Theory for R(D) & R(D*)

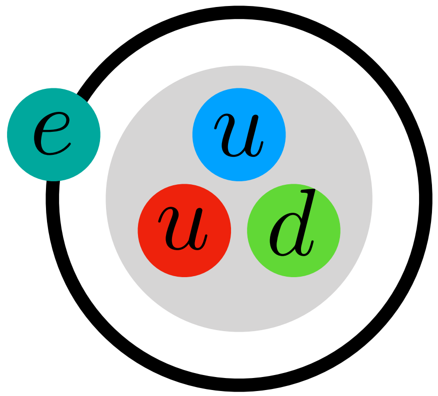
Rodrigo Alonso

Durham University

Beyond the Flavour Anomalies
02 April 2020

The ambitious questions in flavor

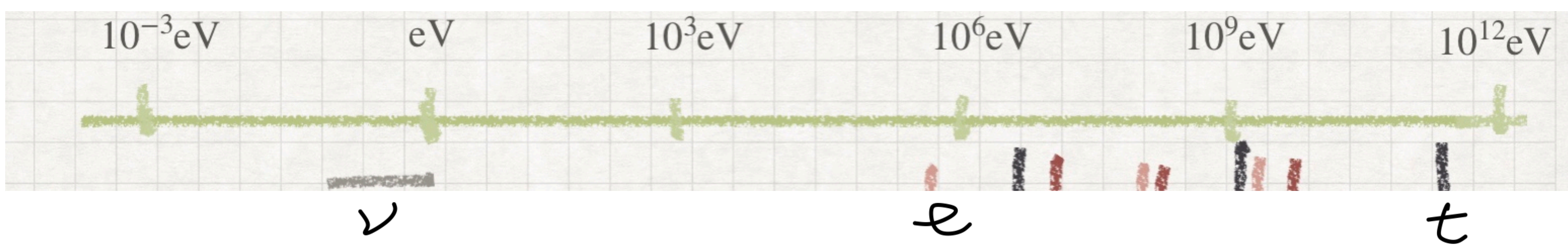
...or who ordered ALL of that?



=US (you and I)

★ **What are the other two generations for?**

★ **CP violation?**



★ **Why is the Flavour structure all over the place?**

Maybe....

Symmetry e.g. Froggatt Nielsen

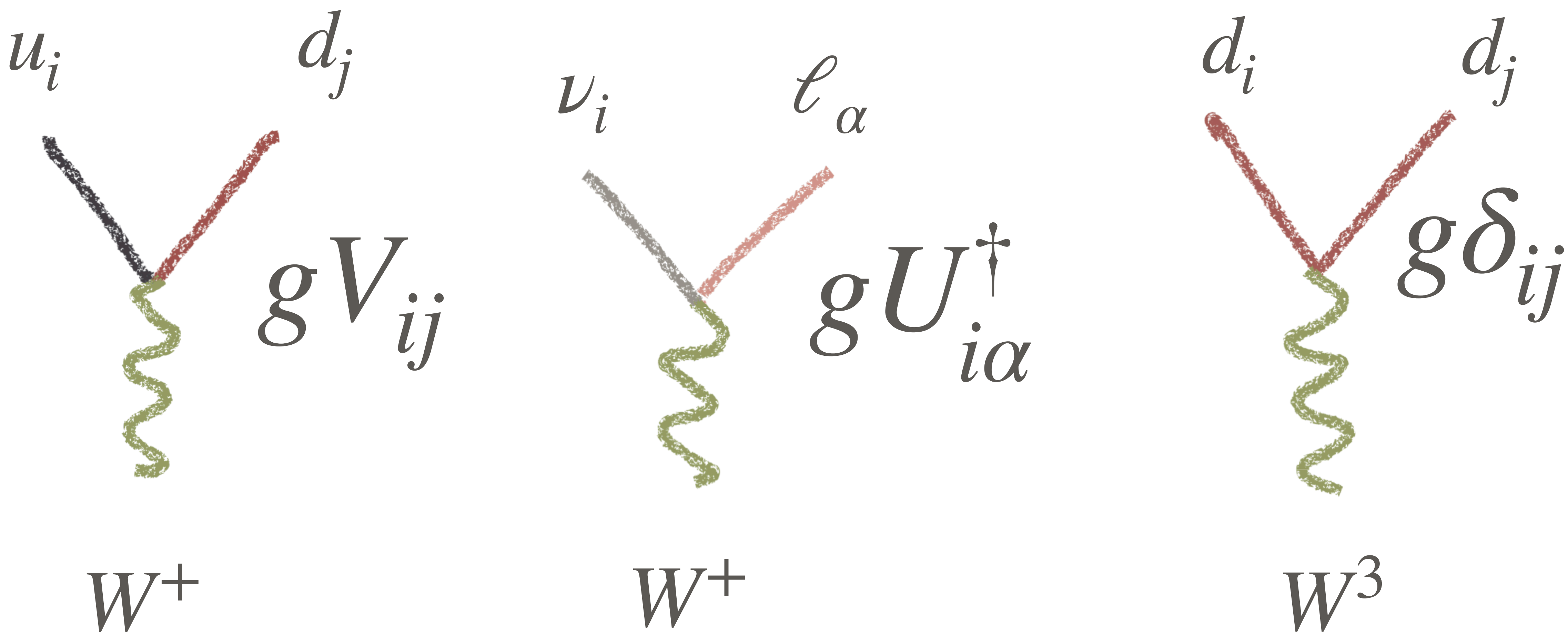
Space-time e.g. Randall Sundrum

...*None of the above*

What we know is Flavour in SM

Flavour transitions originate from charged currents

$SU(2)_L$

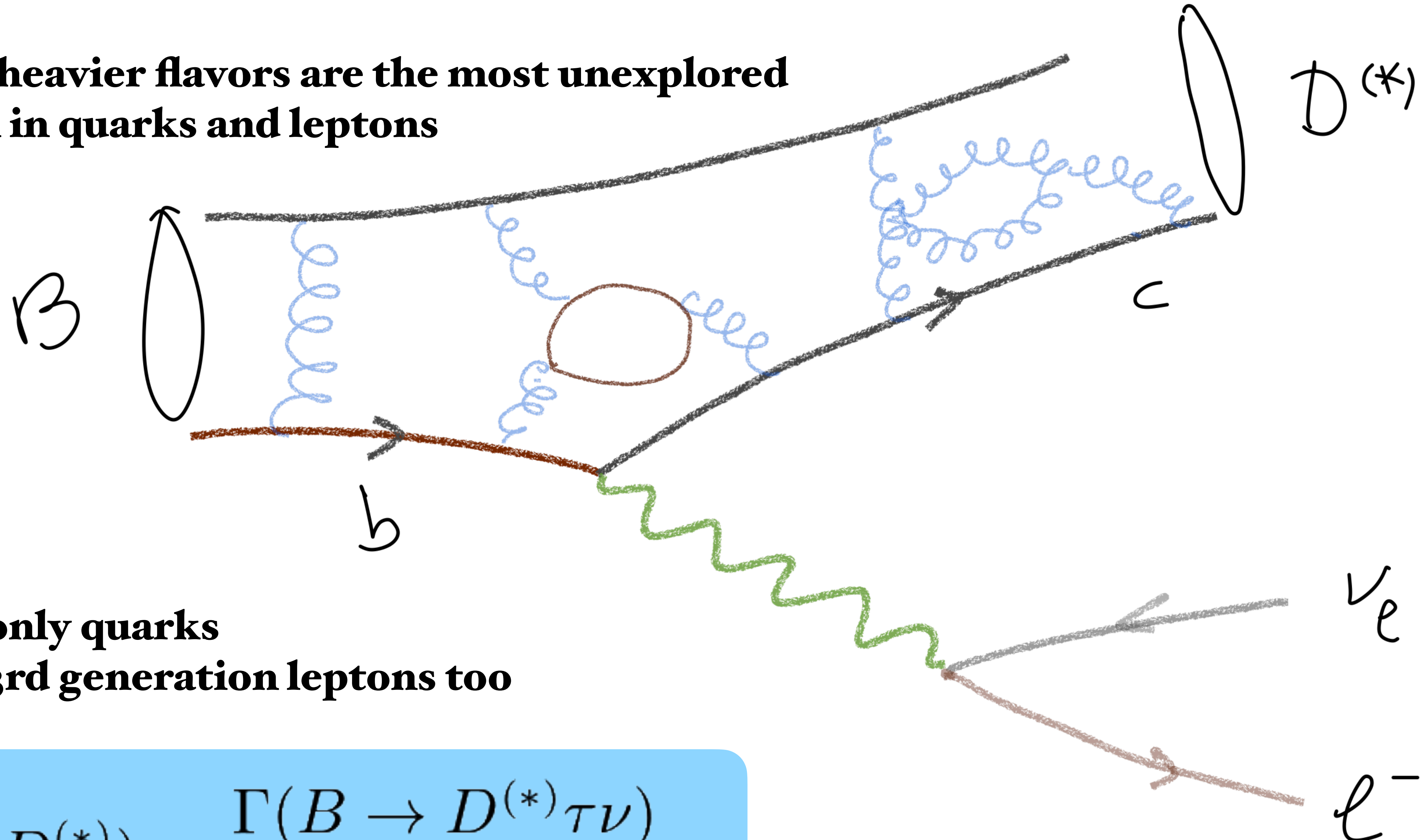


All flavor is in W couplings and in propagation/ phase space

$(\gamma^\mu p_\mu - m)^{-1}$

Testing flavor at tree level

The heavier flavors are the most unexplored both in quarks and leptons



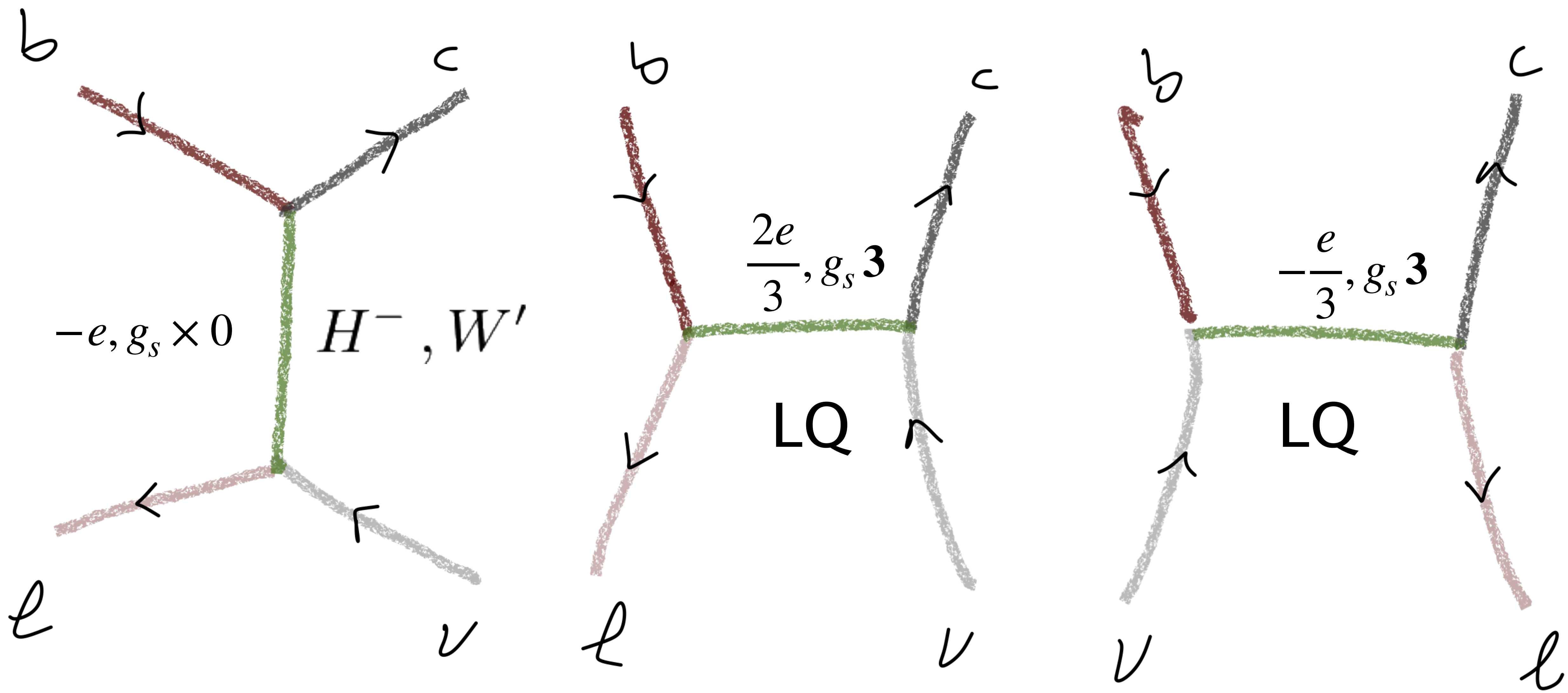
not only quarks
but 3rd generation leptons too

$$R(D^{(*)}) \equiv \frac{\Gamma(B \to D^{(*)}\tau\nu)}{\Gamma(B \to D^{(*)}\ell\nu)}$$

★ **(I)3rd generation**
(II) quark flavour violation
(III) lepton universality

Testing charged flavor at tree level

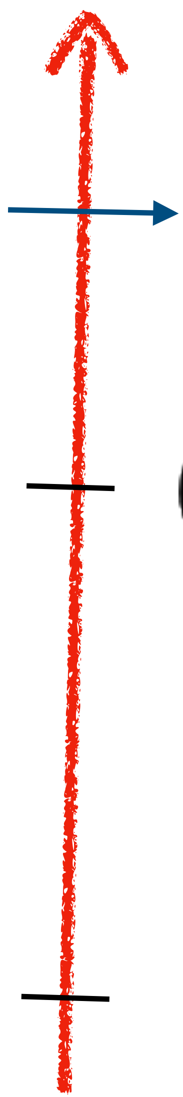
different charged particles, but all charged



Safe to say that they are heavy since we haven't seen them in e.g. LEP

Heavy new physics = EFT

Which is to say work with new interactions since we can integrate new particles out



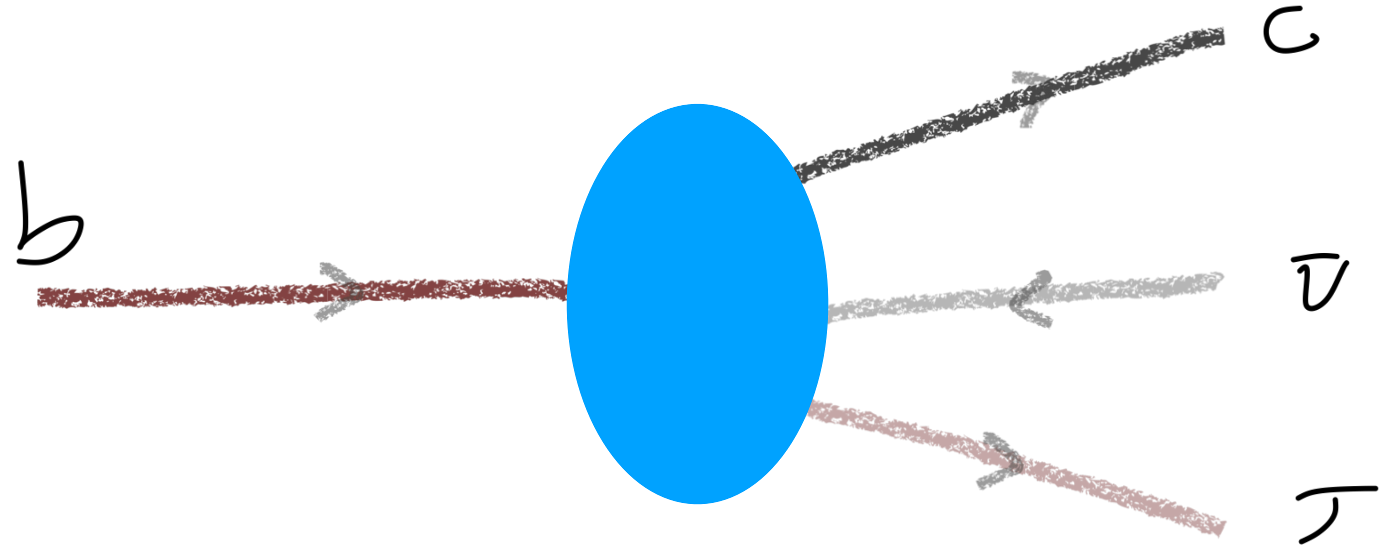
Λ

V $\quad (q_L, W^I_\mu, B_\mu, \ldots) \;/\; '' \times '' \times SU(2)_L \times U(1)_Y$

$m_B \quad (b, c, G^a_\mu, \gamma, \ldots) \;/\; SO(1,3) \times SU_c(3) \times U(1)_{\rm em}$

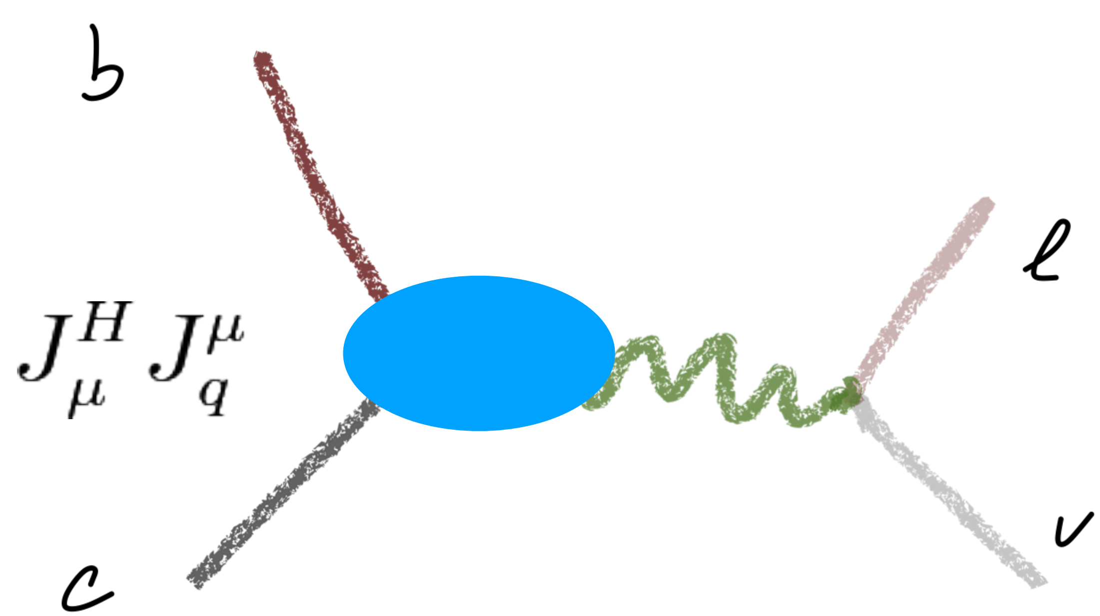
Our expansion is then in $\dfrac{E}{\Lambda}$ or , $\dfrac{v/\lambda}{\Lambda}$ **when normalizing to the SM**

Elementary level matrix elements



$$V_{cb}G_F\left((\bar{c}\sigma^\mu b_L)(\bar{\tau}\sigma_\mu\nu_\tau)+\frac{(v/\lambda\ )^2}{\Lambda^2}\sum C(\bar{c}\Gamma b)\otimes,(\bar{\tau}\Gamma'\nu_\tau)\right)$$

Cirigliano, Jenkins, Gonzalez-Alonso 0908.1754



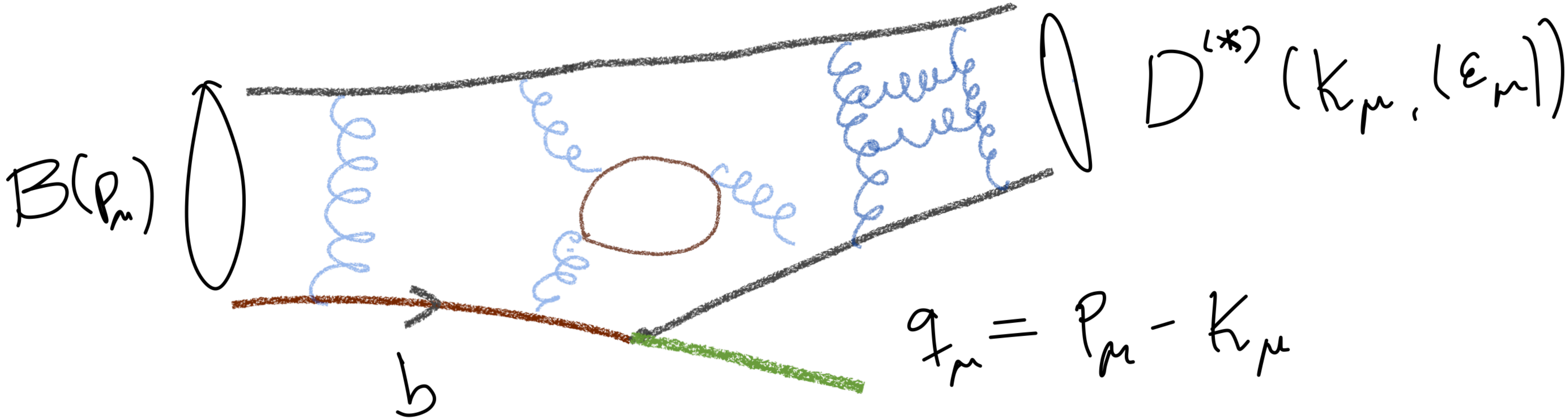
$$(\bar{c}_R\bar{\sigma}^\mu b_R)(\bar{\tau}_L\sigma_\mu\nu_{\tau,L})$$

$U(1)_Y$: -2/3 -1/3 1/2 -1/2

Just 4 parameters

$C_{V_L}, C_{S_{L,R}}, C_T$

Meson matrix elements



$$\langle D^{(*)}(k)|\bar{c}\,\Gamma b|B(p)\rangle = \sum_i f_i(q^2)(\otimes(\varepsilon_\mu, q_\nu, p_\rho))$$

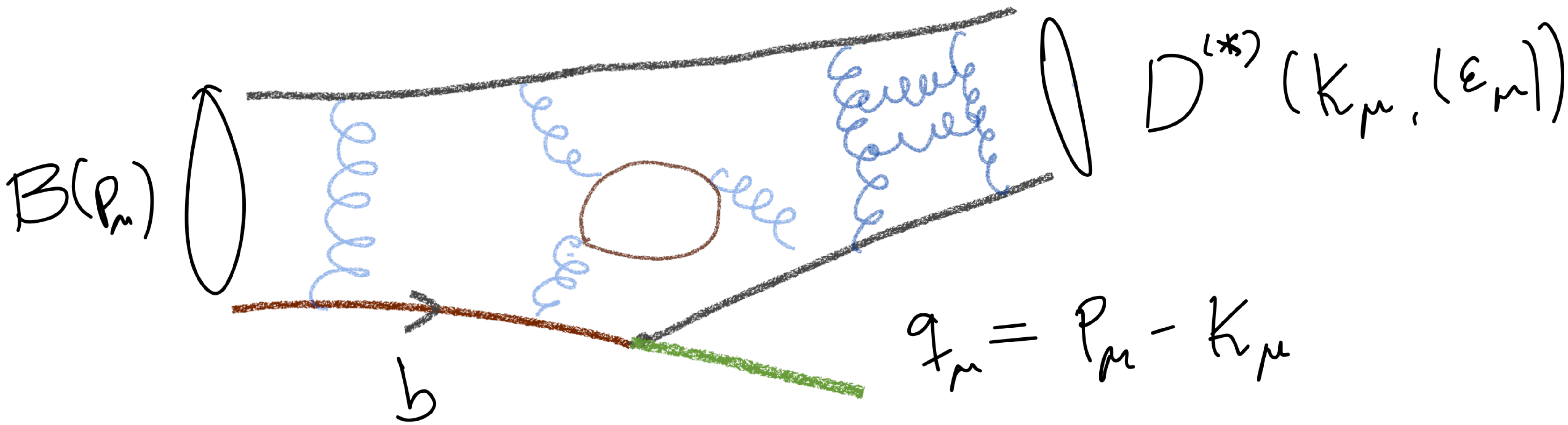
There is a number of form factors which we need as input…

$$\langle D(k)|\bar{c}\,\gamma_\mu b|B(p)\rangle = f_+(q^2)(p+k)^\mu + f_-(q^2)\,q^\mu \quad \Big) \times \bar{\tau}\sigma_\mu \nu_L$$

…which we cannot get around even with ratios

$\propto m_\tau$

Meson matrix elements



$$\langle D^{(*)}(k)|\bar{c}\,\Gamma b|B(p)\rangle = \sum_i f_i(q^2)(\otimes(\varepsilon_\mu, q_\nu, p_\rho))$$

There is a number of ways to extract these (HQET, Unitarity ...) and it matters

e.g. inclusive vs exclusive V_cb

hep-ph/9508211 [Boyd, Grinstein, and Lebed]

hep-ph/9712417 [Caprini, Lellouch, and Neubert]

One can use experimental data to some extent **[Hammer] 2002.00020**

or even rely instead on lattice **1902.08191 [FLAG 2019]**

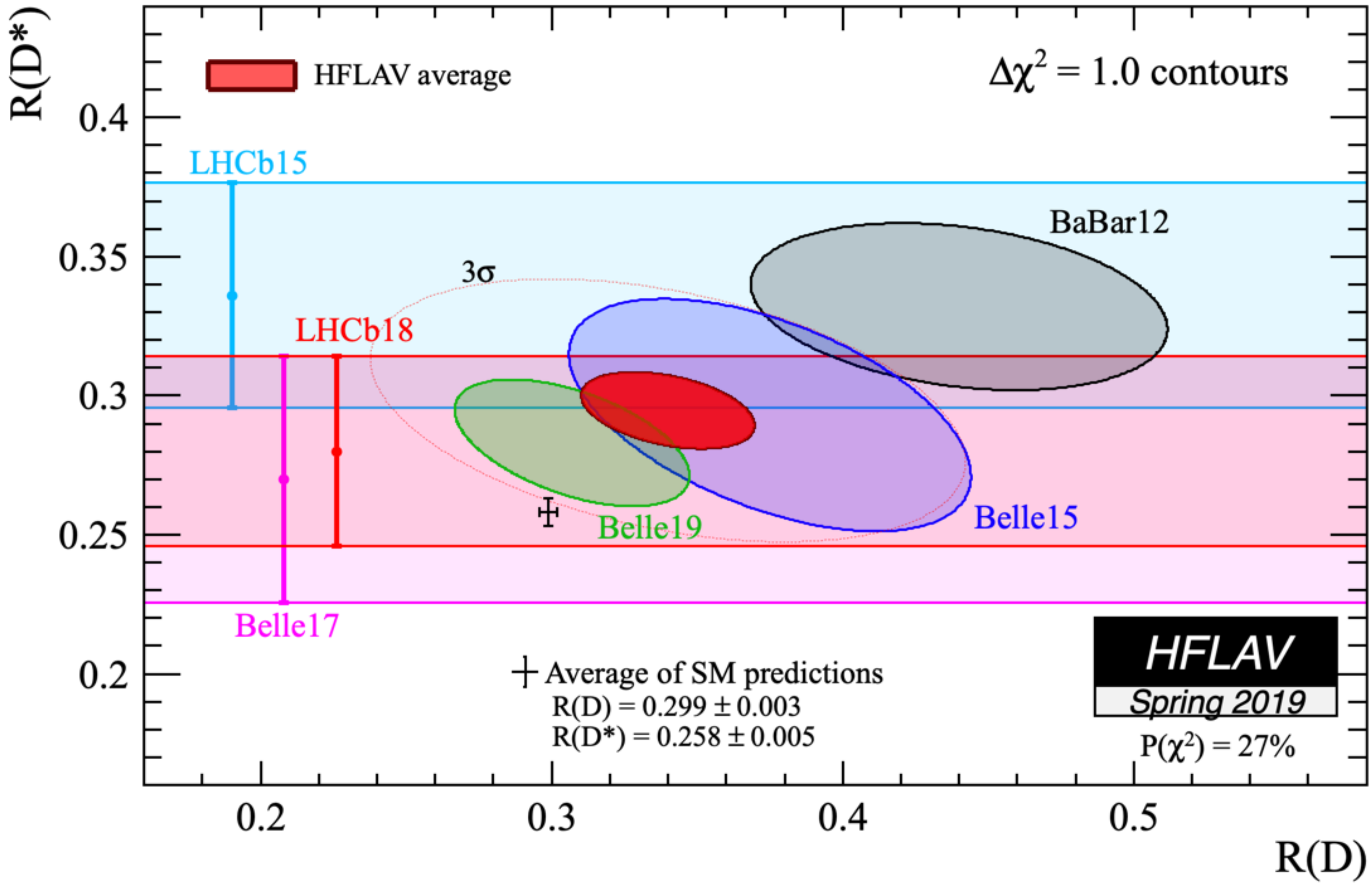
Either way...

SM prediction

Coll.	Approach	$R(D)$	$R(D^*)$	corr.
1607.00299 [FLAG]	Lattice	0.300 ± 0.008	–	–
1606.08030 [Bigi, Gambino]	Lattice + Belle/BaBar	0.299 ± 0.003	—	—
1203.2654 [Fajfer, Kamenik, Nisandzic]	Cont.+ Belle	—	0.252 ± 0.003	—
1703.05330 [Bernlochner, Ligeti, Papucci, & DR]	Lattice + Belle + HQET NLO	0.299 ± 0.003	0.257 ± 0.003	0.44
1707.09509 [Bigi, Gambino, Schacht]	BGL + BLPR + $1/m_c^2$ error estimate	—	0.260 ± 0.008	—
1707.09977 [Jaiswal, Nandi, Patra]	BGL/HQET + $1/m_c^2$ parameter	0.299 ± 0.004	0.257 ± 0.005	~ 0.1
HFLAV	Arithmetic average	$\mathbf{0.299 \pm 0.003}$	$\mathbf{0.258 \pm 0.005}$	–

Taken from D. Robinson's talk at FPCP '19

Experimental data



What it might point at if true

The deviation on both observables gives an "easy" modification, in the SM we have

$$\langle D^{(*)}|\,(J_V^\mu - J_A^\mu)\,|B\rangle \;\to\; \begin{array}{c} D(\mathrm{QCD})\text{ selects } J_V \\ D^*(\mathrm{QCD})\text{ selects } J_A \end{array}$$

So new physics current with the same chiral structure would do the job

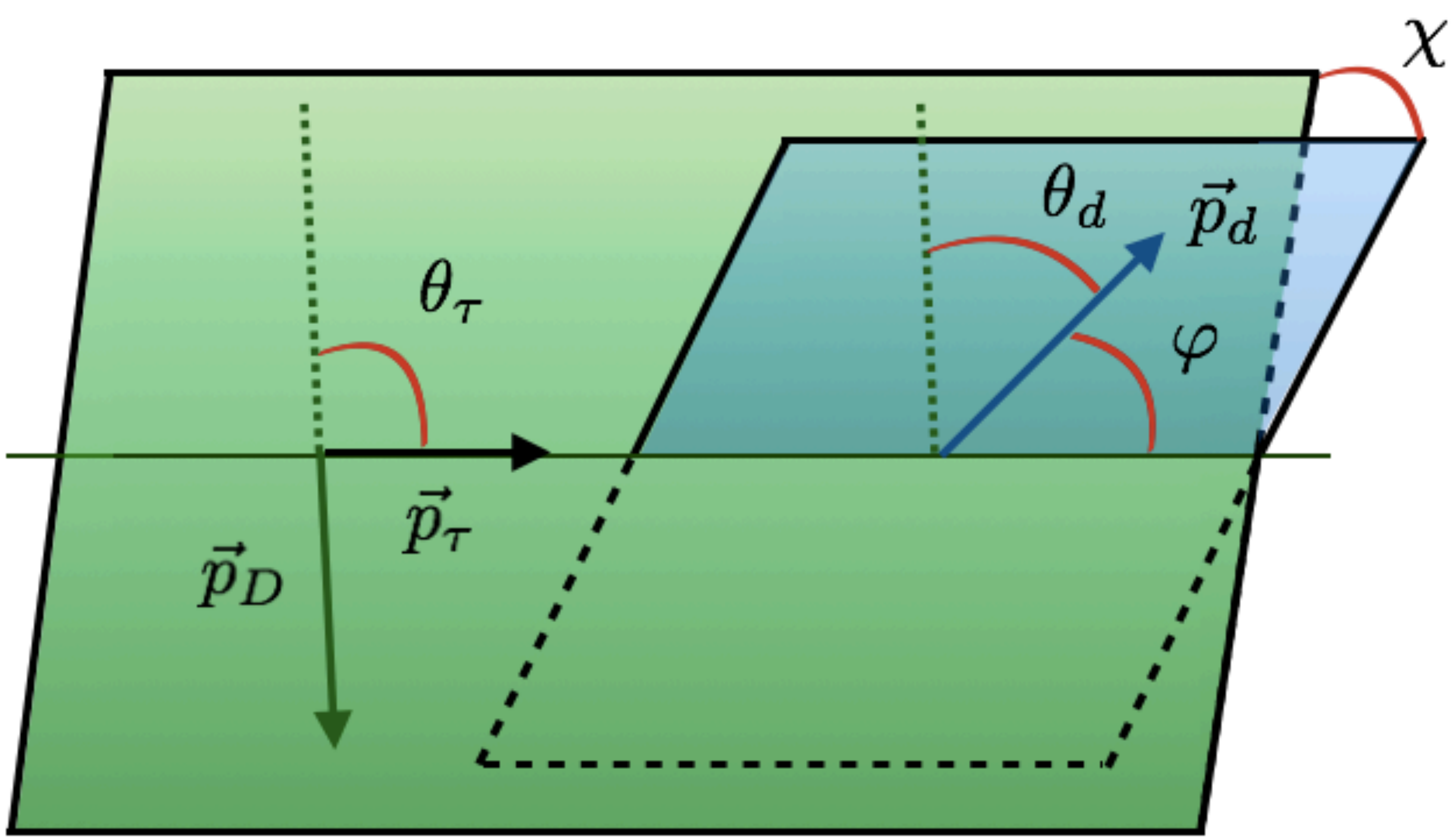
$$J^{\mathrm{NP}}_{V-A}\,(C_{V_L})?$$

However fitting to two numbers with 4 parameters leaves degeneracies....

Getting more out of it

Polarization! tanaka hep-ph/9411405

We have the different helicity amplitudes, what do they say about the spin structure?



Use 'polarization fractions'

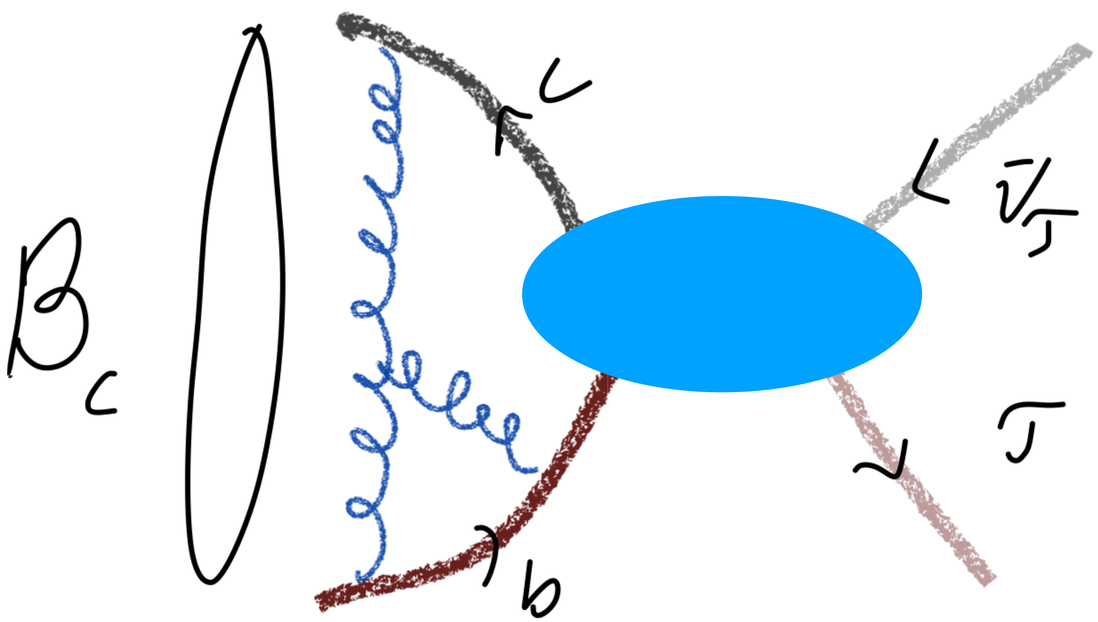
P_τ τ polarization

$F^L_{D^*}$ D^* polarization

Belle 1709.00129
Belle 1903.03102

One unavoidable observable

Li, Yang & Zhang 1605.09308, RA, & Grinstein 1611.06676
Akeroyd & Chen 1708.04072

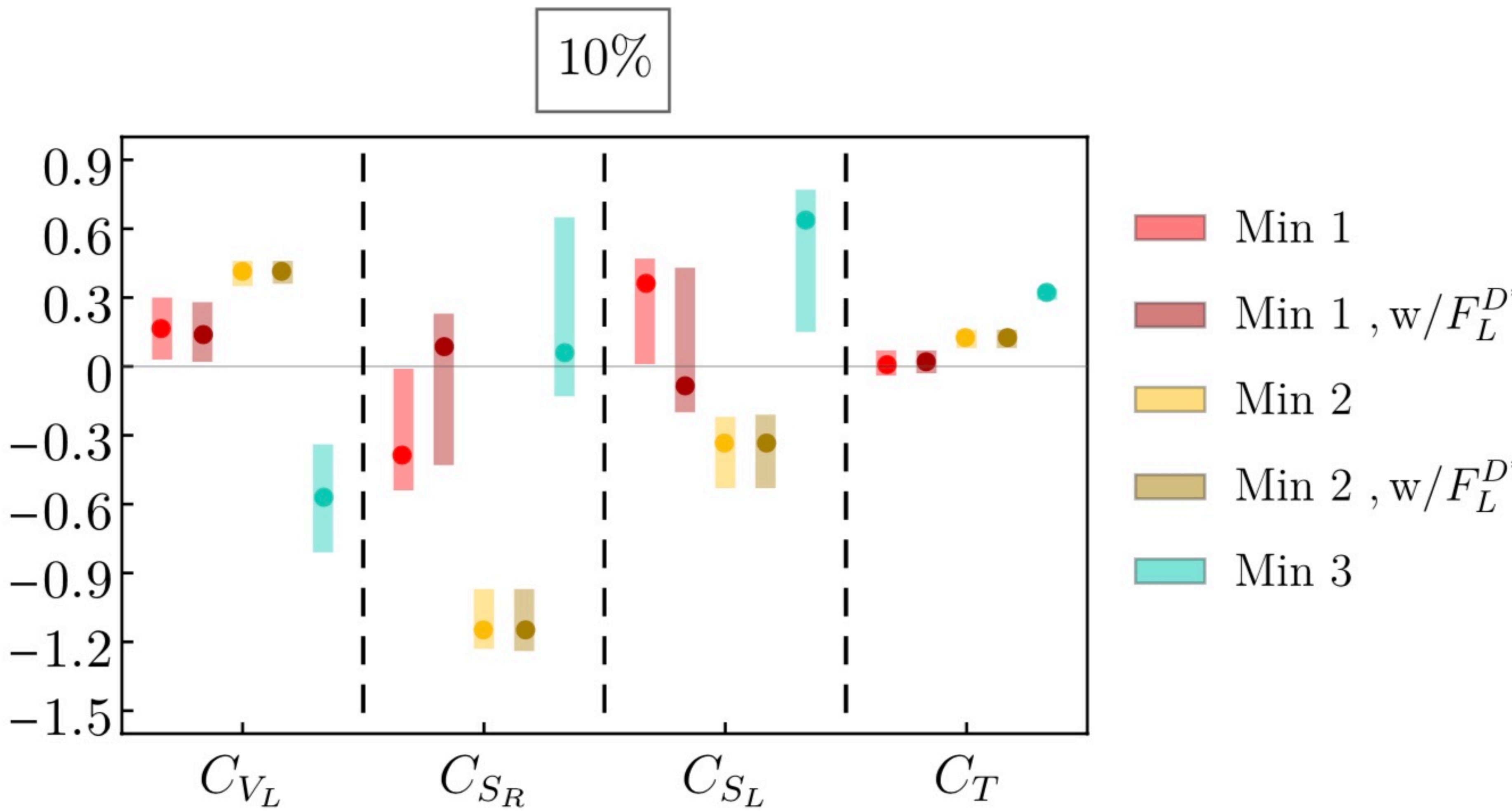


Although this decay has not been measured the width cannot be larger than 30% (10%) which is enough for a relevant constraint

$$\frac{\Gamma(B_c \to \tau\nu)}{\Gamma(B_c \to \tau\nu)_{\rm SM}} = \left| 1 + C_{V_L} + \frac{m_{B_c}^2}{m_\tau(m_b+m_c)}(C_{S_R} - C_{S_L}) \right|^2$$

With all the above: fit

Murgui, Penuelas, Jung & Pich 1904.09311

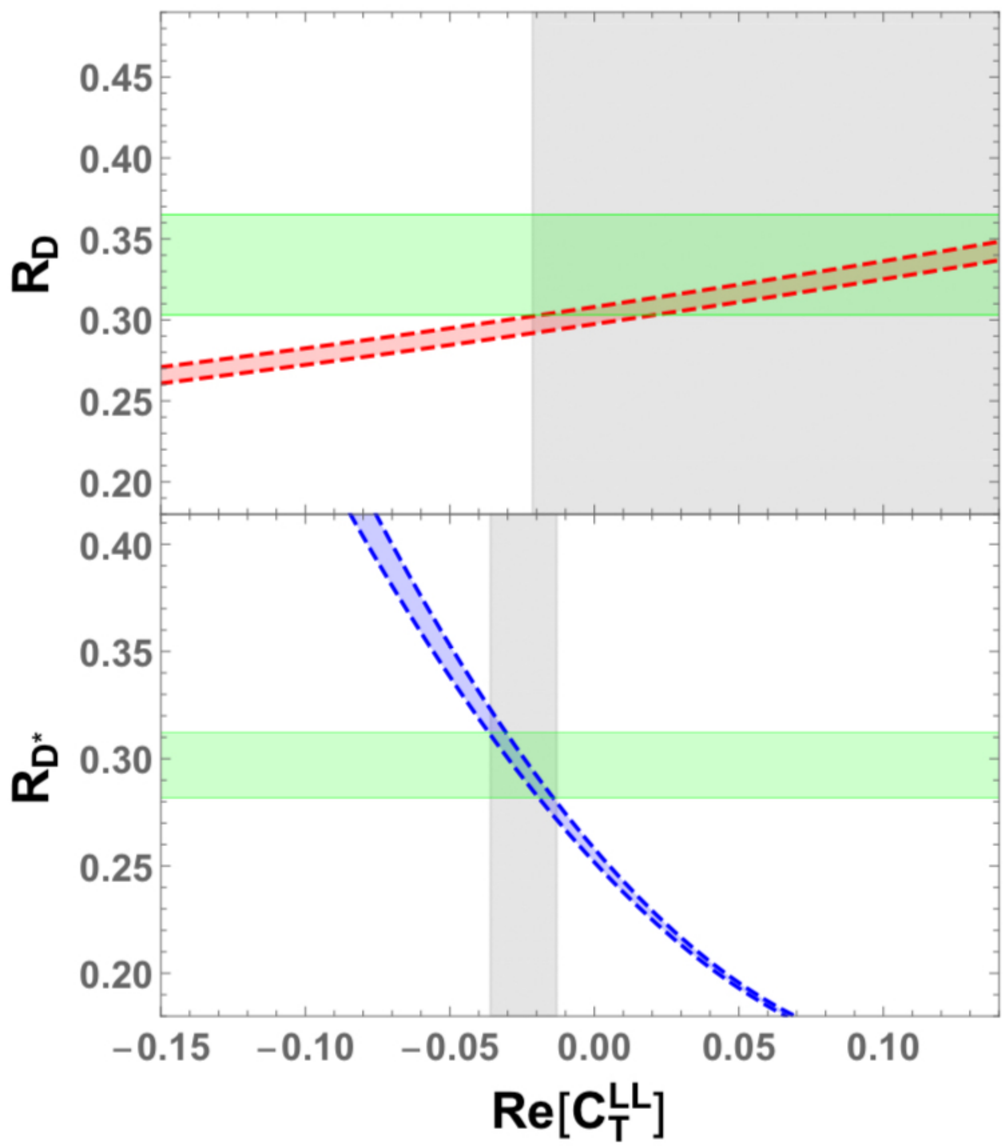


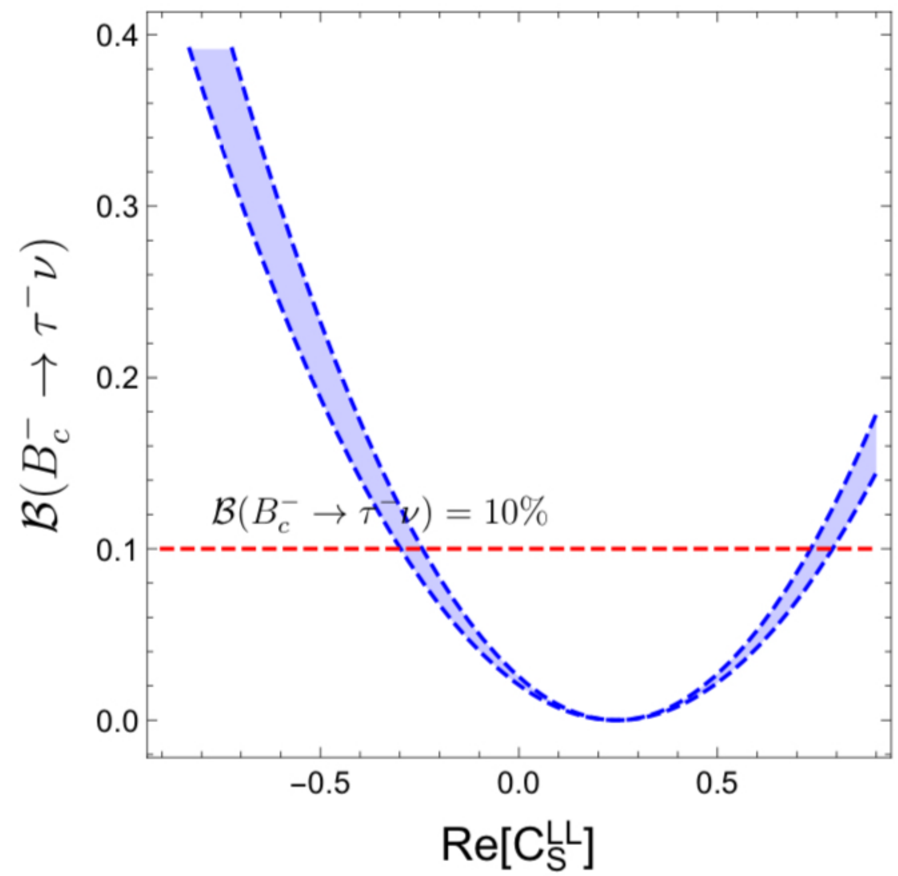
***) Some degeneracies in minima make the bars 'wide'**
***) The single coefficient solution is still V_L**
***) Scalar solutions saturate B_c**

With the updated data...

Post MoriondEW 19

Bardhan & Gosh 1904.10432,

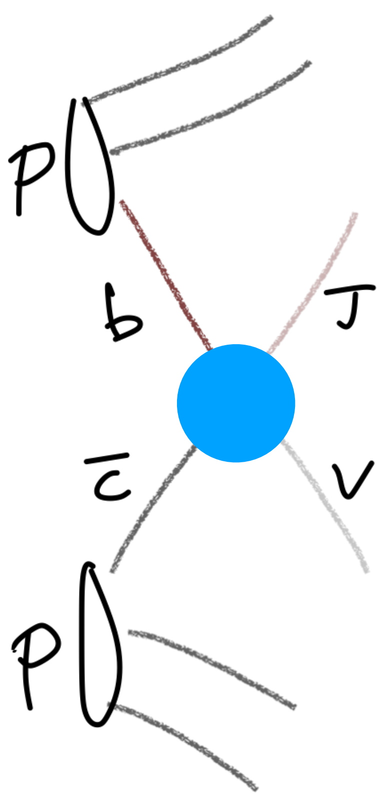


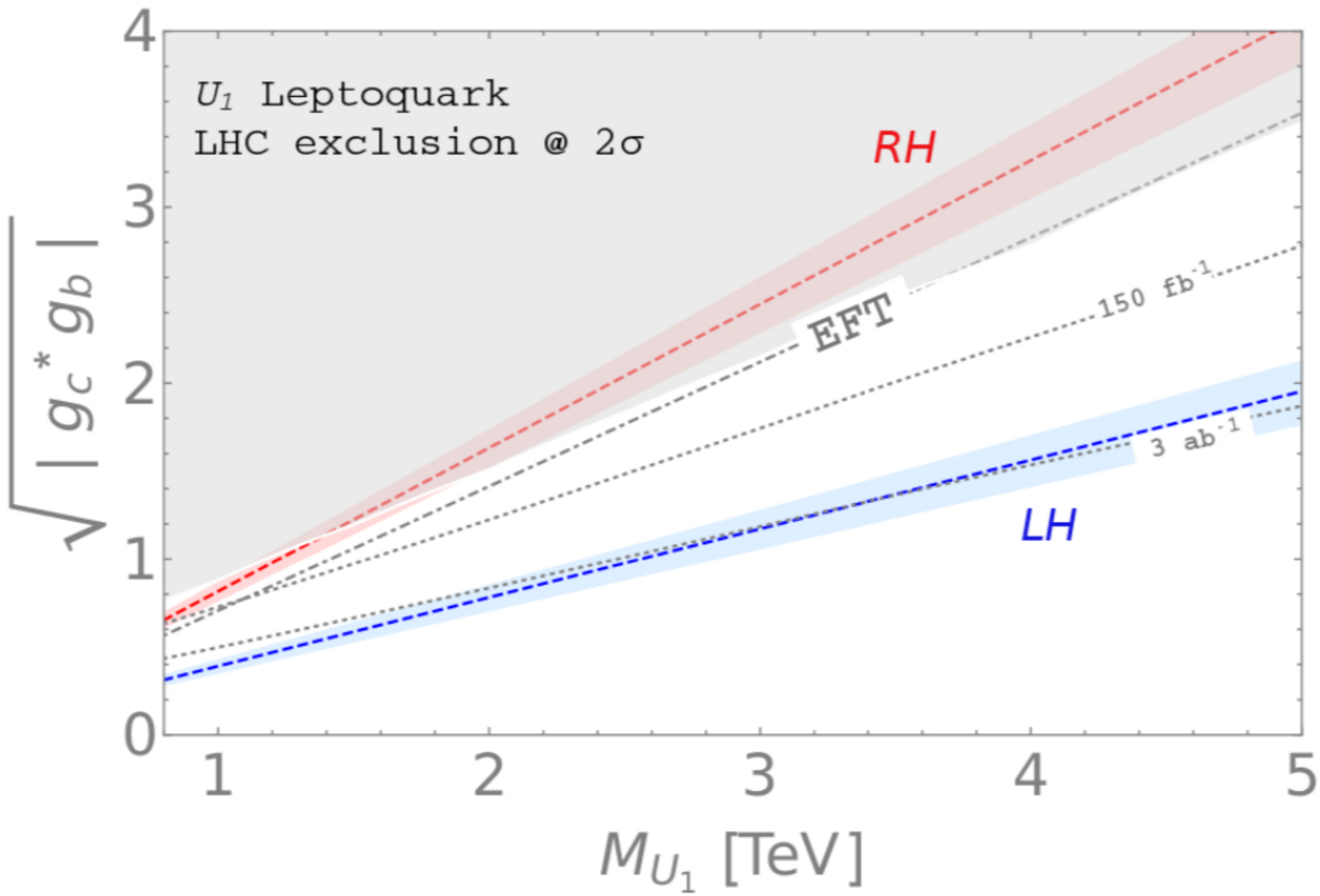


The effect required is smaller now
which relaxes tensions with other data, e.g. the tensor operator C_T

LHC searches

Greljo, Camalich & Ruiz-Alvarez 1811.07920,





U1

$$\frac{2e}{3}, g_s \mathbf{3}$$

SU(2) partners, RGE (Feruglio Paradisi & Pattori 1705.00929)…

Conclusions

The anomaly in

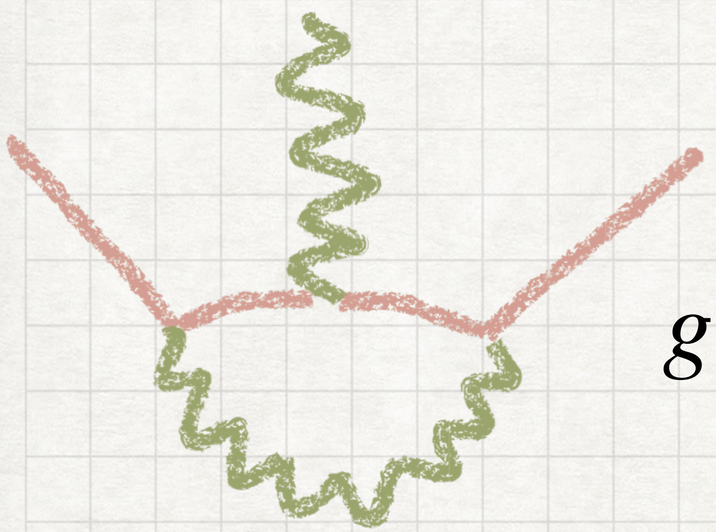
$$R(D^{(*)}) \equiv \frac{\Gamma(B \to D^{(*)}\tau\nu)}{\Gamma(B \to D^{(*)}\ell\nu)}$$

is the closest new physics within reach

&

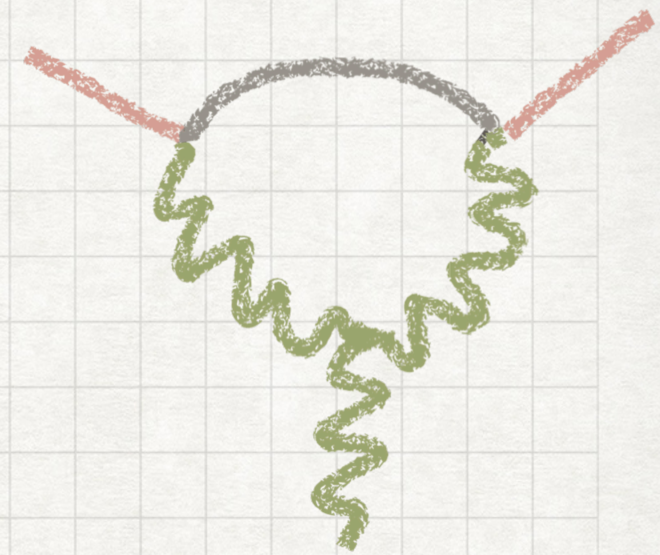
a multi-experiment effort will bring timely resolution

Lepton Universality (LU)



LUV **LFV & LUV**

$$g^3\left(\frac{m_\alpha\delta_{\alpha\beta}[q,\gamma]}{16\pi^2 M_W^2}+\frac{U_{\alpha i}m_{\nu_i}^2U^\dagger_{i\beta}\gamma}{16\pi^2 M_W^2}\right)$$



$$\frac{Z\to\ell\ell}{Z\to\ell'\ell'}=1\pm0.1\,\%\quad\text{(LEP)}$$

$$\frac{Z\to\ell'\ell}{Z\to\ell\ell}<10^{-6}\quad\text{(LEP)}$$