New Physics in CP violation and rare DECAYS: Where we are and what´s next

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Blois conference

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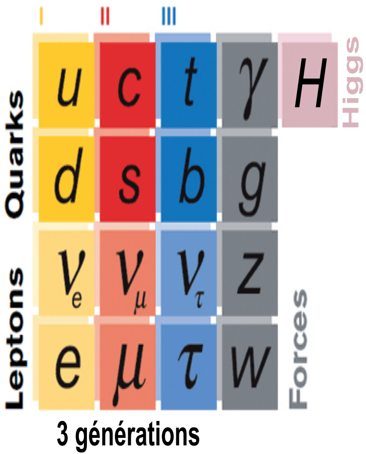
Central question of QFT-based particle physics

$$\mathcal{L} =?$$



+ ?

i.e. which degrees of freedom, symmetries, scales ?

SM best answer up to now, but

- neutrino masses
- dark matter
- dark energy
- baryon asymmetry of the universe
- hierarchy problem

$\Longrightarrow$3 generations playing a particular role in the SM

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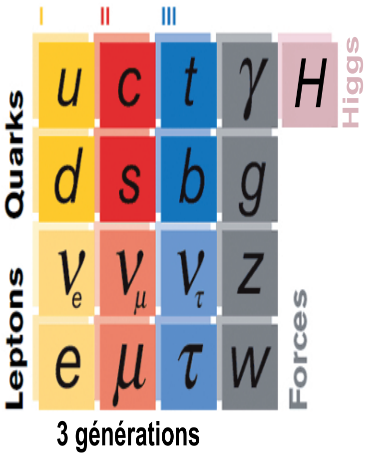

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$+ \, ?$

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$\Longrightarrow$3 generations playing a particular role in the SM

$$\mathcal{L}_{SM} = \mathcal{L}_{gauge}(A_a, \psi_j) + \mathcal{L}_{Higgs}(\phi, A_a, \psi_j)$$

Gauge part $\mathcal{L}_{gauge}(A_a, \psi_j)$

- Highly symmetric (gauge symmetry, flavour symmetry)
- Well-tested experimentally (electroweak precision tests)
- Stable with respect to quantum corrections

Higgs part $\mathcal{L}_{Higgs}(\phi, A_a, \psi_j)$

- Ad hoc potential
- Dynamics not fully tested
- Not stable w.r.t quantum corrections
- Origin of flavour structure of the Standard Model

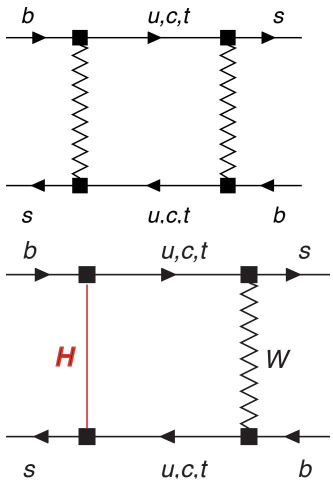
Flavour structure: Quark masses and CKM matrix from diagonalisation of Yukawa couplings after EWSB

Flavour-Changing Neutral Currents a tool to test the flavour structure

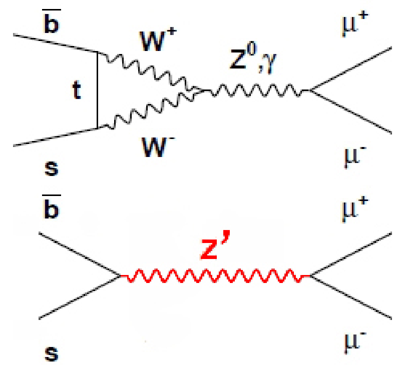
Forbidden in SM at tree level, and suppressed by GIM at one loop

so good place for NP to show up (tree or loops)

$\triangle F = 2$: B_s mixing

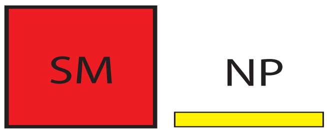


$\triangle F = 1$: $B_s \to \mu\mu$



Experimental and theoretical effort
on interesting FCNC transitions

Different processes for different goals

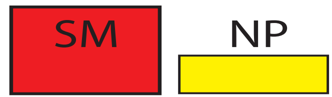


SM expected to be dominant (tree dominated) [semi/leptonic dec.]

Metrology of SM

$\Downarrow$

Source of hadronic inputs in SM.

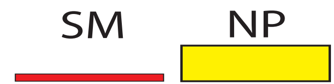


SM and NP competing (loop dominated) [rare processes]

Constraints on NP

$\Downarrow$

Require theoretical accuracy of SM prediction and of experimental measurement.



SM very small (“forbidden” by SM symmetry) [ultrarare processes]

Smoking guns of NP

$\Downarrow$

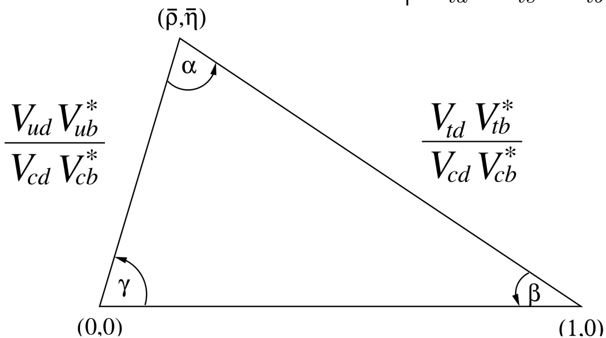
Experimental observation implies New Physics.

Assessing the CKM paradigm in the SM

CP-violation : the four parameters

In SM weak charged transitions mix quarks of different generations

Encoded in unitary CKM matrix $V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$. From off-diagonal $V_{CKM}^\dagger V_{CKM} = 1$



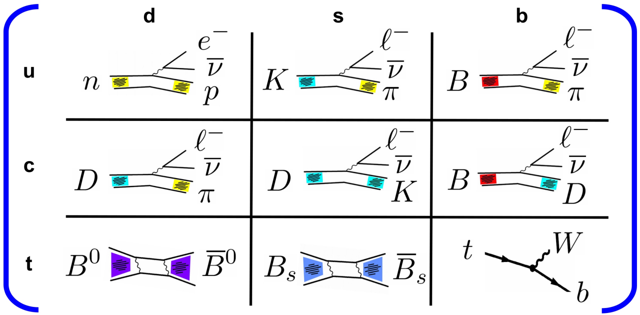
- 3 generations $\Longrightarrow$ 1 phase, only source of CP-violation in SM
- Wolfenstein parametrisation, defined to hold to all orders in λ and rephasing invariant

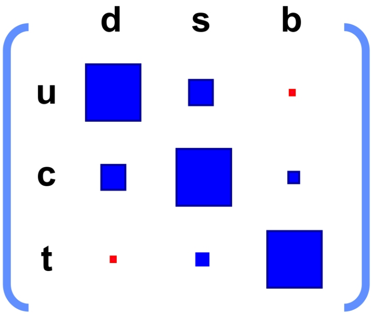
$$\lambda^2 = \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2} \qquad A^2\lambda^4 = \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2} \qquad \bar\rho + i\bar\eta = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

$\Longrightarrow$ 4 parameters describing the CKM matrix,

to determine from data under the SM hyp.

V =

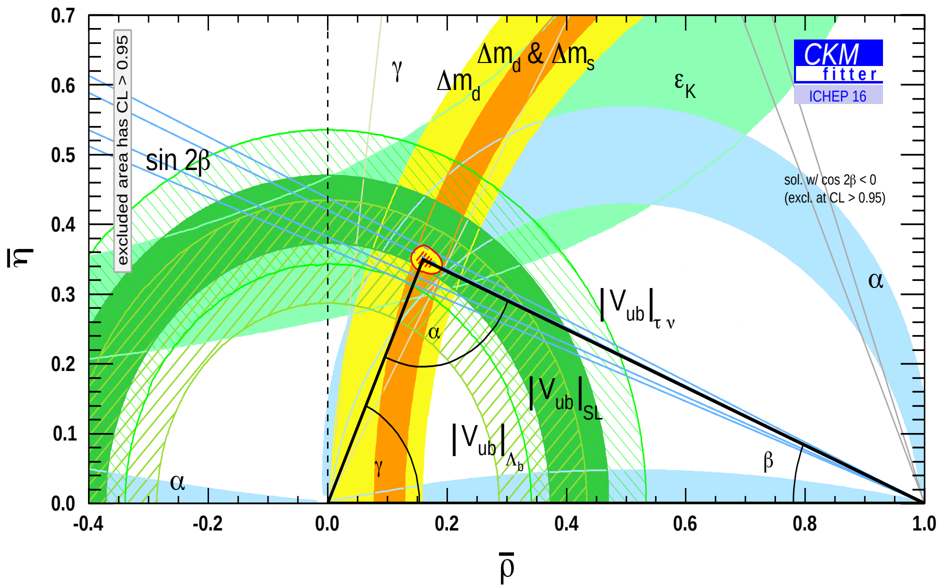




- CP-invariance of QCD to build hadronic-indep. CP-violating asym.
  or to determine hadronic inputs from data
- Statistical framework to combine data and assess uncertainties

	Exp. uncert.		Theoretical uncertainties	
Tree	$B \to DK$	γ	$B(b) \to D(c)\ell\nu$	$\lvert V_{cb}\rvert$ vs form factor (OPE)
			$B(b) \to \pi(u)\ell\nu$	$\lvert V_{ub}\rvert$ vs form factor (OPE)
			$M \to \ell\nu$	$\lvert V_{UD}\rvert$ vs f_M (decay cst)
Loop	$B \to J/\Psi K_s$	β	ϵ_K (K mixing)	$(\bar\rho, \bar\eta)$ vs B_K (bag parameter)
	$B \to \pi\pi, \rho\rho$	α	$\Delta m_d, \Delta m_s$ (B_d, B_s mixings)	$\lvert V_{tb}V_{tq}\rvert$ vs $f_B^2 B_B$ (bag param)

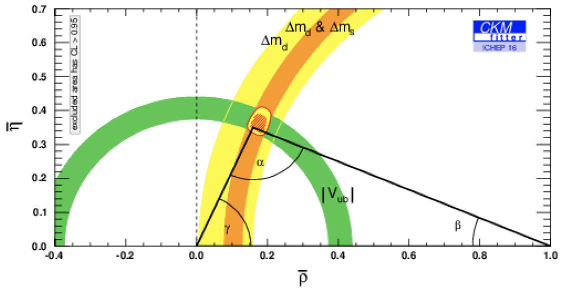
Frequentist approach (CKMfitter). See also UTfit approach (Guido's talk).
Look for inconsistent determinations of UT-angles, UT- sides.
Small Yellow region: preferred region by all observables (C.L. $< 95.45\%$)



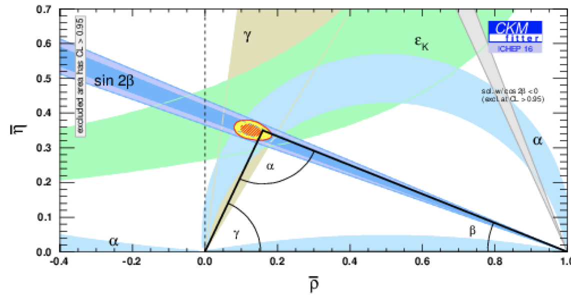
$|V_{ud}|$, $|V_{us}|$
$|V_{cb}|_{SL}$, $|V_{ub}|_{SL}$
$B \to \tau\nu$
Δm_d, Δm_s
ϵ_K
$\sin 2\beta$
α
γ

$$A = 0.825^{+0.007}_{-0.012}$$
$$\lambda = 0.2251^{+0.0003}_{-0.0003}$$
$$\bar\rho = 0.160^{+0.008}_{-0.007}$$
$$\bar\eta = 0.350^{+0.006}_{-0.006}$$

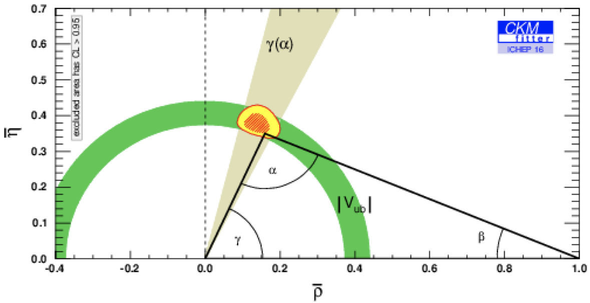
Consistency of the KM mechanism: Many different determinations



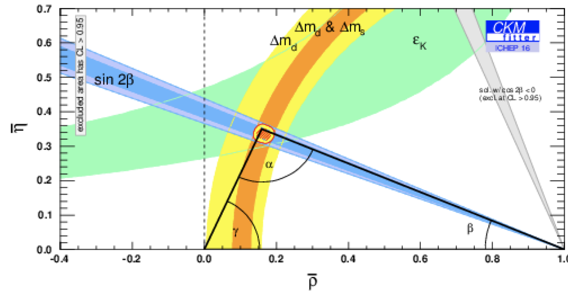
CP-conserving only



CP-violating only



Tree only



Loop only

Validity of Kobayashi-Maskawa picture of CP violation: No significant deviation observed

But two tensions: V_{ub} and V_{cb}

V_{ub} and V_{cb} affects the identification of NP.

Problem: Inclusive and Exclusive determinations in tension (different theory & experiment).

TABLE 1. Status of exclusive and inclusive $|V_{cb}|$ determinations

Exclusive decays	$|V_{cb}| \times 10^3$
$\bar{B} \to D^* l \bar{\nu}$	
FLAG 2016 [23]	$39.27 \pm 0.49_{\rm exp} \pm 0.56_{\rm latt}$
FNAL/MILC 2014 (Lattice $\omega = 1$) [20]	$39.04 \pm 0.49_{\rm exp} \pm 0.53_{\rm latt} \pm 0.19_{\rm QED}$
HFAG 2012 (Sum Rules) [27, 28, 21]	$41.6 \pm 0.6_{\rm exp} \pm 1.9_{\rm th}$
$\bar{B} \to D l \bar{\nu}$	
Global fit 2016 [35]	40.49 ± 0.97
Belle 2015 (CLN) [34, 29]	39.86 ± 1.33
Belle 2015 (BGL) [34, 29, 33]	40.83 ± 1.13
FNAL/MILC 2015 (Lattice $\omega \neq 1$) [29]	$39.6 \pm 1.7_{\rm exp+QCD} \pm 0.2_{\rm QED}$
HPQCD 2015 (Lattice $\omega \neq 1$) [33]	$40.2 \pm 1.7_{\rm latt+stat} \pm 1.3_{\rm syst}$
Inclusive decays	
Gambino et al. 2016 [100]	42.11 ± 0.74
HFAG 2014 [24]	42.46 ± 0.88
Indirect fits	
UTfit 2016 [101]	41.7 ± 1.0
CKMfitter 2015 (3σ) [102]	$41.80^{+0.97}_{-1.64}$

Refs from 1610.04387 (Giulia Ricciardi)

$$|V_{cb}|$$

- Most precise determinations:
  - 1st) Lattice determination in exclusive $B \to D^*$ channel,
  - 2nd) inclusive measurements,
  - 3rd) semileptonic $B \to D$.
- Tension among latest inclusive and latest $B \to D^*$ is 3σ. NO tension if Sum Rules used.
- Indirect Fit using CKM, CPV and flavour data (except direct decays) closer to inclusive determination.

But two tensions: V_{ub} and V_{cb}

TABLE 2. Status of exclusive $|V_{ub}|$ determinations and indirect fits

Exclusive decays	$|V_{ub}| \times 10^3$
$\bar{B} \to \pi l \bar{\nu}_l$	
FLAG 2016 [23]	3.62 ± 0.14
Fermilab/MILC 2015 [138]	3.72 ± 0.16
RBC/UKQCD 2015 [139]	3.61 ± 0.32
HFAG 2014 (lattice) [24]	3.28 ± 0.29
HFAG 2014 (LCSR) [145, 24]	3.53 ± 0.29
Imsong et al. 2014 (LCSR, Bayes an.) [150]	$3.32^{+0.26}_{-0.22}$
Belle 2013 (lattice + LCSR) [133]	3.52 ± 0.29
$\bar{B} \to \omega l \bar{\nu}_l$	
Bharucha et al. 2015 (LCSR) [153]	$3.31 \pm 0.19_{\rm exp} \pm 0.30_{\rm th}$
$\bar{B} \to \rho l \bar{\nu}_l$	
Bharucha et al. 2015 (LCSR) [153]	$3.29 \pm 0.09_{\rm exp} \pm 0.20_{\rm th}$
$\Lambda_b \to p \mu \nu_\mu$	
LHCb (PDG) [154]	3.27 ± 0.23
Indirect fits	
UTfit (2016) [101]	3.74 ± 0.21
CKMfitter (2015, 3σ) [102]	$3.71^{+0.17}_{-0.20}$

Inclusive decays ($|V_{ub}| \times 10^3$)	ADFR [190, 191, 192]	BNLP [193, 194, 195]	DGE [196]	GGOU [197]
HFAG 2014 [24]	$4.05 \pm 0.13^{+0.18}_{-0.11}$	$4.45 \pm 0.16^{+0.21}_{-0.22}$	$4.52 \pm 0.16^{+0.15}_{-0.16}$	$4.51 \pm 0.16^{+0.12}_{-0.15}$

$|V_{ub}|$

- Less precise module of CKM matrix elements.
- Inclusive determination more challenging theoretically than V_{cb}
- Lattice best exclusive determination $B \to \pi$ ($B \to \rho, \omega$) systematically lower.
- Tension exclusive-inclusive at 2-3σ.
- Indirect Fit using CKM, CPV and flavour data (except direct decays) closer to exclusive determination.
- $|V_{ub}|$ from $\mathcal{B}(B^+ \to \ell^+ \nu_\ell)$ consistent with both inclusive and exclusive (not yet competitive).

Is there a New Physics solution for those tensions exclusive/inclusive?

Apparently there seems NOT to be a NP solution [A. Crivellin et al.].

- Inclusive always larger than exclusive determinations (in both $|V_{cb}|$ and $|V_{ub}|$)
- EFT approach to test it in a model independent way.

Two possibilities NP can affect CKM from tree-level B decays:

$\Rightarrow$ four-fermion operators (generated at tree)

$$\mathcal{O}_R^S = \bar{\ell} P_L \nu \bar{q} P_R b \quad \mathcal{O}_L^S = \bar{\ell} P_L \nu \bar{q} P_L b \quad \mathcal{O}_L^T = \bar{\ell} \sigma_{\mu\nu} P_L \nu \bar{q} \sigma^{\mu\nu} P_L b$$

$q = u, c$. Lack of interference with SM at zero-recoil:

- Exclusive: $|C_L^T|^2$ (all), $|C_R^S + C_L^S|^2$ ($B \to D(\pi)$), $|C_R^S - C_L^S|^2$ ($B \to D^*(\rho)$).
- Inclusive: $|C_L^T|^2$ (all), $|C_R^S|^2 + |C_L^S|^2$.

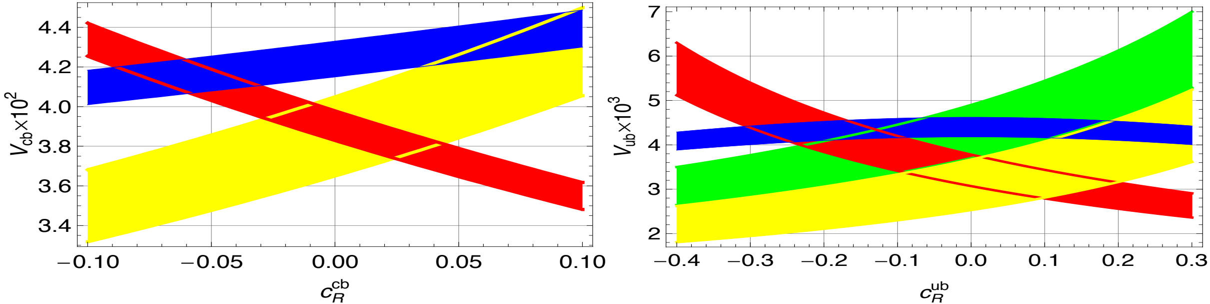
$\rightarrow$ No way to explain Inclusive $>$ Exclusive.

$\Rightarrow$ modified W-qb couplings (generated via loop)

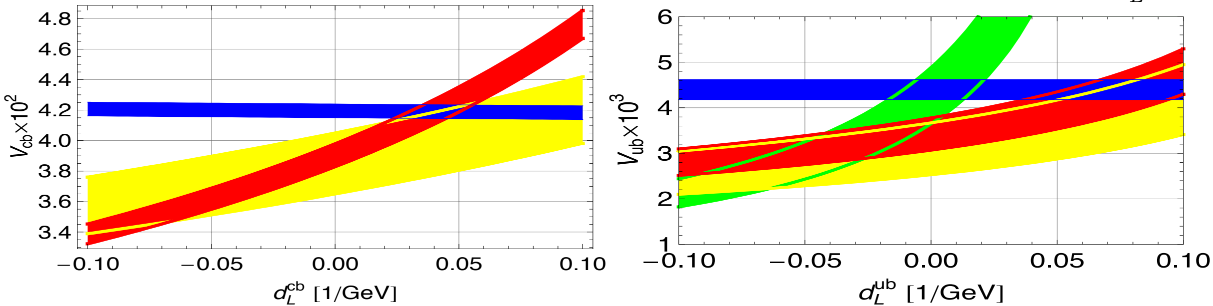
$$H_{eff} = \frac{4 G_F V_{qb}}{\sqrt{2}} \bar{\ell} \gamma^\mu P_L \nu \left((1 + c_L^{qb}) \bar{q} \gamma_\mu P_L b + g_L^{qb} \bar{q} i \overleftrightarrow{D}_\mu P_L b + d_L^{qb} i \partial^\nu \left(\bar{q} i \sigma_{\mu\nu} P_L b \right) + L \to R \right)$$

$V_{cb} \to V_{cb}(c_{L,R}^{cb}, d_{L,R}^{cb}, g_{L,R}^{cb})$ and $V_{ub} \to V_{ub}(c_{L,R}^{ub}, d_{L,R}^{ub}, g_{L,R}^{ub})$

Only c_R can produce differences in exclusive and inclusive but not agreement between incl. (**blue**) and excl. ($B \to D^*(\pi)$ (**Red**), ($B \to D(\rho)$ (**Yellow**), ($B \to \tau\nu$ (**Green**).

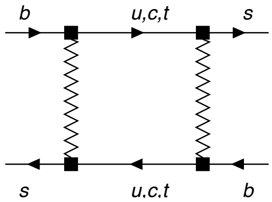


Also the other coefficients fail to get a global agreement, except maybe d_L^{qb}



d_L^{qb}: Agreement between INCL. and EXCL., BUT tension with $B \to \tau\nu$. Also too large $Z - b\bar{b}$ coupling.

Bounding New Physics via FCNC ($\triangle F = 2$)



$$i\frac{d}{dt}\begin{pmatrix} |B_q(t)\rangle \\ |\bar{B}_q(t)\rangle \end{pmatrix} = \left(M^q - \frac{i}{2}\Gamma^q\right)\begin{pmatrix} |B_q(t)\rangle \\ |\bar{B}_q(t)\rangle \end{pmatrix}$$

- Non-hermitian Hamiltonian (only 2 states) but M and Γ hermitian
- Mixing due to non-diagonal terms $M^q_{12} - i\Gamma^q_{12}/2$

$\Longrightarrow$Diagonalisation: physical $|B^q_{H,L}\rangle = p|B_q\rangle \mp q|\bar{B}_q\rangle$ of masses $M^q_{H,L}$, widths $\Gamma^q_{H,L}$

In terms of M^q_{12}, $|\Gamma^q_{12}|$ and $\phi_q = arg\left(-\frac{M^q_{12}}{\Gamma^q_{12}}\right)$ and determined from:

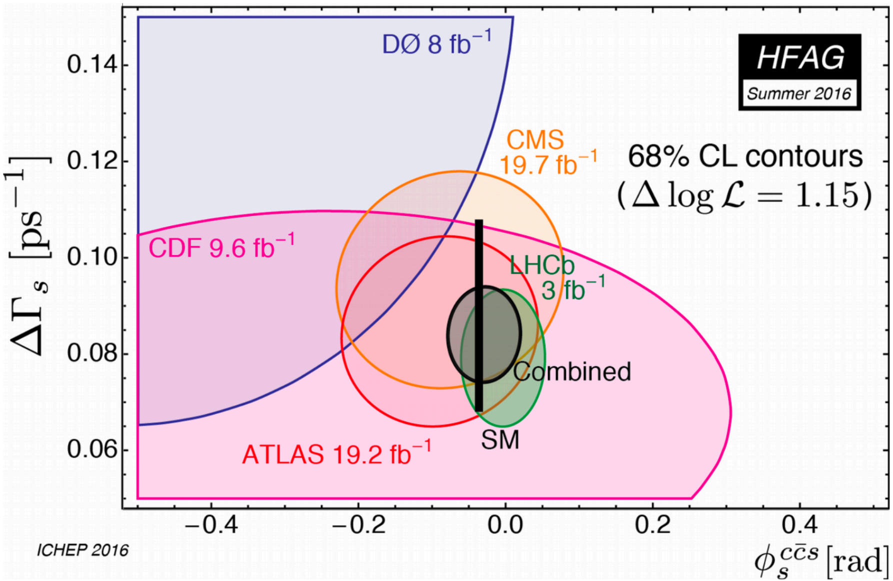
- Mass difference $\Delta m_q = M^q_H - M^q_L$
- Width difference $\Delta\Gamma_q = \Gamma^q_L - \Gamma^q_H$
- $a^q_{SL} = \frac{\Gamma(\bar{B}_q(t)\to\ell^+\nu X)-\Gamma(B_q(t)\to\ell^-\nu X)}{\Gamma(\bar{B}_q(t)\to\ell^+\nu X)+\Gamma(B_q(t)\to\ell^-\nu X)}$ measures CP violation in mixing
- Mixing in time-dependent CP asymetries q/p

Accessible for B_d and B_s at Babar, Belle, CDF, DØ, LHCb... Model-independent parametrisation under the assumption that NP only changes modulus and phase of M^d_{12} and M^s_{12} A. Lenz, U. Nierste, CKMfitter

$$M^q_{12} = (M^q_{12})_{SM} \times \Delta_q \qquad \Delta_q = |\Delta_q|e^{i\phi^\Delta_q} = (1 + h_q e^{2i\sigma_q})$$

Use Δm_d, Δm_s, β, ϕ_s, a^d_{SL}, a^s_{SL}, $\Delta\Gamma_s$ to constrain Δ_d and Δ_s

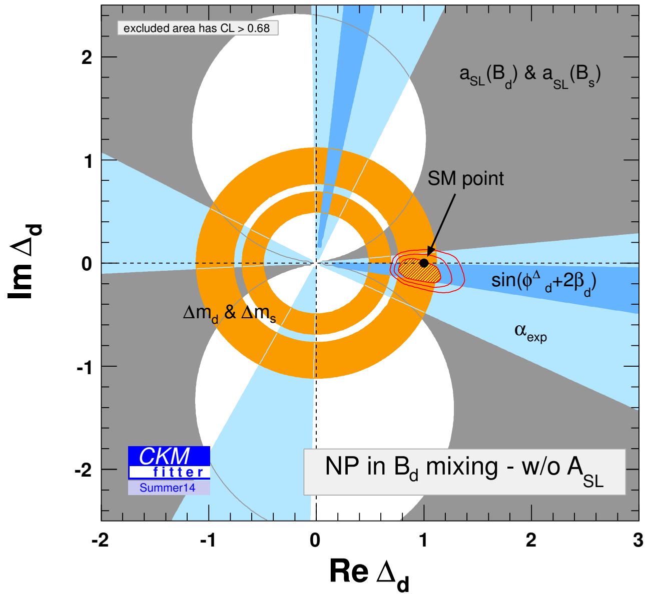
NP in B_s^0 oscillations?



Experimental errors are still larger than theory ones for ϕ_s ....

...but no much room left for NP here.

NP phases shift $2\beta \to 2\beta + \phi_d^\Delta$ in mixing-induced CP asymm. in $B^0 \to J/\psi K_s^0$ and a_{sl}^d

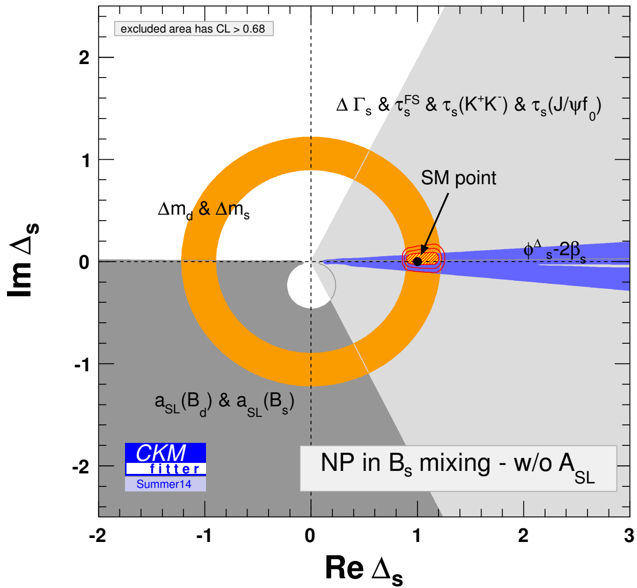


[Constraints @ 68% CL]

- Dominant constraint from β and Δm_d
- Good agreement with other constraints (α, $a_{SL}^{d,s}$)
- Compatible with SM
- Still room for NP in Δ_d at 3σ

$\Delta_d = 0.94^{+0.18}_{-0.15} + i \cdot (-0.11^{+0.11}_{-0.05})$ 2D SM hyp. ($\Delta_d = 1 + i \cdot 0$): 0.9 σ

NP phases shift $2\beta_s \to 2\beta_s - \phi_s^\Delta$ in mixing-induced CP asymm. in $B_s^0 \to J/\psi\phi$ and a_{sl}^s



[Constraints @ 68% CL]

- Dominant constraints from Δm_s and ϕ_s
- ϕ_s favours SM situation
- A_{SL}, combining a_{SL}^d and a_{SL}^s, measured by $D\text{Ø}$ not included
- still room for NP in Δ_s at 3σ

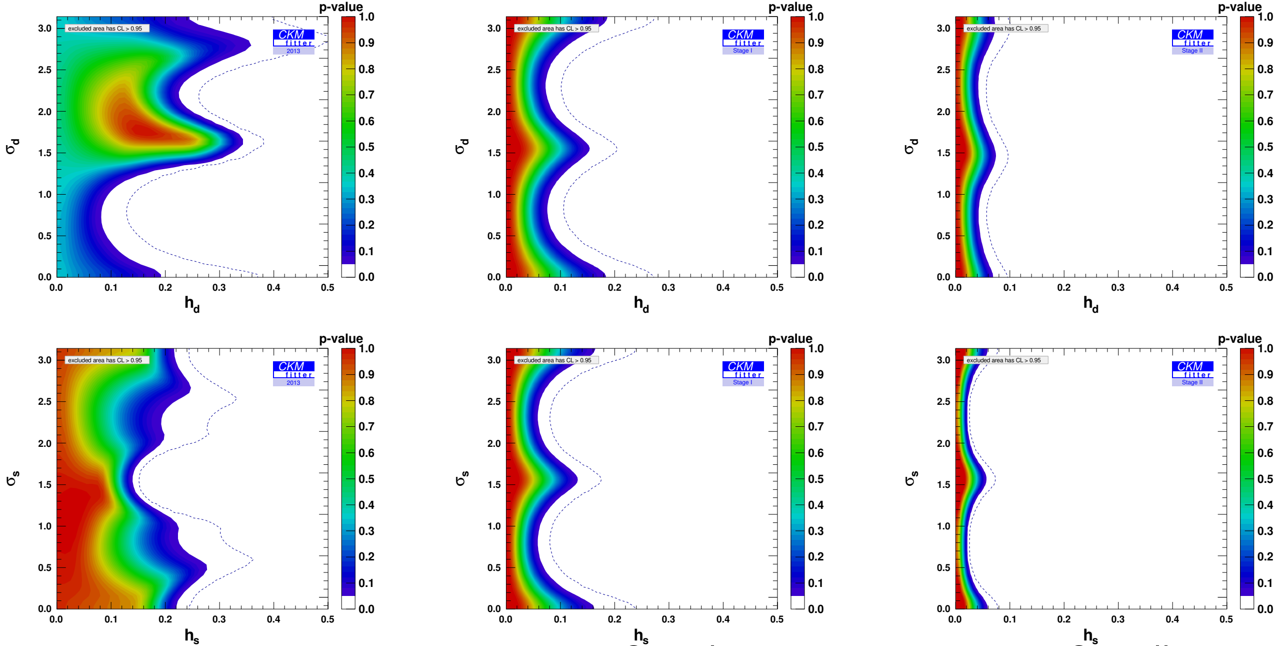
$\Delta_s = 1.05^{+0.14}_{-0.13} + i \cdot (-0.03^{+0.04}_{-0.04})$

2D SM hyp ($\Delta_s = 1 + i \cdot 0$): 0.3 σ

What are the bounds/prospects for New Physics at Stage I: 7 fb^{-1} LHCb data + 5 ab^{-1} Belle II and Stage II: 50 fb^{-1} LHCb data + 50 ab^{-1} Belle II

$\Delta F = 2$: bounds on $h_{d,s} = |\Delta_{d,s} - 1|$

What are the bounds/prospects for New Physics at Stage I: 7 fb^{-1} LHCb data + 5 ab^{-1} Belle II and Stage II: 50 fb^{-1} LHCb data + 50 ab^{-1} Belle II



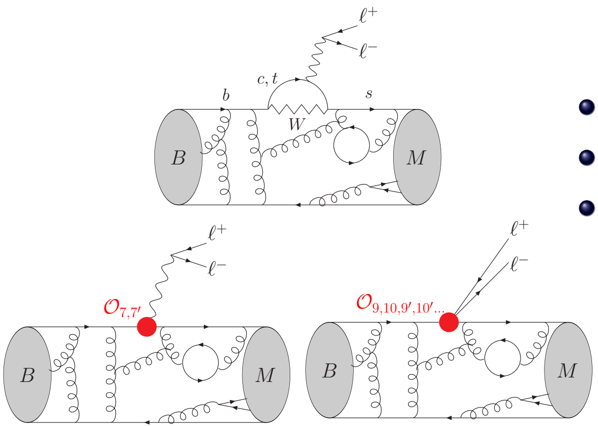
2013 | Stage I | Stage II

Probing New Physics via Rare B decays:

Present situation

concerning New Physics in $b \to s\ell\ell$

and in $b \to c\tau\nu$



$$b \to s\gamma(^*) : \mathcal{H}^{SM}_{\triangle F=1} \propto \sum V^*_{ts} V_{tb} \mathcal{C}_i \mathcal{O}_i + \ldots$$

separate short and long distances ($\mu_b = m_b$)

- $\mathcal{O}_7 = \frac{e}{16\pi^2} m_b \, \bar{s}\sigma^{\mu\nu}(1+\gamma_5) F_{\mu\nu} \, b$ [real or soft photon]
- $\mathcal{O}_9 = \frac{e^2}{16\pi^2} \bar{s}\gamma_\mu(1-\gamma_5) b \; \bar{\ell}\gamma^\mu \ell$ [$b \to s\mu\mu$ via Z/hard $\gamma\ldots$]
- $\mathcal{O}_{10} = \frac{e^2}{16\pi^2} \bar{s}\gamma_\mu(1-\gamma_5) b \; \bar{\ell}\gamma^\mu\gamma_5 \ell$ [$b \to s\mu\mu$ via Z]

$$\mathcal{C}_7^{\rm SM} = -0.29, \; \mathcal{C}_9^{\rm SM} = 4.1, \; \mathcal{C}_{10}^{\rm SM} = -4.3$$

A= $\mathcal{C}_i$ (short dist) $\times$ Hadronic quantities (long dist)

NP changes short-distance $\mathcal{C}_i$ for SM or involve additional operators $\mathcal{O}_i$

- Chirally flipped ($W \to W_R$) $\quad \mathcal{O}_{7'} \propto \bar{s}\sigma^{\mu\nu}(1-\gamma_5) F_{\mu\nu} \, b$
- (Pseudo)scalar ($W \to H^+$) $\quad \mathcal{O}_S \propto \bar{s}(1+\gamma_5) b \bar{\ell}\ell, \mathcal{O}_P$
- Tensor operators ($\gamma \to T$) $\quad \mathcal{O}_T \propto \bar{s}\sigma_{\mu\nu}(1-\gamma_5) b \; \bar{\ell}\sigma_{\mu\nu}\ell$

How do we extract Wilson coefficients: Global analysis of $b \to s\ell\ell$

[Capdevila, Crivellin, Descotes, JM, Virto]

175 observables in total (LHCb, Belle, ATLAS and CMS, no CP-violating obs)

- $B \to K^*\mu\mu$ ($P_{1,2}, P'_{4,5,6,8}, F_L$ in 5 large-recoil bins + 1 low-recoil bin)+available electronic observables.

...April's update of $\mathrm{Br}(B \to K^*\mu\mu)$ showing now a deficit in muonic channel.

...April's new result from LHCb on R_K^*

- $B_s \to \phi\mu\mu$ ($P_1, P'_{4,6}, F_L$ in 3 large-recoil bins + 1 low-recoil bin)
- $B^+ \to K^+\mu\mu$, $B^0 \to K^0\ell\ell$ (BR) ($\ell = e, \mu$) (R_K is implicit)
- $B \to X_s\gamma$, $B \to X_s\mu\mu$, $B_s \to \mu\mu$ (BR).
- Radiative decays: $B^0 \to K^{*0}\gamma$ (A_I and $S_{K^*\gamma}$), $B^+ \to K^{*+}\gamma$, $B_s \to \phi\gamma$

▶ New Belle measurements for the isospin-averaged but lepton-flavour dependent ($Q_{4,5}$):

$$P_i'^{\,\ell} = \sigma_+ \, P_i'^{\,\ell}(B^+) + (1-\sigma_+)\, P_i'^{\,\ell}(\bar{B}^0)$$

▶ New ATLAS and CMS measurements on P_i (details later)

Various tools

- inclusive: OPE
- excl large-meson recoil: QCD fact, Soft-collinear effective theory
- excl low-meson recoil: Heavy quark eff th, Lattice QCD, Quark-hadron duality

How do we extract Wilson coefficients: Global analysis of $b \to s\ell\ell$

[Capdevila, Crivellin, Descotes, JM, Virto]

175 observables in total (LHCb, Belle, ATLAS and CMS, no CP-violating obs)

- $B \to K^*\mu\mu$ ($P_{1,2}, P'_{4,5,6,8}, F_L$ in 5 large-recoil bins + 1 low-recoil bin)+available electronic observables.

...April's update of $\mathrm{Br}(B \to K^*\mu\mu)$ showing now a deficit in muonic channel.

...April's new result from LHCb on R_K^*

- $B_s \to \phi\mu\mu$ ($P_1, P'_{4,6}, F_L$ in 3 large-recoil bins + 1 low-recoil bin)
- $B^+ \to K^+\mu\mu$, $B^0 \to K^0\ell\ell$ (BR) ($\ell = e, \mu$) (R_K is implicit)
- $B \to X_s\gamma$, $B \to X_s\mu\mu$, $B_s \to \mu\mu$ (BR).
- Radiative decays: $B^0 \to K^{*0}\gamma$ (A_I and $S_{K^*\gamma}$), $B^+ \to K^{*+}\gamma$, $B_s \to \phi\gamma$

▶ New Belle measurements for the isospin-averaged but lepton-flavour dependent ($Q_{4,5}$):

$$P_i'^{\,\ell} = \sigma_+ \, P_i'^{\,\ell}(B^+) + (1-\sigma_+) \, P_i'^{\,\ell}(\bar{B}^0)$$

▶ New ATLAS and CMS measurements on P_i (details later)

Various tools

- inclusive: OPE
- excl large-meson recoil: QCD fact, Soft-collinear effective theory
- excl low-meson recoil: Heavy quark eff th, Lattice QCD, Quark-hadron duality

Type-I: Main anomalies currently observed in $b \to s\mu^+\mu^-$ transitions:

- Optimized observables: P_5'
- FFD observables: Systematic deficit of muonic modes at large and low-recoil of several BR

$$B \to K^*\mu^+\mu^-,\ B^+ \to K^{*+}\mu^+\mu^-,\ B_s \to \phi\mu^+\mu^-,\ B^{+,0} \to K^{+0}\mu^+\mu^-.$$

Largest pulls	$\langle P_5' \rangle_{[4,6]}$	$\langle P_5' \rangle_{[6,8]}$	$\mathcal{B}^{[2,5]}_{B_s\to\phi\mu^+\mu^-}$	$\mathcal{B}^{[5,8]}_{B_s\to\phi\mu^+\mu^-}$	$\mathcal{B}^{[15,18.8]}_{B_s\to\phi\mu^+\mu^-}$	$\mathcal{B}^{[15,19]}_{B^+\to K^{*+}\mu^+\mu^-}$
Exp.	-0.30 ± 0.16	-0.51 ± 0.12	0.77 ± 0.14	0.96 ± 0.15	1.62 ± 0.20	1.60 ± 0.32
SM	-0.82 ± 0.08	-0.94 ± 0.08	1.55 ± 0.33	1.88 ± 0.39	2.20 ± 0.17	2.59 ± 0.25
Pull (σ)	-2.9	-2.9	+2.2	+2.2	+2.2	+2.5

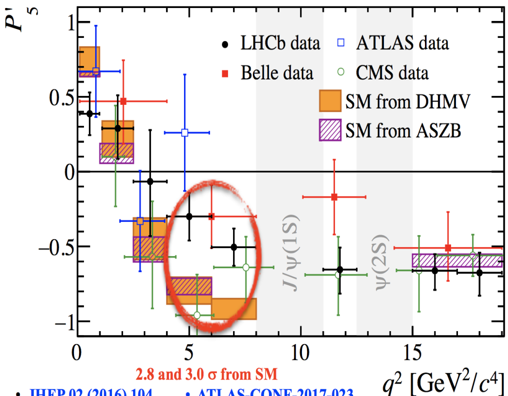
$\Rightarrow$ New Physics in muonic Wilson coefficients.

Type-II: Anomalies in LFUV observables: Ratios of BR ($B \to [P,V]\mu^+\mu^-$)/BR ($B \to [P,V]e^+e^-$).

Largest pulls	$R_K^{[1,6]}$	$R_{K^*}^{[0.045,1.1]}$	$R_{K^*}^{[1.1,6]}$
Exp.	$0.745^{+0.097}_{-0.082}$	$0.66^{+0.113}_{-0.074}$	$0.685^{+0.122}_{-0.083}$
SM	1.00 ± 0.01	0.92 ± 0.02	1.00 ± 0.01
Pull (σ)	+2.6	+2.3	+2.6

$\Rightarrow$ Hints that Nature does not treat electrons and muons in the same way (opposite to SM predictions).

P_5'.... the most tested anomaly (Type-I)



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

P_5' was proposed in DMRV, JHEP 1301(2013)048

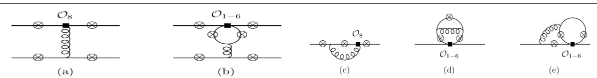
Idea: all FF $\to \xi_{\perp,\|}$, cancel leading $\xi_{\perp,\|}$ term.

$$P_5' = \sqrt{2}\frac{\mathrm{Re}(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*})}{\sqrt{|A_0|^2(|A_\perp|^2+|A_\||^2)}} = P_5^\infty\,(1+\mathcal{O}(\alpha_s\xi_\perp)+\text{p.c.})\ .$$

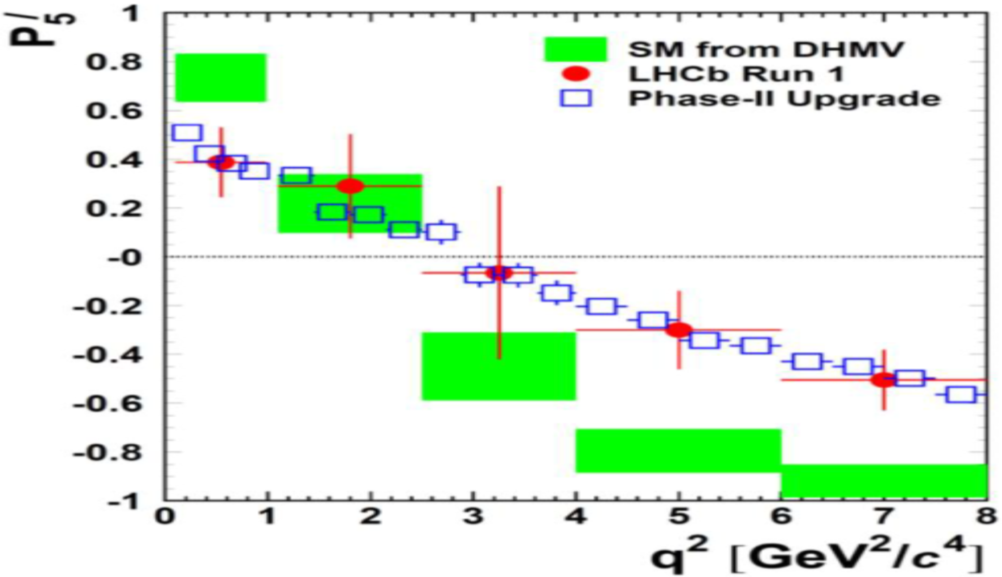
Optimized Obs.: Soft form factor ($\xi_\perp$) cancellation at LO.

- 2013: 1fb^{-1} dataset LHCb found 3.7σ.
- 2015: 3fb^{-1} dataset LHCb (**black**) found 3σ in 2 bins.
  $\Rightarrow$ Predictions (**in orange**) from DHMV.
- Belle (**red**) confirmed it in a bin [4,8] few months ago.

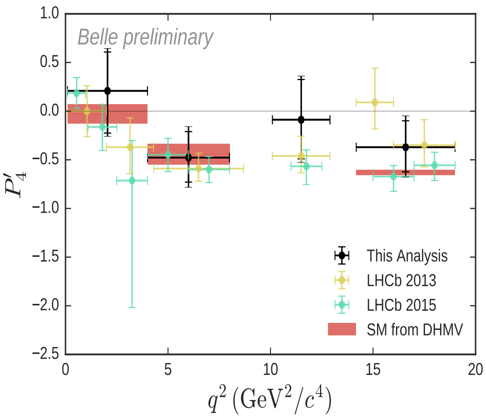
$\boxed{1}$ Computed in i-QCDF + KMPW+ 4-types of corr. $F^{full}(q^2) = F^{soft}(\xi_\perp,\xi_\|) + \triangle F^{\alpha_s}(q^2) + \triangle F^{p.c.}(q^2)$

type of correction	Factorizable	Non-Factorizable
α_s-QCDF	$\triangle F^{\alpha_s}(q^2)$	
power-corrections	$\triangle F^{p.c.}(q^2)$	LCSR with single soft gluon contribution

Projections from LHCb for P_5' in Phase-II Upgrade. [Taken from LHCb]



P_4'.... an important cross-check



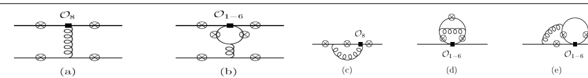
P_4' was proposed in **DMRV, JHEP 1301(2013)048**

$$P_4' = \sqrt{2}\,\frac{\mathrm{Re}(A_0^L A_\parallel^{L*} + A_0^R A_\parallel^{R*})}{\sqrt{|A_0|^2(|A_\perp|^2 + |A_\parallel|^2)}} = P_4^\infty\,(1 + \mathcal{O}(\alpha_s \xi_\perp) + \mathrm{p.c.})\ .$$

Optimized Obs.: Soft form factor ($\xi_\perp$) cancellation at LO.

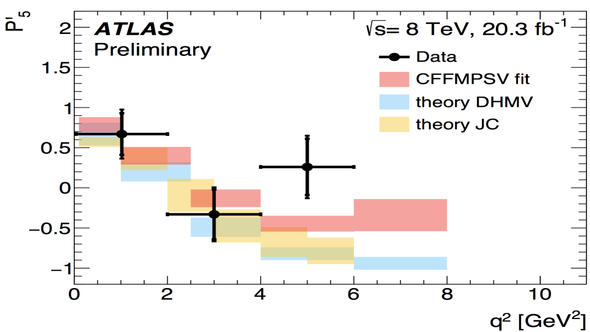
- 2013: 1fb^{-1} dataset LHCb found consistency with SM
- 2015: 3fb^{-1} dataset LHCb found consistency with SM.
  $\Rightarrow$ Predictions (**in red**) from DHMV.
- Belle also found consistency with SM and with LHCb.

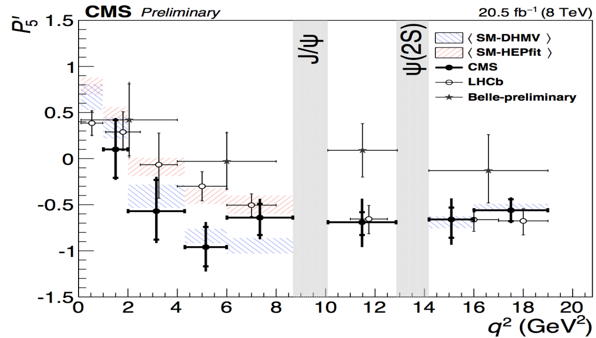
$\boxed{1}$ Computed in i-QCDF + KMPW+ 4-types of corr. $\mathbf{F^{full}(q^2)} = F^{soft}(\xi_\perp, \xi_\parallel) + \triangle F^{\alpha_s}(q^2) + \triangle F^{p.c.}(q^2)$

type of correction	Factorizable	Non-Factorizable
α_s-QCDF	$\triangle F^{\alpha_s}(q^2)$	
power-corrections	$\triangle F^{p.c.}(q^2)$	LCSR with single soft gluon contribution

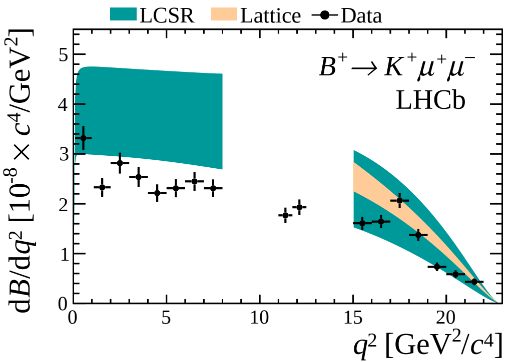
ATLAS and CMS also!

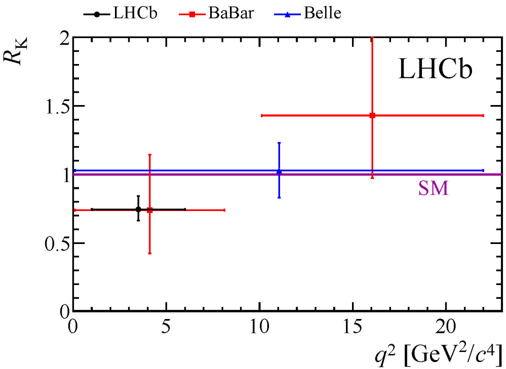
⇒ ATLAS & CMS proven able to measure optimized observables. **Method**: folding technique.
Plots include two theory predictions and a fit CFFMPSV (not a prediction) to LHCb:

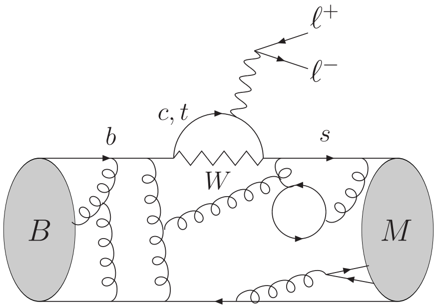




- The full basis (except P_2) is measured P_1, P_4', P_5', P_6', P_8' and F_L (large-recoil).
- ATLAS observe a large deviation in P_5' in agreement with LHCb and Belle.
- Also a large deviation in P_4' is observed in disagreement with LHCb and Belle.
- Only P_1 and P_5', P_5' seems consistent with SM (except [6-8]). CMS in tension with LHCb, Belle, ATLAS.
- Suggestions to test the robustness of analysis:
  - extract F_L , P_1 and P_5' from same folding like ATLAS and LHCb. Important to test correct normalization.
  - Implement directly the constraint: $P_5'^2 - 1 \leq P_1$



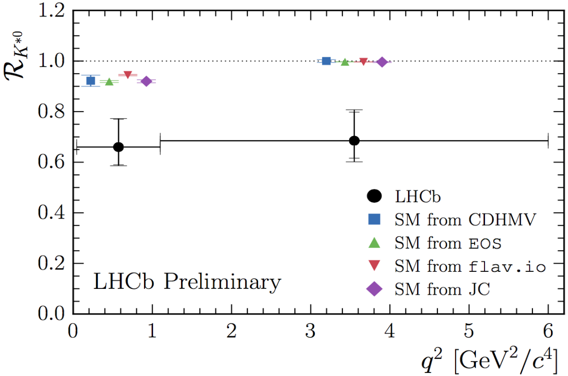


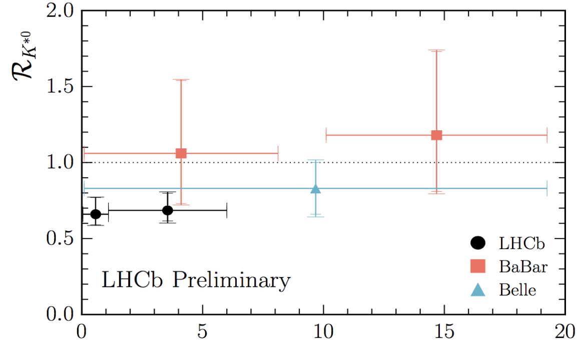


- q^2 invariant mass of $\ell\ell$ pair
- $Br(B \to K\mu\mu)$ too low compared to SM
- $R_K = \left.\frac{Br(B\to K\mu\mu)}{Br(B\to Kee)}\right|_{[1,6]} = 0.745^{+0.090}_{-0.074} \pm 0.036$
- equals to 1 in SM (universality of lepton coupling), 2.6 σ dev
- NP coupling $\neq$ to μ and e

$$R_{K^\star} = \frac{Br(B^0 \to K^{*0}\mu^+\mu^-)}{Br(B^0 \to K^{*0}e^+e^-)}$$

pulls	$R_{K^*}^{[0.045,1.1]}$	$R_{K^*}^{[1.1,6]}$
Exp.	$0.66^{+0.113}_{-0.074}$	$0.685^{+0.122}_{-0.083}$
SM	0.92 ± 0.02	1.00 ± 0.01





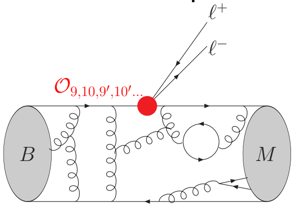
- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

q^2 [GeV$^2/c^4$]

- Both R_K and R_{K^*} are very clean **but ONLY in the SM and for $q^2 \geq 1$ GeV^2**.
  - Long distance charm is universal and cannot explain the tensions.
  - Lepton mass effects even in the SM are important in the first bin.
    $\to$ Our error size in 1st and 2nd bin in agreement with Isidori et al. (including QED $\to 0.03$).
- In presence of New Physics or for $q^2 < 1$ GeV^2 **hadronic uncertainties return.**
  - Typical wrong statement "R_{K,K^*} are ALWAYS very clean observable", indeed is substantially less clean and more FF dependent than any optimized observable.

There have been some **attempts** by a few groups to try to explain **a subset of** the previous **anomalies** using two arguments:

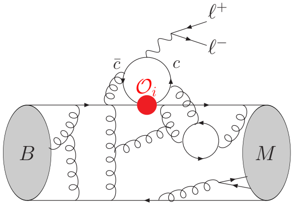
- factorizable power corrections (**easy to discard arg (see back-up)**)



- They have to be included in a correct way. **DHMV included them and also BSZ (full-FF) and results agree.**
- In [Jaeger-Camalich'12,'14] emphatic claims of large impact but two important missing points:
  - scheme choice inflates artificially error x4
  - correlations among FPP of observables. Leading P_5' FPP missing in JC14.

Summary: [JC] present now two sizes of errors(small/large) but two problems mention above not addressed.

- or unknown charm contributions... (**more difficult to discard but also possible with a global fit**)



A detailed explanation of where those "'explanations" fails in [JHEP 1412 (2014) 125, JHEP 1704 (2017) 016]

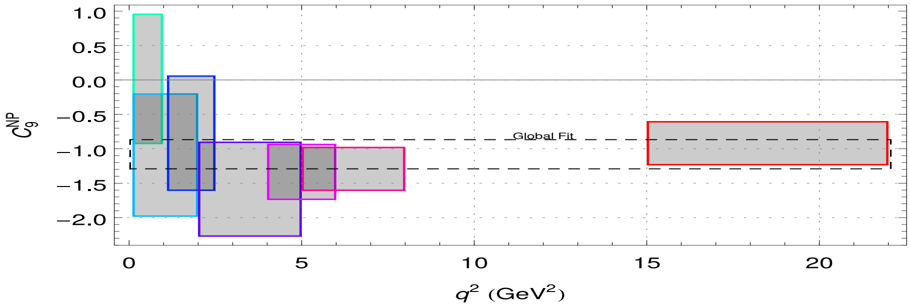
Problem: Charm-loop yields q^2- and hadronic-dependent contribution with $O_{7,9}$ structures that may mimic New Physics.

$$C_{9i}^{\rm eff}(q^2) = C_{9\,\rm SMpert} + C_9^{\rm NP} + \mathbf{C_{9i}^{c\bar{c}}(q^2)}. \qquad \mathbf{i} = \perp, \|, \mathbf{0}$$

How to disentangle? Is our long-dist $c\bar{c}$ estimate using KMPW as order of magnitude correct?

$\boxed{1}$ Fit to C_9^{NP} bin-by-bin of $b \to s\mu\mu$ data:

- NP is universal and q^2-independent.
- Hadronic effect associated to $c\bar{c}$ dynamics is (likely) q^2-dependent.



- The excellent agreement of bins [2,5], [4,6], [5,8]: $C_9^{NP\,[2,5]} = -1.6 \pm 0.7$, $C_9^{NP\,[4,6]} = -1.3 \pm 0.4$, $C_9^{NP\,[5,8]} = -1.3 \pm 0.3$ shows **no indication of <u>additional</u> q^2- dependence.**

[Ciuchini et al.] introduced a polynomial in each amplitudes and fitted the $h_i^{(K)}$ ($i = \perp, \|, 0$ and $K = 0, 1, 2$):

$$A^0_{L,R} = A^0_{L,R}(Y(q^2)) + \frac{N}{q^2}\left(h_0^{(0)} + \frac{q^2}{1GeV^2}h_0^{(1)} + \frac{q^4}{1GeV^4}h_0^{(2)}\right)$$

THIS IS A FIT to LHCb of only $B \to K^*\mu\mu$ large-recoil data NOT A COMPUTATION
They use BSZ-FF for predictions so form factors must no be an issue for them...

$\boxed{a}$ Unconstrained Fit finds constant contribution similar for all helicity-amplitudes.

→ In full agreement with our global fit.
→ Problem: They interpret this constant universal contribution as of unknown hadronic origin??
Interestingly: the same constant also explains R_K ONLY if it is of NP origin and NOT if hadronic origin.

$\boxed{b}$ Constrained Fit: Imposing SM+ $C_{9i}^{c\bar{c}}$ (from KMPW) at $q^2 < 1$ GeV^2 is highly controversial:

→ arbitrary choice that tilts the fit, inducing spurious **large** q^4-dependence.
→ fit to first bin that misses the lepton mass approximation by LHCb
→ Imposing $Re[|C_{9i}^{c\bar{c}}|_{fitted}]^2 + Im[|C_{9i}^{c\bar{c}}|_{fitted}]^2 = Re[C_{9i}^{c\bar{c}}|_{KMPW}]^2 + Im[C_{9i}^{c\bar{c}}|_{KMPW}]^2$, is inconsistent since $Im[C_{9i}^{c\bar{c}}]$ was never computed in KMPW!!

Same authors have repeated their analysis but using more data besides $B \to K^*\mu^+\mu^-$ and the result...

From Mauro Valli's talk of Silvestrini et al. group.

NOT SO LONG TIME BACK ...

@LHCb-implications '15

[Ciuchini et al'15] "SM gives a very good description of data and h_-^2 near 2σ from 0."

[Ciuchini et al'17] in unconstrained fit find up to 7σ on C_9^{NP} even missing low-recoil! and $h_\lambda^{(1,2)}$ now compatible with 0. Alternative NP solution C_{10}^e proposed unable to explain any Type-I.

Frequentist analysis: $\mathcal{C}_i(\mu_{ref}) = \mathcal{C}_i^{SM} + \mathcal{C}_i^{NP}$, with $\mathcal{C}_i^{NP}$ assumed to be real (no CPV)

- Experimental correlation + theoretical inputs (form factors. . .) with correlation matrix computed treating all theo errors as Gaussian random variables
- Hypotheses "NP in some $\mathcal{C}_i$ only" (1D, 2D, 6D) to be compared with SM

Pull$_{SM}$ tells you how much the SM is disfavoured w.r.t. a New Physics hypothesis to explain data.

$\rightarrow$ A scenario with a large SM-pull $\Rightarrow$ big improvement over SM and better description of data.

	All				
1D Hyp.	Best fit	1 σ	2 σ	Pull$_{\rm SM}$	p-value
$\mathcal{C}_{9\mu}^{\rm NP}$	-1.10	$[-1.27, -0.92]$	$[-1.43, -0.74]$	5.7	72
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$	-0.61	$[-0.73, -0.48]$	$[-0.87, -0.36]$	5.2	61
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}'_{9\mu}$	-1.01	$[-1.18, -0.84]$	$[-1.33, -0.65]$	5.4	66
$\mathcal{C}_{9\mu}^{\rm NP} = -3\mathcal{C}_{9e}^{\rm NP}$	-1.06	[-1.23,-0.89]	[-1.39,-0.71]	5.8	74

	LFUV				
1D Hyp.	Best fit	1 σ	2 σ	Pull$_{\rm SM}$	p-value
$\mathcal{C}_{9\mu}^{\rm NP}$	-1.76	$[-2.36, -1.23]$	$[-3.04, -0.76]$	3.9	69
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$	-0.66	$[-0.84, -0.48]$	$[-1.04, -0.32]$	4.1	78
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}'_{9\mu}$	-1.64	$[-2.12, -1.05]$	$[-2.52, -0.49]$	3.2	31
$\mathcal{C}_{9\mu}^{\rm NP} = -3\mathcal{C}_{9e}^{\rm NP}$	-1.35	$[-1.82, -0.95]$	$[-2.38, -0.59]$	4.0	71

Global fit test the ***coherence*** *of a set of deviations with a NP hypothesis versus SM hyp.*

2D hypothesis

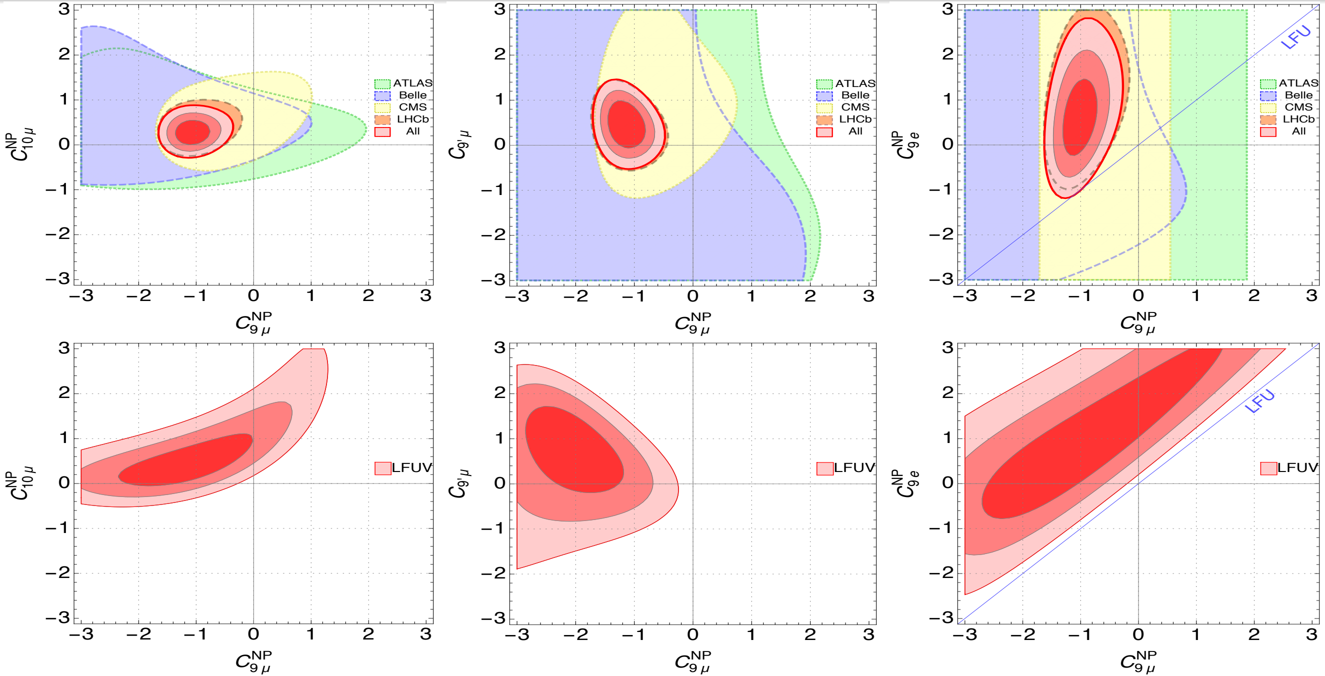


Figure: Allowed regions with all available data (upper) and only LFUV (lower) in good agreement. Constraints from $b \to s\gamma$ observables, $\mathcal{B}(B \to X_s\mu\mu)$ and $\mathcal{B}(B_s \to \mu\mu)$ always included. Experiments at 3σ.

6D fit the most important one

	$\mathcal{C}_7^{\rm NP}$	$\mathcal{C}_{9\mu}^{\rm NP}$	$\mathcal{C}_{10\mu}^{\rm NP}$	$\mathcal{C}_{7'}$	$\mathcal{C}_{9'\mu}$	$\mathcal{C}_{10'\mu}$
Best fit	+0.017	-1.12	+0.33	+0.03	+0.59	+0.07
1 σ	$[-0.01,+0.05]$	$[-1.34,-0.85]$	$[+0.09,+0.59]$	$[+0.00,+0.06]$	$[+0.01,+1.12]$	$[-0.23,+0.37]$
2 σ	$[-0.03,+0.07]$	$[-1.51,-0.61]$	$[-0.10,+0.80]$	$[-0.02,+0.08]$	$[-0.50,+1.56]$	$[-0.50,+0.64]$

The SM pull moved from 3.6 $\sigma \to$ 5.0 σ (fit "All' with the latest CMS data at 8 TeV included)

The pattern (very similar to DHMV15):

$$\mathcal{C}_7^{\rm NP} \gtrsim 0,\ \mathcal{C}_{9\mu}^{\rm NP} < 0,\ \mathcal{C}_{10\mu}^{\rm NP} > 0,\ \mathcal{C}_7' \gtrsim 0,\ \mathcal{C}_{9\mu}' > 0,\ \mathcal{C}_{10\mu}' \gtrsim 0$$

$\mathcal{C}_{9\mu}$ is compatible with the SM beyond 3 σ, all the other coefficients at 1-2 σ.

Looking into the near future: New LFUV to come (Disentangling)

Observables sensitive to the difference between $b \to s\mu\mu$ and $b \to see$:

$\boxed{1}$ They cannot be explained by neither factorizable power corrections nor long-distance charm.

$\boxed{2}$ They share same explanation than P_5' anomaly, assuming NP in e-mode is suppressed (OK with fit).

- Other ratios of Branching Ratios

$$R_\phi = \frac{\mathrm{BR}(B_s \to \phi\mu\mu)}{\mathrm{BR}(B_s \to \phi ee)} \quad (1)$$

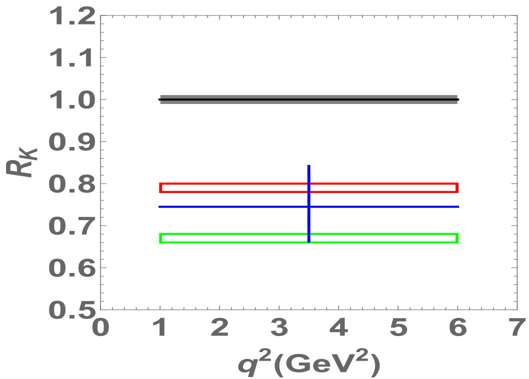
- Difference of Optimized observables: $Q_i = P_i^\mu - P_i^e$.

[CDMV'16]

$\to$ Inheritate the excellent properties of optimized observables

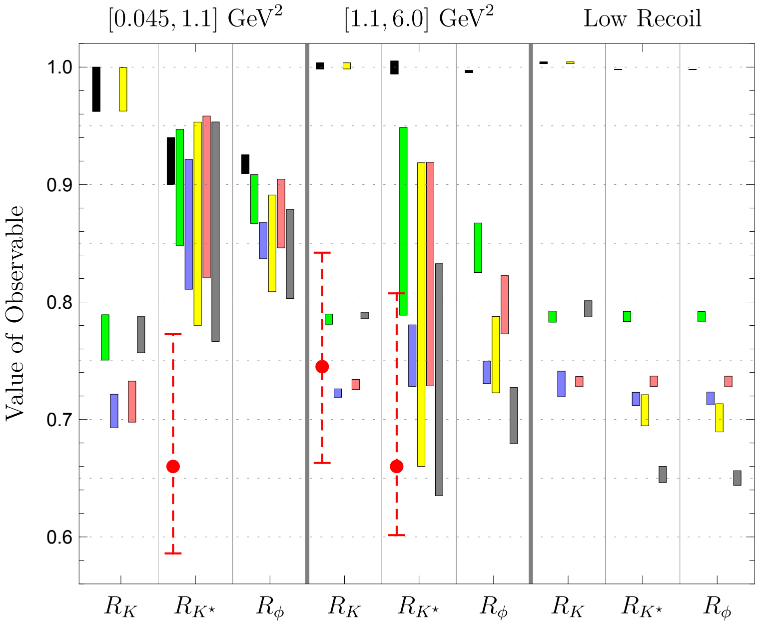
- Ratios of coefficients of angular distribution. $B_i = J_i^\mu / J_i^e - 1$ with i=5,6s.
- Ratios of non-optimized observables $T_i = \frac{S_i^\mu - S_i^e}{S_i^\mu + S_i^e}$

$C_{9\mu}^{\mathrm{NP}} = -1.1, C_{9e}^{\mathrm{NP}} = 0$ **and**
$C_{9\mu}^{\mathrm{NP}} = -C_{10\mu}^{\mathrm{NP}} = -0.65$, $C_{9,10e}^{\mathrm{NP}} = 0$



All are useful to find deviations from SM with tiny uncertainty, but to disentangle different NP scenarios Q_i and B_i (maybe T_i) are key observables.

Disentangling New Physics: Ratios of Branching Ratios



SM-[BLACK]

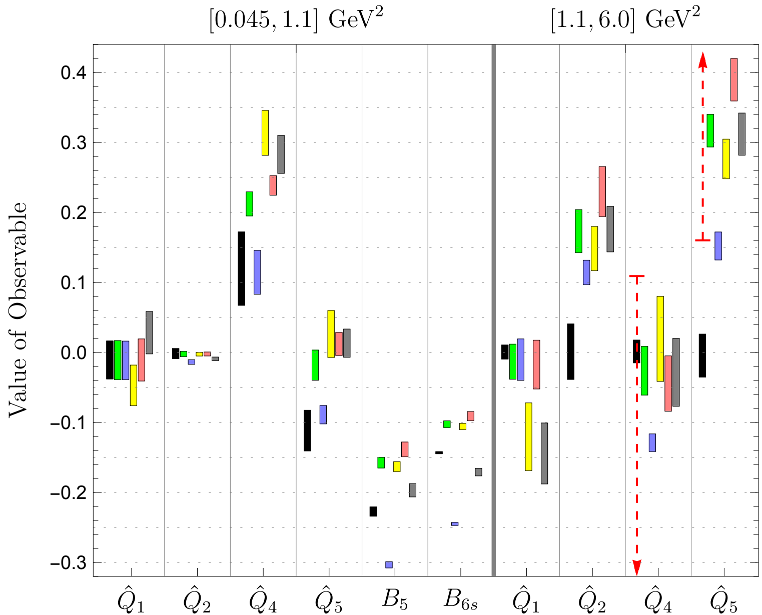
Five "good" scenarios:

- Sc. 1 [GREEN]: $C_{9\mu}^{\rm NP} = -1.1$,
- Sc. 2 [BLUE]: $C_{9\mu}^{\rm NP} = -C_{10\mu}^{\rm NP} = -0.61$,
- Sc. 3 [YELLOW]: $C_{9\mu}^{\rm NP} = -C'_{9\mu} = -1.01$,
- Sc. 4 [ORANGE]: $C_{9\mu}^{\rm NP} = -3C_{9e}^{\rm NP} = -1.06$,
- Sc. 5:[GRAY]: The best fit point in the six-dimensional fit.

R_{K^*} is computed using very conservative KMPW-FF but R_ϕ using BSZ-FF (only available).

ATTENTION: In presence of NP $R_{K,K^*,\phi}$ are largely sensitive to FF choices

Q_i observables are better to disentangle NP: Q_i inheritates the properties of optimized observables.



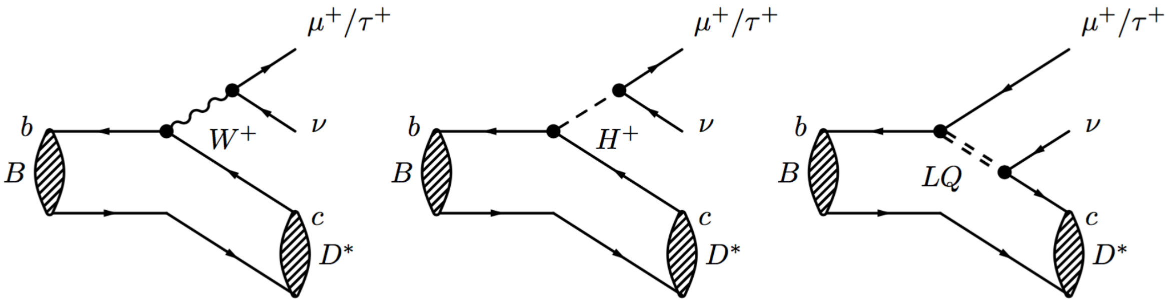
$$Q_i = P_i^\mu - P_i^e$$

SM-[BLACK] and dashed-red [BELLE data]

Five “good” scenarios:

- Sc. 1 [GREEN]: $C_{9\mu}^{\rm NP} = -1.1$,
- Sc. 2 [BLUE]: $C_{9\mu}^{\rm NP} = -C_{10\mu}^{\rm NP} = -0.61$,
- Sc. 3 [YELLOW]: $C_{9\mu}^{\rm NP} = -C'_{9\mu} = -1.01$,
- Sc. 4 [ORANGE]: $C_{9\mu}^{\rm NP} = -3C_{9e}^{\rm NP} = -1.06$,
- Sc. 5:[GRAY]: The best fit point in the six-dimensional fit.

A precise measurement of Q_5 in [1,6] can discard the solution $C_9 = -C_{10}$ in front of all other sols.



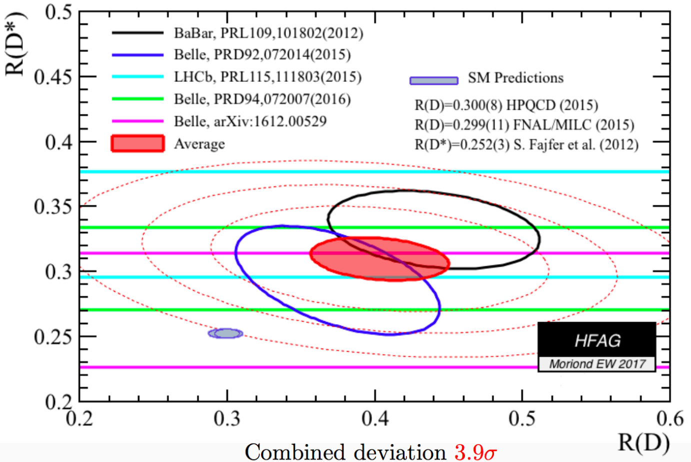
SM NP

Semi-tauonic B decays are charged current processes that can probe also New Physics.
Experimentally (in analogy to R_{K,K^*}) a LFUV ratio:

$$R_{D^{(*)}} = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$

The ratio:

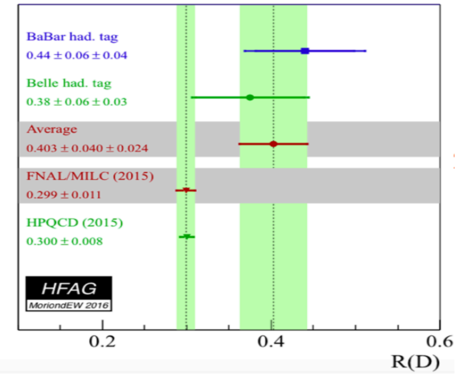
- differs in lepton mass: τ versus $\ell = \mu, e$ mass.
- cancels: form factors, V_{cb}, experimental systematics



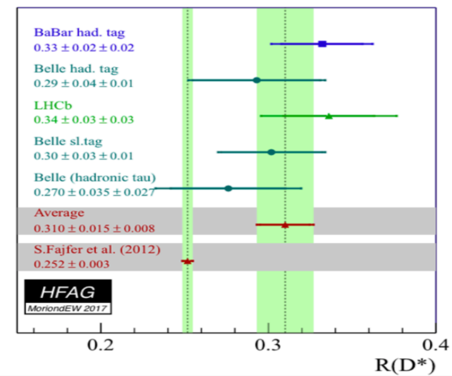
Combined deviation 3.9σ

- Excess that becomes significant 3.9σ after combining experiments: Babar and Belle ($\ell = \mu, e$), LHCb ($\ell = \mu$).

- Intriguing since this is a tree level process contrary to $b \to s\ell\ell$ related ones.



- (HFAG) $R_D^{exp} = 0.403 \pm 0.040 \pm 0.024$
- Lattice computation of $B \to D$ FF: F^+, F^0 (precise).
- (FLAG 2016): 0.300 ± 0.008
- Latest SM prediction: combined fit HQET (incl. $\mathcal{O}(\Lambda/m_{c,b}, \alpha_s)$)+ measured $B \to D\ell\nu$ distributions together with LQCD and QCDSR inputs: $R_D^{SM} = 0.299 \pm 0.003$ ([Bernlochner et al.'17]) ($\mathbf{2.2}\sigma$)



- (HFAG) $R_{D^*}^{exp} = 0.310 \pm 0.015 \pm 0.008$
- Lattice computation of $B \to D$ FF: V, $A_{0,1,2}$, $T_{1,2,3}$. (no non-zero recoil LQCD)
- Latest SM prediction: combined fit HQET (incl. $\mathcal{O}(\Lambda/m_{c,b}, \alpha_s)$)+ measured $B \to D^*\ell\nu$ distributions together with LQCD and QCDSR inputs: $R_{D^*}^{SM} = 0.257 \pm 0.003$ ([Bernlochner et al.'17]) ($\mathbf{3.1}\sigma$)

Scale of New physics

Flavour observables are sensitive to higher scales than direct searches at colliders

... if NP affects flavour it is not surprising that we detect it first.

What is the scale of NP for $b \to s\ell\ell$? Reescaling the Hamiltonian by $H_{eff}^{\rm NP} = \sum \frac{\mathcal{O}_i}{\Lambda_i^2}$

- Tree-level induced (semi-leptonic) with $\mathcal{O}(1)$ couplings ($\times\sqrt{g_{bs}\, g_{\mu\mu}}$):

$$\Lambda_i^{\rm Tree} = \frac{4\pi v}{s_w g} \frac{1}{\sqrt{2|V_{tb}V_{ts}^*|}} \frac{1}{|C_i^{\rm NP}|^{1/2}} \sim \frac{35{\rm TeV}}{|C_i^{\rm NP}|^{1/2}}$$

- Loop level-induced (semi-leptonic) with $\mathcal{O}(1)$ couplings:

$$\Lambda_i^{\rm Loop} \sim \frac{35{\rm TeV}}{4\pi|C_i^{\rm NP}|^{1/2}} = \frac{2.8{\rm TeV}}{|C_i^{\rm NP}|^{1/2}}$$

- MFV with CKM-SM, extra suppression $\sqrt{|V_{tb}V_{ts}^*|} \sim 1/5$

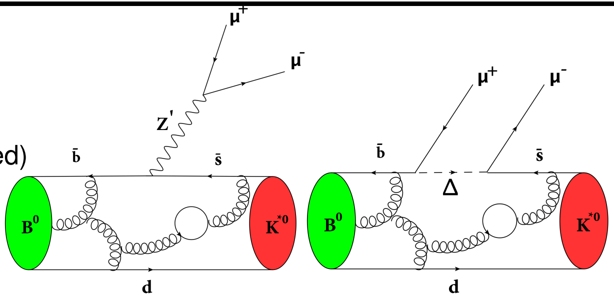
Solution $C_9^{\rm NP} \sim -1.1$ (scale is $\sim$ numerator) or $C_9^{\rm NP} = -C_{10}^{\rm NP} \sim -0.6$ (30 % higher scale).

Similar exercise for $b \to c\tau\nu$ taking a 15% enhancement over SM:

$$\Lambda^{\rm NP} \sim 1/(\sqrt{2}G_F|V_{cb}|0.15)^{1/2} \sim 3.2{\rm TeV}$$

$b \to s\ell\ell$	$R(D) - R(D^*)$	a_μ
Z'	Charged scalars (problems with B_c lifetime)	Z'
Leptoquarks	Leptoquarks (strong impact on $qq \to \tau\tau$)	Leptoquarks
Loop effects	W' (fine-tunning required)	MSSM
Compositeness...	Compositeness...	Scalars

- Z' solution:
  - Heavy: LOOP (no FVQ coupling req.) and TREE (require FVQ couplings)
  - Light (easy to discard if low-recoil tensions confirmed)
- Leptoquarks solution:
  - Vector (Tree)
  - Scalar (Tree or Loop with a fermion)



Conclusions

- CP-violation: No significant deviation observed from the CKM paradigm.
  .... still inclusive/exclusive tensions in $|V_{cb}|$ and $|V_{ub}|$ persist.

- B meson Rare decays: A global analysis of $b \to s\ell\ell$ observables shows a clear pattern of deviations w.r.t. SM:
  - Systematic exp. deficit in muonic modes versus SM: P_5' and branching ratios.
  - Hints of ULFV in R_K, R_K^* and $Q_{4,5}^{BELLE}$ at 4σ level.

  GLOBAL Pull$_{\rm SM}$ at 1,2 and 6D disfavour the SM solution versus NP mainly in C_9 by $> 5\sigma$.

- Also $b \to c\tau\nu$ points at LFUV at 3.9σ significance with $R(D) - R(D^*)$ observables.

....exciting times finally coming

- Soon LHCb may provide new results on LFUV observables ($Q_i = P_i'^{\mu} - P_i'^{e}$ and R_ϕ and more) that may help to disentangle the precise scenario beyond C_9.

$\to$ important implications/guideline for direct searches.

BACK-UP slides

Few misconceptions on a global analysis

"It is not possible to get a large significance from a set of 2-3 sigma tensions".

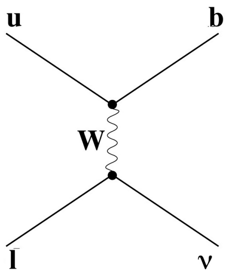
This misleading statement confuses and mixes:
the pulls of data versus SM predictions WITH the $\text{Pull}_{\rm SM}$ that TEST an hyp. of NP versus SM hyp.

- *A global fit can help to distinguish a set of statistical fluctuations from a* **coherent** *set of deviations consistent with a NP hypothesis. Example:*

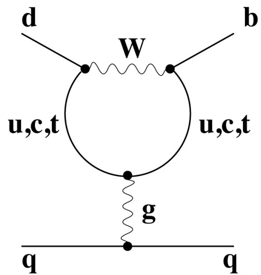
  $\rightarrow$ A set of 2-3 σ pulls taken together gives a 5.7σ of $\text{Pull}_{\rm SM}$ for a solution with $C_9^{\rm NP} = -1.1$.
  $\rightarrow$ SAME set of 2-3 σ but only changing the SIGN of a few of them the significance of $\text{Pull}_{\rm SM}$ drops to 0.7 σ.

- *A* **large deviation** *in one single observable (or a few) may be* **not significant**. *One out of 175 observables having a tension of 5 σ w.r.t the SM is not very significant ("Look-elsewhere effect"). The global fit accounts for this automatically and the Pull_{SM} could be in the range 1-2σ.*

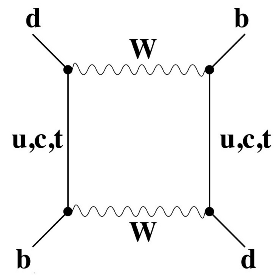
- **Theory+experimental correlations are fundamental.** Example: the fit with no correlations gives a $\text{Pull}_{SM} > 8\sigma$ for many NP hypothesis.



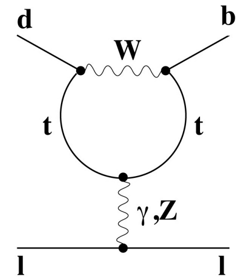
Semi/leptonic



Penguins



Mixing



Radiative

	Semi/leptonic	Penguins	Mixing	Radiative
Process	$\triangle F = 1$ FCCC	$\triangle F = 1$ FCCC	$\triangle F = 2$ FCNC	$\triangle F = 1$ FCNC
NP sensitiv.	Small	Large ?	Large	Large
B	$B \to D\ell\nu, B \to \tau\nu$	$B \to \pi\pi$	$\triangle m_d, \triangle m_s$	$B \to K^*\mu\mu, B_s \to \mu\mu$
D	$D \to K\ell\nu, D_s \to \mu\nu$	$D \to K\pi$	x, y, ϕ	$D \to X_u\ell\ell$
K	$K \to \pi\ell\nu, \tau \to K\nu$	$K \to \pi\pi$	ϵ_K	$K \to \pi\nu\nu, K \to \mu\mu$

Different Form Factor determinations

B-meson distribution amplitudes.

FF-KMPW	$F^i_{BK^{(*)}}(0)$	b^i_1
f^+_{BK}	$0.34^{+0.05}_{-0.02}$	$-2.1^{+0.9}_{-1.6}$
f^0_{BK}	$0.34^{+0.05}_{-0.02}$	$-4.3^{+0.8}_{-0.9}$
f^T_{BK}	$0.39^{+0.05}_{-0.03}$	$-2.2^{+1.0}_{-2.00}$
V^{BK^*}	$\mathbf{0.36^{+0.23}_{-0.12}}$	$-4.8^{+0.8}_{-0.4}$
$A_1^{BK^*}$	$\mathbf{0.25^{+0.16}_{-0.10}}$	$0.34^{+0.86}_{-0.80}$
$A_2^{BK^*}$	$0.23^{+0.19}_{-0.10}$	$-0.85^{+2.88}_{-1.35}$
$A_0^{BK^*}$	$0.29^{+0.10}_{-0.07}$	$-18.2^{+1.3}_{-3.0}$
$T_1^{BK^*}$	$0.31^{+0.18}_{-0.10}$	$-4.6^{+0.81}_{-0.41}$
$T_2^{BK^*}$	$0.31^{+0.18}_{-0.10}$	$-3.2^{+2.1}_{-2.2}$
$T_3^{BK^*}$	$0.22^{+0.17}_{-0.10}$	$-10.3^{+2.5}_{-3.1}$

Table: The $B \to K^{(*)}$ form factors from LCSR and their z-parameterization.

Light-meson distribution amplitudes+EOM (NOT LATEST).

- Interestingly in BSZ (update from BZ) most relevant FF from BZ moved towards KMPW. For example:

$$V^{BZ}(0) = 0.41 \to 0.37 \quad T_1^{BZ}(0) = 0.33 \to 0.31$$

- The size of uncertainty in BSZ = size of error of p.c.

FF-BSZ	$B \to K^*$	$B_s \to \phi$	$B_s \to K^*$
$A_0(0)$	0.391 ± 0.035	0.433 ± 0.035	0.336 ± 0.032
$A_1(0)$	$\mathbf{0.289 \pm 0.027}$	0.315 ± 0.027	0.246 ± 0.023
$A_{12}(0)$	0.281 ± 0.025	0.274 ± 0.022	0.246 ± 0.023
$V(0)$	$\mathbf{0.366 \pm 0.035}$	0.407 ± 0.033	0.311 ± 0.030
$T_1(0)$	0.308 ± 0.031	0.331 ± 0.030	0.254 ± 0.027
$T_2(0)$	0.308 ± 0.031	0.331 ± 0.030	0.254 ± 0.027
$T_{23}(0)$	0.793 ± 0.064	0.763 ± 0.061	0.643 ± 0.058

Table: Values of the form factors at $q^2 = 0$ and their uncertainties.

$\Rightarrow$ β:

- Mode $B^0 \to J/\psi K^0_S$ access to φ_d (phase between decay and mixing+decay):
SM: decay dominated by single CKM phase (neglect penguins)+ B_0-mixing: top-top box diagram.

$$\sin 2\beta^{\rm meas} = 0.691 \pm 0.017 < \sin 2\beta^{\rm indirect} = 0.740^{+0.020}_{-0.025}$$

$\rightarrow$ fit to $B \to J/\psi P$+SU(3) and SCET $\Rightarrow$ penguin small.
$\rightarrow$ 2nd solution of β disfavoured from $B^0 \to J/\psi K^{*0}$.
$\rightarrow \sin 2\beta^{q\bar{q}s} = 0.655 \pm 0.032$ from loop-induced $b \to q\bar{q}s$ transitions.

$\Rightarrow$ α

- $b \to u$ transitions ($B \to \rho\rho, \pi\pi, \pi\rho$) polluted by $b \to s$ penguins.
- Challenging for th & exp. Unitary used. Isospin analysis for $B \to \pi\pi$ using all channels.

$$\alpha^{\rm measured} = (88.8^{+2.3}_{-2.3})^0 \quad \text{versus} \quad \alpha^{\rm fit} = (92.1^{+1.5}_{-1.1})^0$$

$\Rightarrow$ γ

- Less precisely known angle. Tree $B \to DK$ decays; interference between $b \to c$ (CA) and $b \to u$ (CS) topologies. Important test of CKM paradigm. Different methods (GLW,GGSZ,ADS).

$$\gamma^{\rm measured} = (72.1^{+5.4}_{-5.8})^0 ({\rm B-factories+LHCb}) \quad \text{versus} \quad \gamma^{\rm fit} = (65.31^{+1.0}_{-2.5})^0$$

Long-distance contributions from $c\bar{c}$ loops where the lepton pair is created by an electromagnetic current.

1. The γ couples universally to $\mu^\pm$ and $e^\pm$: R_K nor any LFVU cannot be explained by charm-loops.

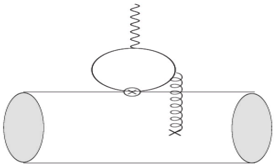
2. KMPW is the only real computation of long-distance charm.

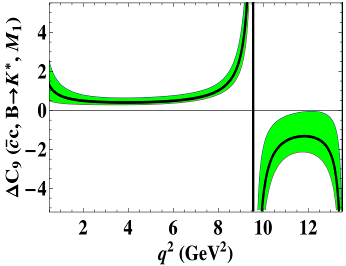
$$C_9^{\text{eff i}} = C_9^{\text{eff}}{}_{\text{SM pert}}(q^2) + C_9^{\text{NP}} + s_i \delta C_9^{c\bar{c}(i)}{}_{\text{KMPW}}(q^2)$$

KMPW implies $s_i = 1$, but we vary $s_i = 0 \pm 1$, $i = 0, \perp, \|$.

$$\delta C_9^{\text{LD},(\perp,\|)}(q^2) = \frac{a^{(\perp,\|)} + b^{(\perp,\|)} q^2 [c^{(\perp,\|)} - q^2]}{b^{(\perp,\|)} q^2 [c^{(\perp,\|)} - q^2]}$$

$$\delta C_9^{\text{LD},0}(q^2) = \frac{a^0 + b^0 [q^2 + s_0][c^0 - q^2]}{b^0 [q^2 + s_0][c^0 - q^2]}$$





Inputs

CKM matrix within a frequentist framework ($\simeq \chi^2$ minim.)
+ specific scheme for theory uncertainties (Rfit)

data = weak $\otimes$ QCD $\Longrightarrow$Need for hadronic inputs (mostly lattice)

$\lvert V_{ud}\rvert$	superallowed β decays	PRC91, 025501 (2015)
$\lvert V_{us}\rvert$	$K \to \pi\ell\nu$ (Flavianet)	$f_+(0) = 0.9681 \pm 0.0014 \pm 0.0022$
	$K \to \ell\nu, \tau \to K\nu_\tau$	$f_K = 155.2 \pm 0.2 \pm 0.6$ MeV
$\lvert V_{us}/V_{ud}\rvert$	$K \to \ell\nu/\pi \to \ell\nu, \tau \to K\nu_\tau/\tau \to \pi\nu_\tau$	$f_K/f_\pi = 1.1959 \pm 0.0010 \pm 0.0029$
ϵ_K	PDG	$\hat{B}_K = 0.7567 \pm 0.0021 \pm 0.0123$
$\lvert V_{ub}\rvert$	inclusive and exclusive	(see later)
$\lvert V_{cb}\rvert$	inclusive and exclusive	(see later)
Δm_d	last WA B_d-$\bar{B}_d$ mixing	$B_{B_s}/B_{B_d} = 1.007 \pm 0.014 \pm 0.014$
Δm_s	last WA B_s-$\bar{B}_s$ mixing	$B_{B_s} = 1.320 \pm 0.016 \pm 0.030$
β	last WA $J/\psi K^{(*)}$	
α	last WA $\pi\pi, \rho\pi, \rho\rho$	isospin
γ	last WA $B \to D^{(*)}K^{(*)}$	GLW/ADS/GGSZ
$B \to \tau\nu$	$(1.08 \pm 0.21) \cdot 10^{-4}$	$f_{B_s}/f_{B_d} = 1.205 \pm 0.003 \pm 0.006$
		$f_{B_s} = 225.1 \pm 1.5 \pm 2.0$ MeV

Can factorizable power corrections be an acceptable explanation?

NO. Two main reasons:

$$\mathbf{F^{full}(q^2)} = F^{soft}(\xi_\perp, \xi_\|) + \triangle F^{\alpha_s}(q^2) + \mathbf{\triangle F^{\Lambda}(q^2)} \qquad \triangle F^{\Lambda} = (a_F + \triangle a_F) + (b_F + \triangle b_F) q^2/m_B^2 + ...$$

$\boxed{1}$ **Scheme dependence**: choice of definition of SFF $\xi_{\perp,\|}$ in terms of full-FF.

ALERT: Observables are scheme independent only if all correlations (including correlations of $\triangle \mathbf{a_F}$...) are included.

Not including the later ones [Jaeger et.al. and DHMV] $\triangle F^{\rm PC} = F \times \mathcal{O}(\Lambda/m_B)$ require careful scheme choice:

$\rightarrow$ risk to inflate artificially the error in observables.

$\boxed{2}$ **Correlations** among observables via (a_F,...) power corrections. Require a global view.

Two methods:

- *Our I-QCDF using SFF+corrections+KMPW-FF* [Descotes-Genon, Hofer, Matias, Virto]
- *Full-FF + eom using BSZ-FF* [Bharucha, Straub, Zwicky]

radically different treatment of factorizable p.c. give SM-predictions for P_5' in very good agreement (1σ or smaller).

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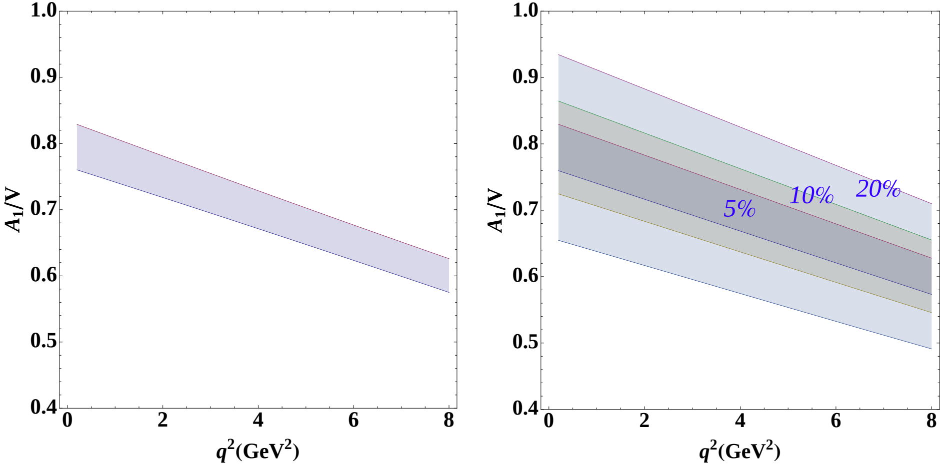
radically different treatment of factorizable p.c. give SM-predictions for P_5' in very good agreement (1σ or smaller).

Compare the ratio A_1/V (that controls P_5') computed using BSZ (including correlations) and computed with our approach for different size of power corrections.



Assigning a 5% error (we take 10%) to the power correction error reproduces the full error of the full-FF!!!

Let's illustrate now points 1 and 2 with two examples.

Scheme-dependence (illustrative example-I)

Model independent ⟵⟶ Full LCSR information

$\boxed{1}$

- ★ $\triangle F^{\rm PC} = F \times \mathcal{O}(\Lambda/m_B)$ $\sim F \times 10\%$
- ★ **correlations** from large-recoil sym. $\to \xi_{\perp,\parallel}, \triangle F^{\rm PC}$ uncorr.

$\boxed{2}$

- ★ $\triangle F^{\rm PC}$ from fit to LCSR
- ★ **correlations** from large-recoil sym. $\to \xi_{\perp,\parallel}, \triangle F^{\rm PC}$ uncorr.

$\boxed{3}$

- ★ $\triangle F^{\rm PC}$from fit to LCSR
- ★ **correlations** from LCSR $\to \xi_{\perp,\parallel}, \triangle F^{\rm PC}$ corr.

$P_5'[4.0, 6.0]$	scheme 1 [CDHM]	scheme 2 [JC]
$\boxed{1}$	$-0.72 \pm \mathbf{0.05}$	$-0.72 \pm \mathbf{0.12}$
$\boxed{2}$	-0.72 ± 0.03	-0.72 ± 0.03
$\boxed{3}$	-0.72 ± 0.03	-0.72 ± 0.03
full BSZ	$-0.72 \pm \mathbf{0.03}$	

errors only from pc with BSZ form factors

[Capdevila, Descotes, Hofer, JM]

- [Bharucha, Straub, Zwicky] as example (correlation provided)
- scheme indep. restored if $\triangle F^{\rm PC}$ from fit to LCSR, with expected magnitude
- sensitivity to scheme can be understood analytically
- no uncontrolled large power corrections for $P_{5'}$

Correlations (illustrative example-II)

- How much I need to inflate the errors from factorizable p.c. to get 1-σ agreement with data for $P'_{5\,[4,6]}$ and $P_{1\,[4,6]}$ individually?

  $\star$ One needs near 40% p.c. for $P'_{5\,[4,6]}$ and 0% for $P_{1\,[4,6]}$.

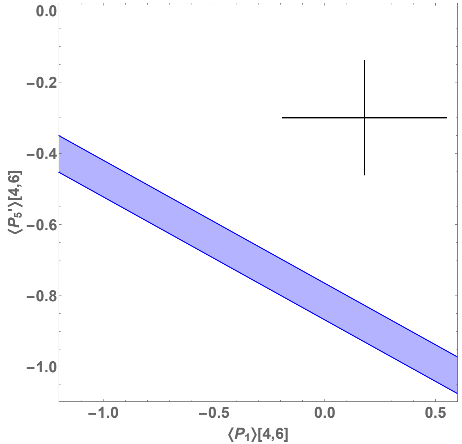
  $\star$ This would be in direct conflict with the two existing LCSR computations: KMPW and BSZ.

- But including the **strong correlation between p.c. of** $P'_{5\,[4,6]}$ **and** $P_{1\,[4,6]}$ **[CDHM] more than** 60% **(**$> 80\%$ **in bin [6,8]) is required!!!**

$$P'_5 = P'_5|_\infty \left(1 + \frac{2a_{V_-} - 2a_{T_-}}{\xi_\perp} \frac{C_7^{\rm eff}(C_{9,\perp}C_{9,\|} - C_{10}^2)}{(C_{9,\perp} + C_{9,\|})(C_{9,\perp}^2 + C_{10}^2)} \frac{m_b m_B}{q^2} \right.$$
$$\left. - \frac{\mathbf{2a_{V_+}}}{\xi_\perp} \frac{\mathbf{C_{9,\|}}}{\mathbf{C_{9,\perp} + C_{9,\|}}} + \ldots\right.$$

$$P_1 = -\frac{\mathbf{2a_{V_+}}}{\xi_\perp} \frac{\mathbf{(C_9^{\rm eff} C_{9,\perp} + C_{10}^2)}}{\mathbf{C_{9,\perp}^2 + C_{10}^2}} + \ldots$$

The leading term **in red** in P'_5 is missing in JC'14.



Factorizable power corrections

$$\mathbf{F^{full}(q^2)} = F^{soft}(\xi_\perp, \xi_\|) + \triangle F^{\alpha_s}(q^2) + \triangle \mathbf{F}^\Lambda(\mathbf{q^2}) \qquad \triangle F^\Lambda = (a_F + \triangle a_F) + (b_F + \triangle b_F) q^2/m_B^2 + ...$$

• [Our approach]: We determine p.c. from conservative KMPW-FF and assign an error of $\mathcal{O}(\Lambda/m_b) \times FF$. Correlations included from symmetries not from LCSR to be more conservative.

• [BSZ approach]: Full form factor using BSZ, power corrections included. Correlations from LCSR. Result with good agreement with us but smaller error.

[Jaeger-Camalich]: Emphatic claims of large errors obtained. Two fundamental points missing:

→ Error estimate sensitive to definition of SFF ($\xi_{\perp,\|}$) in terms of full FF (scheme dependence).
Bad choice of scheme in [JC] inflate error x4 or more if worst schemes are taken.

→ Correlations among observables:

$$P_5' = P_5'|_\infty \left(1 + \frac{2a_{V_-} - 2a_{T_-}}{\xi_\perp} \frac{C_7^{\rm eff}(C_{9,\perp}C_{9,\|} - C_{10}^2)}{(C_{9,\perp} + C_{9,\|})(C_{9,\perp}^2 + C_{10}^2)} \frac{m_b m_B}{q^2} - \frac{\mathbf{2a_{V_+}}}{\xi_\perp} \frac{\mathbf{C_{9,\|}}}{\mathbf{C_{9,\perp} + C_{9,\|}}} + ...\right.$$

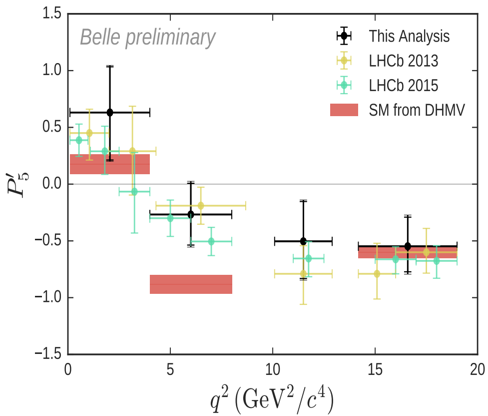
$$P_1 = -\frac{\mathbf{2a_{V_+}}}{\xi_\perp} \frac{(\mathbf{C_9^{\rm eff} C_{9,\perp} + C_{10}^2})}{\mathbf{C_{9,\perp}^2 + C_{10}^2}} + ...$$

Surprisingly the leading term in red in P_5' missing in [JC'14].

	All			LFUV		
2D Hyp.	Best fit	$\mathrm{Pull}_{\mathrm{SM}}$	p-value	Best fit	$\mathrm{Pull}_{\mathrm{SM}}$	p-value
$(\mathcal{C}_{9\mu}^{\mathrm{NP}}, \mathcal{C}_{10\mu}^{\mathrm{NP}})$	(-1.17,0.15)	5.5	74	(-1.13,0.40)	3.7	75
$(\mathcal{C}_{9\mu}^{\mathrm{NP}}, \mathcal{C}_{7}^{\prime})$	(-1.05,0.02)	5.5	73	(-1.75,-0.04)	3.6	66
$(\mathcal{C}_{9\mu}^{\mathrm{NP}}, \mathcal{C}_{9^\prime\mu})$	(-1.09,0.45)	5.6	75	(-2.11,0.83)	3.7	73
$(\mathcal{C}_{9\mu}^{\mathrm{NP}}, \mathcal{C}_{10^\prime\mu})$	(-1.10,-0.19)	5.6	76	(-2.43,-0.54)	3.9	85
$(\mathcal{C}_{9\mu}^{\mathrm{NP}}, \mathcal{C}_{9e}^{\mathrm{NP}})$	(-0.97,0.50)	5.4	72	(-1.09,0.66)	3.5	65
Hyp. 1	(-1.08,0.33)	5.6	77	(-1.74,0.53)	3.8	77
Hyp. 2	(-1.00, 0.15)	4.9	61	(-1.89,0.27)	3.1	39
Hyp. 3	(-0.65,-0.13)	4.9	61	(0.58,2.53)	3.7	73
Hyp. 4	(-0.65,0.21)	4.8	59	(-0.68,0.28)	3.7	72

Table: Most prominent patterns of New Physics in $b \to s\mu\mu$ with high significances. The last four rows corresponds to hypothesis 1: $(\mathcal{C}_{9\mu}^{\mathrm{NP}} = -\mathcal{C}_{9^\prime\mu}, \mathcal{C}_{10\mu}^{\mathrm{NP}} = \mathcal{C}_{10^\prime\mu})$, 2: $(\mathcal{C}_{9\mu}^{\mathrm{NP}} = -\mathcal{C}_{9^\prime\mu}, \mathcal{C}_{10\mu}^{\mathrm{NP}} = -\mathcal{C}_{10^\prime\mu})$, 3: $(\mathcal{C}_{9\mu}^{\mathrm{NP}} = -\mathcal{C}_{10\mu}^{\mathrm{NP}}, \mathcal{C}_{9^\prime\mu} = \mathcal{C}_{10^\prime\mu})$ and 4: $(\mathcal{C}_{9\mu}^{\mathrm{NP}} = -\mathcal{C}_{10\mu}^{\mathrm{NP}}, \mathcal{C}_{9^\prime\mu} = -\mathcal{C}_{10^\prime\mu})$. The "All" columns include all available data from LHCb, Belle, ATLAS and CMS, whereas the "LFUV" columns are restricted to R_K, R_{K^*} and $Q_{4,5}$ (see text for more detail). The p-values are quoted in % and $\mathrm{Pull}_{\mathrm{SM}}$ in units of standard deviation.

P'_5.... the most tested anomaly (Type-I)



P'_5 was proposed in **DMRV, JHEP 1301(2013)048**

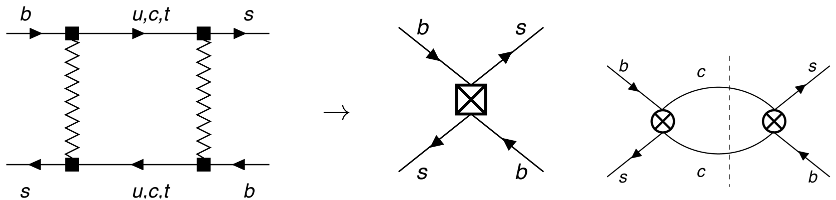
$$P'_5 = \sqrt{2}\,\frac{\mathrm{Re}(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*})}{\sqrt{|A_0|^2(|A_\perp|^2 + |A_{\|}|^2)}} = P_5^\infty\,(1 + \mathcal{O}(\alpha_s \xi_\perp) + \mathrm{p.c.})\ .$$

Optimized Obs.: Soft form factor ($\xi_\perp$) cancellation at LO.

- 2013: $1\mathrm{fb}^{-1}$ dataset LHCb found 3.7σ (yellow).
- 2015: $3\mathrm{fb}^{-1}$ dataset LHCb (**green**) found 3σ in 2 bins.
  $\Rightarrow$ Predictions (**in red**) from DHMV.
- Belle (**black)** confirmed it in a bin [4,8] few months ago.

$\Delta F = 2$: computation of the observables

Eff. Hamiltonian integrating out heavy W, Z, t



$$A_{\Delta B=2} = \langle \bar{B} | \mathcal{H}_{\text{eff}}^{\Delta B=2} | B \rangle - \frac{1}{2} \int d^4x d^4y \langle \bar{B} | T \mathcal{H}_{\text{eff}}^{\Delta B=1}(x) \mathcal{H}_{\text{eff}}^{\Delta B=1}(y) | B \rangle$$

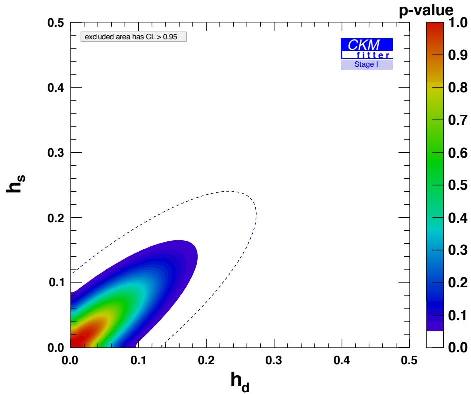
- M_{12}^q dominated by dispersive part of top boxes [Re[loops]]
  - related to heavy virtual states ($t\bar{t}\dots$)
  - easily affected by NP, e.g., if heavy new particles in the box
- Γ_{12}^q dominated by absorptive part of charm boxes [Im[loops]]
  - common B and $\bar{B}$ decay channels into final states with $c\bar{c}$ pair
  - affected by NP if changes in (constrained) tree-level decays

Model-independent parametrisation under the assumption that NP only changes modulus and phase of M_{12}^d and M_{12}^s A. Lenz, U. Nierste, CKMfitter

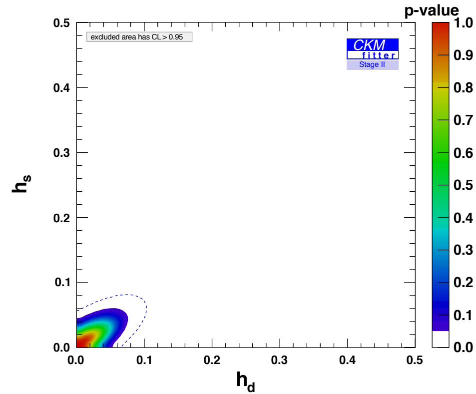
$$M_{12}^q = (M_{12}^q)_{SM} \times \Delta_q \qquad \Delta_q = |\Delta_q| e^{i\phi_q^\Delta} = (1 + h_q e^{2i\sigma_q})$$

Use Δm_d, Δm_s, β, ϕ_s, a_{SL}^d, a_{SL}^s, $\Delta\Gamma_s$ to constrain Δ_d and Δ_s

$\Delta F = 2$: bounds on energy scale



Stage I



Stage II

From $C_{ij}^2/\Lambda^2 \times (\bar{b}_L \gamma^\mu q_{j,L})^2$

$$h \simeq 1.5 \frac{|C_{ij}|^2}{|V_{ti} V_{tj}|^2} \frac{(4\pi)^2}{G_F \Lambda^2}$$

Couplings	NP loop order	Scales (in TeV) probed by B_d mixing	Scales (in TeV) probed by B_s mixing
$\lvert C_{ij}\rvert = \lvert V_{ti} V_{tj}^*\rvert$ (CKM-like)	tree level	17	19
	one loop	1.4	1.5
$\lvert C_{ij}\rvert = 1$ (no hierarchy)	tree level	2×10^3	5×10^2
	one loop	2×10^2	40