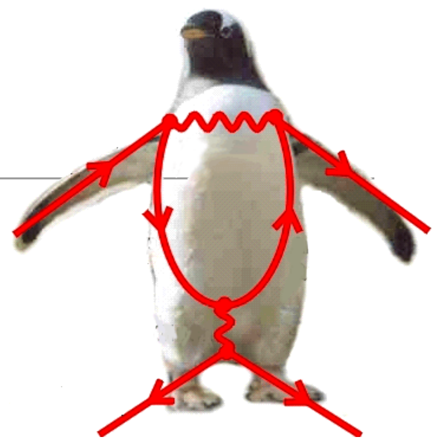
Flavor physics in the SM and beyond



Lecture I: Concepts of Quark Flavor Physics

Lecture II: Effective Weak Hamiltonians

Lecture III: Connecting UV Physics to Experiments

- Running couplings and modern view on QFT
- Standard Model as an effective field theory (SMEFT)
- Flavor sources beyond the SM
- Emergence of a bigger picture?

Construction of effective Lagrangians (summary)

Integrating out heavy particles in the generating functional is impractical in all but the simplest cases

Practical procedure:

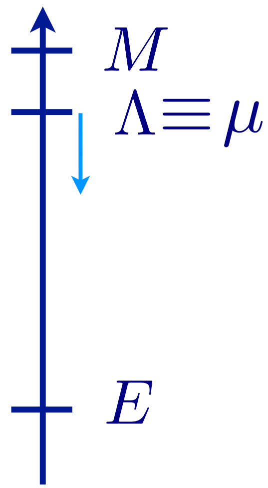
- write down complete set (basis) of operators $\{O_i\}$ at given dimension δ, which respect all symmetries of problem at hand
- if UV theory is known: determine their Wilson coefficients $\{g_i\}$ (often called C_i) at $\mu \sim M$ from perturbative matching procedure; else: treat these as free parameters
- evolve the coefficients down to $\mu \sim E$ (energy of experiment), thereby resuming large logs $\sim [\alpha_s \ln(M/E)]^n$ to all orders of perturbation theory
- determine low-energy matrix elements $\langle f|\, O_i(\mu)\, |i\rangle$ using a nonperturbative approach (lattice QCD)

Wilson coefficients as running couplings

Often the fields ϕ_H correspond to heavy particles, whose effects become unimportant at low energies

But the frequency decomposition implies that **high-energy excitations of massless particles** (such as gauge bosons) are also integrated out from the low-energy effective theory

Consider now the situation where we lower the cutoff Λ without crossing the threshold for a heavy particle that could be integrated out:



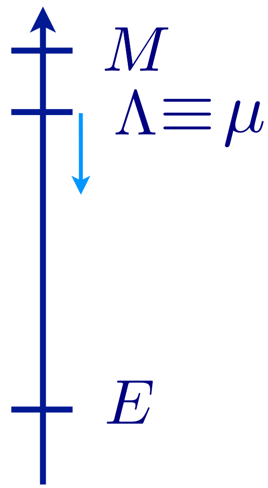
- the structure of the operators Q_i in the effective Lagrangian remains the same
- hence, the effect of lowering the cutoff must be entirely absorbed into the values of the coupling constants g_i

Wilson coefficients as running couplings

Follows that $g_i = g_i(\mu)$ are running, μ-dependent parameters!

Their scale dependence is calculable in perturbation theory and governed by renormalization-group equations (RGEs):

$$\mu \frac{d}{d\mu} g_i(\mu) = \Gamma_{ji}(\alpha_s)\, g_j(\mu)$$



Wilson coefficients as running couplings

Derivation of the RGE:

$$\mu \frac{d}{d\mu}\left[g_i(\mu)\, O_i(\mu)\right] = 0$$

$$\left[\mu \frac{d}{d\mu}\, g_i(\mu)\right] O_i(\mu) = -g_i(\mu)\left[\mu \frac{d}{d\mu}\, O_i(\mu)\right]$$

$$\mu \frac{d}{d\mu}\, O_i(\mu) = -\Gamma_{ij}\, O_j(\mu) \qquad \text{[completeness of basis]}$$

$$\left[\mu \frac{d}{d\mu}\, g_i(\mu)\, \delta_{ij} + g_i(\mu)\, \Gamma_{ij}\right] O_j(\mu) = 0$$

$$\mu \frac{d}{d\mu}\, g_j(\mu) + g_i(\mu)\, \Gamma_{ij} = 0 \qquad \text{[independence of basis operators]}$$

Wilson coefficients as running couplings

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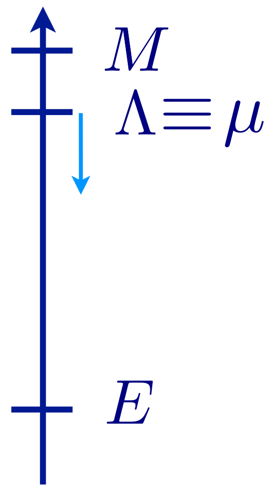
Their scale dependence is calculable in perturbation theory and governed by renormalization-group equations (RGEs):

$$\mu \frac{d}{d\mu} g_i(\mu) = \Gamma_{ji}(\alpha_s)\, g_j(\mu)$$

Solving this equation allows us to evolve (“run”) the coefficients from the high scale (μ~m_W in the SM, μ~$M_{\rm NP}$ in the presence of new physics) down to the low scales μ~$E_{\rm exp}$ relevant to flavor experiments!



At this low scale, the operator matrix elements are evaluated using some nonperturbative approach

Modern view on quantum field theory

Very likely, all QFTs are low-energy effective theories of some more fundamental theory:

- low-energy physics depends on the **short-distance dynamics** of the fundamental theory only through a small number of running, **relevant and marginal couplings,** and possibly through some irrelevant couplings if our measurements are sufficiently precise
- this finite number of couplings can be renormalized (i.e., infinities can be removed consistently) using a finite number of experimental data
- old textbook criterion of “renormalizability” is **automatically fulfilled** by any effective field theory

Modern view on quantum field theory

Very likely, all QFTs are low-energy effective theories of some more fundamental theory:

- contrary to the old paradigm of strictly forbidding non-renormalizable interactions, we **always expect them to be present** and give rise to small effects, which may or may not be observable at a given level of accuracy
- this provides an **“indirect way”** to search for hints of physics beyond the (current) Standard Model:

low-energy, high-precision measurements

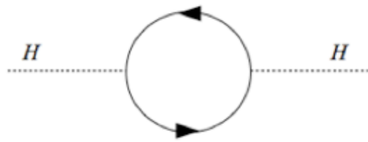
Modern view on quantum field theory

While “irrelevant” operators are particularly interesting, relevant (“super-renormalizable”) interactions cause problems!

Consider, e.g., the mass term $m^2\phi^2$ in scalar field theory

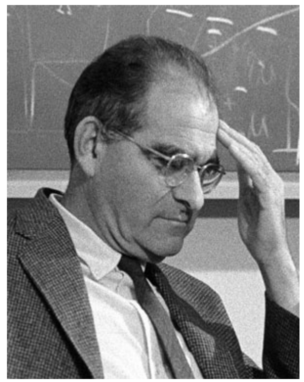
Dimensional analysis suggests that $m^2 \sim M^2 \sim \Lambda_{\mathrm{UV}}^2$

But then a light scalar particle should not be present in the low-energy effective theory:



Hierarchy problem!

The same argument applies for all mass terms in any QFT (and likewise for the cosmological constant)



Victor Weisskopf

Modern view on quantum field theory

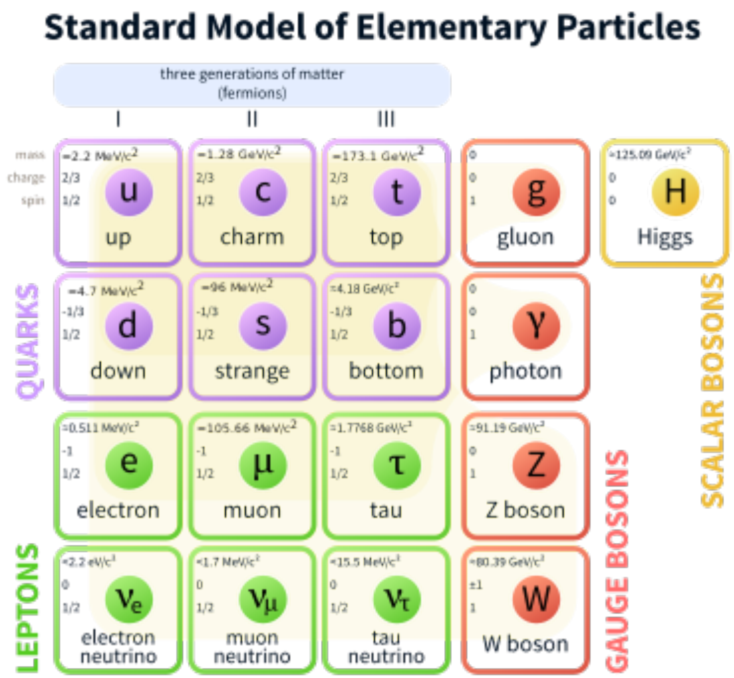
Ideally, EFTs should be **natural** in the sense that **all mass terms are forbidden** by (exact or broken) symmetries!

Indeed:

- **gauge invariance:** forbids mass terms for gauge fields (photons and gluons in the Standard Model)
- **chiral symmetry:** forbids mass terms for fermions (all matter fields in the Standard Model)

Explains why the SM is a **chiral gauge theory**!

- **Supersymmetry:** would link the masses of scalars and fermions and, in combination with chiral symmetry, forbid mass terms for scalar fields (solves the hierarchy problem)
  … but nature does not seem to care!?


Standard Model of Elementary Particles
three generations of matter
(fermions)
I
II
III
mass
charge
spin
u
up
c
charm
t
top
g
gluon
H
Higgs
d
down
s
strange
b
bottom
γ
photon
e
electron
μ
muon
τ
tau
Z
Z boson
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
W
W boson
QUARKS
LEPTONS
GAUGE BOSONS
SCALAR BOSONS

SMEFT

Standard Model as an effective field theory

Interesting insights can be gained by considering the Standard Model (SM) as a low-energy effective theory of some more fundamental theory (supersymmetry, extra dimensions, GUT, ...)

We denote the **scale of New Physics** by *M*; this could be as large as 10^{16} GeV for some applications, but as small as 10^3 GeV for others

The SM Lagrangian should then be extended to an effective Lagrangian, which besides the SM terms contains **additional, irrelevant operators**

These operators must respect the **symmetries of the SM** (gauge invariance, Lorentz symmetry, CPT) but are otherwise unrestricted

Standard Model as an effective field theory

The EFT extension of the SM is called "SMEFT":

Higgs mass (hierarchy problem)

cosmological constant

renormalizable quantum field theories

$$\mathcal{L}_{\rm EFT} = c^{(0)}\, M^4 + c^{(2)}\, M^2\, O^{(d=2)} + \sum_i c_i^{(4)}\, O_i^{(d=4)}$$

$$+ \frac{1}{M} \sum_i c_i^{(5)}\, O_i^{(d=5)} + \frac{1}{M^2} \sum_i c_i^{(6)}\, O_i^{(d=6)} + \dots$$

neutrino masses
(see-saw mechanism)

possible effects of "new physics",
proton decay, flavor physics, …

Standard Model as an effective field theory

We will discuss a couple of interesting aspects of SM physics from the perspective of this construction:

- weak interactions at low energies
- neutrino masses and the see-saw mechanism
- baryon and lepton number conservation
  (accidental symmetries)
- proton decay
- flavor sources beyond the SM

Weak interactions at low energies

Fermi's description of the weak interactions is a prime example of an effective field theory, which has provided first evidence for the scale of electroweak symmetry breaking

Since the **leading operators** in the low-energy effective theory have **dimension 6,** it follows that the corresponding couplings are irrelevant and proportional to M_W^2, indeed:

$$\boxed{\frac{G_F}{\sqrt{2}} = \frac{g_2^2}{8M_W^2}}$$

The strong suppression of these contributions at low energies explains why we refer to these interactions as the **weak interactions**, even though the relevant gauge couplings are as large as the electromagnetic coupling constant

Neutrino masses and the see-saw mechanism

The discovery of **non-zero neutrino masses** is often described as a departure from the SM

But this is no longer true if we consider the SM as an effective low-energy theory

Without a right-handed neutrino (which indeed is not part of the SM), it is impossible to write a neutrino mass term at the level of relevant or marginal operators

However, it is possible to write a gauge-invariant **neutrino mass term** at the level of **irrelevant operators** of dimension 5:

$$\boxed{\mathcal{L}_{\text{neutrino mass}} = \frac{g}{M}\,(\tilde{l}_L^T\,\Phi^*)\,C\,(\tilde{\Phi}\,l_L)}$$

Neutrino masses and the see-saw mechanism

After electroweak symmetry breaking, this gives rise to a **Majorana mass term** of the form:

$$\boxed{\mathcal{L}_{\text{neutrino mass}} = -\frac{v^2 g}{2M}\,\tilde{\nu}_L^T C\,\nu_L}$$

The SM as an effective field theory **predicts** that neutrinos should be massive, with $m_\nu \sim v^2/M$ suppressed by the fundamental scale of some BSM physics

Experiments hint at the fact that the fundamental scale relevant for the generation of neutrino masses may be very heavy,

$$\boxed{M \sim 10^{14}\,\text{GeV}}$$

which is not far from the scale of grand unification

Neutrino masses and the see-saw mechanism

Extensions of the SM containing **heavy, right-handed neutrinos** (with masses that are naturally of order M) provide explicit examples of fundamental theories which yield such a Majorana mass term when the heavy, right-handed neutrinos are integrated out **(see-saw mechanism)**

Baryon and lepton number conservation

In the construction of the SM, the conservation of baryon and lepton number is not imposed as a condition

There are no corresponding U(1) symmetries of the Lagrangian

How can we understand that we have not seen any hints of baryon- or lepton-number violating processes?

The answer is that **it is impossible** to construct any relevant or marginal operators that would respect the gauge symmetries of the SM and **violate baryon or lepton number!**

Hence, at the level of renormalizable interactions, baryon- and lepton-number conservation are **accidental symmetries** of the SM, but we do not expect them to be fundamental symmetries of nature

Proton decay

Suppose you know the gauge symmetry $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ of the SM but nothing else (no GUTs). What could you say about proton decay?

The effective Lagrangian must contain at least **three quark fields** (change baryon number by 1 unit) and **one lepton field** (change lepton number by 1 unit)

Hence:

$$\mathcal{L}_{\text{proton decay}} \sim \frac{g}{M^2}\, qqq\ell$$

Since the lowest-dimension operators have dimension 6 (corresponding to $\gamma_i = -2$), the proton can be made sufficiently long-lived by raising the fundamental scale *M* into the 10^{16} GeV range

Proton decay

Now imagine that you do not know about the existence of quarksbut you do know about protons and pions

Then an effective Lagrangian giving proton decay could be:

$$\mathcal{L}_{\text{proton decay}} \sim g\,\pi\,\bar{\psi}_e\,\psi_p$$

This is a marginal operator, and hence proton decay would not be suppressed by any large mass scale!

In some sense, we see that the **longevity of the proton** provides a hint for a substructure of the proton: **replacing a fundamental field by a composite of several fields** raises the dimension of the operators and hence gives rise to additional suppression

Proton decay

The same trick can be applied to other fine-tuning problems

For example, the hierarchy problem can be solved by supposing that the **Higgs boson is not an elementary scalar** particle but instead a **composite of a pair of elementary fermions**

If this is the case, then the Higgs mass term corresponds to a four-fermion operator, which is irrelevant

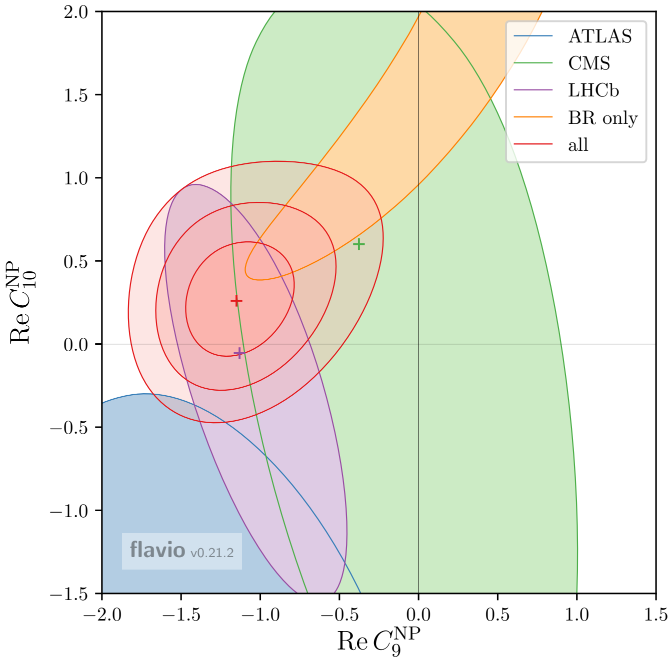
This is the main idea of **composite-Higgs theories**

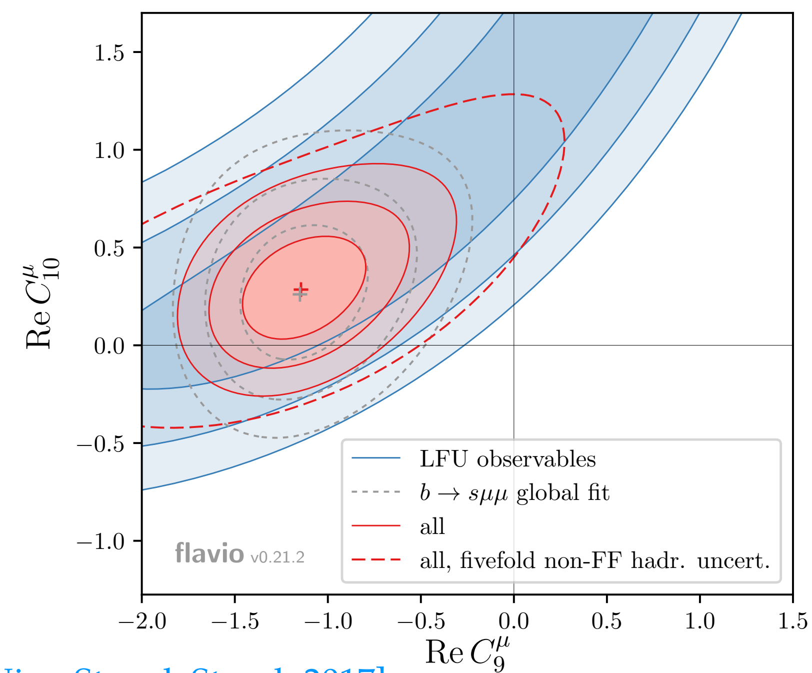
Flavor sources beyond the SM

Hints from the B-meson flavor anomalies

Addressing the anomalies requires **new heavy particles** with masses in the one-few TeV range

Global fits to Wilson coefficients prefer new physics in **left-handed** quark and (to a lesser extent) lepton currents





[Altmannshofer, Nies, Stangl, Straub 2017]

[see also: Capdevila, Crivelin, Descotes-Genon, Matias, Virto 2017; Hurth, Mahmoudi, Neshatpour 2016; Ciuchini, Coutinho, Fedele, Franco, Paul, Silvestrini, Valli 2017; …]

Hints from the B-meson flavor anomalies

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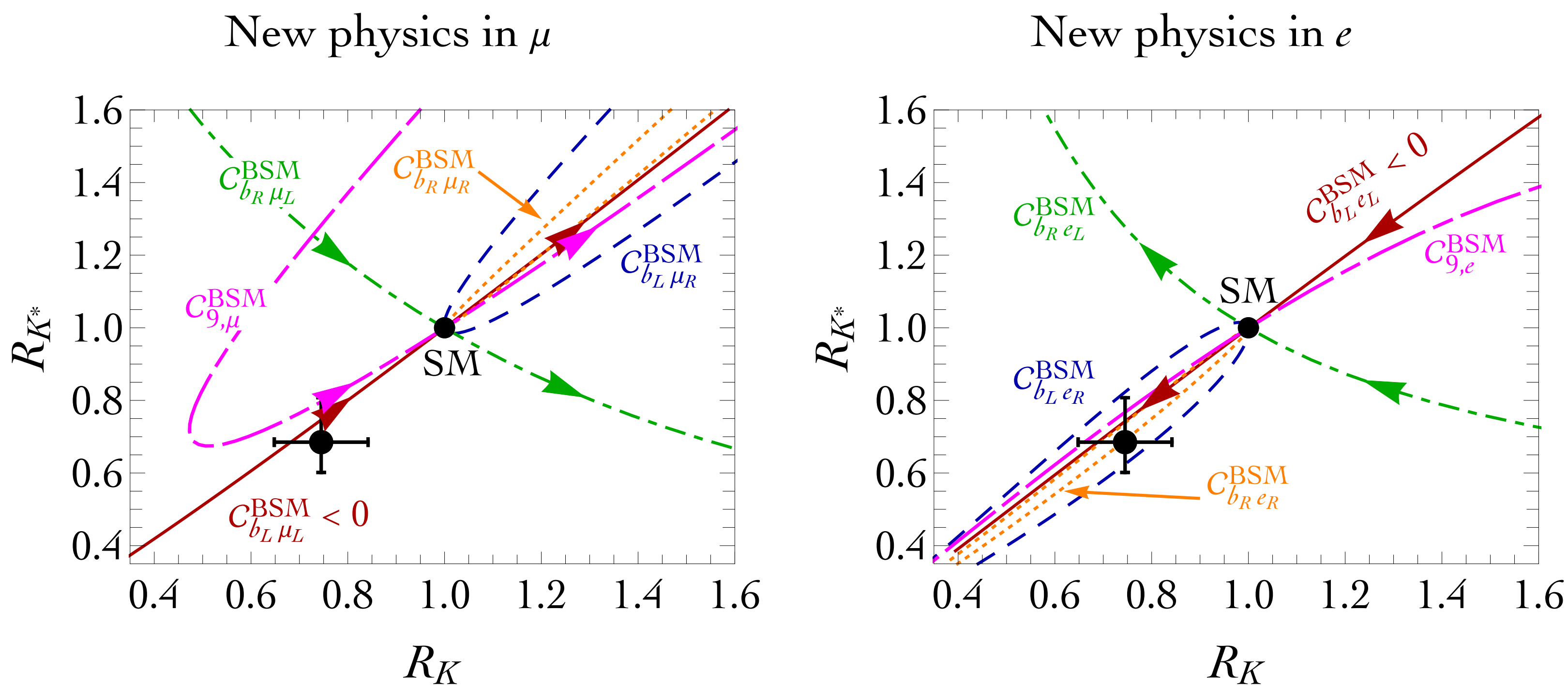


[D'Amico, Nardecchia, Panci, Sannino, Strumia, Torre, Urbano 2017; Geng, Grinstein, Jäger, Martin Camalich, Ren, Shi 2017]

Hints from the B-meson flavor anomalies

Addressing the anomalies requires **new heavy particles** with masses in the one-few TeV range

UV theory describing these particles must **respect the gauge structure** of the SM, and hence the effective weak Hamiltonian describing their effects should be $SU(2)_L \otimes U(1)_Y$ invariant

This implies **interesting relations** between operators describing **different processes**!

Most general new physics coupling to left-handed quark and lepton currents:

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

Contributes to both $b \to c\ell^-\bar{\nu}$ and $b \to s\ell^-\ell^+$ transitions!

Hints from the B-meson flavor anomalies

Interesting framework for addressing all flavor anomalies:

[Buttazzo, Greljo, Isidori, Marzocca 2017]

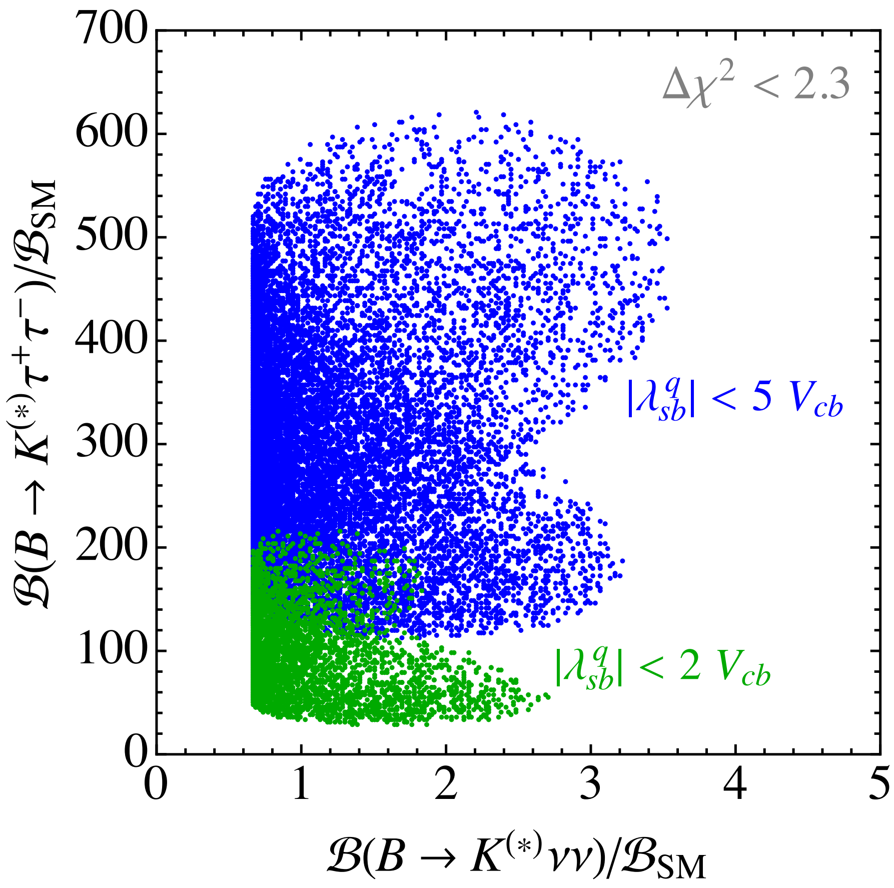
- assume new physics couples only to left-handed currents
- hypothesis that NP couples primarily to 3rd generation fermions explains enhancement of $b \to c\tau\bar{\nu}$ over $b \to s\mu^+\mu^-$ and absence of anomalies in *K*, π, τ decays [Glashow, Guadagnoli, Lane 2014]
- impose flavor structure governed by minimally broken $U(2)_q \times U(2)_l$ flavor symmetry: [Barbieri, Isidori, Jones-Perez, Lodone, Straub 2011]

$$\lambda^q_{sb} \sim V_{cb}\,, \qquad \lambda^\ell_{\tau\mu} \sim V_{\tau\mu}\,, \qquad \lambda^\ell_{\mu\mu} \sim V^2_{\tau\mu}$$

Possible mediators could be colorless new vector bosons or scalar/vector leptoquarks

Hints from the B-meson flavor anomalies

Smoking-gun signature: strong enhancement of $B \to K^{(*)}\tau^+\tau^-$ branching ratio by orders of magnitude



[Buttazzo, Greljo, Isidori, Marzocca 2017]

Emergence of a bigger picture?

Required new particles in few TeV range, precisely where we (now) expect a solution to the hierarchy problem!

Leptoquarks can arise from GUTs, neutrino mass models, SUSY models, or as pNGBs [Popov, White 2016]

E.g. composite-Higgs models with partial fermion compositeness [Buttazzo, Greljo, Isidori, Marzocca 2016 …]

- address hierarchy and flavor problems at ~10 TeV, light scalar leptoquarks (~TeV) as pNGBs
- interesting challenges for model building

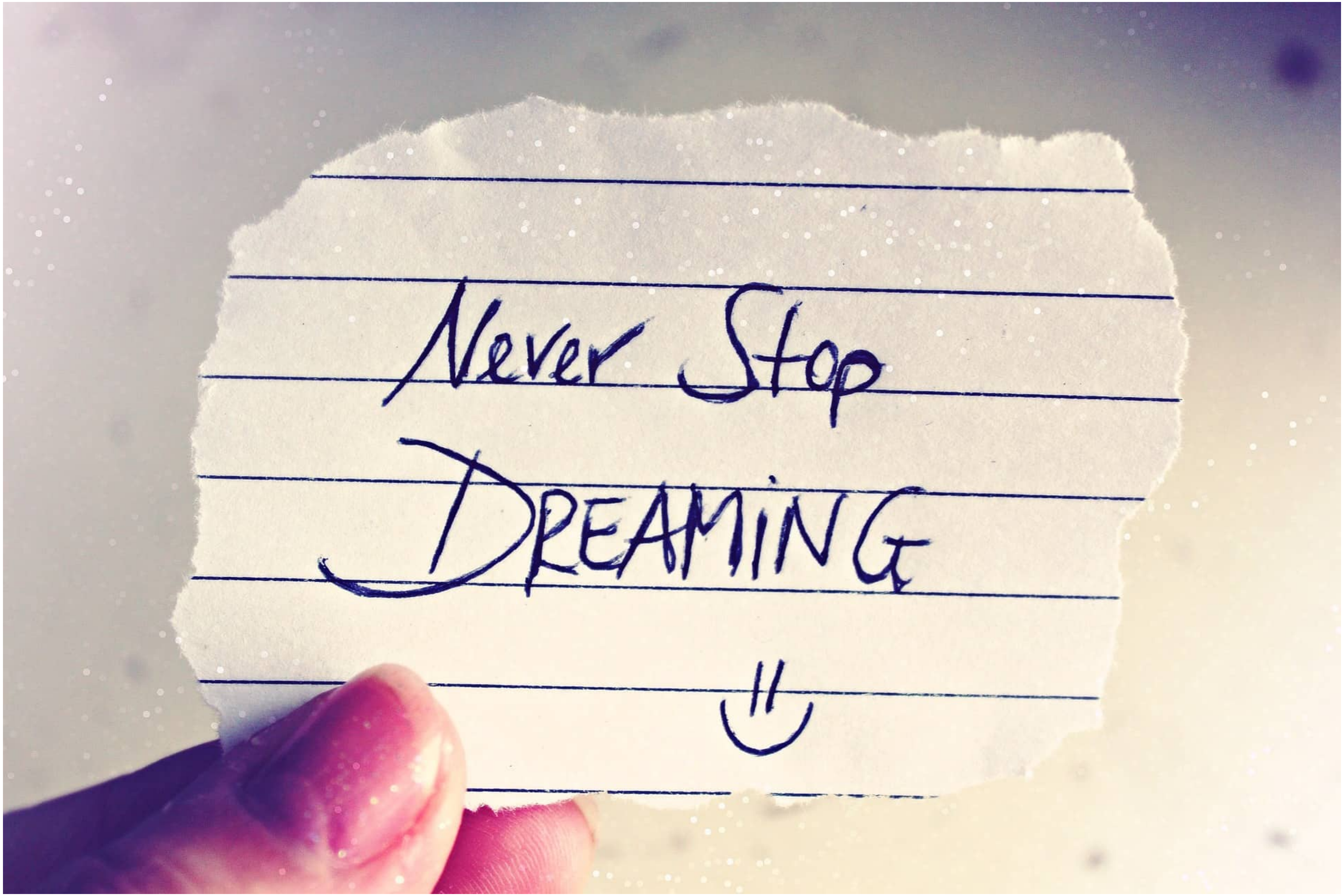
Emergence of a bigger picture?

Flavor data may teach us an important lesson:

- complementarity of different fields
- intimate connection between flavor and high-p_T physics

Imagine the LHC legacy:

- discovery of the Higgs boson (2012)
- discovery of lepton-flavor non-universality (2019?)
- discovery of the predicted leptoquarks/vector bosons (202??)
- emergence of a consistent, unified theory of flavor and electroweak symmetry breaking (20???)


Never Stop
DREAMING

Last words …

If confirmed, the B-meson flavor anomalies are perhaps the most important discovery in particle physics since the discovery of the weak gauge bosons:

- point to existence of new heavy particles in few-TeV range
- possibly, these might be connected to a fundamental theory of electroweak symmetry breaking and flavor
- strong physics case for future high-energy colliders

We live in exciting times!

Please visit us in Mainz:

Mainz Institute of Theoretical Physics (MITP):
Theory Summer School "Nonperturbative Phenomena and the Early Universe" (22 July — 9 August 2019)

http://www.mitp.uni-mainz.de

Cluster of Excellence "Precision Physics, Fundamental Interactions and Structure of Matter" (PRISMA)

http://www.prisma.uni-mainz.de