Introduction: SUSY with 5 fb-1 at the LHC

Maxim Perelstein, LEPP/Cornell University

May 2, 2012, BNL

Cornell University
Laboratory for Elementary-Particle Physics

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No Evidence For Supersymmetry Has Been Discovered in the 2011 LHC Data

Questions for the Workshop

- Do we still think SUSY is a good candidate for TeV-scale physics?

(My personal opinion: Yes, I do. In fact my assessment of likelihood of TeV SUSY has not changed that much in 2011)

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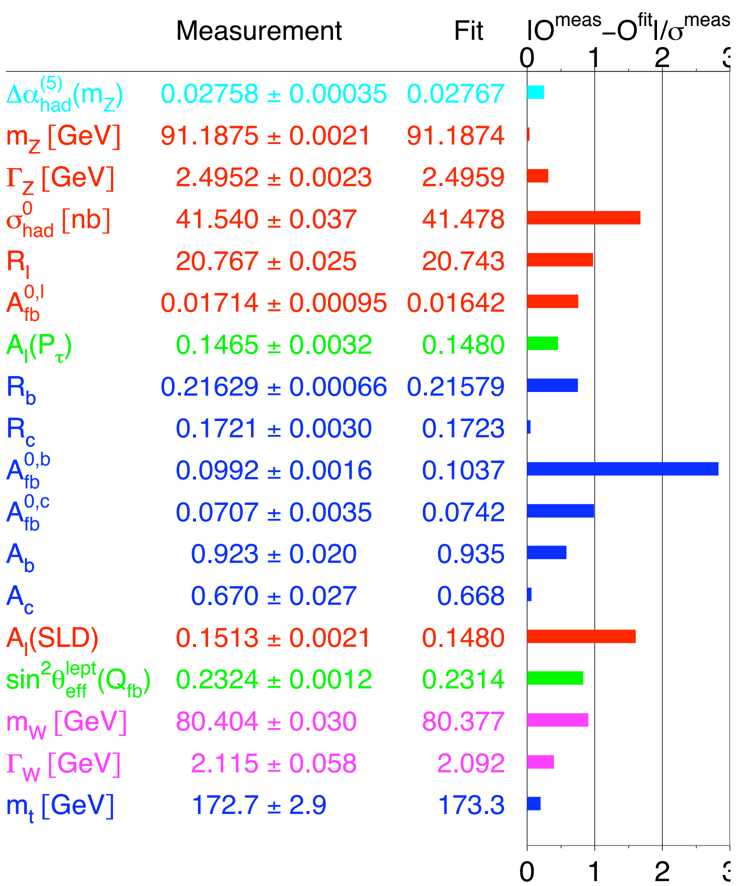
- How did 2011 data affect our ideas about how exactly SUSY might be realized?
- How should SUSY search strategies at the LHC be affected by these new ideas?

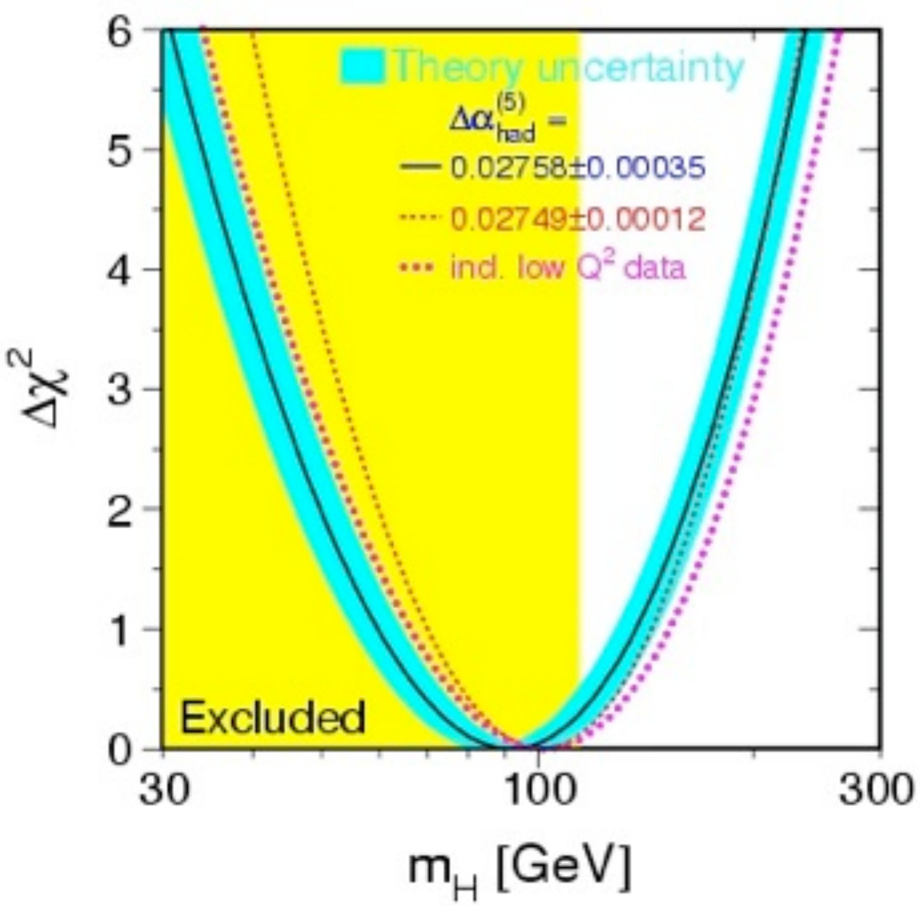
Central Question since ~1980
Electroweak Symmetry Breaking: Strong or Weak Coupling?

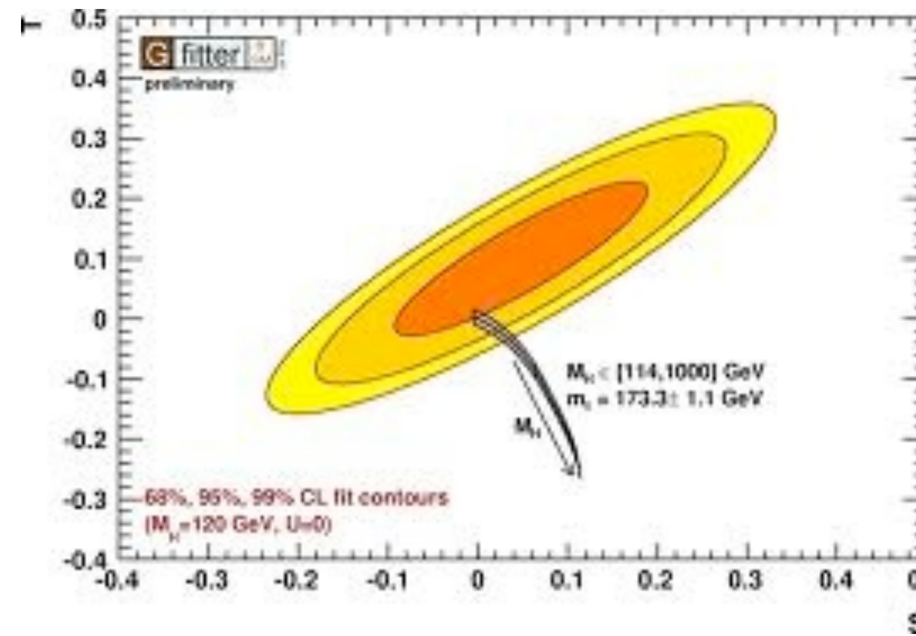
- Strong Coupling: fermion condensate breaks EW symmetry
- Just like in QCD, only higher scale ("technicolor")
- Dimensional transmutation - $M_Z \ll M_{\rm Pl}$ no more surprising than $\Lambda_{\rm QCD} \ll M_{\rm Pl}$

- Weak Coupling: a scalar field, the Higgs field, gets vev, breaks EW symmetry
- Calculable and testable: new spin-0 particle!
- Needs new physics at TeV to be natural, SUSY is the most elegant candidate

1990’s: Precision Electroweak Constraints

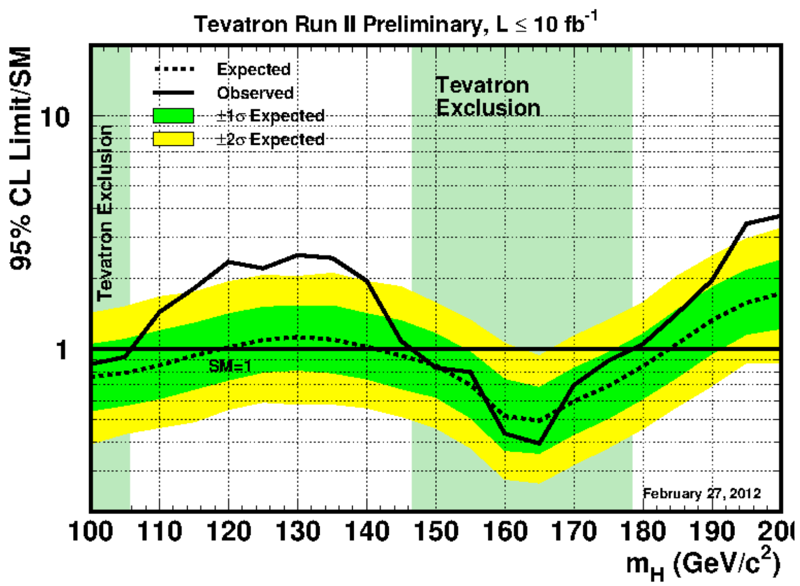


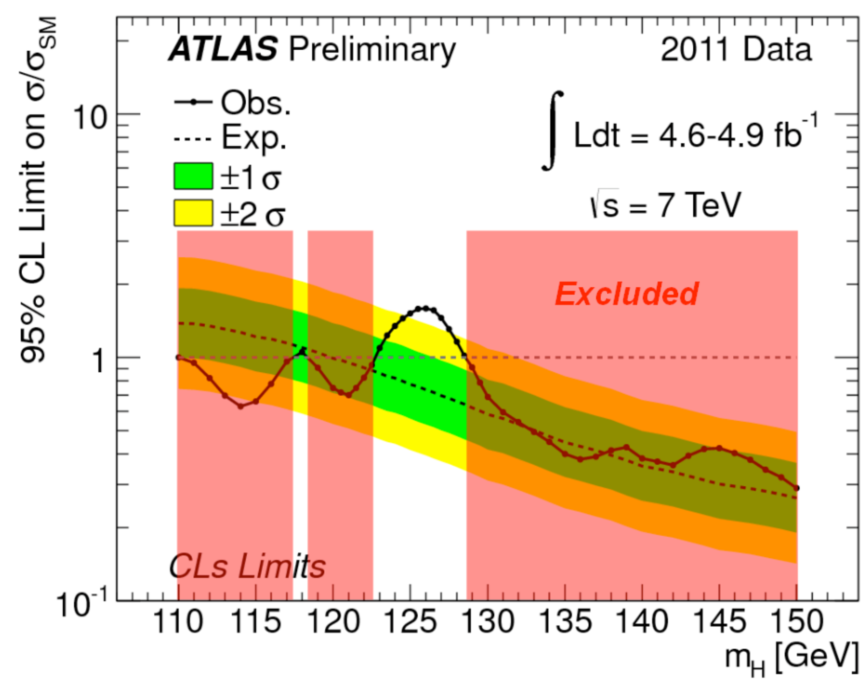




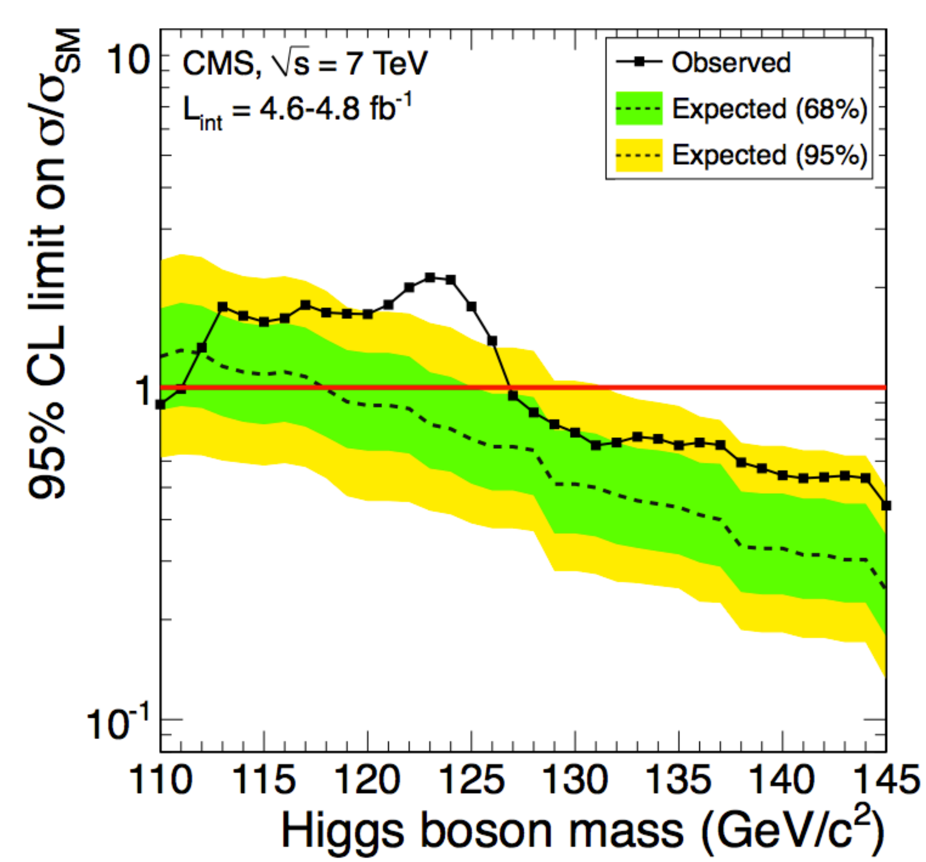
➡ strong hint for weakly-coupled EWSB, but with a caveat: new physics effects in loops might cancel

The Final Nail in the TechniCoffin?





Low mass region



Looks like a solid, direct hint for a new particle, consistent with a 125 GeV BFKAH*.

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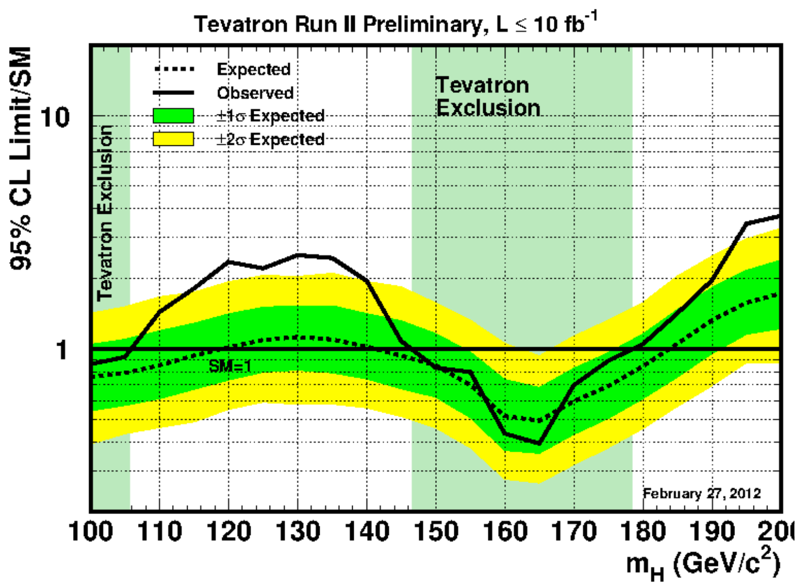

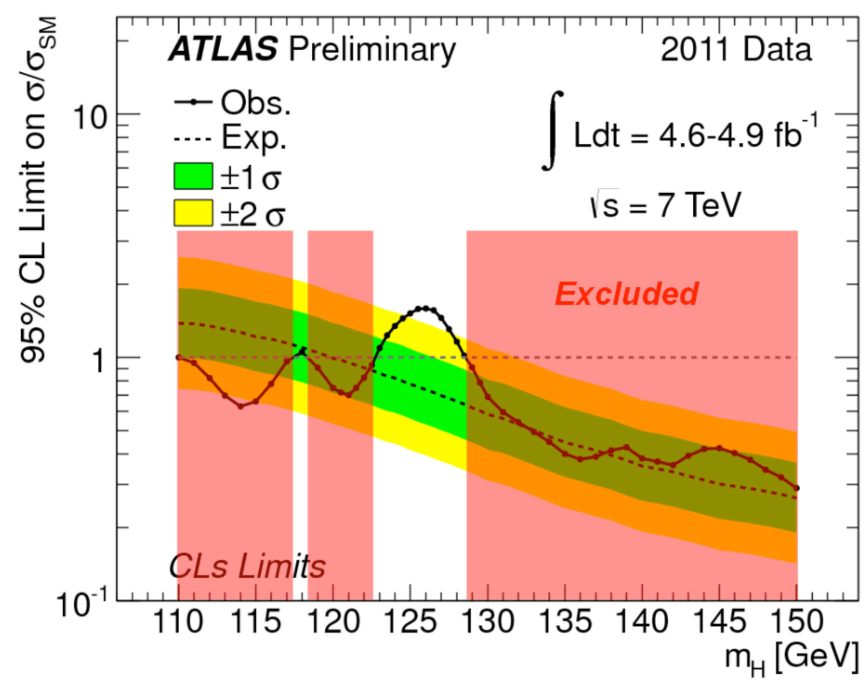

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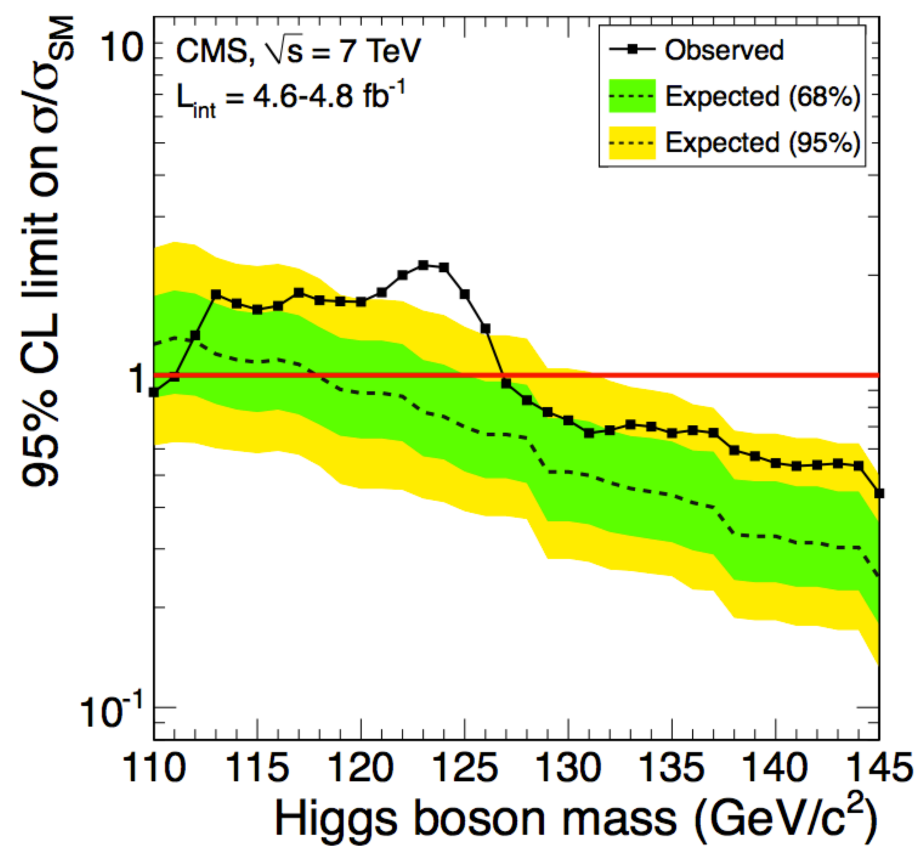

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* Boson Formerly Known As Higgs

SUSY and the 125 GeV Higgs

- Big picture: Light Higgs ➡ weakly-coupled EWSB ➡ hierarchy problem ➡ TeV-scale SUSY is by far the most elegant solution ➡ SUSY seems very likely!

- But, there are some unsettling details

Minimal Supersymmetric Standard Model (MSSM)

- Promote each SM field to a superfield + 1 extra Higgs doublet (needed for holomorphic masses, anomaly cancellation)
- Write most general superpotential + soft SUSY-breaking terms, imposing R-parity to avoid rapid proton decay (>100 new free parameters)
- FCNC and CPV constraints ⇨ same soft masses for 1st and 2nd generations, no new phases ⇨ pMSSM (20 free parameters)

MSSM and the Higgs Mass

- In spite of this huge parameter space, MSSM is more predictive than the SM on the Higgs mass
- Reason: in the SM $V = -\frac{\mu^2}{2}h^2 + \frac{\lambda}{4}h^4$ $m_h = \sqrt{2\lambda}v$

free parameter!

- In the MSSM $\lambda = \frac{1}{8}(g^2 + g'^2)$ (D-terms only!)
- Firm upper bound: $m_h \leq M_Z$
- However, this prediction has been falsified by LEP-2 more than 10 years ago! ($m_h \geq 114\ \mathrm{GeV}$)

Loops to the Rescue!

- "Loop-hole": the upper bound is tree-level, loop corrections can increase the Higgs mass

- However, there is a price to pay: Fine-Tuning!

- EWSB in the MSSM:

$$m_Z^2 = -M_{H_u}^2(1-\sec 2\beta) - M_{H_d}^2(1+\sec 2\beta) - 2|\mu|^2$$

- If $|M_{H_u}^2| \gg M_Z^2$, need terms on the RHS to cancel precisely: fine-tuning!

- Problem: same loops that raise m_h also raise $|M_{H_u}^2|$

Aside: On Fine-Tuning

- Definition of fine-tuning: $A = B - C$ FT if $B \gg A$

  Observable

  Contributions of different physical origin

- A clever model may correlate B and C in just the right way; "Presumption of Guilt" is a good start

- Other definitions (e.g. sensitivity to parameters) agree in most cases, though care is needed

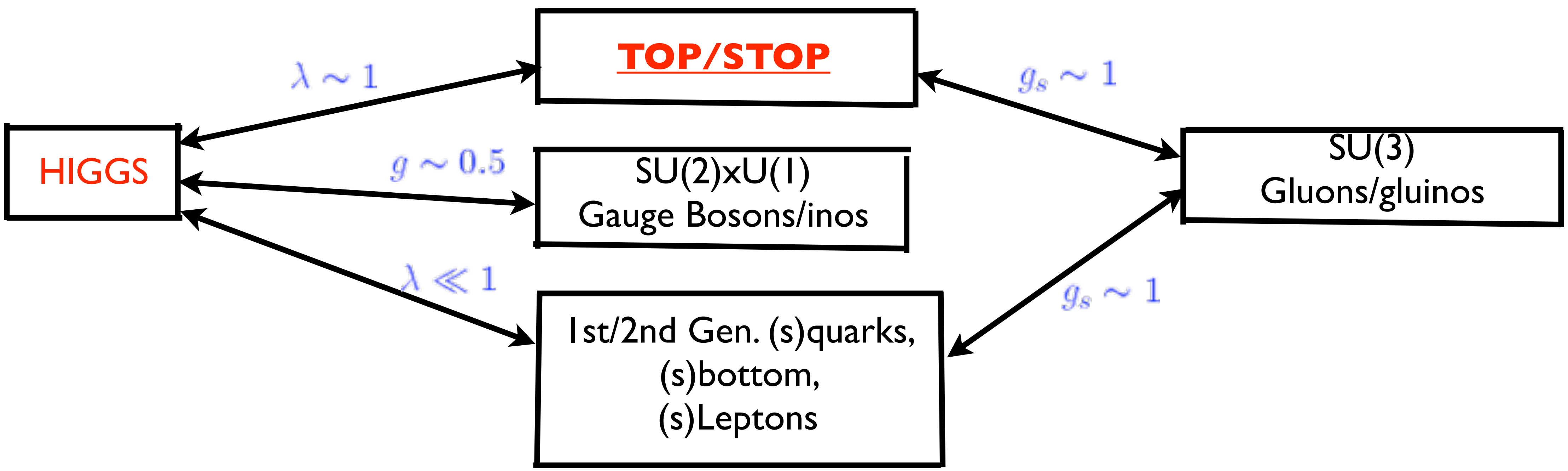
- Different definitions may give numbers differing by order-one factors, but not order-ten

- Imperfect, but it is the only meaningful metric to impose on SUSY parameter space

Higgs and Top, Alone Together

- Higgs physics in the MSSM is to a good degree independent of most of the >100 parameters

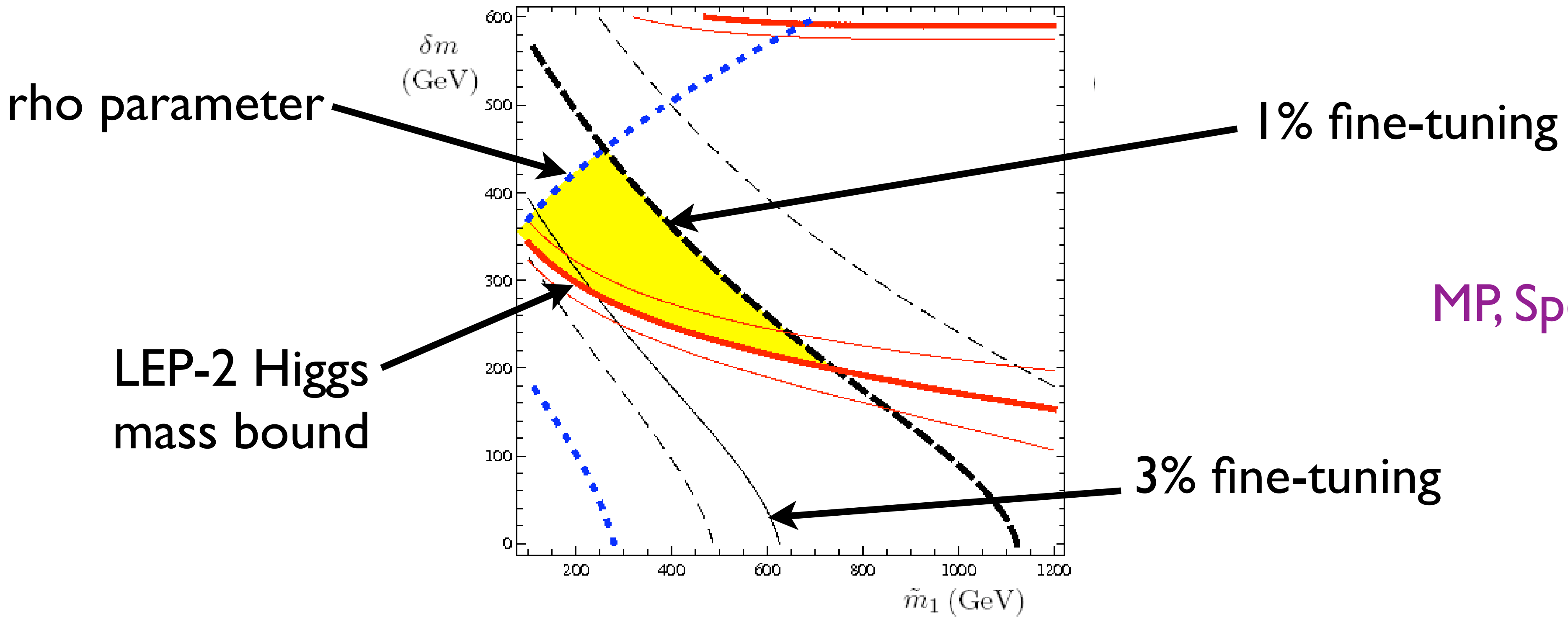
- Higgs couples weakly, or not at all, to most SM fields



- So, a decent approximation is just consider Higgs +top alone ⇨ few parameters, can build intuition

The Little Hierarchy Problem...

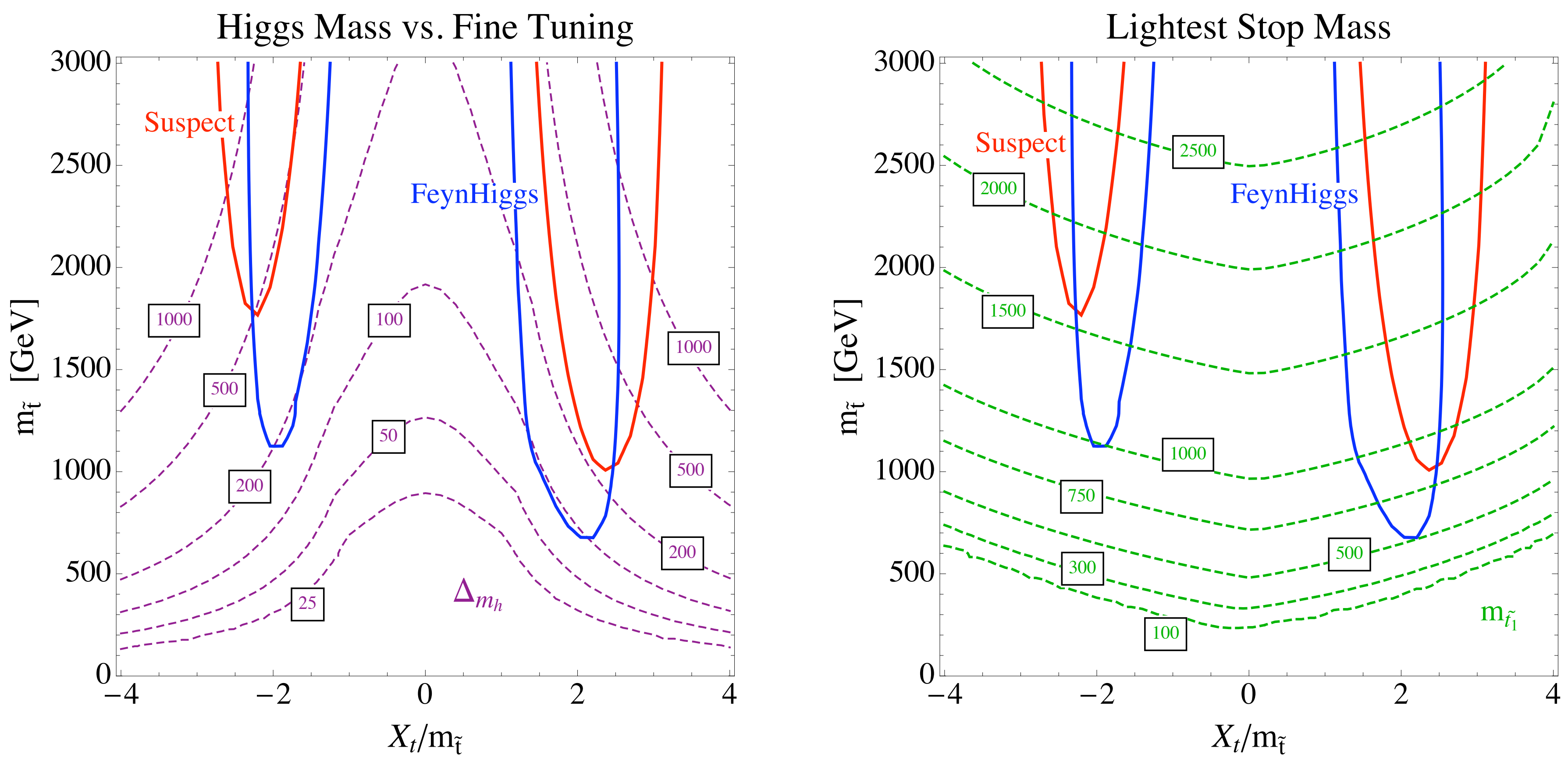
- Three soft parameters in the top sector: $m^2_{Q_3}, m^2_{u_3}, A_t$
- One-loop corrections to both m_h and $|M^2_{H_u}|$ are proportional to linear combs. of these (*logs)



[Figure:
MP, Spethmann, '07]

- A few % tuning at least is required for >114 GeV ("SUSY little hierarchy problem", a.k.a. "the LEP Paradox")

... Just Got a Little Bigger!



[Hall, Pinner, Ruderman, 1112.2703]

- With a 125 GeV Higgs, minimal fine-tuning in the MSSM is 1%
- Minimal stop mass is about 500 GeV

Beyond the Minimal: Next-to-MSSM

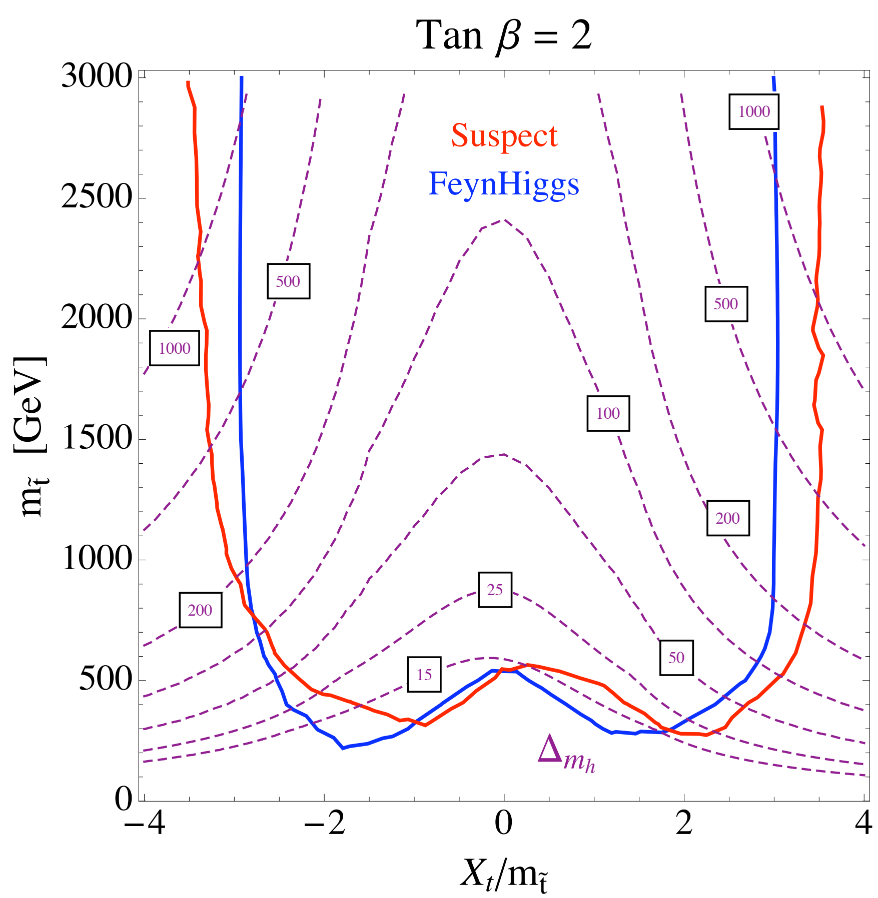
- Need to change the tree-level prediction for the Higgs mass
- Simple idea: add a singlet field S , coupled via $W = \lambda S H_u H_d$
- Tree-level expression for the (~SM) Higgs mass:

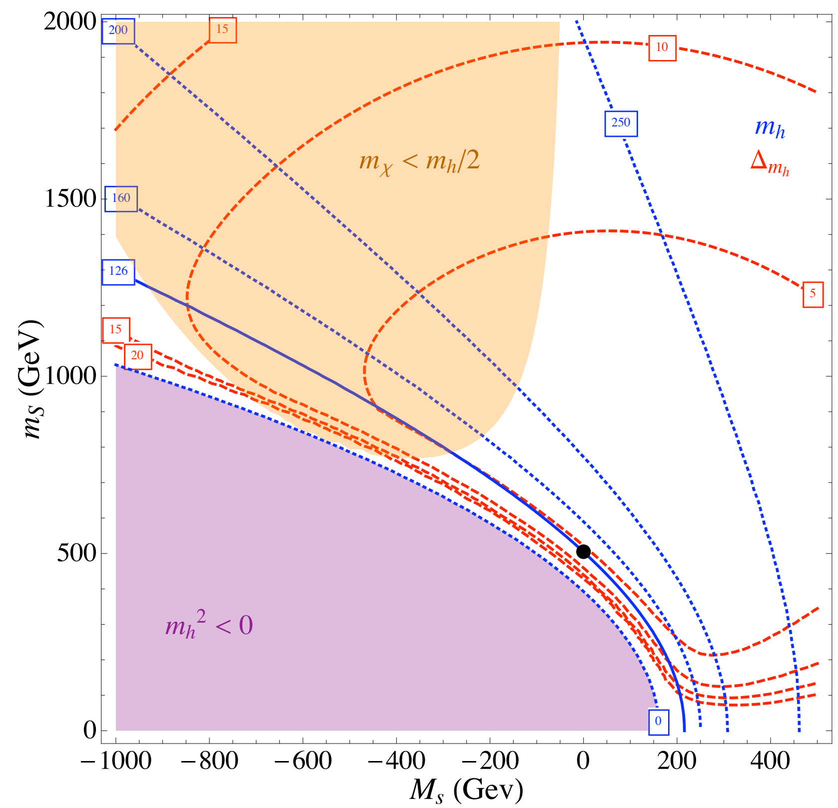
$$m_h^2 = m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta$$

- Problem: λ runs, gets stronger at higher scales, hits a Landau pole
- No L.p. up to $M_{\rm GUT}$ ➡ $\lambda \leq 0.8$; up to $10\ \mathrm{TeV}$ ➡ $\lambda \leq 2.0$

  "$\lambda - \mathrm{SUSY}$"

NMSSM Is Less Tuned





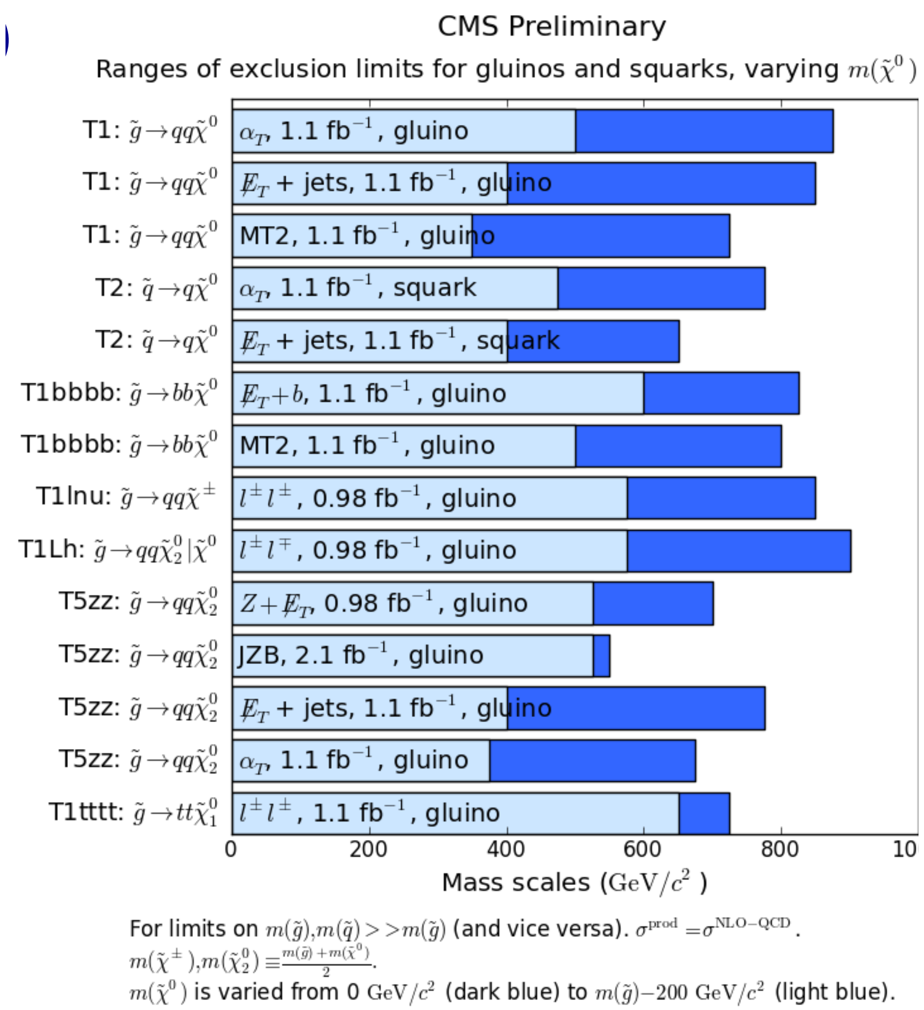
Tuning ~ 10% $\lambda = 0.7$

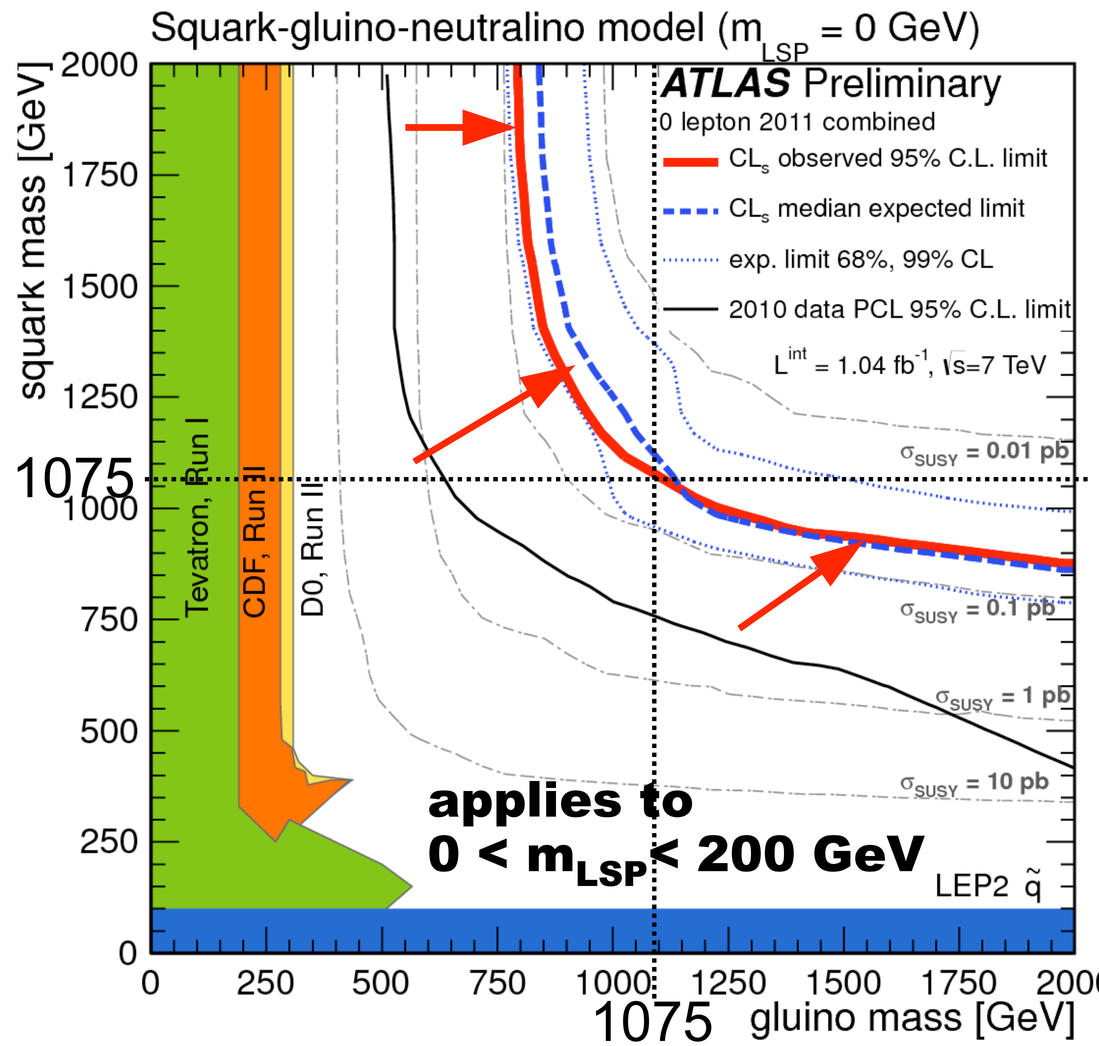
Tuning ~ 20% $\lambda = 2.0$

[Hall, Pinner, Ruderman, 1112.2703]

What About Superpartners?

1 fb^{-1} summary





Bottom line: gluino/squark mass bounds are above 1 TeV

Is Supersymmetry in Trouble?

- Higgs mass parameter renormalization:

$$-\mu^2 = -\mu^2_{\text{tree}} + \frac{c^2}{16\pi^2}\Lambda^2 + \ldots$$

- Two possibilities:
    - "Natural" Higgs with New Physics (e.g. SUSY) at $\Lambda < 4\pi\mu \approx 1\ \text{TeV}$
    - "Fine-Tuned Higgs" with $\Lambda > 1\ \text{TeV}$ and precise cancellation between the tree and loop terms
- Superpatrner mass scale plays the role of the scale Λ
- Is SUSY already being pushed from "natural" into "fine-tuned" territory?

BBC NEWS

SCIENCE & ENVIRONMENT

27 August 2011 Last updated at 02:41 ET

LHC results put supersymmetry theory 'on the spot'

By Pallab Ghosh
Science correspondent, BBC News

Results from the Large Hadron Collider (LHC) have all but killed the simplest version of an enticing theory of sub-atomic physics.

Researchers failed to find evidence of so-called "supersymmetric" particles, which many physicists had hoped would plug holes in the current theory.

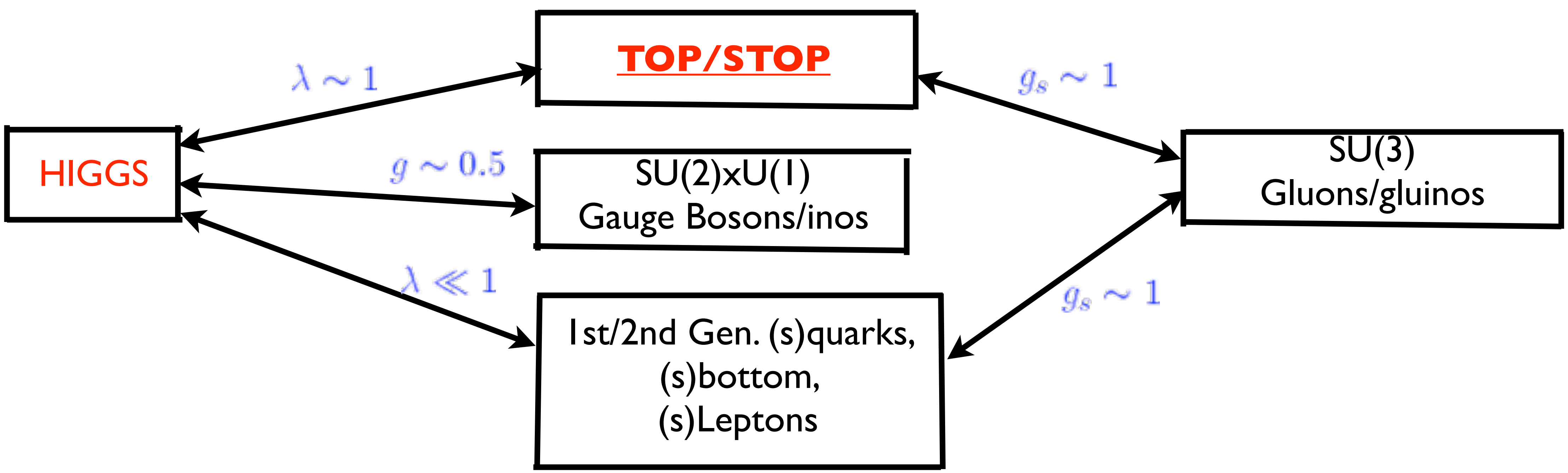
But Wait a Second...

- This argument is a bit too fast!

$$-\mu^2 = -\mu^2_{\rm tree} + \frac{c^2}{16\pi^2}\Lambda^2 + \ldots \qquad\qquad c = \kappa_X^2 N_X$$

- κ_X = Higgs-X coupling constant, N_X = # of d.o.f. in X

- Recall: Most SM fields couple only weakly, or not at all, to the Higgs!



- The real "one-loop naturalness upper bound" on the mass of SUSY partner of particle X is not 1 TeV, but

$$\frac{1\ \mathrm{TeV}}{c_X^2}$$

- For 1st, 2nd gen. squarks, sbottom, sleptons, this bound is 10 TeV or more.

- For stop, it's in fact lower: $c_t = 6\lambda_t^2 \approx 6 \Rightarrow m_t < 400\ \mathrm{GeV}$ is required for (complete) naturalness

- NB: since left-handed top and bottom are in the same SU(2) doublet, their superpartners must be close in mass $\Rightarrow$ one light bottom is required.

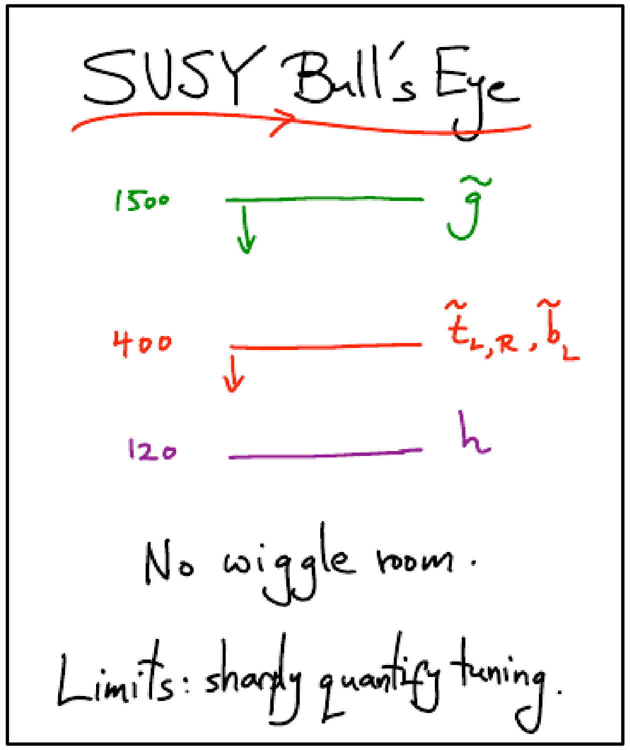
- There's no one-loop upper bound on gluino mass: $c_g = 0$

- However two-loop naturalness requires $m_g < 2m_t$ (Majorana gluinos)

  $m_g < 4m_t$ (Dirac gluinos)

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

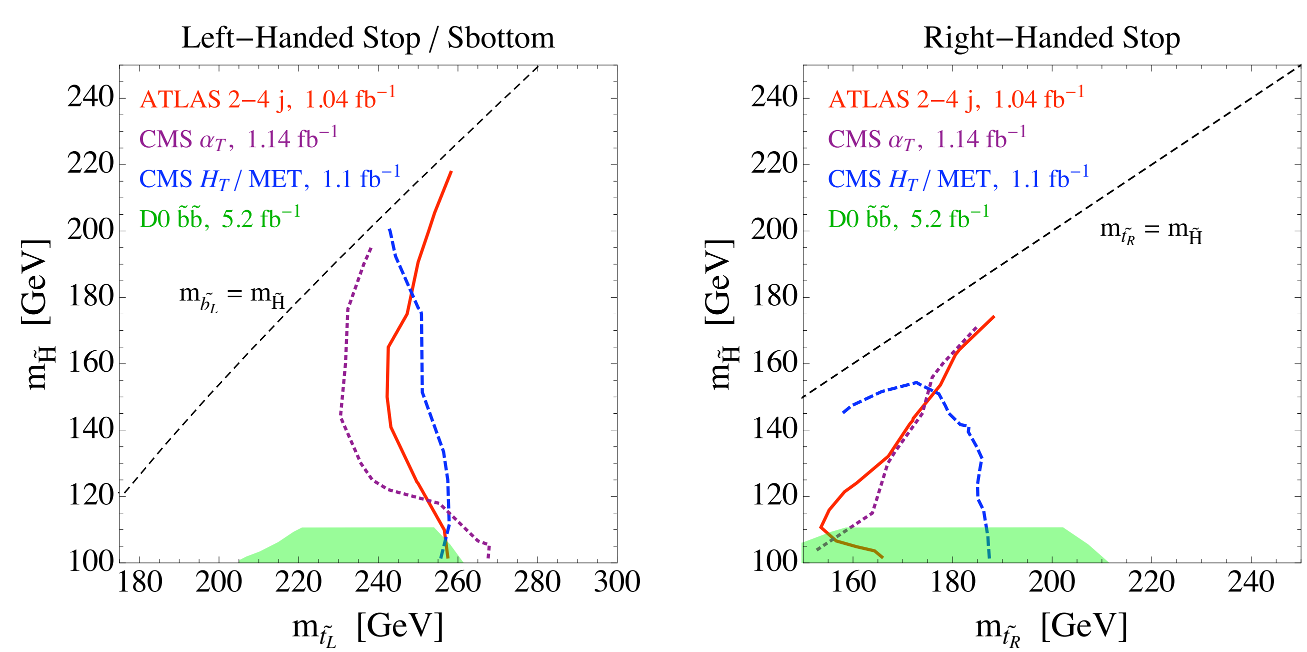
SUSY In the Era of Austerity

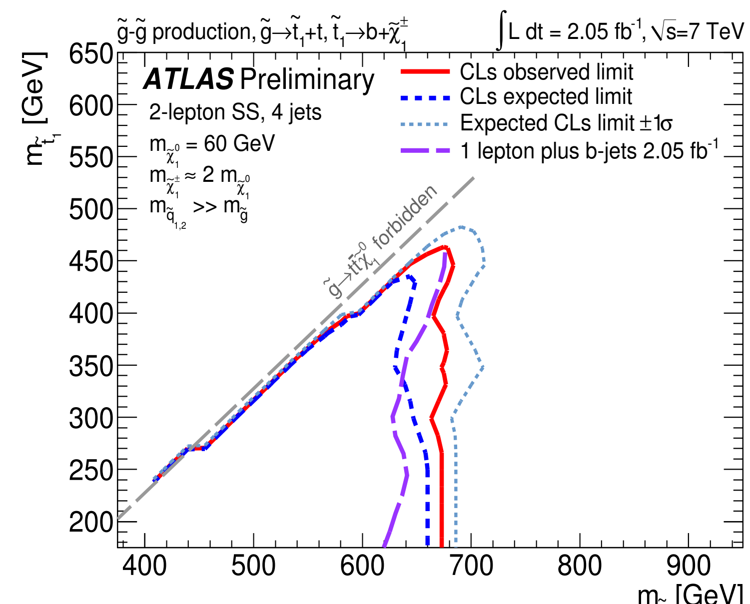


Arkani-Hamed - LPCC workshop 10/31/2011

- "Ascetic" SUSY spectrum is completely consistent with the 5 fb-1 constraints, and helps with SUSY flavor problem

[Cohen, Kaplan, Nelson, '95]





$\tilde{g}\tilde{g} \to \tilde{t}\tilde{t}\tilde{t}\tilde{t} \to tb\chi^{\pm}tb\chi^{\pm}$

Ascetic-SUSY Search Example: Boosted Tops from Gluino Decays

[Berger, MP, Saelim, Spray, '11]

- Most gluinos decay via tops:

$$\tilde{g} \to t + \tilde{t}, \quad \tilde{t} \to t + \tilde{\chi}^0$$

- For typical allowed parameters, most tops are relativistic: e.g.

$$m_{\tilde{g}} = 800 \text{ GeV}, \quad m_{\tilde{t}} = 400 \text{ GeV}$$

$\Rightarrow$ $\gamma_t \approx 1.8$ (in gluino rest frame)

- Hadronic top decays $\Rightarrow$ top jets!

- Use recently developed top-jet tagging capabilities, search for events with top-jets+MET

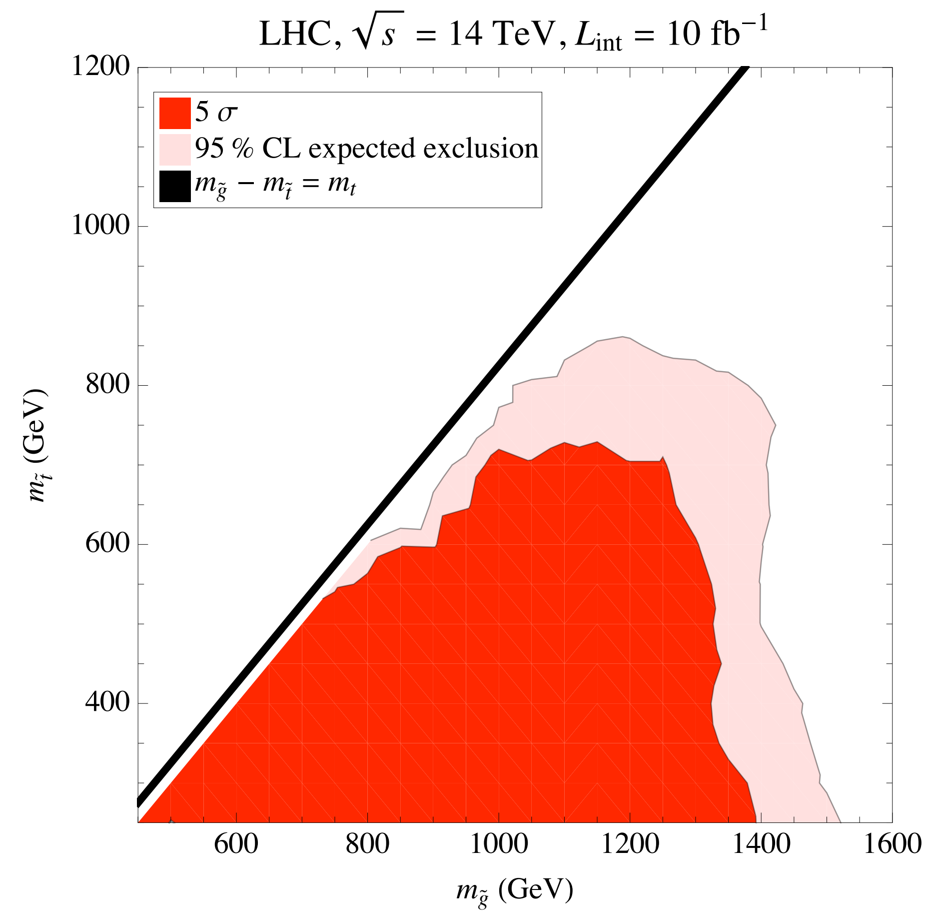


FIG. 3: The 95% c.l. expected exclusion and 5-sigma discovery reach of the proposed search at the 14 TeV LHC run with 10 fb^{-1} integrated luminosity.

Errors Stat.-only; S/B>10 everywhere

Impact on Models of SUSY-Breaking

- So far, all discussion was in the context of the MSSM (>100 par.) or pMSSM (20 par.): all soft SUSY-breaking terms treated as free parameters

- Deeper theory: understand how SUSY is broken, "predict" soft terms (or at least reduce the number of parameters)

- Modular structure

- NO UNIQUE "BEST" MODEL (despite > 20 yrs of trying). Some ideas:

  - Gravity mediation: $M_{\rm soft}(Spin) \Rightarrow M_{\rm soft}(\tilde{t}) = M_{\rm soft}(\tilde{c}, \tilde{u})$

  - Gauge mediation: $M_{\rm soft}(g_3, g, g') \Rightarrow M_{\rm soft}(\tilde{t}) = M_{\rm soft}(\tilde{c}, \tilde{u})$

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TOO SIMPLE?

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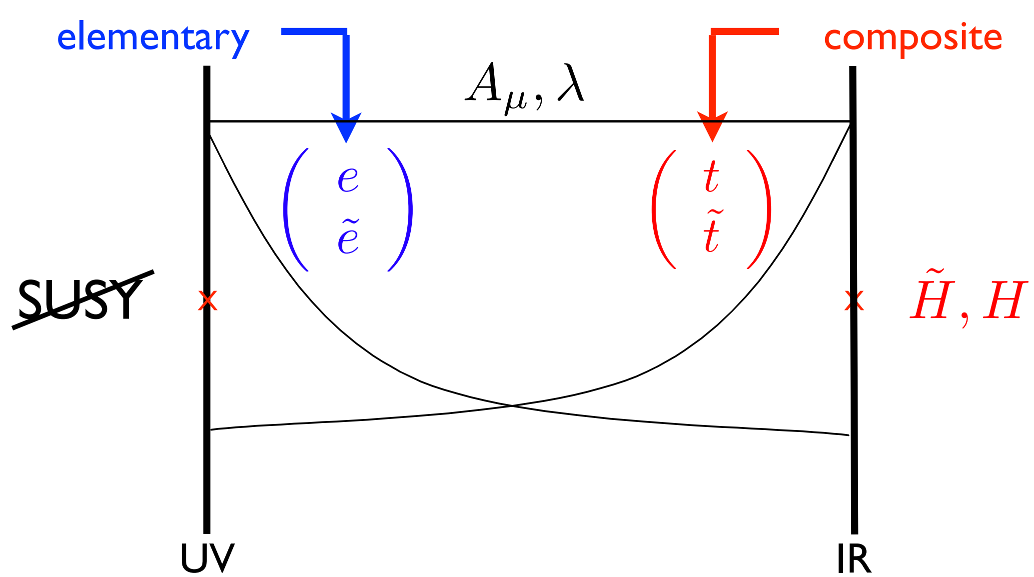
Generating Ascetic SUSY

- Basic point: 3rd generation of quarks already looks special, why not 3rd generation of squarks?

- A Warped 5D example: "Accidental SUSY" [Gherghetta, Pomarol, '03]

SUSY broken at UV scale



bulk mass parameter

$$\begin{pmatrix} \psi \\ \tilde{\phi} \end{pmatrix} \propto e^{(\frac{1}{2}-c)ky}$$

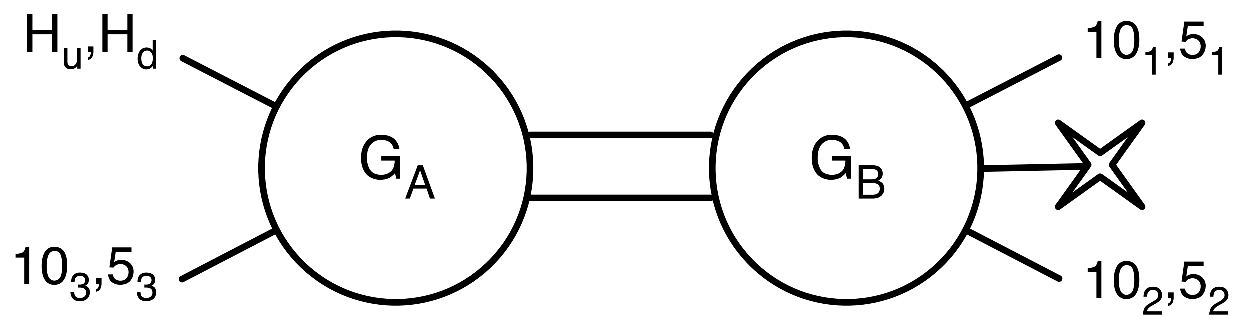
Fermion mass spectrum determines sparticle spectrum!

Low-energy SUSY spectrum $\quad \tilde{t}, \tilde{H} \qquad (\tilde{f}_{1,2}, \lambda \quad \text{decouple})$

KK spectrum $\quad m_f^{(n)} \simeq m_{\tilde{f}}^{(n)} \qquad n = 1, 2, \ldots$

Generating Ascetic SUSY

- Don't like 5D? Use AdS/CFT to construct a 4D dual - composite 3rd generation! [Csaki, Randall, Terning, '11]
- Or, just plain old deconstruction



[Craig, Green, Katz, '11]

[Craig, Dimopoulos, Gherghetta, '12]

Super-Ascetic Supersymmetry?

- Recall: To lower fine-tuning needed to get a 125 GeV Higgs, extend MSSM to NMSSM with large λ : say $\lambda = 2$ (λ-SUSY)

- The old EWSB formula still works:

$$m_Z^2 = -M_{H_u}^2(1 - \sec 2\beta) - M_{H_d}^2(1 + \sec 2\beta) - 2|\mu|^2$$

- But now μ is not an input parameter, but a vev of the singlet field S ⇨ need to solve for it!

- When expressed in terms of Lagrangian parameters, $m_Z^2 \propto \left(\frac{g^2}{\lambda^2}\right) m_{H_u}^2 + \ldots$

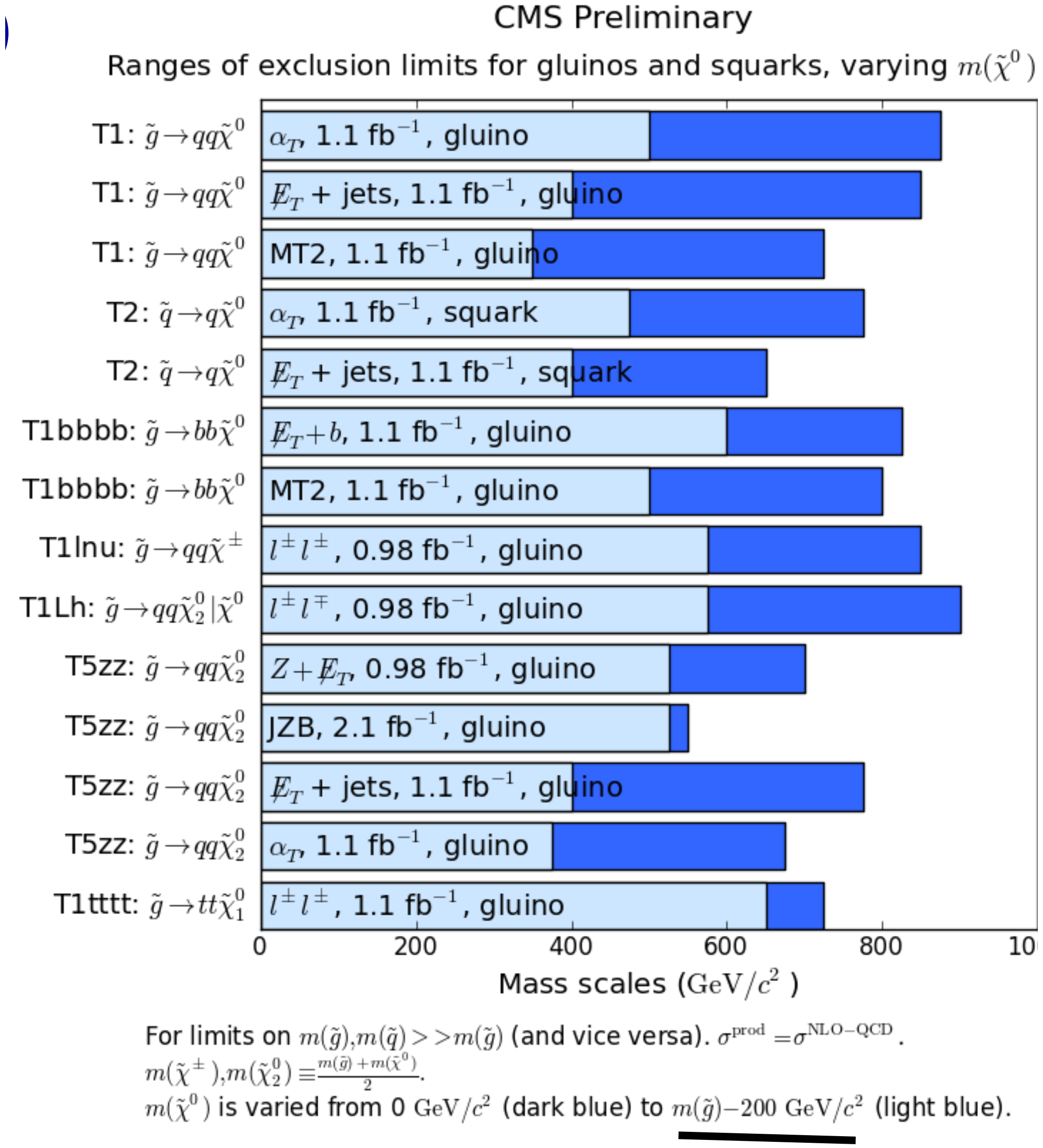
- Tuning suppressed by $\frac{g^2}{\lambda^2} \sim 0.1$, stop bound raised from 400 GeV to 1.2 TeV!

- So, NO colored superpartners below TeV are required for naturalness!

Low-MET ("Stealthy") SUSY

- Experiments place significant MET cuts to suppress SM backgrounds
- In SUSY events with X production, $\mathrm{MET} \propto M_X - M_{\mathrm{LSP}}$
- For example: no bound on gluino from MET+jets if $M_{\mathrm{LSP}} > 250\ \mathrm{GeV}$
- No strong degeneracies in the spectrum are required - pretty generic possibility, not a "hole"!
- Very important to explore this region: lower MET cuts? ISR tagging?

1 fb^{-1} summary



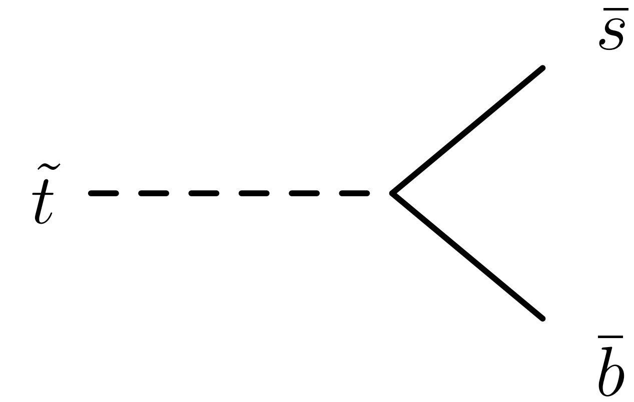
No-MET SUSY: Visible (N)LSP

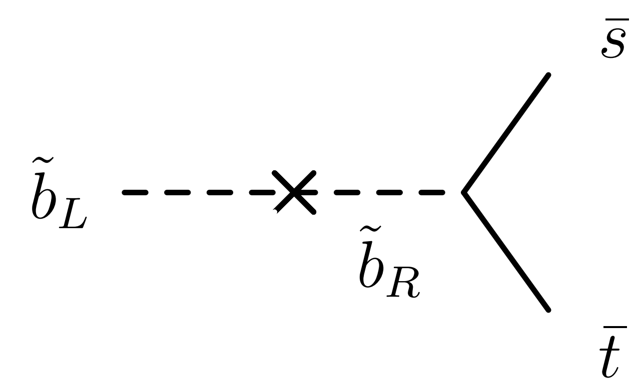
- In the MSSM, ANY superpartner can be the LSP: neutral LSP NOT predicted
- Motivation for neutralino LSP is cosmological: good dark matter candidate, strong bounds on electrically charged and colored relics
- However: many other good DM candidates (e.g. axion); charged/colored bounds rely on untested assumption of standard cosmology before BBN
- If LSP is gravitino, NLSP lifetime is basically a free parameter (with cosmological bound <1 sec)
- NLSP may travel and decay in any part of the detector, or outside
- SUSY searches for stable/quasi-stable charged/colored LSP are just as important as the standard MET searches, should be pursued with equal vigor!

[Example: Graham, Kaplan, Rajendran, Saraswat, '12]

No-MET SUSY: R-Parity Violation

- R-Parity is a discrete symmetry that's not required by SUSY, but imposed in most models to forbid operators leading to super-fast proton decay
- R-parity is responsible for stability of the LSP much of "SUSY phenomenology"
- There are OTHER WAYS to stop proton from decaying: e.g. impose lepton or baryon number conservation, or confine R-violation to 3rd generation
- Resulting theories have very long-lived proton but unstable LSP   no MET or stable exotics!
- Example: Approximate, accidental R-parity follows from minimal flavor violation hypothesis for the MSSM (which is needed anyway to avoid FCNCs)





[See the talk by Josh Berger tomorrow]

[Csaki, Grossman, Heidenreich'12]

CONCLUSIONS

- 2011: SUSY searches at the LHC have begun in earnest
- Possible Higgs discovery overall good news for SUSY
- 125 GeV Higgs requires 1% tuning in Minimal SUSY model ⇒ non-minimal scalar sector?
- Lack of superpartner discovery is not yet too worrisome: we're just getting started

CONCLUSIONS

- Several ways to accommodate current bounds, with no fine-tuning required:
    - Ascetic SUSY: minimal sub-TeV spectrum
    - Low-MET SUSY: modest spectrum degeneracy (~30% is sufficient)
    - No-MET SUSY: RPV or quasi-stable (N)LSP
- Not "holes": all are generic in MSSM (unless specific SUSY-breaking schemes are assumed)

Looking Forward to 2012

- Definitive data on the Higgs
- Dedicated ascetic SUSY search results (this Friday?)
- RPV/Quasi-stable NLSP searches?
- New data-driven theory ideas on SUSY breaking?

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SUSY DISCOVERY?