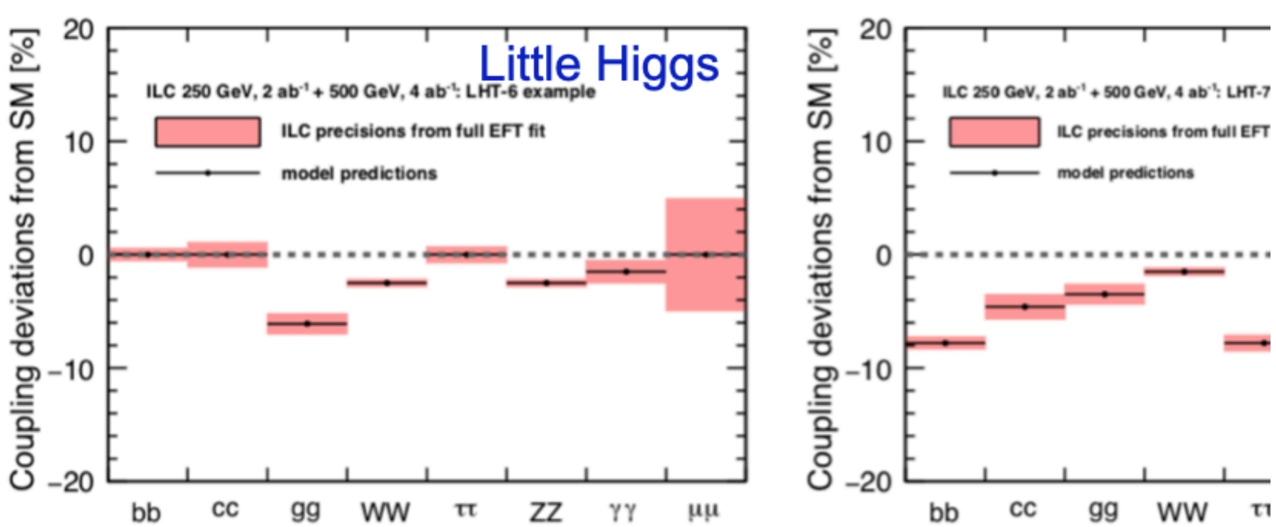
What are the key open questions in particle physics ?



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The organizers invited me to discuss this topic but also asked me to present this survey in 22 minutes.

I have tried to make my reply as sharp as possible, perhaps at the expense of oversimplification. Please excuse me if your favorite topic is omitted.

Here are my questions:

1. Why is flavor symmetry violated ?
2. Why does the universe not look like the Standard Model ?
3. Why does the Higgs boson … ?
4. What are the limits of reductionism ?

1. Why is flavor symmetry violated ?

Particle physics was hardly a mystery when there were only electrons, protons, and neutrons. Today we know that there are 12 types of SM fermions with masses ranging over

$$m_e = 0.5 \text{ MeV}, \; m_u = 1.5 \text{ MeV}, \; \cdots, \; m_t = 164,000 \text{ MeV}$$

(MSbar masses at Q = 164 GeV). To the best of our knowledge, the strong, weak, and electromagnetic couplings of these particles are given by the same values for (e,μ,τ), (u,c,t), (d,s,b).

So where did these large mass ratios come from ?

In the SM, the fermion mass pattern comes from the Higgs boson Yukawa couplings.

$$\mathcal{L} = -y_e^{ij} L_a^{\dagger i} \Phi_a e_R^j - y_d^{ij} Q_a^{\dagger i} \Phi_a d_R^j - y_u^{ij} Q_a^{\dagger i} \epsilon_{ab} \Phi_b^* u_R^j$$

We are allowed to put in any 3x3 complex matrices for y_e, y_d, y_u. This introduces a very large number of parameters, 3 x 18 = 54. Most of these parameters can be removed by changes of variables. What is left is the 9 quark and charged lepton masses and the 4 parameters of the CKM matrix. To interpret these 13 numbers, we need to guess the underlying pattern.

In 1977, Harold Fritzsch guessed a pattern that gave

$$\sin\theta_C = \sqrt{m_d/m_s}$$

Since then, we have more and better data, but our understanding has only decreased.

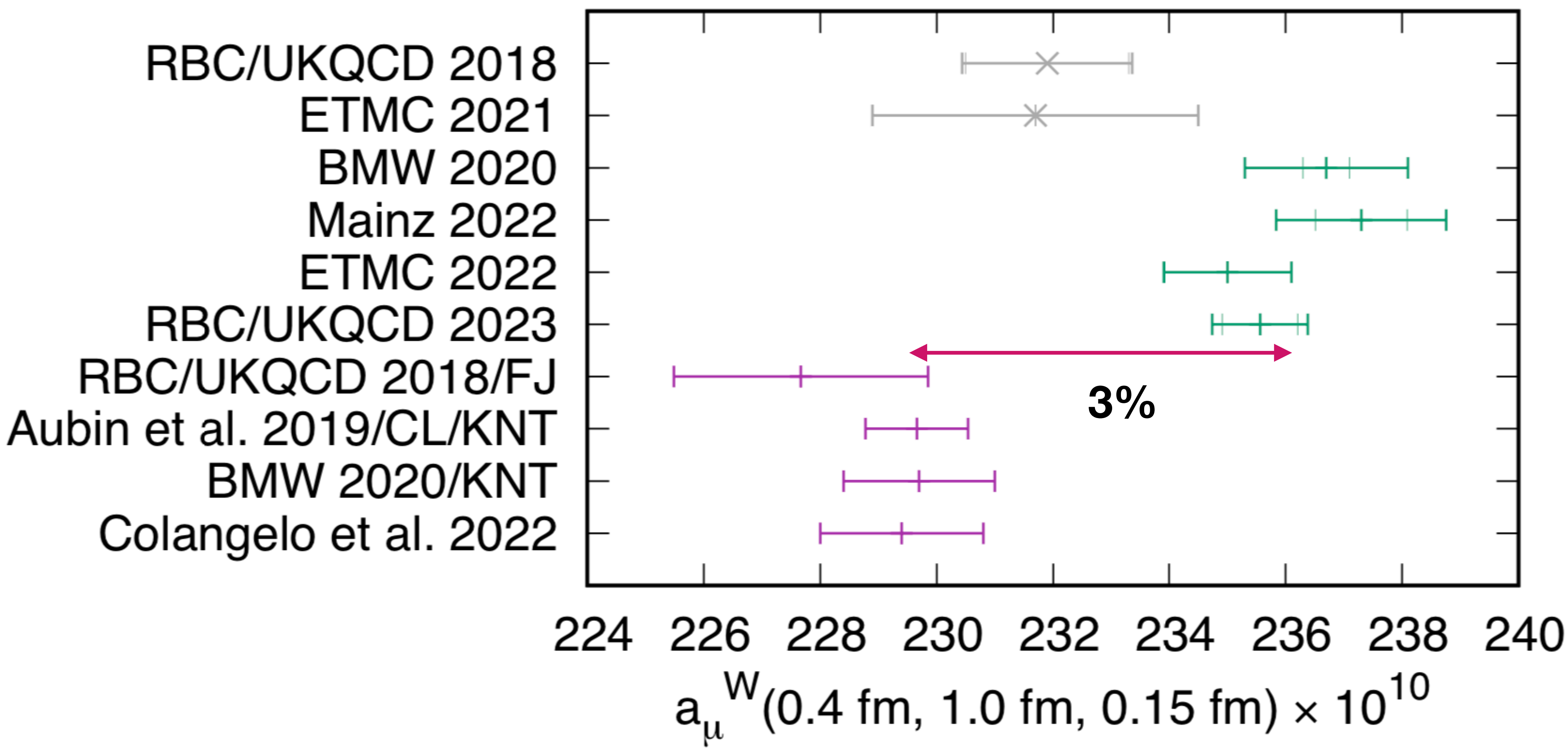
Are there new forces that act differently on different flavors ? These are potentially visible as anomalies in quark and lepton weak decays. Such anomalies would point to new particles with flavor-dependent interactions in the 2-5 TeV mass range.

These may be leptoquarks, but also they may be flavor-changing heavy Higgs bosons (Altmannshofer and Gori).

A challenge is that the observed effects must be unambiguously free of hadronic uncertainties.

In the past year, two such effects that did seem unambiguous are now going away. These are

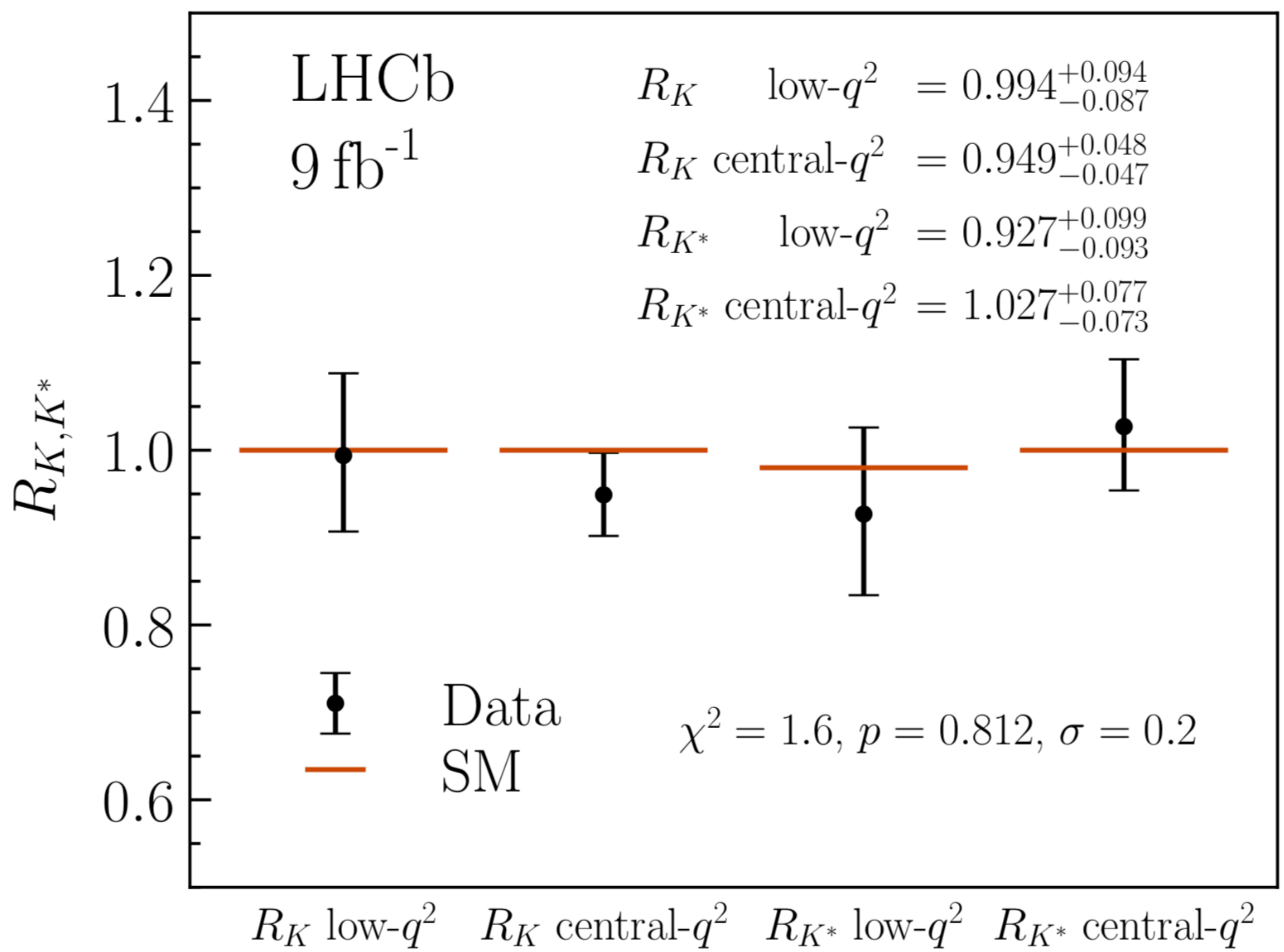
muon g-2 : new lattice evaluations of the hadronic vacuum polarization move toward the experimental value:



“intermediate window” Blum, arXiv:2301.08696

LHCb violation of e/μ universality in $B \to K^{(*)}\ell^+\ell^-$

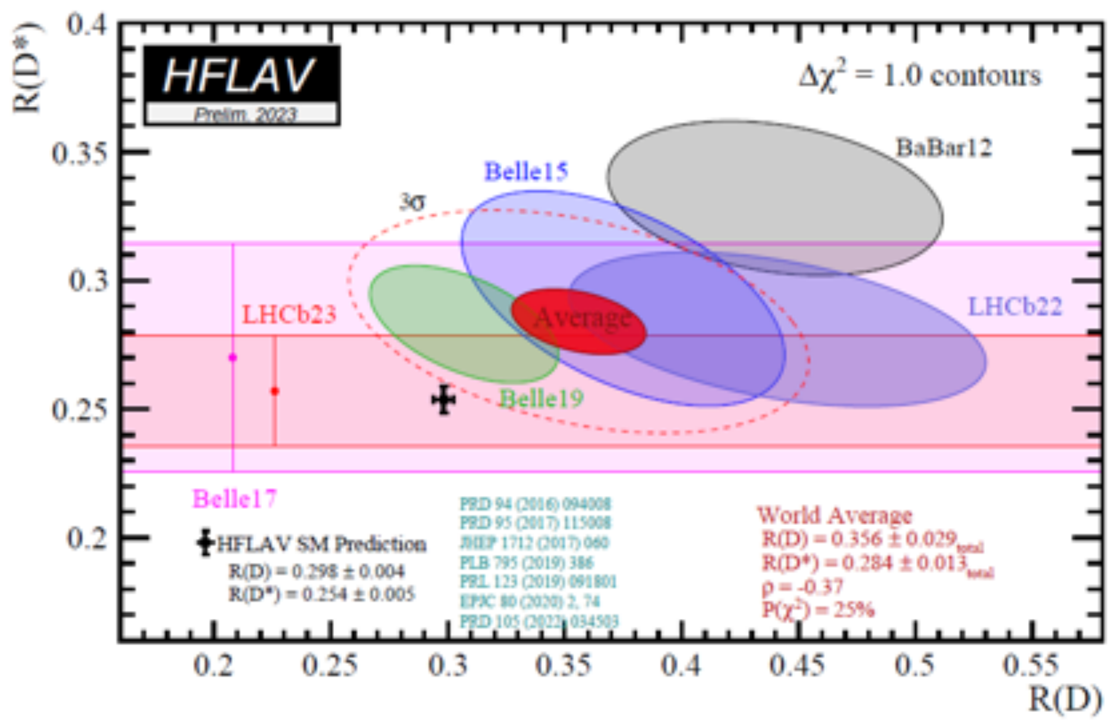
after higher purity selections to remove hadronic decays



LHCb Collaboration, arXiv:2212.09153

Many possibilities remain:

The situation of $B \to D\tau\nu$ decays is still uncertain.



LHCb
arXiv:2302.02886

These are difficult experiments dominated by non-τ background. I am eager to see Belle II resolve this.

It is very important to continue the search for lepton flavor violating decays. Important channels are:

$\mu \to e\gamma$	MEG II, Fermilab Mu2e
$\tau \to \mu\gamma, e\gamma$	Belle II opportunity
$h \to \mu\tau, e\tau, bs$	expected in many BSM Higgs models

Neutrino mass is part of the theory of flavor, but I do not see this as part of the most sensitive tests.

Neutrino masses are a billion times smaller than quark and lepton massesd. This seems to require a new mechanism. The simplest is the type-1 seesaw (Yanagida, Ramond et al.)

$$\mathcal{L} = -y_\nu^{ij} L_a^{\dagger i} \epsilon_{ab} \Phi_a^* N_b^j - \mathcal{M}^{ij} N_a^i \epsilon_{ab} N_b^j + h.c.$$

This leads to Majorana masses for the light neutrinos, with a mass matrix of the form

$$\mathbf{M} = y_\nu^T \frac{1}{\mathcal{M}} \, y_\nu^*$$

It is very tempting to guess that the y_ν lead to small mixing angles, like the quark Yukawas, while $\mathcal{M}$ gives rise to the large mixing of ν_μ and ν_τ .

Unfortunately, it is not possible to test these hypotheses with low-energy experiments alone.

Two important goals are:

verification that the neutrino masses are Majorana
(observation of neutrinoless double beta decay)

observation of CP violation in the PMNS matrix
(check of the idea that CP violation appears
wherever it is allowed to appear)

On the other hand, this structure makes it very difficult to interpret the values of the PMNS mixing angles.

2. Why does the universe not look like the Standard Model ?

The observed universe differs from the SM in four important respects:

the presence of structure, born from near-scale-invariant Gaussian perturbations

the preponderance of matter over antimatter

the presence of dark matter

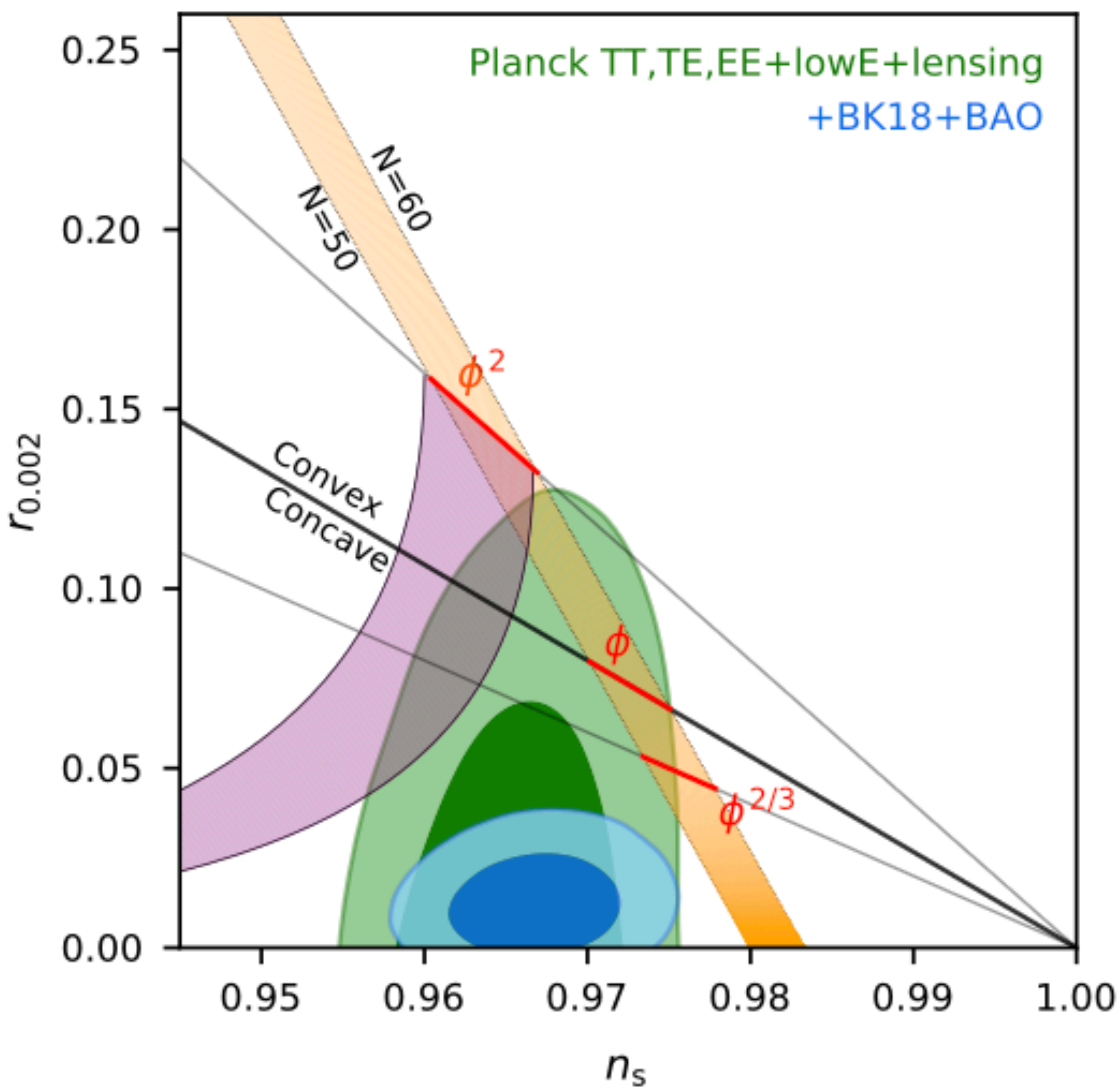
the presence of dark energy

(I reserve the last of these for discussion later.)

The initial conditions for cosmic structure formation are given by a near-scale invariant, near-Gaussian set of density fluctuations.   This is the expectation for an almost free scalar field in a universe with a large cosmological constant leading to rapid expansion.

This is cosmic inflation. (Guth)

We know hardly anything about this scalar field except for limits on its couplings and the curvature of its potential. The energy scale V of the CC is now known to be close to or less than the Planck scale.



$$r \approx 0.03\ (V/10^{18}\ \text{GeV})^4$$

BICEP-KEK
arXiv:2110.00483

Snowmass writeup on Inflation
Pimentel, Wallish, Wu et al.
arXiv:2203.08128

In models with inflation, the baryon-antibaryon asymmetry must be generated in the early universe. Only a small asymmetry is needed, of order 10^{-10}. But this requires, among other things, CP violation (Sakharov).

The CP violation might be that of the SM, but — since any zero quark mass allows this to be rotated away — any SM mechanism is suppressed by a factor

$$\prod_f \left(\frac{m_f}{T}\right) \sim 10^{-15}$$ even for T = 100 GeV.

It is very difficult to escape this restriction.
(Sather and Huet, hep-ph/9404302)

So, the baryon asymmetry must be due to a new source of CP violation not present in the SM.

There are many possible origins of this CP violation. Any scalar field coupling can potentially be complex-valued.

This scalar field can arise from

a multi-Higgs system at the scale of the electroweak phase transition

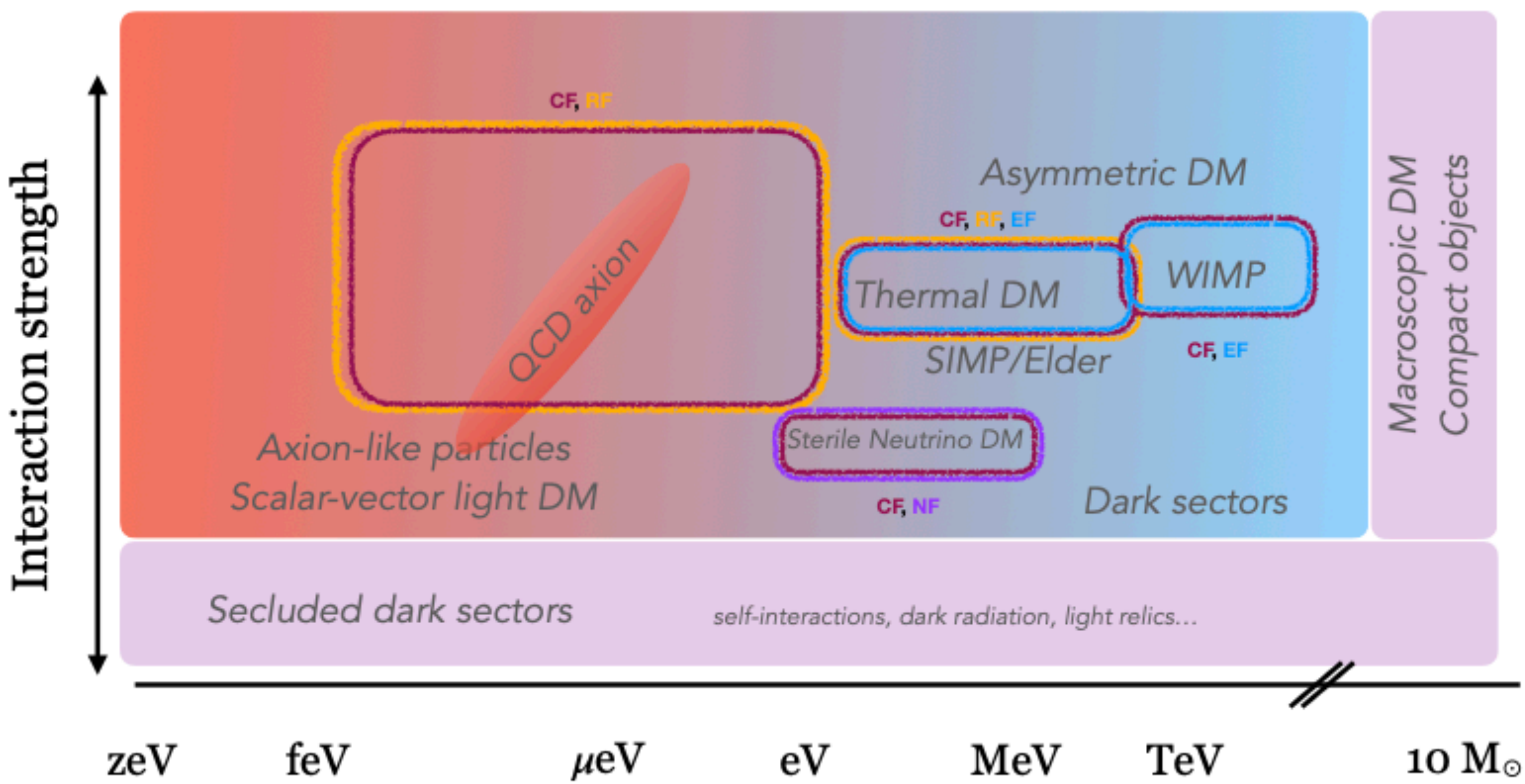
flavor-violating scalars at 30-100 TeV

the scalars that generate the neutrino mass $\mathcal{M}$ at $10^{10} - 10^{14}$ GeV

This last choice, called leptogenesis (Fukugita-Yanagida) is very popular with neutrino physicists. But, it cannot be tested. Neutrino CP violation at low energies comes from a different phase angle.

Dark matter is now known to account for 27% of the energy density of the universe. I do not need to argue for that to this audience; anyway, there is no time.

There is a huge range of models of dark matter, covering a range that is large in mass, interaction strength, and conceptual origin: (Boveia et al, arXiv:2210.01770)



For particle physicists, the big question is, what is the relation of dark matter to the SM ? The possibilities are:

dark matter comes from a natural extension of the SM (supersymmetric DM candidates, sterile neutrinos)

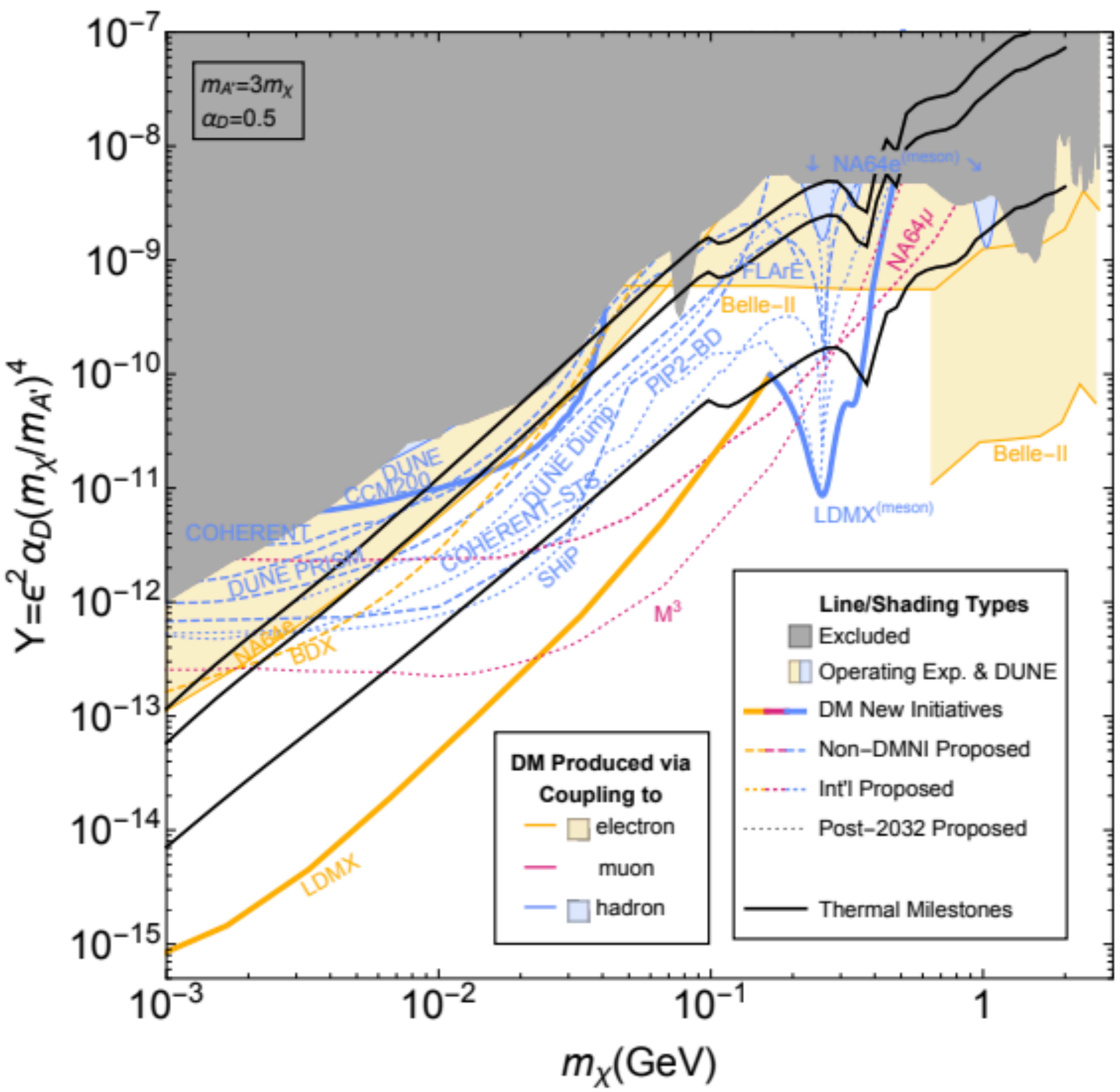
dark matter is associated with a new high-energy scalar sector (axion, ALP)

dark matter comes from a new sector with no relation to the SM except for a highly suppressed "portal" coupling (dark photon, dark Higgs models)

dark matter is composed of macroscopic objects not created from baryons (primordial black holes)

Recently, there has been much interest in dark sector candidates. These live a phase space that we can exclude now, with tabletop and fixed target accelerator experiments.

(Bjorken, Essig, Schuster, Toro, arXiv:0906.0580)



Snowmass Dark Sector report
Gori, Williams, et al.
arXiv:220904671

I would like to call attention to two scenarios that are highly motivated but are difficult and, maybe for that reason, receive less attention:

Heavier WIMPs, with masses of 1-10 TeV, coupling directly to the SM. An example is the unmixed Higgsino of supersymmetry (1 TeV).

Axions with f_a near the grand unification scale. In string theory, there are typical many such scalars.
(Svrcek and Witten, hep-th/0605206)

It is necessary to explain why, during inflation, the axion field stays close to its CP-conserving value.

3. Why does the Higgs boson … ?

A recurring theme in the previous discussion is the role of scalar bosons. We need scalars to give flavor-dependent masses to fermions, to induce neutrino masses, to create CP violation, to create density perturbations in inflation, maybe to provide the dark matter.

For vector bosons, their couplings are fixed by the gauge principle. This structure is rigid, it has no freedom. For scalars it is the opposite — any choices are permitted! Unless there is a corresponding "scalar principle", we cannot understand why scalar couplings have the needed values.

In 1981, Lev Okun called this "Problem #1" in particle physics. It still is.

I do not have a good idea of what this “scalar principle” would be.

It might be the idea that all scalars are composite and that we can compute their couplings if we know their internal structure.

It might be that there is an organizing principle based on symmetry. N=1 supersymmetry is not strong enough. What can we add ?

Today, we know one apparently fundamental scalar, the Higgs boson. Its couplings explain (or do not explain) all of the mysteries of the SM.

For me, the most troubling aspect is the lack of explanation for the spontaneous electroweak symmetry breaking that allows the Higgs to fulfill its other roles. In the SM, we write the most general renormalizable potential

$$V = m_\Phi^2 |\Phi|^2 + \lambda |\Phi|^4$$

and then simply assume $m_\Phi^2 < 0$. That isn't physics! Compare this to the theory of superconductivity by Cooper pairing. That is an explanation, in terms of more fundamental particles and interactions.

I find this logic exciting:

If electroweak symmetry breaking has a physics explanation, that explanation much be given in terms of new particles and forces that act at short distances that we have not yet explored.

These new forces wait to be discovered.

We might find hints of these forces in current experiments, but, ultimately, we need to go to characterize these forces with higher energy experiments.

As a first step, we need to understand our one example, the Higgs boson, much better.

Within the SM, and using the information of the Higgs boson mass, all couplings and decays of the Higgs boson are predicted. Any deviations must come from new particles, outside the SM, that couple to the Higgs field.

In models, predicted deviations are $<$ 10% effects. So, at the LHC, we have not begun to address this question yet.

The ideal setting to demonstrate deviations in the Higgs boson couplings is an e+e- collider operating in the CM energy range of 240 - 600 GeV, an e+e- Higgs factory.

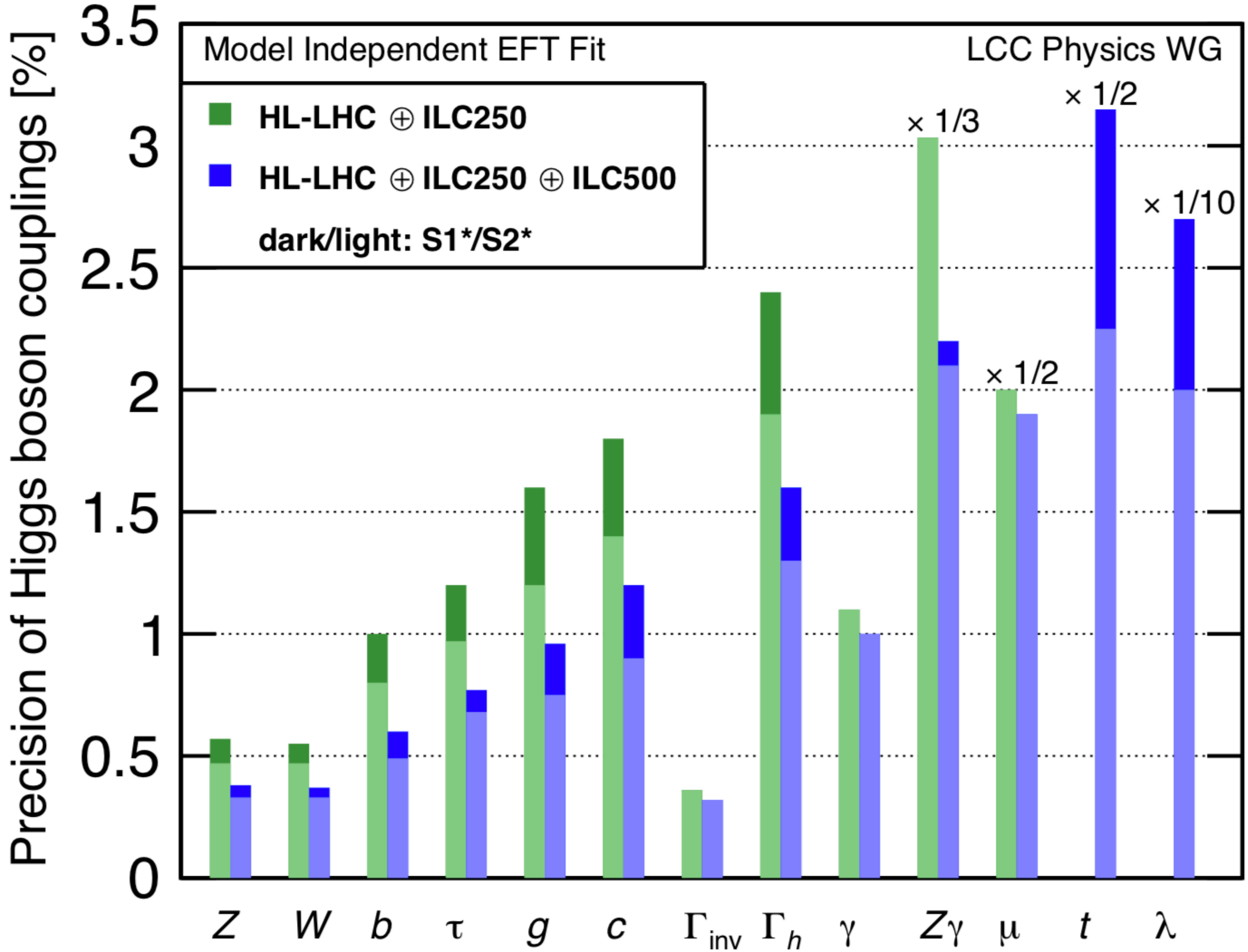
Realizations based in different technologies are under consideration in different parts of the world:

ILC	in Japan	(From a technological
FCC-ee	at CERN	point of view, any
CEPC	in China	of these could be built
C^3	in the US	in any place.)

Any one will measure Higgs couplings to the 1% level and below.

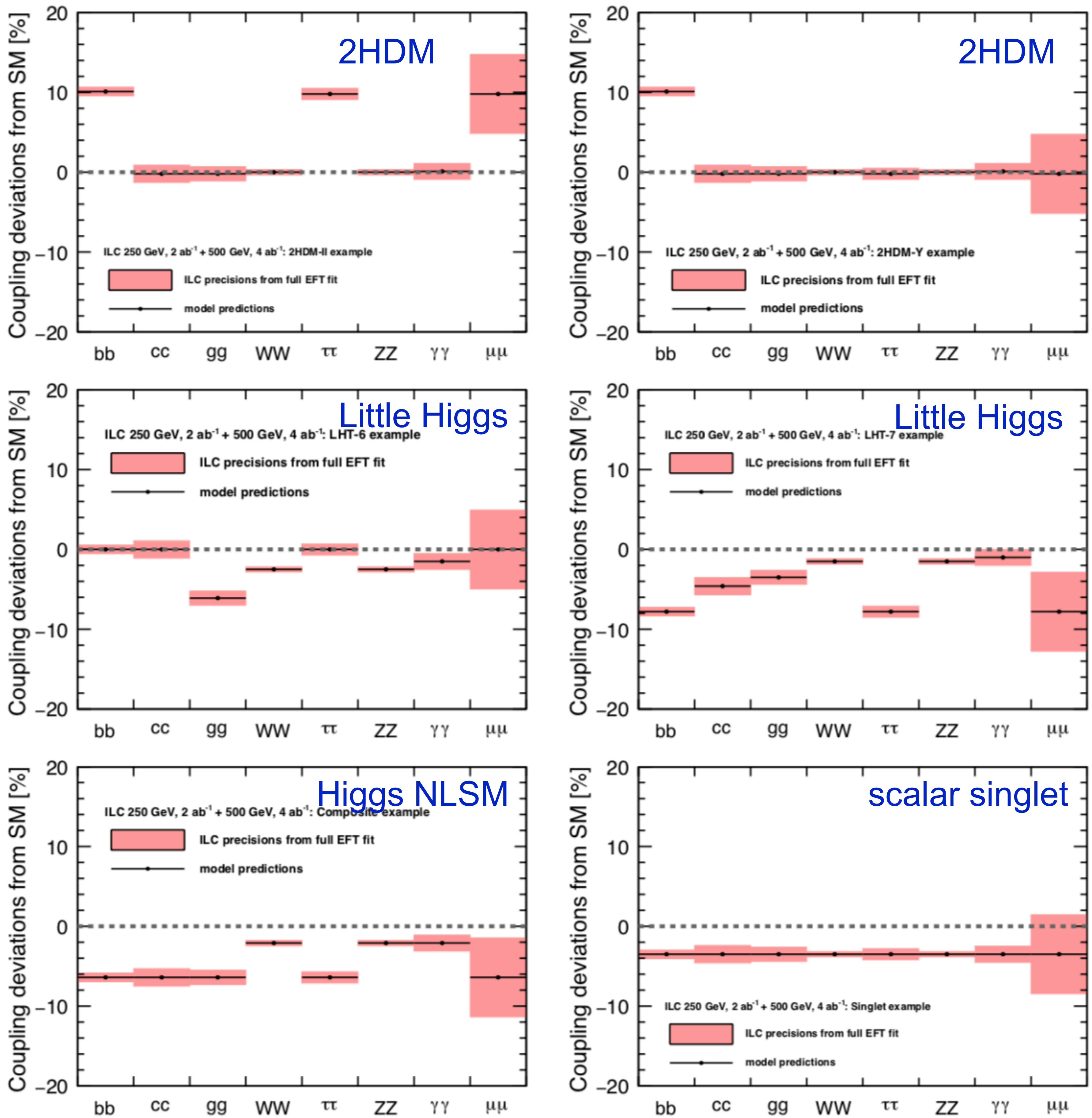
This is the best opportunity we have now to learn the nature of physics beyond the SM.

As an example, here are the expectations for the ILC:



Every model of new particles has its own characteristic pattern of deviations.

Which does nature choose ?



4. What are the limits of reductionism ?

Finally, let's discuss dark energy or the cosmological constant, the energy of the vacuum.

There is no known mechanism to naturally obtain a very small but positive vacuum energy.

In supersymmetric theories, there are solutions with zero vacuum energy. Typically, there are also solutions with negative vacuum energy, in anti-de Sitter space.

So it is very unlikely that our local vacuum will be stable forever. We know already that the SM is unstable for the observed values of its parameters.

In models of inflation, different patches of the universe can reach local minima of the potential, which then locally inflate. This produces a multiverse. The presence of multiverse is generic in theories with inflation beyond a certain level of complexity. (Linde)

So it is terribly likely that our local vacuum is an accident of history, which sooner or later will be corrected.

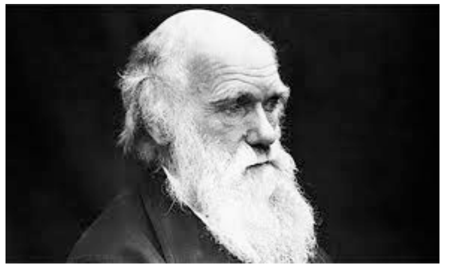
For me, it is compelling (unfortunately) that our vacuum energy is chosen among many possibilities for historical reasons, that is, so that intelligent observers have time to evolve. (Weinberg)

In fact, there is constantly a tension in science about reductionist explanations and historical explanations.

Laplace

Reductionist: The university is governed by simple equations with unique solutions.

Historical: The laws of the universe admit many possibilities. Which solutions are chosen are a matter of history and chance.



Darwin

Eventually, our description of the universe should be expected to rest on some contingencies, some random choices.

Einstein said (to Ernst Strauss, quoted by Carl Seelig):
"What really interests me is whether God could have created the world any differently; in other words, whether the demand for logical simplicity leaves any freedom at all."

Probably he was wrong: There could be a boundary at which simply finding the right equations is not enough.

Physicists are now asking, on which side of that boundary will we find the answers to the questions I have highlighted in this lecture ?? —

electroweak symmetry breaking, flavor and mass generation, CP violation, dark matter, inflation.

As particle physicists, we have signed up to the search for the reductionist path. We must fight as hard as we can for explanations from fundamental laws, and the verification of these explanations by experiment.

Ultimately, it is a matter of faith in our endeavor.

Without that faith, we never find the answers. With it, we can discover new worlds.