Flavour Anomalies

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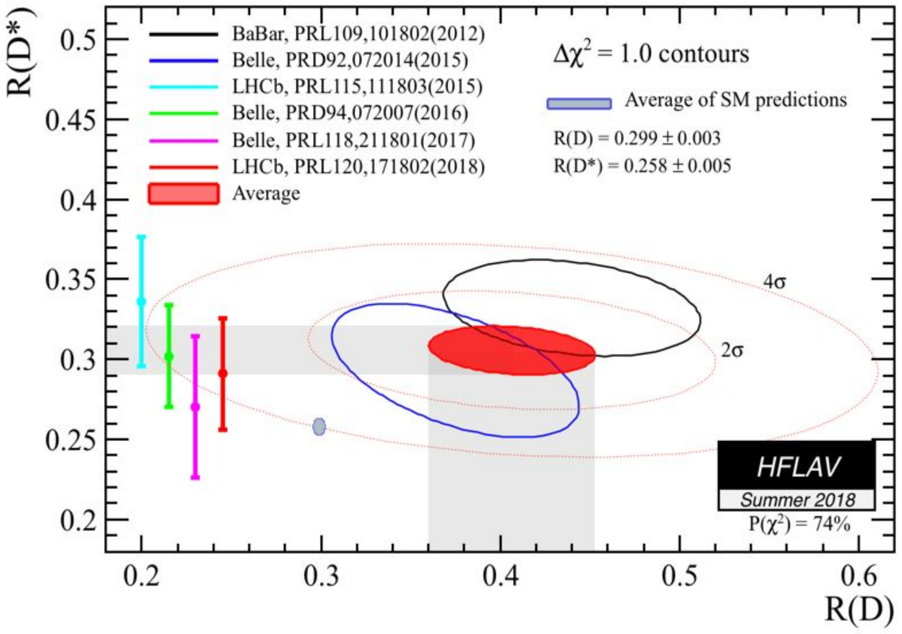


Introduction to Flavour Physics

Flavour, Universality & Tests

The Standard Model

- Gauge Group: $G_{\rm SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$
- Lagrangian: $\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm kin} + \mathcal{L}_{\rm Higgs} + \mathcal{L}_{\rm Yukawa}$
- Fermions: (in 3 generations $i = 1, 2, 3$)

$$Q_{Li}\ (3,2)_{+1/6}\,, \quad U_{Ri}\ (3,1)_{+2/3}\,, \quad D_{Ri}\ (3,1)_{-1/3}\,, \quad L_{Li}\ (1,2)_{-1/2}\,, \quad E_{Ri}\ (1,1)_{-1}$$

with doublets $Q_{Li} = (U_{Li}, D_{Li})$ & $L_{Li} = (\nu_{Li}, E_{Li})$

- Higgs inducing SSB: $SU(2)_L \times U(1)_Y \to U(1)_{EM}$

$$\phi\ (1,2)_{+1/2}\,, \quad \phi = \frac{1}{\sqrt{2}}(0, v+H)$$

Flavour (Physics)

- Flavour = species of fermion
  in SM: 6 quark and 6 lepton flavours: $u, d, c, s, t, b, \quad e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau$
- Kinetic terms induce couplings of flavours to gauge bosons through gauge covariant derivative
- After SSB: (focus on $W^\pm$, Z and on coupling of left-handed fermions)

$$-\mathcal{L}^q_{\text{kin}} \supset \frac{g}{\sqrt{2}}\, \bar{U}_{Li}\, \gamma^\mu\, \delta_{ij}\, D_{Lj}\, W^+ + \text{h.c.}$$

$$+ \frac{g}{\sqrt{2}}\, \bar{U}_{Li}\, \gamma^\mu\, \delta_{ij}\, U_{Lj}\, Z + \frac{g}{\sqrt{2}}\, \bar{D}_{Li}\, \gamma^\mu\, \delta_{ij}\, D_{Lj}\, Z$$

flavour mixing

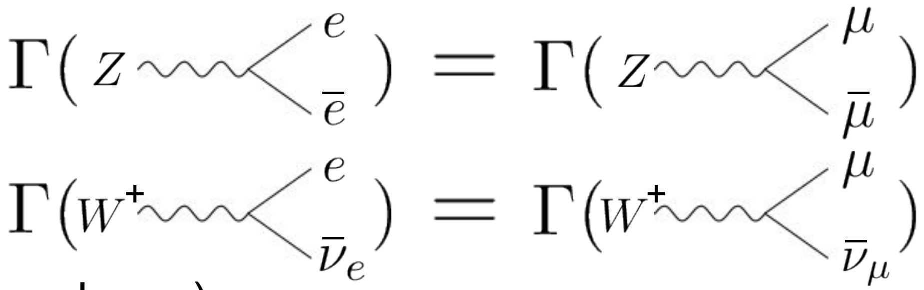
no generation mixing!?

⇒ $W^\pm$ can induce flavour change (*no flavour changing neutral current (FCNC)* via Z or gluons or photon), same holds true for lepton kinetic term

(Flavour) Universality

- (Flavour) Universality = flavour-independent coupling to all gauge bosons
  ⇒ for $E \gg m$, we have

  or



  (for finite energies: mass dependence)
- We focus on $SU(2)_L$-sector
  For leptons it has been measured: $g_e = g_\mu = g_\tau$
- Compare previous form of gauge boson couplings: *looks* universal
  But universality is a basis independent property ⇒ Go to mass eigenbasis
  This is the basis we use when measuring particles

Quark vs Lepton Flavour Universality: Quarks

Diagonalize Yukawa interaction

$$\mathcal{L}^q_{\text{Yukawa}} \supset Y^U_{ij}\ \bar{Q}_{Li}\,\tilde{\phi}\,U_{Rj} + Y^D_{ij}\ \bar{Q}_{Li}\,\phi\,D_{Rj} \ \rightarrow\ \text{diagonal mass terms}$$

Do this by *unitary* field transformation of left-handed doublet

$$U_{Li} \rightarrow V^U_{ij} U_{Lj}\,,\ D_{Li} \rightarrow V^D_{ij} D_{Lj}\,,$$ *(some transf. of right-handed quarks)*

The (so far diagonal) coupling term to W, $\bar{U}_{Li}\delta_{ij}D_{Lj}\ W^+$, transforms to

$$\delta_{ij} \rightarrow (V^U)^\dagger_{ik}\delta_{kl}(V^D)_{lj} = (V_{\text{CKM}})_{ij}$$

⇒ Non-universal due to *independent* transf. of components of $SU(2)_L$-doublet

Note that e.g. $\bar{U}_{Li}\delta_{ij}U_{Lj}\ Z$ stays diagonal/universal (→ still no FCNC)

Quark vs Lepton Flavour Universality: Leptons

Repeat for lepton sector…

$$\mathcal{L}^l_{\text{Yukawa}} \supset Y^l_{ij} \; \bar{L}_{Li}\phi E_{Rj} + \text{h.c.} \;\; \rightarrow \;\; \text{diagonal mass terms}$$

$$L_{Li} \rightarrow V^L_{ij} L_{Lj} \; ,$$ *(some transf. of right-handed leptons)*

Important difference: Components of doublet transformed together

(there is only *one* Yukawa matrix to be diagonalized)

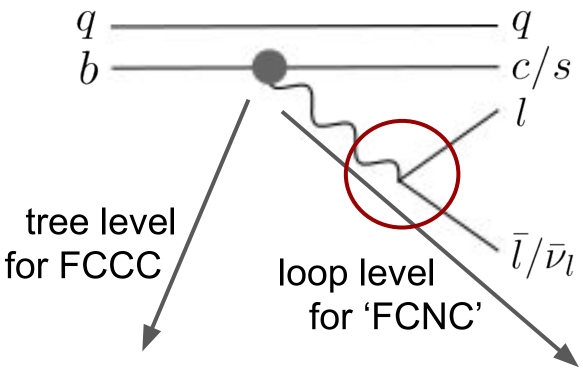
Therefore the $W^{\pm}$-coupling transforms like

$$\delta_{ij} \rightarrow (V^l)^{\dagger}_{ik}\delta_{kl}(V^l)_{lj} = \delta_{ij}$$

⇒ *Lepton Flavour Universality (LFU)* in the SM

Testing LFU: B to D/K

Consider B-meson decays to D- or K-mesons:

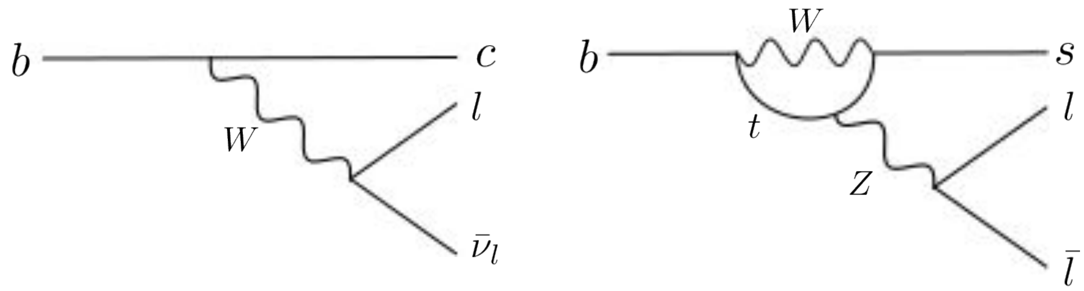


where e.g.

$$\Gamma(B \to D\, l\, \bar{\nu}_l) = \Gamma(b \to c\, l\, \bar{\nu}_l) \cdot F_{\mathrm{QCD}}$$

$\to$ F_{QCD} is independent of l and $\bar{\nu}_l$

⇒ consider ratios such that lepton-independent factors drop out

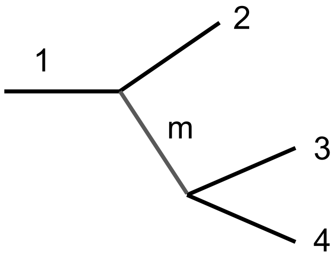


Testing LFU: Factorization Question

Almost all the calculations of the branching ratios in flavour physics rely on the narrow width approximation (NWA):
Intermediate particle *created on-shell* with subsequent decay

Works well when:

- Mass peak is narrow: $\Gamma_m \ll m$.
- Propagator is separable from matrix element.
- Sub-processes are kinematically allowed: $\sqrt{s} \gg m + m_2$, $m \gg m_3 + m_4$.
- No interference.



$$\Gamma(1 \to 234) = \Gamma(1 \to 2m) \times Br(m \to 34)$$

Testing LFU

$$\frac{\Gamma(B \to D\, l\, \bar{\nu}_l)}{\Gamma(B \to D\, l'\, \bar{\nu}_{l'})} = \frac{Br(W \to l\, \bar{\nu}_l)}{Br(W \to l'\, \bar{\nu}_{l'})}\,\frac{\Gamma(b \to c\, W)}{\Gamma(b \to c\, W)}\,\frac{F_{\mathrm{QCD}}}{F_{\mathrm{QCD}}}$$

$$= \frac{Br(W \to l\, \bar{\nu}_l)}{Br(W \to l'\, \bar{\nu}_{l'})} \stackrel{?}{=} 1$$

Test: Ratios of decay rates that only differ by final lepton content *(e.g.* $B \to D\, l\, \bar{\nu}_l$ *)* should be unity (up to lepton mass dependence).

Experimental Signatures of Flavour Anomalies

Signature Part - General Idea

- Measure B decays that only differ in final lepton content (Test LFU)

$$B \to X l \nu_l \qquad\qquad B \to X l l$$

where X is meson under study

$$R_X \equiv \frac{BR(B \to Xll/l\nu)}{BR(B \to Xl'l'/l'\nu')}$$

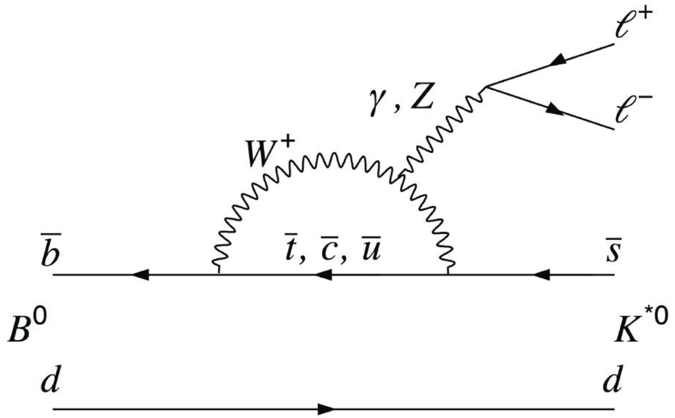
- rare loop induced b decays $R_{K^*}(b \to s)$
- tree-level tauonic decays $R_{D^*}, R_{J/\Psi}(b \to c)$

FCNC (RK)

$$R_{K^{(*)}} \equiv \frac{BR(B \to K^{(*)}\ \mu^+\ \mu^-)}{BR(B \to K^{(*)}\ e^+\ e^-)}$$

- Loop process, rare in SM, good chance for new physics
- Theoretical uncertainties factor out and cancel
- In measurement: double ratio to J/Psi, first order systematic cancellation

From SM: **RK(*) = 1 + phase space corr.**



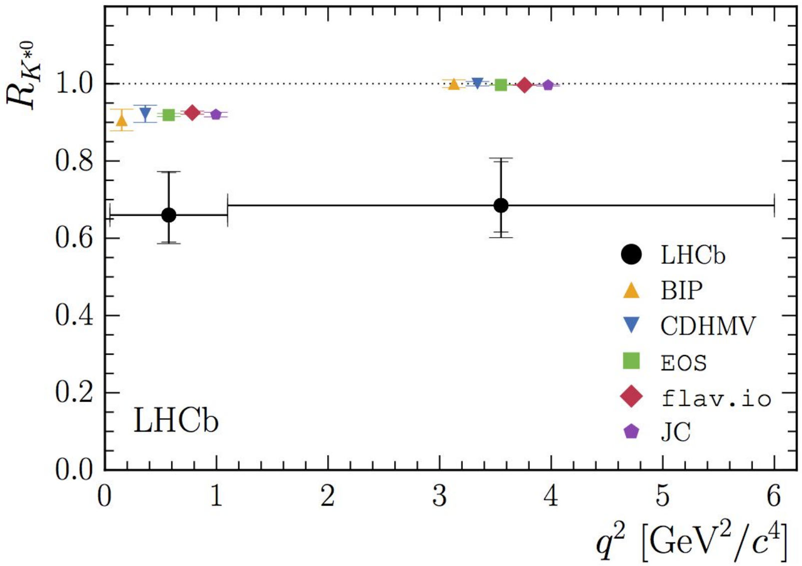
[LHCb, 1705.05802]

FCNC discrepancies

- Two bins:
  → low-q^2 0.0045 GeV^2-1.1 GeV^2

  → central-q^2 1.1 GeV^2 - 6 GeV^2

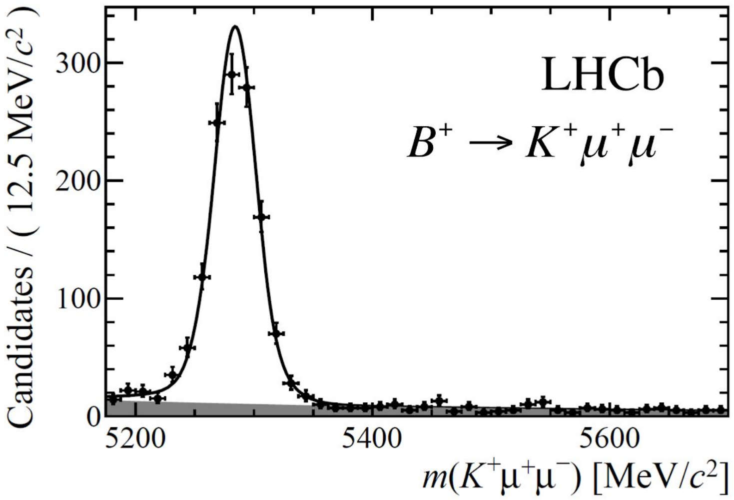
  → good theoretical description

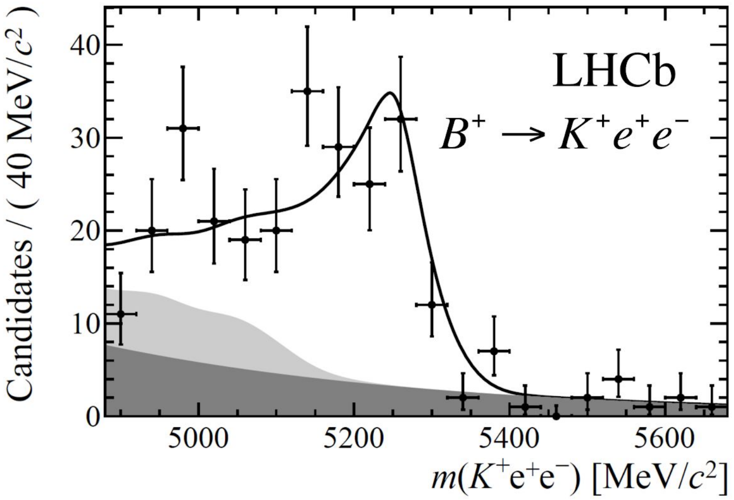


$$R_{K^*} = 0.66\,^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) \quad \text{for } 0.045 < q^2 < 1.1\ \text{GeV}^2/c^4$$
$$R_{K^*} = 0.69\,^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) \quad \text{for } 1.1 < q^2 < 6.0\ \text{GeV}^2/c^4$$

- SM compatibility at 2.2-2.5σ level

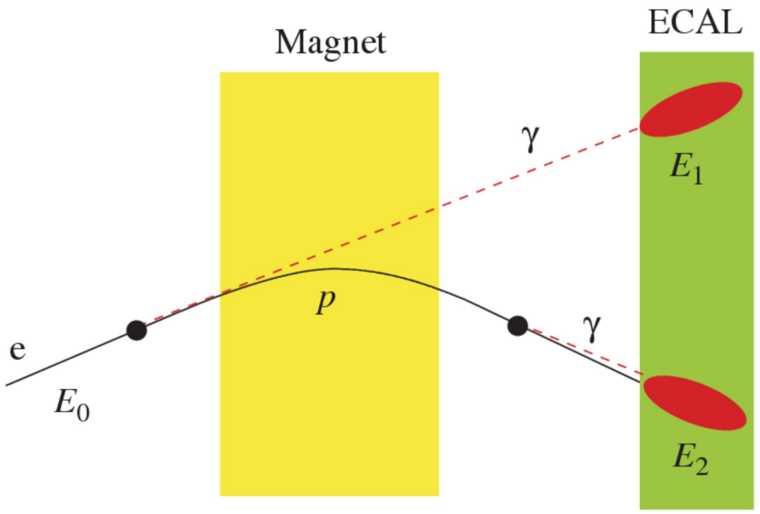
Experimental Difficulties





- Muons very clean
- Electrons more problematic

Difficulties in electron reconstruction



CERN-THESIS-2016-237

- Electron reconstruction difficult
- Bremsstrahlung affects resolution & efficiencies
- Can be partially corrected

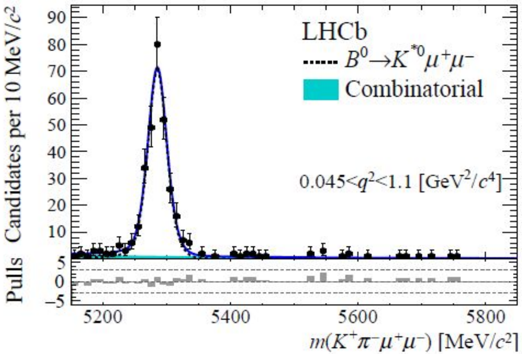
Also: Higher Trigger Threshold for e-

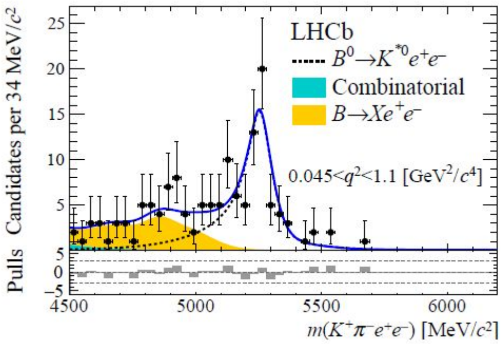
Outlook for the RK(*) anomaly

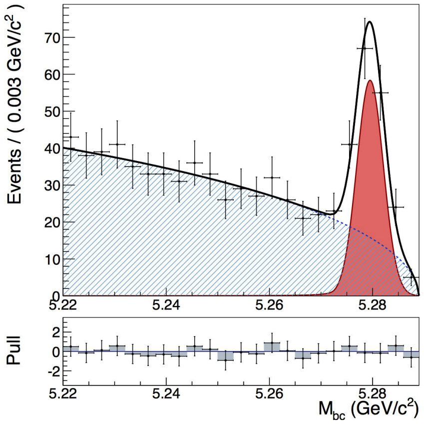
→ Higher statistics from LHCb

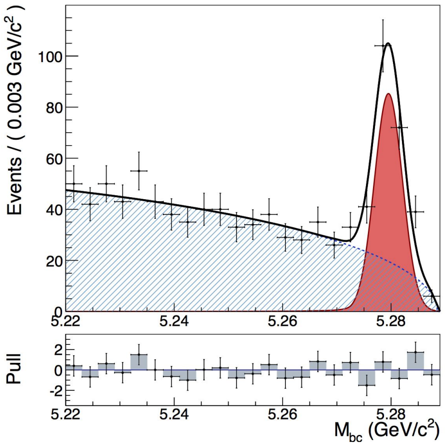
→ New experiment: Belle II

→ Improved resolution in electron channel

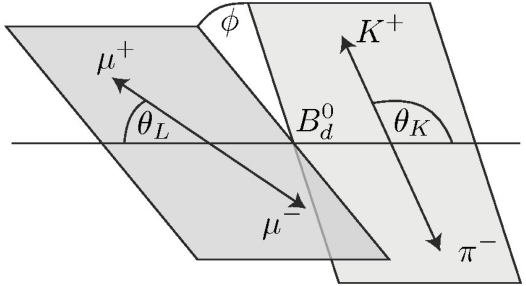






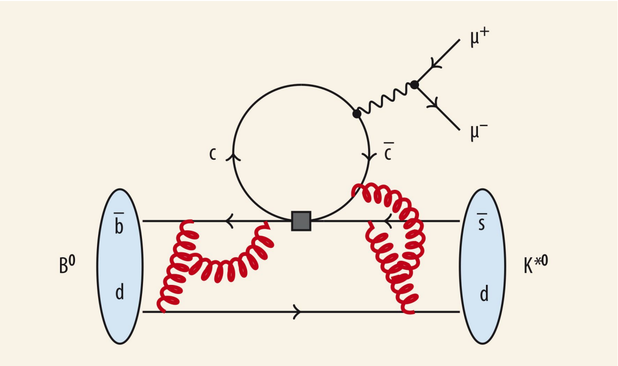


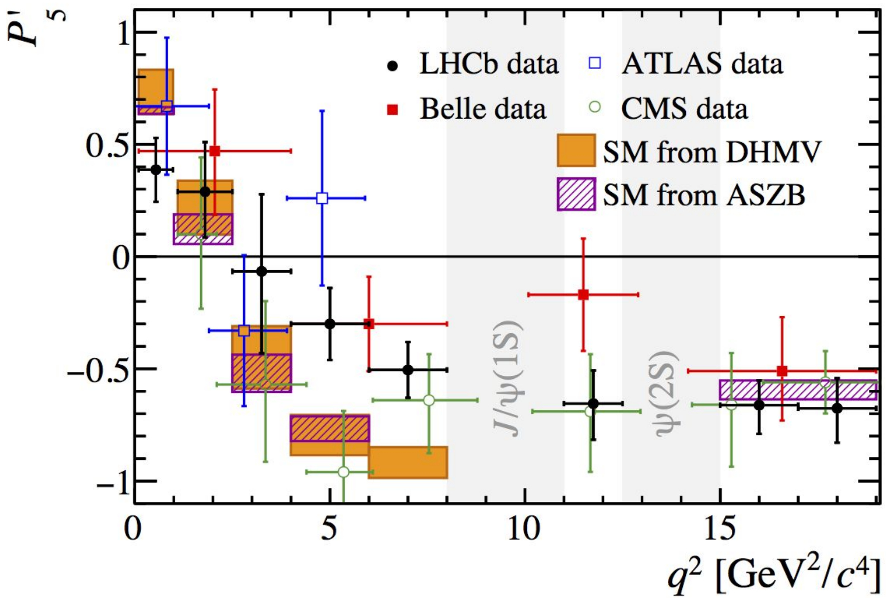
Angular Observable for FCNC



- angular observable P_5'
  -> form factor uncertainties cancel at leading order
- significant tension of 3.4 sigma
- J/Psi: theo. prediction difficult

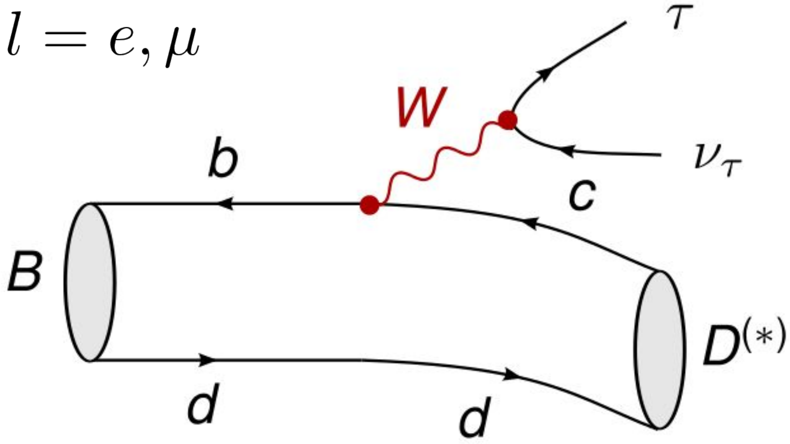
$$\frac{d^4\Gamma}{d\cos\theta_\ell \, d\cos\theta_K \, d\phi \, dq^2}$$





Tree Level (RD,RD*)

$$R_{D^{(*)}} \equiv \frac{BR(B \to D^{(*)}\ \tau\ \bar{\nu}_\tau)}{BR(B \to D^{(*)}\ l\ \bar{\nu}_l)}, \quad \text{with } l = e, \mu$$



→ $R_D \cong 0.3$, $R_{D^*} \cong 0.25$

Problem: $\tau^- \to e^- \bar{\nu}_e \nu_\tau$ or $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$

→ Similar final states in numerator & denominator

[D.Straub, Flavour anomalies, MPIK 2018]

Interlude: Advantages of Belle

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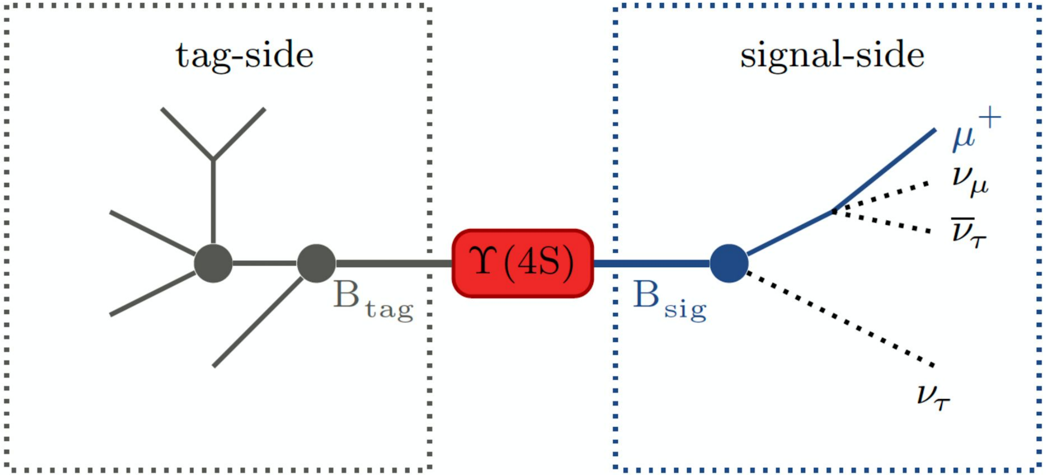
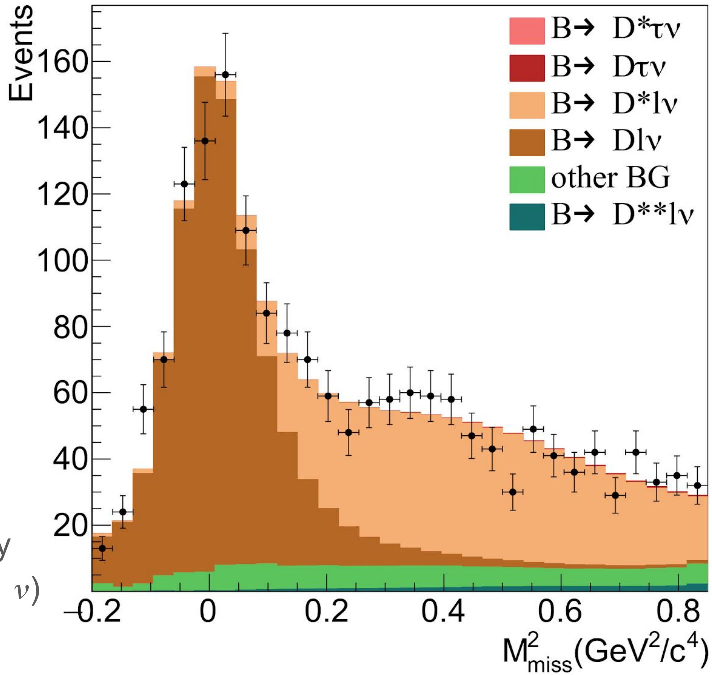


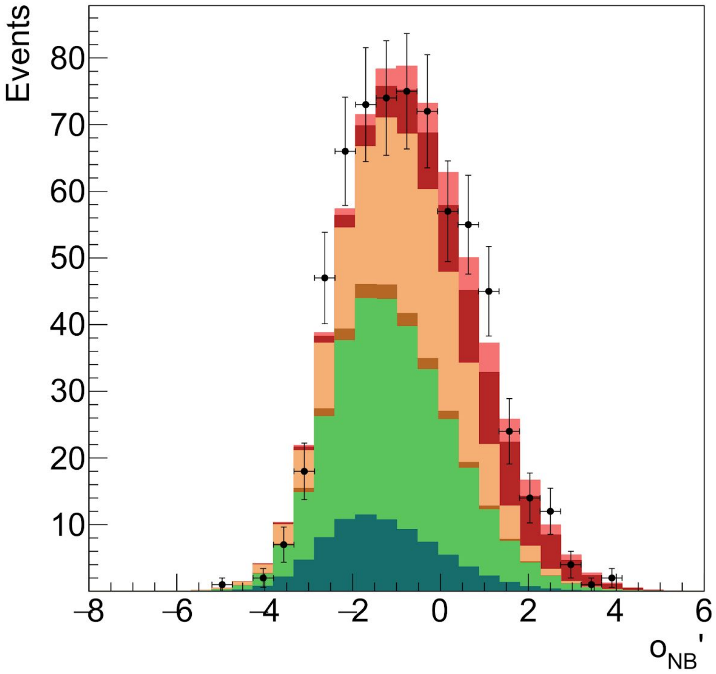
E.g. hadronic: $p_{\text{invisible}} = p_{\text{beam}} - p_{\text{tag}} - p_{\text{visible}}$

→ Different $p_{\text{invisible}}$ for numerator (3 ν) and denominator (1 ν)

M_{miss} distribution sg/bkg

dominated by denominator (1 ν)



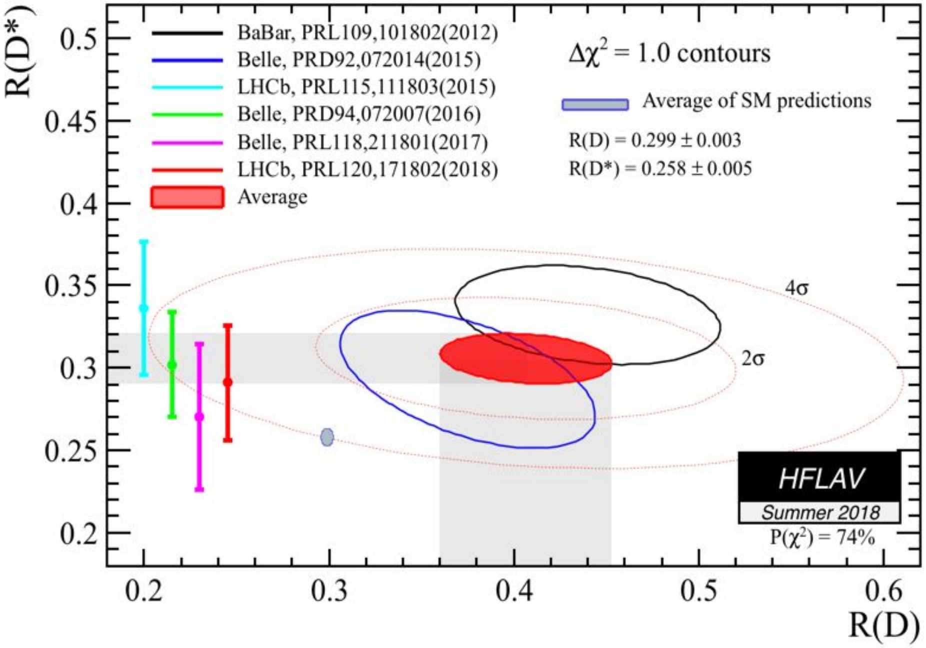


dominated by numerator (3 ν)

$M^2_{miss} < 0.85$

$M^2_{miss} > 0.85$ (+ neural net)

Results (RD,RD*) anomaly



Theory & Model-building

b → s anomalies	**b → c anomalies**
Found by LHCb (and perhaps hinted by Belle)	Found by several experiments (LHCb, BaBar and Belle)
Many observables: global pattern	Two observables: R(D) and R(D*)
Neutral current	Charged current
1-loop (and CKM-suppressed) in the SM	Tree-level in the SM
The New Physics can be heavy	The New Physics must be light

[A. Vicente, Post-FPCP School 2018]

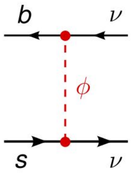
General consideration and remarks

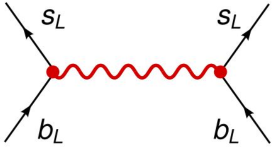
- angular and BR anomalies can be faked by hadronic uncertainties -> QCD effect?
- LFU ratios are “clean” (cannot be mimiced by hadronic physics) -> deviation still below 3 σ

Anomalies can go away

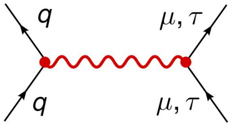
Long list of experimental constraints:

- other flavor observables: Bs-mixing, $B \to K^{(*)}\bar{\nu}\nu$, $b \to s\gamma$

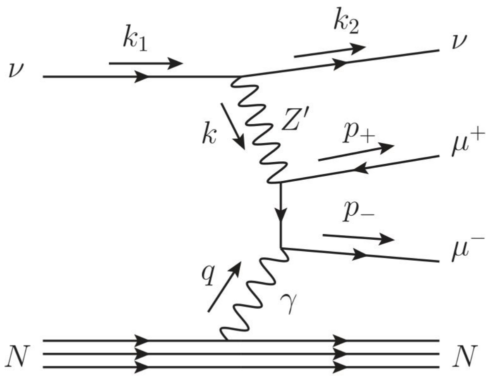




- direct LHC search: $pp \to \mu\mu, \tau\tau$



- lepton universality test: $Z \to ll$
- neutrino trident production
- precision EW data



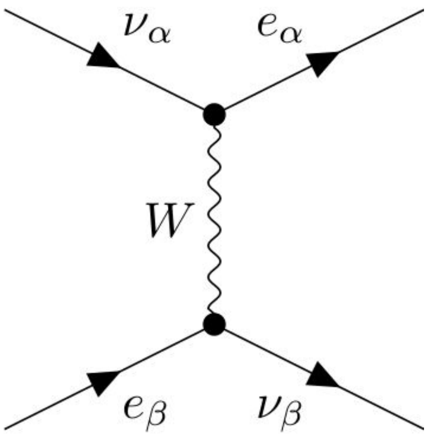
[A. Vicente, Post-FPCP School 2018]

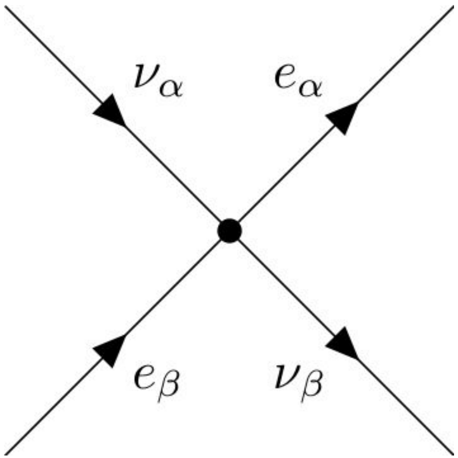
EFT as model-independent approach

Assume:

1. Anomalies caused by New physics
2. new states are "heavy": $\Lambda \gg m_b$

perfect playground for EFT!





$$\frac{g^2}{8m_W^2} \longrightarrow \frac{G_F}{\sqrt{2}}$$

[D.Straub, Flavour anomalies, MPIK 2018]

weak EFT for (b-s) anomaly:

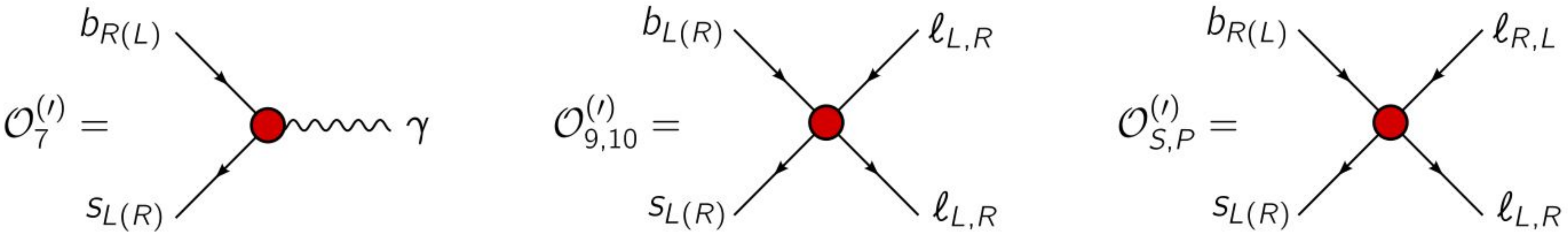
$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}}\frac{e^2}{16\pi^2}V_{tb}V_{ts}^*\sum_i C_i O_i + \text{h.c.}$$

- non-renormalisable operators O_i + Wilson coefficients C_i
- C_i receive contributions from SM and NP
- SM reaction calculable and known with high precision
- **important** for anomaly: $\mathcal{C}_9,\ \mathcal{C}_{10}$

$$O_7^{(\prime)} = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu}$$

$$O_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\ell) \qquad O_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$

$$O_S^{(\prime)} = (\bar{s}P_{R(L)}b)(\bar{\ell}\ell) \qquad O_P^{(\prime)} = (\bar{s}P_{R(L)}b)(\bar{\ell}\gamma_5\ell)$$

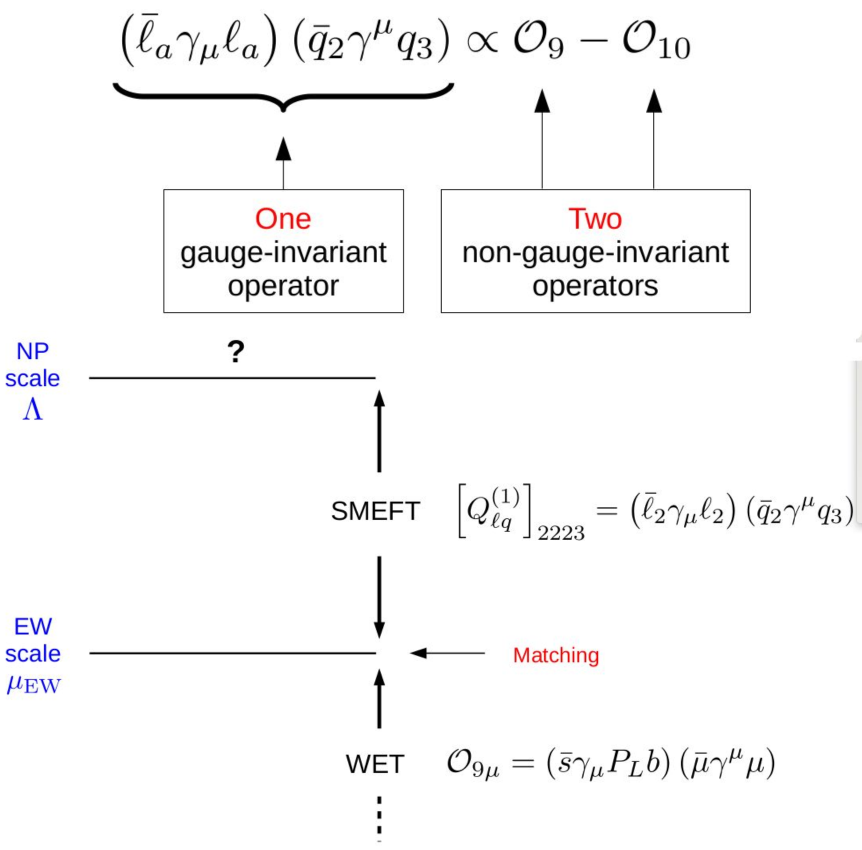


Gauge-invariant EFT approach: SMEFT

- non-gauge invariant EFTs **miss** relations among operators
- formulate EFT in terms of gauge-invariant operators
  - up to dim-6
  - 2499 real parameters
  - full 1-loop RGEs computed

SMEFT operator	Definition	Matching	Order
$[Q_{\ell q}^{(1)}]_{aa23}$	$(\bar{\ell}_a \gamma_\mu \ell_a)(\bar{q}_2 \gamma^\mu q_3)$	$\mathcal{O}_{9,10}$	Tree
$[Q_{\ell q}^{(3)}]_{aa23}$	$(\bar{\ell}_a \gamma_\mu \tau^I \ell_a)(\bar{q}_2 \gamma^\mu \tau^I q_3)$	$\mathcal{O}_{9,10}$	Tree
$[Q_{qe}]_{23aa}$	$(\bar{q}_2 \gamma_\mu q_3)(\bar{e}_a \gamma^\mu e_a)$	$\mathcal{O}_{9,10}$	Tree
$[Q_{\ell d}]_{aa23}$	$(\bar{\ell}_a \gamma_\mu \ell_a)(\bar{d}_2 \gamma^\mu d_3)$	$\mathcal{O}'_{9,10}$	Tree
$[Q_{ed}]_{aa23}$	$(\bar{e}_a \gamma_\mu e_a)(\bar{d}_2 \gamma^\mu d_3)$	$\mathcal{O}'_{9,10}$	Tree
$[Q_{\varphi \ell}^{(1)}]_{aa}$	$\left(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi\right)(\bar{\ell}_a \gamma^\mu \ell_a)$	$\mathcal{O}_{9,10}$	1-loop
$[Q_{\varphi \ell}^{(3)}]_{aa}$	$\left(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi\right)(\bar{\ell}_a \gamma^\mu \tau^I \ell_a)$	$\mathcal{O}_{9,10}$	1-loop
$[Q_{\ell u}]_{aa33}$	$(\bar{\ell}_a \gamma_\mu \ell_a)(\bar{u}_3 \gamma^\mu u_3)$	$\mathcal{O}_{9,10}$	1-loop
$[Q_{\varphi e}]_{aa}$	$\left(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi\right)(\bar{e}_a \gamma^\mu e_a)$	$\mathcal{O}_{9,10}$	1-loop
$[Q_{eu}]_{aa33}$	$(\bar{e}_a \gamma_\mu e_a)(\bar{u}_3 \gamma^\mu u_3)$	$\mathcal{O}_{9,10}$	1-loop

[A. Vicente, Post-FPCP School 2018]



Global fits

Inclusive

$B \to X_s\gamma$ (BR) .... $C_7^{(\prime)}$

$B \to X_s\ell^+\ell^-$ (dBR/dq²) .... $C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$

Exclusive leptonic

$B_s \to \ell^+\ell^-$ (BR) .... $C_{10}^{(\prime)}$

Exclusive radiative/semileptonic

$B \to K^*\gamma$ (BR, S, A_I) .... $C_7^{(\prime)}$

$B \to K\ell^+\ell^-$ (dBR/dq²) .... $C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$

$B \to K^*\ell^+\ell^-$ (dBR/dq², angular obs.) ... $C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$

$B_s \to \phi\,\ell^+\ell^-$ (dBR/dq², angular obs.) ... $C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$

[A. Vicente, Post-FPCP School 2018]

- same Wilson coefficients enter several observables
- use pattern of deviations to extract "best" value

→ NP preferred over SM by more than 4-5σ !

→ C9μ seems to be crucial !

	All					LFUV				
1D Hyp.	Best fit	1 σ	2 σ	$\mathrm{Pull_{SM}}$	p-value	Best fit	1 σ	2 σ	$\mathrm{Pull_{SM}}$	p-value
$\mathcal{C}_{9\mu}^{\rm NP}$	-1.10	$[-1.27, -0.92]$	$[-1.43, -0.74]$	5.7	72	-1.76	$[-2.36, -1.23]$	$[-3.04, -0.76]$	3.9	69
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$	-0.61	$[-0.73, -0.48]$	$[-0.87, -0.36]$	5.2	61	-0.66	$[-0.84, -0.48]$	$[-1.04, -0.32]$	4.1	78
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{9\mu}^{\prime}$	-1.01	$[-1.18, -0.84]$	$[-1.33, -0.65]$	5.4	66	-1.64	$[-2.12, -1.05]$	$[-2.52, -0.49]$	3.2	31
$\mathcal{C}_{9\mu}^{\rm NP} = -3\mathcal{C}_{9e}^{\rm NP}$	-1.06	[-1.23,-0.89]	[-1.39,-0.71]	5.8	74	-1.35	$[-1.82, -0.95]$	$[-2.38, -0.59]$	4.0	71

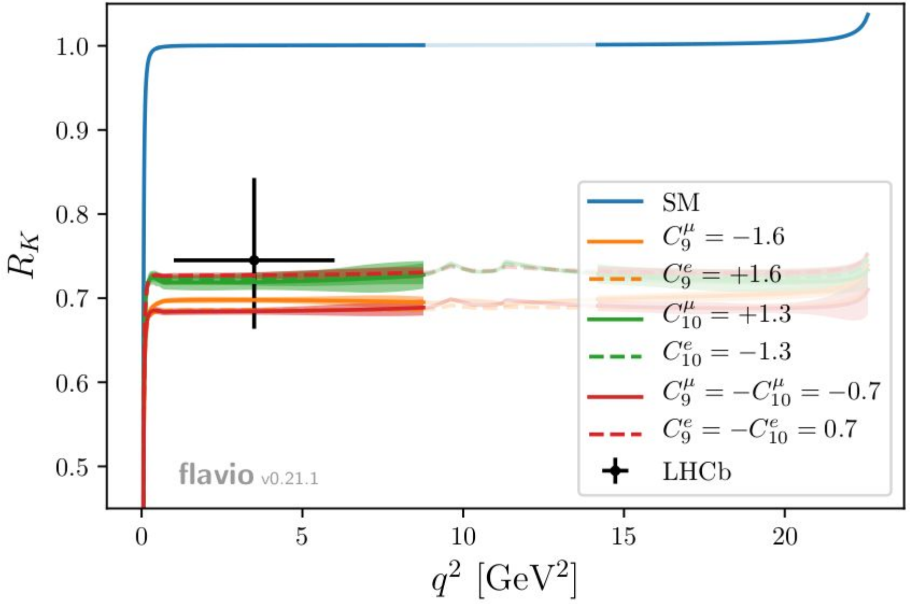
All observables
"clean" + "dirty"

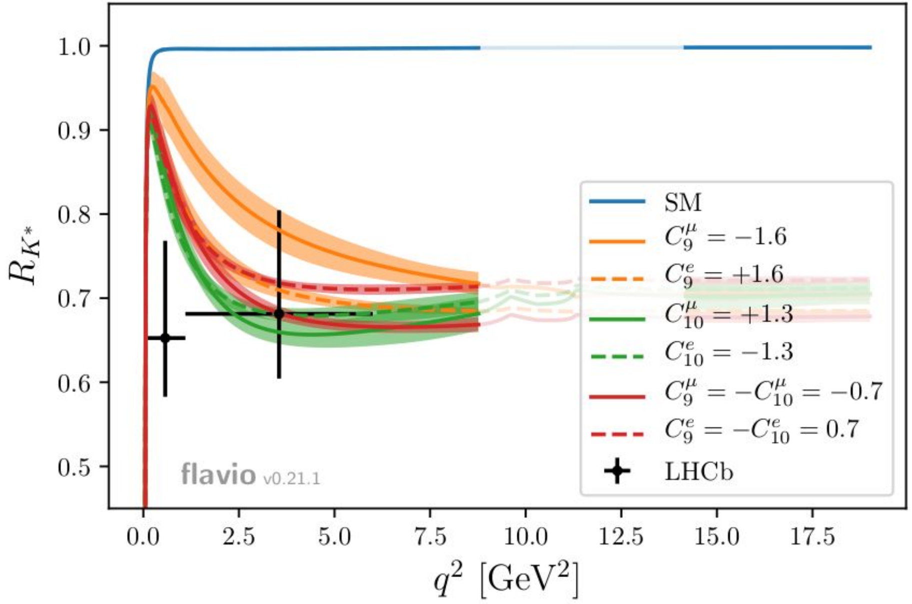
Only LFUV observables
"clean"

[Capdevila et al, 1704.05340]

Model-independent fits to $\mathcal{C}_{9,10}^{(\prime)}$

e.g. in context of $R_{K^{(*)}}$





More observables needed for discrimination among different best-fit scenarios !

[D.Straub, Flavour anomalies, MPIK 2018]

UV models: difficulties & common features

- Loop suppression of neutral currents with respect to the charged ones.
- NP: $J_{quark} \times J_{lepton}$ with no traces in $J_{quark} \times J_{quark}$ (constraints from B_s mixing) and $J_{lepton} \times J_{lepton}$ (constraints from pure LFV/LUV decays).
- Most models involve:
  - New charged (coloured) states.
  - Mass ~TeV (to explain relatively large effects).
  - Significant coupling to the 3rd-generation SM fermions (constraints from resonances decaying to $\tau\tau$ pairs).

Typical UV complete theory contains new states that are:

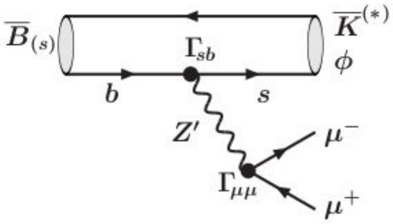
- Lorentz scalars/vectors
- $SU(3)_c$: singlet/triplet; $SU(2)_L$: singlet/doublet/triplet.

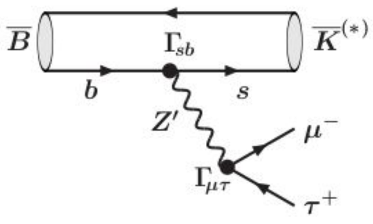
[1703.02804]

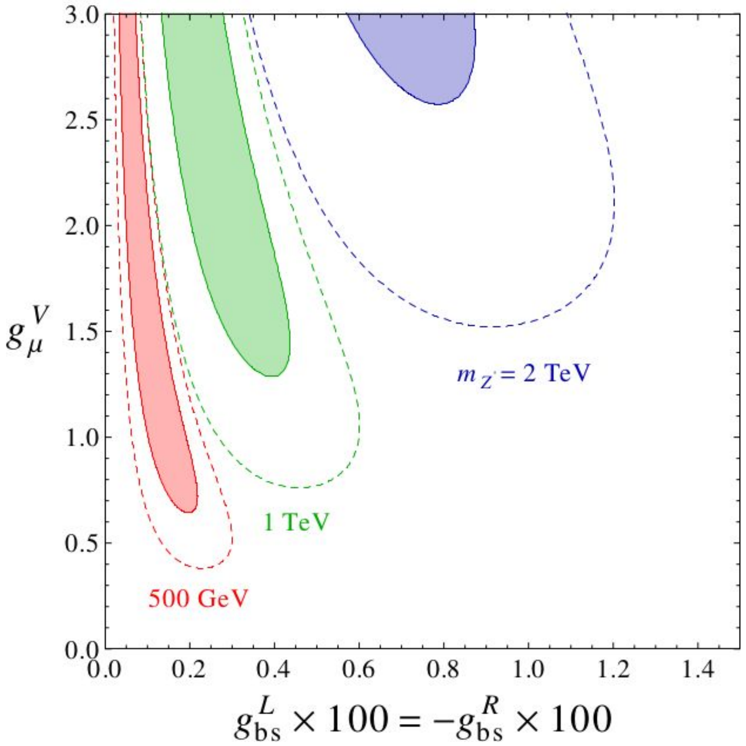
Example #1: Z′

Explains B → K anomalies for m_Z~TeV

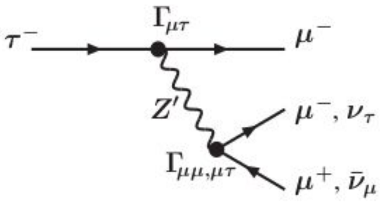
Additional $U(1)_x$ generates O_9, O_{10}:

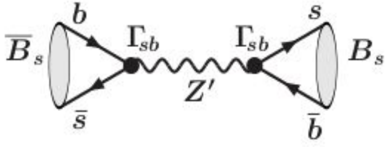






But also:





[1504.07928, 1308.1501]

Example #2: leptoquark

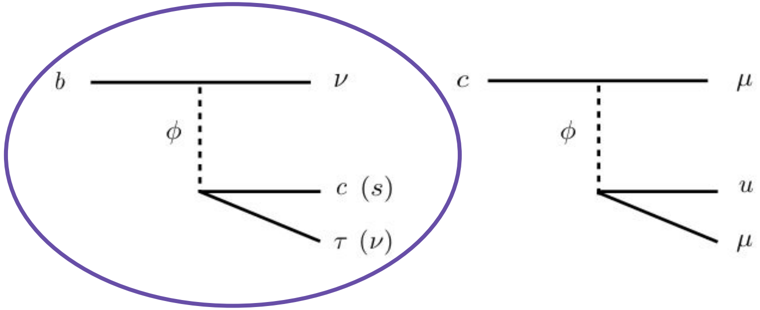
New scalar field: $SU(3)_c$-triplet, $SU(2)_L$- singlet.

Can it explain both B → K & B → D anomalies?

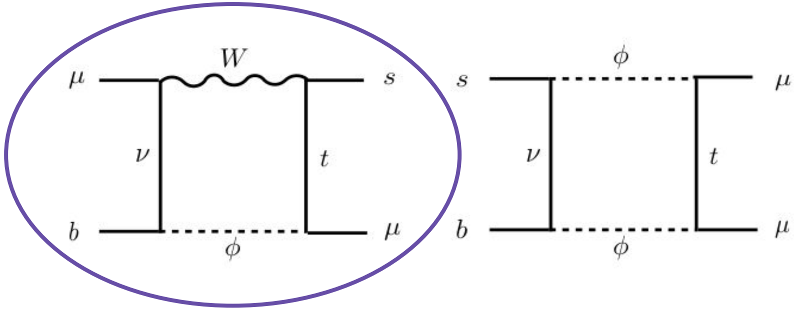
Requiring also electric charge equal to -⅓...

Example #2: leptoquark

B → D*τν: tree-level

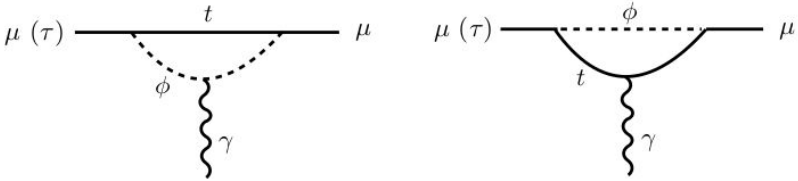


B → K*ll: only at 1-loop level



[1511.01900]

But also:



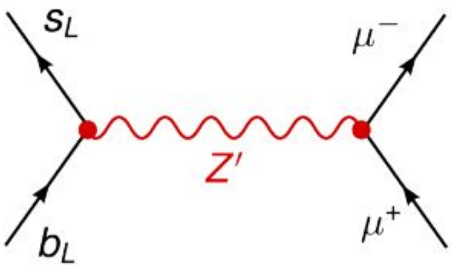
(Bounds from $B_S - \bar{B}_S$ mixing, $D \to \mu^+\mu^-$, $\tau \to \mu\gamma$)

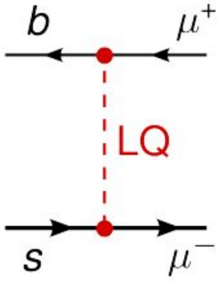
Explains both B → K & B → D anomalies for m_ϕ~TeV *

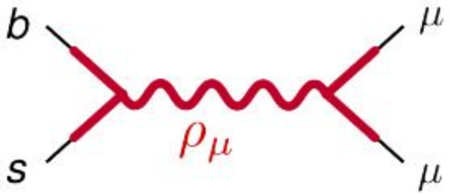
*According to 1608.07583, accurate calculation of the loop-induced effects makes $R^{\tau/l}_D$ inconsistent with data.

Mainstream models:

1. Z’
   - flavor-changing coupling to LH quarks
   - VL couplings to leptons
   - flavor violation or non-universality in lepton sector
2. Leptoquarks
   - scalar or vector
   - not simult. lepton non-universal and L conserving
3. Compositeness
   - neutral resonance, coupling to muons (part. composite)
   - lepton flavor violating couplings
   - constrained by LEP (Z-width) and B_s-B_s-mixing







[N. Mahmoudi, DM@LHC 2018]

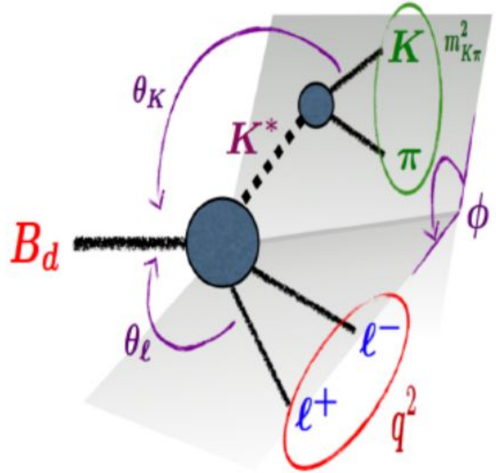
Summary: Flavor could be around the corner!

- SM prediction: LFU!
- Several anomalies in B physics
  - b->s μμ BR & P_5' - hadr. uncertainties, but significant
  - $R_K^{(*)}$ - theo. clean but not too significant
  - $R_D^{(*)}$ - theo. clean and significant
- NP highly constrained, but combined NP solution for all anomalies possible!
- More data and new experiments crucial
  - LHC Run 2
  - Belle-II experiment

Backup

Angular observables

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\Big[J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_l$$
$$+J_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + J_4\sin 2\theta_K\sin 2\theta_l\cos\phi + J_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+(J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_l + J_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+J_8\sin 2\theta_K\sin 2\theta_l\sin\phi + J_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$



[Figure borrowed from Javier Virto]

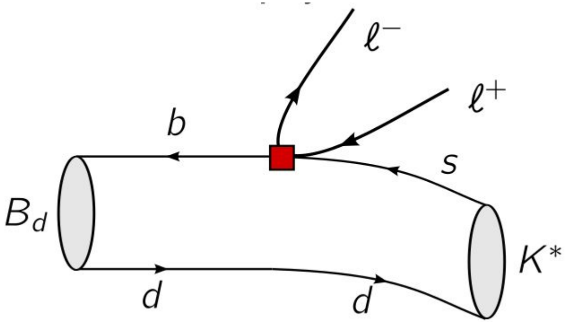
$$J_i \,:\, \text{functions of}\, q^2, C_i, \text{FF}$$

Optimized observables
[Descotes-Genon et al, 2012, 2013]

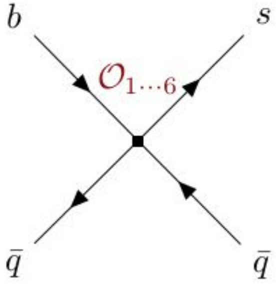
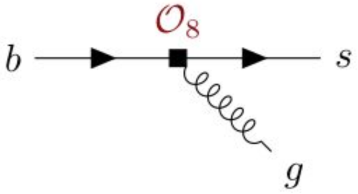
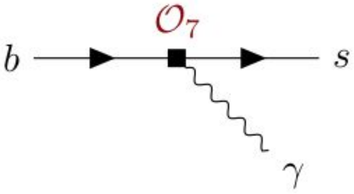
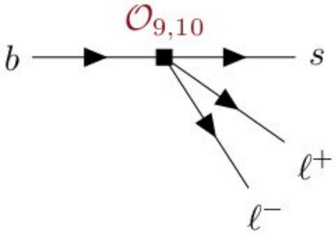
$$P_5' = \frac{J_5}{2\sqrt{-J_{2s}J_{2c}}}$$

[A. Vicente, Post-FPCP School 2018]

weak EFT operators



Operator set for $b \to s$ transitions:

4-quark operators	chromomagnetic dipole operator	electromagnetic dipole operator	semileptonic operators
			
$\mathcal{O}_{1,2} \propto (\bar{s}\Gamma_\mu c)(\bar{c}\Gamma^\mu b)$ $\mathcal{O}_{3,4} \propto (\bar{s}\Gamma_\mu b)\sum_q(\bar{q}\Gamma^\mu q)$	$\mathcal{O}_8 \propto (\bar{s}\sigma^{\mu\nu} T^a P_R) G^a_{\mu\nu}$	$\mathcal{O}_7 \propto (\bar{s}\sigma^{\mu\nu} P_R) F^a_{\mu\nu}$	$\mathcal{O}_9^\ell \propto (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell)$ $\mathcal{O}_{10}^\ell \propto (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\gamma_5 \ell)$

+ the chirality flipped counter-parts of the above operators, $\mathcal{O}_i'$

[N. Mahmoudi, DM@LHC 2018]

Typical EFT scales

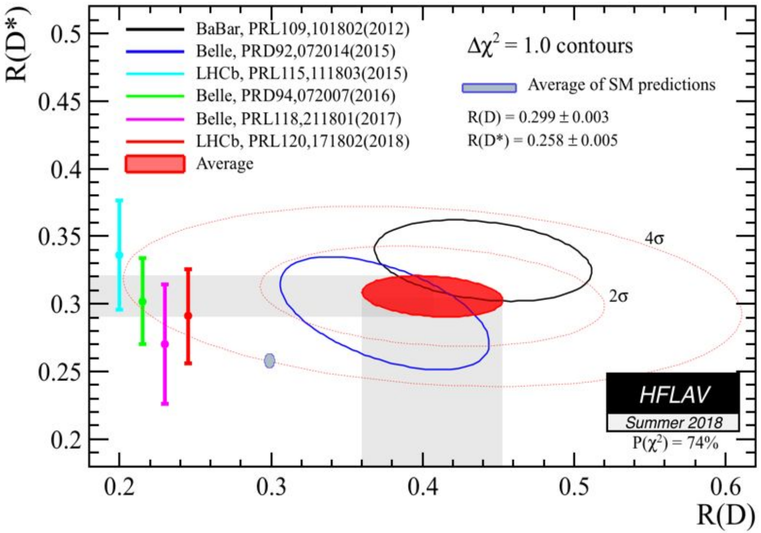
All scales Λ_i probed so far appear to be rather large:

Order	Observable	New-physics scale for g=O(1)
D=5	Neutrino oscillations	$\Lambda \sim 10^9$ TeV
D=6	Proton decay	$\Lambda > 10^{12}$ TeV
D=6	Flavor physics	$\Lambda > 1$–10^5 TeV
D=6	EWPT	$\Lambda > 1$ TeV
D=6	Higgs couplings	$\Lambda > 0.5$–1 TeV

[M. Neubert, Exotic Hadrons & Flavor Physics 2018]

combination of measurements

- “orthogonal” systematic uncertainties
- test different regions of parameter space
- plot
- combined significance…
- future improvements and prospects
- projected uncertainty and limitations



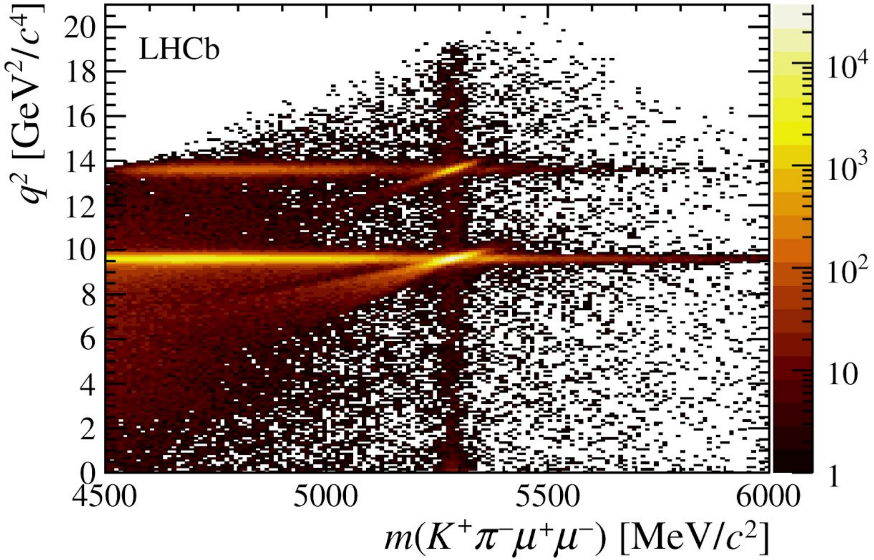
-> final comment:LHCb+Belle -> final data samples will be sufficient to confirm discovery of anomalies or rule it out

-> hot topic that could guide us to new physics -> Theory consideration part

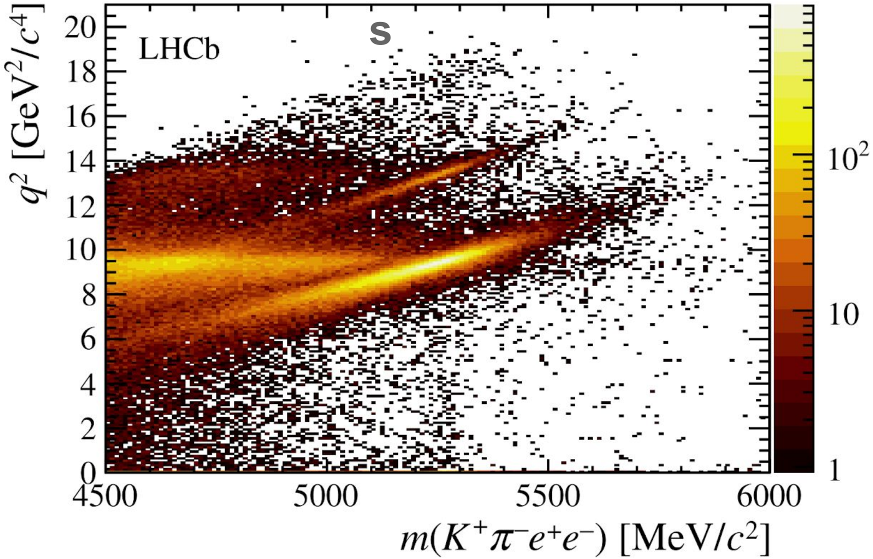
PID - q^2 versus mass

JHEP08(2017)055

Muons



Electron



- J/Psi & Y(2s) visible as horizontal lines
- Vertical line: B-> $K^*l^+l^-$

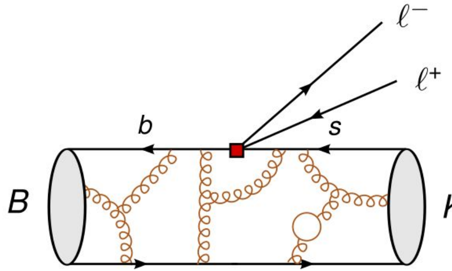
Challenges on both sides ...

Experimental measurements:

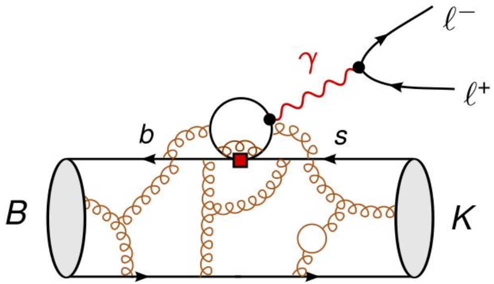
- tbd
- tbd

Theoretical calculations:

- form factors: require non-perturbative calculations



- “non-factorisable” hadronic effects: problematic since easily generated at tree-level



[D.Straub, Flavour anomalies, MPIK 2018]