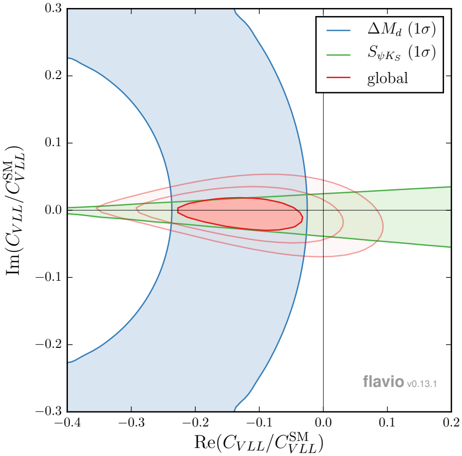
THEORY

- be patient

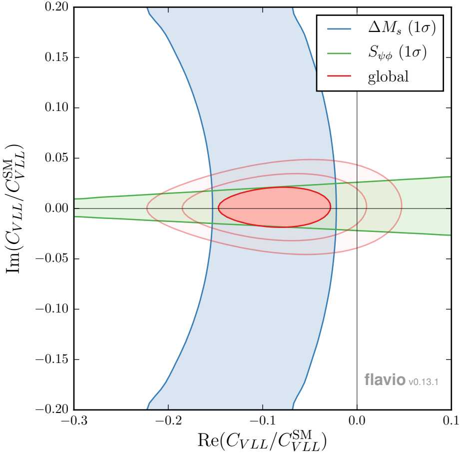
Looking ahead
(a few examples)

Status: new physics in B^0 mixing



- Using CKM from tree and matrix element from FNAL/MILC
- best fit **1.5σ** from SM
- Currently probing SM at 10% level in CP conserving, few-% level in CP violating observable

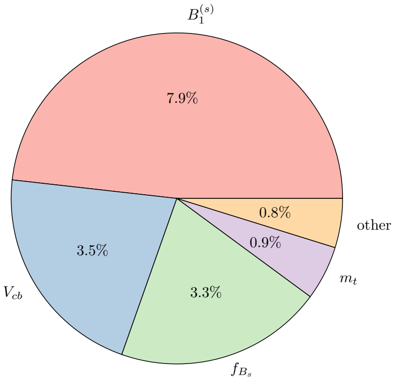
Status: new physics in B_s mixing



- Using CKM from tree and matrix element from FNAL/MILC
- best fit again **1.5σ** from SM

ΔM_s error budget

$$\Delta M_s \propto f_{B_s}^2 \hat{B}_{B_s} |V_{tb} V_{ts}^*|^2 = f_{B_s}^2 \hat{B}_{B_s} \left[V_{cb}^2 (1 + O(\lambda^2)) \right]$$



Relative uncertainty:

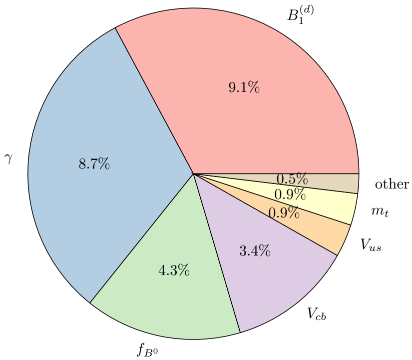
- Theory: **9%**
- Experiment: **0.1%**

Clearly, need lattice & CKM from tree to make progress!

(Using FNAL/MILC bag parameters and neglecting the correlation between f_{B_s} and $B_1^{(s)}$)

ΔM_d error budget

$$\Delta M_s \propto f_{B_d}^2 \hat{B}_{B_d} |V_{tb} V_{td}^*|^2 \approx f_{B_d}^2 \hat{B}_{B_d} \left(V_{ub}^2 + V_{cb}^2 V_{us}^2 - 2 V_{ub} V_{cb} V_{us} \cos\gamma \right)$$

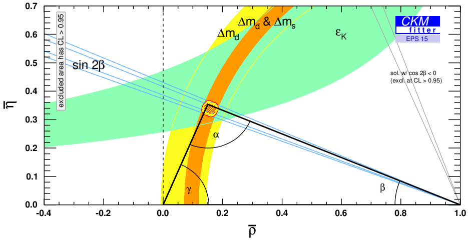


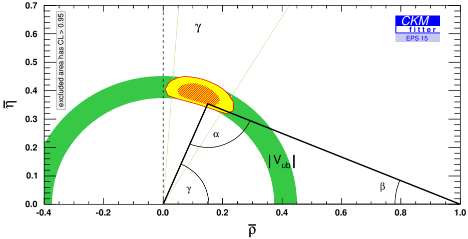
Relative uncertainty:

- Theory: **15%**
- Experiment: **0.4%**

(Using FNAL/MILC bag parameters and neglecting the correlation between f_{B^0} and $B_1^{(d)}$)

Tree vs. loop

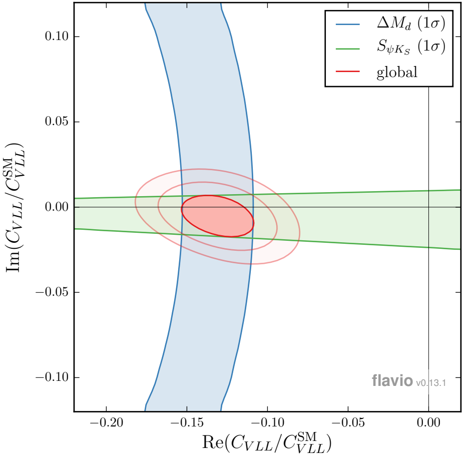




Crucial to test UT from tree vs. loop processes: importance of γ

Talk by D. Johnson

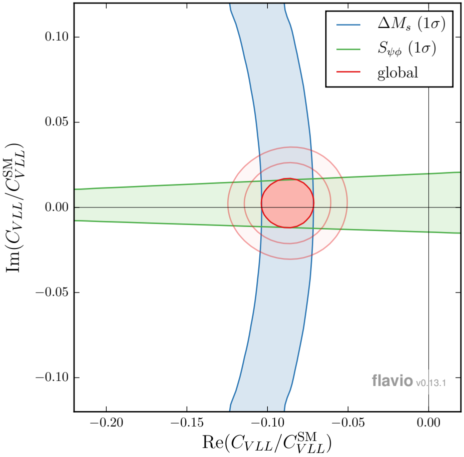
Future constraints from B^0 mixing



Dream scenario:

- current central values
- f_{B^0} to 0.5%
- $\hat{B}_{B^0}$ to 0.5%
- V_{ub} and V_{cb} to 1%
- γ to 0.5°

Future constraints from B_s mixing

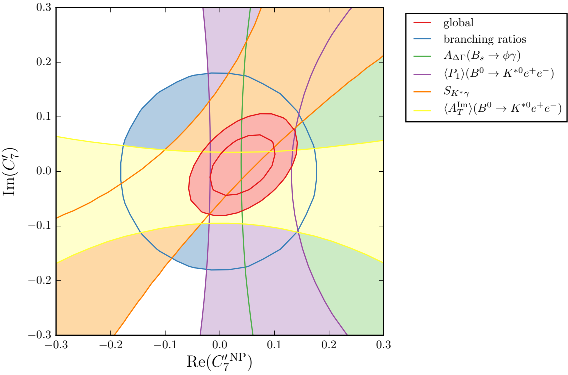


Dream scenario:

- current central values
- f_{B_s} to 0.5%
- $\hat{B}_{B_s}$ to 0.5%
- V_{ub} and V_{cb} to 1%
- γ to 0.5°

Determining the chirality of $b \to s\gamma$

- Wilson coefficient C_7' strongly suppressed in the SM
- Need exclusive decays to determine chirality
- recent LHCb measurements of $B \to K^* e^+ e^-$ angular observables and $B_s \to \varphi\gamma$ time-dependent decay rate



Paul and Straub 1608.02556

Future exclusive constraints on $b \to s\gamma$

Even more info on chirality and CP phases from

- Amplitude analysis of $B \to K\pi\pi\gamma$
- $\Lambda_b \to \Lambda\gamma$

New FCNC frontiers

- $b \to s$ transitions
  - $\Lambda_b \to \Lambda$ decays
  - $b \to s\tau^+\tau^-$ transitions
- $b \to d$ transitions
  - LCHb: 1st measurements of $B \to \pi\mu^+\mu^-$, $B \to \rho(\to \pi\pi)\mu^+\mu^-$, slight excess in $B_d \to \mu^+\mu^-$. Only the beginning!
  - Theory: better understanding of $O(V_{ub}V_{ud}^*)$ effects in semi-leptonic decays? see e.g. Hambrock et al. 1506.07760
- $c \to u$ transitions
  - Rare charm decays Talk by S. de Boer & V. Chobanova
  - Charm mixing Talk by A. Davis & A. Petrov

Conclusion

- Indirect searches crucial to find new physics $\to$ 300 fb^{-1} extremely well motivated
- Significant tensions in $b \to s\mu^+\mu^-$ transitions could be new physics, but SM explanations possible with current data
- Simultaneous new physics explanations of all $b \to s\mu^+\mu^-$ and $b \to c\tau\nu$ anomalies increasingly challenged by interplay of direct & indirect constraints
- Many exciting physics opportunities at LHCb run 2-3-4-5 (and Belle-II) that I didn't mention
- Time for new data!