Quark flavour physics in the time of European strategy

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INFN ROMA TRE

- Precision flavour physics
- Flavour physics & European strategy
- Prospects for the UT analysis
- (Prospects for $b \to s$ anomalies)
- Conclusions

The stage

* the Higgs boson discovery closed up the quest for the Standard Model: an extremely successful story which however left us with a well-known list of problems (fermion masses and mixing, strong CP, EW hierarchy, …) and no clear clue for the next step

* the absence of NP discoveries at the LHC has *weakened* the naturalness argument requiring new particles at close-by energies: future physics programs rely more and more on indirect searches (EWPO, Higgs couplings & potential, …)

Precision flavour physics: a tool of choice for indirect NP searches

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{\mathcal{L}_5}{\Lambda_{\rm NP}} + \frac{\mathcal{L}_6}{\Lambda^2_{\rm NP}} + \ldots$$

has (approximate) accidental symmetries

may violate accidental symmetries

* rich phenomenology (a variety of FCNCs, mixing, CPV observables in several meson and baryon sectors)

* NP sensitivity is strongly boosted by the suppression of flavor and CP violation present in the SM (weak coupling, small mixing, GIM mechanism in FCNCs & CPV, LF & LFU approximate conservation, ...)

* important successes in the low-precision regime (charm from $K\to\mu\mu$, 3rd gen. from ε_K, heavy m_t from *B* mixing+SL decays)

To achieve sensitivity on subleading NP amplitudes, indirect searches require that the theoretical uncertainty on SM amplitudes matches the experimental error

In flavour physics dominant SM uncertainties are typically the hadronic ones. Input from a non-perturbative technique able to compute hadronic amplitudes at sub-percent level is needed

Lattice QCD is expected to achieve sub-percent accuracy on several hadronic parameters. Yet LQCD is not always applicable (non-local operators, amplitudes with 2+ hadrons in the final state, …)

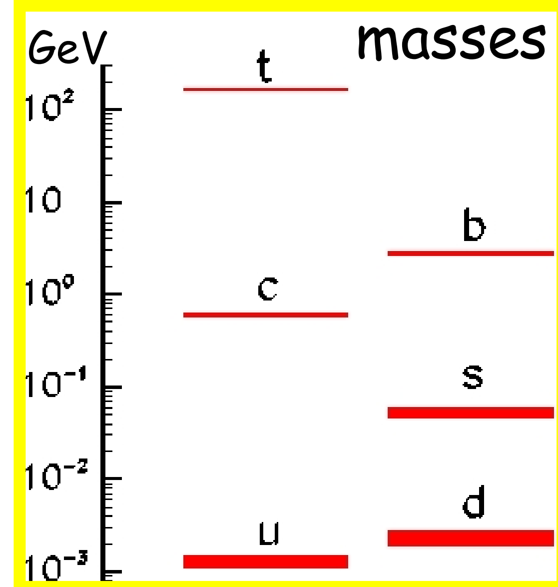
Pysics briefing book, arXiv:1910.11775

Quantity	Ref.	present error	short-term	mid-term
$(\Delta m_s/\Delta m_d)_{\text{exp}}$	[33]	0.4%	-	-
ξ for $(\Delta m_s/\Delta m_d)_{\text{theor}}$	[309]	1.4%	0.3%	0.3%
$B\to\pi$: $\lvert V_{ub}\rvert_{\text{exp}}$	[309, 334, 340]	2.3%	1.6%	1.1%
$B\to\pi$: $\lvert V_{ub}\rvert_{\text{theor}}$	[309]	2.9%	1%	1%
$B\to D$: $\lvert V_{cb}\rvert_{\text{exp}}$	[309, 340]	2.0%	1.4%	-
$B\to D$: $\lvert V_{cb}\rvert_{\text{theor}}$	[309]	1.4%	0.3%	0.3%
$B\to D^*$: $\lvert V_{cb}\rvert_{\text{exp}}$	[340]	1.2%	-	-
$B\to D^*$: $\lvert V_{cb}\rvert_{\text{theor}}$	[309]	1.4%	0.4%	0.4%
$\Lambda_b\to p(\Lambda_c)$: $\lvert V_{ub}/V_{cb}\rvert_{\text{exp}}$	[334]	6%	1%	1%
$\Lambda_b\to p(\Lambda_c)$: $\lvert V_{ub}/V_{cb}\rvert_{\text{theor}}$	[309]	4.9%	1.2%	1.2%

In specific cases, strategies can be envisaged which rely less on theory inputs, using instead data to control the SM uncertainty (e.g. the UT angles, $b\to c$ inclusive SL decays, …)

Finally null tests: no theory input needed for those observables having negligible SM contribution (e.g. LFV, CPV in D mixing, …)

Flavour physics is not just a tool: SM has its own flavour puzzle

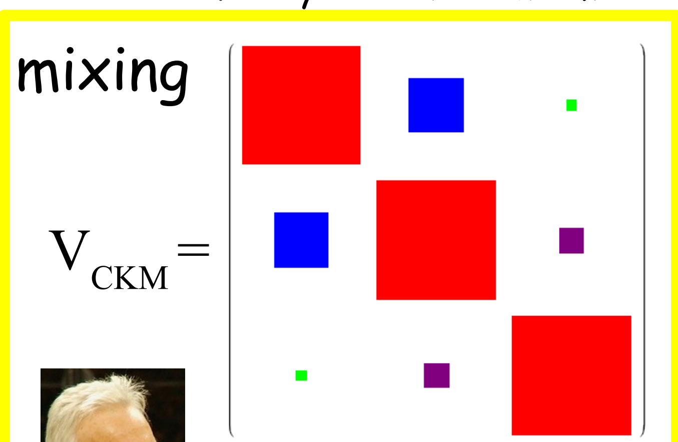


$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{EWSB}} + \mathcal{L}_{\text{kin}} + \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Y}}$$

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

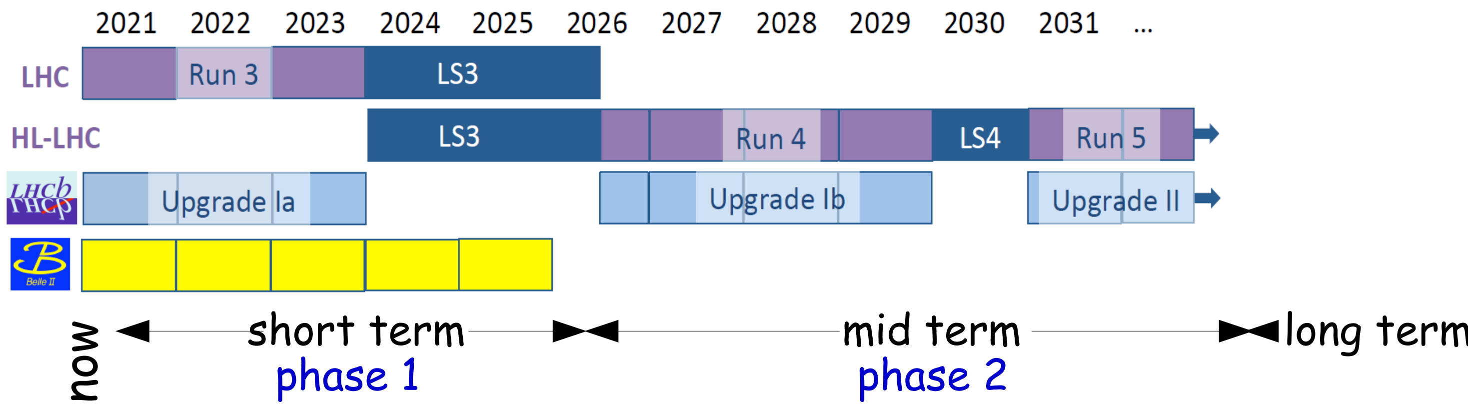


The pattern of masses, mixing, and CPV may already be a NP signal we have not been able to interpret within a full-fledged theory so far

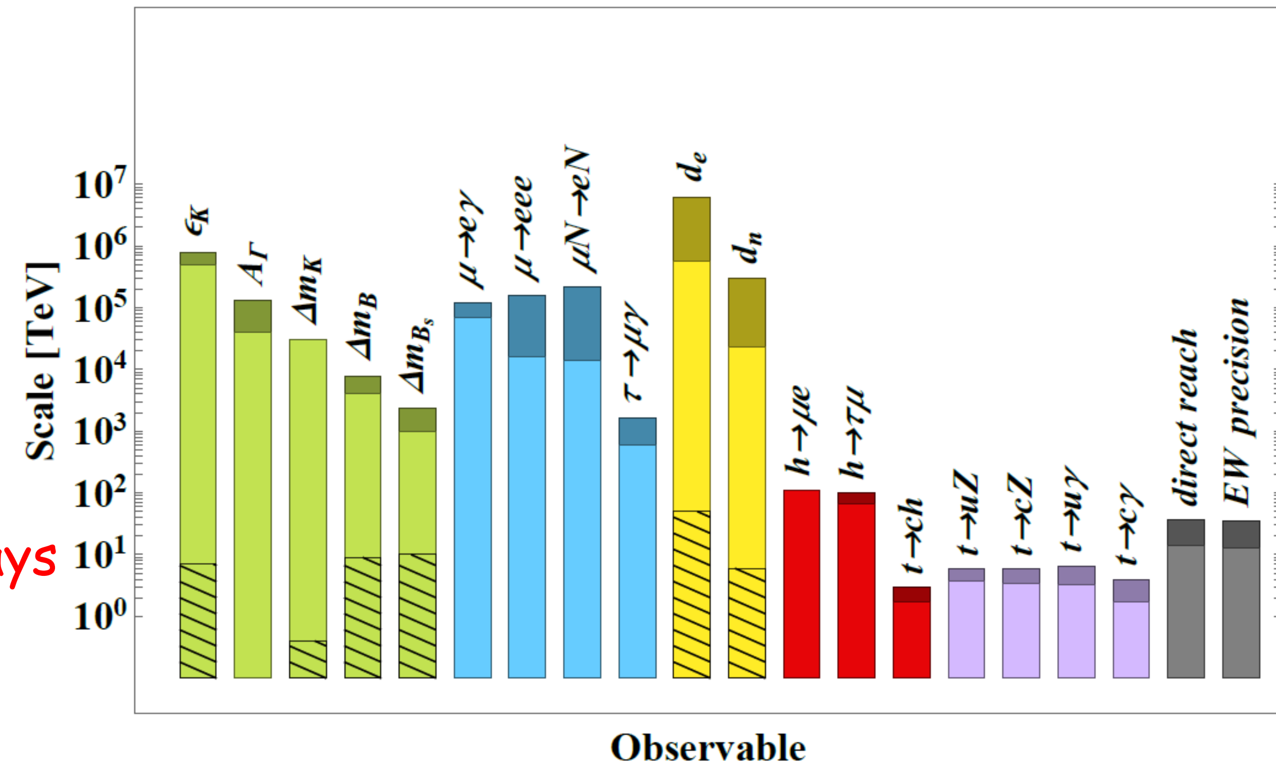
European strategy for particle physics: flavour physics in the briefing book

Physics Briefing Book, arXiv:1910.11775

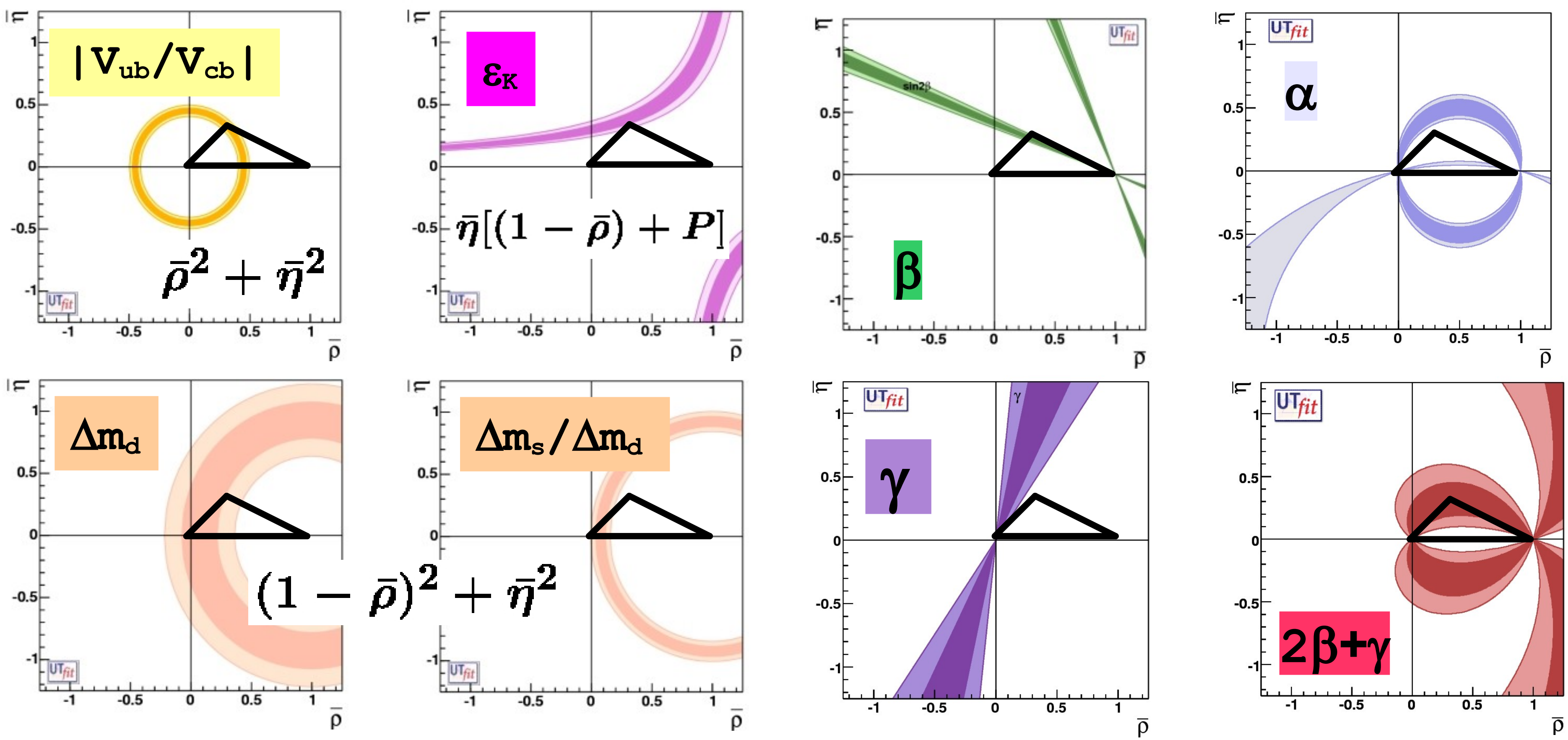
Report of WG4 on the physics at the HL-LHC and perspectives at the HE-LHC, arXiv:1812.07638



- EDMs: neutron, e, …
- FV in lepton decays (μ and τ)
- K ultra-rare decays and CPV
- Heavy flavour physics
  - selected FCNCs
    - e.g. $BR(B_d \to \mu\mu)/BR(B_s \to \mu\mu)$
  - LFV, LFUV, …
    - e.g. R_{D/D^*}, R_{K/K^*} + $B_d \to K^*\mu\mu$
  - CPV in charm mixing and decays
- Dark sector, e.g. $D^* \to D\ \gamma_{dark}$
- Unitarity Triangle Analysis



Unitarity Triangle Analysis



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

Overconstrained fit:
- predict observables & hadronic parameters **or <u>constrain NP</u>**

UTA beyond the SM

generic NP contributions to mixing amplitudes

		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	$\tau(B_s)$, $\Delta\Gamma_s/\Gamma_s$				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): $\mathrm{Im}\, A_K = C_\varepsilon \, \mathrm{Im}\, A_K^{SM}$

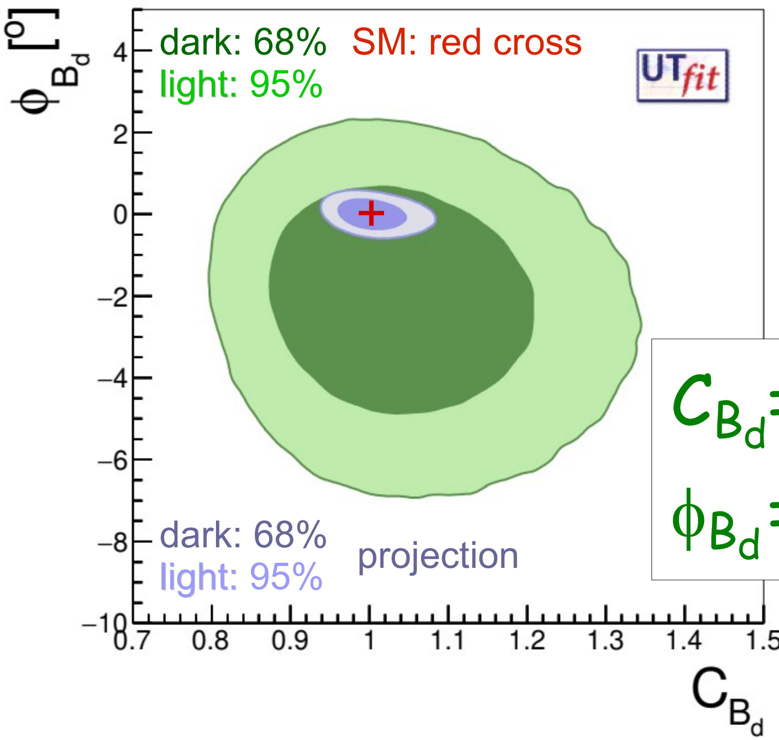
B_d and B_s mixing amplitudes (2+2 real parameters):

- two parametrizations -

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

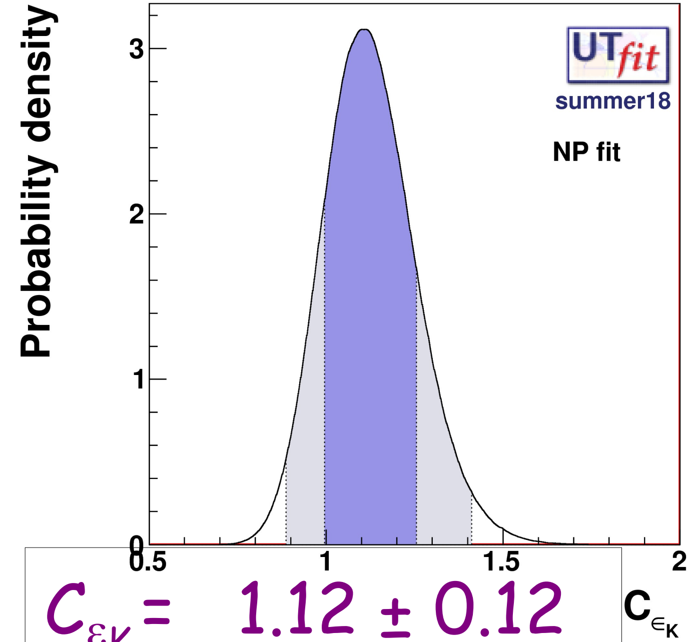
$$A_q e^{2i\phi_q} = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}} = \left[1+\frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP}-\phi_q^{SM})}\right] A_q^{SM} e^{2i\phi_q^{SM}}$$

New Physics parameters



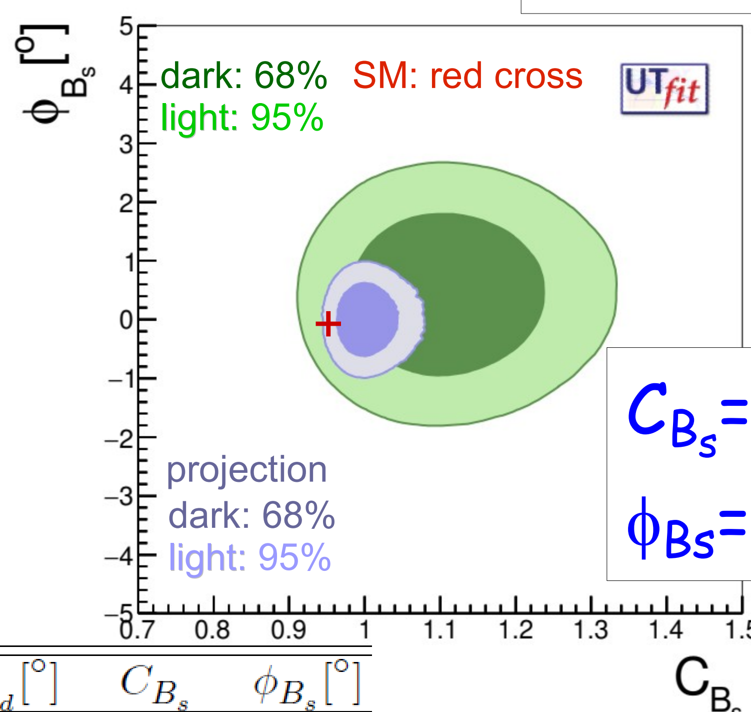
C_{B_d} = 1.05 ± 0.11

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_{B_s} = (0.42 ± 0.89)°

	$\bar\rho$	$\bar\eta$	C_{ε_K}	C_{B_d}	$\phi_{B_d}[^\circ]$	C_{B_s}	$\phi_{B_s}[^\circ]$
Current	0.030	0.028	0.12	0.11	1.8	0.09	0.89
Phase 2	0.0047	0.0040	0.036	0.030	0.28	0.026	0.29

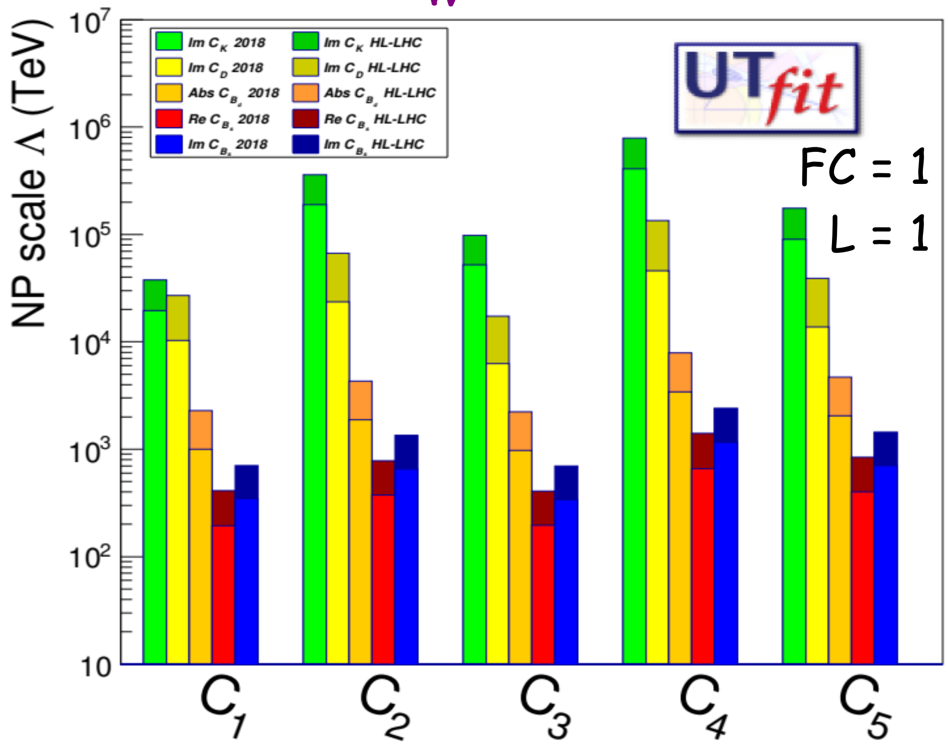
$$Q_1 = \bar{q}_L^\alpha \gamma_\mu b_L^\alpha \, \bar{q}_L^\beta \gamma^\mu b_L^\beta \quad \text{(SM/MFV)}$$
$$Q_2 = \bar{q}_R^\alpha b_L^\alpha \, \bar{q}_R^\beta b_L^\beta \qquad Q_3 = \bar{q}_R^\alpha b_L^\beta \, \bar{q}_R^\beta b_L^\alpha$$
$$Q_4 = \bar{q}_R^\alpha b_L^\alpha \, \bar{q}_L^\beta b_R^\beta \qquad Q_5 = \bar{q}_R^\alpha b_L^\beta \, \bar{q}_L^\beta b_R^\alpha$$
$$\widetilde{Q}_i = Q_i[L \leftrightarrow R]$$

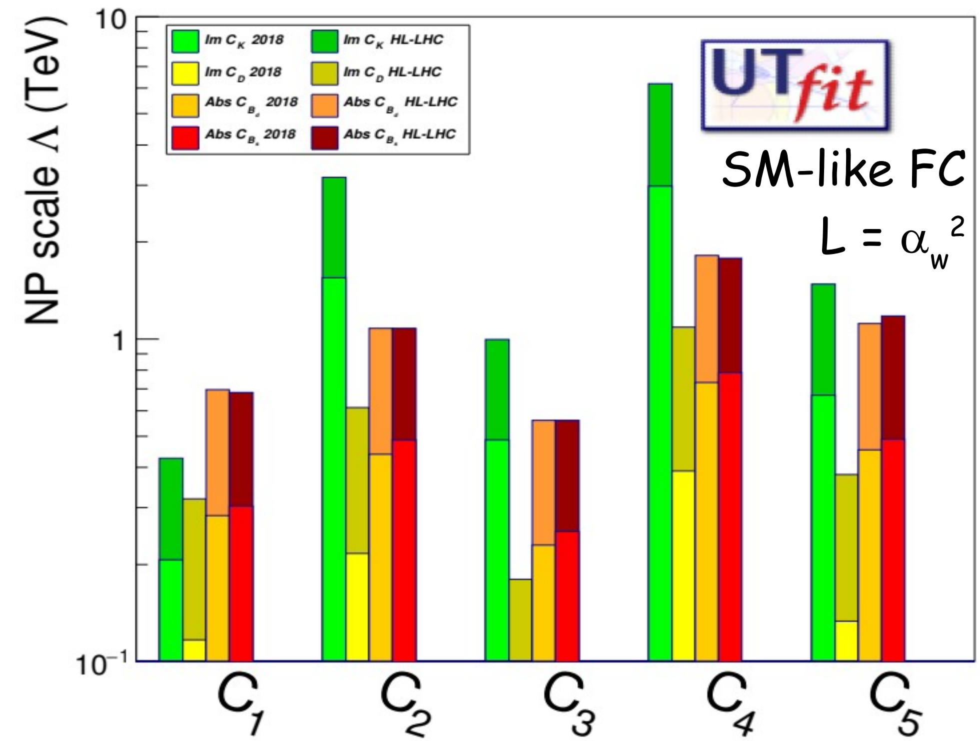
$$H_{eff}^{\Delta B=2} = \sum_{i=1}^{5} C_i(\mu) Q_i(\mu) + \sum_{i=1}^{3} \widetilde{C}_i(\mu) \widetilde{Q}_i(\mu)$$

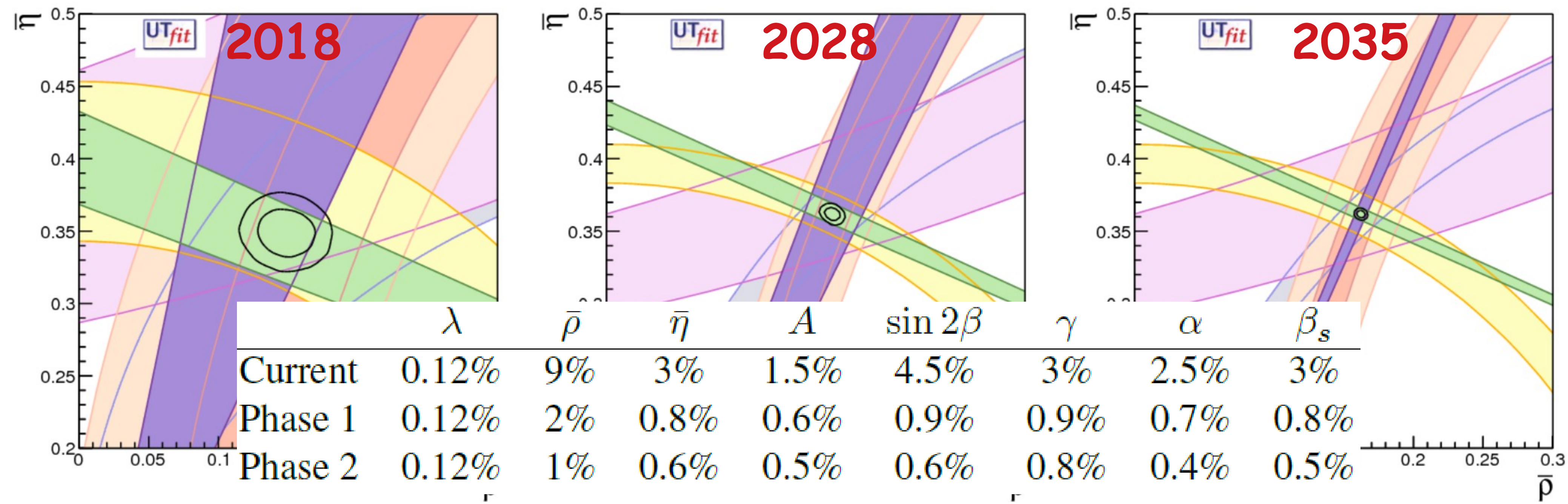
Lower bound on the NP scale Λ from ΔF=2 transitions (TeV @95% prob.)

$$C_i(\Lambda) = \frac{L \cdot FC}{\Lambda^2}$$

	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~α_W^2	3	0.4	0.7	0.8







	λ	$\bar{\rho}$	$\bar{\eta}$	A	$\sin 2\beta$	γ	α	β_s
Current	0.12%	9%	3%	1.5%	4.5%	3%	2.5%	3%
Phase 1	0.12%	2%	0.8%	0.6%	0.9%	0.9%	0.7%	0.8%
Phase 2	0.12%	1%	0.6%	0.5%	0.6%	0.8%	0.4%	0.5%

* $\delta\varepsilon_K$ ~ 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
* $\delta\alpha$ ~ 1%, limited by unknown isospin-breaking corrections
* exclusive semilep. 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 sub-percent level QED effects need to be included

New opportunities

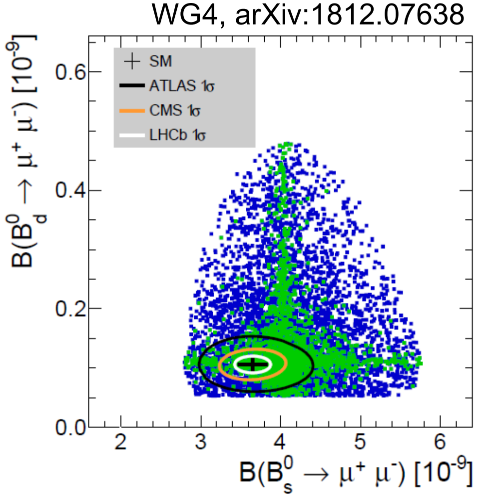
High precision provides new opportunities

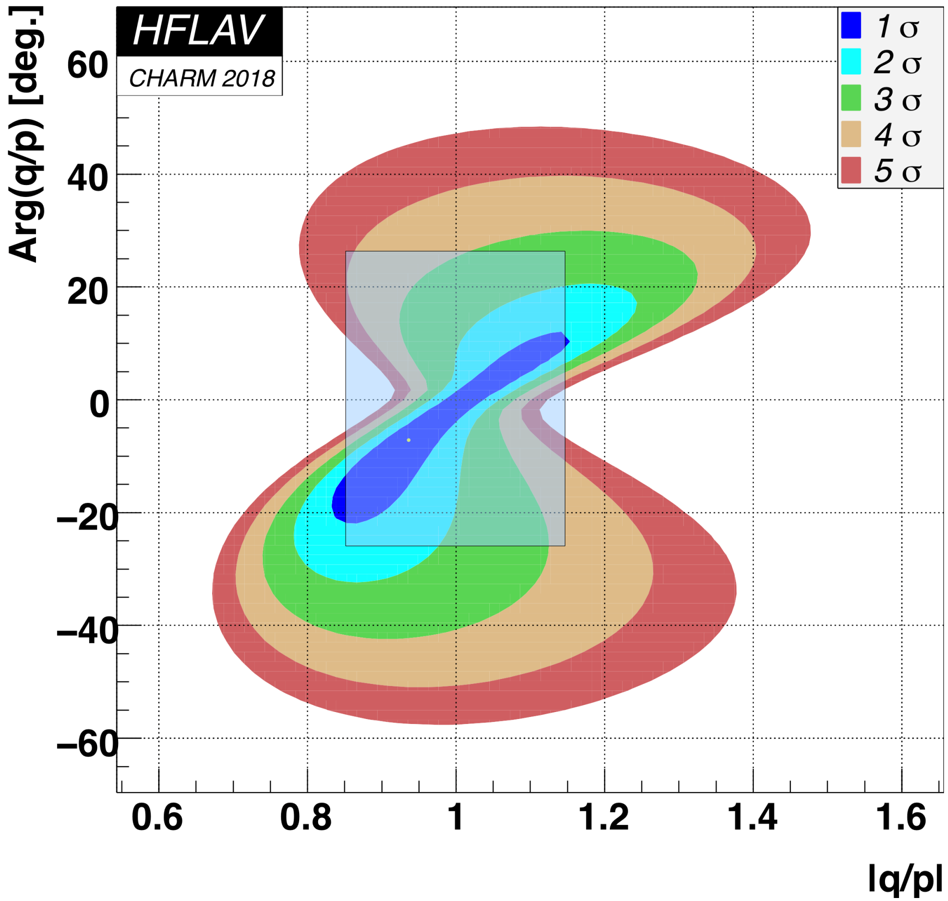
For example:

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 amplitude and NP in $\Delta F=1$ decays

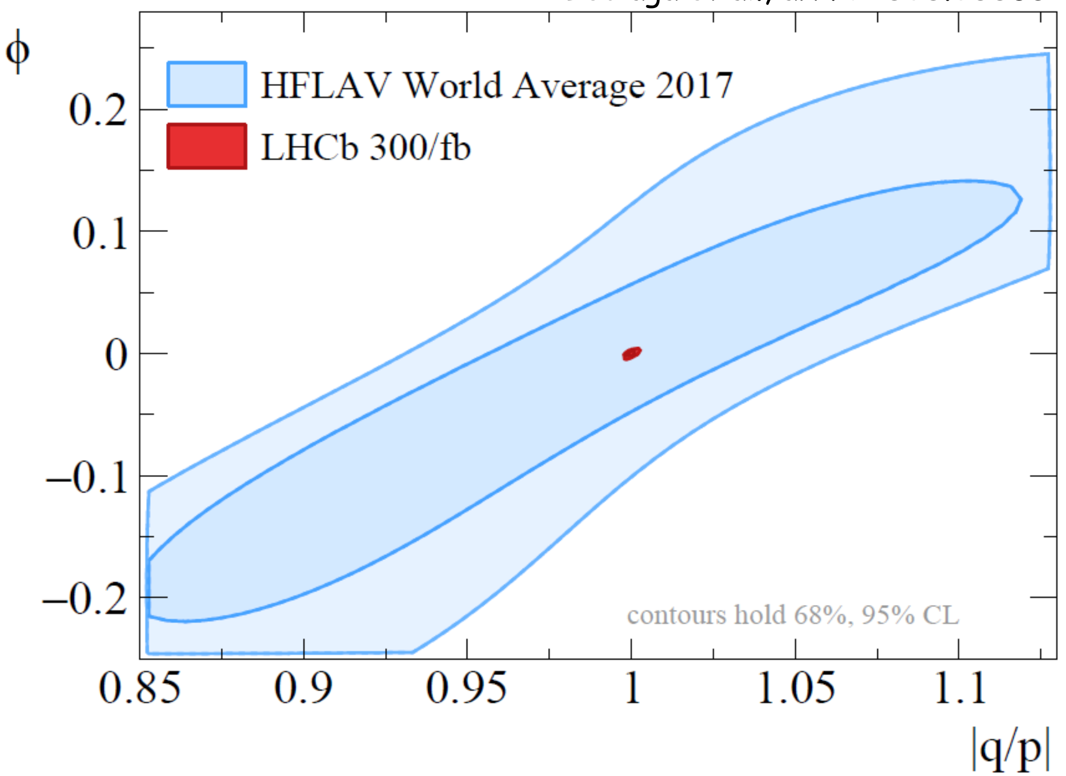
* $|V_{ts}|/|V_{td}|$ from $BR(B_s \to \mu\mu)$ / $BR(B_d \to \mu\mu)$
  less effective than Δm_s / Δm_d, but affected by NP in $\Delta F=1$ transitions instead of $\Delta F=2$





New Physics parameters: CPV in D-Dbar mixing

Bediaga et al., arXiv:1808.08865

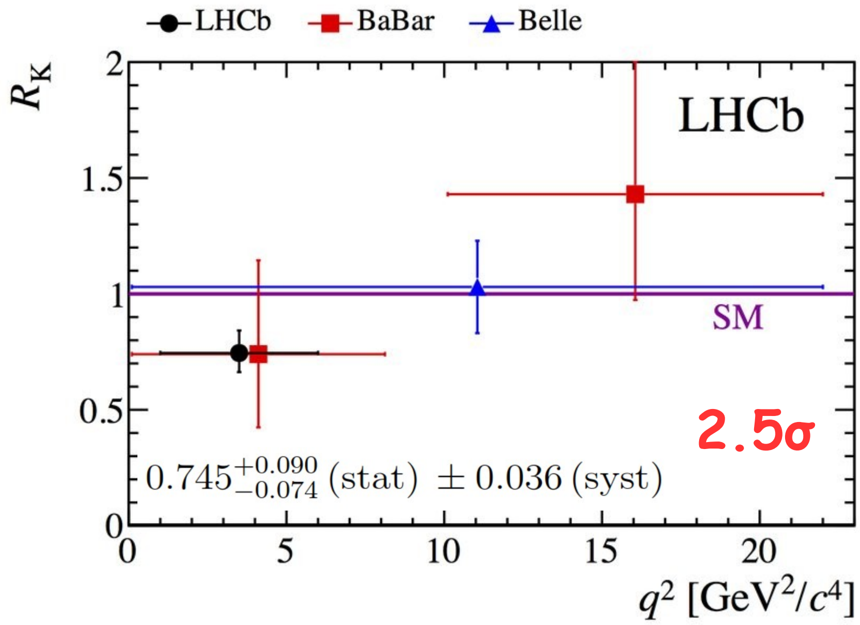


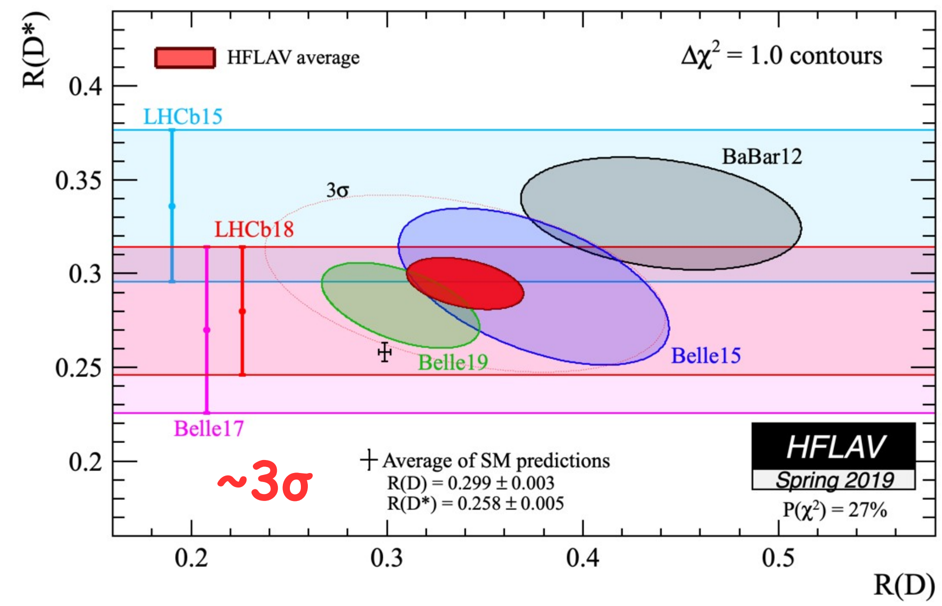
SM amplitudes are approximately real

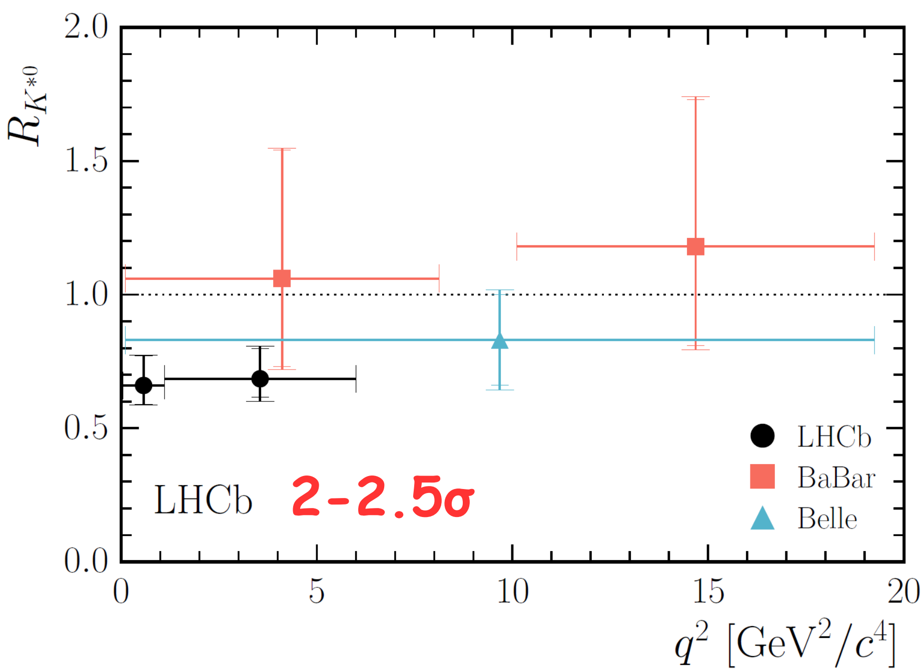
CPV is generated by NP

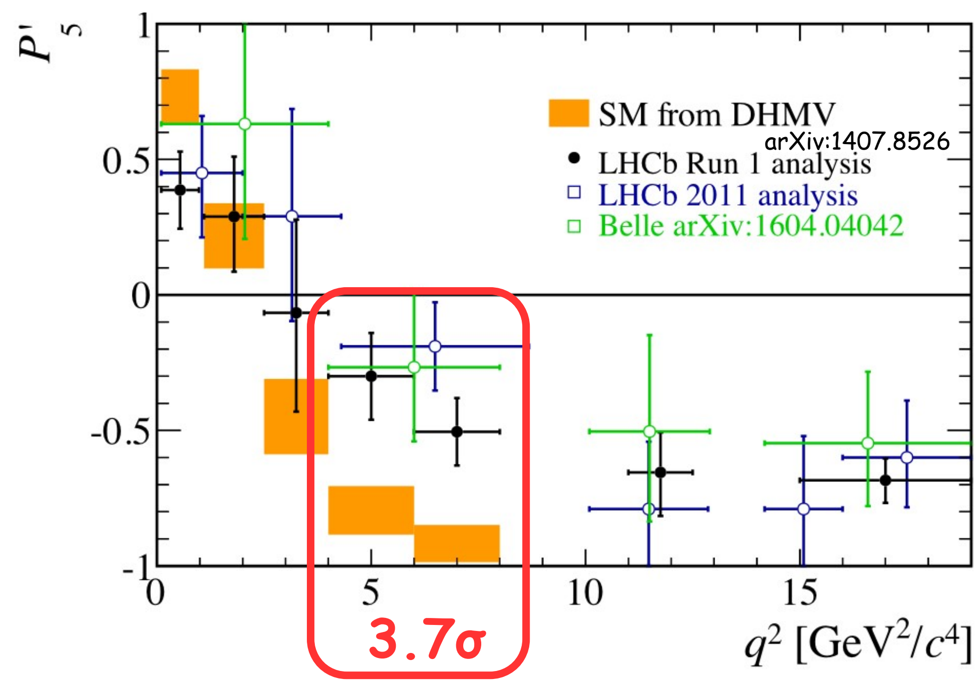
$|q/p| \neq 1 \Leftrightarrow \arg(q/p) \neq 0$

ΔB=1: the B "anomalies"









Global fits to b→s FCNCs

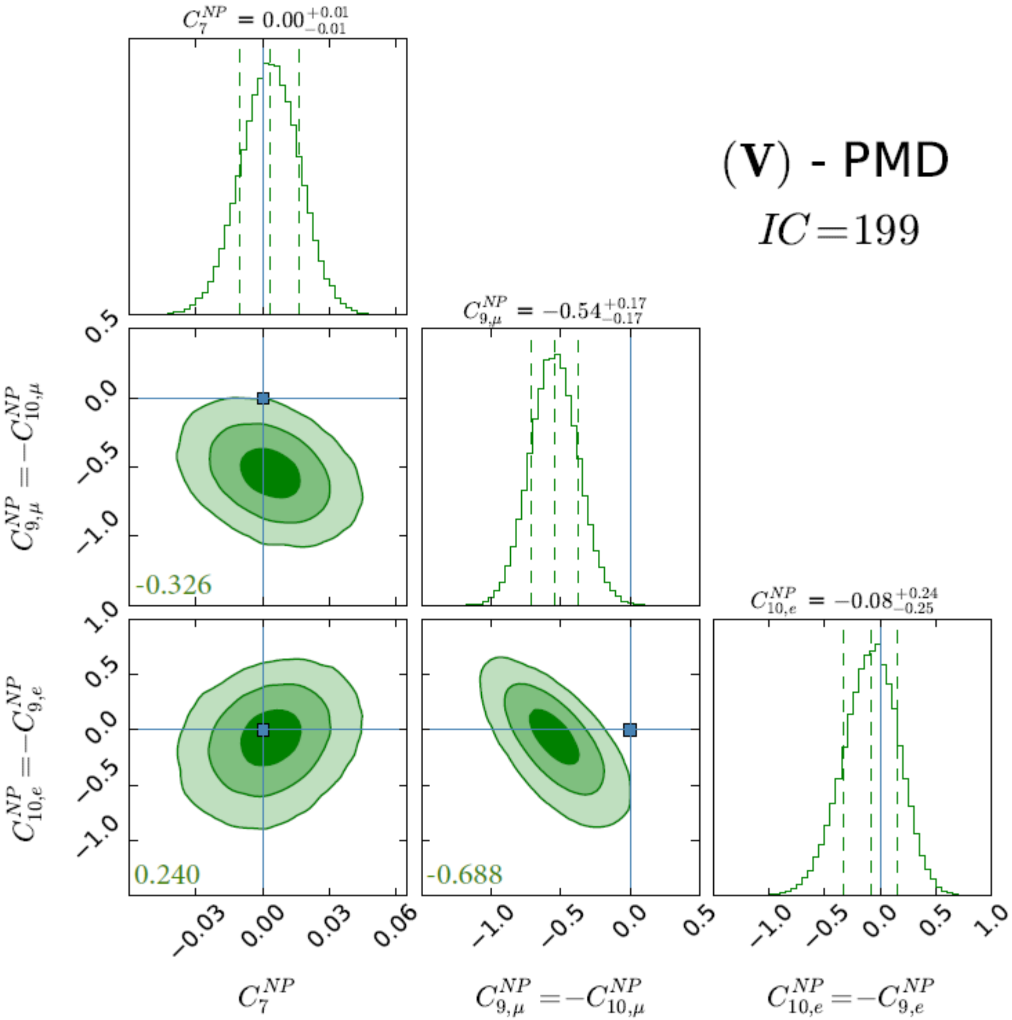
$$Q_7 = \frac{e}{16\pi^2} m_b \bar{s}_L \sigma_{\mu\nu} F^{\mu\nu} b_R$$

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

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

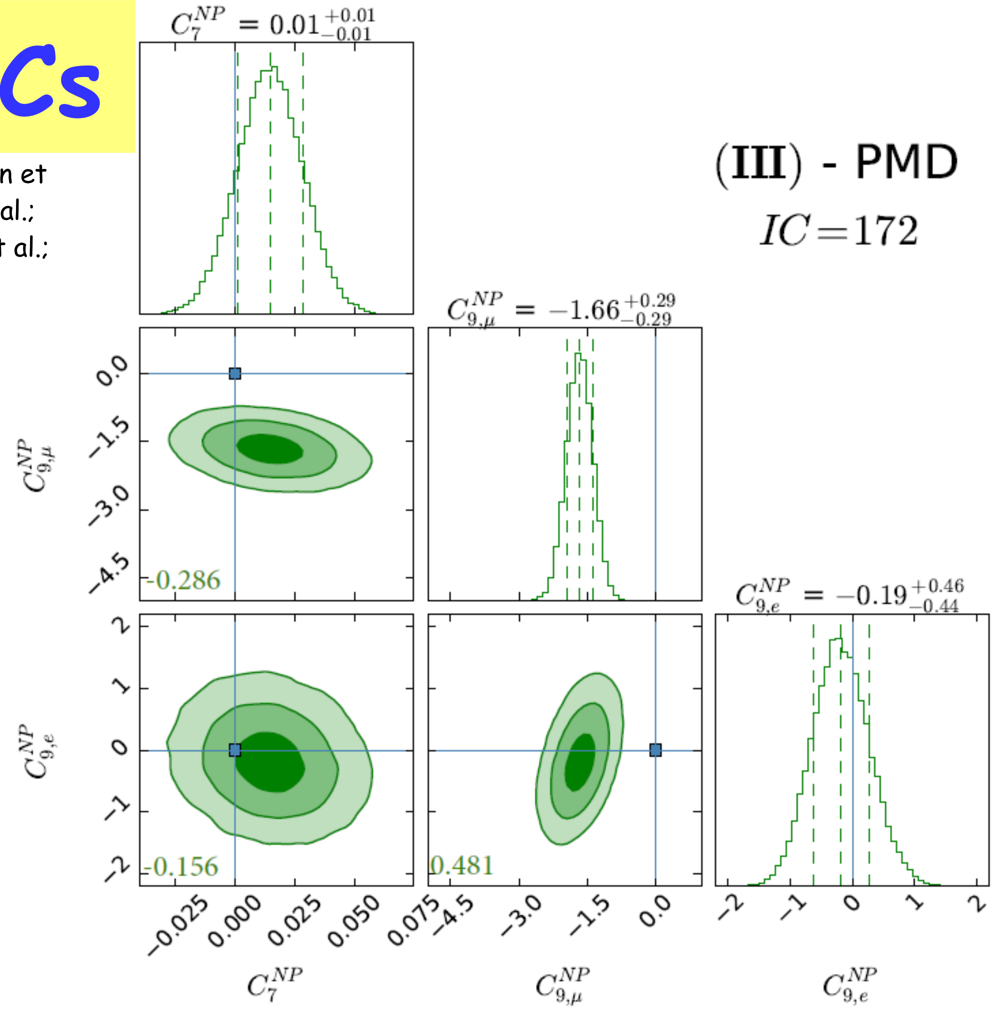
Hiller&Kruger; Descotes-Genon et al.; Jaeger et al.; Capdevila et al.; Altmannshofer et al.; Hurth et al.; ...

MC et al., arXiv:1704.05447



(V) - PMD

$IC = 199$



(III) - PMD

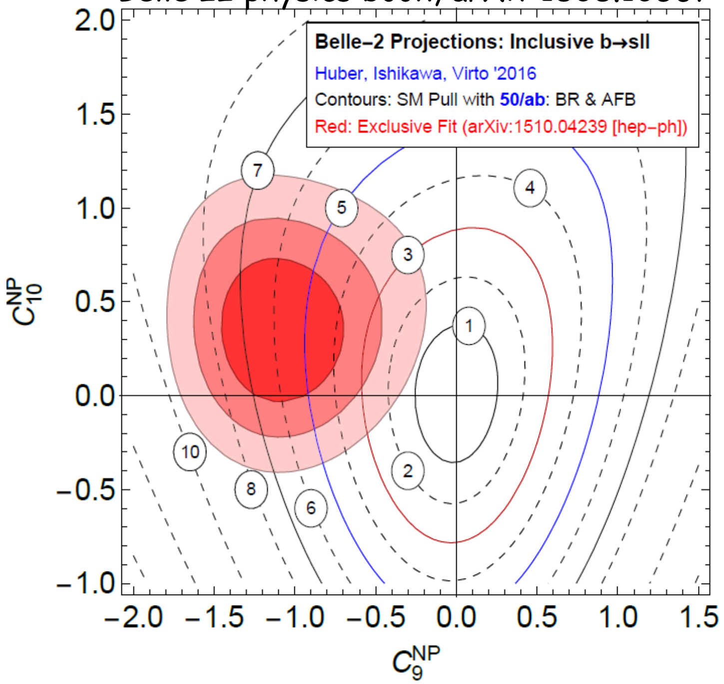
$IC = 172$

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

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

MC et al., arXiv:1704.05447

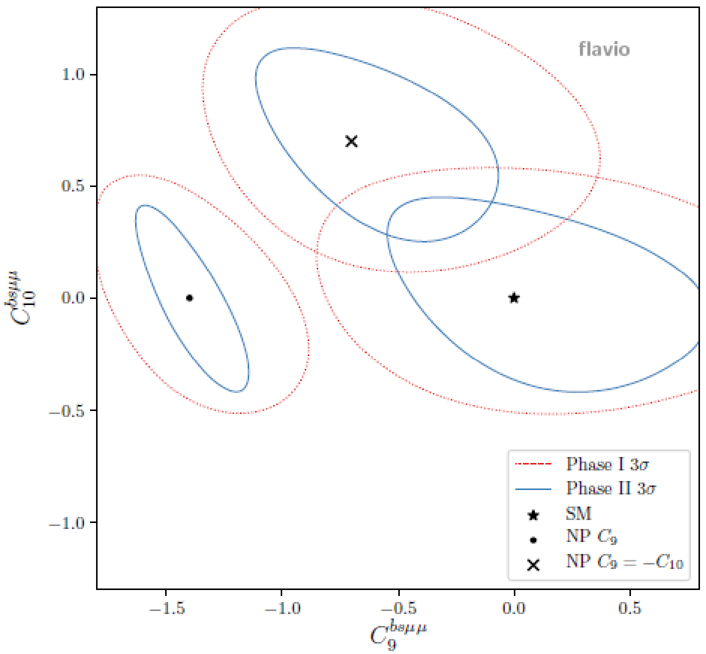
Belle II physics book, arXiv:1808.10567



Short term: important to confirm the anomaly in $B \to K^*\mu\mu$ with different systematics and theoretical uncertainties

Inclusive $B \to X_s \ell\ell$ @Belle II

WG4, arXiv:1812.07638



Mid term: bounds on $C_{9/10,\mu}$ from $B \to K^*\mu\mu$ and $B_s \to \mu\mu$ can be improved by a factor ~2, probing up to a scale Λ_{NP}~100 TeV

Summary

In a time when indirect searches become increasingly inportant, flavour physics remains a tool of choice

The SM picture looks very consistent, but so far we have typically excluded NP corrections at the 10% level …AND we are now entering the "percent era"!

Anomalies are present in recent $\Delta B=1$ data: despite the caveats, it is remarkable that there is a simple EFT interpretation for all of them

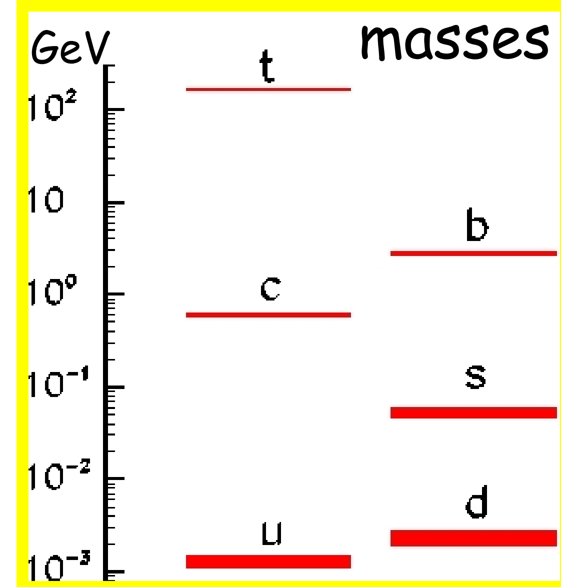
Theoretical progresses (QED corrections, isospin breaking, bilocal operators, …) in lattice QCD results are needed to convert exp. precision in NP sensitivity

As precision further increases, observables with weak/null theory input may take the scene

Thank you
and
stay safe!

Backup

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



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

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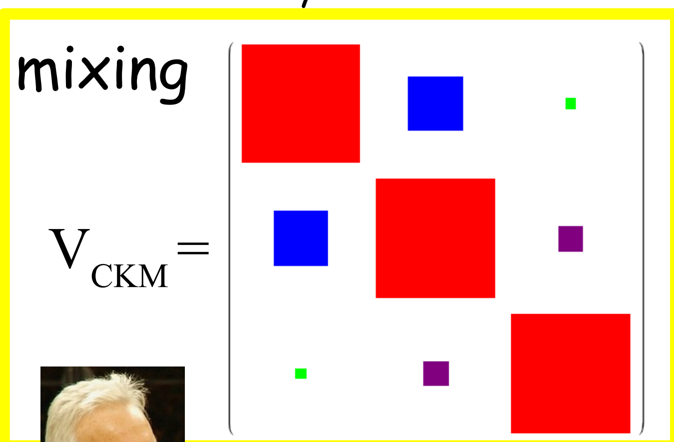


Beyond the SM: a powerful indirect probe of the New Physics scale Λ

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

has accidental (approximate) symmetries

may violate accidental symmetries

Going BSM with flavour physics: why?

Searches through virtual effects of new particles in loops: a game of suppression and correlation

* SM FCNCs and CPV occur at the loop level
* SM quark FV and CPV are governed by the weak interactions and suppressed by small mixing angles
* SM quark CPV comes from a single source (neglecting θ_{QCD})
* LF and LFU (approximately) conserved in quark decays

New Physics does not necessarily share the SM pattern of FV and CPV: huge NP effects are possible (and excluded)

Past (SM) successes anticipating new 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 B 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

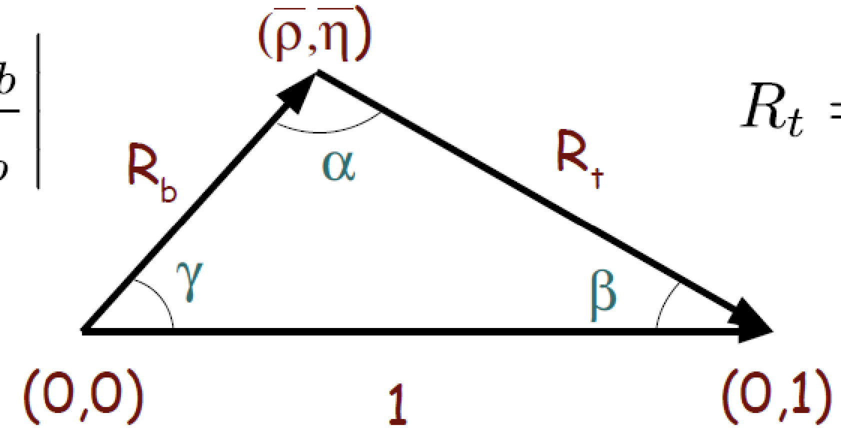
* several NP-sensitive observables not limited by systematics or theoretical uncertainties

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

- CKM unitarity implies triangular relations:
  $(V^\dagger V)_{bd}=0=V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^*$

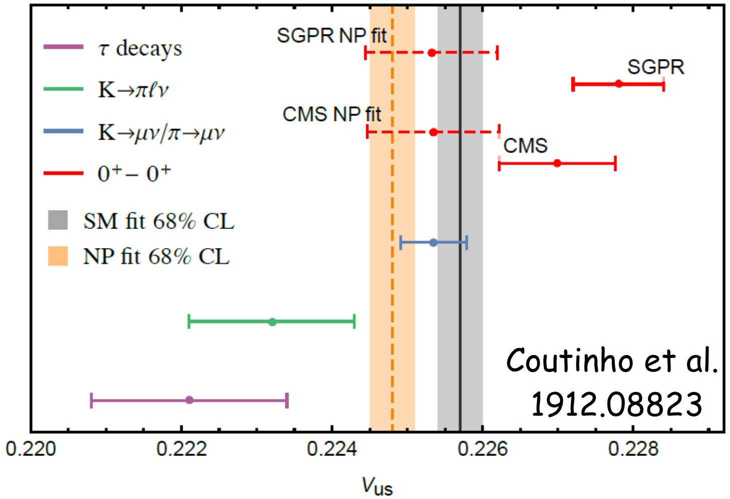
$$R_b = \left|\frac{V_{ud}V_{ub}}{V_{cd}V_{cb}}\right| \qquad R_t = \left|\frac{V_{td}V_{tb}}{V_{cd}V_{cb}}\right|$$



$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) \quad \beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \quad \gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

Setting the scale of the UT:

- $\lambda = \sin\theta_c = 0.22574 \pm 0.00089$
  from K_{l3}, K_{l2}/π_{l2}, $0^+ \to 0^+$ β decays
- $|V_{cb}|$ from semileptonic $b \to c$ decays



Coutinho et al.
1912.08823

The CKM matrix in the SM

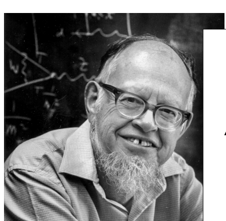
$$
\begin{array}{c} \\ u \\ c \\ t \end{array}
\begin{array}{c}
\begin{array}{ccc} d & s & b \end{array} \\
\begin{pmatrix}
0.97431(12) & 0.22514(55) & 0.00365(10)e^{-i66.8(2.0)^\circ} \\
-0.22500(54)e^{i0.0351(10)^\circ} & 0.97344(12)e^{-i0.00188(5)^\circ} & 0.04241(65) \\
0.00869(14)e^{-i22.2(0.6)^\circ}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

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

s_{12}= 0.2250 ± 0.0010 s_{23}= (4.200 ± 0.059)x10^{-2}

s_{13}= (3.68 ± 0.10)x10^{-3} δ = (66.8 ± 2.0)°

Wolfenstein parametrization: λ, A, ρ, η



λ = 0.2250 ± 0.0010 A = 0.826 ± 0.012

ρ = 0.152 ± 0.014 η = 0.357 ± 0.010

SM UT analysis

Summer 2018

SM determination of the Unitarity Triangle

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

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

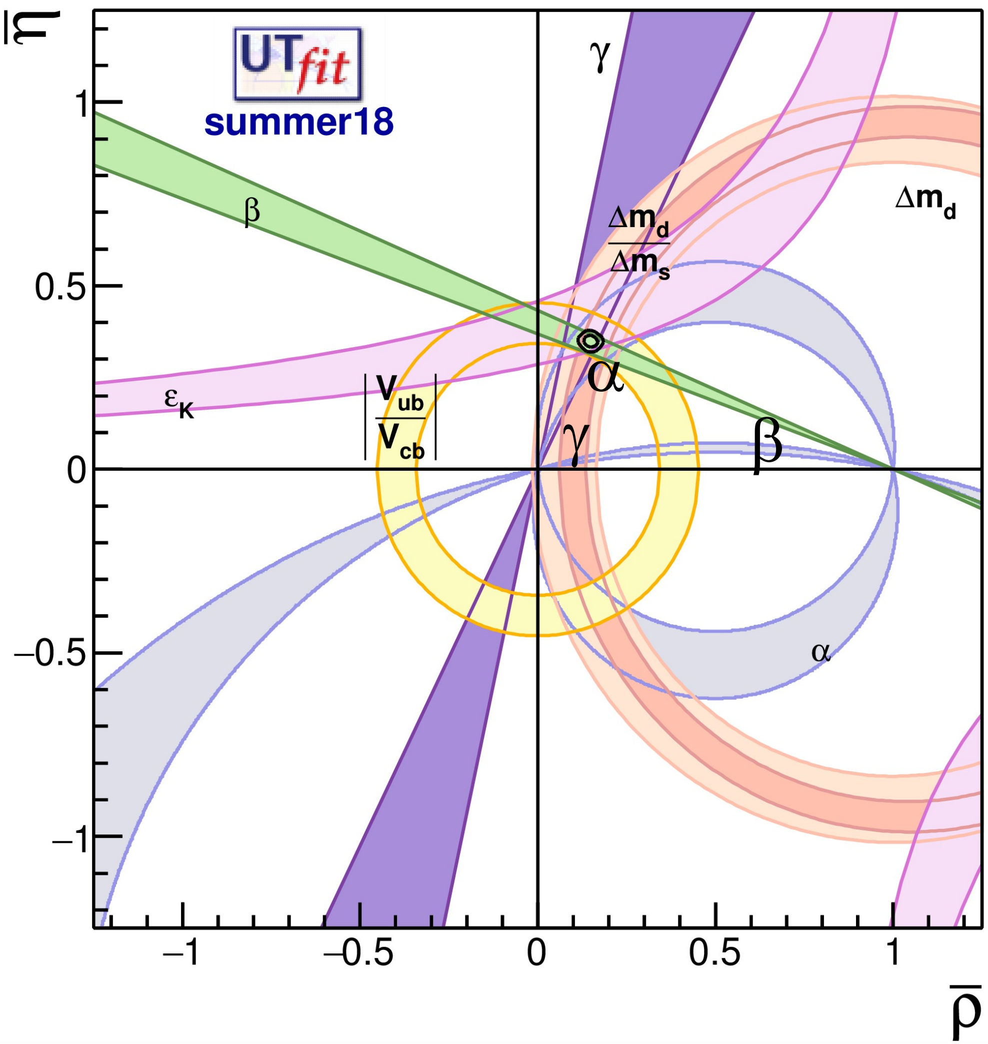
$R_u = 0.380 \pm 0.011$

$R_t = 0.920 \pm 0.014$

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

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

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



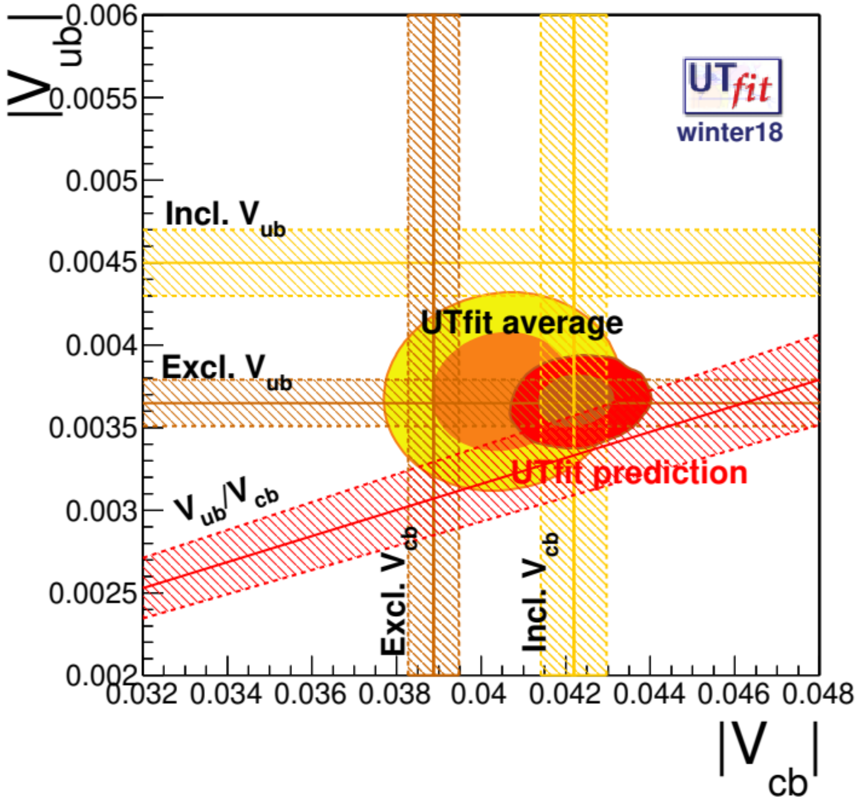
apex coordinates

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

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

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

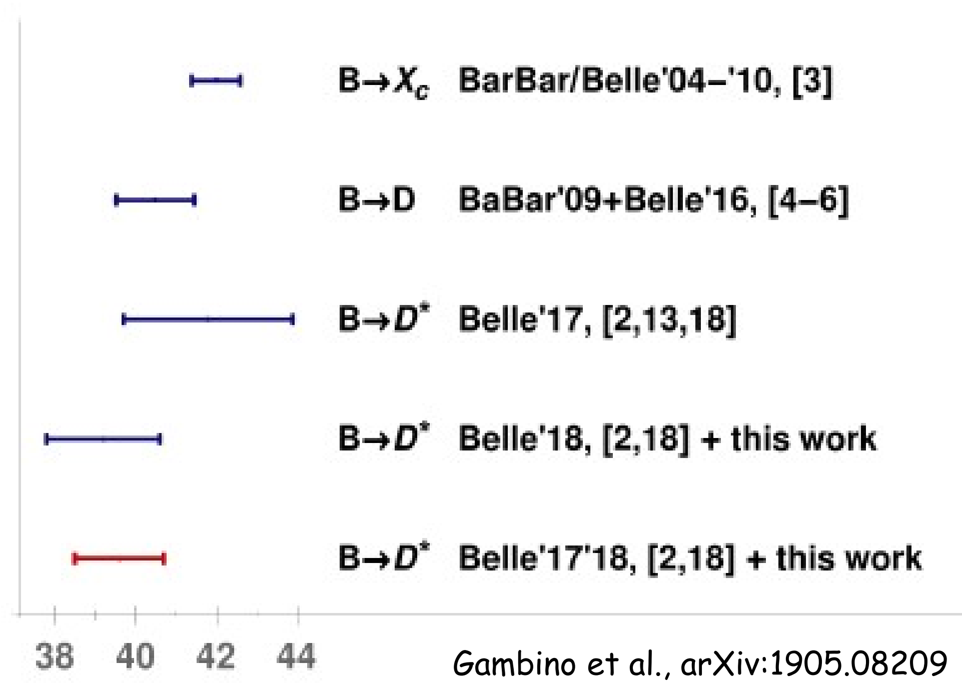


Long-standing problem for semileptonic B decays: inclusive vs exclusive

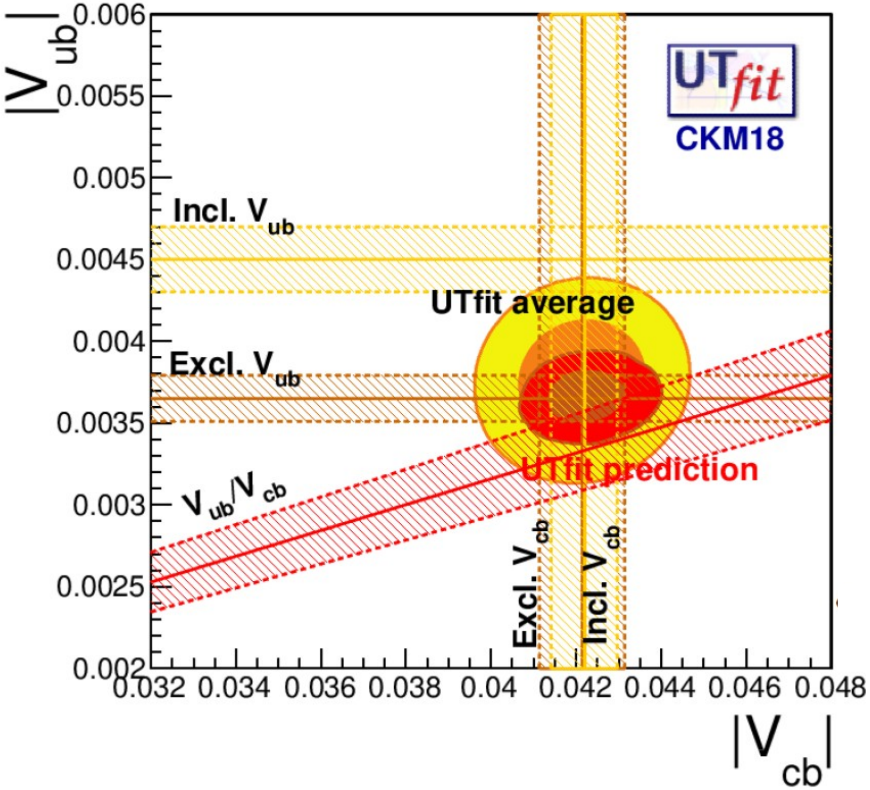
Reconsidering the CLN parametrization of the FFs for $|V_{cb}|$: exclusive → inclusive

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



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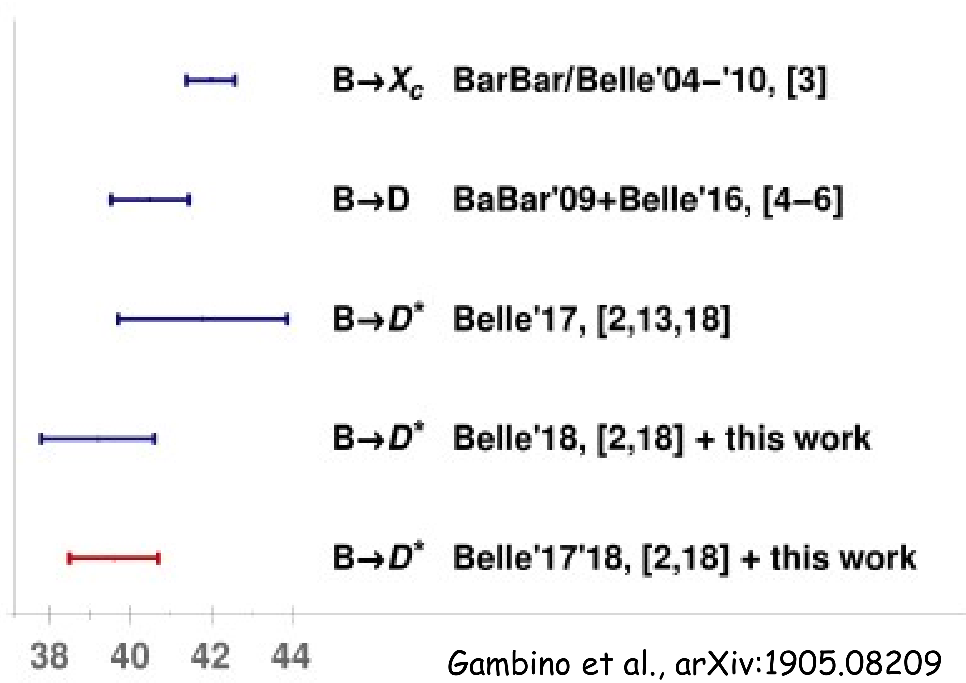
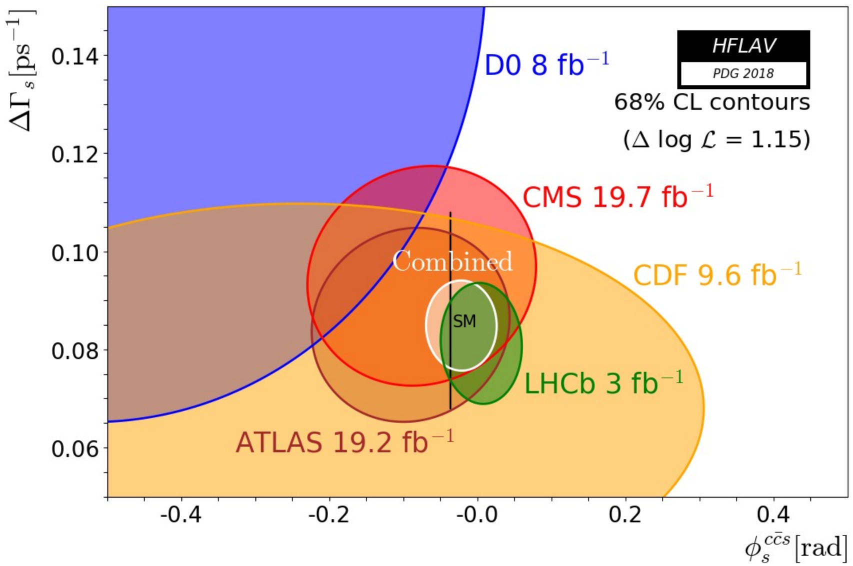
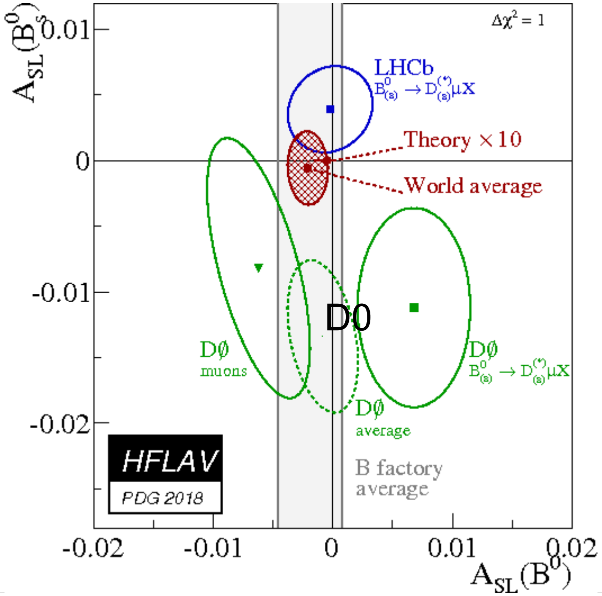


Gambino et al., arXiv:1905.08209

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





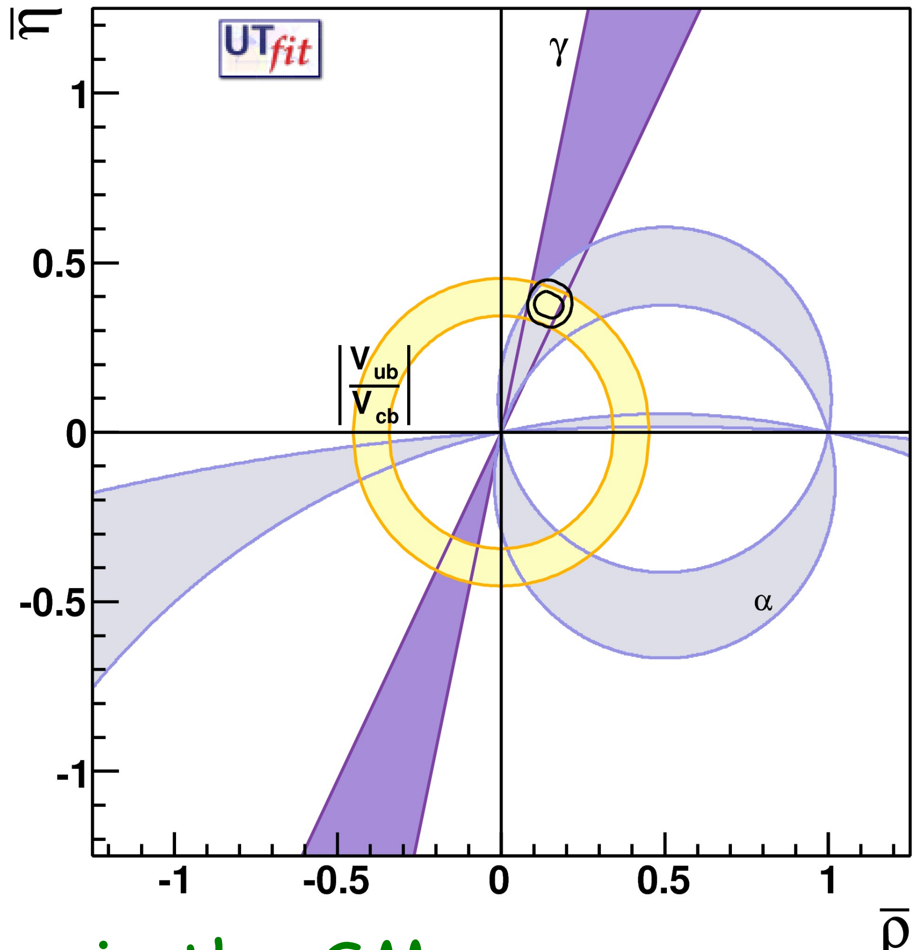
UT parameters in the presence of NP

model-independent determination of the CKM parameters

assumptions:
* three generations
* negligible NP in tree decays

$\bar{\rho}$ = 0.147 ± 0.030

$\bar{\eta}$ = 0.377 ± 0.028



in the SM was:

$\bar{\rho}$ = 0.148 ± 0.013

$\bar{\eta}$ = 0.348 ± 0.010

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

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

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

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

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

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

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

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

$C_i(\Lambda)$ 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

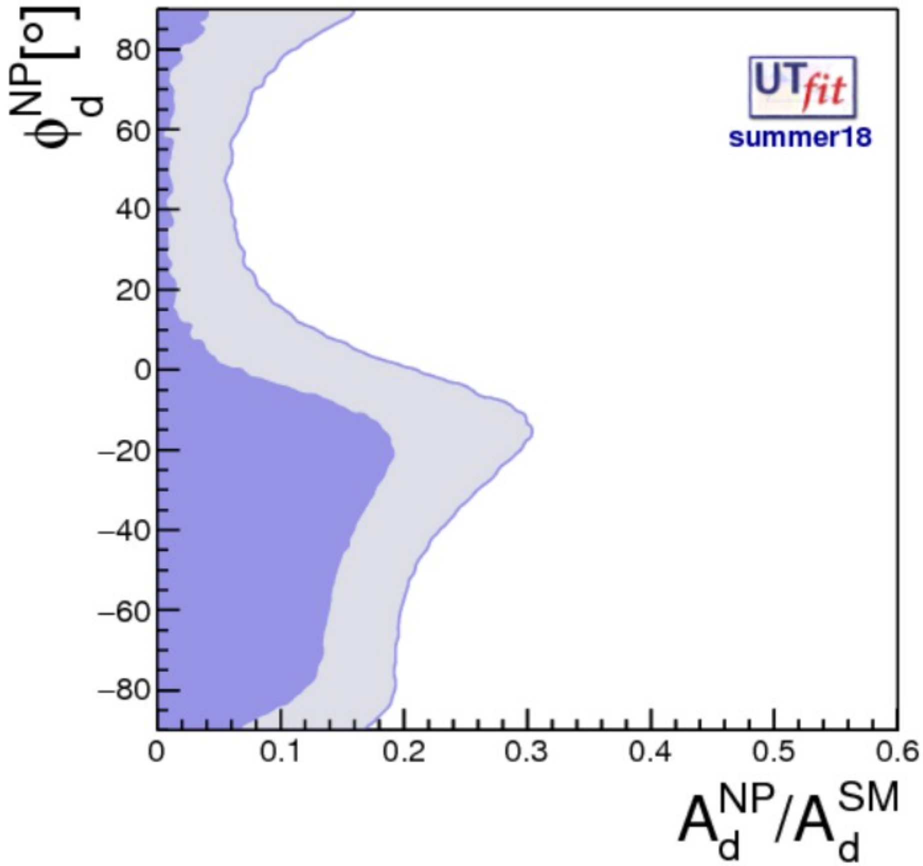
$$\Lambda = \sqrt{\frac{L \cdot FC}{C_i(\Lambda)}}$$

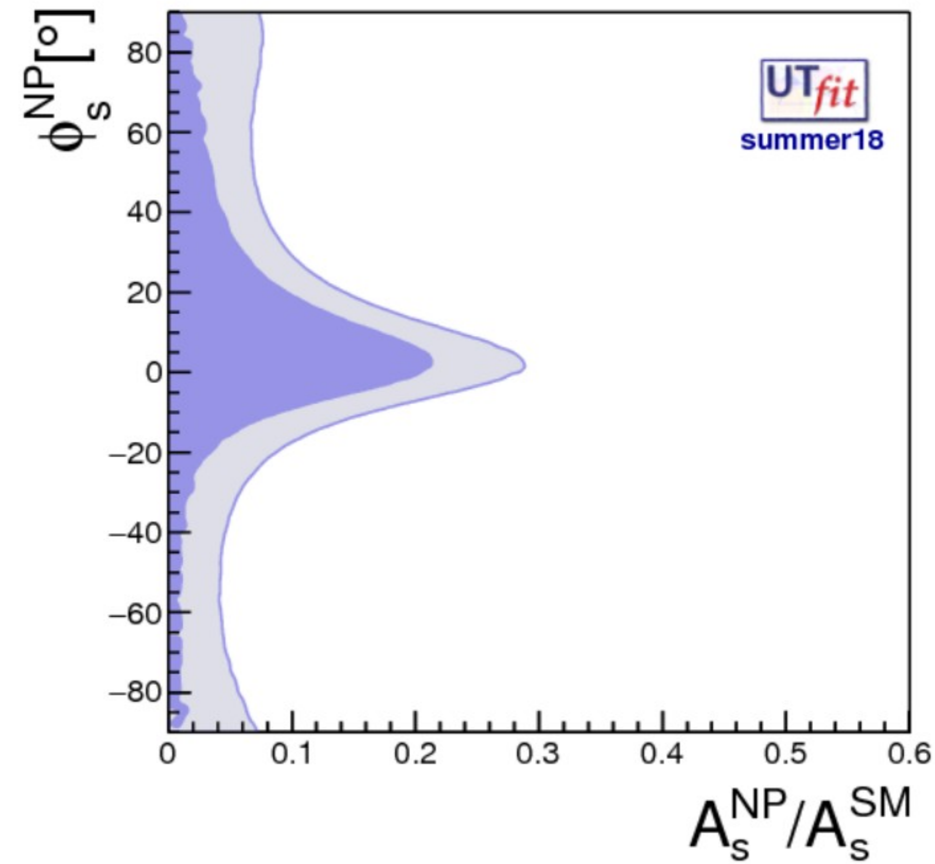
Flavor couplings FC:

(i) generic	(ii) SM-like
$\lvert FC \rvert \sim 1$	$\lvert FC \rvert \sim F_{SM}$

arbitrary phases

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

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

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, RBC-UKQCD dimension-8 operators need to be controlled MC et al., in progress

→ α: isospin breaking Gronau, Zupan, hep-ph/0502139 Charles et al., arXiv:1705.02981

→ β: subleading amplitude $A(B^0 \to J/\psi K) = V_{cb}^* V_{cs} T + \boxed{V_{ub}^* V_{us} P}$ bound using SU(3)-related b→d decays $B_s \to J/\psi K_S$ and $B \to J/\psi \pi^0$ 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, ...

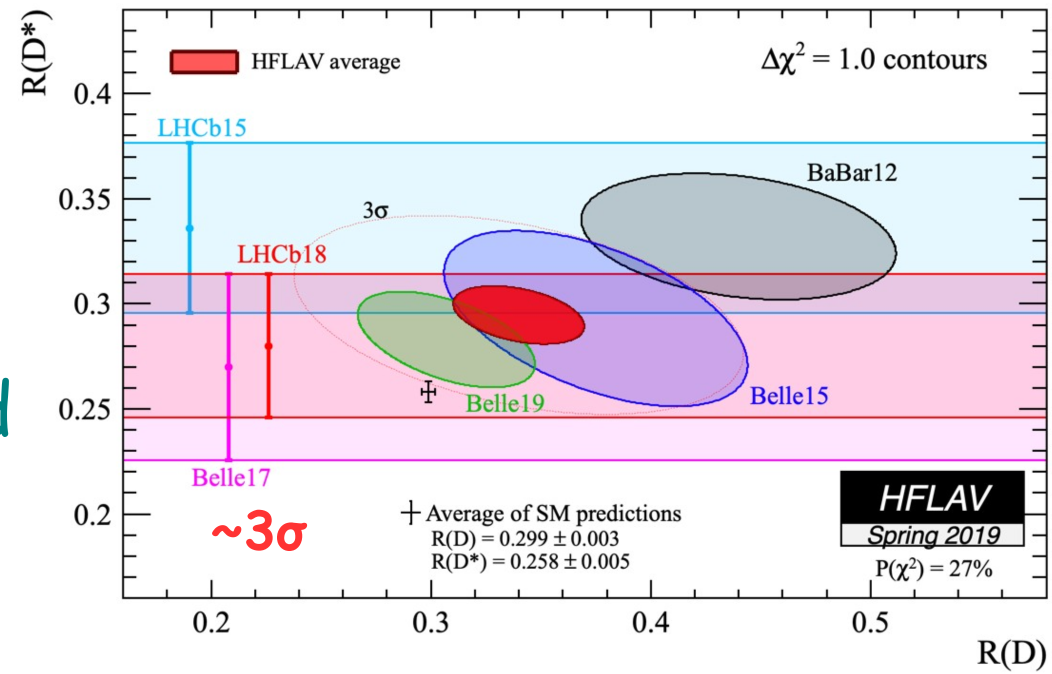
→ β_s: same as β, but trickier (larger effect, ϕ is not a pure octet, ...). Still likely controllable De Bruyn, Fleischer, arXiv:1412.6834

Quantity	Published averages	Reference	error (to be published/not in FLAG-2016)	Phase I	Phase II
$f_{K^\pm}$	155.7(7) MeV	$N_f = 2+1$ [66]	0.4%	0.4%	0.4%
$f_{K^\pm}/f_{\pi^\pm}$	1.193(3)	$N_f = 2+1+1$ [66]	0.25%(0.15%, symmet. [822])	0.15%	0.15%
$f_+^{K\to\pi}(0)$	0.9706(27)	$N_f = 2+1+1$ [66]	0.28% (0.20% [1527])	0.12%	0.12%
B_K	0.7625(97)	$N_f = 2+1$ [66]	1.3%	0.7%	0.5%
f_{D_s}	248.83(1.27)	$N_f = 2+1+1$ [66]	0.5%(0.16% [822])	0.16%	0.16%
f_{D_s}/f_{D^+}	1.1716(32)	$N_f = 2+1+1$ [66]	0.27%(0.14% [822])	0.14%	0.14%
f_{B_s}	228.4(3.7)	$N_f = 2+1$ [66]	1.6%(0.56% [822])	0.5%	0.5%
f_{B_s}/f_{B^+}	1.205(7)	$N_f = 2+1+1$ [66]	0.6%(0.4% [822])	0.4%	0.4%
B_{B_s}	1.32(5)/1.35(6)	$N_f = 2/N_f = 2+1$ [66]	$\sim 4\%$	0.8%	0.5%
B_{B_s}/B_{B_d}	1.007(21)/1.032(28)	$N_f = 2/N_f = 2+1$ [66]	2.1%/2.7%	0.5%	0.3%
ξ	1.206(17)	$N_f = 2+1$ [66]	1.4%	0.3%	0.3%
$\overline{m}_c(\overline{m}_c)$	1.275(8) GeV	$N_f = 2+1$ [66]	0.6%	0.4%	0.4%
$B\to\pi$ for $\lvert V_{ub}\rvert_{\rm theor}$		$N_f = 2+1$ [66]	2.9%	1%(1.4%)	1%
$B\to D$ for $\lvert V_{cb}\rvert_{\rm theor}$		$N_f = 2+1$ [66]	1.4%	0.3%(1%)	0.3%
(first param. BCL z-exp.)		$N_f = 2+1$ [66]	1.5%	0.5%(1.1%)	0.5%
$B\to D^*$ for $\lvert V_{cb}\rvert_{\rm theor}$ $h_{A_1}^{B\to D^*}(\omega=1)$		$N_f = 2+1$ [66]	1.4%	0.4%(0.7%)	0.4%
$P_1^{B\to D^*}(\omega=1)$		No LQCD available		1-1.5%	1%
$\Lambda_b\to p(\Lambda_c)$ for $\lvert V_{ub}/V_{cb}\rvert_{\rm theor}$		[71]	4.9%	1.2%(1.6%)	1.2%
$B\to K$ (first param. BCL z-exp.)		$N_f = 2+1$ [66]	2%	0.7%(1.2%)	0.7%
$B_s\to K$ (first param. BCL z-exp.)		$N_f = 2+1$ [66]	4%	1.3%(1.7%)	1.3%

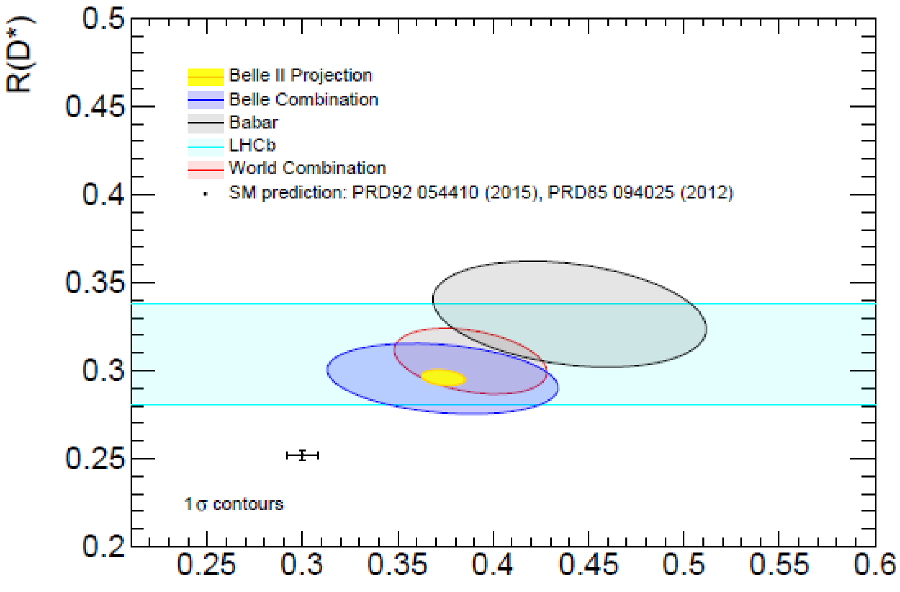
	λ	$\bar\rho$	$\bar\eta$	A	$\sin 2\beta$	γ	α	β_s
Current	0.12%	9%	3%	1.5%	4.5%	3%	2.5%	3%
short-term	0.12%	2%	0.8%	0.6%	0.9%	0.9%	0.7%	0.8%
mid-term	0.12%	1%	0.6%	0.5%	0.6%	0.8%	0.4%	0.5%

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 $B \to \tau\nu$ washed out in time (perhaps)

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

$\Lambda_{NP} \sim$ 2-3 TeV

* 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

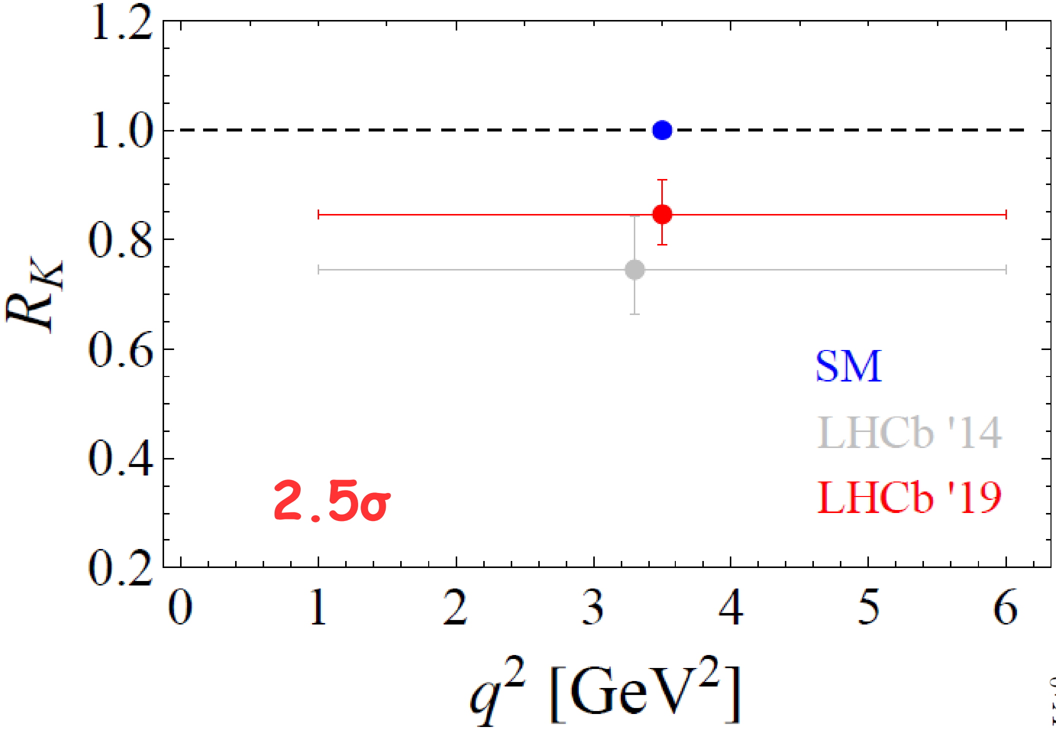
* New physics parametrization

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

- 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, ...

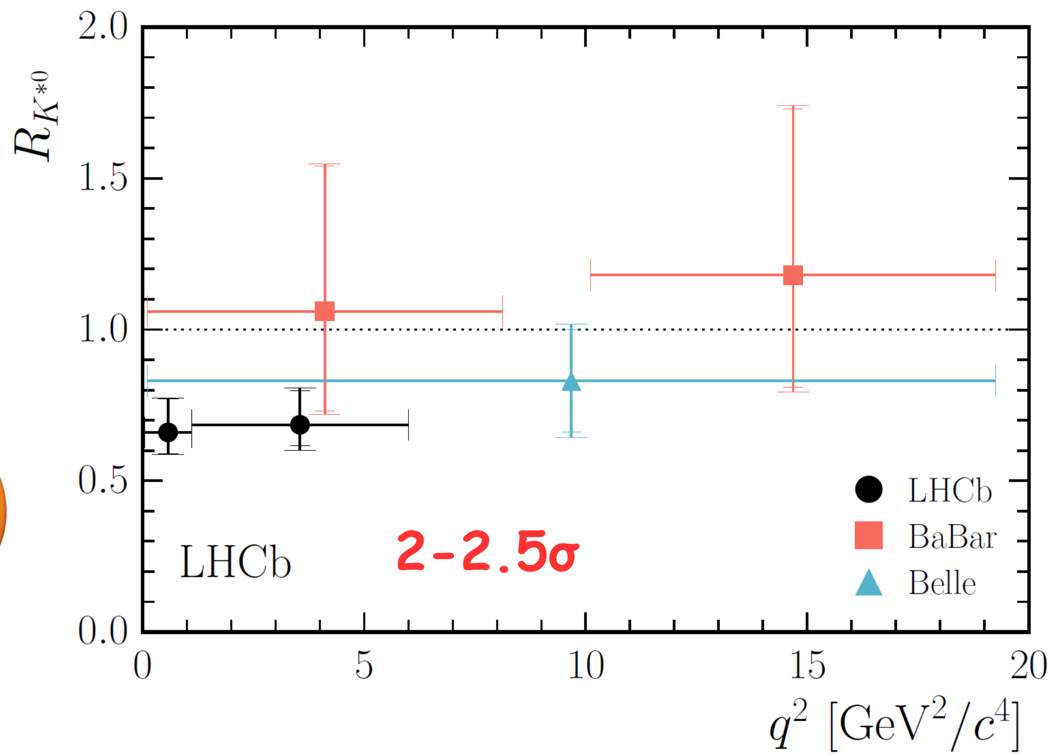
The anomalous anomalies



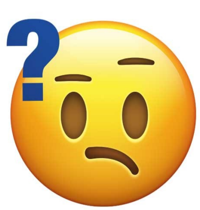
$$R_K = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+ \to K^+\mu^+\mu^-]}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+ \to K^+e^+e^-]}{dq^2} dq^2}$$

Single experiment result

Not very significant (yet?)



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



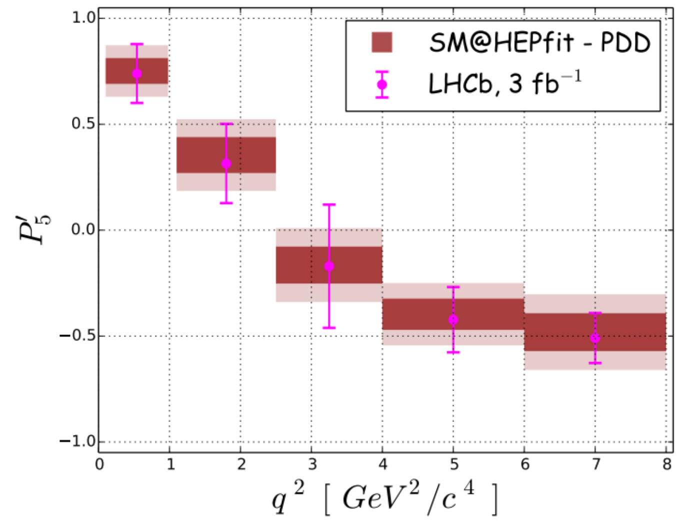
Λ_{NP} ~ 40 TeV

The anomalous anomalies

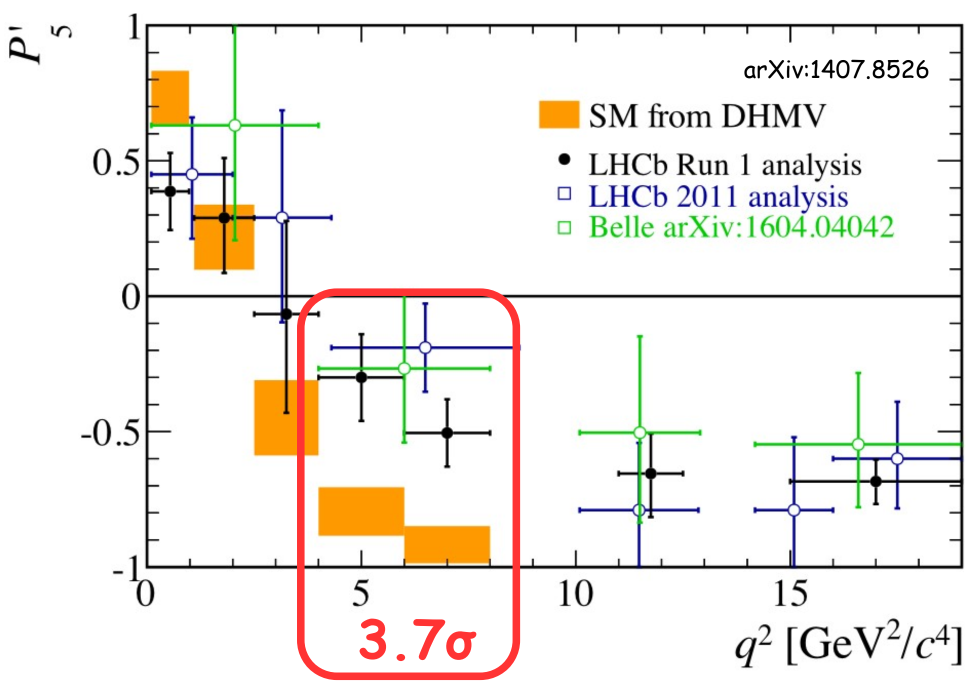
$$\frac{d^{(4)}\Gamma}{dq^2\, d(\cos\theta_l) d(\cos\theta_k) d\phi} = \frac{9}{32\,\pi} \Big(I_1^s \sin^2\theta_k + I_1^c \cos^2\theta_k + (I_2^s \sin^2\theta_k + I_2^c \cos^2\theta_k)\cos 2\theta_l$$
$$+ I_3 \sin^2\theta_k \sin^2\theta_l \cos 2\phi + I_4 \sin 2\theta_k \sin 2\theta_l \cos\phi$$
$$+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

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

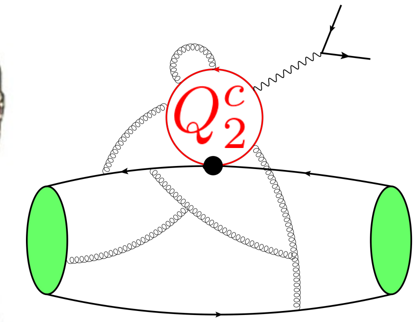
angular analysis



Are theory estimates reliable close to the resonant region?

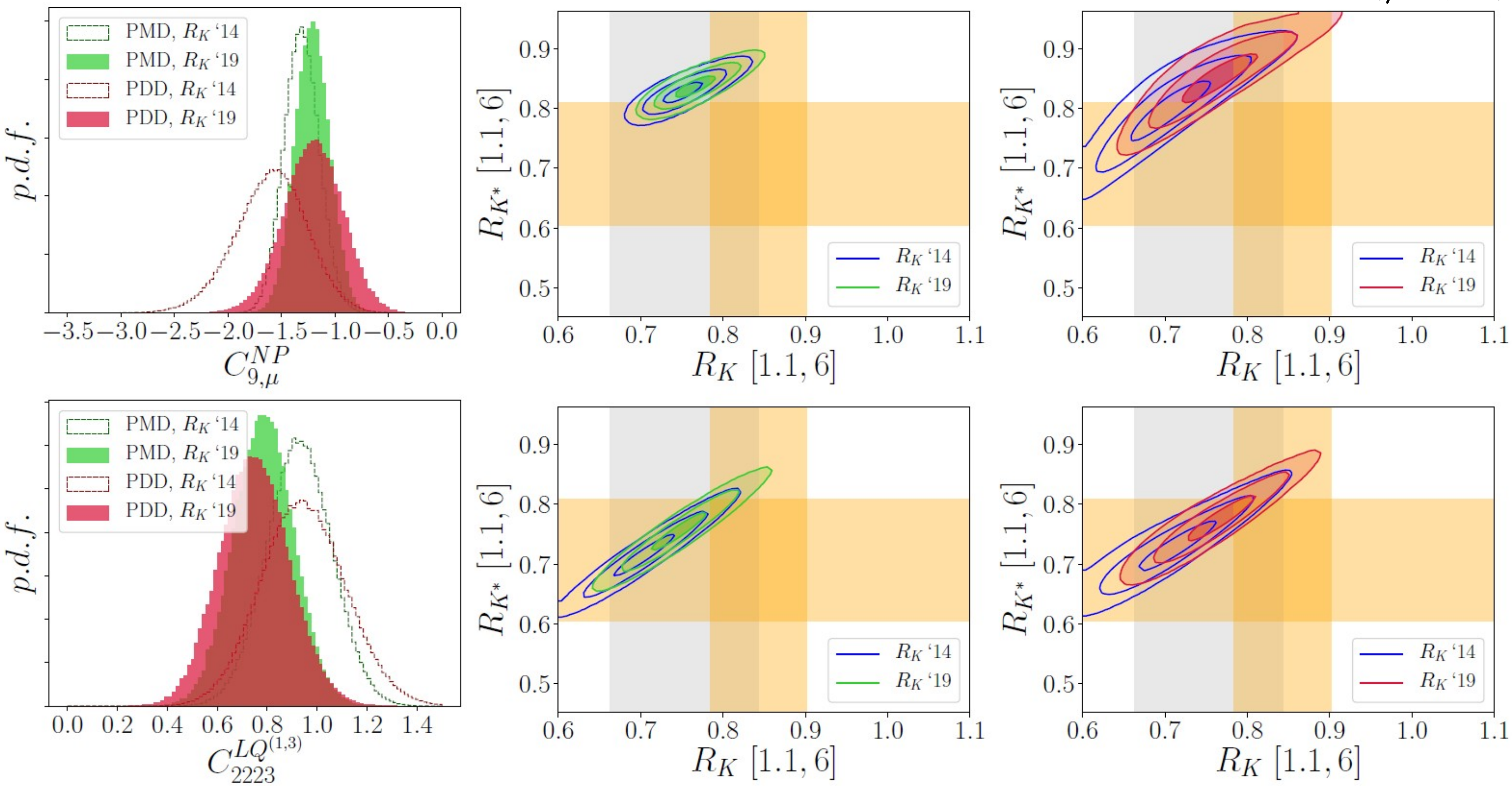


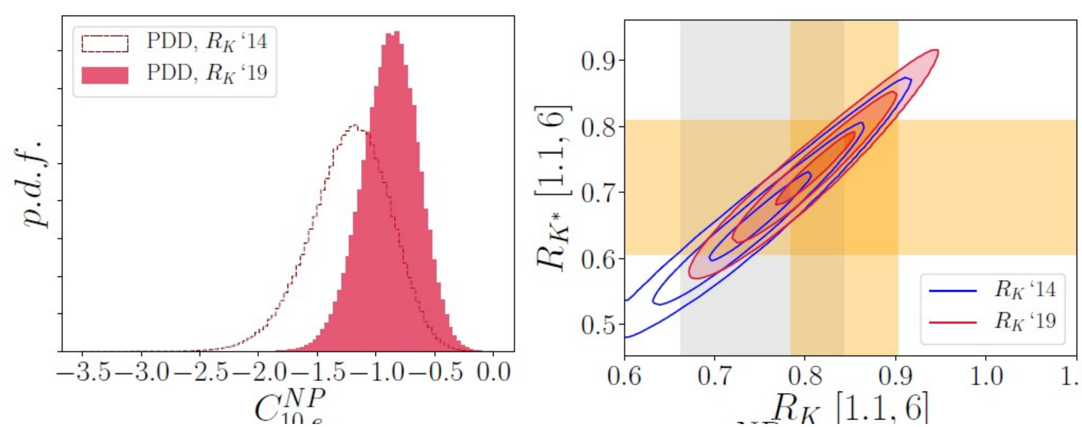
the charm-loop monster



Impact of the 2019 R_K measurement

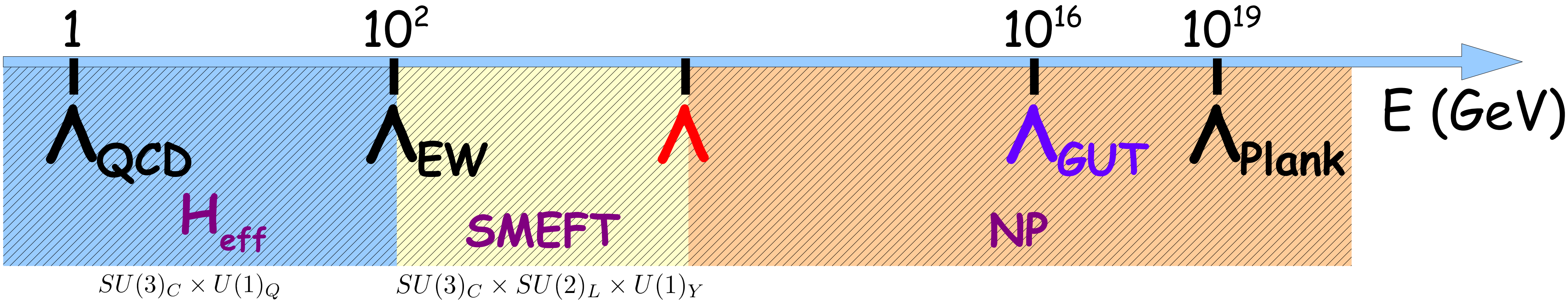
MC et al., arXiv:1903.09632





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*)

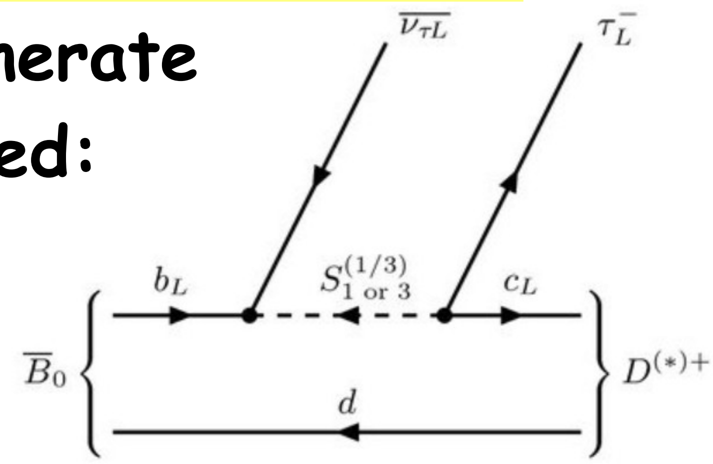
large tree-level effect in charged currents from Q_T

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:

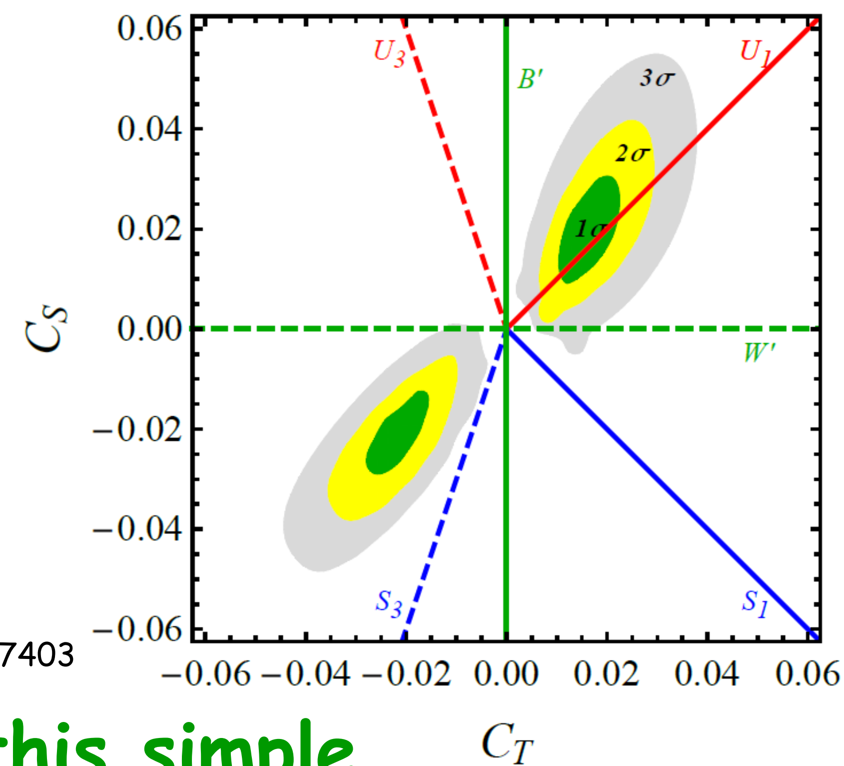


Buttazzo et al., arXiv:1706.07808

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

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…

Implications of LFUV for NP flavour breaking

NP needs to respect SM gauge symmetry

$$\mathcal{Q}_i[Q, D, U, L, E]$$

At EW scale: in terms of four-fermion operators

$R_{K^{(*)}}$

$$\epsilon^{L}_{ij}\epsilon^{Q}_{kl}(\bar{L}_i L_j)(\bar{Q}_k Q_l)$$

$$\epsilon^{E}_{ij}\epsilon^{Q}_{kl}(\bar{E}_i E_j)(\bar{Q}_k Q_l)$$

$$\epsilon^{EL}_{ij}\epsilon^{QD}_{kl}(\bar{E}_i H^\dagger L_j)(\bar{Q}_k H D_l)$$

$$\epsilon^{LE}_{ij}\epsilon^{QU}_{kl}(\bar{L}_i H E_j)(\bar{Q}_k \tilde{H} U_l)$$

$R(D^{(*)})$

*B_c lifetime, decays
Alonso et al., 1611.06676
Akeroyd & Chen, 1708.04072

Buttazzo et al., 1706.07808

$$\epsilon^{L,E}_{\mu\mu},\ \epsilon^{Q}_{sb} \neq 0$$

$$\epsilon^{L,EL}_{\tau i},\ \epsilon^{Q,QD}_{cb} \neq 0$$

$$\epsilon^{LE}_{i\tau},\ \epsilon^{QU}_{bc} \neq 0$$

*right-handed currents
Asadi et al., 1804.04135
Greljo et al., 1804.04642
Azatov et al., 1807.10745
Robinson et al., 1807.04753

Simplest UV: Z'/W' $\quad$ LQ's $\quad$ $H^\pm$

courtesy of J. Kamenik, TH Institutre 2020

Immediate implications for LHC

Flavour alignment implies lower NP scale:

$$(\bar{Q}_3 Q_3)(\bar{L}_3 L_3) \to V_{cb}(\bar{c}b)(\bar{\tau}\nu)$$

$\Rightarrow$ $R(D^{(*)})$ anomaly

$$\Lambda\sqrt{|V_{cb}|} \sim 500\,\mathrm{GeV}$$

$$(\bar{Q}_3 Q_3)(\bar{L}_2 L_2) \to V_{tb}V_{ts}(\bar{s}b)(\bar{\mu}\mu)$$

$\Rightarrow$ $R_{K^{(*)}}$ anomaly

$$\Lambda\sqrt{|V_{ts}|} \sim 8\,\mathrm{TeV}$$

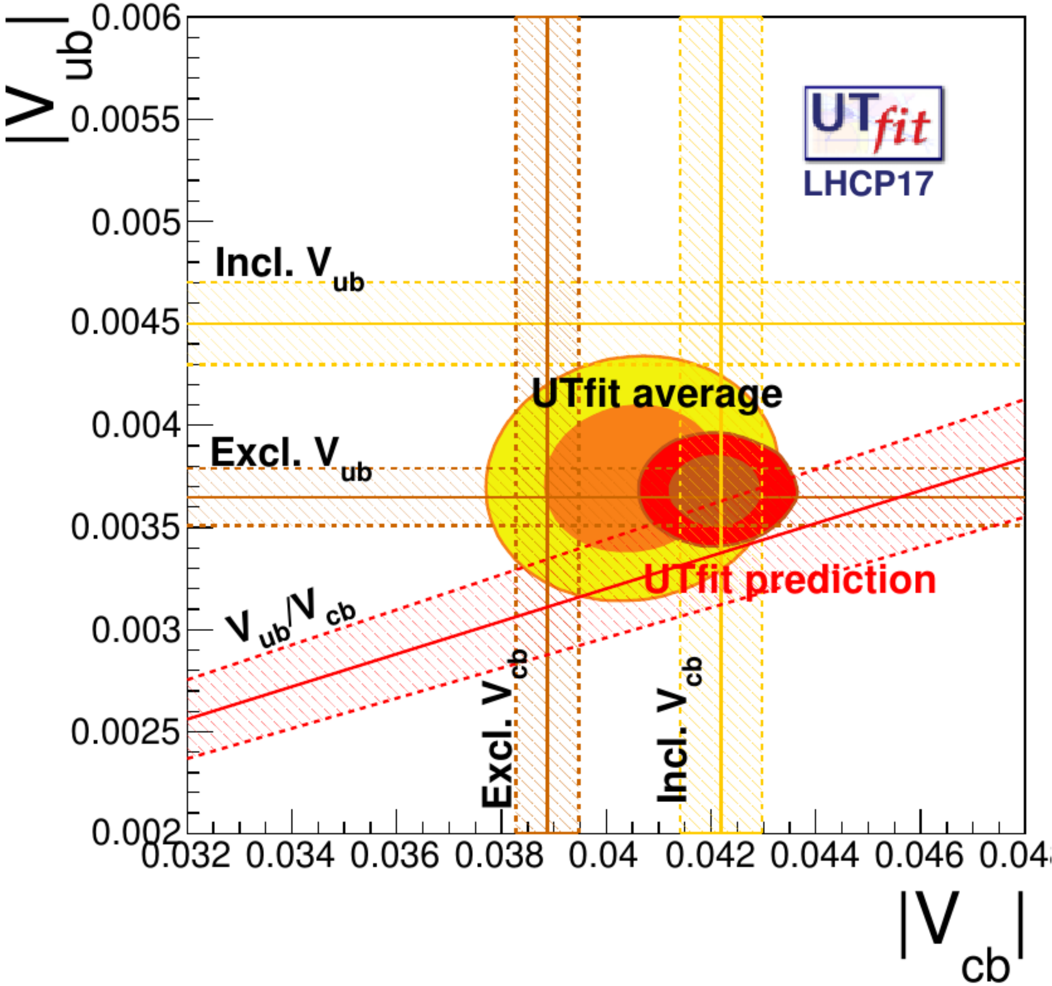
Well within LHC reach!

see e.g. Abdullah et al., 1805.01869
Robinson et al., 1807.04753

Still only marginally!

courtesy of J. Kamenik, TH Institutre 2020

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...

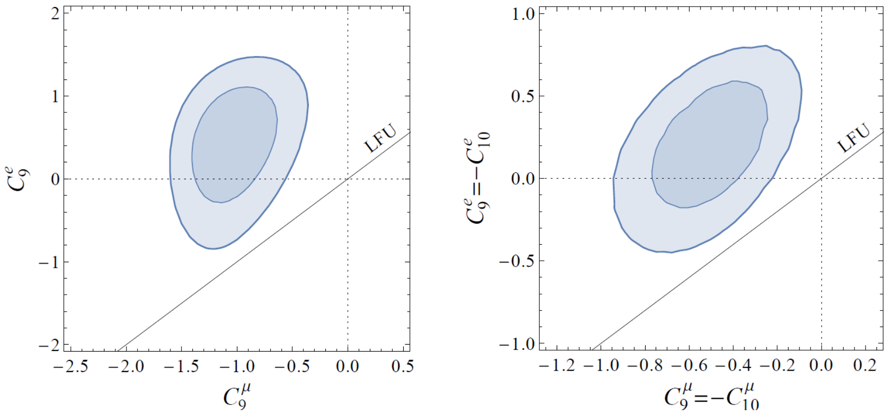
Grinstein, Kobach, arXiv:1703.08170
Bigi, Gambino, Schacht, arXiv:1703.0612

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

Martinelli et al., in progress

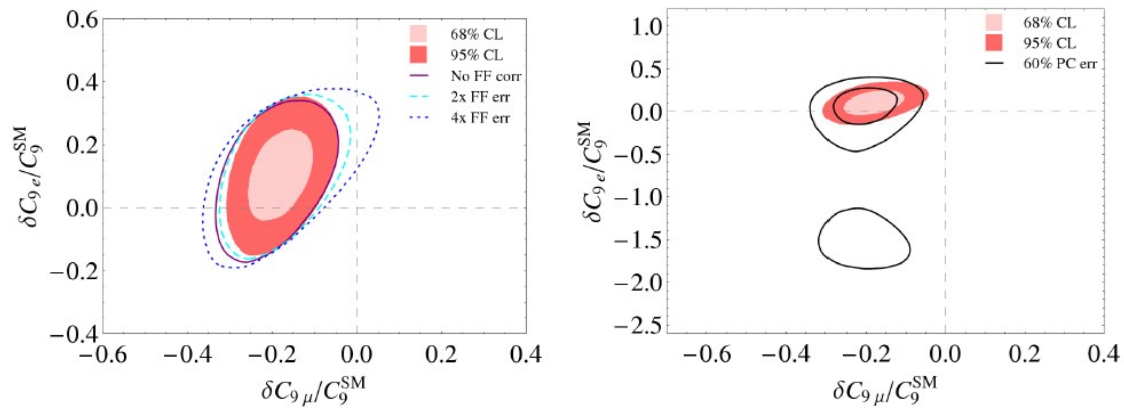
EFT global analysis

Altmannshofer, Straub., arXiv:1411.3161

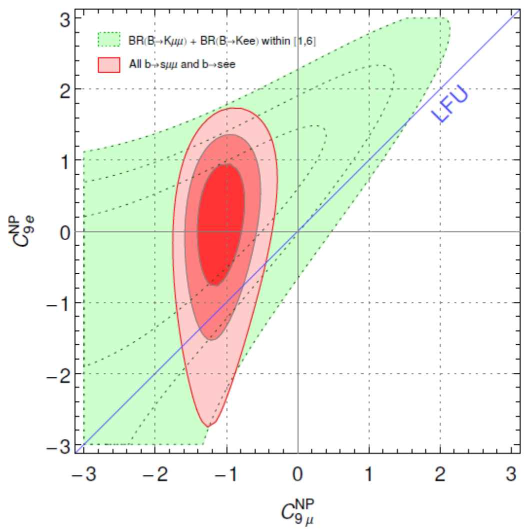


* $B \to K^{(*)} \mu\mu$
* $B \to X_s \gamma$
* $B_s \to \phi \mu\mu$
* R_K
* $B \to K^* \gamma$

Hurth et al., arXiv:1603.00865



Descotes-Genon et al., arXiv:1605.06059



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

Angular analysis of B → K*μμ

angular analysis

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

$$S_i = \left(I_i^{(s,c)} + \bar{I}_i^{(s,c)}\right) / \Gamma'$$

$$(2\,\Gamma' \equiv d\Gamma/dq^2 + d\bar{\Gamma}/dq^2)$$

8 CP-AVERAGED OBSERVABLES

$$F_L, A_{FB}, S_{3,4,5,7,8,9}$$

In the helicity amplitude formalism $(m_\ell \sim 0)$, we need to compute few helicity amplitudes: $H^{\lambda}_{V,A}$ $\lambda = 0, \pm$

$$I_1^c = -I_2^c = \frac{F}{2}\left(|H_V^0|^2 + |H_A^0|^2\right),$$

$$I_1^s = 3I_2^s = \frac{3}{8}F\left(|H_V^+|^2 + |H_V^-|^2 + |H_A^+|^2 + |H_A^-|^2\right),$$

$$I_3 = -\frac{F}{2}\mathrm{Re}\left[H_V^+(H_V^-)^* + H_A^+(H_A^-)^*\right],$$

$$I_4 = \frac{F}{4}\mathrm{Re}\left[(H_V^+ + H_V^-)(H_V^0)^* + (H_A^+ + H_A^-)(H_A^0)^*\right],$$

$$I_5 = \frac{F}{4}\mathrm{Re}\left[(H_V^- - H_V^+)(H_A^0)^* + (H_A^- - H_A^+)(H_V^0)^*\right],$$

$$I_6^s = F\mathrm{Re}\left[H_V^-(H_A^-)^* - H_V^+(H_A^+)^*\right],$$

$$I_6^c = 0,$$

$$I_7 = \frac{F}{2}\mathrm{Im}\left[(H_A^+ + H_A^-)(H_V^0)^* + (H_V^+ + H_V^-)(H_A^0)^*\right],$$

$$I_8 = \frac{F}{4}\mathrm{Im}\left[(H_V^- - H_V^+)(H_V^0)^* + (H_A^- - H_A^+)(H_A^0)^*\right],$$

$$I_9 = \frac{F}{4}\mathrm{Im}\left[H_V^+(H_V^-)^* + H_A^+(H_A^-)^*\right].$$

$$H_V{}^\lambda = \frac{4iG_F m_B}{\sqrt{2}}\frac{\alpha_e}{4\pi}\lambda_t\left\{C_9^{\rm eff}\tilde{V}_{L\lambda} + \frac{m_B^2}{q^2}\left[\frac{2m_b}{m_B}C_7^{\rm eff}\tilde{T}_{L\lambda} - 16\pi^2 h_\lambda\right]\right\},$$

$$H_A{}^\lambda = \frac{4iG_F m_B}{\sqrt{2}}\frac{\alpha_e}{4\pi}\lambda_t C_{10}\tilde{V}_{L\lambda}. \qquad \lambda = 0, \pm$$

NNLO Wilson coefficients from the ΔB=1, ΔS=1 effective Hamiltonian:

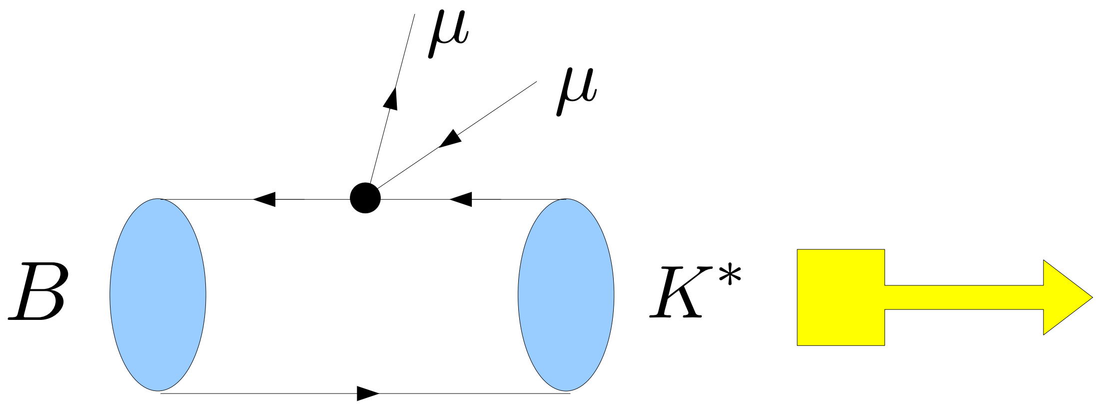
$$\mathcal{H}_{\rm eff}^{\Delta B=1} = \mathcal{H}_{\rm eff}^{sl+\gamma} + \mathcal{H}_{\rm eff}^{had}$$

$$\mathcal{H}_{\rm eff}^{sl+\gamma} = -\frac{4G_F}{\sqrt{2}}\lambda_t\left(C_7 Q_{7\gamma} + C_9 Q_{9V} + C_{10}Q_{10A}\right)$$

$$Q_{7\gamma} = \frac{e}{16\pi^2}m_b\bar{s}_L\sigma_{\mu\nu}F^{\mu\nu}b_R\,,$$

$$Q_{9V} = \frac{\alpha_e}{4\pi}(\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\ell)\,,$$

$$Q_{10A} = \frac{\alpha_e}{4\pi}(\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\gamma^5\ell)\,.$$

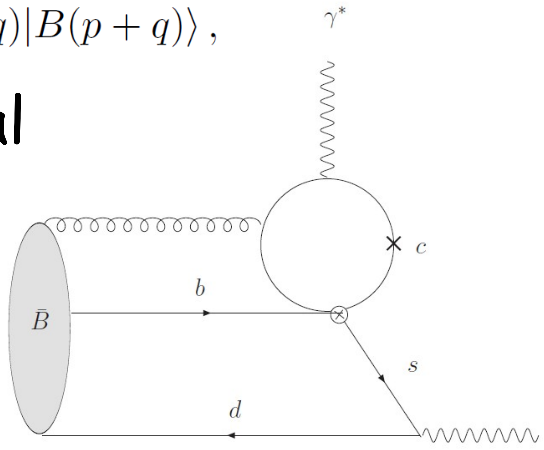


Hadronic matrix elements of quark currents: FORM FACTORS

An estimate in 2 steps:

Khodjamirian, Mannel, Pivovarov, Wang, arXiv:1006.4945

1. at $q^2 \ll 4m_c^2$ the charm loop is dominated by light-cone dynamics.
   One can write the ME $\left[\mathcal{H}_\mu^{(B\to K^{(*)})}(p,q)\right]_{non\,fact} = 2C_1\langle K^{(*)}(p)|\widetilde{\mathcal{O}}_\mu(q)|B(p+q)\rangle\,,$
   where $\widetilde{\mathcal{O}}_\mu(q) = \int d\omega\, I_{\mu\rho\alpha\beta}(q,\omega)\bar{s}_L\gamma^\rho\delta[\omega - \frac{(in_+\mathcal{D})}{2}]\widetilde{G}_{\alpha\beta}b_L$ is a non-local operator representing the first subleading term of an expansion in $\Lambda^2/(4m_c^2-q^2)$ (single soft gluon approximation), whose ME is computed using light-cone sum rules



step 1 estimate of the hadronic contribution at small q^2 < few GeV^2
<u>but</u> large uncertainties (100%? more?)
no hard gluons, no phases, no scale and scheme dependence, …

2. extend the previous result to larger q^2 using a dispersion relation, modeling the spectral function (2 physical $\Psi^{(\prime)}$ + effective poles)

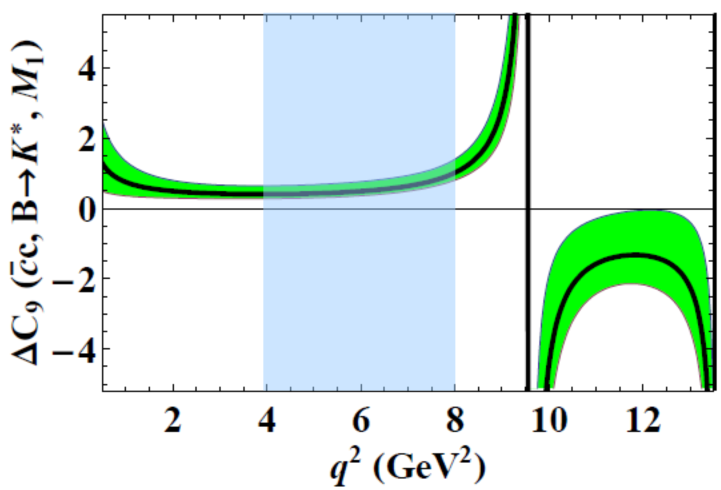
step 2

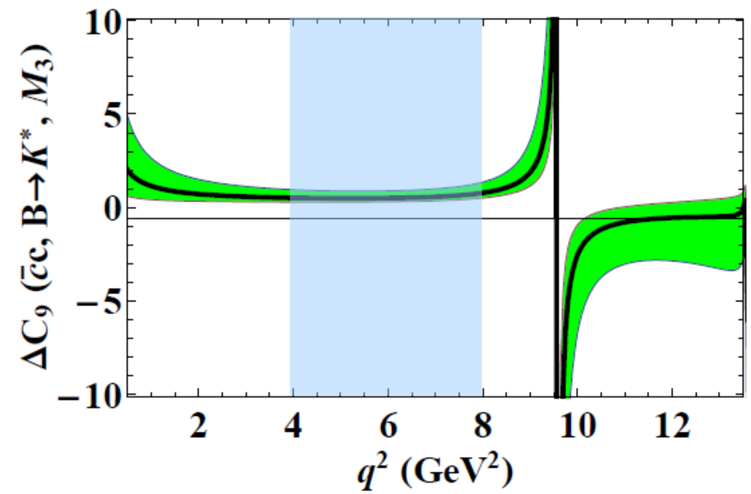
$$\Delta C_{9,i}^{(c\bar{c})}(q^2) = \frac{r_{1,i}\left(1-\frac{\bar{q}^2}{q^2}\right) + \Delta C_{9,i}^{(c\bar{c})}(\bar{q}^2)\frac{\bar{q}^2}{q^2}}{1 + r_{2,i}\frac{\bar{q}^2-q^2}{m_{J/\psi}^2}}$$

$r_{1,i}$	$r_{2,i}$
$0.10^{+0.02}_{-0.00}$	$1.13^{+0.00}_{-0.01}$
$0.09^{+0.01}_{-0.00}$	$1.12^{+0.00}_{-0.01}$
$0.06^{+0.04}_{-0.10}$	$1.05^{+0.05}_{-0.04}$

but model dependence, no pert. gluons and phases: uncertainty ?

Khodjamirian, Mannel, Pivovarov, Wang, arXiv:1006.4945





2010 → today

Step 1: no new non-perturbative calculation. However an hierarchy among contributions in the helicity basis has been found

Jäger, Camalich, arXiv:1212.2263

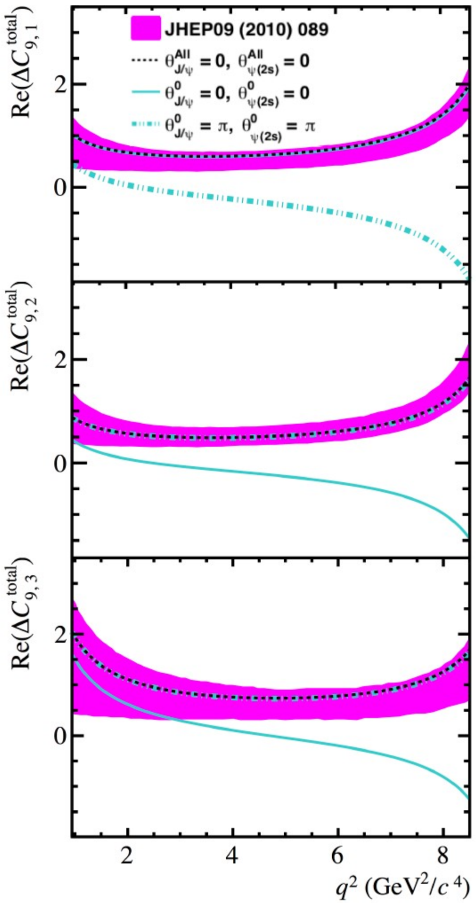
$$h_+ \sim \mathcal{O}\left(\frac{\Lambda}{m_b}\right) h_-$$

Step 2: recent attempts to gain more control over the q^2 dependence improving the dispersion relation approach

1. empirical model using resonance data over the full dimuon spectrum
   Blake, Egede, Owen, Pomery, Petridis, arXiv:1709.03921
2. replace the dispersion relation with a z-expansion of h_λ, constraining the coefficients using analiticity and
   Bobeth, Chrzaszcz, van Dyk, Virto, arXiv:1707.07305
   1. resonant $B \to \Psi^{(n)} K^*$ data (masses and amplitudes)
   2. LCSR + QCDF theoretical results at small/negative q^2

empirical model

Blake, Egede, Owen, Pomery, Petridis, arXiv:1709.03921
see also LHCb collaboration, arXiv:1612.06764



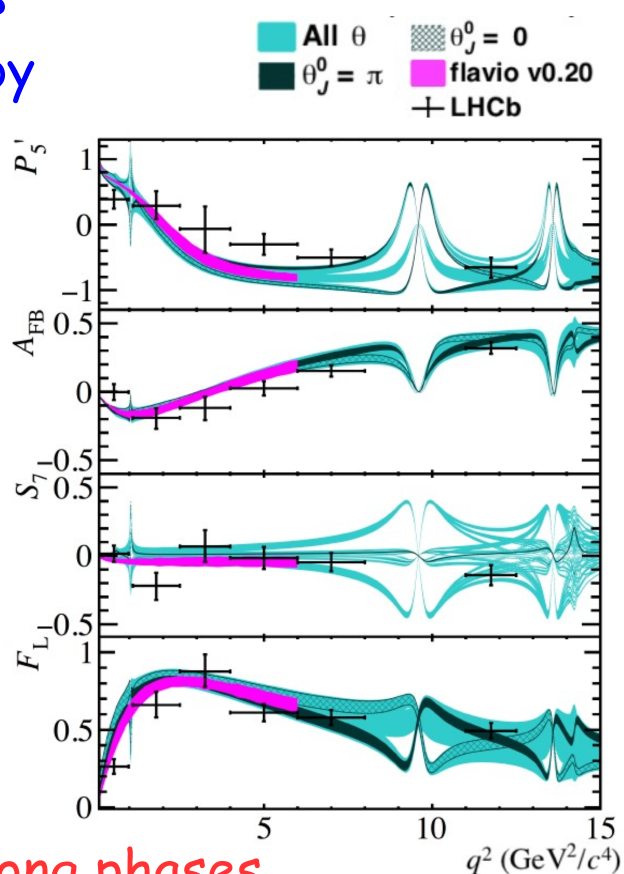
The hadronic contribution is modeled as the sum of 1^{--} resonances represented by relativistic Breit-Wigner functions

$$\Delta C_{9\,\lambda}^{\rm had}(q^2) = \sum_j \eta_j^\lambda e^{i\theta_j^\lambda} A_j^{\rm res}(q^2)$$

$$A_j^{\rm res}(q^2) = \frac{m_{{\rm res}\,j}\Gamma_{{\rm res}\,j}}{(m^2_{{\rm res}\,j} - q^2) - i m_{{\rm res}\,j}\Gamma_j(q^2)}$$

Open issues:

Why should it work far from the resonances? What about double counting? How large is the model uncertainty?



Illustrate nicely the importance of strong phases

c loop from analyticity

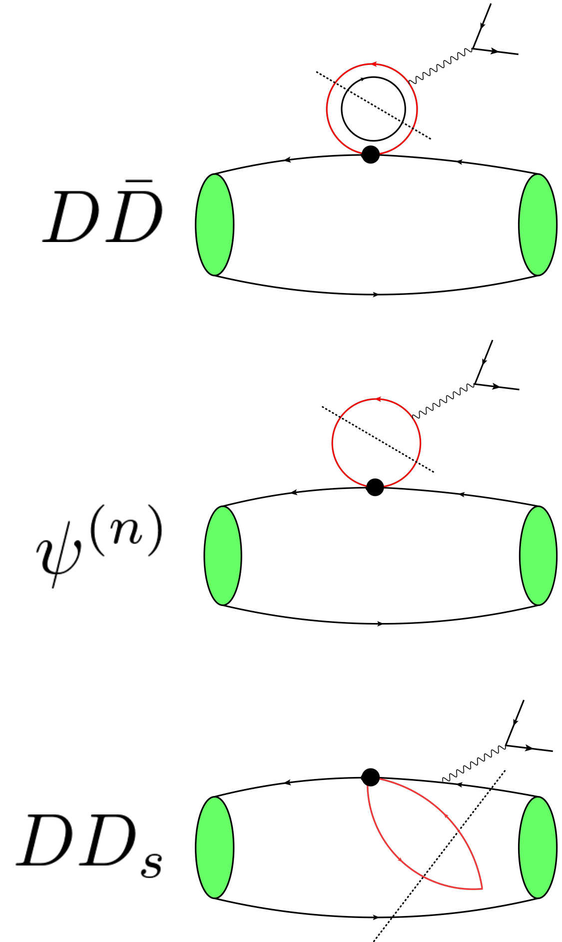
Bobeth, Chrzaszcz, van Dyk, Virto, arXiv:1707.07305

Features:

- get rid of DD branch cut modeling by mapping it at the boundary of the expansion region
- exploits the $\psi^{(\prime)}$ resonance data to constrain the expansion

Open issues:

- strong phases related to the DD_s cut in p^2 are taken from LCSR and QCDF calculations. Are they reliable?



k	0	1	2
$\mathrm{Re}[\alpha_k^{(\perp)}]$	-0.06 ± 0.21	-6.77 ± 0.27	18.96 ± 0.59
$\mathrm{Re}[\alpha_k^{(\parallel)}]$	-0.35 ± 0.62	-3.13 ± 0.41	12.20 ± 1.34
$\mathrm{Re}[\alpha_k^{(0)}]$	0.05 ± 1.52	17.26 ± 1.64	–
$\mathrm{Im}[\alpha_k^{(\perp)}]$	-0.21 ± 2.25	1.17 ± 3.58	-0.08 ± 2.24
$\mathrm{Im}[\alpha_k^{(\parallel)}]$	-0.04 ± 3.67	-2.14 ± 2.46	6.03 ± 2.50
$\mathrm{Im}[\alpha_k^{(0)}]$	-0.05 ± 4.99	4.29 ± 3.14	–

- z expansion: no sign of convergence for the typical values |z|~ 0.2-0.4

NB: z expansion of FF at much smaller values

Parametrizing the charm loop

Jäger, Camalich, arXiv:1212.2263
MC, Fedele, Franco, Mishima, Paul, Silvestrini, Valli, arXiv:1512.07157
+ preliminary update

$$
\begin{aligned}
H_V^- &= -iN \left\{ \left(C_9^{\rm eff} + h_-^1\right) V_{L-} + \frac{m_B^2}{q^2}\left[\frac{2m_b}{m_B}\left(C_7^{\rm eff} + h_-^0\right) T_{L-} - 16\pi^2 h_-^2\, q^4\right]\right\} \\
H_V^0 &= -iN \left\{ \left(C_9^{\rm eff} + h_-^1\right) \tilde{V}_{L0} + \frac{m_B^2}{q^2}\left[\frac{2m_b}{m_B}\left(C_7^{\rm eff} + h_-^0\right) \tilde{T}_{L0} - 16\pi^2 \left(\tilde{h}_0^0 + \tilde{h}_0^1\, q^2\right)\right]\right\} \\
H_V^+ &= -iN \left\{ \left(C_9^{\rm eff} + h_-^1\right) V_{L+} + \frac{m_B^2}{q^2}\left[\frac{2m_b}{m_B}\left(C_7^{\rm eff} + h_-^0\right) T_{L+} - 16\pi^2 \left(h_+^0 + h_+^1\, q^2 + h_+^2\, q^4\right)\right]\right\}
\end{aligned}
$$

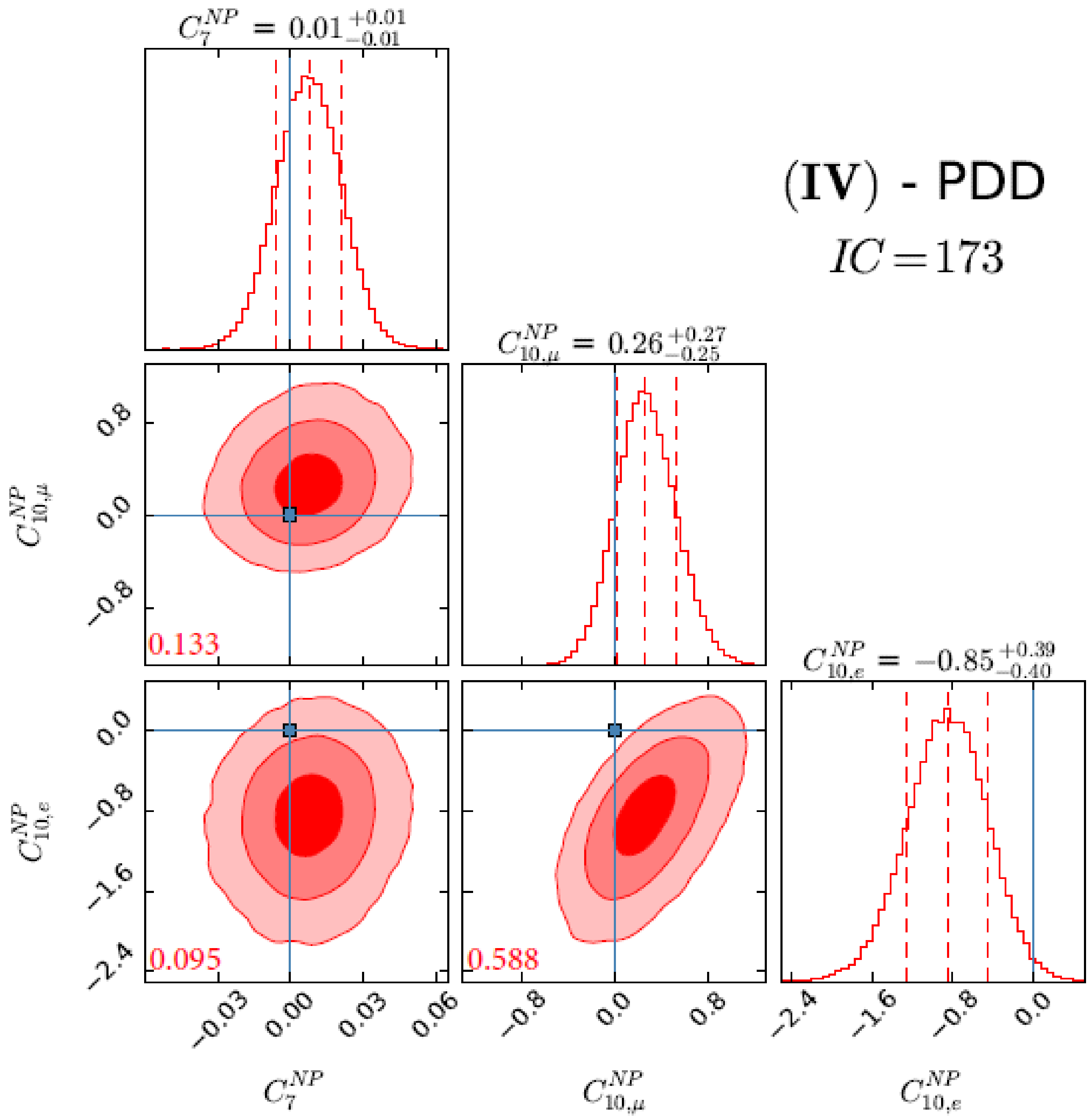
$\Delta C_7^{(cc)} = h_-^0$ and $\Delta C_9^{(cc)} = h_-^1$ shift the corresponding Wilson coefficients (as NP contributions do), while the other parameters have no short-distance counterparts

Fitting hadronic parameters

- Compute all amplitudes using QCD factorization and form factors from LQCD (Bailey et al. '15) and LCSR (Bharucha, Straub & Zwicky '15)
- add hadronic parameters and
  - use LCSR calculation from KMPW at low q^2 (0 and 1 GeV^2) only (PDD)

    or
  - extrapolate LCSR calculation to larger q^2 using KMPW (PMD)
- fit all available experimental data using the HEPfit code
- compare different models using $IC = -2\overline{\log L} + 4\sigma^2_{\log L}$

MC et al., arXiv:1704.05447



(IV) - PDD

$IC = 173$

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)

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

(Buras et al., arXiv:1507.06345)

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

- 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($B \to \mu\mu$)**

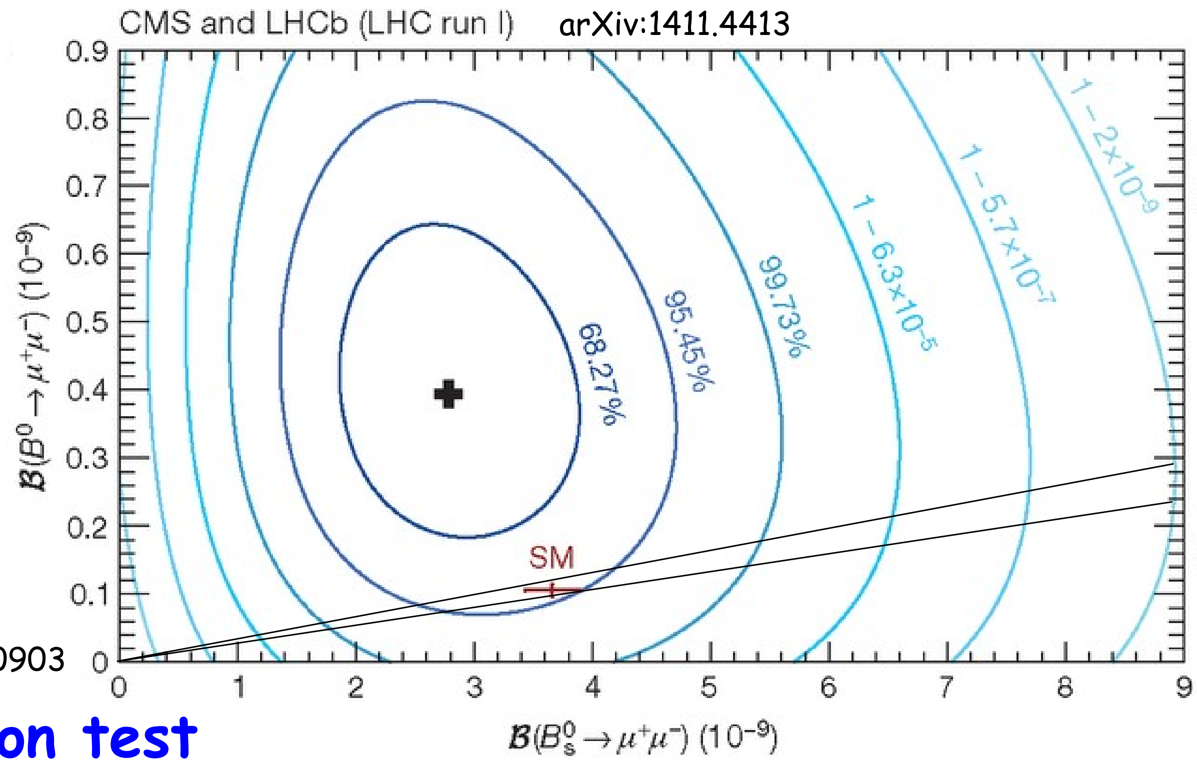
$\mathrm{BR}(\mathrm{B}_s \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$

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

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

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

SM predictions from Bobeth et al., arXiv:1311.0903



Minimal Flavour Violation test