Naturalness at FCC

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November 12, 2020

Summary

- **The hierarchy problem** motivates new energy-frontier colliders. It's one of the strongest reasons to study the Higgs in particular, rather than high-energy processes in general. We should talk more clearly about its importance.

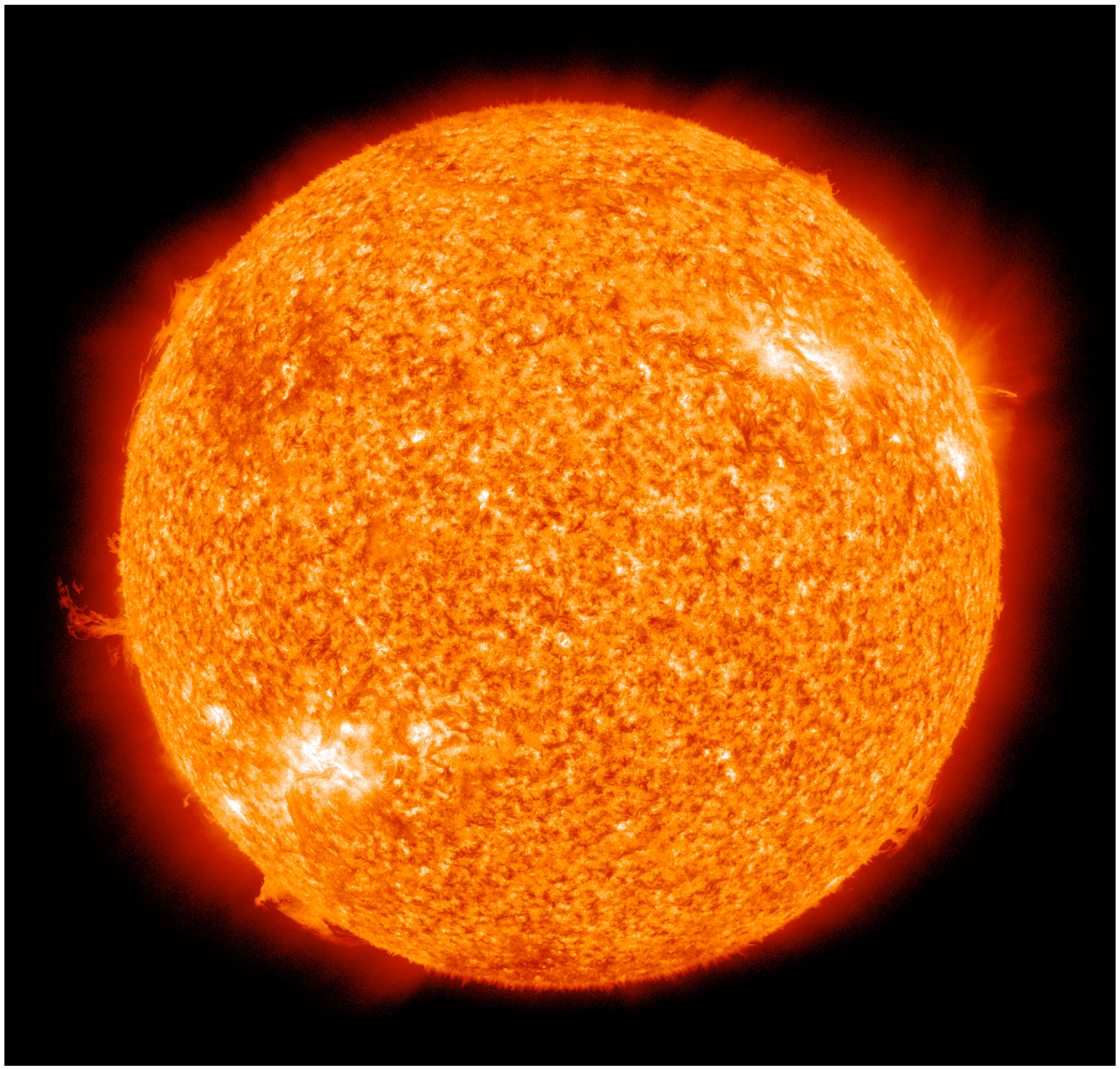
- What will the physics landscape look like when FCC starts? One exciting prospect is that **flavor or CP violation** experiments that are advancing rapidly could give us crucial hints first.

- Finally, **what will we learn at the FCC itself**? Through high mass reach and potential production of many BSM particles, FCC could help unravel the physics of the electroweak hierarchy.

About the Hierarchy Problem

The electroweak hierarchy and our world

The mysterious number that best motivates new colliders is the electroweak hierarchy. We should not lose sight of how important it is to understand.



The electroweak hierarchy is not just an obscure fact about high-energy physics. It is crucial for the existence of large objects like stars and planets.

$$
\begin{aligned}
M_\odot &\approx 2 \times 10^{30}\ \mathrm{kg} \\
&\approx 1.1 \times 10^{57}\ \mathrm{GeV} \\
&\approx 0.6 \left(\frac{M_{\mathrm{Pl,unred}}}{m_{\mathrm{proton}}} \right)^3 m_{\mathrm{proton}}
\end{aligned}
$$

[Details: V. Weisskopf, *Science* **187**(4177):605–612 (1975); Burrows and Ostriker, *PNAS* 111 (7):2409-2416 (2014).]

What is the hierarchy problem?

A good solution to the hierarchy problem should leave us feeling like we ***understand*** **the origin of the weak scale** in terms of some more fundamental physics.

A good example comes from QCD: we can ***compute*** the QCD scale from the gauge coupling measured at some higher energy, and it comes out exponentially small in a robust manner:

$$\Lambda_{\mathrm{QCD}} \sim M\, \mathrm{e}^{-8\pi^2/(b g(M)^2)}$$

Or BCS superconductivity: Cooper pairing from similar running of marginal interaction. (Shankar, Polchinski)

EW hierarchy: not literally the same, but *want* same qualitative character of allowing us to compute the scale from something more microscopic.

What is the hierarchy problem?

A further remark about the QCD scale:

$$\Lambda_{\mathrm{QCD}} \sim M\, \mathrm{e}^{-8\pi^2/(b g(M)^2)}$$

By some simple fine-tuning measures, this is “fine-tuned”; e.g. Barbieri-Giudice,

$$\frac{\partial \log \Lambda_{\mathrm{QCD}}}{\partial \log g} = 2 \log \frac{\Lambda_{\mathrm{QCD}}}{M} \sim 100$$

This doesn’t bother me. Shouldn’t be too quick to dismiss a theory because of moderate sensitivity to an underlying parameter.

What is the hierarchy problem?

At the most fundamental level, the question we want to ask is really:

where did the weak scale come from?

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where did the weak scale come from?

Various refinements of this question, or related questions, are:

- Can we *explain* or *compute* the weak scale in terms of a more fundamental theory beyond the Standard Model?
- Are there microscopic *dynamics* that tell us why electroweak symmetry breaking happened, or that make it more likely?
- What is the shape of the Higgs potential? (Strong motivation for measuring the Higgs self-coupling.)
- Is the Higgs boson a fundamental particle, or is it composite?
- What would happen if we heated up the universe above the weak scale?

What is the hierarchy problem NOT?

The question is ***NOT***

how do I regulate a loop diagram?

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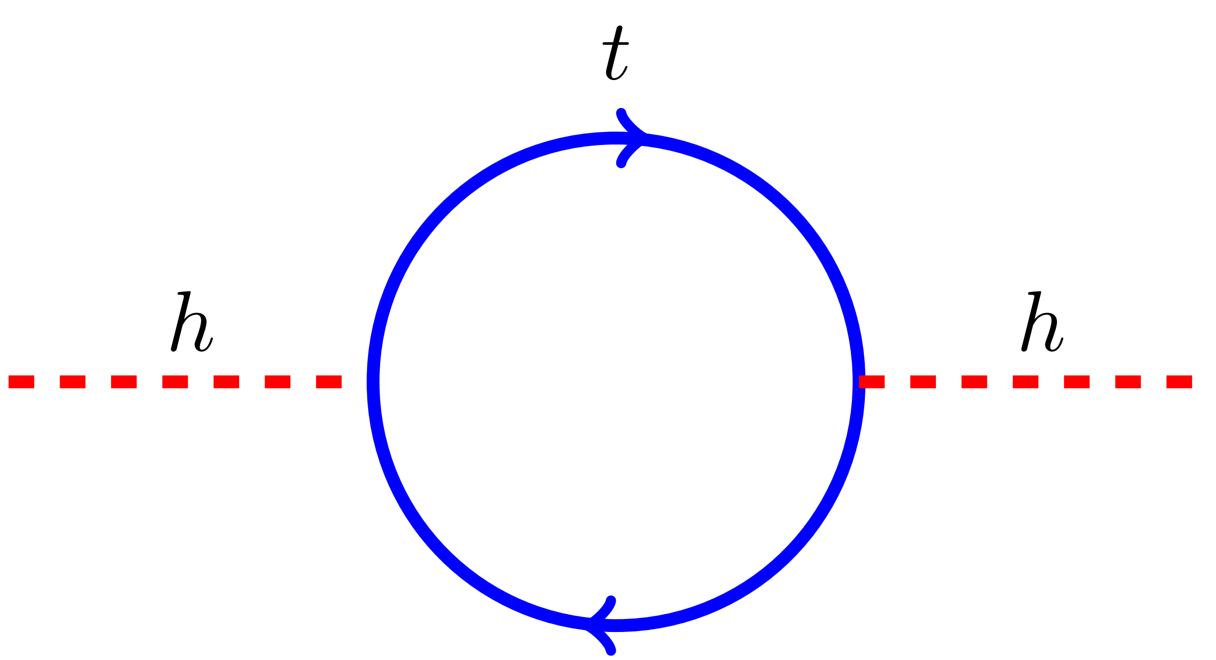
The question is ***NOT***

how do I regulate a loop diagram?

- The problem will *not* go away just because you like to use dimensional regularization, which has no power divergences.
- The problem will *not* go away simply because you like a different choice of “fine-tuning measure.”
- The fact that you can measure Standard Model parameters and do calculations to high precision that match data at the weak scale does *not* mean there is nothing to explain.

What not to say

Like many other people, I have given talks where, due to lack of time or wanting to focus on other points, I have just said things like:



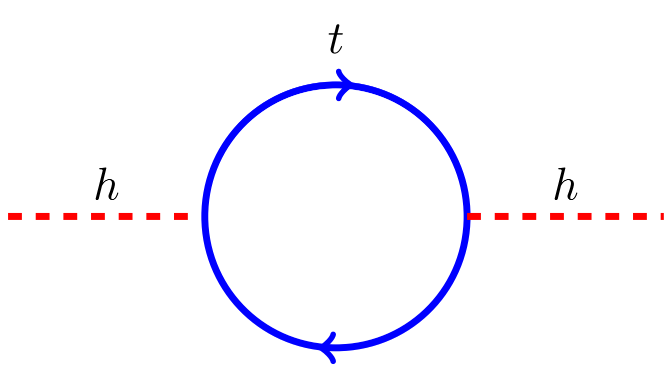
$$\delta m_H^2 \sim \frac{y_t^2}{16\pi^2}\Lambda_{\mathrm{UV}}^2$$

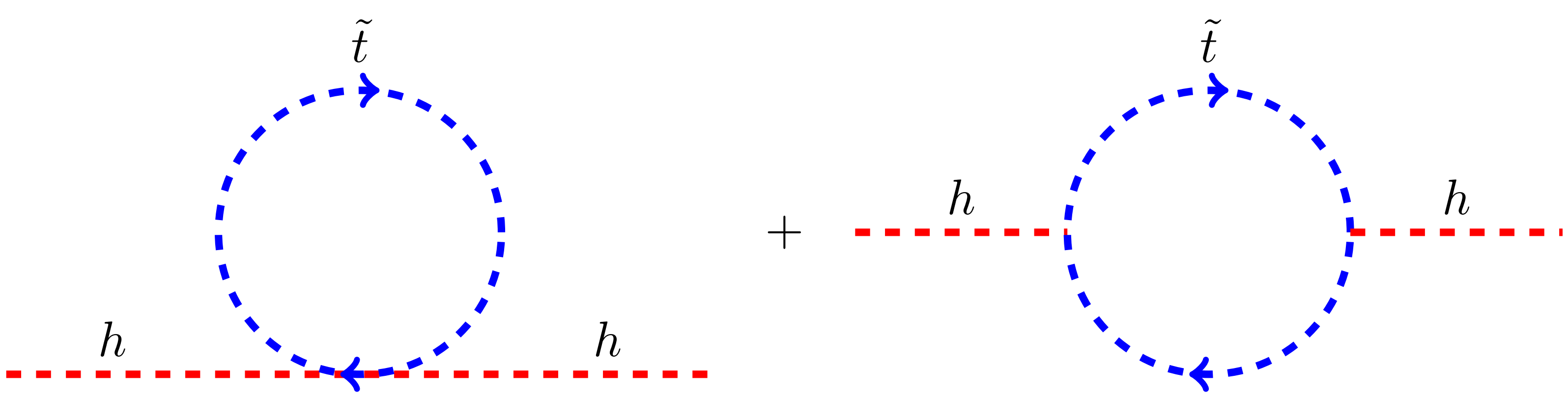
This diagram is quadratically divergent, so the weak scale is quadratically sensitive to UV scales. We need a low cutoff or a cancelation of this divergence.

Because then…

Some people respond "power divergences are unphysical" or "when you use the renormalized mass in a calculation, there is no problem" or any number of other things you've probably heard before.

Or maybe we are a little more careful and we say something like:





$$\delta m_{H_u}^2 = -\frac{3}{8\pi^2} y_t^2 \left(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + |A_t|^2 \right) \log \frac{\Lambda}{\mathrm{TeV}}.$$

What we have is *quadratic sensitivity* to *physical scales*.

Can we do better?

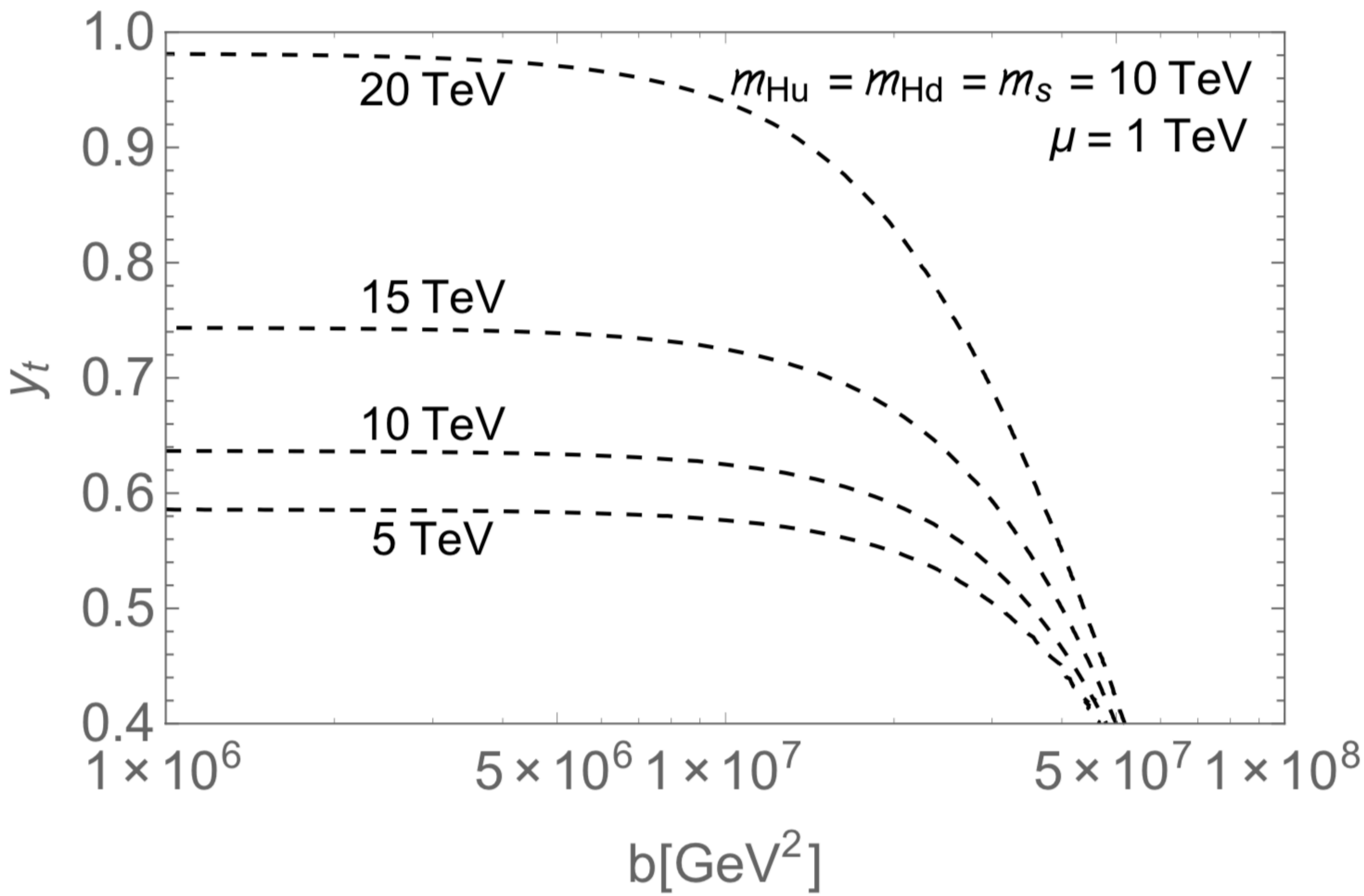
The better way to frame the problem, and the role of fine-tuning, is that we are seeking a theory that explains **the *origin* of the EW scale**.

If, within that theory, the EW scale is extremely sensitive to input parameters, it's not a very good explanation. The theory does not generically describe a universe like the one we live in.

If moving around in parameter space just produces modest changes in the low-energy physics, that's a compelling theory that predicts a world like ours.

SUSY and the hierarchy problem

When we say that weak-scale SUSY solves the hierarchy problem, we mean something simple:

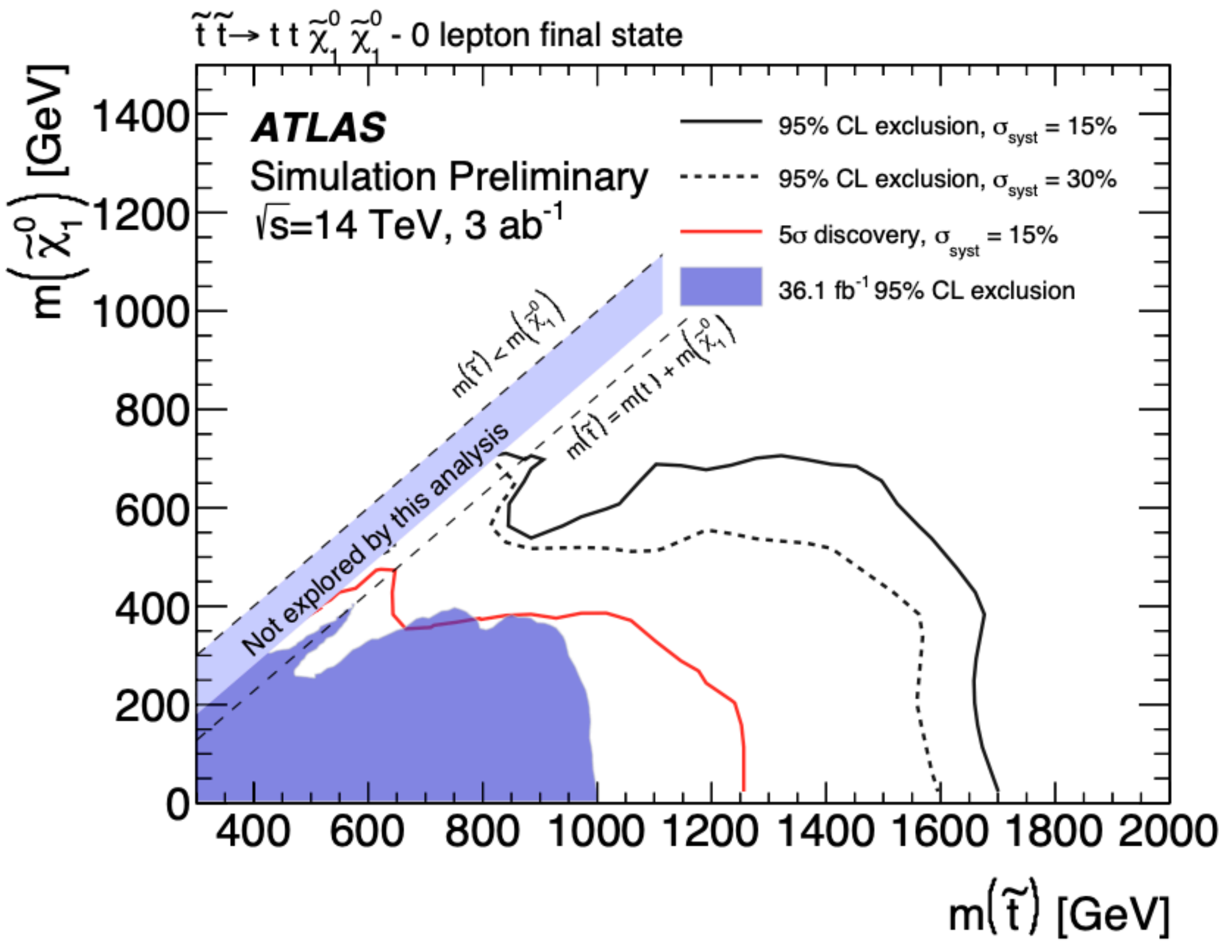


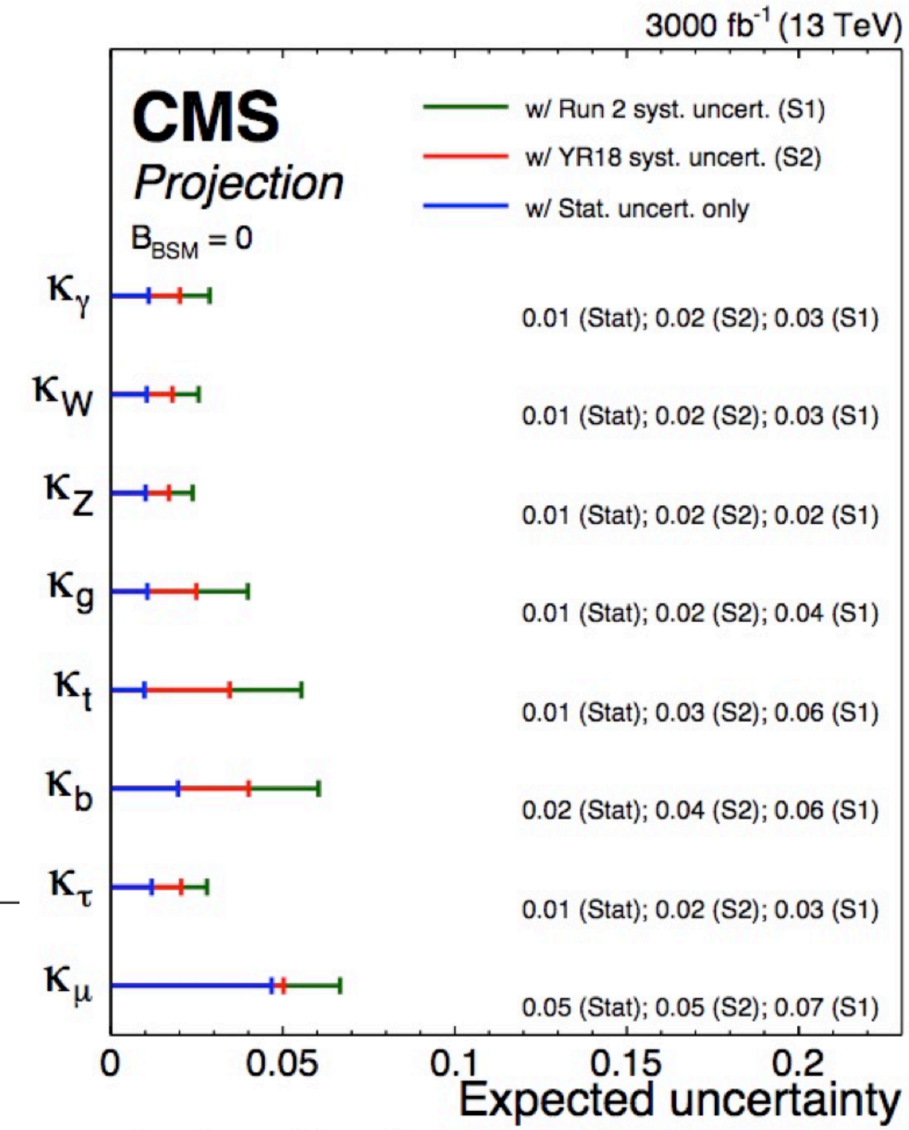
The weak scale can be ***computed*** from input parameters, and is *typically* of order* the SUSY breaking parameters.

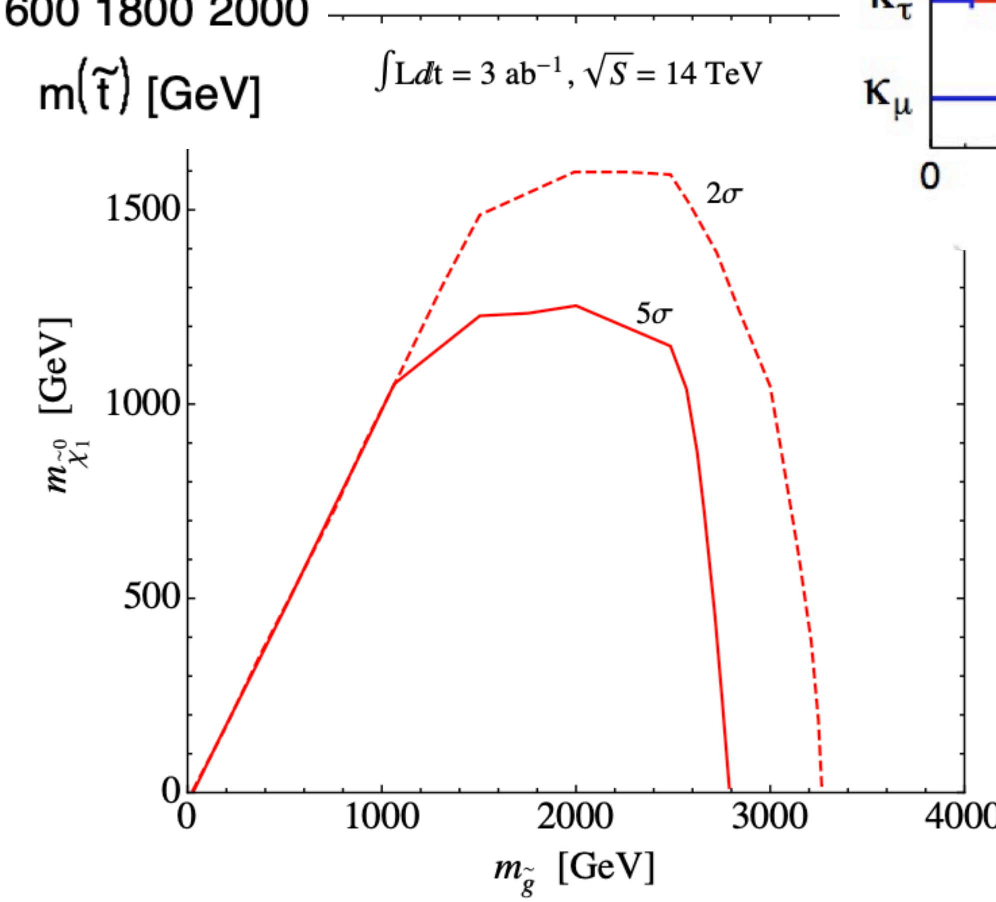
* leaves room for small accidents

The Naturalness Landscape at the Start of FCC?

Naturalness: LHC Implications

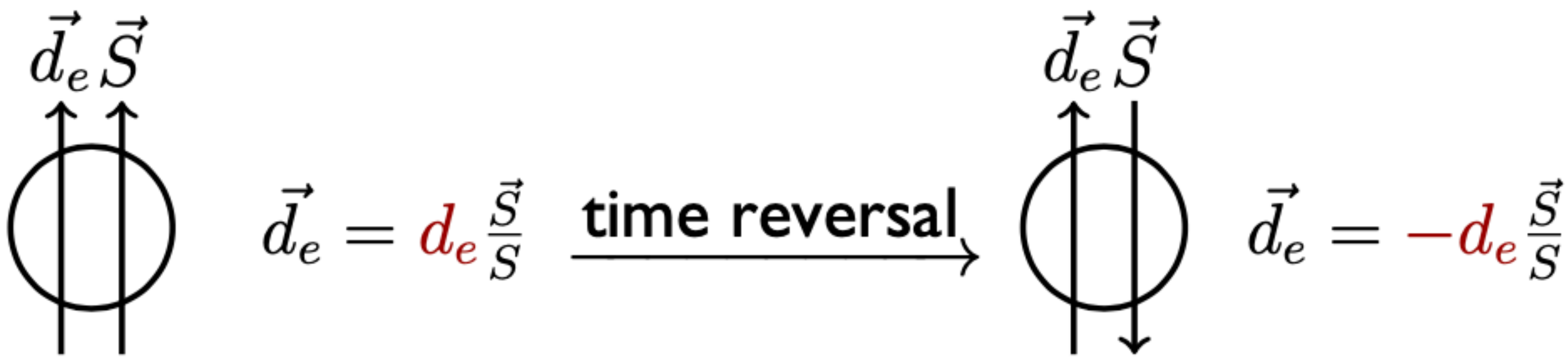






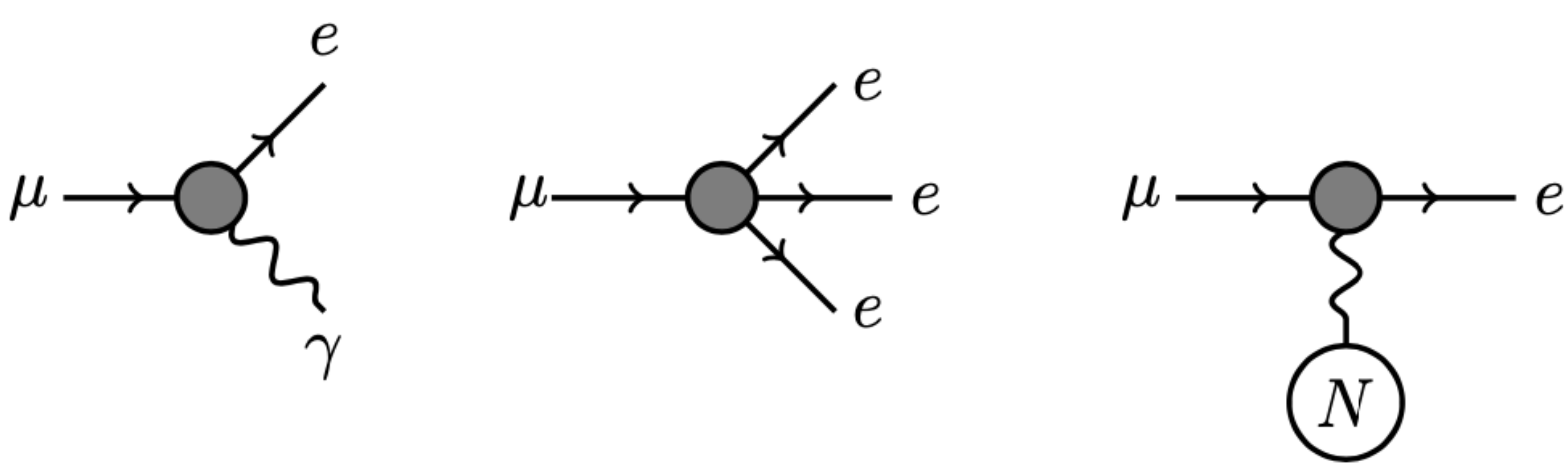
CP and Flavor Implications

CP violating: electric dipole moments (EDMs)



[figures from Qianshu Lu]

Charged lepton flavor violation (CLFV)



Making rapid advances, and could discover **new physics involving the Higgs boson**!

EDMs and CLFV: the Higgs Connection

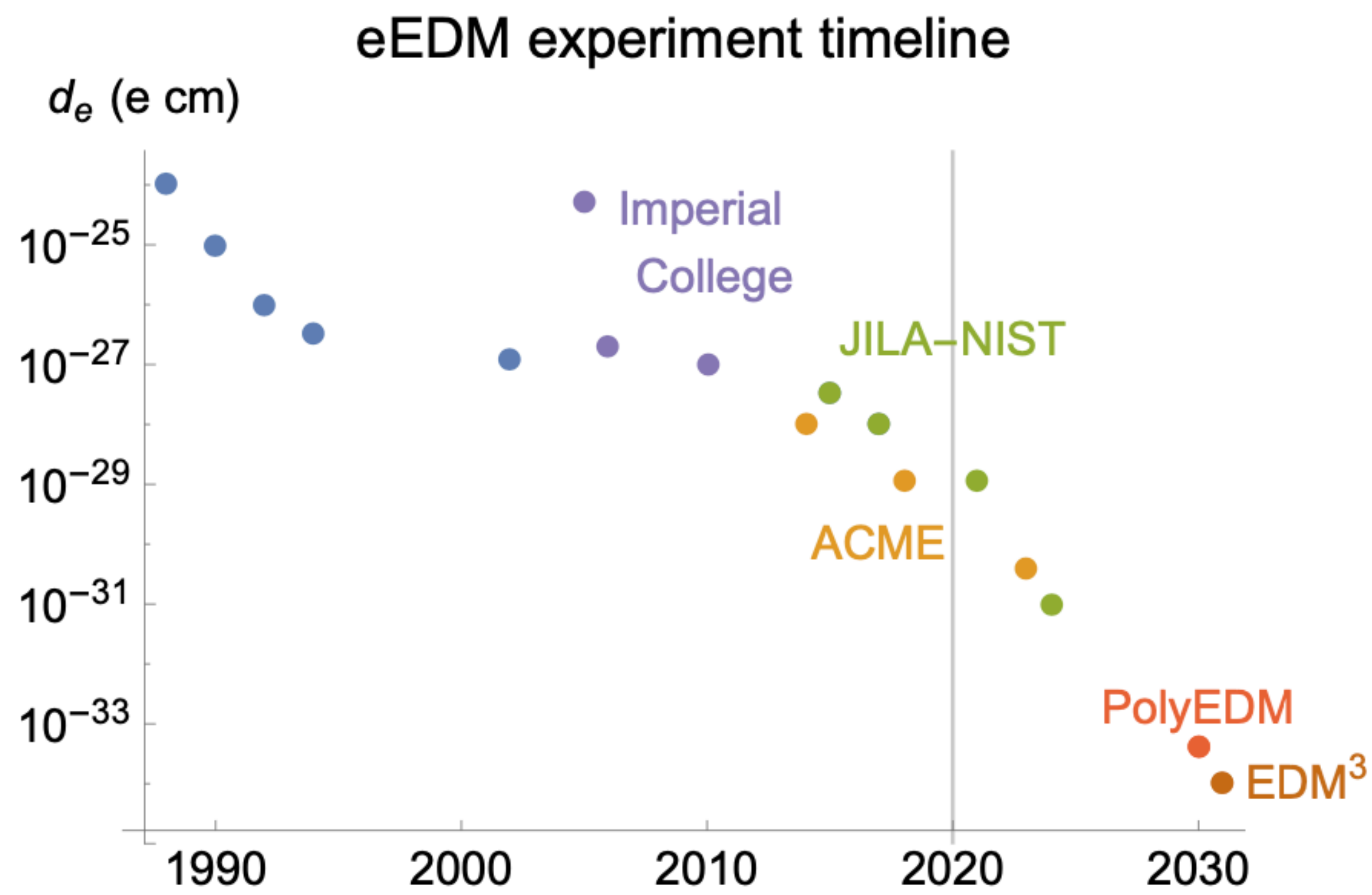
- Chirality-violating effects ⇒ necessarily involve the Higgs. True of both the EDM and $\mu \to e\gamma$

- Operators like $h^\dagger \ell_i \bar{\sigma}^{\mu\nu} \bar{e}_j B_{\mu\nu}$

- Rapid experimental progress:

  Within 10 years, EDM will probe 1-loop new physics at ~PeV, 2-loop at ~50 TeV

  CLFV probing ~10-100 TeV scale (depending on flavor model)



[figure from Qianshu Lu]

Electron EDM

The 2018 bound from ACME is: $|d_e| \lesssim 1.1 \times 10^{-29}\, e\,\mathrm{cm}$

This improves on the previous, 2013, ACME bound by about an order of magnitude.

EDMs violate chirality, so putting in the electron mass a spurion, we expect an effect of order:

$$d_e \sim \delta_{\mathrm{CPV}} \left(\frac{\lambda}{16\pi^2}\right)^k \frac{m_e}{M^2}$$

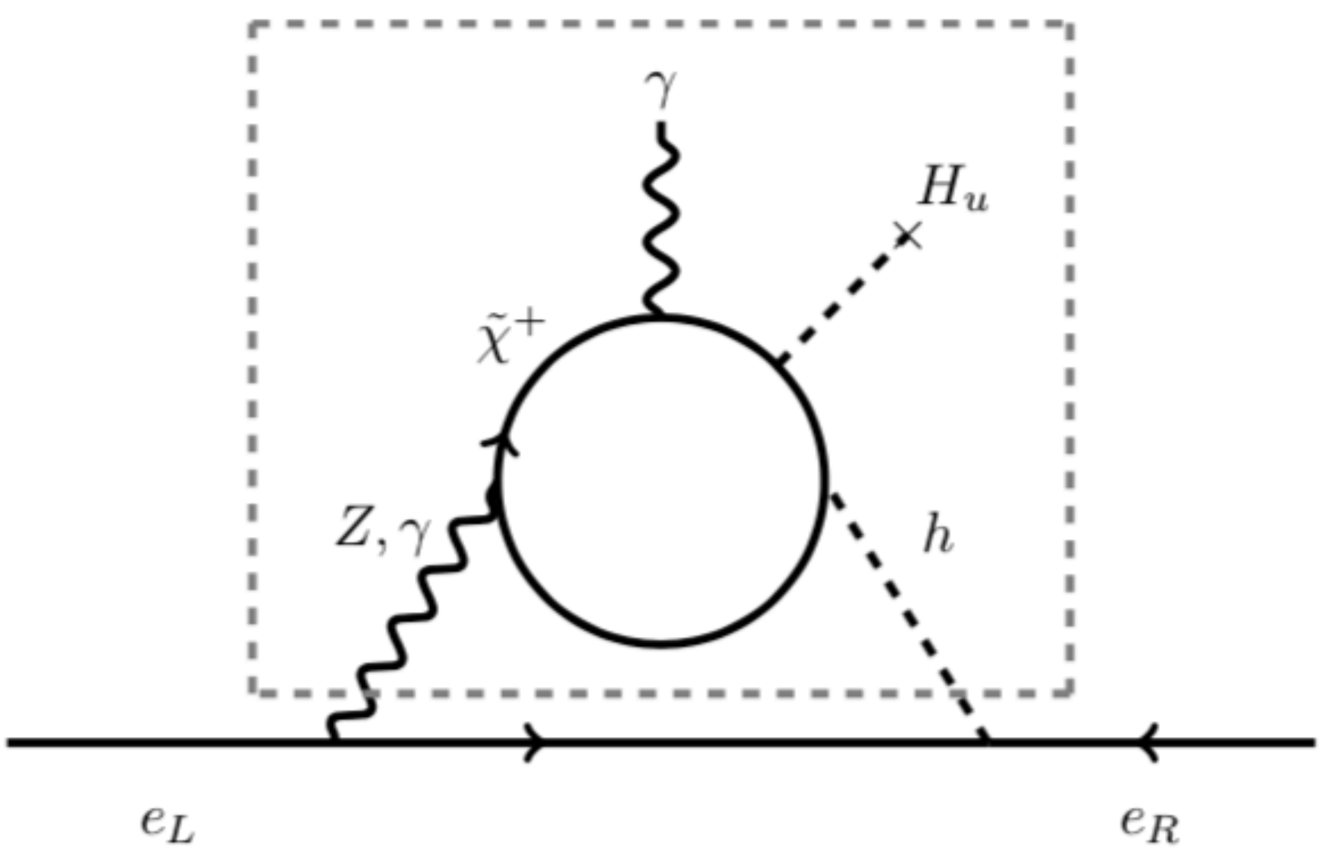
Then dimensional analysis tells us that the experiment probes masses

0-loop	1-loop	2-loop
1000 TeV	50 TeV	3 TeV

for order-one CPV phases this often exceeds LHC reach!

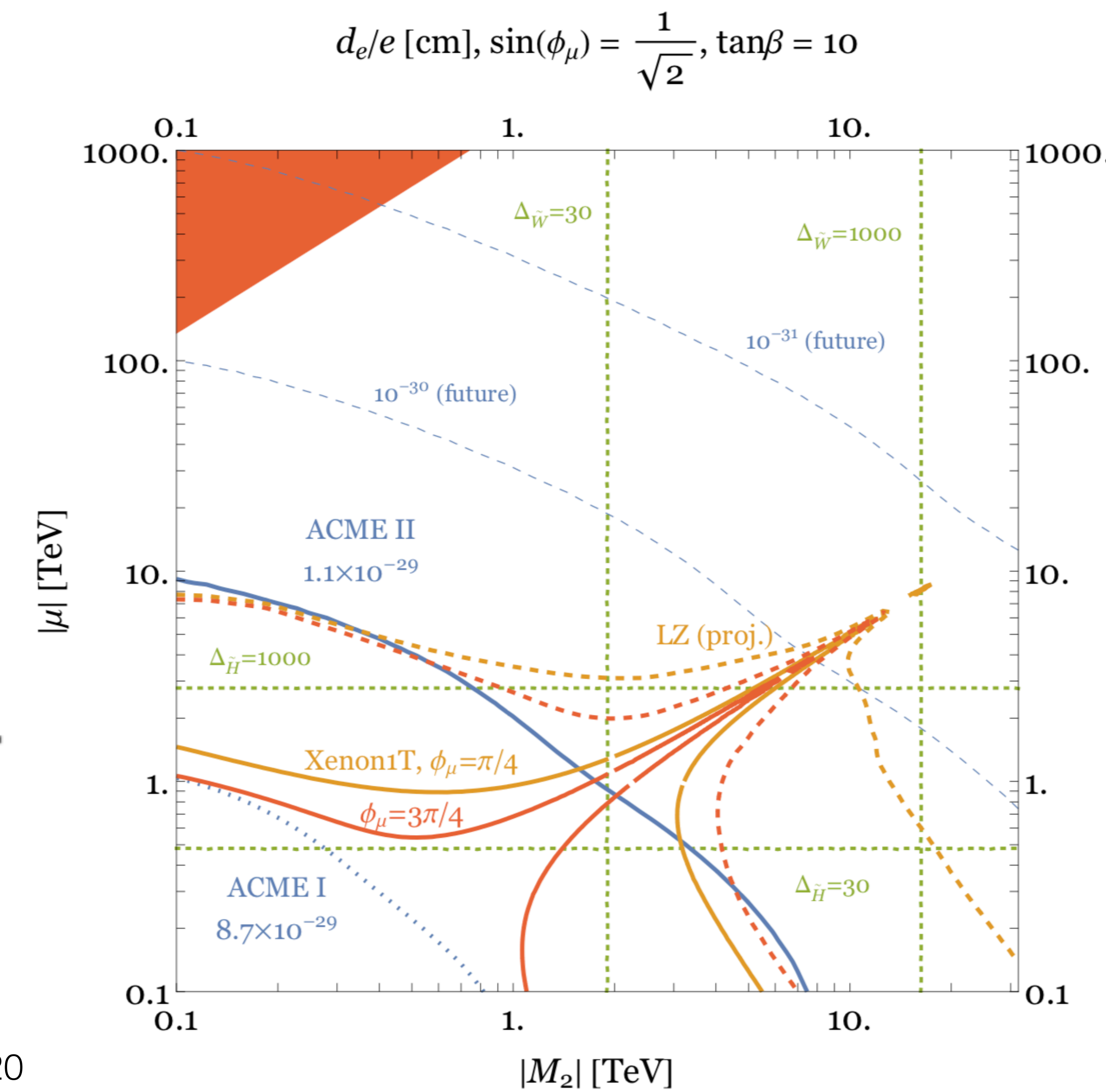
Electron EDM vs. Electroweak Physics

Quite generally, electroweak new physics coupling to the Higgs boson gives rise to an electron EDM (Barr-Zee).



[Cesarotti, Lu, Nakai, Parikh, MR, '18]

Powerful split SUSY electroweakino constraints from ACME 2!



Future EDM experiments

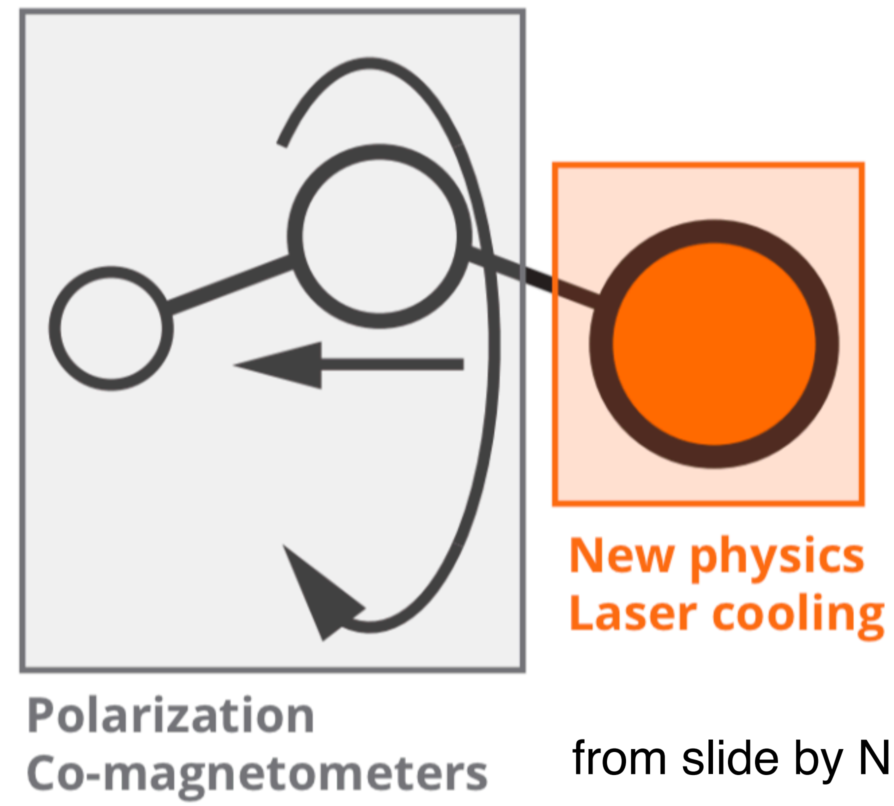
To improve, need more molecules, longer coherence times. Need special molecules:

Laser cooling can produce many slow-moving molecules to study. Avoid exciting molecular rotational, vibrational modes.

EDM systematics need "internal co-magnetometer."

Hutzler & Kozyryev 2017: **polyatomic molecules can give both! (ex: YbOH)**

Polyatomic EDM



from slide by N. Hutzler

Time scale of 5-10 years:

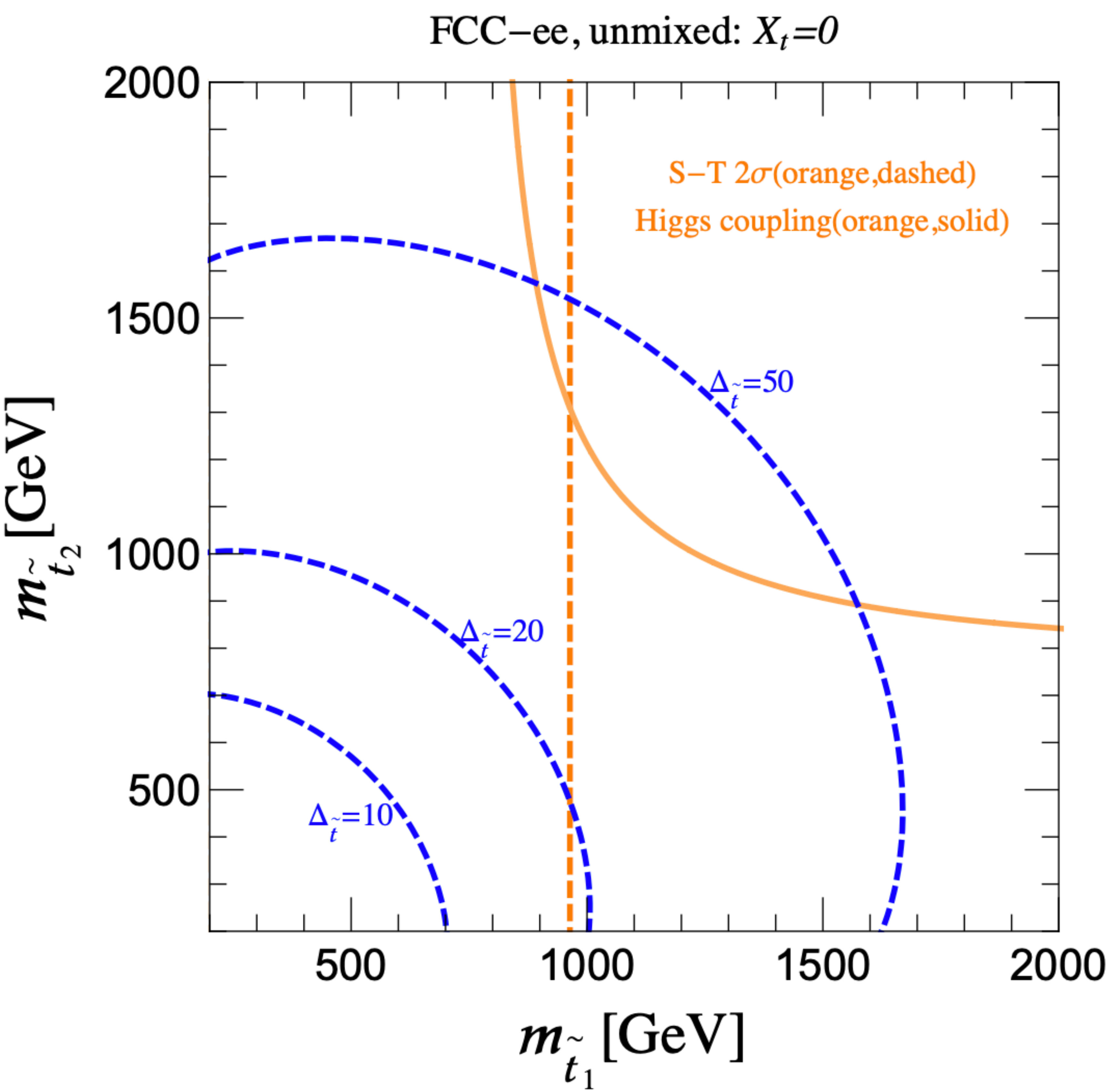
$$|d_e| \lesssim 10^{-32}\, e\,\mathrm{cm}$$

1-loop, PeV scale sensitivity

Other planned experiments: trapped molecular ions (Cornell, Ye, JILA), YbF (Hinds, Imperial), EDM^3 (Vutha, Horbatsch, Hessels, Toronto/York), …

FCC Physics and the Hierarchy Problem

Precision EW Constraints on SUSY Stops



Higgs couplings (gluons and photons) probe left- and right-handed stops roughly equally well.

The *T* parameter probes left-handed stops.

Fan, MR, Wang
1412.3107

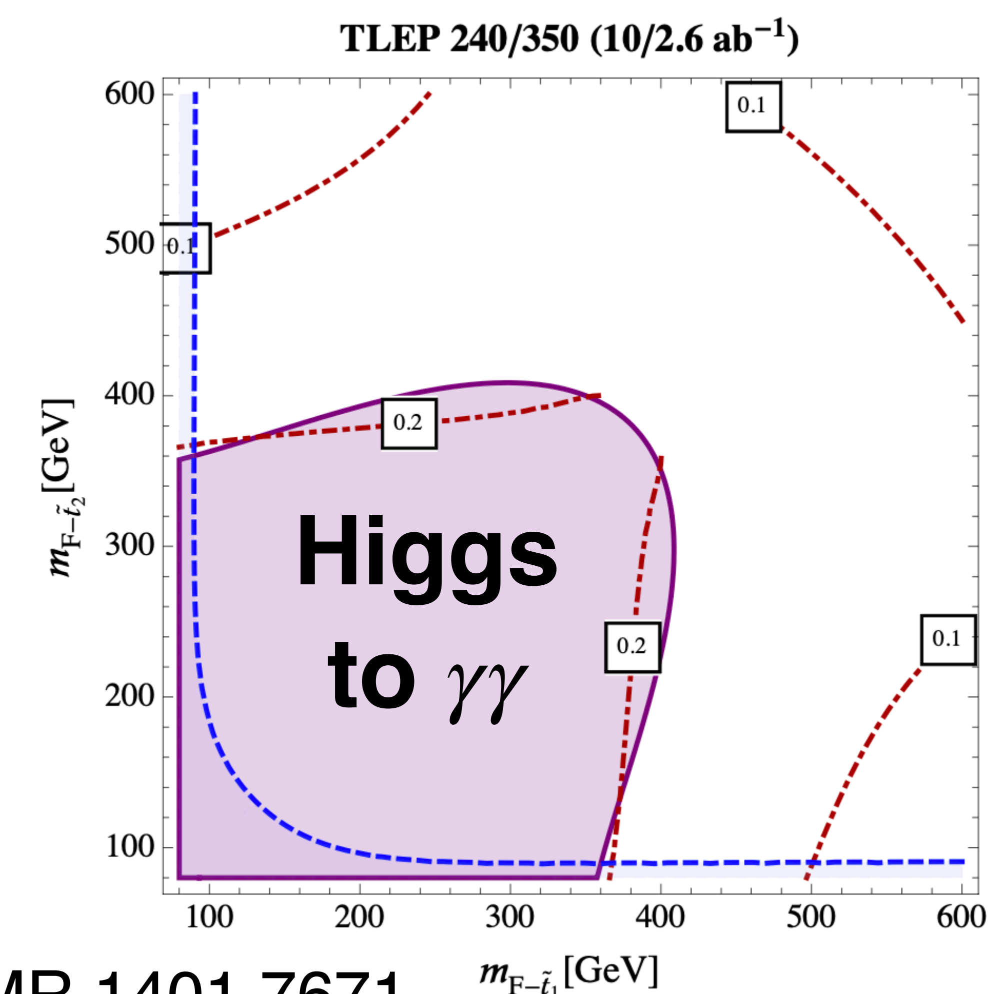
Folded SUSY: Uncolored Naturalness

In folded SUSY, stops have **no QCD color** (makes life difficult at LHC). But still have electroweak interactions.

Measuring Higgs decays to photons and the *T* parameter can help constrain folded SUSY stops.

The *T*-parameter bounds previously shown for stops are *exactly* the same for folded stops!

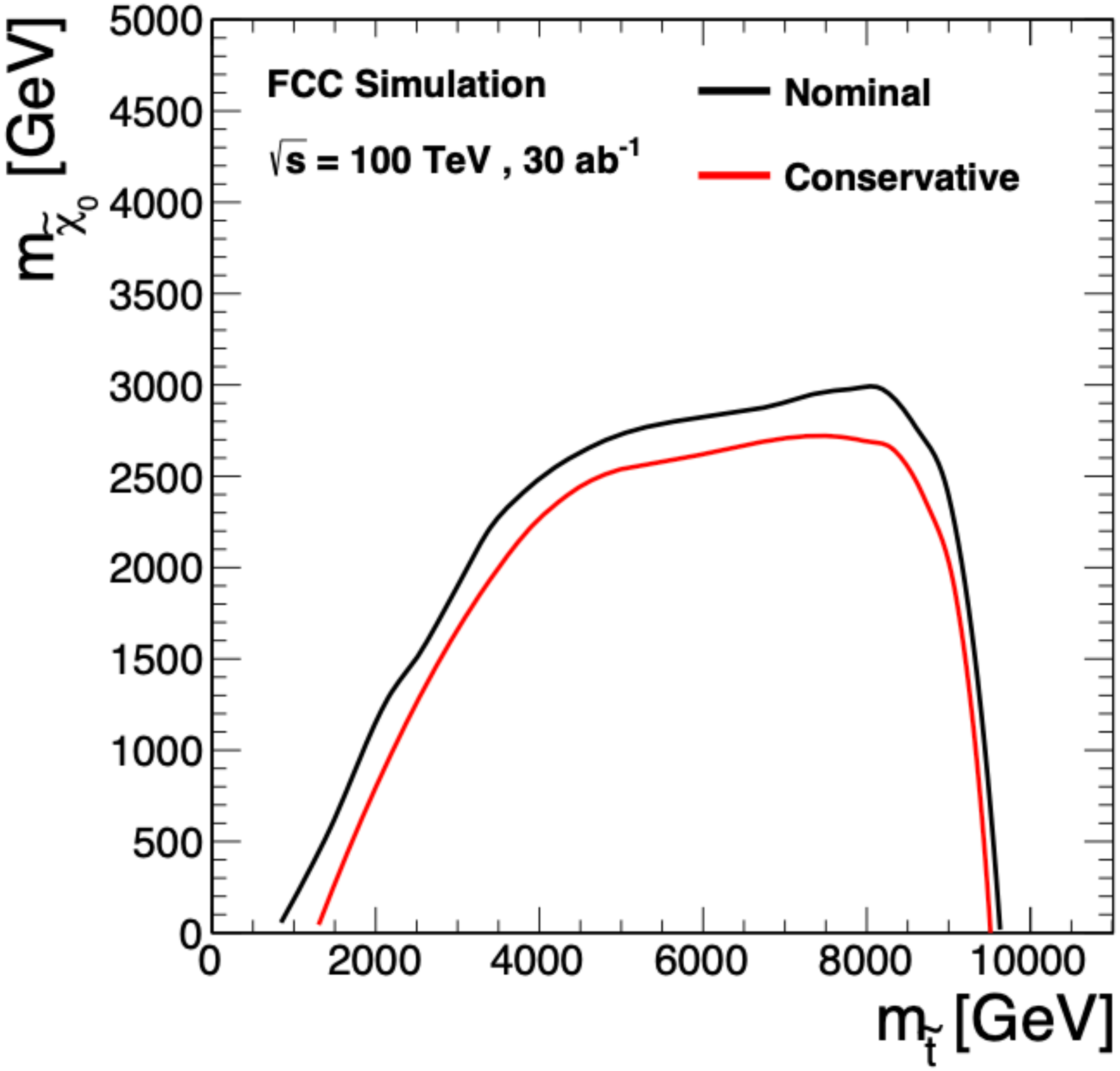
Another way that FCC-ee has exciting potential for uncolored naturalness!



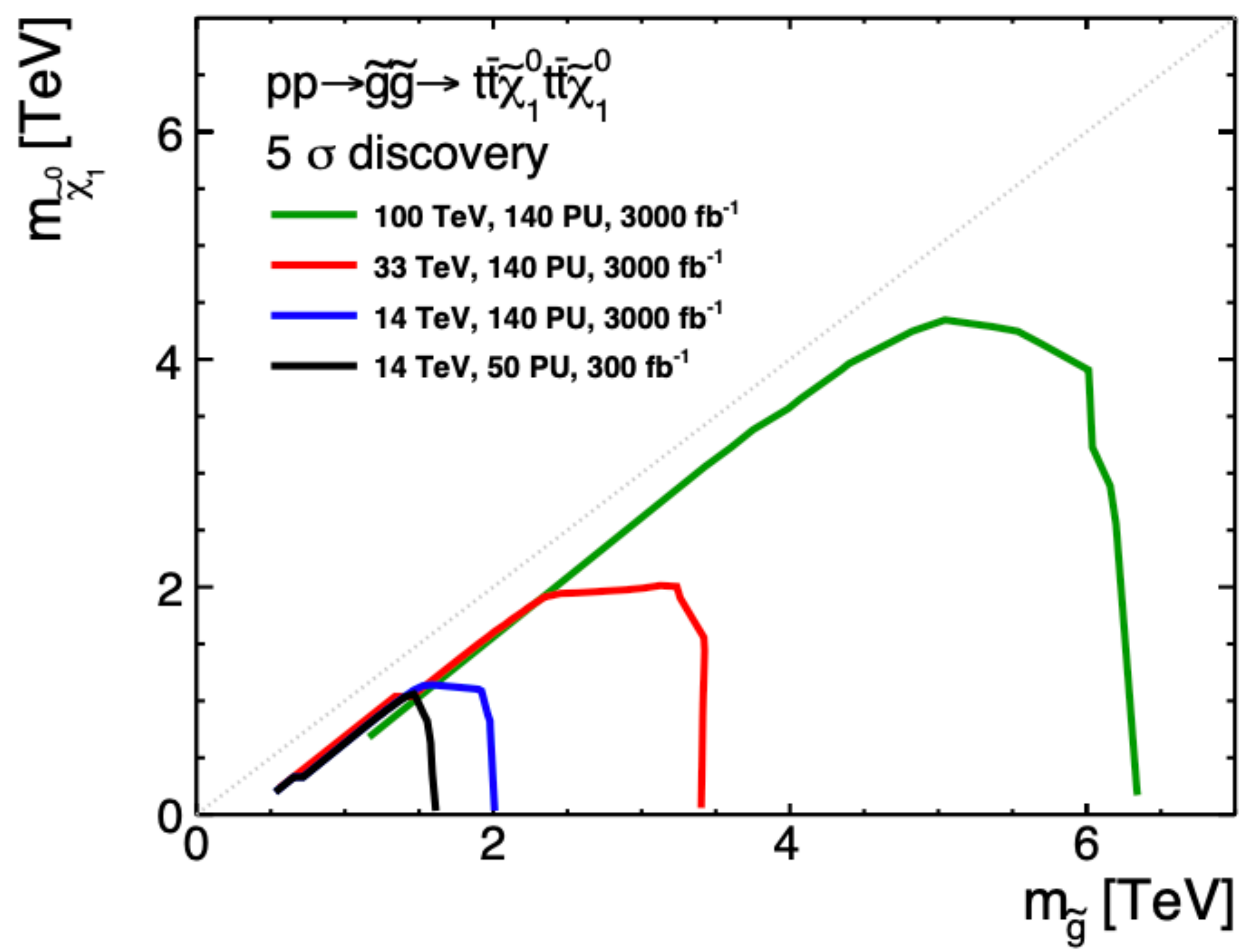
Fan, MR 1401.7671

Naturalness at FCC-hh: direct searches

Discovery potential



Gouskos, Sung, Incandela
CERN-ACC-2019-036



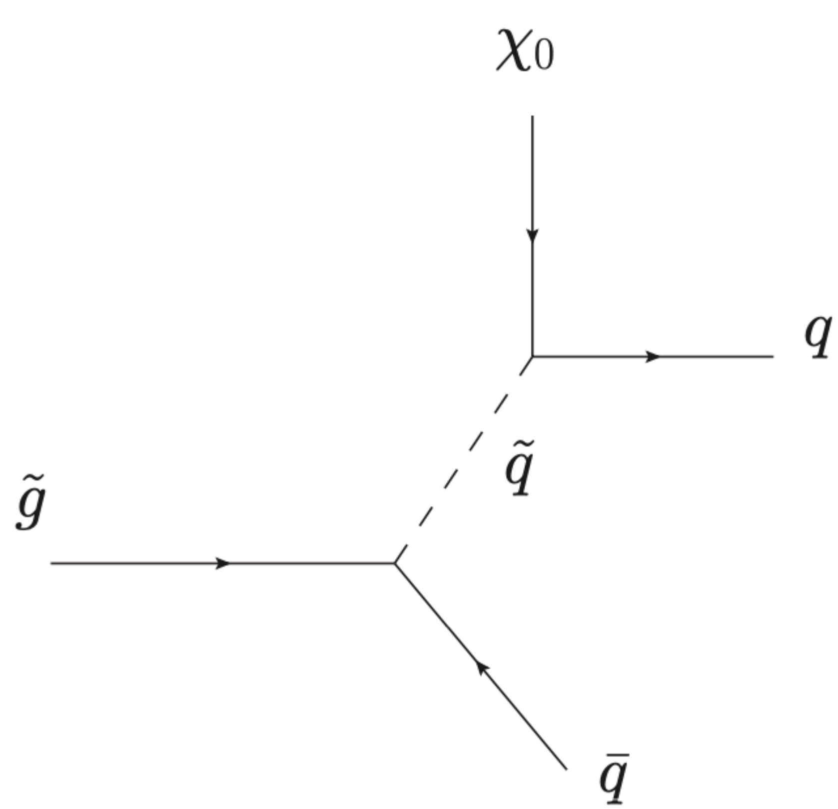
Golling et al., 1606.00947

Meso-tuning and simple models at FCC-hh

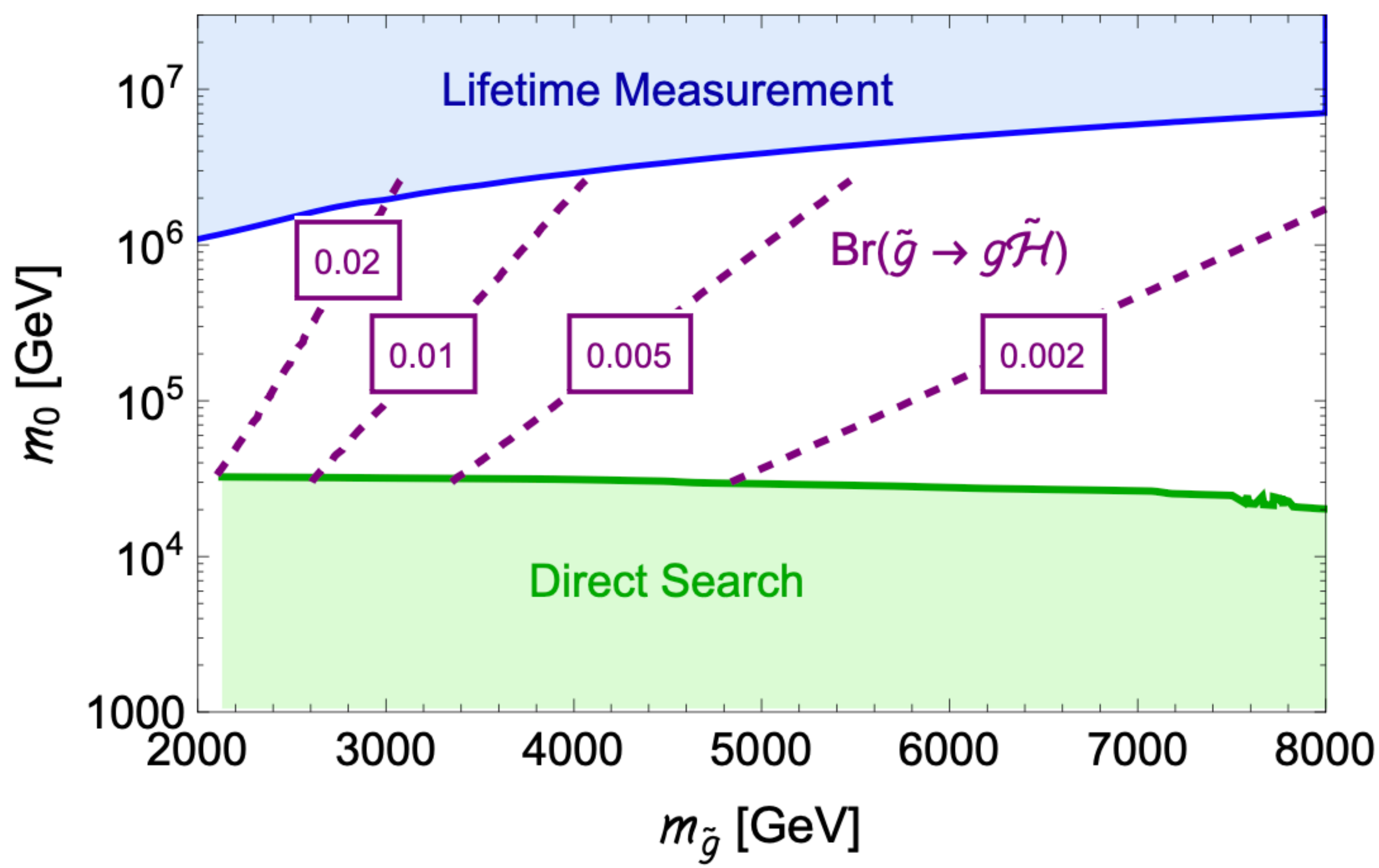
Naturalness arguments are *heuristic*, not sharp: probabilistic (Bayesian) reasoning. Always possible that we end up somewhere that looks somewhat fine-tuned, even if only by chance.

Some theories even have top-down pressure, e.g., toward $M_{\text{scalar}} \gg M_{\text{gaugino}}$ in many models of SUSY breaking.

(moderately) split SUSY



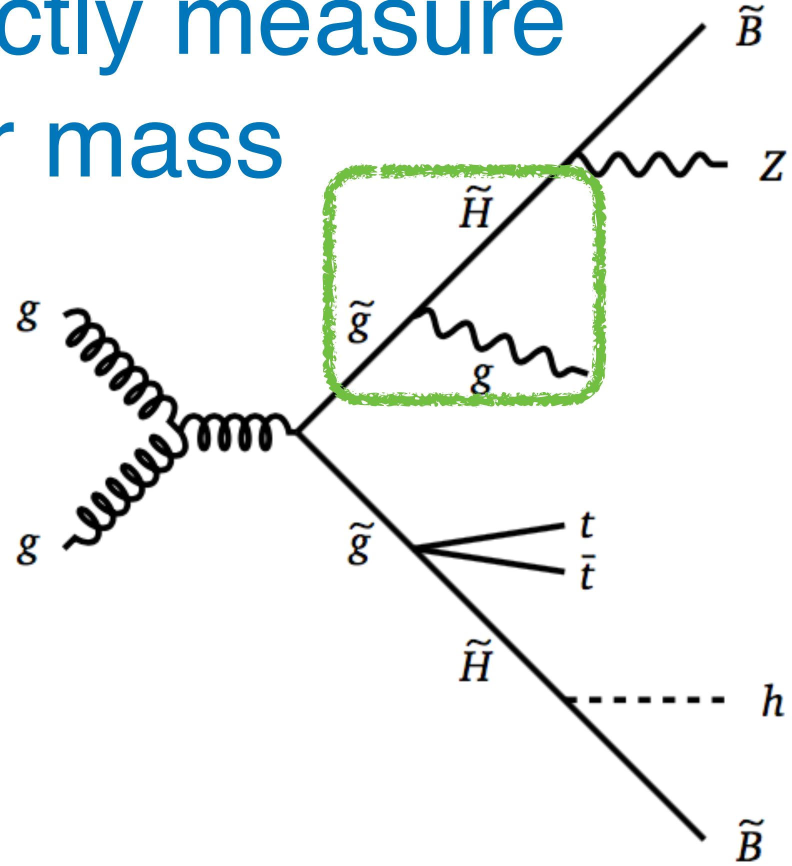
Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski ’12



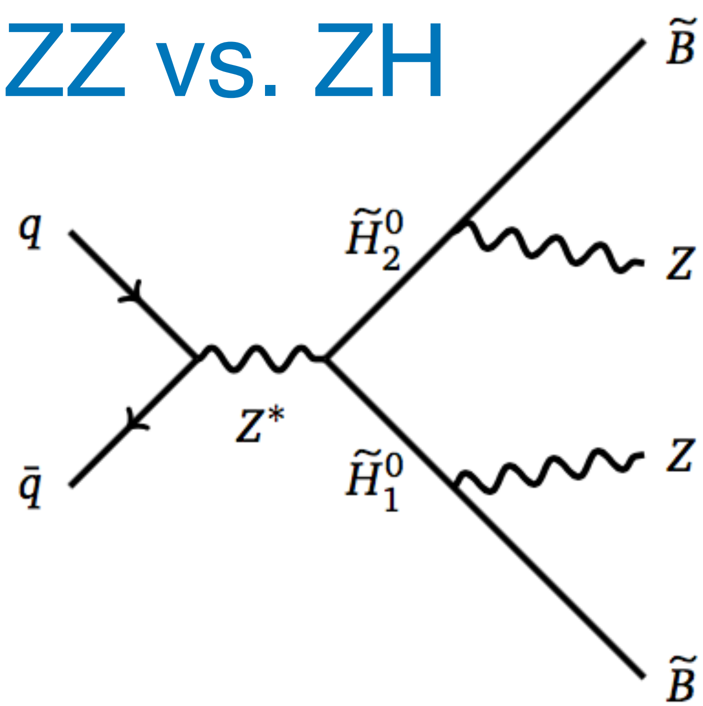
Agrawal, Fan, MR, Xue, ’17

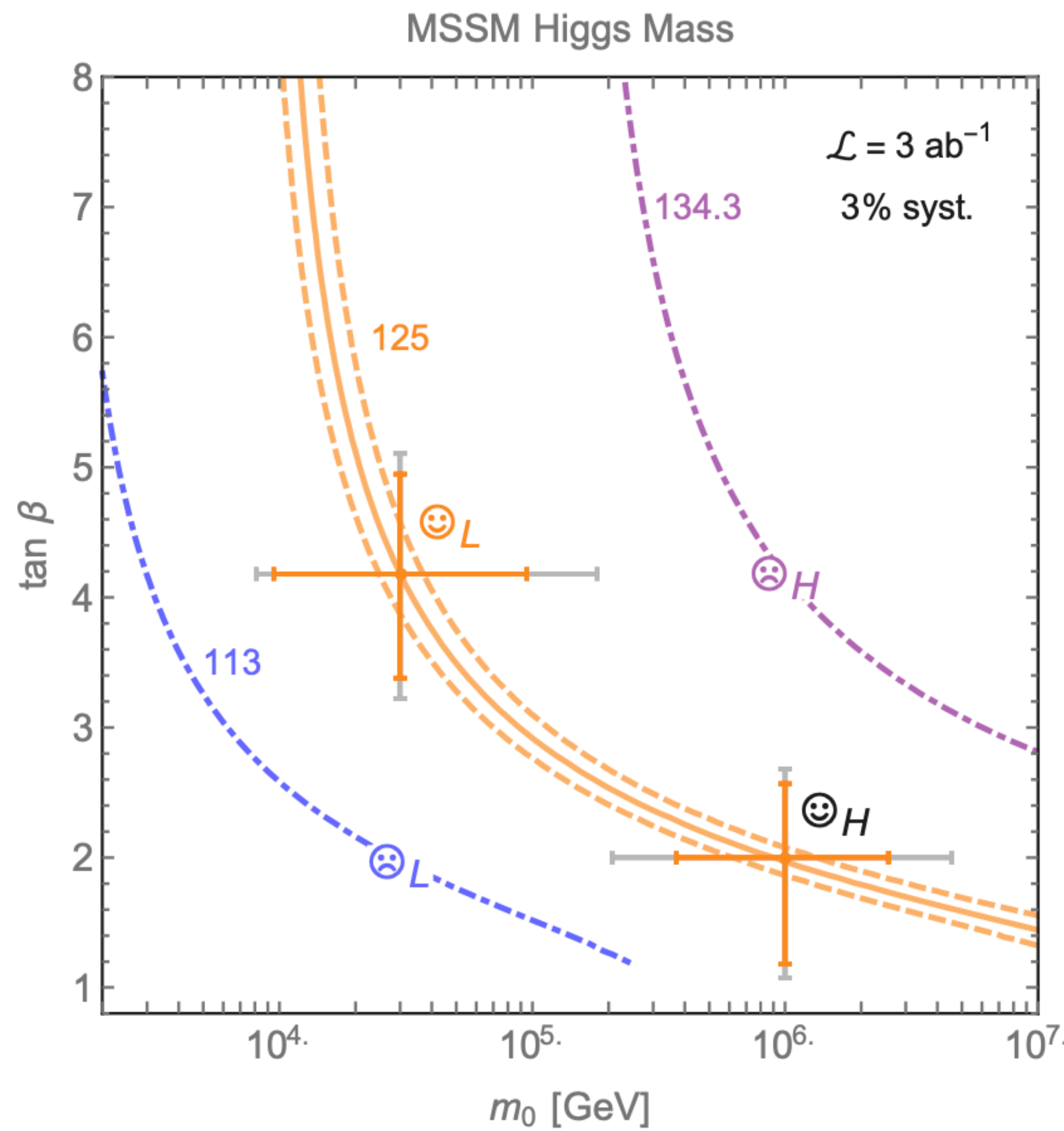
Precision SUSY: FCC-hh as gluino factory

indirectly measure scalar mass



tan β: ZZ vs. ZH



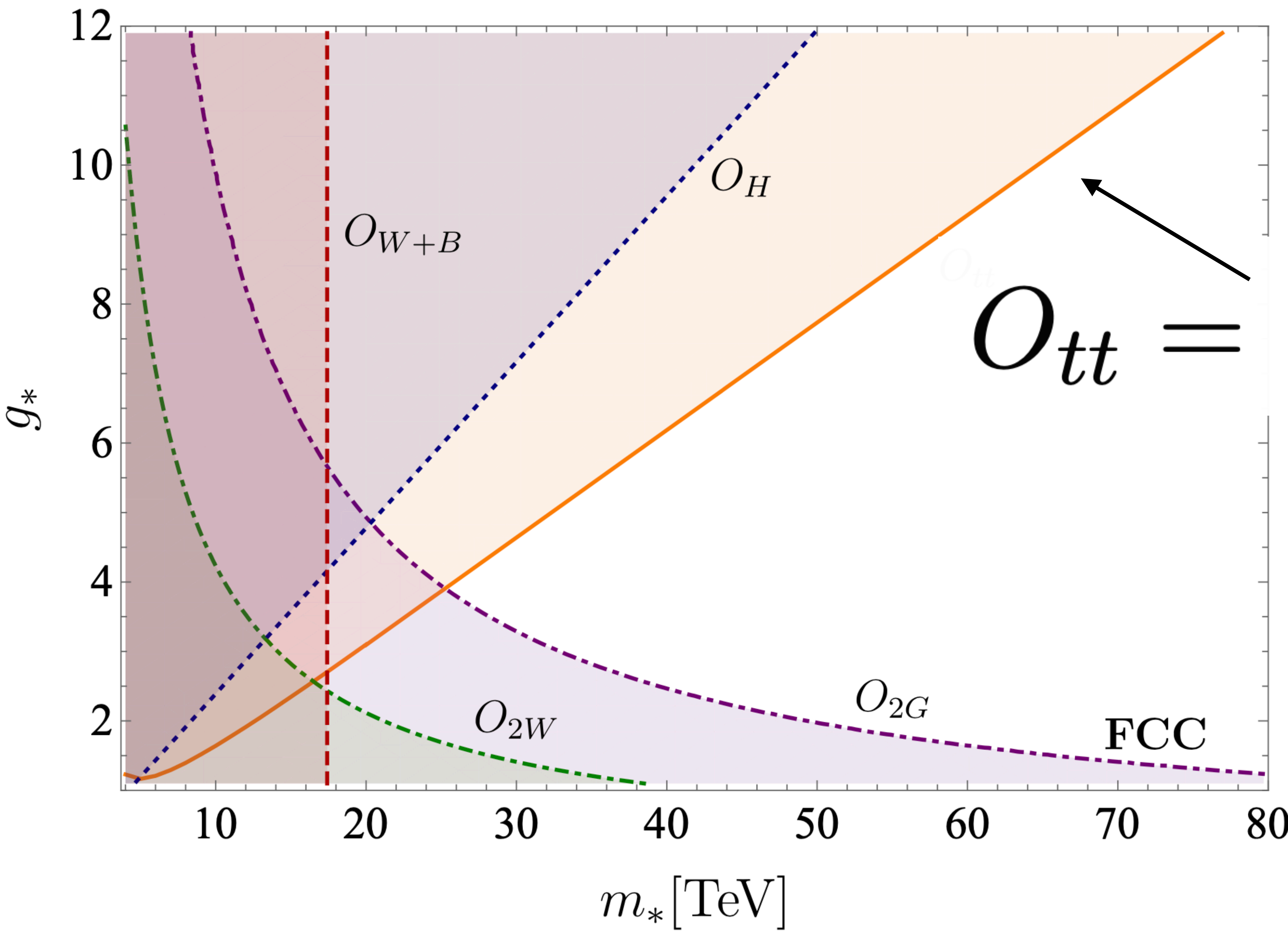


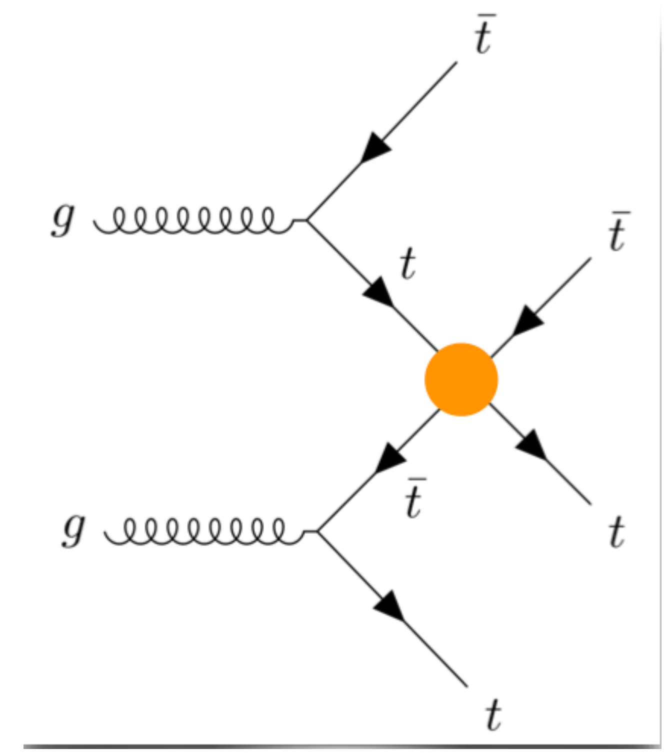
Agrawal, Fan, MR, Xue 1702.05484

Compositeness at FCC-hh: 4 Tops

Banelli, Salvioni, Serra, Theil, Weiler
2010.05915

[see Ennio Salvioni's slides yesterday]





$$O_{tt} = (\bar{t}_R \gamma_\mu t_R)^2$$

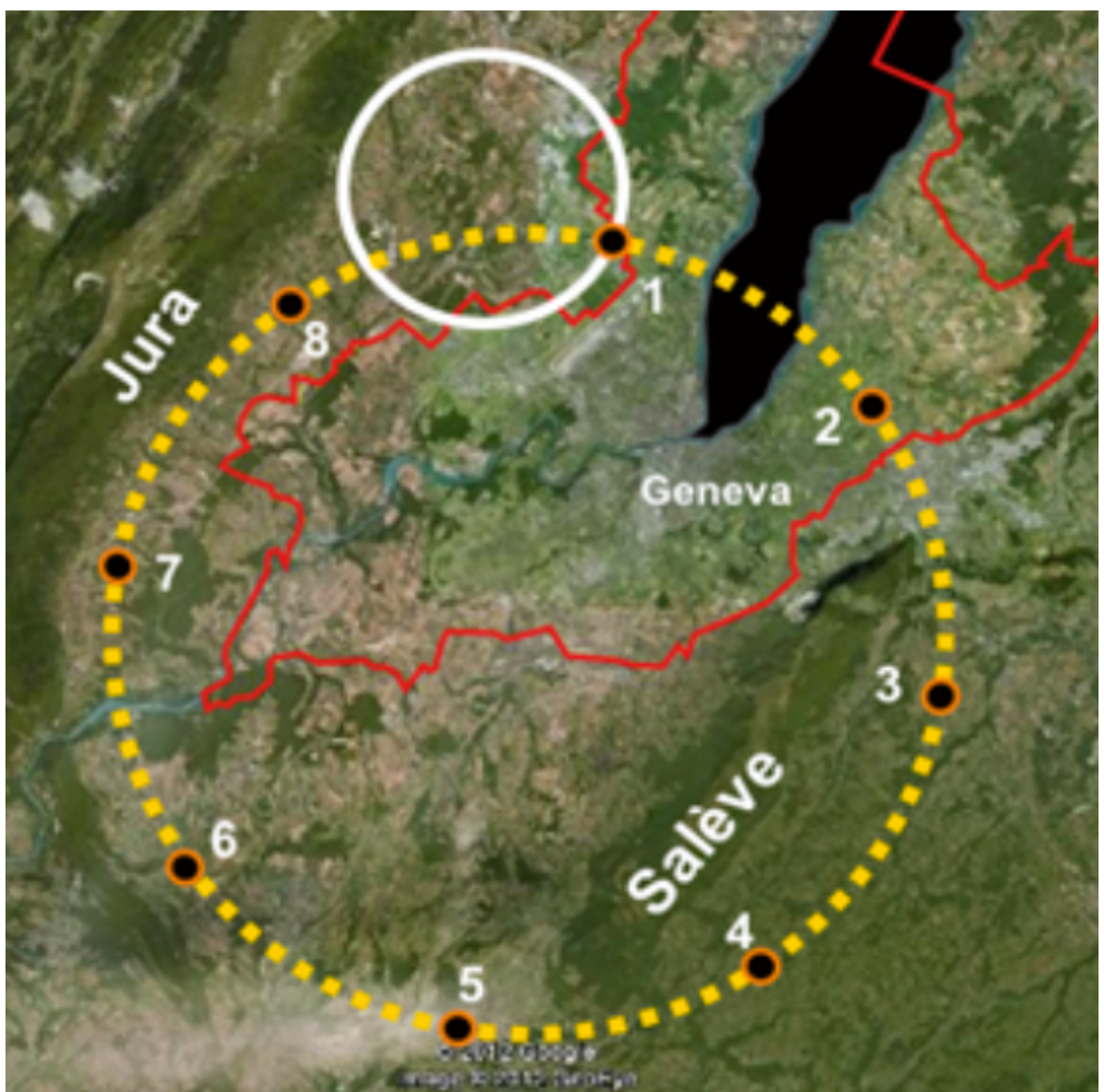
$$\frac{m_*}{g_*} > 6.5\ \mathrm{TeV}$$

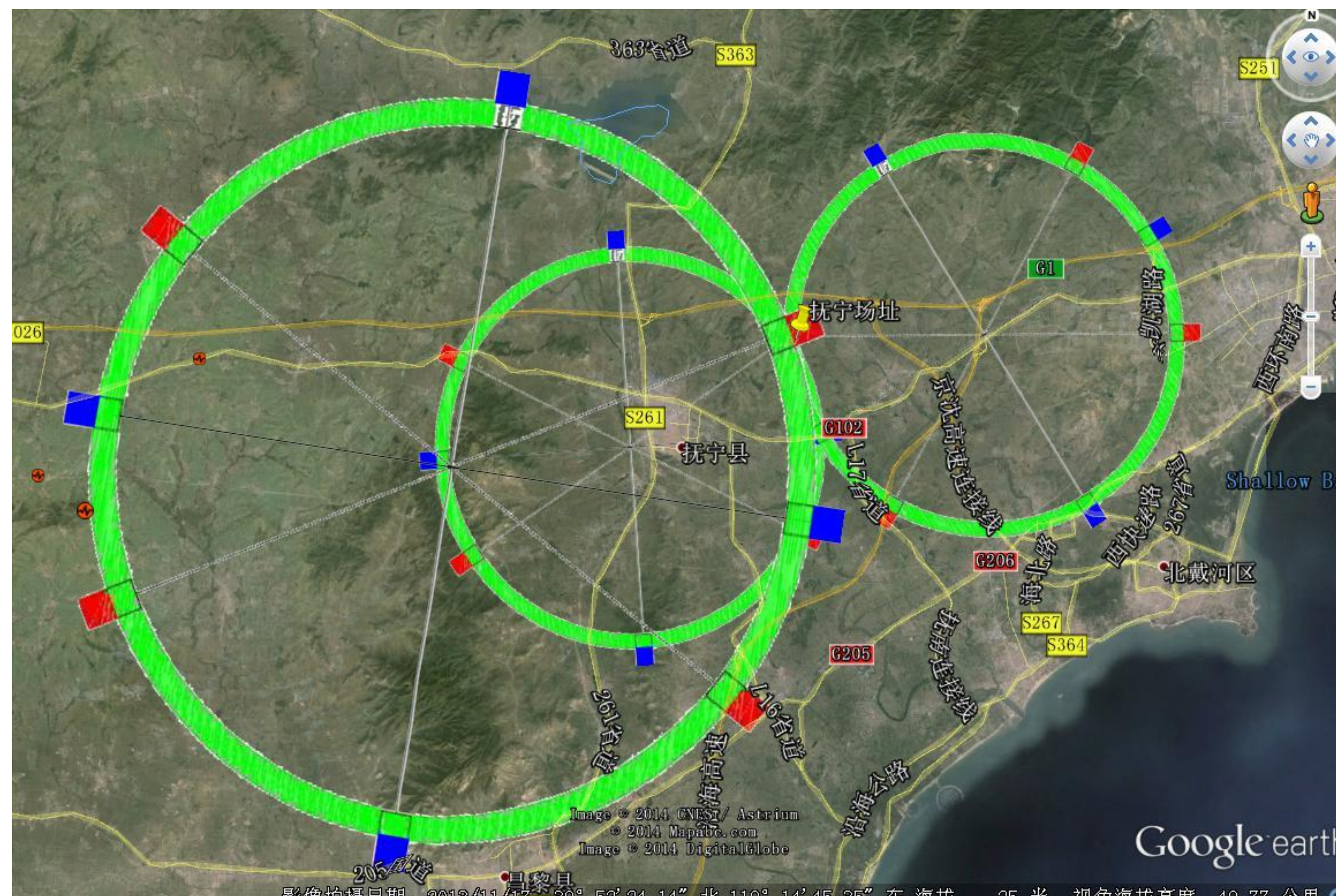
Big Tunnels: The Future of Our Field

New physics could be decisively ***discovered*** by an EDM experiment.

New physics can be thoroughly ***understood*** at a high-energy collider.

Whether near Geneva, Qinhuangdao, or somewhere else entirely, this is what we need for our future:





Summary

The LHC found what looks like an elementary spin-0 Higgs boson. Still, ***we do not understand the weak scale***.

We need to make good use of the LHC, but also plan for the future. ***Important to emphasize the big-picture questions.***

Keep an eye out for important discoveries from beyond the world of colliders, like **EDM searches** or dark matter.

However, to really ***understand*** new physics:

Particle physics needs new energy-frontier colliders!

Some big questions about small numbers

- Hierarchy problem: why is $m_W^2/M_{\rm Pl}^2 \approx 10^{-33}$?
- Strong CP problem: why is $|\bar{\theta}| \lesssim 10^{-10}$?
- Flavor: why the wide range of Yukawa couplings and of mixings, e.g. $y_e \approx 3 \times 10^{-6}$ but $y_t \approx 0.95$?
- Neutrino masses: why so small? $m_\nu \sim \dfrac{v^2}{10^{15}\ \text{GeV}}$ or $m_\nu \sim 10^{-13} v$?
- Cosmological constant problem: why $\rho_\Lambda \sim 10^{-120} M_{\rm Pl}^4$?
- Matter/antimatter asymmetry: why $(n_B - n_{\bar{B}})/n_\gamma \sim 10^{-9}$?
- Dark matter abundance: why $n_{\rm DM}/n_\gamma \sim 10^{-12} m_{\rm DM}/\text{TeV}$?
- Primordial density perturbations: why $\delta\rho/\rho \sim 10^{-5}$?

Common theme: when we see small numbers, we're not satisfied until we can *explain* them in terms of some underlying mechanism.

The electroweak hierarchy and our world

It's possible to do a more detailed estimate of both the minimum and maximum size of an ordinary star. A star should be hot enough for nuclear fusion to happen in its core.

$$P_{\text{fuse}}(E) \sim \exp(-E/T - \mathcal{O}(\alpha)\sqrt{m_p/E})$$

Boltzmann

Gamow (WKB)

The rate peaks at $E_g \sim \alpha^{2/3} m_p^{1/3} T^{2/3}$. In order to not have too much suppression, we need

$$T \gtrsim E_g \quad \Rightarrow \quad T \gtrsim \alpha^2 m_p$$

We need thermal pressure to balance gravitational attraction, and for the star *not* to be so compact that electron degeneracy pressure is important. Putting the pieces together gives a bound on stellar mass.

[Details: V. Weisskopf, *Science* **187**(4177):605–612 (1975); Burrows and Ostriker, *PNAS* 111 (7):2409-2416 (2014).]

The electroweak hierarchy and our world

The detailed estimate, assuming a ball of hydrogen gas that is hot enough for nuclear fusion to work despite Coulomb repulsion, leads to a scaling like:

$$\frac{M_{\rm star}}{m_{\rm proton}} \gtrsim \left(\frac{M_{\rm Pl}}{m_{\rm proton}}\right)^{3} \left(\frac{m_{\rm proton}}{m_{\rm electron}}\right)^{3/4} \alpha^{3/2}$$

In fact, a star also cannot be too much heavier than this without collapsing.

Similar reasoning reveals that the maximum mass of a rocky planet scales like

$$\frac{M_{\rm rocky\ planet}}{m_{\rm proton}} \lesssim \left(\frac{M_{\rm Pl}}{m_{\rm proton}}\right)^{3} \alpha^{3/2}$$

If the Higgs VEV were near the Planck scale, the Universe would be a very different place!

[Details: V. Weisskopf, *Science* **187**(4177):605–612 (1975); Burrows and Ostriker, *PNAS* 111 (7):2409-2416 (2014).]

Technical naturalness

A theory in which the hierarchy becomes “technically natural”—that is, in which you can compute radiative corrections and don’t find dramatic changes—*might or might not* solve the hierarchy problem.

If the theory introduces a tiny number by hand, from my viewpoint it hasn’t solved the problem, even if that number is stable. But it has, perhaps, *made the problem more tractable*.

Putting too much emphasis on radiative stability would discard other problems, like the Strong CP problem, which in my mind are every bit as important as the hierarchy problem.

Indeed, tiny technically natural couplings seem to be problematic in UV-complete gravitational theories (this is a whole other talk, about the Weak Gravity Conjecture).

Recasting the hierarchy problem

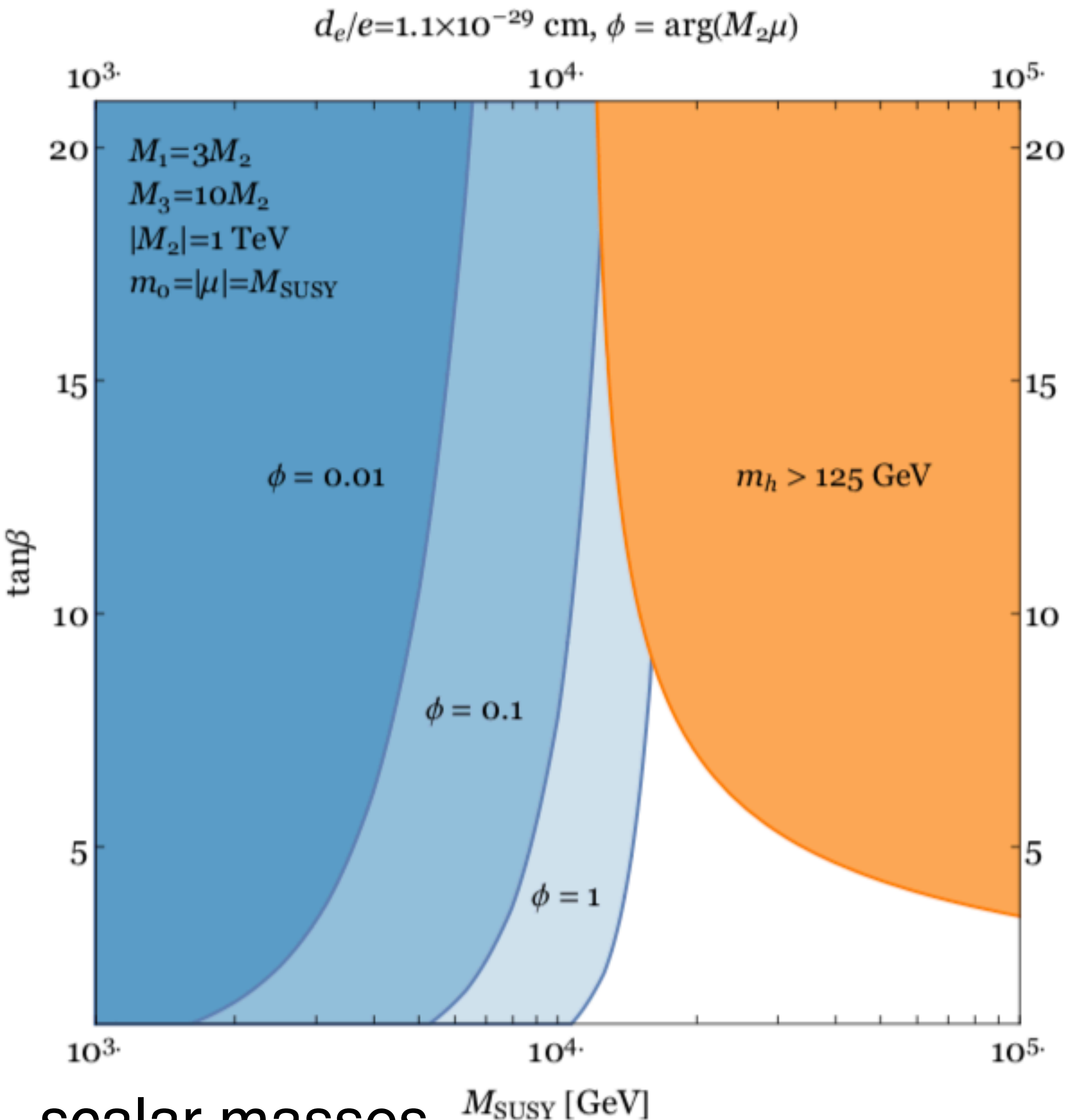
Many known solutions to the hierarchy problem really *recast* the problem into a different problem: what is the origin of the…

- scale of supersymmetry breaking?
- compositeness scale?
- volume of extra dimensions?
- extreme flatness of the relaxion potential?

They allow the electroweak scale to be **computed** from other inputs, but explaining the origin of those inputs is a new problem.

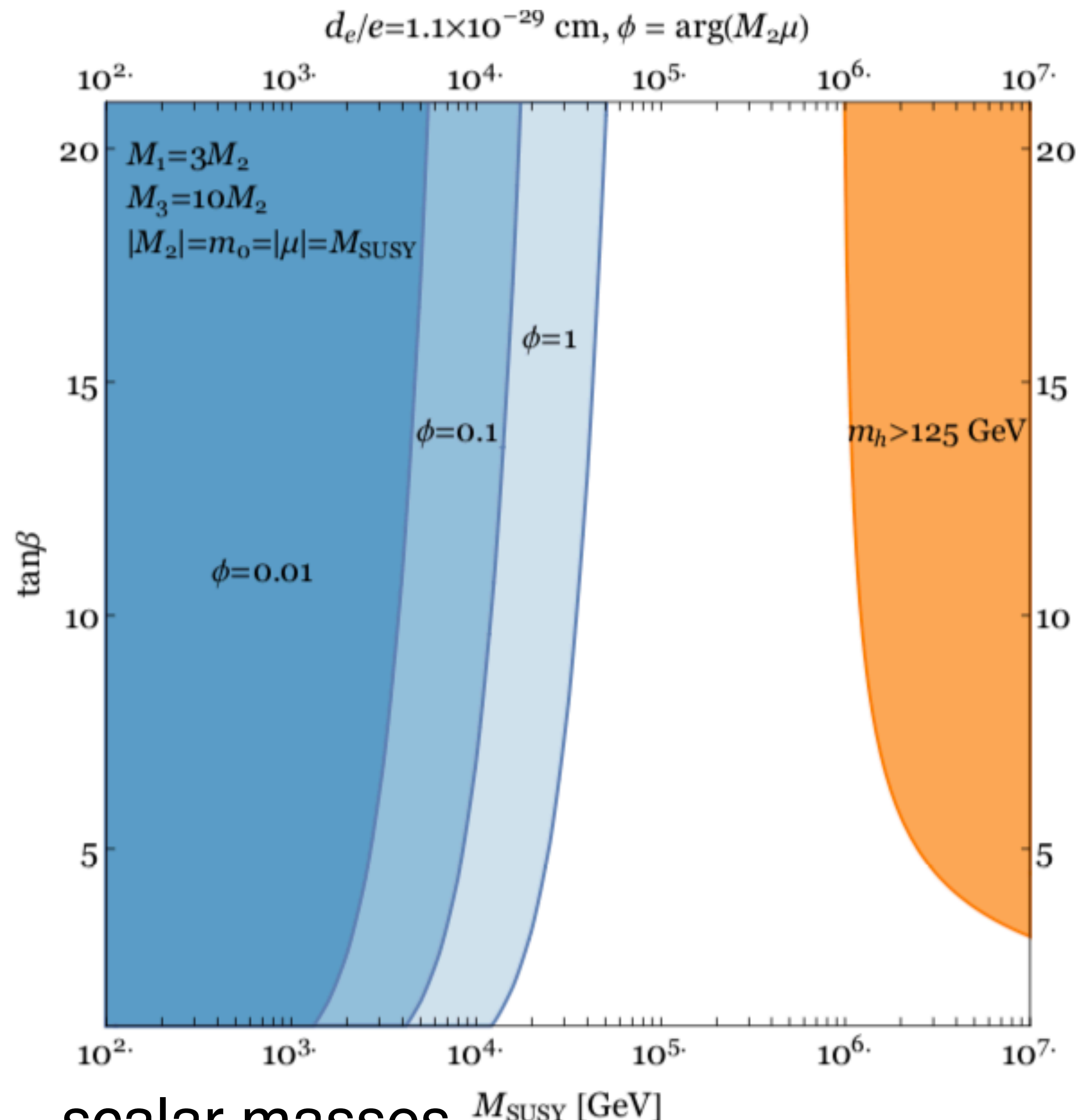
By changing the character of the problem, they allow for new kinds of solutions—often dimensional transmutation.

Electron EDM vs. MSSM



scalar masses

Split SUSY



scalar masses

High-Scale SUSY

One-loop effects: Cari Cesarotti, Qianshu Lu, Yuichiro Nakai, Aditya Parikh, MR, ’18