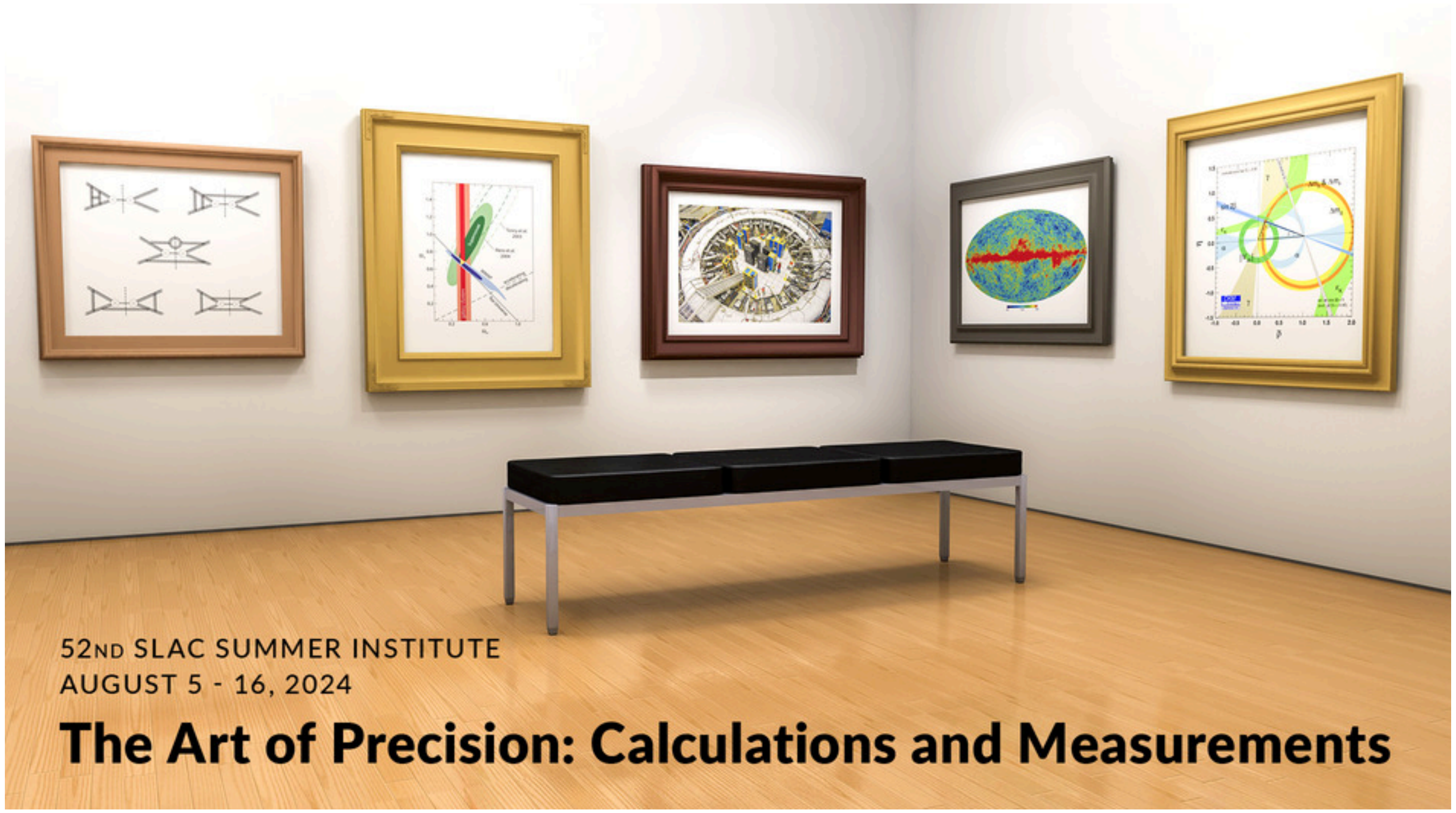
A Precise Future



M. E. Peskin
SSI 2024
August 2024

The motto of RIchard Hamming's famous book on Numerical Methods is:

The purpose of computing is insight, not numbers.

A corollary is:

The purpose of precision is to make discoveries, not to improve the error bars.

A precision measurement that is successful, in this sense, changes the way that we think about nature.

Kevin McFarland showed us how this can occur:

by demonstrating that a basic symmetry of our theories is not respected by our observations, or, conversely, that observations obey a new symmetry or regularity to an unexpected degree

by demonstrating that detailed calculations based on theories that we expect are fundamental do not in fact account for the results of experiment.

In both cases, our accepted theories must be flawed, and must be replaced. If these theories are rooted in a more general world-view, then we are looking at the world in the wrong way.

This criterion for a successful precision measurement carries a heavy burden of proof.

We consider theories fundamental when they are not ad hoc descriptions of observations but rather have a beauty and inner logic. It is not easy to give this up. Fundamental theories explain a broad array of experimental results. It is not easy to give up an array of successes for one failure, however strong.

Thus, typically, we require:

statistically powerful departures from expectations

comprehensive evaluation and control of systematic uncertainties

replication by a second experiment using a different, complementary method

An experimental campaign that hopes for discovery should build in these ingredients from the beginning.

In addition, the connection of the measurement to theory must be considered carefully.

Does the theory to be challenged give robust symmetry predictions, or are there simple ways to escape these ?

Does the theory to be challenged allow predictions with uncertainties comparable to the measurement uncertainties? Do these predictions depend on inputs that might themselves be uncertain ?

Are the predictions dependent on fundamental aspects of the theory, or only on an interpretation of the underlying ideas ?

Challenges to accepted theory need to be thought through in detail. We theorists, when we cannot find a pleasing model, say, "Every experimental discovery must be tested by theory." Maybe the needed new hypothesis is near at hand. But sometimes striking new experimental findings require profound creativity.

In the rest of this talk, I will pick up these themes in relation to examples that we have discussed in this school. But first, why do we need to worry about this ?

It is because of the unusual situation that we have today in particle physics:

The Standard Model is manifestly incomplete.

The Standard Model works too well.

Theorists had many ideas about extensions of the Standard Model to repair its gaps, but these are now strongly constrained by LHC and flavor experiments.

We have no accelerator technology today to explore much higher energies.

So, higher precision is, for the moment, our best hope to find evidence of needed new interactions beyond the Standard Model.

I hope you will excuse me that this talk is almost all about particle physics.

Precision cosmology is in a very similar situation. We have a Standard Model — ΛCDM with noninteracting cold dark matter — that explains a wide-ranging set of observations. This theory is also manifestly incomplete.

There are some remaining tensions, in particular, in the epoch-dependence of the Hubble constant, but these have not suggested interesting theoretical alternatives.

To reach the 1% level in cosmological parameters, we need to address "incalculable" effects due to galaxy structure and evolution.

I do not have more to say about these issues that you just heard from Manu Schaan.

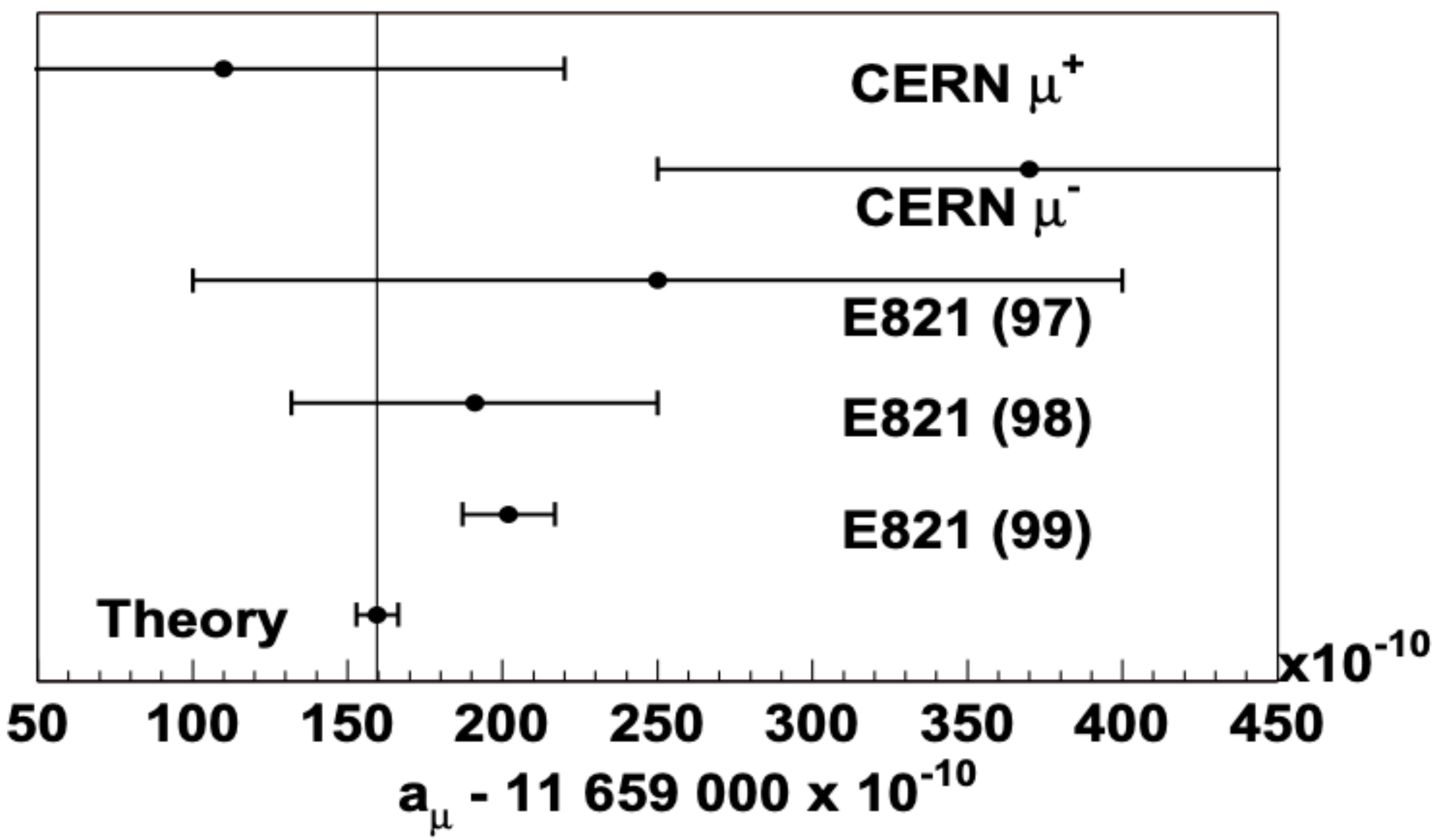
muon g-2 :

The magnetic moments of the electron and muon have been a source of precision tests of fundamental theory since the 1940's, with the work of Polykarp Kusch and Julian Schwinger. Originally, this was a test of the first complete quantum field theory, QED.

Today, this program is sensitive to loop effects from new particles with masses of order 1 TeV. These effects can be visible by comparing very precise experiments to similarly precise quantum field theory calculations.

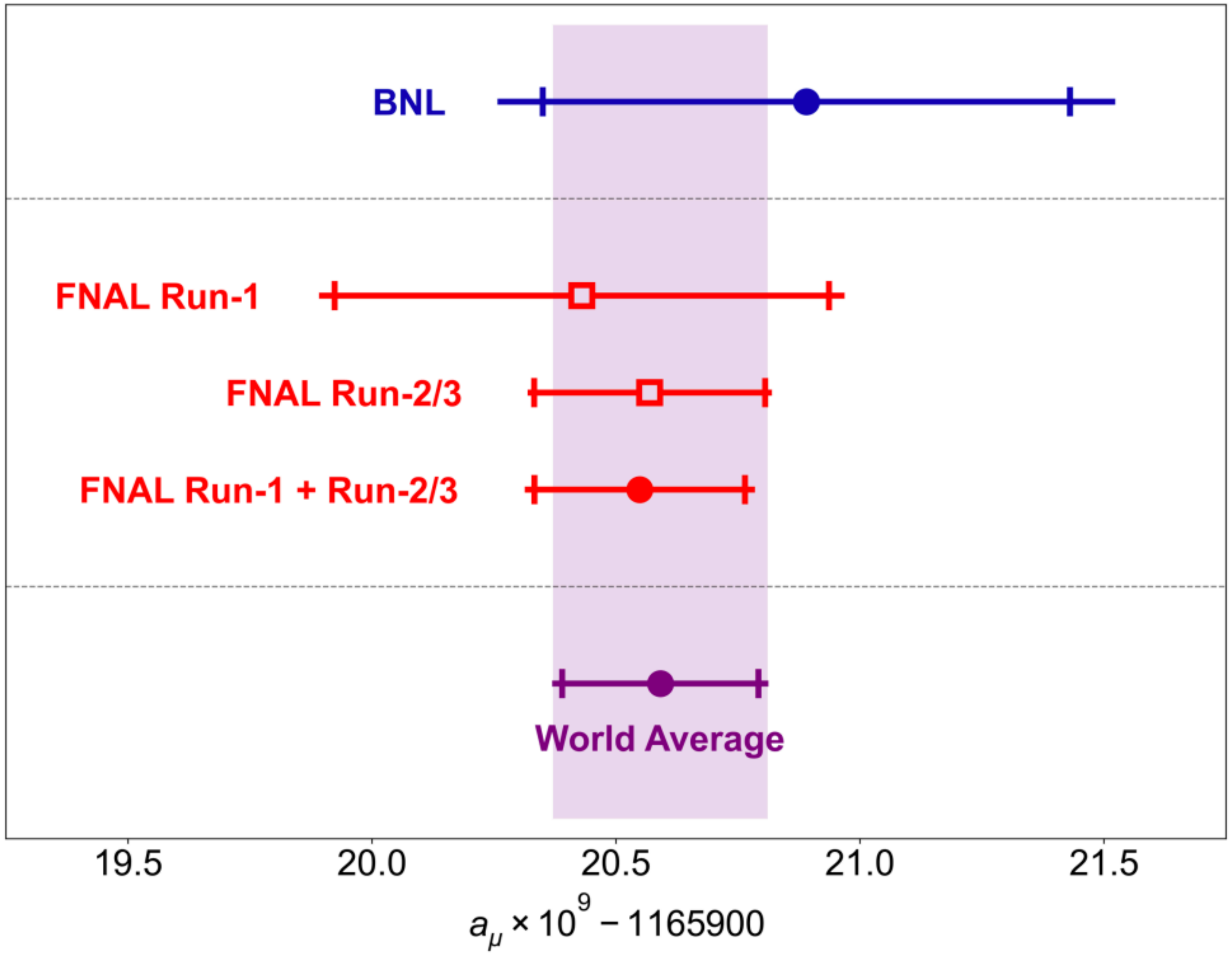
The largest new physics effects would come in the muon g-2, where they are enhanced by m_μ^2/m_e^2 . The measurement of the muon g-2 is the result of a decades-long effect, highlighted by the CERN g-2 experiments of the 1970's, led by Emilio Picasso. These used the trick of the "magic γ" to cancel dependence on external fields and allow a precision of 7.3 parts per million.

Around the year 2000, a new collaboration at BNL aimed to improve this measurement to ~ 100 parts per billion. They found a tantalizing discrepancy between theory and experiment.



Brown et al, hep-ex.0102017

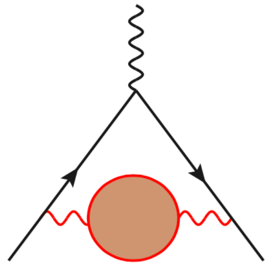
James Mott described for us the status of this experiment. It has survived very close scrutiny, including the transport of the storage ring to Fermilab and its upgrade by a new cast of characters, leading to greatly improved field quality and control of other systematics.



This passes all tests for a high-quality precision result!   The collaboration aims for a final uncertainty of ~ 100 ppb.

The recent surprise is on the side of the theory prediction.

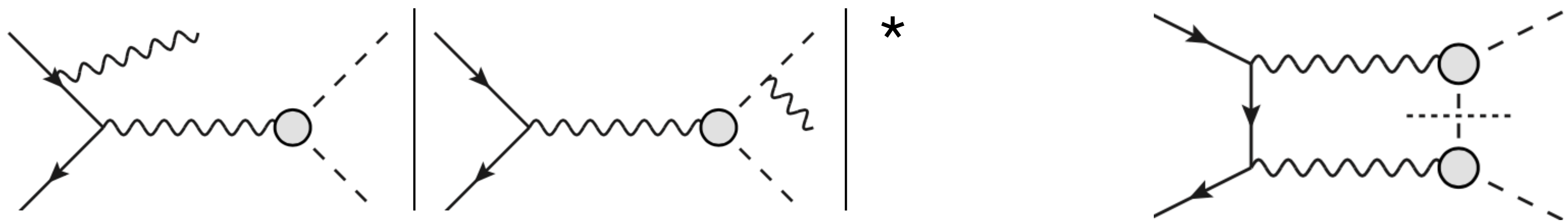
Due to 40 years of effort by Kinoshita and others, the perturbative part of the muon g-2 theory is under very good control. Martin Hofenrichter reviewed this situation for us. The dominant source of uncertainty is in the hadronic vacuum polarization diagram.



This is traditionally calculated from an integral over measured e+e- -> hadrons cross sections.

$$a_\mu^{\mathrm{HVP,LO}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{s_{\mathrm{thr}}}^{\infty} ds \frac{\hat{K}(s)}{s^2} R_{\mathrm{had}}(s) \qquad R_{\mathrm{had}}(s) = \frac{3s}{4\pi\alpha^2}\sigma_{\mathrm{tot}}(e^+e^- \to \mathrm{hadrons}(+\gamma))$$

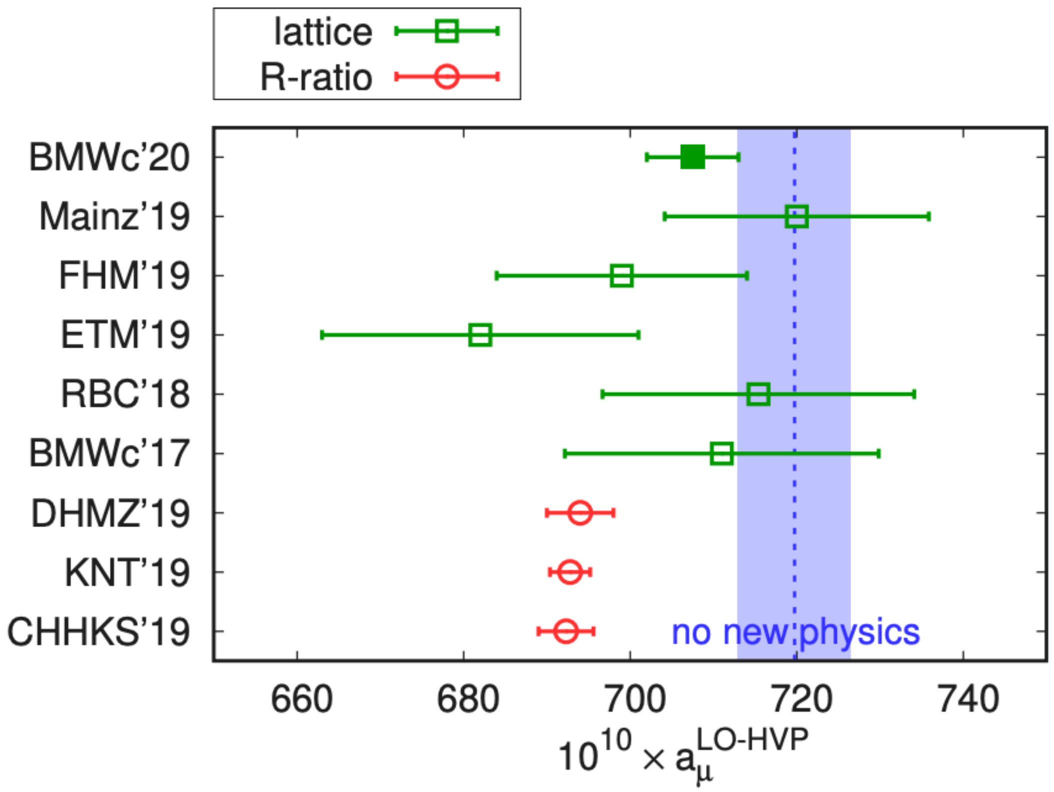
There are subtleties here. Acceptance must be known to better than 1% over multiple detectors from various epochs. Some radiative corrections to the cross sections do not appear in the vacuum polarization and need to be subtracted, leading to a modelling error.



These effects were thought to be under control.

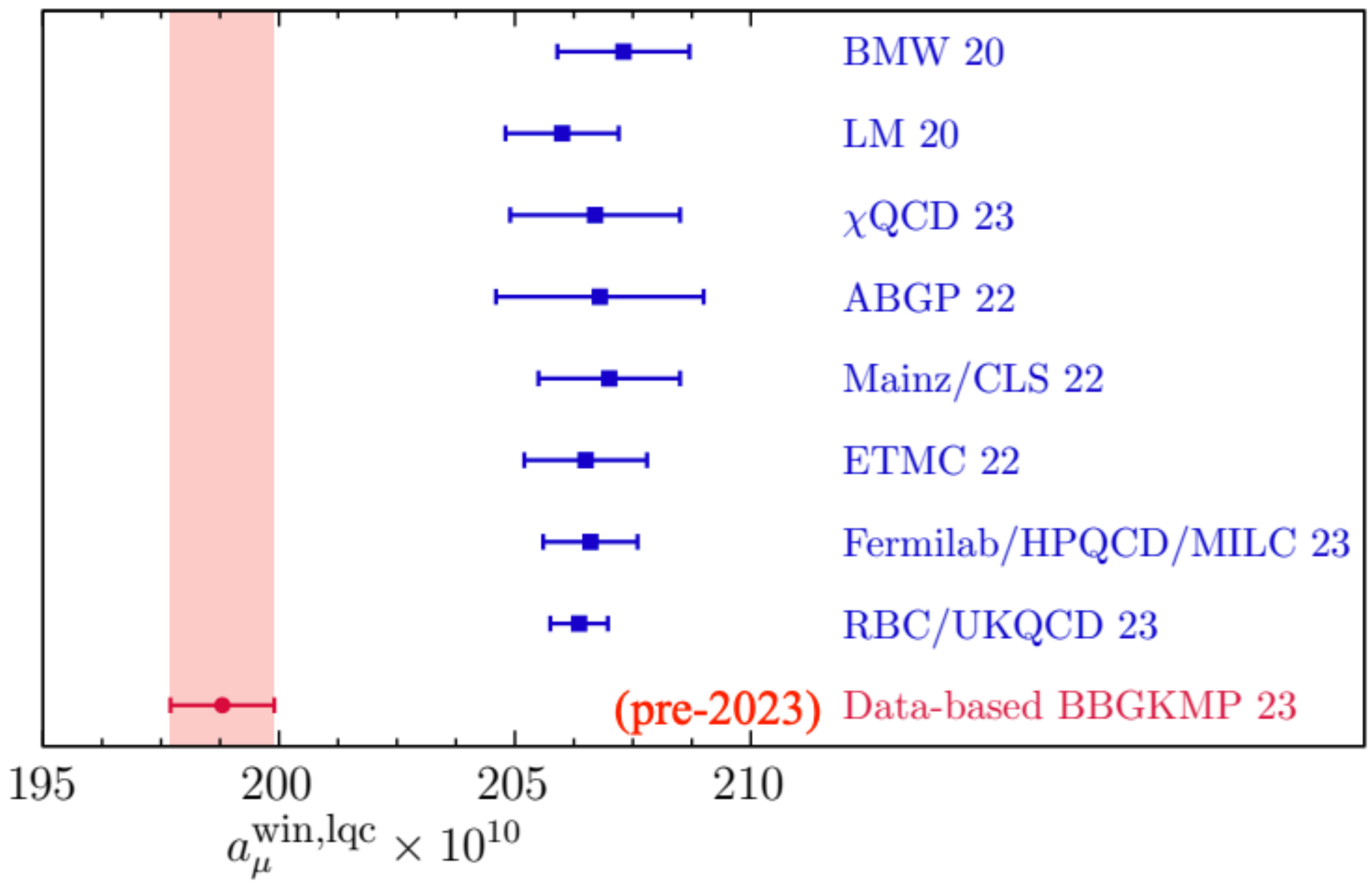
However, simultaneously with the first announcement from Fermilab, the Budapest-Marseille-Wupperthal (BMW) lattice QCD calculation published an ab initio estimate of the hadronic vacuum polarization, in conflict with phenomenological estimates and much closer to the experimental result.

Borsanyi et al.
arXiv:2002.12347 [hep-lat]



Can we test this result without new, large lattice QCD statistics ? Divide the needed integral into 3 regions according to Euclidean time. The intermediate region, which contains the ρ resonance, requires less statistics.

Now, many different lattice QCD groups agree with BMW in the contribution from this region, with a significant discrepancy from the phenomenological estimates.



Multiple calculations of the complete hadronic vacuum polarization are due this fall.

Aida El-Khadra gave us a detailed explanation of the lattice QCD method. There are many subtleties related to control of the lattice UV and IR cutoffs. However, lattice QCD does not depend on details of a constructed detector and contains exactly the needed QED diagrams and no more. It is intrinsically in the spacelike region that we need for g-2. It is anchored in very precisely known QCD observables - the masses of stable hadrons. It is systematically improvable as computers become faster.

I believe that lattice QCD is the future for knowledge of low-energy QCD parameters. This will be important for precision electroweak tests and other higher energy tests of the Standard Model.

Quark Flavor Physics

Wolfgang Altmannshofer and Jim Libby gave us very clear and detailed lectures on the precision calculation and measurement of weak meson decays. These processes give us our only (positive) knowledge about CP violation and, more generally, give us probes in the region of 10 TeV and higher. Many anomalies in flavor physics have come and gone.

What is the relation to the general goals discussed above?

I would first emphasize what I feel is the biggest question about the Standard Model.

The spectrum of quark and lepton masses ranges over 5 orders of magnitude, from the electron (0.5 MeV) to the top quark (170 GeV). We have no idea for the origin of this mass hierarchy, or the origin of the related CKM mixing parameters. In the Standard Model, these come from the Higgs boson couplings to fermions, which are “renormalizable parameters” — that is, we must just put them in by hand.

We are used to this situation, but we shouldn’t be complacent. It likely hides a new, not-yet-discovered, fundamental interaction.

It is very difficult to predict the CKM parameters.

In 1977, Harold Fritzsch gave a 2-generation theory in which

$$\tan\theta_C = \sqrt{\frac{m_d}{m_s}}$$

Since then, many leading theorists have tried to generalize this picture to 3 generations and to improve the model. These people include

Graham Ross, Savas Dimopoulos, Lawrence Hall, Jogesh Pati, Yossi Nir, and Nathan Seiberg

All of the progress has been negative. It is too easy to fit the data with a more complicated theory.

It is not hard to understand why it is so difficult to get insight. In the Standard Model, the quark masses and mixings come from the Lagrangian terms

$$\mathcal{L} = -Y_d^{ij} Q_a^{\dagger i} \Phi_a d_R^j - Y_u^{ij} Q_a^{\dagger i} \epsilon_{ab} \Phi_a^* u_R^j + h.c.$$

This contains 2 complex-valued 3x3 matrices -> 36 parameters. Fundamental structures in the Yukawa terms are given this basis (“textures”).

To discuss observables, we make changes of variables to reduce the parameters to 10 observable combinations —

6 masses, 3 angles, and 1 CP-violating phase.

These data alone do not give us insight to see the pattern.

For this reason, the main thrust of flavor physics has been to discover evidence of new interactions beyond those of the Standard Model. These can be of one of three types, listed in order of decreasing confidence:

violation of manifest Standard Model regularities — lepton flavor conservation and universality

anomalies explicitly associated with 3rd generation particles

quantitative deviations from SM Effective Theory

Anomalies in the 3rd category depend on the shapes of decay distributions. Lattice QCD can help here, but shapes are not yet within the state of the art.

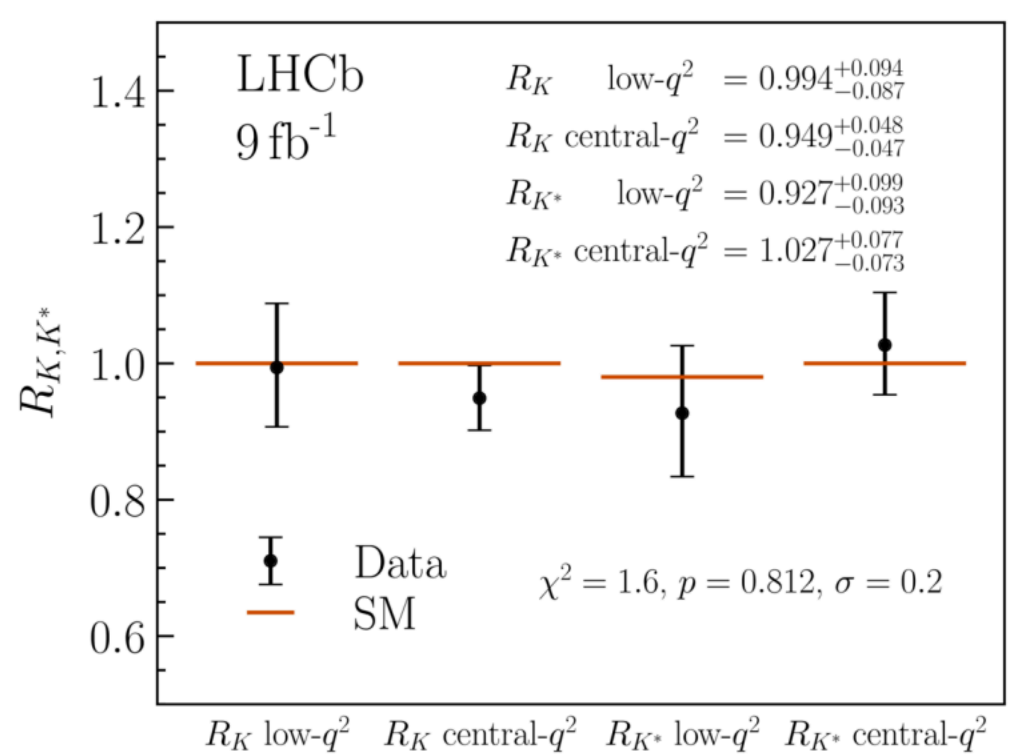
In 2014, the LHCb collaboration announced evidence for a violation of lepton universality, with

$$R_K = \frac{BR(B^+ \to K^+ \mu^+ \mu^-)}{BR(B^+ \to K^+ e^+ e^-)} < 1 \qquad \text{by } 2.6\ \sigma$$

This is a discrepancy of the first type, and it excited great interest. Such an effect, if it would be seen at higher statistics, could not be explained within the Standard Model.

Unfortunately, the original LHCb analysis missed an important systematic effect, the faking of electrons by produced hadrons. Their 2022 analysis gives results consistent with $R_K = 1$.

LHCb 2212.09152, 2212.09153



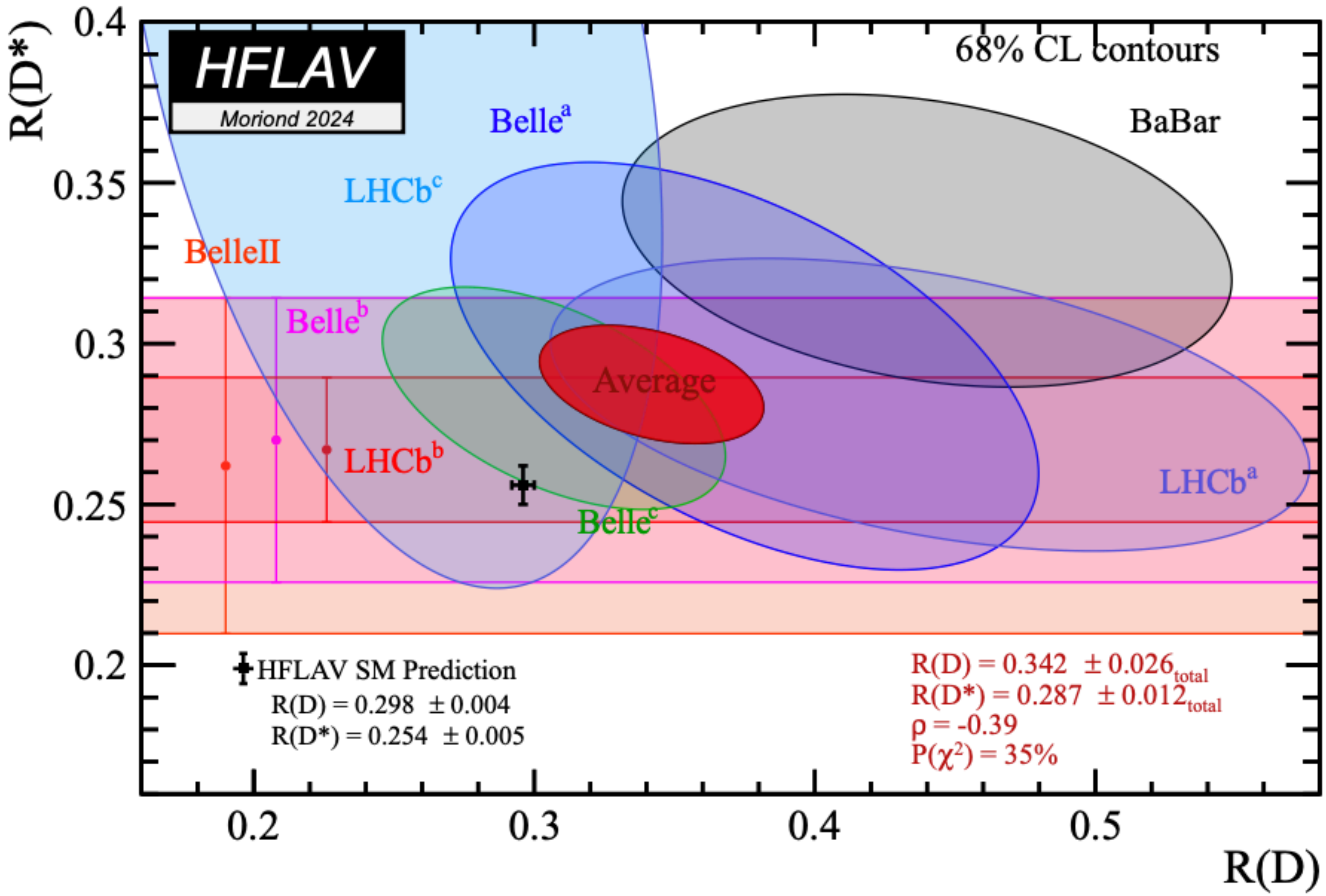
Today, the most persuasive discrepancy from the Standard Model comes in an anomaly of the second type, an excess of $B \to D\tau\nu$ decays over the result expected from decays to light leptons.

$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\ell\nu)} > SM$$

In the Standard Model, $R_{D^{(*)}} \sim 0.30\ (0.25)$ due to the smaller phase space for τ's, but this is also affected by the form factor for the $B \to D$ transition.

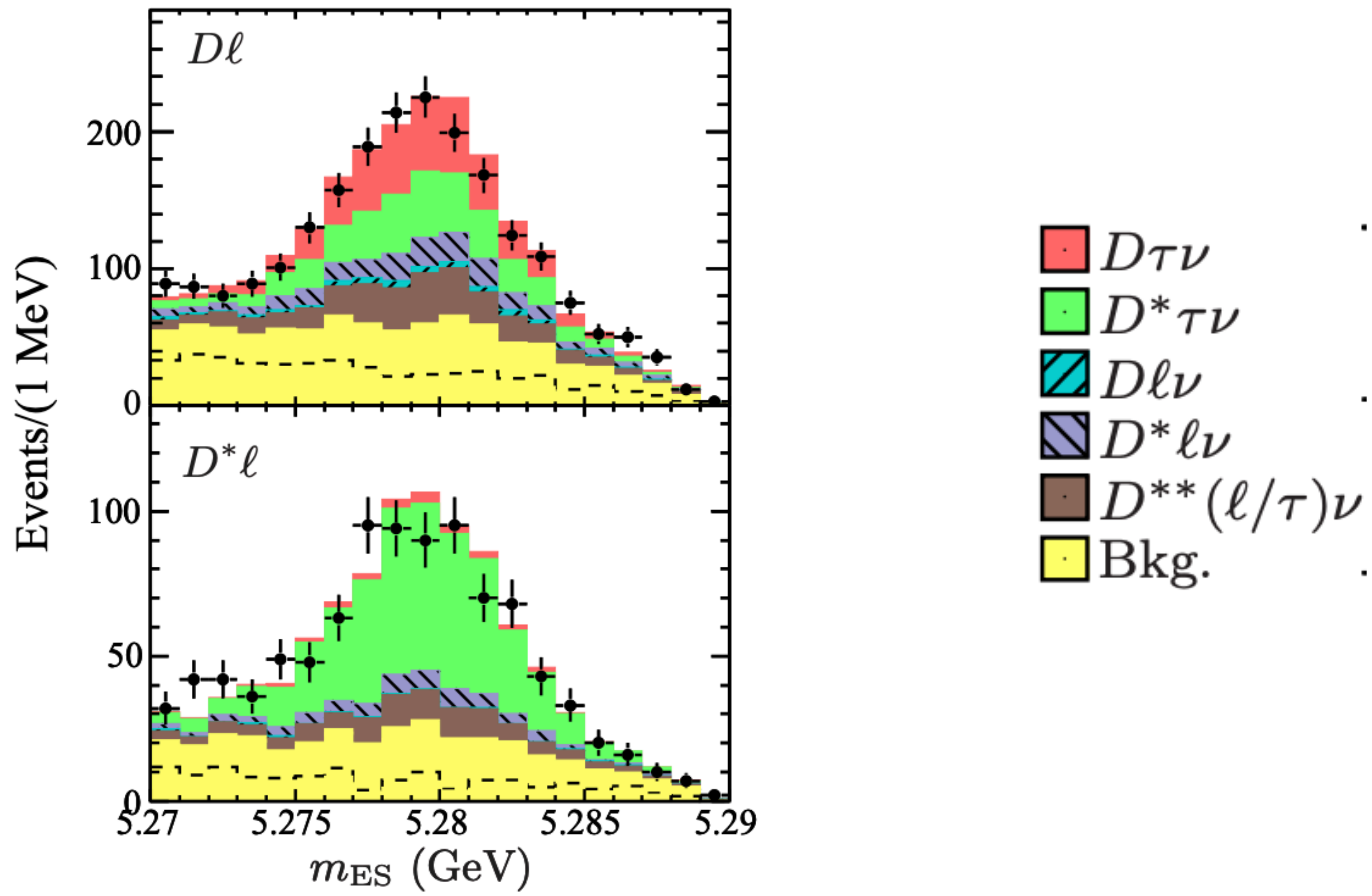
Wolfgang argued to us that the prediction for this ratio within the Standard Model is under very good control. Lattice QCD is used to determine the form factor.

Here is the current experimental situation:



I would like to emphasize that these are difficult experiments to carry out with high precision. The τ is recognized in 1-prong modes with e, μ, π. There are many sources of combinatoric ambiguity.

Here are the discovery plots from Babar (arXiv:1303.0571)



This situation will be clarified by measurements with completely reconstructed B's on the opposite side. However, this will require from Belle II luminosity samples of about 10 x Babar and BELLE.

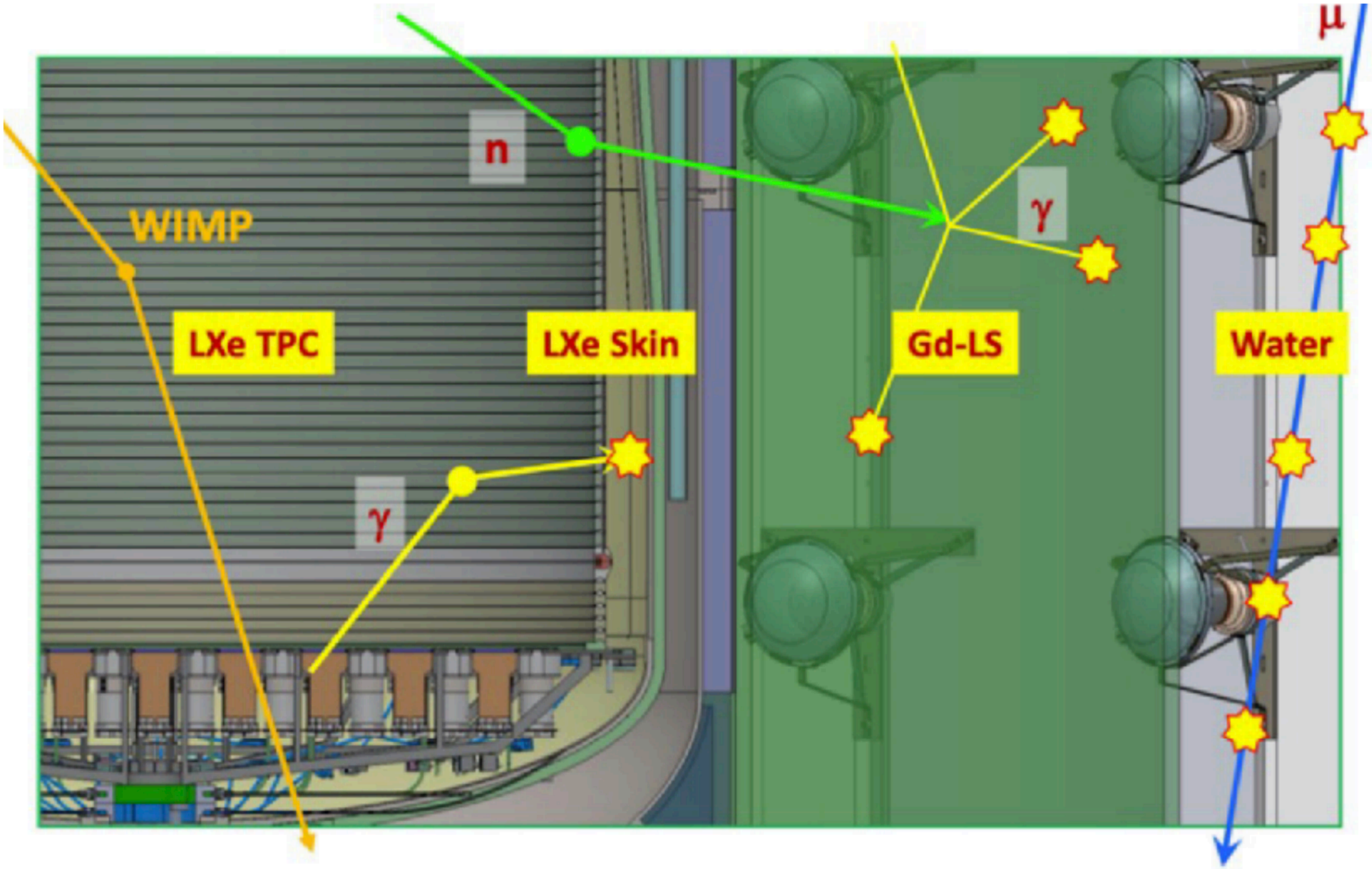
Dark Matter

Another experimental target is the appearance of new particles from beyond the Standard Model with very weak couplings to Standard particles.   These can appear in particle physics environments (accelerator searches, meson decays) and also coming in from the dark matter halo of the galaxy.

Searches for these particies confront an unexplored region of very weak coupling. Where there is white space with no constraints, there can be a "race to the bottom".

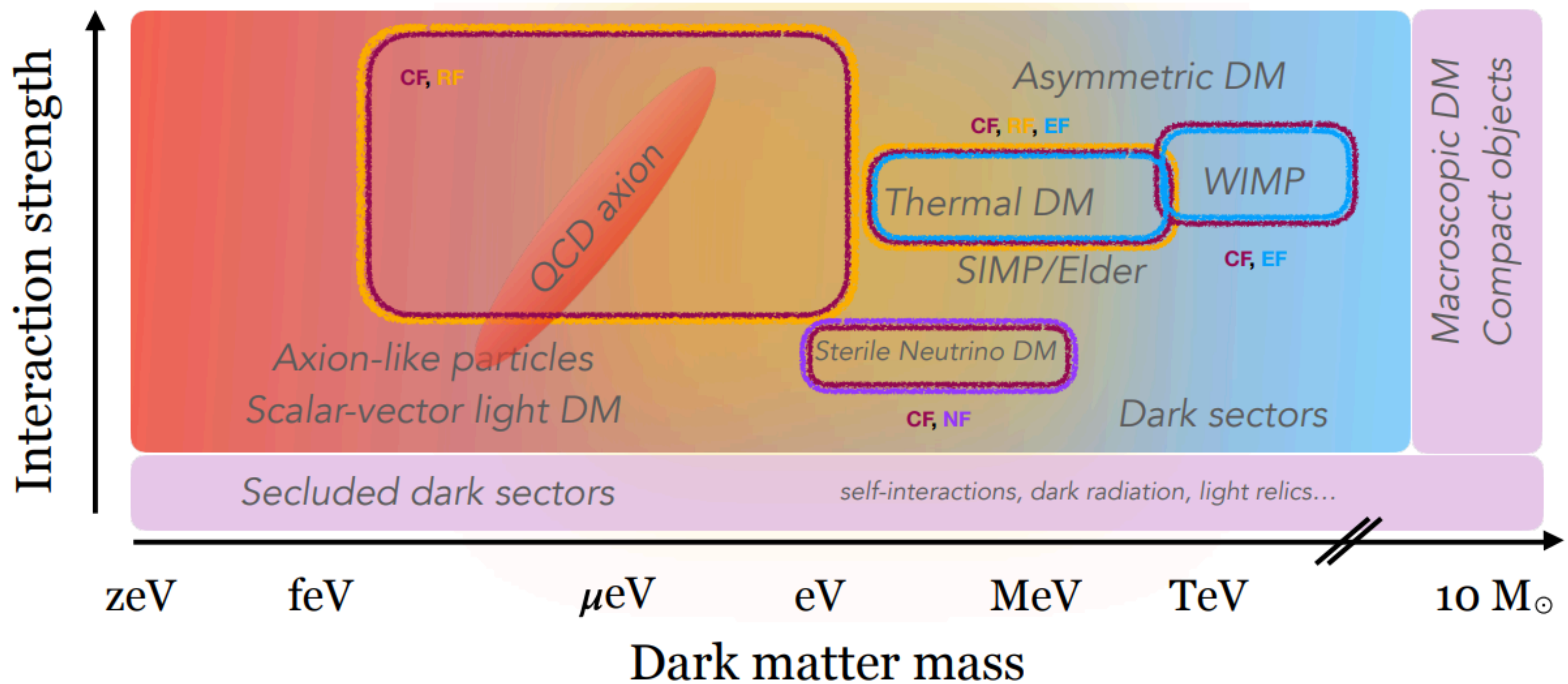
The search for these is a precision experiment in a certain sense, because every possible effect from ordinary particles that contributes to a similar energy deposition must be vetoed or subtracted.

Hugh Lippincott explained to us the level of detail needed to suppress radioactive backgrounds to WIMP detection in the LZ detector. Extraordinary care is needed in choice of materials and design of vetos.



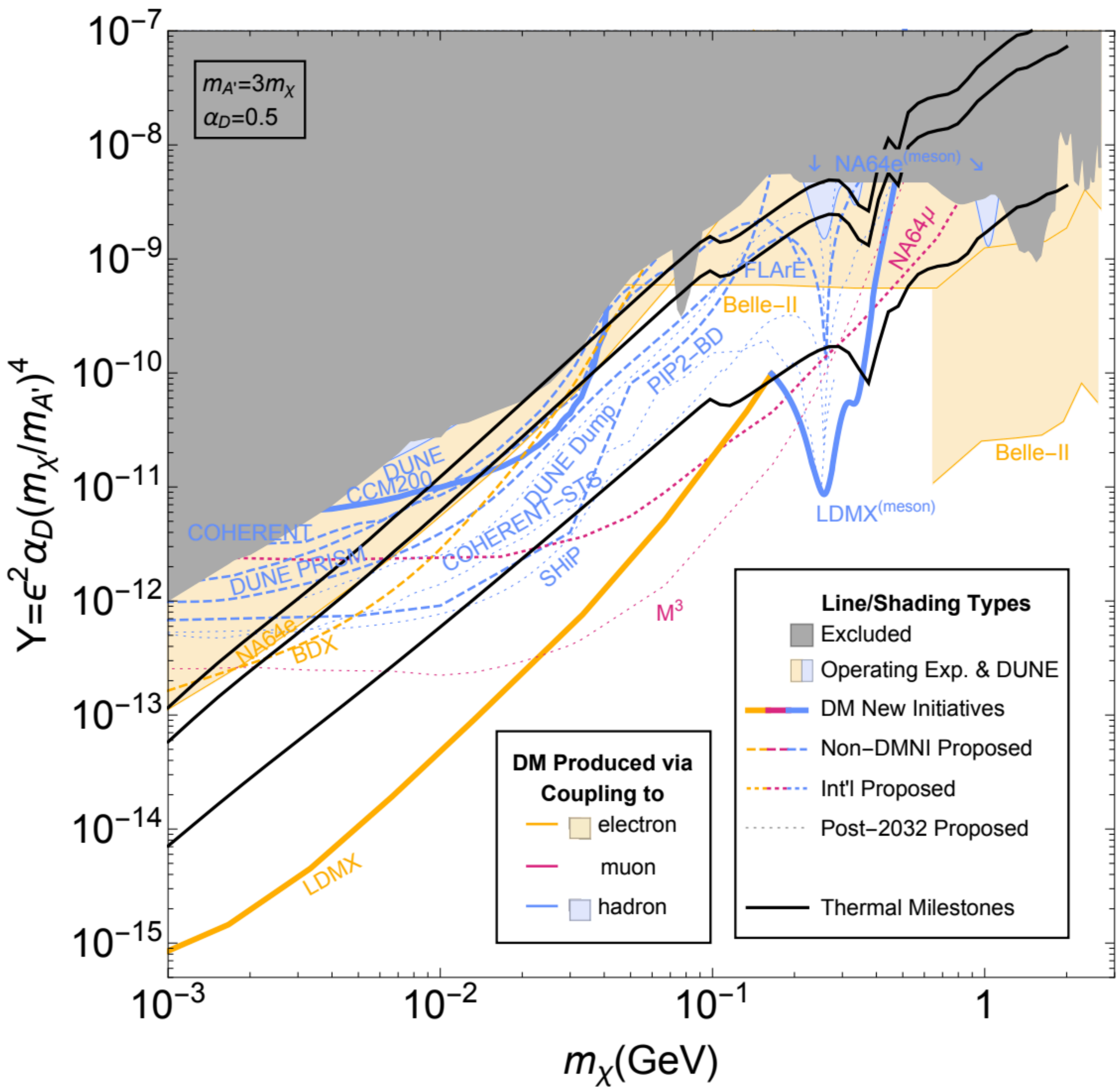
All that we know about dark matter is its mass density in the universe, with bounds on the weakness of its interactions with itself and with ordinary matter. This allows dark matter candidates over an enormous range in mass. To explore these hypotheses without prejudice, we need to explore this entire range. Unfortunately, each decade in mass might be a life's work.

arXiv:2210.01770



Very light particles can be the consequence of new physics at high mass scales. For example, a flavor symmetry breaking at mass scale M may give rise to a pseudo-Goldstone boson (or ALP) with $f \sim M$, so that $m^2 \sim \mathrm{GeV}^3/f$, and its interactions are proportional to $1/f$.

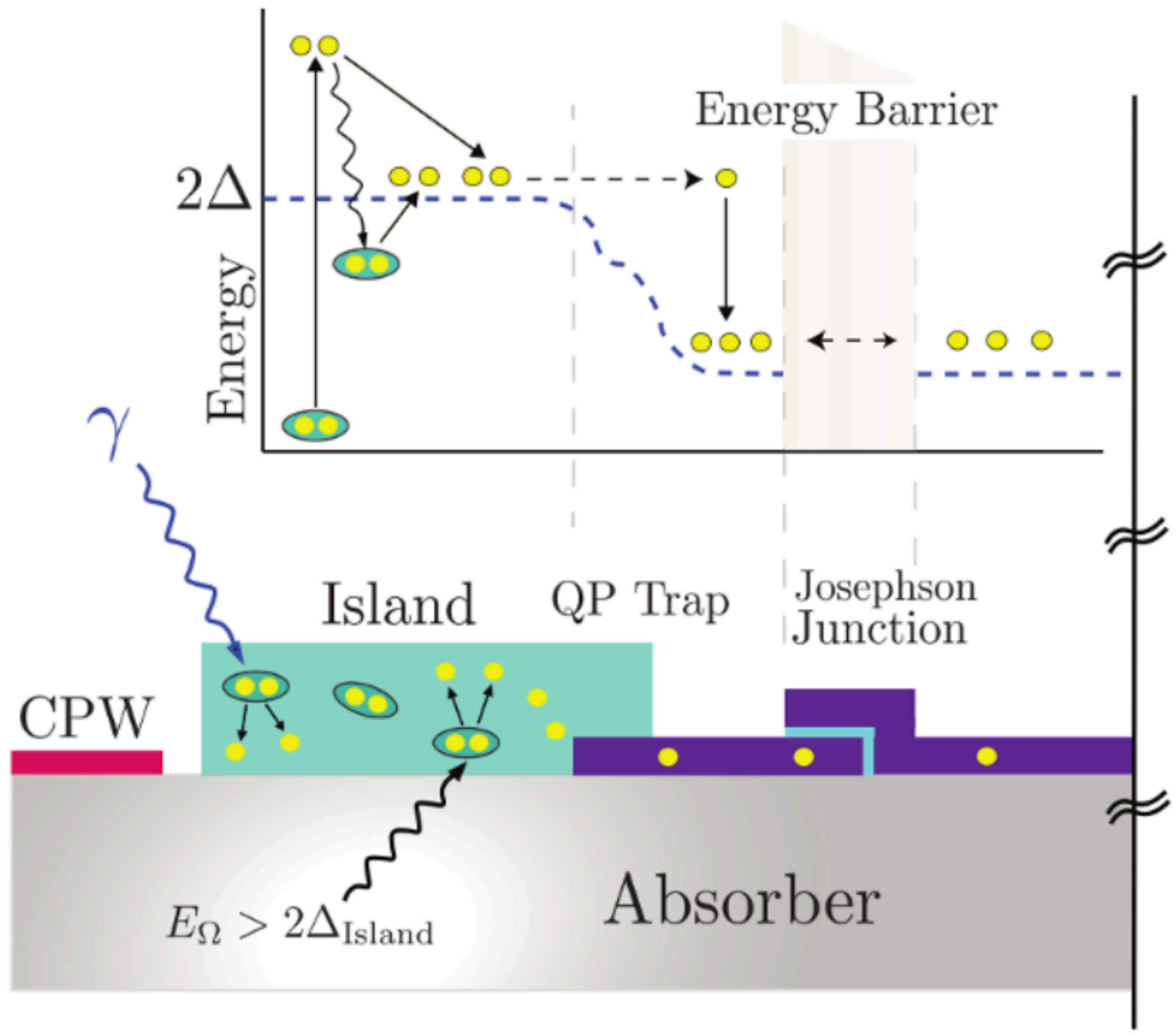
For dark matter particles in the MeV-GeV mass range, high-rate fixed target accelerator experiments are the best setting for discovery. This plot show the reach in mass and coupling strength for a number of proposed experiments, including LDMX planned for End Station A at SLAC.



arXiv:2209.04671

Astrophysics gives us the mass density of dark matter. As dark matter particles become lighter, their number density increases proportionally. For dark matter candidates with masses in the sub-MeV range, lab-scale detectors based on condensed matter physics and quantum sensors become relevant.

Noah Kurinsky gave us some fascinating examples of these technologies applicable to meV energy depositions:



Neutrinos

The goals of future long-baseline neutrino experiments are

to resolve the mass hierarchy and discover CP violation in the neutrino mass matrix

to precisely measure the neutrino masses and mixings

to discover or put limits on possible sterile neutrinos

We hope that these measurements will shed light on the origin of neutrino mass

I have little to say about sterile neutrinos except that (a) they are weakly coupled particles included in the “race to the bottom” already discussed, and (b) they have been targets of a long and frustrating search in the Fermilab short baseline program. I am not a believer.

As with quark flavor, the relation between measured neutrino mixing parameters and the underlying flavor matrices is very unclear.

For Dirac neutrinos, the Lagrangian has a form similar to that of quarks

$$\mathcal{L} = -Y_e^{ij} L_a^{\dagger i} \Phi_a e_R^j - Y_\nu^{ij} L_a^{\dagger i} \epsilon_{ab} \Phi_a^* \nu_R^j + h.c.$$

and there is the same problem of 10 observables but 36 parameters. The elements of Y_ν are of order 10^{-12}, but this can be arranged.

For neutrinos with Majorana masses due to the seesaw mechanism, we add Majorana masses for the ν_R's,

$$\mathcal{L} = (\mathrm{above}) - \frac{1}{2} M_{ij} \nu_{Ra}^i \epsilon_{ab} \nu_{Rb}^i + h.c.$$

If M_{ij} has large mass eigenvalues, then the Majorana masses of the light neutrinos are

$$m(\nu_L)_{ik} = Y_\nu^{ik} (\frac{1}{M})_{kl} Y_\nu^{jl} \langle \Phi \rangle^2$$

so we add 9 more unknown parameters. It is suggested that the large mixings in the neutrino sector arise from mixings in M_{ij}, but this is difficult to test experimentally.

At SSI, we heard informative talks by Kendall Mahn, Alex Friedland, and Deborah Harris on neutrino detection and the modelling of neutrino interactions. Excuse me, but the content leaves me quite worried, especially about the prospects for the DUNE experiment.

We learned that

DUNE will operate in a wide-band neutrino beam spanning energies up to 6-7 GeV. This spans the quasi-elastic region, the baryon resonance region, and the start of the deep inelastic region.

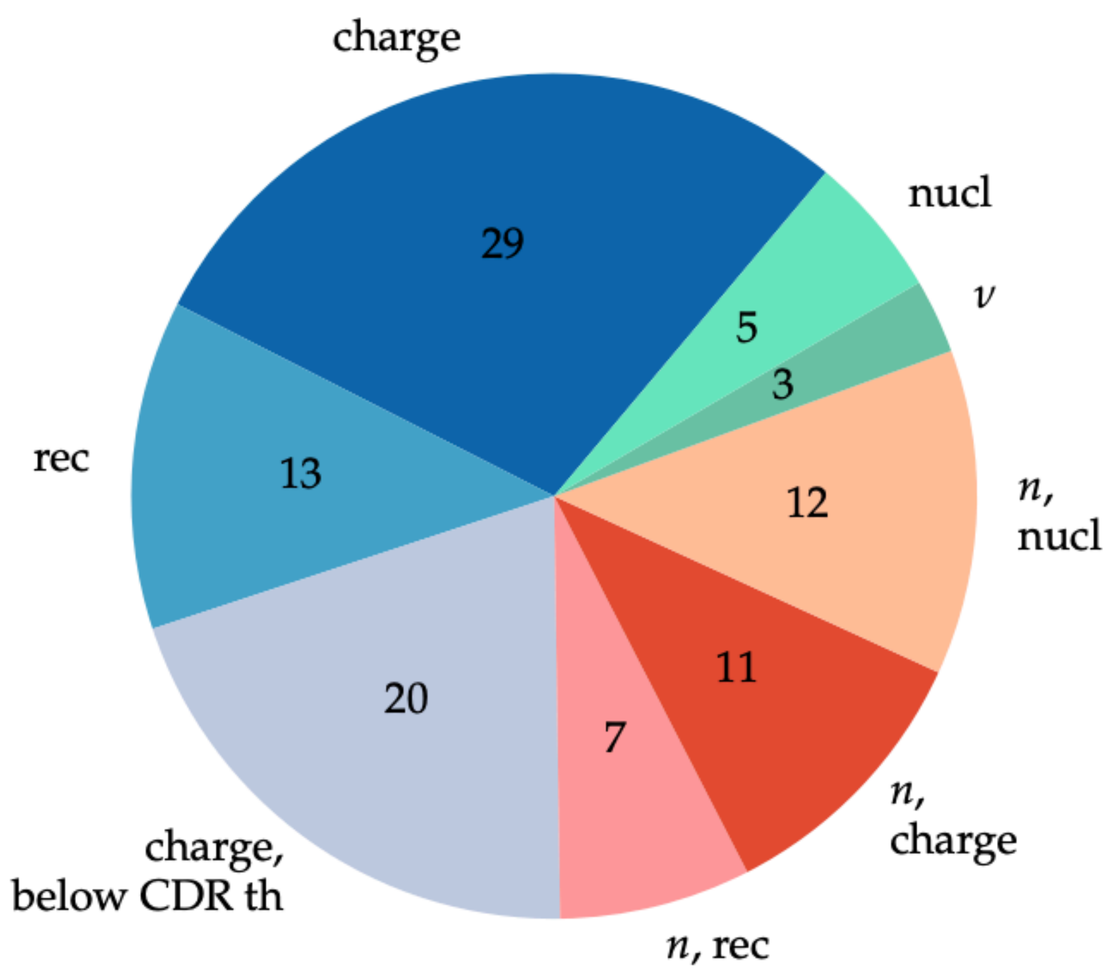
The liquid argon detectors of DUNE are effective in tracking charged particles but have issues in identifying neutrons and measuring neutral energy. Disruption of a nucleus ejects neutrons, and these create a loss of visible energy.

Current event generators for neutrino-nucleus collisions fail to describe the baryon resonance region. So they cannot be used for unfolding.

So, the circle does not close. This is a major issue for DUNE to produce precision, or even quantitative, results.

Here are a few snapshots from Alex’s work:

Energy partition for a sample of 4 GeV neutrinos on liquid Ar:



nucl - nuclear breakup

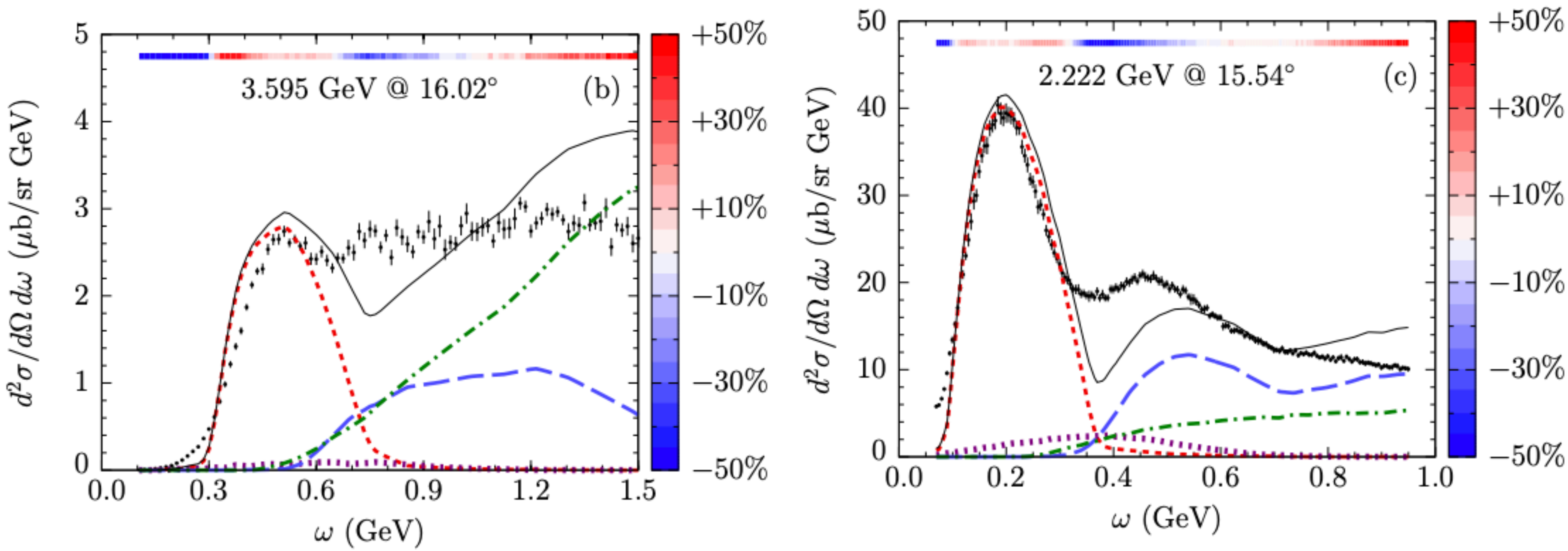
rec - recombination

v - lost to neutrinos

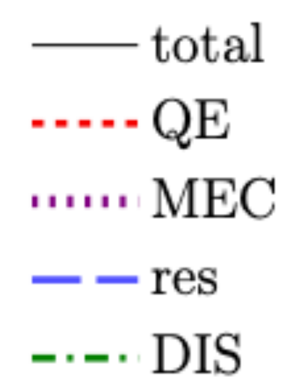
dark blue and red shows the visible ionization (40%)

arXiv:1811.06159, w. S. Li

comparisons of the GENIE event generator with e- scattering data



The description is reasonable in the quasi-elastic and deep inelastic regions, where the physics is well understood. It is order-1 incorrect in the baryon resonance region.



Oddly, most theory work on neutrino cross sections concerns the quasi-elastic region, i.e., the easy part.

arXiv:2006.11944, w. A. Ankowski

If neutrino-nucleus event generators work so poorly, why was this not known before ?

The answer is that neutrino experiments have too many unobservable kinematic quantities and too low statistics to make precision tests. Neutrino generators must be validated against electron scattering data!

This is realized in the development of the new generator ACHILLES. Still we need appropriate data from JLab, and from LDMX at SLAC.

Unfortunately, electrons probe only the vector current. Lattice QCD can provide information for the axial current matrix elements in the quasi-elastic region.

Neutrino physics is a major part of the US particle physics program. To achieve the potential of DUNE, these problems must be given high priority. New ideas are needed to solve them.

Higgs Boson

Much of the first week of the school was devoted to LHC physics. I recommend particularly the first lecture of Josh Bendavid, which is a superb introduction to collider experimentation.

Here, however, I will concentrate on one topic, the Higgs boson.

The Higgs boson is the most recently discovered elementary particle, known only since 2012. Is it too early to discuss precision studies ?

No! This topic is essential.

At several points in this lecture, I complained that the apparently straightforward measurements of CKM angles, neutrino masses, CP violation are not actually interpretable because necessary information is missing.

In all of these cases, this is due to our lack of knowledge of the nature of the Higgs boson.

The couplings of Standard Model particles to the Higgs boson is what is ultimately responsible for

fermion masses and mixings

CP violation

baryogenesis in the early universe

and, quite likely, it is also connected to the dark matter problem.

The answers to these questions depend on the intrinsic nature of the Higgs particle and field

a fundamental scalar ?

a supersymmetric particle ?

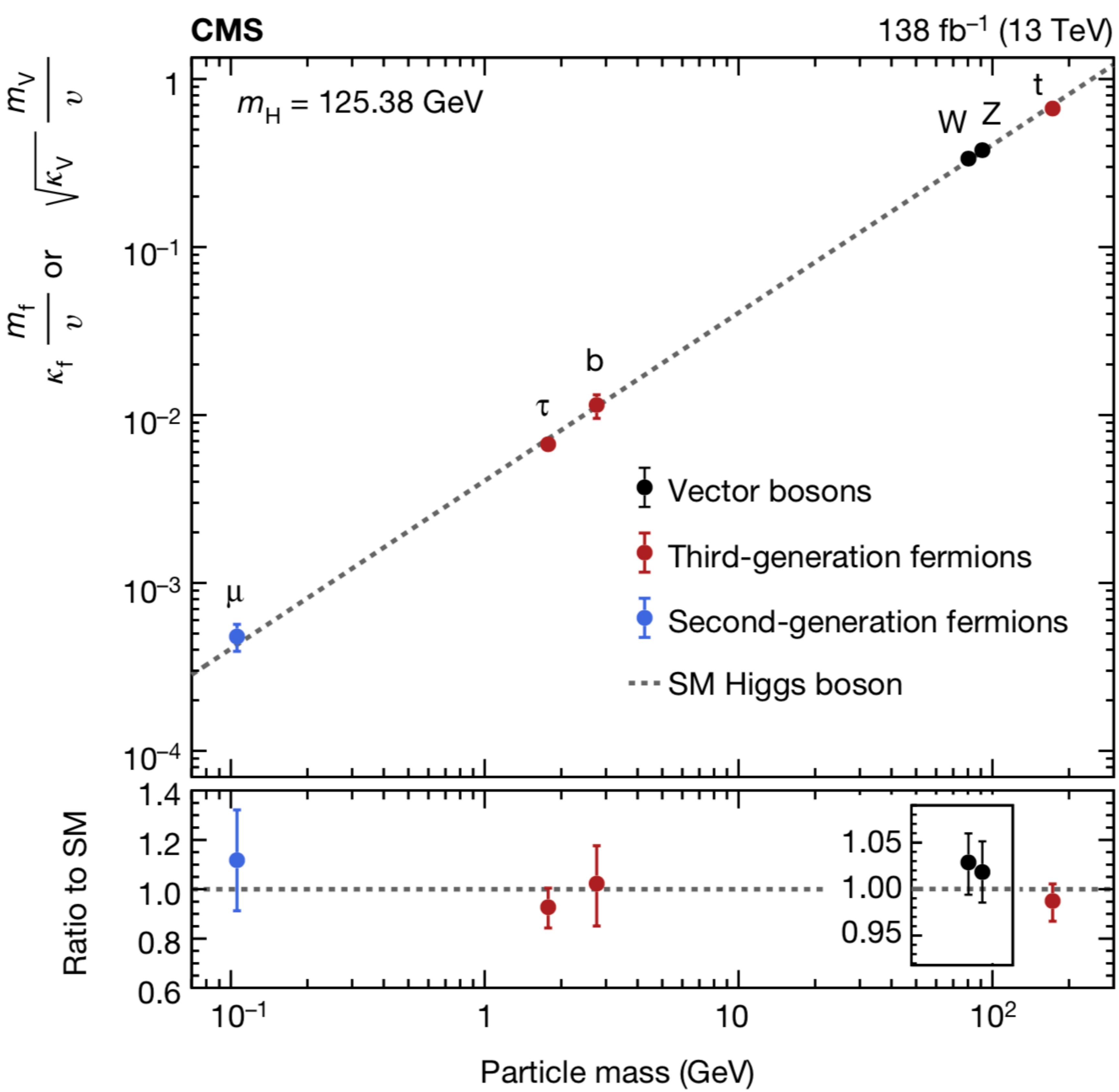
a composite of more elementary constituents ?

These questions all point back to another one (maybe too abstruse for experimenters): Why is electroweak symmetry broken ? Why does the Higgs field acquire a vacuum expectation value ?

As long as we are putting this physics in by hand, we will not be able to make progress on any of the questions highlighted above.

This last question implies that there is a new force of nature, still undiscovered, that we have the chance to find.

In the study of the Higgs boson at the LHC to date, this particle seems to fit the Standard Model. Valentina Cairo showed you this plot:



CMS
Nature 2022

This plot suggests that electroweak symmetry breaking is uniquely due to the Higgs field. Actually, at the LHC, we see the Higgs boson and no other new particles below about 1 TeV. This seems to be the lesson we have learned from the LHC.

We can describe this situation with a low-energy effective field theory containing the Standard Model fields — including 1 Higgs boson — and nothing else. The Standard Model is the most general renormalizable model with SU(3)xSU(2)xU(1) gauge symmetry containing only the known particles and fields. If there are new particles of large mass M that couple to the Higgs field, their effects can be described by an effective field theory (SMEFT) that adds to the Standard Model gauge-invariant operators of higher dimension.

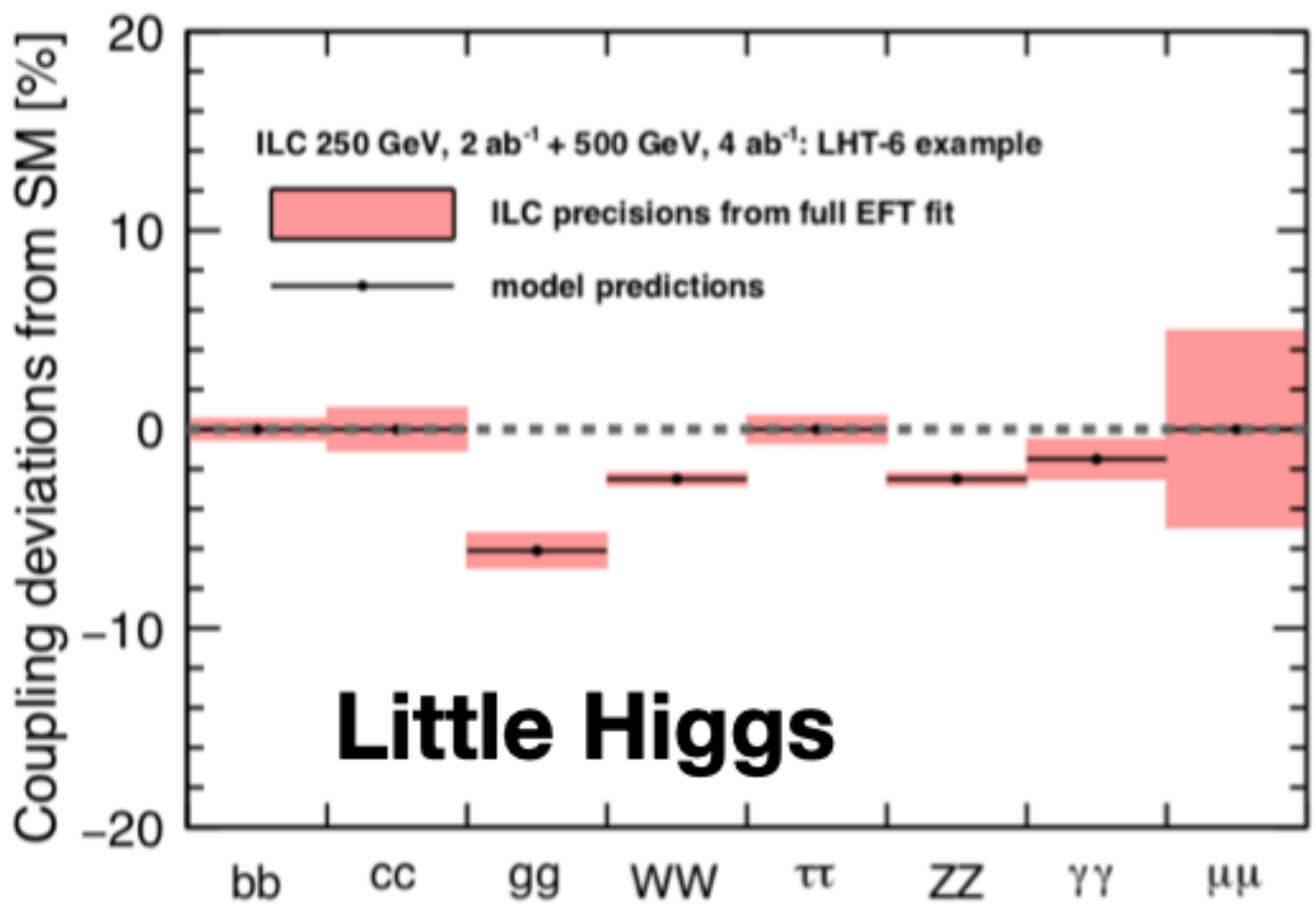
In SMEFT, the influence of such heavy particles is of order

$$m_h^2/M^2$$

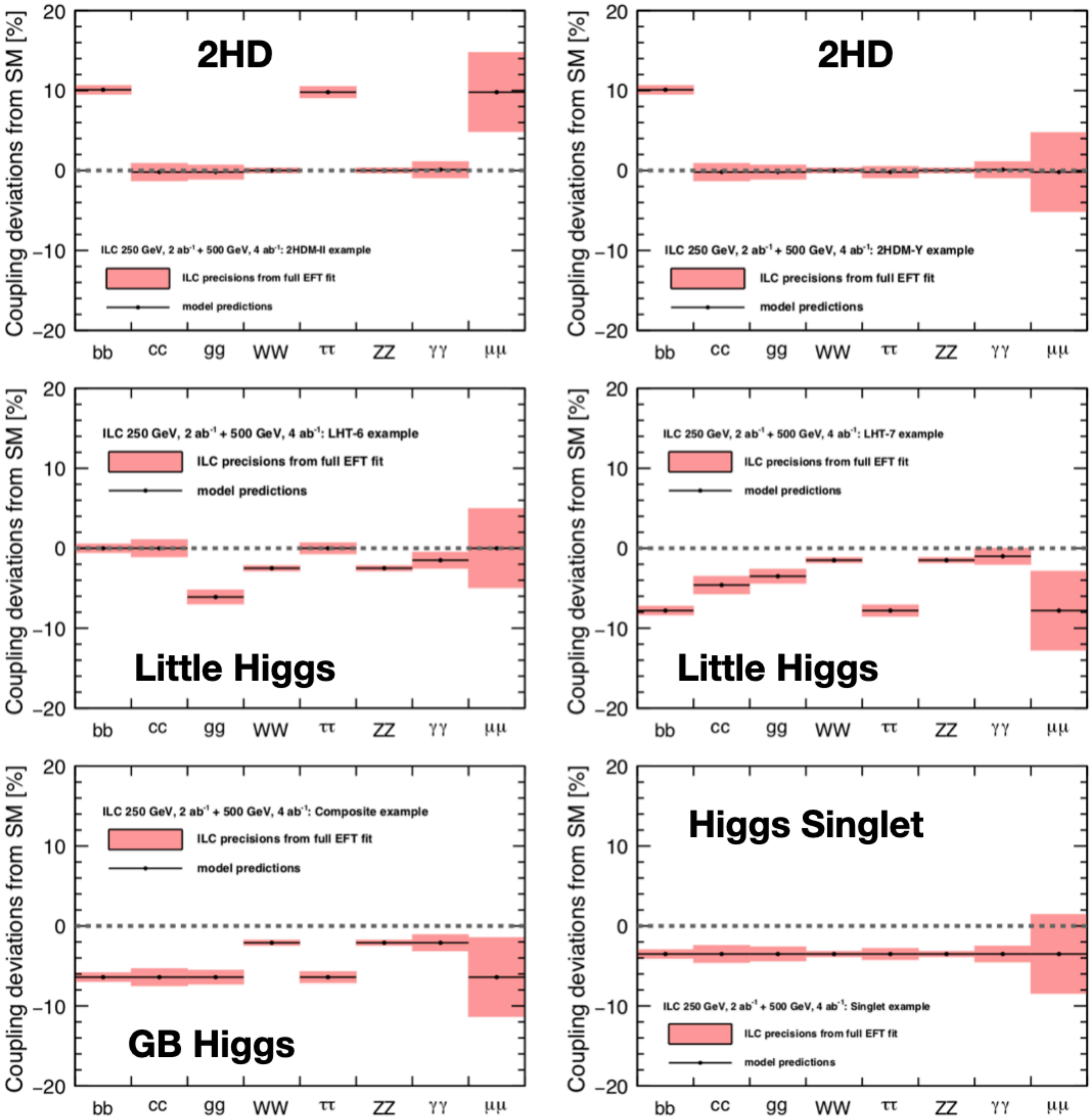
This is an effect of a few percent, maybe as much as 10% if the coupling is strong.

Thus, we can look for signs of new physics by studying the couplings of the Higgs boson. But, precision measurements are necessary. With the current uncertainties of 10-20%, we are not yet in the game.

By improving our knowledge of the Higgs boson to the 1% level, we could uncover deviations from the predictions of the Standard Model. Since many Higgs boson couplings are available, there could be a pattern of deviations, each of which points to a different model of new particles couplings to the Higgs field. Here is an example:

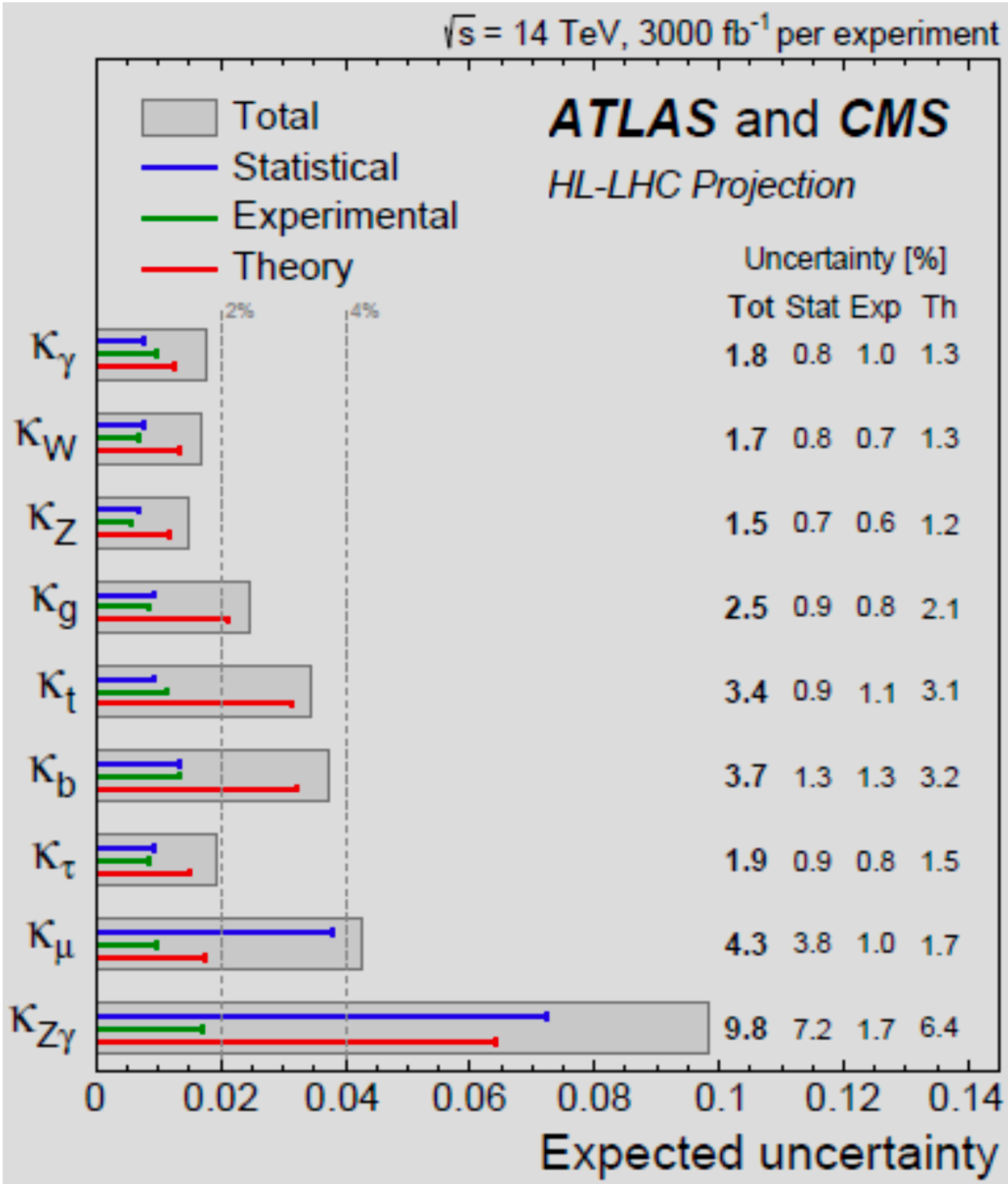


And compare:



arXiv:1708.08912

We will achieve some of this improvement in precision at the High-Luminosity LHC. Sarah Eno showed the current expectations for the end of HL-LHC:



but also

"theory" includes generators and event modelling

signals are extracted from much larger backgrounds using machine learning

fits involve tens of interdependent parameters and thousands of nuisance parameters

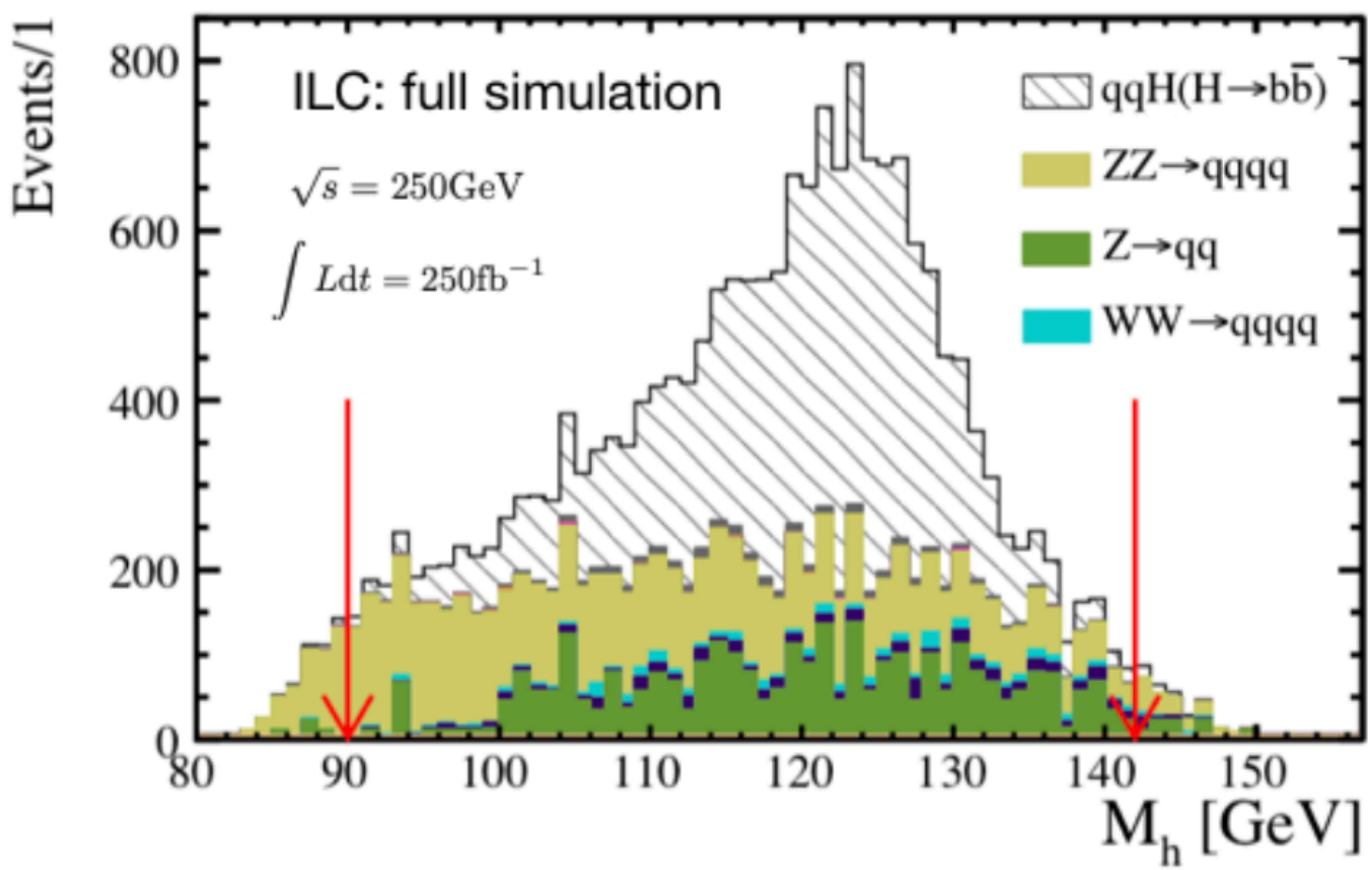
Sarah expressed concern that a deviation would not be robust enough to meet the standard of proof.

The current controversy over the mass of the W, described by Josh Bendavid, is a troubling example.

To discover these deviations to the community’s satisfaction, we will need a simpler and less opaque technique.

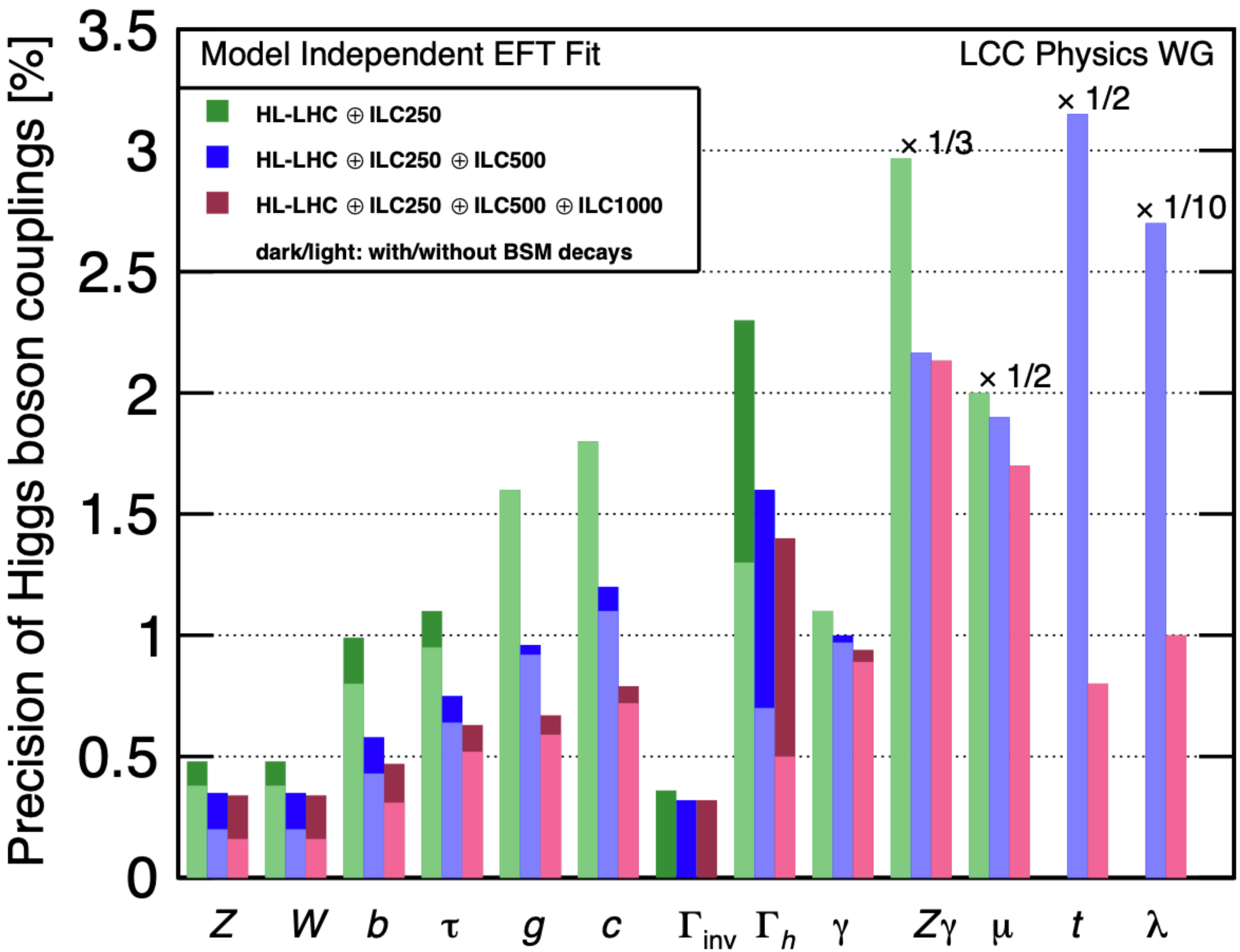
To achieve this, we should build an e+e- collider capable of producing and studying the Higgs boson. This is an “e+e- Higgs factory”. Several candidates are now being discussed: the FCC at CERN, the CEPC in China, and the linear e+e- colliders ILC and C^3 .

At these colliders, step 1 is easy. The Higgs boson signals appear manifestly above (precisely calculable) backgrounds. We can start from here to build methods for ultimate precision



arXiv:2203.07622

Here are the coupling projections for ILC. The results for other colliders are very similar. These are the error bars shown on p. 42.



arXiv:2203.07622

Results from Higgs factories can be compared to precision theoretical predictions. Today, the parameters of the Standard Model are known and give specific predictions for Higgs couplings. Not all of the theory work is done, but these predictions can be computed to better than 1 part per mil.

Some phenomenological inputs are needed, in particular: $m_b,\ m_c,\ \alpha_s$
These will be provide by lattice QCD to the required precision. See Lepage, Mackenzie, and MEP, arXiv:1404.0319.

It seems strange to me that the best place use precision analysis to look for signs of physics beyond the Standard Model is the last place that we will try.

But it is not too late.

In this lecture, we have surveyed many aspects of precision measurement aimed at the discovery of the next stage of fundamental physics beyond the Standard Model.

With persistence — and careful attention to systematic uncertainties — we will break through.

I wish you the best along any direction you might choose.