Looking Beyond the Standard Model

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Historic Achievement

- 120 years ago:
  - Do atoms exist?   Real, or just an organizing concept?
  - If so, what governs the structure of the periodic table?
  - What determines chemistry, the emission of light, etc?

- 83 years ago:
  - Special & general relativity, quantum mechanics
  - Electron, photon, proton discovered, masses known
  - Neutron, neutrino, nuclear forces unknown

- 50 years ago:
  - Conflict between parity-violating weak interaction and electron mass
  - QED; but quantum theory of strong, weak interactions elusive
  - Massive vector bosons in data and in theory (rho mesons & W bosons)

Historic Achievement

- 25 years ago:
  - Three-generation Standard Model fully formed
    - Hadron structure, quarks rather well understood
    - W, Z bosons, gluons discovered
  - Only missing pieces:
    - t , ν_τ
    - H field and its particle (nothing known)
  - Multiple conceptual puzzles with Standard Model

- 2 years ago: Not much had changed
  - Great advances in techniques for calculations
  - SM tested at precision level through quantum effects
    - Precision tests correctly imply surprisingly heavy top quark
  - After top quark mass known, precision tests →
    - Higgs particle is not heavy (< 200 GeV) if SM is correct

What do we know since 2010?

- A SM-Higgs-like particle
  - Mass < 200 GeV, as predicted
- A vast array of alternatives to the SM now excluded

SM is in very good shape…

Could the Standard Model Be Correct?

- As a theory of everything, no way.
  - Gravity not included (though can be included at semiclassical level)
  - Neutrino masses not zero (though higher dimension operators)
  - Dark matter not predicted (though primordial black holes?)
  - Strong CP problem not addressed
  - Cosmological constant (“dark `energy’”) not predicted/explained
  - Specific choices of particles and interactions
  - Mass ratios and mixings, strengths of forces all put in by hand

- As a theory of physics accessible to the LHC, possibly.
  - pp collisions at the LHC perhaps insensitive to all entries on list above
  - No known verifiable conflicts with predictions of SM and LHC data

No matter what happens at the LHC,
we must look beyond the Standard Model !

But when? And in which direction(s)?

The Arguments Pro/Con the SM at LHC

- **For**: SM is simplest and most elegant theory consistent with data
  - Completely self-contained; no missing parts, no inconsistencies
  - No confirmed conflicts with any existing experiments!
  - Simplest and most elegant → the one most likely to be right

- **Against**: SM is not very simple or elegant, and is extremely radical
  - The Standard Model is ugly and baroque
    - 3 forces, 3 generations of 15 fermions, 1 SU(2)-doublet of scalars
    - Masses, mixings scattered all over the place
    - Strong CP problem
  - The Standard Model contains something never previously observed:
    - **a particle with mass very low relative to apparent ultraviolet scales, but not protected by any principle**

What Does Data Say?

- Can we say with confidence that the SM explains all LHC data?
  - **Definitely not yet! (And not soon.)**

- Experiment is far from over:
  - LHC has taken less than 1/10 of its data, and at 60% of its energy.
  - The new particle is still cursorily studied.
  - Many searches of the data have not yet been undertaken

- Theory is far from convincing:
  - Many classes of theories have a **decoupling limit**, in which
    - The theory has a SM-Higgs-like particle
    - All new particles may be heavy and/or weakly-interacting

What Does Data Say?

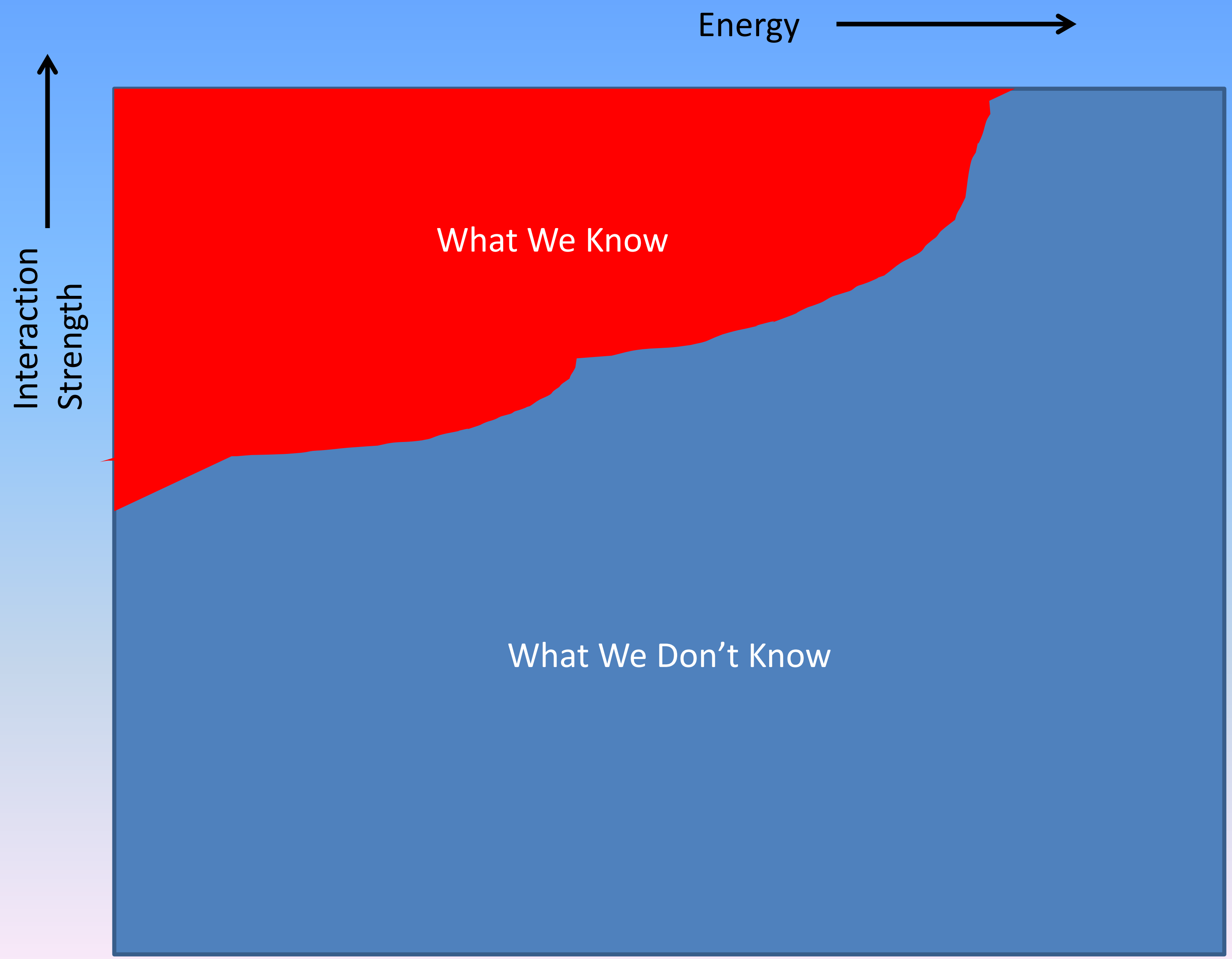
- Do we have any evidence that SM does **not** explain all LHC data?
  - **Definitely not yet! (And probably not soon.)**
  - $^2/_3$ of 2011-2012 data analyzed; no >2σ deviations of H properties from SM
  - ½ of data analyzed, no strong signs of deviations in other measurements
- Therefore becoming unlikely that any question **already asked** will yield convincing deviations from the SM using 2011-2012 data
- Any deviations before end-2015 **will likely come from questions that have not yet been asked**

- If the SM is not valid at LHC, where are some good places to seek discoveries in 2013-2014?

- If the SM is valid at LHC, what are we going to have to do next?

Some As Yet Unasked Questions that Could Generate Discoveries in 2013-2014

Remember What We (Don't) Know



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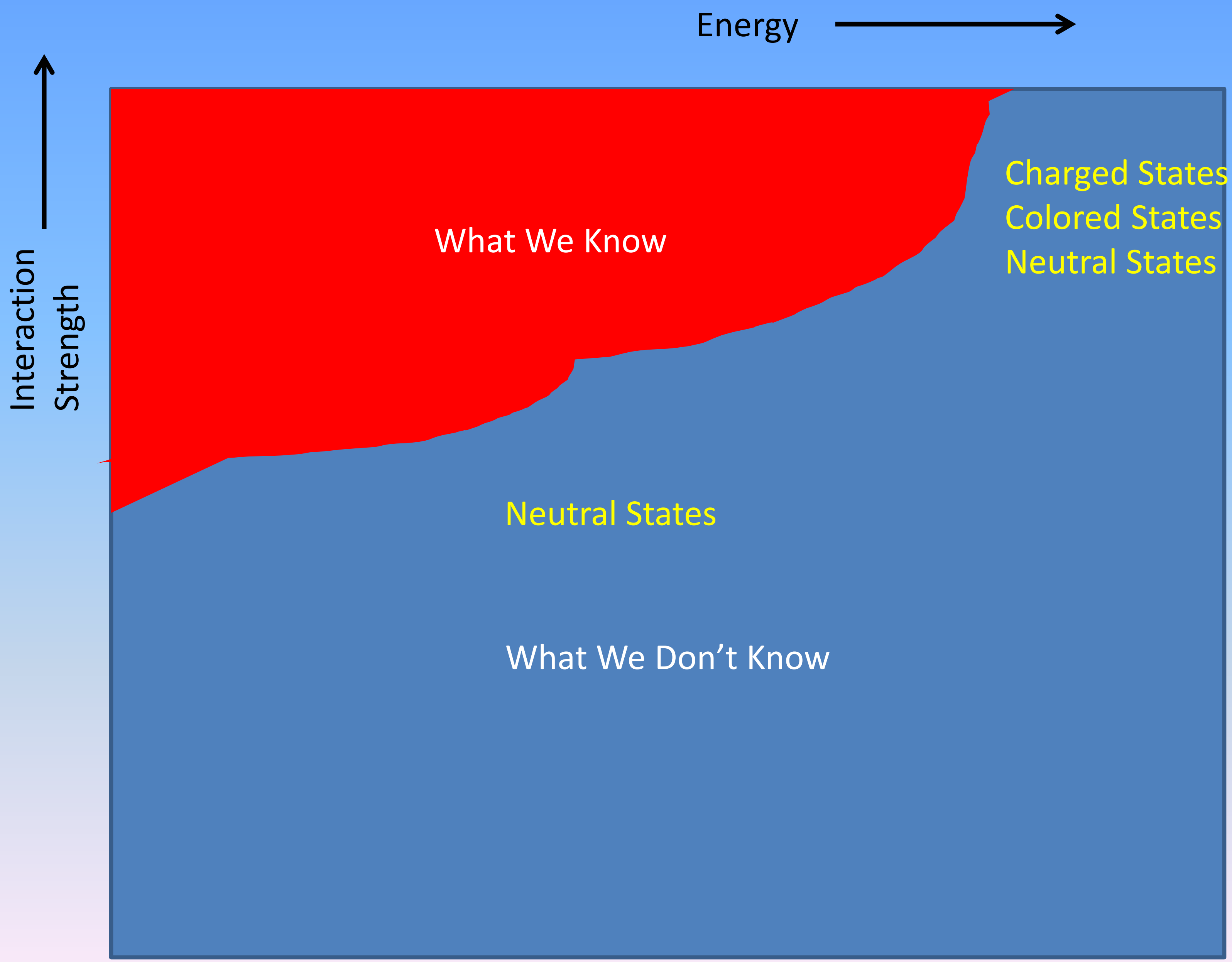

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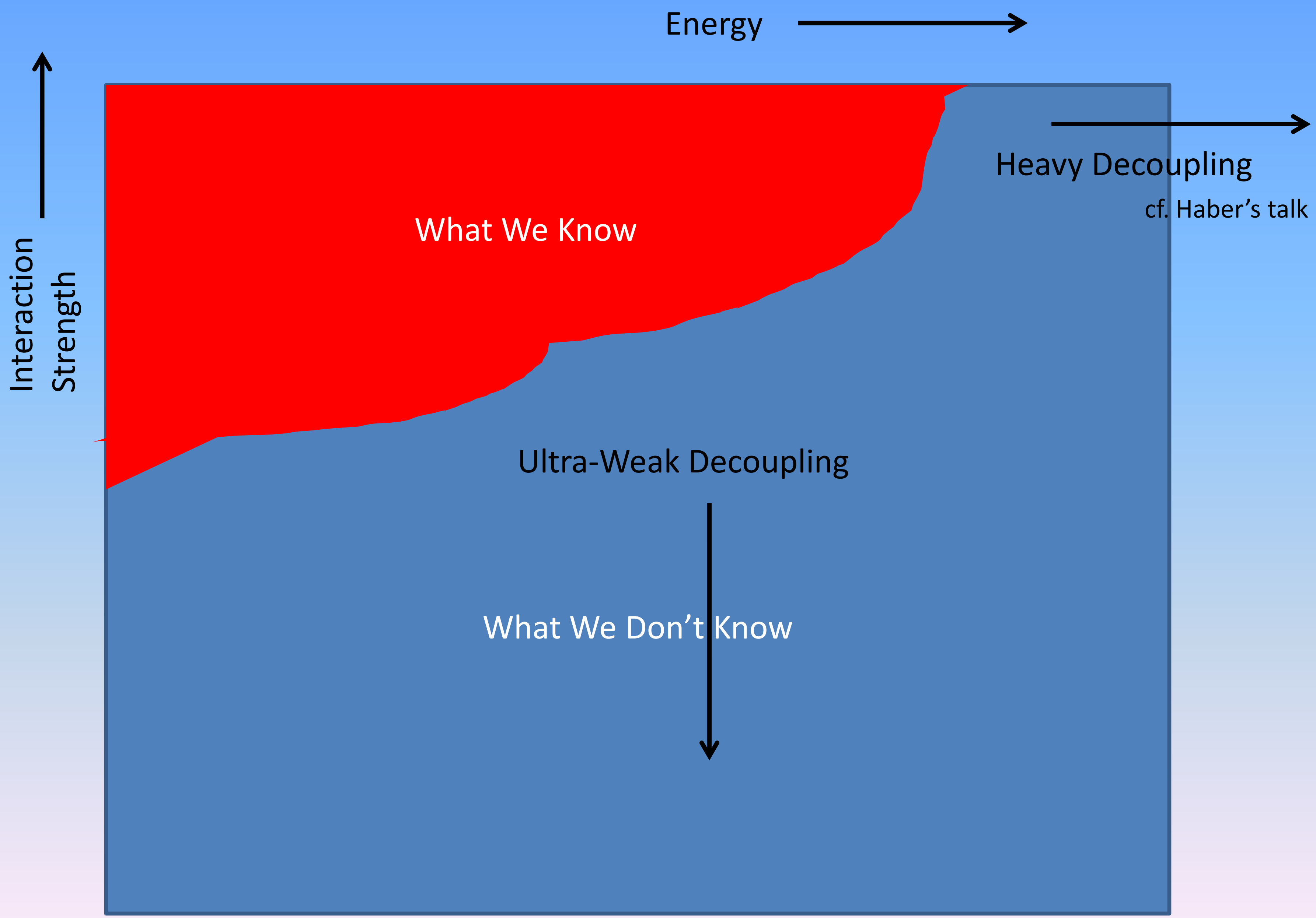


Questions That Have Not Been Asked

- Beyond-the-Standard-Model physics
  - May lie at higher masses than 8 TeV can reach (wait for 2015-2018)
  - May be sitting in the 2011-2012 data but difficult to extract
    - Swamped by large and/or uncertain backgrounds
    - Requiring a non-standard analysis strategy
    - Motivated by non-minimal versions of popular models

- Personal View: Greatest risks at the LHC beyond 2012
    - Not enough attention to controlling SM backgrounds
    - Not enough diversity and risk-taking in search strategies
    - Theory and experimental bias toward minimal models

Dangers of Bias Toward Minimal Models

- Why do we discuss MSUGRA, MSSM, NMSSM…?
- Because we deeply believe minimal is better.
  - Theorists like it
    - Elegance
    - More predictive
  - Experimentalists like it
    - Easier to search for and exclude

- Bias : non-minimal models are viewed as “Unmotivated”
  - Motivation, however, is sociological and time-dependent

- **Note that the modern Standard Model wasn’t minimal or motivated**
  - Could have had no weak neutral currents, and < 3 generations.
  - The modern SM could not have been published in 1967!

Dangers of Bias Toward Minimal Models

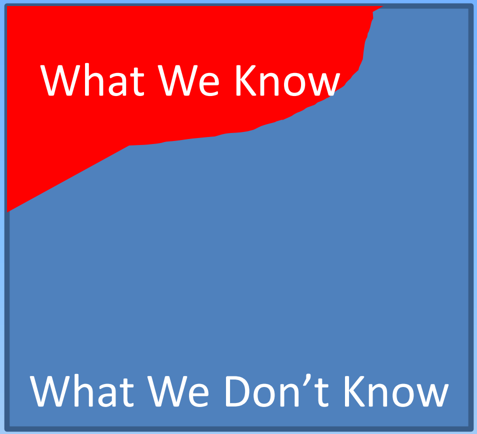
- Non-minimal models solve the same problem as the minimal one
  - Solution to flavor or hierarchy or other problem just as good
  - Lagrangian not much different
- But **collider phenomenology may be unrecognizable**
  - Large MET signal → Small MET signal
  - No leptons → Many displaced leptons
  - High-energy spherical event with many jets → few low-energy jets + MET
- Often “classic” searches don’t rule out non-minimal versions!

Non-SM Higgs Behavior (NSMH)

- Our new particle
  - May have friends that we haven't found yet
  - May be produced in ways not expected in SM
  - May decay in ways not expected in SM
- Existence of Decoupling Limit ➔
  - SM-like behavior of H does not make these signals unlikely
  - In many models this will be the **first** sign of new physics
  - In some models this will be the **only** new physics at LHC
- Up to now, very few results on these possibilities have appeared
- One of the most likely areas for discoveries during the shutdown!!
  - This should be a major area of research at ATLAS/CMS/LHCb in 2013-2014!

NSMH1: Exotic Higgs States

- Just because we see a SM-like H doesn't mean it has no friends
  - Heavy states
  - Light weakly coupled states
  - Light difficult-to-observe states



- New neutral states
  - With mostly SM decays
    - But small rate and possibly small width
      - e.g. narrow ZZ or $\gamma\gamma$ peak at high mass
  - Or with mainly exotic decays
    - Nobody has yet looked!

NSMH2: Non-SM Higgs Production

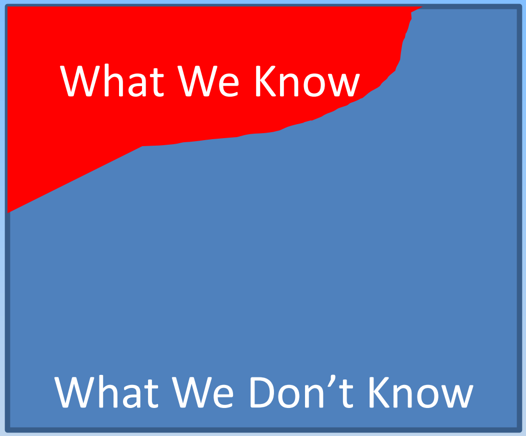
- Any heavy particle with mass > 125 GeV might decay to H.
  - Only example in SM is top:
    - t → c + H (events with lepton, 3 b's and a bb resonance)
  - Many examples beyond SM
    - Neutralino → gravitino + H (possibly displaced)
    - t' → t + H
    - H' → H + H
    - W' → W+ H, Z' → Z + H
- Combine standard search for H with search for non-SM production
  - W + H search can look for W' → W + H
  - t t H search can look for t' t' → t H t H

NSMH2: Non-SM Higgs Production

- Look for exotic Higgs production where SM production is low
  - High p_T H
  - High MET or S_T events
  - Events with many jets
    - Exotic production → e.g. a small $\gamma\gamma$ signal over tiny background
  - Displaced H
- **Opportunity: Do not look only at 125 GeV!!!**
- Any searches for 125 GeV H should also look for other H-like states
    - Over as wide a range as possible!!! 0.1 GeV to 1000 GeV!
  - Blind search around 125
  - Non-blind search at other masses

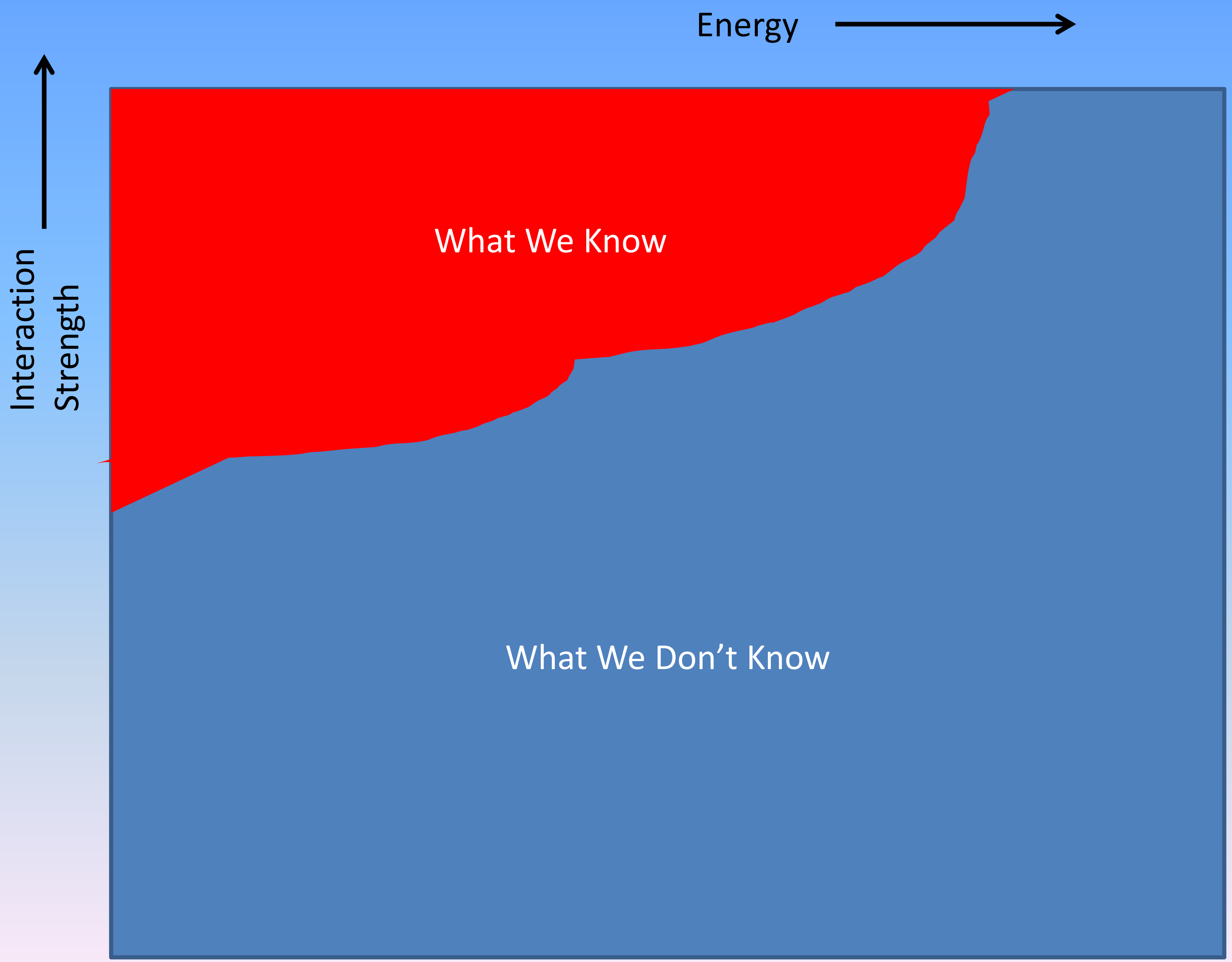
More Generally

- New neutral light particles
    - H, extra Higgses, non-minimal SUSY, hidden valleys
  - Can give di-photon bump (like SM Higgs) or di-lepton bump (like Z)
  - Rates often low and often swamped in SM background



- There are few searches dedicated to looking for such things.
  - Clearly some might have been found by accident
    - … but we don't know what we don't know
  - *Prove to me that these are already excluded from the 2011-2012 data*

Remember What We (Don't) Know



NSMH3: Non-SM Higgs Decays

- **The most important priority for 2013-2014!**
  - Newly discovered particle needs its PDG table:

- Warning:
  - H has no non-zero quantum numbers
  - Therefore, a huge list of allowed decays!!!

- Won't learn much from SM decays til 2015
  - Current results use $^2/_3$ of 2011-2012 data
  - Sum of Br = 1 with big error bar

- 125 GeV SM-like H
  - **Extremely sensitive to new physics**
  - **Easily develops new <u>non-SM</u> decay modes**

Z DECAY MODES

	Mode			Fraction (Γ_i/Γ)	S Conf
Γ_1	e^+e^-			(3.363 ±0.004) %	
Γ_2	$\mu^+\mu^-$			(3.366 ±0.007) %	
Γ_3	$\tau^+\tau^-$			(3.370 ±0.008) %	
Γ_4	$\ell^+\ell^-$		[a]	(3.3658±0.0023) %	
Γ_5	invisible			(20.00 ±0.06) %	
Γ_6	hadrons			(69.91 ±0.06) %	
Γ_7	$(u\overline{u}+c\overline{c})/2$			(11.6 ±0.6) %	
Γ_8	$(d\overline{d}+s\overline{s}+b\overline{b})/3$			(15.6 ±0.4) %	
Γ_9	$c\overline{c}$			(12.03 ±0.21) %	
Γ_{10}	$b\overline{b}$			(15.12 ±0.05) %	
Γ_{11}	$b\overline{b}b\overline{b}$			(3.6 ±1.3) $\times 10^{-4}$	
Γ_{12}	ggg			< 1.1 %	
Γ_{13}	$\pi^0\gamma$			< 5.2 $\times 10^{-5}$	
Γ_{14}	$\eta\gamma$			< 5.1 $\times 10^{-5}$	
Γ_{15}	$\omega\gamma$			< 6.5 $\times 10^{-4}$	
Γ_{16}	$\eta'(958)\gamma$			< 4.2 $\times 10^{-5}$	
Γ_{17}	$\gamma\gamma$			< 5.2 $\times 10^{-5}$	
Γ_{18}	$\gamma\gamma\gamma$			< 1.0 $\times 10^{-5}$	
Γ_{19}	$\pi^\pm W^\mp$		[b]	< 7 $\times 10^{-5}$	
Γ_{20}	$\rho^\pm W^\mp$		[b]	< 8.3 $\times 10^{-5}$	
Γ_{21}	$J/\psi(1S)X$			(3.51 $^{+0.23}_{-0.25}$) $\times 10^{-3}$	
Γ_{22}	$\psi(2S)X$			(1.60 ±0.29) $\times 10^{-3}$	
Γ_{23}	$\chi_{c1}(1P)X$			(2.9 ±0.7) $\times 10^{-3}$	
Γ_{24}	$\chi_{c2}(1P)X$			< 3.2 $\times 10^{-3}$	
Γ_{25}	$\Upsilon(1S)\,X+\Upsilon(2S)\,X$			(1.0 ±0.5) $\times 10^{-4}$	
Γ_{44}	anomalous $\gamma+$ hadrons		[d]	< 3.2 $\times 10^{-3}$	
Γ_{45}	$e^+e^-\gamma$		[d]	< 5.2 $\times 10^{-4}$	
Γ_{46}	$\mu^+\mu^-\gamma$		[d]	< 5.6 $\times 10^{-4}$	
Γ_{47}	$\tau^+\tau^-\gamma$		[d]	< 7.3 $\times 10^{-4}$	
Γ_{48}	$\ell^+\ell^-\gamma\gamma$		[e]	< 6.8 $\times 10^{-6}$	
Γ_{49}	$q\overline{q}\gamma\gamma$		[e]	< 5.5 $\times 10^{-6}$	
Γ_{50}	$\nu\overline{\nu}\gamma\gamma$		[e]	< 3.1 $\times 10^{-6}$	
Γ_{51}	$e^\pm\mu^\mp$	LF	[b]	< 1.7 $\times 10^{-6}$	
Γ_{52}	$e^\pm\tau^\mp$	LF	[b]	< 9.8 $\times 10^{-6}$	
Γ_{53}	$\mu^\pm\tau^\mp$	LF	[b]	< 1.2 $\times 10^{-5}$	
Γ_{54}	pe	L,B		< 1.8 $\times 10^{-6}$	
Γ_{55}	$p\mu$	L,B		< 1.8 $\times 10^{-6}$	

Why 125 GeV H is Sensitive

- In SM, 125 GeV H has Γ_H/m_H ~ 2 x 10^{-5}
  - Couplings to b, τ etc. are small
  - Decays to W and Z suppressed because one W or Z off-shell
  - Couplings to g, γ loop-suppressed

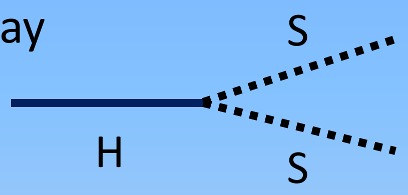
- Ultra-weakly coupled particles → non-SM decays of H with moderate Br
  - No effect on production
  - Br ~ 100% was possible; current data allows ~20% exotic Br
  - ~ 400,000 H produced at both ATLAS and CMS in 2012 alone!
    - So potential sensitivity to Br of 10^{-1} – 10^{-4}

- Even rare two-body decays could be affected
  - Expected small: H → $\mu\mu$, Zγ
  - FCNCs: H → $\tau\mu$ (and cf. t → cH)

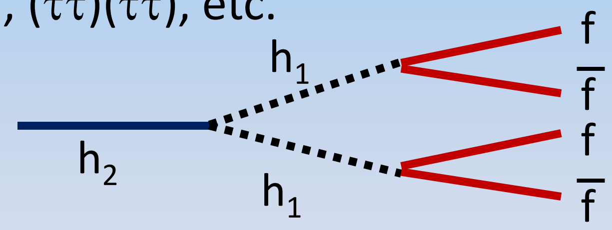
Minimal Source of Non-SM Decays

$$V(H,S) = V_H(H^2) + V_S(S^2) + \eta\, H^2 S^2$$

- Two phases:
  - $\langle H \rangle \neq 0$, $\langle S \rangle = 0$; then $H \rightarrow S\,S$ (if allowed) gives invisible decay



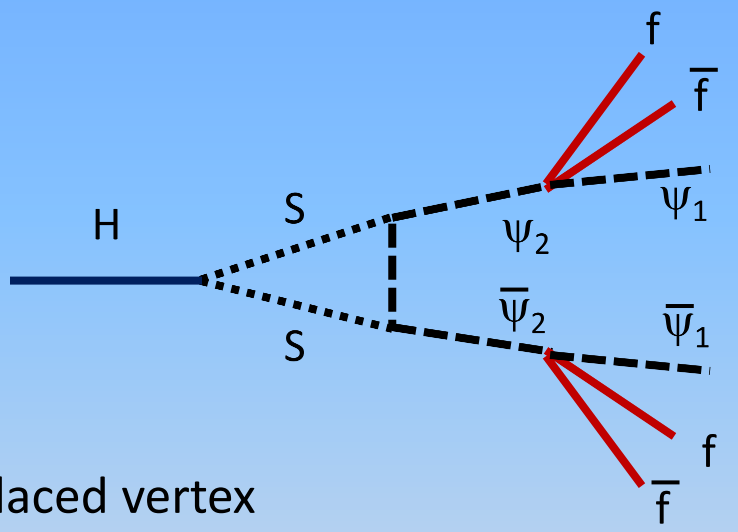
  - $\langle H \rangle \neq 0$, $\langle S \rangle \neq 0$; then H and S mix
    - Two states h_1, h_2 (call h_2 the heavier one) each SM-like
      - If h_1 is 125 GeV H, may have exotic H production
      - If h_2 is 125 GeV H, may have $H \rightarrow (bb)(bb)$, $(\tau\tau)(\tau\tau)$, etc.
  - Note: a range of small η for which the h_1 is mostly S and decays displaced



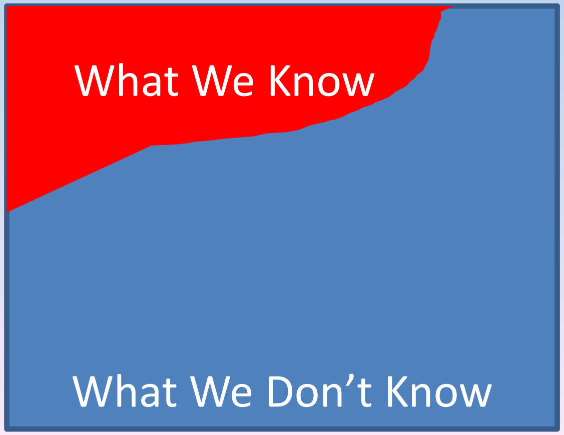
- Similar, "motivated" phenomenology in NMSSM
  - (cf. Dermisek and Gunion 04, Chang, Fox & Weiner 05)

Non-Minimal Sources:

- Two additional singlet fermions with S ψ_i ψ_j coupling,   i,j = 1,2

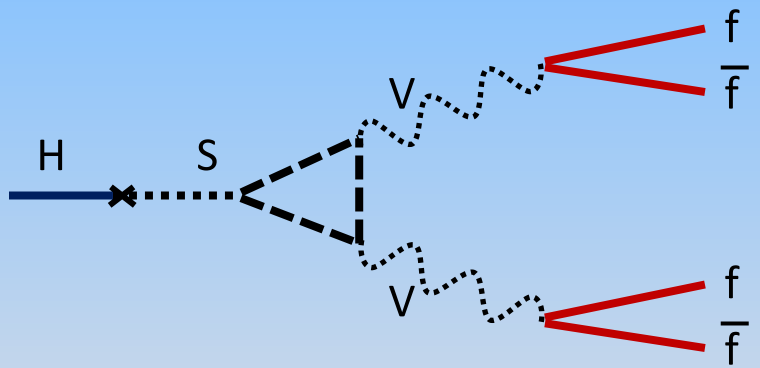


  - Two fermion pairs + MET
  - Visible objects may appear at displaced vertex
  - Similar pheno in GMSB, in NMSSM, etc.
    - Matchev Thomas '99



Non-Minimal Sources:

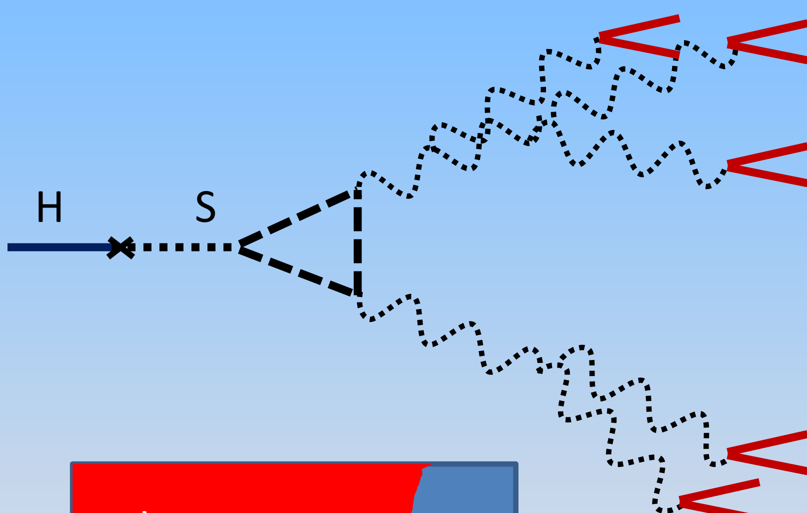
- Add gauge bosons V
  - If (for instance) ψ_i are charged, loop generates S → V V
  - If abelian, V can mix with photon and decay to visible ff pair
    - In this case light leptons are more common

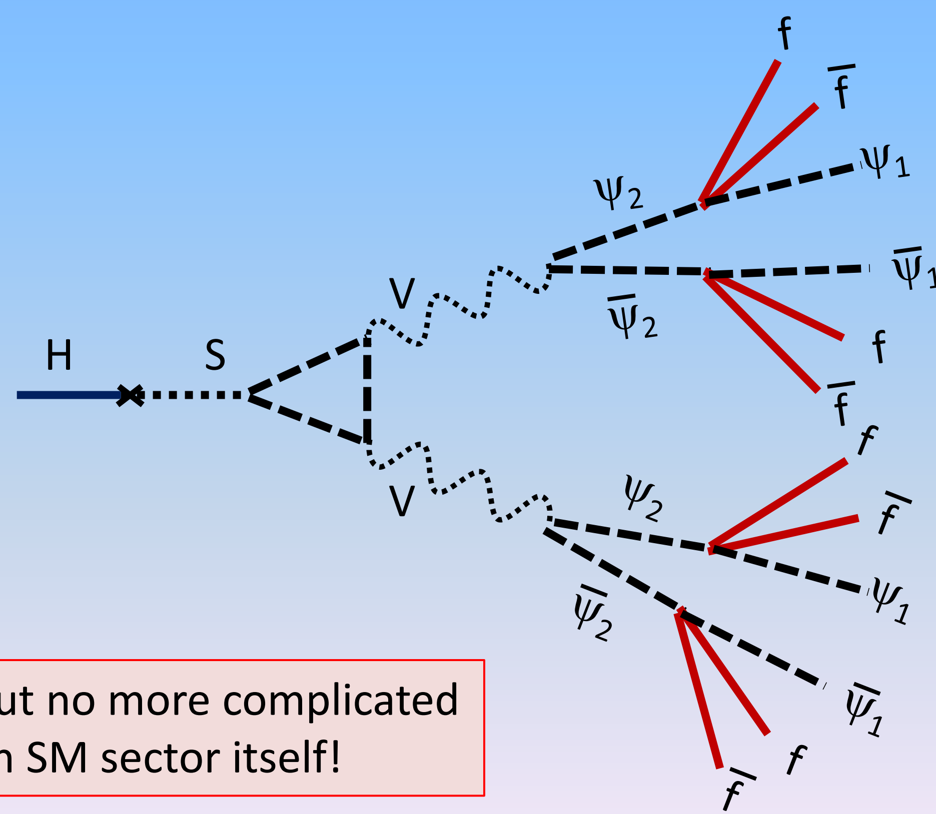


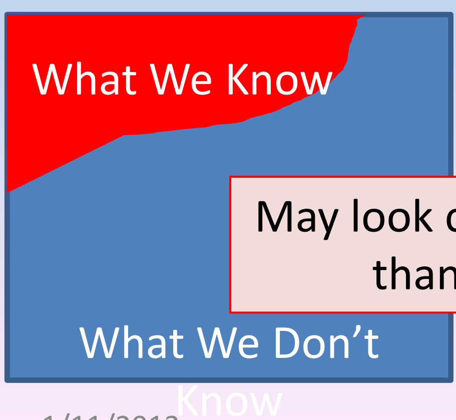
- More 4-body decays
  - e or μ pairs, q or g pairs; b pairs, τ pairs
    - Cf. Dark Matter model of Arkani-Hamed, Finkbeiner, Slatyer, Weiner 09

Non-Minimal Sources:

- Hidden sector may be strongly interacting or have multiple cascades
  - Very complex final states with many clustered particles
  - Long lifetime are rather common due to various suppression factors







May look complicated --- but no more complicated than what happens in SM sector itself!

H As Portal to Ultra-Weak Sector

- General: H can decay to hidden sector – "portal"

MJS & Zurek 4/06
cf. Schabinger&Wells 05
Patt & Wilczek 5/06

- Hidden Valley – generic hidden sector with MJS & Zurek 4/06
  - Self-interacting particles with masses well within LHC reach… ← Valley
  - …such that some decay back to SM on detector time scales ← Discoverable

Generic predictions for HVs (MJS & Zurek 2006)
- ➢ New light neutral particles – often several types
- ➢ Most easily produced in decays of heavy particles
- ➢ esp. H but also Z, W, t, LSP, etc.
- ➢ Produced singly or in groups, often boosted
- ➢ Produced promptly or displaced

- Unmotivated?
  - Dark matter; string theory; SUSY breaking
  - New, specific hidden valley models with varying motivations appear every year

- Also, experiment motivates!
  - **We have the data;** we ought to be looking broadly at the H
  - Opportunity in 2013-2014 for discoveries

Few Studies Performed Yet

- The number of experimental studies done so far is quite small
  - Scattered and unsystematic; needs to be a more detailed program
- The number of theoretical studies done so far is also quite small
  - Need calculations of SM rates for non-SM-enhanced processes
  - Need signal/background studies
    - This makes it hard for the experimentalists to know how to prioritize
  - **Need theorists to contribute to this program!**
- Putting this off until 2018-2020 would mean delaying possible discoveries in favor of slightly improved precision measurements

Aside: Exotic Decays of Top, W, Z

- ATLAS/CMS have world's largest samples of TAGGED top and W
  - Select events with one reconstructed top;
  - Other top or its W may have rare exotic decay
    - $t \rightarrow c\ H$
    - $t \rightarrow c\ X$ followed by *(use your hidden valley imagination here)*
      - $X \rightarrow j\ j$, $\tau\ \tau$ etc.
      - $X \rightarrow Y\ Y \rightarrow j\ j\ j\ j$, etc.
    - $t \rightarrow b\ W$
      - $W \rightarrow e\ q\ q\ \nu$, $e\ \tau\ \tau\ \nu$ (may obtain better limits than LEP)
- Harder to recognize rare Z decays as such
  - cf. $Z \rightarrow$ 4 leptons
  - $Z \rightarrow$ new long-lived particles…?

But Maybe SM Works at the LHC.

What Then?

What if the SM is Perfect at LHC?

- We won't know until ~ 2020 at least
- We will still have to look beyond the SM
- But **where** do we look?
- And what do we do about naturalness/hierarchy problem?
  - We have to start thinking about these issues immediately, just in case.

Taking Proper Stock

SM correct at LHC scales? Stunning! What explains hierarchy?

- Dynamical effect generates large hierarchy?
  - No dynamics that produces this situation easily has ever been proposed
  - No dynamics producing large hierarchy observed in solid-state physics
- Hierarchy not so large?
  - Maybe natural theory is at 10-100 TeV instead of 1 TeV
  - Minor accident suppressing the Higgs mass and vev by factor of 10-100?
- Selection effect? (``structure'' or ``anthropic'' principle)
    - As proposed for cosmological constant ("dark 'energy'")
  - Neither unique nor (usually) testable
  - Understanding of dynamics still needed, to buttress any such argument

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Or is this our Michelson-Morley moment?

Is our failure a profound clue that our understanding of quantum field theory, as applied to high-energy physics, is fundamentally wrong?

Pre-LHC, Preferred Experimental Targets

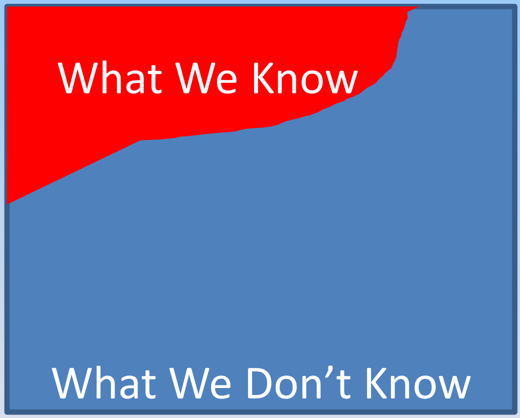
- So what should we aim at?
  - Before 1900 we had atoms (eV)
  - 1900 – 1950 we had nuclei (keV - MeV)
  - 1930 – 1970 we had nucleons (GeV)
  - After Fermi 1933 we had weak scale (TeV)

- Long ago knew SM without Higgs was not consistent
  - Knew either new particles or new interactions by TeV energy scale
  - Motivated a powerful multipurpose high energy machine (SSC or LHC)
  - Higher priority than searches for rare processes (not sharp enough)

- But now…
  - SM with Higgs is internally consistent
  - No energy scale between TeV and the GUT or Planck scale clearly identified

Obvious Targets – all with Pros and Cons

- Energy Frontier: Just keep going to higher energy
- Cosmological Frontier: Direct dark matter searches
  - Neutralino-type, axion-type
    - Are we sure DM is made from particles?
    - Couldn't those particles couple to us only via gravity?
- Intensity Frontier: Many options
  - Precision studies of the new heavy particles (t,W,Z,H)
  - Flavor physics – rare decays of quarks
  - Neutrino properties [but $M_{LL} = M_{LR} (M_{RR})^{-1} M_{RL}$]
  - Axion-like particles
  - New sectors of quasi-hidden fields/particles
    - Common in string theory
    - Maybe light and couple not too weakly to visible sector (hidden valleys)



Non-Obvious Targets?

- It would be wise to explore a wider range of possibilities
- Michelson-Morley result did not obviously suggest
  - Measuring the kinematic relation between energy and momentum
  - Measuring location of stars near the sun during an eclipse
- Are there questions that we should be asking of LHC data (or other data) that seem pointless or hopeless at first glance?
  - Checks of basic principles, such as relativity and quantum field theory, CPT, locality, etc.
  - Effects that by rights should be orders of magnitude too small to observe, but for which LHC exceeds sensitivity of any previous experiment.

Need To Exploit New Technology

- Recent technology has not been our best friend at high energy
  - No transformative advances in accelerator technology
  - No entirely new classes of high-energy particle detectors

- Maybe advances in astronomy/astrophysics can help?
  - Neutrino properties
  - Precision tests of constancy of couplings
  - Tests of equivalence principle via timing of light from distant explosions
  - Black hole super-radiance

- Maybe advances at much lower energy
  - Atomic methods
  - Nanotechnology
  - Quantum entanglement

- **What else can we measure inexpensively and well?**

Conclusions

- We cannot know whether SM describes LHC data until we have done a thorough, systematic search through all of that data
  - Looking for non-minimal models and non-standard signatures
  - Requires unusual and sometimes difficult search strategies
- Any deviation from the SM is an instant game-changer
  - All attention will focus on this chink in the SM's armor
  - Need to look broadly, and use our time and personnel wisely
  - Natural place to look for 2013-2014: non-SM behavior in Higgs(es)
- No deviations? A more spectacular but gradual game-changer
  - Over a century of focused work finally leaves us with no preferred target
  - Are we aiming at the right targets? With the right tools?

A Professor and His Boson

- Nature exhibits an SM-like Higgs boson
- Whether or not this is the whole story at the LHC, it is a spectacular achievement for the field of particle physics
- Today we celebrate Peter Higgs' bright ideas
- Tomorrow we return to the hard work of improving upon them