

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
 $b \rightarrow sll$ (angular observables, global fits)

How

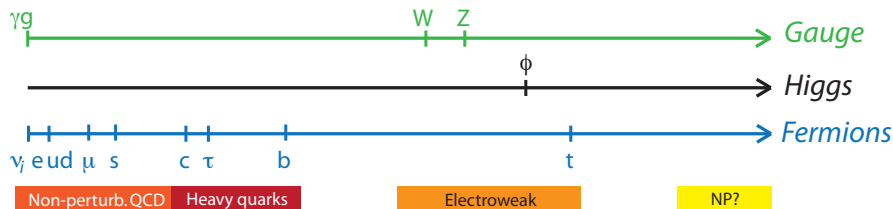
- To pronounce my name : [se-bas-ti-en] [de-co-te je-non]
- Hard for you ? also hard for the French. . .

General ideas

Lepton flavour universality in hadron decays ?

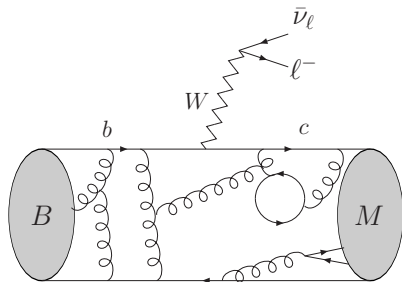
- Theo: Both quarks and leptons involved
- Exp: Leptonic and semileptonic decays of hadrons
- Involve charged leptons
- Hints of non-universality among the generations of leptons
- Which might be connected with lepton flavour violation
at least in some NP models. . .

Lepton flavour universality in hadron decays ?



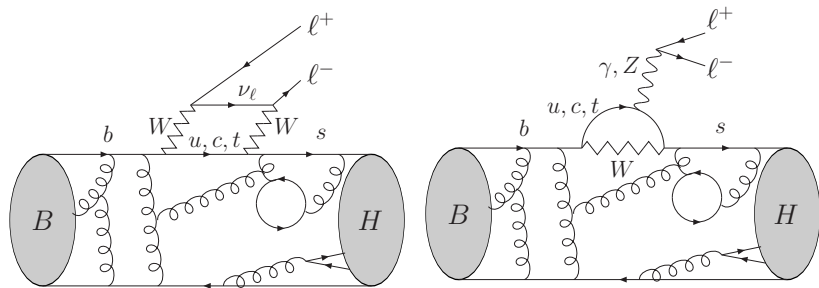
- Tough multi-scale challenge with 3 interactions intertwined
- GeV (QCD and m_q), 100 GeV (electroweak), 1 TeV or more (NP)
- All challenging, but main theo problem from hadronisation of quarks into hadrons (source of uncertainties)
- Hierarchy of scales \implies notion of Effective Field Theory

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 $SU(3)_C \otimes U(1)_Y$ 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
<hr/>					
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
d_R	d_R	3	0	-1/3	-1/3

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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

$$\mathcal{L}_{\text{gauge},\psi} = \sum_{\psi,i} \bar{\psi}_i \mathbf{D} \psi_i = \sum_{\psi,i} \bar{\psi} \partial \psi + g(W_\mu^+ J_{W^+}^\mu + W_\mu^- J_{W^-}^\mu + Z_\mu J_Z^\mu) + e A_\mu J_{em}^\mu$$

$$J_{W^+}^\mu = \frac{1}{\sqrt{2}}(\bar{\nu}_L^i \gamma^\mu e_L^i + \bar{u}_L^i \gamma^\mu d_L^i) \quad J_{W^-}^\mu = \frac{1}{\sqrt{2}}(\bar{e}_L^i \gamma^\mu \nu_L^i + \bar{d}_L^i \gamma^\mu u_L^i)$$

$$J_Z^\mu = \frac{1}{c_W} \left\{ \frac{1}{2} \bar{\nu}_L^i \gamma^\mu \nu_L^i + \left(s_W^2 - \frac{1}{2} \right) \bar{e}_L^i \gamma^\mu e_L^i + s_W^2 \bar{e}_R^i \gamma^\mu e_R^i \right. \\ \left. + \left(\frac{1}{2} - \frac{2}{3} s_W^2 \right) \bar{u}_L^i \gamma^\mu u_L^i - \frac{2}{3} s_W^2 \bar{u}_R^i \gamma^\mu u_R^i + \left(\frac{1}{3} s_W^2 - \frac{1}{2} \right) \bar{d}_L^i \gamma^\mu d_L^i + \frac{1}{3} s_W^2 \bar{d}_R^i \gamma^\mu d_R^i \right\}$$

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

- $c_W = g/\sqrt{g^2 + g'^2}$, $s_W = \sqrt{1 - c_W^2}$ weak mixing (W_μ^3, B_μ) \leftrightarrow (Z_μ^0, A_μ)
- 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

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

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

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

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

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

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

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

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

- W bosons couple to charged currents J_W^μ 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

$$J_W^\mu = \bar{u}_L^i \gamma^\mu d_L^i \rightarrow \bar{u}'_L V_{UL}^\dagger \gamma^\mu V_{DL} d'_L = \bar{u}'_L V \gamma^\mu d'_L$$

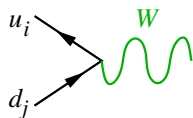
- Potential misalignment between (unitary) rotations: $V_{UL} \neq V_{DL}$, so matrix $V = V_{UL}^\dagger V_{DL}$ is unitary but not identity

CKM for FCCC

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- Flavour-changing charged currents at tree level



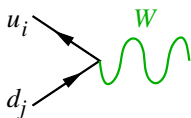
$$\frac{g}{\sqrt{2}} [\bar{u}_L^i V_{ij} \gamma^\mu d_L^j W_\mu^+ + \bar{d}_L^j V_{ij}^* \gamma^\mu u_L^i W_\mu^-]$$

unitary Cabibbo-Kobayashi-Maskawa matrix

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- 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 $J_{Z,A}^\mu$ 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

$$\bar{u}_L^i \gamma^\mu u_L^i \rightarrow \bar{u}'_L V_{UL}^\dagger \gamma^\mu V_{UL} u'_L = \bar{u}'_L \gamma^\mu u'_L,$$

$$\bar{u}_R^i \gamma^\mu u_R^i \rightarrow \bar{u}'_R V_{UR}^\dagger \gamma^\mu V_{UR} u'_R = \bar{u}'_R \gamma^\mu u'_R$$

and same for d_L and for d_R separately

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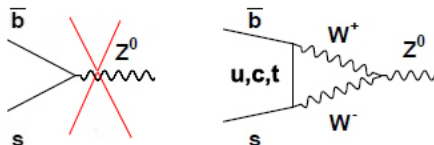
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... but absent only at tree level ! They can occur in loops



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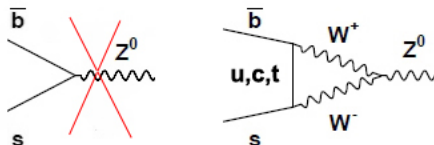
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Q: Why are FCNC very small in the SM ? (several arguments)

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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 $\psi_{L,R} \rightarrow e^{i\alpha/3} \psi_{L,R}$ [$\psi = u, d, s, c, b, t$] **not broken**

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

\implies conservation of **baryon number**

Number of physical parameters of the CKM matrix

CKM unitary matrix, but how many physical parameters ?

- $U(3)_Q \otimes U(3)_U \otimes U(3)_D \rightarrow U(1)_B$

- $3 \times 3 \rightarrow 0$ real parameters

- $3 \times 6 \rightarrow 1$ 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

⇒ 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 $b \rightarrow u$ and $t \rightarrow d$ transitions ?

And for leptons ?

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

$$\mathcal{L}_{\text{Higgs,leptons}} = \bar{Q}_L^i Y_E^{ik} e_R^k \phi + h.c. + \dots$$

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

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

- 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

- 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

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

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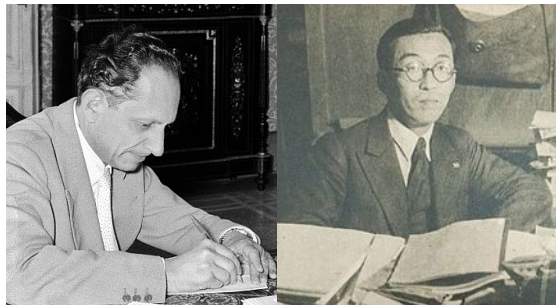
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- In SM with $m_\nu = 0$, $V_{\nu L}$ can be arbitrarily chosen to get $W = 1$
- But in presence of m_ν , potential misalignment: $V_{\nu L} \neq V_{EL}$, so PMNS matrix $W = V_{\nu L}^\dagger V_{EL}$ is unitary but not identity

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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

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- $U(1)_{E-L}$ global phase redefinition
 $(e_R, \mu_R, \tau_R) \rightarrow e^{i\delta} (e_R, \mu_R, \tau_R)$
 $(L_{1L}, L_{2L}, L_{3L}) \rightarrow e^{-i\delta} (L_{1L}, L_{2L}, L_{3L})$ broken

broken to $U(1)_e \otimes U(1)_\mu \otimes U(1)_\tau$ (larger than for quarks)

\implies 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
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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 \implies LFC, and thus LFV \implies LFUV (not equivalence)

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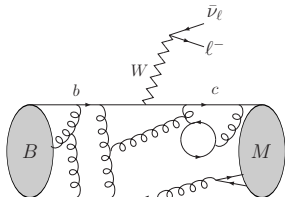
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Q: Take a Z' coupling to 3 generations of lepton mass eigenstates

$$\alpha_{ij}(\bar{e}_L^i \gamma^\mu e_L^j + \bar{e}_R^i \gamma^\mu e_R^j) Z'_\mu$$

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 $b \rightarrow c\tau\nu_\tau$ process (leptonic or semileptonic decay)

- If $m_\nu = 0$, no PMNS, but what to do since $m_\nu \neq 0$?
- Actually $b \rightarrow c\tau\nu_i$ where i any of the three neutrino mass states since no experimental way of knowing the nature of ν mass state

$$\Gamma \propto \sum_i |A(b \rightarrow c\tau\nu_i)|^2 = |V_{cb}|^2 \sum_i |V_{\tau i}|^2 |A_i|^2$$

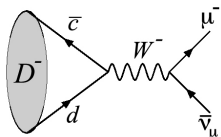
- Assuming A_i independent of ν_i flavour and PMNS unitary

$$\Gamma \propto |V_{cb}|^2 |A|^2 \sum_i |V_{\tau i}|^2 = |V_{cb}|^2 |A|^2 \times 1$$

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

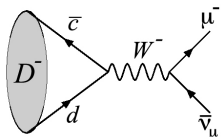
FCNC leptonic decays



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

- 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

FCNC leptonic decays



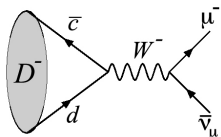
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$$-\frac{g_W^2}{2} \times \frac{-i}{p_D^2 - M_W^2} \times \bar{u}_{(\mu)} \gamma_\rho (1 - \gamma_5) v_{(\nu)} \times g^{\rho\sigma} \times V_{cd} \langle 0 | \bar{c} \gamma_\sigma (1 - \gamma_5) d | D^- \rangle$$

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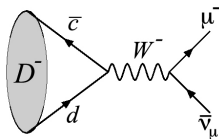
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$$\begin{aligned} \langle \mu^- \bar{\nu}_\mu | \mathcal{H}_{SM} | D^- \rangle = \\ -\frac{g_W^2}{2} \times \frac{-i}{p_D^2 - M_W^2} \times \bar{u}_{(\mu)} \gamma_\rho (1 - \gamma_5) v_{(\nu)} \times g^{\rho\sigma} \times V_{cd} \langle 0 | \bar{c}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

- 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



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

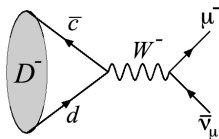
- One obtains the amplitude (where $G_F = g^2 / (4 / \sqrt{2} M_W^2)$)

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

- Squaring the amplitude, one gets the branching ratio

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

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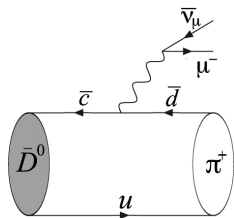
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- Ratio of branching ratios for different leptons
 - No QCD uncertainties (decay constant cancel), no CKM
 - Lepton Flavour Universal up to phase space but also higher-order (QED) corrections (δ_{em})

FCNC 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 $D \rightarrow \rho$?

FCNC semileptonic decays

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

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

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

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

Other ratios measured, but no deep estimate of the uncertainties

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

And which tests for B mesons ?



- Leptonic:

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

- Semileptonic:

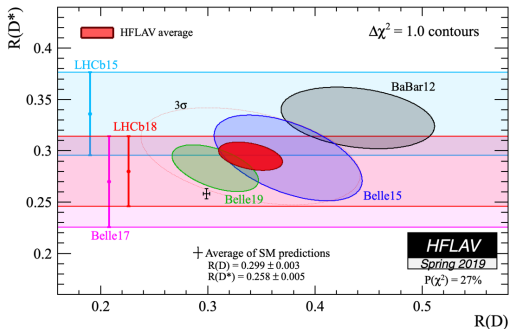
- For the comparison between e and μ , only $b \rightarrow c l \nu$, averaging naively results from Babar and Belle

	Exp		Exp
$\frac{\Gamma(B \rightarrow D \mu \nu)}{\Gamma(B \rightarrow D e \nu)}$	0.98 ± 0.07	$\frac{\Gamma(B \rightarrow D^* \mu \nu)}{\Gamma(B \rightarrow D^* e \nu)}$	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 $b \rightarrow c\tau\nu$



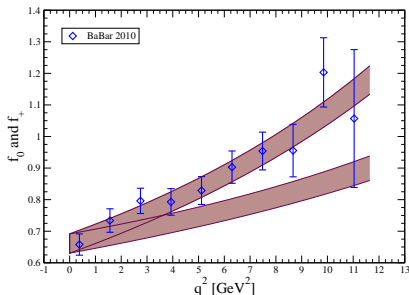
$$R_{D^{(*)}} = \frac{Br(B \rightarrow D^{(*)}\tau\nu)}{Br(B \rightarrow D^{(*)}\ell\bar{\nu}_\ell)}$$

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

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

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

- \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

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

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

- H_λ describing $B \rightarrow D^*(\rightarrow D\pi)\ell\bar{\nu}_\ell$ with λ helicity of $V^* \rightarrow \ell\bar{\nu}_\ell$
- 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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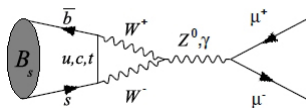
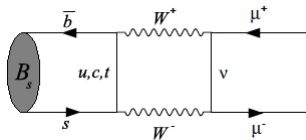
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Q: What kind of information would be given by an angular analysis ?

Lepton Flavour Universality in Flavour Changing Neutral Currents

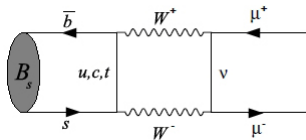
FCNC leptonic decays



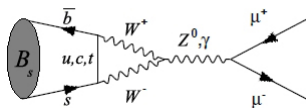
- Good example of FCNC : $B_s \rightarrow \mu\mu$
- More complicated (loop) decay
- Amplitude has a summation over internal quark flavour

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

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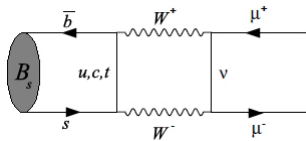


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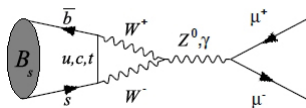
- It can be reexpressed using the CKM matrix unitarity

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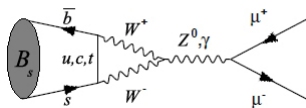
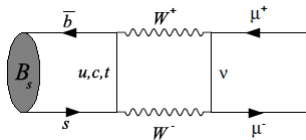
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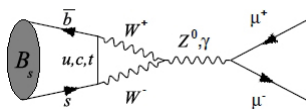
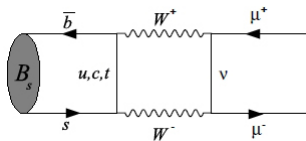
- m_q -independent part of A cancels, $m_u, m_c \ll M_W \sim m_t$
- Decay dominated by (m_t -dep part of) diagrams with top quark + other heavy degrees of freedom (W, Z)

FCNC leptonic decays



- Separation of scale explicit
 - short distances (W, t, Z diagrams computed perturbatively)
 - long distances amount to $\langle 0 | \bar{s} \gamma_\mu \gamma_5 b | \bar{B}_s \rangle$ (decay constant)
- Applies also for $b \rightarrow d l l$, but not for $c \rightarrow u l l$ and $s \rightarrow d l l$ FCNC (light quark loops large, hard to estimate)

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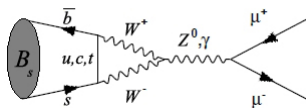
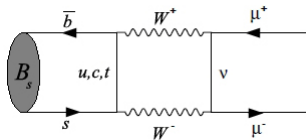
- Yields the branching ratio

$$Br(B_s \rightarrow \mu\mu) = \frac{G_F^2 \alpha_{em}^2 f_{B_s}^2 m_\mu^2 m_{B_s} \tau_{B_s}}{16\pi^2 \sin^2 \theta_W} \sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}} |V_{tb}^* V_{ts}|^2 Y^2 \left(\frac{m_t^2}{M_W^2} \right)$$

with decay constant f_{B_s} and Y perturbative Inami-Lim function

- Higher-order radiative corrections can be evaluated

FCNC leptonic decays



- Separation of scale explicit
 - short distances (W, t, Z diagrams computed perturbatively)
 - long distances amount to $\langle 0 | \bar{s} \gamma_\mu \gamma_5 b | \bar{B}_s \rangle$ (decay constant)
- Applies also for $b \rightarrow d l l$, but not for $c \rightarrow u l l$ and $s \rightarrow d l l$ FCNC (light quark loops large, hard to estimate)

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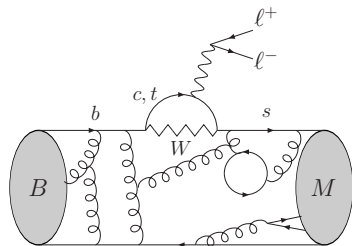
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Q: Check that argument for $B_d \rightarrow \mu\mu$. What about $D \rightarrow \mu\mu, K \rightarrow \mu\mu$?

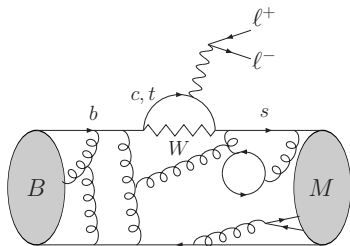
FCNC semileptonic decays

- Same argument as for B_d and B_s leptonic decays ?
- Dimuon pair with inv mass q^2 varying from $4m_\mu^2$ to $(m_B - m_M)^2$
 - $t\bar{t}$ always very virtual, can be computed perturbatively
 - $c\bar{c}$ can become real, and resonant for $q^2 = m_{J/\psi}^2, m_{\psi(2S)}^2 \dots$
 - $u\bar{u}$ still CKM suppressed $V_{ub}^* V_{us} = O(\lambda^4) \ll V_{cb}^* V_{cs}, V_{tb}^* V_{ts} = O(\lambda^2)$
- Separation of long- and short-distances can still be performed, but long-distance contributions from charm must be taken care of



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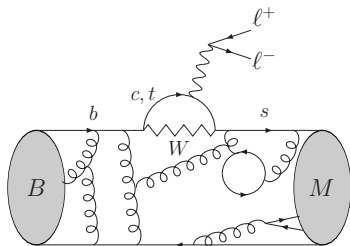
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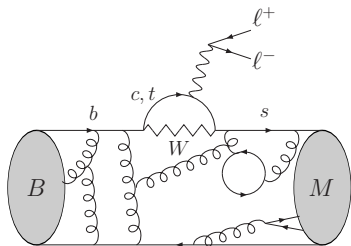
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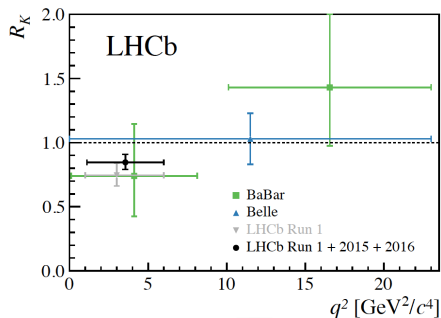
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Q: Why were long-distance contributions not such an issue for FCCC ?

LFU violation in $b \rightarrow sll$

Two updates@Moriond 2019



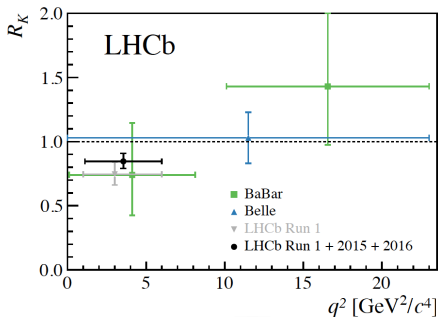
- LHCb:

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

- From 2.6σ to 2.5σ
deviation wrt SM

LFU violation in $b \rightarrow sll$

Two updates@Moriond 2019

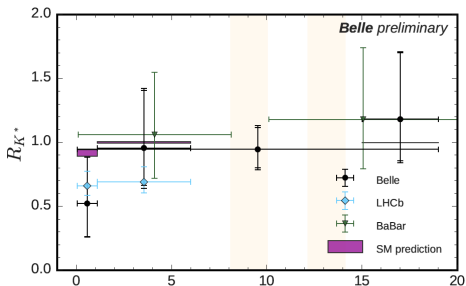


- Belle: $R_{K^*} = \frac{B(B \rightarrow K^* \mu \mu)}{B(B \rightarrow K^* e e)}$
- OK with SM, but also LHCb [2.3 (2.6) σ from SM for $R_{K^*}^{[0.045, 1.1]}$ ([1.1, 6])]

- LHCb:

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

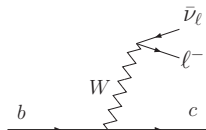
- From 2.6 σ to 2.5 σ deviation wrt SM



Looking for an explanation of LFUV

Two sets of "anomalies"

$$b \rightarrow cl\bar{\nu}_\ell$$



SM

tree (charged) ($V - A$)

Spin 0

$$\bar{B} \rightarrow D l \bar{\nu}_\ell$$

Spin 1

$$\bar{B} \rightarrow D^* l \bar{\nu}_\ell$$

Observables
with

Total Br

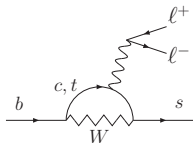
$$l = \tau, \mu, e$$

LFUV tensions

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

Other tensions

$$b \rightarrow sl^+ l^-$$



loop (neutral)

$$B \rightarrow K ll$$

$$B \rightarrow K^* ll, B_s \rightarrow \phi ll$$

$d\Gamma/dq^2 + \text{Angular obs}$

$$l = \mu, e$$

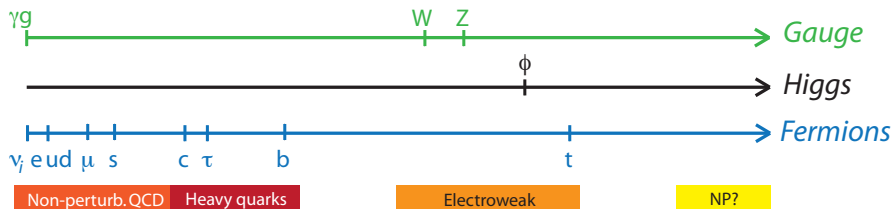
$$R_{K^{(*)}} = \frac{Br(B \rightarrow K^{(*)} \mu \mu)}{Br(B \rightarrow K^{(*)} ee)}$$

$$Br(K, K^*, \phi + \mu \mu)$$

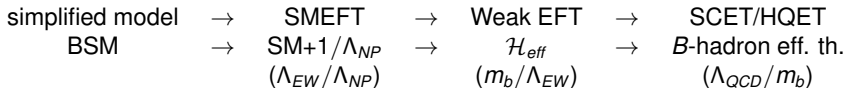
angular obs (e.g., P'_5)

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

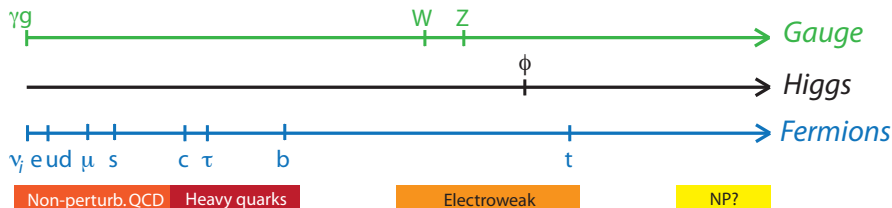
A multi-scale problem



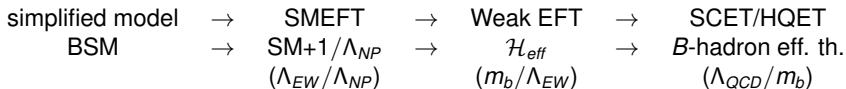
• Several steps to separate/factorise scales



A multi-scale problem



- Several steps to separate/factorise scales

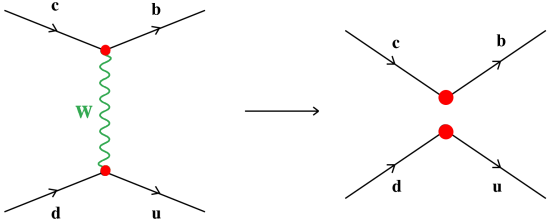


- Main theo problem from hadronisation of quarks into hadrons
description/parametrisation in terms of QCD quantities
decay constants, form factors, bag parameters...
- Long-distance non-perturbative QCD: source of uncertainties
lattice QCD simulations, sum rules, effective theories...

Effective approaches

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

Short dist/Wilson coefficients and Long dist/local operator


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

Effective approaches

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

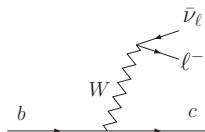
Fermi theory carries some info on the underlying theory

- 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 $\mu = m_b$

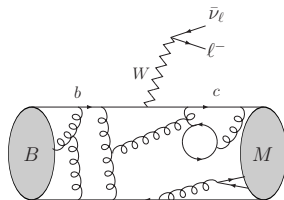
$$\mathcal{H}^{\text{eff}} = CKM \times \mathcal{C}_i \times \mathcal{O}_i$$
$$\langle M | \mathcal{H}^{\text{eff}} | B \rangle = CKM \times \mathcal{C}_i \times \langle M | \mathcal{O}_i | B \rangle$$



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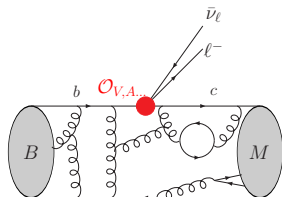
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involving hadronic quantities such as **form factors**

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
- \implies 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 C_i only once for given theory
- NP at a high scale will only shift the values of C_i
- Describes all hadron decays with same quark-level process
 - Same short-distance physics, and thus same C_i
 - Different long-distance physics, with different $\langle M | \mathcal{O}_i | B \rangle$
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- fix $C_i = C_i^{\text{SM}}$, compute SM and compare with the data
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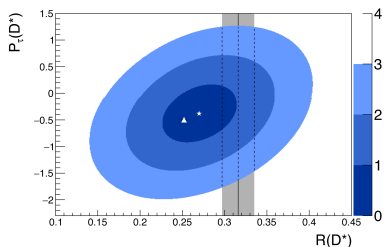
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Model-independent determination of \mathcal{C}_i

- 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

$b \rightarrow c l \bar{\nu}_l$: in addition to R_D, R_{D^*}



$\sqrt{\chi^2}$ τ polarisation in $B \rightarrow D^* \tau \nu$

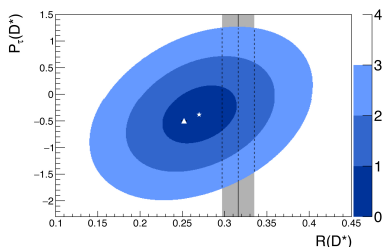
- Belle with $\tau \rightarrow X \nu$, $X = \rho$ (or π)

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

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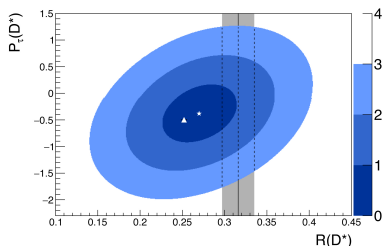
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D^* polarisation in $B \rightarrow D^* \tau \nu$

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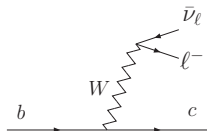
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$R_{J/\psi}$ ($B_c \rightarrow J/\psi\ell\bar{\nu}_\ell$)

- LHCb: $R_{J/\psi} = 0.71 \pm 0.17 \pm 0.18$
- Form factors based on models with uncertainties difficult to assess

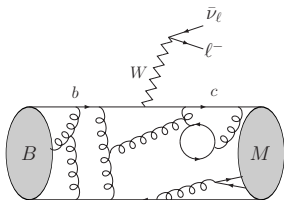
$$\frac{R_D}{R_{D;SM}} \simeq \frac{R_{D^*}}{R_{D^*;SM}} \simeq \frac{R_{J/\psi}}{R_{J/\psi;SM}}$$

$b \rightarrow cl\bar{\nu}_\ell$ effective Hamiltonian



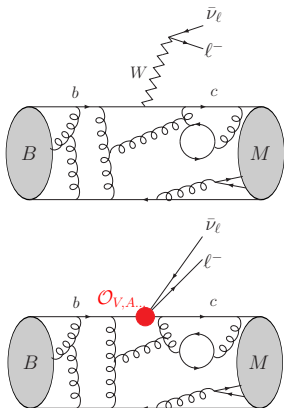
$$\mathcal{H}^{\text{eff}}(b \rightarrow cl\nu) \propto G_F V_{cb} \sum C_i \mathcal{O}_i$$

$b \rightarrow c l \bar{\nu}_l$ effective Hamiltonian



$$\mathcal{H}^{\text{eff}}(b \rightarrow c l \nu) \propto G_F V_{cb} \sum C_i \mathcal{O}_i$$

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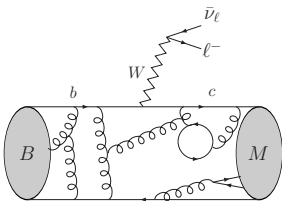
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- In the SM

- $\mathcal{O}_{V_L} = (\bar{c} \gamma^\mu P_L b)(\bar{l} \gamma_\mu P_L \nu_l)$ [W exchange]
- $C_{V_L} = 1$ and universal for all three leptons

- Hadronic uncertainties in form factors defined from $\langle M | \mathcal{O}_i | B \rangle$ and already discussed previously!

$b \rightarrow c l \bar{\nu}_l$ effective Hamiltonian



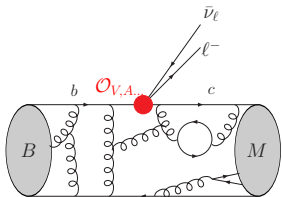
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- Chirally flipped ($W \rightarrow W_R$)

$$\mathcal{O}_{V_L} \rightarrow \mathcal{O}_{V_R} \propto (\bar{c} \gamma^\mu P_R b)(\bar{l} \gamma_\mu P_L \nu_l)$$

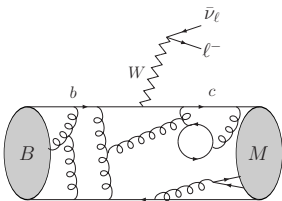
- (Pseudo)scalar ($W \rightarrow H^+$)

$$\mathcal{O}_{V_L} \rightarrow \mathcal{O}_{S_L} \propto (\bar{c} P_L b)(\bar{l} P_L \nu_l), \mathcal{O}_{S_R}$$

- Tensor operators ($W \rightarrow T$)

$$\mathcal{O}_{V_L} \rightarrow \mathcal{O}_{T_L} \propto (\bar{c} \sigma^{\mu\nu} P_L b)(\bar{l} \sigma_{\mu\nu} P_L \nu_l)$$

$b \rightarrow c l \bar{\nu}_l$ effective Hamiltonian



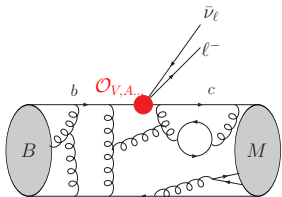
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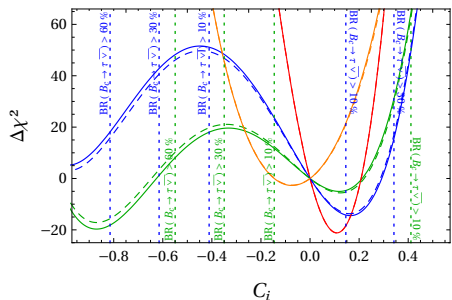
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Q: In presence of which kind of NP are $C_{V_L}, C_{V_{L\mu}}, C_{V_{LT}}$ related?

Global fits for $b \rightarrow cl\bar{\nu}_\ell$

[Bhattacharyya,Nandi,Patra;Alok,Kumar,Kumar,Kumbhakar,Uma Sankar;Kumar,London,Watanabe;Freytsis,Ligeti,Ruderman;

Greljo, Camalich, Ruiz-Alvarez...



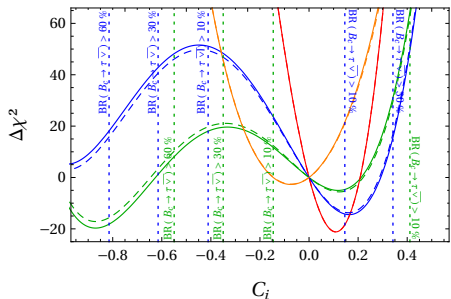
[Blanke,Crivellin,de Boer,Moscato,Nierste, Nišandžić, Kitahara]

- Fits to R_D , R_{D^*} , $P_\tau(D^*)$, $F_L(D^*)$, sometimes $R_{J/\psi}$
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Global fits for $b \rightarrow c l \bar{\nu}_\ell$

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— C_T^l

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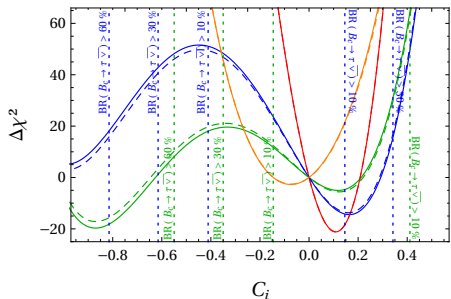
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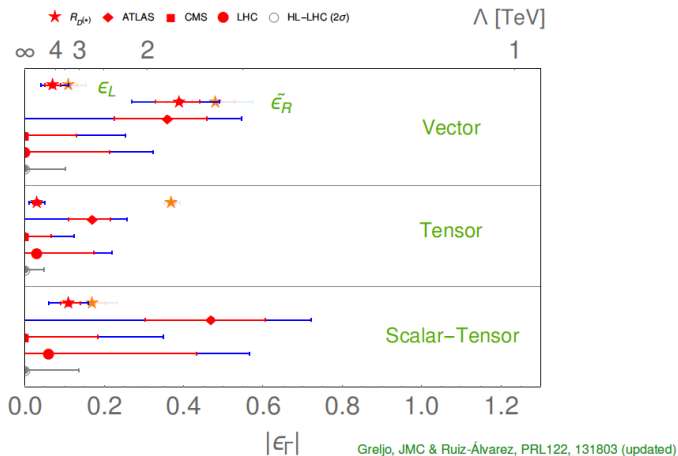
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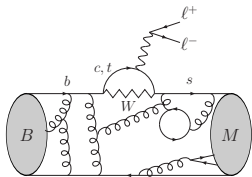
Q: Why is the B_c width a constraint here ?

Global fits for $b \rightarrow c l \bar{\nu}_l$



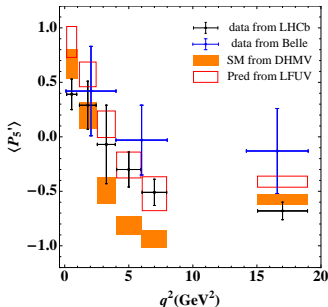
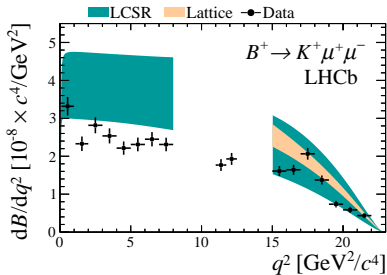
- LHC constraints from $pp \rightarrow \tau \nu X$
- Various explanations in terms of single mediators, but leptoquarks preferred over W' or charged Higgs

$b \rightarrow sll$: In addition to R_K, R_{K^*}



- Many observables for $B \rightarrow K\mu\mu$, $B \rightarrow K^*\mu\mu$, $B_s \rightarrow \phi\mu\mu$
- 2-3 σ deviations observed w.r.t. SM
 - BR for $B \rightarrow K\mu\mu$, $B \rightarrow K^*\mu\mu$, $B_s \rightarrow \phi\mu\mu$ (require knowledge of hadronic uncertainties)
 - Angular distr of $B \rightarrow K^*\mu\mu$ with optimised obs (eg P'_5), where part of hadronic uncertainties cancel
 - Hints of lepton flavour universality violation: $b \rightarrow see$ vs $b \rightarrow s\mu\mu$

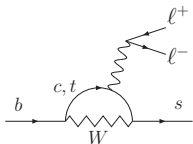
[LHCb, Belle, ATLAS, CMS]



$b \rightarrow sll$ effective Hamiltonian

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

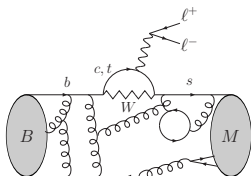
to separate short and long distances ($\mu_b = m_b$)



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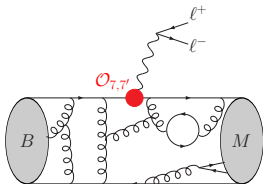
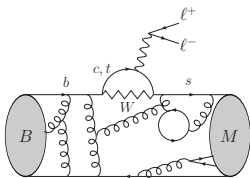


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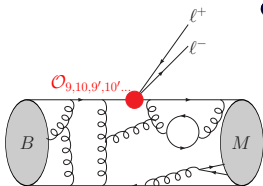
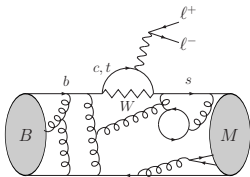


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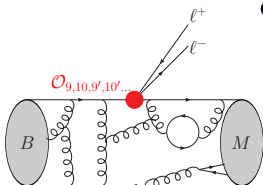
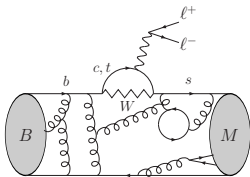
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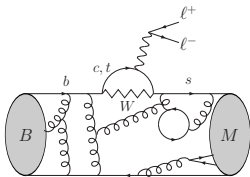
universal for all 3 lepton flavours



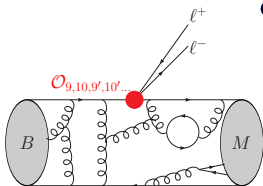
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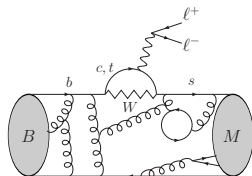
universal for all 3 lepton flavours

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

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

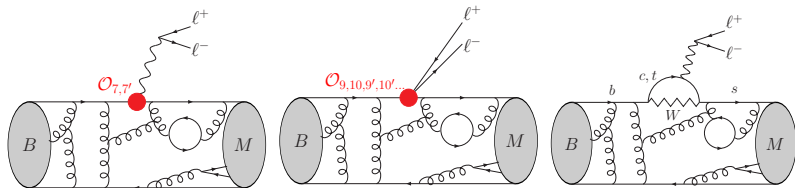
Two sources of hadronic uncertainties

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



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Form factors (local)

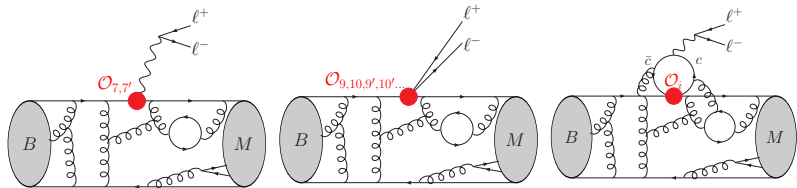
- Local contributions (more terms if NP in non-SM \mathcal{C}_i): **form factors**

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

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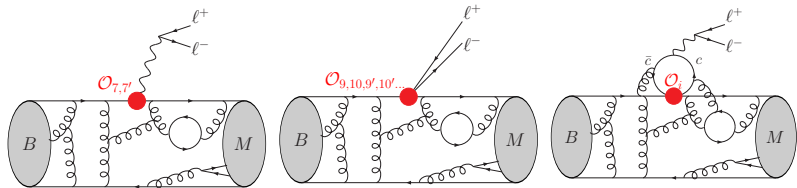
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- Non-local contributions (charm loops): **hadronic contribs.**

T_μ contributes like $O_{7,9}$, depends on q^2 and hadrons

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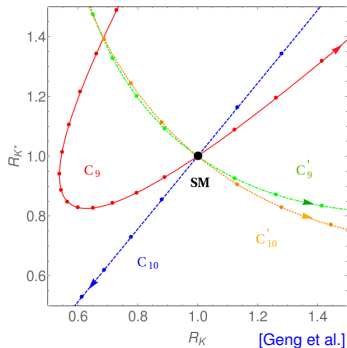
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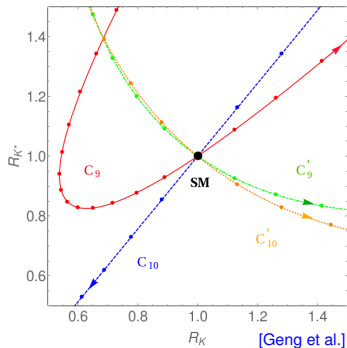
- Overall agreement about both contributions, using various tools

R_K and R_{K^*} in EFT



- R_K : $Br(B \rightarrow K\ell\ell)$ involves one amplitude depending on
 - 3 $B \rightarrow K$ form factors (one suppr by m_ℓ^2/q^2 , one by C_7)
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- \implies hadronic contrib cancel for R_K , very accurate for all q^2 and C_i

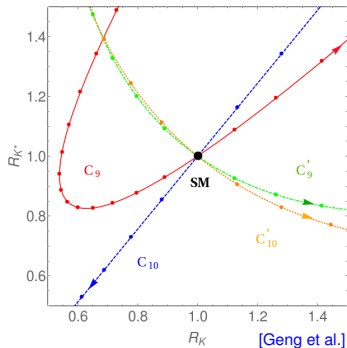
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Q: Why are charm-loop contributions LFU ?

Global fits for $b \rightarrow sll$

Many observables

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

- $B \rightarrow K^* \mu\mu, B_s \rightarrow \phi\mu\mu$ (Br, ang.obs in several bins)
- $B \rightarrow K^* ee$ (ang obs in several bins)
- $B \rightarrow K\mu\mu$ (Br in several bins)
- $B_s \rightarrow \mu\mu$ (Br)
- $B \rightarrow X_S \gamma, B_s \rightarrow \phi\gamma, B \rightarrow K^* \gamma$ (Br)
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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

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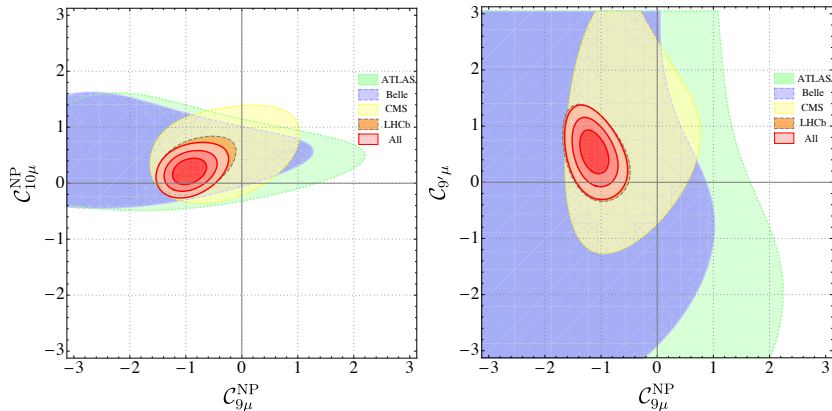
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Global fit analysis

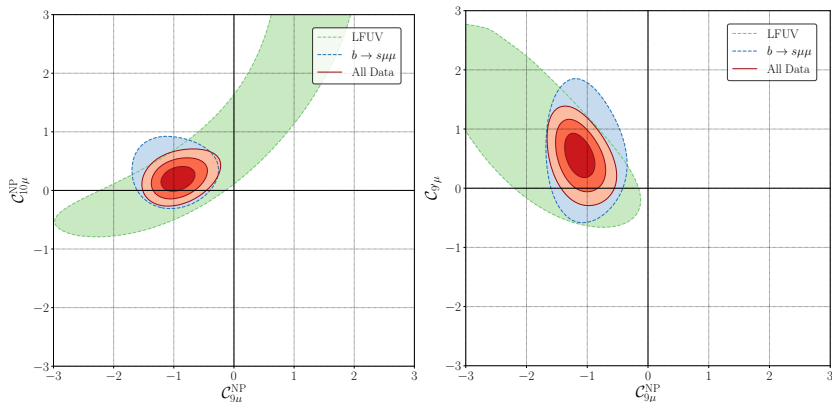
- $C_i(\mu_{ref}) = C_i^{SM} + C_i^{NP}$, with C_i^{NP} assumed to be real (no CPV)
- Most of the discussion on

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



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

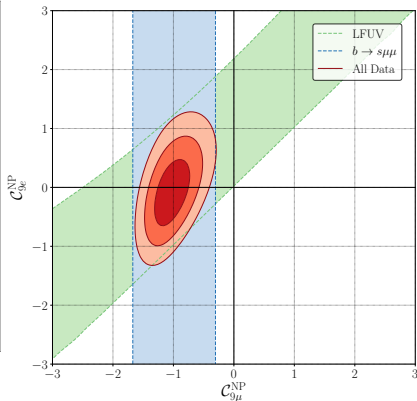
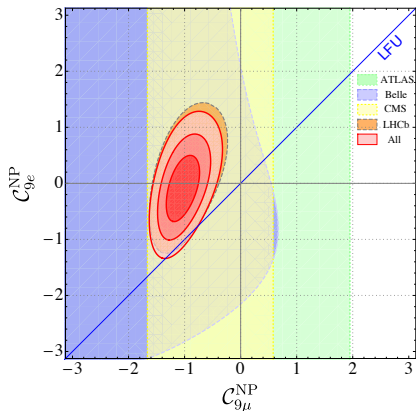
- $C_{9\mu}^{\text{NP}} \simeq -1 + \text{NP in other } C_{i\mu}^{\text{NP}}$,
- $(C_{9\mu}^{\text{NP}}, C_{10\mu}^{\text{NP}})$: 5.9σ (left-handed, SM-like)
- $(C_{9\mu}^{\text{NP}}, C_{g\mu})$: 6.1σ (right-handed currents)



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

- R_K and R_{K^*} favours $C_{10\mu}^{\text{NP}} > 0$ and $C_{9'\mu}^{\text{NP}} > 0$
- $b \rightarrow s\mu\mu$ essentially in favour of $C_{9\mu}^{\text{NP}} < 0$

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



NP in $(C_{9\mu}, C_{9e})$

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

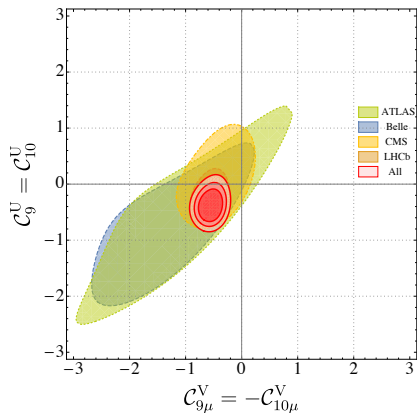
LFUV but also LFU NP ?

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

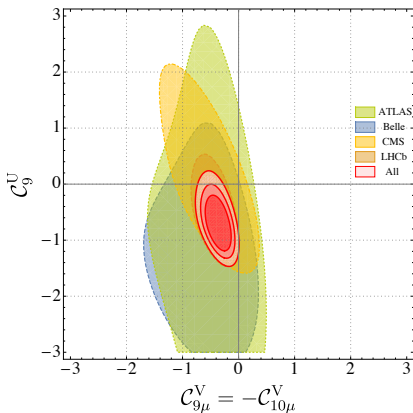
$$C_{ie} = C_i^U \quad C_{i\mu} = C_i^U + C_{i\mu}^V$$

[Algueró et al]

Favoured scenarios (SM pulls 5.8-5.9 σ) with LFU and LFUV 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 ($\Lambda_{NP} \gg m_{t,W,Z}$)

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

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

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

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A first EFT connection

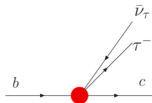
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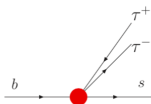
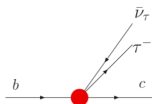
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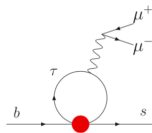
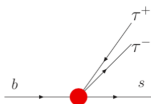
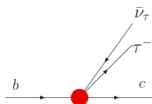
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 - Through radiative effects, (small) NP contribution to C_9^U



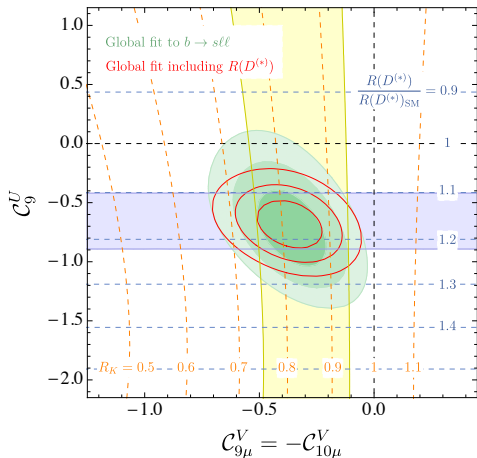
A first EFT connection

Scenario LFU + LFUV NP

- $C_{9\mu}^V = -C_{10\mu}^V$ from small $\mathcal{O}_{2322} [b \rightarrow s\mu\mu]$
- C_9^U from radiative corr from large $\mathcal{O}_{2333} [b \rightarrow c\tau\nu \text{ and } b \rightarrow s\mu\mu]$

Generic flavour structure and NP at the scale Λ yields

$$C_9^U \approx 7.5 \left(1 - \sqrt{\frac{R_{D^{(*)}}}{R_{D^{(*)};\text{SM}}}} \right) \times \left(1 + \frac{\log(\Lambda^2/(1\text{TeV}^2))}{10.5} \right)$$



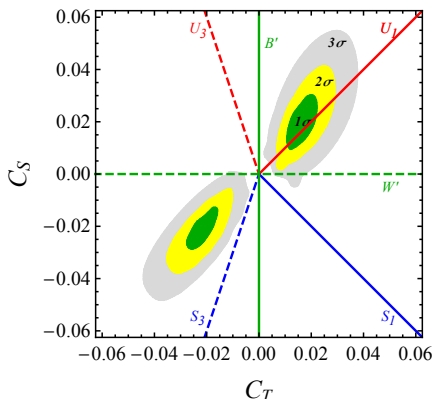
\implies Agreement with (R_D, R_{D^*}) for $\Lambda = 1 - 10$ TeV

Connecting through flavour symmetries

- $U_q(2) \otimes U_\ell(2)$ flavour symmetry
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- Restrictive (but reasonable) assumptions yield same flavour structure for 2 ops, with 3 couplings $\lambda_{sb}^q, \lambda_{\tau\mu}^\ell, \lambda_{\mu\mu}^\ell$ to be fitted

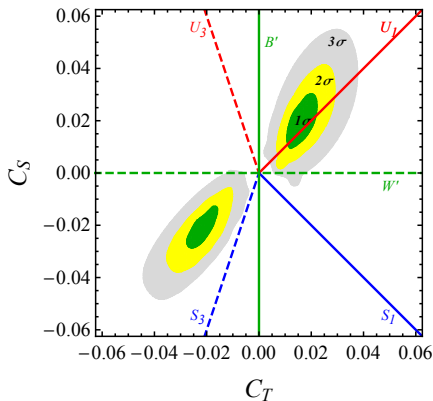


[Butazzo, Greljo, Isidori, Marzocca]

$$\lambda_{ij}^q \lambda_{ab}^\ell \left[C_S (\bar{Q}_L^i \gamma_\mu Q_L^j) (\bar{L}_L^a \gamma^\mu L_L^b) + C_T (\bar{Q}_L^i \gamma_\mu \sigma^\alpha Q_L^j) (\bar{L}_L^a \gamma^\mu \sigma^\alpha L_L^b) \right]$$

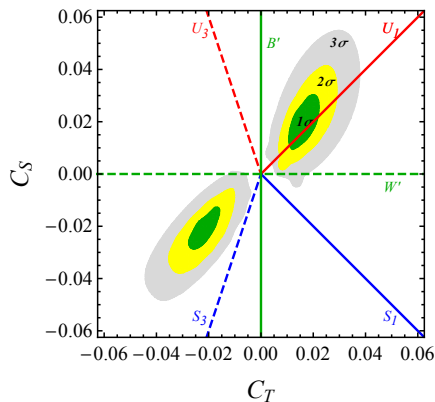
$$Q_L^i = \begin{pmatrix} V_{ji}^* u_L^j \\ d_L^i \end{pmatrix} \quad L_L^a = \begin{pmatrix} \nu_L^a \\ \ell_L^a \end{pmatrix}$$

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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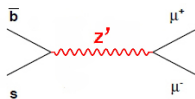
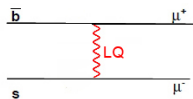


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U_1 leptoquark

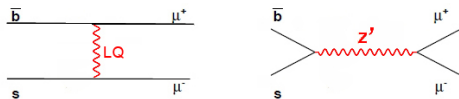
- Passes LHC constraints on direct production ($pp \rightarrow \tau X, \tau\tau X$)
- Could also accommodate (small) right-handed couplings
- Requires additional particles for UV completion (at least a Z')

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
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Many **constraints** to accommodate

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