BSM options for Neutral Current Anomalies

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18 April 2018, "From Flavour to New Physics", Lyon

Flavour Anomalies

$b \to s\mu\mu$ (LHCb from 2013)

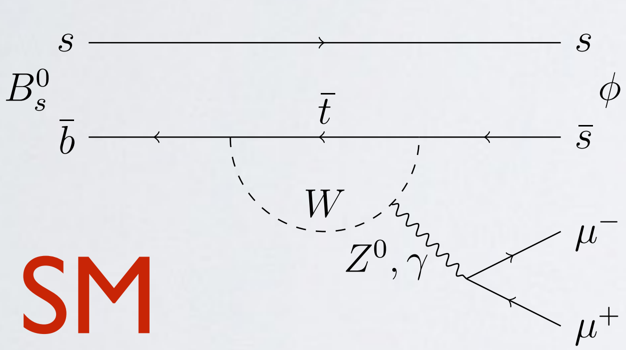
1) Angular observables in $B \to K^* \mu^+ \mu^-$ $\sim 4\sigma$ (?!)

2) Branching ratios $\gtrsim 3.5\sigma$ (?!)

3) LFU violation in R_K 2.6σ

4) LFU violation in R_{K^*} (2 bins) $2.3\sigma,\ 2.6\sigma$

"clean" only $\approx 4\sigma$



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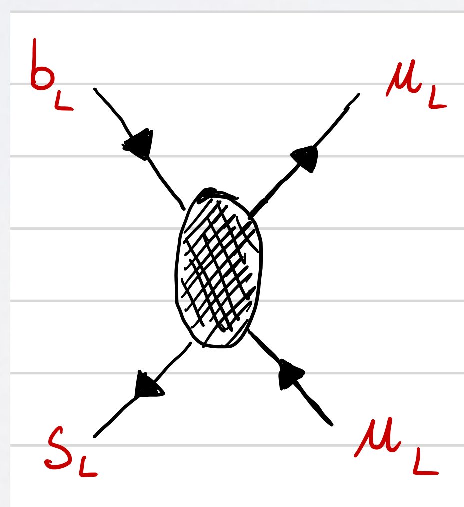
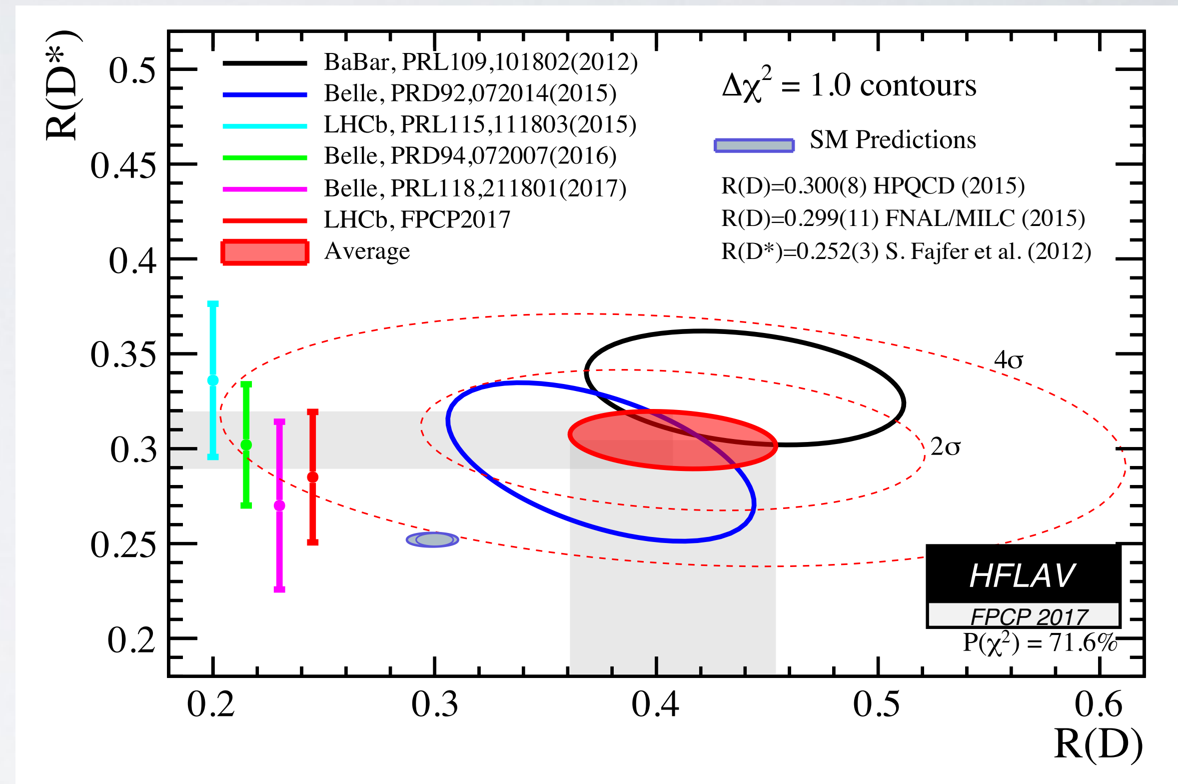


$$\mathcal{L}_{eff} = \frac{1}{\Lambda_{R_K}^2} \bar{s}_L \gamma^\mu b_L\ \bar{\mu}_L \gamma_\mu \mu_L + h.c.$$

$|C_\mu^{NP}| \gg |C_e^{NP}|$ $\Lambda_{R_K} = 31$ TeV

$b \to c\tau\nu$ Babar+Belle+LHCb from 2012



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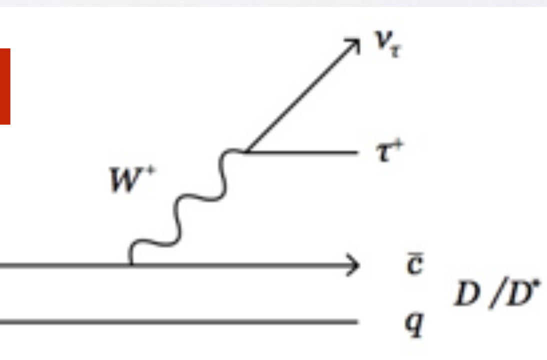

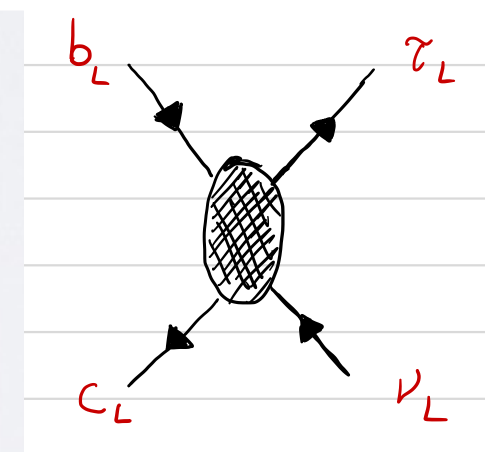

$$\mathcal{L}_{eff} = -\frac{2}{\Lambda_{R_D}^2} \bar{c}_L \gamma^\mu b_L\ \bar{\tau}_L \gamma_\mu \nu_L + h.c.$$

$|C_\tau^{NP}| \gg |C_\mu^{NP}|, |C_e^{NP}|$ $\Lambda_{R_D} = 3.4$ TeV

- *What is the scale of New Physics?*

$$\Lambda_{R_{D^{(*)}}} = 3.4 \pm 0.4 \text{ TeV}\,,$$
$$\Lambda_{R_{K^{(*)}}} = 31 \pm 4 \text{ TeV}\,,$$

"Measured" Fermi constant

$$\frac{1}{\Lambda^2} = \frac{C}{M^2}$$

Model dependent part

C= (loops) x (couplings) x (flavour)

On-shell effects @ colliders

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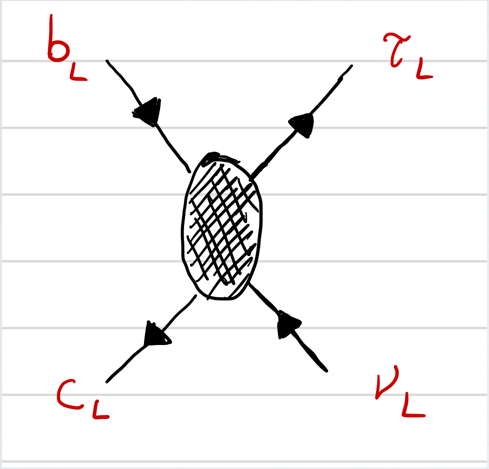
- *What do we expect?* (Worst case scenario)



$$\mathcal{A}(\psi\psi \to \psi\psi) \propto s$$

Tree-Level Pertubative Unitarity criterium

$$|\mathcal{A}_{J=0}| < 1/2$$

[Di Luzio, MN, 1706.01868]

$$\begin{cases} \sqrt{s}_{max} \equiv \Lambda_U = 9 \text{ TeV} & b \to c\tau\nu \\ \sqrt{s}_{max} \equiv \Lambda_U = 80 \text{ TeV} & b \to s\mu\mu \end{cases}$$

An old lesson:VV scattering…

$\Lambda_U = 2$ TeV$, m_h = 125$ GeV

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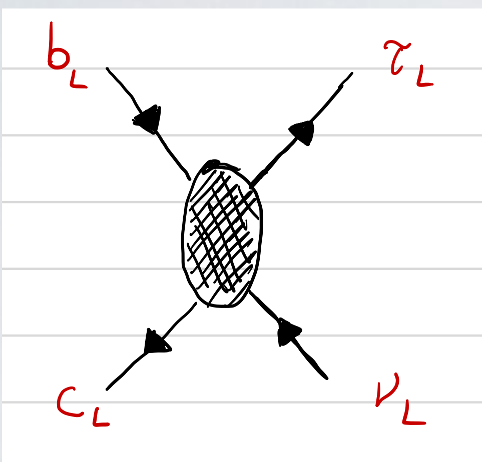

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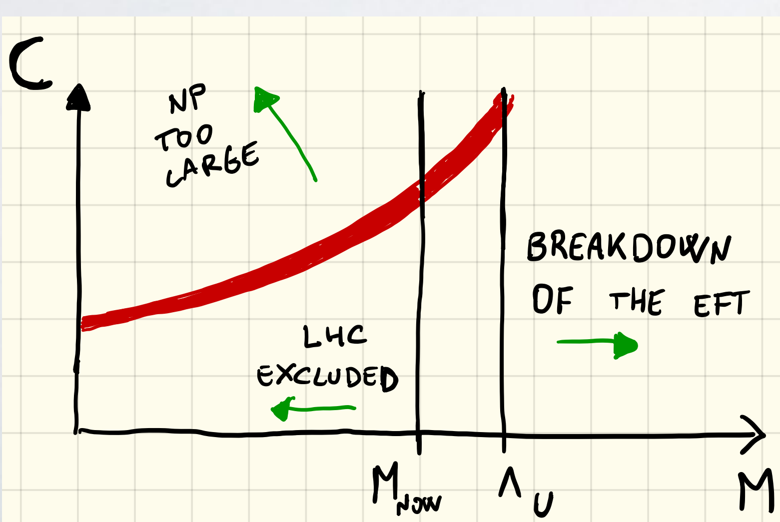
An old lesson: VV scattering…
$\Lambda_U = 2 \text{ TeV}, m_h = 125 \text{ GeV}$

- *What do we expect?* (Warning: a simplified cartoon!)

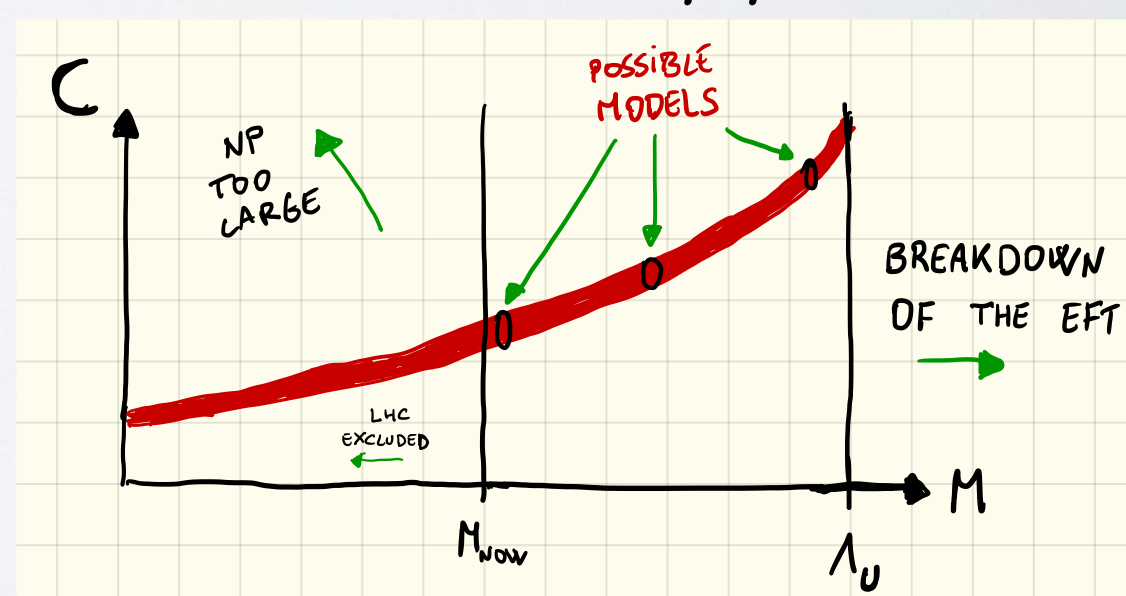
$$b \to c\tau\nu$$



Absence of New Physics at high energy

$$M_{now} \gtrsim 1 \text{ TeV}$$

$$b \to s\mu\mu$$

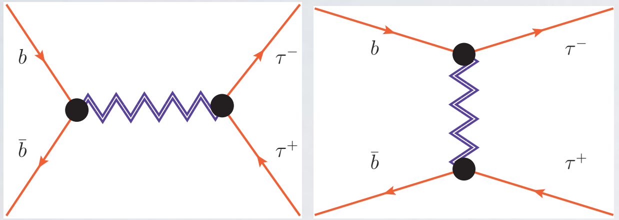


Why Neutral Current only?

- A couple of (personal) prejudices…

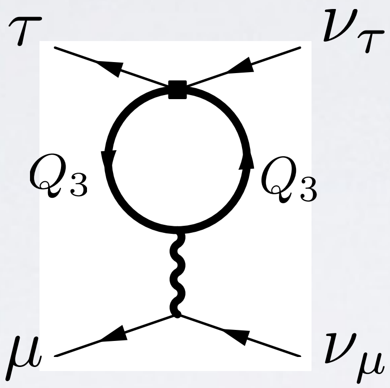
1) The very low NP scale hinted by the anomalies in charged currents is problematic

Direct searches



[Faroughy,Greljo,Kamenik, 1609.07138]

Radiative contraints



[Feruglio, Paradisi, Pattori, 1606.00524,1705.00929]

Other indirect probes

$$\begin{cases} B \to K^{(*)}\overline{\nu}\nu \\ B_s, K, D \text{ mixing} \\ \ldots \end{cases}$$

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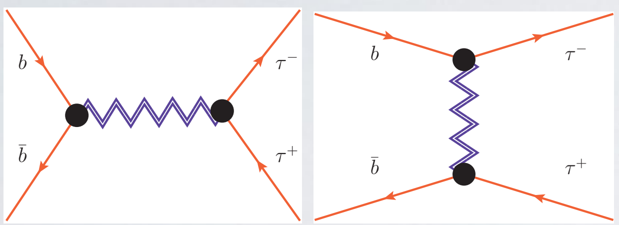

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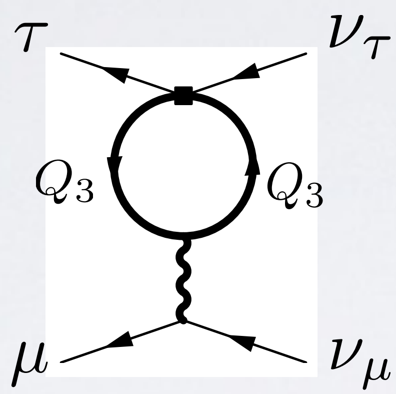

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- However, models can be constructed… separately, bounds can be satisfied. The interplay of various constraints is very important (some models, seems naively ok but…)
- Even if allowed, large couplings are required (calculability is lost?)

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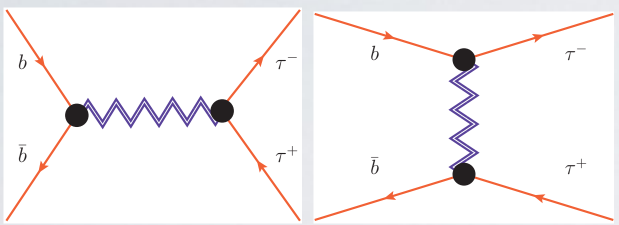

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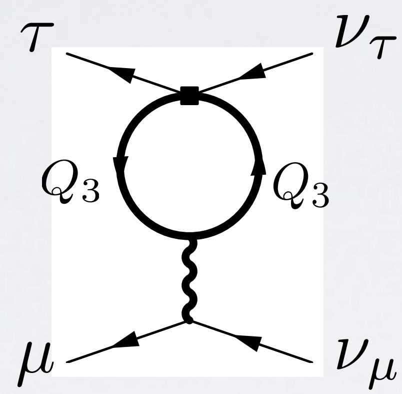

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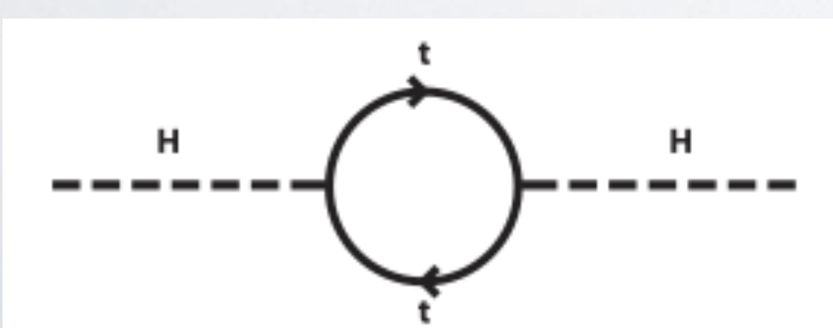
Other indirect probes

$$\begin{cases} B \to K^{(*)}\overline{\nu}\nu \\ B_s, K, D \text{ mixing} \\ \ldots \end{cases}$$

- However, models can be constructed… separately, bounds can be satisfied. The interplay of various constraints is very important (some models, seems naively ok but…)
- Even if allowed, large couplings are required (calculability is lost?)

2) Models addressing the anomalies (in CC) do not fit well in frameworks that address the issue of the naturalness problem of the EW scale



Some attempts:

1) SUSY [Altmannshofer, Dev, Soni 1704.06659]

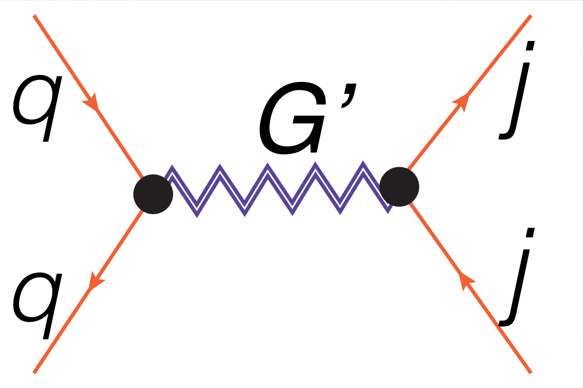
2) Composite Higgs [Tesi, Barbieri, 1712.06844 Marzocca, 1803.19072 Frigerio, MN, Serra,Vecchi, 18xx.xxxx]

2bis) Warped ED [D'Ambrosio, Iyer, 1712.08122]

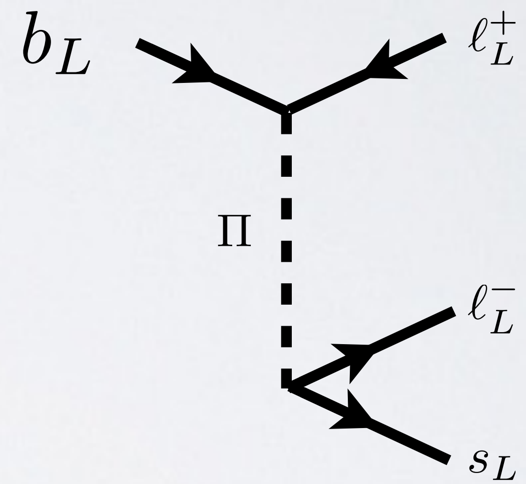
Bottom-up

Theoretical input / bias

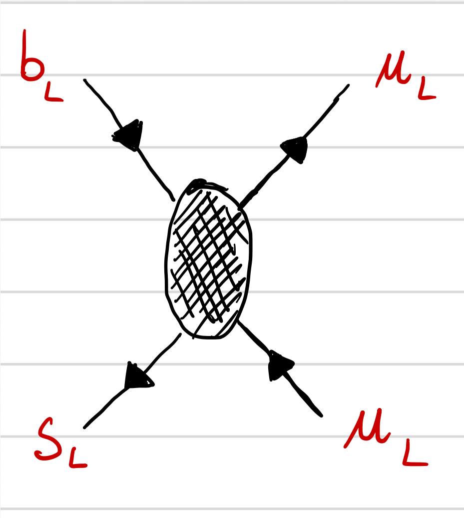
"Complete" Models — Address more questions/open problems: naturalness, origin of flavour,…



Simplified Models — Introducing explicitly New Physics, in the simplest way as possible



EFT — New Physics in a model independent way



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

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

Experimental input

New Physics (Model Independent)

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

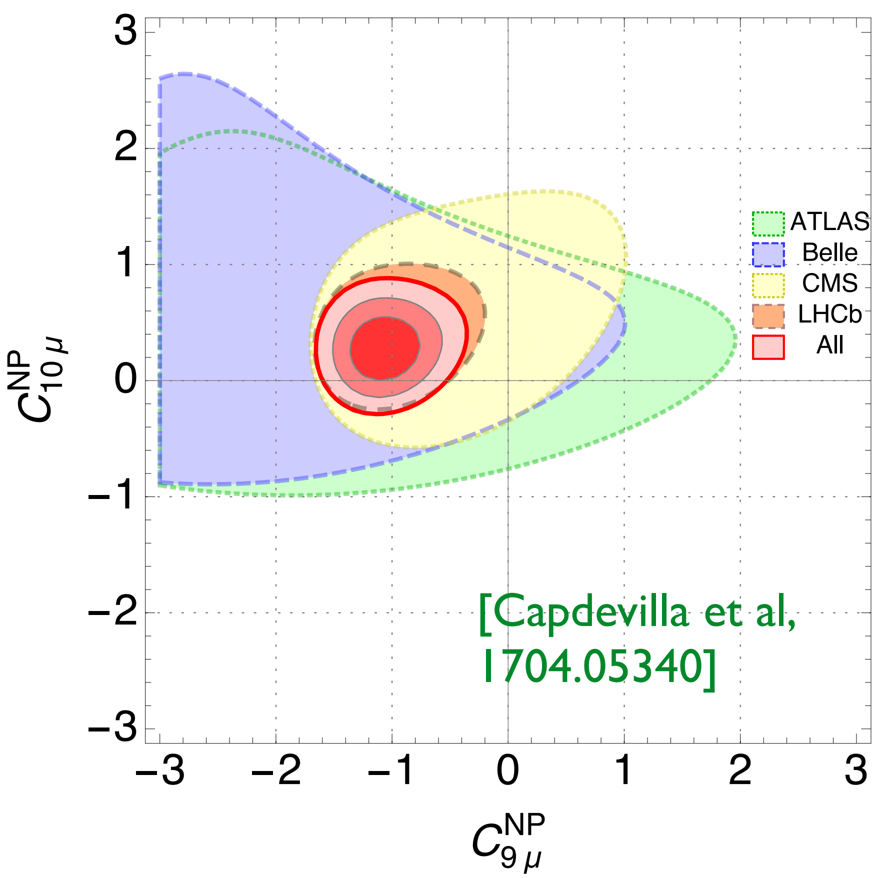
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} (V_{ts}^* V_{tb}) \sum_i C_i^\ell(\mu)\, \mathcal{O}_i^\ell(\mu)$$

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

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

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

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

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

Best Fit with Left-Left currents

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

New physics in the muon sector									
Wilson coeff.	Best-fit			1-σ range			$\sqrt{\chi^2_{\rm SM}-\chi^2_{\rm best}}$		
	'clean'	'HS'	all	'clean'	'HS'	all	'clean'	'HS'	all
$C^{\rm BSM}_{b_L\mu_L}$	-1.27	-1.33	-1.30	-0.94 -1.62	-1.01 -1.68	-1.07 -1.55	4.1	4.6	6.2
$C^{\rm BSM}_{b_L\mu_R}$	0.64	-0.73	-0.30	1.17 0.11	-0.40 -1.03	0.02 -0.59	1.2	2.1	0.9
$C^{\rm BSM}_{b_R\mu_L}$	0.05	-0.20	-0.14	0.33 -0.23	-0.04 -0.29	0.00 -0.25	0.2	1.3	1.0
$C^{\rm BSM}_{b_R\mu_R}$	-0.44	0.41	0.27	0.08 -0.97	0.61 0.18	0.48 0.04	0.8	1.7	1.2
New physics in the electron sector									
Wilson coeff.	Best-fit			1-σ range			$\sqrt{\chi^2_{\rm SM}-\chi^2_{\rm best}}$		
	'clean'	'HS'	all	'clean'	'HS'	all	'clean'	'HS'	all
$C^{\rm BSM}_{b_Le_L}$	1.72	0.15	0.99	2.31 1.21	0.69 -0.39	1.30 0.70	4.1	0.3	3.5
$C^{\rm BSM}_{b_Le_R}$	-5.15	-1.70	-3.46	-4.23 -6.10	0.33 -2.83	-2.81 -4.05	4.3	0.9	3.6
$C^{\rm BSM}_{b_Re_L}$	0.085	-0.51	0.02	0.39 -0.21	0.29 -1.55	0.30 -0.25	0.3	0.7	0.1
$C^{\rm BSM}_{b_Re_R}$	-5.60	2.10	-3.63	-4.66 -6.56	3.52 -2.70	-2.65 -4.43	4.2	0.5	2.5

Table 1. Best fits assuming a single chiral operator at a time, and fitting only the 'clean' R_K, R_{K^*}, and $\mathrm{BR}(B_s \to \mu^+\mu^-)$, or only the 'Hadronic Sensitive' observables (denoted by 'HS' in the table) as discussed in the text, or combining them in a global fit. The full list of observable can be

- Chiral Basis
- Clean vs "Hadronic Sensitive"
- Electron VS Muon
- Clean obs:

$$\begin{cases} R_K \\ R_{K^*} \quad q^2 \in [0.045, 1.1] \\ R_{K^*} \quad q^2 \in [1.1, 6] \\ \mathrm{BR}(B_s \to \mu\mu) \end{cases}$$

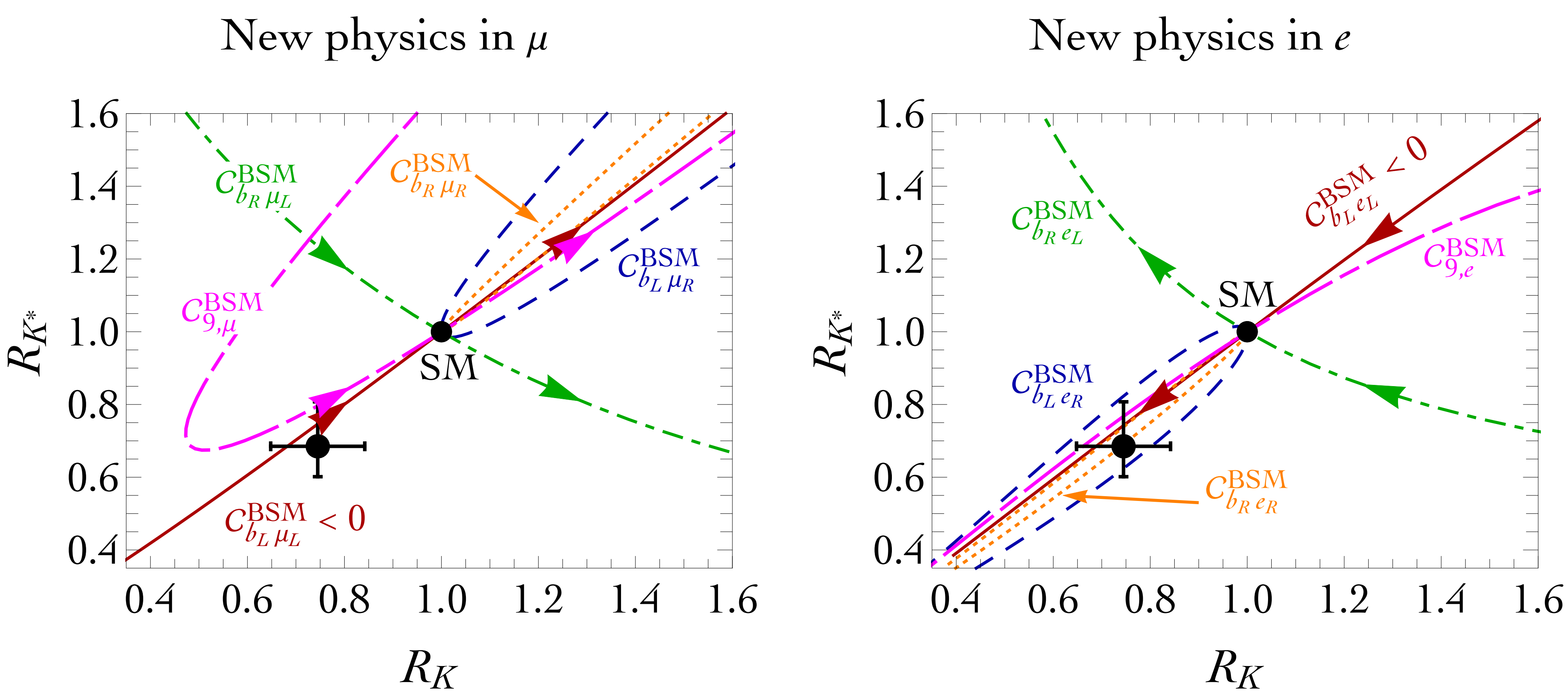
- HS using FLAVIO https://flav-io.github.io/

[D'Amico, MN, Panci Strumia, Torre, Urbano JHEP, 1704.05438]

After R_{K^*}

[D'Amico, et al. JHEP, 1704.05438]

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



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

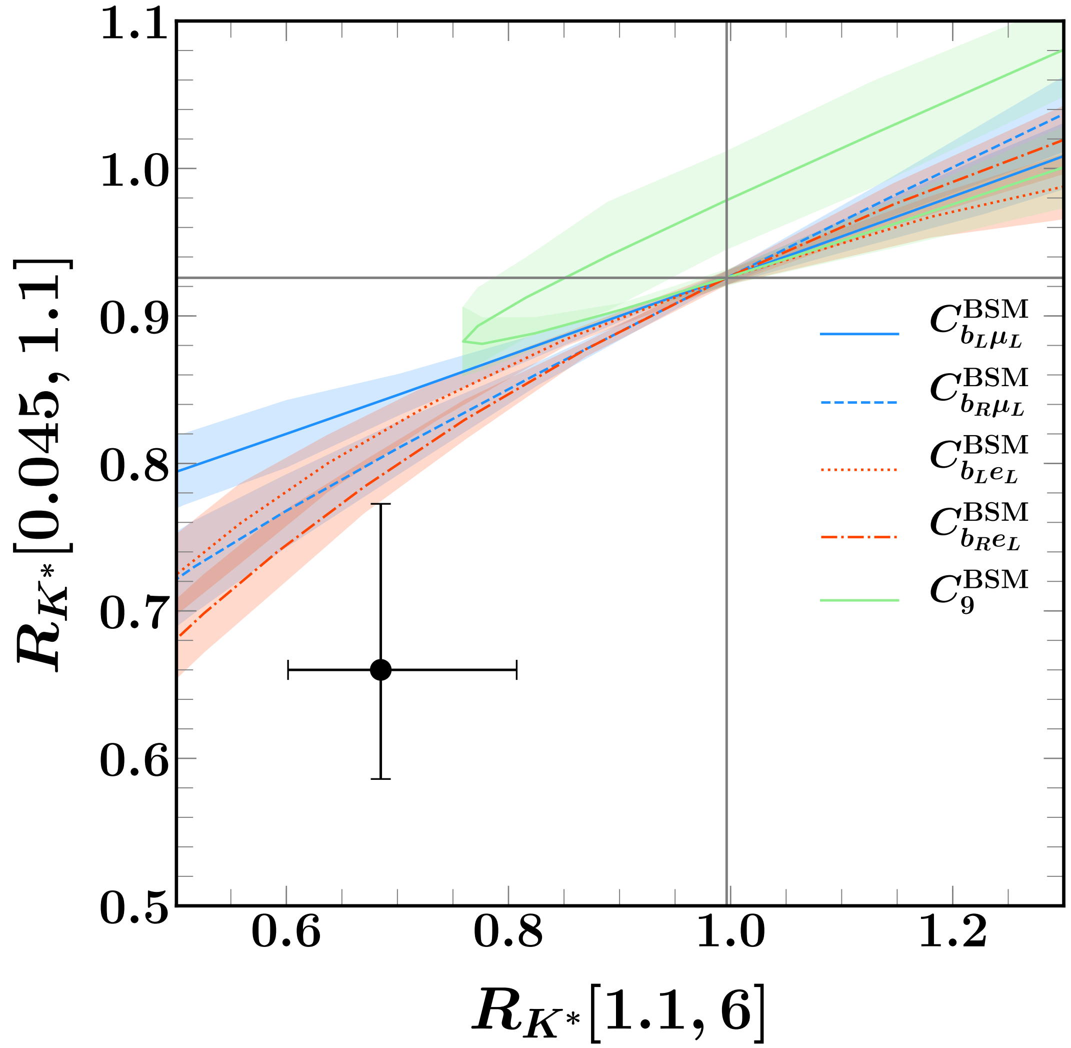
$$4p/C^{\rm SM}_{b_L\mu_L} \approx 0.40$$

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

- 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….
- Motivated flavour models can give an effect in both electron and muon channels (an example using U(2) symmetry: Falkowski, MN, Ziegler 1509.01249)

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

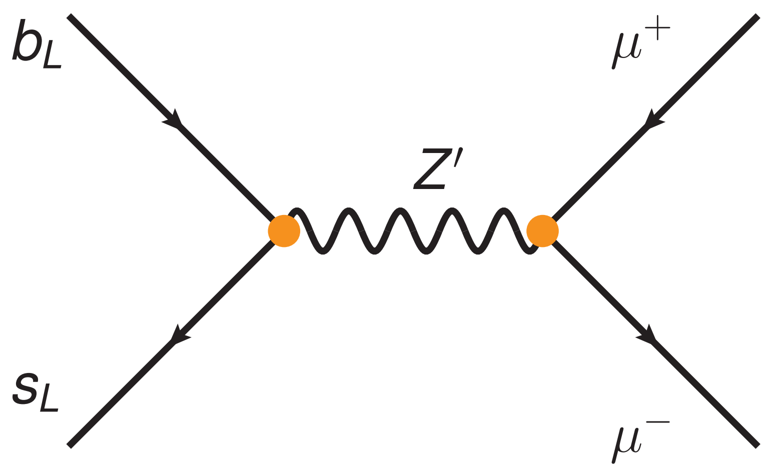


[D'Amico, et al. JHEP, 1704.05438]

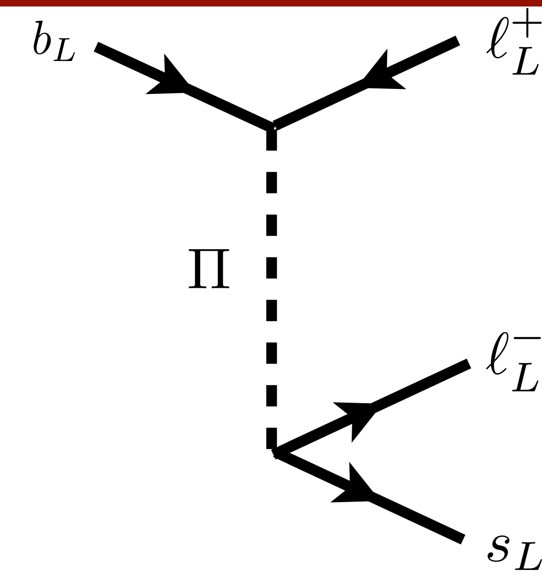
- Can be a sanity check of the measurement
- Having a large effect here requires light long range New Physics

[see for example 1711.07494]

Simplified Models



$$\frac{\Delta_{bs}\Delta_{\mu\mu}}{m_{Z'}^2} \approx \frac{1}{(30\mathrm{TeV})^2}$$



[more than
100 papers]

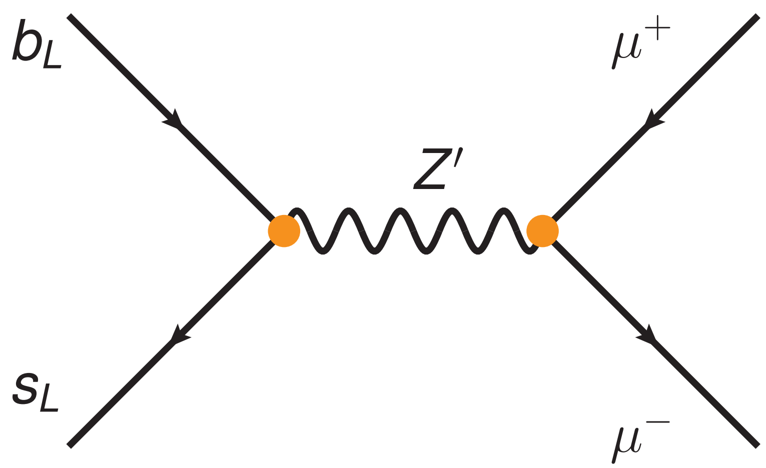
$$\frac{\lambda_{b\mu}\lambda_{s\mu}}{m_{\Pi}^2} \approx \frac{1}{(30\,\mathrm{TeV})^2}$$

- Main constraint to face is Bs mixing:
  - Z' way out: $\Delta_{bs} \ll \Delta_{\mu\mu}$
  - Leptoquark way out: tree VS loop

- Direct searches: need more theoretical input

[See also Tevong's talk]

Simplified Models



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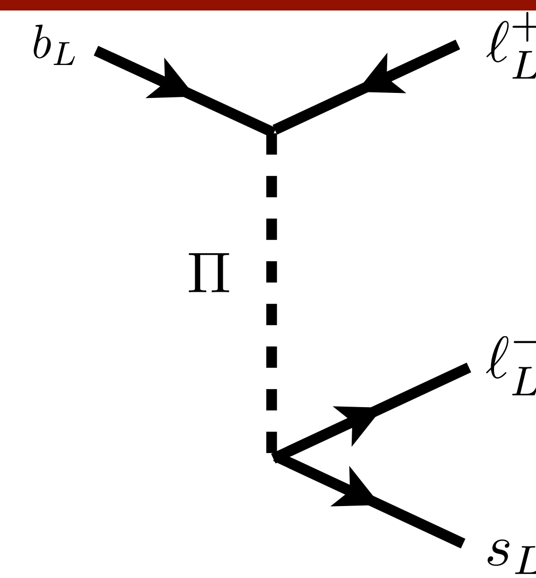

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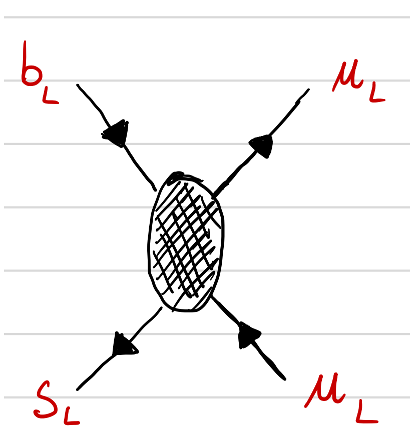
- (Worst case scenario)

[Di Luzio, MN, 1706.01868]



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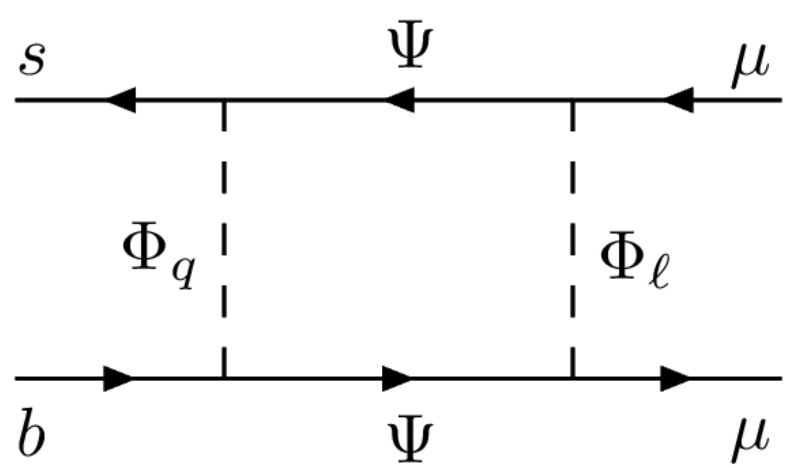
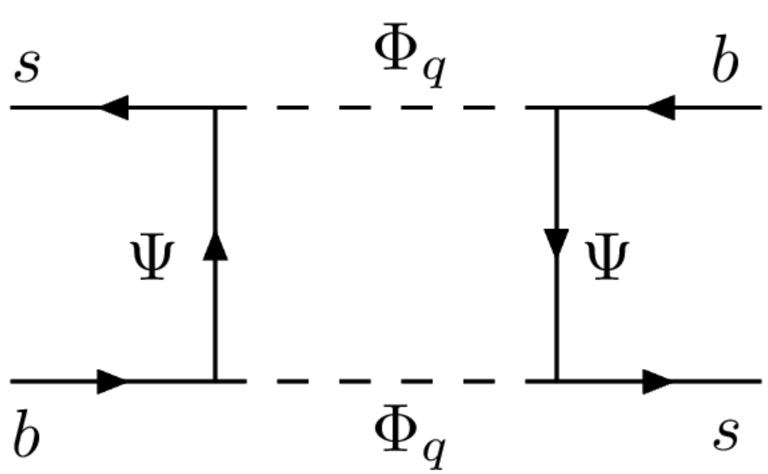
Loop induced

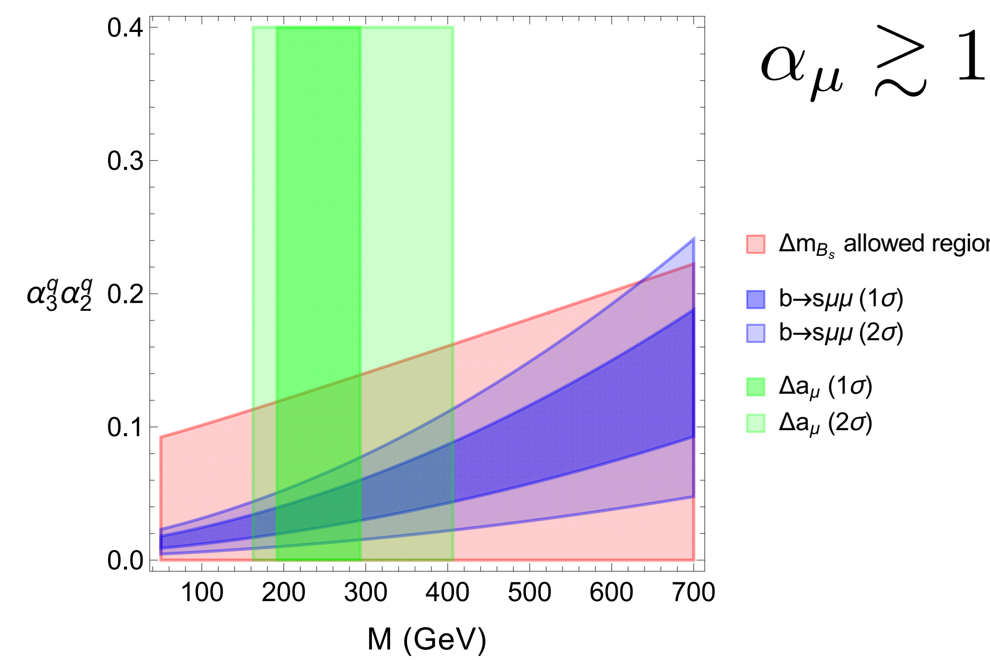
[Gripaios, MN, Renner 1509.05020
see also 1608.07832]



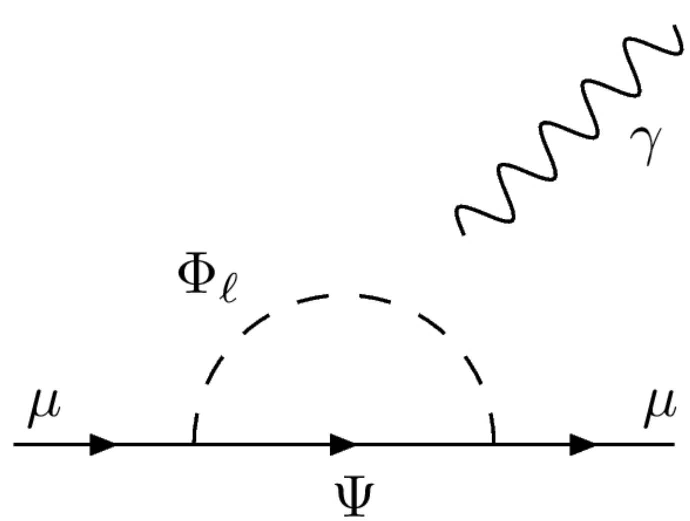
$$\alpha_i^q \overline{\Psi} Q_L^i \Phi_q + \alpha_i^\ell \overline{\Psi} L_L^i \Phi_\ell + \text{h.c.}$$



- Main constraint



$\alpha_\mu \gtrsim 1$



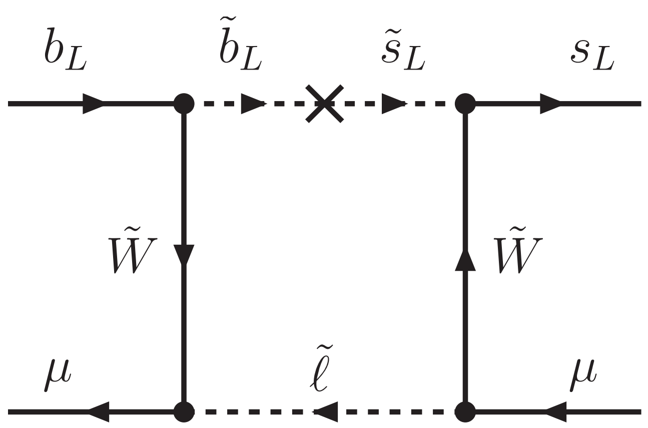
- muon g-2, large leptonic coupling

- Direct searches are important

MSSM

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

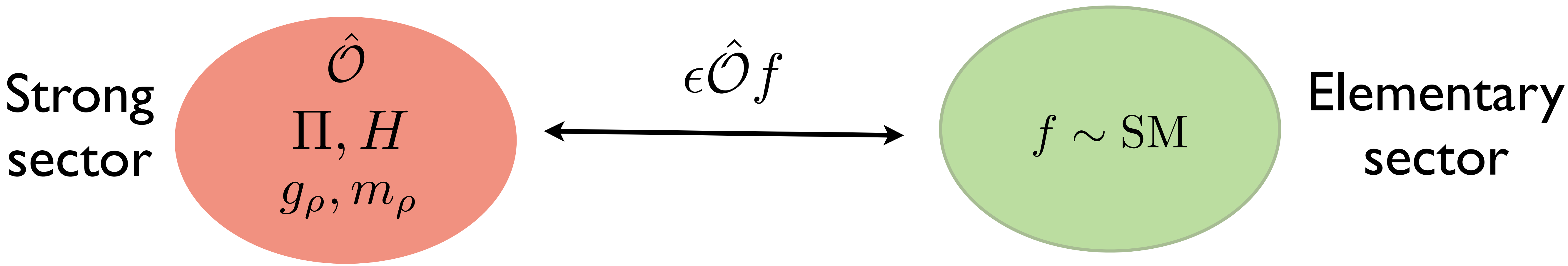
Altmannshofer, Straub, 1411.3161
D'Amico et al, 1704.05438

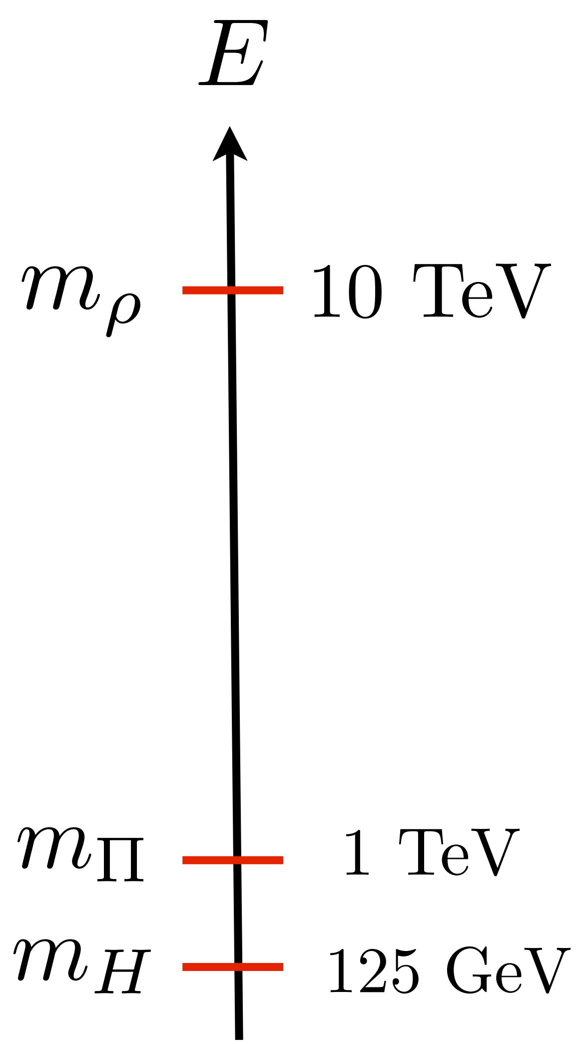


- Lepton universality is broken by slepton masses $m_{\tilde{e}} \gg m_{\tilde{\mu}}$
- Box diagrams are numerically small, very light particles in the loop
- No free parameter on the Feynman vertices: EW couplings
- Direct searches (LHC+LEP) give strong constraints, (probably) no hope left (but a careful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

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

Composite Higgs Framework





- Being PGB, Higgs and Leptoquarks are lighter than the other resonances coming from the strong sector

- SM fermion masses are generated by the mechanism of partial compositeness

$$|SM\rangle = \cos\epsilon |f\rangle + \sin\epsilon |\mathcal{O}\rangle$$

- BSM Flavour violation regulated by the same mechanism

- Naturalness (…)

Based on 1412.5942, JHEP,
Ben Gripaios and Sophie Renner

Conclusions

- Still premature to claim a discovery of New Physics in B meson decays.

- Current anomalies in B decays have a simple and consistent interpretation at the effective field theory level (model independent)

- Models addressing anomalies in charged current are severely challenged by multiple observables.

- After the measurement of RK*, various conclusions can be drawn using only 'clean' observables.

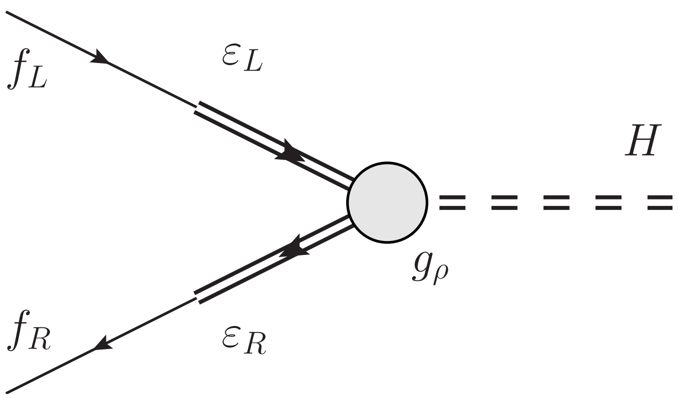
- Anomalies in neutral currents can be explained through the tree level exchange of a leptoquark or a Z' boson, as well as new states in the loop

- Motivated models connecting FV in the SM and the NP exist giving rise to interesting and testable predictions at LHC and other colliders.

- New data from Run 2 are ready to be analysed by the LHCb collaboration

Partial Compositeness in CH models

- Yukawa sector:



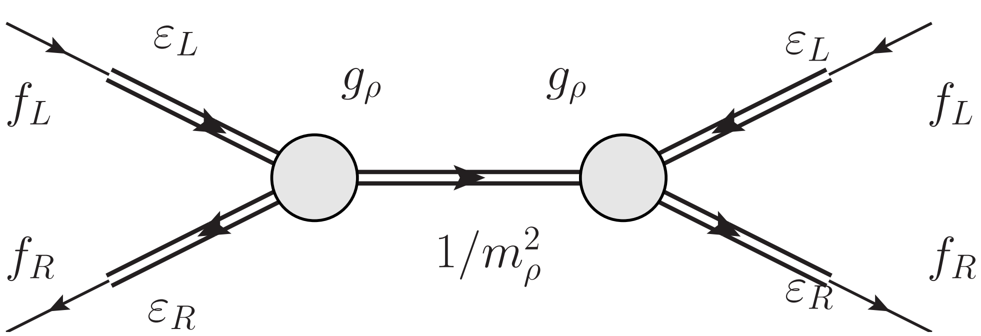
$$\mathcal{L}_{\rm elem} = i\overline{f}\gamma^\mu D_\mu f$$

$$\mathcal{L}_{\rm comp} = \mathcal{L}_{\rm comp}(g_\rho, m_\rho, H)$$

$$\mathcal{L}_{\rm mix} = \epsilon_L\, f_L \mathcal{O}_L + \epsilon_L\, f_R \mathcal{O}_R + h.c.$$

$$Y^{ij} = c_{ij}\, \epsilon_L^i \epsilon_R^j\, g_\rho \longrightarrow Y^{ij} \sim \epsilon_L^i \epsilon_R^j g_\rho$$

- Flavor violation beyond the CKM one is generated:



$$\sim \frac{g_\rho^2}{m_\rho^2}\epsilon_L^i \epsilon_R^i \epsilon_L^j \epsilon_R^j$$

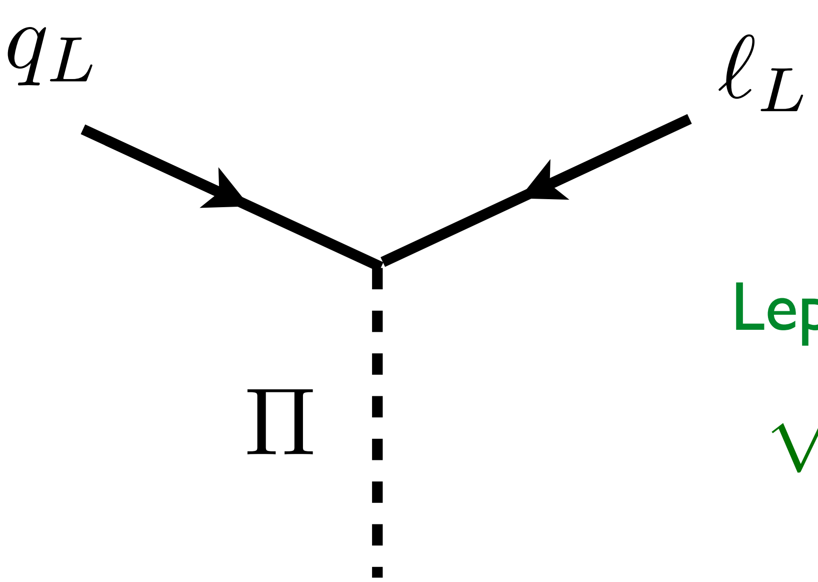
FV related to the SM one but not in a Minimal FV way

Flavour Violation & Leptoquarks

- Comment later about the flavour physics associated with m_ρ

- Relevant Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + (D^\mu \Pi)^\dagger D_\mu \Pi - M^2 \Pi^\dagger \Pi + \lambda_{ij}\, \overline{q}^c_{Lj} i\tau_2 \tau_a \ell_{Li}\, \Pi + \text{ h.c.}$$



Quarks →

Leptons $\sqrt{Y_\ell}$ ↓

$\lambda_{ij}/(c_{ij} g_\rho^{1/2} \epsilon_3^q)$	$j=1$	$j=2$	$j=3$
$i=1$	1.92×10^{-5}	8.53×10^{-5}	1.67×10^{-3}
$i=2$	2.80×10^{-4}	1.24×10^{-3}	2.43×10^{-2}
$i=3$	1.16×10^{-3}	5.16×10^{-3}	0.101

- c are O(1) parameters

- Only 3 fundamental parameters reduced to a single combination in all the flavour observable!

$$(g_\rho, \epsilon_3^q, M) \rightarrow \sqrt{g_\rho}\epsilon_3^q/M$$

Predictions

- We expect large effects coming from third families of leptons

Lepton $\sqrt{Y_\ell}$

$\lambda_{ij}/(c_{ij} g_\rho^{1/2} \epsilon_3^q)$	$j=1$	$j=2$	$j=3$
$i=1$	1.92×10^{-5}	8.53×10^{-5}	1.67×10^{-3}
$i=2$	2.80×10^{-4}	1.24×10^{-3}	2.43×10^{-2}
$i=3$	1.16×10^{-3}	5.16×10^{-3}	0.101

- Decay channels with taus are difficult to be reconstructed $b \longrightarrow s\tau^+\tau^-$

- More interesting are channels with tau neutrinos in the final state

Buras et al. arXiv:1409.4557

$$R_K^{*\nu\nu} \equiv \frac{\mathcal{B}(B \to K^* \nu\overline{\nu})}{\mathcal{B}(B \to K^* \nu\overline{\nu})_{SM}} < 3.7,$$

$$R_K^{\nu\nu} \equiv \frac{\mathcal{B}(B \to K \nu\overline{\nu})}{\mathcal{B}(B \to K \nu\overline{\nu})_{SM}} < 4.0.$$

- Considering just $B \longrightarrow K^* \overline{\nu}_\mu \nu_\mu$ gives

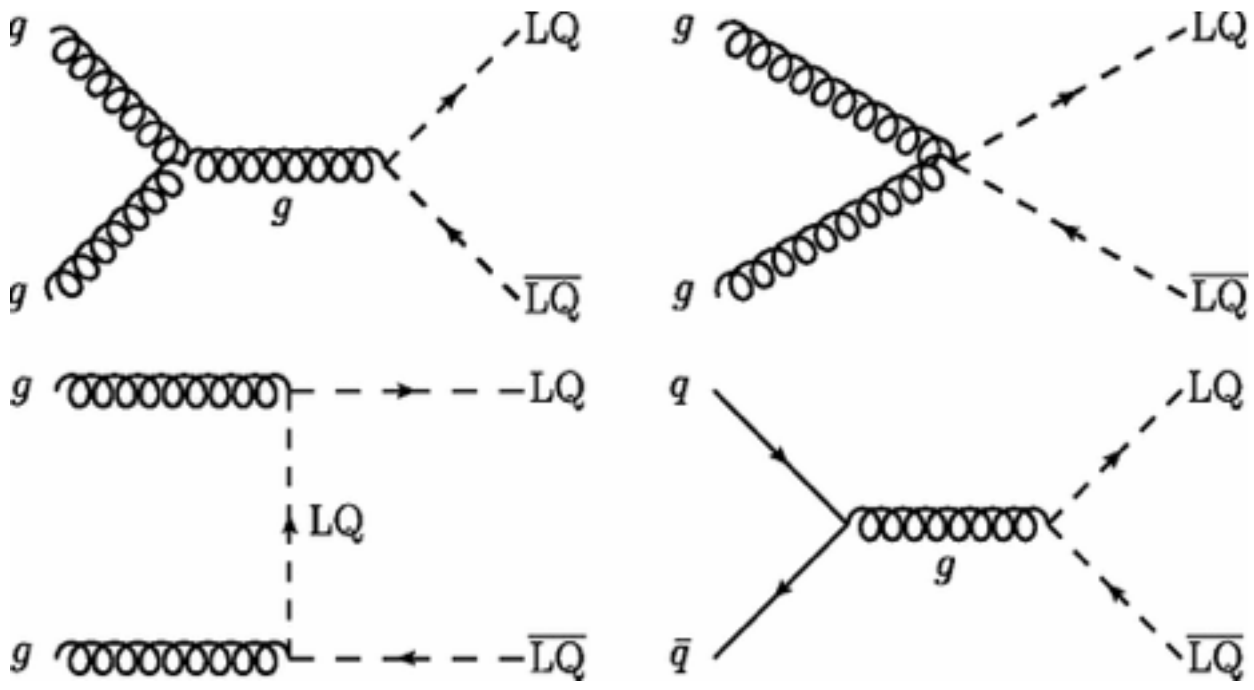
$$\Delta R_K^{(*)\nu\nu} < \text{ few } \%$$

- Including $\mathrm{BR}(B \longrightarrow K \nu_\tau \overline{\nu}_\tau)$, large deviation $\Delta R_K^{(*)\nu\nu} \sim 50\%$

Testable at Belle II

See 1002.5012

LHC



- Production via strong interaction

- Decay to fermions of the third family

$$\Pi_{4/3} \to \overline{\tau}\,\overline{b}, \quad M > 850 \text{ GeV}$$
$$\Pi_{1/3} \to \overline{\tau}\,\overline{t} \text{ or } \Pi_{1/3} \to \overline{\nu_\tau}\,\overline{b}, \quad M > 570 \text{ GeV}$$
$$\Pi_{-2/3} \to \overline{\nu_\tau}\,\overline{t}. \quad M > 950 \text{ GeV}$$

- Stop and sbottom + dedicated leptoquark searches

[ATLAS-CONF-2017-020]
[CMS arXiv:1703.03995]

- Small SU(2) breaking in the spectrum $M \gtrsim 950 \text{ GeV}$