UV aspects of B-physics anomalies

Marco Nardecchia

26 September, University of Zurich.

Outline

- Review of the flavour anomalies in charged and neutral currents

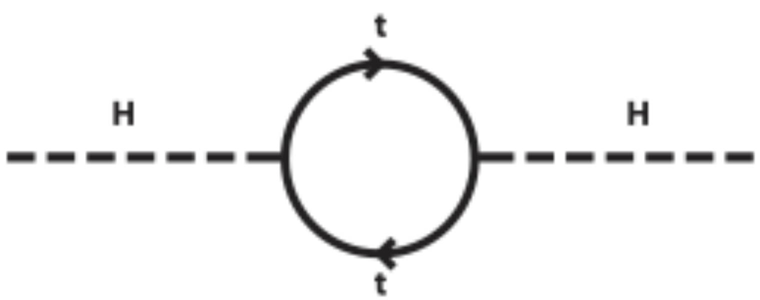
- Combined explanations (EFT and simplified models)

- The UV challenge: a weakly coupled and renormalizable model featuring a gauge leptoquark

- Conclusions

Pre-LHC prejudice VS data

- Upper bound from naturalness of the Higgs mass $\Lambda < 1\ \mathrm{TeV}$



$$m_H^2 = m_{\mathrm{tree}}^2 + \delta m_H^2$$

$$\delta m_H^2 = \frac{3}{\sqrt{2}\pi^2} G_F m_t^2 \Lambda^2 \approx (0.3\,\Lambda)^2$$

- Lower bounds from FCNC

$$\Lambda > \begin{cases} 1.3 \times 10^4\ \mathrm{TeV} \times |c_{sd}|^{1/2} \\ 5.1 \times 10^2\ \mathrm{TeV} \times |c_{bd}|^{1/2} \\ 1.1 \times 10^2\ \mathrm{TeV} \times |c_{bs}|^{1/2} \end{cases}$$

- Two (problematic) possibilities:

(i) Non canonical, $\Lambda \gg 1\ \mathrm{TeV}$ and $c_{ij} = \mathcal{O}(1)$ Hierarchy Problem

(ii) Canonical, $\Lambda < 1\ \mathrm{TeV}$ and $c_{ij} \ll 1$ BSM Flavour Problem

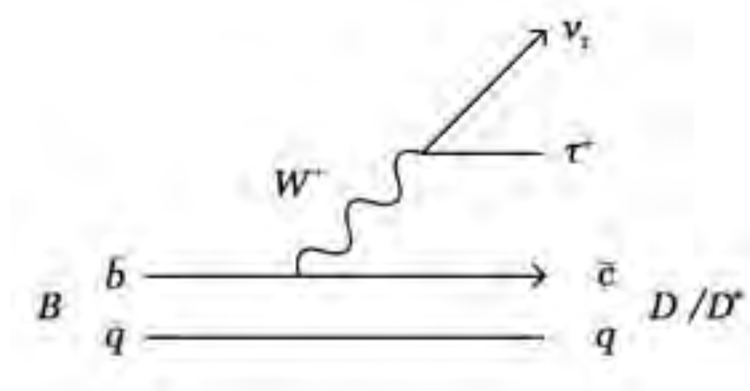
- "Standard" solution to (ii): exciting NP at ATLAS-CMS, boring flavour physics at LHCb protected by MFV

- However data are suggesting the opposite…. no on-shell effects but very interesting series of flavour anomalies….

Flavour Anomalies (B-decays)

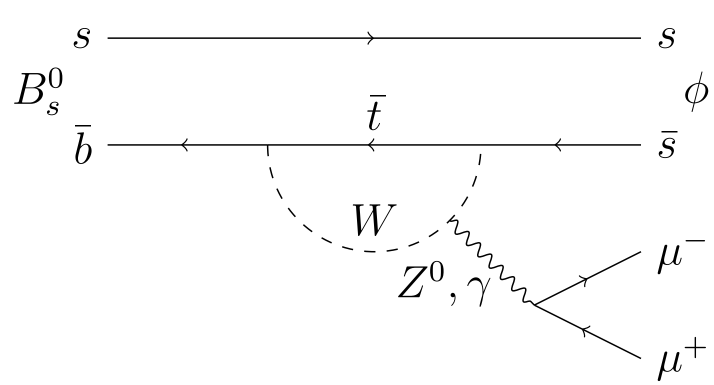
Two different set of measurements

1) Flavour Changing Charged Current $b \to c\,\ell\,\nu_\ell$ $(B \to D^{(*)}\tau\nu, \ldots)$



2) Flavour Changing Neutral Current $b \to s\ell\ell$

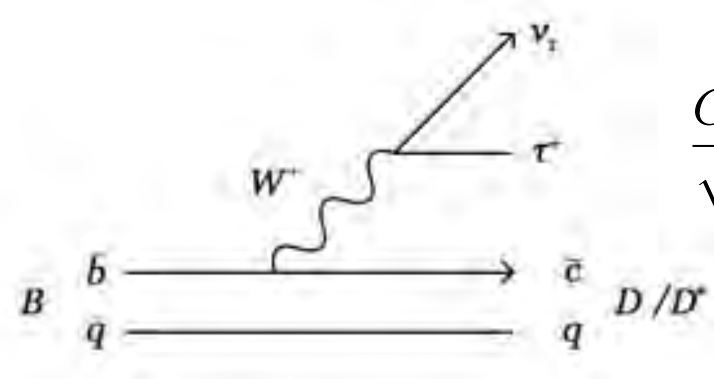
$$(B \to K^*\mu\mu, B \to \phi\mu\mu, R_K, \ldots)$$



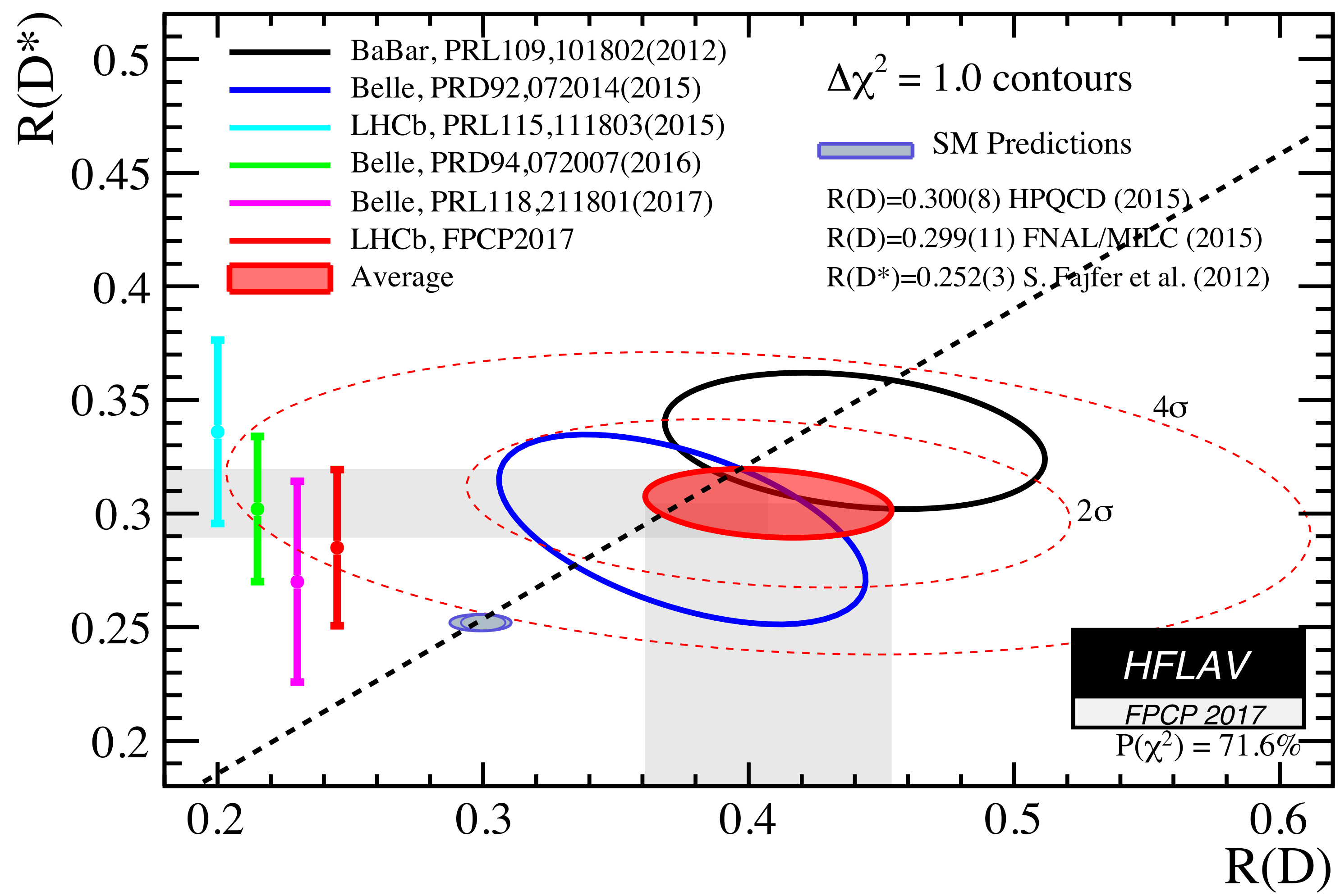
$b \to c\tau\nu$

$$R(X) = \frac{\mathcal{B}(\bar{B} \to X\tau\bar{\nu})}{\mathcal{B}(\bar{B} \to Xl\bar{\nu})} \qquad X = D, D^* \quad l = \mu, e$$

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} V_{bc}^* (\bar{b}_L \gamma^\alpha c_L)(\bar{\tau}_L \gamma_\alpha \nu_\tau)$$



$$\frac{G_F}{\sqrt{2}} V_{bc}^* = \frac{1}{(1.7\ \text{TeV})^2}$$



- SM predictions are quite robust
- Seen in 3 different experiments in a consistent way, combined significance 4.1σ
- Measurements are consistent with e/mu universality
- In the SM the flavour transition is unsurpassed by loop factor (tree-level charged current)
- Assuming central values, NP has to be large, fits prefer SM structure (left current)
- Data could be fitted by new interactions with mediator at the EW scale
- Various constraints on model building, EWPT, other flavour observables, direct searches
- Best fit: purely left operator SM(1+30%)

Lepton Flavor Universality: $R(J/\psi)$ NEW

LHCb-PAPER-2017-035

- Generalization of $R(D^*)$ to the B_c sector

$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu)}$$

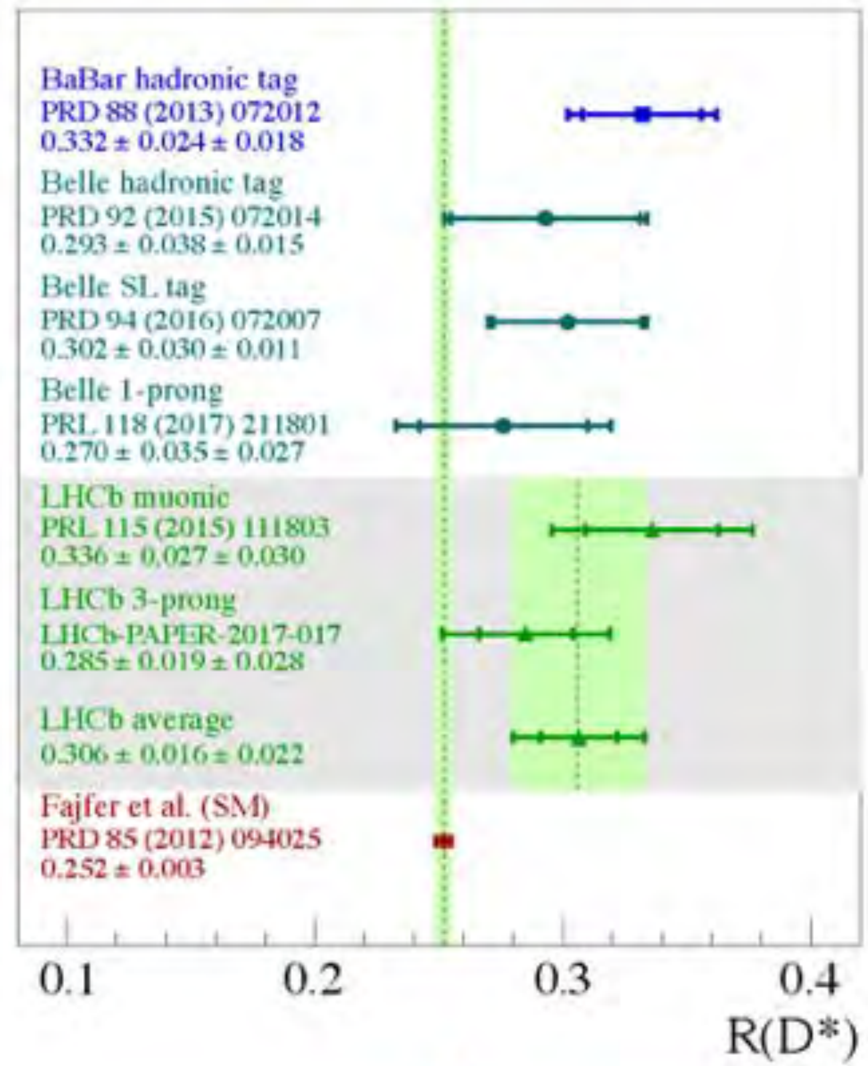
- B_c decay form factors unconstrained experimentally: theoretical prediction not yet precise 0.25-0.28
- Reconstruct signal with $\tau \to \mu \nu_\mu \nu_\tau$ (17%)
- Dataset: Run 1 (3 fb^{-1})

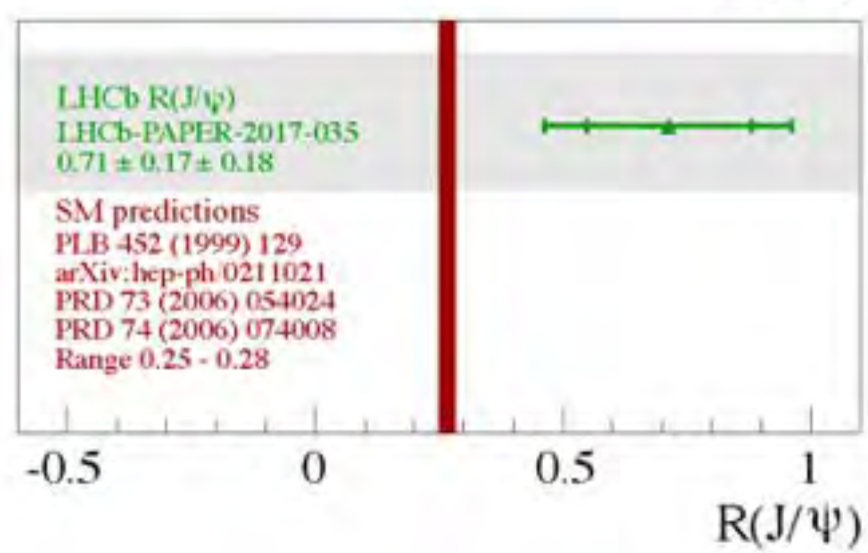
$$R(J/\psi) = 0.71 \pm 0.17 \pm 0.18$$

(about 2 σ from SM)

Excellent future prospects:

- Run I + Run II data with extra MC allow finer binning in missing mass
- Form factors systematics reduced by LQCD work + dedicated form factor study
- Only LHCb can perform this measurement





$b \to s\ell\ell$

1) Tension in the LHCb data coming from $B \to K^* \mu^+ \mu^-$ angular observables

2) Various measurements of branching ratios are low compared to the SM prediction

(in particular $B_S^0 \to \phi \mu^+ \mu^-$)

3) Hint of violation of lepton universality in R_K R_{K^*}

[4) Leptonic decay $B_s \to \mu^+ \mu^-$]

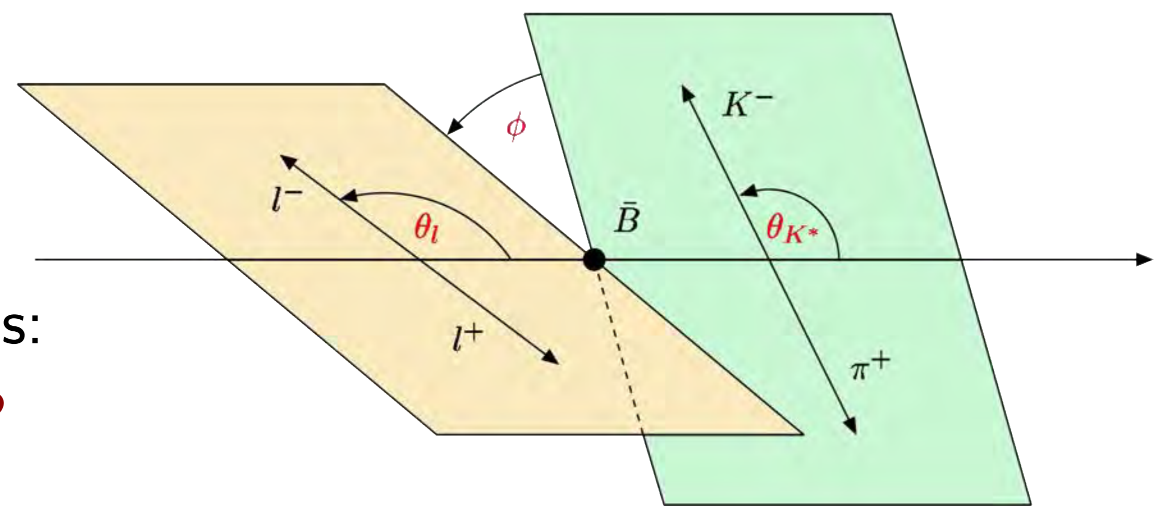
Coherently explained invoking New Physics in a single effective operator

$$\left(\frac{1}{30 \text{ TeV}} \right)^2 \bar{b}_L \gamma^\mu s_L \, \mu \gamma_\mu \mu$$

$B \to K^* \mu^+ \mu^-$

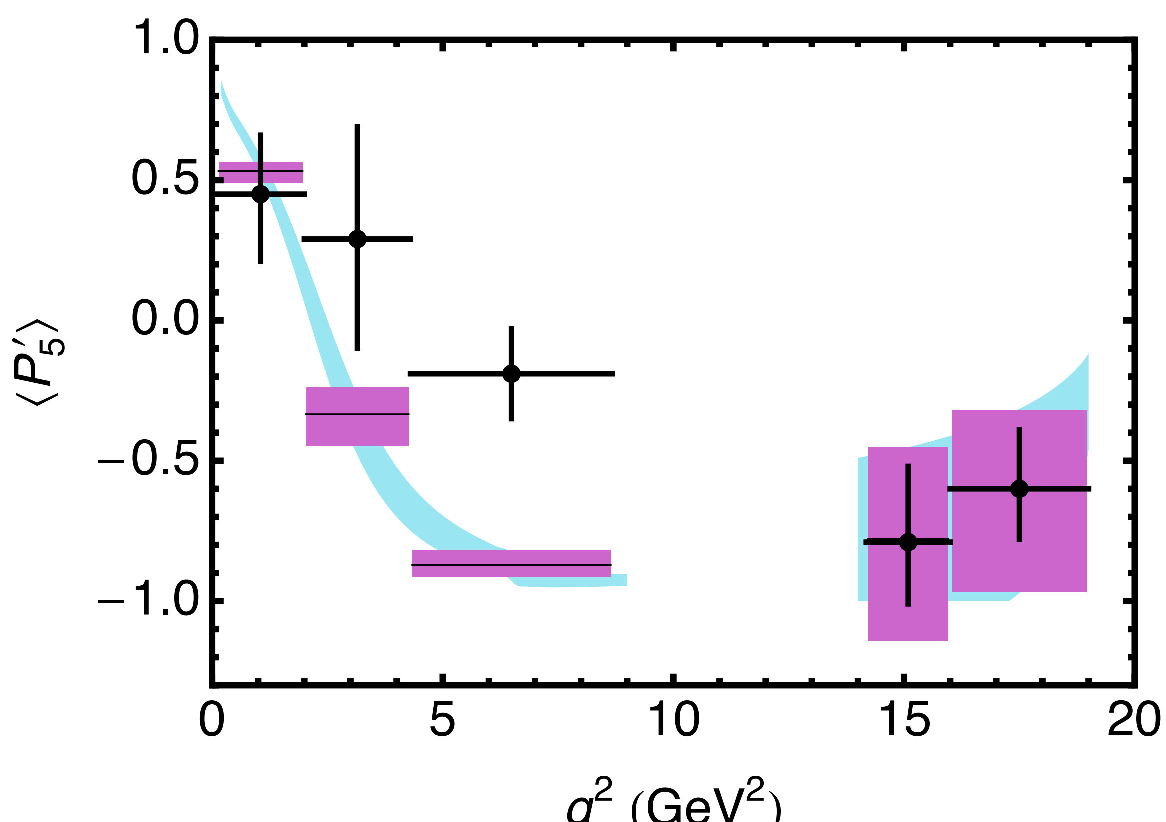
Angular distributions

$\bar{B}^0 \to \bar{K}^{*0}\ell^+\ell^-$ $(\bar{K}^{*0} \to K^-\pi^+)$ full angular distribution described by four kinematic variables: q^2 (dilepton invariant mass squared), θ_ℓ, θ_{K^*}, ϕ



$$\frac{d^4\Gamma[B \to K^*(\to K\pi)\ell\ell]}{dq^2\, d\cos\theta_\ell\, d\cos\theta_{K^*}\, d\phi}$$

LHCb,1308.1707, PRL



SM=JHEP,1303.5794

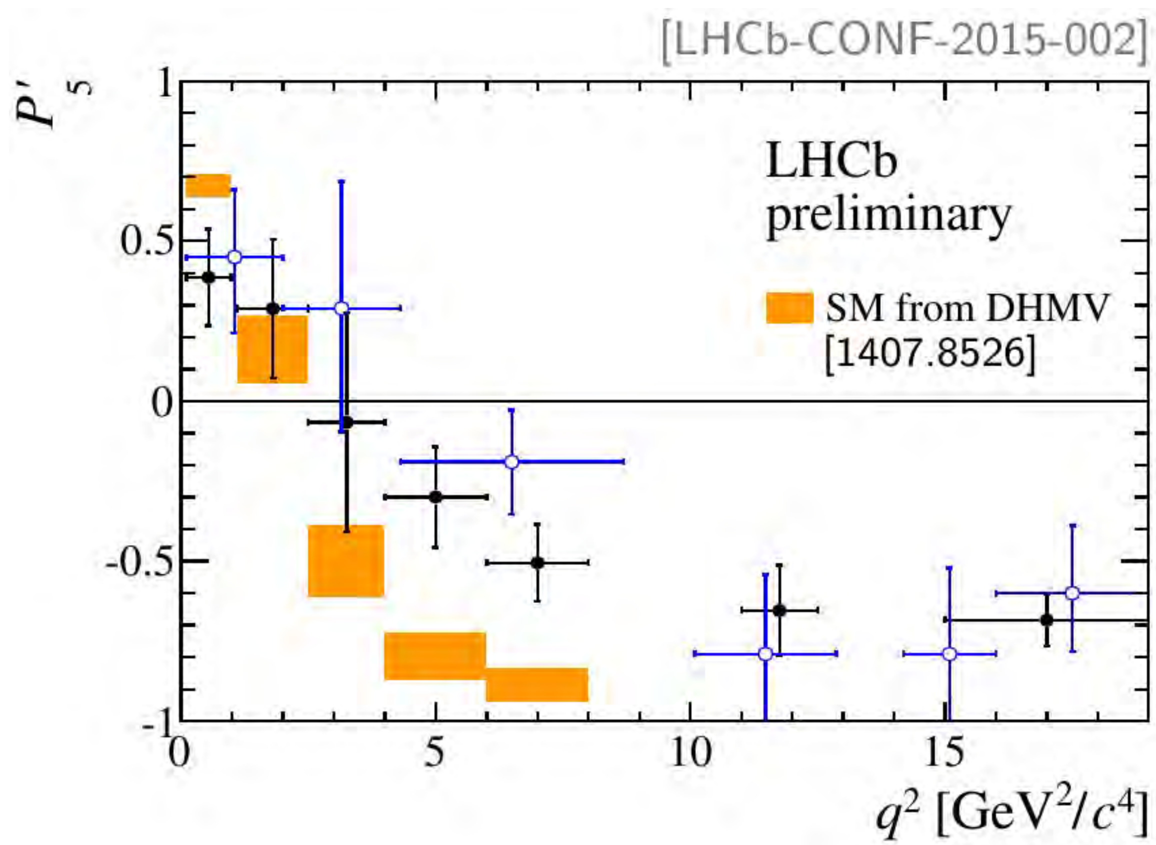
3.7σ discrepancy in one of q^2 bins

Explanations:

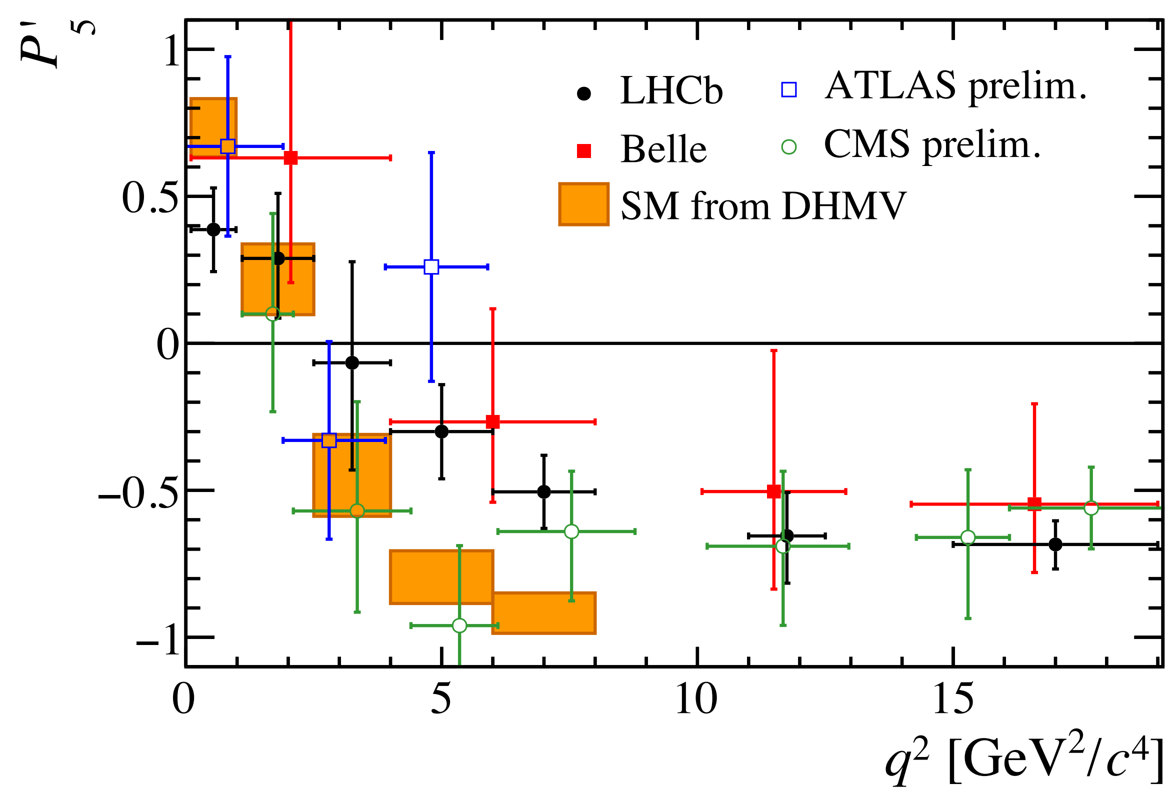
1. Statistical fluctuation?
2. Hadronic uncertainties
3. New Physics

2. From Ciuchini, et al., JHEP,1512.07157
"No deviation is present once all the theoretical uncertainties are take into account"

$B \to K^* \mu^+ \mu^-$



Moriond EW
2015



Moriond EW
2017

Branching ratios

Various measurements of branching ratios are low compared to the SM prediction

Decay	obs.	q^2 bin	SM pred.	measurement		pull
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[2, 4.3]$	0.81 ± 0.02	0.26 ± 0.19	ATLAS	$+2.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[4, 6]$	0.74 ± 0.04	0.61 ± 0.06	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	$[4, 6]$	-0.33 ± 0.03	-0.15 ± 0.08	LHCb	-2.2
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[1.1, 6]$	-0.44 ± 0.08	-0.05 ± 0.11	LHCb	-2.9
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[4, 6]$	-0.77 ± 0.06	-0.30 ± 0.16	LHCb	-2.8
$B^- \to K^{*-}\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	$[4, 6]$	0.54 ± 0.08	0.26 ± 0.10	LHCb	$+2.1$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8 \frac{dBR}{dq^2}$	$[0.1, 2]$	2.71 ± 0.50	1.26 ± 0.56	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8 \frac{dBR}{dq^2}$	$[16, 23]$	0.93 ± 0.12	0.37 ± 0.22	CDF	$+2.2$
$B_s \to \phi\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	$[1, 6]$	0.48 ± 0.06	0.23 ± 0.05	LHCb	$+3.1$

[Altmannshofer, Straub 1503.06199]

[recently updated, LHCB 1506.08777] 0.26 ± 0.04 $+3.5$

1. Statistical fluctuation (now in different channels)
2. Hadronic uncertainties
3. New Physics

Lepton Flavour Universality

LHCb, 1406.6482, PRL
LHCb, 1705.05802, JHEP

$$R_M[q^2_{\min},\, q^2_{\max}] = \frac{\displaystyle\int_{q^2_{\min}}^{q^2_{\max}} dq^2 \frac{d\Gamma(B\to M\mu^+\mu^-)}{dq^2}}{\displaystyle\int_{q^2_{\min}}^{q^2_{\max}} dq^2 \frac{d\Gamma(B\to Me^+e^-)}{dq^2}}$$

Exp. Measurements

$$R_K\left[1\ \text{GeV}^2,\ 6\ \text{GeV}^2\right] = 0.745^{+0.090}_{-0.074} \pm 0.036\ ,$$

$$R_{K^*}[0.045,\ 1.1] = 0.660^{+0.110}_{-0.070} \pm 0.024$$

$$R_{K^*}[1.1,\ 6.0] = 0.685^{+0.113}_{-0.069} \pm 0.047$$

SM predictions

[from Bordone, Isidori, Pattori, 1605.07633]

$$R_{K^+}[1.0,\ 6.0]^{\text{SM}} = 1.00 \pm 0.01_{\text{QED}}$$

$$R_{K^*}[0.045, 1.1]^{\text{SM}} = 0.906 \pm 0.020_{\text{QED}} \pm 0.020_{\text{FF}}$$
$$= 0.906 \pm 0.028_{\text{th}}\ .$$

$$R_{K^*}[1.1,\ 6.0]^{\text{SM}} = 1.00 \pm 0.01_{\text{QED}}$$

Explanations:

1. Statistical fluctuation
2. ~~Hadronic uncertainties~~
3. New Physics

New Physics (Model Independent)

• Model independent analysis via a low-energy effective hamiltonian, assuming short-distance New Physics in the following operators

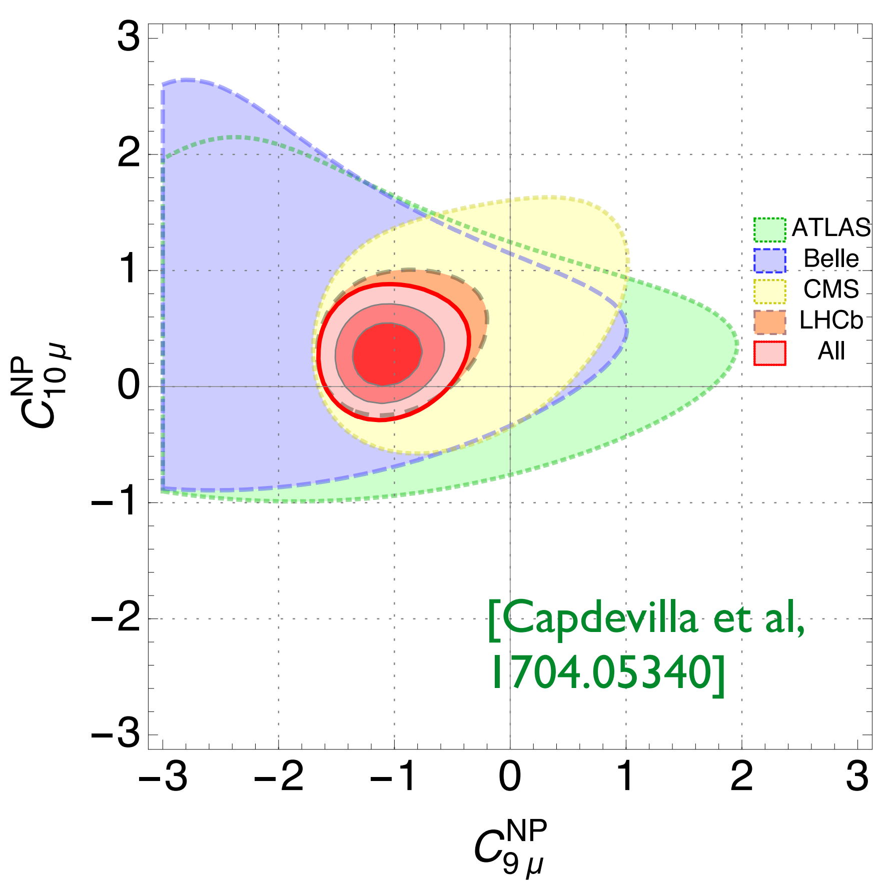
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} (V_{ts}^* V_{tb}) \sum_i C_i^\ell(\mu)\, \mathcal{O}_i^\ell(\mu)$$

$$\mathcal{O}_7^{(\prime)} = \frac{e}{16\pi^2} m_b \left(\bar{s}\sigma_{\alpha\beta} P_{R(L)} b\right) F^{\alpha\beta}\,, \qquad C_7^{SM} = -0.319,$$

$$\mathcal{O}_9^{\ell(\prime)} = \frac{\alpha_{\rm em}}{4\pi} \left(\bar{s}\gamma_\alpha P_{L(R)} b\right) \left(\bar{\ell}\gamma^\alpha \ell\right)\,, \qquad C_9^{SM} = 4.23,$$

$$\mathcal{O}_{10}^{\ell(\prime)} = \frac{\alpha_{\rm em}}{4\pi} \left(\bar{s}\gamma_\alpha P_{L(R)} b\right) \left(\bar{\ell}\gamma^\alpha \gamma_5 \ell\right). \qquad C_{10}^{SM} = -4.41.$$

SM gives lepton flavour universal contribution



• Preference for lepton vector current $C_9^{\mu,NP} \approx -1$

• Short distance effects from New Physics are expected to have a chiral structure

$$\bar{\ell}\gamma^\alpha \ell \qquad \bar{\ell}\gamma^\alpha\gamma_5 \ell \longrightarrow \bar{\ell}_L\gamma^\alpha \ell_L \qquad \bar{\ell}_R\gamma^\alpha \ell_R$$

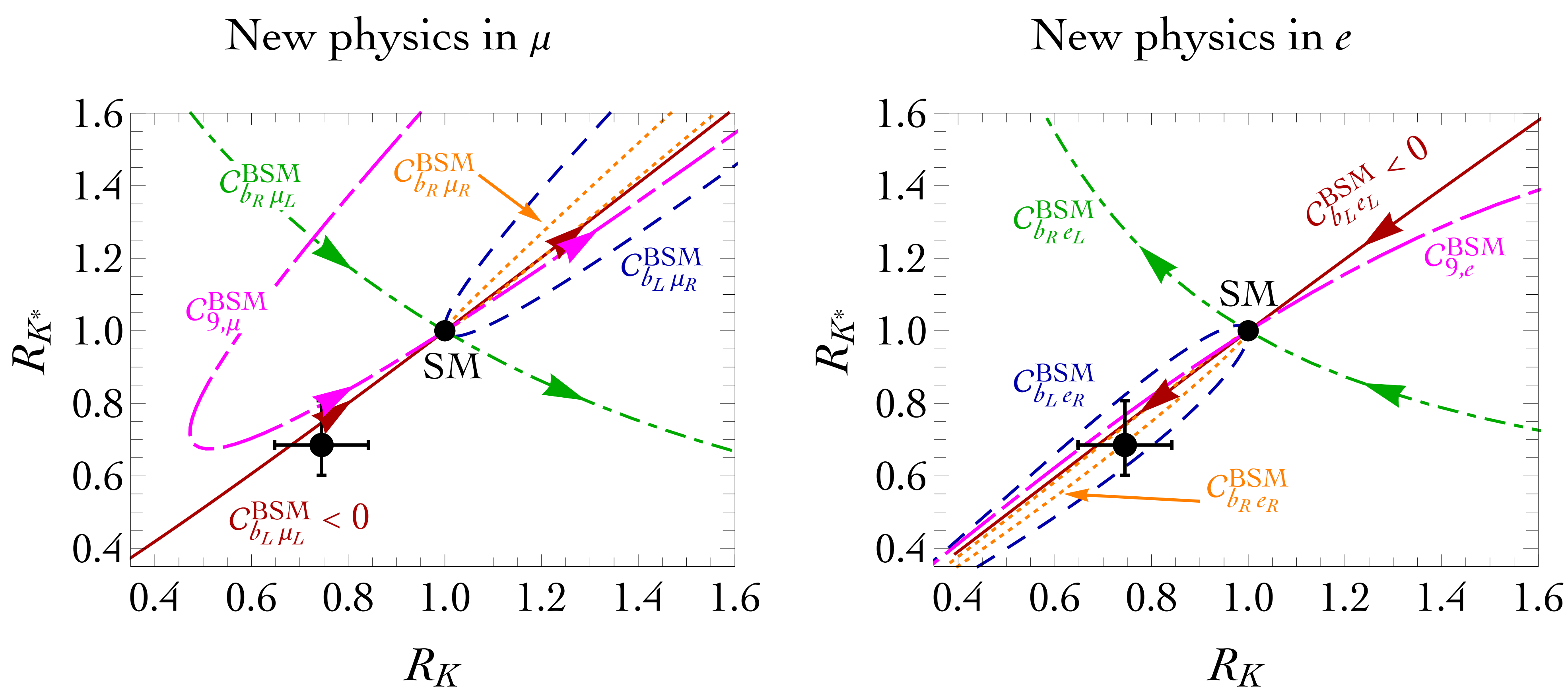
Best Fit with Left-Left currents

$$C_9^{\mu,NP} = -C_{10}^{\mu,NP}$$

After R_{K^*}

- RK and RK* observables alone are now sufficient to draw various conclusions (without doing fits!)

[1704.05340, 1704.05435 1704.05438, 1705444, 17054446, 1705447]



$$R_{K^*} \simeq R_K - 4p\frac{\mathrm{Re}\, C^{\rm BSM}_{b_R(\mu-e)_L}}{C^{\rm SM}_{b_L\mu_L}}$$

$$4p/C^{\rm SM}_{b_L\mu_L} \approx 0.40$$

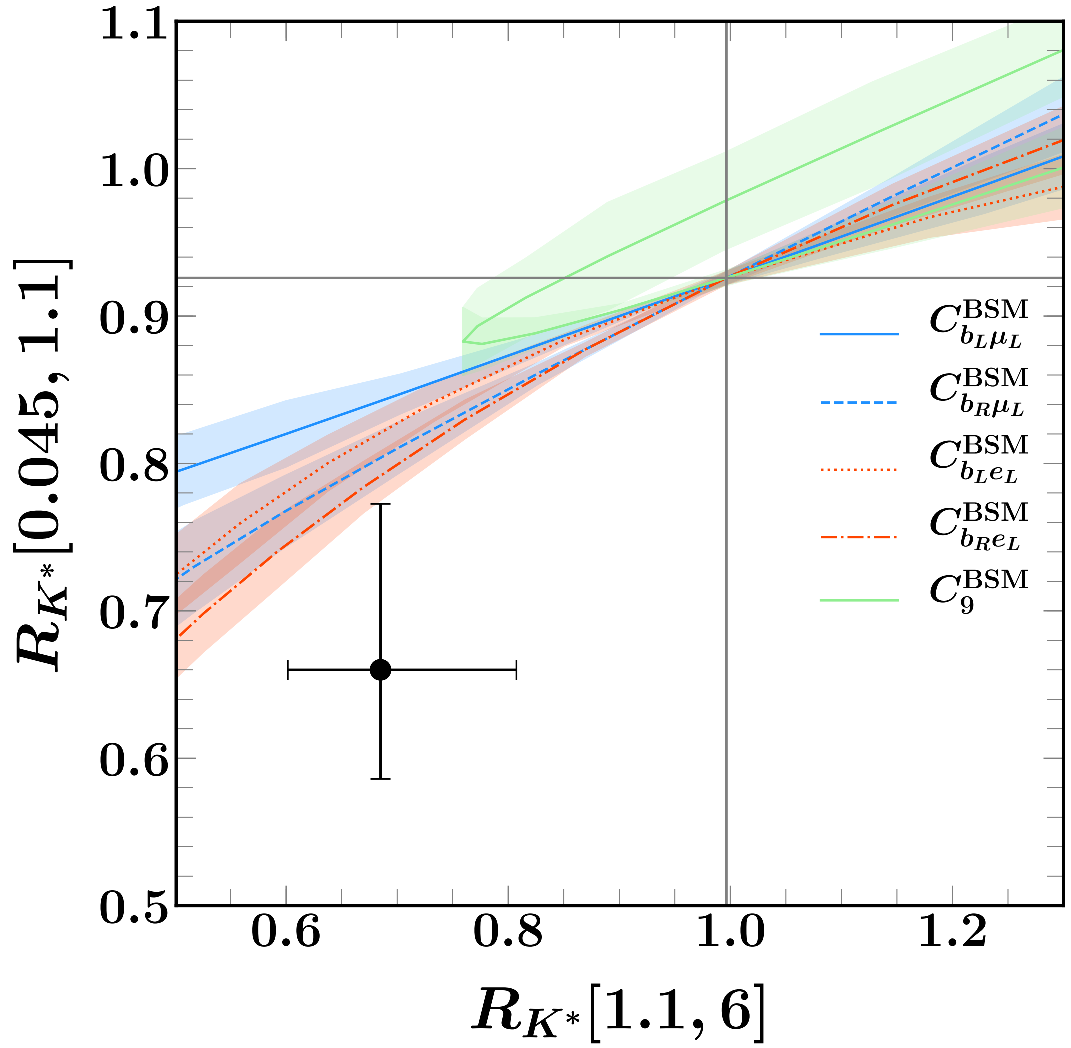
$$R_K \simeq 1 + 2\frac{\mathrm{Re}\, C^{\rm BSM}_{b_{L+R}(\mu-e)_L}}{C^{\rm SM}_{b_L\mu_L}}$$

[1704.05438]

- Deviation from the Standard Model, using only the most cleaner observable gives $\sim 4\sigma$
- New Physics in muons wants destructive interference with the SM
- New Physics in electrons is possible, but cannot explain angular observables and low branching ratios….

The low q^2 bin

- At low q^2, Standard Model contribution is dominate by dipole operator (due the photon pole)
- NP effects are reduced in this bin



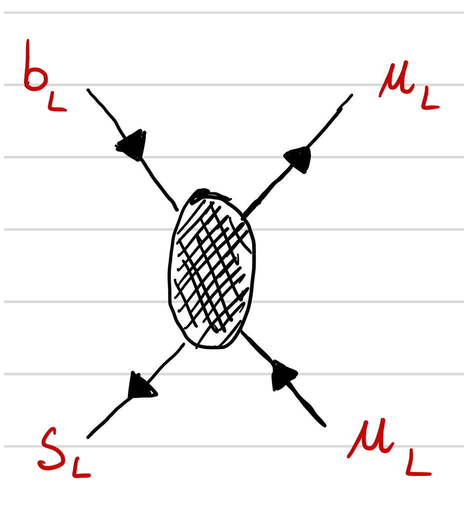
[D'Amico, et al. 1704.05438]

- Can be a sanity check of the measurement
- Having a large effect here requires light long range New Physics [1704.06188,1704.06240]

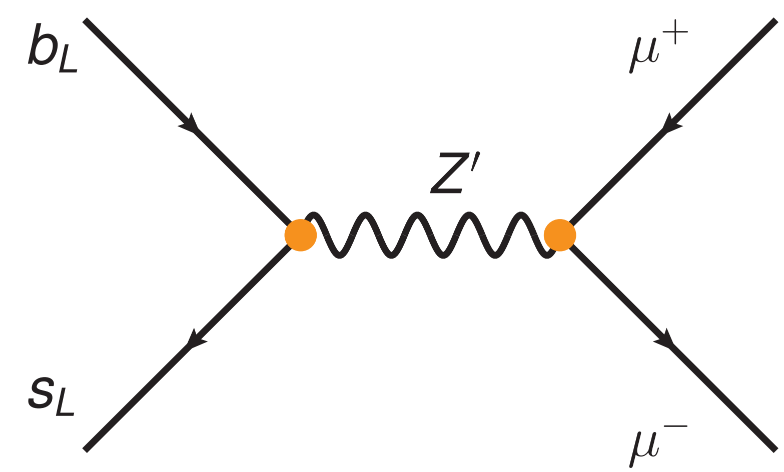
Simplified models

- Addressing the flavour anomalies in FCNC alone is quite easy:

[more than 100 papers, MSSM doesn't work!]



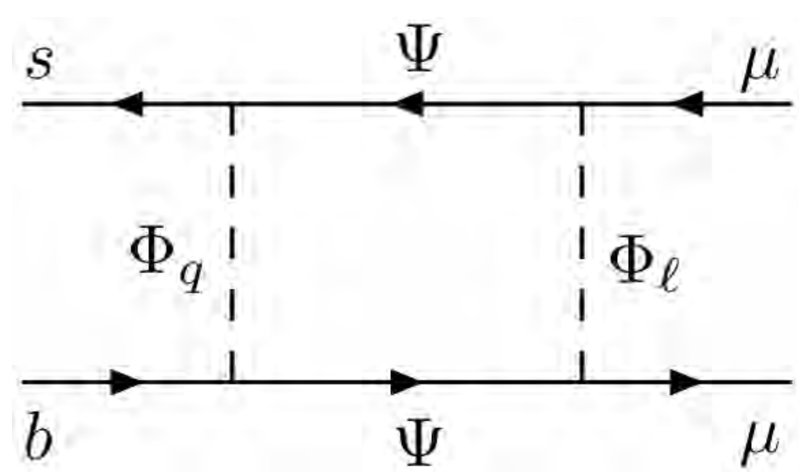
=

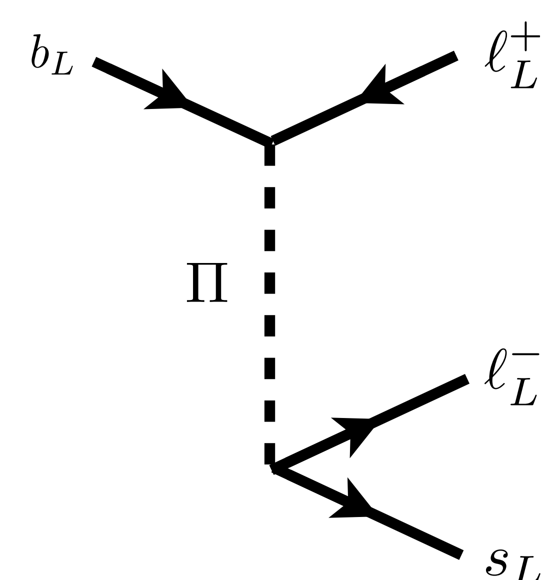


$$\mathcal{L}_{eff} = \frac{1}{\Lambda^2_{R_K}} \bar{s}_L \gamma^\mu b_L \, \bar{\mu}_L \gamma_\mu \mu_L + h.c.$$

$$\Lambda_{R_K} = 31 \text{ TeV}$$

$$\Lambda^2_{R_K} \gg G_F^{-1}$$





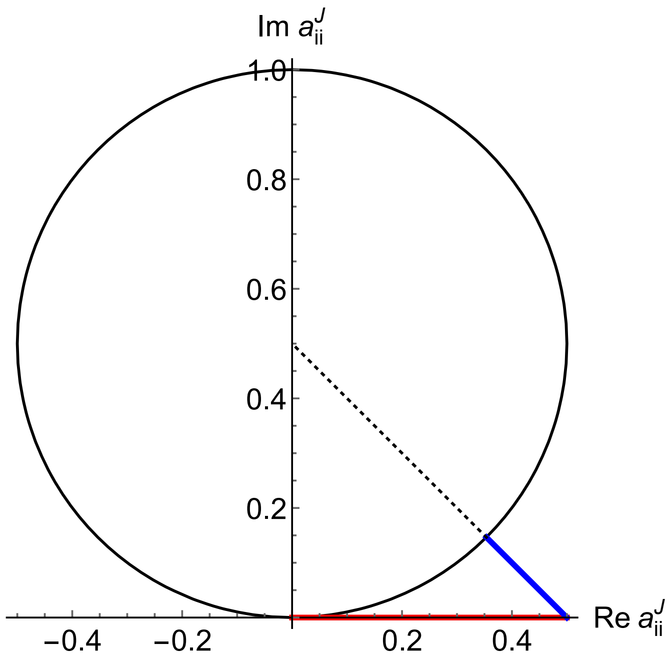
Perturbative unitarity

- Unitarity (an axiom of QFT)

$$SS^\dagger = 1 \longrightarrow \frac{1}{2i}\left(a^J_{fi} - a^{J*}_{if}\right) \geq \sum_{h \in \text{2-particle}} a^{J*}_{hf} a^J_{hi}$$

- For f = i (optical theorem)

$$\operatorname{Im} a^J_{ii} \geq |a^J_{ii}|^2 \longrightarrow \left(\operatorname{Re} a^J_{ii}\right)^2 + \left(\operatorname{Im} a^J_{ii} - \frac{1}{2}\right)^2 \leq \frac{1}{4}$$

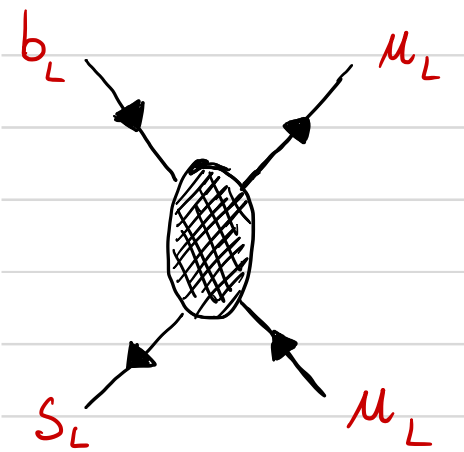


- In practical perturbative calculations S-matrix unitarity is always approximate

- perturbative expansion breaks down for

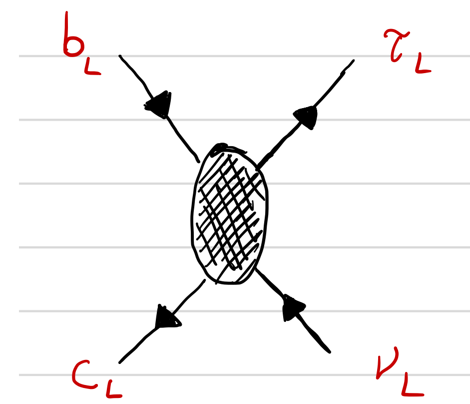
$$\left|\operatorname{Re}\left(a^J_{ii}\right)^{\text{Born}}\right| \leq \frac{1}{2}$$

What is the scale of New Physics?



$$\mathcal{L}_{eff} = \frac{1}{\Lambda_{R_K}^2} \bar{s}_L \gamma^\mu b_L \, \bar{\mu}_L \gamma_\mu \mu_L + h.c.$$

$$\Lambda_{R_K} = 31 \text{ TeV}$$



$$\mathcal{L}_{eff} = -\frac{2}{\Lambda_{R_D}} \bar{c}_L \gamma^\mu b_L \, \bar{\tau}_L \gamma_\mu \nu_L + h.c.$$

$$\Lambda_{R_D} = 3.4 \text{ TeV}$$

[Di Luzio, Nardecchia 1706.01868]

- Energy, coupling, mass ambiguity

$$\frac{1}{\Lambda^2} = \frac{g^2}{M^2}?$$

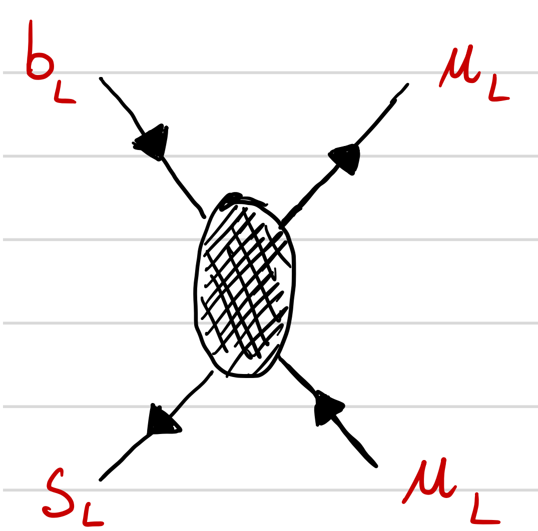
- In the EFT 2-to-2 scatterings of fermions grows with energy

$$a_0 = \frac{\sqrt{3}}{8\pi} \frac{s}{\Lambda_{QL}^2} \qquad \text{tree-level unitarity criterium} \qquad |a_0| < 1/2$$

- No-lose theorem, completely model independent $\sqrt{s}_{R_D} < 9.2 \text{ TeV}\,,\ \sqrt{s}_{R_K} < 84 \text{ TeV}$

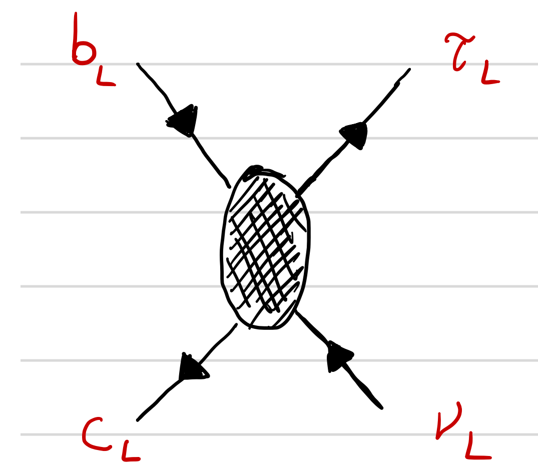
- Previous bound quite conservative, typically scattering of the third family are enhanced…

Simultaneous explanation



$$\mathcal{L}_{eff} = \frac{1}{\Lambda_{R_K}^2} \bar{s}_L \gamma^\mu b_L \, \bar{\mu}_L \gamma_\mu \mu_L + h.c.$$

$$\Lambda_{R_K} = 31 \text{ TeV}$$



[The Zurich Hunter's Guide 1706.07808]

$$\mathcal{L}_{eff} = -\frac{2}{\Lambda_{R_D}} \bar{c}_L \gamma^\mu b_L \, \bar{\tau}_L \gamma_\mu \nu_L + h.c.$$

$$\Lambda_{R_D} = 3.4 \text{ TeV}$$

Hint 1: "vertical" structure. These operators could be generate by the same SU(2)xU(1) structure:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\ (\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\ (\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$

[See also 1412.5472, 1505.05164]

Hint 2: "horizontal" structure. NP structure seems linked somehow to the SM Yukawa structure

$$\Lambda_{R_D} \ll \Lambda_{R_K}$$
$$|\lambda^\ell_{\tau\tau}| \gg |\lambda^\ell_{\mu\mu}|$$

Hint of an approximate flavour symmetry

$$U(2)_q \times U(2)_\ell$$

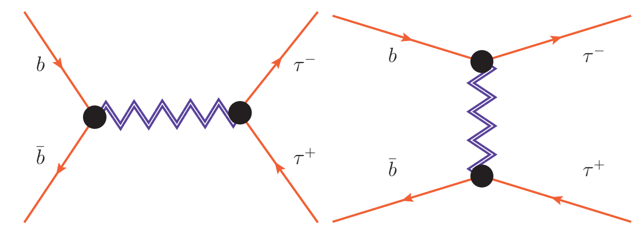
[1105.2296, 1512.01560 1702.07238]

Problems

1) Direct searches.

$$\mathcal{L}_{eff} = -\frac{2}{\Lambda_{R_D}} \bar{c}_L \gamma^\mu b_L \, \bar{\tau}_L \gamma_\mu \nu_L + h.c. \rightarrow \left(\frac{1}{1\ \mathrm{TeV}}\right)^2 \bar{b}_L \gamma^\mu b_L \bar{\tau}_L \gamma^\mu \tau_L$$

$$\Lambda_{R_D} = 3.4\ \mathrm{TeV}$$

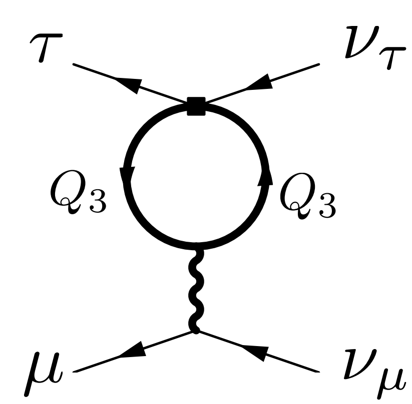


[Faroughy,Greljo,Kamenik, 1609.07138]

2) Radiative contraints

$$(\overline{Q}_L \gamma^\mu Q_L)(\overline{L}_L \gamma_\mu L_L) \rightarrow (\overline{L}_L \gamma^\mu L_L)(\overline{L}_L \gamma_\mu L_L)$$

$$\delta g^Z_{\tau_L}, \delta g^Z_{\nu_\tau}, \delta g^W_\tau, \mathcal{B}(\tau \rightarrow 3\mu)$$



[Feruglio, Paradisi, Pattori, 1606.00524,1705.00929]

3) FCNC with neutrinos.

$$\mathcal{B}(B \rightarrow K^{(*)}\nu\nu) \approx \mathcal{B}(B \rightarrow K^{(*)}\nu_\tau\nu_\tau) \gg \mathcal{B}(B \rightarrow K^{(*)}\nu\nu)_{SM}$$

$$\frac{\mathcal{B}(B \rightarrow K^{(*)}\nu\nu)}{\mathcal{B}(B \rightarrow K^{(*)}\nu\nu)_{SM}} \lesssim 4$$

EFT result

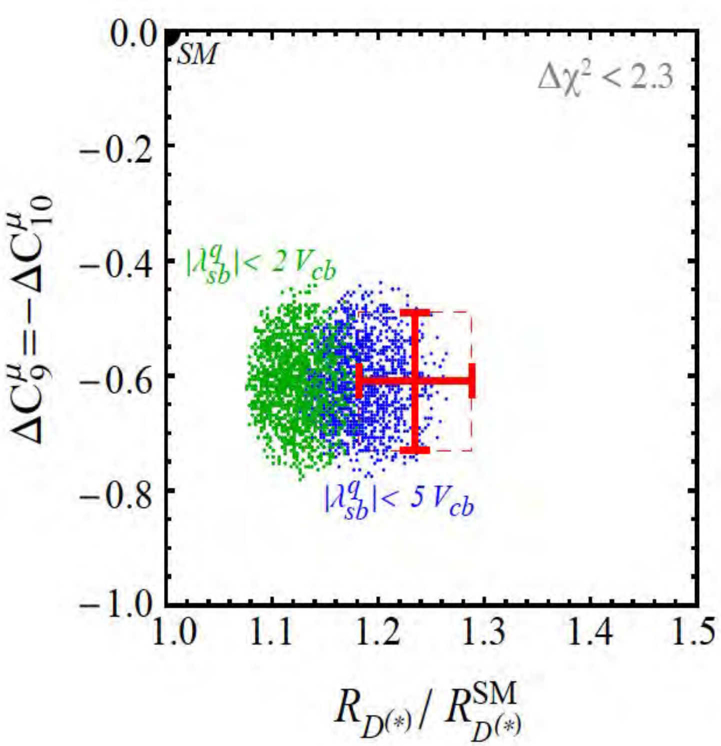
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} - \frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\,(\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\,(\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right] \qquad Q^i_L = \begin{pmatrix} V^*_{ji}u^j_L \\ d^i_L \end{pmatrix}, \qquad L^\alpha_L = \begin{pmatrix} \nu^\alpha_L \\ \ell^\alpha_L \end{pmatrix}$$

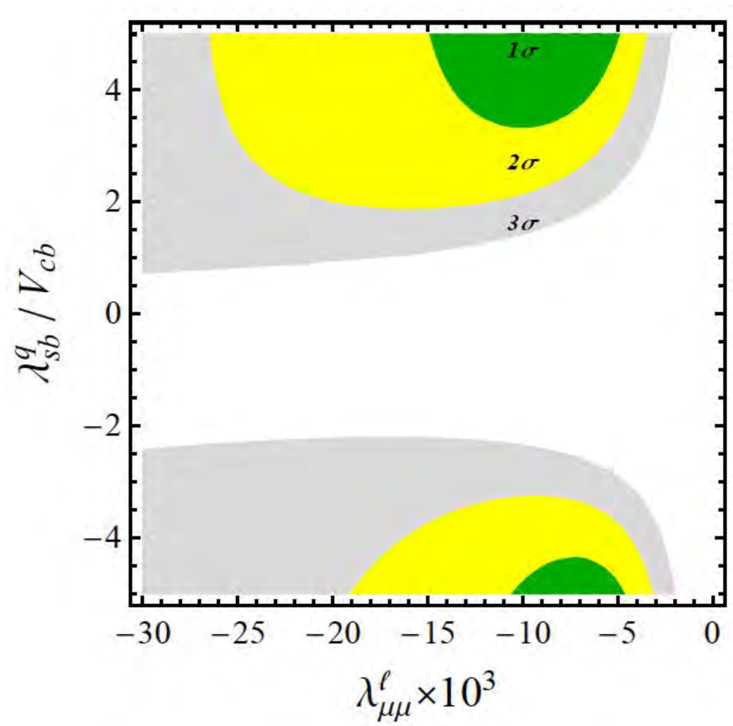
$$\lambda^q_{bb} = \lambda^\ell_{\tau\tau} = 1$$

4 parameters fit:

$$C_S, C_T, \lambda^q_{bs}, \lambda^\ell_{\mu\mu}$$

Observable	Experimental bound	Linearised expression
$R^{\tau\ell}_{D^{(*)}}$	1.237 ± 0.053	$1 + 2C_T(1 - \lambda^q_{sb}V^*_{tb}/V^*_{ts})(1 - \lambda^\ell_{\mu\mu}/2)$
$\Delta C^\mu_9 = -\Delta C^\mu_{10}$	-0.61 ± 0.12 [36]	$-\frac{\pi}{\alpha_{\text{em}}V_{tb}V^*_{ts}}\lambda^\ell_{\mu\mu}\lambda^q_{sb}(C_T + C_S)$
$R^{\mu e}_{b\to c} - 1$	0.00 ± 0.02	$2C_T(1 - \lambda^q_{sb}V^*_{tb}/V^*_{ts})\lambda^\ell_{\mu\mu}$
$B_{K^{(*)}\nu\bar{\nu}}$	0.0 ± 2.6	$1 + \frac{2}{3}\frac{\pi}{\alpha_{\text{em}}V_{tb}V^*_{ts}C^{\text{SM}}_\nu}(C_T - C_S)\lambda^q_{sb}(1 + \lambda^\ell_{\mu\mu})$
$\delta g^Z_{\tau_L}$	-0.0002 ± 0.0006	$0.033C_T - 0.043C_S$
$\delta g^Z_{\nu_\tau}$	-0.0040 ± 0.0021	$-0.033C_T - 0.043C_S$
$\lvert g^W_\tau/g^W_\ell\rvert$	1.00097 ± 0.00098	$1 - 0.084C_T$
$\mathcal{B}(\tau \to 3\mu)$	$(0.0 \pm 0.6) \times 10^{-8}$	$2.5 \times 10^{-4}(C_S - C_T)^2(\lambda^\ell_{\tau\mu})^2$





1) Combined explanation in the EFT is viable

2) Singlet/triplet analysis clear guideline for models (see next)

3) U(2) flavour structure is rather good

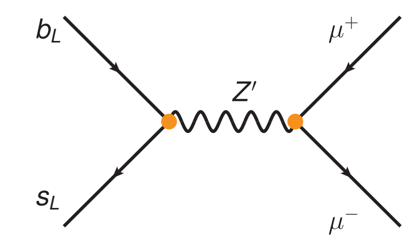
$\lambda^q_{bs} = \mathcal{O}(V_{cb})$ th. expectation

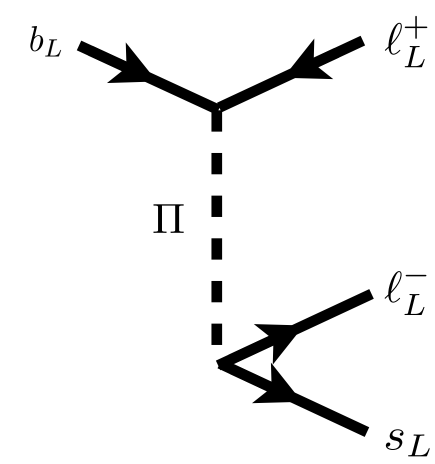
$\lambda^q_{bs} \approx 5\,V_{cb}$ preferred from fit

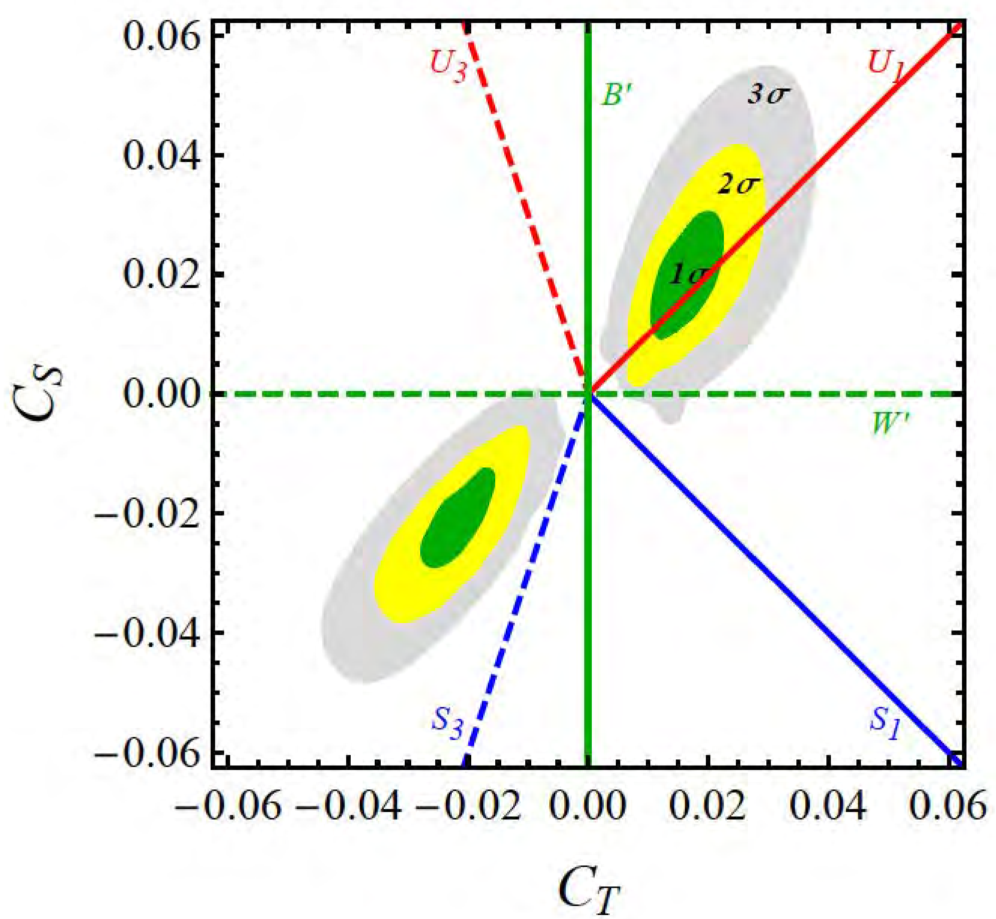
Simplified models

Which is the right mediator? $\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\ (\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\ (\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$

Simplified model	Spin	SM irrep	c_1/c_3	$R_{D^{(*)}}$	$R_{K^{(*)}}$
Z'	1	$(1, 1, 0)$	∞	×	✓
V'	1	$(1, 3, 0)$	0	✓	✓
S_1	0	$(\bar{3}, 1, 1/3)$	-1	✓	×
S_3	0	$(\bar{3}, 3, 1/3)$	3	✓	✓
U_1	1	$(3, 1, 2/3)$	1	✓	✓
U_3	1	$(3, 3, 2/3)$	-3	✓	✓







- A clear winner! $U_\mu = (3, 1, 2/3)$

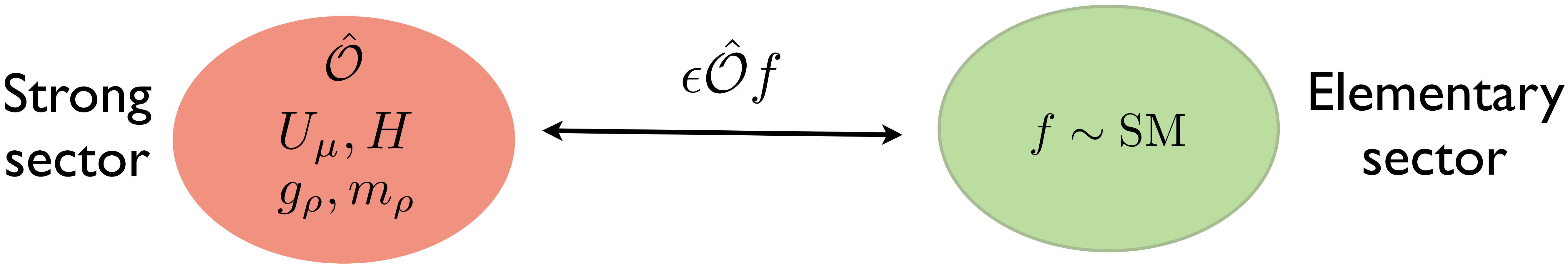
- Combinations of different mediators are possible (S1+S3) or (Z'+W'), however some tunings/adjustments are required

- Next task: find a UV model….

The Composite Leptoquark

- Ambitious idea: leptoquark and Higgs composite

[Barbieri, Isidori, Pattori, Senia 1512.01560
Barbieri, Murphy, Senia 1611.0493]



- Postulate a dynamics such that, Higgs is a Goldstone boson and U vector resonance

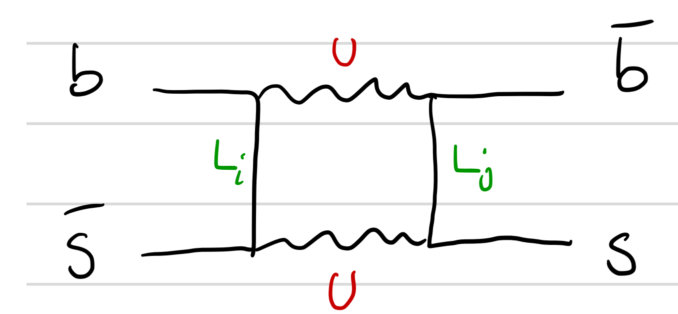
$$\frac{G}{H} = \frac{SU(4) \times SO(5) \times U(1)_X}{SU(4) \times SO(4) \times U(1)_X} \qquad SU(4) \supset SU(3)_C$$

+) Address the naturalness problem: Higgs composite and light because of its pNGB nature

+) SM flavour structure as well as BSM effects are dictated by the mechanism of partial compositeness

-) U has to be light, this brings down the whole spectrum (issues with direct searches as well as EWPT)

-) Intrinsically non-renomarlizable, important effects can only be guessed by NDA, basically all questions are postponed to a complete UV realisation



$$\mathcal{A}_{\Delta F=2} \propto g_4^4 \frac{\Lambda^2}{m_U^4}$$

The UV Completion Challenge

Is it possible to find a weakly coupled and renomarlizable model to explain the whole set of the flavour anomalies?

[with A. Greljo and L. Di Luzio 1708.08450]

A tale divided in various chapters

1) How to get the right mediator? $U_\mu = (3, 1, 2/3)$

2) How to get the right interactions? (Coupling to quark and lepton doublets)

3) How to pass low energy constraints? (How to find other indirect effects?)

4) How to escape the direct searches? (How to discover new states @ high pT?)

5) Discussion

1) How to get the right mediator?

Spin one particle → Composite dynamics $\sim \rho_\mu$ [previous case]

Spin one particle → Gauge boson $\sim W_\mu$ → π_L Composite [non-trivial coset? pNGB?]

Gauge boson $\sim W_\mu$ → π_L Elementary $\langle H \rangle \neq 0$ [this talk]

- In all cases symmetry breaking G/H leads to extra states
- Quantum numbers of the leptoquark known, easiest option: Pati-Salam

$$G_{PS} = SU(4)_{PS} \times SU(2)_L \times SU(2)_R \qquad G_{PS} \to G_{SM}$$

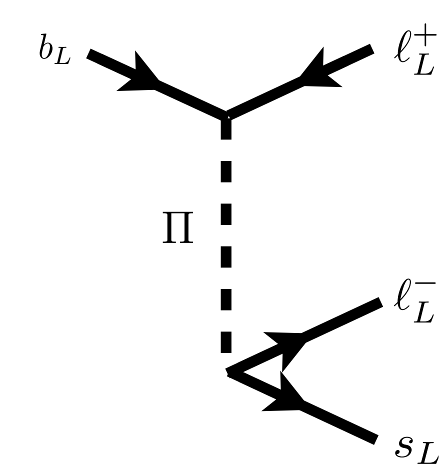
$$SU(4)_{PS} \supset SU(3)_C \times U(1)_X$$

$$Y = X + T_{3R} \qquad G/H \supset U_\mu(3,1,2/3)$$

- Matter field

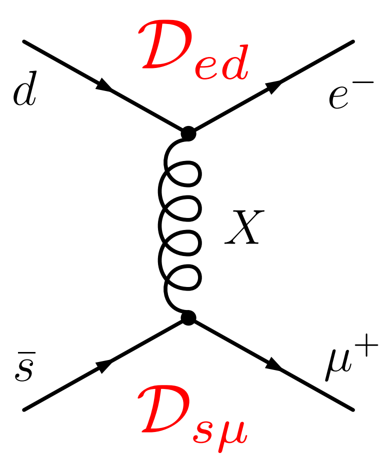
$$\Psi_L^i = \begin{pmatrix} Q_L^i \\ L_L^i \end{pmatrix} \qquad \Psi_R^i = \begin{pmatrix} Q_R^i \\ L_R^i \end{pmatrix} = \begin{pmatrix} u_R^i & d_R^i \\ \nu_R^i & \ell_R^i \end{pmatrix}$$

$$(4,2,1) \qquad (4,1,2)$$



Pati-Salam: the problem

- The problem: simultaneous presence of both left- and right-handed current breaking lepton chirality + large coupling to first family



$M_U \gtrsim 100$ TeV

$M_U \lesssim 2$ TeV
(from the anomalies)

Experimental limit	Ref.	Bound
$\frac{\Gamma(\pi^+ \to e^+\nu_e)}{\Gamma(\pi^+ \to \mu^+\nu_\mu)} = (1.2310 \pm 0.0037) \times 10^{-4}$	32–34	$\frac{M_X}{\lvert\text{Re}(\mathcal{D}_{ed}\mathcal{U}^*_{eu})\rvert^{1/2}} > 210$ TeV
$\frac{\Gamma(K^+ \to e^+\nu_e)}{\Gamma(K^+ \to \mu^+\nu_\mu)} = (2.493 \pm 0.031) \times 10^{-5}$	35	$\frac{M_X}{\lvert\text{Re}(\mathcal{D}_{es}\mathcal{U}^*_{eu})\rvert^{1/2}} > 150$ TeV
$Br(K^+ \to \pi^+\mu^+e^-) < 1.3 \times 10^{-11}$	36	$\frac{M_X}{\lvert\mathcal{D}_{ed}\mathcal{D}_{\mu s}\rvert^{1/2}} > 240$ TeV
$Br(K^+ \to \pi^+\mu^-e^+) < 5.2 \times 10^{-10}$	37	$\frac{M_X}{\lvert\mathcal{D}_{es}\mathcal{D}_{\mu d}\rvert^{1/2}} > 100$ TeV
$Br(K^0_L \to \mu^+\mu^-) = (6.84 \pm 0.11) \times 10^{-9}$	38, 39	$\frac{M_X}{\lvert\text{Re}(\mathcal{D}_{\mu d}\mathcal{D}^*_{\mu s})\rvert^{1/2}} > 1100$ TeV
$Br(K^0_L \to e^\pm\mu^\mp) < 4.7 \times 10^{-12}$	40	$\frac{M_X}{\lvert\mathcal{D}_{ed}\mathcal{D}^*_{\mu s} + \mathcal{D}_{es}\mathcal{D}^*_{\mu d}\rvert^{1/2}} > 2100$ TeV
$Br(K^0_L \to e^+e^-) = \left(9^{+6}_{-4}\right) \times 10^{-12}$	41	$\frac{M_X}{\lvert\text{Re}(\mathcal{D}_{ed}\mathcal{D}^*_{es})\rvert^{1/2}} > 2400$ TeV
$\frac{\sigma(\mu^-\text{Au} \to e^-\text{Au})}{\sigma(\mu^-\text{Au} \to \text{capture})} < 0.7 \times 10^{-12}$	42	$\frac{M_X}{\lvert\mathcal{D}_{ed}\mathcal{D}_{\mu d}\rvert^{1/2}} > 1000$ TeV

- Some wishful thinking in:

  Assad, Fornal, Grinstein [1708.06350], D matrices are unitary - good luck!

  Calibbi, Crivellin, Li [1709.00692], non-trivial matter embedding, D are not unitary

  - unsuppressed (strong) coupling of the Z' with first family of quarks (Drell-Yann)

- Our strategy: find a model where the leptoquark couples only to left-handed doublets with reduced coupling to the first generation

2) How to get the right interactions?

- We need two ingredients: an enlarged gauge structure and extra matter fields

$$G = SU(4) \times SU(3)' \times SU(2)_L \times U(1)'$$

$$\downarrow \langle\Omega_3\rangle, \langle\Omega_1\rangle$$

$$G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$$

New states from the breaking:

1) A leptoquark $M_U = \frac{1}{2} g_4 \sqrt{v_1^2 + v_3^2}\,,$

2) A coloron $M_{g'} = \frac{1}{\sqrt{2}} \sqrt{g_4^2 + g_3^2}\, v_3\,,$

3) A gauge singlet $M_{Z'} = \frac{1}{2} \sqrt{\frac{3}{2}} \sqrt{g_4^2 + \frac{2}{3} g_1^2} \sqrt{v_1^2 + \frac{1}{3} v_3^2}\,.$

$$SU(3)_C = [SU(3)_4 \times SU(3)']_{diag} \qquad g_s = \frac{g_4 g_3}{\sqrt{g_4^2 + g_3^2}}$$

$$Y = X + Y' \qquad g_Y = \frac{g_4 g_1}{\sqrt{g_4^2 + \frac{2}{3} g_1^2}}$$

Starting point:
Diaz, Schmaltz,Zhong [1706.05033]

- Field content

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$
$q_L'^i$	1	3	2	1/6
$u_R'^i$	1	3	1	2/3
$d_R'^i$	1	3	1	$-1/3$
$\ell_L'^i$	1	1	2	$-1/2$
$e_R'^i$	1	1	1	-1
Ψ_L^i	4	1	2	0
Ψ_R^i	4	1	2	0
H	1	1	2	1/2
Ω_3	$\bar{4}$	3	1	1/6
Ω_1	$\bar{4}$	1	1	$-1/2$

} would-be SM states ($q_L'^i$ … $e_R'^i$)

$$\mathcal{L}_{“SM”} + \ldots$$

No leptoquark interaction.

} vector-like states (Q+L) (Ψ_L^i, Ψ_R^i)

Leptoquark interactions with SU(2)_L doublet only!

} symmetry breaking (H, Ω_3, Ω_1)

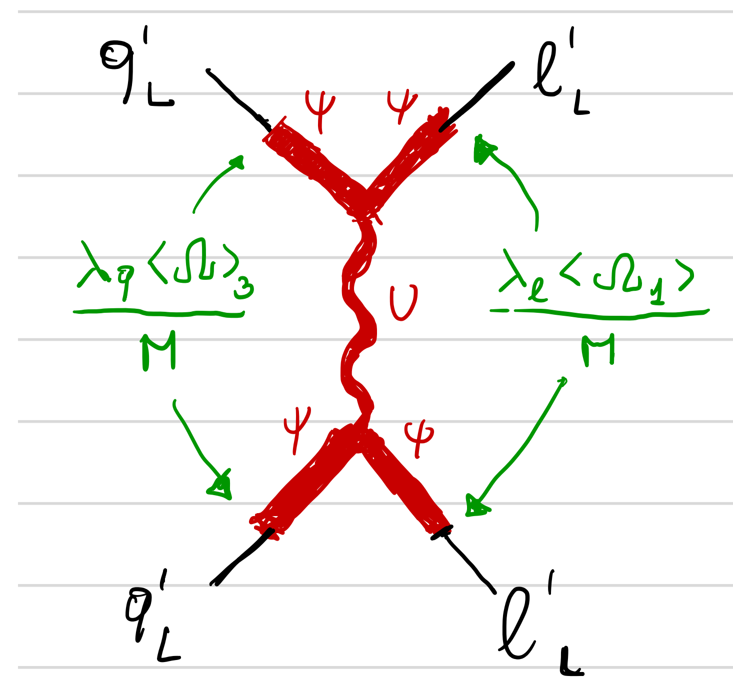
Yukawa interactions connects the two sector

Yukawa sector and the anomalies

- The Yukawa sector

$$\mathcal{L}_Y \supset -\overline{q}'_L\, Y_d\, H d'_R - \overline{q}'_L\, Y_u\, \tilde{H} u'_R - \overline{\ell}'_L\, Y_e\, H e'_R \qquad (9)$$
$$- \overline{q}'_L\, \lambda_q\, \Omega_3^T \Psi_R - \overline{\ell}'_L\, \lambda_\ell\, \Omega_1^T \Psi_R - \overline{\Psi}_L\, M\, \Psi_R + \text{h.c.}\ ,$$

$$\mathcal{M}_d = \begin{pmatrix} \frac{v}{\sqrt{2}} Y_d^{\rm diag} & \frac{v_3}{\sqrt{2}} \lambda_q \\ 0 & M^{\rm diag} \end{pmatrix}, \quad \mathcal{M}_e = \begin{pmatrix} \frac{v}{\sqrt{2}} Y_e^{\rm diag} & \frac{v_1}{\sqrt{2}} \lambda_\ell \\ 0 & M^{\rm diag} \end{pmatrix},$$
$$\mathcal{M}_u = \begin{pmatrix} \frac{v}{\sqrt{2}} V^\dagger Y_u^{\rm diag} & \frac{v_3}{\sqrt{2}} \lambda_q \\ 0 & M^{\rm diag} \end{pmatrix}, \quad \mathcal{M}_\nu = \begin{pmatrix} 0 & \frac{v_1}{\sqrt{2}} \lambda_\ell \\ 0 & M^{\rm diag} \end{pmatrix}.$$



- A deeper look, the net effect of the second line is to project SM fields into Ψ^i_L

$$\Psi^b_L = \begin{pmatrix} c_b\, q_3 + \text{heavy} \\ c_{b\mu}\, \ell_2 + c_{b\tau}\, \ell_3 + \text{heavy} \end{pmatrix} \qquad \Psi^s_L = \begin{pmatrix} c_s\, q_3 + \text{heavy} \\ c_{s\mu}\, \ell_2 + c_{s\tau}\, \ell_3 + \text{heavy} \end{pmatrix}$$

- Integrating away the leptoquark and projecting along the anomalies gives

[Leptoquark simplified model 1706.07808]

$$R_{K^{(*)}} \to -\frac{g_4^2}{2M_U^2} c_b c_s c_{b\mu} c_{s\mu} = \frac{1}{(31\ \text{TeV})^2}$$
$$R_{D^{(*)}} \to -\frac{g_4^2}{2M_U^2} c_b c_{b\tau} \left[c_b c_{b\tau} V_{cb} + c_s c_{s\tau} V_{cs}\right] = -\frac{2}{(3.5\ \text{TeV})^2}$$

$$\begin{cases} g_4 \gtrsim 2 \\ M_U \lesssim 2\,\text{TeV} \\ |c_b| \sim |c_\tau| \gtrsim 0.7 \\ |c_b| \gg |c_s|, |c_\tau| \gg |c_\mu| \end{cases}$$

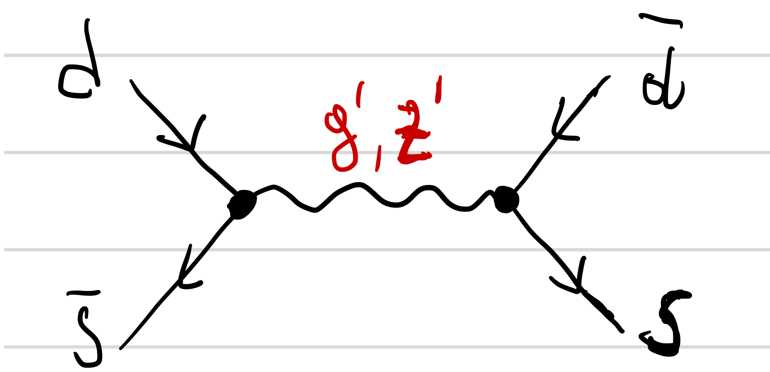
3) Low energy constraints

- The Yukawa sector

$$\mathcal{L}_Y \supset -\overline{q}'_L\, Y_d\, H d'_R - \overline{q}'_L\, Y_u\, \tilde{H} u'_R - \overline{\ell}'_L\, Y_e\, H e'_R \qquad (9)$$
$$- \overline{q}'_L\, \lambda_q\, \Omega_3^T \Psi_R - \overline{\ell}'_L\, \lambda_\ell\, \Omega_1^T \Psi_R - \overline{\Psi}_L\, M\, \Psi_R + \text{h.c.}\ ,$$

B and L number are conserved accidentally!

- The extra gauge bosons contributes to FCNC and CPV in the quark sector



Contrary to the leptoquark contribution, all quarks contribute. We need a protection mechanism in particular for FCNC in the down sector, 2 possibilities:

1) *Full flavour alignment*: No FCNC in the up and down sector! However unsuppressed couplings with first family implying large coupling to valence quark

$M^{ij} \propto \lambda_q^{ij}$

$M, \lambda_q, Y_d = \text{diagonal}$

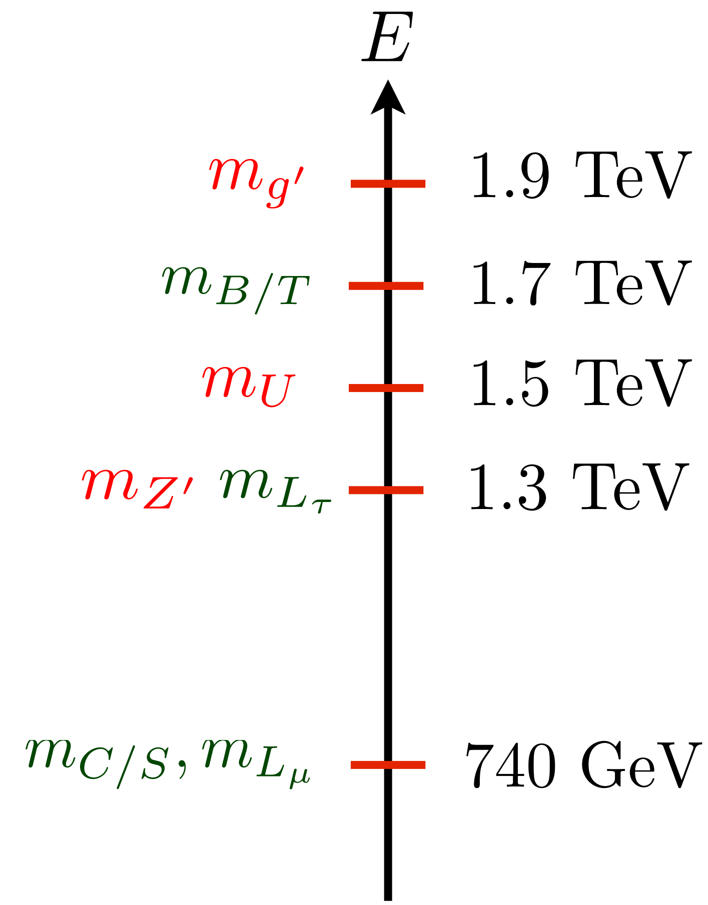
2) *Down alignment*: No FCNC in the down sector, misalignment with the up sector leads to contribution to D mixing.

- Both cases can be motivated by flavour symmetry (see later)
- EWPT, Z and W constraints under control for the leptoquark, less important for the other gauge bosons (because EW singlets). [1706.07808]
- Purely leptonic processes induced by the Z' at the tree level are under control $(\tau \to 3\mu, \tau \to \mu\nu\nu)$
- Constraints due vector-like mixing are protected by mass suppression [1304.4219]

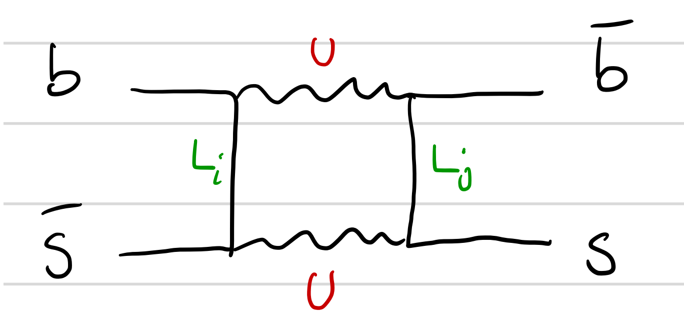
A working benchmark point

- A working benchmark point

$$\begin{cases} M_1 = 737 \text{ GeV}, M_2 = 707 \text{ GeV} \\ \lambda_q^s = -0.081, \lambda_q^b = 2.6 \\ \lambda_\ell^{\tau 1} = 1.8, \lambda_\ell^{\tau 2} = 2.4 \\ \lambda_\ell^{\mu 1} = 0.14, \lambda_\ell^{\mu 2} = -0.27 \\ v_1 = 541 \text{ GeV}, v_3 = 845 \text{ GeV} \\ g_3 = 3.0 \end{cases}$$



- Conceptually important, we can compute!



$$\mathcal{A}_{\Delta F=2} \propto g_4^4 \frac{\Lambda^2}{m_U^4}$$ simplified models

$$\mathcal{A}_{\Delta F=2} \propto \frac{g_4^4}{m_U^2}$$ UV complete model

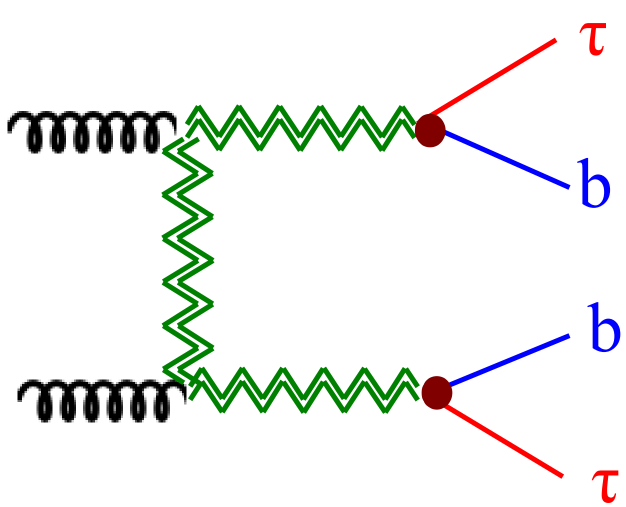
- Important also for production cross section

$$\mathcal{L}_U = -\frac{1}{2} U_{\mu\nu}^\dagger U^{\mu\nu} + M_U^2 U_\mu^\dagger U_\mu + \mathcal{L}_{an} \qquad \mathcal{L}_{an} = -i g_s k_s (U_\mu^\dagger \frac{\lambda^a}{2} U_\nu) G^{\mu\nu^a} - i g' \frac{2}{3} k_Y U_\mu^\dagger U_\nu B^{\mu\nu}$$

In our model is calculable! $k_s = k_Y = 1$

4) Direct Searches (gauge boson)

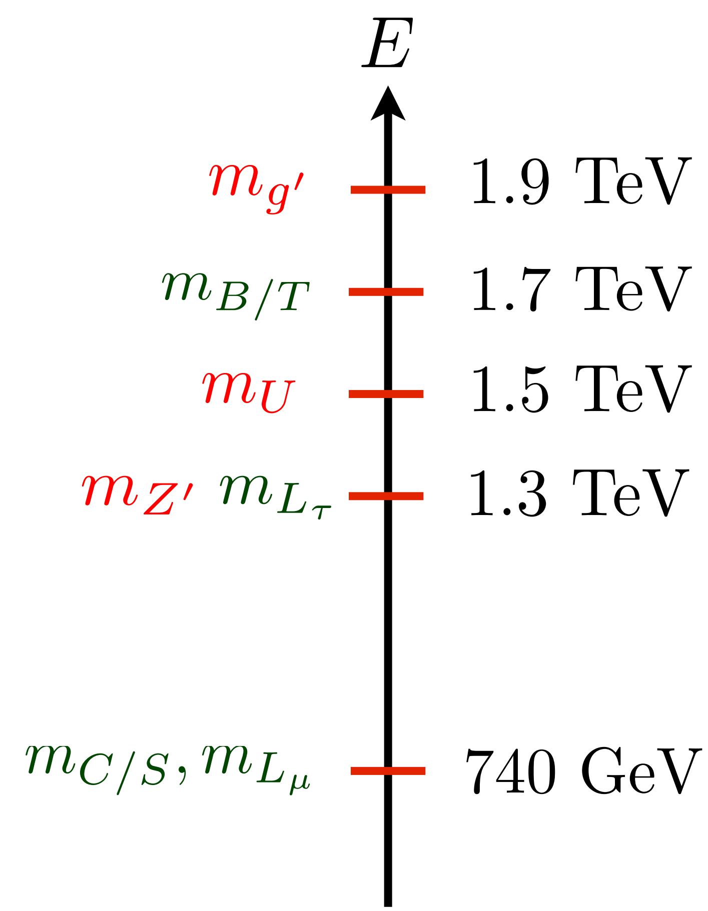
- Leptoquark, pair production by QCD interactions, decay into third family fixed by the anomaly:



$$\begin{cases} U \to b\tau^+, & \text{BR} = 50\ \% \\ U \to t\bar{\nu}, & \text{BR} = 50\ \% \end{cases}$$

(CMS search for spin-0 1703.03995)
(recast for spin-1 in 1706.01868)
(see also 1706.05033)

$m_U > 1.3\ \text{TeV}$ leptoquark mass sets the overall scale



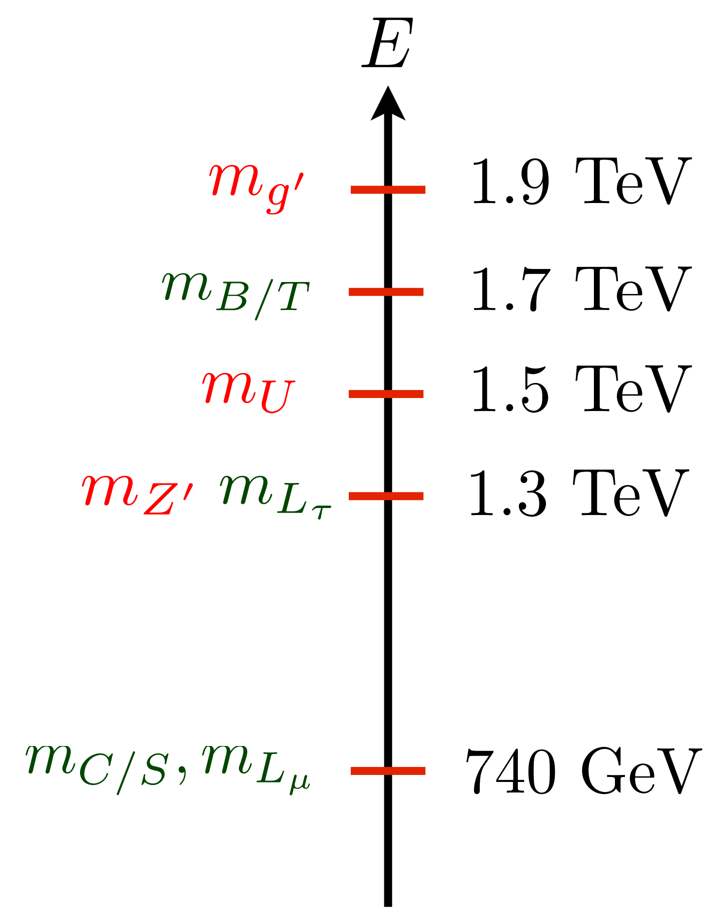
- Z', dangerous Drell-Yann processes suppressed because coupling to the first family is reduced due to small U(1)' coupling.

- g', coupling to the first family given by the SU(3)' factor $\sim g_s/g_4$ resonant dijets search particularly sensitive (ATLAS 1703.09127)

- However bump searches loose in sensitivity when the width-to-mass ratio is too large, in our case the decay width is naturally large because of the decay into heavy quarks

$\frac{\Gamma}{m} \lesssim 15\%$ from exp. analysis $\quad\quad$ $\frac{\Gamma_{g'}}{m_{g'}} = 28\%$ our benchmark

4) Direct Searches (fermions+scalars)



- Top-bottom partners, a physics case well know motivated by scenario such as the composite Higgs. Dedicated searches combining different channels.

  (ATLAS 1707.03347)
  (CMS in 1708.01062)

  $$m_{T/B} \gtrsim 900 \text{ GeV}$$

- g' assisted production does not dominate over QCD

  (discussed in 1407.4466)

- Charm-strange partners, background are larger due to jets in final state

- Leptonic partners, production cross section suppressed

- Heavy Scalars, these set includes a color octet, a color triplet and 3 SM fields. Phenomenology depends on the detail of the scalar potential, however they do not pose particular phenomenological issue.

5) Discussion

- A good fit can be obtained, however a large gauge coupling is required $g_4 \simeq 3$

  Is our model calculable? Let us compare some criteria

  0) Naive loop expansion $g_4^2/(16\,\pi^2) < 1 \;\rightarrow\; g_4 \lesssim 4\pi$

  1) Rate of change of the coupling $|\beta_{g_4}/g_4| < 1 \;\rightarrow\; g_4 \lesssim 4$

  2) Unitarity of the 2 to 2 scattering $|a_0| < 1/2 \;\rightarrow\; g_4 \lesssim 5$

  3) Landau poles in the UV? No, g4 is asymptotically free!

- Light g' an Z' are clean prediction of the framework, changing the sources of gauge breaking does not allow for decoupling from the leptoquark mass.

- Other aspects (to be studied in detail) (in preparation with A. Greljo and L. Di Luzio)

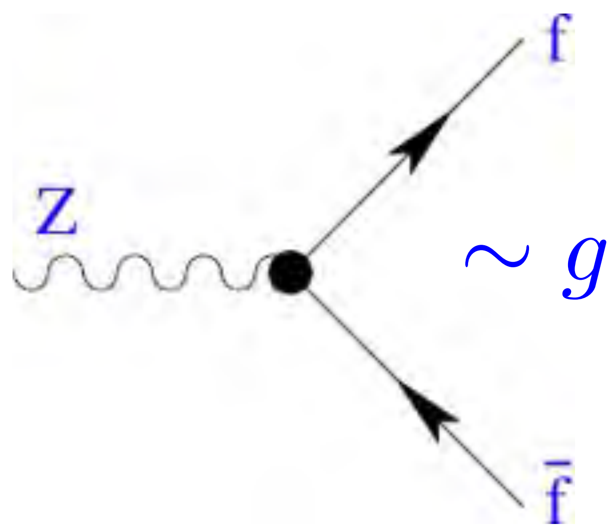
  - Full computation of observables
  - More detailed direct search analysis
  - Scan of the parameter space
  - Unification of the gauge group
  - Naturalness and the scalar sector
  - Discussion of the flavour symmetry

Conclusions

- Flavour anomalies are surviving in a coherent way in both charged current (2012) and neutral current (2013)
- There is a physics program ongoing from LHCb: we are waiting for run 2 results, as well as new measurements $\Delta P_5', R(\phi), R(\Lambda), R(D_s), R(\Lambda_c), R(\Lambda_c^*), + \ldots$
- Current anomalies in B decays have a simple and consistent interpretation at the effective field theory level (model independent)
- Explaining the anomalies in FCNC is relatively easy, serious challenges are posed in charged current. Most of the proposal are in the context of effective non-renormalizable model.
- I presented a weakly coupled and renomalizable model addressing the combined explanation of the anomalies.

Lepton Flavour in the Standard Model

- Leptons appear in the Standard Model in the gauge and in the Yukawa sectors:



$\sim g\,\delta_{ij}$

$$\mathcal{L}_{SM} \supset i\left(\overline{L}_L^i \gamma^\mu D_\mu L_L^i + \overline{E}_R^i \gamma^\mu D_\mu E_R^i\right)$$

- Global symmetry $U(3)_{L_L} \times U(3)_{E_R}$

- Gauge interactions are Lepton Flavour Universal (LFU)

- Yukawa sector breaks the universality in two ways $\mathcal{L}_{\rm SM} \supset Y^E_{ij} \overline{L}_L^i E_R^j H + {\rm h.c}$

1) In the mass terms $m_e \neq m_\mu \neq m_\tau$
2) Higgs interactions (negligible for flavour physics)

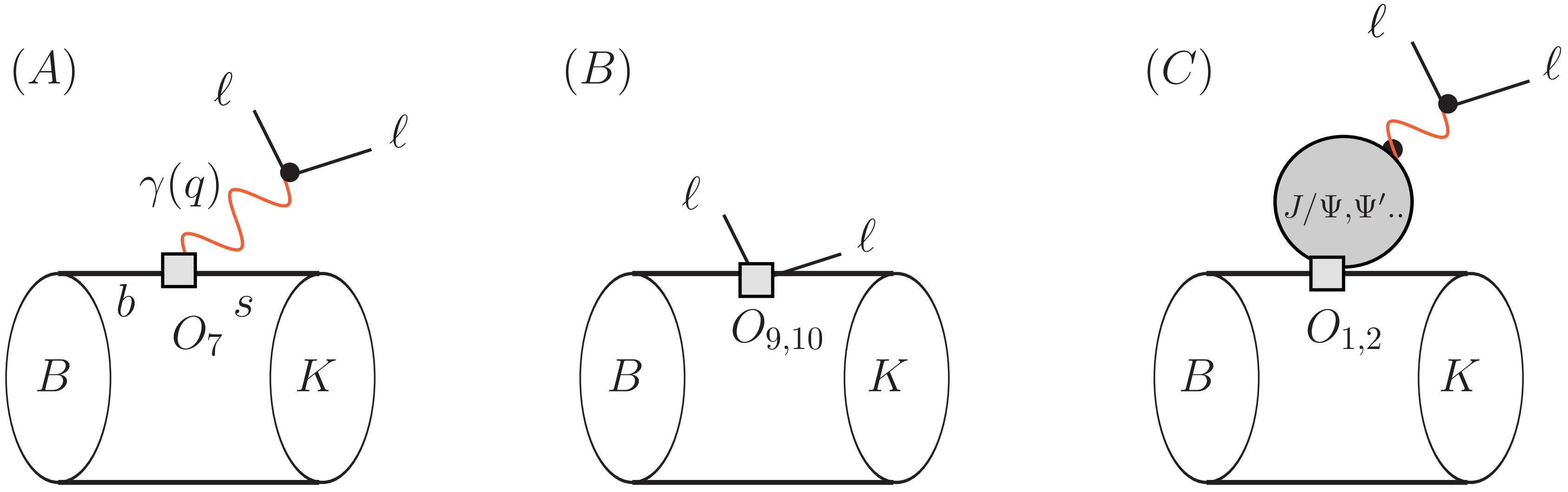
- The Standard Model is Lepton Flavour Non Universal (LFNU) but it is NOT Lepton Flavour Violating (LFV)

$\mu \to e\gamma,\ \tau \to 3\mu,\ B \to K\tau\mu, \ldots$ forbidden because of $U(1)_e \times U(1)_\mu \times U(1)_\tau$

- Anomalies in flavour physics suggest a pattern similar to SM (LFNU without LFV)

- (Neutrino physics is LFV, a possible link with the anomalies?)

Theoretical uncertainties



1. Form factors, however at low q^2 can use Light-Cone Sum Rules (LCSR) and at high q^2 lattice result

$$\langle M(\lambda)|\bar{s}\not{\epsilon}^*(\lambda)P_{L(R)}b|\bar{B}\rangle$$

2. Contributions from hadronic weak hamiltonian (non local effects)

$$-i\frac{e^2}{q^2}\int d^4x e^{-iq\cdot x}\langle\ell^+\ell^-|j_\mu^{\text{em,lept}}(x)|0\rangle\int d^4y\, e^{iq\cdot y}\langle M|j^{\text{em,had},\mu}(y)\mathcal{H}_{\text{eff}}^{\text{had}}(0)|\bar{B}\rangle$$

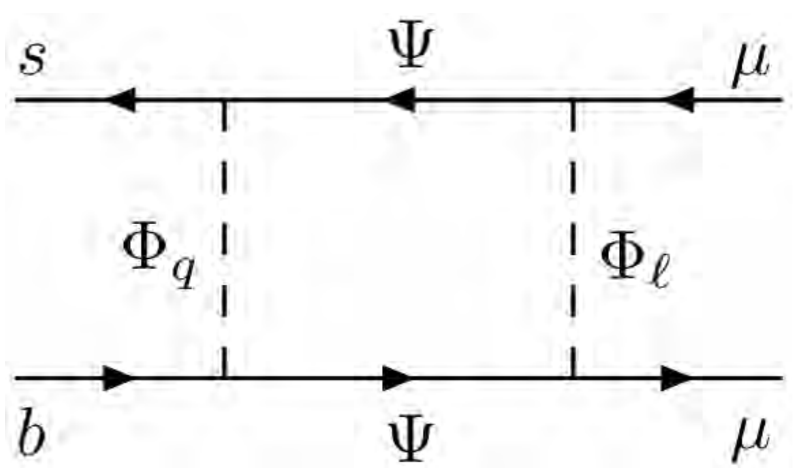
Main effect is encoded in

$$h_\lambda(q^2) = \frac{\epsilon_\mu^*(\lambda)}{m_B^2}\int d^4x e^{iqx}\langle\bar{K}^*|T\{j_{\text{em}}^\mu(x)\mathcal{H}_{\text{eff}}^{\text{had}}(0)\}|\bar{B}\rangle$$
$$= h_\lambda^{(0)} + \frac{q^2}{1\,\text{GeV}^2}h_\lambda^{(1)} + \frac{q^4}{1\,\text{GeV}^4}h_\lambda^{(2)}\,,$$

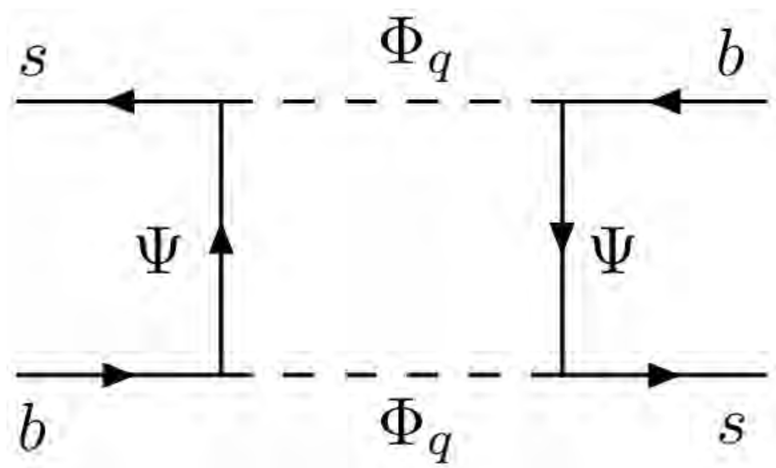
[Aggressive 1701.08672
Conservative 1512.07157]

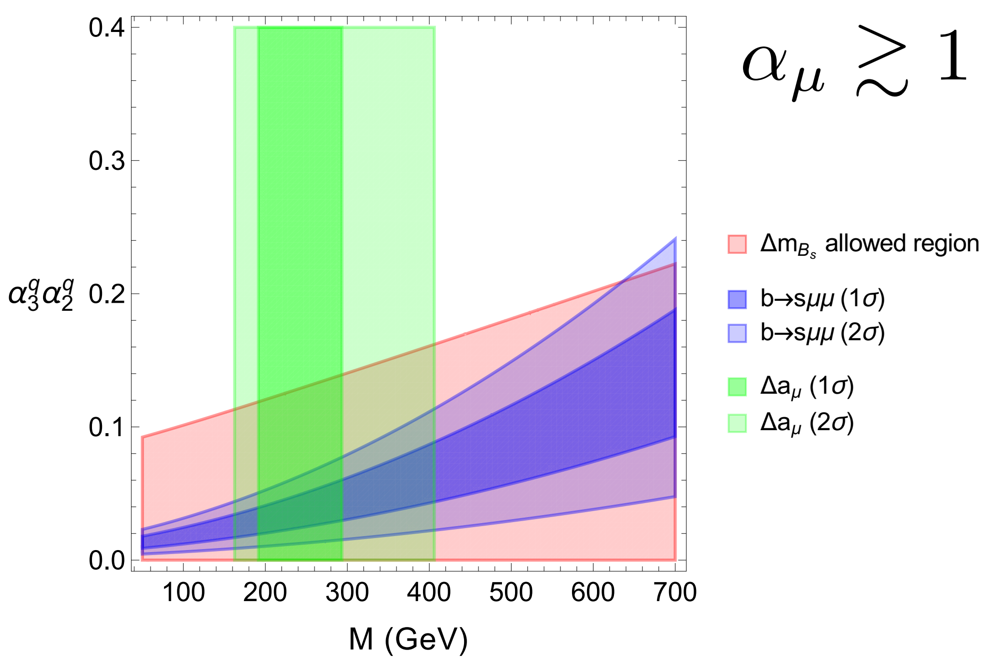
Loop induced

[Gripaios, MN, Renner 1509.05020
see also 1608.07832]



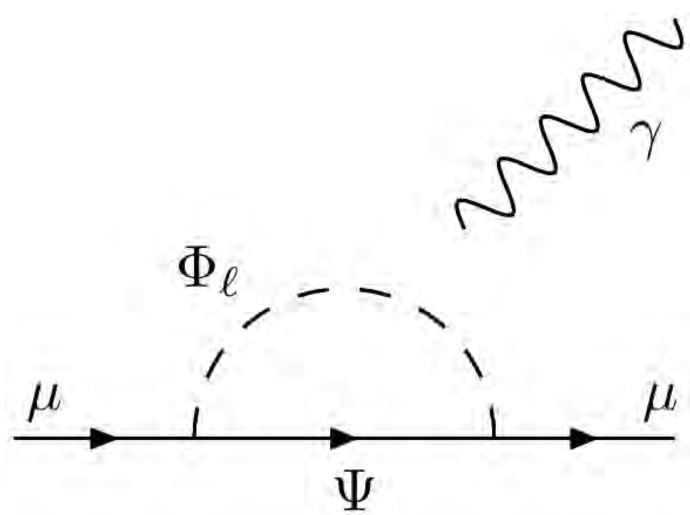
$$\alpha_i^q \, \overline{\Psi} Q_L^i \Phi_q + \alpha_i^\ell \, \overline{\Psi} L_L^i \Phi_\ell + \text{h.c.}$$





$\alpha_\mu \gtrsim 1$

- Main constraint



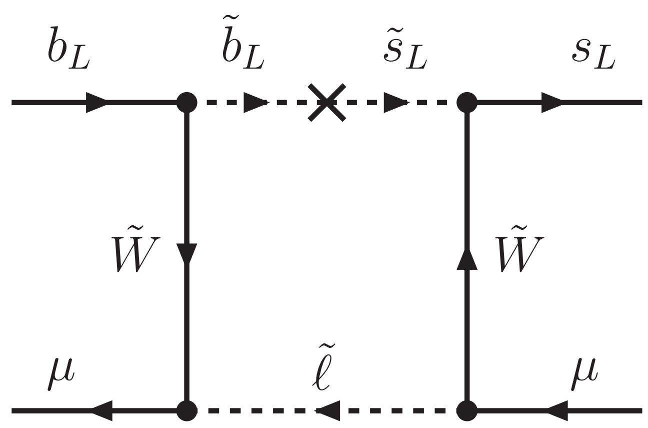
- muon g-2, large leptonic coupling

- Direct searches are important

MSSM (ask me)

- LFU in the MSSM without R-Parity Violation: loop level

Altmannshofer, Straub, 1411.3161
D'Amico et al, 1704.05438



- Lepton universality is broken by slepton masses $m_{\tilde{e}} \gg m_{\tilde{\mu}}$
- Box diagrams are numerically small, very light particles in the loop
- No free parameter on the Feynman vertices: EW couplings
- Direct searches (LHC+LEP) give strong constraints, probably no holes left (but a careful analysis is required)

- MSSM wit R-Parity Violation: basically SM + some specific leptoquark

The LHCb results with large effect in muons suggest an extensions of the MSSM

A theoretical prejudice

- Motivated patter? Horizontal

$$C_\tau \gg C_\mu \gg C_e$$

- FCCC: R(D) and R(D*)
- FCNC: tau exp difficult
- FCNC: neutrinos (Belle2)

- semi-leptonic FCNC anomalies

- no observable effects

- Motivated patter? Vertical

$$(\bar{Q}_L \gamma^\mu Q_L)\,(\bar{L}_L \gamma_\mu L_L) + (\bar{Q}_L \gamma^\mu \tau^a Q_L)\,(\bar{L}_L \gamma_\mu \tau^a L_L)$$

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

$$\frac{G_W}{\sqrt{2}}\bar{\nu}\gamma_\mu(1+\gamma_5)\nu\left\{\frac{(3g^2-g'^2)}{2(g^2+g'^2)}\bar{e}\gamma^\mu e+\tfrac{3}{2}\bar{e}\gamma^\mu\gamma_5 e\right\}.$$

If $g \gg e$ then $g \gg g'$, and this is just the usual e-ν scattering matrix element times an extra factor $\frac{3}{2}$. If $g \simeq e$ then $g \ll g'$, and the vector interaction is multiplied by a factor $-\frac{1}{2}$ rather than $\frac{3}{2}$. Of course our model has too many arbitrary features for these predictions to be taken very seriously, but it is worth keeping in mind that the standard calculation[8] of the electron-neutrino cross section may well be wrong.