Lepton Flavour Universality in hadron decays

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A few words on me

Where

- France, Paris, Orsay
- Laboratoire de Physique Théorique / Theoretical Physics Lab
- CNRS and Univ. Paris-Sud

What

- Theorist in flavour physics
- Strong: Nonperturbative QCD, Effective Field Theories
  Chiral Perturbation Theory, Heavy Quark Effective Theory…
- Electroweak: Determination of the CKM matrix
  CKMfitter collaboration: http://ckmfitter.in2p3.fr
- New Physics: Rare decays
  $b \to s\ell\ell$ (angular observables, global fits)

How

- To pronunce my name : [se-bas-ti-en] [de-co-te je-non]
- Hard for you ? also hard for the French…

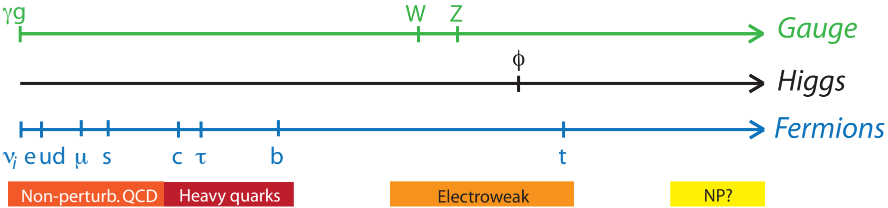
General ideas

Lepton flavour universality in hadron decays ?

- Theo: Both quarks and leptons involved
- Exp: Leptonic and semileptonic decays of hadrons
- Involve charged leptons
- Hints of non-universality among the generations of leptons
- Which might be connected with lepton flavour violation

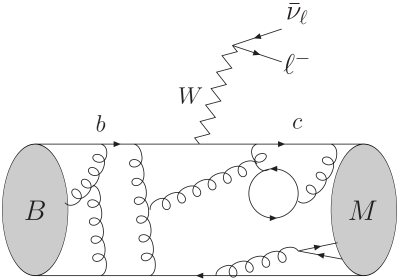
  at least in some NP models…

Lepton flavour universality in hadron decays ?



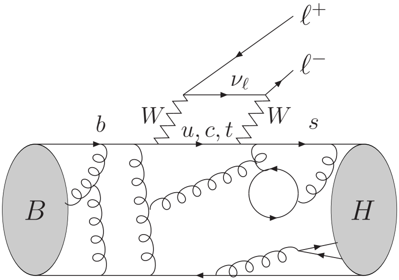
- Tough multi-scale challenge with 3 interactions intertwined
- GeV (QCD and m_q), 100 GeV (electroweak), 1 TeV or more (NP)
- All challenging, but main theo problem from hadronisation of quarks into hadrons (source of uncertainties)
- Hierarchy of scales $\Longrightarrow$notion of Effective Field Theory

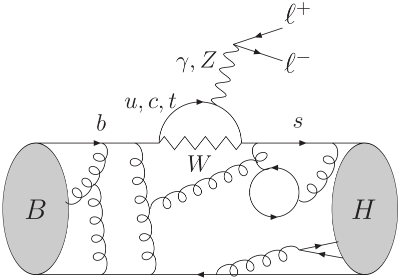
Flavour-Changing Charged Currents (FCCC)



- Changing quark flavour numbers by 1 unit
- Different electric charges for the two quarks
- Involve one charged and one neutral lepton
- Tree-level contribution in SM
- One power of the CKM matrix [V_{cb}]

Flavour-Changing Neutral Currents (FCNC)





- Changing quark flavour numbers by 1 unit
- Same electric charges for the two quarks
- Involve either two charged and two neutral leptons
- Loop-level contribution in SM
- Two powers of the CKM matrix $[V_{tb}V_{ts}^*]$

Back to SM

- Gauge group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$
- Broken spontaneously into $SU(3)_C \otimes U(1)_{em}$ by Higgs field ϕ
- Specific assignment of the fermion fields (here first generation)

	Fields	$SU(3)_C$	T_{3L}	Y	$Q = T_{3L} + Y$
L_L	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	**1**	1/2	-1/2	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$
e_R	e_R	**1**	0	-1	-1
ν_R	ν_R	**1**	0	0	0
Q_L	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}_L$	**3**	1/2	1/6	$\begin{pmatrix} 2/3 \\ -1/3 \end{pmatrix}$
u_R	u_R	**3**	0	2/3	2/3
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- Three identical generations with $i = 1, 2, 3$, with same gauge assignment, charges and couplings
- ν_R no interactions (needed only for neutrino masses)

Electroweak currents

Lagrangian for massless $\psi^{i=1,2,3} \in \{E_L, e_R, Q_L, u_R, d_R\}^i$
in terms of mass eigenstates for bosons

$$\mathcal{L}_{gauge,\psi} = \sum_{\psi,i} \bar{\psi}_i \not{D} \psi_i = \sum_{\psi,i} \bar{\psi} \not{\partial} \psi + g(W_\mu^+ J^\mu_{W^+} + W_\mu^- J^\mu_{W^-} + Z_\mu J^\mu_Z) + eA_\mu J^\mu_{em}$$

$$J^\mu_{W^+} = \frac{1}{\sqrt{2}}(\bar{\nu}^i_L \gamma^\mu e^i_L + \bar{u}^i_L \gamma^\mu d^i_L) \qquad J^\mu_{W^-} = \frac{1}{\sqrt{2}}(\bar{e}^i_L \gamma^\mu \nu^i_L + \bar{d}^i_L \gamma^\mu u^i_L)$$

$$J^\mu_Z = \frac{1}{c_W}\left\{\frac{1}{2}\bar{\nu}^i_L \gamma_\mu \nu^i_L + \left(s_W^2 - \frac{1}{2}\right)\bar{e}^i_L \gamma_\mu e^i_L + s_W^2 \bar{e}^i_R \gamma_\mu e^i_R\right.$$
$$\left. + \left(\frac{1}{2} - \frac{2}{3}s_W^2\right)\bar{u}^i_L \gamma^\mu u^i_L - \frac{2}{3}s_W^2 \bar{u}^i_R \gamma^\mu u^i_R + \left(\frac{1}{3}s_W^2 - \frac{1}{2}\right)\bar{d}^i_L \gamma^\mu d^i_L + \frac{1}{3}s_W^2 \bar{d}^i_R \gamma^\mu d^i_R\right\}$$

$$J^\mu_{em} = -\bar{e}^i \gamma^\mu e^i + \frac{2}{3}\bar{u}^i \gamma^\mu u^i - \frac{1}{3}\bar{d}^i \gamma^\mu d^i$$

- $c_W = g/\sqrt{g^2 + g'^2}, s_W = \sqrt{1 - c_W^2}$ weak mixing $(W^3_\mu, B_\mu) \leftrightarrow (Z^0_\mu, A_\mu)$
- charged-currents only left-handed $\psi_L = [(1 - \gamma_5)/2]\psi$
- neutral currents both left- and right-handed (and vector for photon)

From quark Yukawas to CKM

- Yukawa interaction between Higgs and (3 families of) quarks

$$\mathcal{L}_{Higgs,quarks} = \bar{Q}_L^i Y_D^{ik} d_R^k \phi + \bar{Q}_L^i Y_U^{ik} u_R^k \phi_c + h.c. + \ldots$$

- Higgs vacuum expectation value $\langle\phi\rangle \neq 0$ yields "mass" matrices

$$\mathcal{L}_{Higgs,quarks} = \bar{d}_L^i M_D^{ik} d_R^k + \bar{u}_L^i M_U^{ik} u_R^k + \ldots$$

- "Diagonalise" (SVD) the "mass" matrices $M_Q = Y_Q \langle\phi\rangle/\sqrt{2}$ with

$$M_Q = V_{QL} m_Q V_{QR}^\dagger \quad m_D = \mathrm{diag}(m_d, m_s, m_b), m_U = \mathrm{diag}(m_u, m_c, m_t)$$

- Mass eigenstates ψ' different from weak-interaction eigenstates ψ

$$u_L = \begin{pmatrix} u \\ c \\ t \end{pmatrix}_L = V_{UL} \begin{pmatrix} u' \\ c' \\ t' \end{pmatrix}_L \qquad d_L = \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L = V_{DL} \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_L$$

and same for right-handed states u_R and d_R with V_{UR} and V_{DR}

CKM for FCCC

- W bosons couple to charged currents J^μ_W for left-handed quarks
- Connect only quarks of the same generation in the weak basis
- Which in mass eigenstate basis involve unitary flavour matrix V

$$J^\mu_W = \bar{u}^i_L \gamma^\mu d^i_L \to \bar{u}'_L V^\dagger_{UL} \gamma^\mu V_{DL} d'_L = \bar{u}'_L V \gamma^\mu d'_L$$

- Potential misalignement between (unitary) rotations: $V_{UL} \neq V_{DL}$, so matrix $V = V^\dagger_{UL} V_{DL}$ is unitary but not identity

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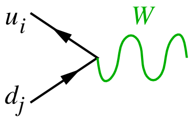
- Flavour-changing charged currents at tree level



$$\frac{g}{\sqrt{2}} [\bar{u}_L^i V_{ij} \gamma^\mu d_L^j W_\mu^+ + \bar{d}_L^j V_{ij}^* \gamma^\mu u_L^i W_\mu^-]$$

unitary Cabibbo-Kobayashi-Maskawa matrix

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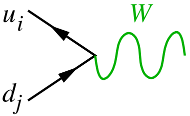

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unitary Cabibbo-Kobayashi-Maskawa matrix

- Hermitian lagrangian: V and V^* for CP-conjugates, so CP-violation for weak quark decays if V with imaginary part

No CKM for FCNC

- Z^μ and A^μ couple to neutral currents $J^\mu_{Z,A}$ involving both left- and right-handed quarks
- But connect only quarks of the same generation in weak basis
- Neutral currents remain flavour-diagonal in mass basis

$$\bar{u}^i_L \gamma^\mu u^i_L \to \bar{u}'_L V^\dagger_{UL} \gamma^\mu V_{UL} u'_L = \bar{u}'_L \gamma^\mu u'_L,$$
$$\bar{u}^i_R \gamma^\mu u^i_R \to \bar{u}'_R V^\dagger_{UR} \gamma^\mu V_{UR} u'_R = \bar{u}'_R \gamma^\mu u'_R$$

and same for d_L and for d_R separately

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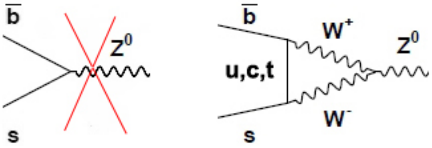
- No flavour-changing neutral currents in SM

…but absent only at tree level ! They can occur in loops



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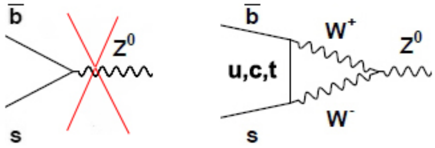

Q: Why are FCNC very small in the SM ? (several arguments)

Global quark flavour symmetries

Yukawas break very large flavour symmetry $U(3)_Q \otimes U(3)_U \otimes U(3)_D$ of the rest of the SM Lagrangian or equivalently

$$SU(3)_Q \otimes SU(3)_U \otimes SU(3)_D \otimes U(1)_B \otimes U(1)_{Yq} \otimes U(1)_{PQ}$$

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- $U(1)_{PQ}$ global phase redefinition for D_R only (Peccei-Quinn-like)
  $(d_R, s_R, b_R) \to e^{i\delta}(d_R, s_R, b_R)$ broken

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broken explicitly by Y_U and Y_D down to $U(1)_B$

$\Longrightarrow$conservation of baryon number

Number of physical parameters of the CKM matrix

CKM unitary matrix, but how many physical parameters ?

- $U(3)_Q \otimes U(3)_U \otimes U(3)_D \to U(1)_B$
  - $3 \times 3 \to 0$ real parameters
  - $3 \times 6 \to 1$ imaginary parameters

  triggered by $Y_{u,d}$ containing 2×9 real and 2×9 imaginary params
- So it remains in $Y_{u,d}$ as physical parameters
  - $2 \times 9 - (9 - 0)$ real parameters: 6 for quark masses and 3 for CKM
  - $2 \times 9 - (18 - 1)$ imaginary parameters: 1 for CKM

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For three generations, CKM with

- 3 moduli
- 1 phase, unique source of CP violation in quark sector

$\Longrightarrow$extremely predictive model for CP violation embedded in SM

Structure of CKM matrix

Cabibbo-Kobayashi-Maskawa matrix

$V = 1 + O(\lambda)$, close to unity

$$V = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \simeq \begin{bmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\bar{\rho} - i\bar{\eta}) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \bar{\rho} - i\bar{\eta}) & -A\lambda^2 & 1 \end{bmatrix} + O(\lambda^4)$$

where we have exploited the observed hierarchy of matrix elements, using the so-called Wolfenstein parametrisation

Q: For which processes is there an imaginary part (and thus CP-violation) ? Is it only for $b \to u$ and $t \to d$ transitions ?

And for leptons ?

- Yukawa interaction between Higgs and (3 families of) leptons

$$\mathcal{L}_{Higgs,leptons} = \bar{L}^i_L Y^{ik}_E e^k_R \phi + h.c. + \ldots$$

but in SM with no ν_R, there is only one type of term

- Higgs vacuum expectation value $\langle\phi\rangle \neq 0$ yields “mass” matrix

$$\mathcal{L}_{Higgs,leptons} = \bar{e}^i_L M^{ik}_E e^k_R + \ldots$$

- “Diagonalise” (SVD) the “mass” matrix $M_E = Y_E\langle\phi\rangle/\sqrt{2}$ with

$$M_E = V_{EL} m_E V^\dagger_{ER} \quad m_E = \mathrm{diag}(m_e, m_\mu, m_\tau)$$

- Mass eigenstates ψ' different from weak-interaction eigenstates ψ

$$e_L = \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix}_L = V_{eL} \begin{pmatrix} e' \\ \mu' \\ \tau' \end{pmatrix}_L$$

same for e_R, but also for ν if additional mechanism to provide m_ν

PMNS

- W bosons couple to charged currents J_W^μ for left-handed fermions
- Connect only leptons of the same generation in the weak basis
- Which in mass eigenstate basis involve unitary flavour matrix W

$$J_W^\mu = \bar{\nu}_L^i \gamma^\mu e_L^i \to \bar{\nu}_L' V_{\nu L}^\dagger \gamma^\mu V_{EL} e_L' = \bar{\nu}_L' W \gamma^\mu e_L'$$

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- In SM with $m_\nu = 0$, $V_{\nu L}$ can be arbitrarily chosen to get $W = 1$
- But in presence of m_ν, potential misalignement: $V_{\nu L} \neq V_{EL}$, so PMNS matrix $W = V^\dagger_{\nu L} V_{EL}$ is unitary but not identity

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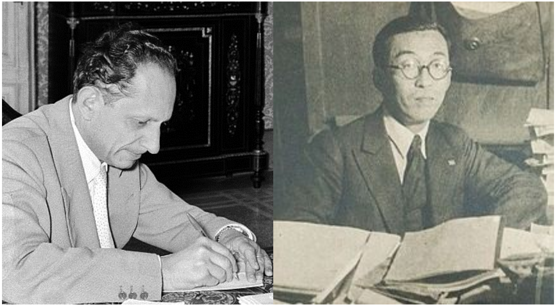

PMNS = Pontecorvo-Maki-Nakagawa-Sakata

(only P and S here)

Global lepton flavour symmetries

Y_E break large flavour symmetry $U(3)_L \otimes U(3)_E$ of the rest of the SM Lagrangian or equivalently

$$SU(3)_L \otimes SU(3)_E \otimes U(1)_L \otimes U(1)_{E-L}$$

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  $(e_R, \mu_R, \tau_R) \to e^{i\delta}(e_R, \mu_R, \tau_R)$
  $(L_{1L}, L_{2L}, L_{3L}) \to e^{-i\delta}(L_{1L}, L_{2L}, L_{3L})$ broken

Global lepton flavour symmetries

Y_E break large flavour symmetry $U(3)_L \otimes U(3)_E$ of the rest of the SM Lagrangian or equivalently

$$SU(3)_L \otimes SU(3)_E \otimes U(1)_L \otimes U(1)_{E-L}$$

- $SU(3)_{L,E}$ redefinition like $E_R = \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix}_R \to V_{ER}\, E_R \ldots$ broken
- $U(1)_L$ global phase redefinition associated with lepton number
  $\psi_{L,R} \to e^{i\alpha/3}\psi_{L,R} \qquad [\psi = e, \mu, \tau, \nu_1, \nu_2, \nu_3]$ not broken
- $U(1)_{E-L}$ global phase redefinition
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  $(L_{1L}, L_{2L}, L_{3L}) \to e^{-i\delta}(L_{1L}, L_{2L}, L_{3L})$ broken

broken to $U(1)_e \otimes U(1)_\mu \otimes U(1)_\tau$ (larger than for quarks)
$\Longrightarrow$conservation of lepton flavour number for each generation
(up to corrections coming from the mechanism to generate m_ν)

Lepton flavour universality and conservation

In the SM ($m_\nu = 0$), we have

- Lepton flavour universality (LFU): all gauge couplings are the same, diff among generations come only from Yukawa
- Lepton flavour conservation (LFC): only leptons from the same generation are involved in any interaction (vertex)

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New Physics

- LFU: NP couplings diagonal in flavour space or functions of Y_e (only source of breaking for $m_\nu = 0$)
- LFC: NP obey $U(1)_e \otimes U(1)_\mu \otimes U(1)_\tau$
- At low energies, SMEFT = SM lagrangian + higher-dim operators, for which LFU $\Longrightarrow$LFC, and thus LFV $\Longrightarrow$LFUV (not equivalence)

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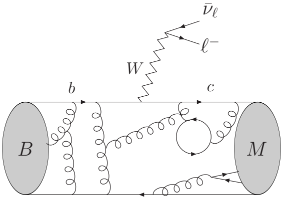
Q: Take a Z' coupling to 3 generations of lepton mass eigenstates

$$\alpha_{ij}(\bar{e}^i_L\gamma^\mu e^j_L + \bar{e}^i_R\gamma^\mu e^j_R)Z'_\mu$$

LFU/LFC if $\alpha_{ij} = \alpha\delta_{ij}$? $\alpha_{ij} = \alpha\delta_{i2}\delta_{j2}$? $\alpha_{ij} = \alpha\delta_{i2}\delta_{j3}$? $\alpha_{ij} = \delta_{ij} m_i/m'_Z$?

The last slide on PMNS



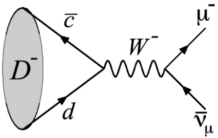
Let us look at a $b \to c\tau\nu_\tau$ process (leptonic or semileptonic decay)

- If $m_\nu = 0$, no PMNS, but what to do since $m_\nu \neq 0$?
- Actually $b \to c\tau\nu_i$ where i any of the three neutrino mass states since no experimental way of knowing the nature of ν mass state
  $$\Gamma \propto \sum_i |A(b \to c\tau\nu_i)|^2 = |V_{cb}|^2 \sum_i |V_{\tau i}|^2 |A_i|^2$$
- Assuming A_i independent of ν_i flavour and PMNS unitary
  $$\Gamma \propto |V_{cb}|^2 |A|^2 \sum_i |V_{\tau i}|^2 = |V_{cb}|^2 |A|^2 \times 1$$

So no contribution from PMNS matrix (incoherent sum of ν_i), only from CKM matrix (exclusive on quark flavours)

Lepton Flavour Universality in Flavour Changing Charged Currents

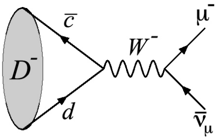
FCCC leptonic decays



$$\langle \mu^- \bar{\nu}_\mu | \mathcal{H}_{SM} | D^- \rangle \ ?$$

- Neglecting interactions between quark and lepton parts
- Write what is known perturbatively: lepton part in terms of sols of the free Dirac equation, propagation of the W
- But not what is not known: keep the quark/hadronic part

FCCC leptonic decays



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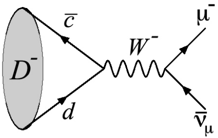
  $\langle \mu^- \bar{\nu}_\mu | \mathcal{H}_{SM} | D^- \rangle =$
  $-\frac{g_W^2}{2} \times \frac{-i}{p_D^2 - M_W^2} \times \bar{u}_{(\mu)} \gamma_\rho (1-\gamma_5) v_{(\nu)} \times g^{\rho\sigma} \times V_{cd} \langle 0 | \bar{c} \gamma_\sigma (1-\gamma_5) d | D^- \rangle$

FCCC leptonic decays



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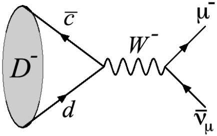
- We can parametrise the last term based on (Lorentz) symmetry
  $$\langle 0 | \bar{c} \gamma_\sigma (1-\gamma_5) d | D^- \rangle = \langle 0 | \bar{c} \gamma_\sigma (-\gamma_5) d | D^- \rangle = -i f_D (p_D)_\sigma$$
- f_D decay constant ($\simeq$ 210 MeV) to be computed using lattice QCD

Q: Why is only the axial part contributing ?

FCCC leptonic decays



$$\langle \mu^- \bar{\nu}_\mu | \mathcal{H}_{SM} | D^- \rangle \text{ ?}$$

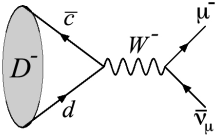
- One obtains the amplitude (where $G_F = g^2/(4/\sqrt{2}M_W^2)$)

$$\langle \mu^- \bar{\nu}_\mu | \mathcal{H}_{SM} | D^- \rangle = i \times 2\sqrt{2} G_F V_{cd} \times \bar{u}_{(\mu)} \gamma_\rho (1-\gamma_5) v_{(\nu)} \times f_D p^\rho$$

- Squaring the amplitude, one gets the branching ratio

$$Br(D^- \to \mu^- \bar{\nu}_\mu) = \frac{G_F^2 m_D m_\mu^2}{8\pi} \left(1 - \frac{m_\mu^2}{m_D^2}\right)^2 |V_{cd}|^2 f_D^2 \tau_D (1 + \delta_{em}^{D\mu 2})$$

FCCC leptonic decays



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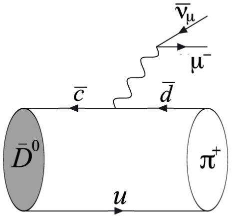
- Ratio of branching ratios for different leptons
  - No QCD uncertainties (decay constant cancel), no CKM
  - Lepton Flavour Universal up to phase space but also higher-order (QED) corrections (δ_{em})

FCCC semileptonic decays



$\langle \pi^+ \mu^- \bar{\nu}_\mu | \mathcal{H}_{SM} | \bar{D}^0 \rangle$?

- Same separation as for the leptonic decay: lepton part and W propagation easy to compute
- We parametrise the QCD matrix element

$$\langle \pi^+ | \bar{c} \gamma_\rho (1 - \gamma_5) d | \bar{D}^0 \rangle = \langle \pi^+ | \bar{c} \gamma_\rho d | \bar{D}^0 \rangle = f_+ (p_D + p_\pi)_\rho + (f_0 - f_+) \frac{M_D^2 - M_\pi^2}{q^2} q_\rho$$

where $q = p_D - p_\pi$ and f_+, f_0 are form factors, functions of q^2

Q: Why f_+ and f_0 depend on q^2 for semileptonic decays, whereas f_D was a constant for leptonic decays ?

Q: What would be the differences in the case of $D \to \rho$?

FCCC semileptonic decays

- Branching ratio $P \to P$ involving with 2 form factors f_+ and f_0

$$\frac{d\Gamma(\bar{D}^0 \to \pi^+ \mu^- \bar{\nu})}{dq^2} = \frac{G_F^2 |V_{cd}|^2}{24\pi^3} \frac{(q^2 - m_\mu^2)^2 \sqrt{E_\pi^2 - m_\pi^2}}{q^4 m_D^2}$$
$$\times \left[\left(1 + \frac{m_\mu^2}{2q^2}\right) m_D^2 (E_\pi^2 - m_\pi^2) |f_+(q^2)|^2 + \frac{3m_\mu^2}{8q^2} (m_D^2 - m_\pi^2)^2 |f_0(q^2)|^2 \right]$$

- Suppression for scalar form factor f_0 (proportional to m_μ^2)
- Ratio of branching ratios for different leptons not necessarily independent of hadronic uncertainties
  - Pseudoscalar to pseudoscalar, e and μ: approximate cancellation of form factors
  - Non-scalar hadrons, τ versus e and μ: requires knowledge of form factors (for instance using lattice QCD simulations)
- Harder to compute higher-order corrections (QED...)

A few tests for pions, kaons, charmed mesons

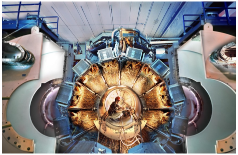
	SM pred	Exp
$\frac{\Gamma(\pi^-\to e^-\bar\nu)}{\Gamma(\pi^-\to\mu^-\bar\nu)}$	$(1.2352 \pm 0.0001)\cdot 10^{-4}$	$(1.230 \pm 0.004)\cdot 10^{-4}$
$\frac{\Gamma(K^-\to e^-\bar\nu)}{\Gamma(K^-\to\mu^-\bar\nu)}$	$(2.477 \pm 0.001)\cdot 10^{-5}$	$(2.488 \pm 0.009)\cdot 10^{-5}$
$\frac{\Gamma(D_s^-\to\tau^-\bar\nu)}{\Gamma(D_s^-\to\mu^-\bar\nu)}$	(9.76 ± 0.10)	(9.95 ± 0.61)

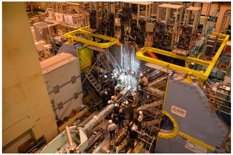
	SM pred	Exp
$\frac{\Gamma(D^0\to\pi^-\mu^+\nu)}{\Gamma(D^0\to\pi^-e^+\nu)}$	0.985 ± 0.002	0.922 ± 0.037
$\frac{\Gamma(D^+\to\pi^0\mu^+\nu)}{\Gamma(D^+\to\pi^0e^+\nu)}$	0.985 ± 0.002	0.964 ± 0.045

Other ratios measured, but no deep estimate of theo uncertainties

	Exp		Exp
$\frac{\Gamma(K^+\to\pi^0\mu^+\nu)}{\Gamma(K^+\to\pi^0e^+\nu)}$	0.6618 ± 0.0029	$\frac{\Gamma(D_s^+\to\phi\mu^+\nu)}{\Gamma(D_s^+\to\phi e^+\nu)}$	0.86 ± 0.29
$\frac{\Gamma(D_s^+\to\eta\mu^+\nu)}{\Gamma(D_s^+\to\eta e^+\nu)}$	1.05 ± 0.24	$\frac{\Gamma(D_s^+\to\eta'\mu^+\nu)}{\Gamma(D_s^+\to\eta' e^+\nu)}$	1.14 ± 0.68

And which tests for B mesons ?





- Leptonic:

	SM pred	Exp
$\frac{\Gamma(B^-\to\mu^-\bar\nu)}{\Gamma(B^-\to\tau^-\bar\nu)}$	$(4.45\pm 0.01)\cdot 10^{-3}$	$(5.92\pm 2.83)\cdot 10^{-3}$

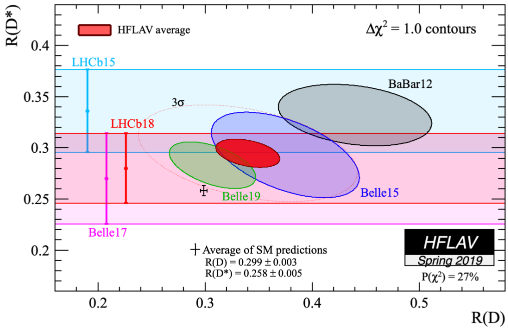
- Semileptonic:
  - For the comparison between e and μ, only $b\to c\ell\nu$, averaging naively results from Babar and Belle

	Exp		Exp
$\frac{\Gamma(B\to D\mu\nu)}{\Gamma(B\to De\nu)}$	0.98 ± 0.07	$\frac{\Gamma(B\to D^*\mu\nu)}{\Gamma(B\to D^*e\nu)}$	1.03 ± 0.05

both expected to be 1 up to a good accuracy

  - But we can also compare τ and lighter leptons. . .

LFU violation in $b \to c\tau\nu$



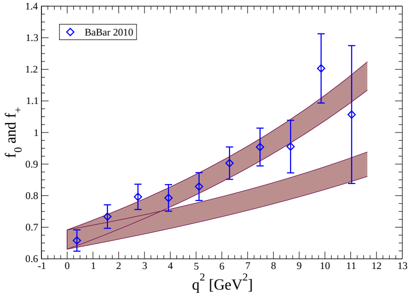
$$R_{D^{(*)}} = \frac{Br(B \to D(^*)\tau\nu)}{Br(B \to D(^*)\ell\bar{\nu}_\ell)}$$

- Update from Belle at Moriond 2019
- $R(D)$ and $R(D^*)$ exceed SM predictions by 1.4 σ and 2.5 σ
- difference with SM preds around 3.1σ level (used to be larger)
- consistent with 10% enhancement for $b \to c\tau\bar{\nu}_\tau$
- also a measurement of $R_{J/\psi}$ ($B_c \to J/\psi\ell\bar{\nu}_\ell$) going in the same direction but larger exp and theo unc

$B \to D\ell\bar{\nu}_\ell$ branching ratio

$$\frac{d\Gamma(B \to D\ell\bar{\nu}_\ell)}{dq^2} \propto |V_{cb}|^2 \left(1 - \frac{m_\ell^2}{q^2}\right)^2 |\vec{p}|^2 \left[\left(1 - \frac{m_\ell^2}{2q^2}\right)^2 M_B^2 |\vec{p}|^2 f_+^2(q^2) + \frac{3m_\ell^2}{8q^2}(M_B^2 + M_D^2)^2 f_0^2(q^2)\right]$$

- $\vec{p}$ D-momentum in B-frame, $q^2 = (p_B - p_D)^2$ lepton invariant mass



- Two form factors $f_+(q^2)$ (vector) and $f_0(q^2)$ (scalar)
  NP extension requires one more form factor f_T (tensor)
- From lattice QCD, extrapolated over whole kinematic range
- Used to compute R_D in the SM

$B \to D^* \ell \bar{\nu}_\ell$ branching ratio

$$\frac{d\Gamma(B \to D^* \ell \bar{\nu}_\ell)}{dq^2} \propto |V_{cb}|^2 \left(1 - \frac{m_\ell^2}{q^2}\right)^2 |\vec{q}| q^2 \left[\left(1 + \frac{m_\ell^2}{2q^2}\right)^2 (|H_+|^2 + |H_-|^2 + |H_0|^2) + \frac{3m_\ell^2}{2q^2}|H_t|^2\right]$$

- H_λ describing $B \to D^*(\to D\pi)\ell\bar{\nu}_\ell$ with λ helicity of $V^* \to \ell\bar{\nu}_\ell$
- Four form factors $V, A_{0.1,2}$ (vector and axial)

NP extension requires 3 more form factors $T_{1,2,3}$ (tensor)

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- No complete lattice determination, need other approaches
  - HQET: Form factors related in the limit $m_b, m_c \to \infty$,
    providing ratios of form factors up to $O(\Lambda/m)$ corrections
  - Fit to Belle differential decay rate $B \to D^*\ell\bar{\nu}_\ell$ ($\ell = e, \mu$)
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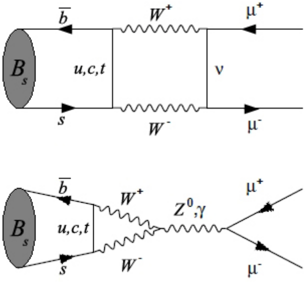
Q: What kind of information would be given by an angular analysis ?

Lepton Flavour Universality in Flavour Changing Neutral Currents

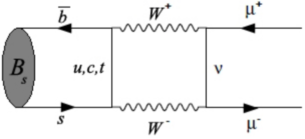
FCNC leptonic decays

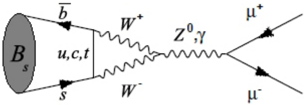


- Good example of FCNC : $B_s \to \mu\mu$
- More complicated (loop) decay
- Amplitude has a summation over internal quark flavour

$$\langle \mu\mu | \mathcal{H}_{SM} | \bar{B}_s \rangle \propto \sum_{q=u,c,t} V_{qb}^* V_{qs} A \left(\frac{m_q^2}{M_W^2} \right)$$

FCNC leptonic decays





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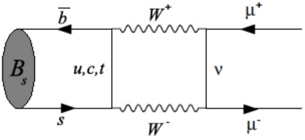
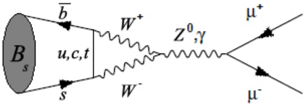
- It can be reexpressed using the CKM matrix unitarity

$$V_{tb}^* V_{ts}\left[A\left(\frac{m_t^2}{M_W^2}\right) - A\left(\frac{m_c^2}{M_W^2}\right)\right] + V_{ub}^* V_{us}\left[A\left(\frac{m_u^2}{M_W^2}\right) - A\left(\frac{m_c^2}{M_W^2}\right)\right]$$

FCNC leptonic decays





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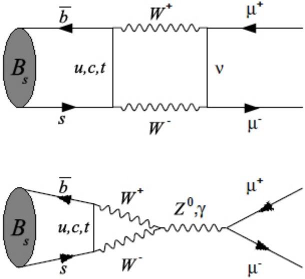
- m_q-independent part of A cancels in total, $m_u, m_c \ll M_W \sim m_t$ and CKM hierarchy $V^*_{tb} V_{ts} = O(\lambda^2) \gg V^*_{ub} V_{us} = O(\lambda^4)$
- Decay dominated by (m_t-dep part of) diagrams with top quark + other heavy degrees of freedom (W, Z)

FCNC leptonic decays



- Separation of scale explicit
  - short distances (W, t, Z diagrams computed perturbatively
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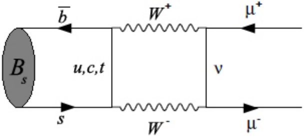
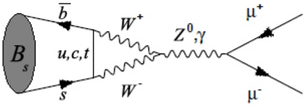
FCNC leptonic decays





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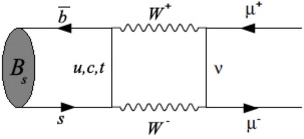

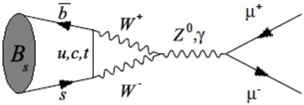

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Q: Check that argument for $B_d \to \mu\mu$. What about $D \to \mu\mu$, $K \to \mu\mu$?

FCNC semileptonic decays

- Same argument as for B_d and B_s leptonic decays ?
- Dimuon pair with inv mass q^2 varying from $4m_\mu^2$ to $(m_B - m_M)^2$
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  - $c\bar{c}$ can become real, and resonant for $q^2 = m^2_{J/\psi}, m^2_{\psi(2S)} \dots$
  - $u\bar{u}$ still CKM suppressed $V^*_{ub}V_{us} = O(\lambda^4) \ll V^*_{cb}V_{cs}, V^*_{tb}V_{ts} = O(\lambda^2)$
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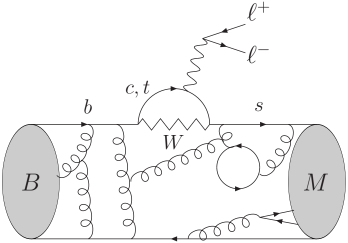

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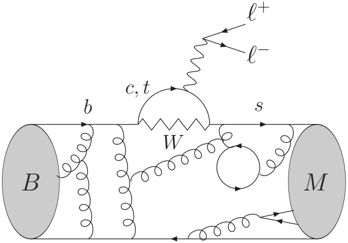

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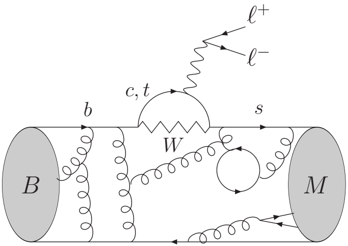

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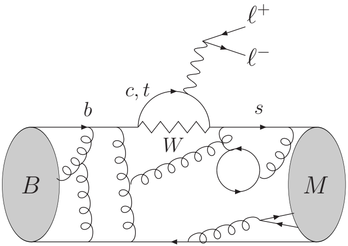

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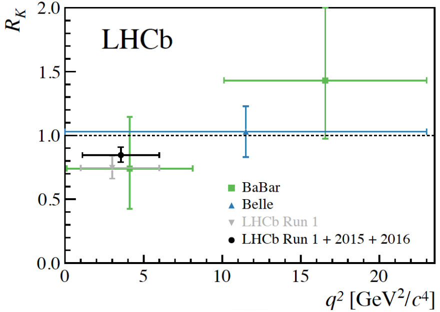
Q: Why were long-distance contributions not such an issue for FCCC ?

LFU violation in $b \to s\ell\ell$

Two updates@Moriond 2019



- LHCb:

$$R_K^{[1.1,6]} = \frac{Br(B \to K\mu\mu)}{Br(B \to Kee)}$$
$$= 0.846^{+0.060+0.016}_{-0.054-0.014}$$

- From 2.6σ to 2.5σ deviation wrt SM

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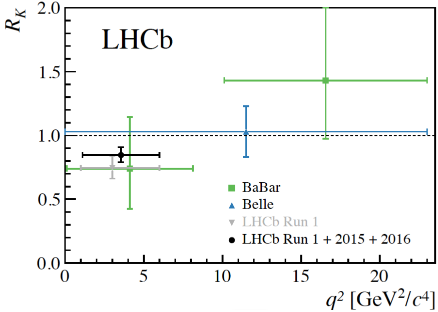

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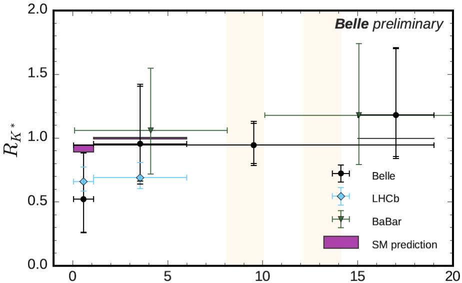
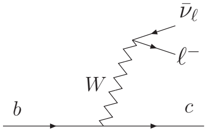
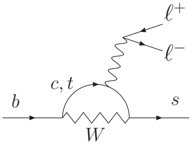
- From 2.6σ to 2.5σ deviation wrt SM

- Belle: $R_{K^*} = \dfrac{B(B \to K^*\mu\mu)}{B(B \to K^*ee)}$
- OK with SM, but also LHCb [2.3 (2.6) σ from SM for $R_{K^*}^{[0.045,1.1]}$ ($^{[1.1,6]}$)]



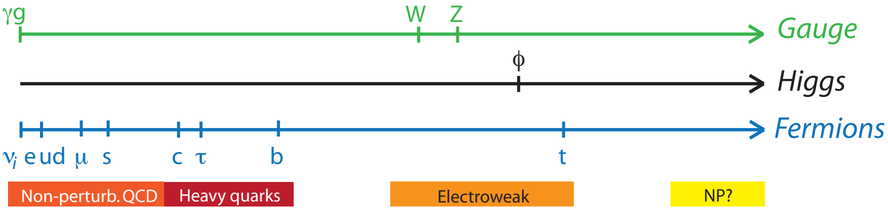
Looking for an explanation of LFUV

Two sets of “anomalies”

	$b \to c\ell\bar{\nu}_\ell$	$b \to s\ell^+\ell^-$
		
SM	tree (charged) $(V-A)$	loop (neutral)
Spin 0	$\overline{B} \to D\ell\bar{\nu}_\ell$	$B \to K\ell\ell$
Spin 1	$\overline{B} \to D^*\ell\bar{\nu}_\ell$	$B \to K^*\ell\ell$, $B_s \to \phi\ell\ell$
Observables	Total Br	$d\Gamma/dq^2$ + Angular obs
with	$\ell = \tau, \mu, e$	$\ell = \mu, e$
LFUV tensions	$R_{D(*)} = \dfrac{Br(B \to D(^*)\tau\nu)}{Br(B \to D(^*)\ell\bar{\nu}_\ell)}$	$R_{K(*)} = \dfrac{Br(B \to K(^*)\mu\mu)}{Br(B \to K(^*)ee)}$
Other tensions		$Br\ (K, K^*, \phi + \mu\mu)$ angular obs (e.g., P_5')

Two transitions exhibiting interesting patterns of deviations from SM with in particular lepton-flavour universality violation (LFUV)

A multi-scale problem



- Several steps to separate/factorise scales

simplified model	$\rightarrow$	SMEFT	$\rightarrow$	Weak EFT	$\rightarrow$	SCET/HQET
BSM	$\rightarrow$	SM+$1/\Lambda_{NP}$	$\rightarrow$	$\mathcal{H}_{eff}$	$\rightarrow$	B-hadron eff. th.
		$(\Lambda_{EW}/\Lambda_{NP})$		(m_b/Λ_{EW})		(Λ_{QCD}/m_b)

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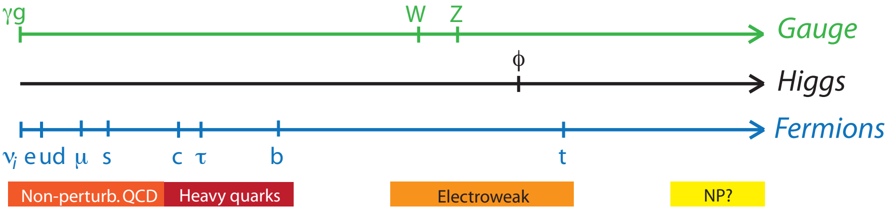

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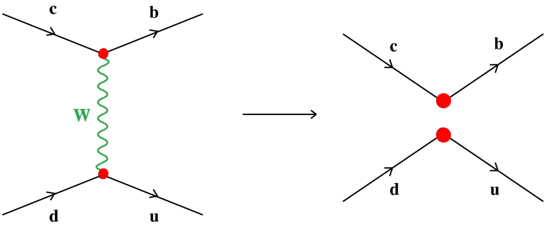
		$(\Lambda_{EW}/\Lambda_{NP})$		(m_b/Λ_{EW})		(Λ_{QCD}/m_b)

- Main theo problem from hadronisation of quarks into hadrons
  description/parametrisation in terms of QCD quantities
  decay constants, form factors, bag parameters...
- Long-distance non-perturbative QCD: source of uncertainties
  lattice QCD simulations, sum rules, effective theories...

Effective approaches

Fermi-like approach (for decoupling th): separation of different scales

Short dist/Wilson coefficients and Long dist/local operator



$$V_{ud} V_{cb}^* \frac{G_F}{\sqrt{2}} \frac{m_W^2}{m_W^2 - p_W^2} \; \bar{u}\gamma_\mu(1-\gamma_5)d\bar{b}\gamma^\mu(1-\gamma_5)c$$

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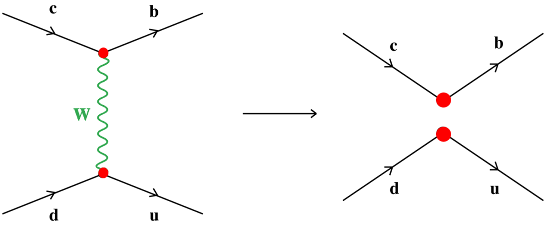


$$V_{ud} V_{cb}^* \frac{G_F}{\sqrt{2}} \bar{u}\gamma_\mu(1-\gamma_5)d\bar{b}\gamma^\mu(1-\gamma_5)c + O(1/M_W^2)$$

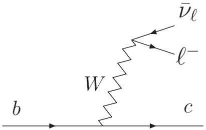
Fermi theory carries some info on the underlying theory

- G_F: scale of underlying physics ($\propto g^2/M_W^2$)
- $\mathcal{O}_i$: interaction with left-handed fermions, through charged spin 1
- Losing some info (gauge structure, Z^0 ...)
- But a good start to build models if no particle (=W) already seen

Effective Hamiltonian for B decays

From the SM (or an extension)
down to $\mu = m_b$

$$\mathcal{H}^{\text{eff}} = CKM \times \mathcal{C}_i \times \mathcal{O}_i$$
$$\langle M|\mathcal{H}^{\text{eff}}|B\rangle = CKM \times \mathcal{C}_i \times \langle M|\mathcal{O}_i|B\rangle$$



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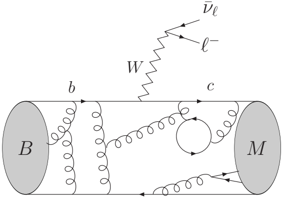

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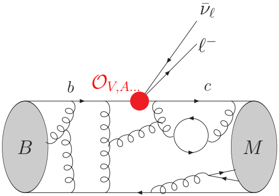

involving hadronic quantities such as form factors
selecting processes for accurate predictions:

- leptonic or semileptonic decays (decay constants, form factors)
- ratios of BRs with different leptons (LFU)
- ratios of observables with similar dependence on form factors

$\Longrightarrow$observables with limited sensitivity to (ratio of form) factors

Advantages of the effective Hamiltonian

Separation of scales (short vs long distances)

- Compute short-distance part $\mathcal{C}_i$ only once for given theory
- NP at a high scale will only shift the values of $\mathcal{C}_i$
- Describes all hadron decays with same quark-level process
  - Same short-distance physics, and thus same $\mathcal{C}_i$
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- fix $\mathcal{C}_i = \mathcal{C}_i^{\rm SM}$, compute SM and compare with the data
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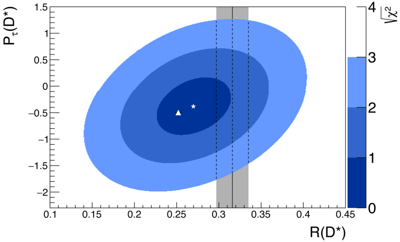
Model-independent determination of $\mathcal{C}_i$

- provide global framework to analyse all data including correlations
- check the consistency of the deviations without a theory bias
- can be followed by NP model building to reproduce $\mathcal{C}_i$

$b \to c\ell\bar{\nu}_\ell$: in addition to R_D, R_{D^*}



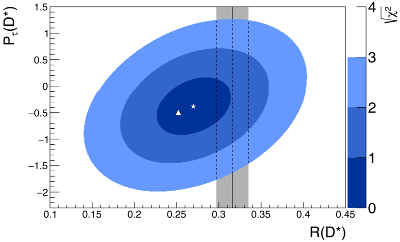
τ polarisation in $B \to D^*\tau\nu$

- Belle with $\tau \to X\nu$, $X = \rho$ (or π)

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{1}{2}\left[1 + \alpha_X P_\tau \cos\theta_\tau\right]$$

θ_τ angle $(\vec{p}_X, -\vec{p}_{\tau\nu})$

- Large stat unc, SM compatible, $P_\tau > 0.5$ excluded at 90% CL



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D^* **polarisation** in $B \to D^*\tau\nu$

- Angular analysis: $\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{3}{4}\left[2F_L\cos^2\theta_{D^*} + (1-F_L)\sin^2\theta_{D^*}\right]$
- Belle: $F_L = 0.60 \pm 0.08 \pm 0.04$, agree with SM at 1.7 σ

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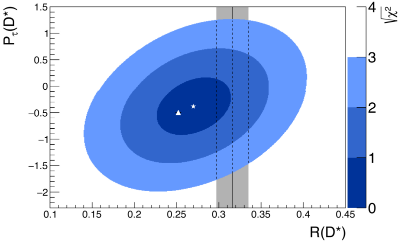

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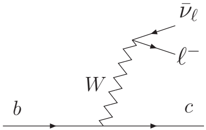
$R_{J/\psi}$ $(B_c \to J/\psi\ell\bar{\nu}_\ell)$

- LHCb: $R_{J/\psi} = 0.71 \pm 0.17 \pm 0.18$

$$\frac{R_D}{R_{D;SM}} \simeq \frac{R_{D^*}}{R_{D^*;SM}} \simeq \frac{R_{J/\psi}}{R_{J/\psi;SM}}$$

- Form factors based on models with uncertainties difficult to assess

$b \to c\ell\bar{\nu}_\ell$ effective Hamiltonian



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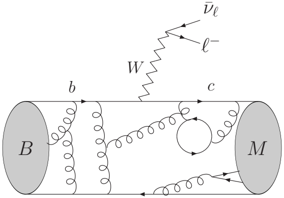

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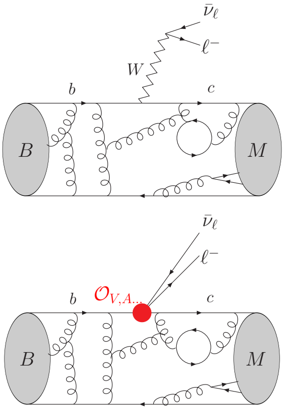

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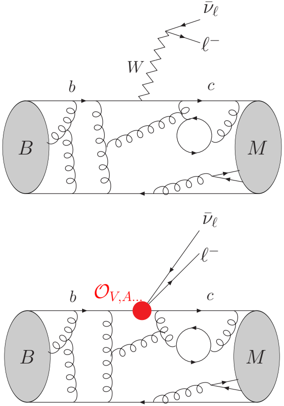

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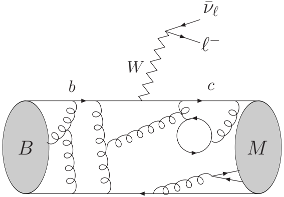
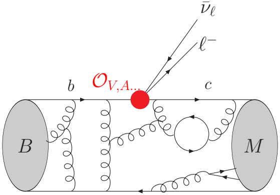
- Hadronic uncertainties in form factors defined from $\langle M|\mathcal{O}_i|B\rangle$ and already discussed previousl
- NP changes short-distance $\mathcal{C}_{i\ell}$ for SM or new long-distance ops $\mathcal{O}_{i\ell}$

- Chirally flipped ($W \to W_R$) $\mathcal{O}_{V_L\ell} \to \mathcal{O}_{V_R\ell} \propto (\bar{c}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu P_L \nu_\ell)$
- (Pseudo)scalar ($W \to H^+$) $\mathcal{O}_{V_L\ell} \to \mathcal{O}_{S_L} \propto (\bar{c}P_L b)(\bar{\ell}P_L \nu_\ell), \mathcal{O}_{S_R\ell}$
- Tensor operators ($W \to T$) $\mathcal{O}_{V_L\ell} \to \mathcal{O}_{T_L\ell} \propto (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\ell}\sigma_{\mu\nu} P_L \nu_\ell)$

$b \to c\ell\bar{\nu}_\ell$ effective Hamiltonian





$$\mathcal{H}^{\text{eff}}(b \to c\ell\nu) \propto G_F V_{cb} \sum \mathcal{C}_i \mathcal{O}_i$$

- In the SM
  - $\mathcal{O}_{V_L\ell} = (\bar{c}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu P_L \nu_\ell)$ [W exchange]
  - $\mathcal{C}_{V_L\ell} = 1$ and universal for all three leptons
- Hadronic uncertainties in form factors defined from $\langle M|\mathcal{O}_i|B\rangle$ and already discussed previousl
- NP changes short-distance $\mathcal{C}_{i\ell}$ for SM or new long-distance ops $\mathcal{O}_{i\ell}$

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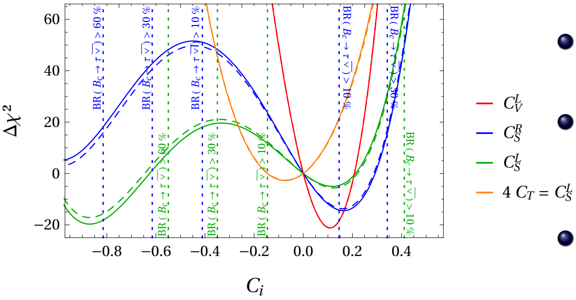
Q:Which relation between $\mathcal{C}_{V_L e}, \mathcal{C}_{V_L \mu}, \mathcal{C}_{V_L \tau}$ if LFU NP ? if LFC NP ?

Global fits for $b \to c\ell\bar{\nu}_\ell$

[Bhattacharyaa,Nandi,Patra;Alok,Kumar,Kumar,Kumbhakar,Uma Sankar;Kumar,London,Watanabe;Freytsis,Ligeti,Ruderman;
Greljo, Camalich, Ruiz-Alvarez. . .



[Blanke,Crivellin,de Boer,Moscati,Nierste, Nišandžić, Kitahara]

- Fits to R_D, R_{D^*}, $P_\tau(D^*)$, $F_L(D^*)$, sometimes $R_{J/\psi}$
- Often NP only in $\ell = \tau$, with real Wilson coeffs (no CP violation)
- Fit to one or two NP couplings at a time

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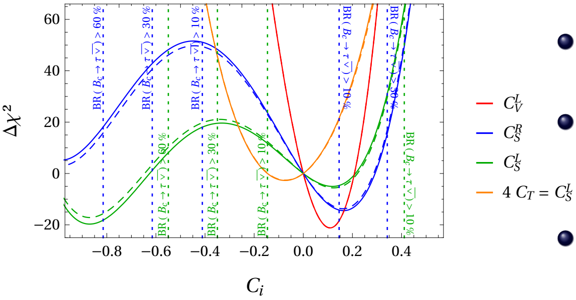

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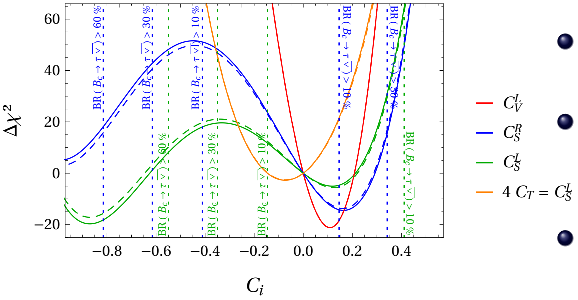
[Blanke,Crivellin,de Boer,Moscati,Nierste, Nišandžić, Kitahara]

- Right-handed and (pseudo)scalar couplings slightly disfavoured by B_c width and shape of $d\Gamma(B \to D^*\tau\nu)/dq^2$
- Tensor disfavoured by F_L, but often together with scalar in models, which can pass constraints
- Most simple explanation: NP in $\mathcal{C}_{V_L\tau}$ [change of G_F for $b \to c\tau\bar{\nu}_\tau$]

Global fits for $b \to c\ell\bar{\nu}_\ell$

[Bhattacharyaa,Nandi,Patra;Alok,Kumar,Kumar,Kumbhakar,Uma Sankar;Kumar,London,Watanabe;Freytsis,Ligeti,Ruderman; Greljo, Camalich, Ruiz-Alvarez. . .



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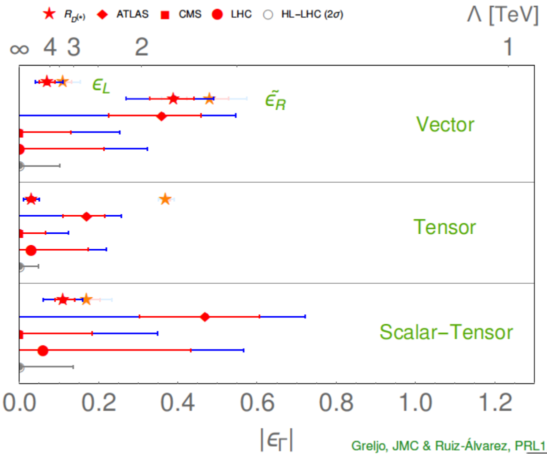
Q: Why is the B_c width a constraint here ?

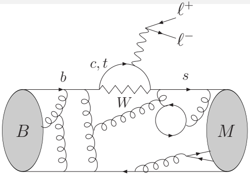
Global fits for $b \to c\ell\bar{\nu}_\ell$



Greljo, JMC & Ruiz-Álvarez, PRL122, 131803 (updated)

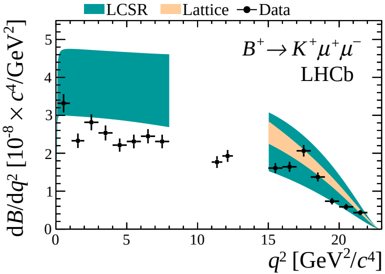
- LHC constraints from $pp \to \tau\nu X$
- Various explanations in terms of single mediators, but leptoquarks preferred over W' or charged Higgs

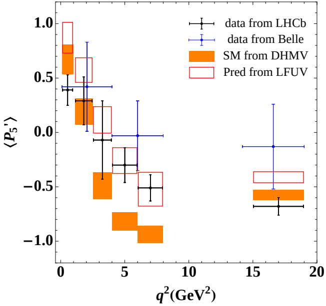
$b \to s\ell\ell$: In addition to R_K, R_{K^*}



- Many observables for $B \to K\mu\mu$, $B \to K^*\mu\mu$, $B_s \to \phi\mu\mu$
- 2-3σ deviations observed w.r.t. SM
  - BR for $B \to K\mu\mu$, $B \to K^*\mu\mu$, $B_s \to \phi\mu\mu$ (require knowledge of hadronic uncertainties)
  - Angular distr of $B \to K^*\mu\mu$ with optimised obs (eg P_5'), where part of hadronic uncertainties cancel
  - Hints of lepton flavour universality violation: $b \to see$ vs $b \to s\mu\mu$

[LHCb, Belle, ATLAS, CMS]





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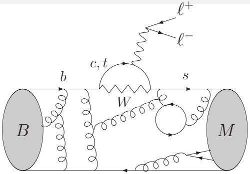

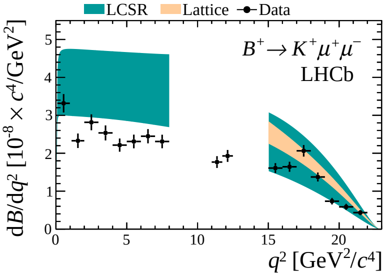

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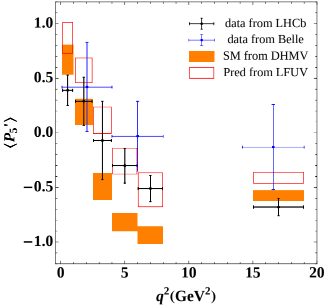
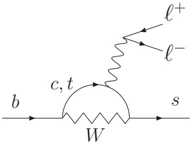


[LHCb, Belle, ATLAS, CMS]

Q: Why is there a missing band at intermediate q^2 ?

$b \to s\ell\ell$ effective Hamiltonian

$$\mathcal{H}(b \to s\gamma(^*)) \propto G_F V_{ts}^* V_{tb} \sim \mathcal{C}_i \mathcal{O}_i$$



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

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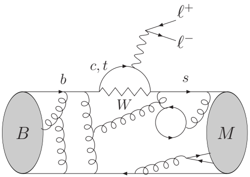

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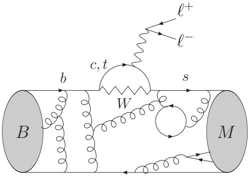

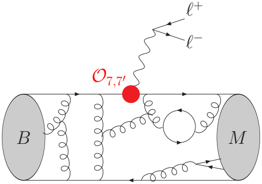

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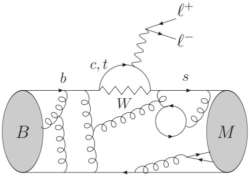
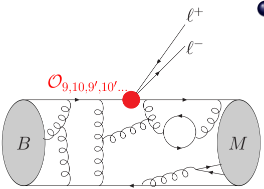
- $\mathcal{O}_7 = \frac{e}{g^2} m_b \bar{s}\sigma^{\mu\nu}(1+\gamma_5)F_{\mu\nu}\, b$ [real or soft photon]

$b \to s\ell\ell$ effective Hamiltonian





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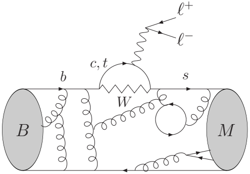
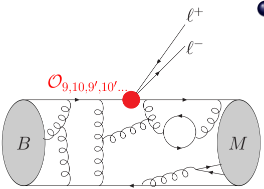
- $\mathcal{O}_{10\ell} = \frac{e^2}{g^2}\bar{s}\gamma_\mu(1-\gamma_5)b\ \bar{\ell}\gamma^\mu\gamma_5\ell$ [$b \to s\mu\mu$ via Z]

$b \to s\ell\ell$ effective Hamiltonian

$$\mathcal{H}(b \to s\gamma(^*)) \propto G_F V_{ts}^* V_{tb} \sim \mathcal{C}_i \mathcal{O}_i$$





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$$\mathcal{C}_7^{\rm SM} = -0.29, \; \mathcal{C}_{9\ell}^{\rm SM} = 4.1, \; \mathcal{C}_{10\ell}^{\rm SM} = -4.3$$

universal for all 3 lepton flavours

$b \to s\ell\ell$ effective Hamiltonian

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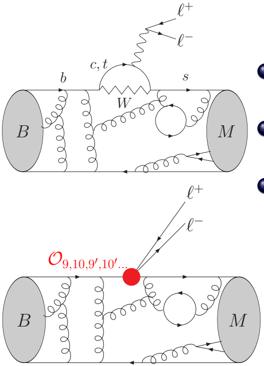

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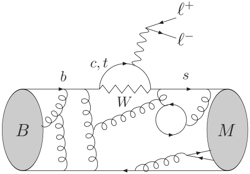
universal for all 3 lepton flavours

NP changes short-distance $\mathcal{C}_i$ or add new operators $\mathcal{O}_i$

- Chirally flipped ($W \to W_R$) $\quad \mathcal{O}_7 \to \mathcal{O}_{7'} \propto \bar{s}\sigma^{\mu\nu}(1-\gamma_5)F_{\mu\nu}\, b$
- (Pseudo)scalar ($W \to H^+$) $\quad \mathcal{O}_9, \mathcal{O}_{10} \to \mathcal{O}_S \propto \bar{s}(1+\gamma_5)b\bar{\ell}\ell, \mathcal{O}_P$
- Tensor operators ($\gamma \to T$) $\quad \mathcal{O}_9 \to \mathcal{O}_T \propto \bar{s}\sigma_{\mu\nu}(1-\gamma_5)b\;\bar{\ell}\sigma_{\mu\nu}\ell$

Two sources of hadronic uncertainties

$$A(B \to M\ell\ell) = \frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* [(A_\mu + T_\mu)\bar{u}_\ell \gamma^\mu v_\ell + B_\mu \bar{u}_\ell \gamma^\mu \gamma_5 v_\ell]$$



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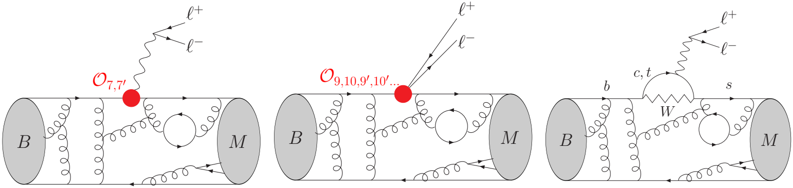

Form factors (local)

- Local contributions (more terms if NP in non-SM $\mathcal{C}_i$): form factors

$$A_\mu = -\frac{2m_b q^\nu}{q^2} \mathcal{C}_7 \langle M|\bar{s}\sigma_{\mu\nu} P_R b|B\rangle + \mathcal{C}_9 \langle M|\bar{s}\gamma_\mu P_L b|B\rangle$$

$$B_\mu = \mathcal{C}_{10} \langle M|\bar{s}\gamma_\mu P_L b|B\rangle$$

Two sources of hadronic uncertainties

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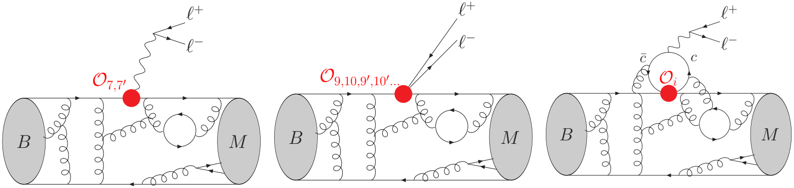

Form factors (local) Charm loop (non-local)

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$$B_\mu = \mathcal{C}_{10} \langle M|\bar{s}\gamma_\mu P_L b|B\rangle$$

- Non-local contributions (charm loops): hadronic contribs.

T_μ contributes like $\mathcal{O}_{7,9}$, depends on q^2 and hadrons

Two sources of hadronic uncertainties

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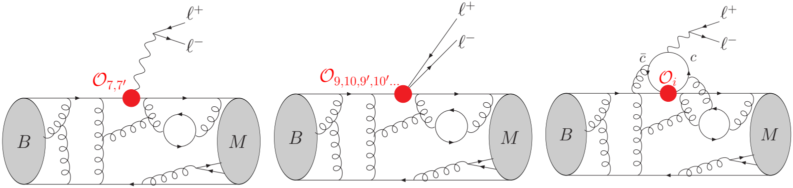

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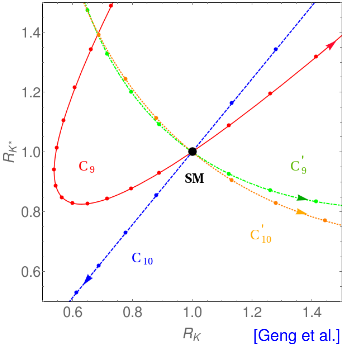
- Agreement about both contributions, using various theo tools

R_K and R_{K^*} in EFT

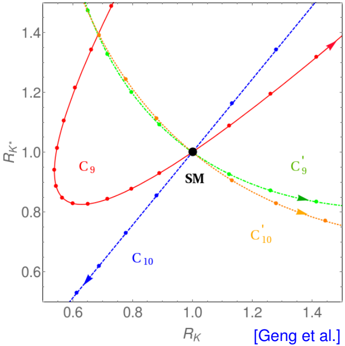


[Geng et al.]

- R_K: $Br(B \to K\ell\ell)$ involves one amplitude depending on
  - 3 $B \to K$ form factors (one suppr by m_ℓ^2/q^2, one by $\mathcal{C}_7$)
  - charmonium contributions (process-dependent but LFU)
  - $\mathcal{C}_9 + \mathcal{C}_{9'}$ and $\mathcal{C}_{10} + \mathcal{C}_{10'}$

$\Longrightarrow$hadronic contrib cancel for R_K, very accurate for all q^2 and $\mathcal{C}_i$

R_K and R_{K^*} in EFT



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  - $\mathcal{C}_9 + \mathcal{C}_{9'}$ and $\mathcal{C}_{10} + \mathcal{C}_{10'}$

  $\Longrightarrow$hadronic contrib cancel for R_K, very accurate for all q^2 and $\mathcal{C}_i$

- R_{K^*}: $Br(B \to K^*\ell\ell)$ involve several helicity ampl depending on
  - 7 $B \to K^*$ form factors (one suppressed by m_ℓ^2/q^2)
  - charmonium contributions (process-dependent but LFU)
  - depending on helicity amplitude: $\mathcal{C}_9 \pm \mathcal{C}_{9'}$ and $\mathcal{C}_{10} \pm \mathcal{C}_{10'}$

  $\Longrightarrow$hadronic contrib cancel for R_{K^*} in SM because right-handed helicities suppressed but less efficient with NP (slightly larger unc)

Global fits for $b \to s\ell\ell$

Many observables

[Alguero et al.; Aebischer et al; Alok et al.; Ciuchini et al; Arbey et al ...]

- $B \to K^*\mu\mu$, $B_s \to \phi\mu\mu$ (Br, ang.obs in several bins)
- $B \to K^*ee$ (ang obs in several bins)
- $B \to K\mu\mu$ (Br in several bins)
- $B_s \to \mu\mu$ (Br)
- $B \to X_s\gamma, B_s \to \phi\gamma, B \to K^*\gamma$ (Br)
- R_K, R_{K^*} (in several bins)

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- $B \to K^*\mu\mu$, $B_s \to \phi\mu\mu$ (Br, ang.obs in several bins)
- $B \to K^* ee$ (ang obs in several bins)
- $B \to K\mu\mu$ (Br in several bins)
- $B_s \to \mu\mu$ (Br)
- $B \to X_s\gamma, B_s \to \phi\gamma, B \to K^*\gamma$ (Br)
- R_K, R_{K^*} (in several bins)

Various computational approaches

- inclusive: OPE
- large meson recoil: QCD fact, Soft-collinear eff theory, sum rules
- low meson recoil: Heavy quark eff th, Quark-hadron duality, lattice

Global fits for $b \to s\ell\ell$

Many observables

[Alguero et al.; Aebischer et al; Alok et al.; Ciuchini et al; Arbey et al . . .]

- $B \to K^*\mu\mu$, $B_s \to \phi\mu\mu$ (Br, ang.obs in several bins)
- $B \to K^* ee$ (ang obs in several bins)
- $B \to K\mu\mu$ (Br in several bins)
- $B_s \to \mu\mu$ (Br)
- $B \to X_s\gamma, B_s \to \phi\gamma, B \to K^*\gamma$ (Br)
- R_K, R_{K^*} (in several bins)

Various computational approaches

- inclusive: OPE
- large meson recoil: QCD fact, Soft-collinear eff theory, sum rules
- low meson recoil: Heavy quark eff th, Quark-hadron duality, lattice

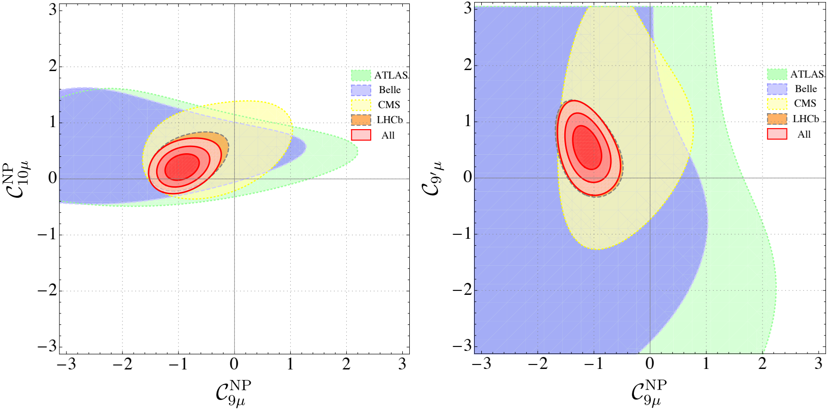
Global fit analysis

- $\mathcal{C}_i(\mu_{ref}) = \mathcal{C}_i^{SM} + \mathcal{C}_i^{NP}$, with $\mathcal{C}_i^{NP}$ assumed to be real (no CPV)
- Most of the discussion on

$$\mathcal{O}_9 \sim L_q \otimes V_\ell \quad \mathcal{O}_{10} \sim L_q \otimes A_\ell \quad \mathcal{O}_{9'} \sim R_q \otimes V_\ell \quad \mathcal{O}_{10'} \sim R_q \otimes A_\ell$$

Global fits for $b \to s\ell\ell$

[Algueró et al.]



Scenarios with good SM pulls (improvement of the fit wrt SM)

- $\mathcal{C}_{9\mu}^{\rm NP} \simeq -1$ + NP in other $\mathcal{C}_{i\mu}^{\rm NP}$,
- $(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_{10\mu}^{\rm NP})$: 5.9$\sigma$ (left-handed, SM-like)
- $(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_{9'\mu})$: 6.1$\sigma$ (right-handed currents)

Global fits for $b \to s\ell\ell$

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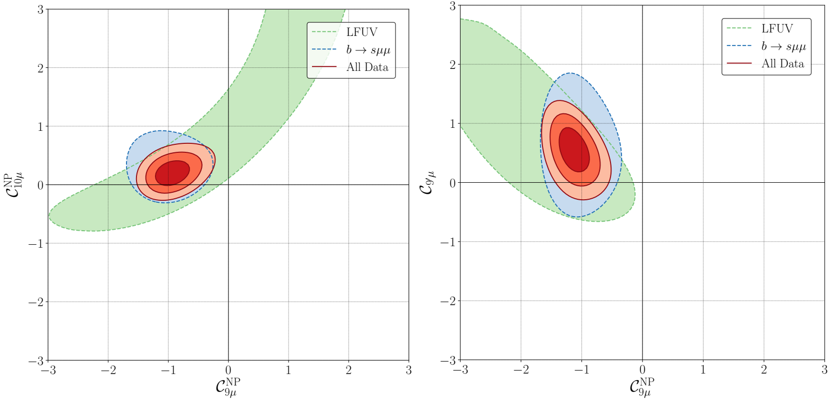
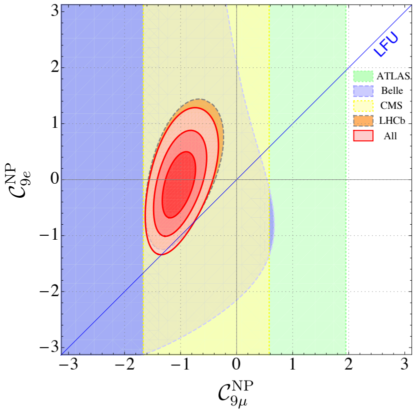
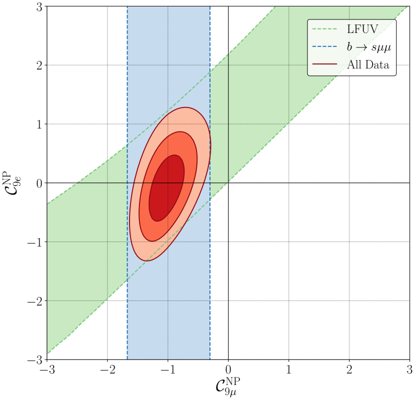


Separating 3 σ regions for $b \to s\mu\mu$ and purely LFUV

- R_K and R_{K^*} favours $\mathcal{C}^{\rm NP}_{10\mu} > 0$ and $\mathcal{C}^{\rm NP}_{9'\mu} > 0$
- $b \to s\mu\mu$ essentially in favour of $\mathcal{C}^{\rm NP}_{9\mu} < 0$

NP in both $b \to s\mu\mu$ and $b \to see$?





NP in $(\mathcal{C}_{9\mu}, \mathcal{C}_{9e})$

- Compatible with no NP in electrons
- But some room available
- improvement compared to SM (pull) 5.5 σ

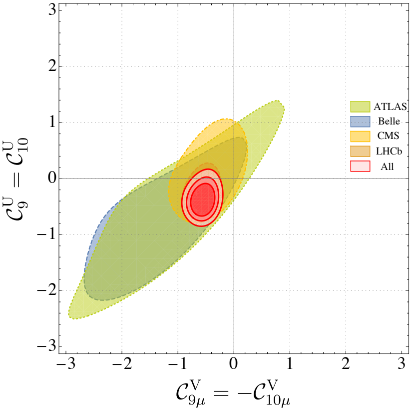
LFUV but also LFU NP ?

R_K and R_{K^*} support LFUV NP, but there could also be a LFU piece

$$\mathcal{C}_{ie} = \mathcal{C}_i^{\mathrm{U}} \qquad \mathcal{C}_{i\mu} = \mathcal{C}_i^{\mathrm{U}} + \mathcal{C}_{i\mu}^{\mathrm{V}}$$

[Algueró et al]

Favoured scenarios (SM pulls 5.8-5.9σ) with LF**U** and LFU**V** contribs



LFUV-NP $L_q \otimes L_\ell$, LFU-NP $L_q \otimes R_\ell$ — LFUV-NP $L_q \otimes L_\ell$, LFU-NP $L_q \otimes V_\ell$

Connecting the anomalies

From EFT to simplified models

EFT very efficient tool

- Separate hadronic long distance and EW/NP short distances
- Analyse all deviations without theoretical prejudice
- Extract a simple set of short-distance contributions for NP models

but with obvious drawbacks

- Requires a large set of observables for the same quark process
- Unable to connect with other sectors of the theory

Interest of simplified models

- Exchange of one or two mediators to explain EFT results
- Determine the consequences for other type of processes : 4 quarks or 4 leptons, other generations. . .
- Not necessarily a complete theory (requires further more massive particles), but already a hint of preferred models

A first EFT connection

Connect the two anomalies within SMEFT ($\Lambda_{NP} \gg m_{t,W,Z}$)

$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}_{d>4}$ with higher-dim ops involving only SM fields

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- Two operators with left-handed doublets (*ijkl* generation indices)

$$\mathcal{O}^{(1)}_{ijkl} = [\bar{Q}_i \gamma_\mu Q_j][\bar{L}_k \gamma^\mu L_l] \qquad \mathcal{O}^{(3)}_{ijkl} = [\bar{Q}_i \gamma_\mu \vec{\sigma} Q_j][\bar{L}_k \gamma^\mu \vec{\sigma} L_l]$$

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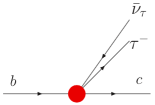
- FCCC part of $\mathcal{O}^{(3)}_{2333}$ can describe $R_{D^{(*)}}$ (rescaling of G_F)



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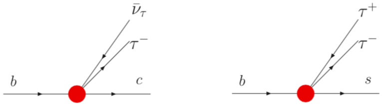

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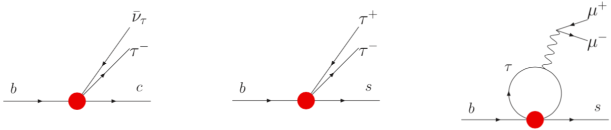

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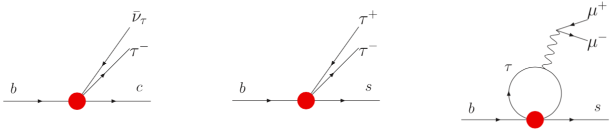


LFUV NP + radiative SM effects yield often (suppressed) LFU NP

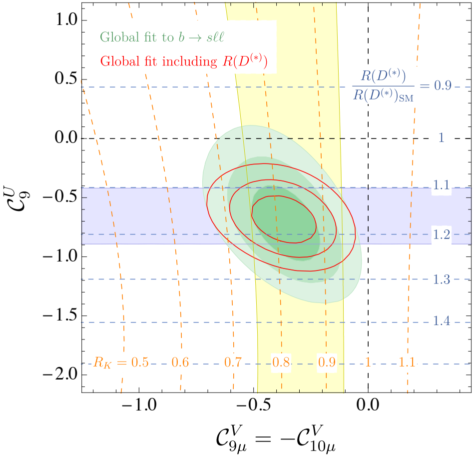
A first EFT connection

Scenario LFU + LFUV NP

- $\mathcal{C}^{\mathrm{V}}_{9\mu} = -\mathcal{C}^{\mathrm{V}}_{10\mu}$ from small $\mathcal{O}_{2322}$ $[b \to s\mu\mu]$
- $\mathcal{C}^{\mathrm{U}}_{9}$ from radiative corr from large $\mathcal{O}_{2333}$ $[b \to c\tau\nu$ and $b \to s\mu\mu]$

Generic flavour structure and NP at the scale Λ yields

$$\mathcal{C}^{\mathrm{U}}_{9} \approx 7.5\left(1-\sqrt{\frac{R_{D^{(*)}}}{R_{D^{(*)};\mathrm{SM}}}}\right) \times \left(1+\frac{\log(\Lambda^2/(1\,\mathrm{TeV}^2))}{10.5}\right)$$



$\Longrightarrow$ Agreement with (R_D, R_{D^*}) for $\Lambda = 1 - 10$ TeV

Connecting through flavour symmetries

- $U_q(2) \otimes U_\ell(2)$ flavour symmetry
  - Large(ish) NP in $b \to c\tau\nu$ compared to SM tree contribution
  - Small NP in $b \to s\mu\mu$ compared to SM loop contribution
  - $U(2)$ protects first two generations from large NP contributions

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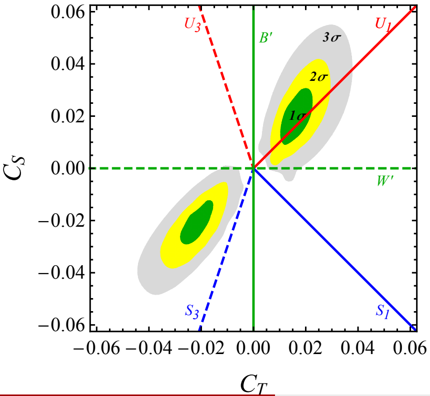
  - $U(2)$ protects first two generations from large NP contributions
- Restrictive (but reasonable) assumptions yield same flavour structure for 2 ops, with 3 couplings λ^q_{sb}, $\lambda^\ell_{\tau\mu}$, $\lambda^\ell_{\mu\mu}$ to be fitted

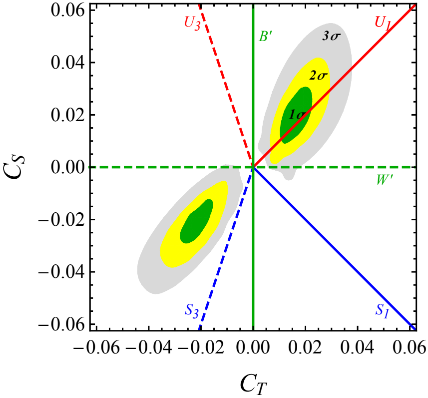


[Butazzo, Greljo, Isidori, Marzocca]

$$\lambda^q_{ij}\lambda^\ell_{ab}\Big[C_S(\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^a_L\gamma^\mu L^b_L) + C_T(\bar{Q}^i_L\gamma_\mu\sigma^\alpha Q^j_L)(\bar{L}^a_L\gamma^\mu\sigma^\alpha L^b_L)\Big]$$

$$Q^i_L = \begin{pmatrix} V^*_{ji}u^j_L \\ d^i_L \end{pmatrix} \qquad L^a_L = \begin{pmatrix} \nu^a_L \\ \ell^a_L \end{pmatrix}$$

Resulting single-mediator models



- Several possible mediators
- Disfavours colourless vectors (W', Z', green) and coloured scalars (S_1, S_3 leptoquarks, blue)
- Favours U_1 vector leptoquark $(3, 1, 2/3)$
- Same conclusions taking a general structure of the couplings [Kumar, London, Watanabe]

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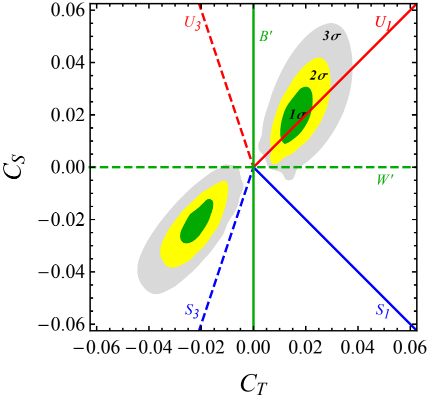

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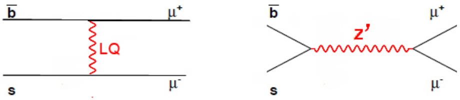
U_1 leptoquark

- Passes LHC constraints on direct production ($pp \to \tau X, \tau\tau X$)
- Could also accomodate (small) right-handed couplings
- Requires additional particles for UV completion (at least a Z')

Other simplified models



- Two scalar leptoquarks $S_1(\bar{3}, 1, 1/3)$ and $S_3(\bar{3}, 3, 1/3)$, purely left-handed currents
- Two scalar leptoquarks $R_2(3, 2, 7/6)$ and $S_3(\bar{3}, 3, 1/3)$, generating both left- and right-handed currents, easily embedded in GUT
- But no succesful models with heavy Higgses or W', Z' only

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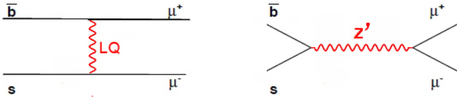

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Many constraints to accommodate

- flavour (CKM, 1st and 2nd gen decays, $B_s\bar{B}_s$ mixing, $B \to K(^*)\nu\bar{\nu}$)
- LFV bounds $B \to K(^*)e\mu, \mu\tau; B_s \to e\mu; K_L \to e\mu; \mu \to e\gamma; \mu \to 3e$
- LEP electroweak constraints
- LHC direct production $pp \to \tau\tau X$, $b\bar{b}X$, $t\bar{t}X$
  - simple or double leptoquark production
  - other particles (like Z' or coloured excited boson G')

As a conclusion

LFU in hadron decays

Excellent probes of the SM

- Separation of scales/tools between electroweak and strong
- QCD encoded in hadronic parameters sources of uncertainties
- Which often (but not always) cancel in LFU-testing ratios
- Many modes measured, with LFUV for $b \to c\ell\nu$ and $b \to s\ell\ell$

Various processes

- Analysed separating short- and long-distance physics
- FCCC: tree level in SM, rather simple to analyse
- FCNC: loop level in SM, more challenging due potential long-distance QCD effects

Analysis of LFUV deviations

- Model-independent separation approach through EFT
- Fit short-distance Wilson coeffs to determine NP contributions
- Simplified models to reproduce these NP contributions

News expected soon from LHCb and Belle II (and others !)