Questions for Particle Physics, 2015-35

Maxim Perelstein, Cornell

Snowmass on the Pacific, KITP, May 31 2013

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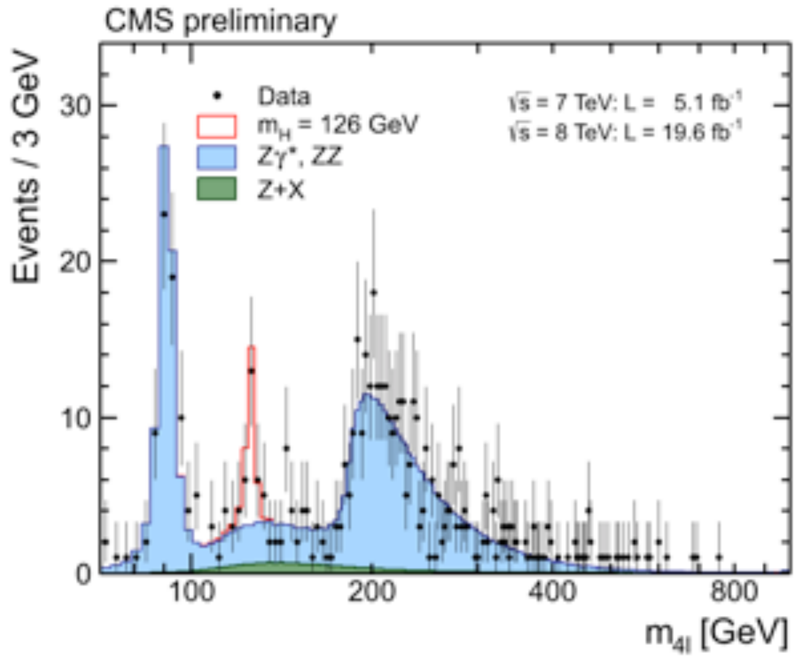
Introduction

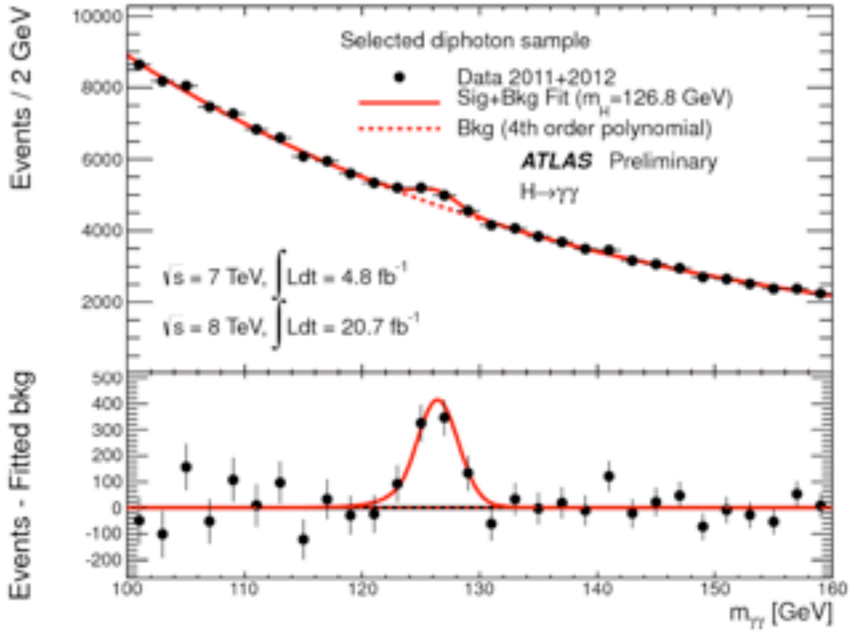
- Technological developments and new ideas make a dizzying array of experiments in particle physics feasible on the relevant time scales
- However resources and manpower are not limited; somebody, somewhere, somehow, will need to make some choices
- The primary goal of our field is to determine the laws governing Nature at the most fundamental level possible
- Experimental programs should be judged according to how much they advance this goal; we theorists must provide this input. It will be convoluted with technological/political considerations by others.
- In this talk I will focus on three physics questions which (a) I care about; and (b) can be tackled experimentally within relevant time span
- They will be organized according to the three frontiers (thus contradicting the main idea of this workshop - sorry!)

Energy Frontier:

Is the Electroweak Scale Natural?

2012: Year of the Higgs





A Lesson from the Higgs Story

- Discovery of the Higgs is wonderful, but it is not surprising

- Since the 1990's, the existence of the Higgs was very strongly hinted at, and the "where to look" was pretty well constrained, by Precision Electroweak studies

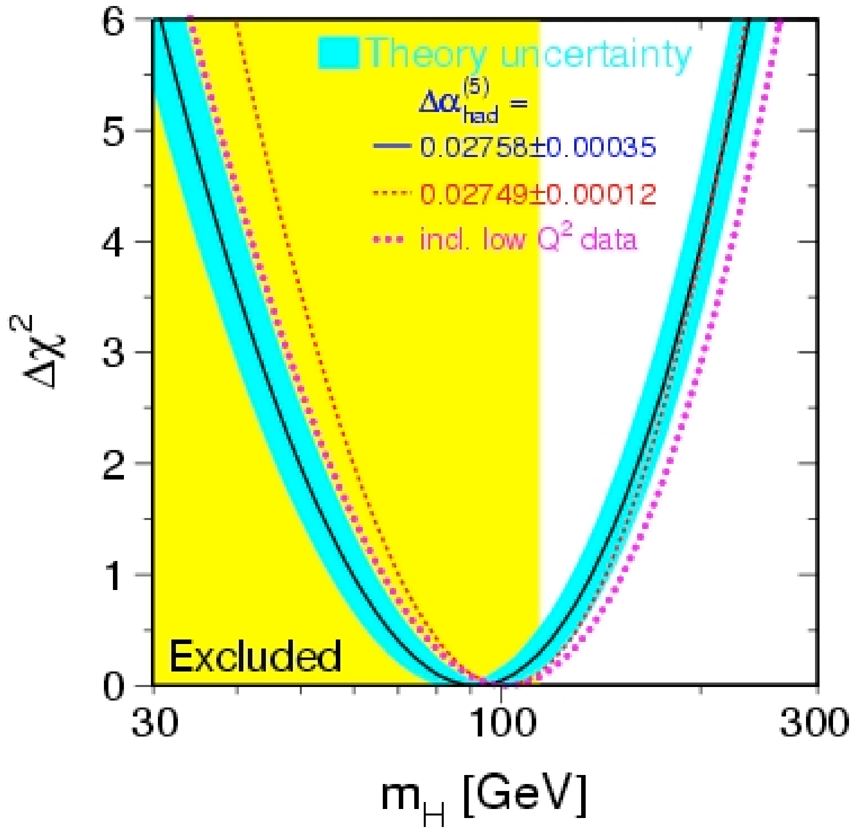


Figure: LEP EWWG, 2006

- The observed mass is perfectly consistent with this plot

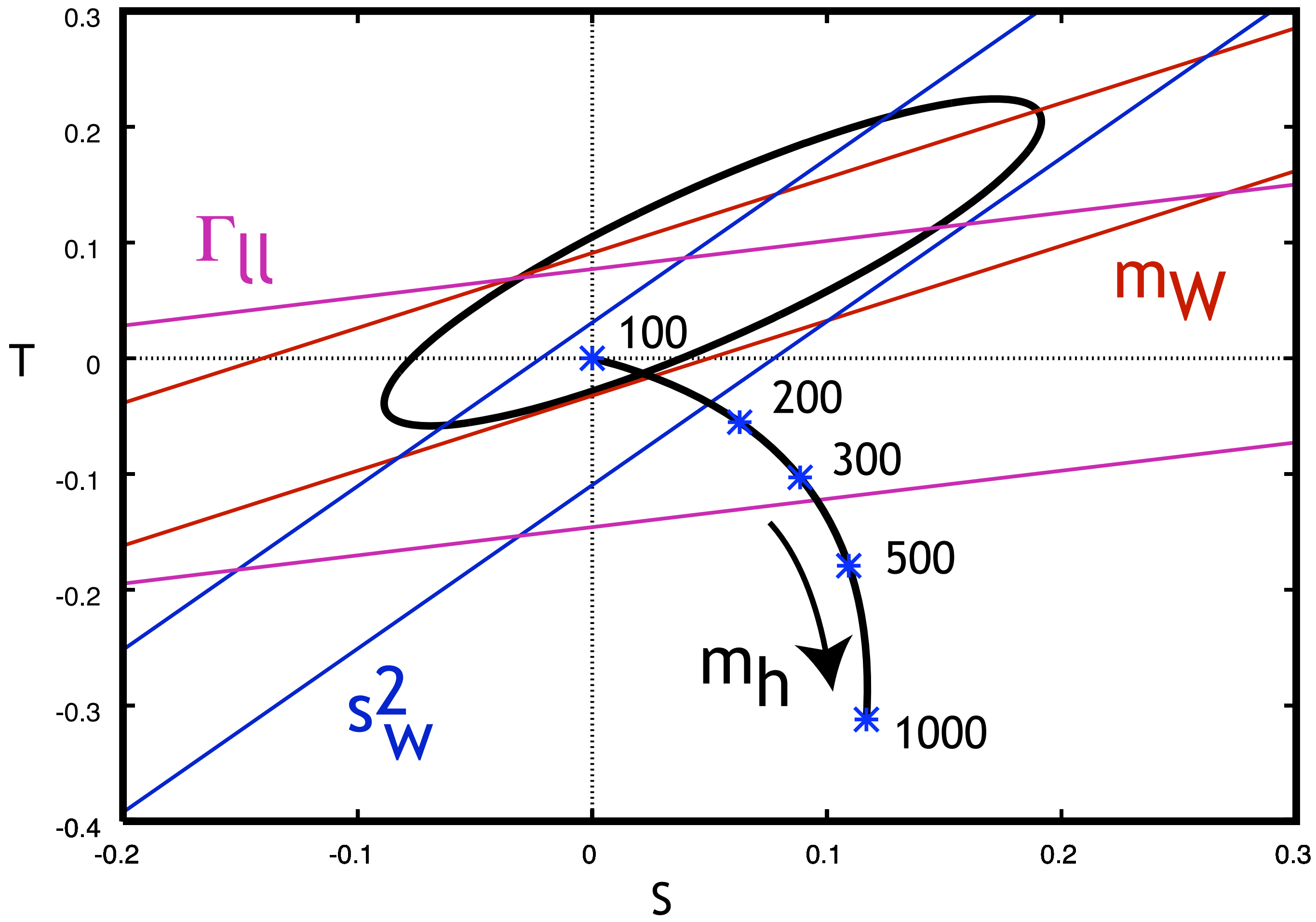
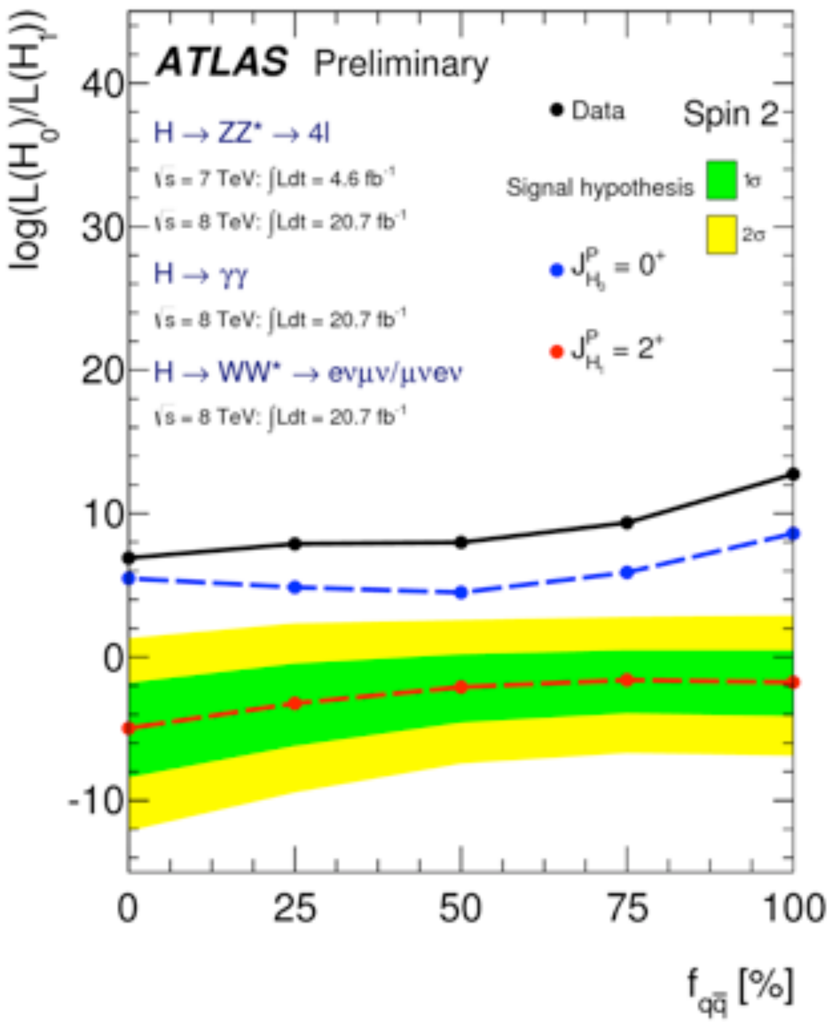


Figure: M. Peskin, 2006

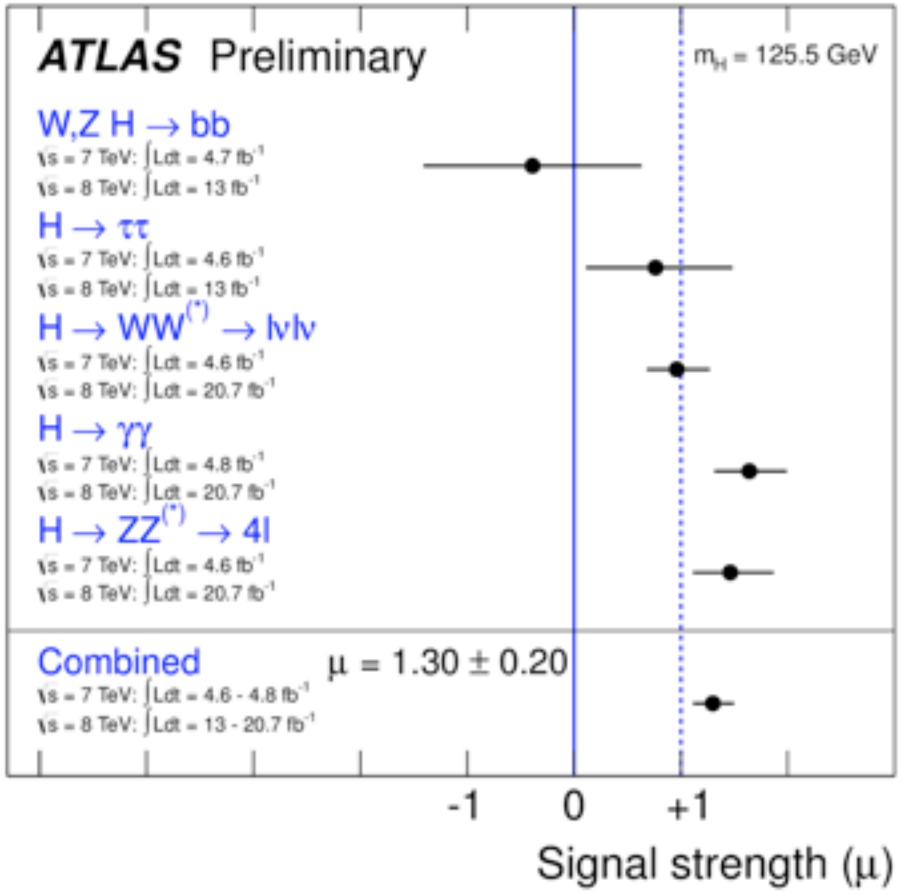
- Quantum loops of a heavy Higgs introduce corrections to S and T parameters, which can be predicted from the SM
- They could have been canceled by contributions from some other new physics, carefully tuned at a ~1/10 or ~1/100 level; they are not.
- Lesson: (yet again) Nature is not a sneaky, mean-spirited, malicious beast. Nature is natural.

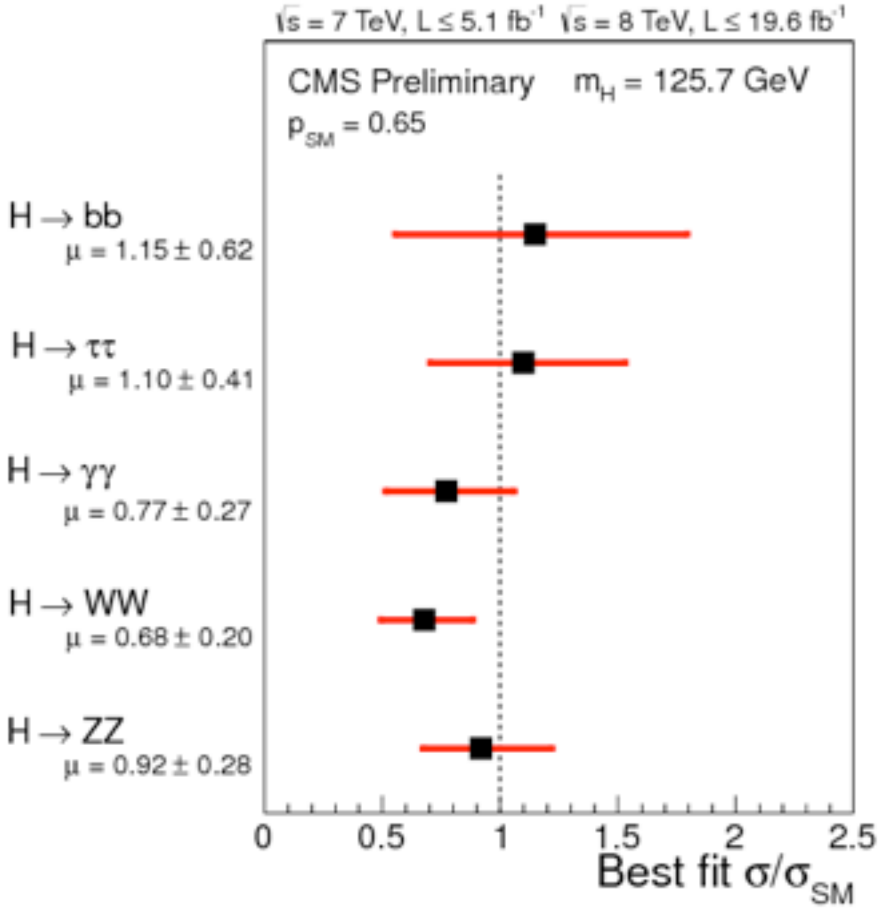
Higgs Properties are Beginning to Emerge at the LHC

- Spin-parity: looks like it is indeed 0+
- Some alternatives are excluded on very general theoretical grounds (e.g. Landau-Yang theorem)
- Others are increasingly constrained by measurements



Rates: SM-like at ~30% level





Working Hypothesis: SM Higgs to "0-th order";
Deviations from SM, if any, suppressed systematically by a small parameter

SM Higgs: Lagrangian and Physical Parameters

- The SM Higgs potential has two terms → two parameters:

$$V = -\frac{\mu^2}{2} h^2 + \frac{\lambda}{4} h^4$$

- Higgs gets a vacuum expectation value, known from e.g. the W mass:

$$v = \frac{\mu}{\sqrt{\lambda}} \qquad M_W = \frac{gv}{2} = 80.4 \text{ GeV} \rightarrow v = 246 \text{ GeV}$$

- The physical Higgs boson mass is

$$m_h = \sqrt{2}\,\mu$$

- Higgs mass at ~126 GeV gives

$$\mu = 88.4 \text{ GeV}, \quad \lambda = 0.13$$

- Question: how reasonable ("natural") are these values?
- Focus on the mass parameter; quartic also important, but more model-dependent

SM Higgs:Renormalization

- Higgs mass parameter receives radiative corrections:

$$-\mu^2 = \mu^2_{\rm tree} + \frac{c_X^2}{16\pi^2}\Lambda_X^2 \qquad\qquad c_X^2 = \kappa_X^2 N_X$$

- κ_X = Higgs-X coupling constant, N_X = # of d.o.f. in X (X=SM fields)
- Naturalness: $\frac{c_X^2}{16\pi^2}\Lambda_X^2 \lesssim \mu^2$ ➡ $\Lambda_X \lesssim \frac{4\pi\mu}{c_X} \approx \frac{1\ \mathrm{TeV}}{c_X}$
- Simple measure of unnaturalness:

$$\Delta = \frac{\delta\mu^2}{\mu^2}$$

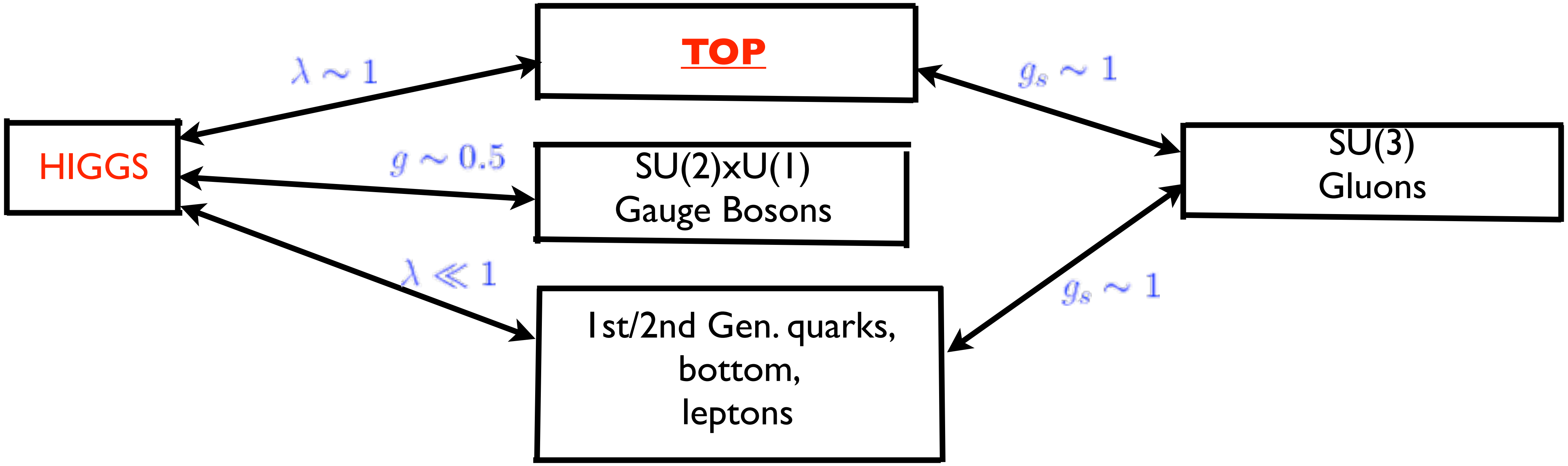
($\Delta > 1$ = fine-tuning)

- An alternative measure (usually agree up to O(1) factors):

$$\delta\mu^2 = f(p_i),\, \Delta = \max_i \left|\frac{\partial \log \mu^2}{\partial \log p_i}\right|$$

Natural New Physics Scales

- Hierarchy of SM Higgs couplings



TOP

HIGGS

SU(2)xU(1)
Gauge Bosons

SU(3)
Gluons

1st/2nd Gen. quarks,
bottom,
leptons

- Cutoff scales required by naturalness are inversely related to the couplings:

$$\Lambda_X \lesssim \frac{4\pi\mu}{c_X} \approx \frac{1\ \mathrm{TeV}}{c_X} \qquad c_X^2 = \kappa_X^2 N_X$$

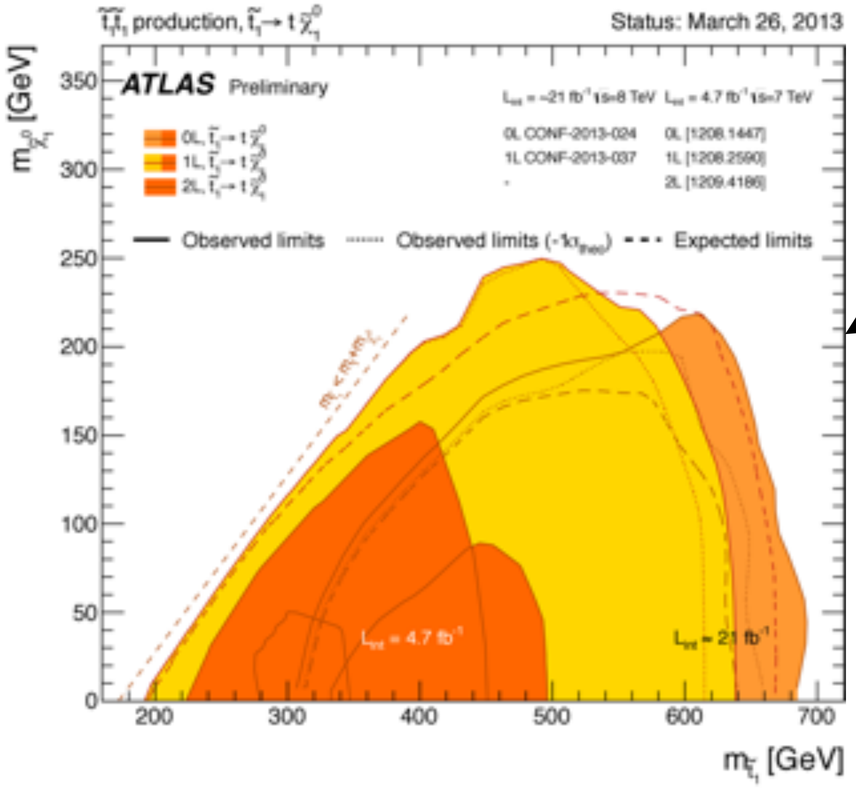
- Top quark: $c_t = 6\lambda_t^2 \approx 6$ ➡ $\Lambda_t \lesssim 400\ \mathrm{GeV}$

- This energy scale is already being probed at the LHC, and will be definitively probed in the next decade

Options for New Physics

- Brute-force solution: Strong dynamics at Λ_t , with Higgs being a composite particle bound by new strong interactions, a la QCD mesons
- However, precision electroweak constraints imply a lower bound on the new strong interactions scale of ~a few TeV
- Thus, such Higgs models are typically fine-tuned at a ~1% level
- Alternative: Naturalness restored by weakly coupled physics at sub-TeV scale
- This would require relations between new particles' and SM couplings to the Higgs → symmetries. Highly non-trivial requirement.
- Two promising solutions: SUSY (complete) and pNGB/Little Higgs (partial, needs to be combined with compositeness/strong coupling at ~10 TeV)
- Definitive experimental tests of naturalness are feasible on the relevant time scales

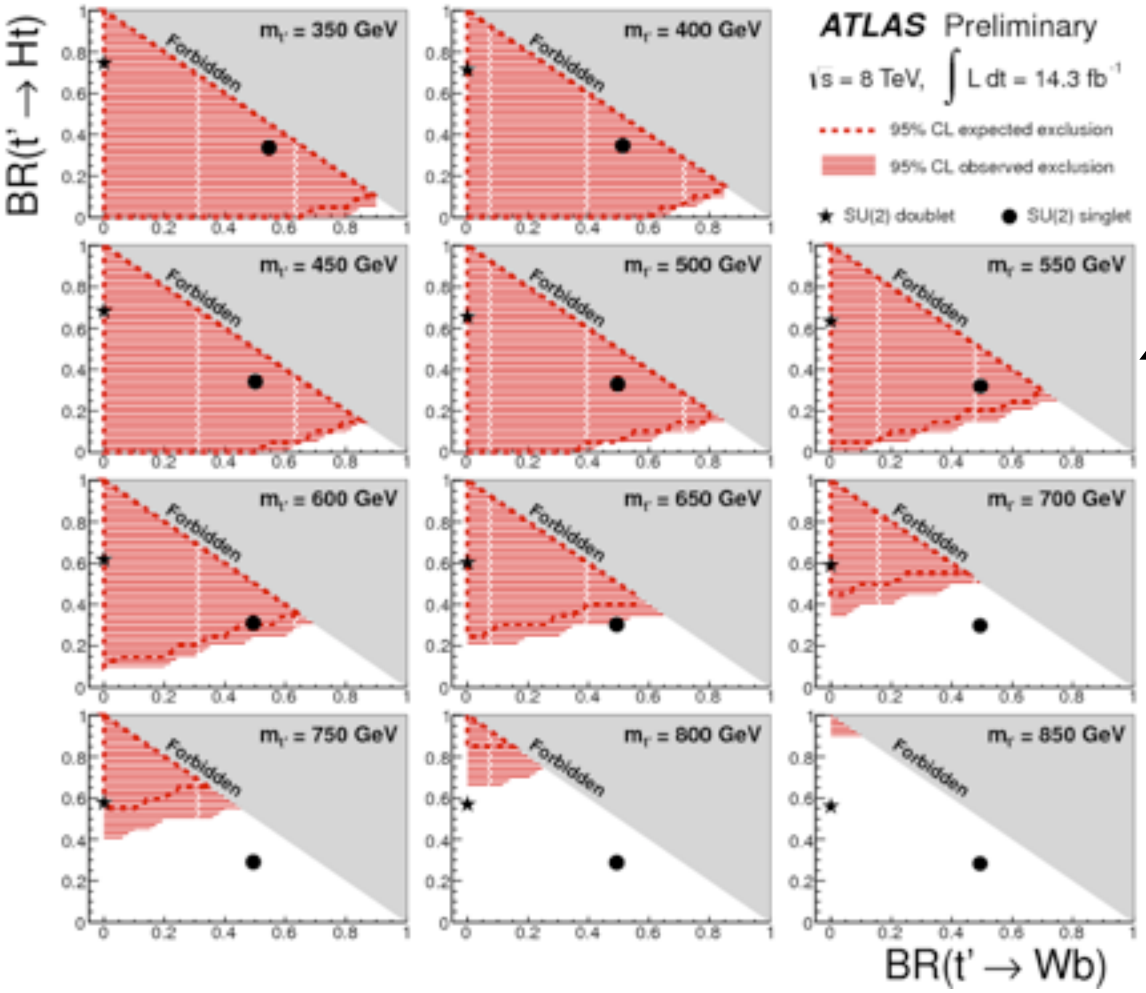
Top Partners: Direct Searches



Spin-0 top partner, a.k.a. “stop” (SUSY)

- The current “headline” LHC bound on stop mass is ~700 GeV; this implies ~10% fine-tuning
- However, there are several large “holes”:
  - No bound at all for $m(\tilde{\chi}_1^0) > 250\ \mathrm{GeV}$ - “mildly compressed” spectrum
  - No bound if $m(\tilde{t}) \approx m(t)$ - “stealthy” spectrum
  - No bound if $\tilde{t} \rightarrow \bar{b}\bar{s}$ - R-parity violating models (e.g. MFV/RPV)

Top Partners: Direct Searches



Spin-1/2 top partner,
a.k.a. "big T"
(e.g. Little Higgs)

- The bound on T is ~650 GeV, implies ~10% fine-tuning
- Holes probably exist, papers have not been written due to relative lack of popularity of models compared to SUSY

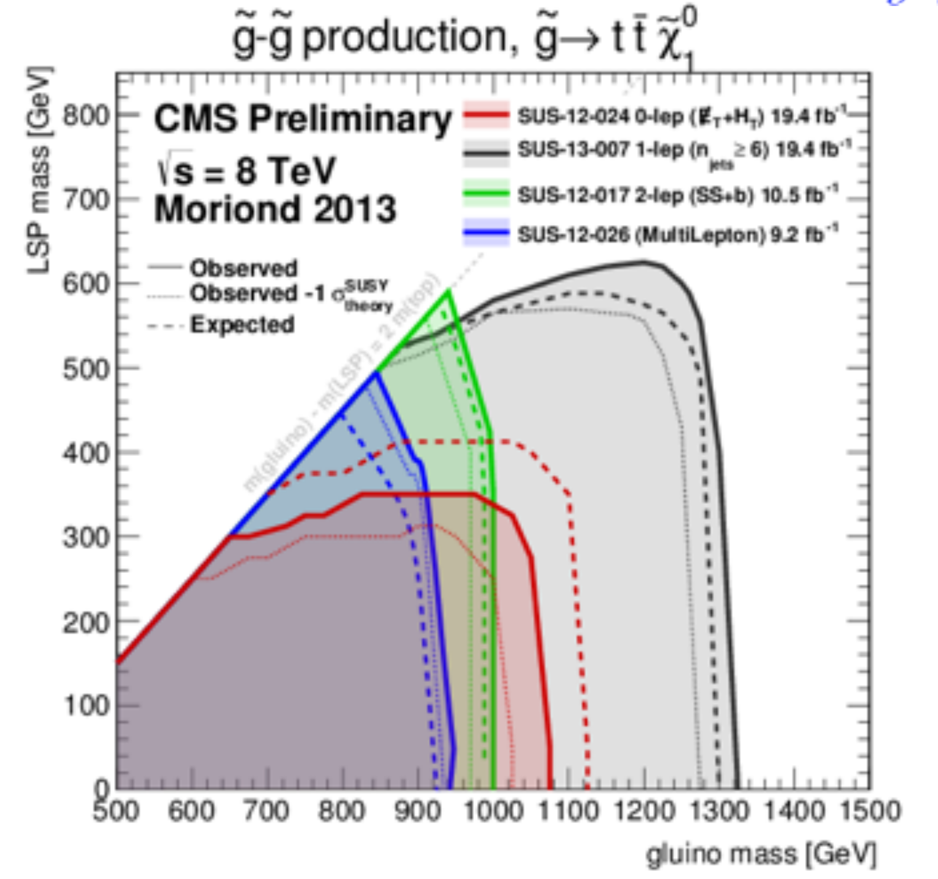
Gluinos and Naturalness

- Rad. corrections to the stop mass also need to be cut off (stop=scalar!)
- Dominated by QCD; cut off by the gluino → naturalness requires

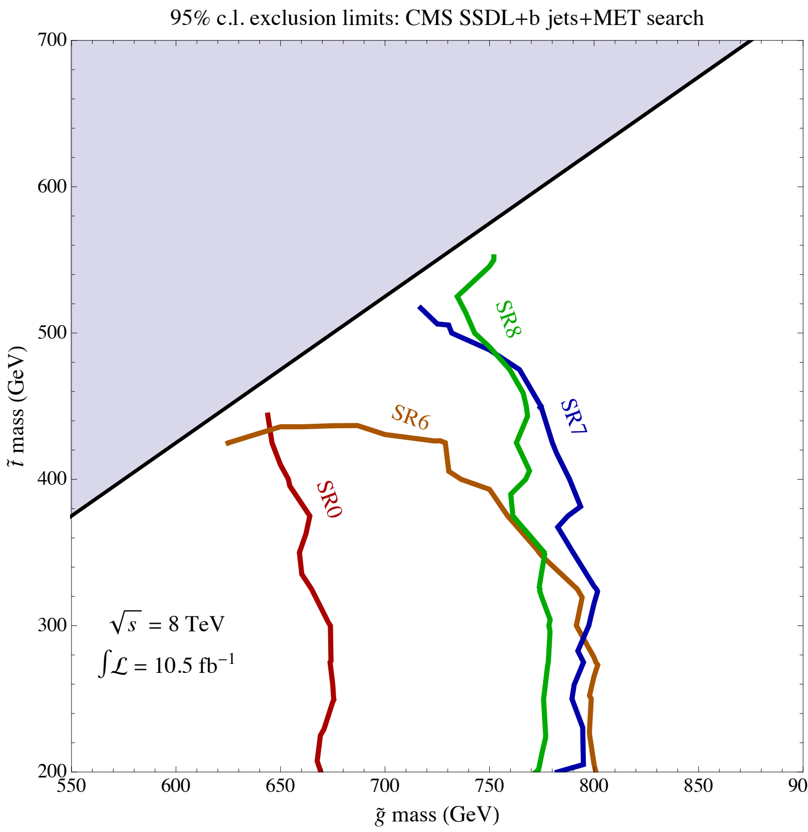
$m_g \lesssim 2m_t$ (Majorana gluinos, as in MSSM)

$m_g \lesssim 4m_t$ (Dirac gluinos)

[Brust, Katz, Lawrence, Sundrum, '11]



R-parity conserving

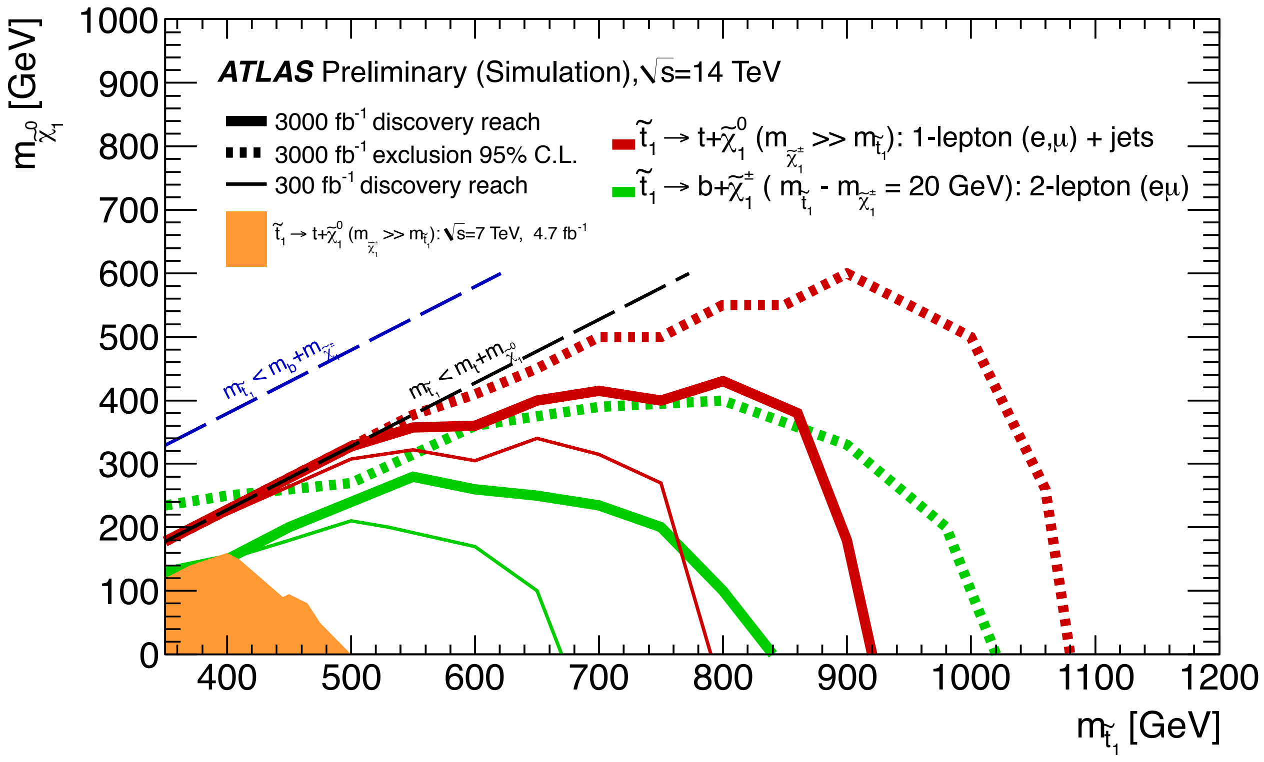


R-parity violating (SSDL)

[Figure: Berger, MP, Saelim, Tanedo]

Reduces some of the holes: stealthy and RPV stops cannot be fully natural

Future of Direct Searches



ATLAS, for ESPP 2012
Very Conservative!

- Two obvious directions: up in mass, and close the holes
- The latter requires new ideas/observables [join NP/Top working group!]
- For example, compressed spectrum may be explored with ISR tagging, given enough luminosity
- Important question for Snowmass: Are there holes that can only be closed at a lepton collider? Are those "big" enough to matter?

Tree-Level Tuning in SUSY

- So far, we focused on tree vs. loop tuning, which appears in all models
- In SUSY, there is a separate issue: two distinct tree-level contributions to m^2

$$m^2 = -m_{H_u}^2 + \mu^2$$

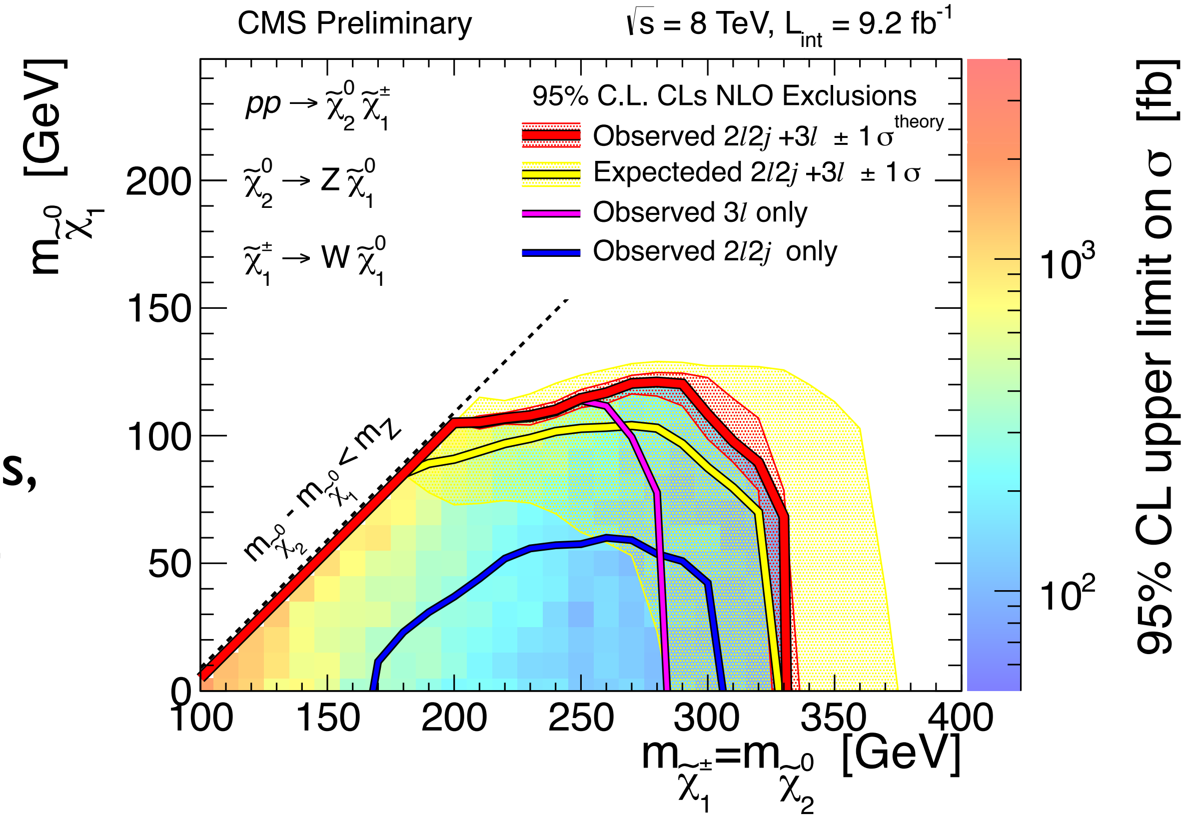
SUSY-breaking soft mass

SUSY-preserving F-term

- Naturalness: $m^2 > \mu^2$ ➡ expect light (~100 GeV) Higgsinos

Search for Higgsinos decaying to binos; the bound implies ~10% tuning with usual caveats

If neutral Higgsinos are the only light particles, the LHC will probably not be able to find it (but please prove me wrong!)



"Minimal" (sort of) spectrum

Higgs Couplings and Naturalness

Farina, MP, Rey Le-Lorier, 1305.6068

- One-loop quantum corrections to Higgs potential are given by the Coleman-Weinberg formula:

$$V_{\rm CW}(h) \;=\frac{1}{2}\sum_k g_k(-1)^{F_k}\int\frac{d^4\ell}{(2\pi)^4}\,\log\left(\ell^2+m_k^2(h)\right)$$

- The only input is Higgs-dependent masses of all particles; focus on tops

- The famous mass renormalization is just $\delta\mu^2\equiv\frac{\delta^2 V_{\rm CW}}{\delta h^2}|_{h=0}$.

- Top partner mass is $m^2(T_i)=m_{0,i}^2+c_i h^2+\cdots$

- Cancellation of quadratic divergence gives a sum rule: $6y_t^2=\sum_i g_i(-1)^{F_i}c_i$

- Potential fine-tuning comes from the next (log-divergent) term:

$$\Delta=\frac{\delta\mu^2}{\mu^2}\approx 0.78\left(\sum_i g_i(-1)^{F_i}c_i\left(\frac{m_{0,i}}{1\ {\rm TeV}}\right)^2\log\frac{\Lambda^2}{m_{0,i}^2}-6y_t^2\left(\frac{m_t}{1\ {\rm TeV}}\right)^2\log\frac{\Lambda^2}{m_t^2}\right)$$

Higgs Couplings and Naturalness

- Low-Energy Theorems give the top partner contributions to hgg and $h\gamma\gamma$ in terms of the same object: Higgs-dependent top-partner mass

$$\mathcal{L}_{h\gamma\gamma} = \frac{2\alpha}{9\pi v} C_\gamma h F_{\mu\nu} F^{\mu\nu}\,, \quad \mathcal{L}_{hgg} = \frac{\alpha_s}{12\pi v} C_g h G_{\mu\nu} G^{\mu\nu}$$

$$C_\gamma = 1 + \frac{3}{8} \sum_f^{Dirac\ fermions} N_{c,f} Q_f^2 \frac{\partial \ln m_f^2(v)}{\partial \ln v} + \frac{3}{32} \sum_s^{scalars} N_{c,s} Q_s^2 \frac{\partial \ln m_s^2(v)}{\partial \ln v}$$

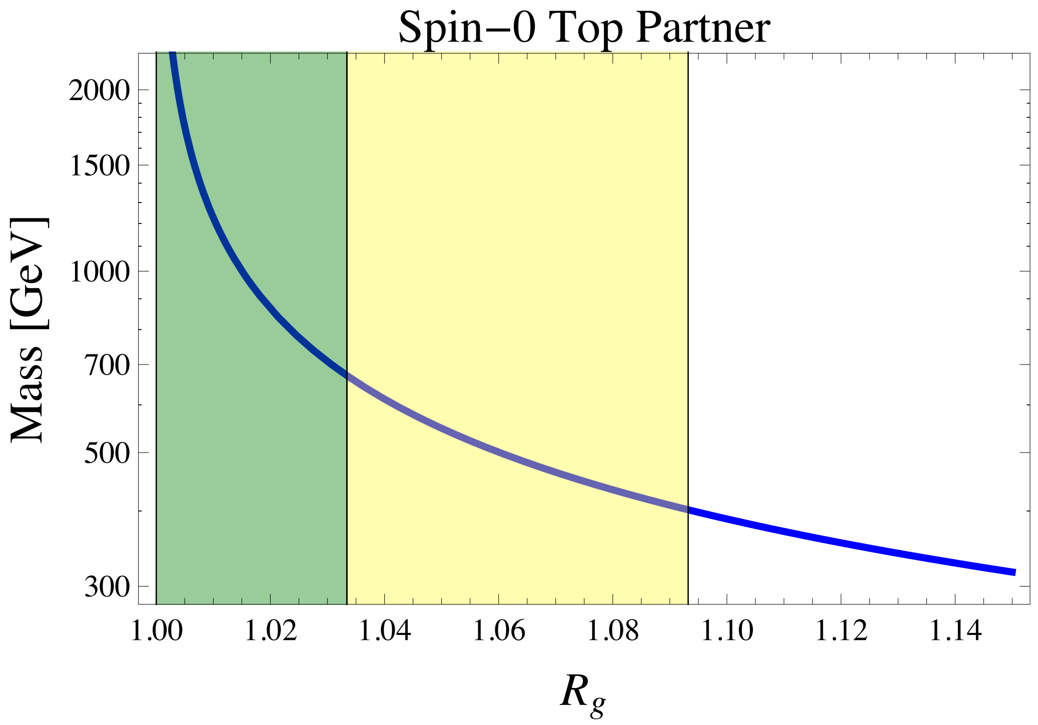
$$C_g = 1 + \sum_f^{Dirac\ fermions} C(r_f) \frac{\partial \ln m_f^2(v)}{\partial \ln v} + \frac{1}{4} \sum_s^{scalars} C(r_s) \frac{\partial \ln m_s^2(v)}{\partial \ln v}\,,$$

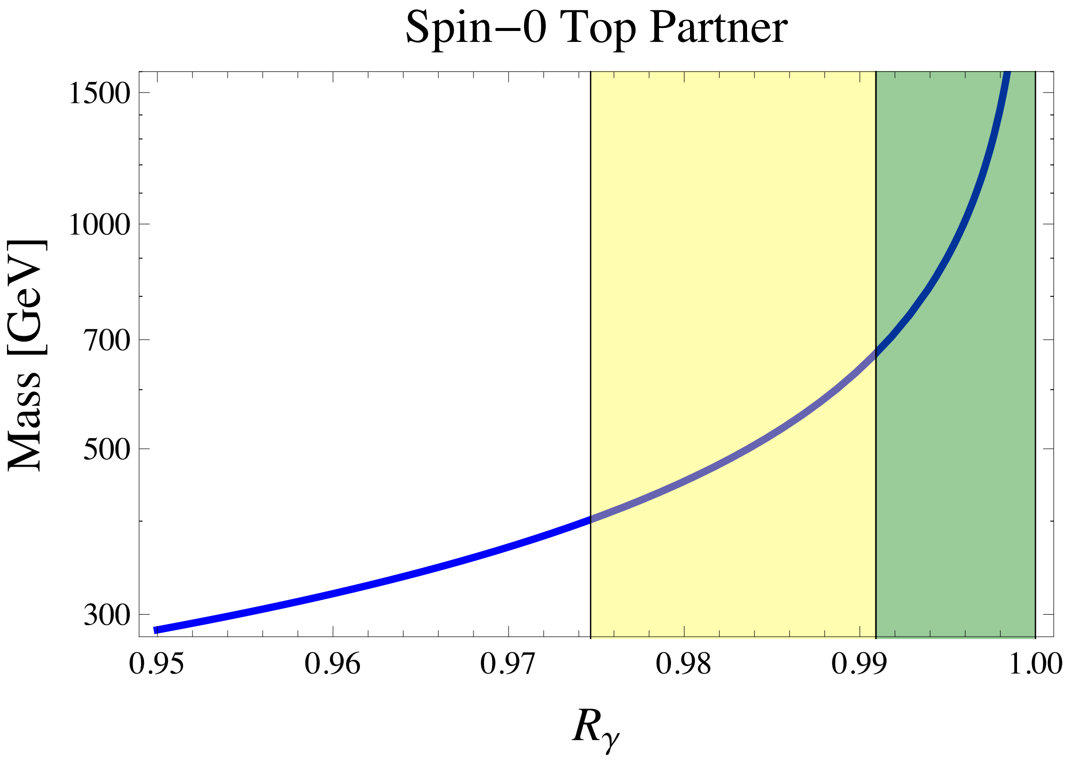
- Very general, very robust result: inverse correlation between fine-tuning and non-SM contributions to hgg and $h\gamma\gamma$

- Only exceptions: non-colored, non-charged partners (see M. McCullough's talk on Wed); or accidental cancellations (but Nature's not mean)

- Benchmark example: a single top partner, spin 0 or 1/2, with quantum numbers of the SM top (e.g.: MSSM with degenerate stops)

Higgs Couplings and Naturalness





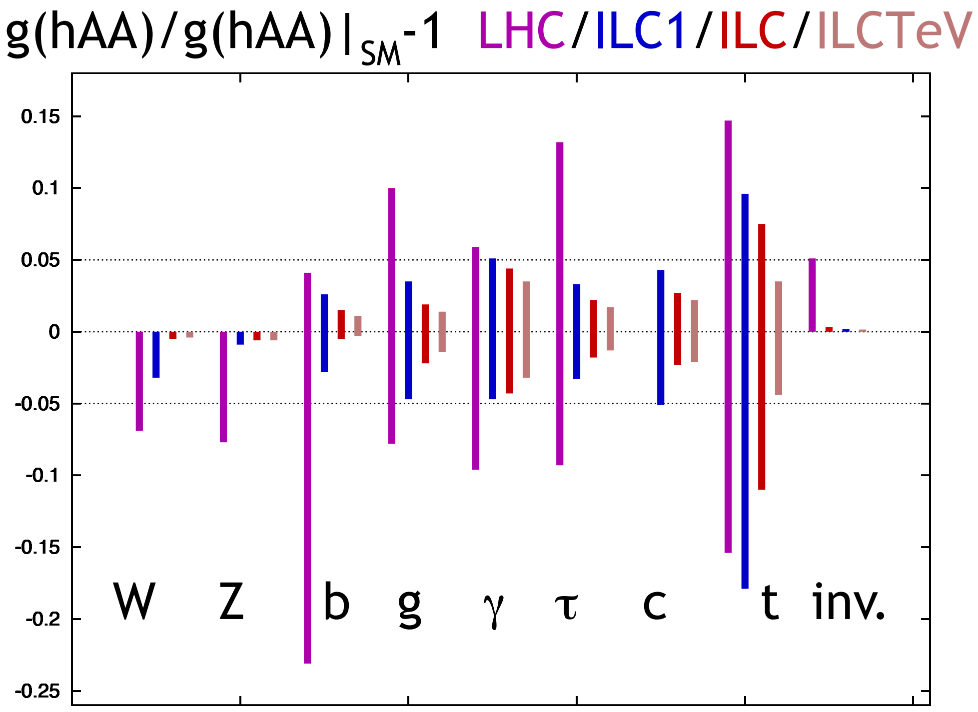
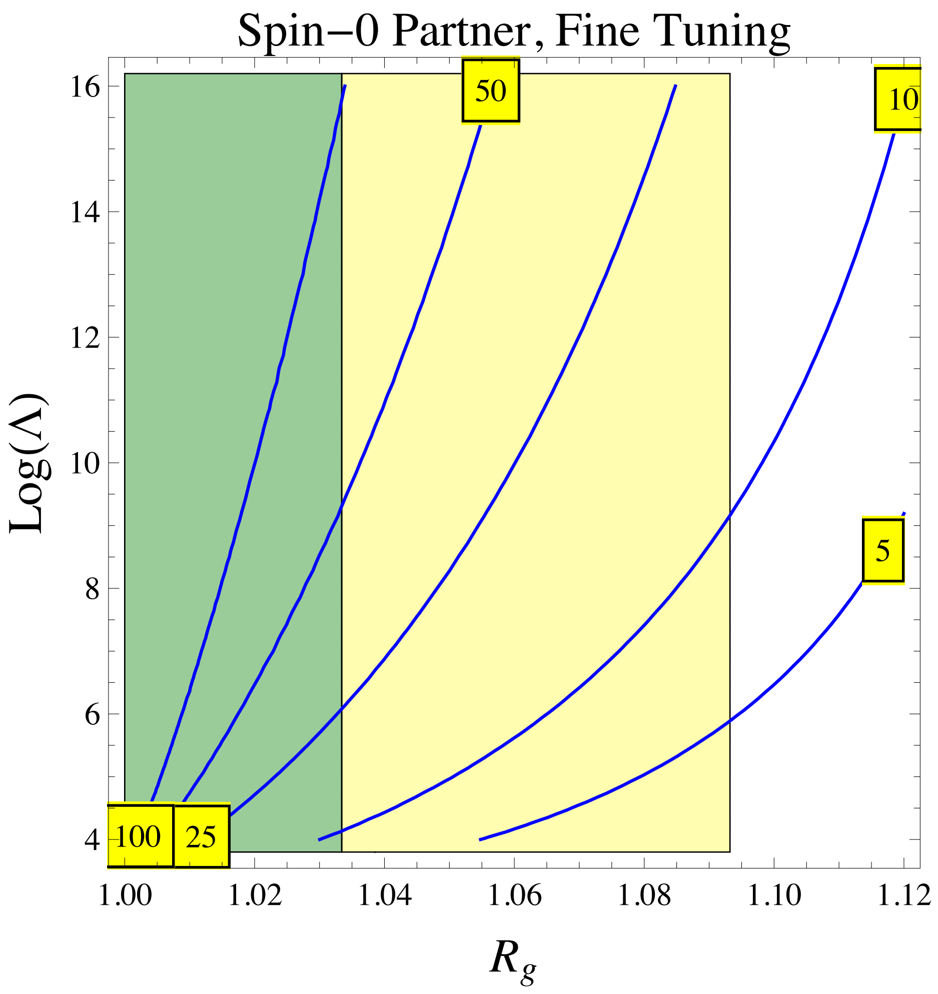
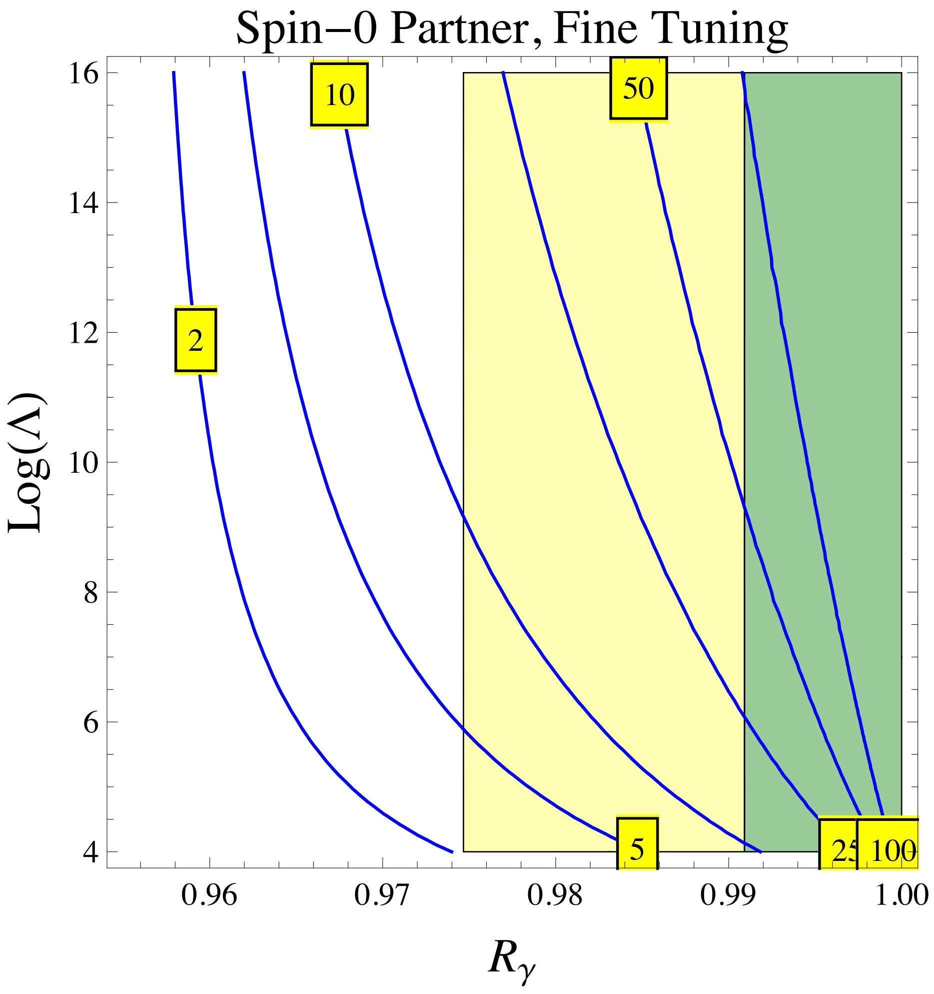


Figure: M. Peskin, 2012

A 1% measurement of R_g would probe the top partner mass of ~1.2 TeV...

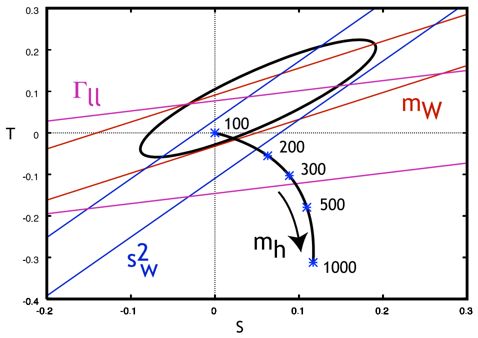
Higgs Couplings and Naturalness

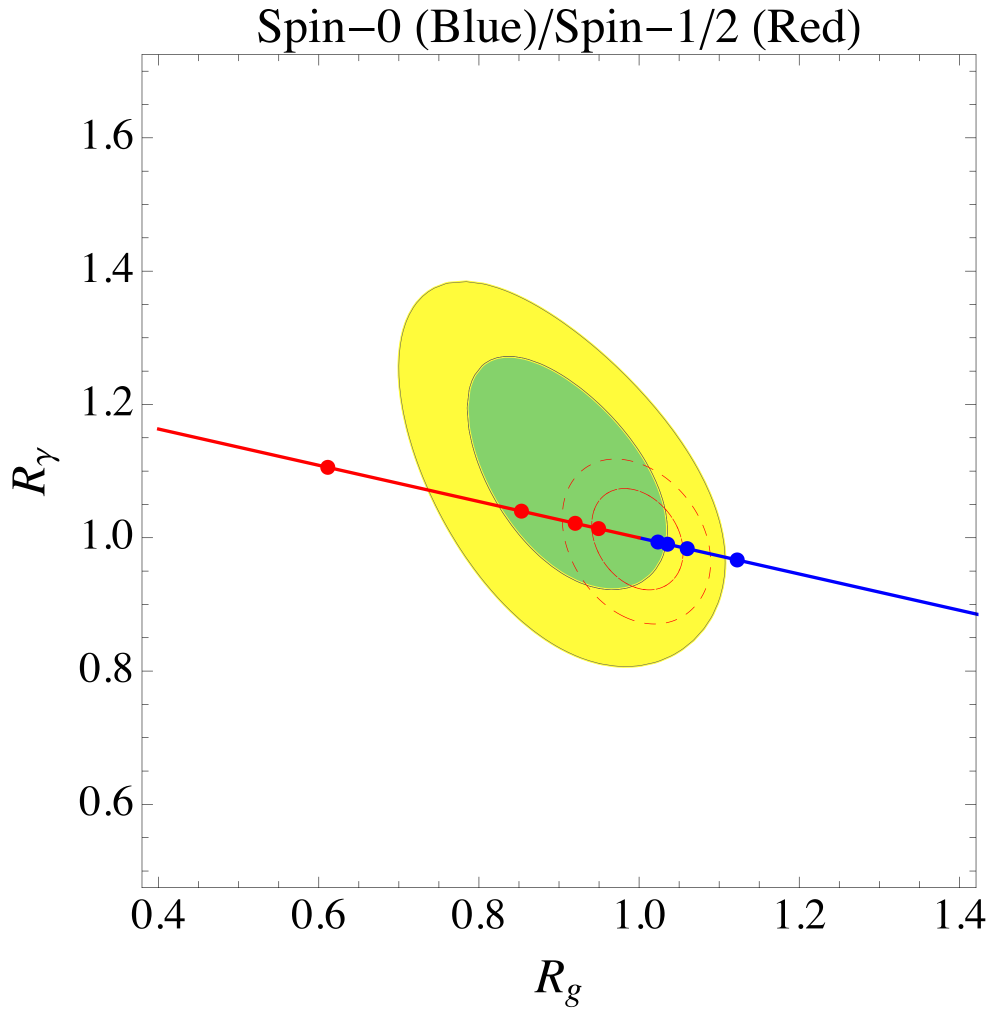




... and imply fine-tuning of at least 1/25 if no deviation from the SM is seen

Higgs Couplings and Naturalness





Dots: 350, 500, 650, 800 GeV
top partners

Ellipses: LHC-8/LHC-14

Precision Higgs coupling measurements give a robust test of naturalness, similar to strongly/weakly-coupled EWSB test via electroweak precision

Complementary to direct stop searches: no compressed, stealthy, RPV holes

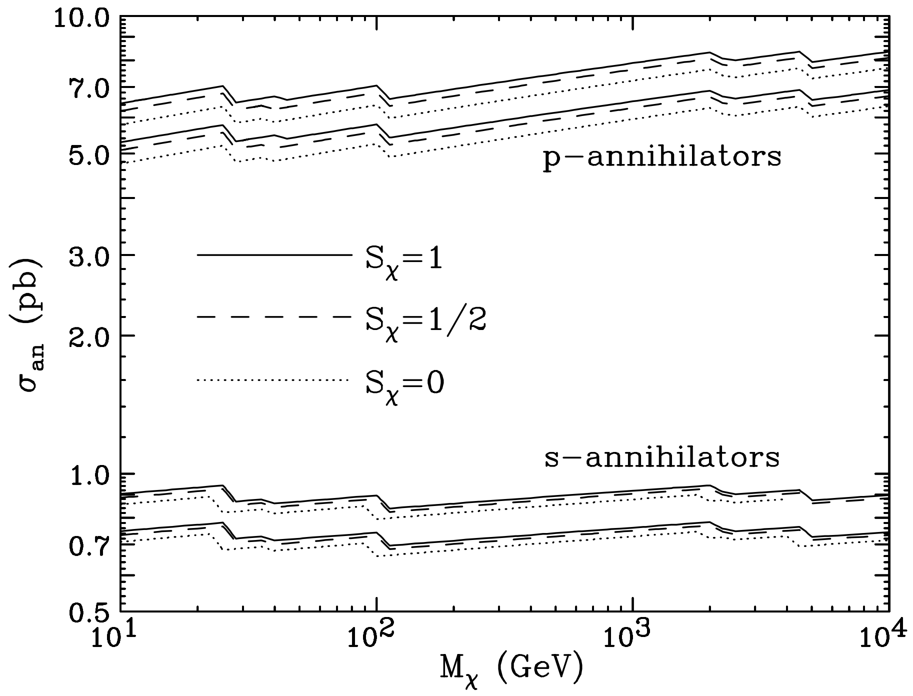
Naturalness: What's at Stake

- Robust experimental probes of naturalness of Electroweak Symmetry Breaking, at a ~1% level, are within our reach
- My bet: we will discover new physics
- If we don't, it will be a tremendously important result, with profound implications for our understanding of Nature, and the future of physics
- If no new physics at TeV, the observed value of the electroweak symmetry breaking scale must be regarded as a ~1/100 coincidence
- There are examples in Nature of coincidences at this level: e.g. Sun & Moon angular sizes coincide to ~1/50 (⇨ eclipses)
- We are not surprised: our Solar system is one of billions; we can see others
- The only reasonable framework to make sense of non-natural EWSB is to regard our physical laws as randomly selected from a large set of possibilities
- Unlike the Sun/Moon, we cannot see the patches of the universe where other possibilities are realized; our evidence for this hypothesis has to be indirect

Cosmic Frontier:
Is Dark Matter a Thermal Relic?

Thermal Relic Dark Matter

- The existence of dark matter is an incontrovertible experimental fact
- The non-SM nature of dark matter seems overwhelmingly likely
- DM is a somewhat massive (> keV), electrically and color neutral, stable (or extremely long lived) particle
- There are (too) many particle physics models; a useful zeroth-order classification is by cosmological history: "thermal" vs "non-thermal"
- Vanilla thermal relic scenario is rather predictive: total pair-annihilation cross section ⇔ present density, which is well known



$\sigma(\chi\chi \to \mathrm{SM}) \sim 1\ \mathrm{pb}$

$$\sigma \sim \frac{\pi\alpha^2}{M^2}$$

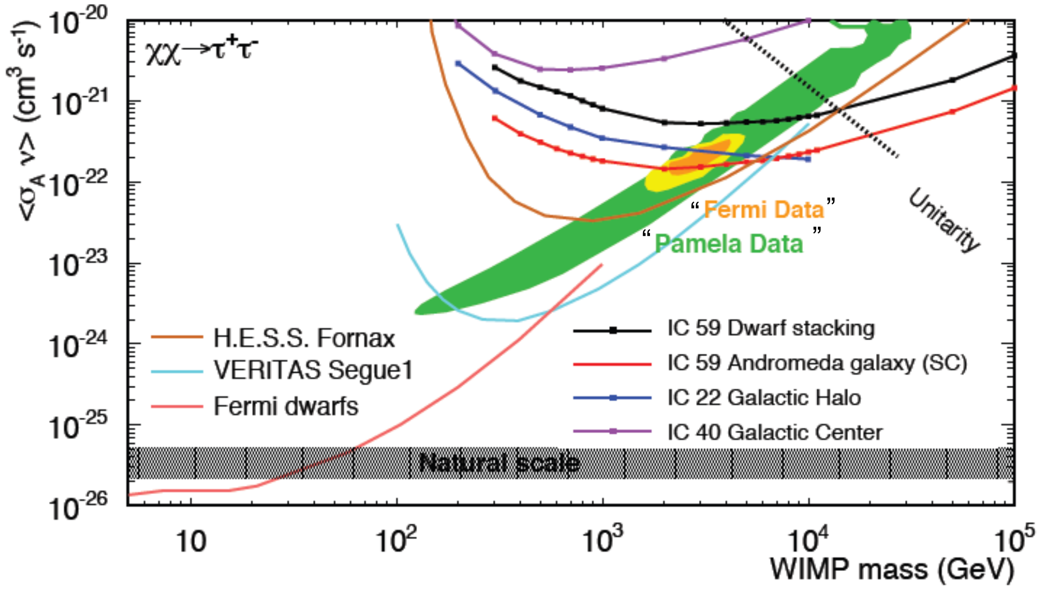
$$\alpha \sim 0.1\ldots0.01 \Rightarrow M \sim 0.1\ldots1\ \mathrm{TeV}$$

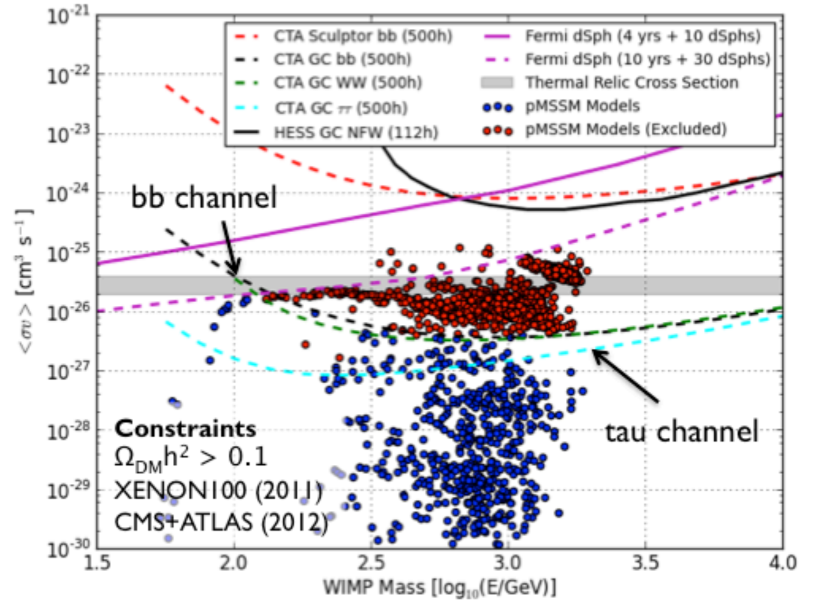
WIMPs!

Figure: Birkedal, Matchev, MP

Indirect Detection

- The most direct prediction of vanilla thermal relic is for indirect detection: same annihilation processes, happening today in our neighborhood
- An important caveat: only know the total annihilation rate, summed over final states ⇨ need a broad range of probes: photons, neutrinos, positrons, ...
- An equally important caveat: astrophysical backgrounds are in many cases not understood at the level needed to enable a real DM search (a cautionary example: Pamela/AMS)
- Indirect detection experiments will begin to get into the interesting cross range (with caveats)

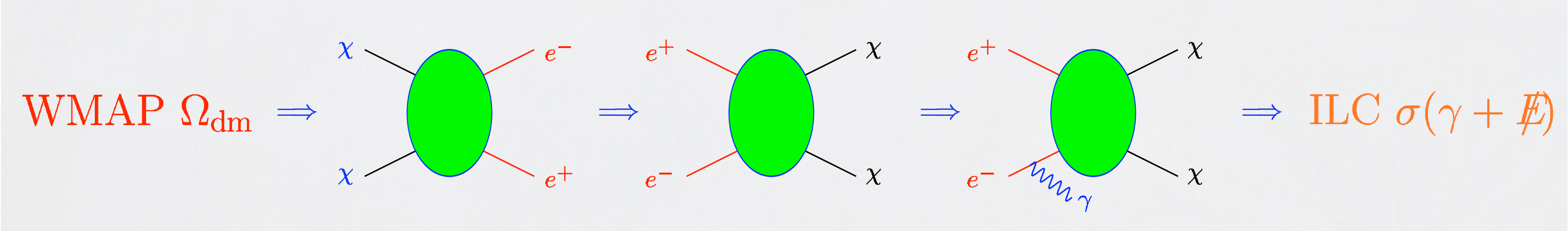




Figures:S. Ritz's talk on Wed

Colliders

- DM production rates at colliders can be predicted, for a vanilla thermal relic, through a simple, robust, model-independent calculation



- Potentially observable rates of tag+MET predicted for both hadron and lepton colliders

- Caveats: Strong dependence on the DM mass; only know the total annihilation rate, summed over final states, but only collide one type of particles at a time

- Still: e.g. ILC can discover DM even if only ~1% annihilate into electrons

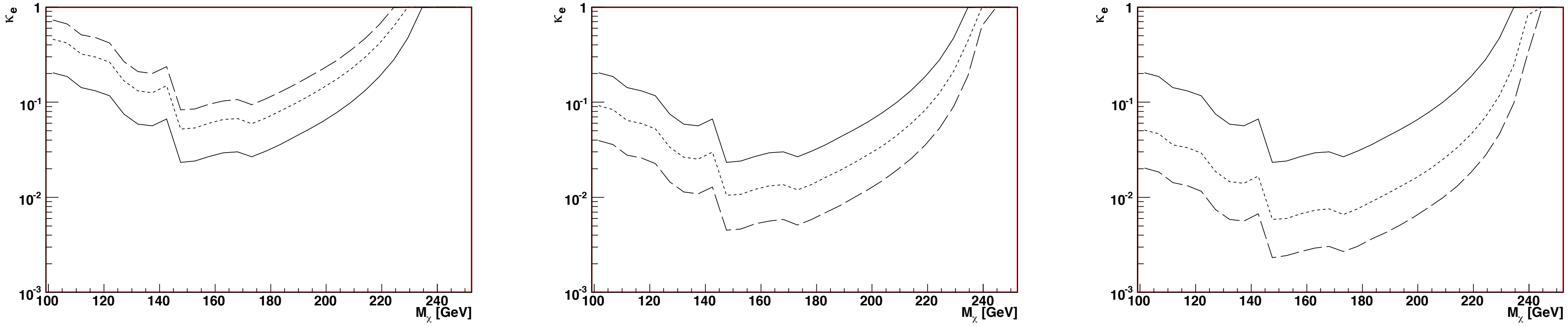


Figure: Bartels and List

Direct Detection

- Unfortunately, prediction of vanilla thermal relic for elastic DM-nucleus scattering (a.k.a. direct detection) requires further theoretical assumptions
- A simple, general framework in which this can be done is effective operator approach
- In this framework, current and future direct detection experiments are probing the interesting cross section range, with mass regions complementary to indirect and collider searches

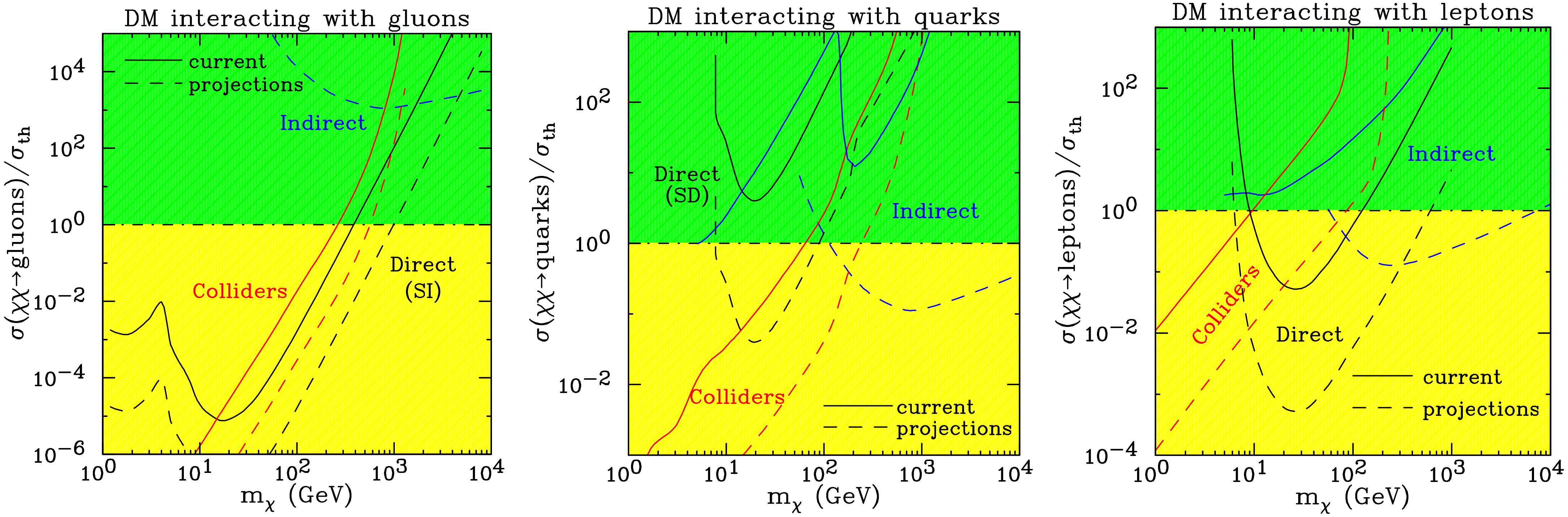


Figure: Snowmass DM Complementarity WG

Dark Matter: What's at Stake

- It seems that on the relevant time scales we might have a chance to test definitively the (vanilla) thermal relic dark matter framework, through a combination of probes
- It would be nice to have this case clearly spelled out somewhere
- My bet: we'll discover it
- My worry: Indirect detection seems very important, especially at high masses, but how can we eliminate astrophysical explanations? (Smoking-gun line signals are likely suppressed.)
- If I'm wrong: Non-thermal, or non-minimal thermal, DM would not be shocking from theory point of view. However it's not nearly as predictive - too many options. Some attractive ideas: asymmetric (especially if CDMS's 3 events are real), or axions.

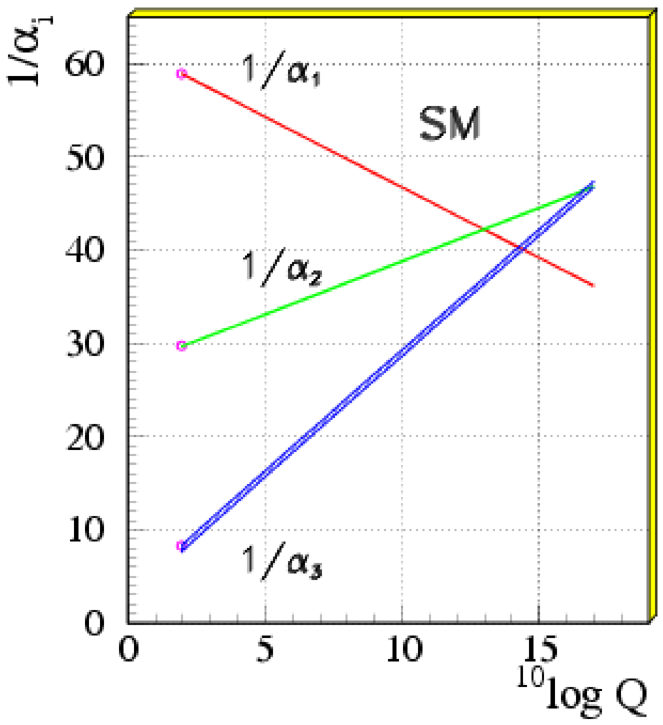
Intensity Frontier:

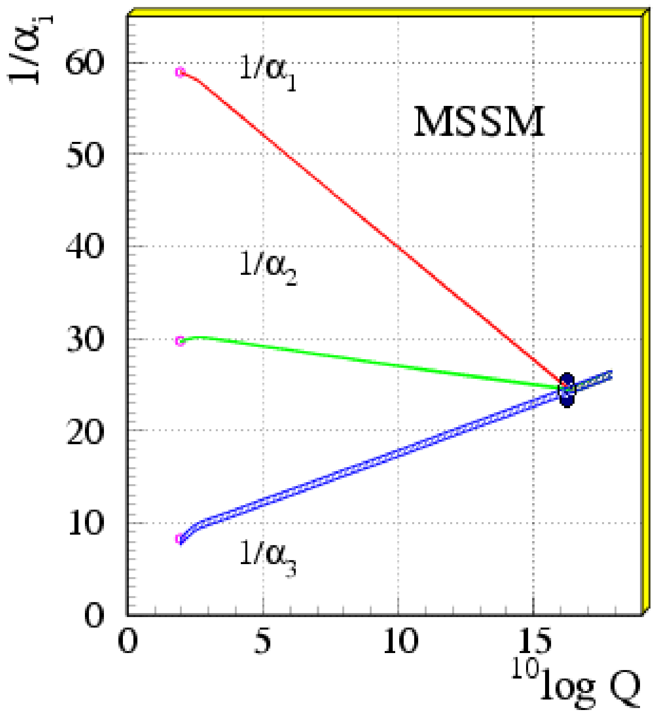
Is There Grand Unification?

- ## Three strong hints for Grand Unification:

  - Electric charge quantization ⇨ SM U(1) must be embedded in non-Abelian group
  - Fermion quantum numbers in the SM beg to be unified in SU(5) or larger multiplets
  - Extrapolated SM gauge couplings approximately meet at the high scale, even in the SM (and much better with SUSY)

- Even in an unnatural world, I would bet that some version of gauge unification occurs





- Neutrino Mass discovery hints at SO(10) unification:
  - Full SM generation in a single multiplet, right-handed neutrino is mandatory
  - GUT-scale mass for ν_R is predicted, with light neutrino masses at $\sim \frac{v^2}{m_R}$ via see-saw mechanism
  - Measured m_ν ⇨ estimate $m_R \sim 10^{14}\ \mathrm{GeV}$, reasonably close to the gauge coupling unification scale

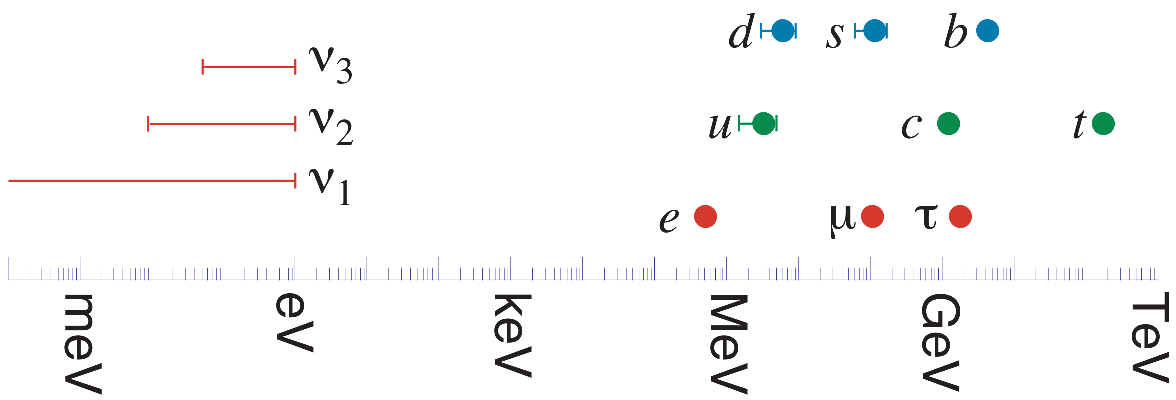
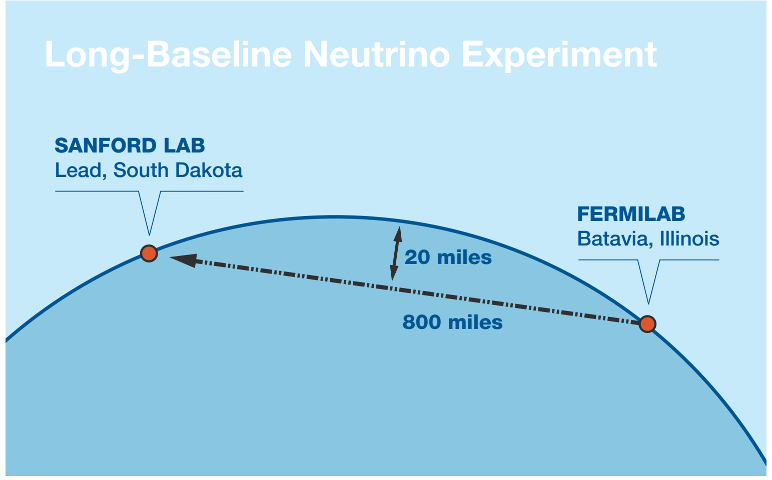


Figure: Intensity Frontier Report, 2011

Neutrinos: Next Steps



- Overall mass scale (CMB+LSS)
- Normal vs. Inverted mass hierarchy (CMB+LSS, LBNE)
- CP Violation (LBNE)
- BSM searches: sterile neutrinos, non-standard interactions, ... (my bet: no)

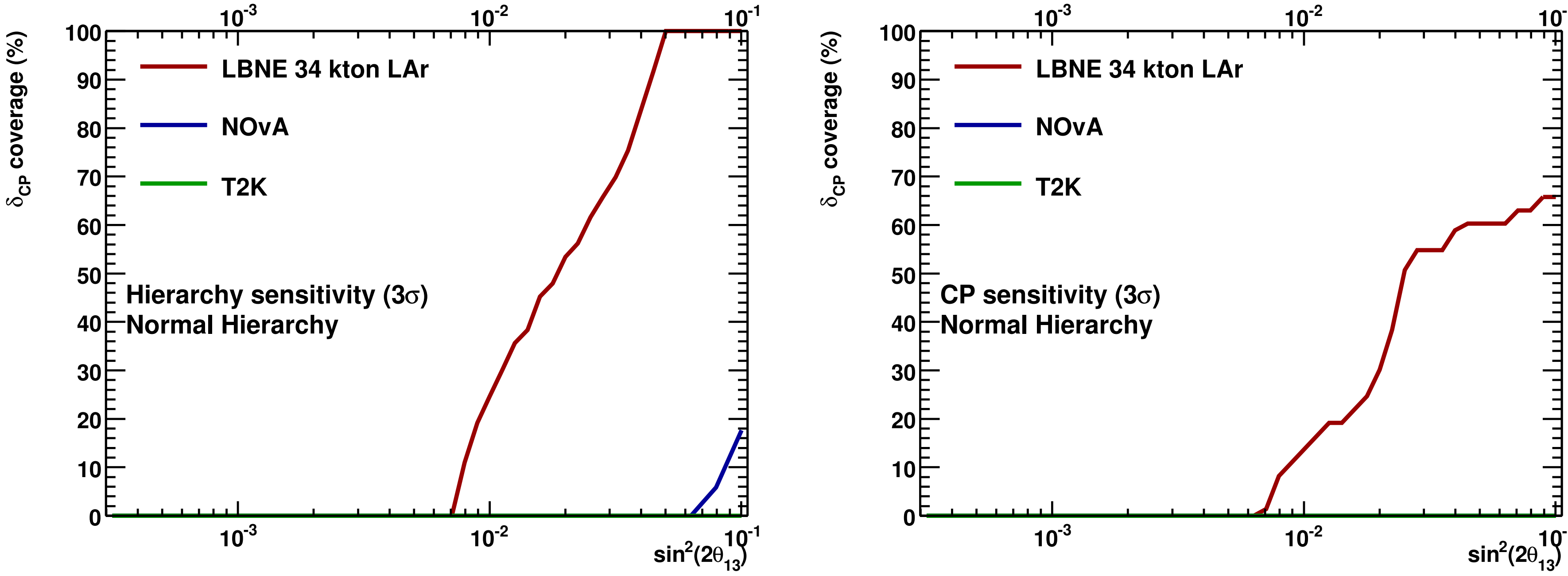


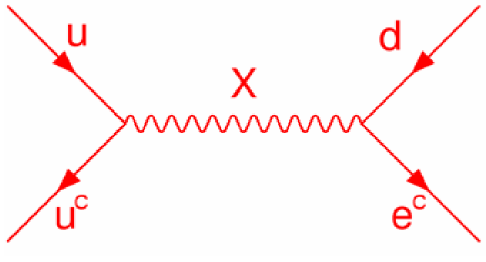
Figure: Intensity Frontier Report, 2011

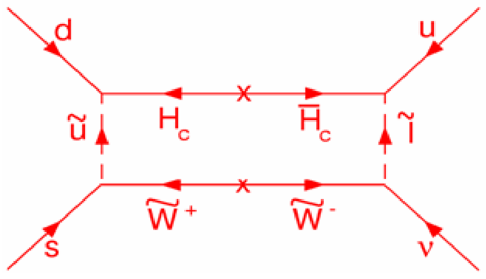
GUTs: What's Next

- Physical scales involved in GUTs are probably too high for a precise, definitive experimental proof of this paradigm
- Instead, proceed by collecting low-energy hints ("echoes"), and gradually building up confidence
- Neutrino mass/CP measurements cannot, in my opinion, make a significant impact on the overall case for GUTs, though they may help those who already believe in it to refine their models
- A striking, generic, not-yet-confirmed prediction of GUTs is violation of baryon and lepton number
- If either is observed, the case for GUTs would receive another major boost

B Violation: Proton Decay

- Theoretical predictions highly uncertain: both operators and scales are model-dependent





- But: Dim-6 operator gives

$$\tau \sim \left(\frac{\Lambda}{10^{16}\ \text{GeV}}\right)^4 \times 10^{34}\ \text{yrs}$$

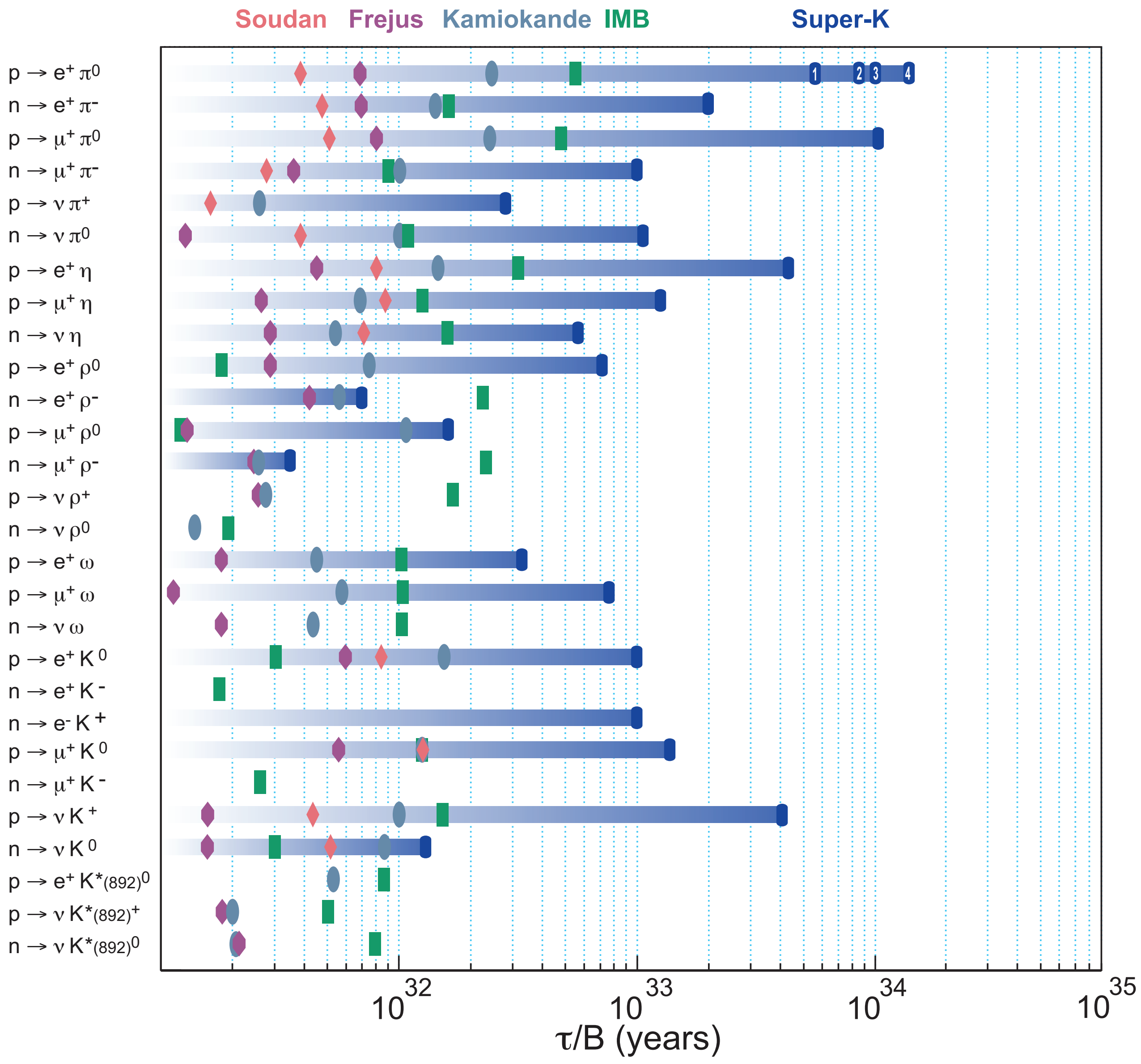
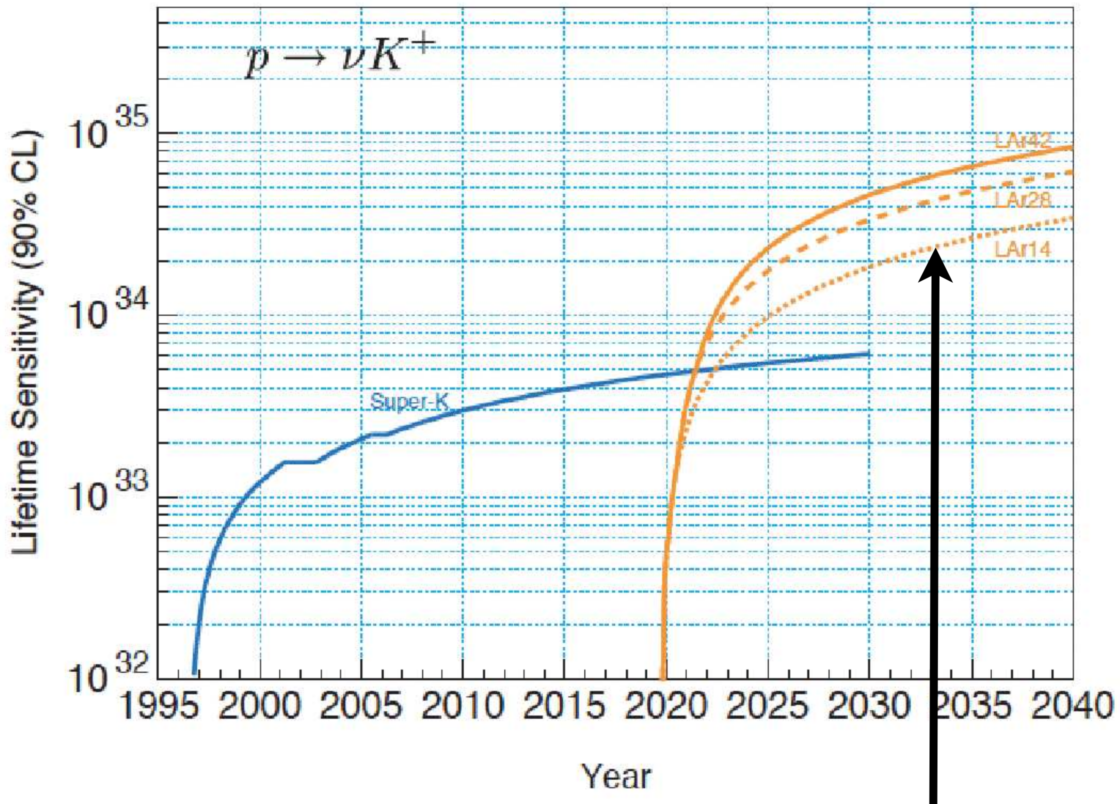
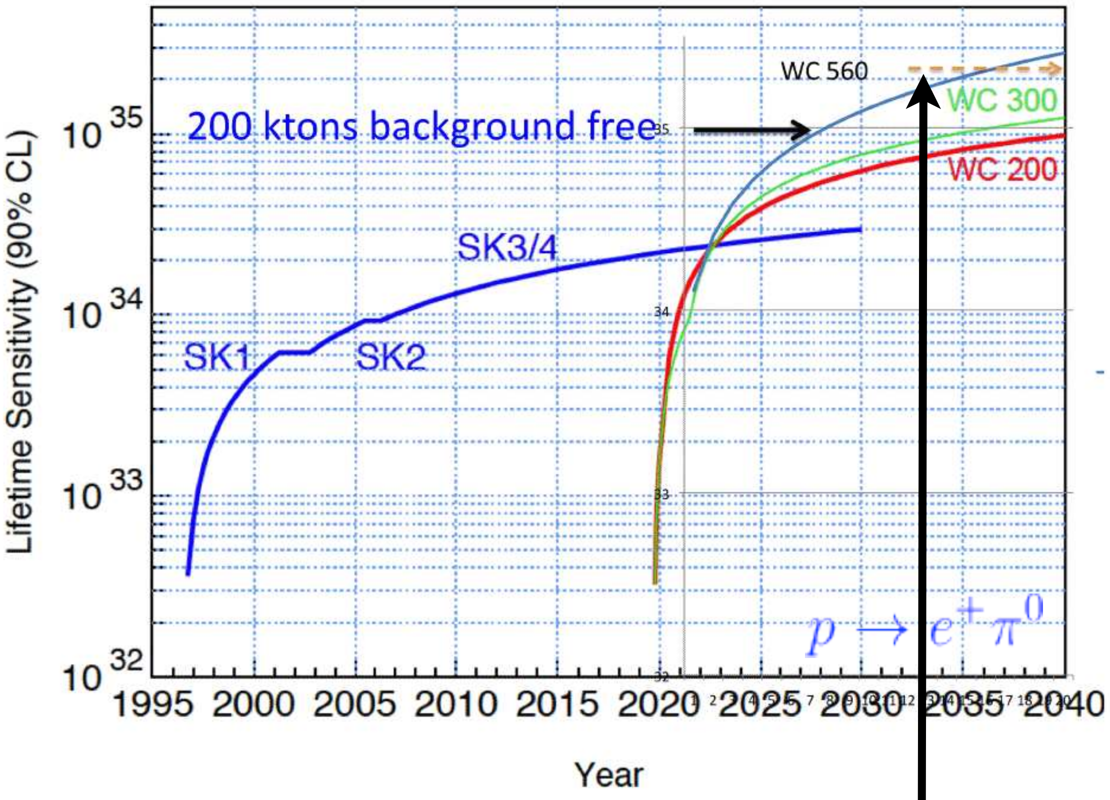


Figure: Intensity Frontier Report, 2011

Proton Decay Future





LBNE @
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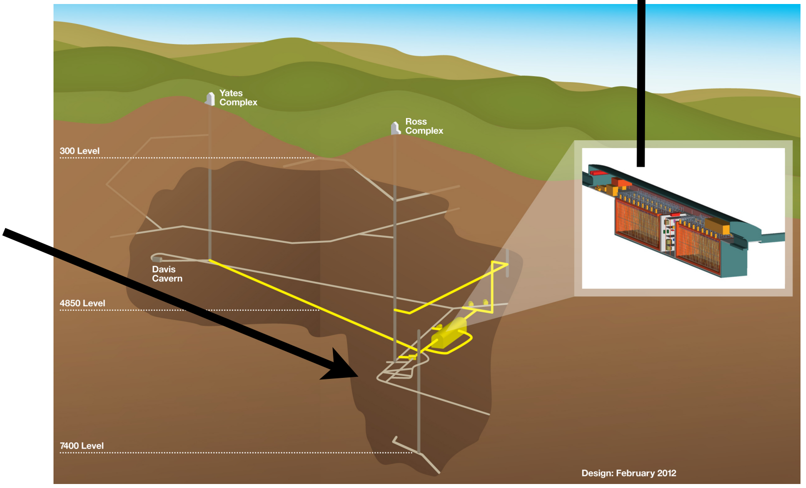
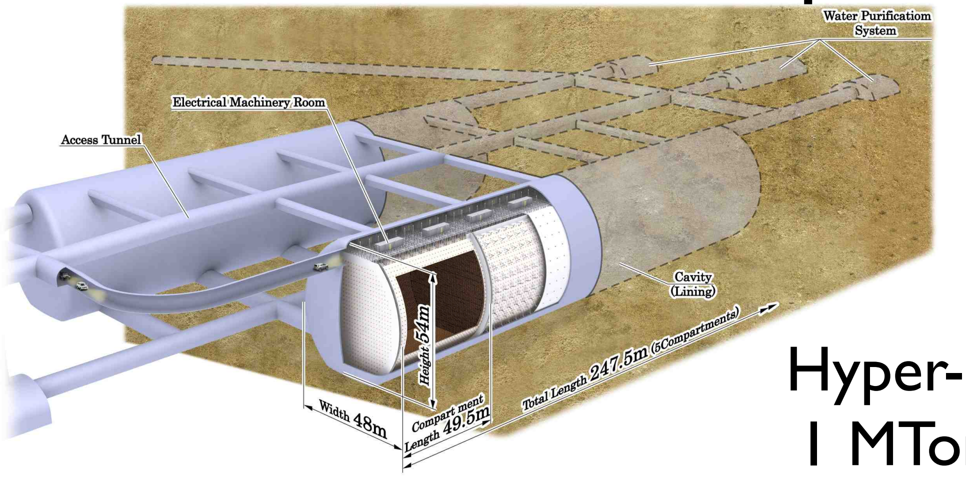




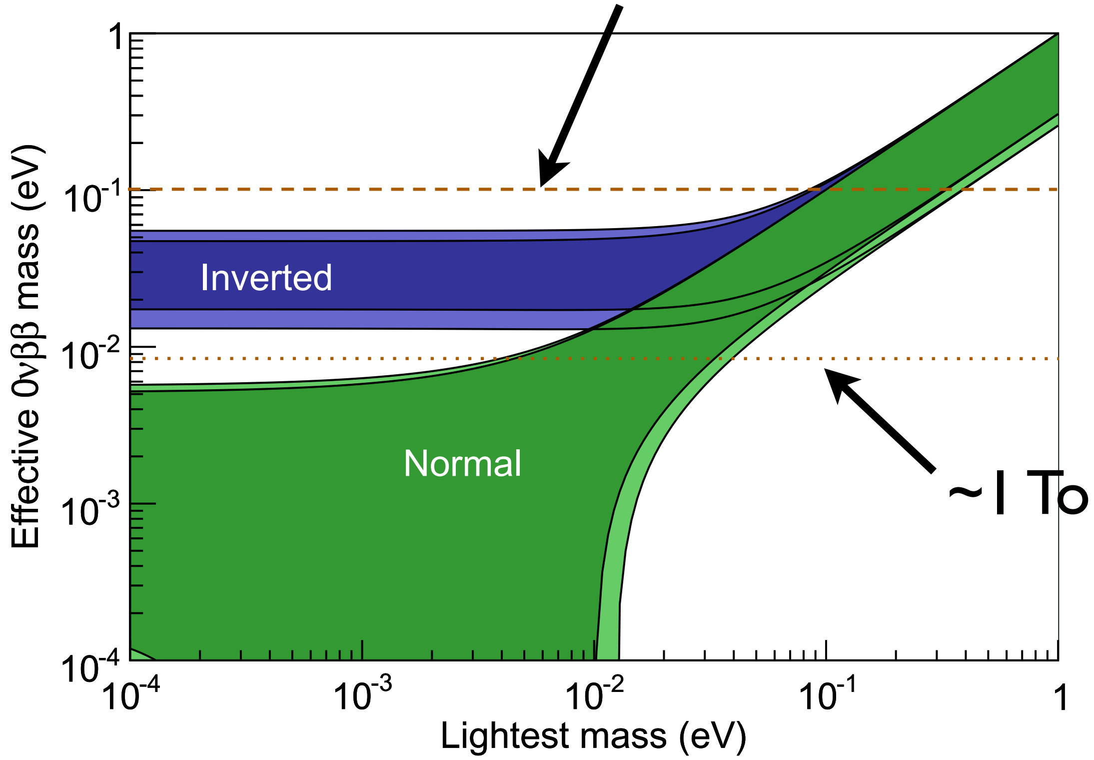
Hyper-K
1 MTon

Real chance (though no guarantee) of discovery!

L Violation: Neutrino-less Double Beta Decay

- If neutrino masses are indeed from unification/see-saw, they are Majorana and so, L-violating
- Fairly robust predictions for the rate of $0\nu\beta\beta$
- If inverted mass hierarchy, good chance of discovery in the conceivable future

~100 kg: CUORE, EXO-200, MAJORANA, SNO+, ...



~1 Ton

Figure: Intensity Frontier Report, 2011

GUTs: What's at Stake

- Observation of B or L violation would make the case for GUTs overwhelming
- Even in an unnatural universe, I would bet on grand unification
- I would not bet on discovery on the relevant time scale, but the odds look decent
- In general, lack of discovery at this point would not have strong implications due to strong uncertainties in theoretical predictions
- However, if it turns out that neutrino mass hierarchy is inverted, neutrino-less double beta decay will provide a very robust test of L in a not-too-far-distant future

Summary

- In this talk, I shared my views about some of the important physics questions that may be addressed by experimental programs under discussion

- Probing naturalness of the electroweak scale seems to me the single most important issue on this list

- A combination of direct probes and precision Higgs physics offers an opportunity to settle this issue; huge impact on physics whichever way it goes

- I hope that the US community will have an opportunity to make a major contribution to this quest

- Wait, that's not all...

Visions for Snowmass

Love Fest?

戰國時代 (The Warring States)?

Symposium

What we do best: Free and honest discussion of physics

Thanks to KITP and the Workshop Organizers!