Status and expected progress of global fits

Luiz Vale Silva

University of Sussex

Apr 17th, 2018

Warwick, "*Towards the Ultimate Precision in Flavour Physics*"

Outline

Outline

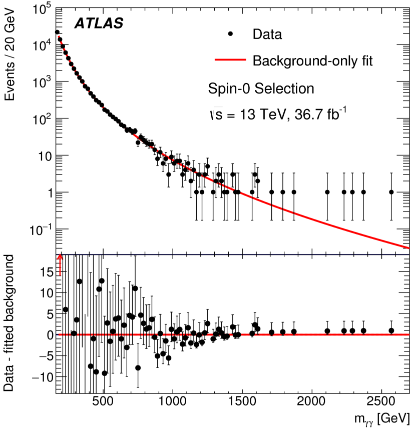
Towards the Ultimate Precision in Flavour Physics

- Precision (exp. & theo.): apart from improving SM, look for NP
- This decade has not been dominated by NP discoveries @ LHC, thus reinforcing the need to scrutinize low-energy obs. for NP

No significant diphoton excess

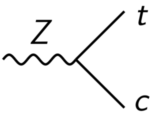
[ATLAS: Phys. Lett. B 775 (2017) 105-125]

[CMS: Phys. Lett. B 767 (2017) 147]

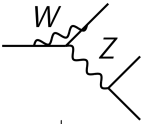


Why rare decays

- In the SM, first at one loop (*GIM mechanism*)
- Privileged way to look for NP manifestations, and shape its structure

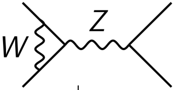


etc., not possible at tree



$+\dots$

e.g., $K \to \pi\nu\bar{\nu}$ CKM suppressed



$+\dots$

e.g., $B_{(s)} \to \ell^+\ell^-$ helicity suppressed

Less ideal: $s \to d\ell^+\ell^-$ and $c \to u\ell^+\ell^-$ transitions, etc.

Going beyond the SM

- Striking evidences of NP (requiring "less" theo. precision): e.g., LFN violating processes: $\mu \to e\gamma$, etc.
- Emerging deviations

Going beyond the SM

- Striking evidences of NP (requiring “less” theo. precision): e.g., LFN violating processes: $\mu \to e\gamma$, etc.
- Emerging deviations

HERE: rare B-decays, i.e., $b \to s(\gamma, \ell^+\ell^-)$ transitions

experimental side: [talks by Thomas Blake, Rafael S. Coutinho, Giampiero Mancinelli]
theoretical aspects: [this talk, and talks by Joaquim Matias, Marco Ciuchini, Patrick H. Owen]
pheno consequences: [talks by Dario Buttazzo, Gudrun Hiller, Diego Guadagnoli]

Outline

Theoretical description of exclusive decays

$$\langle(\gamma^{(*)}, \ell^+\ell^-)M_{(\lambda)}|\mathcal{H}_{\rm eff}|\bar{B}\rangle = \frac{G_F\alpha}{\sqrt{2}\pi} V_{tb}V_{ts}^*[(A_\nu + T_\nu)\bar{u}_\ell\gamma^\nu v_\ell + B_\nu \bar{u}_\ell\gamma^\nu\gamma_5 v_\ell],$$
$$M_{(\lambda)} = \bar{K}, \bar{K}^*_\lambda, \ldots, \; q^2_{\ell\ell} \equiv q^2$$

Short-distances (SD) above $\simeq m_b$, Long-distances (LD) below $\simeq m_b$

Theoretical description of exclusive decays

$$\langle (\gamma^{(*)}, \ell^+\ell^-) M_{(\lambda)} | \mathcal{H}_{\text{eff}} | \bar{B} \rangle = \frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* [(A_\nu + T_\nu) \bar{u}_\ell \gamma^\nu v_\ell + B_\nu \bar{u}_\ell \gamma^\nu \gamma_5 v_\ell],$$

$$M_{(\lambda)} = \bar{K}, \bar{K}^*_\lambda, \ldots, \; q^2_{\ell\ell} \equiv q^2$$

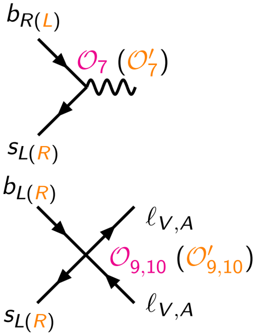
Short-distances (SD) above $\simeq m_b$, Long-distances (LD) below $\simeq m_b$

$$A_\nu = -\frac{2 m_b q^\rho}{q^2} C_7^{\text{eff}} \langle M_{(\lambda)} | \bar{s} \sigma_{\nu\rho} P_R b | \bar{B} \rangle + C_9 \langle M_{(\lambda)} | \bar{s} \gamma_\nu P_L b | \bar{B} \rangle$$

$$B_\nu = C_{10} \langle M_{(\lambda)} | \bar{s} \gamma_\nu P_L b | \bar{B} \rangle$$

Wilson coefficients: C_7, C_9, C_{10}, ...
known up to NNLO-QCD

[Huber+'05, Gambino+'03, Gorbahn+'04, Bobeth+'03, Misiak+'06]



Theoretical description of exclusive decays

$$\langle(\gamma^{(*)}, \ell^+\ell^-) M_{(\lambda)}|\mathcal{H}_{\rm eff}|\bar{B}\rangle = \frac{G_F\alpha}{\sqrt{2}\pi} V_{tb}V_{ts}^*[(A_\nu + T_\nu)\bar{u}_\ell\gamma^\nu v_\ell + B_\nu \bar{u}_\ell\gamma^\nu\gamma_5 v_\ell],$$

$$M_{(\lambda)} = \bar{K}, \bar{K}^*_\lambda, \ldots, \; q^2_{\ell\ell} \equiv q^2$$

Short-distances (SD) above $\simeq m_b$, Long-distances (LD) below $\simeq m_b$

	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$	$C_{S,P}^{(\prime)}$	$C_{T,T5}$
$B_s \to \ell^+\ell^-$			$\times$	$\times$	
$B \to X_s\gamma$, $B \to K^*\gamma$	$\times$				
$B \to X_s\,\ell^+\ell^-$, $B_{(s)} \to K^{(*)}(\phi)\,\ell^+\ell^-$	$\times$	$\times$	$\times$	$\times$	$\times$

Non-trivial test of the SM and a comprehensive look into NP

[Altmannshofer, Bobeth, Gambino, Gorbahn, Haisch, Hiller, Huber, Lunghi, Matias, Misiak, Steinhauser, Straub, Virto, ...]

Theoretical description of exclusive decays

$$\langle(\gamma^{(*)},\ell^+\ell^-)M_{(\lambda)}|\mathcal{H}_{\rm eff}|\bar{B}\rangle = \frac{G_F\alpha}{\sqrt{2}\pi}V_{tb}V_{ts}^*[(A_\nu + T_\nu)\bar{u}_\ell\gamma^\nu v_\ell + B_\nu \bar{u}_\ell\gamma^\nu\gamma_5 v_\ell],$$
$$M_{(\lambda)} = \bar{K}, \bar{K}^*_\lambda, \ldots,\ q^2_{\ell\ell} \equiv q^2$$

Short-distances (SD) above $\simeq m_b$, Long-distances (LD) below $\simeq m_b$

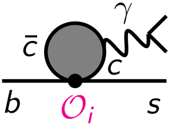
LD: includes *non-local* objects

$$T^\nu \propto \frac{1}{q^2}\int d^4x\, {\rm e}^{iqx}\langle M_{(\lambda)}|{\rm T}\{j^\nu_{\rm e.m.}(x)\mathcal{H}^{\rm had}_{\rm eff}(0)\}|\bar{B}\rangle$$

helicity (λ) and process dependent

cancels the μ dependence of $C_7^{\rm eff}(\mu)$, $C_9(\mu)$

[Beneke+'01,'04]



[talks by Quim, Marco and Patrick]

$$C^{tot}_{9,a}(q^2) = C_9^{SM,SD}(q^2) + C^{NP}_{9,\ell} + C^{SM,c\bar{c}}_{9,a}(q^2)\,,\ \ell = e,\mu,\tau\,,\ a = \perp, \|, 0$$

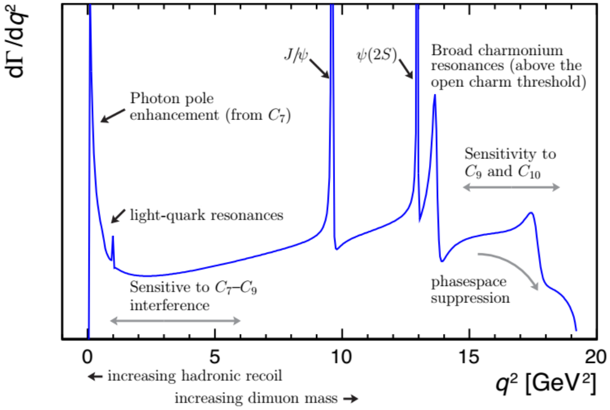
one must not interpret $C^{SM,c\bar{c}}_{9,a}(q^2)$ (i.e., T^ν) as a fake **LFU** $C^{NP}_{9,\ell}$

Theoretical inputs

- Look for sensitivity to SD: avoid J/ψ, $\psi(2S)$ resonances
- High- and low-q^2 rely on different formalisms/techniques for assessing LD effects (QCD factorization, lattice QCD, etc.)

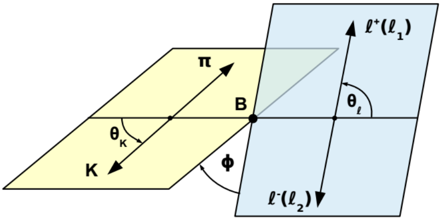
$$Br(B \to K^* \ell^+ \ell^-)$$
$$\text{vs. } q^2_{\ell\ell} \equiv q^2$$

[Charles+'99, Beneke+'00, Grinstein+'04, Beylich+'08, Lyon+'14, LHCb '16, Bobeth+'17, Blake+'17]



Observables in $B \to V\ell^+\ell^-$ decays

$B \to K^*[\to K\pi]\ell^+\ell^-$ decays: q^2 dependent angular observables



$$\frac{d^{(4)}\Gamma}{dq^2 d(\cos\theta_\ell) d(\cos\theta_K) d\phi} = \frac{9}{32\pi} \times$$

$$\Big(I_1^s \sin^2\theta_K + I_1^c \cos^2\theta_K + (I_2^s \sin^2\theta_K + I_2^c \cos^2\theta_K) \cos 2\theta_\ell + I_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi$$
$$+ I_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi + I_5 \sin 2\theta_K \sin\theta_\ell \cos\phi + (I_6^s \sin^2\theta_K + I_6^c \cos^2\theta_K) \cos\theta_\ell$$
$$+ I_7 \sin 2\theta_K \sin\theta_\ell \sin\phi + I_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + I_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \Big)$$

Angular observables

I: functions of the helicity amp. $H^{\lambda}_{V,A}$, $\lambda = 0, \pm$ (below, $m_\ell \to 0$)

$I_2^c = -\frac{F}{2}(|H_V^0|^2 + |H_A^0|^2)$ "longitudinal" rate F_L, Br

$I_2^s = \frac{F}{8}(|H_V^+|^2 + |H_V^-|^2) + (V \to A)$ "transverse" rate

$I_6^s = F\mathrm{Re}[H_V^-(H_A^-)^* - H_V^+(H_A^+)^*]$ lepton FB asym. A_{FB} or P_2

$I_4 = \frac{F}{4}\mathrm{Re}[(H_V^- + H_V^+)(H_V^0)^*] + (V \to A)$ $P'_{4,5}$

$I_5 = \frac{F}{2}\mathrm{Re}[(H_V^- - H_V^+)(H_A^0)^*] + (V \leftrightarrow A)$ [Descotes+'12,'13]

$I_3 = -\frac{F}{2}\mathrm{Re}[H_V^+(H_V^-)^*] + (V \to A)$ "wrong-helicity"

$I_9 = \frac{F}{2}\mathrm{Im}[H_V^+(H_V^-)^*] + (V \to A)$ (suppressed in SM)

$(F = \frac{\sqrt{\lambda} q^2}{3 \times 2^5 \pi^3 m_B^3} BF(K^* \to K\pi))$

Some representative observables

- HQE @ high-recoil: $\{V, A_{0,1,2}, T_{1,2,3}\}$ FFs $\to$ $\{\xi_\perp, \xi_\|\}$ FFs
- Improved sensitivity on FFs

$$\mathcal{B}r(B \to K^* \mu^+ \mu^-) = \mathcal{O}(\xi_\perp^2, \xi_\|^2)$$

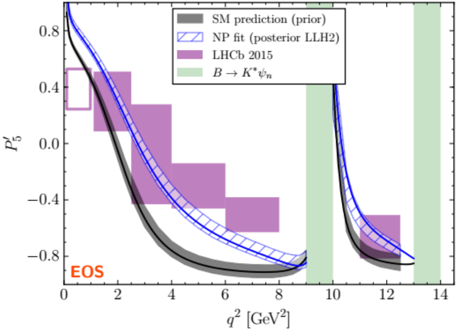
$$F_L, S_i = \mathcal{O}(\xi_\perp^2 / \xi_\|^2)$$

$$P_5' \equiv \frac{I_5}{\sqrt{-I_2^s I_2^c}}$$

$$P_5' = P_5'^{\infty}(1 + \mathcal{O}(\alpha_s \xi_\perp)) + \text{p.c.}$$

Further corrections in α_s and Λ_{QCD}/m_b (= p.c.)

[Jäger+'12,'14, Hurth+'15,'17, Capdevila+'17]



Analyticity of $h_\lambda (\propto T \cdot \varepsilon)$
Theo. model (LCSR) $q^2 \lesssim 0$
Exp. data below J/ψ

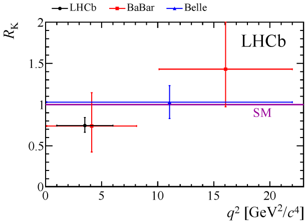
[Bobeth+'17; Blake+'17] [talk by Patrick]

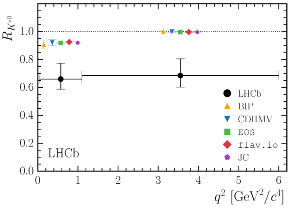
LFU violation testing observables

- SM: universal gauge couplings, small lepton masses (w.r.t. $\sqrt{q^2}$)

$$R_{K^{(*)}}[q_1^2, q_2^2] = \frac{\int_{q_1^2}^{q_2^2} dq^2 Br(B \to K^{(*)}\mu^+\mu^-)}{\int_{q_1^2}^{q_2^2} dq^2 Br(B \to K^{(*)}e^+e^-)} \stackrel{SM}{\simeq} 1$$

- In the SM, $R_{K^{(*)}}$ largely independent of unc. (for large q^2)
- (tiny) Correction induced by final-state photon radiation





Another promising observable $Q_i \equiv P'^{\mu}_i - P'^{e}_i$, $i = 4, 5$ [Belle '16]

Outline

Testing the SM and looking for NP

$\mathcal{H}_{\rm eff}$: shifts to C_7^ℓ, C_9^ℓ, C_{10}^ℓ, $C_7'^\ell$, $C_9'^\ell$, $C_{10}'^\ell$, etc.

(some) Available observables (LHCb, Belle, ATLAS, CMS)

- $B \to K^* \mu\mu$ ($P_{1,2}$, $P'_{4,5,6,8}$, F_L, Br), also R_{K^*}, $Q_{4,5}$
- $B_s \to \phi\mu\mu$ (P_1, $P'_{4,6}$, F_L)
- $B^+ \to K^+\mu\mu$, $B^0 \to K^0\ell\ell$ (Br), $\ell = e, \mu$: R_K
- $B \to X_s\gamma$, $B \to X_s\mu\mu$ (Br); $B_s \to \mu\mu$ (Br)
- $B^0 \to K^{*0}\gamma$ (A_I, $S_{K^*\gamma}$), $B^+ \to K^{*+}\gamma$, $B_s \to \phi\gamma$

Different groups

$\neq$ statistical approaches (frequentist, Bayesian, etc.),

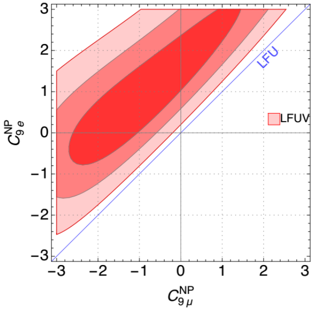
$\neq$ angular observables (e.g., P_i vs. S_i), [cf. Hurth+'17]

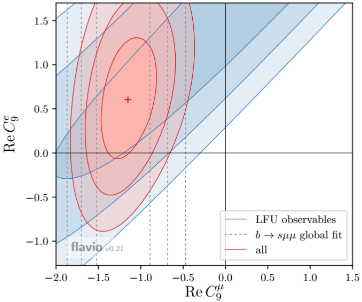
$\neq$ form factor inputs ([LCSR, low-q^2: Khodjamirian+'10] vs. [fit LCSR + lattice: Bharucha+'16]),

$\neq$ treatment of had. effects ([Khodjamirian+'10], $h_\lambda(q^2) \simeq h_\lambda^{(0)} + \frac{q^2}{(1\,\mathrm{GeV})^2} h_\lambda^{(1)} + \ldots$)

LFU violating data

- $R^{exp}_{K^{(*)}}$ substantially below $R^{\rm SM}_{K^{(*)}} \simeq 1$
- Extend the SM and fit for $\delta C_9^e \neq \delta C_9^\mu$
- Tension with SM/LFU picture $\delta C_9^e = \delta C_9^\mu$ of $\sim 3\sigma$ (hypothesis testing)

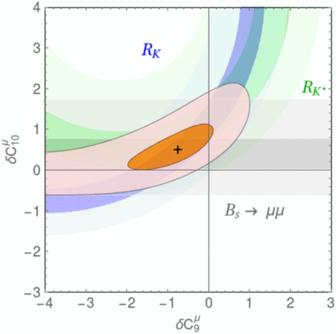




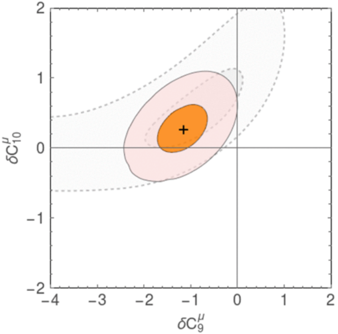
[Specific obs. in plots: Capdevila+'17, Altmannshofer+'17; see also Ciuchini+'17, D'Amico+'17, Geng+'17, Hiller+'17]

Full data set

- Add up $B_s \to \mu^+\mu^-$ (*'clean'*); add up ang. obs. (*'all'*)
- Test for NP effects in the μ sector,
  e.g., δC_9^μ vs. δC_{10}^μ $\to$ central values are $\sim$ 20% of the SM $C_{9,10}$
- Similar numerics for 1D fits; adding $C_9^{\prime\mu}$, etc. also possible



'clean': $\sim 4\sigma$



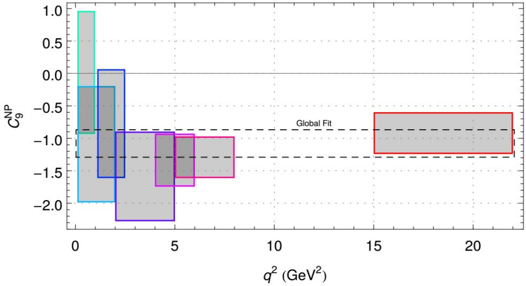
'all': $\gtrsim 4\sigma - 5\sigma$

[Specific obs. in plots: Geng+'17; see also Altmannshofer+'17, Capdevila+'17, Ciuchini+'17, D'Amico+'17]

Correlation of LFU NP and hadronic effects

$$C_{9,a}^{tot}(q^2) = C_9^{SM,SD}(q^2) + C_9^{NP} + C_{9,a}^{SM,c\bar{c}}(q^2)\,,\;\; a = \perp, \parallel, 0$$

- No clear indication of q^2 dependence, that would favor $C_{9,a}^{SM,c\bar{c}}$, thus allowing at the moment to interpret δC_9 as $C_9^{\rm NP}$
- Debate still open, but $C_{9,a}^{SM,c\bar{c}}$ cannot accommodate $R_{K^{(*)}}$

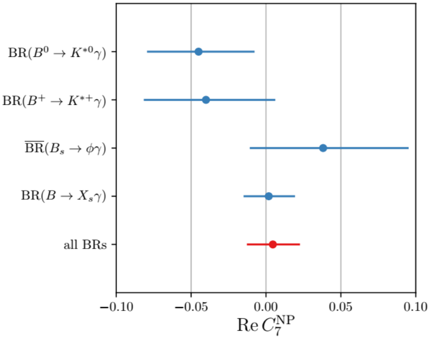


Only $b \to s\mu\mu$; [2, 5]: $\mathrm{Pull}_{SM} = 2.5$, [4, 6]: $\mathrm{Pull}_{SM} = 3.1$, [5, 8]: $\mathrm{Pull}_{SM} = 3.5$, etc.

[talks by Quim and Marco] [Plot from: Descotes-Genon+'16; see also: Ciuchini+'15,'16, Chobanova+'17]

Radiative decays

- Dipole operator: cannot fit $R_{K^{(*)}}^{exp}$
- C_7 vs. C_7' fit: offers complementary picture of possible NP
- Also, four-quark operators $b \to sc\bar{c}$ [Jäger+'17]



[Paul & Straub '16]

Close horizon

LHCb and Belle II

year		2012	2020	2024	2030
LHCb	$\mathcal{L}$ [fb^{-1}]	3	8	22	50
	n($b\bar{b}$)	0.3×10^{12}	1.1×10^{12}	37×10^{12}	87×10^{12}
	$\sqrt{s}$	7/8 TeV	13 TeV	14 TeV	14 TeV
Belle (II)	$\mathcal{L}$ [ab^{-1}]	0.7	5	50	-
	$n(B\bar{B})$	0.1×10^{10}	0.54×10^{10}	5.4×10^{10}	-
	$\sqrt{s}$	10.58 GeV	10.58 GeV	10.58 GeV	-

[Albrecht+'17 (and refs. therein)]

- **More data** on the already measured channels
- **New channels** (with different backgrounds) & **new observables** $\Rightarrow$ test the *consistency* of the LFUV picture

LHCb and Belle II - FCNC

[Albrecht+'17 (and refs. therein)]

Belle II

Observable	q^2 interval	Measurement $0.7\,\mathrm{ab}^{-1}$	Extrapolations $5\,\mathrm{ab}^{-1}$	$50\,\mathrm{ab}^{-1}$
$R(K)$	$1.0 < q^2 < 6.0\,\mathrm{GeV}^2$	-	11%	3.6%
$R(K)$	$q^2 > 14.4\,\mathrm{GeV}^2$	-	12%	3.6%
$R(K^*)$	$1.1 < q^2 < 6.0\,\mathrm{GeV}^2$	-	10%	3.2%
$R(K^*)$	$q^2 > 14.4\,\mathrm{GeV}^2$	-	9.2%	2.8%

LHCb

Observable	q^2 interval	Measurement $3\,\mathrm{fb}^{-1}$	Extrapolations $8\,\mathrm{fb}^{-1}$	$22\,\mathrm{fb}^{-1}$	$50\,\mathrm{fb}^{-1}$
$R(\phi)$	$1.0 < q^2 < 6.0\,\mathrm{GeV}^2$	-	0.159	0.086	0.056
$R(\phi)$	$15.0 < q^2 < 19.0\,\mathrm{GeV}^2$	-	0.137	0.074	0.048
$R(K)$	$1.0 < q^2 < 6.0\,\mathrm{GeV}^2$	$0.745^{+0.090}_{-0.074} \pm 0.036$ [17]	0.046	0.025	0.016
$R(K)$	$15.0 < q^2 < 22.0\,\mathrm{GeV}^2$	-	0.043	0.023	0.015
$R(K^*)$	$0.045 < q^2 < 1.1\,\mathrm{GeV}^2$	$0.66^{+0.11}_{-0.07} \pm 0.03$ [18]	0.048	0.026	0.017
$R(K^*)$	$1.1 < q^2 < 6.0\,\mathrm{GeV}^2$	$0.69^{+0.11}_{-0.07} \pm 0.05$ [18]	0.053	0.028	0.019
$R(K^*)$	$15.0 < q^2 < 19.0\,\mathrm{GeV}^2$	-	0.061	0.033	0.021

~ 2 % stat.

Combined Belle II and LHCb should be able to **establish** $\gg 5\sigma$ **in** $R_{K^{(*)}}$

LHCb and Belle II - FCNC

- LFU Violating obs. $P_5'^{\mu} - P_5'^{e}$ by LHCb, and Belle II
- $B_q \to \mu\mu$: e.g., discovery of $B_d \to \mu\mu$ by CMS (>2030)
- $b \to d\ell\ell$: e.g., $\frac{\mathcal{B}(B^+\to\pi^+\mu\mu)}{\mathcal{B}(B^+\to\pi^+ee)}$ by LHCb ($300\ \mathrm{fb}^{-1}$)
- $B_s^0 - \overline{B}_s^0$ mixing

[talks by Zoltan, Vincenzo]

Sensitivities of modes with $\nu\bar{\nu}$ in the final state

Observables	Belle $0.71\ \mathrm{ab}^{-1}$	Belle II $5\ \mathrm{ab}^{-1}$	Belle II $50\ \mathrm{ab}^{-1}$
$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$	$< 450\%$	30%	11%
$\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu})$	$< 180\%$	26%	9.6%
$\mathcal{B}(B^+ \to K^{*+}\nu\bar{\nu})$	$< 420\%$	25%	9.3%
$f_L(B^0 \to K^{*0}\nu\bar{\nu})$	–	–	0.079
$f_L(B^+ \to K^{*+}\nu\bar{\nu})$	–	–	0.077
$\mathcal{B}(B^0 \to \nu\bar{\nu}) \times 10^6$	< 14	< 5.0	< 1.5

B2TiP Report (in progress)

[τ's in the final state: talk by Giampiero]

Outline

Summary

- Laboratory for SM/QCD and NP
- Interesting/surprising *indications* of NP,
  tensions in $b \to c\ell\nu$ transitions at a similar level
- New techniques being implemented/improved
  to address long-distance effects
- Promising future with LHCb and Belle (II)

Thanks!

[Illustrative figures from Gratrex+'15, Blake+'16]

(and apologies for omissions in the references)

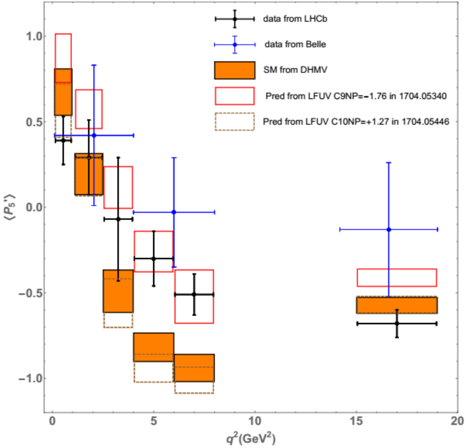
Consistency among experimental data

- Indirect information out of LFU violation agrees with full fit

→ Coherent picture of a large set of observables, of different categories

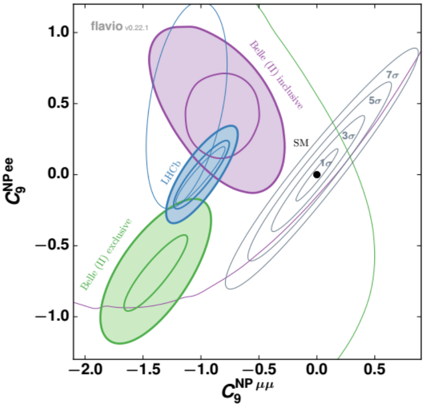
For **illustration** only:
Inputs: $R_{K^{(*)}}$, $Q_{4,5}$
$C_9^\mu = -1.76$ (red)
[$C_{10}^\mu = 1.27$ (brown),
C_{10}^e equiv. to SM (orange)]

[Matias '17]

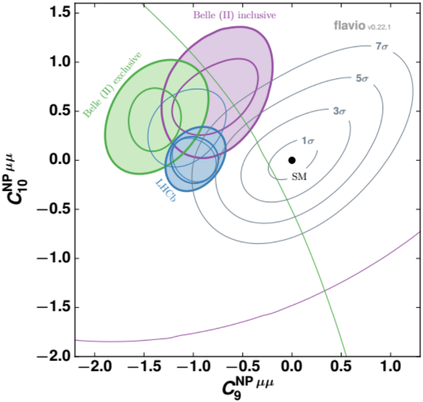


Prospects for the future - 1

[Albrecht+'17 (and refs. therein)]



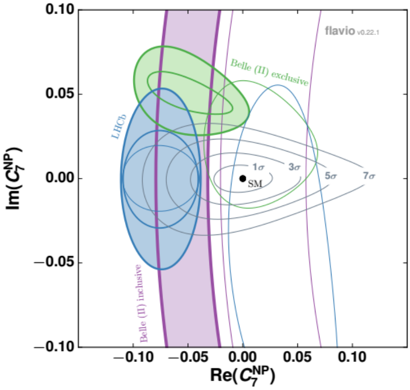
(b) $C_9^{\mathrm{NP}\,\mu\mu}$ versus $C_9^{\mathrm{NP}\,ee}$.



(a) $C_9^{\mathrm{NP}\,\mu\mu}$ versus $C_{10}^{\mathrm{NP}\,\mu\mu}$.

Prospects for the future - 2

[Albrecht+'17 (and refs. therein)]



(c) $\mathcal{R}e\left(C_7^{\mathrm{NP}}\right)$ versus $\mathcal{I}m\left(C_7^{\mathrm{NP}}\right)$.