The Higgs Boson Discovery and the Road Ahead

James Wells
CERN & Univ of Michigan

Time & Matter Conference
Venice, 4-8 March 2013

HISTORICAL SLIDE – 2 YEARS OLD

Should we believe in the Higgs boson?

The Higgs boson is a speculative particle explanation for elementary particle masses.

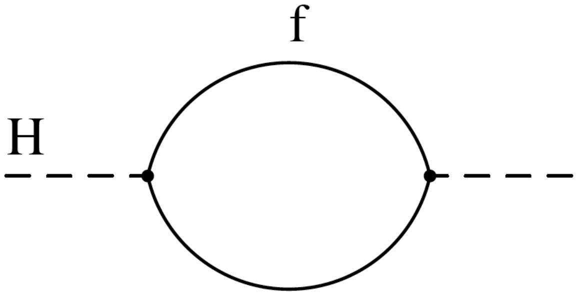
Cons:

1. One particle carries all burdens of mass generation?
2. Fundamental scalar not known in nature.
3. Hasn't been found yet.
4. Too simplistic -- dynamics for vev not built in.
5. Idea not stable to quantum corrections.

Pros: Still consistent with experimental facts!

Higgs boson unstable to QM

A quantum loop is quadratically divergent. Higgs mass, connected to Higgs vev, is unstable to the highest mass scales in the theory.



$$m_H^2 \sim \frac{\alpha_f}{4\pi}\Lambda^2 \quad \Rightarrow \quad \Lambda^2 \sim M_{Pl}^2\ ?$$

Confusing: M_{Pl} is 1,000,000,000,000,000,000 times more massive than hydrogen, whereas the Higgs boson is only 130 times more massive than hydrogen.

Cures of the Naturalness Problem, and the Resulting Higgs boson Entourage

1. Disallow all scalars in the theory (Technicolor).
2. Symmetry cancels quadratic divergences (supersymmetry)
3. Disallow higher mass scales (extra dimensions).

OLD SLIDE – 2 YEARS OLD

New Physics Ideas and Higgs boson viability

Trying to fix and understand Higgs physics leads to new ideas that have states that look very similar to the Standard Model Higgs boson.

Precision Electroweak Data almost demands this to be true.

What does the future hold for the Higgs boson?

DISCOVERY!!

What does "almost 'The' Standard Model Higgs boson" mean?

The boson has the same, measured mass of 126 GeV.

However, its production rates are slightly different, and its probabilities of decaying into various other particles are slightly different.

$$
\begin{aligned}
Br(H \to bb)_{SM} &= 60\% \\
Br(H \to WW)_{SM} &= 20\% \\
Br(H \to \tau\tau)_{SM} &= 6\% \\
Br(H \to \gamma\gamma)_{SM} &= 0.2\% \\
&\vdots
\end{aligned}
$$

$$
\begin{aligned}
Br(H \to bb) &= Br(H \to bb)_{SM}\,(1+\epsilon_b) \\
Br(H \to WW) &= Br(H \to WW)_{SM}\,(1+\epsilon_W) \\
Br(H \to \tau\tau) &= Br(H \to \tau\tau)_{SM}\,(1+\epsilon_\tau) \\
Br(H \to \gamma\gamma) &= Br(H \to \gamma\gamma)_{SM}\,(1+\epsilon_\gamma)
\end{aligned}
$$

The deviations from these e's may be only a few percent or less. Will take many years to be sensitive to that, and perhaps even requires another collider (e+e-).

Physicists Find Elusive Particle Seen as Key to Universe

Pool photo by Denis Balibouse

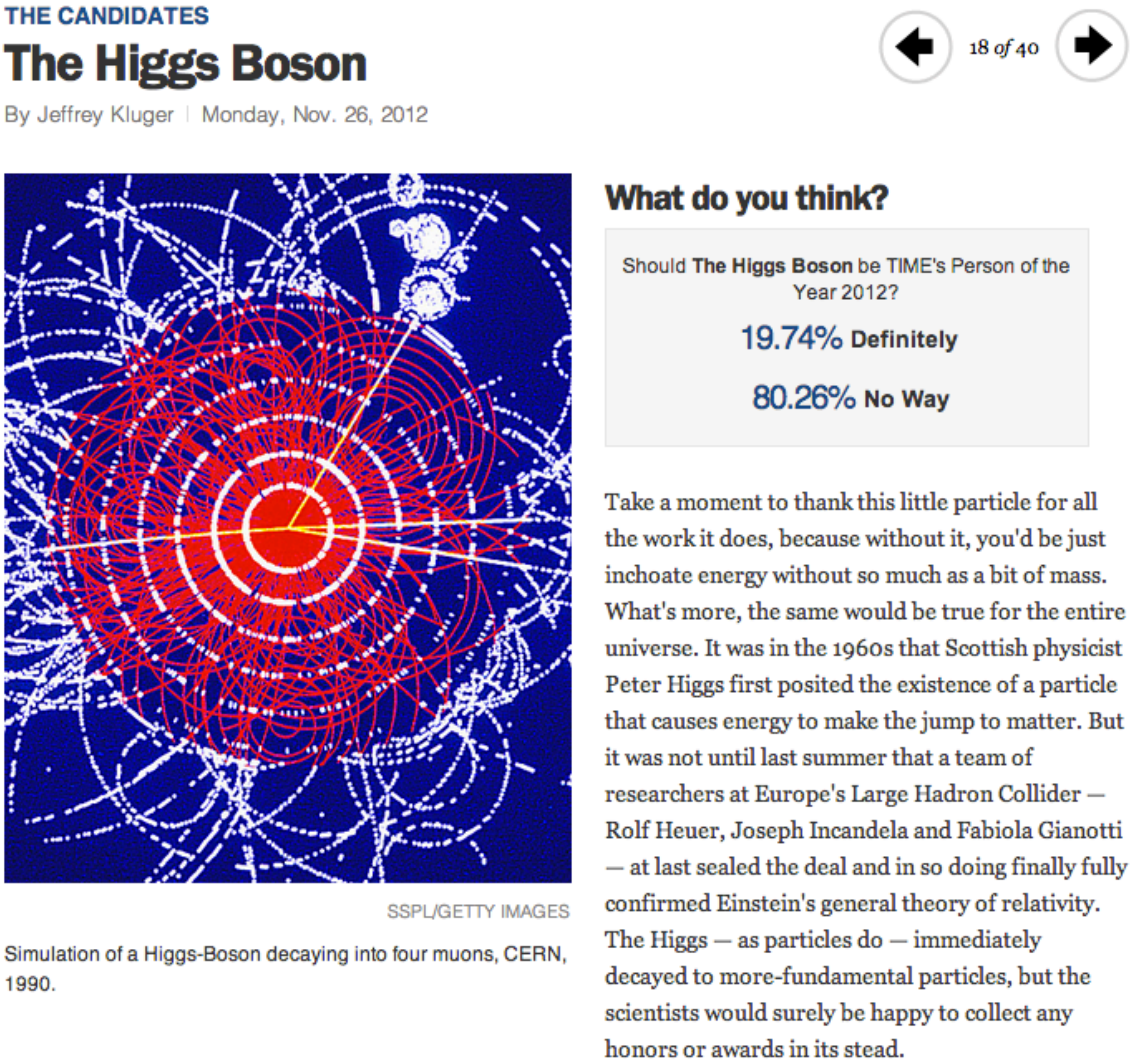
Scientists in Geneva on Wednesday applauded the discovery of a subatomic particle that looks like the Higgs boson.

By DENNIS OVERBYE

Published: July 4, 2012 | 122 Comments

mass = 134 x $M_{\text{Hydrogen}} = M_{\text{Cesium}}$

New York Times



THE CANDIDATES

The Higgs Boson

By Jeffrey Kluger | Monday, Nov. 26, 2012

SSPL/GETTY IMAGES

Simulation of a Higgs-Boson decaying into four muons, CERN, 1990.

What do you think?

Should **The Higgs Boson** be TIME's Person of the Year 2012?

19.74% **Definitely**

80.26% **No Way**

Take a moment to thank this little particle for all the work it does, because without it, you'd be just inchoate energy without so much as a bit of mass. What's more, the same would be true for the entire universe. It was in the 1960s that Scottish physicist Peter Higgs first posited the existence of a particle that causes energy to make the jump to matter. But it was not until last summer that a team of researchers at Europe's Large Hadron Collider — Rolf Heuer, Joseph Incandela and Fabiola Gianotti — at last sealed the deal and in so doing finally fully confirmed Einstein's general theory of relativity. The Higgs — as particles do — immediately decayed to more-fundamental particles, but the scientists would surely be happy to collect any honors or awards in its stead.

Runner-Up: Fabiola Gianotti, the Discoverer

By Jeffrey Kluger | Dec. 19, 2012

Share Like 2.2k Tweet 395 +1 118 Share 23

Ten days is an awfully long time to have a toothache — especially with the kind of week Fabiola Gianotti had ahead of her. It was December 2011, and the annual seminar at the European Organization for Nuclear Research — better known as CERN — was imminent. Gianotti, one of CERN's head scientists, was preparing to present preliminary findings on the hunt for the Higgs boson, the elusive particle that physicists had been seeking for the better part of half a century. Gianotti and the thousands of other scientists who work at CERN's Large Hadron Collider (LHC) were getting very close to bagging the thing, and she was eager to share what she knew. But there was the matter of that toothache.

LEVON BISS FOR TIME

So she took a drugstore painkiller, then started taking two when one didn't work, then went to three. Finally she woke up the night before the seminar with a raging fever and chills and had to be rushed to the hospital for emergency dental surgery. When she was done, the doctor told her she had to stay home. "I said, 'O.K., I can stay home — for 20 minutes,'" she says. That was the time she needed to race back to her house, take a shower and get to CERN.

RELATED

What for the Future?

Manifestly obvious that we should study carefully every Higgs boson property accessible.

This will happen at the LHC and its possible upgrades

This is also the question being asked of the linear collider

Not a totally easy question to answer. With S. Gupta and H. Rzehak we have been looking at this.

Higgs boson mass

Conjecture: There is no value added from better-than-LHC measurements

Implication: Any discussion about how this or that e^+e^- option etc. helps obtain a better Higgs mass determination is of limited value.

I would be happy to be proved wrong, but let me explain why I say this through two important examples:

Fate of the Universe & Supersymmetry tests (no time for susy example).

LHC Measurement of Higgs Mass

It is claimed by CMS and ATLAS [1] that a measurement of the Higgs mass to better than 0.1% accuracy is possible with 30 fb^{-1} at 14 TeV.

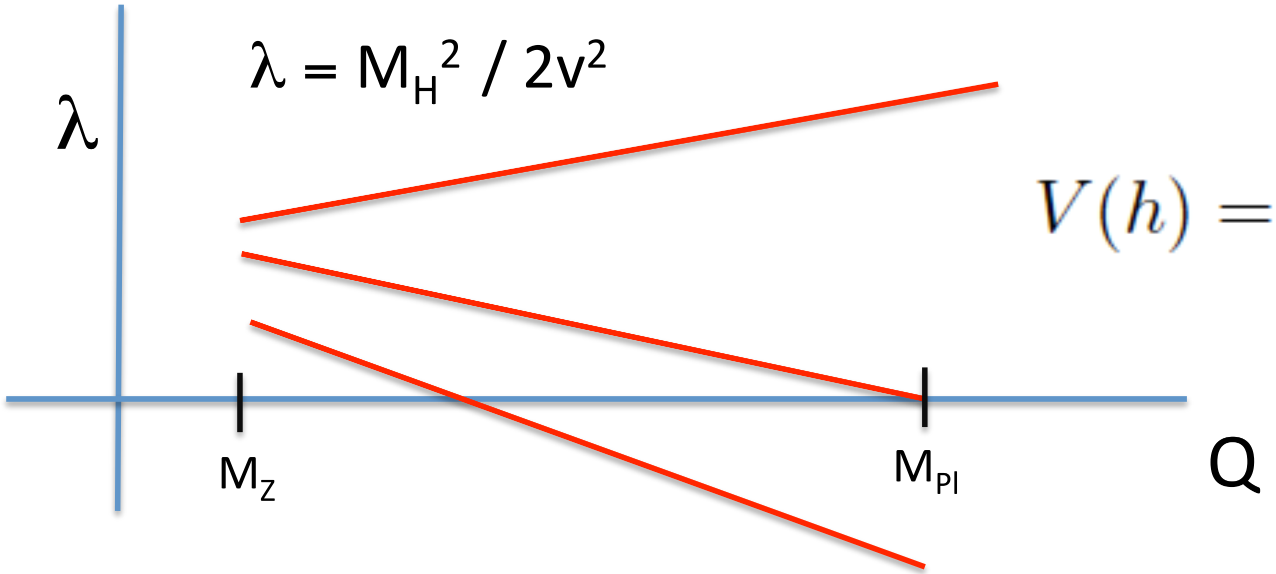
For 126 GeV Higgs mass that means better than 150 MeV mass determination.

Why would we want it better?

[1] See, e.g., Fig 10.37 of CMS TDR vol II (2007). See also Fig. 19-45 of ATLAS TDR.

Fate of the Universe

$$\frac{d\lambda}{dQ} = \frac{1}{16\pi^2}\left(\frac{27}{4}g^4 + \frac{9}{2}g'^2 g^2 - 9\lambda g^2 + \frac{9}{4}g'^4 - 3g'^2\lambda + 12y_t^2\lambda - 36y_t^4 + 4\lambda^2\right)$$



$$V(h) = \frac{\lambda(Q)}{4}h^4 + \cdots$$

Higgs mass lower than some critical value and potential is unstable, and the universe can phase transition to another vacuum.

Fate of universe (cont.)

Equation for the critical mass needed for stability is

$$m_H > 130\,\mathrm{GeV} + 1.8\,\mathrm{GeV}\left(\frac{m_t - 173.2\,\mathrm{GeV}}{0.9\,\mathrm{GeV}}\right) - 0.5\,\mathrm{GeV}\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 3\,\mathrm{GeV}$$

Espinosa et al.

The 3 GeV uncertainty is from unknown higher effects.

The uncertainty on critical M_H from a 300 MeV uncertainty in $M_{top,}$ is already 600 MeV, which well above LHC uncertainties for M_H.

No more measurements of the Higgs mass are going to help this question.

Higgs boson couplings

Enough on the Higgs boson mass. What about its couplings?

How well do we need to know the couplings?

One approach: Who knows?!!!

Unsatisfactory.

Let's first decide on some criteria to answer the question.

How well do we need to measure the Higgs boson coupling?

Criterion: What are the largest coupling deviations away from the SM Higgs couplings that are possible if no other state directly related to EWSB (another Higgs, or “rho meson”) is directly accessible at the LHC.

Let's look at three important examples:
- Supersymmetry
- Singlet Higgs mixed in with the SM Higgs (no time)
- Composite Higgs

Two Higgs Doublets of Supersymmetry

Supersymmetry requires two Higgs doublets. One to give mass to up-like quarks (H_u), and one to give mass to down quarks and leptons (H_d).

8 degrees of freedom. 3 are eaten by longitudinal components of the W and Z bosons, leaving 5 physical degrees of freedom: $H^\pm$, A, H, and h.

As supersymmetry gets heavier ($m_{3/2} >> M_Z$), a full doublet gets heavier together ($H^\pm$,A,H) while a solitary Higgs boson (h) stays light, and behaves just as the SM Higgs boson.

Corrections to Higgs Couplings in MSSM

Two leading corrections are

a) mixing of would-be SM Higgs with heavy Higgs

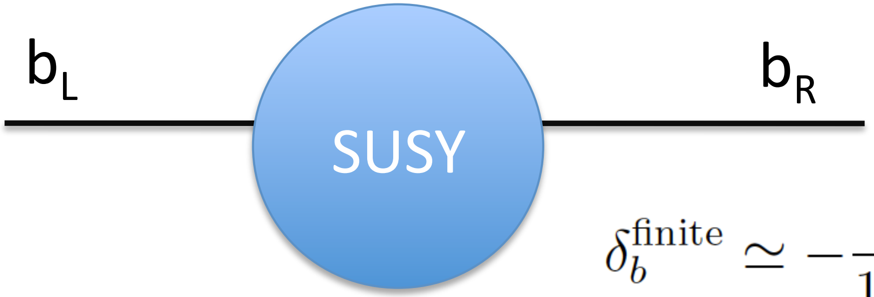
Not mass eigenstate

"H_{SM}"

"H_{heavy}"

mixing angle is ~ m_Z^2 / m_A^2

b) Finite b quark mass corrections, disrupting Yukawa – Mass relation



b_L

SUSY

b_R

$$\delta_b^{\rm finite} \simeq -\frac{g_3^2}{12\pi^2}\frac{\mu M_{\tilde g}\tan\beta}{m_{\tilde b}^2} + \frac{y_t^2}{32\pi^2}\frac{\mu A_t \tan\beta}{m_{\tilde t}^2} + \dots$$

Summary of Higgs Corrections for SUSY

If no extra heavy Higgses are found at LHC at 14 TeV with 300 fb^{-1} of integrated luminosity, the maximum deviations of the light Higgs from the SM couplings are

hZZ, hWW < 1 %, htt = 3 %, hbb = 100 %, $h\gamma\gamma$ derived from these

If we also include that no superpartners are found then it becomes

hZZ, hWW < 1 %, htt = 3 %, hbb = 10 %, $h\gamma\gamma$ derived from these

Composite Higgs Model Dependencies

Several different ways composite Higgs can show up:

1. Precision Electroweak (small effects)
2. Higgs boson decay branching fraction deviations
3. Higgs boson production cross-section deviations
4. Double Higgs production
5. Rho-meson resonance discovery and other dynamics

Different models have different priorities among these observables.

If no other dynamics are found, in particular rho-meson, the maximum deviation of Higgs coupling from SM expectations is

hZZ, hWW = 10%, hbb, htt = tens of %, hγγ derived from these

SUMMARY

	ΔhVV	$\Delta h\bar{t}t$	$\Delta h\bar{b}b$
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	$< 1\%$	3%	$10\%^{a}$, $100\%^{b}$
LHC 14 TeV, $3\,\mathrm{ab}^{-1}$	8%	10%	15%

TABLE I: Summary of the physics-based targets for Higgs boson couplings to vector bosons, top quarks, and bottom quarks. The target is based on scenarios where no other exotic electroweak symmetry breaking state (e.g., new Higgs bosons or ρ particle) is found at the LHC except one: the $\sim 125\,\mathrm{GeV}$ SM-like Higgs boson. For the $\Delta h\bar{b}b$ values of supersymmetry, superscript a refers to the case of high $\tan\beta > 20$ and no superpartners are found at the LHC, and superscript b refers to all other cases, with the maximum 100% value reached for the special case of $\tan\beta \simeq 5$. The last row reports anticipated 1σ LHC sensitivities at 14 TeV with $3\,\mathrm{ab}^{-1}$ of accumulated luminosity [5].

Details in Gupta, Rzehak, JW, arXiv:1206.3560.

Thoughts on Implications for SUSY

First, I am slightly more encouraged about Supersymmetry than I was a year ago….

Why?

A) Limits on superpartners from the old 114 GeV Higgs mass limit was generically more worrisome than any limits LHC at 7 TeV could provide.

B) A light-ish SM-like Higgs boson (less than about 140 GeV) is always what I expected. And it had not shown up yet.

But now we have a Higgs boson, and it looks SM-like. Worry A has not changed at all, and worry B has gone away for SUSY.

But I am not here to convince you that SUSY is around the corner.

I have no idea.

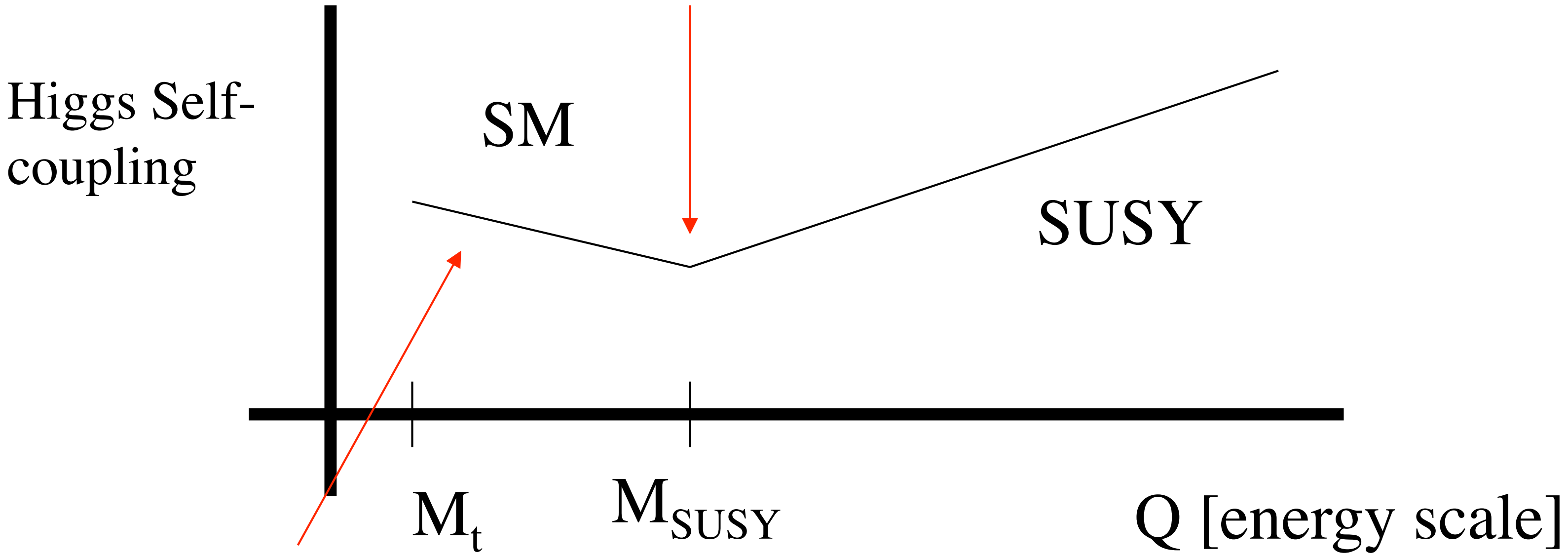
I can tell you what I think SUSY should be if it is part of low-scale nature.

Many ideas abound. I will tell you about one of my favorites, because it’s what I originated (apologies to other good ideas).

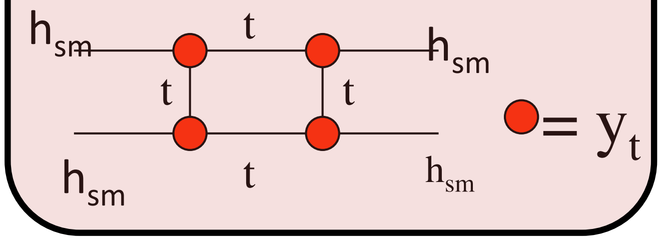
But first, let me remind you about the light Higgs boson mass in Supersymmetry, since that’s really where all the stress is.

Understanding Lightest Higgs Mass Computation

$$\lambda(M_{SUSY}) = \frac{1}{8}(g^2 + g'^2)\cos^2 2\beta$$

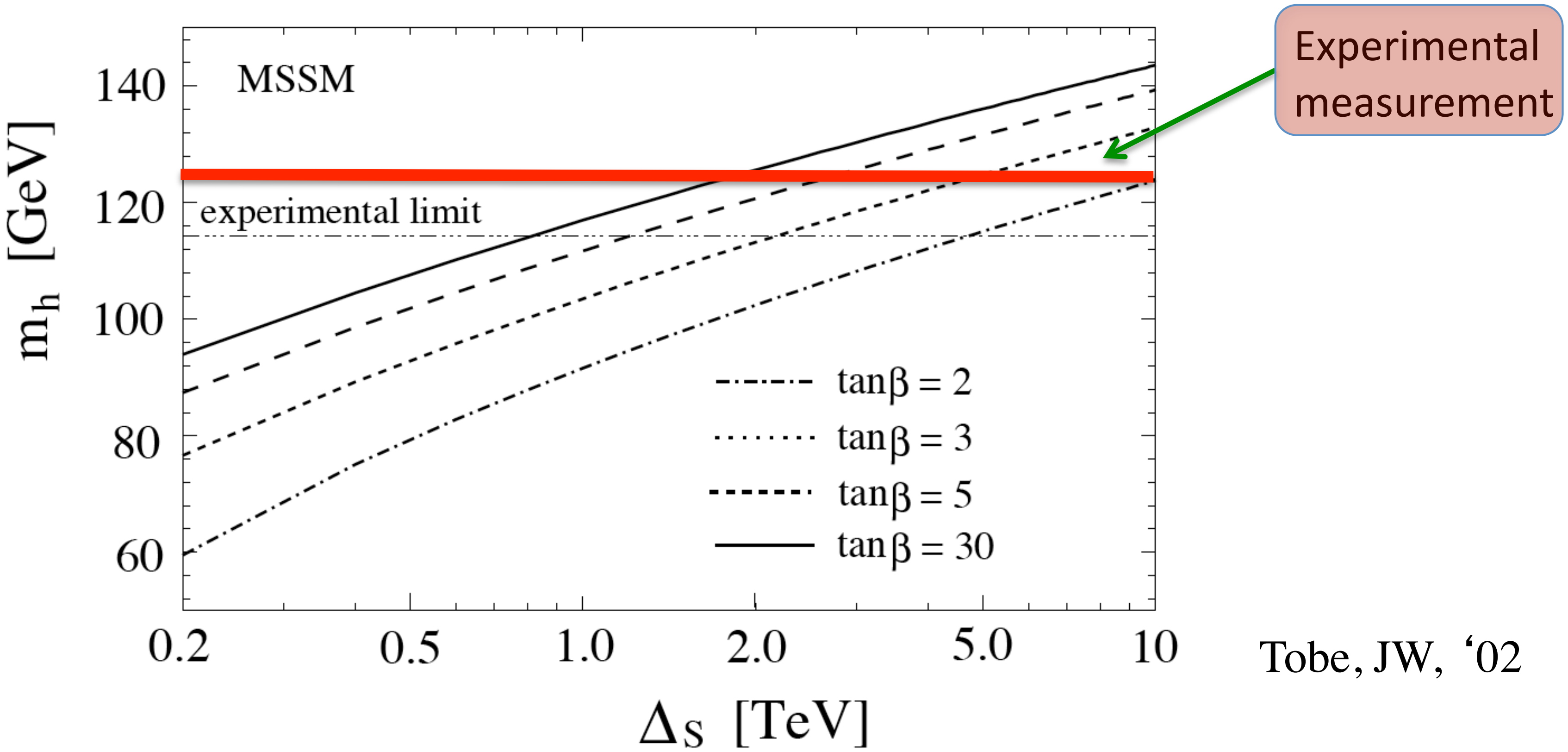


$$\frac{d\lambda}{d\log Q} = -\frac{3}{4\pi^2}y_t^4 + \cdots$$



$$\begin{aligned} m_h^2 &= 2\lambda v^2 = 2\left(\lambda(M_{SUSY}) + \frac{3}{4\pi^2}y_t^4\log\frac{M_{SUSY}}{M_t}\right)v^2 \\ &= M_Z^2\cos^2 2\beta + \frac{3M_t^4}{\pi^2 v^2}\log\frac{M_{SUSY}}{M_t} \end{aligned}$$

Lightest Higgs Mass in the MSSM



Experimental measurement

Tobe, JW, ‘02

$$m_h^2 = M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{2\pi^2 v^2} \ln \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} + \frac{3m_t^2}{v^2} c_{\tilde{t}}^2 s_{\tilde{t}}^2 (m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2) \ln \frac{m_{\tilde{t}_2}^2}{m_{\tilde{t}_1}^2} + \cdots$$

$$\equiv M_Z^2 \cos^2 2\beta + \frac{3G_F m_t^4}{\sqrt{2}\pi^2} \ln \frac{\Delta_S^2}{m_t^2} \quad \text{where } \Delta_S^2 \gtrsim m_{\tilde{t}_1} m_{\tilde{t}_2}$$

Naturalness

Naturalness is strained if M_{SUSY} becomes too large.

From the EW scalar potential of supersymmetry, the minimization conditions yield

$$\frac{1}{2}m_Z^2 + \mu^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1}$$

This is of the generic form of one large number subtracting another and getting a small number:

$$\tilde{m}_1^2 - \tilde{m}_2^2 = m_Z^2$$

PeV-Scale/Split Supersymmetry

Scalar superpartners (squarks and sleptons) are much, much heavier than fermionic superpartners (charginos, neutralinos and gluinos).

This goes under the names of or PeV Scale supersymmetry (JW) or Split Supersymmetry (Arkani-Hamed, Dimopolous, Giudice, Romanino).

Let's begin by building the rationale for this approach.

EW-Scale Naturalness

Appeals to naturalness are murky and controversial. Incompatible views can be reasonable.

Agnostic approach: Delete all reference to naturalness and ask what is the “best” susy model consistent data.

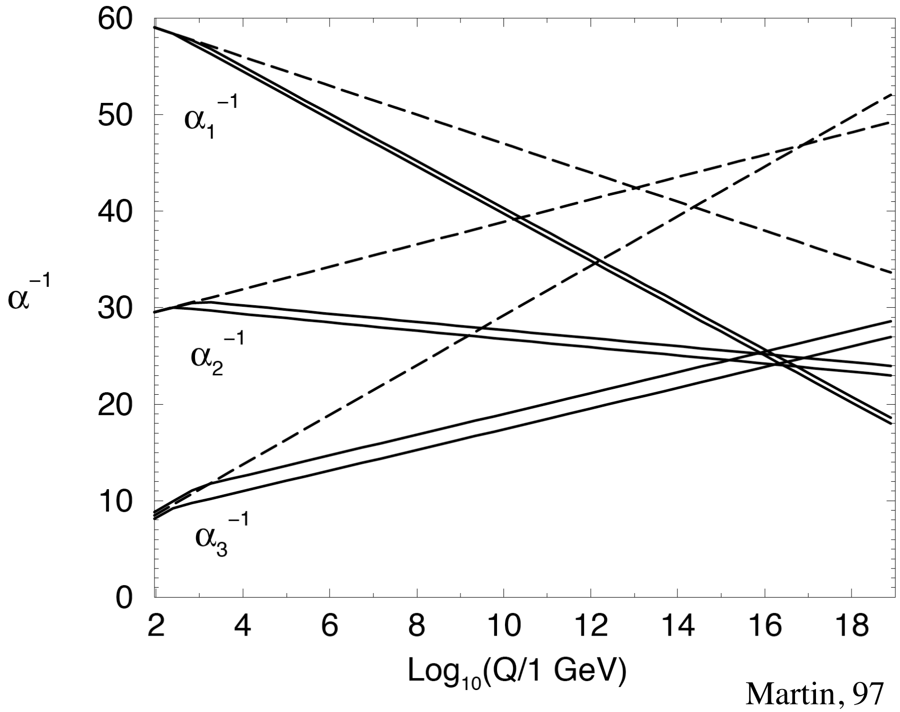
Arbitrary heavy SUSY?

After deleting naturalness from consideration, we should not conclude that SUSY is at some arbitrarily large scale, where it can't cause harm.

We wish to retain good things about SUSY:

- Gauge Coupling unification
- Light Higgs boson mass prediction
- Cold Dark Matter

Gauge Coupling Unification



Martin, 97

“Proximity Factor” for gauge coupling unification is defined to be the factor A needed such that

Generic quantum correction

$$g_U = g_1(M_U) = g_2(M_U) = g_3(M_U) + A\frac{g_U^3}{16\pi^2}$$

In weak-scale MSSM $M_U \simeq 2 \times 10^{16}$ GeV and $A \simeq 1$.

Unification success sensitive to -inos, but not scalars.

CDM Limits and SUSY Mass

Experiment tells us

$$0.09 < \Omega_{CDM} h^2 < 0.13$$

Leads to upper bound constraint on lightest susy mass (neutralino), but others can be much heavier (squarks and sleptons).

$$\Omega h^2 = \frac{A}{\langle \sigma v \rangle} = \frac{A\tilde{m}^2}{\alpha}, \text{ where } \langle \sigma v \rangle = \frac{\alpha}{\tilde{m}^2}$$

$$\frac{A\tilde{m}^2}{\alpha} < 0.13 \quad \rightarrow \quad \tilde{m} < \sqrt{0.13\alpha/A} < \text{ few TeV}$$

Where we are at

Ignoring Naturalness

Eliminating bad things:

1. FCNC
2. Proton decay strains
3. CP Violation
4. Too light Higgs mass

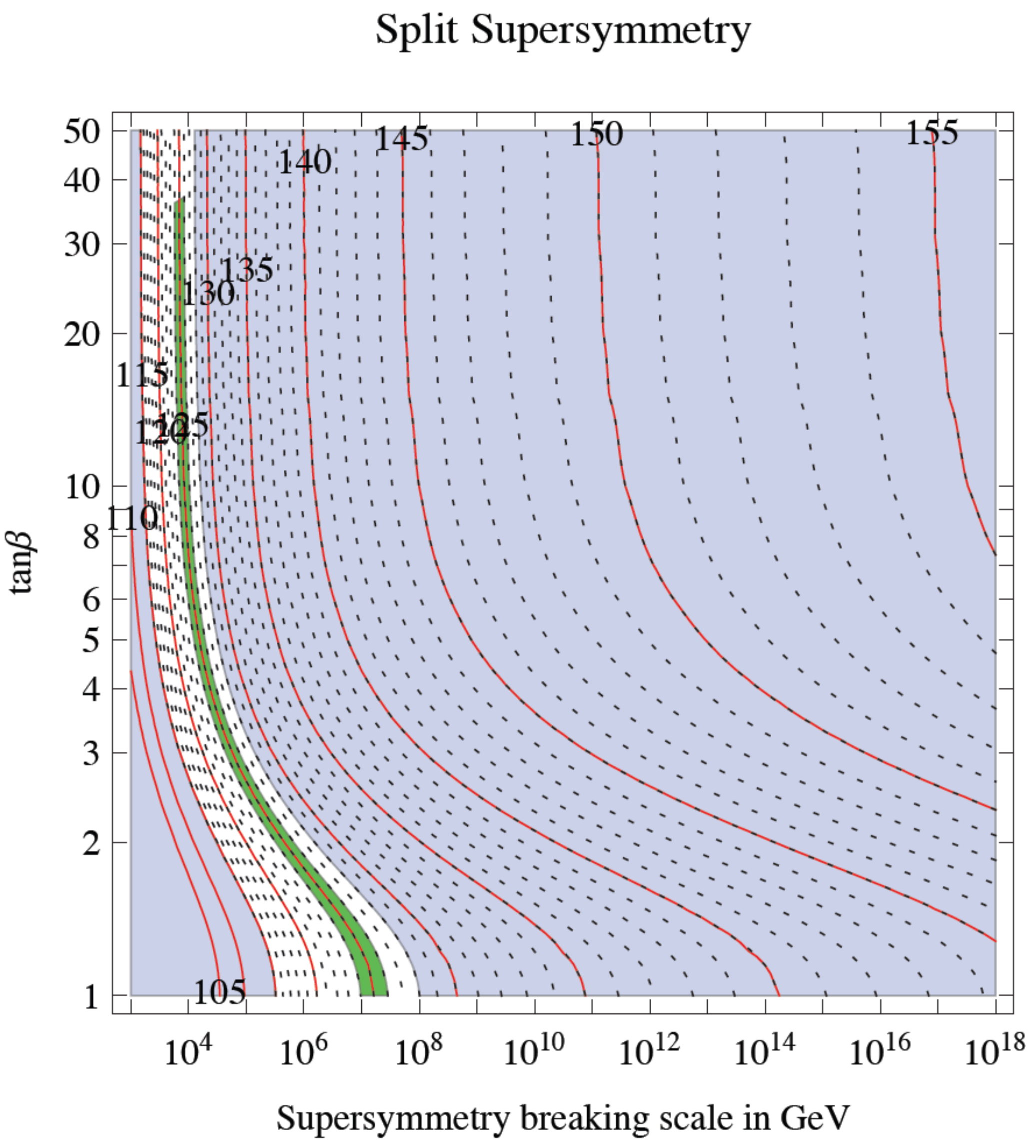
Preserving good things:

- SUSY
- Light Higgs prediction
- Gauge Coupling Unification
- Dark Matter

Accomplished by large scalar susy masses, but light fermion susy masses (gauginos, higgsinos)

Good theory for this? Yes. The -ino masses charged under symmetries (R and PQ) whereas scalars are not. [Split SUSY literature.]

Higgs Boson Mass Implication



There is no trouble for split supersymmetry to accommodate a 125 GeV Higgs boson mass.

Giudice, Strumia, '11

Collider Implications of Heavy Flavor Supersymmetry

Example order of
the spectrum:

Increasing mass

Very heavy squarks/sleptons – flavour masses

Gluinos – best hope

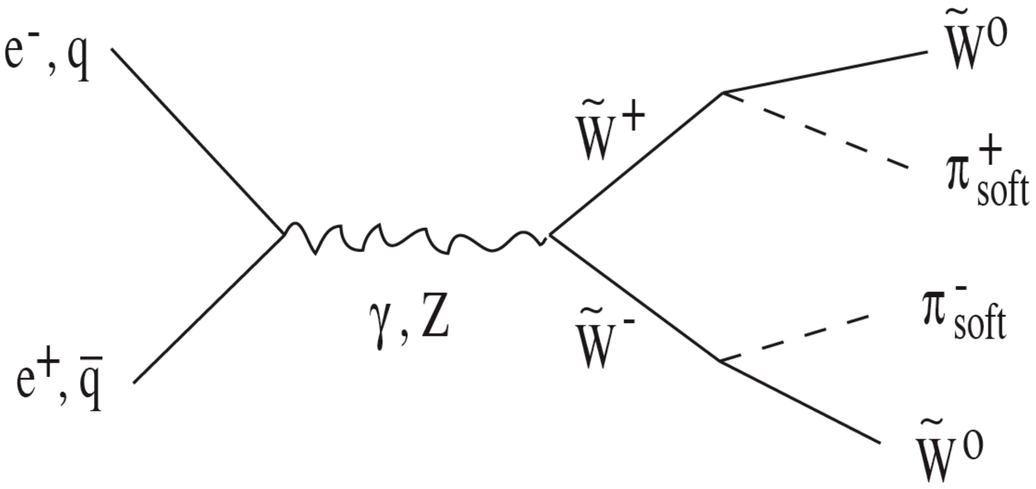
Bino – not produced!

W^+,W^-,W^0 winos -- LSP

- Scalars are out of reach
- Binos are not produced
- Higgs mass of 125 GeV can be accommodated
- Wino and gluino production give colliders hope

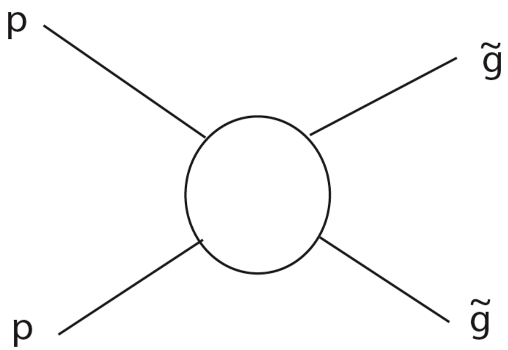
Wino Production and Decays

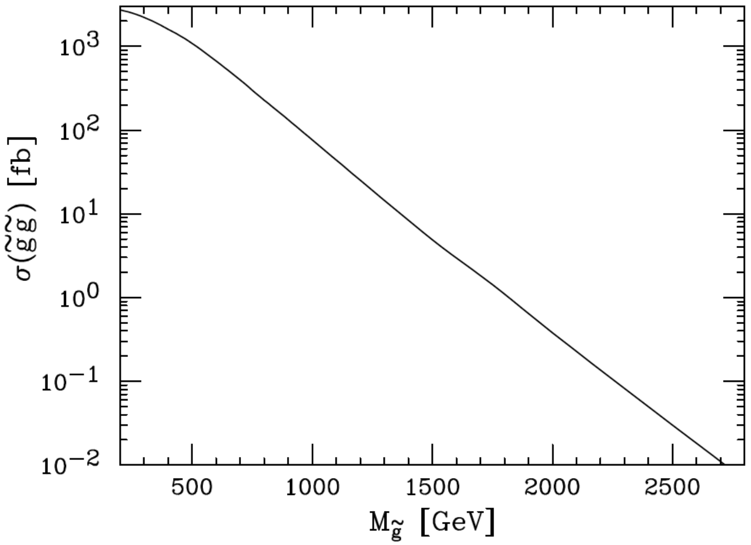
The mass splitting between charged and neutral is tiny.



As it stands, difficult. LEP has limits (next slide).
Hadron colliders cannot trigger on soft pions.
Trigger on initial state gluon (Tevatron/LHC).
Can this be done?

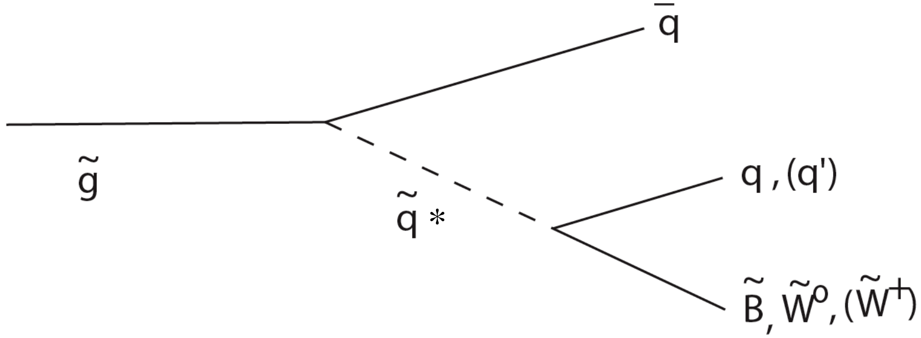
Gluino Production and Decays





Pythia output

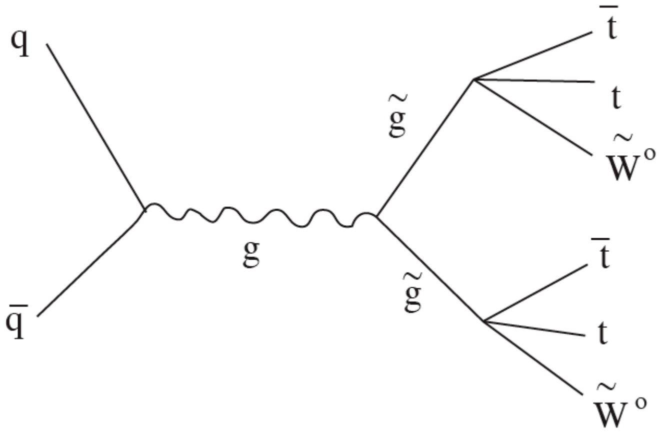
Main decay is three-body through off-shell squark

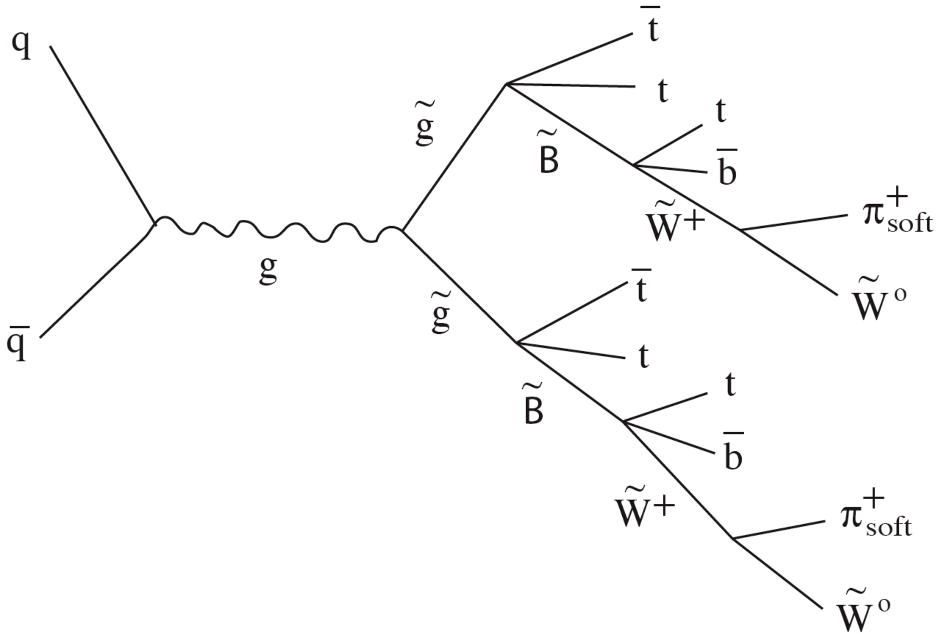


(Toharia, JW for more details on gluino decays within this scenario)

High multiplicity tops+MET events

Simplest event type: 4 top quarks plus missing energy. Can the missing energy be measured?



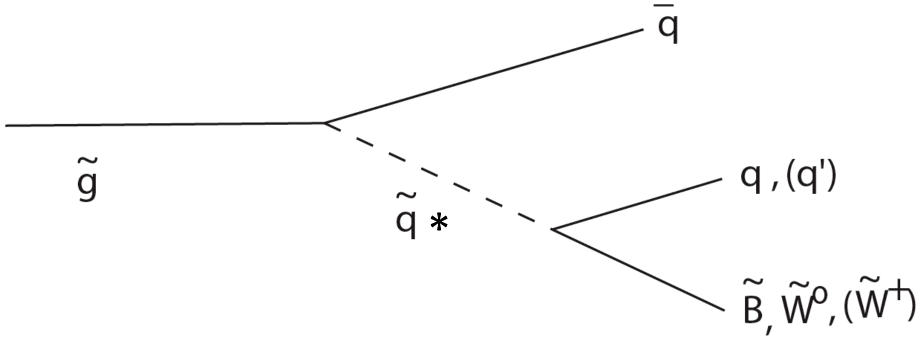


Combinatoric/experimental Challenge.

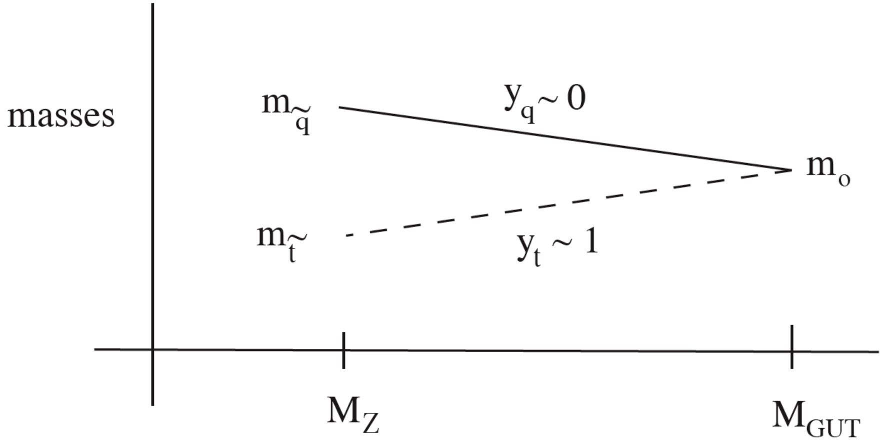
6 tops + 2 b’s + 2 pions + MET

Preference for 3rd generation

The lighter the squark
the higher the BR to
its corresponding quark



$$\frac{d\tilde{m}^2_{q_i}}{d\log Q} = -\frac{32}{3}M_3^2 + a_i y^2_{q_i}\tilde{m}^2_{q_i} + \cdots \quad (a_i \text{ is positive})$$



There is a generic
preference for decays
into 3rd generation
quarks.

Conclusions

Higgs boson discovery was expected.

Higgs boson will have slight deviations from pure SM Higgs boson. It is only a question of how big.

Well-motivated theories give hVV < O(1%) deviation, and hff < O(10%) or perhaps even more.

LHC unlikely to see deviations from our standard BSM scenarios.

"Best theory" of (unnatural) SUSY has no scalars discovered at the LHC, but perhaps gluinos. Third generation quark final states most important to study.