Theory of
Lepton Flavour (Universality) Violation

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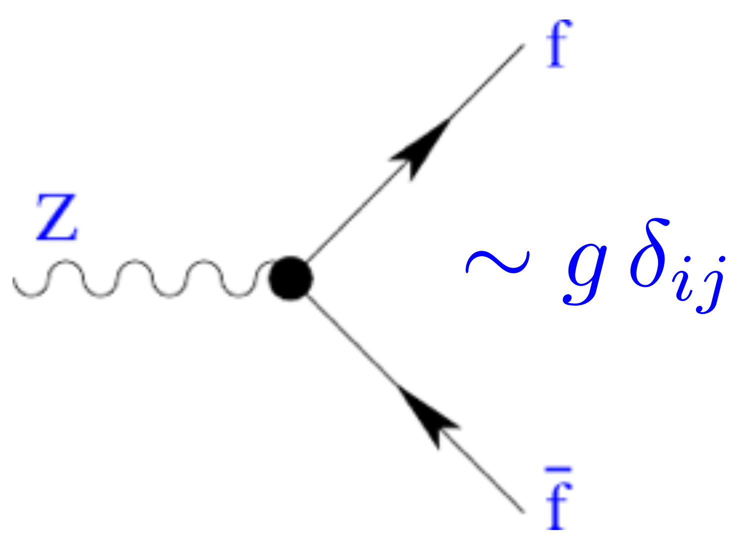
Outline

- Introduction
- Lepton Flavour Universality Violation in charged currents
- Lepton Flavour Universality Violation in neutral currents
- (On natural models: SUSY and composite Higgs)
- (On the scale of New Physics, a No-Lose theorem?)
- Conclusions

Lepton Flavour in the Standard Model

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



$$\mathcal{L}_{SM} \supset i\left(\overline{L}^i_L\gamma^\mu D_\mu L^i_L + \overline{E}^i_R\gamma^\mu D_\mu E^i_R\right)$$

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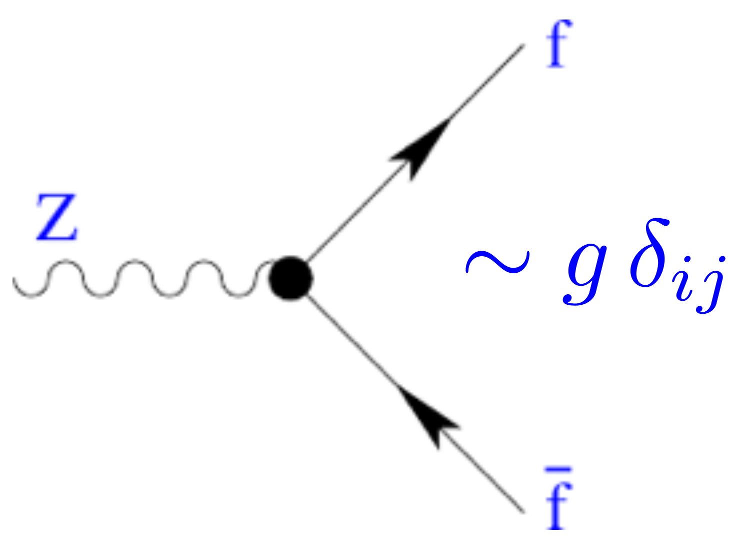

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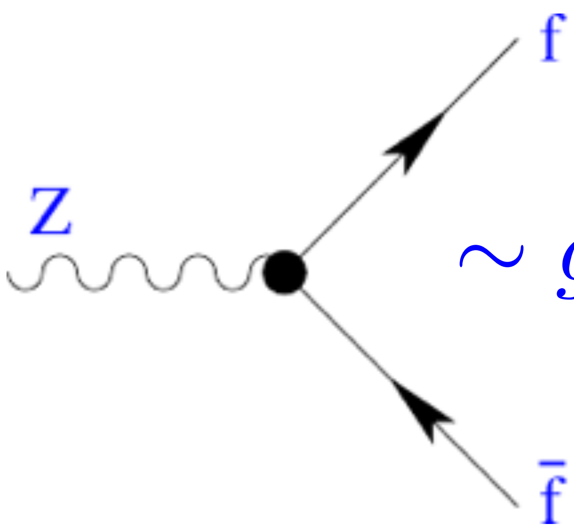

$\sim g\,\delta_{ij}$

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- 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 $U(1)_e \times U(1)_\mu \times U(1)_\tau$

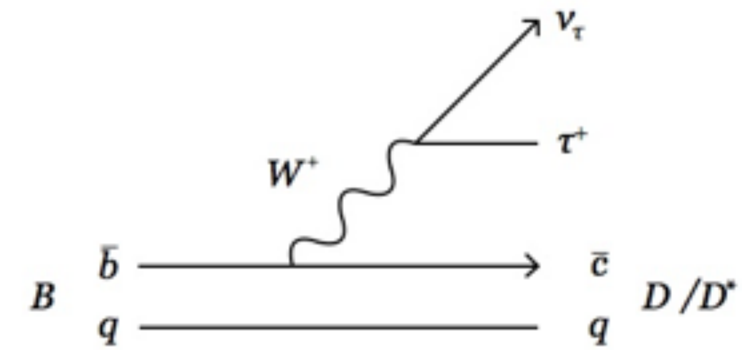
- Anomalies in flavour physics suggest a pattern similar to SM (LFNU without LFV)

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

LFU Violating Anomalies

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

$$|C_\tau^{\rm NP}| \gg |C_\mu^{\rm NP}|, |C_e^{\rm NP}|$$

$\mathcal{A}_{\rm SM} =$ 

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

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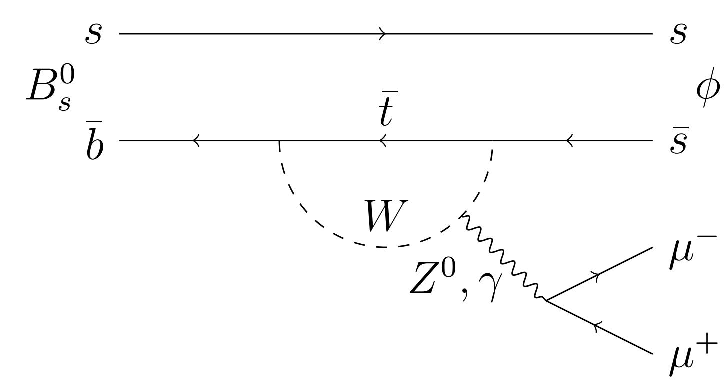
$\mathcal{A}_{\rm SM} =$ 

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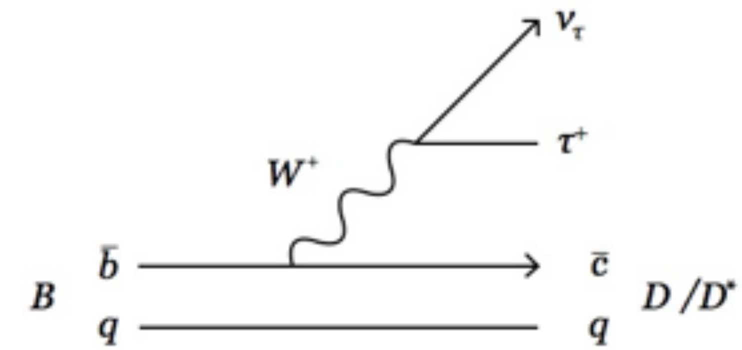

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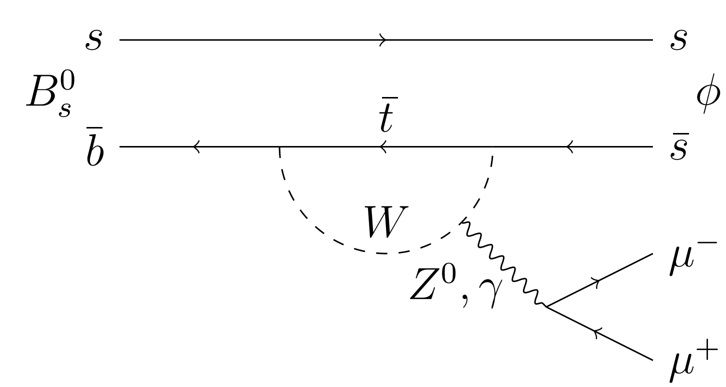


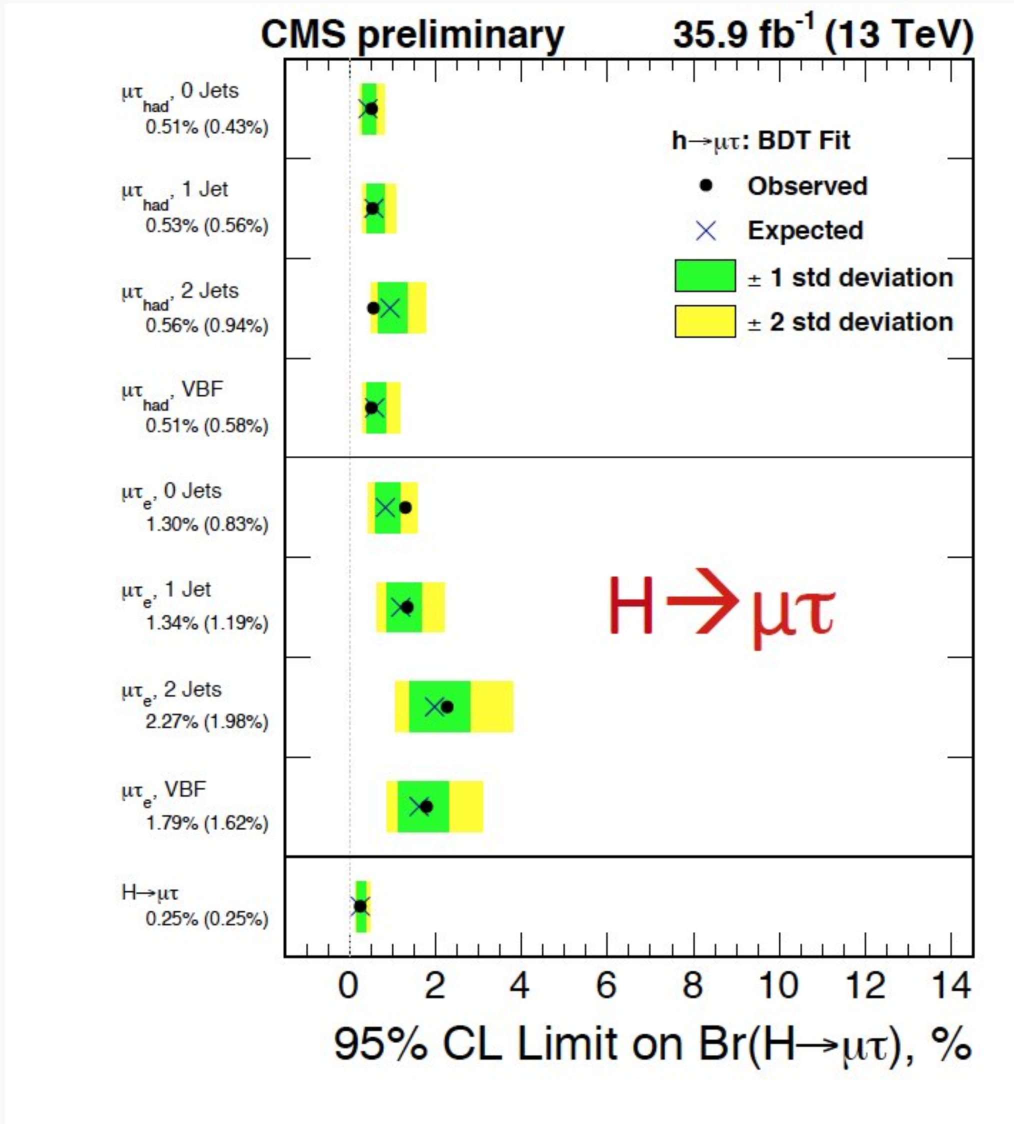
3) g-2 of the muon $|C_\mu^{\mathrm{NP}}| \gg |C_e^{\mathrm{NP}}|$

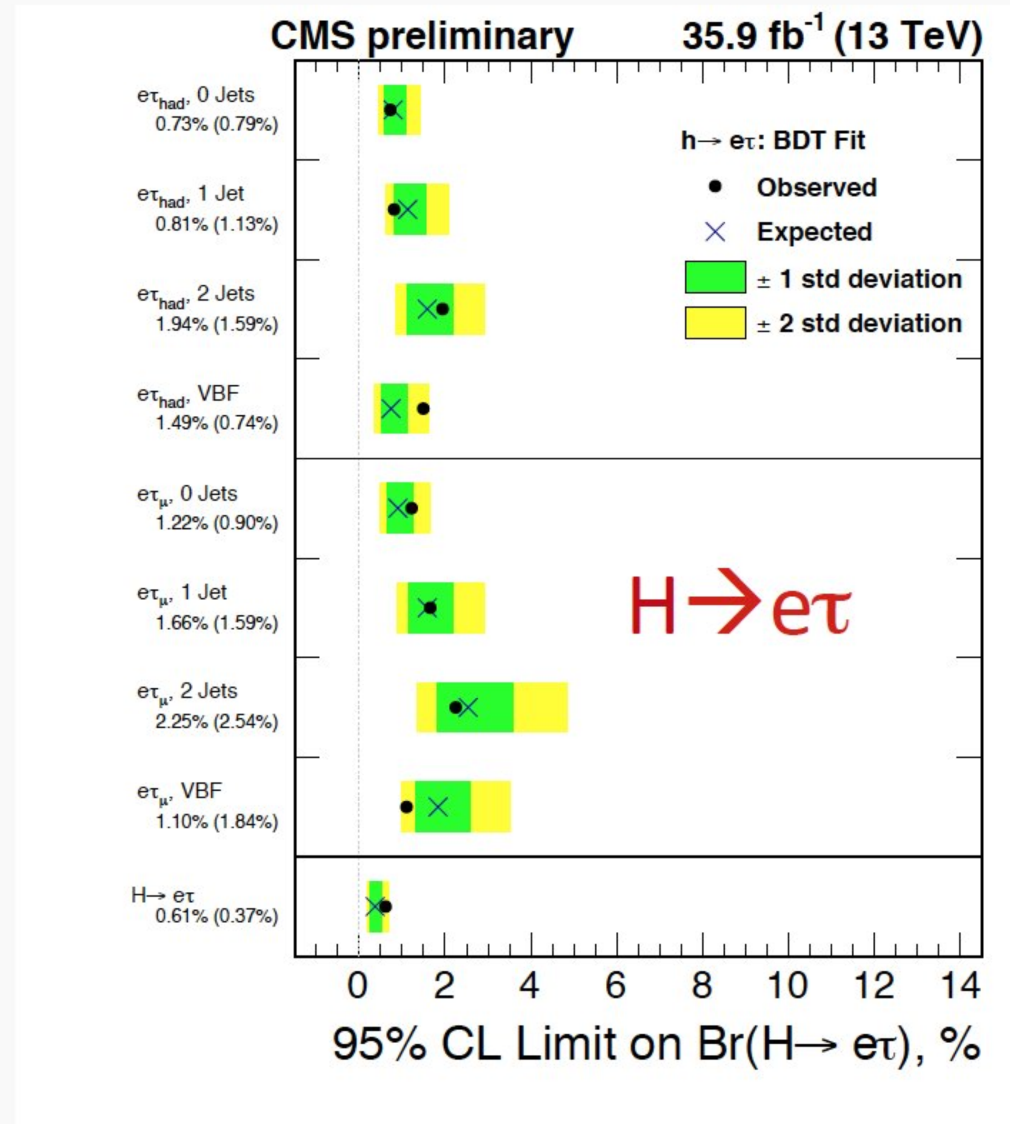
4) LFV Higgs decay $h \to \tau\mu$

…deceased last week
@ LHCP 2017

[CMS Talk @ LHCP 2017, Shanghai]

Results of H→μτ and H→eτ searches





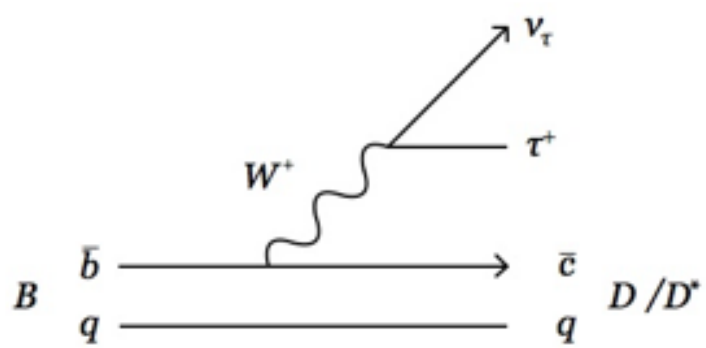
- No excess of data
- Best fit branching fraction: 0.00 ± 0.12%
- B(H→μτ) < 0.25% at 95% CL

- Slight excess of data (1.6 σ)
- Best-fit branching fraction: 0.30 ± 0.18%
- B(H→eτ) < 0.61% at 95% CL

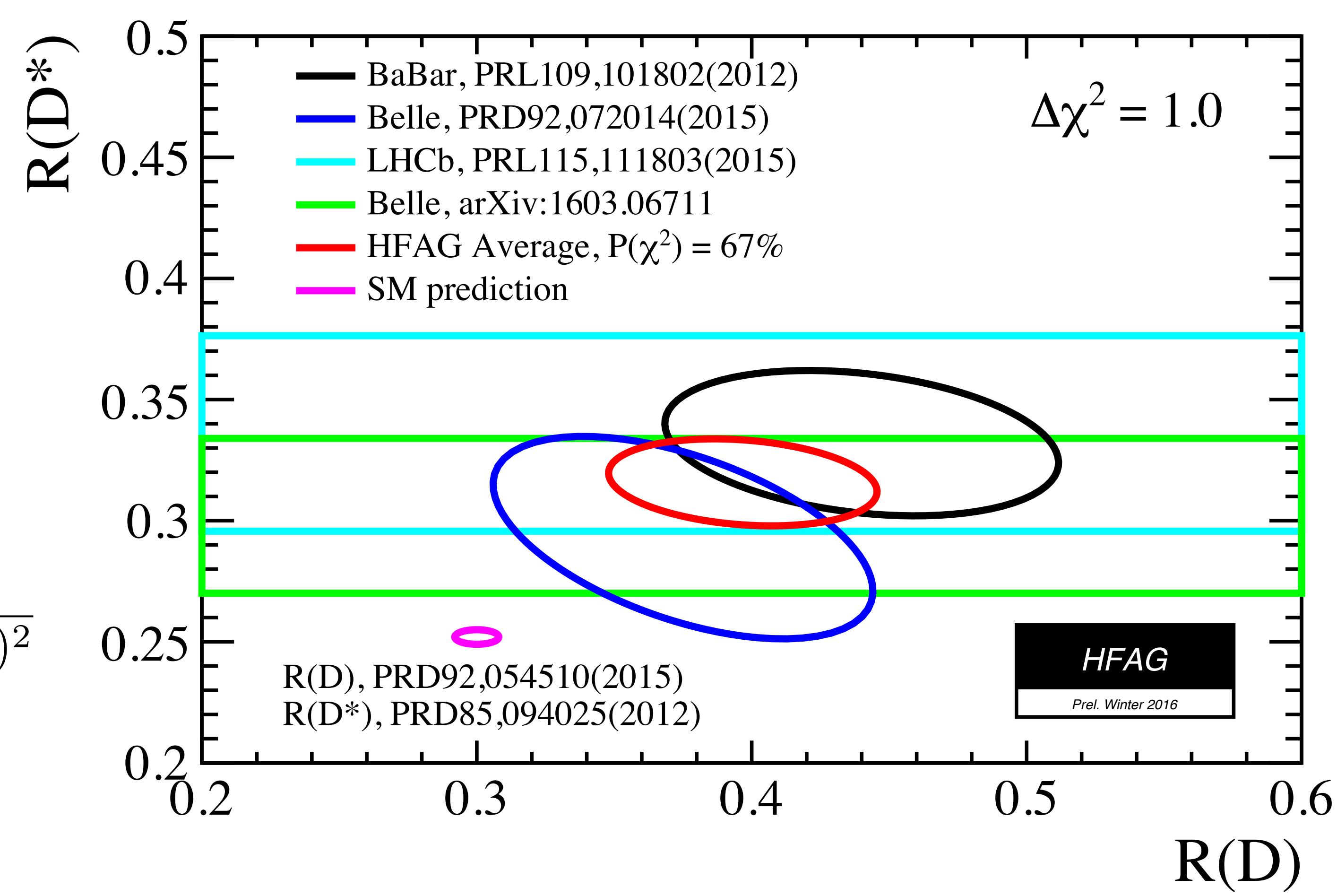
$b \to c\tau\nu$

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

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



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



- SM prediction quite solid (taking ratios helps)
- Seen in 3 different experiments in a consistent way, combined significance 4.0σ (HFAG website)
- 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, easier to have interference with SM (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

$b \to c\tau\nu$

- Effects well described in the EFT by the purely left four fermi operator:

$$\frac{1}{\Lambda^2}\left(\overline{Q}_2\gamma^\mu\sigma^A Q_3\right)\left(\overline{L}_3\gamma_\mu\sigma^A L_3\right) \qquad \Lambda = 3.4\ \text{TeV}$$

- In motivated flavour framework there is (typically) a CKM suppression, reducing the scale:

$$\Lambda < 700\ \text{GeV}$$

$$\frac{1}{\Lambda^2}\left(\overline{Q}_3\gamma^\mu\sigma^A Q_3\right)\left(\overline{L}_3\gamma_\mu\sigma^A L_3\right) \supset \frac{1}{\Lambda^2}\left(2V_{cb}^*\,\overline{c}_L\gamma^\mu b_L\,\overline{\tau}_L\gamma_\mu\nu_L + \overline{b}_L\gamma^\mu b_L\,\overline{\tau}_L\gamma_\mu\tau_L\right)$$

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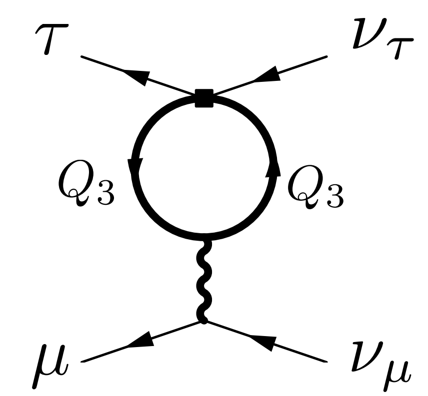
- EW corrections are very important [Feruglio, et al. 1705.00929]

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



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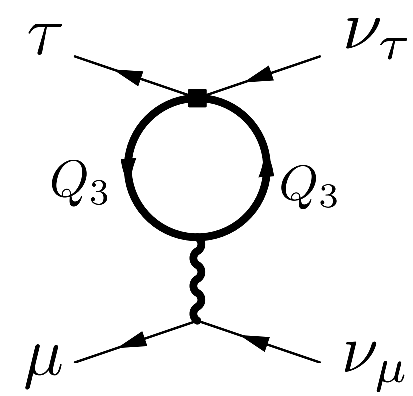

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- Resonant and non resonant searches at LHC are very important

- Link LFUV and High-PT tau lepton searches at the LHC [Faroughy, et al. 1609.07138]

$\sigma(pp \to \tau\tau)$ through $\overline{b}b \to \tau\tau$

$b \to s\ell\ell$

Question on R_{K^*} : Why are you getting excited for just another 2.5 sigma deviation from the Standard Model?

$b \to s\ell\ell$

Question on R_{K^*} : Why are you getting excited for just another 2.5 sigma deviation from the Standard Model?

Answer (biased): It fits nicely in a coherent pattern of correlated anomalies in

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

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

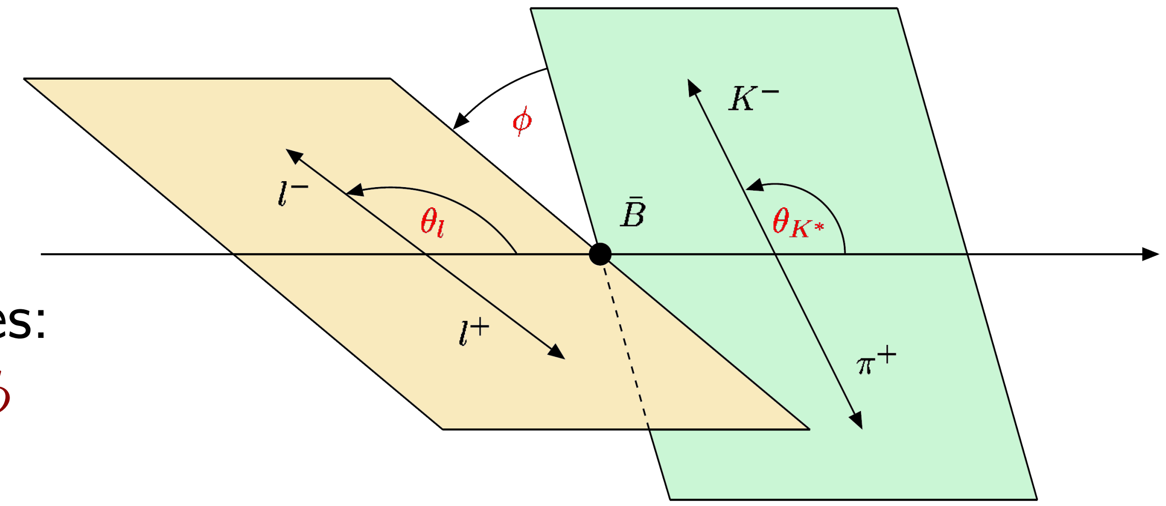
2) Various measurements of branching ratios are low compared to the SM prediction

(such as $B_S^0 \to \phi \mu^+ \mu^-$)

3) Lepton universality violation in R_K

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

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

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

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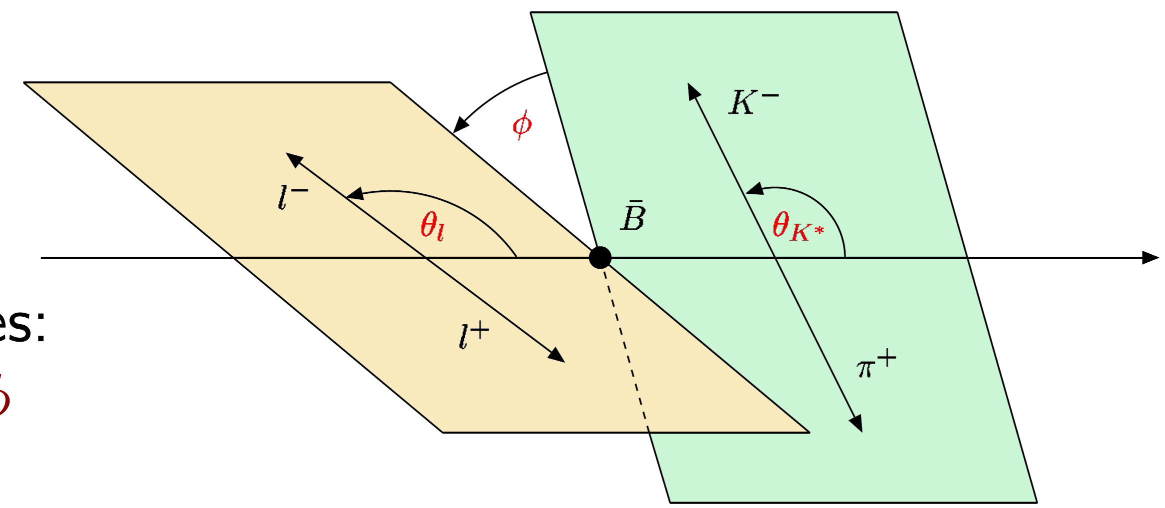

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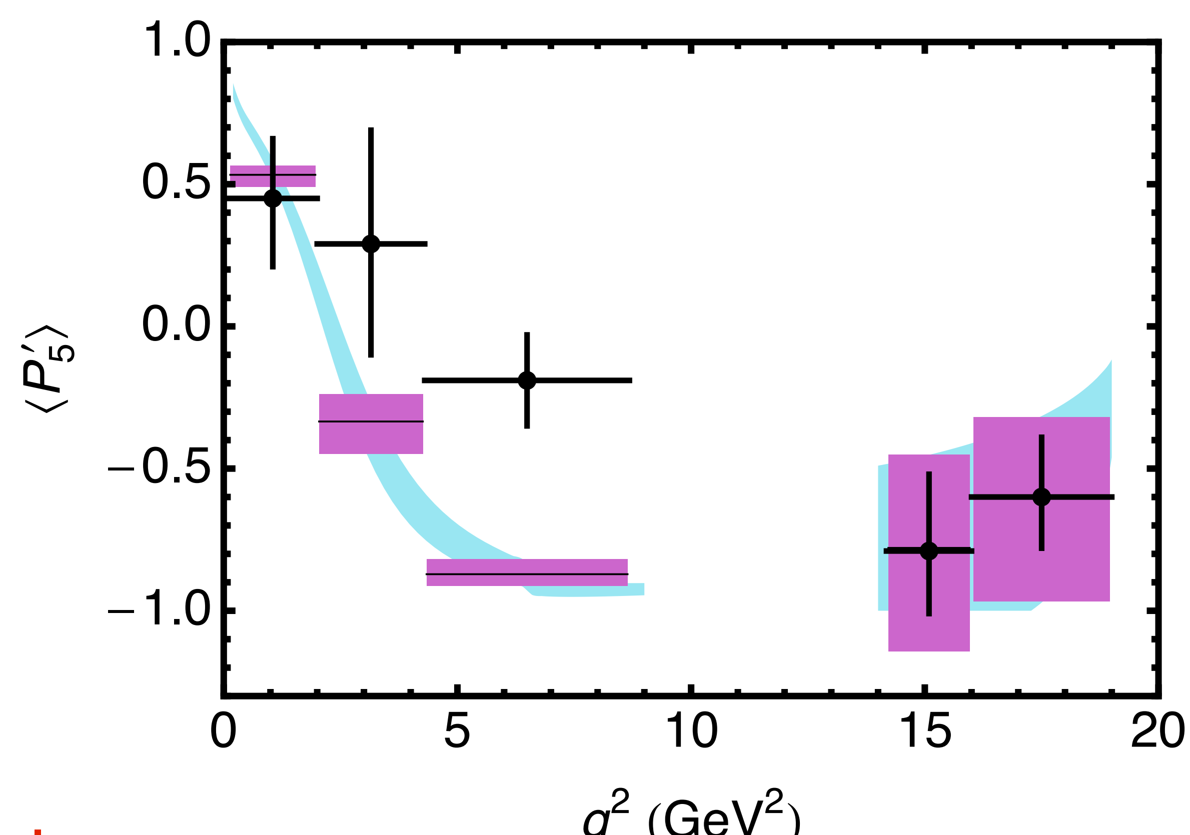
LHCb, 1308.1707, PRL



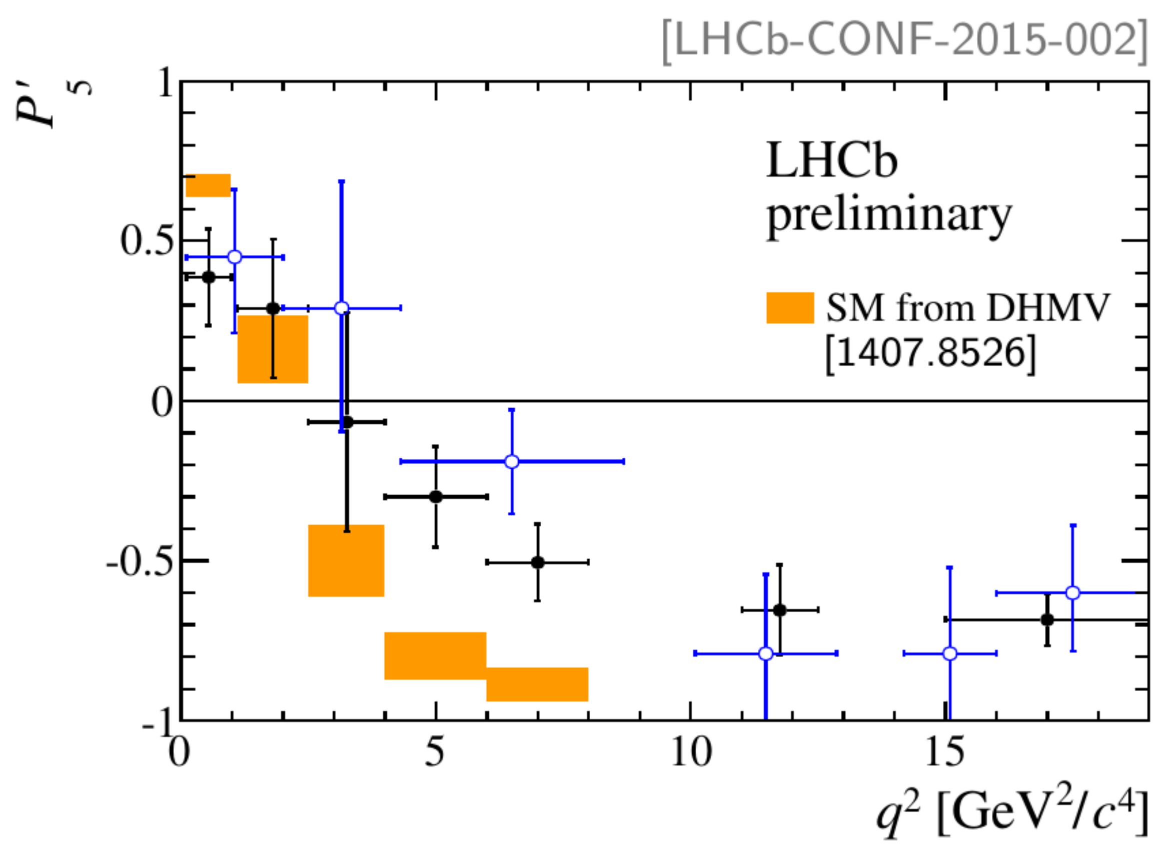
3.7σ discrepancy in one of q^2 bins

Explanations:

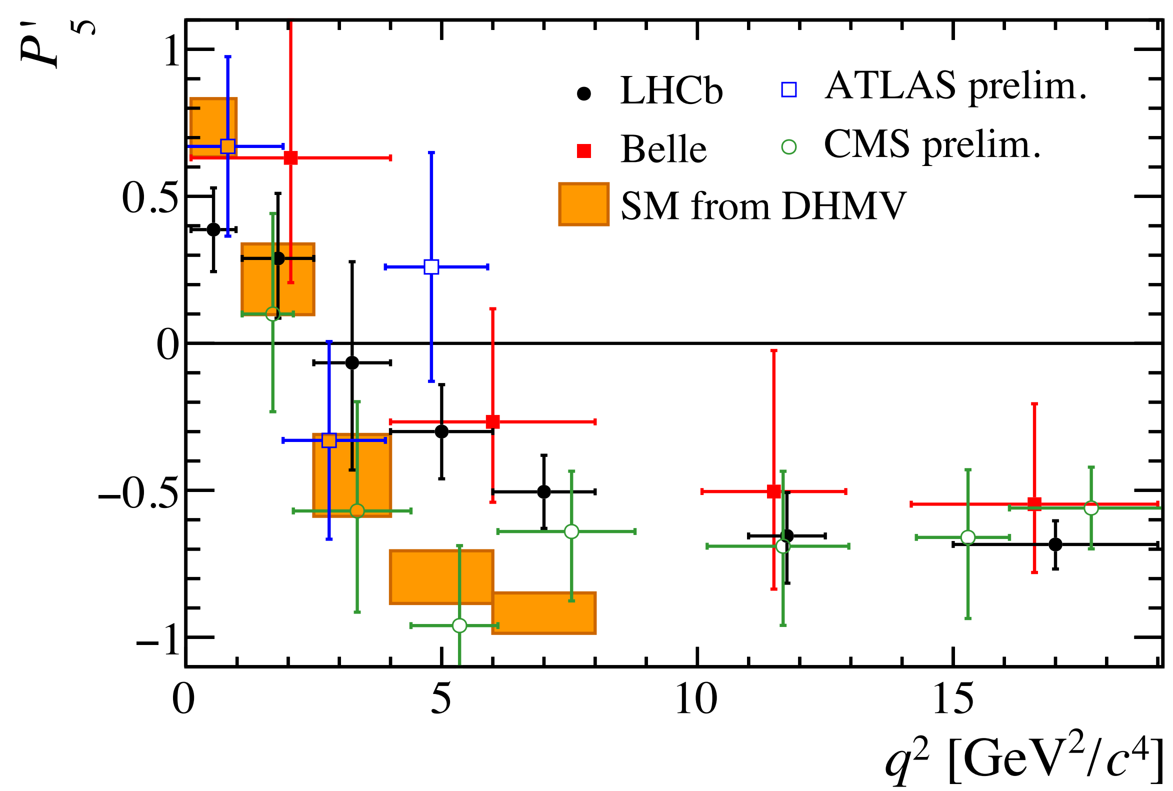
1. Statistical fluctuation
2. Hadronic uncertainties
3. New Physics

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

R_K

LHCb, 1406.6482, PRL

$$R_K = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{\mathrm{d}\Gamma[B^+ \to K^+\mu^+\mu^-]}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{\mathrm{d}\Gamma[B^+ \to K^+e^+e^-]}{\mathrm{d}q^2}\mathrm{d}q^2}$$

$$1 < q^2 < 6\,\mathrm{GeV}^2/c^4$$

$$R_K = 0.745^{+0.090}_{-0.074}\,(\mathrm{stat}) \pm 0.036\,(\mathrm{syst})$$

$$R_K^{SM} = 1 + \delta_{R_K}$$

$$|\delta_{R_K}| < 1\%$$

[Bordone, Isidori, Pattori, 1605.07633]

Explanations:

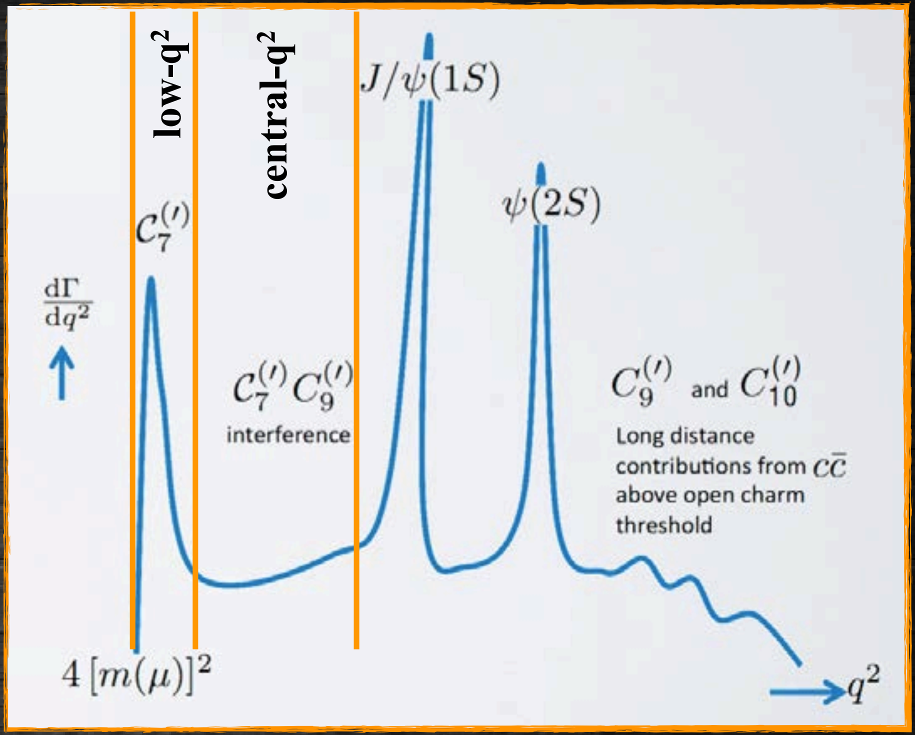
1. Statistical fluctuation
2. ~~Hadronic uncertainties~~
3. New Physics

› Test of LFU with $B^0 \to K^{*0}\mu\mu$ and $B^0 \to K^{*0}ee$, $R_{K^{*0}}$

› **Two regions of q^2**

» Low [0.045-1.1] GeV^2/c^4

» Central [1.1-6.0] GeV^2/c^4



[S. Bifani, LHCb]

$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

1) Clean observable, quite similar to RK
2) main difference: K* has spin 1 particle, 3 polarisations, sensitivity to Lorentz structure slightly different
3) Same channel where a deviation on the angular observables are seen

LHCb Preliminary	**low-q^2**	**central-q^2**
$\mathcal{R}_{K^{*0}}$	$0.660\ ^{+\,0.110}_{-\,0.070} \pm 0.024$	$0.685\ ^{+\,0.113}_{-\,0.069} \pm 0.047$
95% CL	[0.517–0.891]	[0.530–0.935]
99.7% CL	[0.454–1.042]	[0.462–1.100]

2.5σ

in each bin

New Physics (Model Independent)

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

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

$$\begin{aligned}
\mathcal{O}_7^{(\prime)} &= \frac{e}{16\pi^2}\, m_b \left(\bar{s}\sigma_{\alpha\beta} P_{R(L)} b\right) F^{\alpha\beta} \,, \\
\mathcal{O}_9^{\ell(\prime)} &= \frac{\alpha_{\rm em}}{4\pi} \left(\bar{s}\gamma_\alpha P_{L(R)} b\right) \left(\bar{\ell}\gamma^\alpha \ell\right) \,, \\
\mathcal{O}_{10}^{\ell(\prime)} &= \frac{\alpha_{\rm em}}{4\pi} \left(\bar{s}\gamma_\alpha P_{L(R)} b\right) \left(\bar{\ell}\gamma^\alpha \gamma_5 \ell\right).
\end{aligned}
\qquad
\begin{aligned}
C_7^{SM} &= -0.319, \\
C_9^{SM} &= 4.23, \\
C_{10}^{SM} &= -4.41.
\end{aligned}$$

SM gives lepton flavour universal contribution

- Looking at the fit from a Beyond SM physics point of view: short distance above EWSB

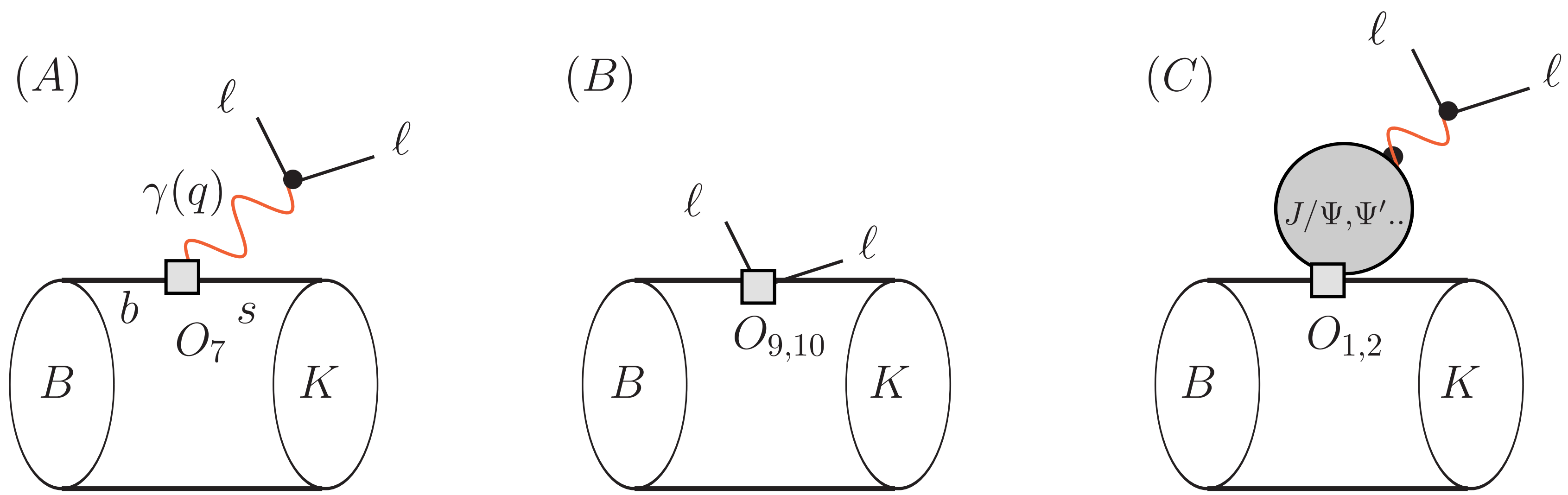
$$\mathcal{O}_{b_X \ell_Y} = (\bar{s}\gamma_\mu P_X b)(\bar{\ell}\gamma_\mu P_Y \ell). \longrightarrow C_{b_X \ell_Y}$$

$$(\overline{s}_L \gamma_\mu b_L)(\overline{\mu}_L \gamma_\mu \mu_L) \longrightarrow C_{b_L \mu_L} = C_9^\mu - C_{10}^\mu$$

- (Also good because the SM contribution is approximately chiral)

$$C_{b_L \ell_L}^{\rm SM} = 8.64$$
$$C_{b_L \ell_R}^{\rm SM} = -0.18$$

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]

Fits

Coeff.	best fit	1σ	2σ	pull
$C_9^{\rm NP}$	-1.19	$[-1.41, -0.97]$	$[-1.61, -0.73]$	4.9σ
C_9'	$+0.13$	$[-0.08, +0.34]$	$[-0.29, +0.55]$	0.6σ
$C_{10}^{\rm NP}$	$+0.64$	$[+0.41, +0.90]$	$[+0.18, +1.16]$	2.8σ
C_{10}'	-0.05	$[-0.22, +0.11]$	$[-0.38, +0.28]$	0.3σ
$C_9^{\rm NP} = C_{10}^{\rm NP}$	-0.33	$[-0.53, -0.12]$	$[-0.70, +0.13]$	1.5σ
$C_9^{\rm NP} = -C_{10}^{\rm NP}$	-0.61	$[-0.74, -0.45]$	$[-0.92, -0.31]$	4.3σ
$C_9' = C_{10}'$	$+0.07$	$[-0.18, +0.32]$	$[-0.44, +0.58]$	0.3σ
$C_9' = -C_{10}'$	$+0.05$	$[-0.05, +0.15]$	$[-0.15, +0.25]$	0.5σ
$C_9^{\rm NP}, C_{10}^{\rm NP}$	$(-1.17, +0.16)$	—	—	4.6σ
$C_9^{\rm NP}, C_9'$	$(-1.25, +0.55)$	—	—	4.9σ
$C_9^{\rm NP}, C_{10}'$	$(-1.34, -0.36)$	—	—	5.0σ
$C_9', C_{10}^{\rm NP}$	$(+0.17, +0.66)$	—	—	2.4σ
C_9', C_{10}'	$(+0.18, +0.05)$	—	—	0.2σ
$C_{10}^{\rm NP}, C_{10}'$	$(+0.64, -0.01)$	—	—	2.4σ

$$\mathcal{O}_7^{(\prime)} = \frac{e}{16\pi^2} m_b \left(\bar{s}\sigma_{\alpha\beta}P_{R(L)}b\right) F^{\alpha\beta} \,,$$
$$\mathcal{O}_9^{\ell(\prime)} = \frac{\alpha_{\rm em}}{4\pi} \left(\bar{s}\gamma_\alpha P_{L(R)}b\right) \left(\bar{\ell}\gamma^\alpha\ell\right) \,,$$
$$\mathcal{O}_{10}^{\ell(\prime)} = \frac{\alpha_{\rm em}}{4\pi} \left(\bar{s}\gamma_\alpha P_{L(R)}b\right) \left(\bar{\ell}\gamma^\alpha\gamma_5\ell\right).$$

[Fits by various groups,
Last update before RK* from
Altmannshofer, Straub, 1703.09189]

- Assuming only one source of NP at high scale, data prefers effects in the muon sector
- If only one Wilson coefficient is allowed to be non vanishing, various groups agree that NP in $\mathcal{O}_9^\mu$ is preferred by the data. $C_9^{\mu,NP} \approx -1$
- Short distance effects from New Physics are expected to have a chiral structure

$$\begin{matrix} \bar{\ell}\gamma^\alpha\ell \\ \bar{\ell}\gamma^\alpha\gamma_5\ell \end{matrix} \longrightarrow \begin{matrix} \bar{\ell}_L\gamma^\alpha\ell_L \\ \bar{\ell}_R\gamma^\alpha\ell_R \end{matrix}$$

Best Fit with
Left-Left currents

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

After R_{K^*}

- Various papers appeared the soon after, with similar model independent conclusions, here I will discuss D'Amico et al., 1704.05438

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

- Most important message (in my opinion): RK and RK* observables alone are now sufficient to draw various conclusions (without doing fits!)

After R_{K^*}

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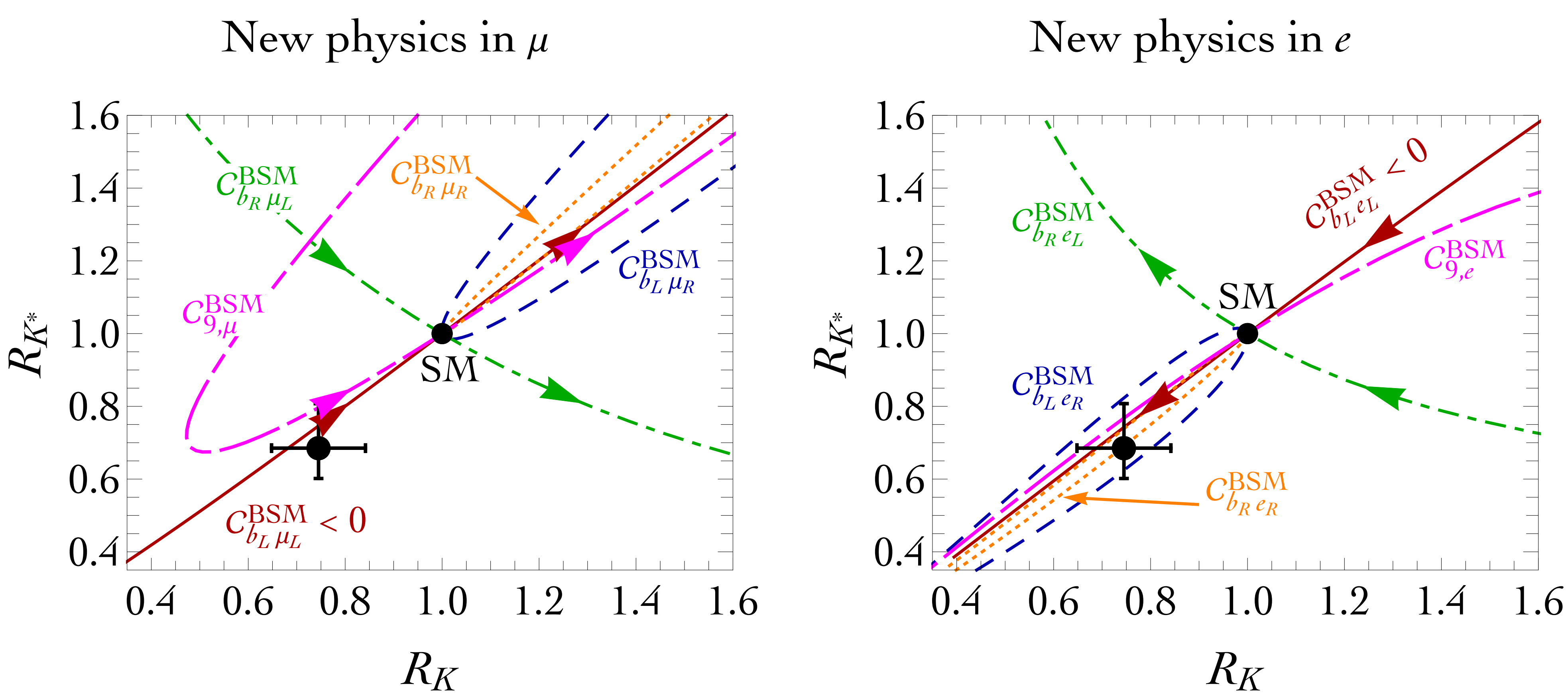


$$R_{K^*} \simeq R_K - 4p\frac{\mathrm{Re}\, C^{\rm BSM}_{b_R(\mu-e)_L}}{C^{\rm SM}_{b_L\mu_L}}$$

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

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

[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….

New physics in the muon sector									
Wilson coeff.	Best-fit			1-σ range			$\sqrt{\chi^2_{\rm SM}-\chi^2_{\rm best}}$		
	'clean'	'dirty'	all	'clean'	'dirty'	all	'clean'	'dirty'	all
$C^{\rm BSM}_{b_L\mu_L}$	-1.33	-1.33	-1.33	-0.99 -1.70	-1.01 -1.68	-1.10 -1.58	4.1	4.6	6.2
$C^{\rm BSM}_{b_L\mu_R}$	0.68	-0.73	-0.35	1.27 0.10	-0.40 -1.03	-0.03 -0.65	1.2	2.1	1.1
$C^{\rm BSM}_{b_R\mu_L}$	0.03	-0.20	-0.15	0.32 -0.26	-0.04 -0.29	-0.01 -0.25	0.1	1.3	1.1
$C^{\rm BSM}_{b_R\mu_R}$	-0.44	0.41	0.29	0.14 -1.00	0.61 0.18	0.50 0.07	0.8	1.7	1.3
New physics in the electron sector									
Wilson coeff.	Best-fit			1-σ range			$\sqrt{\chi^2_{\rm SM}-\chi^2_{\rm best}}$		
	'clean'	'dirty'	all	'clean'	'dirty'	all	'clean'	'dirty'	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

- Clean Observables:

  $R_K\,, R_{K^*}\,, B_s \to \mu\mu$

- Simply chi^2 analysis with our own code*

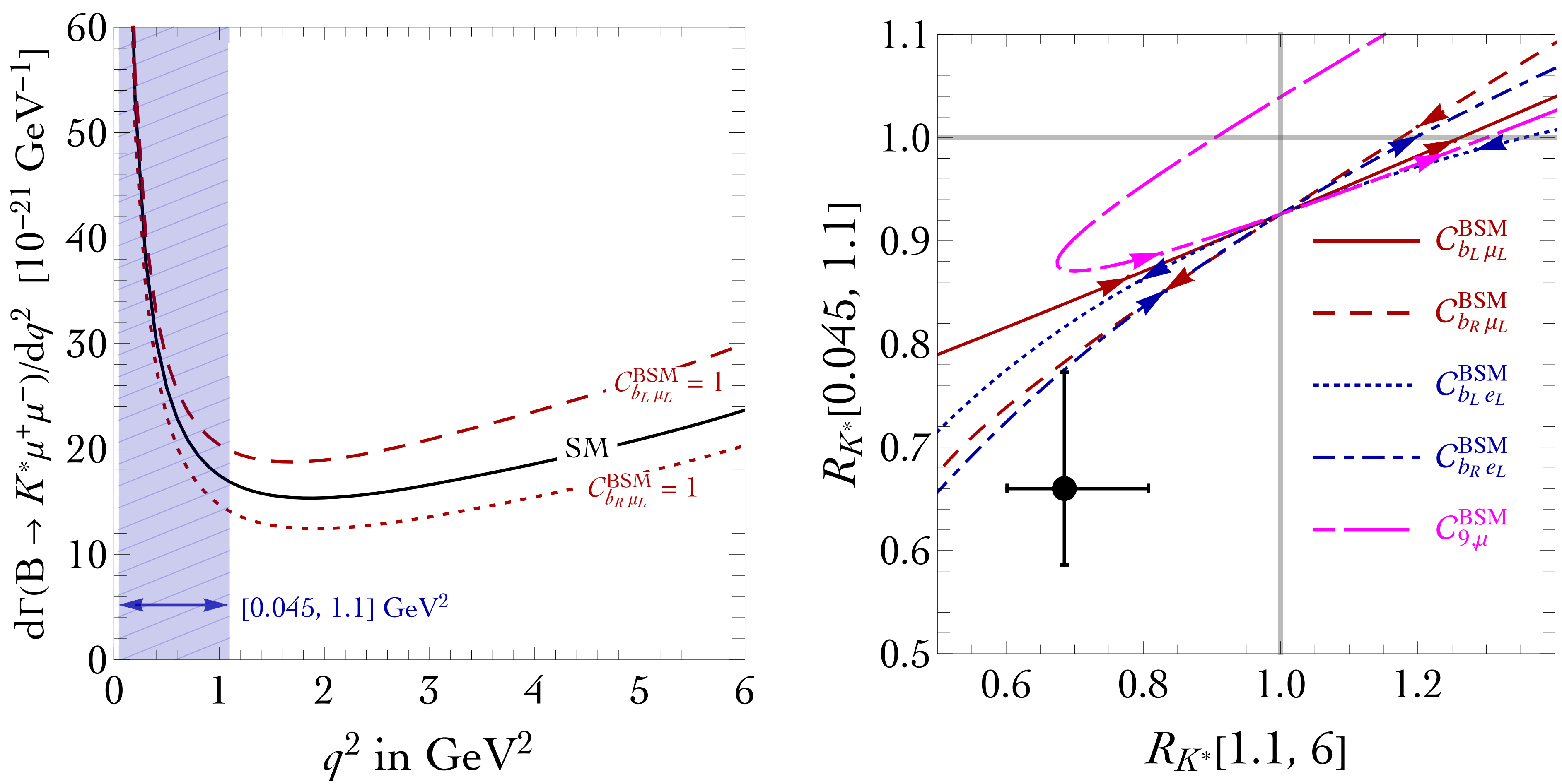
- Dirty Observables, implemented using FLAVIO

[D'Amico, Nardecchia, Panci, Sannino, Strumia, Torre, Urbano 1704.05438]

[*A. Strumia is the main responsible for the name of our code]

The low q^2 bin

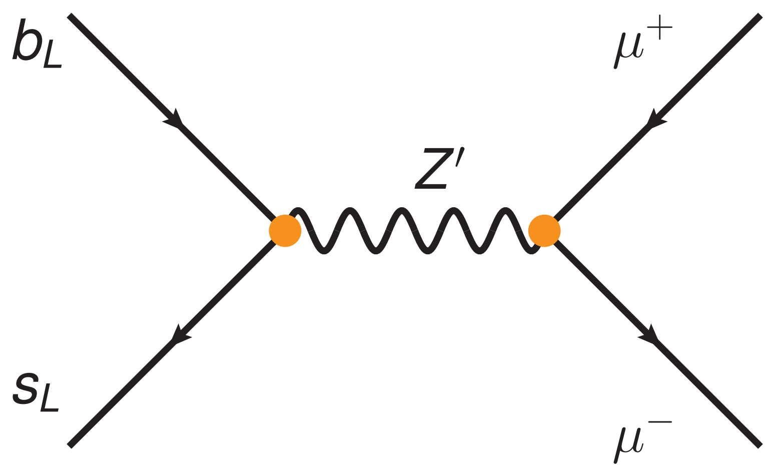
- At low q^2, Standard Model contribution is dominate by dipole operators (due the photon pole)
- This contribution is flavour universal, so NP effects are reduced in this bin



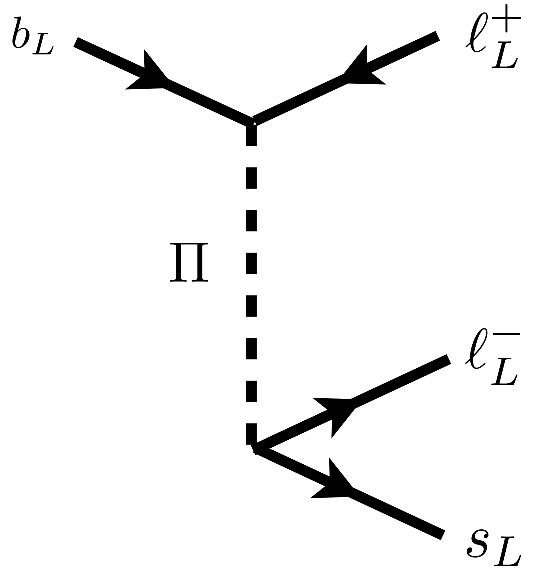
[D'Amico, et al. 1704.05438]

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

Simplified Models



$$\frac{1}{\Lambda^2}(\overline{Q}_L\gamma^\mu Q_L)(\overline{L}_L\gamma_\mu L_L)$$
$$\frac{1}{\Lambda^2}(\overline{Q}_L\gamma^\mu\sigma^A Q_L)(\overline{L}_L\gamma_\mu\sigma^A L_L)$$
$$\Lambda \approx 30\ \mathrm{TeV}$$



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

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

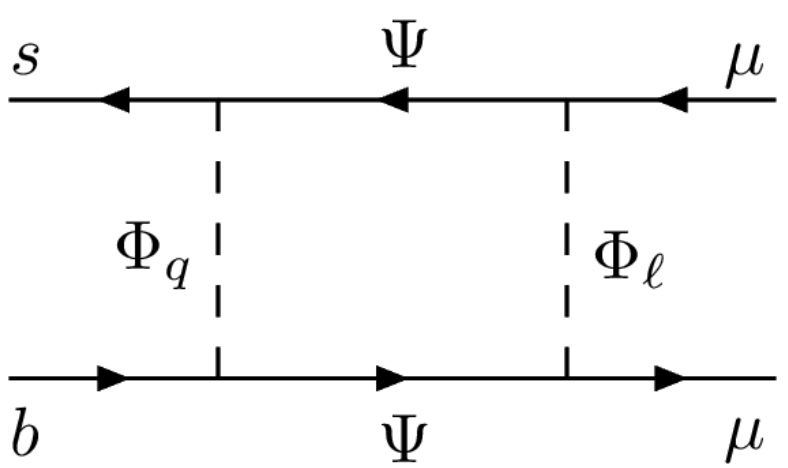
$$Z' \sim (\mathbf{1},\mathbf{1},\mathbf{0})$$
$$Z' \sim (\mathbf{1},\mathbf{3},\mathbf{1})$$

	Spin	Quantum Number	Clean observables new physics in e	Clean observables new physics in μ	All observables
S_3	0	$(\bar{3},3,1/3)$	✓	✓	✓
R_2	0	$(3,2,7/6)$	✓		
$\tilde{R}_2$	0	$(3,2,1/6)$			
$\tilde{S}_1$	0	$(\bar{3},1,4/3)$	✓		
U_3	1	$(3,3,2/3)$	✓	✓	✓
V_2	1	$(\bar{3},2,5/6)$	✓		
U_1	1	$(\bar{3},1,2/3)$	✓	✓	✓

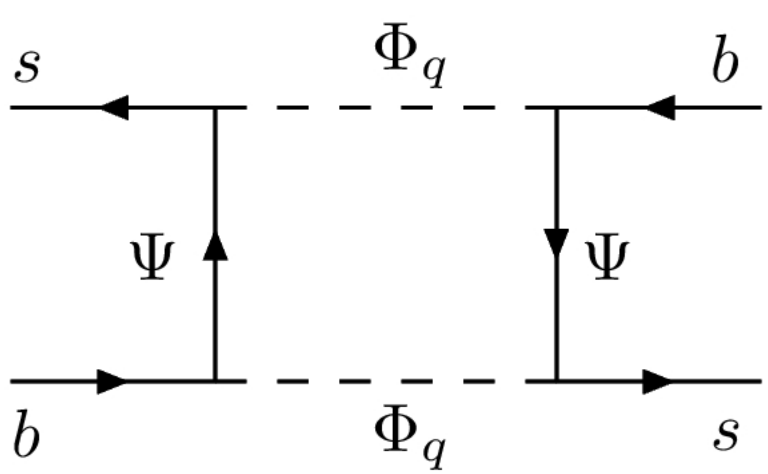
Table 3: *Which lepto-quarks can reproduce which $b \to s\ell^+\ell^-$ anomalies.*

Loop induced

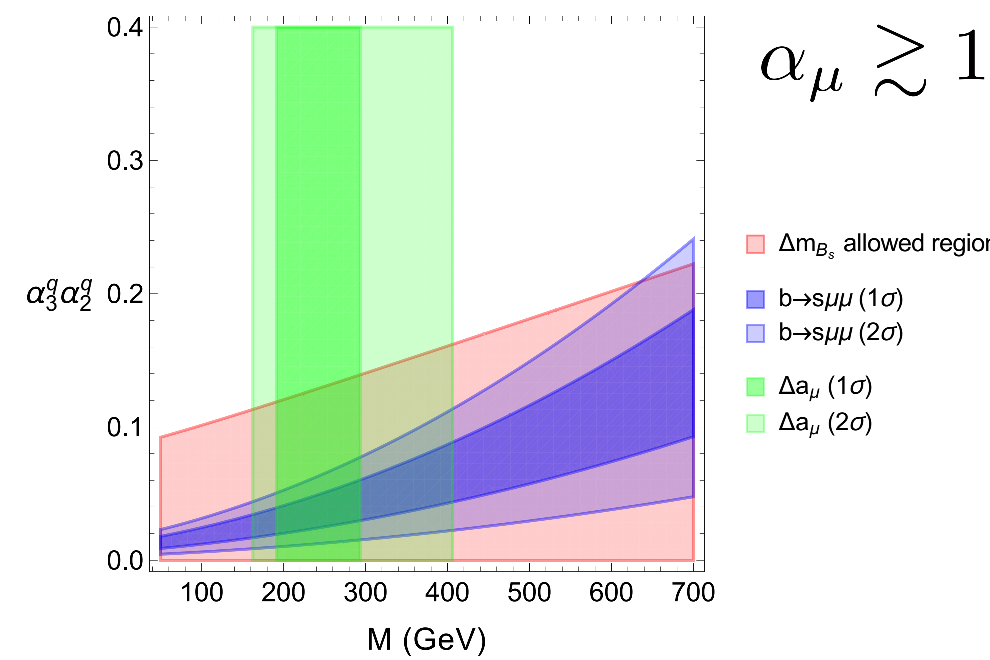
[Gripaios, MN, Renner 1509.05020
see also 1608.07832]



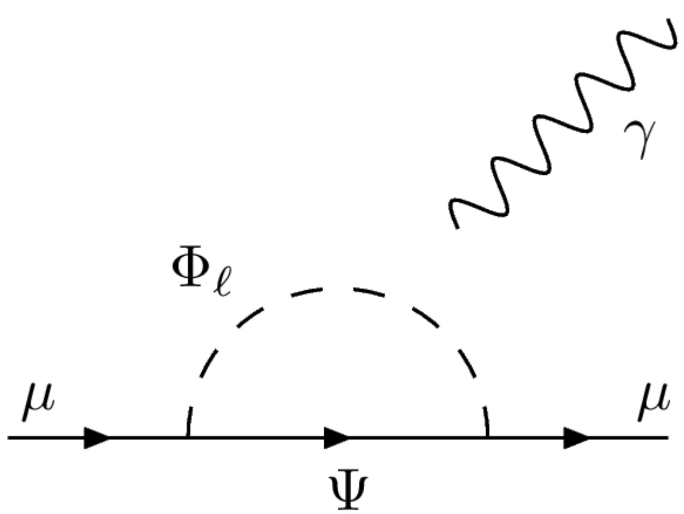
$$\alpha_i^q \, \overline{\Psi} Q_L^i \Phi_q + \alpha_i^\ell \, \overline{\Psi} L_L^i \Phi_\ell + \text{h.c.}$$



- Main constraint



$\alpha_\mu \gtrsim 1$



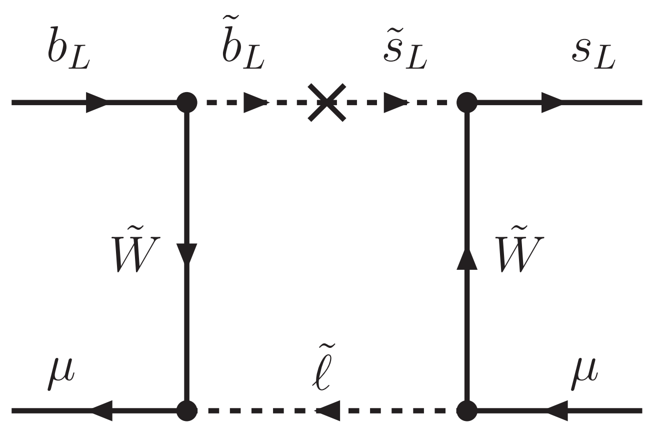
- muon g-2, large leptonic coupling

- Direct searches are important

MSSM (ask me)

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

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



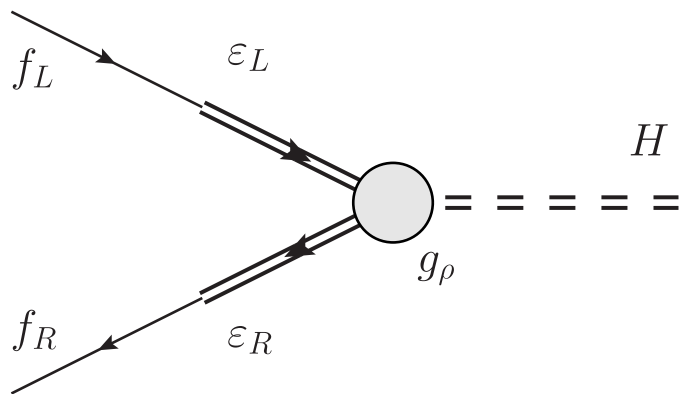
- Lepton universality is broken by slepton masses $m_{\tilde{e}} \gg m_{\tilde{\mu}}$
- Box diagrams are numerically small, very light particles in the loop
- No free parameter on the Feynman vertices: EW couplings
- Direct searches (LHC+LEP) give strong constraints, probably no holes left (but a careful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

Partial Compositeness in CH models

- Yukawa sector:



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

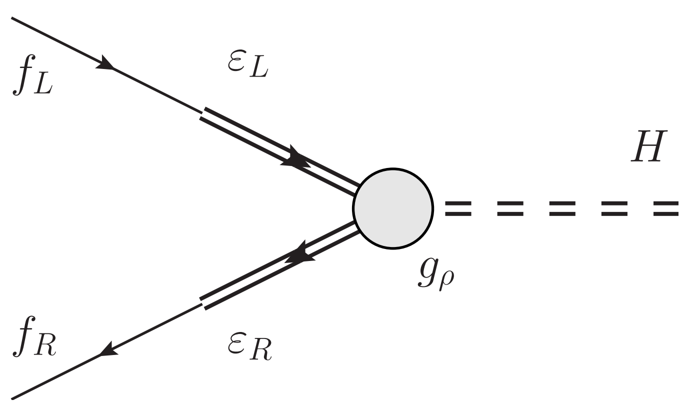
$$\mathcal{L}_{\rm comp} = \mathcal{L}_{\rm comp}(g_\rho, m_\rho, H)$$

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

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

Partial Compositeness in CH models

- Yukawa sector:



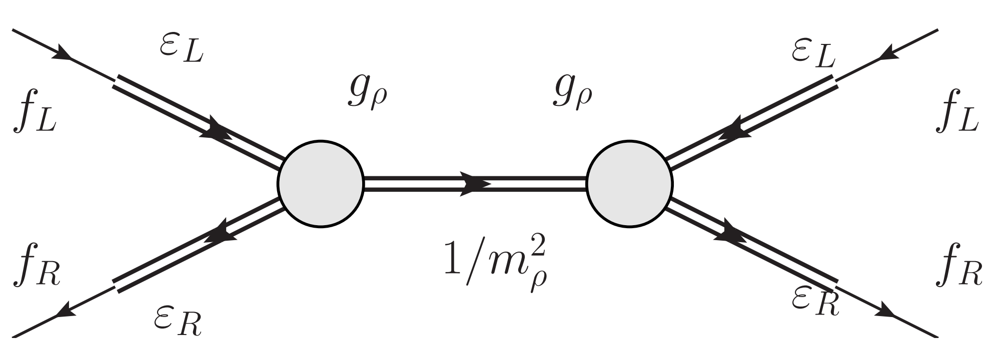
$$\mathcal{L}_{\text{elem}} = i\bar{f}\gamma^\mu D_\mu f$$

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

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

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

- 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

Mixing parameters

- Mixing parameters are related to values of fermion masses and mixing

$$(Y_u)_{ij} \sim g_\rho \epsilon_i^q \epsilon_j^u \qquad (Y_d)_{ij} \sim g_\rho \epsilon_i^q \epsilon_j^d \qquad (Y_e)_{ij} \sim g_\rho \epsilon_i^\ell \epsilon_j^e,$$

- In the quarks sector everything is fixed up to 2 parameters, (g_ρ, ϵ_3^q)

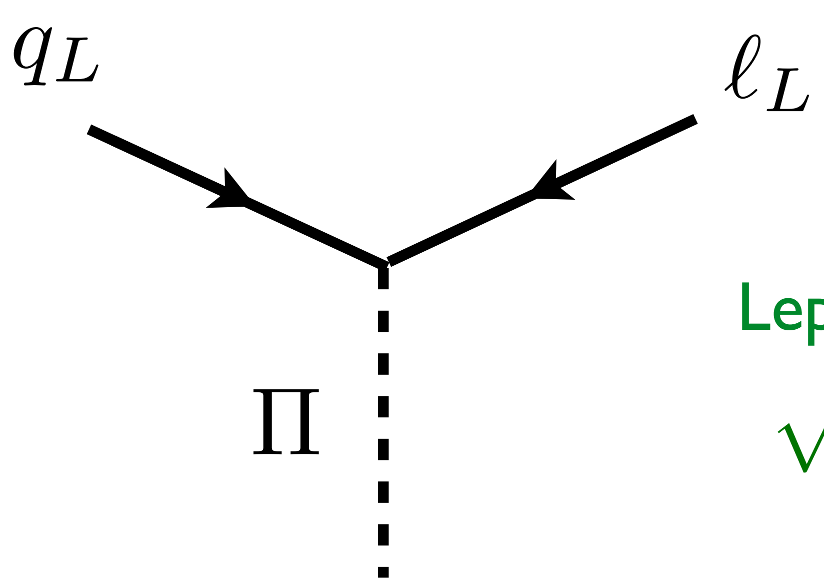
- In the lepton sector parameters cannot be univocally connected to physical inputs, due to our ignorance on neutrino masses, will assume that left and right mixing have similar size

Mixing Parameter	Value
$\epsilon_1^q = \lambda^3 \epsilon_3^q$	$1.15 \times 10^{-2}\, \epsilon_3^q$
$\epsilon_2^q = \lambda^2 \epsilon_3^q$	$5.11 \times 10^{-2}\, \epsilon_3^q$
$\epsilon_1^u = \frac{m_u}{v g_\rho} \frac{1}{\lambda^3 \epsilon_3^q}$	$5.48 \times 10^{-4}/(g_\rho \epsilon_3^q)$
$\epsilon_2^u = \frac{m_c}{v g_\rho} \frac{1}{\lambda^2 \epsilon_3^q}$	$5.96 \times 10^{-2}/(g_\rho \epsilon_3^q)$
$\epsilon_3^u = \frac{m_t}{v g_\rho} \frac{1}{\epsilon_3^q}$	$0.866/(g_\rho \epsilon_3^q)$
$\epsilon_1^d = \frac{m_d}{v g_\rho} \frac{1}{\lambda^3 \epsilon_3^q}$	$1.24 \times 10^{-3}/(g_\rho \epsilon_3^q)$
$\epsilon_2^d = \frac{m_s}{v g_\rho} \frac{1}{\lambda^2 \epsilon_3^q}$	$5.29 \times 10^{-3}/(g_\rho \epsilon_3^q)$
$\epsilon_3^d = \frac{m_b}{v g_\rho} \frac{1}{\epsilon_3^q}$	$1.40 \times 10^{-2}(g_\rho \epsilon_3^q)$
$\epsilon_1^\ell = \epsilon_1^e = \left(\frac{m_e}{g_\rho v}\right)^{1/2}$	$1.67 \times 10^{-3}/g_\rho^{1/2}$
$\epsilon_2^\ell = \epsilon_2^e = \left(\frac{m_\mu}{g_\rho v}\right)^{1/2}$	$2.43 \times 10^{-2}/g_\rho^{1/2}$
$\epsilon_3^\ell = \epsilon_3^e = \left(\frac{m_\tau}{g_\rho v}\right)^{1/2}$	$0.101/g_\rho^{1/2}$

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!

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

On the scale(s) of the New Physics

in progress with
L. Di Luzio,
G. Giudice,
J. Kamenik

- Various scales can be defined
- In the EFT 2-to-2 scatterings of fermions grows with energy

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

A	$\mathcal{O}$	FS_Q	FS_L	$\Lambda_A[\mathrm{TeV}]$	$\Lambda_{\mathcal{O}}[\mathrm{TeV}]$	$\Lambda_U[\mathrm{TeV}]$	$M_*[\mathrm{TeV}]$
$b \to c\tau\nu$	$Q_{23}L_{33}$	1	1	2.4	3.4	9.2	43
$b \to c\tau\nu$	$Q_{33}L_{33}$	V_{cb}	1	2.4	0.69	1.9	8.7
$b \to s\mu\mu$	$Q_{23}L_{22}$	1	1	31	31	84	390
$b \to s\mu\mu$	$Q_{33}L_{22}$	V_{ts}	1	31	6.2	17	78
$b \to s\mu\mu$	$Q_{33}L_{33}$	V_{ts}	m_μ/m_τ	31	1.5	4.1	19
$b \to s\mu\mu$	$Q_{33}L_{33}$	V_{ts}	$(m_\mu/m_\tau)^2$	31	0.37	1.0	4.7

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- Motivated flavour ansatz in the quark sector (MFV, U(2),Partial Compositeness) leads to the same order of magnitude of flavour suppression when left-handed quarks are involved.

$$\frac{\bar{c}\gamma^\mu b}{\bar{t}\gamma^\mu b} = \mathcal{O}(\lambda^2) \quad , \quad \frac{\bar{s}\gamma^\mu b}{\bar{b}\gamma^\mu b} = \mathcal{O}(\lambda^2)$$

- In the lepton sector partial information is available (because of neutrinos). Motivated ansatz can be inferred from the hierarchy of masses in the charged sector.

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

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

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)

- After the measurement of RK*, various conclusions can be drawn using only theoretical robust observables. Standard Model deviation at $\sim 4\sigma$

- Anomalies in neutral current can be explained through the tree level exchange of a leptoquark or a Z' boson

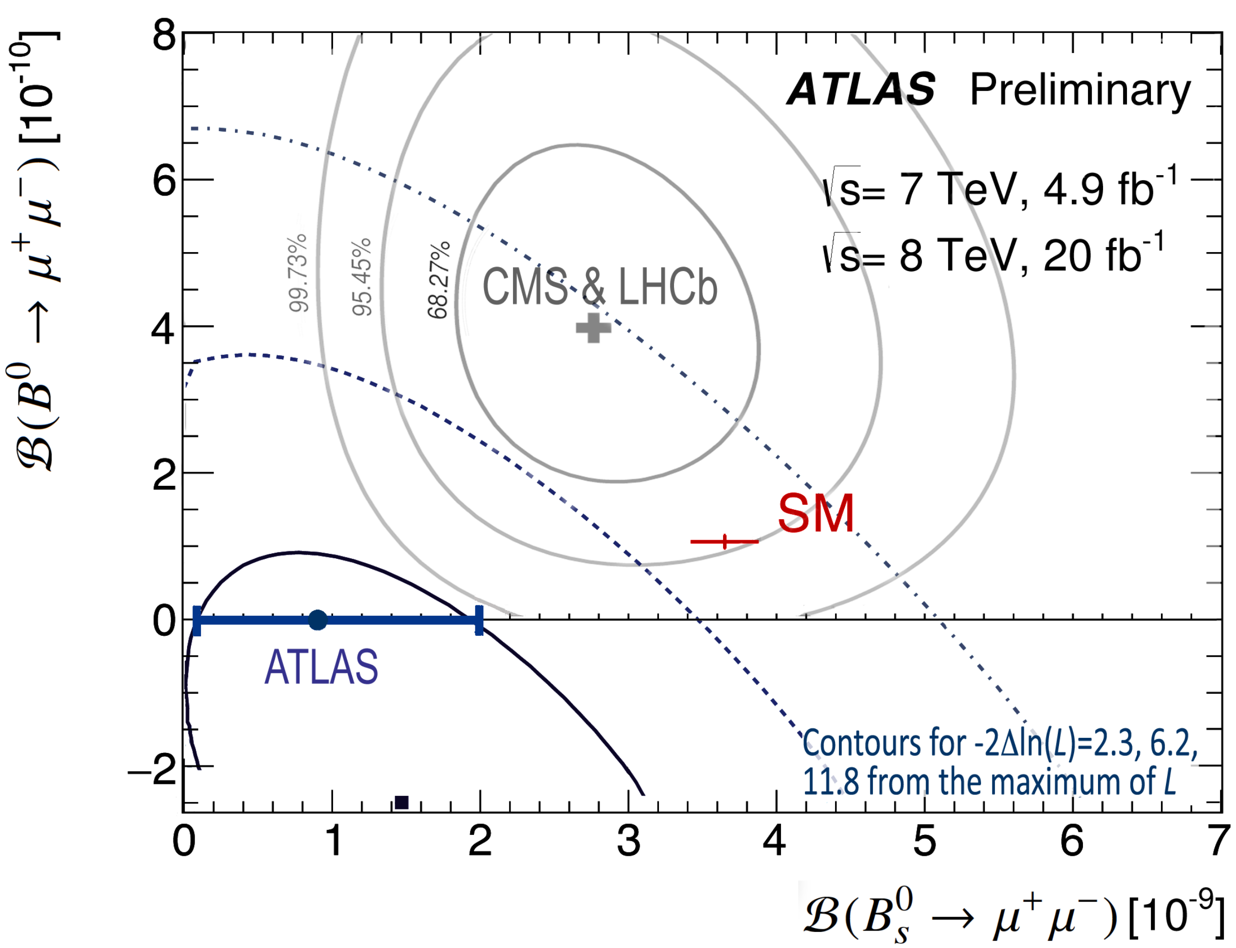
- New data from Run 2 are ready to be analysed by the LHCb collaboration

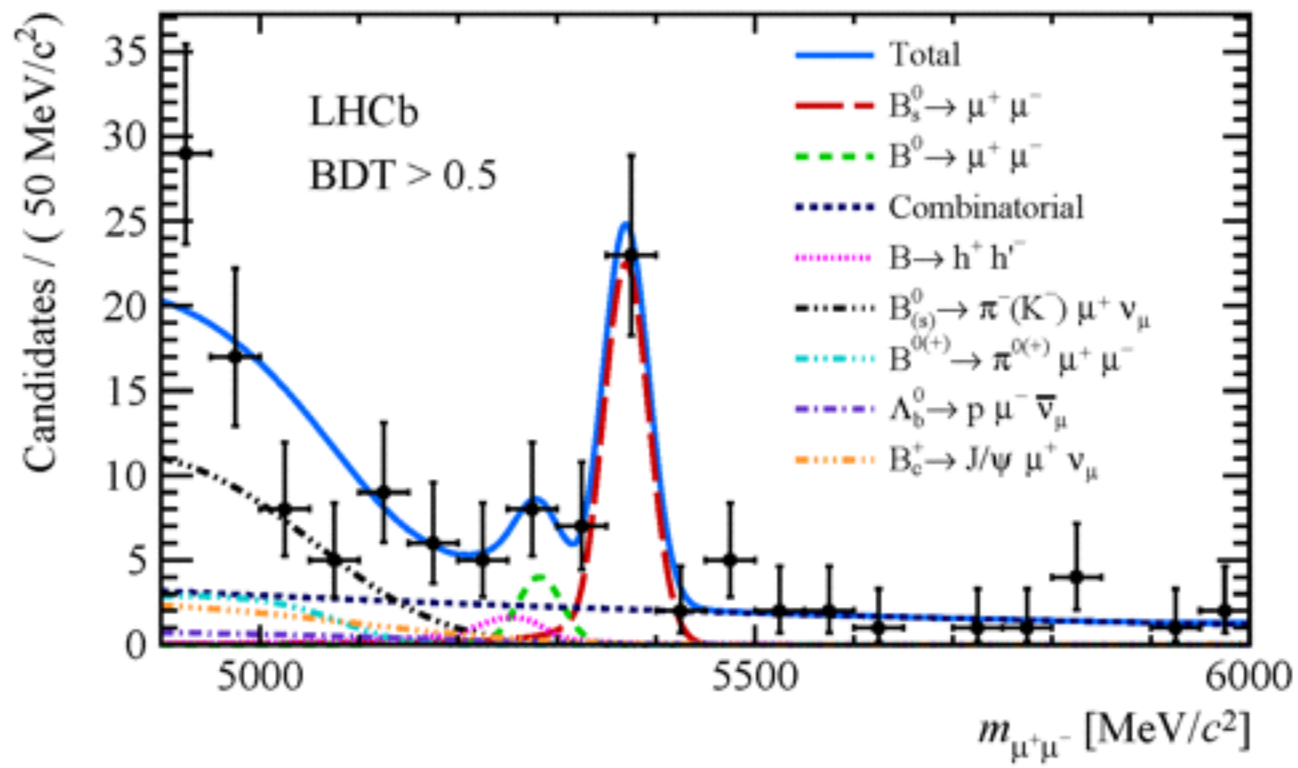
- Final verdict will come from Belle II

Backup

Bs to muons

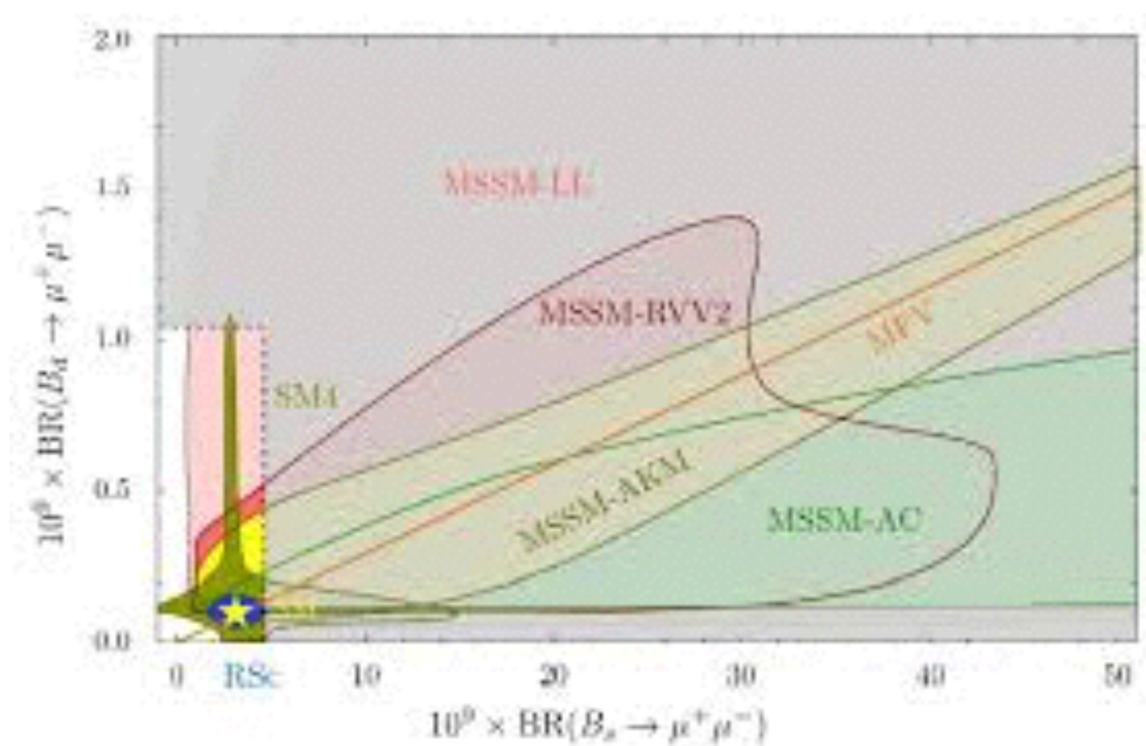
LHCb, 1703.05747





$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{EXP}} = 3.0 \pm 0.6\ \times 10^{-9}$$

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = 3.65 \pm 0.23\ \times 10^{-9}$$



Parameters (quark sector)

- Yukawas are given by

$$(Y_u)_{ij} \sim g_\rho \epsilon_i^q \epsilon_j^u \qquad\qquad (Y_d)_{ij} \sim g_\rho \epsilon_i^q \epsilon_j^d$$

- And diagonalized by

$$(L_u^\dagger Y_u R_u)_{ij} = g_\rho \epsilon_i^u \epsilon_i^q \delta_{ij} \equiv y_i^u \delta_{ij} \,, \qquad (L_d^\dagger Y_d R_d)_{ij} = g_\rho \epsilon_i^d \epsilon_i^q \delta_{ij} \equiv y_i^d \delta_{ij} \,,$$

$$(L_u)_{ij} \sim (L_d)_{ij} \sim \min\left(\frac{\epsilon_i^q}{\epsilon_j^q}, \frac{\epsilon_j^q}{\epsilon_i^q}\right) \,, \qquad (R_{u,d})_{ij} \sim \min\left(\frac{\epsilon_i^{u,d}}{\epsilon_j^{u,d}}, \frac{\epsilon_j^{u,d}}{\epsilon_i^{u,d}}\right)$$

- Link with the CKM $\quad V_{CKM} = L_d^\dagger L_u \sim L_{u,d}$

$$\frac{\epsilon_1^q}{\epsilon_2^q} \sim \lambda \qquad \frac{\epsilon_2^q}{\epsilon_3^q} \sim \lambda^2 \qquad \frac{\epsilon_1^q}{\epsilon_3^q} \sim \lambda^3$$

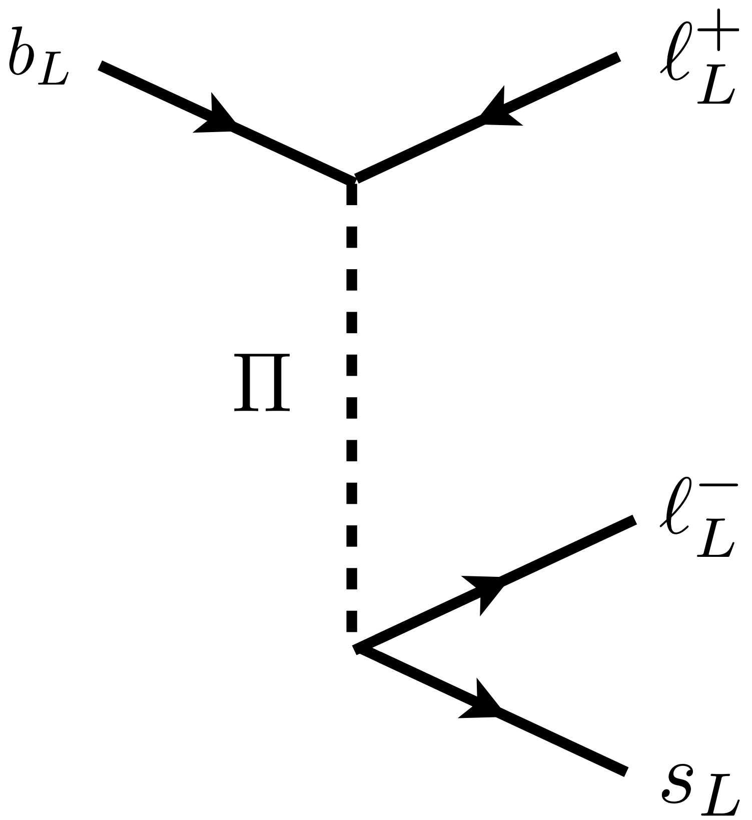
- Everything is fixed up to 2 parameters $\quad g_\rho, \epsilon_i^q, \epsilon_i^u, \epsilon_i^d \qquad 1+3+3+3=10$

$$m_i^u, m_i^d, V_{CKM} \qquad 3+3+2=8$$

(g_ρ, ϵ_3^q) in what follows

New Physics (Model Dependent)

- A leptoquark interpretation Hiller, Schmaltz 1408.1627



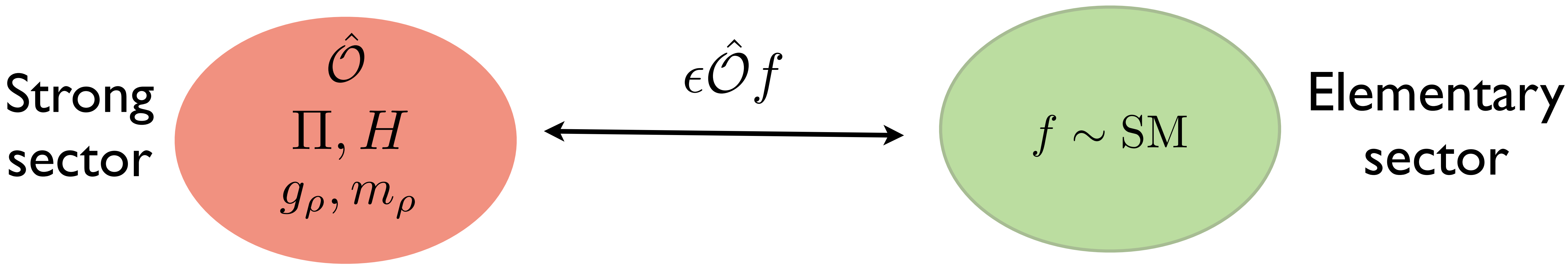
- Quantum number of the new states, uniquely determined by the the Left-Left structure

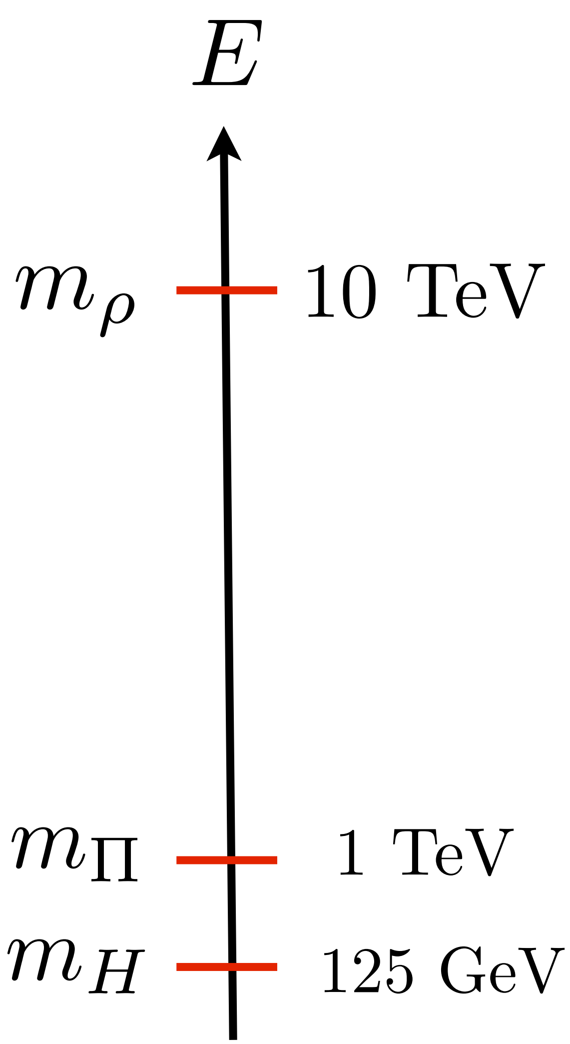
$$\Pi \sim (\overline{\mathbf{3}}, \mathbf{3}, 1/3)$$

$$\lambda_{ij}\, \overline{q}^c_{Lj} i\tau_2\tau_a \ell_{Li}\, \Pi$$

- Anomalies are fitted when $\dfrac{\lambda_{b\mu}\lambda_{s\mu}}{m_\Pi^2} \approx \dfrac{1}{(30\,\mathrm{TeV})^2}$
- Just two, non-vanishing leptoquark coupling
- Scale of New Physics not predicted
- No connection with FV in the SM

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

Fit to the anomalies

- The analysis of $b \to s\mu^+\mu^-$ observable gives

$$C_9^{NP\mu} = -C_{10}^{NP\mu} \in [-0.84, -0.12] \quad (\text{at } 2\sigma)$$

- In our framework gives

$$C_9^{\mu NP} = -C_{10}^{\mu NP} = \left[\frac{4G_F e^2 (V_{ts}^* V_{tb})}{16\sqrt{2}\pi^2}\right]^{-1} \frac{\lambda_{22}^* \lambda_{23}}{2M^2} = -0.49\, c_{22}^* c_{23} (\epsilon_3^q)^2 \left(\frac{M}{\text{TeV}}\right)^{-2} \left(\frac{g_\rho}{4\pi}\right)$$

$$\text{Re}(c_{22}^* c_{23}) \in [0.24, 1.71] \left(\frac{4\pi}{g_\rho}\right) \left(\frac{1}{\epsilon_3^q}\right)^2 \left(\frac{M}{\text{TeV}}\right)^2 \quad (\text{at } 2\sigma)$$

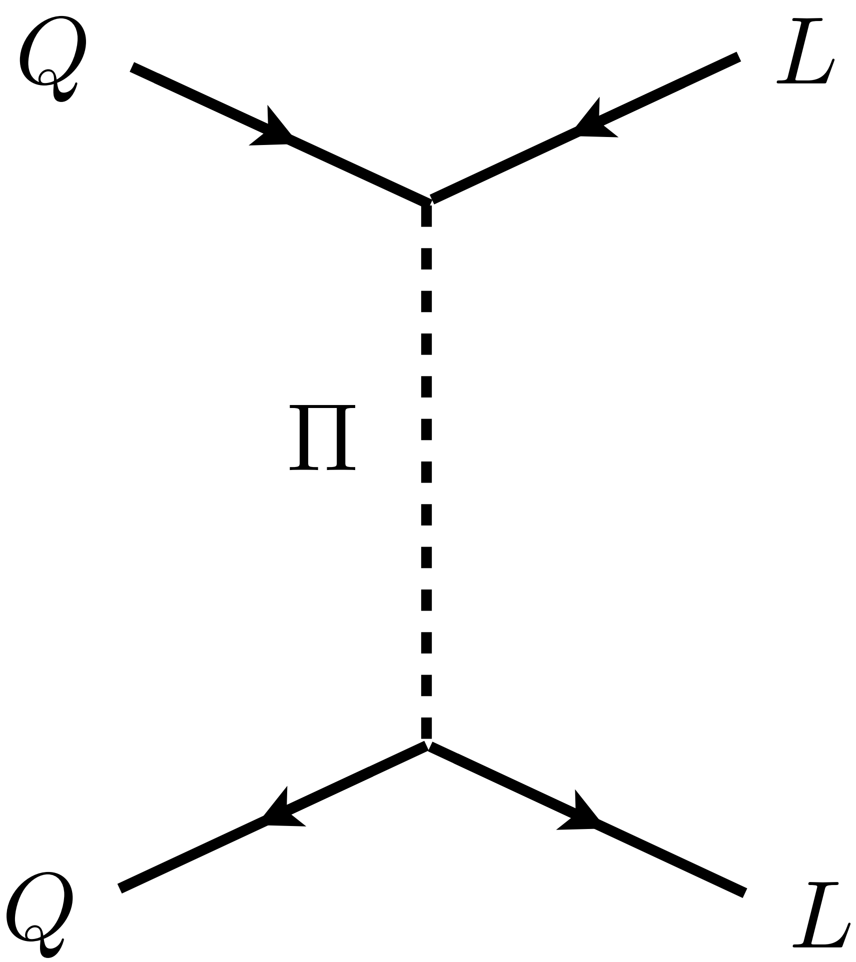
- Due to the partial compositeness structure, negligible contribution to observables involving electrons like $\text{BR}(B \to K e^+ e^-)$. R_K is easily accommodated.

- 3 immediate implications

  1) the composite sector is genuinely strong interacting, $g_\rho \sim 4\pi$
  2) that left-handed quark doublet should be largely composite, $\epsilon_3^q \sim 1$
  3) the mass of the leptoquark states should be low, $M \lesssim 1$ TeV

Flavour violation at the tree level

- Integrating away the leptoquarks fields we get



$$\mathcal{L}_{LQ}^{eff} = \sum_{ij\ell k} \frac{\lambda_{ij}(\lambda_{\ell k})^*}{2M^2} \Big[2\left(\bar{d}_L \gamma^\mu d_L\right)_{kj} \left(\bar{e}_L \gamma_\mu e_L\right)_{\ell i} + 2\left(\bar{u}'_L \gamma^\mu u'_L\right)_{kj} \left(\bar{\nu}_L \gamma_\mu \nu_L\right)_{\ell i}$$

$$+ \left(\bar{d}_L \gamma^\mu d_L\right)_{kj} \left(\bar{\nu}_L \gamma_\mu \nu_L\right)_{\ell i} + \left(\bar{u}'_L \gamma^\mu u'_L\right)_{kj} \left(\bar{e}_L \gamma_\mu e_L\right)_{\ell i}$$

$$+ \left(\bar{u}'_L \gamma^\mu d_L\right)_{kj} \left(\bar{e}_L \gamma_\mu \nu_L\right)_{\ell i} + \left(\bar{d}_L \gamma^\mu u'_L\right)_{kj} \left(\bar{\nu}_L \gamma_\mu e_L\right)_{\ell i} \Big],$$

$$u_L'^j = V_{CKM}^{\dagger jk} u_L^k$$

- "Vertical" correlations induced by SM gauge invariance
- "Horizontal" correlations induced by partial compositeness

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

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

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

- 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

Predictions

- Rare Kaon decay

Hurt et al 0807.5039
NA62 1411.0109

$$\mathcal{B}(K^+ \to \pi^+ \nu\nu) = 8.6(9) \times 10^{-11}[1 + 0.96\delta C_{\nu\bar{\nu}} + 0.24(\delta C_{\nu\bar{\nu}})^2]$$

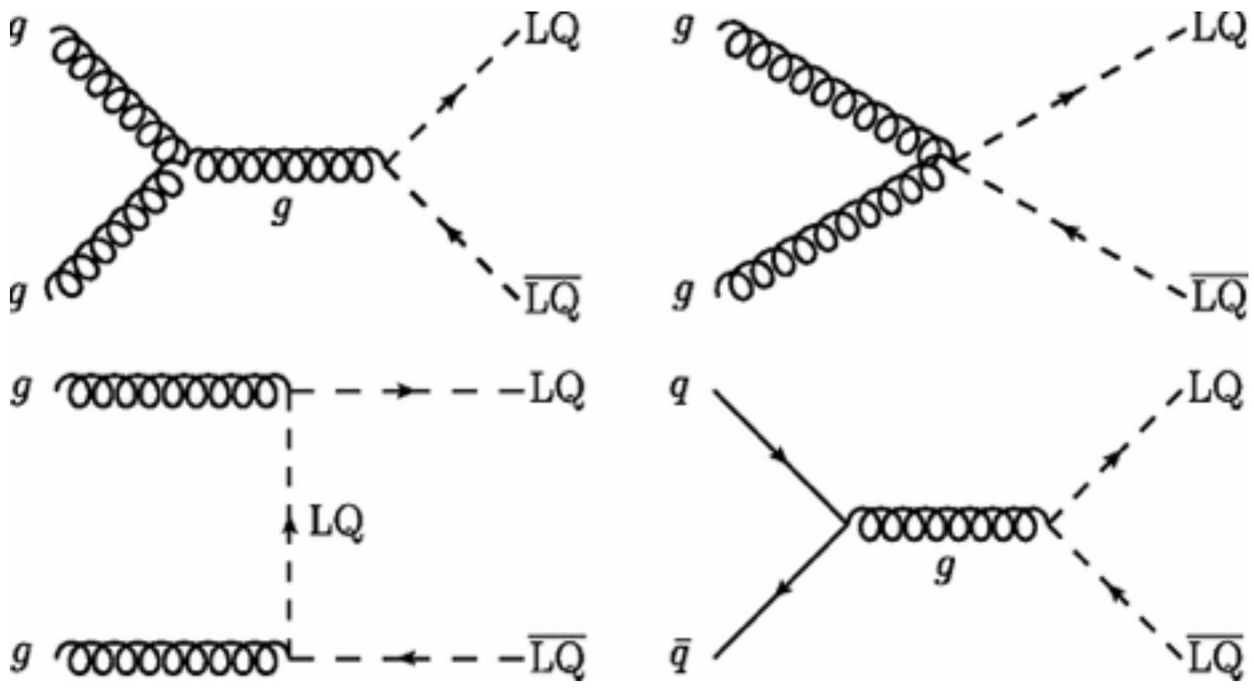
Present bound $\delta C_{\nu\bar{\nu}} \in [-6.3, 2.3]$ NA62 expected sensitivity $\delta C_{\nu\bar{\nu}} \in [-0.2, 0.2]$

Composite leptoquark prediction $\delta C_{\nu\bar{\nu}} = 0.62 \ \mathrm{Re}(c_{31}c_{32}^*) \left(\frac{g_\rho}{4\pi}\right) (\epsilon_3^q)^2 \left(\frac{M}{\mathrm{TeV}}\right)^{-2}$

- Radiative decay $\mu \longrightarrow e\gamma$

$$|c_{23}^* c_{13}| < 1.4 \left(\frac{4\pi}{g_\rho}\right) \left(\frac{M}{\mathrm{TeV}}\right)^2 \left(\frac{1}{\epsilon_3^q}\right)^2$$

LHC



- Production via strong interaction

- Decay to fermions of the third family

$$\Pi_{4/3} \to \overline{\tau}\ \overline{b}, \quad M > 720\ \mathrm{GeV}$$
$$\Pi_{1/3} \to \overline{\tau}\ \overline{t}\ \text{or}\ \Pi_{1/3} \to \overline{\nu_\tau}\ \overline{b}, \quad M > 410\ \mathrm{GeV}$$
$$\Pi_{-2/3} \to \overline{\nu_\tau}\ \overline{t}. \quad M > 640\ \mathrm{GeV}$$

- Stop and sbottom + dedicated leptoquark searches

[ATLAS arXiv:1407.0583]
[CMS arXiv:1408.0806]
[CMS-PAS-EXO-13-010]

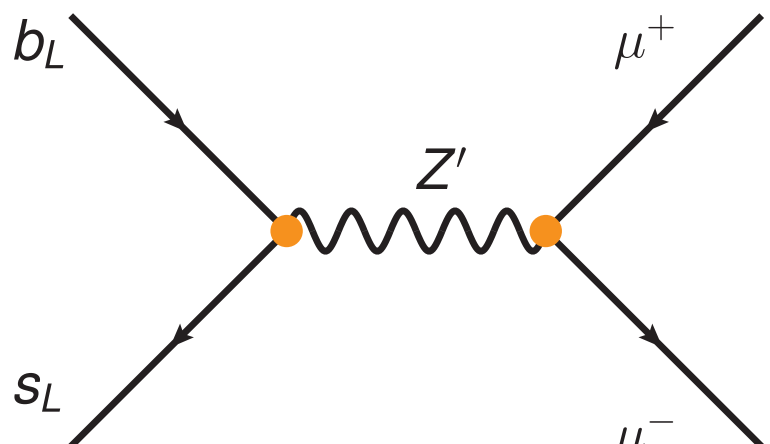
$$M > 720\ \mathrm{GeV}$$

Z' from a U(2) flavour symmetry

Some aspects of flavour symmetry

Based on 1509.01249, JHEP
with A. Falkowski and R. Ziegler

- Allow for an understanding of the hierarchy of masses and mixing in the SM
- Create a connection between BSM and SM flavour violation
- Scale of the flavour dynamics not predicted… but can be fitted with the anomalies



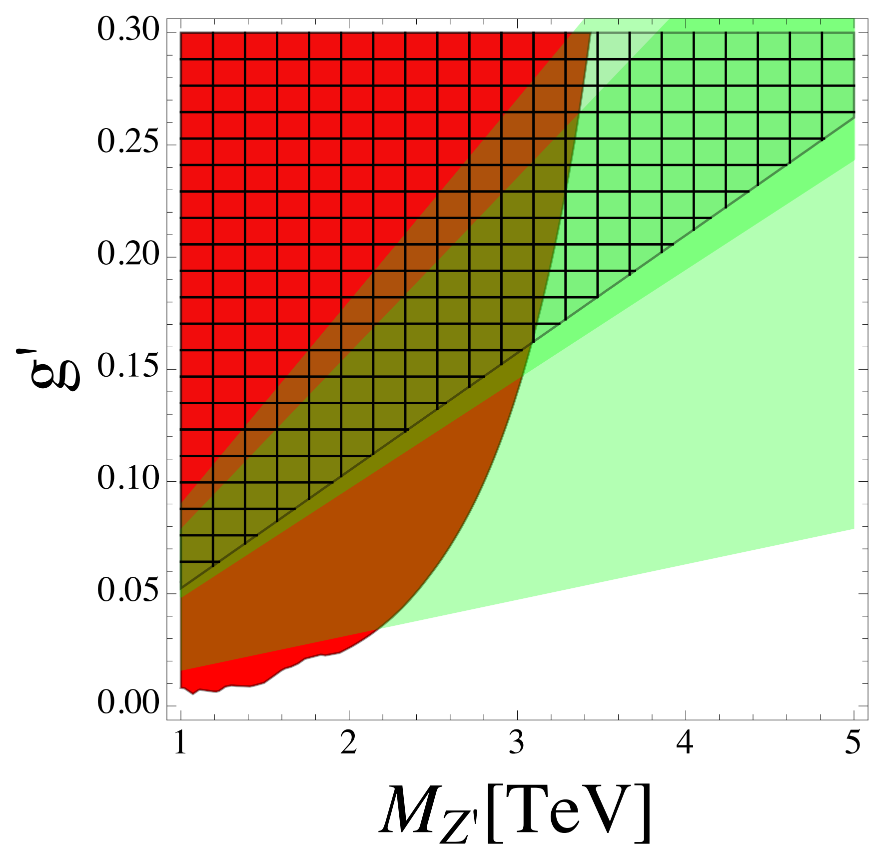
$$\mathcal{L} \supset g' \Delta^{f_i f_j}_{L,R}\, f_i^\dagger \overline{\sigma}^\mu f_j\, Z'_\mu$$

$$\Delta^{d_i d_j}_L \sim \begin{pmatrix} 1 & \lambda^5 & \lambda^3 \\ \lambda^5 & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & \lambda^4 \end{pmatrix}$$

λ = Cabibbo angle

Predictions

- Constructive effect in electron channels
- LFV, mu-e conversion in the nuclei
- Z' at LHC main decay in dielectron…



A possible/plausible end

Figure 2: Alvaro de Rujula's Cemetery of Physics [48], with graves indicating 'false alarms' in frontier physics, and not old physics ideas faded out with time, like epicycles, phlogiston or aether.

A MODEL OF LEPTONS*

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

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.