From Flavour Anomalies Towards New Physics

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Implications of LHCb measurements and future prospects
25–27 October 2023

2024 J. J. Sakurai Prize for Theoretical Particle Physics Recipient

Andrzej J. Buras
Technical University Munich

Citation:

"For exceptional contributions to quark-flavor physics, in particular, developing and carrying out calculations of higher-order QCD effects to electroweak transitions, as well as for drawing phenomenological connections between kaons, D mesons, and B mesons."

Background:

Master Degree, Warsaw University 1971, PhD Niels Bohr Institute, Copenhagen 1972, Postdoctoral Fellow at Niels Bohr Institute (1972-1975), CERN Fellow (1975-1977), Fermilab Scientist (1977-1982), Max-Planck-Institute (Munich) (1982-1988), Full Professor at Technical University Munich (1988-2012), Emeritus of Excellence of TUM (2012 -now). Max Planck Medal 2020 of the German Physical Society, ERC-Advanced Grant 2011-2016, Smoluchowski-Warburg Medal of the German and Polish Physical Societies 2007, Ordinary Member of the Bavarian Academy of Sciences (2010), Foreign member of Polish Academy of Sciences (2013) and of Polish Academy of Arts and Sciences (2011), Member of the Academia Europaea

Sakurai prizes for flavour physics

2004: Anthony Sanda
Ikaros I Bigi

Outline

Introduction

Lepton flavor universality

Anomalies
- B meson anomalies $R_{D^{(*)}}$, P_5', $R^{\nu\nu}_{K^{(*)}}$ (?)
- anomalous muon magnetic moments (?)

SM contributions to anomalous processes

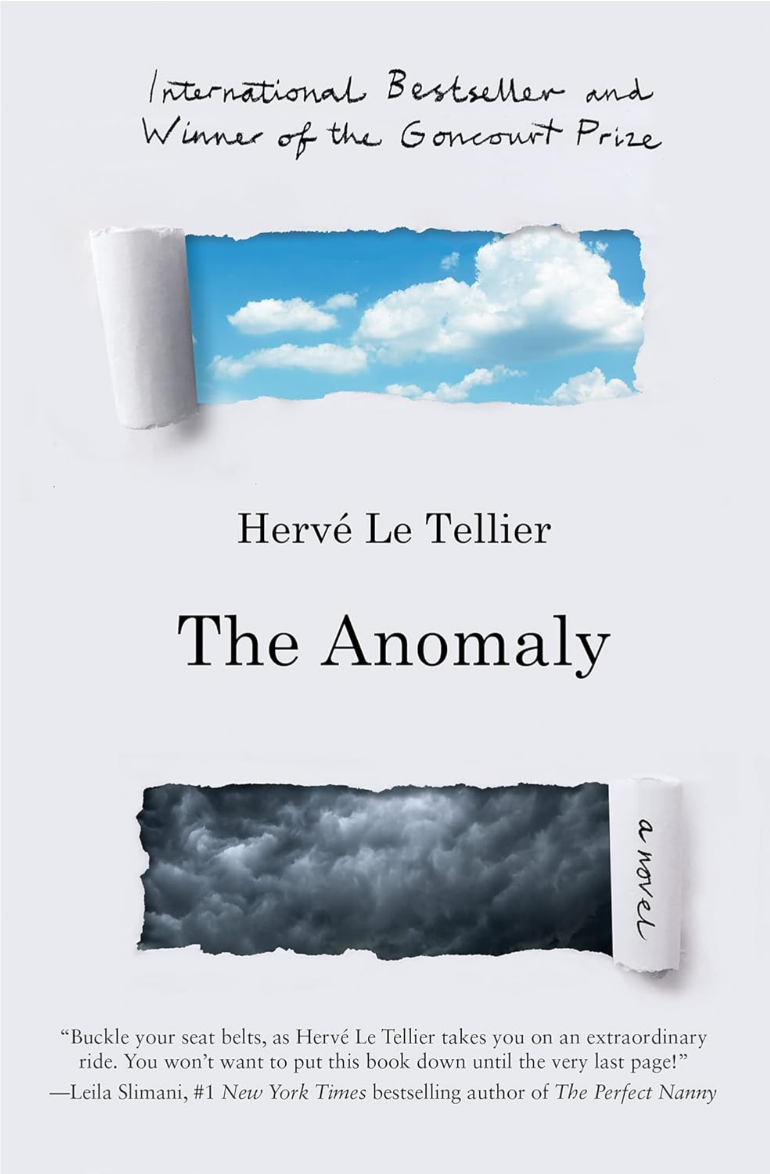
Approaching New Physics
- SMEFT Lagrangian approach
- models of NP

Constraints from low-energy observables & LHC data
Predictions relevant for LHCb, Belle2 &LHC

UV complete theories of NP → ? Flavour puzzle

Outlook

From present anomalies to new anomalies!



After analysing one anomaly, a new anomaly appers….

Anomalies - in the past

2010

D0 Collaboration, 1007.0395

We measure the charge asymmetry $A \equiv (N^{++} - N^{--})/(N^{++} + N^{--})$ of like-sign dimuon events in 6.1 fb^{-1} of $p\bar{p}$ collisions recorded with the D0 detector at a center-of-mass energy $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron collider. From A we extract the like-sign dimuon charge asymmetry in semileptonic b-hadron decays: $A^b_{sl} = -0.00957 \pm 0.00251\,(\text{stat}) \pm 0.00146\,(\text{sys})$. It differs by 3.2 standard deviations from the standard model prediction $A^b_{sl}(\text{SM}) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$, and provides first evidence of anomalous CP violation in the mixing of neutral B mesons.

$$A^b_{sl} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

N_b^{++} and N_b^{--} represent the number of events in which the two muons of highest transverse momentum, have the same positive or negative charges.

$$a^b_{sl} \equiv \frac{\Gamma(\bar{B} \to B \to \mu^+ X) - \Gamma(B \to \bar{B} \to \mu^- X)}{\Gamma(\bar{B} \to B \to \mu^+ X) + \Gamma(B \to \bar{B} \to \mu^- X)} = A^b_{sl}$$

The large forward-backward asymmetry in the production of $t\bar{t}$ pairs at the Tevatron

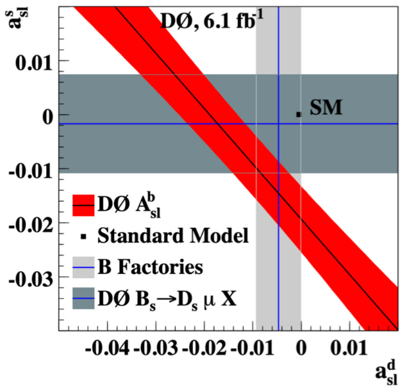


FIG. 3: (Color online) Comparison of A^b_{sl} in data with the SM prediction for a^d_{sl} and a^s_{sl}. Also shown are other measurements of $a^d_{sl} = -0.0047 \pm 0.0046$ [15–17] and $a^s_{sl} = -0.0017 \pm 0.0091$ [18]. The bands represent the ± 1 standard deviation uncertainties on each measurement.

2011

CDF	$A_{t\bar{t}} = 0.193 \pm 0.069$
DØ	$A_{t\bar{t}} = 0.24 \pm 0.14$

These anomalies have disappeared!

Introduction

Why to formulate a new theory?

- observed phenomena, unexplained by existing theory (e.g. neutrino masses, Dark Matter,… in the Standard Model)
- disagreements of the existing theory predictions and data
- trying to cure theoretical problems of the existing theory as e.g. sizable corrections that depend quadratically on the cutoff energy scale for the SM Higgs mass (Supersymmetry, Little Higgs models etc.,…)
- Expectation that the Nature supports unification of fundamental interactions – GUT.
- …

The thing that doesn't fit is the thing that is most interesting.
Richard P. Feynman

Steven Weinberg

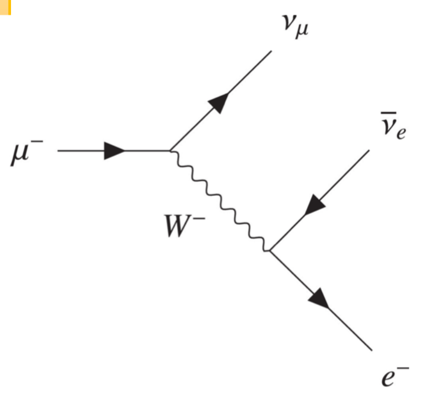
The Making of the Standard Model

"My starting point in 1967 was the old aim, going back to Yang and Mills, of developing a gauge theory of the strong interactions, but now based on the symmetry group that underlies the successful soft- pion predictions, the symmetry group SU(2) × SU(2) [32]. I supposed that
the vector gauge boson of this theory would be the ρ-meson, which was an old idea, while the axial-vector gauge boson would be the a1 meson, an enhancement in the $\pi - \rho$ channel which was known to be needed to saturate certain spectral function sum rules, which I had developed a little earlier that year [33]. Taking the SU(2) × SU(2) symmetry to be exact but spontaneously broken, I encountered the same result found earlier by Higgs and Brout and Englert; the Goldstone bosons disappeared and the a1 meson became massive. But with the isotopic spin subgroup unbroken, then (in accordance with a general result of Kibble [34]) the ρ-meson would remain massless. I could of course put in a common mass for the a1 and ρ by hand, which at first gave encouraging results. The pion now reappeared as a Goldstone boson, and the spontaneous breaking of the symmetry made the a1 mass larger than the ρ mass by a factor of the square root of two, which was just the ratio that had come out of the spectral function sum rules. For a while I was encouraged, but the theory was really too ugly. It was the same old problem: putting in a ρ-meson mass or any gauge boson mass by hand destroyed the rationale for the theory and made the theory less predictive, and it also made the theory not renormalizable. So I was very discouraged.
Then it suddenly occurred to me that this was a perfectly good sort of theory, but I was applying it to the wrong kind of interaction. "

"The gluons are in fact massless, but we don't see them for the same reason that we don't see the quarks, which is that, as a result of the peculiar infrared properties of non-Abelian gauge theories, color is trapped; color particles like quarks and gluons can never be isolated . This has never been proved.
There is now a million dollar prize offered by the Clay Foundation to anyone who succeeds in proving it rigorously, but since it is true I for one am happy to leave the proof to the mathematicians. "

hep-ph/0401010

Lepton Flavour Universality (LFU)



the same coupling of lepton and its neutrino with W for all three lepton generations!

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix} \qquad \Gamma(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau) = \Gamma(\tau^- \to e^- \bar{\nu}_e \nu_\tau)$$

Basic property of the SM: universal g

valid for quarks too!

$$\mathcal{L}_f = \bar{f} i D_\mu \gamma^\mu f \qquad f_L = Q_L, L_L$$

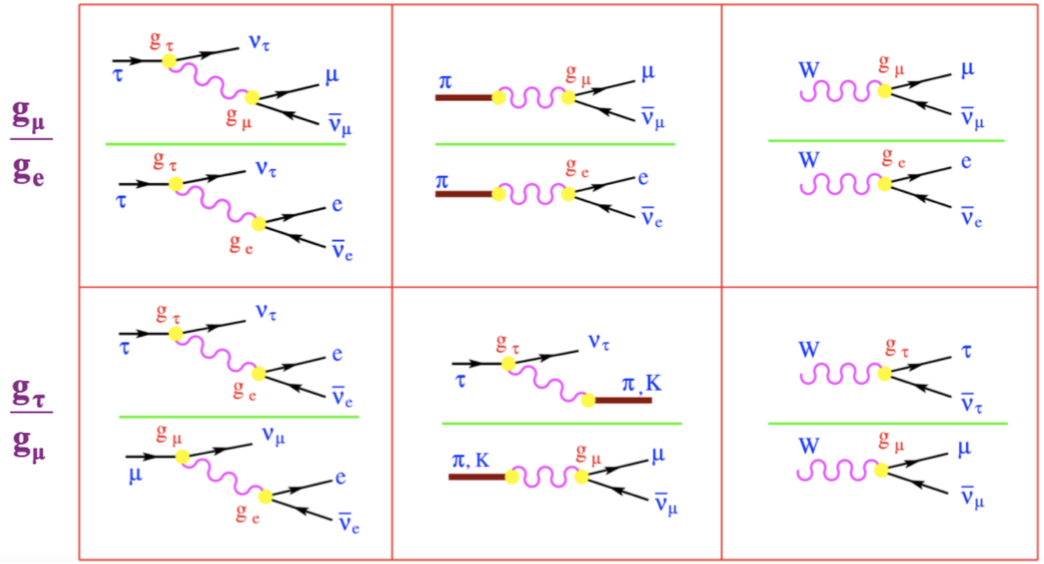
$$\mathcal{L}_{eff} = -\frac{G_F}{\sqrt{2}} J_\mu^\dagger J^\mu$$

$$D_\mu = \partial_\mu + ig\frac{1}{2}\vec{\tau} \cdot \vec{W}_\mu + ig'\frac{1}{2} Y_W B_\mu$$

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

the same for all SM fermions

Flavor changing charged… LFU



From Tony Pich at CHARM 2023,Siegen

$|g_\mu / g_e|$

$B_{\tau\to\mu}/B_{\tau\to e}$	1.0019 ± 0.0014
$B_{\pi\to\mu}/B_{\pi\to e}$	1.0010 ± 0.0009
$B_{K\to\mu}/B_{K\to e}$	0.9978 ± 0.0018
$B_{K\to\pi\mu}/B_{K\to\pi e}$	1.0010 ± 0.0025
$B_{W\to\mu}/B_{W\to e}$	1.001 ± 0.003

$|g_\tau / g_e|$

$B_{\tau\to\mu}\ \tau_\mu/\tau_\tau$	1.0027 ± 0.0014
$B_{W\to\tau}/B_{W\to e}$	1.007 ± 0.010

$|g_\tau / g_\mu|$

$B_{\tau\to e}\ \tau_\mu/\tau_\tau$	1.0009 ± 0.0014
$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	0.9959 ± 0.0038
$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	0.986 ± 0.008
$B_{W\to\tau}/B_{W\to\mu}$	1.001 ± 0.010

Experimental tests do not show violation of LFU

LFU violation in the SM

Obviously LFU in the SM is a consequence of the same gauge coupling!

However, all quarks and leptons have different masses!

Flavour puzzle!

$$\mathcal{L}_{\text{Yukawa}} = -Y_d^{ij}\bar{Q}_L^i H d_R^j - Y_u^{ij}\bar{Q}_L^i H^c u_R^j - Y_\ell^{ij}\bar{L}_L^i H \ell_R^j + \text{h.c.}$$

Within SM LFU is violated by different fermionic masses

The Yukawa interaction breaks

$$\mathcal{G}_{\text{flavour}} \to U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau \times U(1)_Y$$

$$m_i = \frac{f_i v}{\sqrt{2}} \qquad i = u,\, d,\, e$$

Are there any LFU violation behind the SM?

Flavour puzzle - a "blessing" for CP violation

Only Yukawa terms in the SM Lagrangian are not invariant under CP symmetry.

The measure of CP violation is given by Jarlskog invariant

$$J_Y \equiv \mathrm{Im}\left(\det\left[Y_d Y_d^\dagger, Y_u Y_u^\dagger\right]\right)$$

$$J_Y = J_{\mathrm{CP}} \frac{(m_t^2 - m_c^2)}{v^2/2}\frac{(m_t^2 - m_u^2)}{v^2/2}\frac{(m_c^2 - m_u^2)}{v^2/2}\frac{(m_b^2 - m_s^2)}{v^2/2}\frac{(m_b^2 - m_d^2)}{v^2/2}\frac{(m_s^2 - m_d^2)}{v^2/2} \simeq \mathcal{O}(10^{-22})$$

$$J_{\mathrm{CP}} = \mathrm{Im}\left[V_{us}V_{cb}V_{ub}^*V_{cs}^*\right] = c_{12}c_{23}c_{13}^2 s_{12}s_{23}s_{13}\sin\delta_{\mathrm{KM}} \simeq \lambda^6 A^2 \eta \simeq \mathcal{O}(10^{-5})$$

CP would be conserved in the SM, if any of two pairs of masses are equal!

2309.06042 The Curious Early History of CKM Matrix

-miracles happen!-

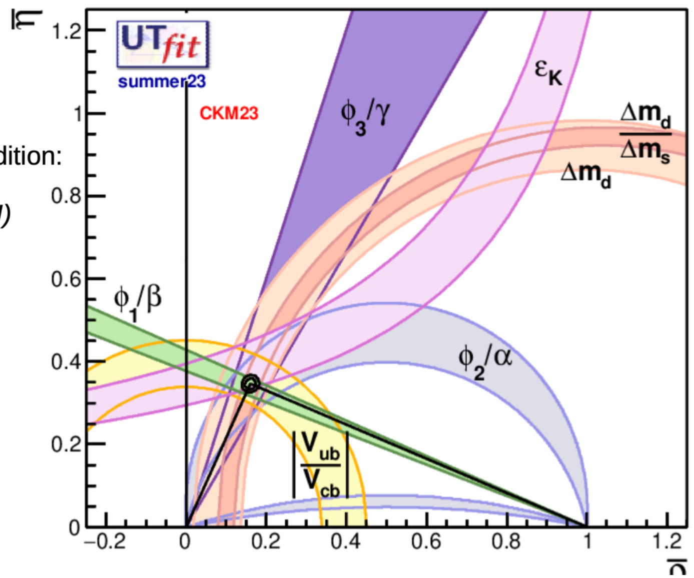
Stephen Lars Olsen

"The Christenson, Cronin, Fitch and Turley discovery of the CP violating decay mode $K_L \to \pi^+\pi^-$ was reported in the summer of 1964 **. This was a relatively low priority experiment that was not aimed at investigating CP violation but, instead, was designed to investigate some anomalies in coherent $K_2 \to K_1$ regeneration measurements that had been reported during the previous year**. It failed to qualify for a spot in the main experimental hall of the then, almost new, AGS synchrotron that was occupied by spectrometers specialized for total cross section determinations, and π, K, $\bar{p}$ and μ-proton elastic scattering measurements. Instead, the experimental apparatus was located in a relatively inaccessible area inside the AGS magnet ring that the laboratory technical staff referred to as "Inner Mongolia," in a neutral particle line that was essentially a hole in the AGS shielding wall that was pointed at a target located in the accelerator's vacuum chamber, as illustrated in Fig. 2a. The high flux of γ-rays emerging from the target were attenuated by a 3.8 cm- thick lead block followed by a collimator and a bending magnet that swept charged particles out of the beam aperture. A double-arm spectrometer consisting of tracking spark chambers before and after two vertically bending magnets measured the directions and momenta of charged particles that were produced by K_L meson decays that occurred in a 2 m-long decay volume that was a plastic bag filled with atmospheric pressure helium—a low-budget approximation of a vacuum chamber."

4 In the 1960s diplomatic relations between the U.S. and China were non-existent, and mainland China, including Inner Mongolia, was considered by most Americans to be about as accessible as the far side of the Moon.

This talk does not contain topics as

Special edition: *homage to Belle (II)*



Bona @ EPS 2023

levels @ 95% Prob

$\bar{\rho} = 0.160 \pm 0.009$
$\bar{\eta} = 0.346 \pm 0.009$

$\lambda = 0.2251 \pm 0.0008$
$A = 0.827 \pm 0.010$

UTfit full fit
$|V_{cb}|_{UTfit} = (41.94 \pm 0.41)\ 10^{-3}$
$|V_{ub}|_{UTfit} = (3.70 \pm 0.08)\ 10^{-3}$

Talk of L. Vittorio yesterday.

$|V_{ub} / V_{cb}| = (8.27 \pm 1.17)\ 10^{-2}$ From B_s to K (LHCb) and UTfit

$|V_{ub} / V_{cb}|$ *(LHCb)* $= (7.9 \pm 0.6)\ 10^{-2}$ From Λ_b, excluded following FLAG

Cabibbo Angle Anomaly (CAA)

No charm- see talks by Solomonidi and Vale Silva!

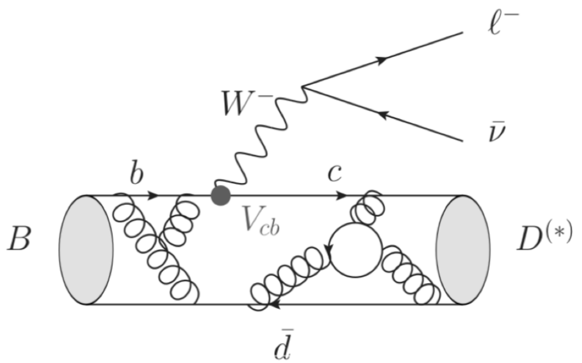
Lepton flavour universality violation in tau decays ($\tau \to \mu\nu\bar{\nu}$)

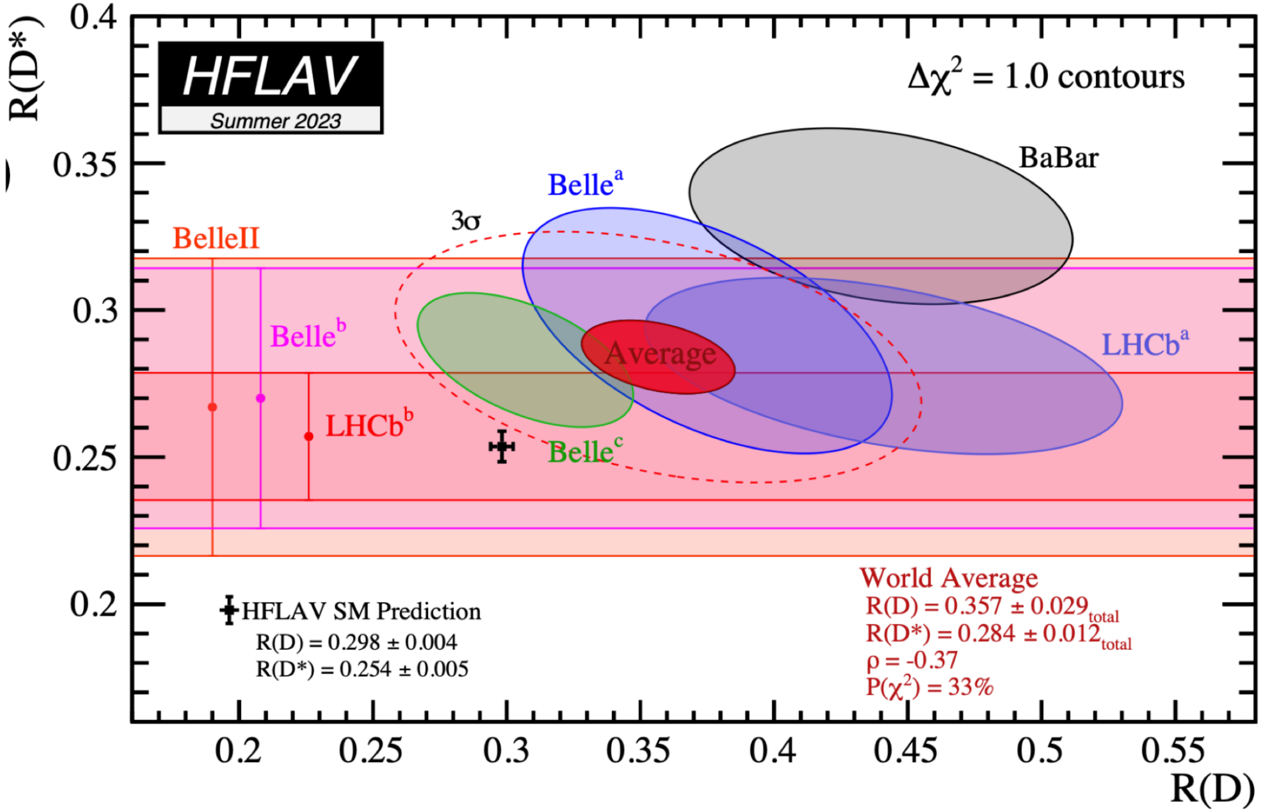
Crivellin and Mellado, 2309.03870

B meson anomalies

$R_{D(*)}$

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)} l\bar{\nu})}\Bigg|_{l\in\{e,\mu\}}$$





- R_D^{exp} and R_{D*}^{exp} : dominated by BaBar!
- In $R_{J/\psi}^{exp}$ and $R_{\Lambda c}^{exp}$ limited precision.

Solution for the puzzle - New Physics!

There are still some issues!

$$< D^{(*)}(p', (\epsilon))|\bar{c}\,\Gamma^{\mu}\, b|B(p) >= \sum_j K_j^{\mu} \mathcal{F}_j(q^2)$$

See Judd Harrison talk yesterday!

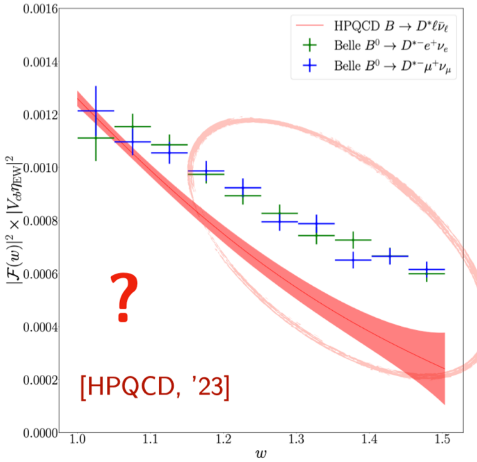
1) $B \to D$: one (two) form-factors with $f_0(0) = f_+(0)$ at $q^2 = 0$;
Lattice QCD at $q^2 \neq q^2_{max}$ for both form-factors.

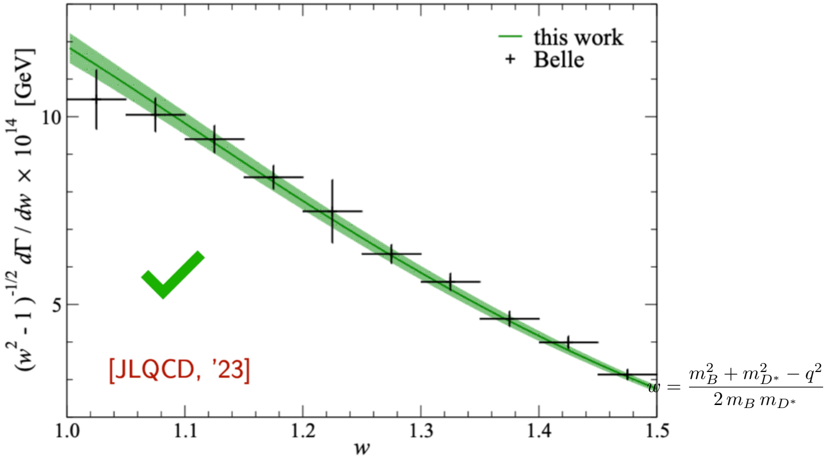
$$R_D^{latt} = 0.293(5)$$

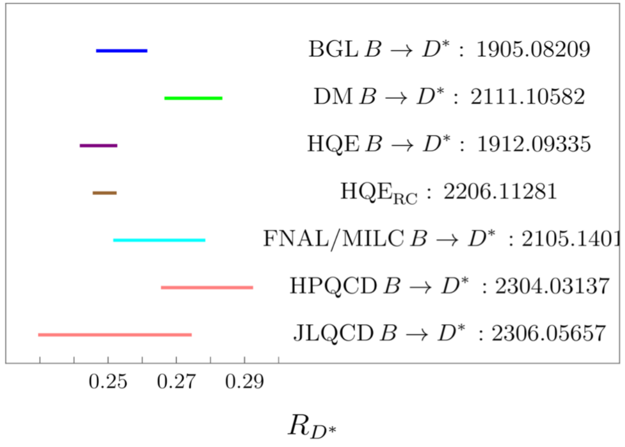
If q^2 spectrum for l= e,μ

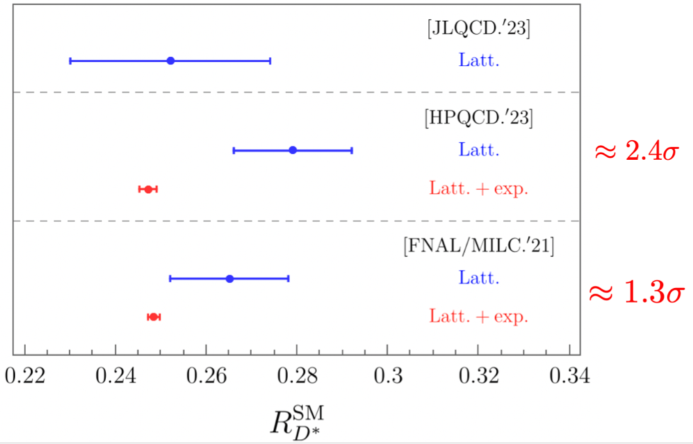
$$R_D^{latt+exp} = 0.295(3)$$

2) $B \to D^*$: three (four) form-factors;
First lattice results at $q^2 \neq q^2_{max}$! Tensions with $B \to D^* l\bar{\nu}$ exp. data









R(D*)=0.252 ± 0.003, S.F., J.F.Kamenik, and I.Nisandzic, 1203.265420
JLQCD, R(D*)=0.252 ± 0.022, Y.Aoki et al.2306.05657

independent LQCD results + Belle-II data needed!

Puzzles in b → s μμ transition

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}$$

$$0.1 < q^2 < 1.1 : \begin{cases} R_K & = 0.994\ ^{+0.090}_{-0.082}(\text{stat})^{+0.029}_{-0.027}(\text{syst}) \\ R_{K^*} & = 0.927\ ^{+0.093}_{-0.087}(\text{stat})^{+0.036}_{-0.035}(\text{syst}) \end{cases}$$

$$1.1 < q^2 < 6.0 : \begin{cases} R_K & = 0.949\ ^{+0.042}_{-0.041}(\text{stat})^{+0.022}_{-0.022}(\text{syst}) \\ R_{K^*} & = 1.027\ ^{+0.072}_{-0.068}(\text{stat})^{+0.027}_{-0.026}(\text{syst}) \end{cases}$$

LHCb
2212.09152, 2212.09153

$R^{\text{SM}}_{K^{(*)}} = 1.00(1)$ Bordone et al., 1605.07633

It is important that LFU (e,μ) holds! – $RK_{(*)}$

$$\mathcal{H}_{\text{eff}} = \mathcal{H}^{\text{SM}}_{\text{eff}} - \frac{4G_F}{\sqrt{2}}\frac{e^2}{16\pi^2}\sum_{q=s,d}\sum_{\ell=e,\mu}\sum_{i=9,10,S,P} V_{tb}V^*_{tq}(C_i^{bq\ell\ell}O_i^{bq\ell\ell} + C_i^{\prime bq\ell\ell}O_i^{\prime bq\ell\ell}) + \text{h.c.}\,.$$

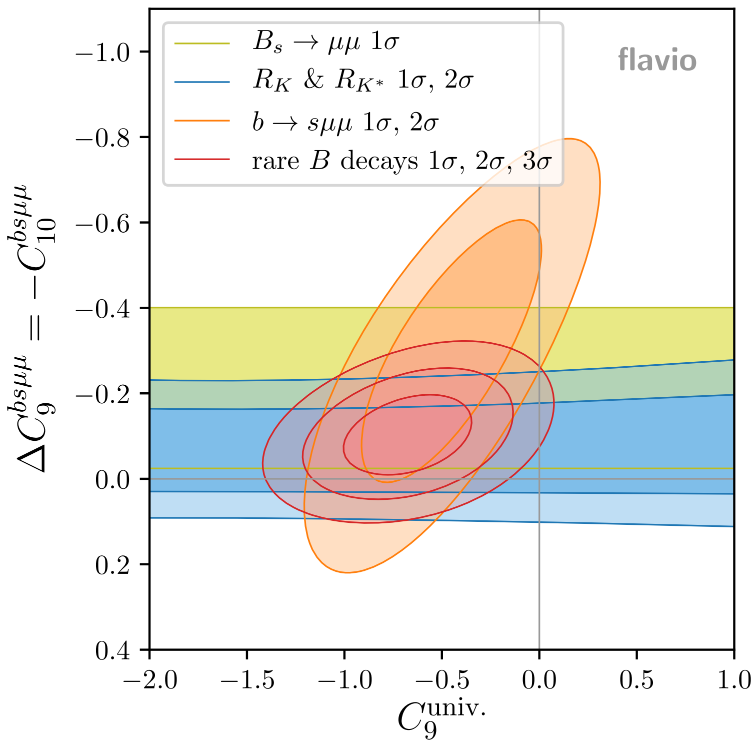
$$C_7^{SM} = 0.29;\ C_9^{SM} = 4.1;\ C_{10}^{SM} = -4.3;$$

$$\begin{aligned} O_9^{bq\ell\ell} &= (\bar{q}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, & O_9^{\prime bq\ell\ell} &= (\bar{q}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)\,, \\ O_{10}^{bq\ell\ell} &= (\bar{q}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5 \ell)\,, & O_{10}^{\prime bq\ell\ell} &= (\bar{q}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu\gamma_5 \ell)\,, \\ O_S^{bq\ell\ell} &= m_b(\bar{q}P_R b)(\bar{\ell}\ell)\,, & O_S^{\prime bq\ell\ell} &= m_b(\bar{q}P_L b)(\bar{\ell}\ell)\,, \\ O_P^{bq\ell\ell} &= m_b(\bar{q}P_R b)(\bar{\ell}\gamma_5\ell)\,, & O_P^{\prime bq\ell\ell} &= m_b(\bar{q}P_L b)(\bar{\ell}\gamma_5\ell)\,. \end{aligned}$$

Buras et al.,hep-ph/9311345;
Altmannshofer et al., 0811.1214;
Bobeth et al., hep-ph/9910220

Greljo et al., 2212.10497 (Ciuchini et al 2212.10516)

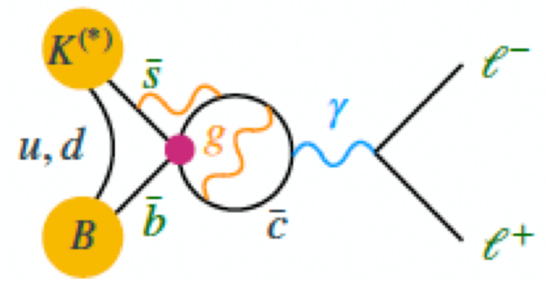
See talk by Smolkovič today



$$C_9^{\text{univ.}} = -0.64 \pm 0.22$$
$$\Delta C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu} = -0.11 \pm 0.06$$

- If NP in muons only, there's now tension between LFU ratios and BR's + $R_{K(*)}$ +P′ 5
- A flavour universal shift in C_9 is now sufficient to account for all b → s μμ
- Still, difficult to distinguish long-distance QCD - "charming penguins" from NP

Angular observables, P_5' still remains (Descotes-Genon et al., 1207.2753, Matias et al., 1202.4266).



Stefanek's illustration

A new anomaly?

$$R_{\nu\nu}^{K^{(*)}} = \mathcal{B}(B \to K^{(*)}\nu\bar{\nu})/\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})^{\rm SM}$$

A new player in the room!

Belle II at EPS conference, 2023

Belle, 1702.03224

$$R_{\nu\nu}^{K} < 3.6 \quad (90\% \text{ C.L.})\,,$$
$$R_{\nu\nu}^{K^*} < 2.7 \quad (90\% \text{ C.L.})$$

Belle II 2023

$$\mathcal{B}(B^\pm \to K^\pm \nu\bar{\nu}) = 2.40(67) \times 10^{-5}$$

2.9 σ larger then SM prediction

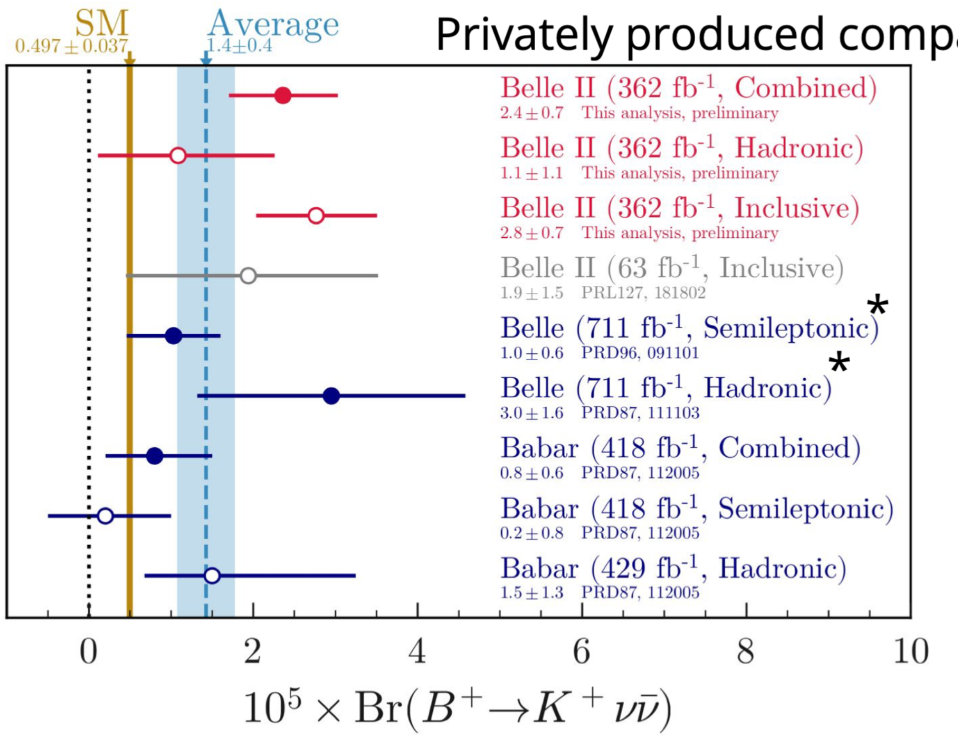
Searching for explanation

Bause et al., 2309.00075
Allwicher et al, 2309.02246
Felkl et al., 2309.02940,
He et al., 2309.12741
…

$$R_{\nu\nu}^{K} = 5.4 \pm 1.5$$

Glazov at EPS 2023

Privately produced comparison

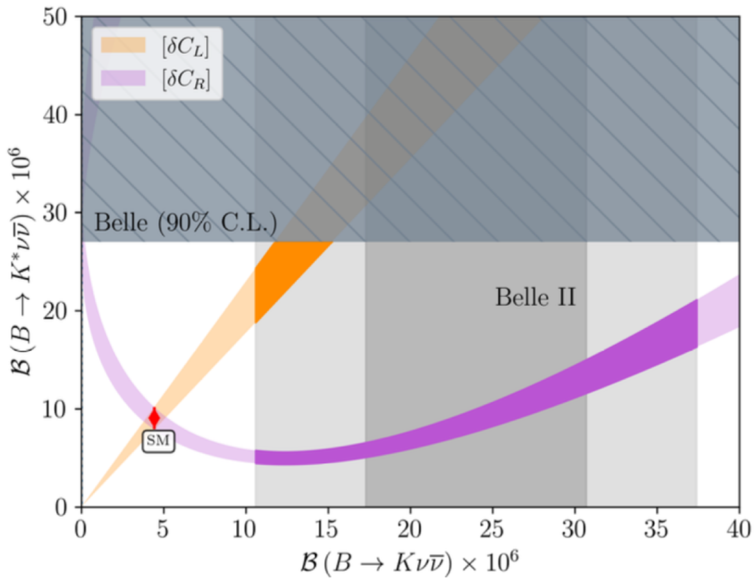


Allwicher et al, 2309.02246

$$\mathcal{L}_{\rm eff}^{\rm b\to s\nu\nu} = \frac{4G_F}{\sqrt{2}}\lambda_t \sum_a C_a\,\mathcal{O}_a + {\rm h.c.}$$

$$\mathcal{O}_L^{\nu_i\nu_j} = \frac{e^2}{(4\pi)^2}(\bar{s}_L\gamma_\mu b_L)(\bar{\nu}_i\gamma^\mu(1-\gamma_5)\nu_j)\,,$$

$$\mathcal{O}_R^{\nu_i\nu_j} = \frac{e^2}{(4\pi)^2}(\bar{s}_R\gamma_\mu b_R)(\bar{\nu}_i\gamma^\mu(1-\gamma_5)\nu_j)\,,$$



SM $\begin{cases} C_L^{\rm SM} = -6.32(7) \\ C_R^{\rm SM} = 0 \end{cases}$

Buras et al.,1409.4557,
Altmannshofer et al., 0902.0160
Buras, 2209.03968

$$C_{L,R}^{\nu_i\nu_j} = \delta_{ij}C_{L,R}^{\rm SM} + \delta C_{L,R}^{\nu_i\nu_j}$$

$$\mathcal{B}(B^\pm\to K^\pm\nu\nu) = (4.44\pm 0.30)\times 10^{-6}\,,$$

$$\mathcal{B}(B^\pm\to K^{\pm *}\nu\nu) = (9.8\pm 1.4)\times 10^{-6}\,,$$

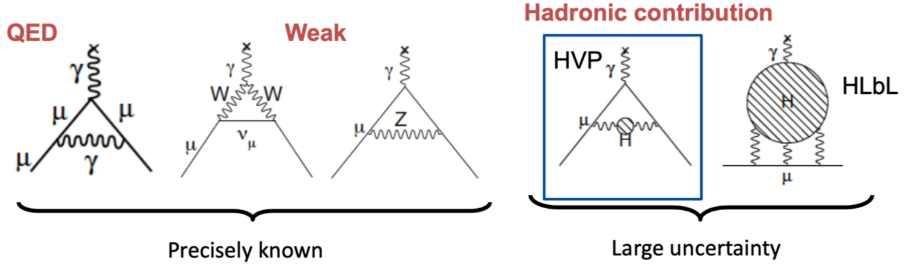
$$\mathcal{B}(B\to K^{(*)}\nu\nu) = \mathcal{B}(B\to K^{(*)}\nu\nu)\Big|_{\rm SM}\left(1+\delta\mathcal{B}_{K^{(*)}}^{\nu\nu}\right),$$

Assuming SM neutrinos a large contribution to the right-handed quark operator necessary!

$$\delta C_L \neq 0:\ \delta C_L \in [-4.2,-3.5]\cup[16.9,17.3],$$
$$R_{\nu\nu}^{K^*} \in (2.4,2.7)\,,$$
$$\delta C_R \neq 0:\ \delta C_R \in [-12.0,-3.5],$$
$$R_{\nu\nu}^{K^*} \in (0.6,2.1)\,,$$

$(g-2)_\mu$ expecting the clarification of the theory

SM prediction

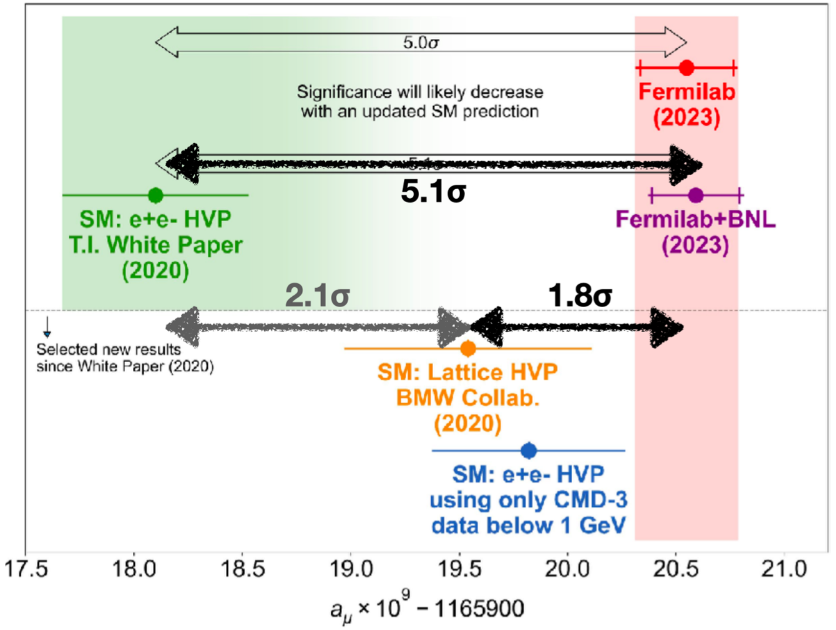


Theory Initiative
T. Aoyama et al. Phys. Rept. 887 (2020)

New results after 2020

Disclaimer: prediction from Lattice taken from Lattice 2023 talk; prediction from CMD3 based on our specific assumption

Comparison of FNAL Run1-3 result with the Theory Initiative's calculation **wp20** is at **5 sigma**



From
G. Venanzoni, EPS-HEP2023, Hamburg,

The **CMD-3** data in $e^+e^- \to \pi\pi$ provides an R-ratio result compatible with the lattice one

The picture is still unclear, however more studies are underway!

$a_\mu(\text{FNAL})=116592055(24) \times 10^{-11}$

Current flavour anomalies

$R_{D^{(*)}}$ disagreement SM and the world average at 3σ level

$B(B \to K\,\nu\bar{\nu}) = 2.40(67) \times 10^{-5}$ is 2.9σ larger than its SM estimate

$(g\text{-}2)_\mu$ theoretically not settled – 5.1σ (1.8σ?)–unsettled HVP

disappearance of $R_{K^{(*)}}$ puzzle

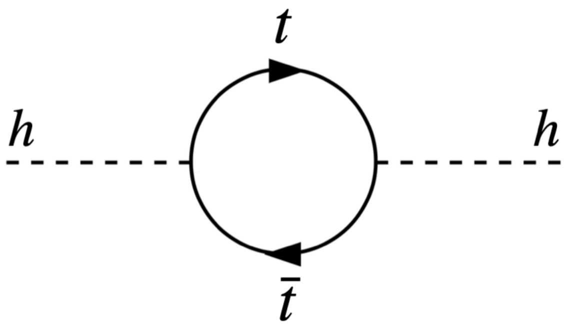
Can we claim any New Physics?

LHC did not find any NP particles

We do not know what the rules of the game are; all we are allowed to do is to watch the playing. Of course, if we watch long enough, we may eventually catch on to a few of the rules. The rules of the game are what we mean by fundamental physics.

Richard Feynman

Why do we expect NP in TeV region?

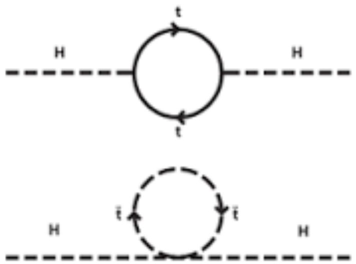


the quadratically divergent radiative correction is given by

$$\delta m_h^2 \simeq \frac{3}{4\pi^2}\Big(- \lambda_t^2 + \frac{g^2}{4} + \frac{g^2}{8\cos^2\theta_W} + \lambda\Big)\Lambda^2$$

Haber & Kane, Phys. Rep.117C 75 (1985)

Supersymmetry



In order to cancel quadratic divergence NP expected in TeV region!

Note that $\frac{\delta m^2_h}{m^2_h} \sim 10^3$ for NP scale $\Lambda = 10$ TeV

Standard model effective field theory (SMEFT)

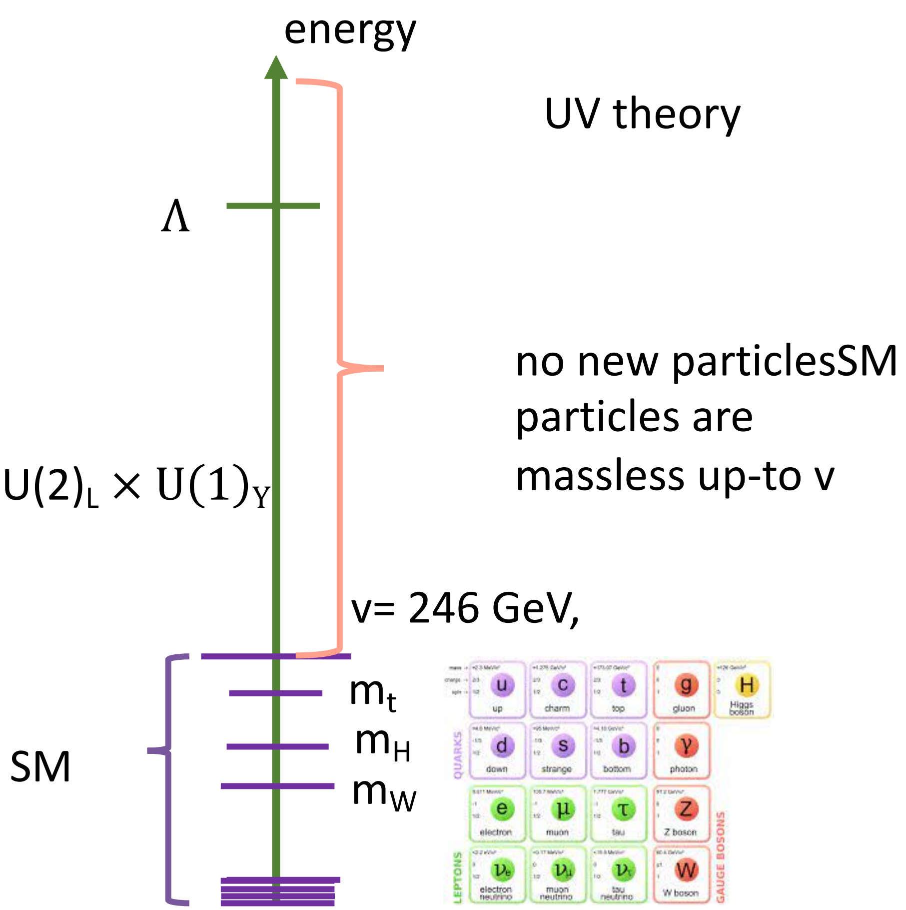
Weak interactions before SM

$$\mathcal{L}_{eff} = -\frac{G_F}{\sqrt{2}} J_\mu^\dagger J^\mu$$

However, we know that at low energies

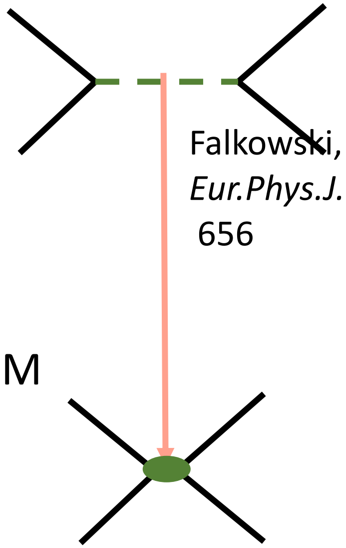
$$\frac{g_2^2}{8\, m_W^2} = \frac{G_F}{\sqrt{2}} = \frac{1}{2\, v^2}$$

Energy scale of $SU(2)_L \times U(1)_Y$



- Expectation: NP appears on high energy scale Λ;
- No new degrees of freedom bellow this scale;
- New NP mediators create operators of dimension d≥ 5;
- Integrating out heavy degrees of freedom we create new operators not present in the SM

SMEFT role towards a theory of NP



Falkowski, *Eur.Phys.J.C* 83 (2023) 7, 656

There are many ways in which higher-dimensional operators can affect observables.

- **New vertices:** interaction vertices in the SMEFT Lagrangian that do not occur in the SM Lagrangian, due to symmetries or accidental reasons.

- **New Lorentz structures:** interaction vertices that do occur in the SM Lagrangian, but which appear in the SMEFT with a different number of derivatives, different contractions of Lorentz orspinor indices, etc.

- **Modified couplings:** corrections to the coupling strengths of the interaction terms present in the SM Lagrangian.

First we study NP within SMEFT , then we can think of a model!

At the large scale Λ, we generate operators and match Wilson coefficients at tree and/or loop level

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{d\geq 5} \frac{C_k^{(d)}}{\Lambda^{d-4}} \mathcal{O}_k^{(d)}$$

Gauge fields, Higgs

Warsaw basis, Grzadkowski et al, 1008.4884

$$\mathcal{L}_{D=6} = \mathcal{L}_{D=6}^{\text{bosonic}} + \mathcal{L}_{D=6}^{\text{Yukawa}} + \mathcal{L}_{D=6}^{\text{current}} + \mathcal{L}_{D=6}^{\text{dipole}} + \mathcal{L}_{D=6}^{\text{4-fermion}}.$$

SMEFT papers: Manohar et al., 1308.2627, 1309.0819, 1310,4838, 1312.2014

- There are 1350 CP-even and 1149 CP-odd parameters in the dimension-six Lagrangian for 3 generations

- Manohar et al. in SMEFT papers calculated the complete order y^2 and y^4 terms and λ, λ^2 and λy^2, of the 2499 × 2499 one-loop anomalous dimension matrix for the dimension-six operators of the SMEFT (y is a generic Yukawa coupling).

- Also they determined (1312.2014) the gauge terms of the one-loop anomalous dimension matrix for the dimension-six operators of the SMEFT

N = 2499 dim-6 operators that conserve B and L — rich flavor structure!

$1 : X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2 : H^6$	
Q_H	$(H^\dagger H)^3$

$3 : H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$4 : X^2 H^2$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$

$5 : \psi^2 H^3 + \mathrm{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$6 : \psi^2 X H + \mathrm{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H}\, G^A_{\mu\nu}$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H}\, W^I_{\mu\nu}$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I H\, W^I_{\mu\nu}$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7 : \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$8 : (\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

$8 : (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8 : (\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8 : (\bar{L}R)(\bar{R}L) + \mathrm{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8 : (\bar{L}R)(\bar{L}R) + \mathrm{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

Many operators!

Symmetries might help in the analysis.

The SM gauge-kinetic sector is invariant under a global flavour symmetry

$$G_F \equiv U(3)^5 = U(3)_q \times U(3)_u \times U(3)_d \times U(3)_l \times U(3)_e$$

The fermion Yukawa couplings to the Higgs ($Y_{u,d,e}$) act as the only sources of breaking in the SM

$$G_F \to U(1)^4 = U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$$

However, first two generations have small Yukawas, the SM has the accidental approximate $U(2)^5$

$$G_F \sim U(2)^5 \equiv U(2)_q \times U(2)_u \times U(2)_d \times U(2)_l \times U(2)_e$$

Maybe it is not accidental, it can be a consequence of NP!

Two approches

- Minimal Flavor Violation (MFV)
- $U(2)^5$

Minimal Flavor Violation (MFV)

- The leading flavour breaking sources are proportional to the lowest powers of the SM Yukawas,

G. D'Ambrosio et al., hep-ph/0207036 ….

All CP and flavor violation in the NP sector originates from the SM Yukawa couplings.

$$\lambda_{\rm FC} \approx (Y_U Y_U^\dagger)_{\rm FC} \approx y_t^2 \begin{pmatrix} 0 & V_{td}^* V_{ts} & V_{td}^* V_{tb} \\ V_{td} V_{ts}^* & 0 & V_{ts}^* V_{tb} \\ V_{td} V_{tb}^* & V_{ts} V_{tb}^* & 0 \end{pmatrix} \sim \begin{pmatrix} 0 & \lambda^5 & \lambda^3 \\ \lambda^5 & 0 & \lambda^2 \\ \lambda^3 & \lambda^2 & 0 \end{pmatrix}$$

top Yukawa

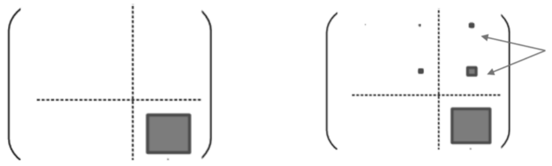
MFV operators	Observables
$\frac{1}{2}(\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)^2$	$\epsilon_K, \quad \Delta m_{B_d}$
$H^\dagger \left(\bar{D}_R \lambda_d \lambda_{\rm FC} \sigma_{\mu\nu} Q_L\right) F_{\mu\nu}$	$B \to X_s \gamma$
$H^\dagger \left(\bar{D}_R \lambda_d \lambda_{\rm FC} \sigma_{\mu\nu} T^a Q_L\right) G^a_{\mu\nu}$	$B \to X_s \gamma$
$(\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(\bar{L}_L \gamma_\mu L_L)$	$B \to (X)\ell\bar{\ell}, \quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$
$(\bar{Q}_L \lambda_{\rm FC} \gamma_\mu \tau^a Q_L)(\bar{L}_L \gamma_\mu \tau^a L_L)$	$B \to (X)\ell\bar{\ell}, \quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$
$(\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(H^\dagger i D_\mu H)$	$B \to (X)\ell\bar{\ell}, \quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$
$(\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(\bar{D}_R \gamma_\mu D_R)$	$B \to K\pi, \quad \epsilon'/\epsilon, \ldots$

LHC complementary searches

The scale Λ is in the TeV region

U(2)^5

- NP is not flavour diagonal!
- New flavour non-universal interactions couple to the third family (TeV region)



U(2) breaking effects

Exact U(2)

flavour diagonal currents

Exact U(3) → $\bar{q}^i \gamma_\mu P_L q^i$ Exact U(2) → $\bar{q}^3 \gamma_\mu P_L q^3 + \epsilon \bar{q}^i \gamma_\mu P_L q^i$

flavour changing currents

MFV minimally broken U(3) → $\bar{q}^i \lambda_{FC}^{ij} \gamma_\mu P_L q^j$ minimally broken U(2) → $\bar{q}^i V_q^i \gamma_\mu P_L q^3$ $V_q \sim \mathcal{O}\begin{pmatrix} V_{td} \\ V_{ts} \end{pmatrix}$

$$(\bar{q}^i V_q^i \gamma_\mu P_L q^3)^2 \rightarrow \Delta M_{B_s}, \Delta M_{B_s}$$

$$(\bar{q}^i V_q^i \gamma_\mu P_L q^3)(\bar{l}^3 \gamma^\mu P_L l^3) \rightarrow (B \rightarrow K^{(*)} \bar{\tau}\tau, B \rightarrow K^{(*)} \bar{\nu}_\tau \nu_\tau, B_s \rightarrow \bar{\tau}\tau)$$

$$(\bar{q}^i V_q^i \gamma_\mu \sigma^I P_L q^3)(\bar{l}^3 \gamma^\mu \sigma^I P_L l^3) \rightarrow (B \rightarrow D^{(*)} \bar{\tau}\bar{\nu}_\tau, \Lambda_b \rightarrow \Lambda_c \bar{\tau}\bar{\nu}_\tau, B_c \rightarrow \bar{\tau}\bar{\nu}_\tau)$$

$$(\bar{q}^i V_q^i \gamma_\mu P_L q^3)(H^\dagger D^\mu H) \rightarrow (B \rightarrow K^{(*)} \bar{\ell}\ell, B \rightarrow K^{(*)} \bar{\nu}_\ell \nu_\ell, B_s \rightarrow \bar{\ell}\ell)$$

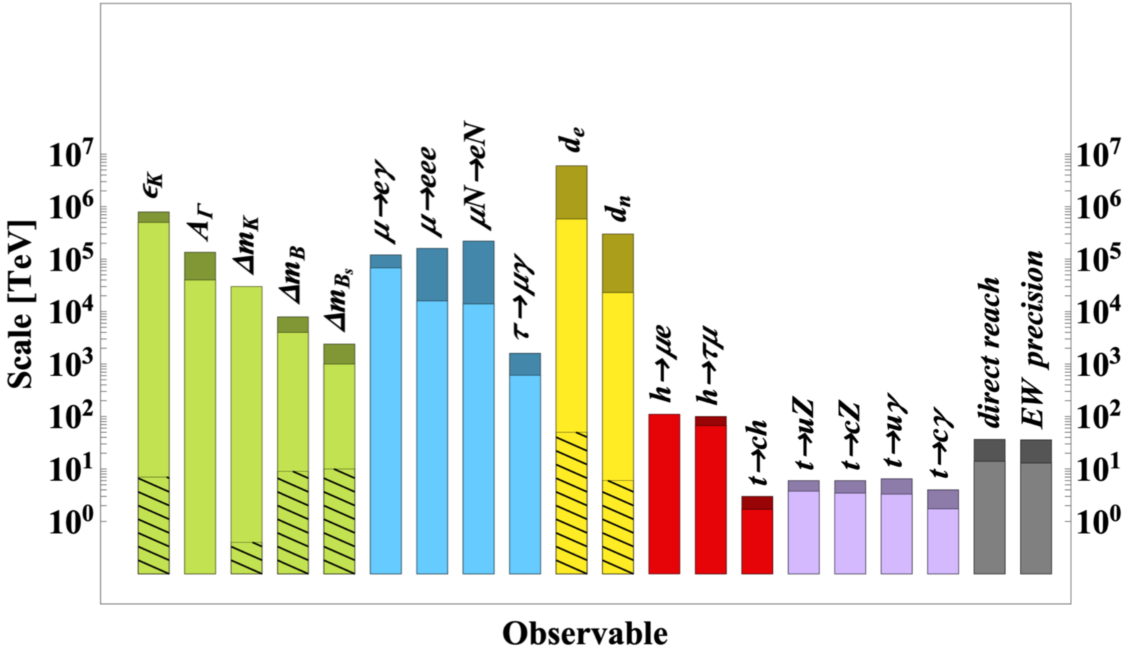
$$y_b (\bar{q}_L^i V_q^i \sigma_{\mu\nu} H P_R b) F^{\mu\nu} \rightarrow (B \rightarrow X_s \gamma)$$

Barbieri et al., 1105.2296,
Barbieri et al., 1203.4218,
Isidori & Straub, 1202.0464,
Fuentes-Martin et al., 1909.2519

- The best probes of the SMEFT operators are rare/forbidden processes in the SM

- LHC processes can be useful to probe these types of scenarios (with lower values for Λ)!

SMEFT CP-odd invariants 699 found in
Bonnefoy et al, 2112.03889



1910.11775

Comment:

There are a number of software tools one can use to generate Wilson ccoeficents and mixind
Wilson, Flavio, DsixTools, Matchmakereft, …

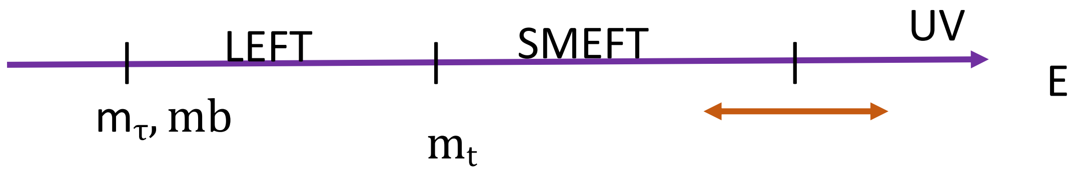
MFV factors (hatch filled surfaces).

Light (dark) colours correspond to present data
(mid-term prospects, including HL-LHC, Belle II, MEG II, Mu3e, Mu2e, COMET, ACME, PIK and SNS)

From SMEFT to low energies (LEFT)

How to connect this set-up to low energy observables?

See talk of J. Šalko, yesterday



1) One connsider renormalisation group evolution (RGE) running of Wilson coefficents from the matching scale down to electroweak scale;

2) Below the weak scale → EFT that is an $SU(3)_c \otimes U(1)_{em}$ gauge theory and contains the SM fermions, but not the top quark (H, W, Z, t are integrated out (1908.05295, Dekens&Stoffer)

3) The LEFT Lagrangian consists of QCD and QED and a tower of additional higher-dimension effective operators

4) The matching condition at the electroweak scale requires that the LEFT and SMEFT S-matrix elements for the light-particle processes agree:

$$M_{LEFT} = M_{SMEFT}$$

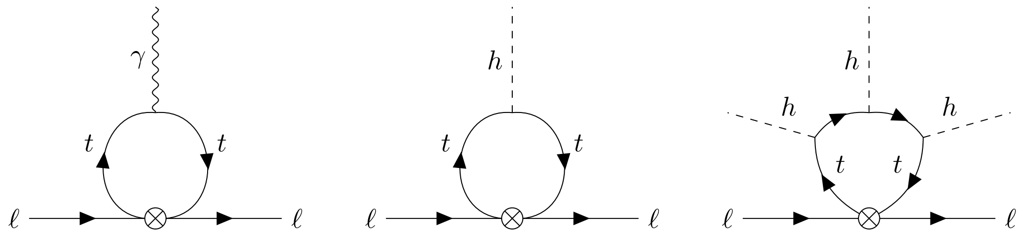
$$\mathcal{M}^{\rm LEFT}_{\rm tree,\ ren.} + \mathcal{M}^{\rm LEFT}_{\rm ct} + \mathcal{M}^{\rm LEFT}_{\rm loop} = \mathcal{M}^{\rm SMEFT}_{\rm tree,\ ren.} + \mathcal{M}^{\rm SMEFT}_{\rm ct} + \mathcal{M}^{\rm SMEFT}_{\rm loop} .$$

Muon anomaloues magnetic moment in SMEFT

$$\mathcal{L}_{SMEFT} \supset C_2^{pr}\bar{\ell}_p\sigma^{\mu\nu}e_r\tau^a\varphi W^a_{\mu\nu} + C_3^{pr}\bar{\ell}_p\sigma^{\mu\nu}e_r\varphi B_{\mu\nu}$$

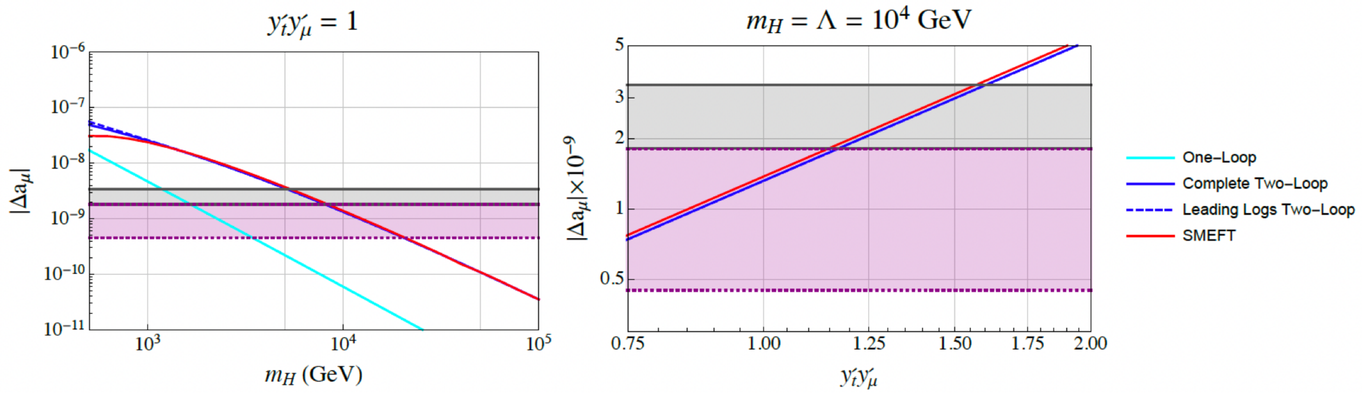
Tree level contributions within SMEFT, dim 6 operator

The one-loop improved RGE evolution and mixing of the relevant operators are considered in SF et al,2103.10859.



For a closed set under the RGE we need to include four- fermion scalar and tensor operators

It can help to that tree-level calculations in the UV model can reproduce the full theory two-loop calculations to remarkable accuracy.



SF et al., 2103.10859 (example 2HDM)

a_μ = 1.7σ ($3.3\ \sigma$)

NP explaining B anomalies

Models of NP

Leptoquarks can accommodate $R_{D(*)}$, $R^{\nu\nu}_{K(*)}$. LQ= $(SU(3)_c,SU(2)_L,U(1)_Y)$

Scalar LQs they can modify Yukawa couplings (S_1(3,1,1/3) and R_2(3,2,7,6) for $R_{D(*)}$)
hopefully can help in understanding origin of flavour masses
and understanding flavour puzzle (why masses of quarks and leptons a so different).

Vector LQs prefarably should be gauge bosons, that requires full UV theory
Some GUTs, Pati-Salam-like theories (the candidate to explain $R_{D(*)}$ U_1 (3,1,2/3)).

Z' as a new gauge boson of additional U(1) gauge group (accompanied by 2HDM)
explanation of Charm CP violation, D meson mixing.

Vectorlike quarks and/or leptons.

"Scepticism is as important for a good journalist as it is for a good scientist." Freeman Dyson

Constraints from flavor observables

Constraints from LFV

If NP couples to b constraints are coming from SU(2)$_L$ singlets

$$q_L^3 \sim \begin{bmatrix} V_{ib}^* u_L^i \\ b_L \end{bmatrix}$$

$(g-2)_\mu$

$B_c \to \tau\nu$ $\quad B \to \tau\nu$

$B \to K^{(*)}\nu\bar{\nu}$

$B_s^0 - \bar{B}_s^0$

$D^0 - \bar{D}^0$

$B \to D\mu\nu_\mu$

$K \to \mu\nu_\mu$

$D_{d,s} \to \tau, \mu\nu$

$K \to \pi\mu\nu_\mu$

$W \to \tau\bar{\nu},\ \tau \to \ell\bar{\nu}\nu$

$Z \to b\bar{b}$ $\quad Z \to l^+l^-$

$\tau \to \mu\gamma$

$\mu \to e\gamma$

$\tau \to K(\pi)\mu(e)$

$K \to \mu e$

$B \to K\mu e$

$\tau \to \mu\mu\mu$

$\tau \to \phi\mu$

$t \to c\ell^+\ell'^-$

Becirevic et al., 1806.05689, 2206.09717,… Alonso et al., 1611.06676,…
Radiative constraints Feruglio et al.,1606.00524; Gherardi et. Al., 2008.09546,…
Cornella et al., 2103.16558,

Scalar and Vector Leptoquarks as NP meditaors

$(SU(3), SU(2), U(1))$	Spin	Symbol	Type	F
$(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	0	S_3	$LL\,(S_1^L)$	-2
$(\mathbf{3}, \mathbf{2}, 7/6)$	0	R_2	$RL\,(S_{1/2}^L)$, $LR\,(S_{1/2}^R)$	0
$(\mathbf{3}, \mathbf{2}, 1/6)$	0	$\tilde{R}_2$	$RL\,(\tilde{S}_{1/2}^L)$, $\overline{LR}\,(\tilde{S}_{1/2}^L)$	0
$(\bar{\mathbf{3}}, \mathbf{1}, 4/3)$	0	$\tilde{S}_1$	$RR\,(\tilde{S}_0^R)$	-2
$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	0	S_1	$LL\,(S_0^L)$, $RR\,(S_0^R)$, $\overline{RR}\,(S_0^{\overline{R}})$	-2
$(\bar{\mathbf{3}}, \mathbf{1}, -2/3)$	0	$\bar{S}_1$	$\overline{RR}\,(\bar{S}_0^{\overline{R}})$	-2
$(\mathbf{3}, \mathbf{3}, 2/3)$	1	U_3	$LL\,(V_1^L)$	0
$(\bar{\mathbf{3}}, \mathbf{2}, 5/6)$	1	V_2	$RL\,(V_{1/2}^L)$, $LR\,(V_{1/2}^R)$	-2
$(\bar{\mathbf{3}}, \mathbf{2}, -1/6)$	1	$\tilde{V}_2$	$RL\,(\tilde{V}_{1/2}^L)$, $\overline{LR}\,(\tilde{V}_{1/2}^{\overline{R}})$	-2
$(\mathbf{3}, \mathbf{1}, 5/3)$	1	$\tilde{U}_1$	$RR\,(\tilde{V}_0^R)$	0
$(\mathbf{3}, \mathbf{1}, 2/3)$	1	U_1	$LL\,(V_0^L)$, $RR\,(V_0^R)$, $\overline{RR}\,(V_0^{\overline{R}})$	0
$(\mathbf{3}, \mathbf{1}, -1/3)$	1	$\bar{U}_1$	$\overline{RR}\,(\bar{V}_0^{\overline{R}})$	0

Dorsner et al., 1603.04993

F=0, these LQs do not have diquark couplings and can not lead to the proton destabilisation.

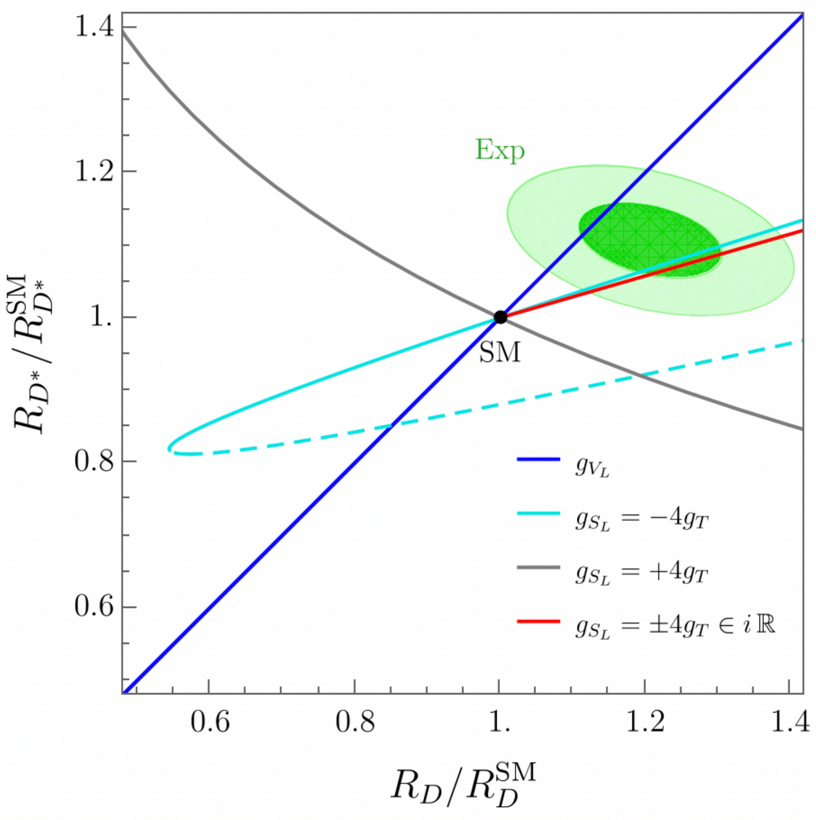
$Q = I_3 + Y$

$R_{D^{(*)}}$ explanation

$$\mathcal{L}_{cc} = -2\sqrt{2}G_F V_{cb}\Big[(1+g_{V_L})\,(\bar{c}_L\gamma_\mu b_L)(\bar{\ell}_L\gamma^\mu\nu_L) + g_{V_R}\,(\bar{c}_R\gamma_\mu b_R)(\bar{\ell}_L\gamma^\mu\nu_L)$$
$$+ g_{S_R}\,(\bar{c}_L b_R)(\bar{\ell}_R\nu_L) + g_{S_L}\,(\bar{c}_R b_L)(\bar{\ell}_R\nu_L) + g_T\,(\bar{c}_R\sigma_{\mu\nu}b_L)(\bar{\ell}_R\sigma^{\mu\nu}\nu_L)\Big] + \text{h.c.}$$

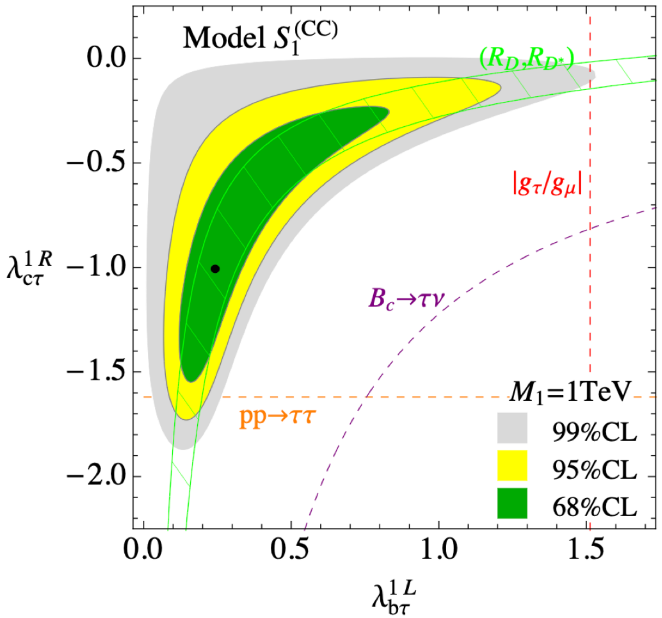
Angelescu et al., 2103.12504.

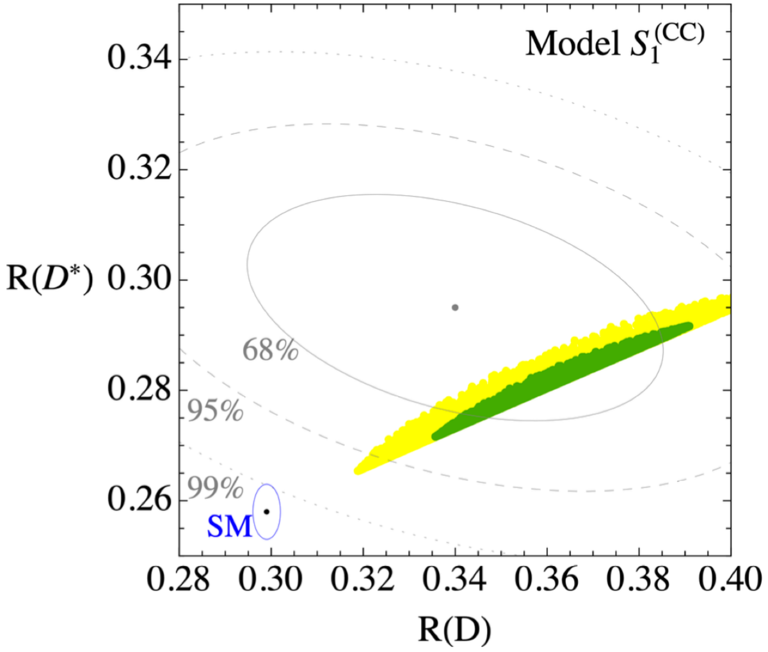
Eff. coeff.	1σ range	$\chi^2_{\rm min}/\text{dof}$
$g_{V_L}(m_b)$	0.07 ± 0.02	$0.02/1$
$g_{S_R}(m_b)$	-0.31 ± 0.05	$5.3/1$
$g_{S_L}(m_b)$	0.12 ± 0.06	$8.8/1$
$g_T(m_b)$	-0.03 ± 0.01	$3.1/1$
$g_{S_L} = +4g_T \in \mathbb{R}$	-0.03 ± 0.07	$12.5/1$
$g_{S_L} = -4g_T \in \mathbb{R}$	0.16 ± 0.05	$2.0/1$
$g_{S_L} = \pm 4g_T \in i\,\mathbb{R}$	0.48 ± 0.08	$2.4/1$



$$U_1 = (3, 1, 2/3):\ g_{VL},\ g_{SR}$$
$$R_2 = (3, 2, 7/6):\ g_{SL} = 4g_T,$$
$$S_1 = (\bar{3}, 1, 1/3):\ g_{SL} = -4g_T,\ g_{VL}$$

SMEFT in $R_{D(*)}$ S_1 Leptoquark





Many papers:

Crivellin et al., 1703.09226

Butazzo et al., 1706.07808

Gherardi et al., et al, 2003.12525, 2008.09548

Bauer and Neubert, 1511.01900

$$\frac{R(D)}{R(D)_{\rm SM}} = 1 + {\rm Re}[2C_{V_L} + 1.49C^*_{S_L} + 1.14C^*_T] + \mathcal{O}(C^2)\ ,$$

$$\frac{R(D^*)}{R(D^*)_{\rm SM}} = 1 + {\rm Re}[2C_{V_L} - 0.11C^*_{S_L} - 5.12C^*_T] + \mathcal{O}(C^2)\ ,$$

$$\frac{P_\tau(D)}{P_\tau(D)_{\rm SM}} = \left(\frac{R(D)}{R(D)_{\rm SM}}\right)^{-1} \left(1 + {\rm Re}[2C_{V_L} + 4.65C^*_{S_L} - 1.18C^*_T] + \mathcal{O}(C^2)\right)$$

$$\frac{P_\tau(D^*)}{P_\tau(D^*)_{\rm SM}} = \left(\frac{R(D^*)}{R(D^*)_{\rm SM}}\right)^{-1} \left(1 + {\rm Re}[2C_{V_L} + 0.22C^*_{S_L} - 3.37C^*_T] + \mathcal{O}(C^2)\right)$$

$$\frac{F_L^{D^*}}{[F_L^{D^*}]_{\rm SM}} = \left(\frac{R(D^*)}{R(D^*)_{\rm SM}}\right)^{-1} \left(1 + {\rm Re}[2C_{V_L} - 0.24C^*_{S_L} - 4.37C^*_T] + \mathcal{O}(C^2)\right)$$

$C_{VL}\to g_{VL}$

$$\frac{{\rm Br}(B_c^+\to\tau^+\nu)}{{\rm Br}(B_c^+\to\tau^+\nu)_{\rm SM}} = 1 + 2\,{\rm Re}[C_{V_L} - 4.33C_{S_L}] + \mathcal{O}(C^2)\ .$$

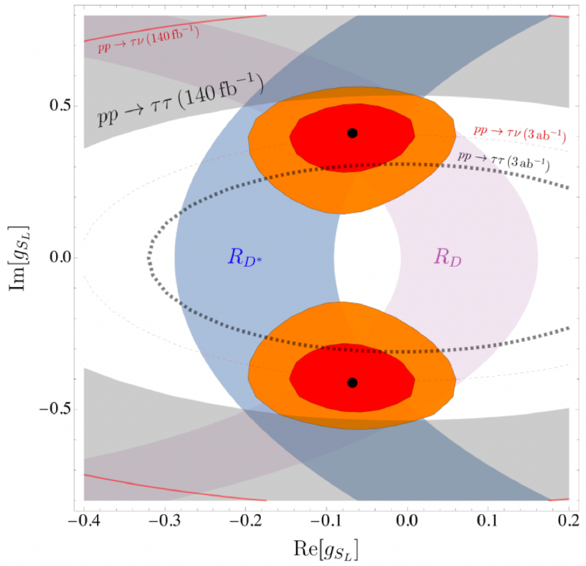
$R_{D^{(*)}}$ with R_2 Leptoquark

$$\mathcal{L} \supset +(VY_R^{(R_2)}E_R^\dagger)^{ij}\bar{u}_{Li}\ell_{Rj}R_2^{\frac{5}{3}} + (Y_R^{(R_2)}E_R^\dagger)^{ij}\bar{d}_{Li}\ell_{Rj}R_2^{\frac{2}{3}} + (U_RY_L^{(R_2)}U)^{ij}\bar{u}_{Ri}\nu_{Lj}R_2^{\frac{2}{3}} - (U_RY_L^{(R_2)})^{ij}\bar{u}_{Ri}\ell_{Lj}R_2^{\frac{5}{3}}$$

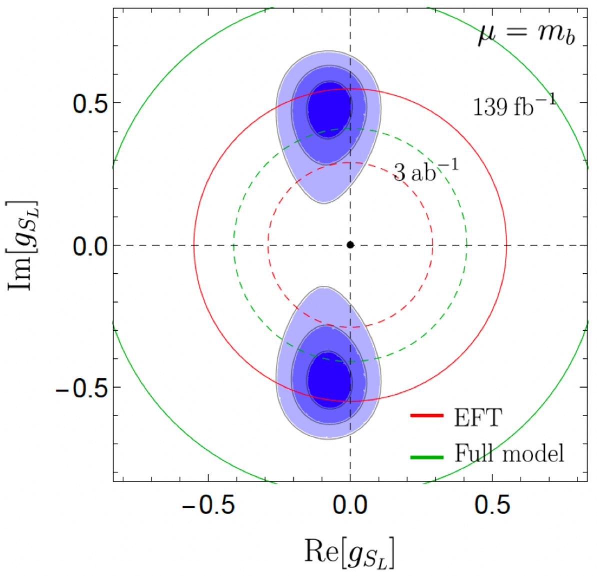
$$g_{S_L}(\Lambda) = 4\,g_T(\Lambda) = \frac{y_L^{c\tau}\;y_R^{b\tau\,*}}{4\sqrt{2}G_F V_{cb}\,m_{R_2}^2}$$

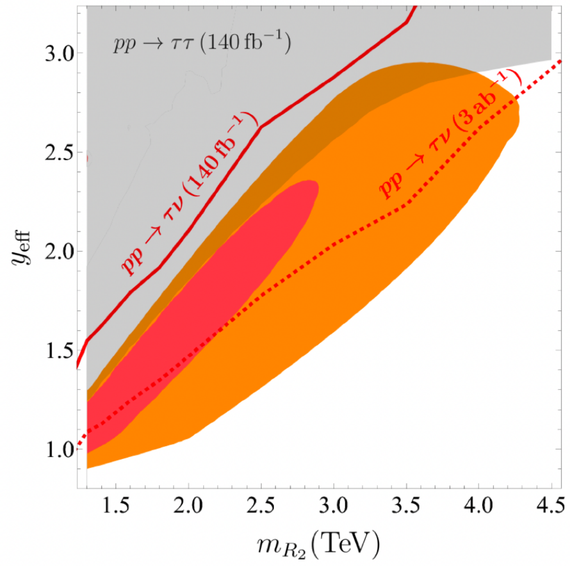
$$\mathcal{H}_{\rm eff}^{b\to c\tau\bar{\nu}} \supset \frac{4\,G_F}{\sqrt{2}}V_{cb}\Big[g_{S_L}(\mu)\,(\bar{c}_R b_L)(\bar{\tau}_R\nu_L) \quad + g_T(\mu)\,(\bar{c}_R\sigma_{\mu\nu}b_L)(\bar{\tau}_R\sigma^{\mu\nu}\nu_L)\Big] + \text{ h.c.}$$

$$g_{S_L}(m_b) \approx 8.1 \times g_T(m_b)$$



$m_{R_2} = 1.3$ TeV





$$y_{eff} = \sqrt{|y_L^{c\tau}\,y_R^{bs*}|}$$

New source of CP violation - Imaginary couplings

U_1 = (3,1,2/3) in B anomalies

Zurich group

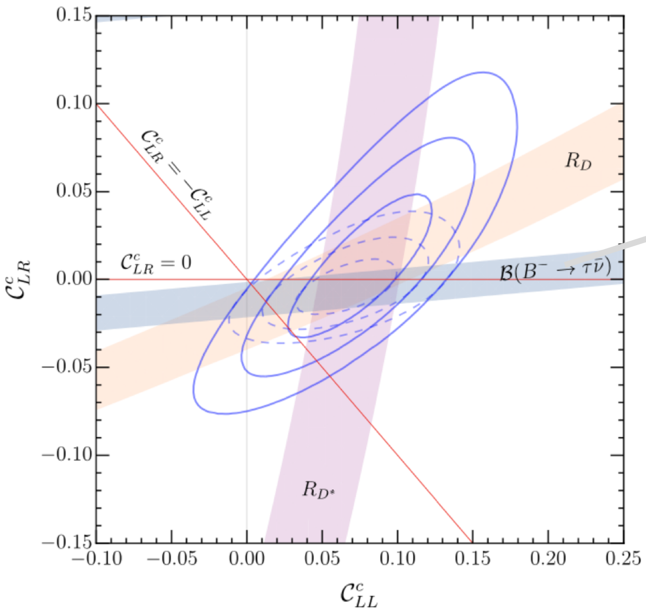
SMEFT operators

$$\mathcal{O}_{LL}^{ij\alpha\beta} = (\bar q_L^i \gamma_\mu \ell_L^\alpha)(\bar\ell_L^\beta \gamma^\mu q_L^j) = \frac{1}{2}\left[Q_{lq}^{(1)} + Q_{lq}^{(3)}\right]^{\beta\alpha ij},$$
$$\mathcal{O}_{LR}^{ij\alpha\beta} = (\bar q_L^i \gamma_\mu \ell_L^\alpha)(\bar e_R^\beta \gamma^\mu d_R^j) = -2\left[Q_{ledq}^\dagger\right]^{\beta\alpha ij},$$
$$\mathcal{O}_{RR}^{ij\alpha\beta} = (\bar d_R^i \gamma_\mu e_R^\alpha)(\bar e_R^\beta \gamma^\mu d_R^j) = \left[Q_{ed}\right]^{\beta\alpha ij},$$

$$\mathcal{C}_{LL}^{ji\beta\alpha} = (\mathcal{C}_{LL}^{ij\alpha\beta})^*,$$
$$\mathcal{C}_{RR}^{ji\beta\alpha} = (\mathcal{C}_{RR}^{ij\alpha\beta})^*.$$

$$\mathcal{L}_{\rm EFT}^{\rm NP} = -\frac{2}{v^2}\left[\mathcal{C}_{LL}^{ij\alpha\beta}\,\mathcal{O}_{LL}^{ij\alpha\beta} + \mathcal{C}_{RR}^{ij\alpha\beta}\,\mathcal{O}_{RR}^{ij\alpha\beta} + \left(\mathcal{C}_{LR}^{ij\alpha\beta}\,\mathcal{O}_{LR}^{ij\alpha\beta} + \text{h.c.}\right)\right]$$

$$\mathcal{L}_{b\to u_i\tau\bar\nu} = -\frac{4G_F}{\sqrt{2}}\sum_{i=1,2}\left[\left(V_{ib} + \sum_{k=1}^{3} V_{ik}\,\mathcal{C}_{LL}^{k3\tau\tau}\right)(\bar u_L^i\gamma_\mu b_L)(\bar\tau_L\gamma^\mu\nu_L) - 2\sum_{k=1}^{3} V_{ik}\,\mathcal{C}_{LR}^{k3\tau\tau}\,(\bar u_L^i b_R)(\bar\tau_R\nu_L)\right]$$



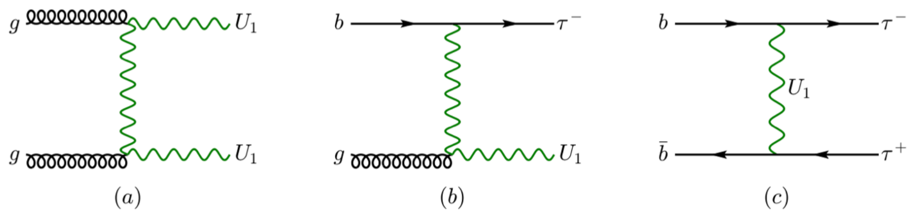
EFT constraints from the $b \to c\tau\bar\nu$ anomalies.
Λ = 2 TeV. The dashed contours denote the fit results taking also the constraint from $B(B^- \to \tau\bar\nu)$ into account, under the hypothesis of minimal $U(2)^5$ breaking.
1σ regions.

Important constraints $B_s - \bar B_s$ mixing

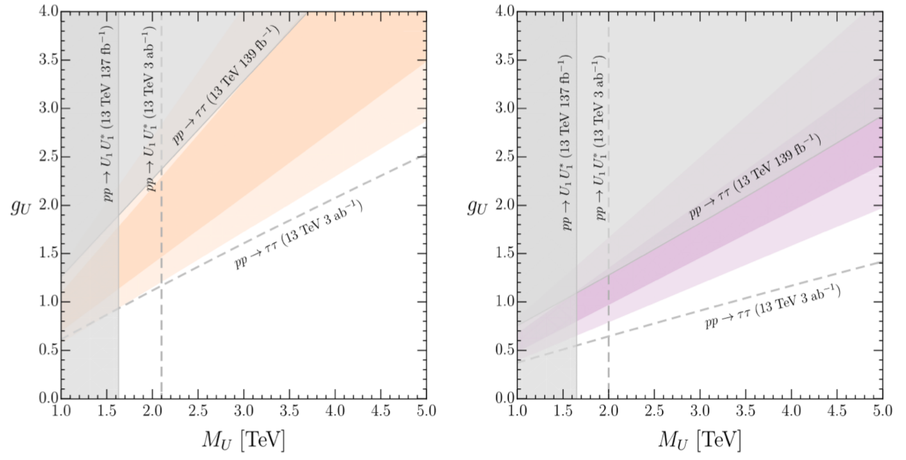
Cornella et al., 2103.16558, Greljo et al., 150601705, Buttazo et al., 1706.07808, Bordone et al., 1712.01368, Fuentes-Martin et al., 1910.13474, Fuentes-Martin et al.2012.10492, Fuentes-Martin et al.2006.16250, Fuentes-Martin et al. 2009.11296, Bordone et al., 1805.09328, Bordone et al., 1605.07633

The most general Lagrangian for a U_1 vector leptoquark coupling to SM particles is given by

$$\mathcal{L}_U = -\frac{1}{2}U^\dagger_{\mu\nu}U^{\mu\nu} + M_U^2 U^\dagger_\mu U^\mu - i g_s(1-\kappa_c)U^\dagger_\mu T^a U_\nu G^{\mu\nu,a} - \frac{2i}{3}g_Y(1-\kappa_Y)U^\dagger_\mu U_\nu B^{\mu\nu} + \frac{g_U}{\sqrt{2}}(U^\mu J^U_\mu + \text{h.c.}),$$



$B \to K^{(*)} \nu \bar{\nu}$

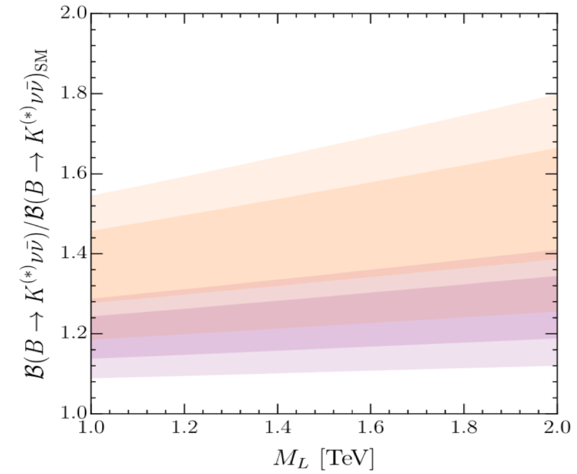


Cornella et al., 2103.16558

NP effects are dominant in the Wilson coefficient involving the third family, while the other flavour combinations receive negligible contributions

Full theory contains new gauge bosons (G',Z'), and vectorlike quarks

M_U = 4 TeV and g_4 = 3, and varying the scale of the scalar degrees of freedom and the Z′ mass in the M_R = [1, 2π] M_U and $M_{Z'}$ = [0.5, 1] M_U ranges.
Orange and purple correspond to the benchmarks $\beta_{b\tau}$ = 0 and $\beta_{b\tau}$ = −1.



New physics in the meson mixing

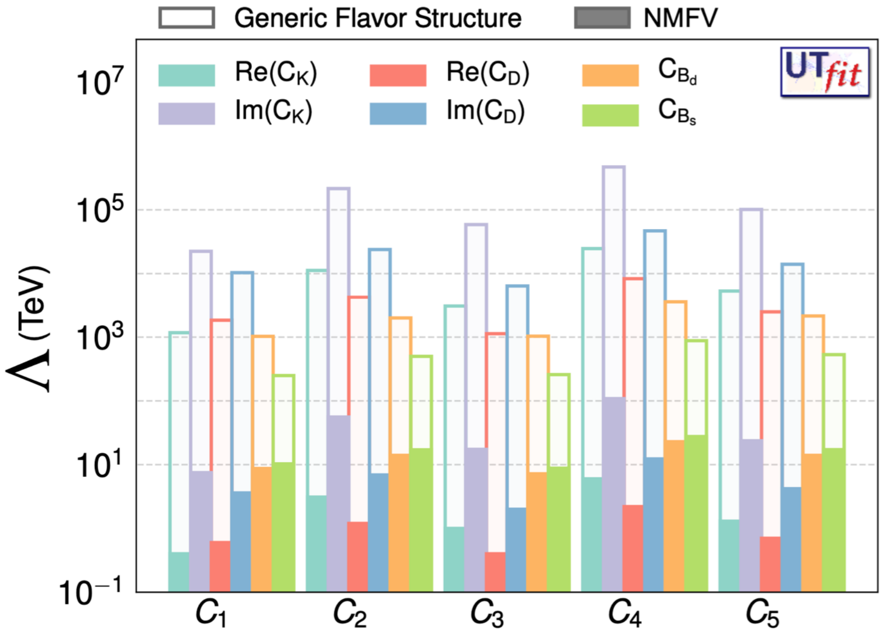
$$\mathcal{H}^q_{\text{eff}} = \mathcal{H}^{\text{SM}}_{\text{eff},q} + \mathcal{H}^{\text{NP}}_{\text{eff},q}$$

$$\mathcal{H}^{\text{NP}}_{\text{eff}} = \sum_i \frac{C_i}{\Lambda^2_{\text{NP},B_q}} Q_{i,q},$$

$$Q_{1,q} = (\bar{b}_L \gamma^\mu q_L)(\bar{b}_L \gamma^\mu q_L),$$
$$Q_{2,q} = (\bar{b}_R q_L)(\bar{b}_R q_L),$$
$$Q_{3,q} = (\bar{b}^\alpha_R q^\beta_L)(\bar{b}^\beta_R q^\alpha_L)$$
$$Q_{4,q} = (\bar{b}_R q_L)(\bar{b}_L q_R),$$
$$Q_{5,q} = (\bar{b}^\alpha_R q^\beta_L)(\bar{b}^\beta_L q^\alpha_R),$$

- Generic: $C(\Lambda) = \alpha/\Lambda^2$
- NMFV: $C(\Lambda) = \alpha \times |F_{SM}|/\Lambda^2$

$$\text{for NP=20\% SM,} \quad K - \bar{K}: \quad (\underbrace{V^*_{ts}}_{\lambda^2} \underbrace{V_{td}}_{\lambda^3})^2 \quad \Rightarrow \quad \Lambda_{\text{NP}} \gtrsim 4 \cdot 10^4 \text{ TeV},$$
$$\text{for NP=20\% SM,} \quad B_d - \bar{B}_d: \quad (\underbrace{V^*_{tb}}_{1} \underbrace{V_{td}}_{\lambda^3})^2 \quad \Rightarrow \quad \Lambda_{\text{NP}} \gtrsim 1.5 \cdot 10^3 \text{ TeV},$$
$$\text{for NP=20\% SM,} \quad B_s - \bar{B}_s: \quad (\underbrace{V^*_{tb}}_{1} \underbrace{V_{ts}}_{\lambda^2})^2 \quad \Rightarrow \quad \Lambda_{\text{NP}} \gtrsim 3 \cdot 10^2 \text{ TeV}.$$



NP scale crucially depends on the assumed flavour structure in the dimensionless Wilson coefficient, Ci

M. Bona @EPS 2023

A.J. Buras "Gauge Theory of Weak Decays: The Standard Model and the Expedition to New Physics Summits", Cambridge University Press
A.J. Buras, "Climbing NLO and NNLO summits of weak decays: 1988–2023", Physics Reports 1025 (2023) 0.

$R^{\nu\nu}_{K(*)}$ and scalar LQS

$$\mathcal{L}_{\rm eff}^{\bar q^i q^j \bar\nu\nu'} = \sqrt{2}G_F\Big[c^{LL}_{ij;\nu\nu'}(\bar q^i_L\gamma_\mu q^j_L)(\bar\nu_L\gamma^\mu\nu'_L) + c^{RR}_{ij;\nu\nu'}(\bar q^i_R\gamma_\mu q^j_R)(\bar\nu_R\gamma^\mu\nu'_R)$$
$$+ c^{LR}_{ij;\nu\nu'}(\bar q^i_L\gamma_\mu q^j_L)(\bar\nu_R\gamma^\mu\nu'_R) + c^{RL}_{ij;\nu\nu'}(\bar q^i_R\gamma_\mu q^j_R)(\bar\nu_L\gamma^\mu\nu'_L)$$
$$+ g^{LL}_{ij;\nu\nu'}(\bar q^i_L q^j_R)(\bar\nu_L\nu'_R) + h^{LL}_{ij;\nu\nu'}(\bar q^i_L\sigma^{\mu\nu}q^j_R)(\bar\nu_L\sigma_{\mu\nu}\nu'_R)$$
$$+ g^{RR}_{ij;\nu\nu'}(\bar q^i_R q^j_L)(\bar\nu_R\nu'_L) + h^{RR}_{ij;\nu\nu'}(\bar q^i_R\sigma^{\mu\nu}q^j_L)(\bar\nu_R\sigma_{\mu\nu}\nu'_L)$$
$$+ g^{LR}_{ij;\nu\nu'}(\bar q^i_L q^j_R)(\bar\nu_R\nu'_L) + g^{RL}_{ij;\nu\nu'}(\bar q^i_R q^j_L)(\bar\nu_L\nu'_R)\Big].$$

LQ	$d_j \to d_i\nu\bar\nu'$ decays	$u_j \to u_i\nu\bar\nu'$ decays
S_3	$c^{LL} = \frac{v^2}{2m^2_{\rm LQ}}(y_3^{LL}U)_{j\nu'}(y_3^{LL}U)^*_{i\nu}$	$c^{LL} = \frac{v^2}{m^2_{\rm LQ}}(V^T y_3^{LL}U)_{j\nu'}(V^T y_3^{LL}U)^*_{i\nu}$
R_2		$c^{RL} = -\frac{v^2}{2m^2_{\rm LQ}}(y_2^{RL}U)_{i\nu'}(y_2^{RL}U)^*_{j\nu}$
$\tilde R_2$	$c^{RL} = -\frac{v^2}{2m^2_{\rm LQ}}(\tilde y_2^{RL}U)_{i\nu'}(\tilde y_2^{RL}U)^*_{j\nu}$ $c^{LR} = -\frac{v^2}{2m^2_{\rm LQ}}\tilde y^{\overline{LR}}_{2\,i\nu'}\tilde y^{\overline{LR}*}_{2\,j\nu}$ $g^{RR} = 4h^{RR} = -\frac{v^2}{2m^2_{\rm LQ}}(\tilde y_2^{RL}U)_{i\nu'}\tilde y^{\overline{LR}*}_{2\,j\nu}$ $g^{LL} = 4h^{LL} = -\frac{v^2}{2m^2_{\rm LQ}}\tilde y^{\overline{LR}}_{2\,i\nu'}(\tilde y_2^{RL}U)^*_{j\nu}$	$c^{LR} = -\frac{v^2}{2m^2_{\rm LQ}}(V\tilde y_2^{\overline{LR}})_{i\nu'}(V y_2^{\overline{LR}})^*_{j\nu}$
S_1	$c^{LL} = \frac{v^2}{2m^2_{\rm LQ}}(y_1^{LL}U)_{j\nu'}(y_1^{LL}U)^*_{i\nu}$ $c^{RR} = \frac{v^2}{2m^2_{\rm LQ}}y^{\overline{RR}}_{1\,j\nu'}y^{\overline{RR}*}_{1\,i\nu}$ $g^{RR} = -4h^{RR} = \frac{v^2}{2m^2_{\rm LQ}}(y_1^{LL}U)_{j\nu'}y^{\overline{RR}*}_{1\,i\nu}$ $g^{LL} = -4h^{LL} = \frac{v^2}{2m^2_{\rm LQ}}y^{\overline{RR}}_{1\,j\nu'}(y_1^{LL}U)^*_{i\nu}$	
$\bar S_1$		$c^{RR} = \frac{v^2}{2m^2_{\rm LQ}}\bar y^{\overline{RR}}_{1\,j\nu'}\bar y^{\overline{RR}*}_{1\,i\nu}$
U_3	$c^{LL} = -\frac{2v^2}{m^2_{\rm LQ}}(x_3^{LL}U)_{i\nu'}(x_3^{LL}U)^*_{j\nu}$	$c^{LL} = -\frac{v^2}{m^2_{\rm LQ}}(Vx_3^{LL}U)_{i\nu'}(Vx_3^{LL}U)^*_{j\nu}$
V_2	$c^{RL} = \frac{v^2}{m^2_{\rm LQ}}(x_2^{RL}U)_{j\nu'}(x_2^{RL}U)^*_{i\nu}$	
$\tilde V_2$		$c^{RL} = \frac{v^2}{m^2_{\rm LQ}}(\tilde x_2^{RL}U)_{j\nu'}(\tilde x_2^{RL}U)^*_{i\nu}$ $c^{LR} = \frac{v^2}{m^2_{\rm LQ}}(V^T\tilde x_2^{\overline{LR}})_{j\nu'}(V^T\tilde x_2^{\overline{LR}})^*_{i\nu}$ $g^{RL} = \frac{2v^2}{m^2_{\rm LQ}}(V^T\tilde x_2^{\overline{LR}})_{j\nu'}(\tilde x_2^{RL}U)^*_{i\nu}$ $g^{LR} = \frac{2v^2}{m^2_{\rm LQ}}(\tilde x_2^{RL}U)_{j\nu'}(V^T\tilde x_2^{\overline{LR}})^*_{i\nu}$
U_1		$c^{LL} = -\frac{v^2}{m^2_{\rm LQ}}(Vx_1^{LL}U)_{i\nu'}(Vx_1^{LL}U)^*_{j\nu}$ $c^{RR} = -\frac{v^2}{m^2_{\rm LQ}}x^{\overline{RR}}_{1\,i\nu'}x^{\overline{RR}*}_{1\,j\nu}$ $c^{LR} = \frac{2v^2}{m^2_{\rm LQ}}(Vx_1^{LL}U)_{i\nu'}x^{\overline{RR}*}_{1\,j\nu}$ $c^{RL} = \frac{2v^2}{m^2_{\rm LQ}}x^{\overline{RR}}_{1\,i\nu'}(Vx_1^{LL}U)^*_{j\nu}$
$\bar U_1$	$c^{RR} = -\frac{v^2}{m^2_{\rm LQ}}x^{RR}_{1\,i\nu'}x^{RR*}_{1\,j\nu}$	

Bause et al., 2309.00075, Allwicher et al, 2309.02246,
assumed that neutrinos are SM-like.
In this case the most suitable candidate is the operator with the right-handed quarks.
Only $\tilde R_2$, (V_2) can have such interactions at the tree level !
Note that these couplings would not generate any contributions to

Allwicher et al, 2309.02246, one or two light lepton flavours,
τ seems to workallowing $R_{D(*)}/R^{SM}_{D*}$ can be achieved if we allow only the coupling to τ and not to other species.
(supported by S. Decotes-Genon et al., 2005.03734)

Constraints also from $B(B_s \to \mu\mu)^{exp}$, B_s- $\bar B_s$ mixing,

$m_{\tilde R_2} \lesssim 3$ TeV $\quad m_{S_1} \lesssim 3.5$ TeV

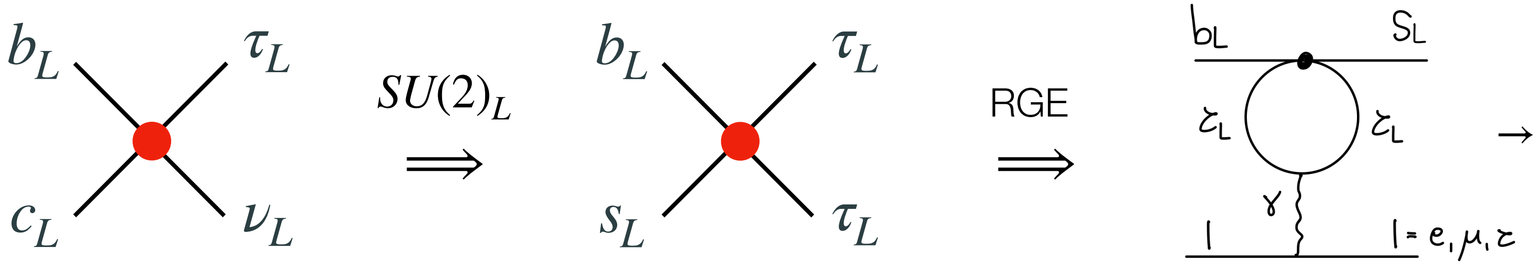
U_1 with left-handed couplings only cannot work

NP in b → s μμ

Talk of Smolkovič today

Universal contribution to C_9

Operators mix under running



$\rightarrow \Delta C_9^U = C_9^U - C_9^{\mathrm{SM}}$

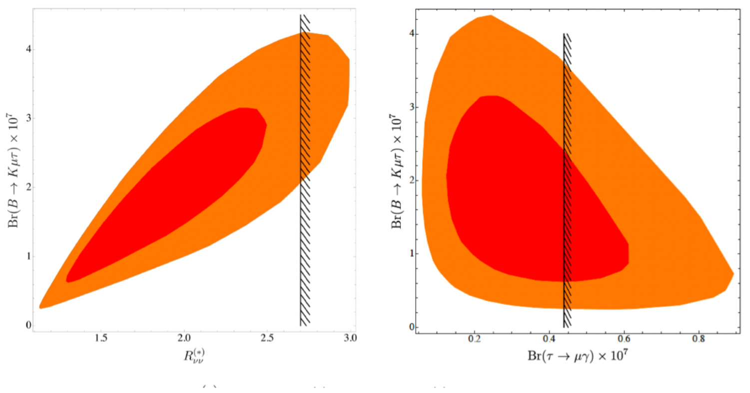
Bobeth, Haisch, arXiv:1109.1826; Crivellin et al., arXiv:1807.02068, Algueró et al., 1695189

Universality in μ e is well established (at $\sim$ 5% level)

However, there are still unsettled issues as presnted in talk by Dan Moise:
Parrott et al. 2207.13371
On theory side: CKM uncetainty, FF unknown at low q^2. To early to make a conclusion on the disagreement!

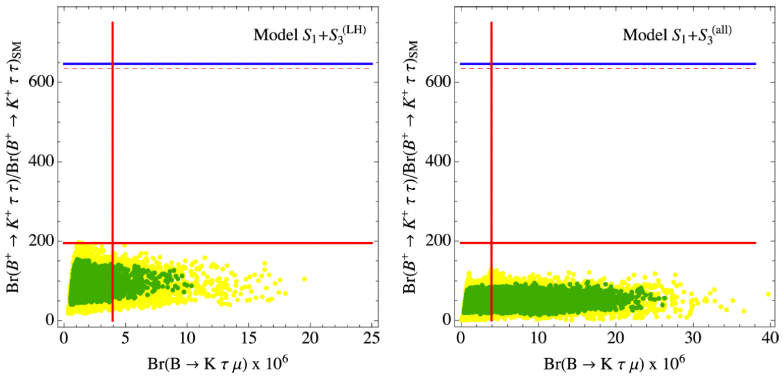
Lepton flavor violating processes

$B \to K\ \tau\mu\ , \tau \to \mu\gamma, R^{\nu\nu}_{K(*)}, B\ \to K\ \tau\tau, \tau \to \mu\mu\mu$

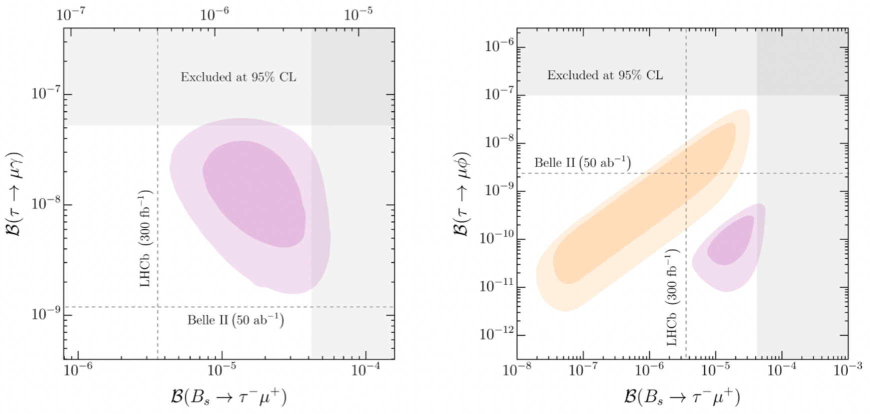


R_2& S_3

Becirevic et al., 2206.09717

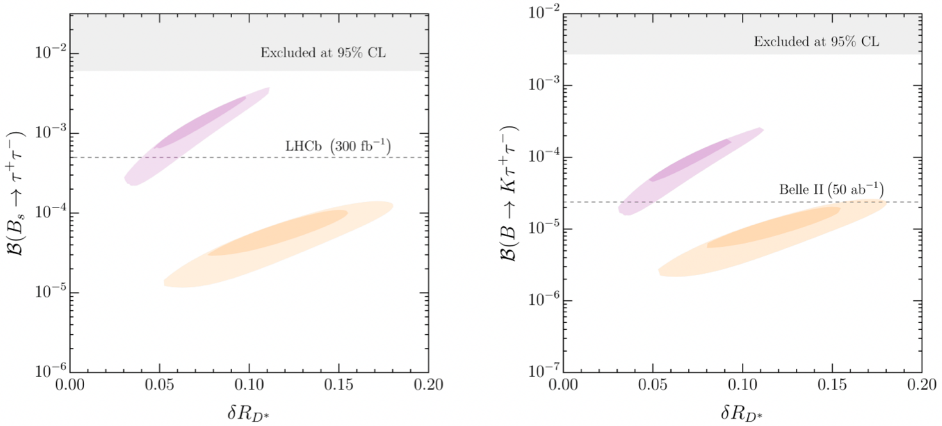


Gherardi et al. 2008.09546



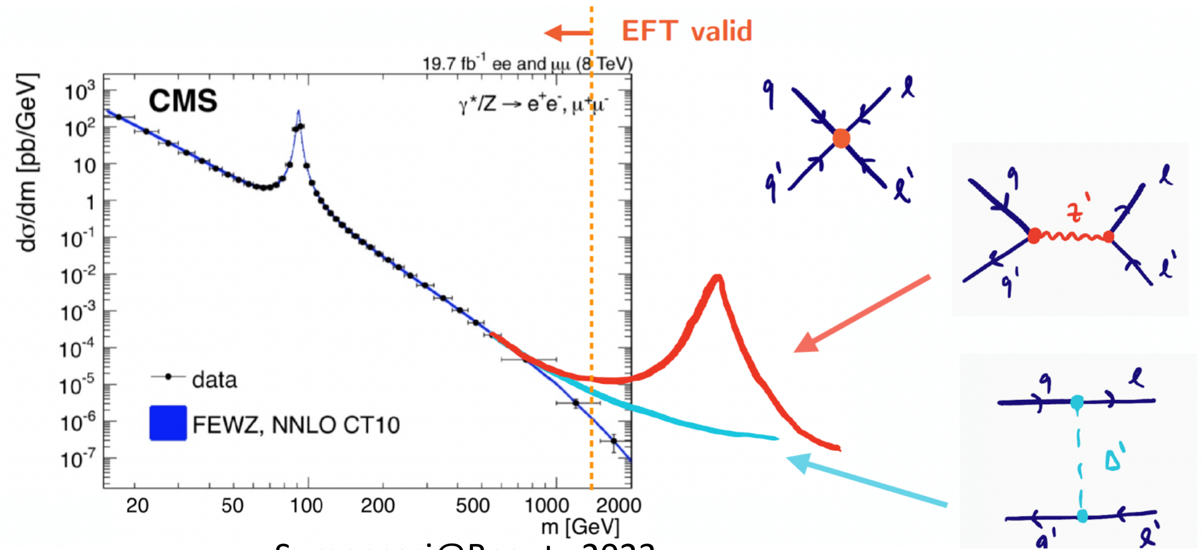
Cornella et al., 2103.16558

Predictions $B \to K\tau\tau$



Cornella et al., 2103.16558

LHC and serches for NP in flavour physics

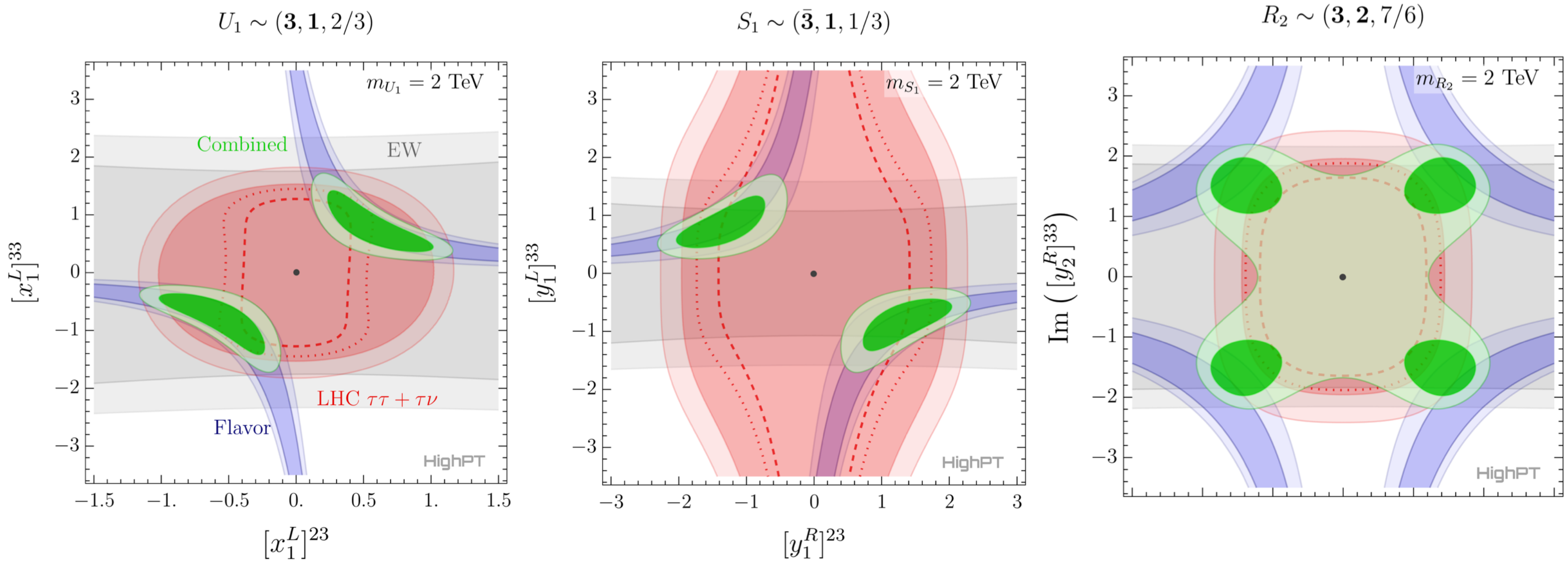


Sumensari@Beauty 2023

Approach: Recast di-lepton searches and look for NP effects in the tails of the invariant-mass distributions (where is large).

EFT must be valid. Otherwise, use explicit model (e.g., leptoquark or Z'). $E \ll \Lambda$

Allwicher et al. 2207.10714



Bounds on the leptoquark couplings from low-energy (blue), electroweak pole (gray) and high-p_T LHC (red) observables. The combined fit is shown in green

Unifying models

Pati Salam model reappearance $SU(4)_{PS} \times SU(2)_L \times SU(2)_R$ Pati & Salam, PRD 10, 275 (1974)

PS - 4321 Di Luzio et al., 1708.08450, Callibi et al, 1709.00692

Gauge group $G \equiv SU(4) \times SU(3)' \times SU(2)_L \times U(1)'$

QCD is $SU(3)_c = SU(3)_4 \times SU(3)'$

$U(1)_Y = (U(1)_4 \times U(1)')_{diag}$

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$	$U(1)_{B'}$	$U(1)_{L'}$
$q_L'^i$	1	3	2	1/6	1/3	0
$u_R'^i$	1	3	1	2/3	1/3	0
$d_R'^i$	1	3	1	−1/3	1/3	0
$\ell_L'^i$	1	1	2	−1/2	0	1
$e_R'^i$	1	1	1	−1	0	1
Ψ_L^i	4	1	2	0	1/4	1/4
Ψ_R^i	4	1	2	0	1/4	1/4
H	1	1	2	1/2	0	0
Ω_3	$\bar{4}$	3	1	1/6	1/12	−1/4
Ω_1	$\bar{4}$	1	1	−1/2	−1/4	3/4

$\Omega_3 = (8,1,0) \oplus (1,1,0) \oplus (3,1,2/3)$ and
$\Omega_1 = (\bar{3}, 1, -2/3) \oplus (1, 1, 0)$.

U_1

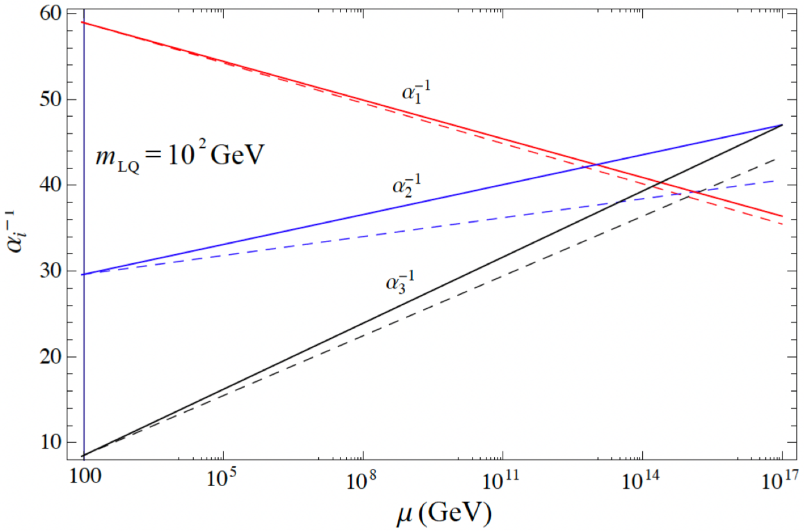
Colorons, and Z’ close in masses of U_1

PS^3 Bordone et al, 1805.09328, 1712.01368
B anomalies + the Standard Model flavour hierarchies
$PS_i = SU(4)_i \times [SU(2)_L]_i \times [SU(2)_R]_i$

SU(5), SO(10)

Not popular- in the minimal set up (non-SUSY) without higher dimensional representations unification is not working

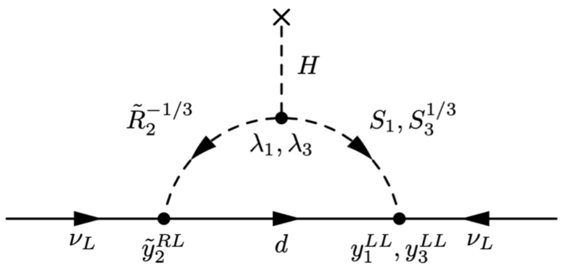
LEPTOQUARK	$SU(5)$
$S_3 \equiv (\overline{\mathbf{3}}, \mathbf{3}, 1/3)$	$\overline{\mathbf{45}}, \overline{\mathbf{70}}$
$R_2 \equiv (\mathbf{3}, \mathbf{2}, 7/6)$	$\overline{\mathbf{45}}, \overline{\mathbf{50}}$
$\tilde{R}_2 \equiv (\mathbf{3}, \mathbf{2}, 1/6)$	$\mathbf{10}, \mathbf{15}, \mathbf{40}$
$\tilde{S}_1 \equiv (\overline{\mathbf{3}}, \mathbf{1}, 4/3)$	$\mathbf{45}$
$S_1 \equiv (\overline{\mathbf{3}}, \mathbf{1}, 1/3)$	$\overline{\mathbf{5}}, \overline{\mathbf{45}}, \overline{\mathbf{50}}, \overline{\mathbf{70}}$
$\bar{S}_1 \equiv (\overline{\mathbf{3}}, \mathbf{1}, -2/3)$	$\mathbf{10}, \mathbf{40}$
$U_3 \equiv (\mathbf{3}, \mathbf{3}, 2/3)$	$\overline{\mathbf{35}}, \overline{\mathbf{40}}$
$V_2 \equiv (\overline{\mathbf{3}}, \mathbf{2}, 5/6)$	$\mathbf{24}, \mathbf{75}$
$\tilde{V}_2 \equiv (\overline{\mathbf{3}}, \mathbf{2}, -1/6)$	$\overline{\mathbf{10}}, \overline{\mathbf{40}}$
$\tilde{U}_1 \equiv (\mathbf{3}, \mathbf{1}, 5/3)$	$\mathbf{75}$
$U_1 \equiv (\mathbf{3}, \mathbf{1}, 2/3)$	$\overline{\mathbf{10}}, \overline{\mathbf{40}}$
$\bar{U}_1 \equiv (\mathbf{3}, \mathbf{1}, -1/3)$	$\mathbf{5}, \mathbf{45}, \mathbf{50}, \mathbf{70}$

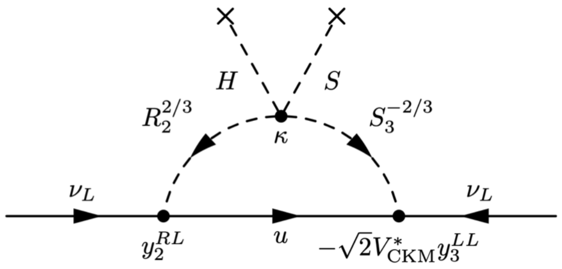


Dorsner et al.,1603.04993

Running of gauge couplings with the SM particle content (solid lines) and with additional fields (dashed lines) comprising one scalar transforming as (1; 2; 1=2) and two scalars transforming as (3; 2; 1=6). Vertical line denotes the mass scale of additional fields

We have learned that with two scalar leptoquarks (relatively light –TeV masses) unification within SU(5) is possible (Dorsner et al., hep-ph/0912.0972, 1701.08322)





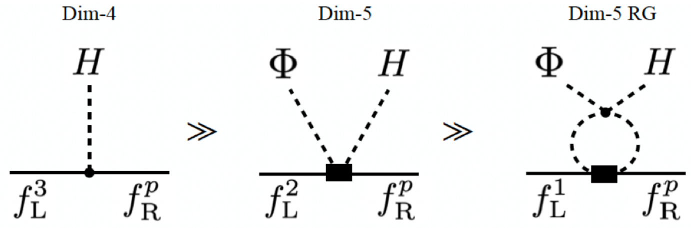
In this scenario even Majorana neutrino masses can be approached.

Do we understand fermion mass hierarchy?

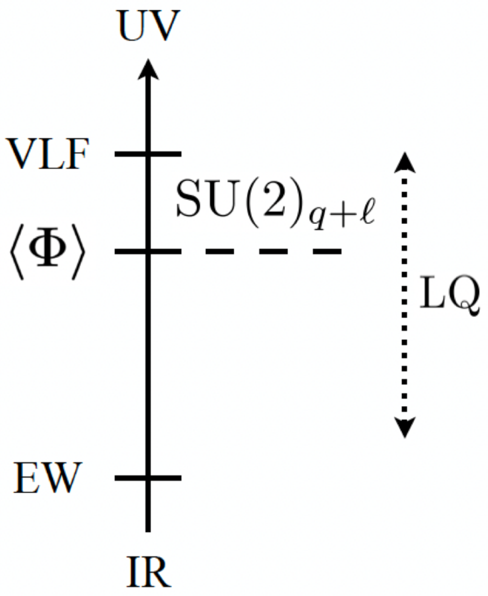
Flavor Hierarchies from a Gauged SU(2) Symmetry

Instead of U(1) Froggatt-Nielsen models Nucl. Phys. B 147 (1979) 277,
$SU(2)_{q+l}$ flavour (horizontal) symmetry group,
under which light generations of left-handed quarks and leptons transform as doublets.

Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$SU(2)_{q+\ell}$
q_L^α	**3**	**2**	1/6	**2**
q_L^3	**3**	**2**	1/6	**1**
u_R^p	**3**	**1**	2/3	**1**
d_R^p	**3**	**1**	-1/3	**1**
ℓ_L^α	**1**	**2**	-1/2	**2**
ℓ_L^3	**1**	**2**	-1/2	**1**
e_R^p	**1**	**1**	-1	**1**
H	**1**	**2**	1/2	**1**
Φ	**1**	**1**	0	**2**

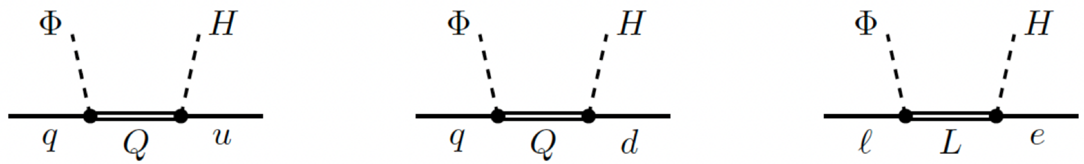


The leading gauge invariant operators under $SU(2)_{q+l}$ horizontal gauged symmetry matching to the SM after SSB by $\langle\Phi\rangle \gg \langle H\rangle$

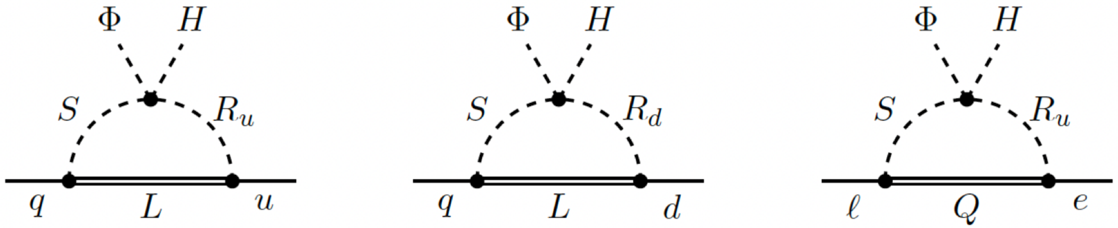


Greljo& Eller Thomsen
2309.11547

$$\mathcal{L} \supset -x_u^p\,\overline{q}^3\widetilde{H}u^p - x_d^p\,\overline{q}^3 H d^p - x_e^p\,\overline{\ell}^3 H e^p + \text{H.c.}$$



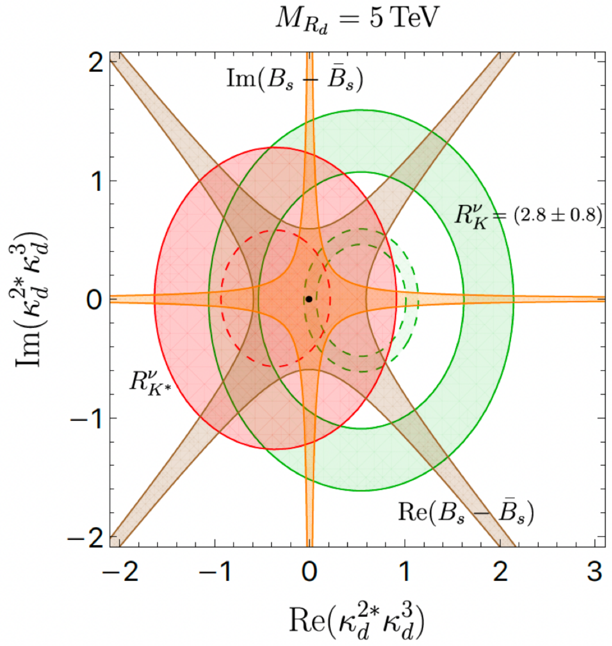
the second SM family



the first SM family

Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$SU(2)_{q+\ell}$
R_u	**3**	**2**	7/6	**1**
R_d	**3**	**2**	1/6	**1**
S	**3**	**1**	2/3	**2**

Scalar leptoquark fields contribute to radiative mass generation in the first family, resulting in rank-3 Yukawa matrices.



Embedding in the Pati–Salam gauge group

$SU(4) \times SU(2)_L \times SU(2)_R \times SU(2)_{q+l}$

$m_L \approx m_Q$

Rich pheonmenology!
Explains the CKM structure
Can explain neutrino masses (type I see-saw)

Summary & outlook

- We need more precision measurements at low and high energies.
  LHCb, Bele II, CMS & ATLAS

- On theory side: lattice QCD + other approaches (dispersive approaches, light-cone sum rules,…)
  improvement on the possible precision a_μ, B $\rightarrow D*$ form factors, and all the inputs.

- b $\rightarrow s$ μμ, still a lot of studies on theory and experiment sides.

- B $\rightarrow K^{(*)}$ invisibles offers many more phenomenological studies.

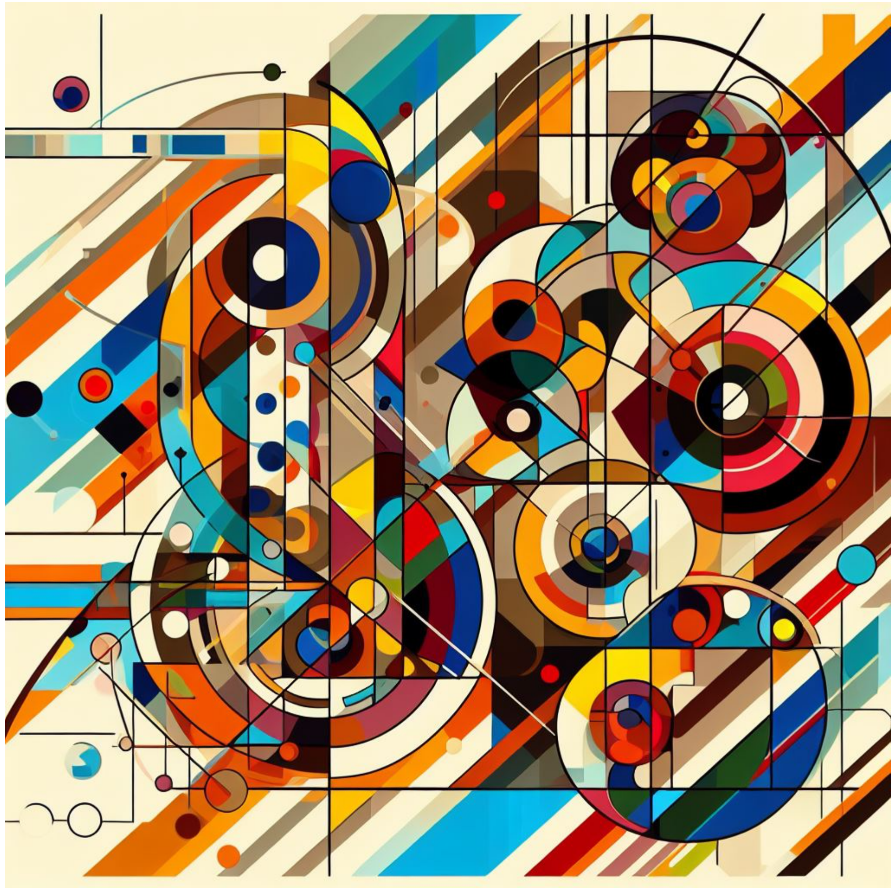
- Improvements of LHC bounds (ATLAS, CMS) on NP couplings.

- Understanding of fermion mass pattern within new theories.

Thanks!

Bing is writing
Here is a poem I wrote on B meson puzzles:

B mesons are made of beauty and light
They decay in different ways that we can measure and write
But some of their ratios do not match the theory
They show deviations that make us weary
Is it a sign of new physics beyond the standard model?
Or just a statistical fluctuation or a subtle fiddle?
We need more data and more precision
To confirm or reject this tantalizing vision
Some leptoquarks may be the solution
They can explain both puzzles with minimal intrusion
But they also predict other effects that we should see
In muon g-2 or tau lepton decays, for example
So we keep searching for the answers with our tools and brains
We hope to find the clues in the LHC or Belle II domains
B mesons are our guides to the unknown frontier
They may reveal the secrets of the universe,
or so we cheer



Bing: B meson puzzles, style of Candinsky

Constrains scalar leptoquarks couplings using the leptonic W and Z couplings

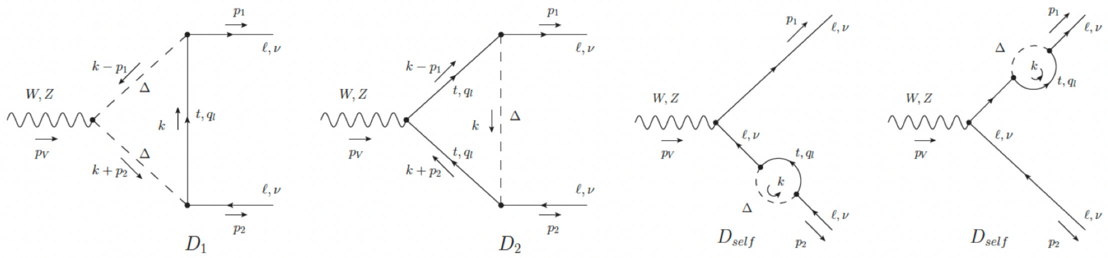
Arnan et al., 1901.06315

LEP results

$$g_V^{e,\,\rm exp} = -0.03817(47)\,, \qquad g_A^{e,\,\rm exp} = -\,0.50111(35)\,,$$
$$g_V^{\mu,\,\rm exp} = -0.0367(23)\,, \qquad g_A^{\mu,\,\rm exp} = -\,0.50120(54)\,,$$
$$g_V^{\tau,\,\rm exp} = -0.0366(10)\,, \qquad g_A^{e,\,\rm exp} = -\,0.50204(64)\,,$$

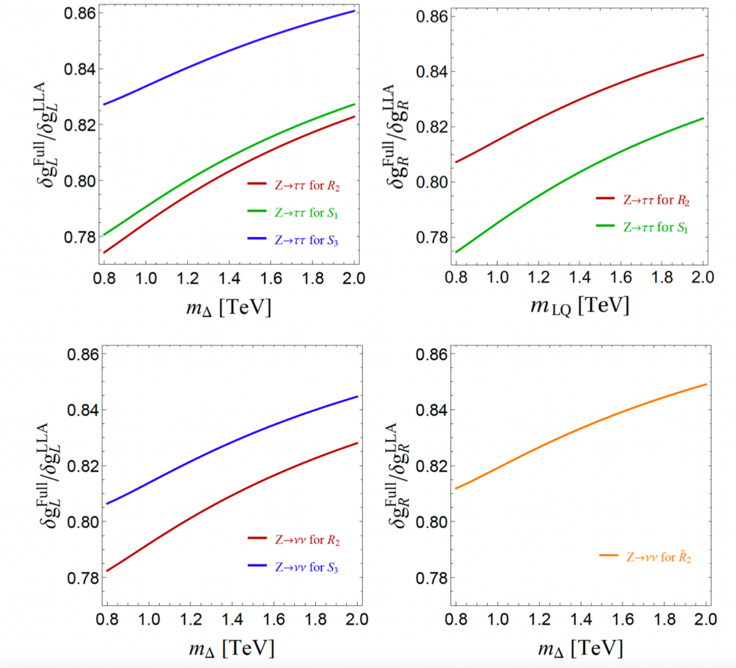
$$N_\nu^{\rm exp} = 2.9840(82)$$

$$\mathcal{L}_{\rm yuk.}^{F=0} = \bar{q}_i \left[l_{ij} P_R + r_{ij} P_L \right] \ell_j \, \Delta + \text{h.c.}$$
$$\mathcal{L}_{\rm yuk.}^{F=2} = \bar{q}_i^{\,C} \left[l_{ij} P_R + r_{ij} P_L \right] \ell_j \, \Delta + \text{h.c.}$$



$$N_\nu = \sum_{i,j} \left[\left| \delta_{ij} + \frac{\delta g_{\nu_L}^{ij}}{g_{\nu_L}^{\rm SM}} \right|^2 + \left| \frac{\delta g_{\nu_R}^{ij}}{g_{\nu_L}^{\rm SM}} \right|^2 \right]$$

Decay	w_{ij}	q	R_2	$\widetilde{R}_2$	S_1	S_3	$\widetilde{S}_1$	$\bar{S}_1$
$Z \to \ell\ell$	r_{ij}	q_u	$-\left(y_{R_2}^L\right)_{ij}$	0	$\left(V^* y_{S_1}^L\right)_{ij}$	$-\left(V^* y_{S_3}^L\right)_{ij}$	0	0
		q_d	0	$-\left(y_{\widetilde{R}_2}^L\right)_{ij}$	0	$-\sqrt{2}\left(y_{S_3}^L\right)_{ij}$	0	0
	l_{ij}	q_u	$\left(V y_{R_2}^R\right)_{ij}$	0	$\left(y_{S_1}^R\right)_{ij}$	0	0	0
		q_d	$\left(y_{R_2}^R\right)_{ij}$	0	0	0	$\left(y_{\widetilde{S}_1}^R\right)_{ij}$	0
$Z \to \nu\nu$	r_{ij}	q_u	$\left(y_{R_2}^L\right)_{ij}$	0	0	$\sqrt{2}\left(V^* y_{S_3}^L\right)_{ij}$	0	0
		q_d	0	$\left(y_{\widetilde{R}_2}^L\right)_{ij}$	$-\left(y_{S_1}^L\right)_{ij}$	$-\left(y_{S_3}^L\right)_{ij}$	0	0
	l_{ij}	q_u	0	$\left(V y_{\widetilde{R}_2}^R\right)_{ij}$	0	0	0	$\left(y_{\bar{S}_1}^R\right)_{ij}$
		q_d	0	$\left(y_{\widetilde{R}_2}^R\right)_{ij}$	$\left(y_{S_1}^{\prime R}\right)_{ij}$	0	0	0



LHC and serches for NP in flavour physics

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{d\geq 5} \frac{C_k^{(d)}}{\Lambda^{d-4}} \mathcal{O}_k^{(d)} \xrightarrow{(\sqrt{\hat{s}} \ll \Lambda)} \hat{\sigma} = \hat{\sigma}_{\rm SM} + \hat{\sigma}_{\rm int} + \hat{\sigma}_{\rm NP^2}$$

$$\propto \frac{1}{\hat{s}} \qquad \propto \frac{\hat{s}}{\Lambda^2}{\rm Re}(\mathcal{C}^{(6)}) \qquad \propto \frac{\hat{s}^2}{\Lambda^4}|\mathcal{C}^{(6)}|^2$$

Parton luminosities

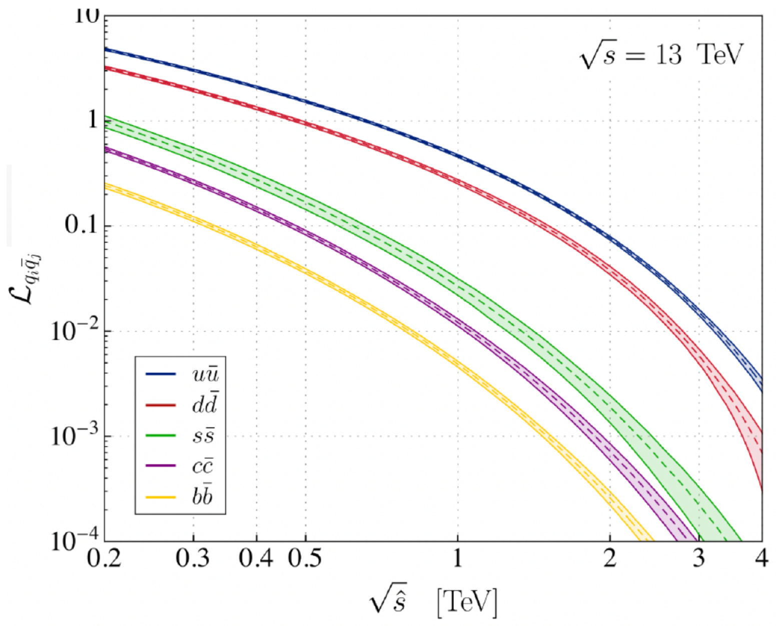
Partonic cross-section

$$\sigma(pp \to \ell\ell') = \sum_{ij} \int \frac{{\rm d}\tau}{\tau} \mathcal{L}_{q_i\bar{q}_j}(\tau)\, \hat{\sigma}(q_i\bar{q}_j \to \ell\ell')_{\hat{s}=s\tau}$$

$$\tau = \hat{s}/s$$

$$\hat{s} = m_{\ell\ell'}^2$$

$$\sqrt{s} = 13 \text{ TeV}$$



Allwicher et al. 2207.10714

Advantage: some processes are poorly constrained at low energies – but can be constrained at high energies

e.g., b → s $\tau\tau$, c→ d $\tau\nu$, c→ d $e\nu$, …

How about the first two generations?

Correlating New Physics Effects in Semileptonic ΔC = 1 and ΔS = 1 Processes

$$\mathcal{L}_{\rm SMEFT} \supset \frac{X_{ij}^{(3,\ell)}}{\Lambda^2}(\bar{Q}_i\gamma_\mu\sigma^a Q_j)(\bar{L}_\ell\gamma^\mu\sigma_a L_\ell) + \frac{X_{ij}^{(1,\ell)}}{\Lambda^2}(\bar{Q}_i\gamma_\mu Q_j)(\bar{L}_\ell\gamma^\mu L_\ell)\,.$$

$$X_{ij}^{(\pm)} = \lambda^{(\pm)}\delta_{ij} + c_a^{(\pm)}(\sigma^a)_{ij}$$

2305.13851, SF, JF Kamenik, N. Kosnik and a. Korajac

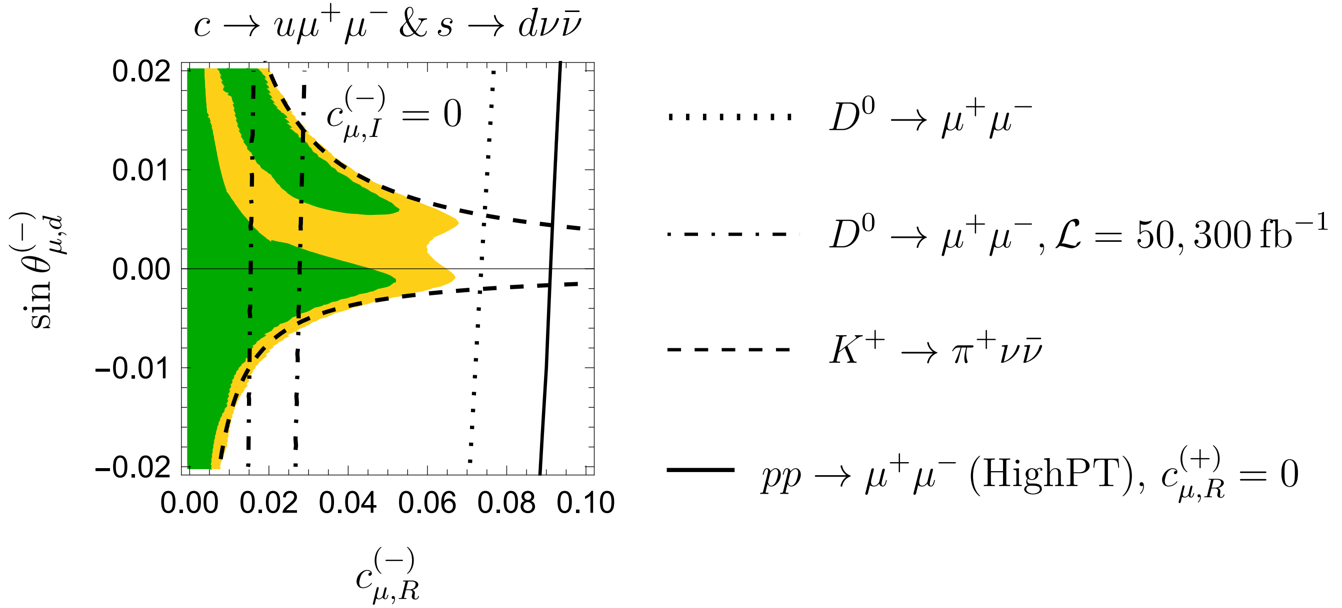
$$s\to d\nu\bar\nu: \quad C_{L,\nu}^{\Delta S=1,\,\rm NP} = \frac{2\pi}{\alpha_{\rm em}}\frac{v^2}{\Lambda^2}\left\{c_R^{(-)}\sin\theta_d^{(-)} - ic_I^{(-)}\right\},$$

$$c\to u\ell^+\ell^-: \quad C_9^{\Delta C=1,\rm NP} = -C_{10}^{\Delta C=1,\rm NP} = \frac{\pi}{\alpha_{\rm em}}\frac{v^2}{\Lambda^2}\left\{c_R^{(-)}\sin(\theta_d^{(-)}-2\theta_c) - ic_I^{(-)}\right\},$$

$$s\to d\ell^+\ell^-: \quad C_9^{\Delta S=1,\rm NP} = -C_{10}^{\Delta S=1,\rm NP} = \frac{\pi}{\alpha_{\rm em}}\frac{v^2}{\Lambda^2}\left\{c_R^{(+)}\sin\theta_d^{(+)} - ic_I^{(+)}\right\}$$

$$c\to u\nu\bar\nu: \quad C_{L,\nu}^{\Delta C=1,\rm NP} = \frac{2\pi}{\alpha_{\rm em}}\frac{v^2}{\Lambda^2}\left\{c_R^{(+)}\sin(\theta_d^{(+)}-2\theta_c) - ic_I^{(+)}\right\}.$$

$$\left|{\rm Im}[c_{\tau,I}^{(+)}]\right| \lesssim 0.15$$



universal ~~CP~~ phases