Standard Model and Beyond

Tim M.P. Tait

NORTHWESTERN UNIVERSITY

Argonne NATIONAL LABORATORY

Northwestern University / Argonne National Laboratory

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Outline of the Lectures

- Lecture I: Introduction to the Standard Model
  - Structure of the SM
  - Successes and Predictions
- Lecture II: Visions for the Physics Beyond
  - Shortcomings of the Standard Model
  - Some of our favorite ways to address them.

Please feel free to stop ~~me~~ Tao with questions at any time!

Beyond the SM?

Traditional techniques for predicting physics beyond the Standard Model include: reading tea leaves, meditating, casting rune stones, drawing tarot cards, gazing into crystal balls, and even talking to theorists!

Foretelling the Future?

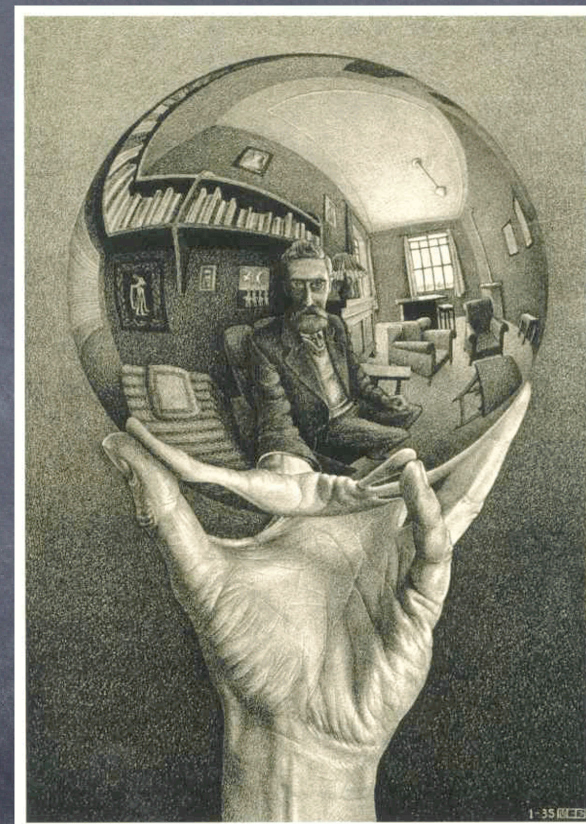
- In this lecture, we will look at some of the weaknesses of the SM and some of the more popular theoretical ideas to shore up those weaknesses.

- Nonetheless, my favorite crystal ball is actually the one by Escher to the right. The lesson it reminds me is that sometimes predicting the future is more about who we ourselves are than what is likely to happen.

- I would be surprised if any of our theoretical constructions turned out to be precisely true.

- But I think it is quite likely that some of them contain **elements** of truth.

- Their value is in their ability to make us think carefully about where the SM makes us uncomfortable, how we could imagine fixing it, what constraints exist, and how we could discover them.



Beyond the SM

- A challenge in preparing these lectures was the fact that it is essentially impossible in the allotted time to give you any proper details about how any of the ideas here work.
- Mostly, I gave up trying. My goal is to motivate the issues in the SM itself that lead us to think about these theories, and to try to say something about how they address those issues, and how we might see some hints of them at some future experiment.
- My hope is that this will at least give you some flavor of where these theories come from, and why they are interesting, even if the details remain largely unexplored. Understanding the issues we are trying to solve is the first step to understanding how the theories actually solve them.

This lecture is even more
idiosyncratic than the first one.

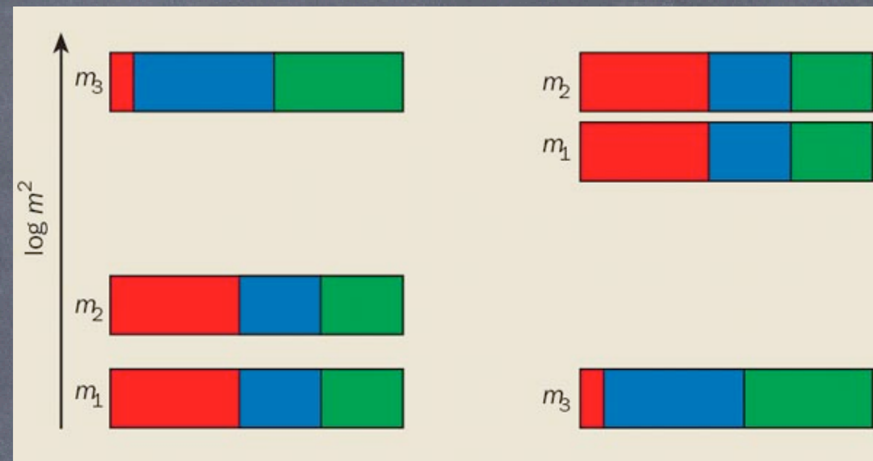
Breaking the SM?

- The attitude I am going to take is that the SM is an effective theory, providing a good approximate description at low energies, but breaking down at some high energy scale where new physics kicks in.
  - Ok, now the question is where does it break down and how?
- The obvious way to answer those questions is to let experimental data guide us. In a few cases, like neutrino masses, that even works.
- However, when we don't have experimental data to guide us, we need to rely on theoretical arguments.
  - We can look for a regime where the SM doesn't make sense and argue that there must be some kind of new physics there.
  - We can look for theories which are more aesthetic or predictive, and try to understand how to "match them onto" the SM at low energies.
  - We can look for features that look unnatural in the SM, and try to invent mechanisms which might explain them more plausibly.
- We'll explore all of these strategies and see how far they take us.

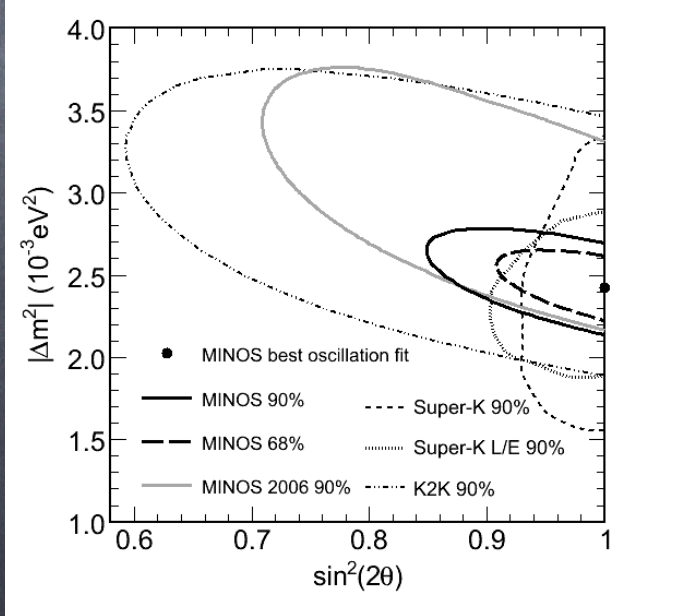
Experimental Motivations

Neutrino Masses

- The easiest place to pick on the Standard Model is with regard to neutrino masses. We have lots of evidence that they are non-zero.
- We saw in the previous lecture that the SM predicts zero neutrino masses.
- Current measurements allow for two 'hierarchies' of masses, with measurements of the 12 and 23 mixings.
- Currently there is only an upper bound on the amount of 13 mixing, but experiments are coming online soon to extend our reach there.
- The real question for BSM is how to extend the SM to include them.



"atmospheric neutrino oscillations"



The νSM?

- Since the SM itself could not generate neutrino masses, we have to abandon one or more of our tenets to include them.
- Two possibilities naturally occur:
  - We can add more particles. If we add some gauge singlets (n), we can write down Yukawa interactions just like we did for the rest of the fermions:

$$(i\sigma_2\Phi^*)Y^{\nu}_{ij}\bar{L}_i n_j + H.c.$$

... leading to Dirac ν masses.

  - We can allow for non-renormalizable interactions. For example:

$$\frac{1}{\Lambda_{ij}}\left(\bar{L}_i\Phi\right)\left(L^c_j\Phi\right) + H.c.$$

  - These operators lead to Majorana neutrino masses (which now in principle need to be diagonalized, leading to mixing in the charged current interactions, just like happened for quarks) once I replace the Higgses by their VEVs:

$$m_\nu = \frac{v^2}{\Lambda}$$

Interlude : Non-Renormalizable Operators

- The dimension 5 operator works great to incorporate neutrino masses into the SM, but now we should ask: Why didn't I start out by doing this?
- Remember, that this operator is non-renormalizable. That means that when I start doing loop calculations, I will typically have to add more even higher dimensional operators to cancel the infinities. Ultimately, my theory has an infinite number of parameters, which makes one wonder if it can actually make any predictions at all.
  - In fact, it is predictive, but only at low energies.
    - Higher dimensional operators have couplings with inverse mass dimension. To hold observables like cross sections at the right mass dimension, these are balanced by positive powers of the energies involved in a given process.

example: Consider a dimensionless observable O which gets contributions from a dimensionless coupling g as $O \propto g$.

A higher dimensional operator whose coupling is $1/\Lambda$ that can contribute to O will contribute as $O \propto E / \Lambda$, where E is some energy already involved in O.

  - At low energies, the effects of higher dimensional operators are suppressed by more powers of E / Λ and can be safely ignored.
  - At energies above Λ, all operators matter and we **lose predictive power**.

Back to Neutrino Masses

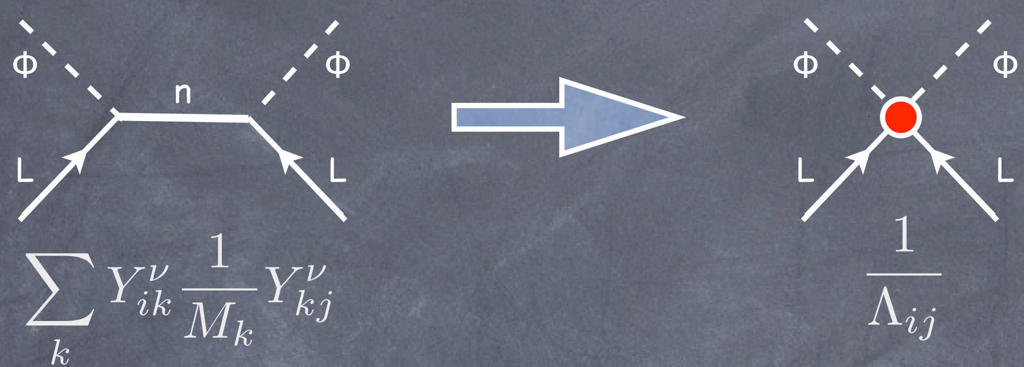
- Coming back to the case of our neutrino mass operator, it turns out this operator is the unique dimension 5 term which can be added to the SM.
    - Nothing else is consistent with the SM gauge symmetries and Lorentz invariance.
    - So we might **expect** it to be the first manifestation of physics beyond the Standard Model, because it is the least suppressed by E / Λ. (Note that E is actually the Higgs VEV v in this example).
- Now lets explore a possible connection between the non-renormalizable operator, and our other idea (to add a gauge singlet n). It turns out the two may be related!
- We add n with its Yukawa couplings, but since it has no gauge transformation, we can also give it a (Majorana) mass term:

$$(i\sigma_2\Phi^*)Y^{\nu}_{ij}\bar{L}_i n_j + M\bar{n}n^c + H.c.$$

- Since a mass for n violated none of the symmetries of the SM, according to the rules I was playing by before, I should really have added it.

νSM : UV Completion

- At energies far below the mass of n, we can't resolve it, and virtual n lines inside Feynman diagrams look contracted to points:



- In other words, at energies far below M, the leading effect of n is just to generate our dimension 5 operator (in theory-speak, we "integrate out n, producing a higher dimensional operator") with a particular value of Λ which is related to the original theory's Y's and M's.

- The theory with the massive n and Yukawa interactions is renormalizable. In particular, it doesn't need to break down and become unpredictive at large energies.

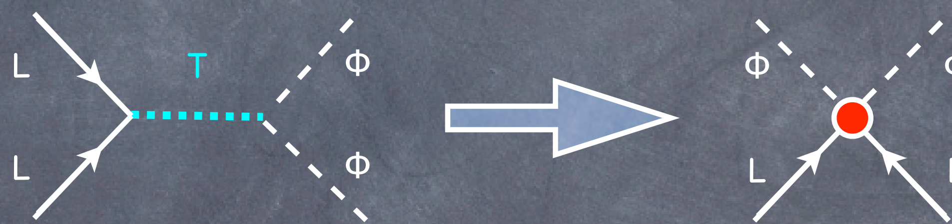
- For that reason, we refer to the theory with Majorana n as a "UV completion" of the theory defined by the SM + the dimension 5 operator. At low energies, the two produce the same physics. At high energies, the theory with n is predictive.

UV Completion II

- However, this UV completion is not **unique**.
- For example, another option is to include a Higgs triplet T, which is allowed to have gauge invariant couplings with both LL and ΦΦ.

$$AT\Phi^2 + \lambda_{ij}\bar{L}_i L_j^c T + H.c.$$

$$\frac{\lambda_{ij}A}{M_T^2}$$

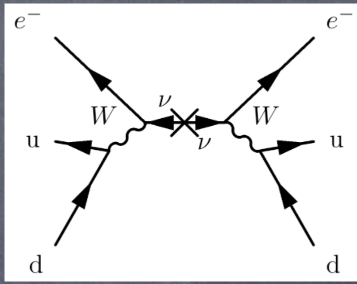


$$\frac{1}{\Lambda_{ij}}$$

- Both have the same common feature: the operator is characterized by an energy scale, which in the UV theory corresponds to the mass of some heavy particle.
- At low energies, the leading effects of each are identical, and captured by the dimension 5 operator itself.
- At high energies, we can see the particles being exchanged explicitly, and the two UV completions differ in their predictions.

Telling Them Apart?

- At low energies, all of the extensions of the SM we have discussed here have the same physics - they predict neutrino masses.
- Even at low energies, the fact that the theory of just Yukawa couplings gave us Dirac neutrinos, whereas our other extensions produced Majorana neutrinos means we can learn something.
  - Majorana (and not Dirac) neutrinos can mediate "neutrino-less double beta decay"!



- At high energies, we can hope to produce the new particles directly.
  - Dirac neutrino masses: Nothing special happens at high energy.
  - Massive n : We produce a new Majorana fermion!
  - Higgs triplet: We produce a new kind of Higgs!

Professor Han is actually in expert in these LHC signals!

- The measured values of the neutrino masses imply relations among the parameters of our SM extension (whatever it is).

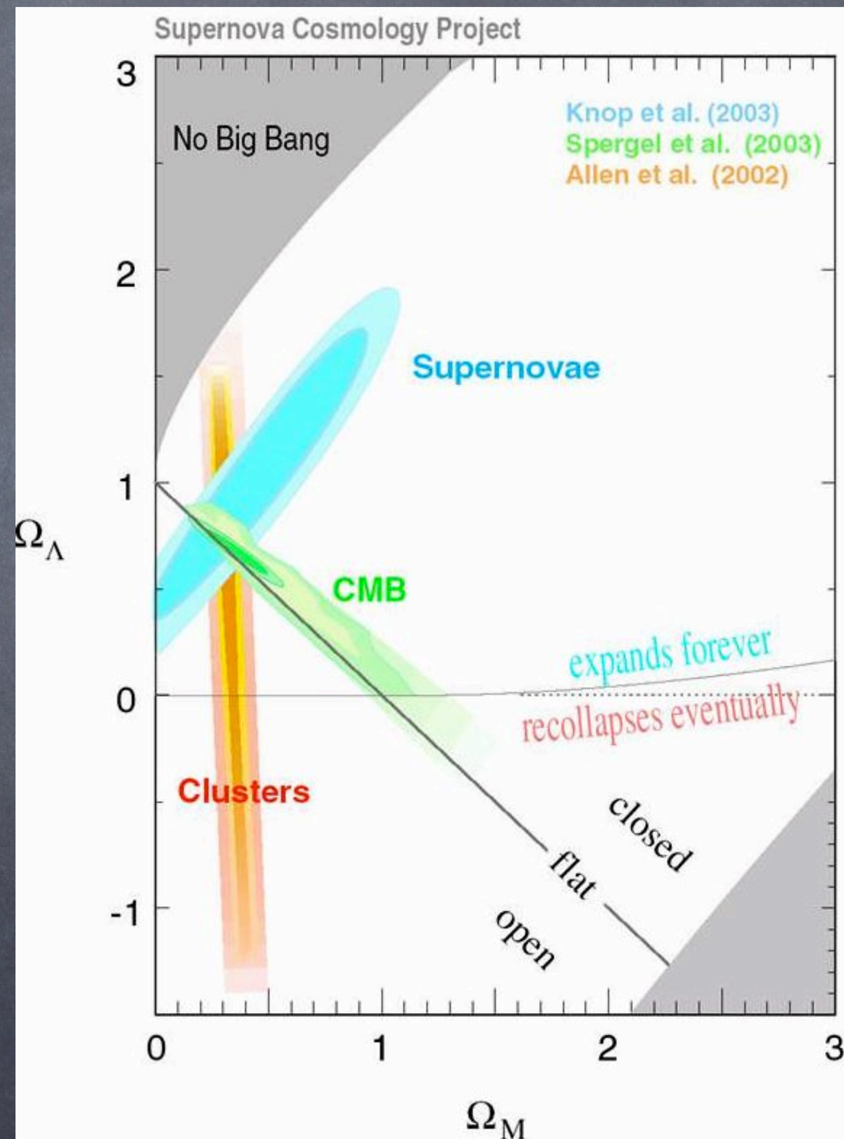
Lessons from the ν Mass Example

- Having data is a good thing!
- A given problem in the SM suggests at least a space of solutions. Often there are still free parameters, but at least the "theory space" tells us what we should be trying to measure, and what is predicted for future experiments, and how to distinguish leading candidate models.
- Non-renormalizable operators are fine, but they are characterized by an energy scale at which the theory will become non-predictive.
  - We usually interpret that energy scale as being related to the masses of some new particles.
    - But note that the observed neutrino masses only fixed Y^2 / M. As Y's range from 1 to very small, a huge range of Ms are predicted...
  - Telling different possible UV completions apart will probably require doing experiments at least close to those energy scales.

“Cold Dark Matter: An Exploded View”
by Cornelia Parker

Dark Matter

- Further indication for BSM physics comes from dark matter.
- Many observations of the Universe at scales ranging from galactic to CMB show a strong indication for a cold, non-interacting component of the Universe.
- The Standard Model contains nothing to play the role of dark matter.



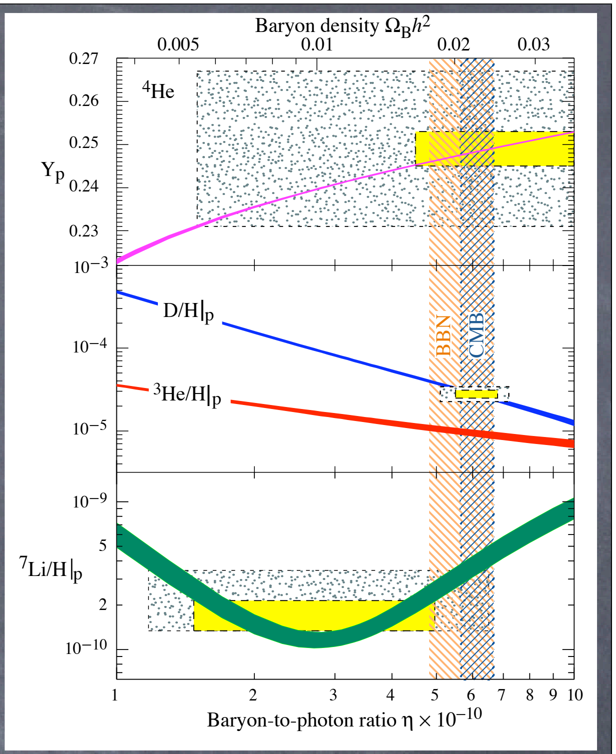
How to include Dark Matter?

- The existence of dark matter is established experimentally, but all of our observations of it (?) have been made gravitationally. So we are left without guidance as to how to couple it to the SM.
  - The usual strategy is to find a weakly interacting massive particle (WIMP) in some other theory we like, and ask if it could play the role of dark matter.
  - That's all well and good, but it may be too unimaginative. Dark matter already exists independently as one of the pillars of modern cosmology.
- There are experimental searches, but right now they are null results or suffer from poorly understood astrophysical inputs, such as the local density of dark matter, or backgrounds from conventional sources that we don't understand very well.
- I think input from the LHC can really help a lot. If we discover a WIMP candidate and measure its properties we would at least have putative control over the particle physics model.
- But for now, I won't present any WIMPs. I'll point them out as they occur later.

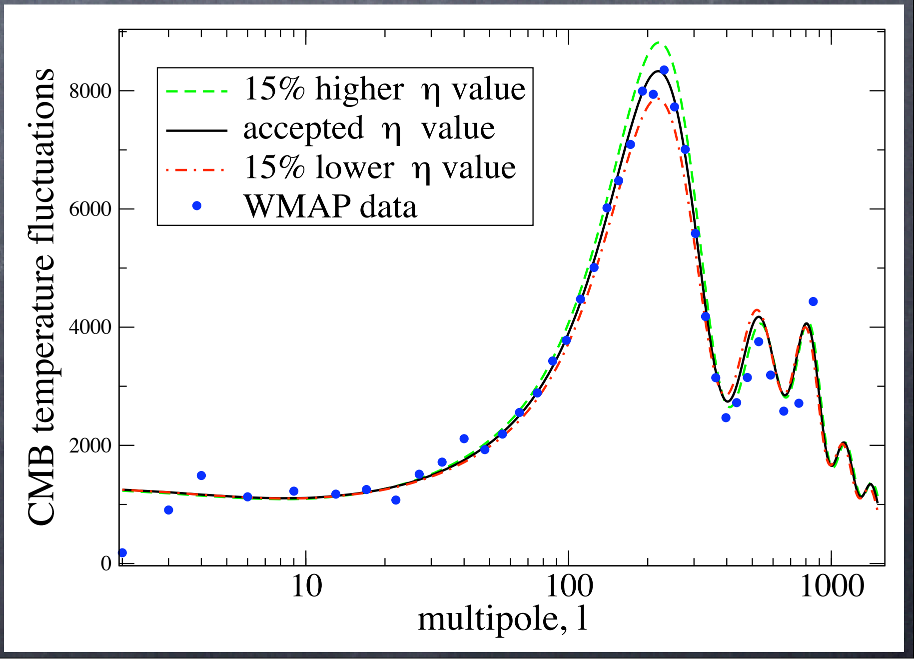
Baryon Asymmetry

- We have striking evidence that our Universe is made out of matter and not anti-matter.
- This is pretty mysterious : perturbatively the SM generates matter and anti-matter in equal amounts.
- We have strong evidence for inflation, which would have wiped out any primordial asymmetry.
- So it looks like we need some kind of physics in operation after the time of inflation (but before nucleosynthesis) which is capable of generating the observed asymmetry.

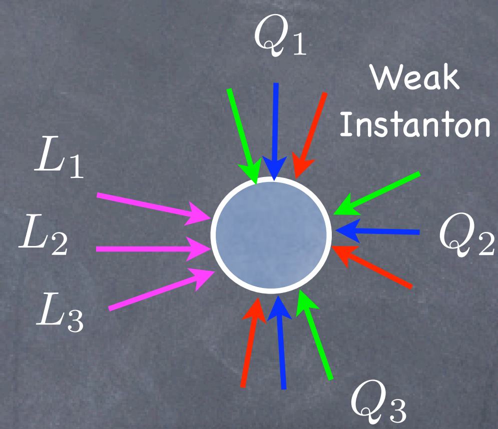
Nucleosynthesis:



CMB:



Electroweak Baryogenesis



- For baryogenesis we need three conditions:
  - Interactions violating baryon number
  - Violation of C and CP.
  - Out of thermal equilibrium
- Amazingly enough the SM could have satisfied all three:
  - Nonperturbative EW effects (instantons) violate baryon number
  - The EW force violates both C and CP.
  - The electroweak phase transition can be an out-of-equilibrium phenomenon if the phase transition is first order.
- However, it doesn't quite do the job:
  - For Higgs masses > 50 GeV or so, the phase transition is second order.
  - The amount of CP violation is not quite enough to explain the magnitude of the observed baryon asymmetry.

Rescuing Baryogenesis

- To explain the baryon asymmetry, we should:

  1. Add a separate mechanism. The decay of heavy Majorana neutrinos as in the see-saw explanation of neutrino masses can work: leptogenesis.

  2. Change the phase transition and add sources of CP violation to the SM.

- We already saw what the first one entails (and the only subtlety is to make sure the decay of the heavy neutrino is out of equilibrium.

- Implementing the second option tells us something about the new physics:

  - It has to violate CP (but still not be ruled out by existing measurements.

  - It needs to change the phase transition. Since this is governed by the thermal corrections to the Higgs potential, that further tells us that the new physics needs to couple strong to the Higgs.

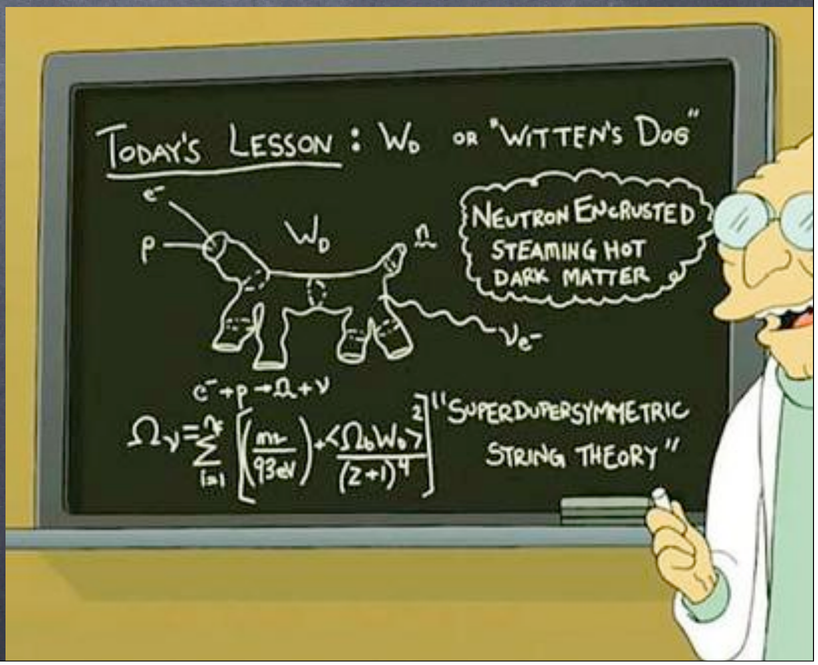
    - Bosons work better than fermions (but either can be made to work).

    - We'll see later that all of these ingredients are present in supersymmetric versions of the Standard Model.

Gravity

- The Standard Model does not include gravity. That is in gross contradiction with everyday experience!
- The gravitational coupling is $1 / M_{Pl}$ where $M_{Pl} \sim 10^{18}$ GeV. The fact that it has negative mass dimension tells us that a description of gravity is non-renormalizable.
- At low energies, including gravity into the SM is fine, but at high energies (or strong fields) the quantum theory will lose predictivity.
- What happens at M_{Pl} certainly requires new physics, probably string theory (LQG?!).
- Naively, we won't learn much about gravity at the LHC, but we possibly might.
  - Theories with extra dimensions might lower the Planck scale to within the LHC's reach!

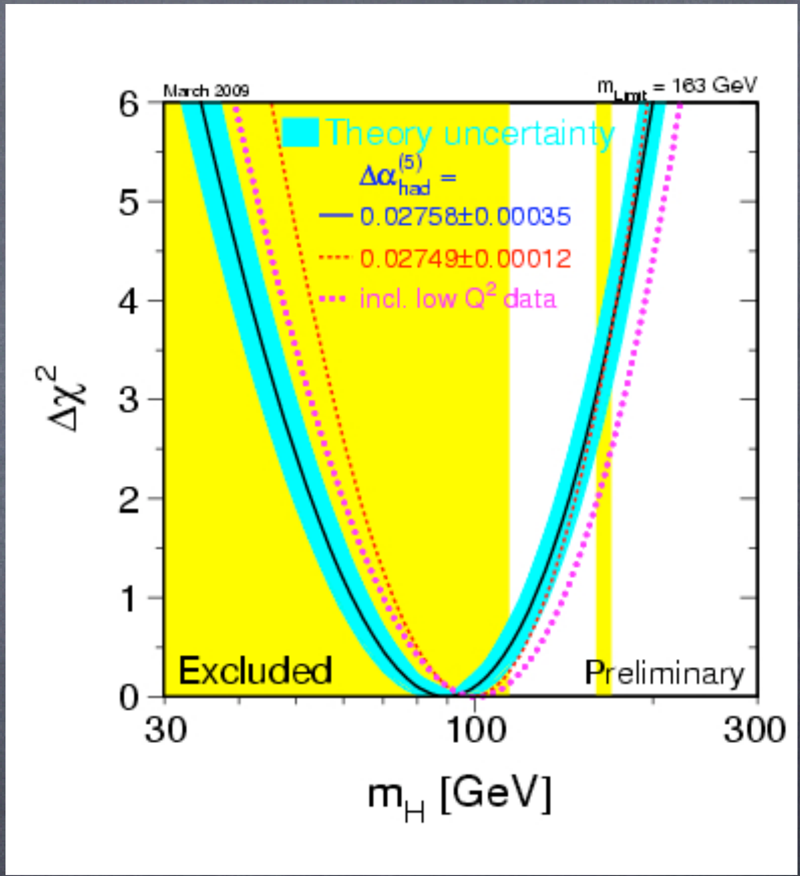
This reminds me that we also don't understand the size of the cosmological constant (dark energy). But no one has any good solution there...



Breaking the SM

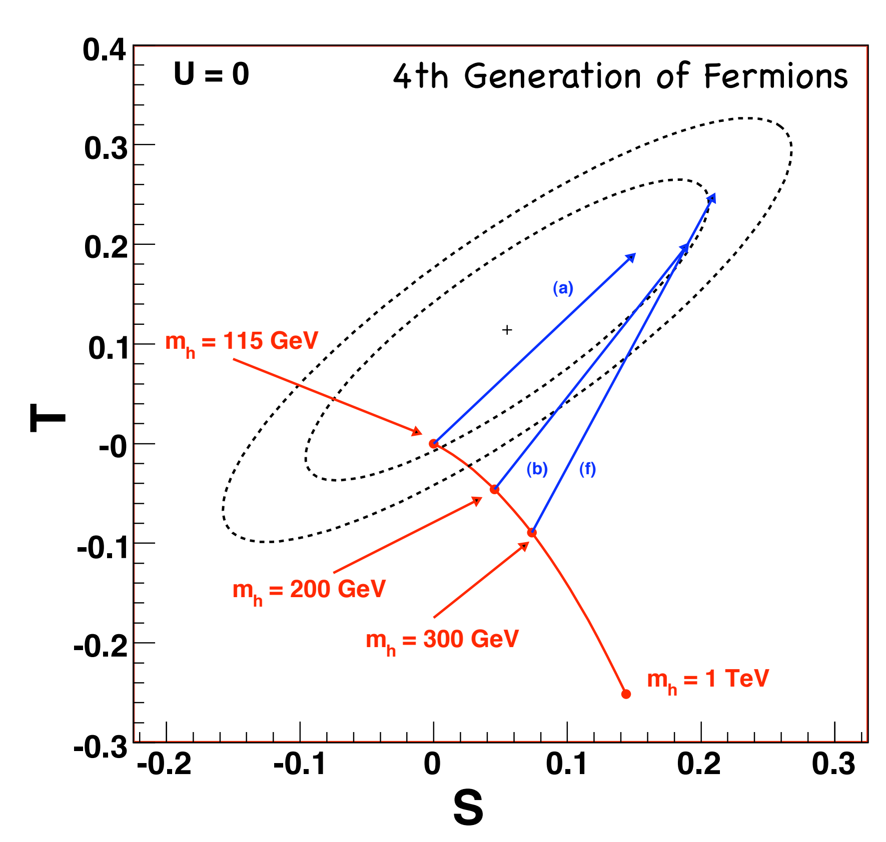
Higgs Mass (again!)

- The fact that we can predict the Higgs mass in the SM even before seeing the Higgs provides an opportunity to test it.
- Once the Higgs is discovered, its mass will either be consistent with the SM range or not.
- If not, we will have finally found an inconsistency in the Standard Model!
- (But be ready for a lot of confusion about exactly what the definition of the top mass being measured at the Tevatron actually turns out to be - we have been assuming it is the pole mass, but experimental errors are getting small enough that we need to stop being sloppy about it...)



"Fixing" a Heavy Higgs

- If we discover a heavy Higgs at the LHC, we will be left asking what went wrong in our interpretation of the EW fit.
- A definitive answer will need some explicit discovery, but we can at least infer some properties. For a heavy Higgs to be compatible with the S & T fits, some new physics must provide:
  - a positive contribution to T.
- This suggests some additions (though very loosely). More interestingly, it picks out regions of parameter space.
- For example, if we add another generation of quarks, it requires relations among their masses.



M_h = 300 GeV

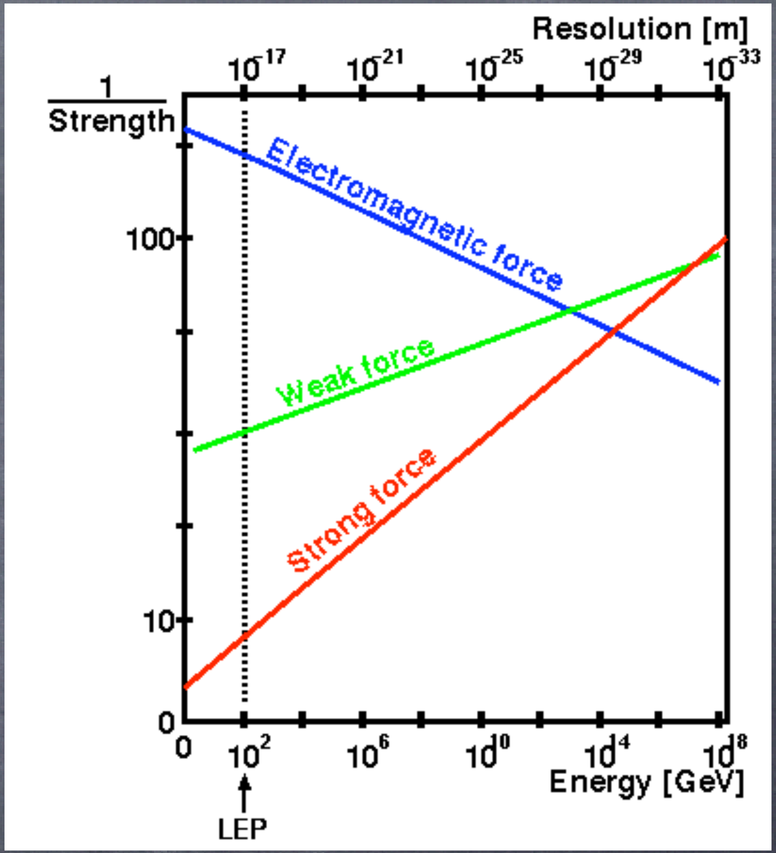
$u_4 = 330$
$d_4 = 260$
$\nu_4 = 100$
$l_4 = 155$

Such light masses are already being probed at Tevatron, and LHC will cover the entire space of masses.

Aesthetic Motivations

Simpler Structures

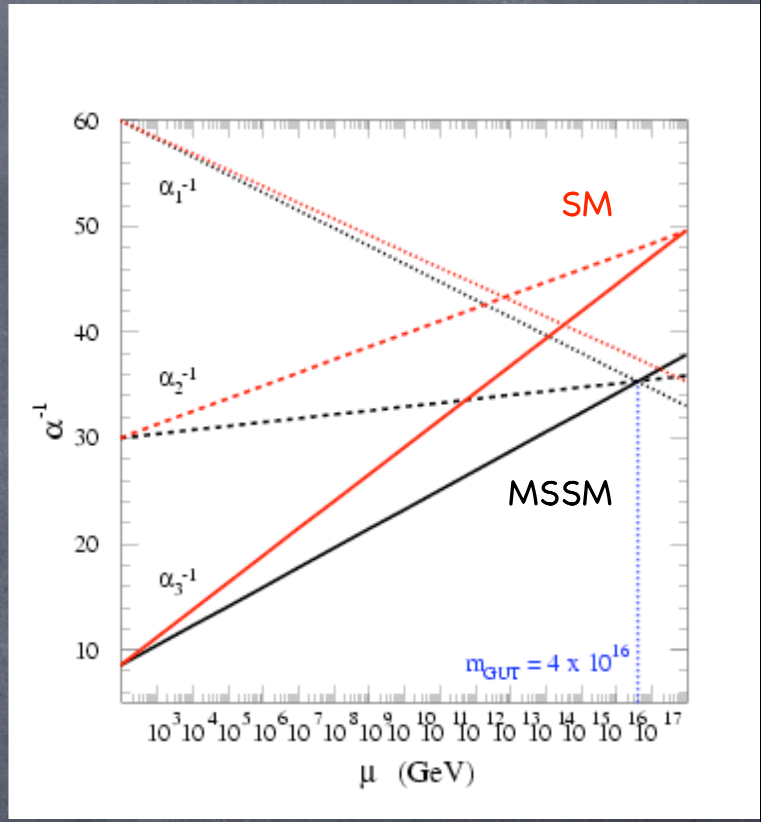
- It would be nice to understand gauge structure and fermion representations of the SM in terms of some more unified description.
- If all of the SM forces and matter fields arise from some larger group like SU(5) or SO(10), it would do a lot to motivate the seemingly ad hoc gauge structure and weird choice of fermion representations.
- In fact, a SM generation fits into a 10 + $\overline{5}$ of SU(5), or (with a gauge singlet that could be the right-handed neutrino) a 16 of SO(10).
- If the forces indeed are unified, we should see the couplings converge at some high energy scale.
- Using the renormalization group equations in the SM, the couplings **almost** do unify!



This is also a reduction of parameters: g_1, g_2, and g_3 are now derived from a single gauge coupling!

Grand Unification

- The RGEs depend on knowing what to put into them. If there are new particles just around the corner, they can influence the running.
- So if we would like grand unification, it suggests we should add more matter in such a way as to improve the convergence of the couplings.
- Too much won't work, because the couplings will become non-perturbative (and thus not predictive) before we reach unification.
- To affect the RGEs, these states carry SM charges and can be produced at colliders.
- Grand unified theories also generically lead to processes like proton decay, which we are (still) looking for.

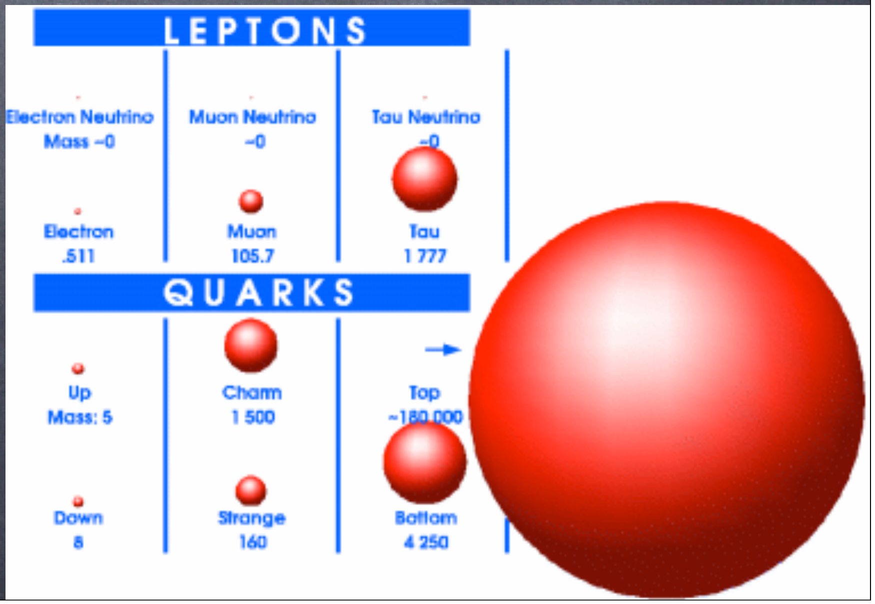


Adding superpartners leads to eerily precise unification!

But adding vector-like quarks also works at a similar level.

The Flavor Puzzle

- We saw that the Standard Model can incorporate fermion masses and mixings.
- However, the pattern of masses and mixings, and the large range of the masses is somewhat unsatisfying.
- The fact that most of the Yukawas are small also feels unnatural, but its not entirely clear what natural means in this context.
  - After all, nothing goes wrong with perturbation theory if couplings are small.
  - Fermion masses are protected from large corrections by a chiral symmetry, so once I declare they are small, they receive no large corrections.
- It's hard to imagine a solution which will really succeed at **predicting** fermion masses and/or mixings.
- But we do have ideas to motivate the hierarchies of fermion masses we see in nature...



Flavor Hierarchies

- There are many proposals to explain the hierarchies in the Yukawa couplings. The Froggatt-Nielsen mechanism invents a new global symmetry, which forbids us to write down Yukawas at all. (Except maybe for the top).
  - The symmetry is spontaneously broken by the VEV of some scalar field. If there is a suitable set of heavy states which mediate interactions between that field and the Standard Model, at low energies the effects of those heavy states look like higher dimensional operators:

example: $\Phi \bar{d} d$ has charge n. The Yukawa coupling arises from: $\left(\frac{S}{\Lambda} \right)^n \Phi \bar{d} d$

  - If the VEV is the only source of the symmetry-breaking, then fermion Yukawa terms with larger charges under this new symmetry require higher dimensional operators than terms with lower charges. A mass hierarchy results based on the dimensions assigned to the operators.
    - If <S> / Λ ~ 1/5, we can explain all of the quark masses and mixings!
- We can look for these new states at colliders, but nothing sets their mass scale. So they may just be too heavy.

“Unnatural” Motivations

The Hierarchy Problem

- One of the major dissatisfactions of the SM picture of EWSB is the hierarchy problem.
- The Higgs mass is quadratically sensitive to new physics.
- Since we believe there IS new physics at least at the GUT or Planck scales, this raises the question: how did the weak scale turn out so low compared to those energies?

Hierarchy Problem

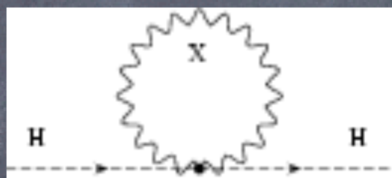
- Usually at this point we start talking about "quadratic divergences" and "cut-off dependence". Let's try this in a little bit more physical way.
- We saw earlier that the Higgs potential has a dimensionful ("mass") term and dimensionless ("quartic") term:

$$-\mu^2|\Phi|^2 - \frac{\lambda}{4}|\Phi|^4$$

  - We saw that the mass parameter μ sets the over-all scale of the VEV v, and thus the weak boson masses.
  - λ controls the size of the Higgs mass, and must be less than about 4π.
- Imagine there are new heavy particles that couple to the Higgs.
  - E.g., the heavy gauge bosons left-over from a GUT theory.
  - E.g., the singlet neutrino needed in the seesaw theory of neutrino masses.
    - These examples couple to the Higgs directly.
  - All particles couple to it through gravity.

Naturalness

- So what does this hypothetical heavy particle do to μ?
- It corrects it through loops. At one loop, in the specific case of a GUT gauge boson, the correction looks like:



$$\Rightarrow \quad \frac{g^2}{16\pi^2} M_{GUT}^2$$

  - The GUT scale has appeared as the mass of the vector boson.
- In perturbation theory, the μ measured in experiments (for example, when we measure M_W at LEP or CDF) is the sum of the tree level piece μ^2_0 (the one we originally wrote down in the Lagrangian) plus all of the higher order corrections:

$$\mu^2 = \mu_0^2 + \frac{g^2}{16\pi^2} M_{GUT}^2 + \ldots$$

  - Here we see the issue: the loops should be small, but if the masses that go into the loops are large, then they are huge.

Fine-Tuning

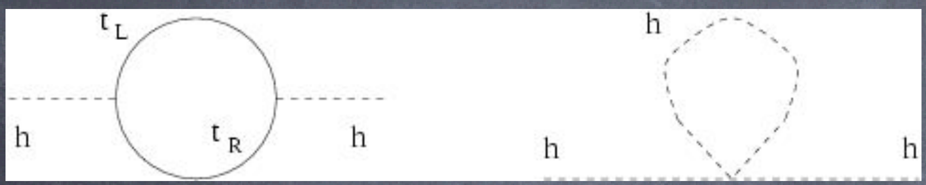
- Our GUT theory doesn't technically have any problem.
  - We can always choose μ_0 such that it compensates for the big corrections, and get μ to turn out the way we need it to.
  - But this is a (drastic!) fine-tuning of parameters.
  - Since we know $M_{GUT} > 10^{16}$ GeV and $v \sim 100$ GeV, we need the tree-level and the higher order corrections to match each other to one part in 10^{28} (since it's **μ-squared**).
- This really seems to be asking for a mechanism to make it work out.
  - The usual solutions work by adding structure which cancels the loop corrections (or makes them small) so that the tree-level piece is dominant.
  - Whatever this new stuff is, it should have mass around v, or it will recreate the problem with the new stuff itself.

Solving the Hierarchy Problem

- There two large classes of solutions to the hierarchy problem:
  - A new symmetry can cancel the loop corrections
    - Supersymmetry
    - Little Higgs
    - Twin Higgs
  - The Higgs particle may be composite, made out of fermions whose masses are protected by chiral symmetry, not unduly sensitive to corrections from UV physics.
    - Technicolor
    - Topcolor
    - Randall-Sundrum (interpreted through AdS/CFT)

Supersymmetry

- Supersymmetry is the best-motivated and best-studied solution to the hierarchy problem.
- Each SM particle gets a super-partner which cancels exactly (if SUSY was exact, anyway) the big contributions to the Higgs potential:



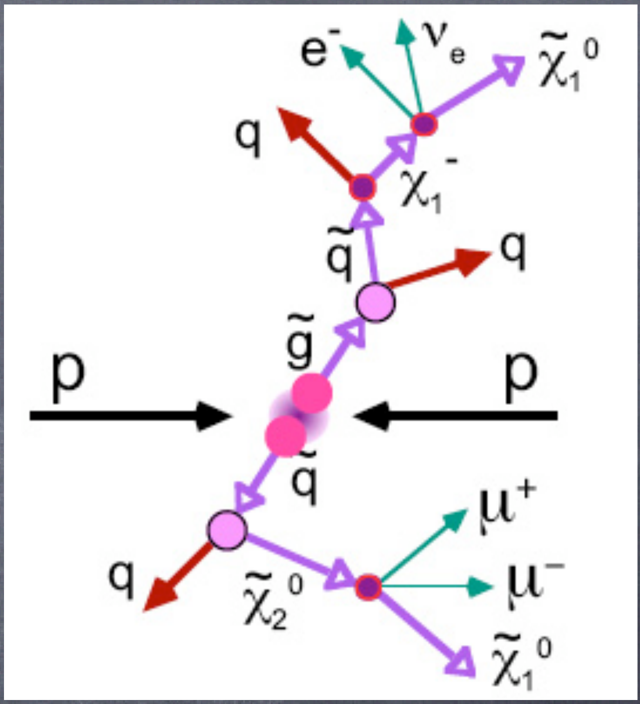
- As an added bonus, most SUSY theories contain a lightest super-partner which is neutral and stable - a dark matter candidate!
- New sources of CP violation and extra degrees of freedom can catalyze EW baryogenesis!
- SUSY has a lot of model parameters (all related to how we break it and give masses to the super-partners).
  - We have some theoretical guidance as to the rough features, but even those arguments aren't infallible.

Supersymmetry Breaking

- There are many, many ideas for SUSY-breaking on the market:
  - **SUGRA**: Gravity mediates SUSY breaking to the MSSM super-partners. Not clear why flavor would work out.
  - **GMSB**: Gauge interactions mediate SUSY breaking - a nice solution to the flavor problem. Less great for dark matter and EWSB.
  - **AMSB**: SUSY breaking is transmitted via the super-Weyl anomaly. Issues with negative slepton masses (squared).
  - **$\tilde{g}$MSB:** Extra dimensional gauge interactions transmit SUSY breaking.
  - **"Orbifold SUSY breaking"**: SUSY breaking by boundary conditions in an extra dimension.
  - **????** : Theorists are constantly looking for new ways to mediate SUSY breaking! (Mirage mediation, direct gauge mediation,...)

Supersymmetry at Colliders

- Supersymmetric theories span a dizzying range of phenomena!
- The usual strategy at hadron colliders is to produce the colored particles, which are usually heavier because of corrections to their masses from QCD.
- The colored states decay down through electroweak partners to the lightest of the new states. If we want this state to be the dark matter, it had better be stable (R-parity should be conserved) and neutral.
- So the most generic signature of supersymmetry, motivated by dark matter, is missing energy, usually accompanied by jets or leptons from the cascade decays of the primary particles.



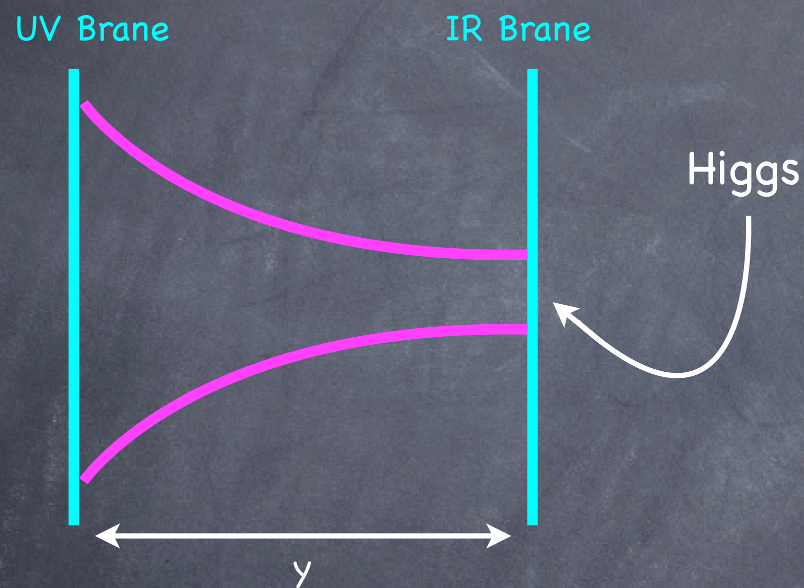
gluino + squark production
leading to:
3 jets
3 charged leptons
and missing energy!

Composite Higgs

- If the Higgs is a composite particle, with characteristic size at the TeV scale, then it is largely immune to the hierarchy problem.
  - The Higgs stops being a fundamental degree of freedom at its compositeness scale, and loop corrections to it stop being meaningful.
  - Since the compositeness scale effectively cuts off the loop corrections, for this idea to work, that scale can't be much larger than the electroweak scale.
  - (Otherwise the corrections induced by the compositeness scale itself just becomes the new incarnation of the hierarchy problem).
- Calculations can be hard to perform reliably because these theories typically involve strong coupling. That is in part why RS/CFT (which can be controlled in its weakly coupled extra dimensional version) has taken over as the dominant paradigm.
- (But you can always just think of RS in extra dimensional terms if you prefer... that's where the serious calculations are performed.)

Randall-Sundrum

- Let's quickly run through the RS model. The original RS model had gravity living on one end of an extra dimension, and the SM living on the other:



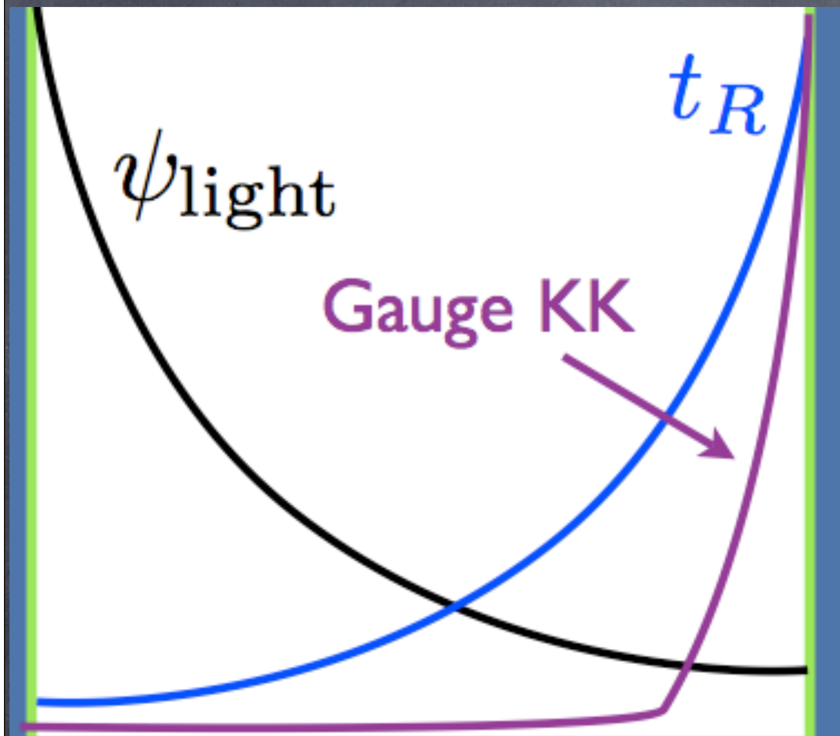
$$ds^2 = e^{-2ky} dx^2 - dy^2$$

$$M(y \sim L) \to M e^{-kL} \sim \text{ TeV}$$

- This solved the hierarchy problem, because the space is warped enough that the fundamental scale of physics on the IR brane is TeV. The solution to the hierarchy problem doesn't really care where most of the SM is, just where the Higgs is.

- The versions theorists are excited about these days have the Higgs still near the IR brane, but the rest of the SM out in the bulk.

Fermion Geography



Fermion geography is another way to understand fermion mass hierarchies!

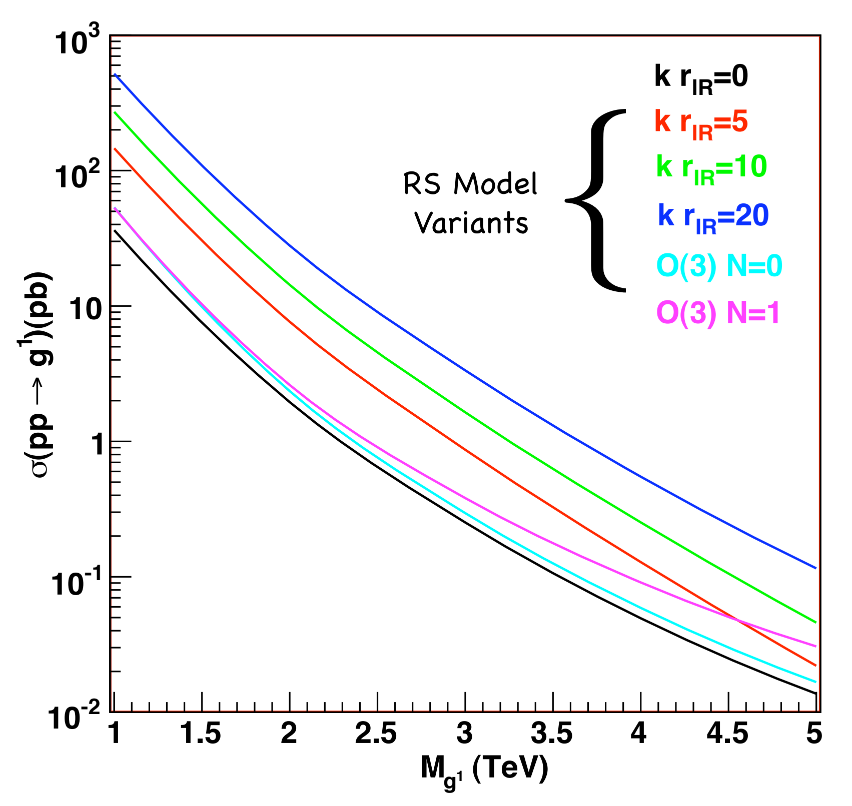
- The way particles couple is given by the integral of their profiles in the extra dimensions:

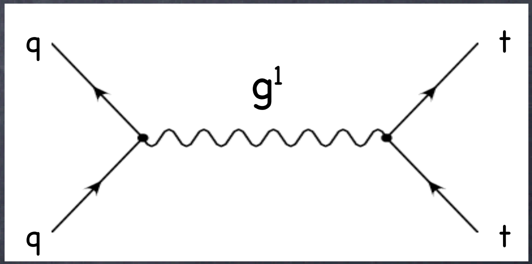
$$g_{ijk} = \int_0^L dy f_i(y) f_j(y) f_k(y)$$

- So the way to understand couplings in RS is to understand where different particles live in the extra dimension.
- The warped space implies that the KK modes always live near the IR brane. So they couple strongly to the Higgs.
- We can arrange the fermions as we like:
  - Light fermions do better close to the UV brane, so they have weaker couplings to KK modes and less constraints from EW.
  - The top MUST live close to the IR brane in order to have a strong enough coupling to the Higgs.

KK Gluon

- A particular signature of the RS models is from the KK modes of the gluons.
- Its couplings are characterized by the strong force, so large production cross sections at the LHC.
- It decays mostly into top quarks, because it couples most strongly to top.
- It typically couples more strongly to right-handed top quarks than to left-handed ones.
- Nonetheless, it has enough coupling to light quarks to be produced in the s-channel at the LHC.
- Studies are promising for masses up to several TeV.





Θ_{QCD}

- I was a little slippery when defining the SM before. I ignored perfectly good gauge invariant terms in the Lagrangian, such as:

$$\theta_{QCD}\ G^a_{\mu\nu}\widetilde{G}^{a\mu\nu}$$

- This term is dimension 4, Lorentz invariant, and gauge invariant.
- Even if I somehow ignore the term from the beginning, when I rephased my quarks to eliminate stray phases from the CKM matrix, one of the phases I had to eliminate would end up here anyway, through the QCD axial anomaly.
- This term violates T and P, and thus can contribute to the neutron's electric dipole moment. Very very strong constraints force the effective value to be tiny, < about 10^{-9}. But again, θ is the combination of the original term plus a phase originally in the Yukawa matrices for the quarks. What arranged for such a very delicate cancellation between two a priori unrelated quantities?
- This is usually referred to as the "strong CP problem".

Axions

- The Peccei-Quinn solution to the strong CP problem is to promote θ to a dynamical field. Its dynamics then cancel any non-zero value which it inherited from the gauge lagrangian or fermion masses.
- The excitations of this field are called axions, which remain a the signal that the PQ mechanism is what solved the strong CP problem.
- The axion is a pseudo-Goldstone boson, whose mass and couplings come about through the QCD anomaly, and are controlled by the scale of the PQ-symmetry breaking scale.
- Axions could be dark matter!
- Axions generally also have electromagnetic couplings, and searches for them can make use of that fact by using strong magnetic fields to convert them into photons which can be detected.

Outlook

- We've looked at some of the issues in the SM which leave us dissatisfied, and ran through some of the proposals to make the situation more palatable.
  - These solutions span a huge range of theory space.
  - But they all had something in common : new particles which couple in some way to the Standard Model.
  - Not all of them are testable in the future, but all of them are testable in principle.
- The Standard Model is an unprecedentedly successful description of nature.
  - But it still leaves a lot of open questions.
  - Answering those questions is going to take a lot of work from both theorists and experimentalists.
  - I bet its going to be a lot of fun!

Bonus Material

MSSM Higgs Mass

- The large top mass has turned out to be essential in the success of the Minimal Supersymmetric Standard Model (MSSM). Let's see how this works.

- We saw before that in the SM, the Higgs quartic λ is a free parameter. The physical Higgs mass is $m_h^2 = \lambda\, v^2$.

- We can adjust the Higgs mass to whatever we like by playing with the value of λ (up to about 1 TeV when the theory gets too strongly coupled and stops making sense).

- In the MSSM, the story is a little bit more complicated, because the theory has two Higgs doublets, so two CP even Higgs bosons which can share the VEV between them.

$$\tan\beta \equiv \frac{\langle H_1 \rangle}{\langle H_2 \rangle}$$

SUSY Little Hierarchy Problem

- Remarkably, in the MSSM λ is not a free parameter. Its value is dictated by supersymmetry to be equal to a combination of the electroweak gauge couplings:

$$\lambda = \sqrt{g_W^2 + g_Y^2}$$

- We already know these couplings : $\lambda = \frac{M_Z}{v}$
- This results in a tree-level prediction for the lighter Higgs:

$$m_h^2 = \lambda v^2 \cos^2 2\beta \leq M_Z^2$$

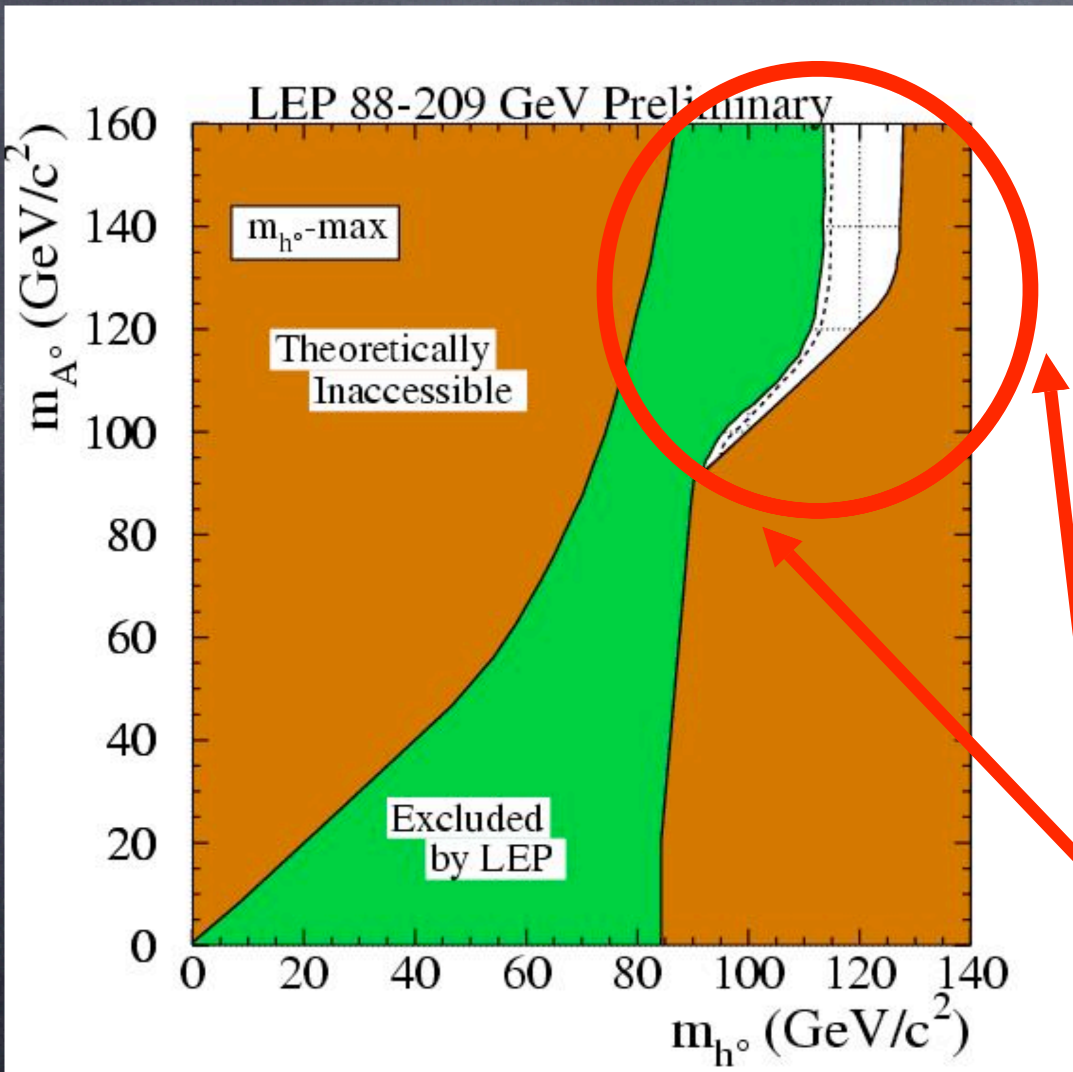
- Such a light Higgs is ruled out by LEP-II's Higgs searches.
- This is just the tree level result. Maybe loops can help? The best hope comes from top - the biggest coupling!

Top to the Rescue!

- The corrections to the MSSM Higgs mass are largest for the top and its supersymmetric partners
  - two stops, one "right-handed" and one "left-handed".
- The over-all size is set by the top Yukawa coupling, since SUSY requires stop and top have the same coupling to the Higgs bosons.
- The correction further depends on the stop masses and the amount of mixing between the left- and right-handed stops:

$$\delta m_h^2 = \frac{3 m_t^4}{8\pi^2 v^2}\left[\log\frac{m_{\tilde{t}}^2}{m_t^2} + \text{stop mixing}\right]$$

LEP II Bounds



- LEP II rules out

$$m_h^{(SM)} \leq 115 \text{ GeV}$$

- The boundary on the right is the MSSM upper limit, assuming M~1 TeV and maximal stop mixing.
- The dashed curves are hypothetical exclusions assuming only SM backgrounds.
- The MSSM lives in the white sliver.

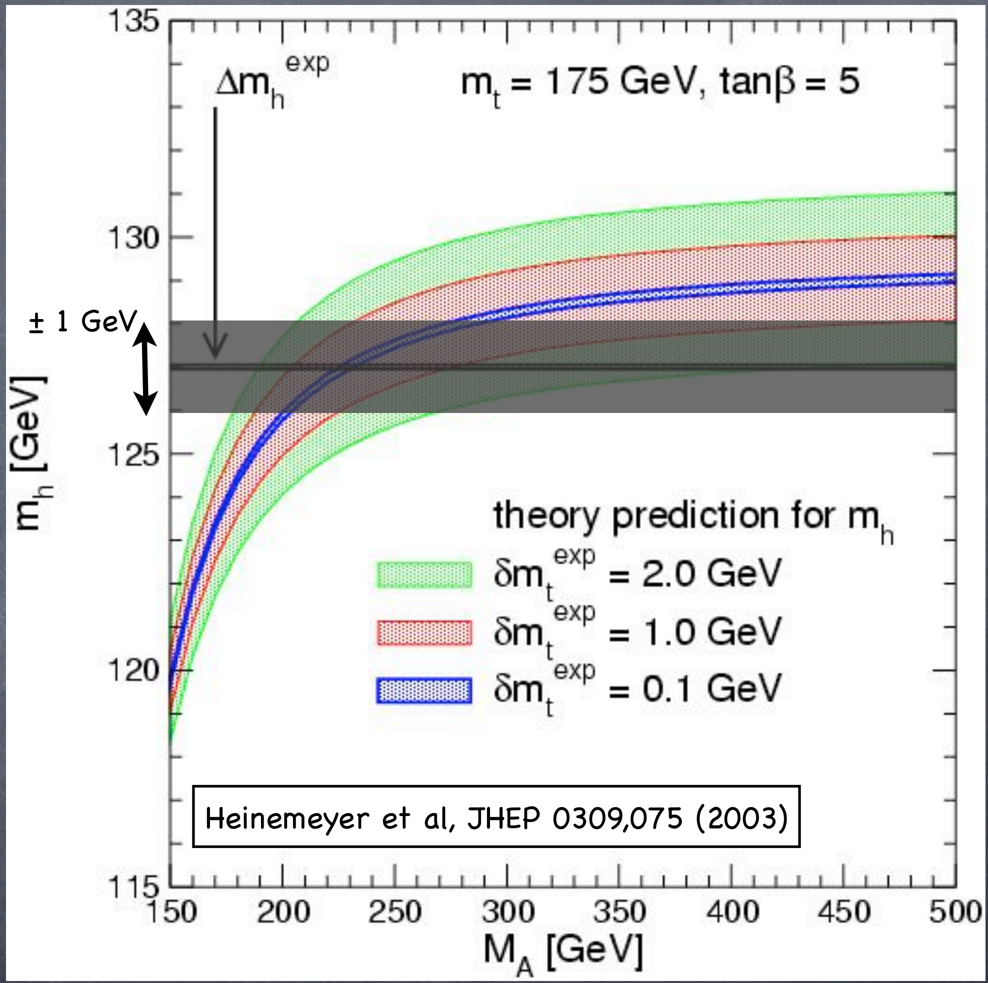
The fact that it is a "sliver" means top is barely able to do the job for reasonable values of the stop masses!

MSSM and the Top Mass

- The MSSM Higgs has a love/hate relationship with the top mass:
  - The Higgs quartic corrections vary as m_t^4.
  - The mass parameter varies as m_t^2.
  - So in the MSSM, a larger top mass does result in a heavier Higgs, with less electroweak fine-tuning.
- The MSSM lives or dies by the top mass!
  - If the top mass were to increase by about 2σ, the SUSY little hierarchy problem would completely cease to be an issue.
  - If the top mass were to decrease by about 2σ, the MSSM would be fine-tuned much below the % level.
  - Below m_t~160 GeV, the stops would have to be higher than **1000 TeV** to survive the LEP-II limit and I would safely say the MSSM was "ruled out".

Top-Stop-Higgs

- There are a few ways to think about the importance of top in the MSSM:
  - Precise measurements of mt and the Higgs mass tell us about the stops (and M_A).
  - A mismatch between m_t, m_h, and the stop parameters tells us we don't have the MSSM, and we need to think about extended SUSY models (like the NMSSM, for example).

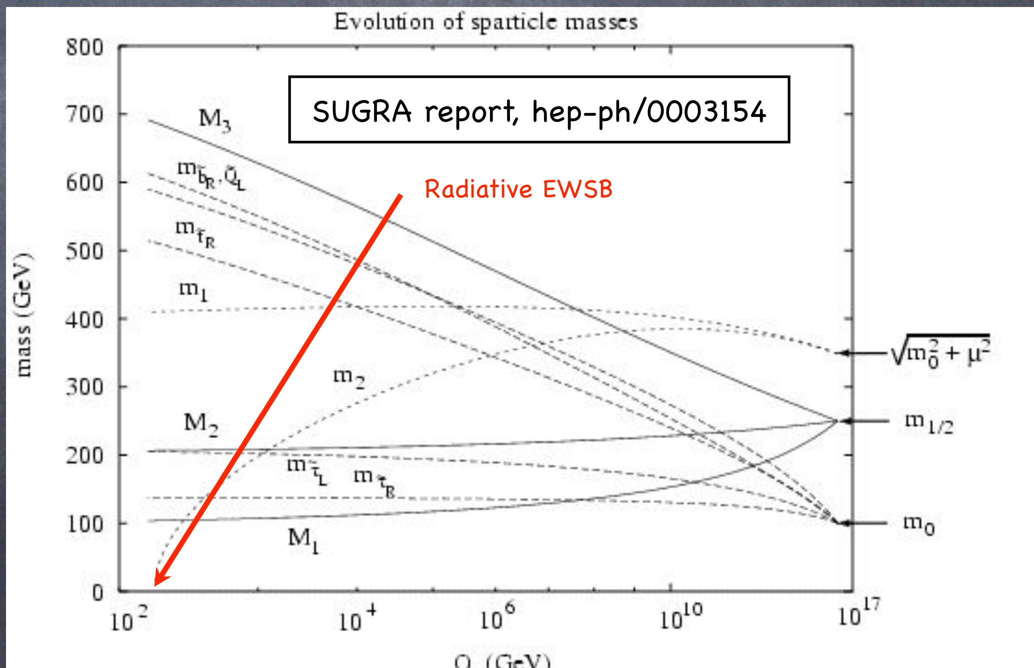


The Bottom Line: m_t is IMPORTANT for the MSSM!

Radiative EWSB

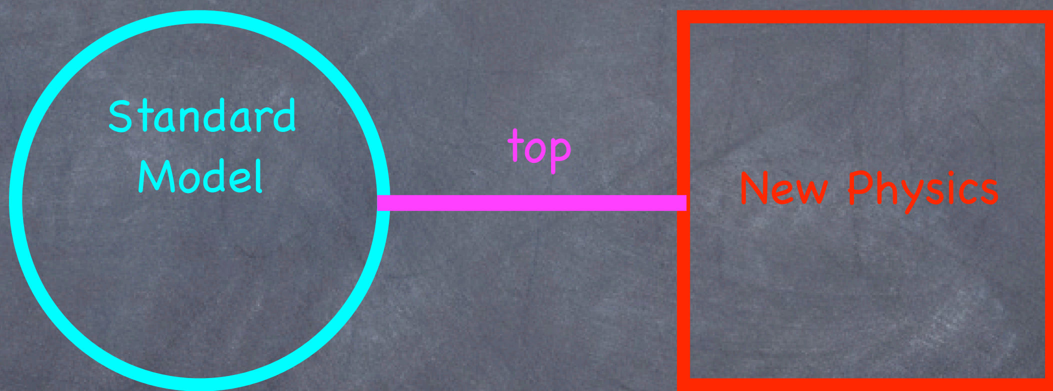
- The strong top coupling to the Higgs allows for radiative electroweak symmetry breaking.
- Even if the Higgs mass^2 is positive at some high scale, loops of the top quark can run it negative at low energies, triggering EWSB.
- This happens naturally in many SUSY theories.
  - In mSUGRA SUSY theories, one uses it to fix the μ parameter.

It is also a phenomenon used by most little Higgs theories, and by theories in which the Higgs is a bound state of top quarks (like top color)



Top as a Portal to BSM

- If the top mass is a clue that the top is special, it may be that top acts as a kind of "bridge" or portal between the Standard Model and the new physics.



- In that case, new physics may be produced in association with the top quark, or may manifest itself in top observables.

Composite Higgs

- One particular illustration of the top as a portal is furnished by theories where the Higgs is composite.
  - (This could itself be a connection to top, as in top-color where the Higgs is a bound state of tops themselves, or it could be a parallel construction, as in technicolor theories).
- But arguing very generically, imagine the Higgs is a composite, meaning it is made out of two or more fundamental particles ("preons"):

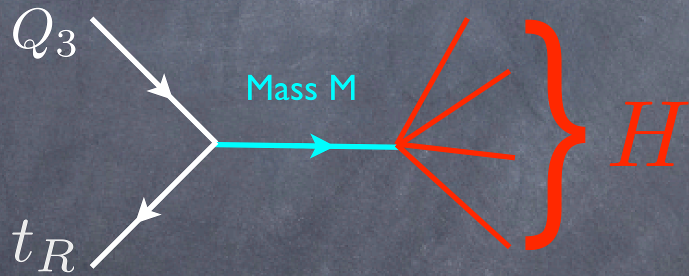
  e.g. Higgs made of two fermions: $$H \leftrightarrow \bar{\psi}_1 \psi_2 / \Lambda^2$$

- The scale Λ is the "confinement scale" of the Higgs binding (something like the size of the composite Higgs).
- Such a composite Higgs presents no problem for generating the W and Z masses. (Because for them it is enough just to say how the symmetry is broken).
- The same hierarchy/naturalness arguments we had before argue that if the Higgs being composite is supposed to solve the hierarchy problem, Λ ~ TeV!

Fermion Masses from a Composite Higgs

- Fermion masses are more tricky. Because the Higgs is fundamentally more than one particle, it can't have renormalizable interactions with t tbar.

- To generate the top mass, I need to introduce even more new physics, to communicate between the top and the preons that make up the Higgs.



$$y_t \sim \frac{\Lambda^2}{M^2}$$

- As the heavy quark in the SM, top requires that the extra physics scale M is basically the same scale as Λ ~ TeV. So there must be some kind of special dynamics for top if the Higgs is composite, in order to generate its mass.

- In Extended technicolor theories (ETC), this was a killer, because it lead to too much flavor violation in Kaons - driven by the large top mass!

Outlook

- Top is important in the Standard Model. But it is really exciting in relation to physics beyond the Standard Model.
    - It motivates the shape of new physics to address the hierarchy problem.
    - Its large mass gives it a unique role in BSM theories such as SUSY.
    - It may be our portal to access BSM physics.
- Tomorrow we'll look at top production and decay in the Standard Model and beyond - and see how all of the theories we discussed today manifest themselves in top observables.