Quark Flavour Physics

status and perspectives

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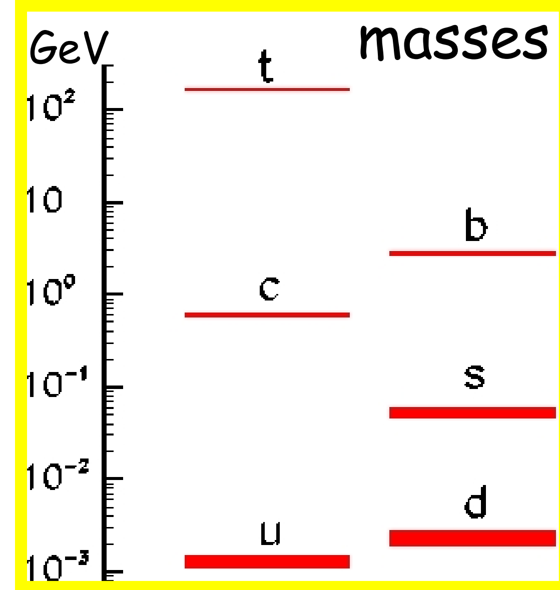
INFN ROMA TRE

- CKM matrix & ΔF=2 transitions
- "Anomalies" in ΔF=1 decays

Flavour physics in the SM: rich phenomenology (FCNC suppression, mixing, CP violation, …) but little understanding of the "why" and the "how"



$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{EWSB}} + \mathcal{L}_{\text{kin}} + \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Y}}$$

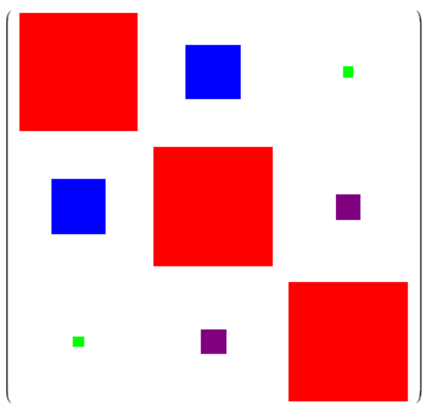
The Yukawa Lagrangian describes quark flavour physics in terms of 10 physical parameters:

6 masses, 3 mixing angles + 1 CPV phase

the Cabibbo-Kobayashi-Maskawa matrix

mixing

$V_{\text{CKM}} =$



Beyond the SM: a powerful indirect probe of the New Physics scale Λ

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{\mathcal{L}_5}{\Lambda} + \frac{\mathcal{L}_6}{\Lambda^2} + \dots$$

has accidental (approximate) symmetries

may violate accidental symmetries

SM UT analysis

Summer 2018

SM determination of the Unitarity Triangle

$$V_{ub}^{*}V_{ud}+V_{cb}^{*}V_{cd}+V_{tb}^{*}V_{td}=0$$

$$R_u\ e^{i\gamma}+R_t\ e^{-i\beta}=1$$

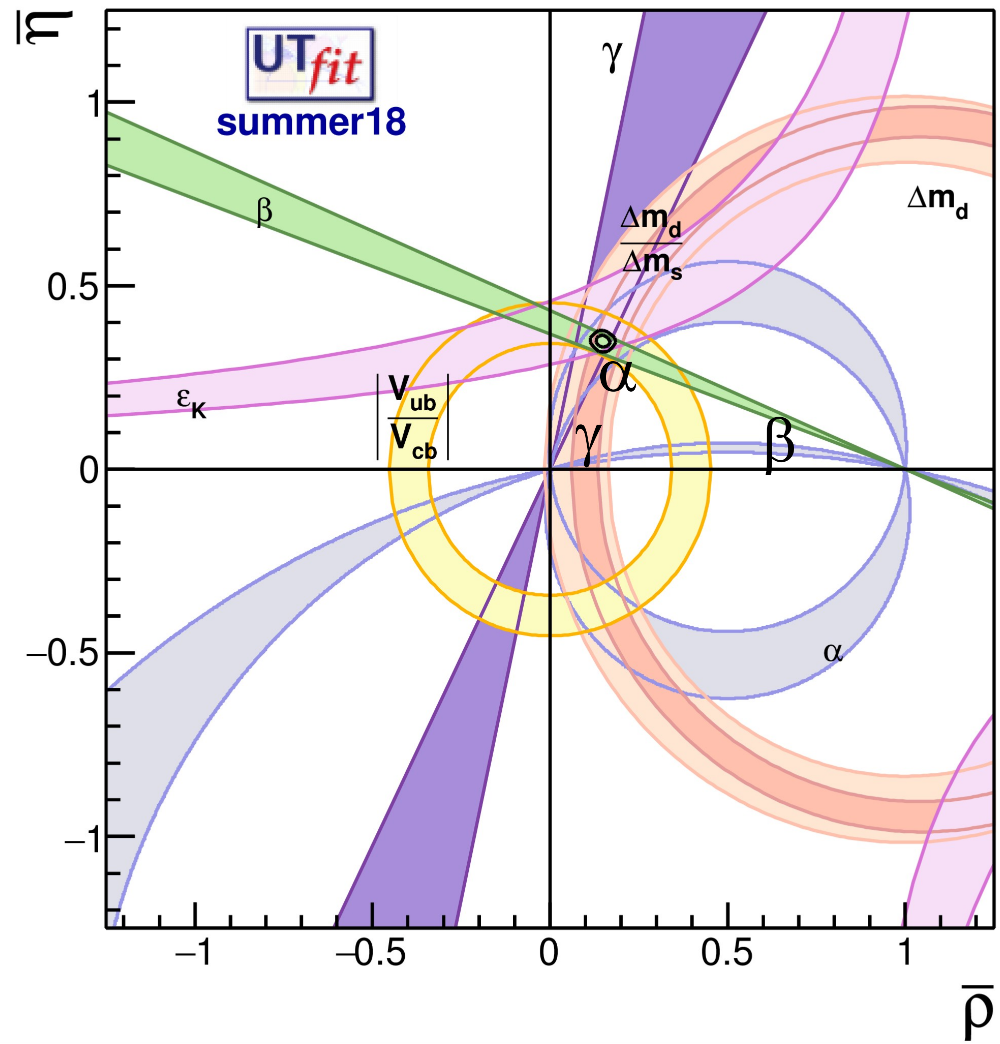
$R_u = 0.380 \pm 0.011$

$R_t = 0.920 \pm 0.014$

$\gamma = (66.8 \pm 2.0)^\circ$

$\beta = (22.25 \pm 0.65)^\circ$

$\alpha = (90.9 \pm 2.0)^\circ$



apex coordinates

$\bar{\rho} = 0.148 \pm 0.013$

$\bar{\eta} = 0.348 \pm 0.010$

The CKM matrix in the SM

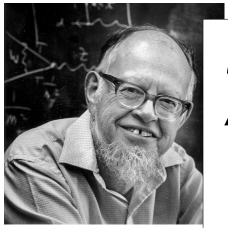
$$\begin{array}{cc} & \begin{array}{ccc} d & s & b \end{array} \\ \begin{array}{c} u \\ c \\ t \end{array} & \begin{pmatrix} 0.97431(12) & 0.22514(55) & 0.00365(10)e^{-i66.8(2.0)^\circ} \\ -0.22500(54)e^{i0.0351(10)^\circ} & 0.97344(12)e^{-i0.00188(5)^\circ} & 0.04241(65) \\ 0.00869(14)e^{-i22.2(0.6)^\circ} & -0.04124(56)e^{i1.056(32)^\circ} & 0.999112(24) \end{pmatrix} \end{array}$$

Standard parametrization (PDG): s_{12}, s_{13}, s_{23}, δ

$s_{12} = 0.2250 \pm 0.0010$ $\quad$ $s_{23} = (4.200 \pm 0.059) \times 10^{-2}$

$s_{13} = (3.68 \pm 0.10) \times 10^{-3}$ $\quad$ $\delta = (66.8 \pm 2.0)^\circ$

Wolfenstein parametrization: λ, A, ρ, η

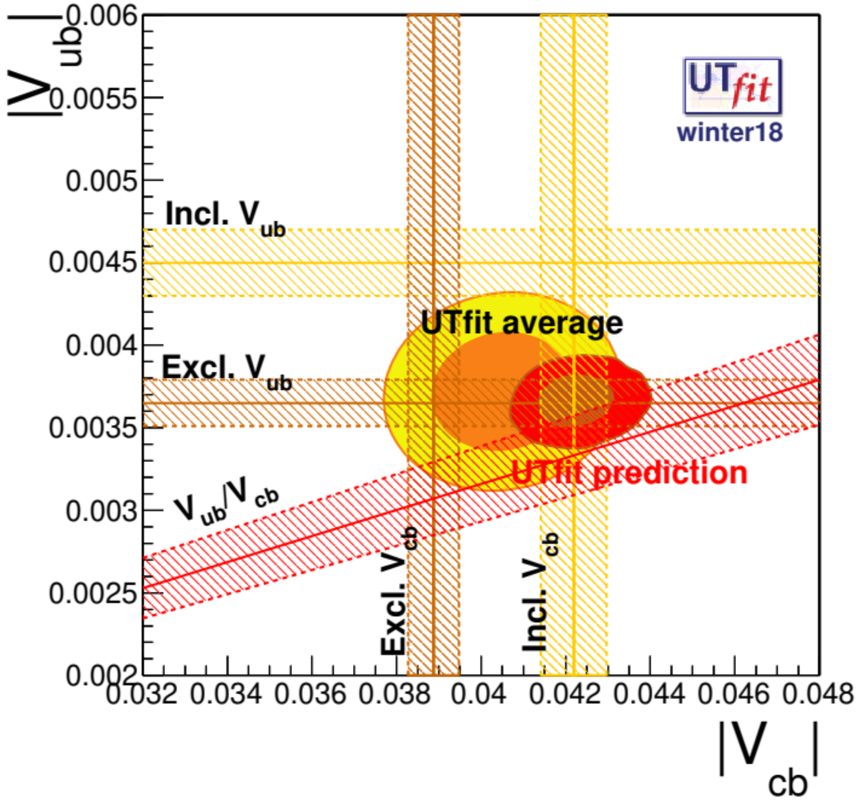


$\lambda = 0.2250 \pm 0.0010$ $\quad$ $A = 0.826 \pm 0.012$

$\rho = 0.152 \pm 0.014$ $\quad$ $\eta = 0.357 \pm 0.010$

SM predictions: B_d & K

	Measurement	%	Prediction	Pull(σ)
$\sin 2\beta$	0.689±0.018	3.5	0.738±0.033	+1.2
γ [°]	71.4±6.5	9	66.9±3.0	< 1
α [°]	92.5±5.5	6	88.1±3.4	< 1
$\lvert V_{cb}\rvert \cdot 10^3$	40.5±1.1	3	42.4±0.7	+1.4
$\lvert V_{ub}\rvert \cdot 10^3$	3.72±0.23	6	3.66±0.11	< 1
$\varepsilon_K \cdot 10^3$	2.228±0.011	0.5	1.97±0.18	-1.1
$BR(B\to\tau\nu)\cdot 10^{-4}$	1.06±0.20	20	0.81±0.07	-1.4

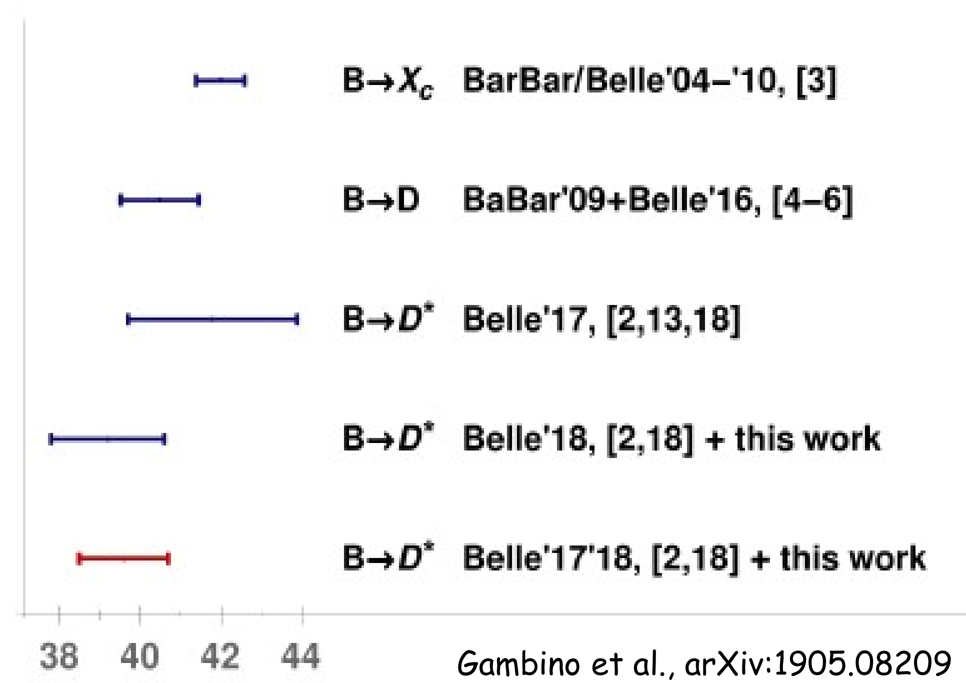


Long-standing problem:
inclusive vs exclusive

Reanalysis of the CLN parametrization for $|V_{cb}|$:
exclusive → inclusive

Grinstein, Kobach, arXiv:1703.08170
Bigi et al., arXiv:1707.09509

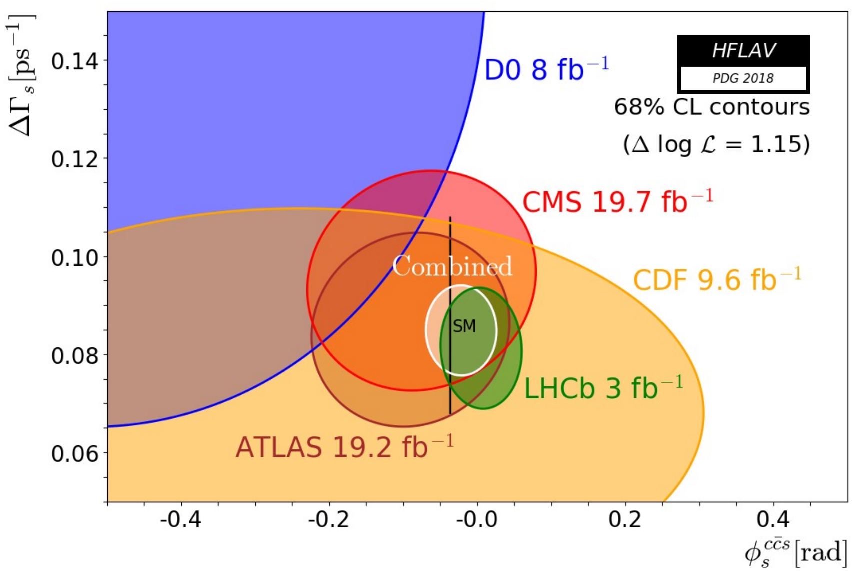
Improved mesurements of $|V_{cb}|$ & $|V_{ub}|$ are crucial for a determination of the CKM parameters independent of New Physics

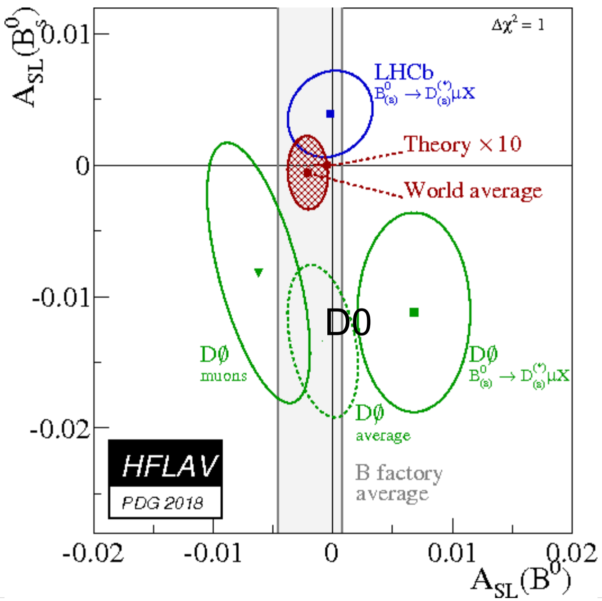


Gambino et al., arXiv:1905.08209

SM predictions: B_s

	Measurement	%	Prediction	Pull (σ)
Δm_s [ps^{-1}]	17.757±0.021	0.1	17.25±0.85	< 1
β_s[°]	0.60±0.89	150	1.06±0.03	< 1
$A_{SL}{}^s \cdot 10^4$	-6±28	450	-0.13±0.01	< 1





CKM matrix beyond the SM

generic NP contributions to mixing amplitudes

Family		ρ,η	C_d	φ_d	C_s	φ_s	$C_{\varepsilon K}$
Tree processes	γ (DK)	X					
	V_{ub}/V_{cb}	X					
1↔3 family	Δm_d	X	X				
	ACP (J/Ψ K)	X		X			
	ACP ($D\pi(\rho)$,$DK\pi$)	X		X			
	A_{SL}		X	X			
	α ($\rho\rho$,$\rho\pi$,$\pi\pi$)	X		X			
	A_{CH}		X	X	X	X	
2↔3 family	τ(Bs), $\Delta\Gamma_s/\Gamma_s$				X	X	
	Δm_s				X		
	ASL(Bs)				X	X	
	ACP (J/Ψ ϕ)	~X				X	
1↔2 familiy	ε_K	X					X

K mixing amplitude (1 real param): $\mathrm{Im}\,A_K = C_\varepsilon\,\mathrm{Im}\,A_K^{SM}$

B_d and B_s mixing amplitudes (2+2 real parameters):

- two parametrizations -

$q=d,s,\quad \phi_d^{SM}=\beta,\quad \phi_s^{SM}=-\beta_s$

$$A_q e^{2i\phi_q} = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}} = \left[1+\frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP}-\phi_q^{SM})}\right] A_q^{SM} e^{2i\phi_q^{SM}}$$

UT parameters in the presence of NP

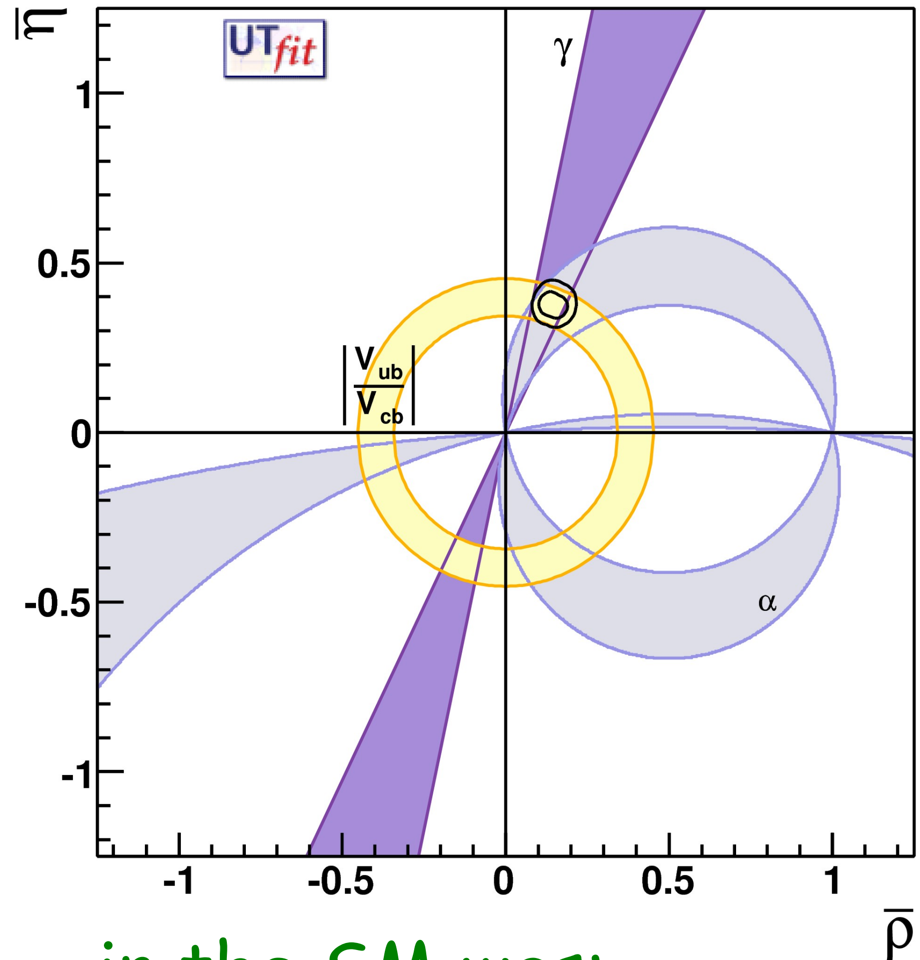
model-independent determination of the CKM parameters

assumptions:

* three generations
* negligible NP in tree decays

$\bar{\rho} = 0.147 \pm 0.030$

$\bar{\eta} = 0.377 \pm 0.028$

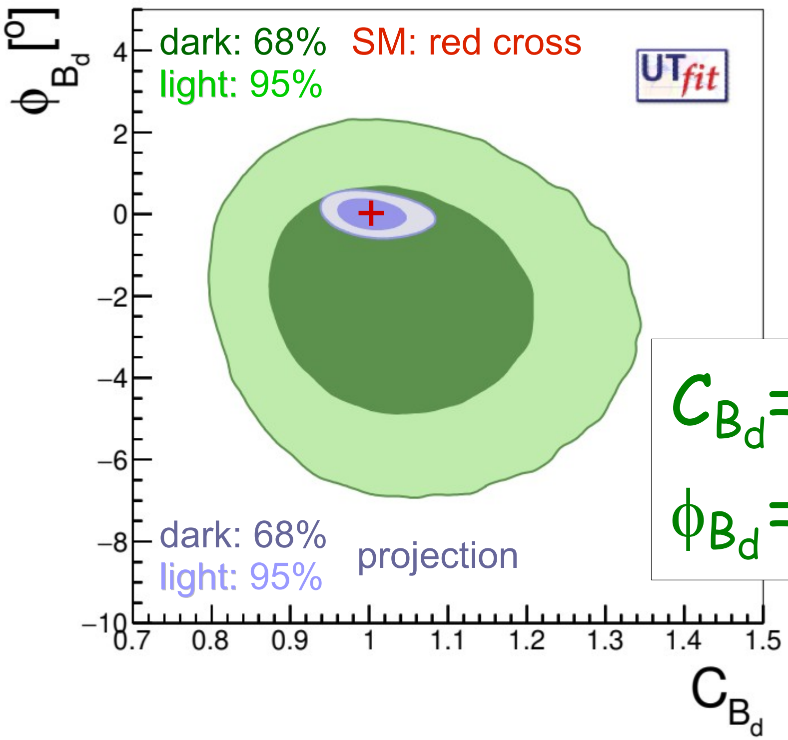


in the SM was:

$\bar{\rho} = 0.148 \pm 0.013$

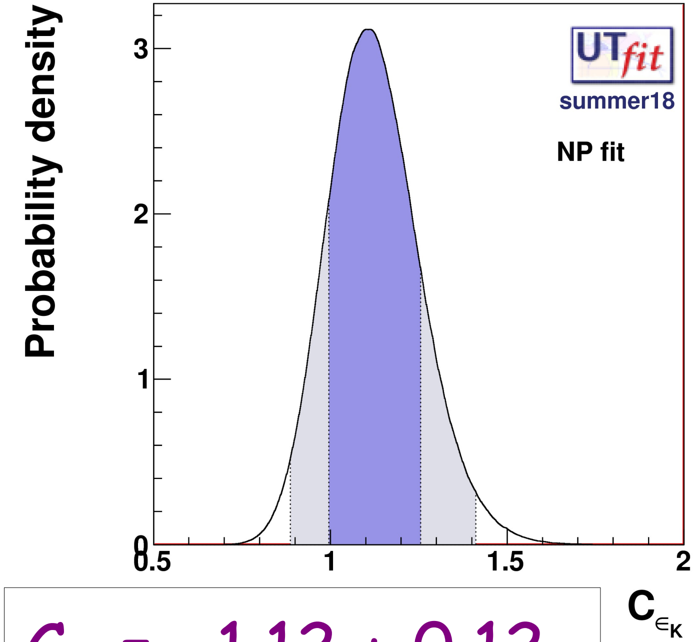
$\bar{\eta} = 0.348 \pm 0.010$

New Physics parameters



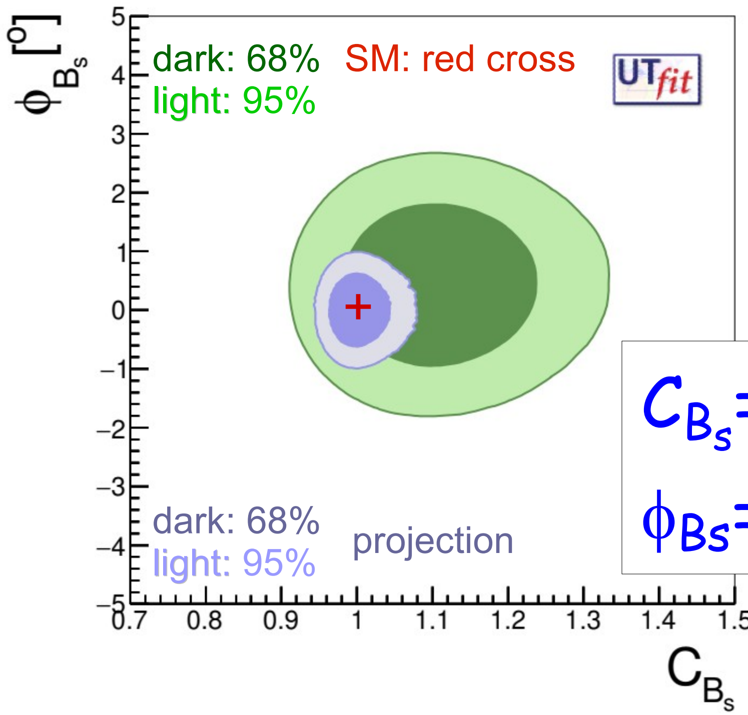
C_{B_d} = 1.05 ± 0.11

ϕ_{B_d} = (-2.0 ± 1.8)°



C_{ε_K} = 1.12 ± 0.12

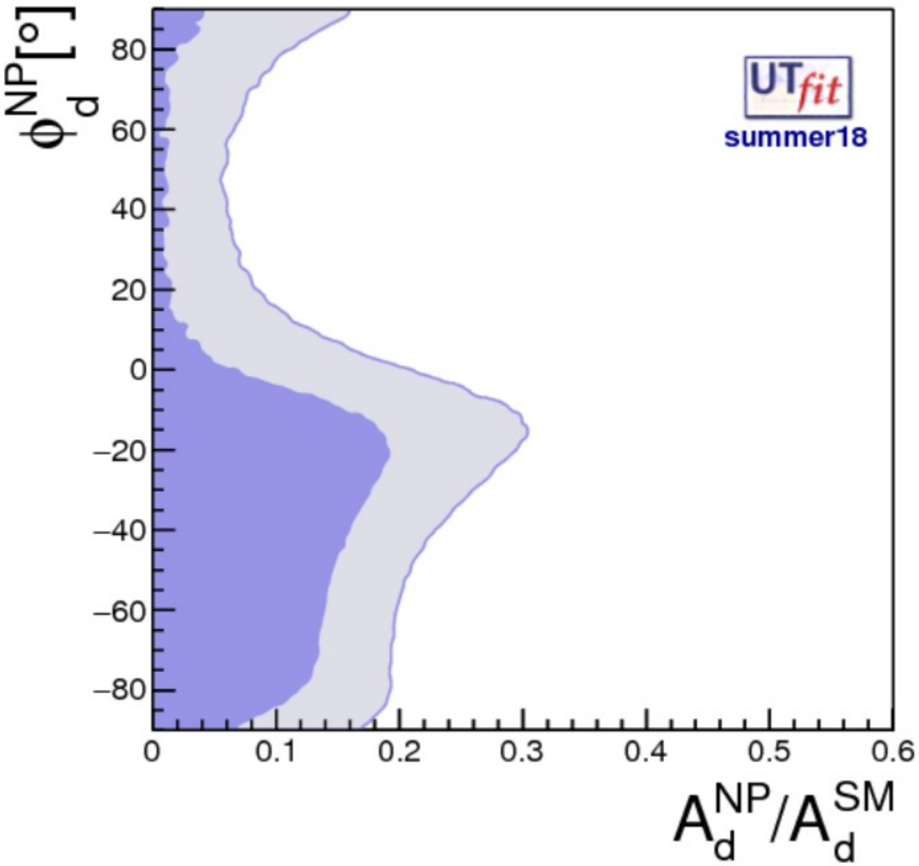
$$\Delta m_d^{\rm exp} = C_{B_d} \Delta m_d^{\rm SM}$$
$$\sin 2\beta^{\rm exp} = \sin(2\beta^{\rm SM} + 2\phi_{B_d})$$
$$\alpha^{\rm exp} = \alpha^{\rm SM} - \phi_{B_d}$$
$$\Delta m_s^{\rm exp} = C_{B_s} \Delta m_s^{\rm SM}$$
$$\phi_s^{\rm exp} = (\beta_s^{\rm SM} - \phi_{B_s})$$
$$\epsilon_K^{\rm exp} = C_{\epsilon_K} \epsilon_K^{\rm SM}$$

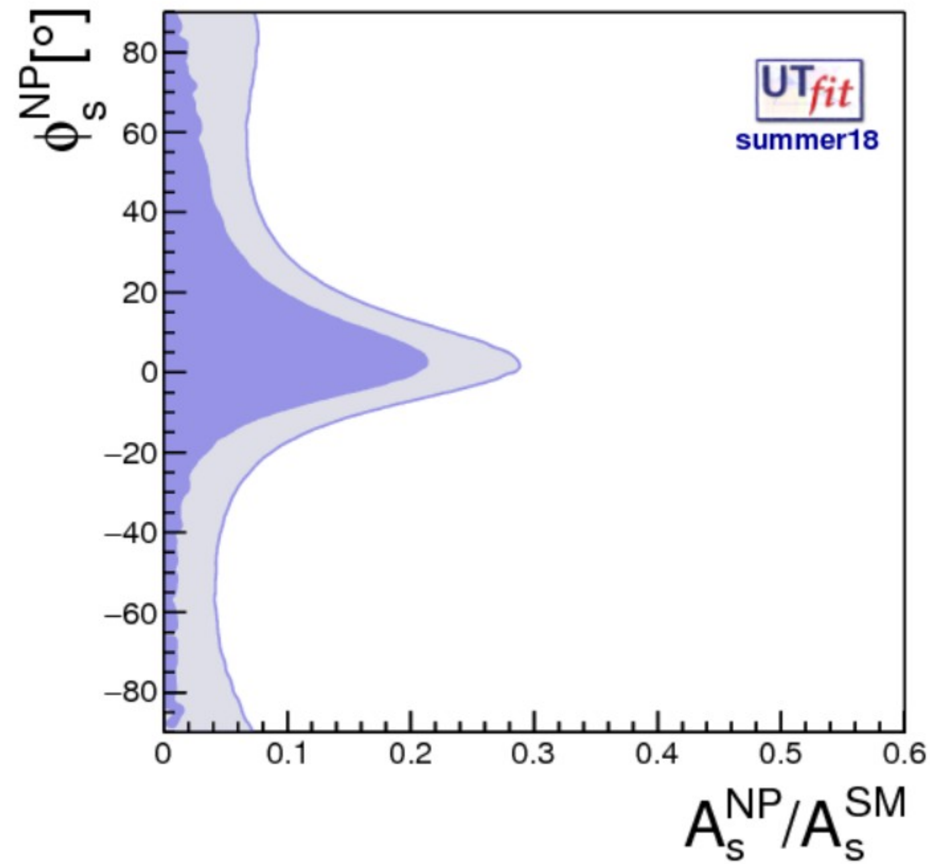


C_{B_s} = 1.11 ± 0.09

ϕ_{Bs} = (0.42 ± 0.89)°

Implications for the NP amplitudes

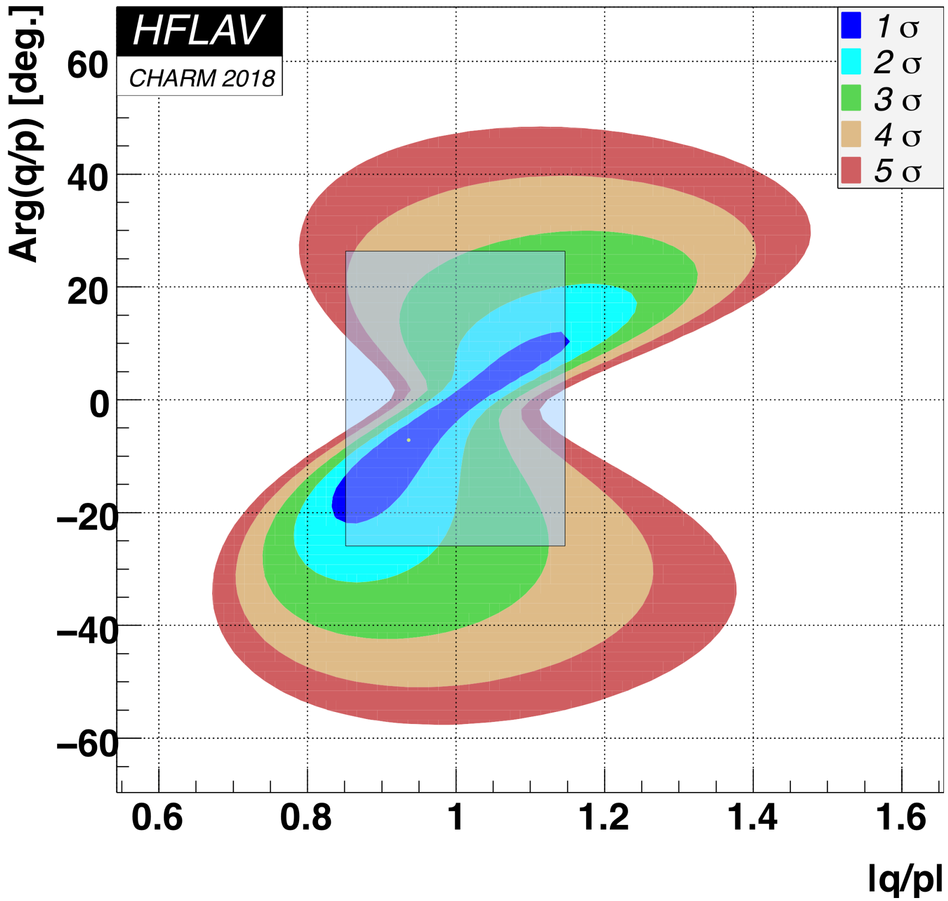




The ratio of NP/SM amplitudes is (if not aligned):

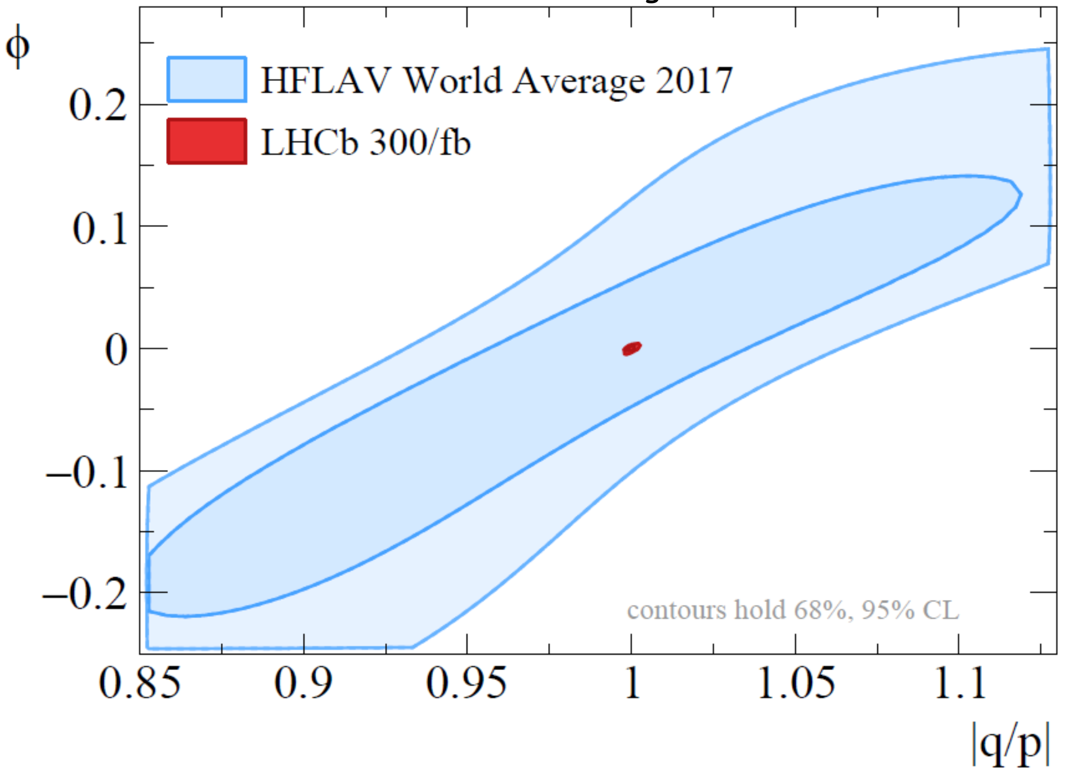
< ~10% @68% prob. (15% @95%) in B_d mixing

< ~2% @68% prob. (5% @95%) in B_s mixing



New Physics parameters - CPV in charm mixing

Bediaga et al., arXiv:1808.08865



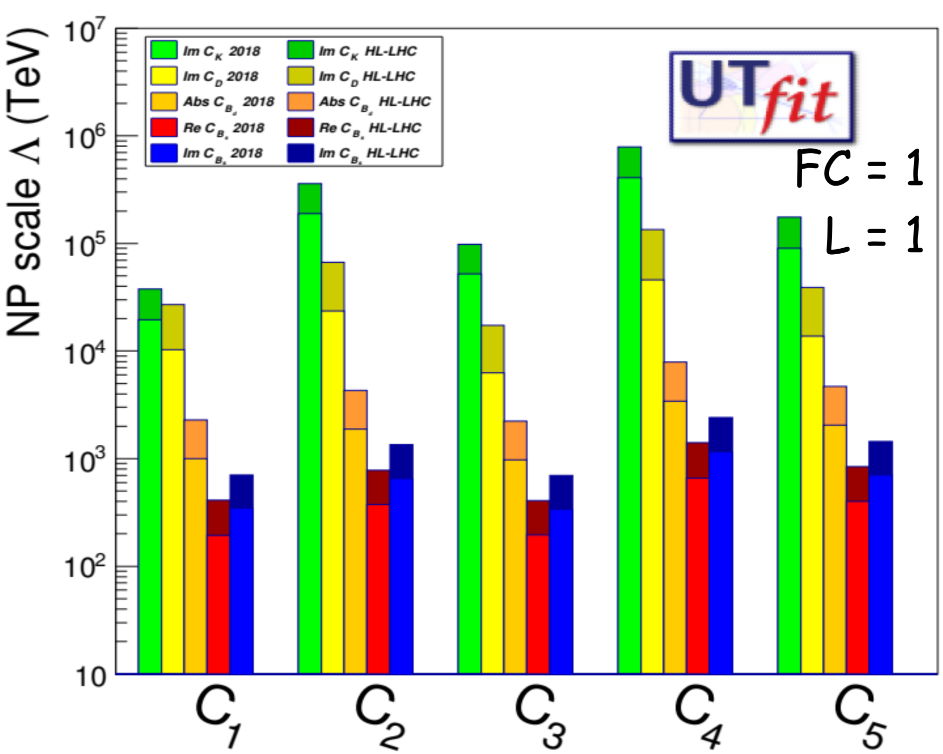
CP violation:

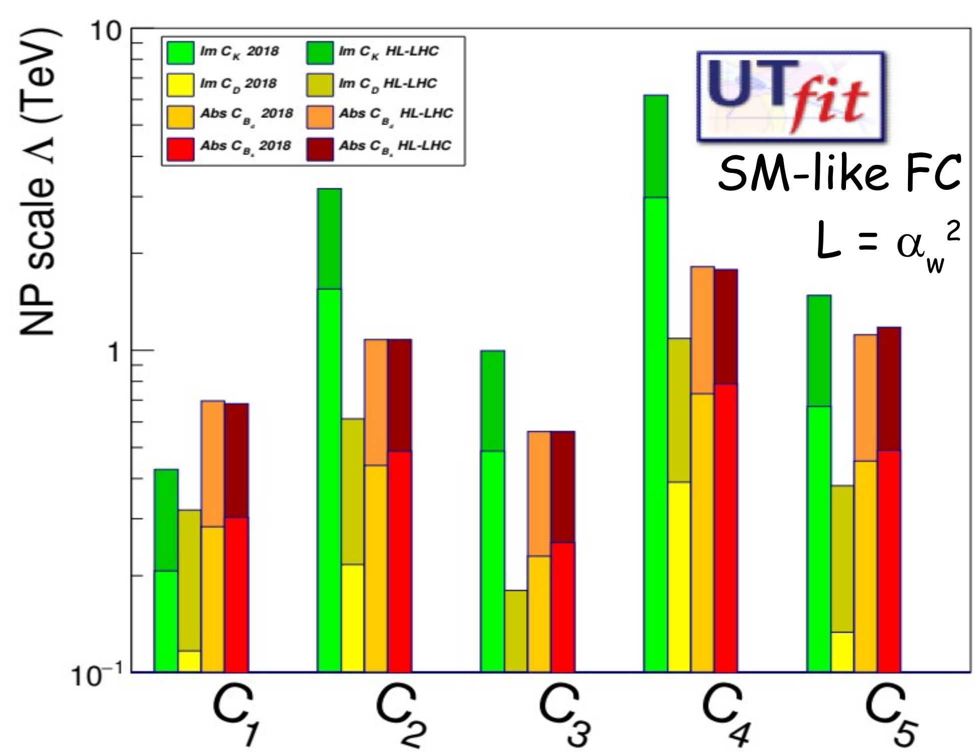
$|q/p| \neq 1$

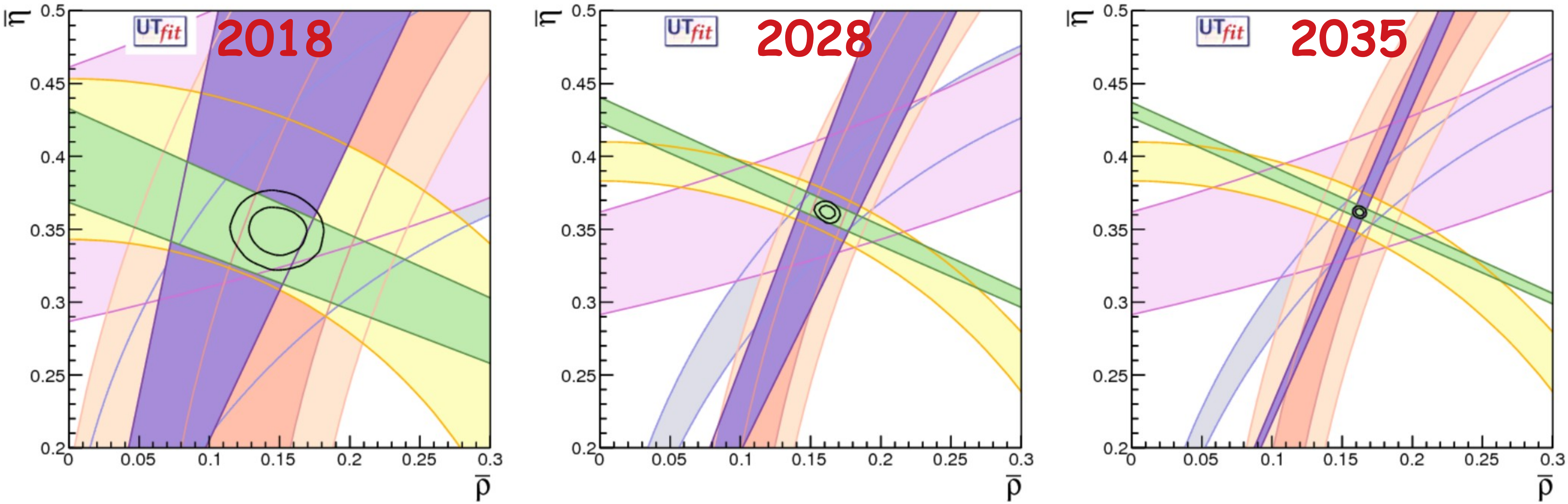
$\arg(q/p) \neq 0$

Lower bound on the NP scale Λ from ΔF=2 transitions (TeV @95% prob.)

	K	D	B_d	B_s
FC~1, L~1	4×10^5	4×10^4	3×10^3	1×10^3
FC~SM, $L\sim\alpha_W^2$	3	0.4	0.7	0.8







* $\delta\varepsilon_K \sim 2\%$, limited by long-distance contributions

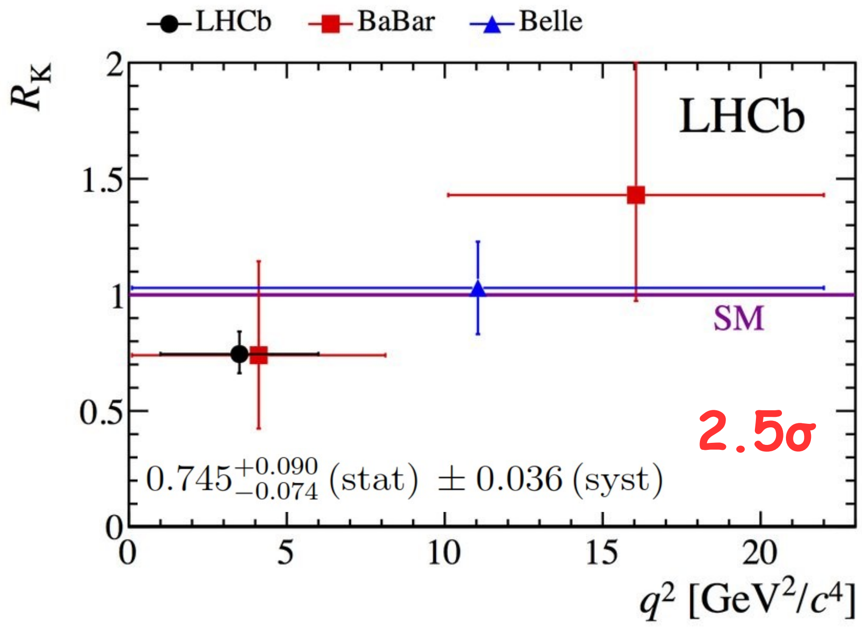
* $\delta\beta$ ($\delta\beta_s$) ~ few % (few tens %), limited by the subleading decay amplitude. Can be reduced by ~10 exploiting $SU(3)_f$-related control channels. Eventually limited by $SU(3)_f$ breaking

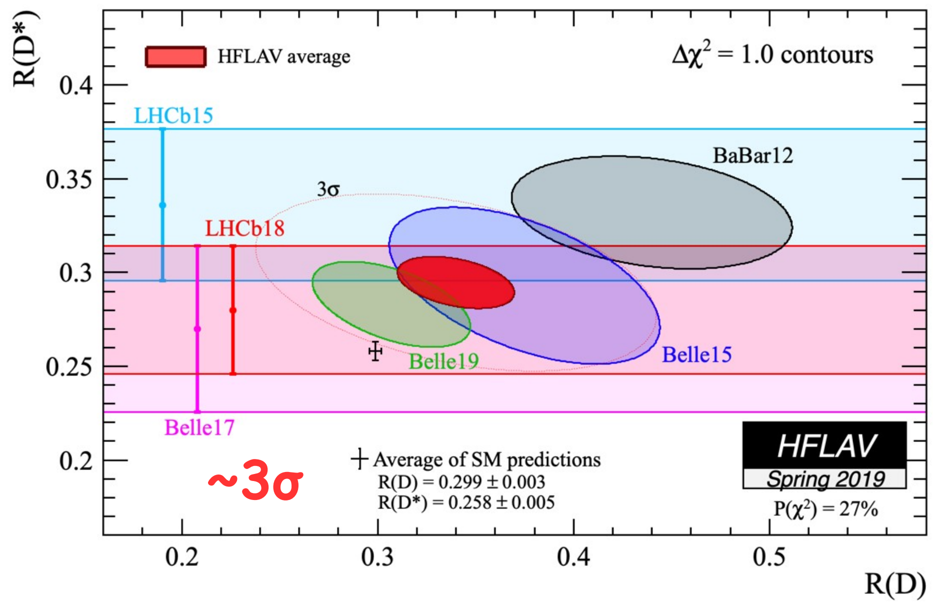
* $\delta\alpha \sim 1\%$, limited by unknown isospin-breaking corrections

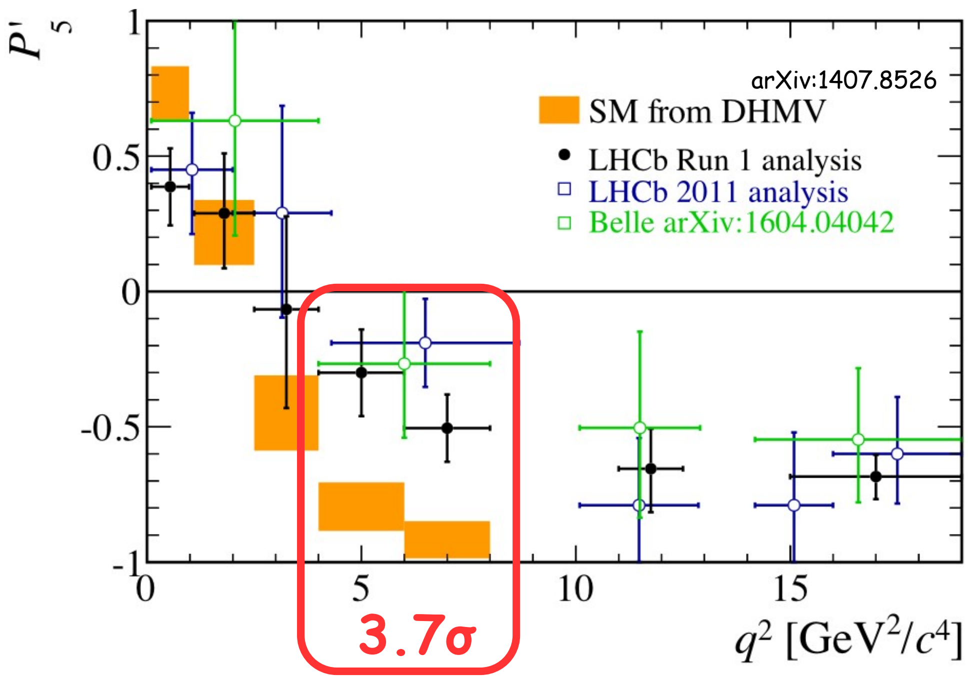
* exclusive SL decay uncertainties scale with lattice FFs, inclusive ones need an increasing number of OPE/SF terms

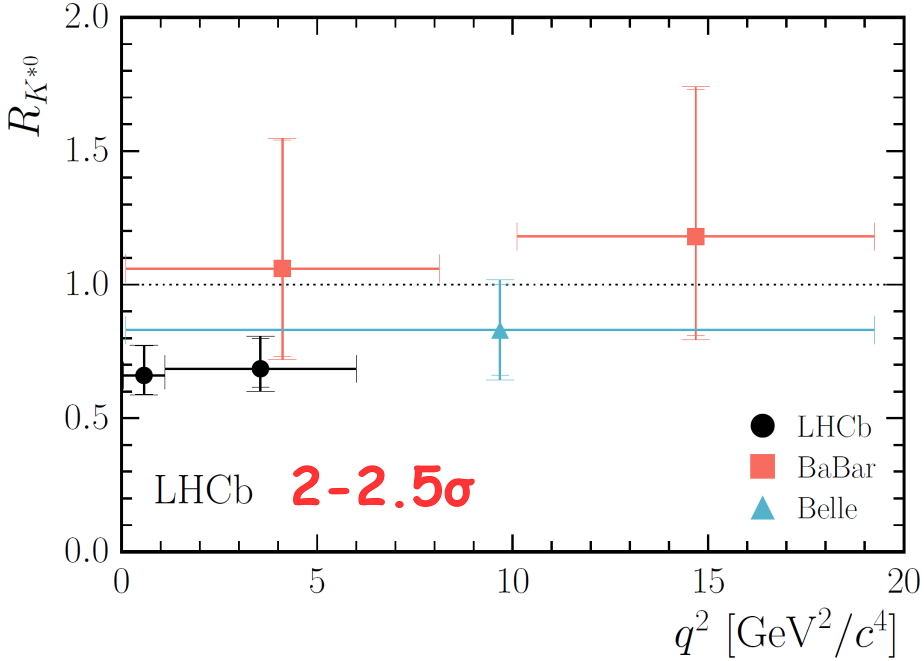
* $B_{d/s}$ mass difference uncertainties scale with lattice ME's, at percent level QED effects need to be included

ΔF=1: The anomalous anomalies



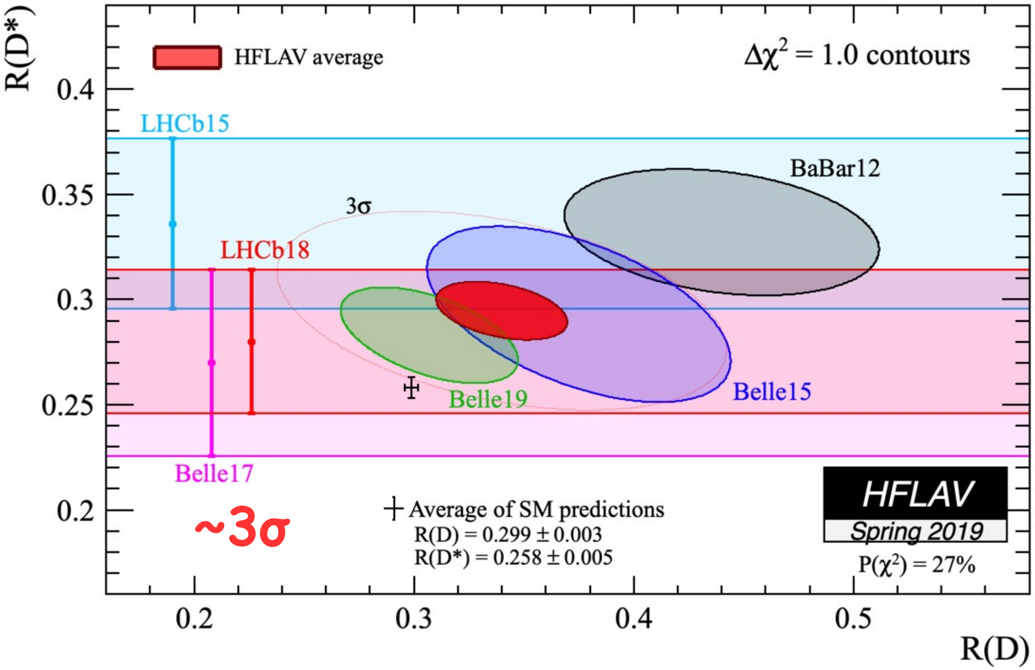




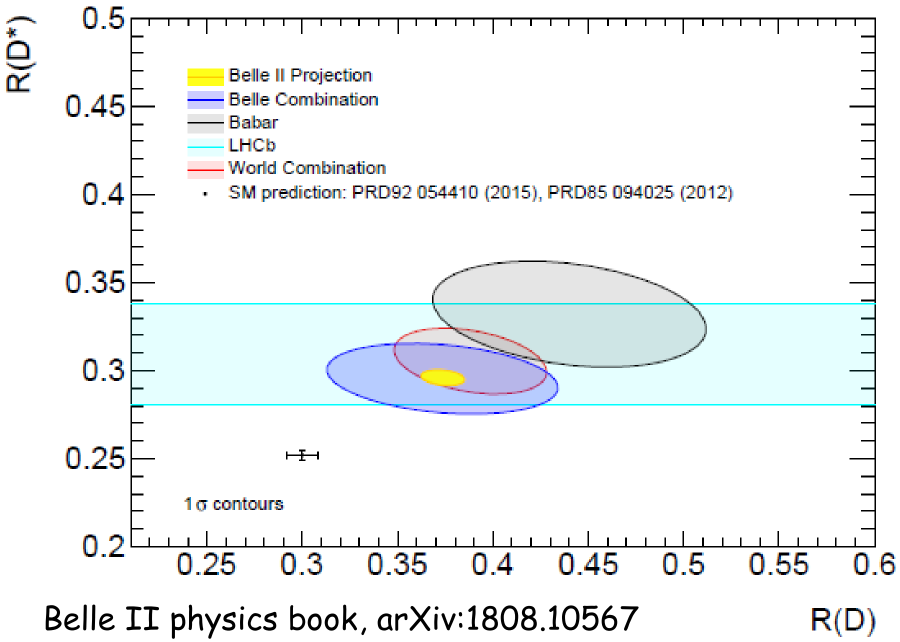


The anomalous anomalies

$$R(X) = \frac{\Gamma(B \to X \tau \nu)}{\Gamma(B \to X \ell \nu)}$$



Large significance driven by the BaBar results, trend of recent measurements is unclear



Belle II physics book, arXiv:1808.10567

Anomaly in B → τν washed out in time (perhaps)

Large new physics in tree-level charged currents? Really??!!

* SM uncertainties

R_D: LQCD calculations of both FF's for $q^2 \leq q^2_{max}$

$$\langle D(k)|\bar{c}\gamma^\mu b|B(p)\rangle = f_+(q^2)\left[(p+k)^\mu - \frac{m_B^2 - m_D^2}{q^2}q^\mu\right] + f_0(q^2)\frac{m_B^2 - m_D^2}{q^2}q^\mu$$

R_{D^*}: LQCD results only at q^2_{max}, scalar form factors not available. FFs from data + HQET

MILC '14/'15, HPQCD '15/'17
Bernlochner et al. '17, Bordone et al. '19
For LCSR results, see Gubernari et al., '18

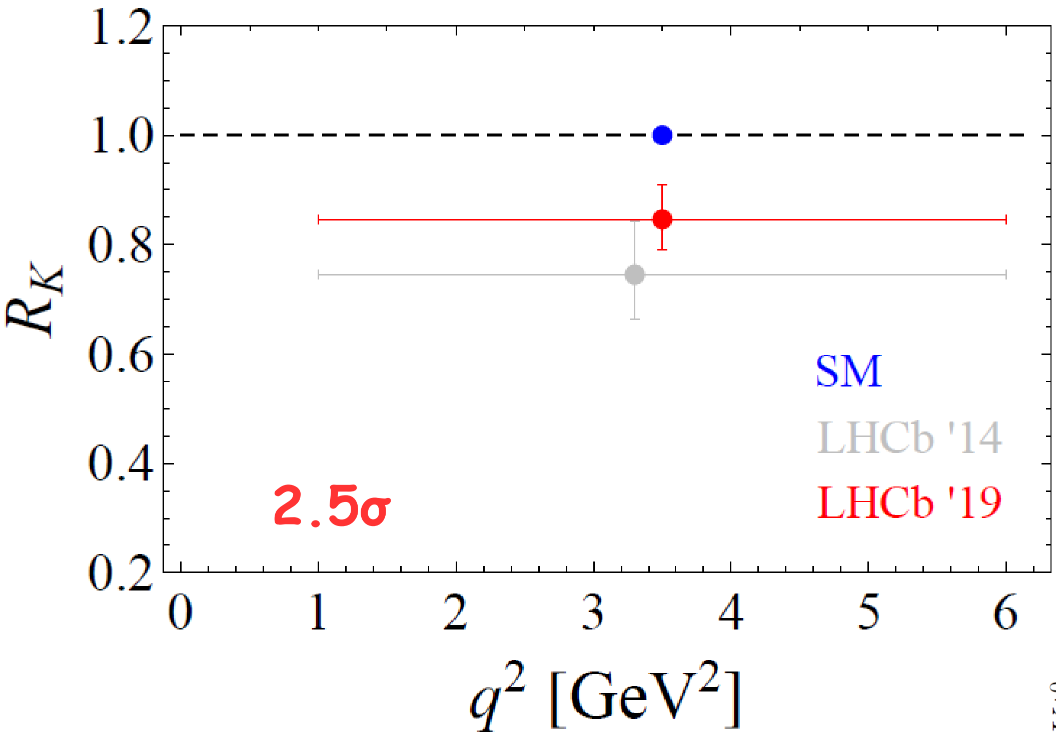
* New physics parametrization

$$\mathcal{L}_{eff} = -2\sqrt{2}G_F V_{cb}\Big[(1+C_{V_L})\bar{c}_L\gamma^\mu b_L\bar{\ell}_L\gamma_\mu\nu_L + C_{V_R}\bar{c}_R\gamma^\mu b_R\bar{\ell}_L\gamma_\mu\nu_L$$
$$+ C_{S_R}\bar{c}_L b_R\bar{\ell}_R\nu_L + C_{S_L}\bar{c}_R b_L\bar{\ell}_R\nu_L + C_T\bar{c}_R\sigma^{\mu\nu}b_L\bar{\ell}_R\sigma_{\mu\nu}\nu_L\Big] + H.c.$$

- C's vanish in the SM
- Data explained by C_{VL} ~ 15%, but there are other viable solutions involving more than one coefficient

M. Blanke et al. '18, R. Shi et al. '19, A. Kumar et al. '19, C. Murgui et al. '19, ...

The anomalous anomalies

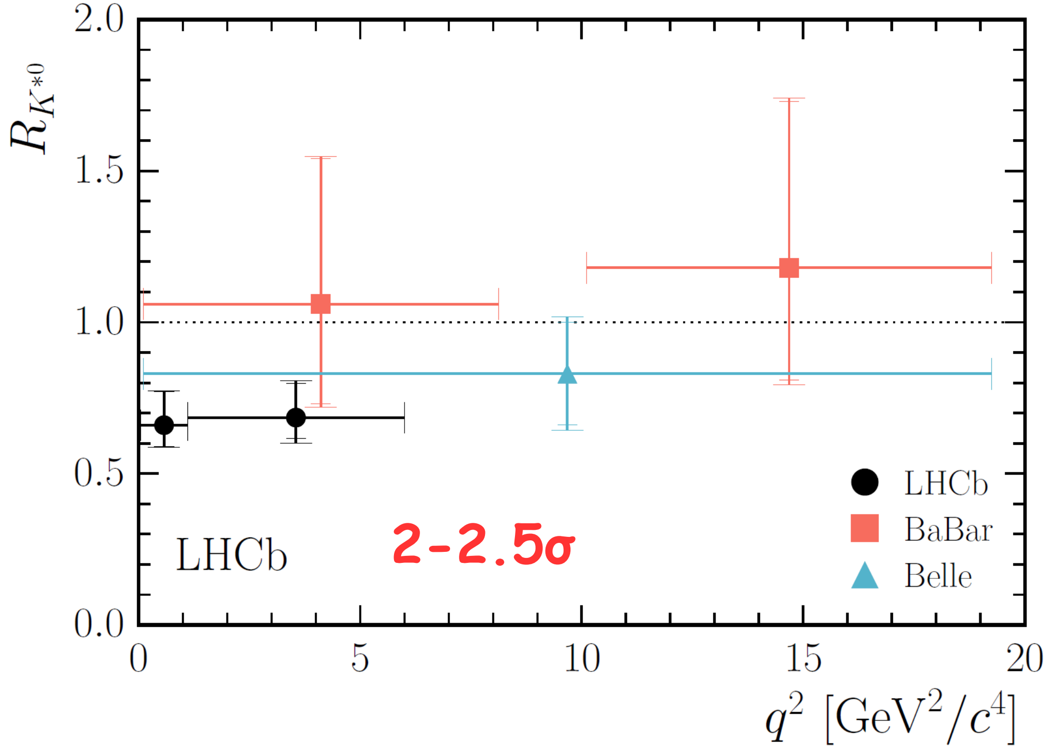


$$R_K = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+ \to K^+\mu^+\mu^-]}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+ \to K^+e^+e^-]}{dq^2} dq^2}$$

Single experiment result

Not very significant (yet?)

Large violation of lepton flavour universality?! Sure??!!

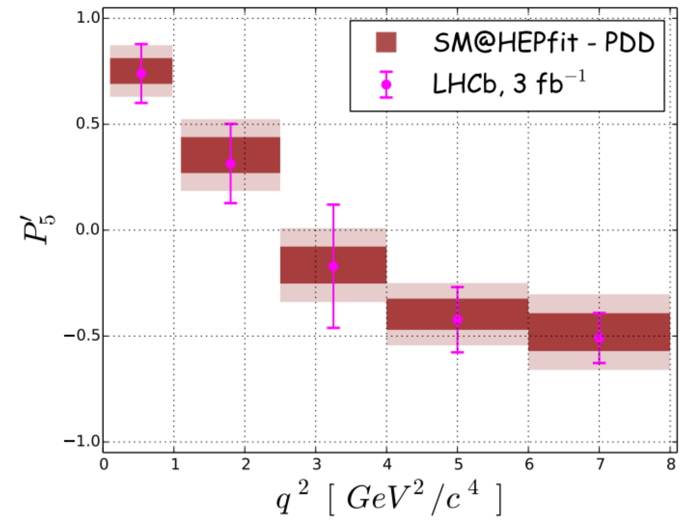


The anomalous anomalies

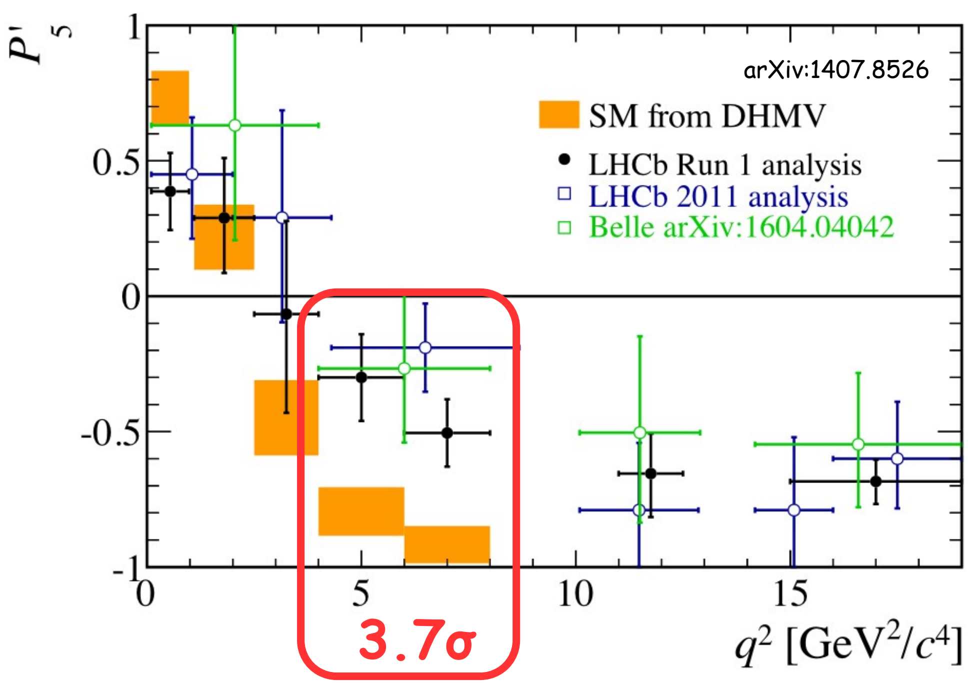
$$\frac{d^{(4)}\Gamma}{dq^2\,d(\cos\theta_l)d(\cos\theta_k)d\phi} = \frac{9}{32\,\pi}\Big(I_1^s \sin^2\theta_k + I_1^c \cos^2\theta_k + (I_2^s \sin^2\theta_k + I_2^c \cos^2\theta_k)\cos 2\theta_l$$
$$+ I_3 \sin^2\theta_k \sin^2\theta_l \cos 2\phi + I_4 \sin 2\theta_k \sin 2\theta_l \cos\phi$$
$$+ I_5 \sin 2\theta_k \sin\theta_l \cos\phi + (I_6^s \sin^2\theta_k + I_6^c \cos^2\theta_K)\cos\theta_l$$
$$+ I_7 \sin 2\theta_k \sin\theta_l \sin\phi + I_8 \sin 2\theta_k \sin 2\theta_l \sin\phi$$
$$+ I_9 \sin^2\theta_k \sin^2\theta_l \sin 2\phi\Big)$$

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

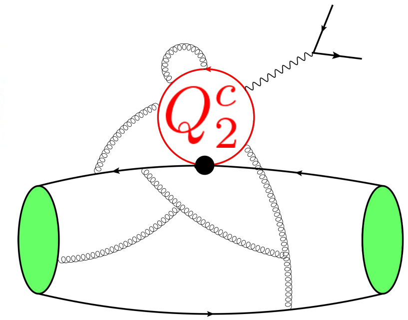
angular analysis



Are theory estimates reliable close to the resonant region?



the charm-loop monster



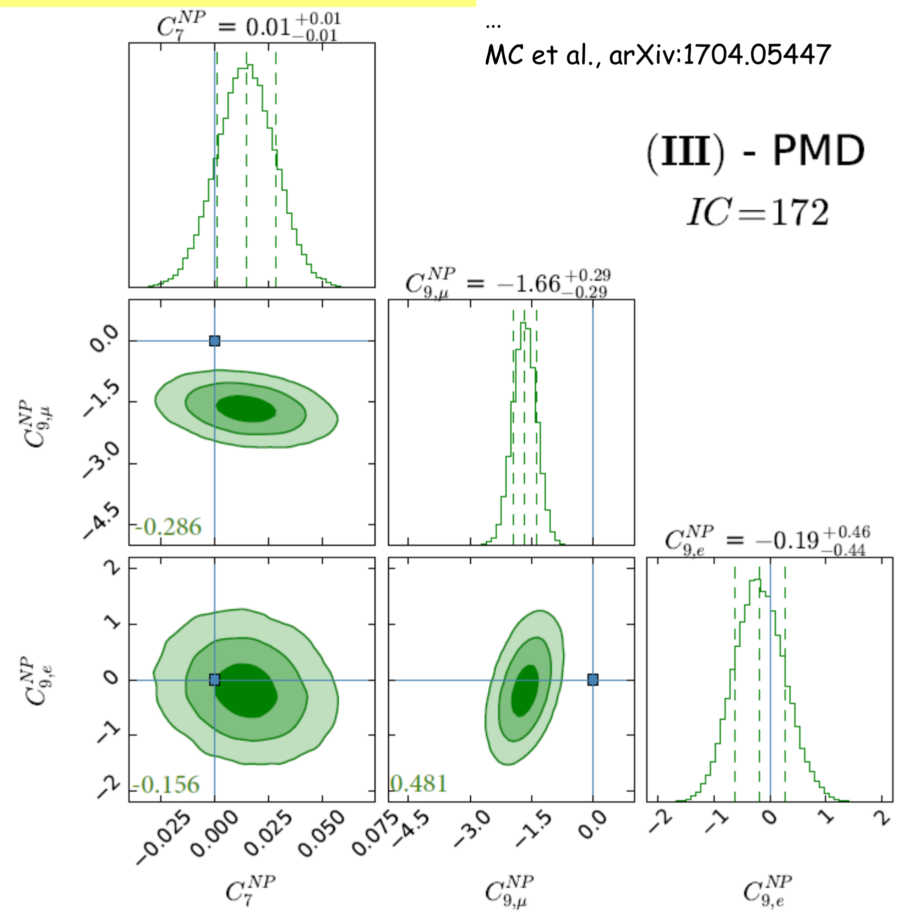
Global fits to b → s FCNCs in EFT

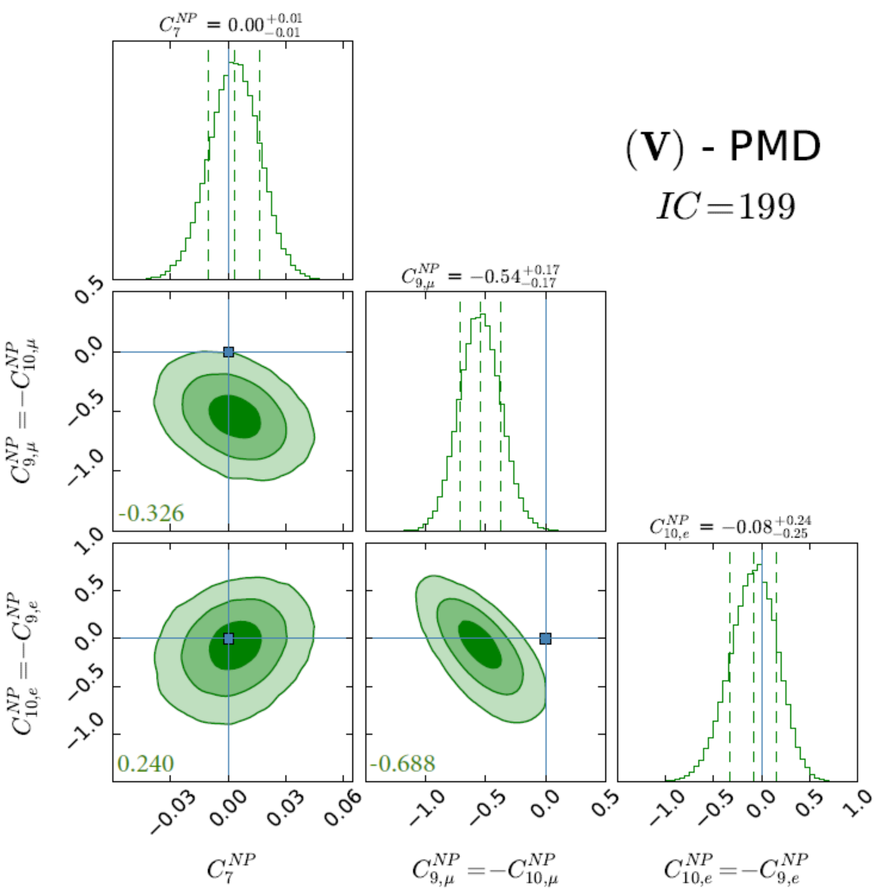
Hiller&Kruger; Descotes-Genon et al.; Jaeger et al.; Capdevila et al.; Altmannshofer et al.; Hurth et al.; …
MC et al., arXiv:1704.05447

$$Q_7 = \frac{e}{16\pi^2} m_b \bar{s}_L \sigma_{\mu\nu} F^{\mu\nu} b_R$$

$$Q_{9,\ell} = \frac{\alpha_e}{4\pi} s_L \gamma_\mu b_L \bar{\ell} \gamma^\mu \ell$$

$$Q_{10,\ell} = \frac{\alpha_e}{4\pi} s_L \gamma_\mu b_L \bar{\ell} \gamma^\mu \gamma_5 \ell$$

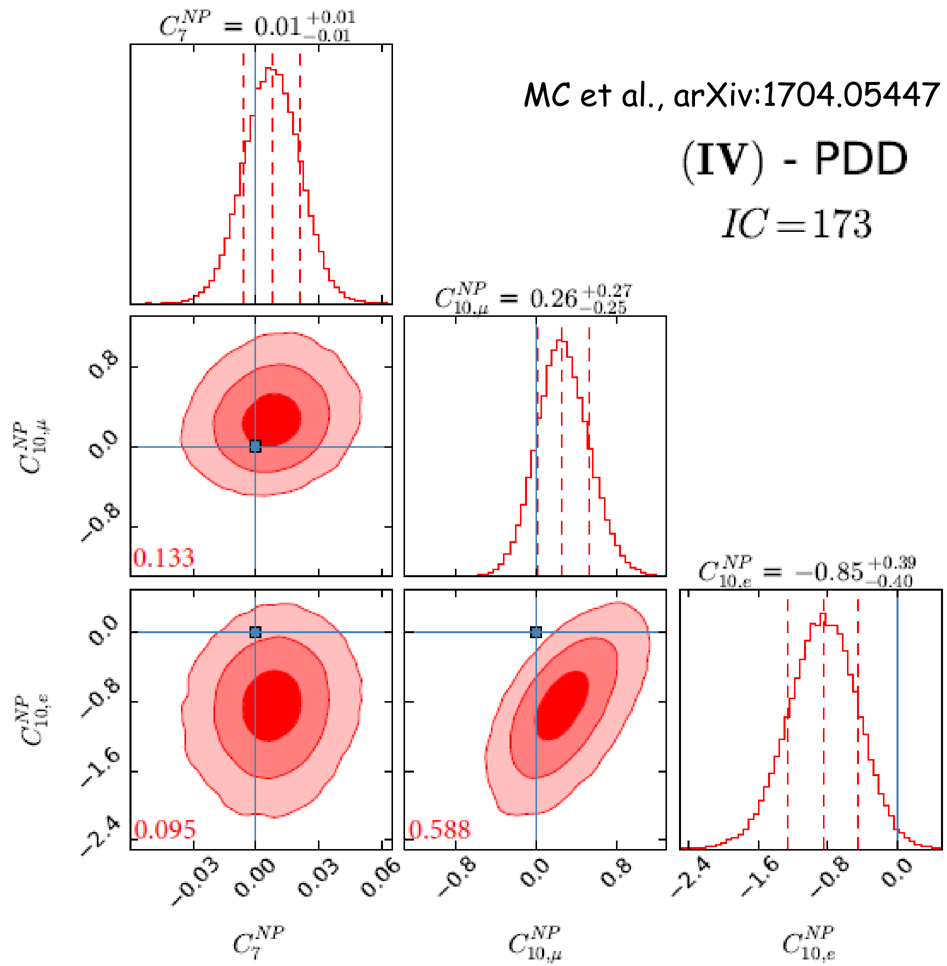




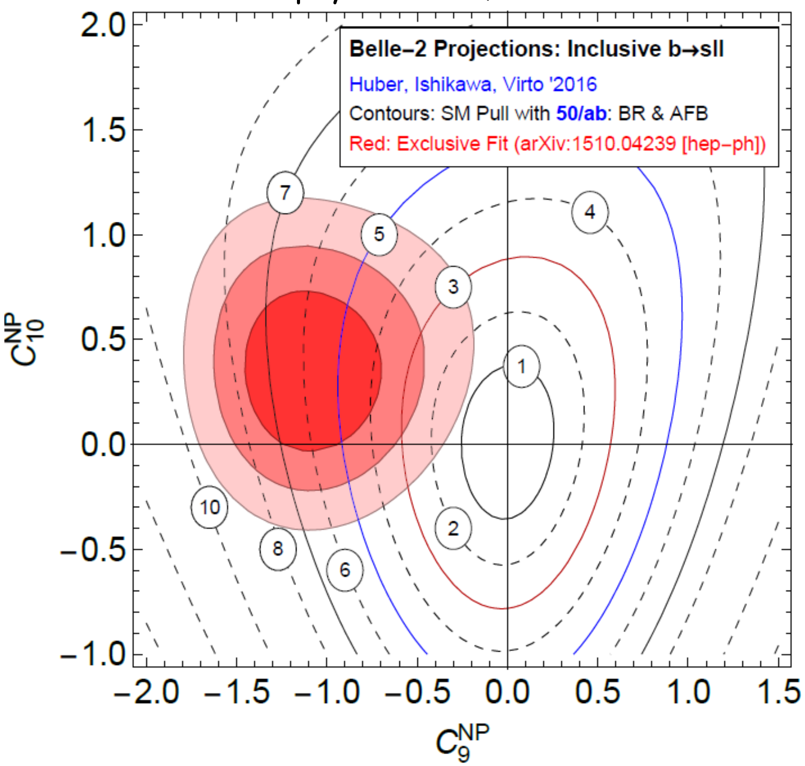
All b→s anomalies, including LFU violation, are accounted for by a large correction (25-30%) to $C_{9,\mu}$

B → K*μμ drives the interpretation of the b→ s anomalies in terms of NP in $C_{9,\mu}$

MC et al., arXiv:1704.05447



Belle II physics book, arXiv:1808.10567

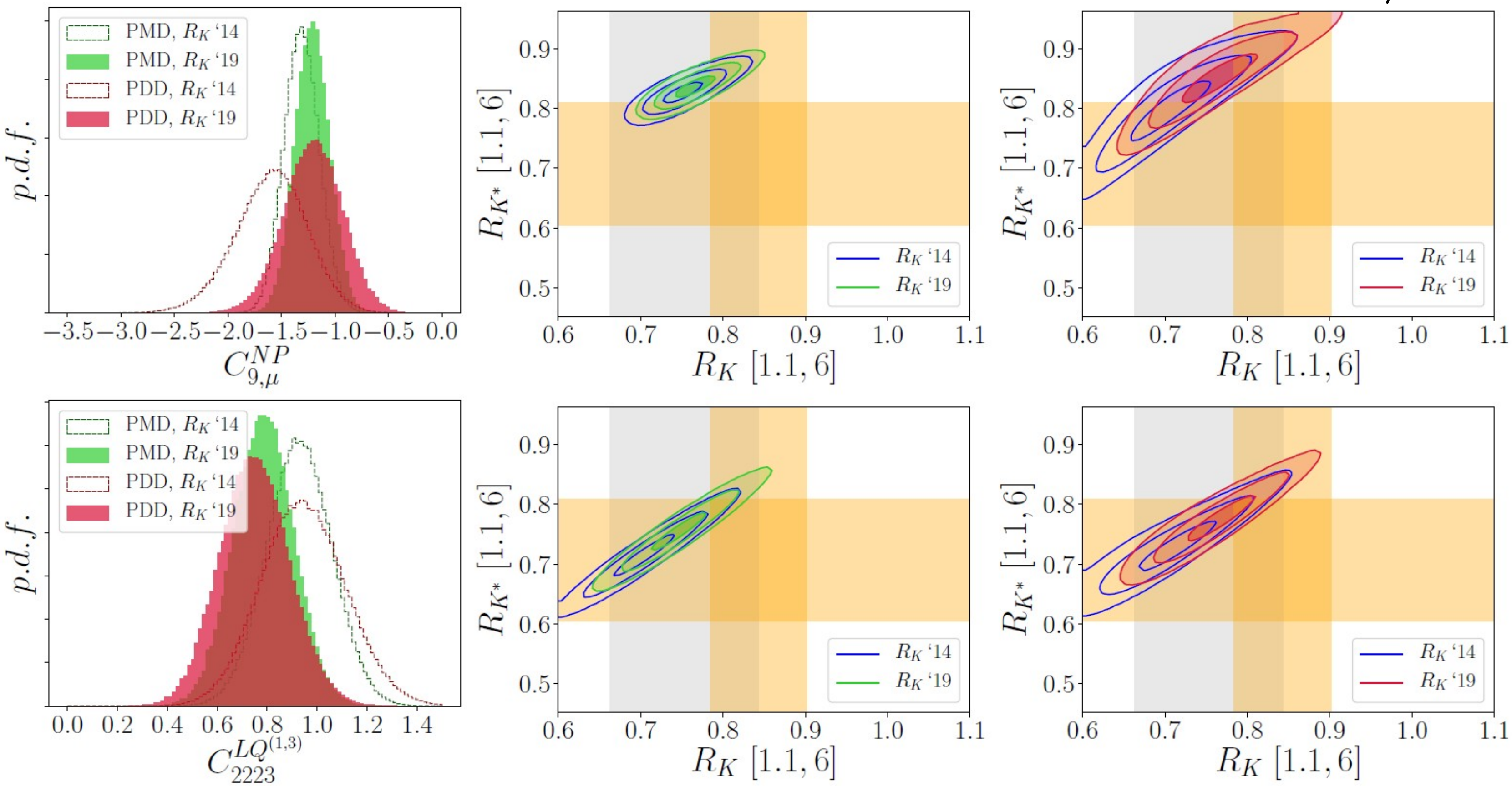


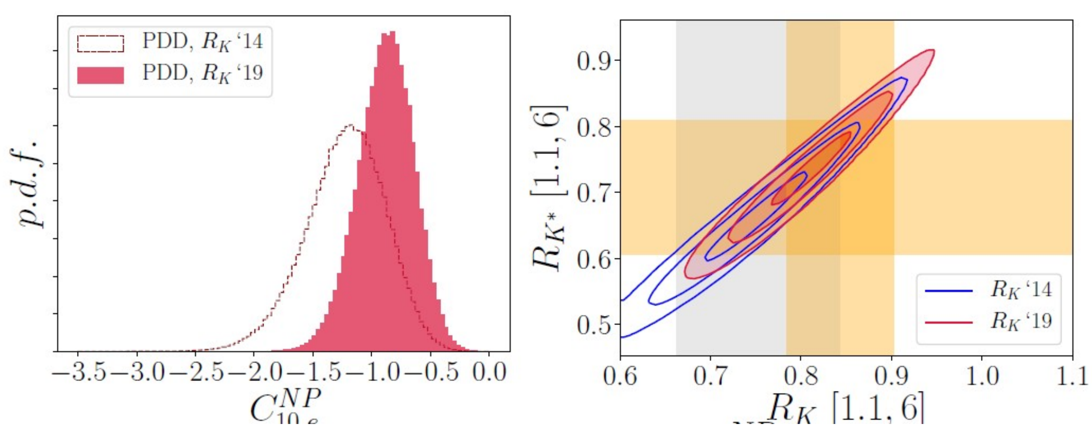
Important to confirm the anomaly
- with different systematics
and theoretical uncertainties

Inclusive B → $X_s\ell\ell$ @Belle II

Impact of the 2019 R_K measurement

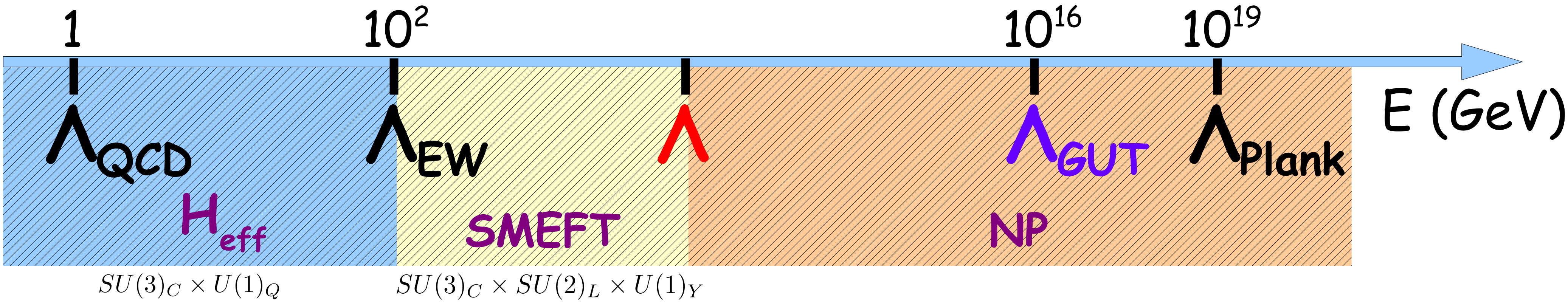
MC et al., arXiv:1903.09632





Single coefficient R_K-R_{K^*} correlation weakened by the new measurement

One EFT to rule them all



In the SMEFT two four-fermion operators produce LFUV in quark decays assuming NP in the 3rd generation

$$Q_S = Q'_{L,3}\gamma_\mu Q'_{L,3} L'_{L,3}\gamma^\mu L'_{L,3}, \quad Q_T = Q'_{L,3}\gamma_\mu \sigma^i Q'_{L,3} L'_{L,3}\gamma^\mu \sigma^i L'_{L,3}$$

i) give typically (but not necessarily) rise to large LFV

generated passing from weak to mass eigenstates

Glashow et al., arXiv:1411.0565
Alonso et al., arXiv:1505.05164

ii) can account for the anomalies in R_K, R_{K^*}, R(D) & R(D*)

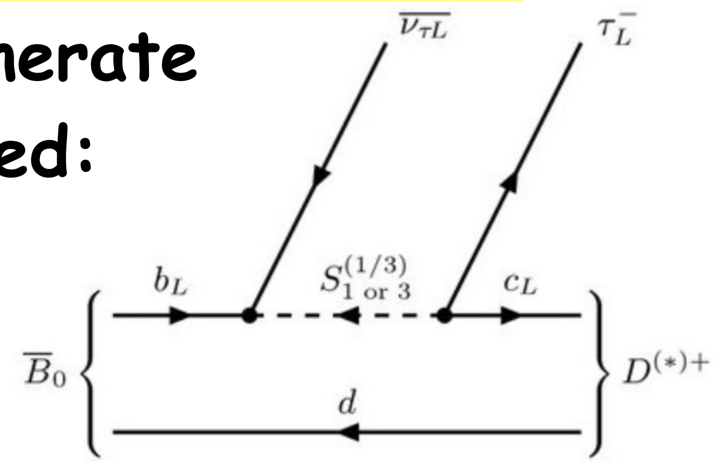
large tree-level effect in charged currents from Q_T

b → s FCNC suppressed to loop level through mixing angles

Bhattacharya et al., arXiv:1412.7164

The leptoquark revenge

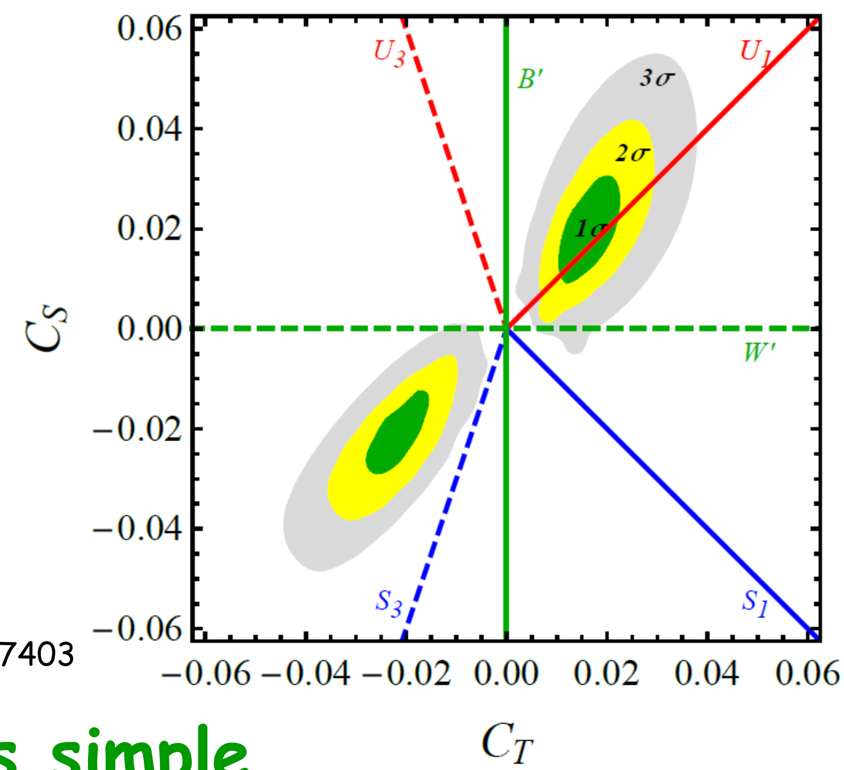
Models with a <u>single</u> mediator which generate Q_S and Q_T at tree-level can be classified:



Field	Spin	$SU(3)_c$	$SU(2)_L$	$\mathcal{U}(1)_Y$
B'_μ	1	**1**	**1**	**0**
W'_μ	1	**1**	**3**	**0**
U_1^μ	1	**3**	**1**	**2/3**
U_3^μ	1	**3**	**3**	**2/3**
S_1	0	$\bar{\mathbf{3}}$	**1**	**1/3**
S_3	0	$\bar{\mathbf{3}}$	**3**	**1/3**

leptoquarks

Buttazzo et al., arXiv:1706.07808



Present data already select one option (vector singlet leptoquark U_1) independently of the flavour structure of the model once all bounds are considered

Kumar et al., arXiv:1806.07403

Actual UV completions are not this simple…

Summary

Flavour physics remains a tool of choice for the indirect search of new physics

The SM picture looks very consistent, but 10% NP corrections to $\Delta B=2$ amplitudes are still possible

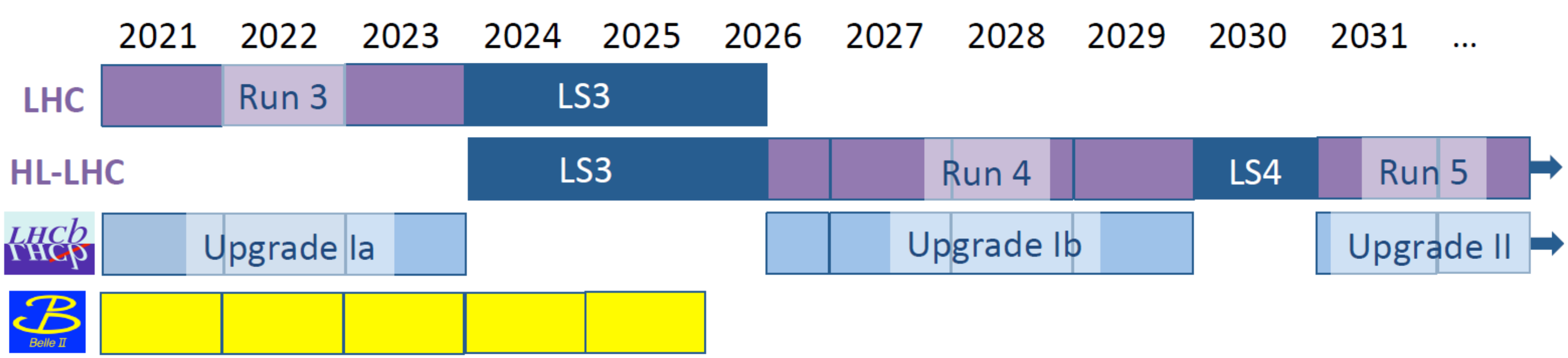
AND now we are entering the "percent era"…

A new bunch of anomalies (tensions in 20th century language) are present in $\Delta B=1$ data (and ε'/ε?): despite the caveats, it is quite remarkable that there exists a simple NP interpretation for them

Theoretical progresses (QED corrections, isospin breaking, bilocal operators, …) in LQCD results needed to convert exp. precision in NP sensitivity

We have at least another 15 years of good old flavour physics in front of us

Thank you!



Backup

Going BSM with flavour physics: why?

Indirect searches look for new physics through virtual effects of new particles in loops

* SM FCNCs and CPV occur at the loop level

* SM FV and CPV are governed by the weak interactions and suppressed by mixing angles

* SM quark CPV comes from a single source (neglecting θ_{QCD})

New Physics does not necessarily share the SM pattern of FV and CPV: very large NP effects are possible

Past (SM) successes anticipating heavy flavours:

1970: charm from $K^0 \to \mu^+\mu^-$ (GIM)

1973: 3rd generation from ϵ_K (Kobayashi & Maskawa)

mid 80s+: heavy top from semileptonic decays & Δm_B

Going BSM with flavour physics: why now?

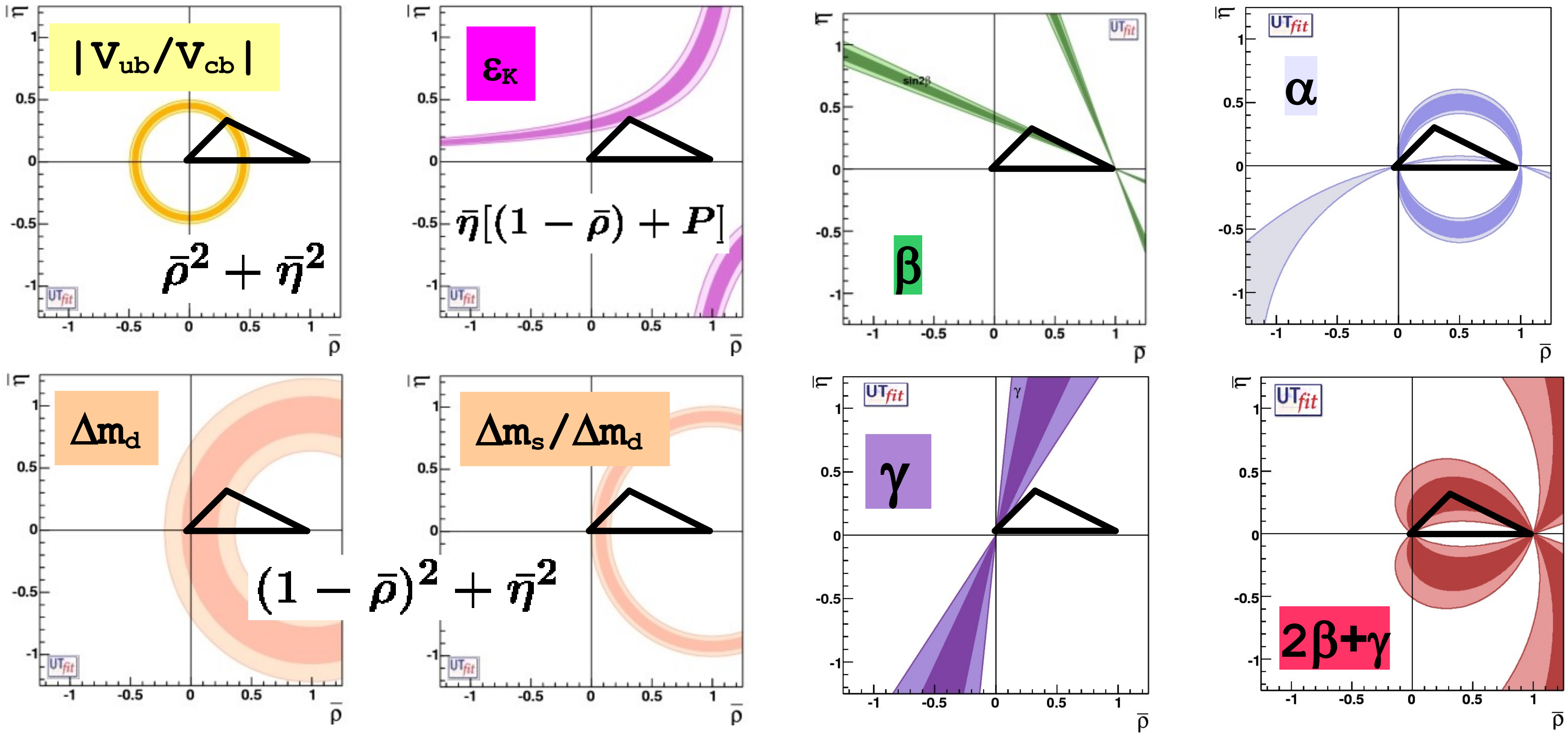
* next-generation flavour experiments will be able to improve the experimental precision/ sensitivity by almost one order of magnitude

* enough NP-insensitive observables to pin down the SM contribution with the required accuracy

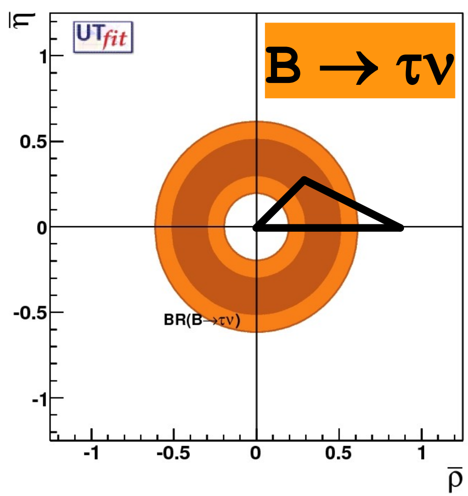
* several NP-sensitive observables not limited by systematics or theoretical uncertainties

Overall, the NP sensitivity extends to (i) the TeV region for SM-like flavour violation and to (ii) 10-100 TeV or even more in less constrained cases

Unitarity Triangle analysis: $V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$



Original goal:
- determine the UT apex and the CKM matrix parameters



Overconstrained fit:
- predict observables, hadronic parameters and constrain NP

Parameter	Input value	Full fit	SM Prediction	Pull
$\bar{\rho}$	–	–	0.148 ± 0.013	–
$\bar{\eta}$	–	–	0.348 ± 0.010	–
ρ	–	–	0.152 ± 0.014	–
η	–	–	0.357 ± 0.010	–
A	–	–	0.826 ± 0.012	–
λ	0.22574 ± 0.00089	–	0.22500 ± 0.00100	-0.6
$\sin\theta_{12}$	–	–	0.22500 ± 0.00100	–
$\sin\theta_{23}$	–	–	0.04200 ± 0.00059	–
$\sin\theta_{13}$	–	–	0.003675 ± 0.000095	–
$\delta[^\circ]$	–	–	66.9 ± 2.0	–
$\lvert V_{ub}\rvert$	0.00372 ± 0.00023	0.003675 ± 0.000095	0.00366 ± 0.00011	-0.3
$\lvert V_{ub}\rvert$(excl)	0.00365 ± 0.00013	–	–	0.0
$\lvert V_{ub}\rvert$(incl)	0.00449 ± 0.00020	–	–	-3.8
$\lvert V_{cb}\rvert$	0.0405 ± 0.0011	0.04200 ± 0.00059	0.04240 ± 0.00070	$+1.4$
$\lvert V_{cb}\rvert$(excl)	0.03887 ± 0.00059	–	–	$+3.9$
$\lvert V_{cb}\rvert$(incl)	0.04218 ± 0.00077	–	–	$+0.2$
$\alpha[^\circ]$	93.3 ± 5.6 and 166.6 ± 0.6	90.9 ± 2.0	90.1 ± 2.2	-0.6
$\beta[^\circ]$	–	22.25 ± 0.65	23.8 ± 1.3	–
$\gamma[^\circ]$	-109.9 ± 4.2 and 70.0 ± 4.2	66.8 ± 2.0	65.8 ± 2.2	-0.9
$J_{cp} \cdot 10^5$	–	–	3.120 ± 0.090	–
$2\beta + \gamma[^\circ]$	-90 ± 56 and 94 ± 52	111.4 ± 2.2	111.4 ± 2.2	$+0.3$
$\sin(2\beta)$	0.689 ± 0.018	0.699 ± 0.016	0.738 ± 0.033	$+1.2$
$\cos(2\beta)$	0.87 ± 0.11	0.712 ± 0.016	0.673 ± 0.036	-1.6
$\beta_s[^\circ]$	0.60 ± 0.88	–	1.060 ± 0.030	$+0.5$

f_{B_s}	0.2260 ± 0.0050	0.2240 ± 0.0040	0.2220 ± 0.0060	-0.6
f_{B_s}/f_{B_d}	1.203 ± 0.013	1.205 ± 0.015	1.225 ± 0.035	$+0.6$
B_{B_s}/B_{B_d}	1.032 ± 0.038	1.050 ± 0.030	1.100 ± 0.050	$+1.0$
B_{B_s}	0.888 ± 0.040	0.878 ± 0.030	0.872 ± 0.046	-0.4
B_k	0.740 ± 0.029	0.755 ± 0.025	0.848 ± 0.072	$+1.3$
$\|\epsilon_k\| \cdot 10^3$	2.228 ± 0.011	2.227 ± 0.010	1.9650 ± 0.1809	-1.4
$\Delta m_s[\mathrm{ps}^{-1}]$	17.757 ± 0.021	17.750 ± 0.050	17.25 ± 0.85	-0.7
$\Delta m_d[\mathrm{ps}^{-1}]$	0.5064 ± 0.0019	–	–	–
$\Delta\Gamma_d/\Gamma_d$	-0.0020 ± 0.0100	–	0.00497 ± 0.00038	$+0.6$
$\Delta\Gamma_s/\Gamma_s$	0.1280 ± 0.0089	–	0.153 ± 0.011	$+1.6$
A_{SL_d}	-0.0020 ± 0.0017	-0.000292 ± 0.000026	-0.000292 ± 0.000026	$+1.0$
A_{SL_s}	-0.00059 ± 0.00280	0.0000131 ± 0.0000011	0.0000131 ± 0.0000011	$+0.2$
$B(B \to \tau\nu) \cdot 10^4$	1.09 ± 0.24	0.826 ± 0.055	0.812 ± 0.054	-1.2

rameter	Input value	Prediction
$\bar{\rho}$	–	0.147 ± 0.030
$\bar{\eta}$	–	0.377 ± 0.028
ρ	–	0.150 ± 0.030
η	–	0.387 ± 0.029
A	–	0.785 ± 0.021
λ	0.22574 ± 0.00089	0.22550 ± 0.00050
$\|V_{ub}\|$	0.00372 ± 0.00023	0.00373 ± 0.00023
$\|V_{cb}\|$	0.0405 ± 0.0011	0.0398 ± 0.0010
$\alpha[^\circ]$	93.3 ± 5.6 and 166.6 ± 0.6	87.1 ± 4.4
$\beta[^\circ]$	–	23.8 ± 1.6
$\gamma[^\circ]$	-109.9 ± 4.2 and 70.0 ± 4.2	68.7 ± 4.2
C_{B_d}	–	1.05 ± 0.11
$\phi_{B_d}[^\circ]$	–	-2.0 ± 1.8
C_{B_s}	–	1.110 ± 0.090
$\phi_{B_s}[^\circ]$	0.60 ± 0.88	0.42 ± 0.89
C_{ϵ_K}	–	1.12 ± 0.12
A_{SL_d}	-0.0020 ± 0.0017	-0.0033 ± 0.0014
A_{SL_s}	-0.00059 ± 0.00280	-0.00013 ± 0.00051

EFT analysis of ΔF=2 transitions: the NP scale Λ

The mixing amplitudes $A_q e^{2i\phi_q} = \langle \bar{M}_q | H_{\text{eff}}^{\Delta F=2} | M_q \rangle$

$$H_{eff}^{\Delta B=2} = \sum_{i=1}^{5} C_i(\mu) Q_i(\mu) + \sum_{i=1}^{3} \tilde{C}_i(\mu) \tilde{Q}_i(\mu)$$

$Q_1 = \bar{q}_L^\alpha \gamma_\mu b_L^\alpha \, \bar{q}_L^\beta \gamma^\mu b_L^\beta$ (SM/MFV)

$Q_2 = \bar{q}_R^\alpha b_L^\alpha \, \bar{q}_R^\beta b_L^\beta$ $\quad Q_3 = \bar{q}_R^\alpha b_L^\beta \, \bar{q}_R^\beta b_L^\alpha$

$Q_4 = \bar{q}_R^\alpha b_L^\alpha \, \bar{q}_L^\beta b_R^\beta$ $\quad Q_5 = \bar{q}_R^\alpha b_L^\beta \, \bar{q}_L^\beta b_R^\alpha$

$\tilde{Q}_1 = \bar{q}_R^\alpha \gamma_\mu b_R^\alpha \, \bar{q}_R^\beta \gamma^\mu b_R^\beta$

$\tilde{Q}_2 = \bar{q}_L^\alpha b_R^\alpha \, \bar{q}_L^\beta b_R^\beta$ $\quad \tilde{Q}_3 = \bar{q}_L^\alpha b_R^\beta \, \bar{q}_L^\beta b_R^\alpha$

$C_i(\Lambda)$ can be extracted from the data (one by one)

Loop factor L:

- tree/strong interact. NP, L ~ 1
- perturbative NP, L ~ α_s^2, α_W^2

$$\Lambda = \sqrt{\frac{L \cdot FC}{C_i(\Lambda)}}$$

Flavor couplings FC: (i) generic $|FC| \sim 1$ | (ii) SM-like $|FC| \sim F_{SM}$

arbitrary phases

Parameter	95% allowed range	Lower limit on Λ (TeV)
$\mathrm{Im}C_K^1$	$[-3.4, 7.0]\cdot 10^{-16}$	$37.9\cdot 10^3$
$\mathrm{Im}C_K^2$	$[-7.7, 3.8]\cdot 10^{-18}$	$359.8\cdot 10^3$
$\mathrm{Im}C_K^3$	$[-5.2, 10.4]\cdot 10^{-17}$	$98.2\cdot 10^3$
$\mathrm{Im}C_K^4$	$[-8.0, 16.0]\cdot 10^{-19}$	$789.5\cdot 10^3$
$\mathrm{Im}C_K^5$	$[-1.6, 3.2]\cdot 10^{-17}$	$176.0\cdot 10^3$
$\mathrm{Im}C_D^1$	$[-1.4, 1.4]\cdot 10^{-15}$	$27.1\cdot 10^3$
$\mathrm{Im}C_D^2$	$[-2.2, 2.2]\cdot 10^{-16}$	$66.8\cdot 10^3$
$\mathrm{Im}C_D^3$	$[-3.3, 3.3]\cdot 10^{-15}$	$17.4\cdot 10^3$
$\mathrm{Im}C_D^4$	$[-5.5, 5.5]\cdot 10^{-17}$	$134.5\cdot 10^3$
$\mathrm{Im}C_D^5$	$[-6.6, 6.5]\cdot 10^{-16}$	$39.0\cdot 10^3$
$\lvert C_{B_d}^1\rvert$	$< 1.9\cdot 10^{-13}$	$2.3\cdot 10^3$
$\lvert C_{B_d}^2\rvert$	$< 5.4\cdot 10^{-14}$	$4.3\cdot 10^3$
$\lvert C_{B_d}^3\rvert$	$< 2.0\cdot 10^{-13}$	$2.2\cdot 10^3$
$\lvert C_{B_d}^4\rvert$	$< 1.6\cdot 10^{-14}$	$7.9\cdot 10^3$
$\lvert C_{B_d}^5\rvert$	$< 4.5\cdot 10^{-14}$	$4.7\cdot 10^3$
$\mathrm{Re}C_{B_s}^1$	$[-4.6, 5.9]\cdot 10^{-12}$	411.7
$\mathrm{Re}C_{B_s}^2$	$[-1.6, 1.3]\cdot 10^{-12}$	782.5
$\mathrm{Re}C_{B_s}^3$	$[-4.7, 6.0]\cdot 10^{-12}$	408.2
$\mathrm{Re}C_{B_s}^4$	$[-3.9, 5.0]\cdot 10^{-13}$	$1.4\cdot 10^3$
$\mathrm{Re}C_{B_s}^5$	$[-1.1, 1.4]\cdot 10^{-12}$	842.2
$\mathrm{Im}C_{B_s}^1$	$[-2.0, 2.0]\cdot 10^{-12}$	705.7
$\mathrm{Im}C_{B_s}^2$	$[-5.5, 5.5]\cdot 10^{-13}$	$1.3\cdot 10^3$
$\mathrm{Im}C_{B_s}^3$	$[-2.1, 2.0]\cdot 10^{-12}$	696.7
$\mathrm{Im}C_{B_s}^4$	$[-1.7, 1.7]\cdot 10^{-13}$	$2.4\cdot 10^3$
$\mathrm{Im}C_{B_s}^5$	$[-4.8, 4.8]\cdot 10^{-13}$	$1.4\cdot 10^3$

Deviations from the SM to keep an eye on

- ε'/ε
- BR(
- R(B
- Γ(B
- q^2 s

Direct CP violation in $K \to \pi\pi$

Long-established experimental result:

$$(\varepsilon'/\varepsilon)_{exp} = (16.6 \pm 2.3) \times 10^{-4}$$

Theory breaking news: all the hadronic matrix elements entering the SM prediction have finally been computed on the lattice

(RBC-UKQCD coll.'s, arXiv:1505.07863)

$$(\varepsilon'/\varepsilon)_{SM} = (1.4 \pm 6.8) \times 10^{-4} \qquad -2.1\sigma$$

(Buras et al., arXiv:1507.06345)

$$= (1.9 \pm 4.5) \times 10^{-4} \qquad -2.9\sigma$$

- a "new" constraint on $\bar{\eta}$ in the UT analysis
- one of the most powerful NP probes in flavour physics finally fully at work!!

Deviations from the SM to keep an eye on

- ε'/ε
- **BR($B_s \to \mu\mu$), BR($B \to \mu\mu$)**

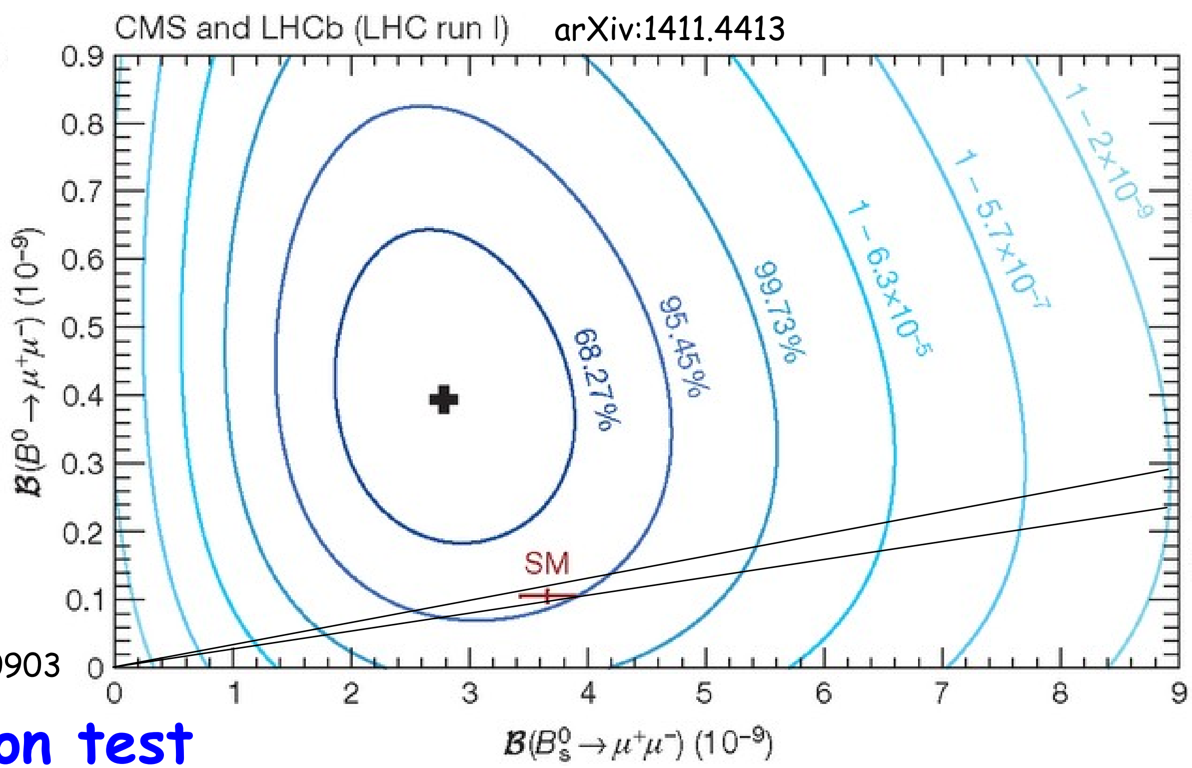
$$\mathrm{BR}(\mathrm{B}_s \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$

$$\mathrm{BR}(\mathrm{B}_s \to \mu^+\mu^-)_{SM} = (3.65 \pm 0.23) \times 10^{-9} \quad +1.2\sigma$$

$$\mathrm{BR}(\mathrm{B} \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$

$$\mathrm{BR}(\mathrm{B} \to \mu^+\mu^-)_{SM} = (1.06 \pm 0.09) \times 10^{-10} \quad -2.2\sigma$$

SM predictions from Bobeth et al., arXiv:1311.0903



Minimal Flavour Violation test

Theoretical issues

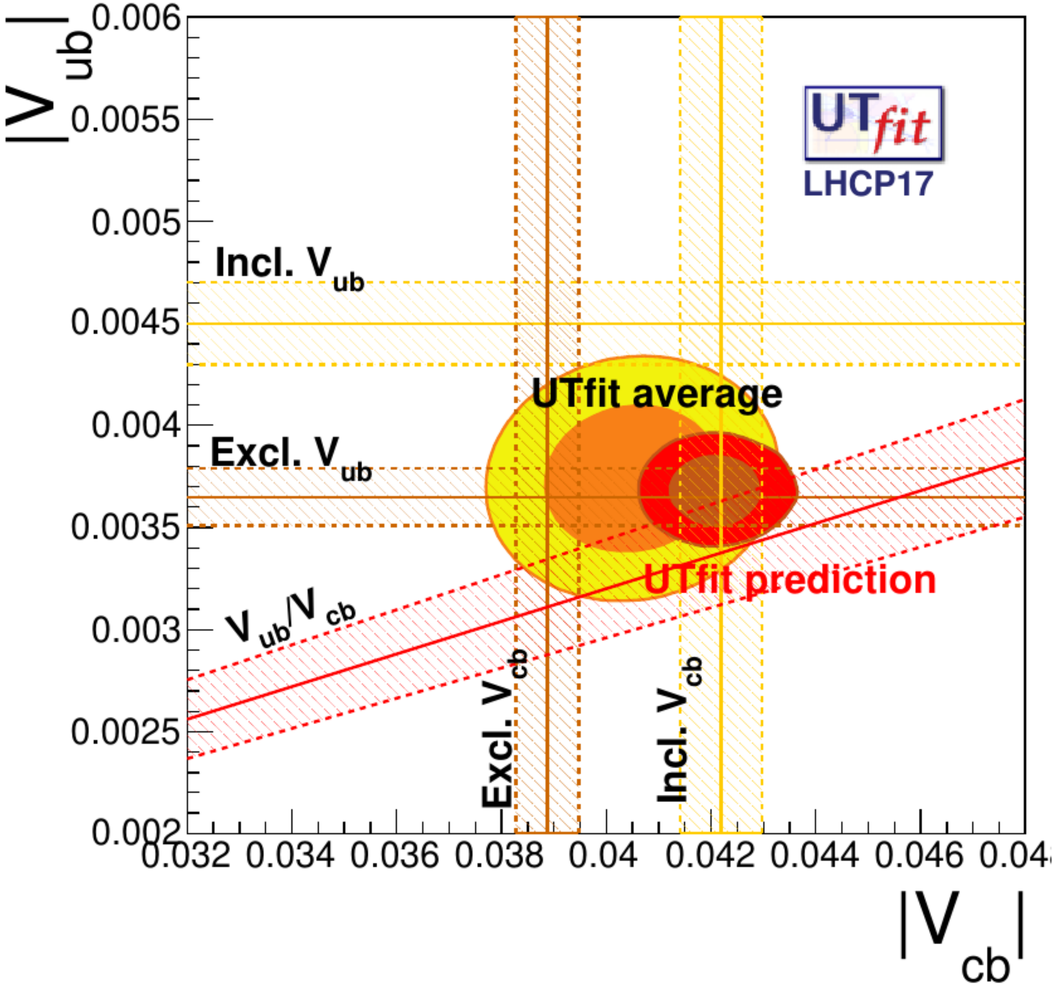
QUITE A FEW!

In the sub-percent era, many solid approximations used so far to compute hadronic amplitudes can't be relied on anymore (e.g. isospin symmetry, no QED corrections, no subleading amplitudes, no higher-dimensional operators, etc.)

Good news: the tree-level determination of γ from $B \to DK$ (GLW, ADS, GGSZ) safely extrapolates to the high precision. D mixing is manageble and EW corrections are still negligible

Brod, Zupan, arXiv:1308.5663

The other tree-level constraints from semileptonic B decays are in less good shape: the long-standing disagreement between incl. and excl. measurements is still there, but there are promising new developments



CLN parametrization of the $B \to D^*$ FF's uses HQ relations which may be responsible for the $|V_{cb}|$ discrepancy.
Still inconclusive, but…

Grinstein, Kobach, arXiv:1703.08170
Bigi, Gambino, Schacht, arXiv:1703.0612

New attempts at computing FF's on the lattice at small q^2

Martinelli et al., in progress

Loop-level constraints: th. prospects

→ Δm_d and Δm_s: decay constants and B parameters @1% call for QED corrections

→ ε_K: QED corrections, long-distance contributions, dimension-8 operators need to be controlled

RBC-UKQCD

MC et al., in progress

→ α: isospin breaking

Gronau, Zupan, hep-ph/0502139
Charles et al., arXiv:1705.02981

→ β: subleading amplitude bound using SU(3)-related

$$A(B^0 \to J/\psi K) = V_{cb}^* V_{cs} T + \boxed{V_{ub}^* V_{us} P}$$

$B \to J/\psi\pi^0$ where the 2nd term is not Cabibbo suppressed

th. error scales with the ones on control channels & matches the measurement accuracy

Fleischer, hep-ph/9903455
MC et al., hep-ph/0507290, ...

→ β_s: same as β, but trickier (larger effect, ϕ is not a pure octet, ...). Still likely controllable

De Bruyn, Fleischer, arXiv:1412.6834

De Bruyn, Fleischer, arXiv:1412.6834

New opportunities

High statistics and high precision also provide new opportunities for CKM metrology

For example:

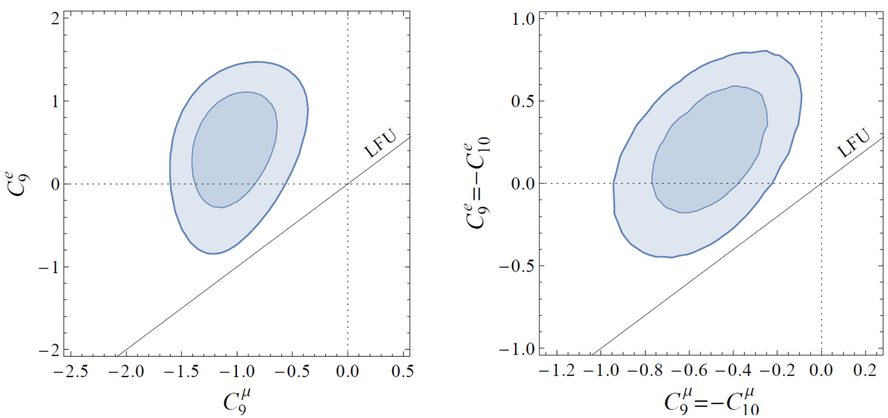
Parameters	$B_s^0 \to D_s^\mp K^\pm$ 23 fb^{-1}	$B_s^0 \to D_s^\mp K^\pm$ 300 fb^{-1}	$B^0 \to D^\mp \pi^\pm$ 23 fb^{-1}	$B^0 \to D^\mp \pi^\pm$ 300 fb^{-1}
S_f, $S_{\bar{f}}$	0.043	0.011	0.0041	0.0010
$A_f^{\Delta\Gamma}$, $A_{\bar{f}}^{\Delta\Gamma}$	0.065	0.016	–	–
C_f	0.030	0.007	–	–

* β from $2\beta+\gamma$ and γ less precise than β from $B \to J/\psi K$, but free from subdominant penguin amplitudes and $\Delta F=1$ NP

* $|V_{ts}|/|V_{td}|$ from $BR(B_s \to \mu\mu) / BR(B_d \to \mu\mu)$ less effective than $\Delta m_s / \Delta m_d$, but affected by different NP, $\Delta F=1$ instead of $\Delta F=2$

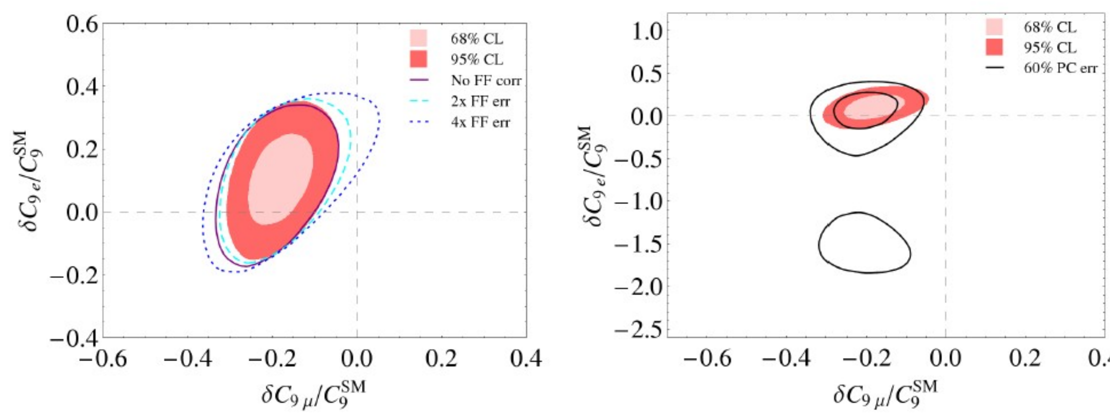
EFT global analysis

Altmannshofer, Straub., arXiv:1411.3161

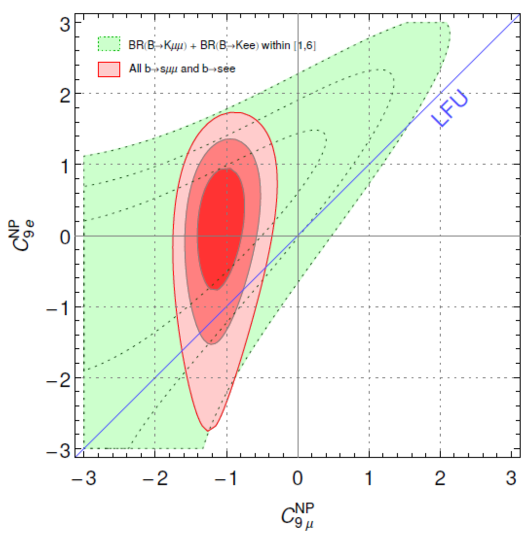


* $B \to K^{(*)} \mu\mu$
* $B \to X_s \gamma$
* $B_s \to \phi \mu\mu$
* R_K
* $B \to K^* \gamma$

Hurth et al., arXiv:1603.00865



Descotes-Genon et al., arXiv:1605.06059



point to an O(1) correction to the WC of $Q_9^\mu = \bar{s}_L \gamma_\alpha b_L \bar{\mu} \gamma^\alpha \mu$