What a Higgs can tell us

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Pheno 2008
April 30, 2007

Outline

- Introduction: What a Higgs does for a theory
- The “Higgs Portal”
- Higgs Decays
- Higgs Production
- Outlook

Electroweak Vandalism

- As we all know, the point of the LHC is to unravel the nature of Electroweak symmetry-breaking - the mechanism by which the SM obtains mass.
- The SM does this with a single scalar doublet. A potential induces the correct expectation value:

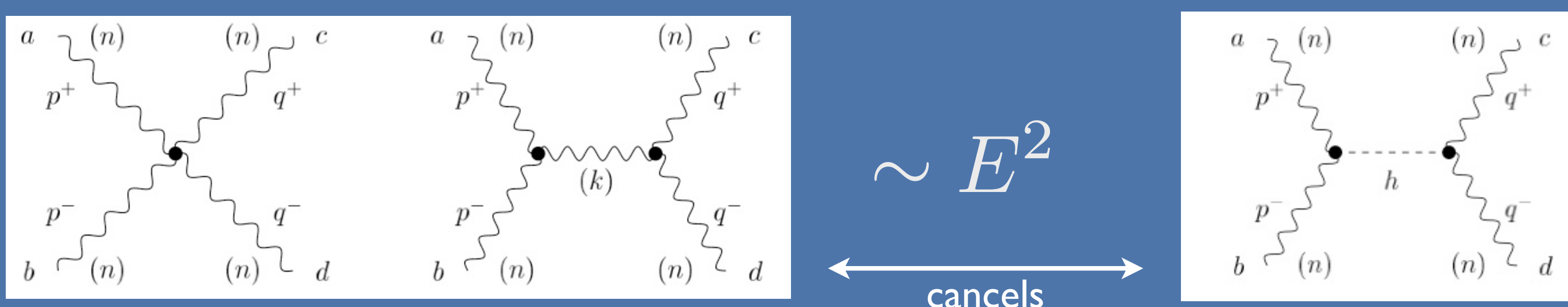
$$V = \lambda \left(|\Phi|^2 - v^2 \right)^2$$

dimensionless quartic (λ) — "mass parameter" (v)

- Three would-be Goldstone bosons are eaten and one physical Higgs remains with mass^2 $=\lambda$ v^2 - the signature of the SM we are looking for at LHC.

Perturbative Unitarity

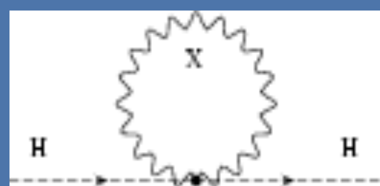
- The Higgs sector of the SM is minimal in that it provides a gauge invariant description that we can imagine could persist to high energies.
- The Higgs particle is something of a leftover. Nevertheless, It is important to cancel bad behavior in the high energy limit of W W scattering.



- To avoid a breakdown of perturbation theory, the Higgs mass must be less than about one TeV.

Why not a SM Higgs?

- The SM Higgs sector makes us uncomfortable.
- The mass parameter is unduly sensitive to heavy mass physics beyond the SM (hierarchy problem).



$$\sim \frac{g^2}{16\pi^2} M_X^2$$

- The quartic becomes non-perturbative at high energies (triviality).

$$\frac{d\lambda}{d\log\mu} = \frac{1}{16\pi^2}\left\{12\lambda^2 + ...\right\}$$

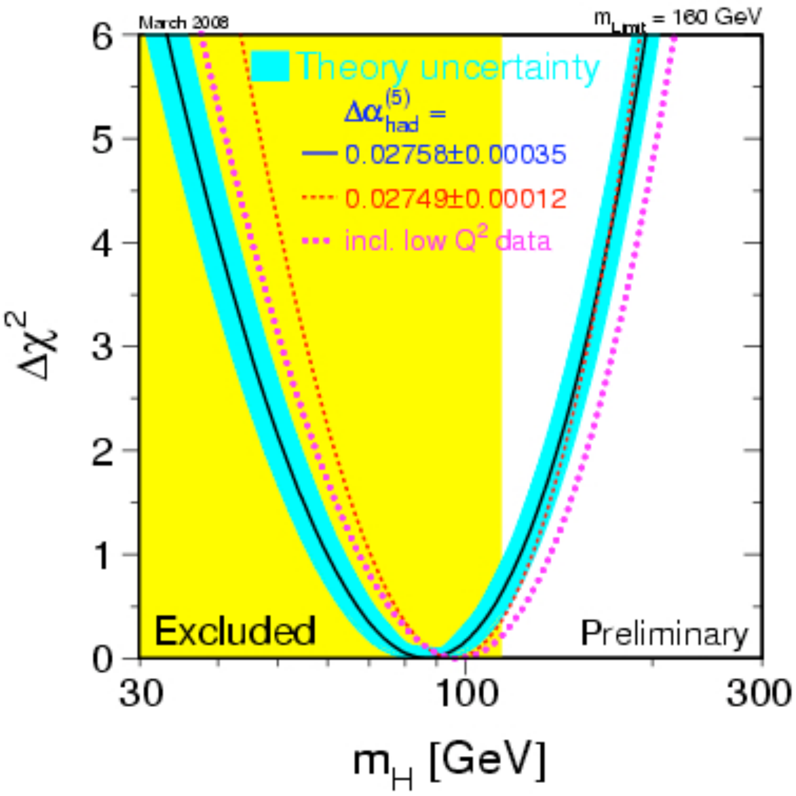
Hsin-Chia told us many ways people propose to solve these problems...

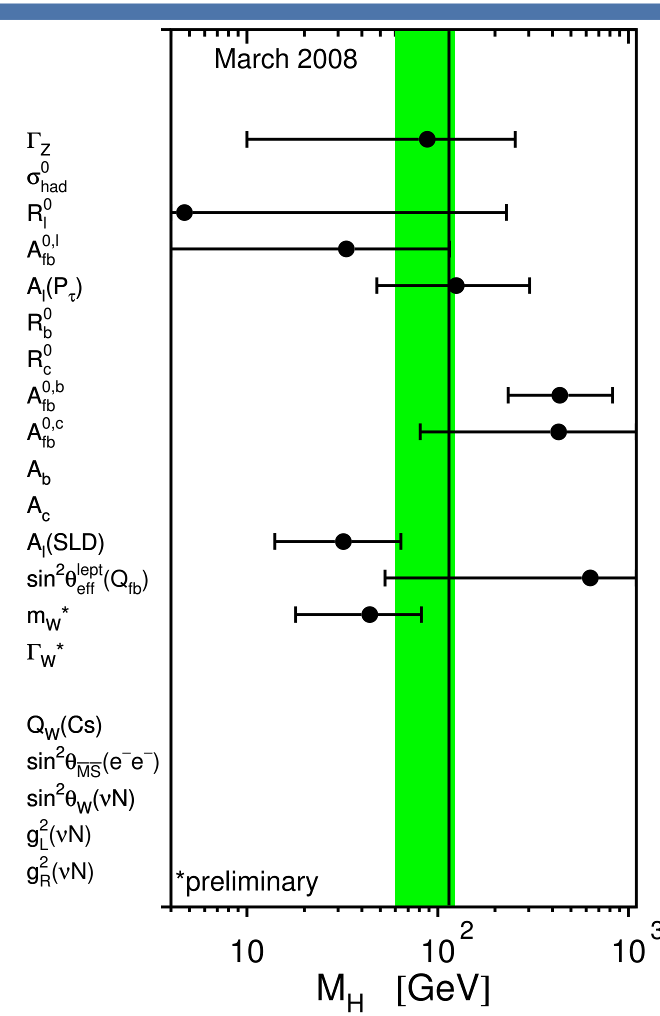
The SM Higgs tells us...

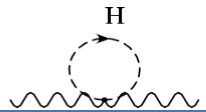
- For the theory, the Higgs maintains gauge invariance (and thus perturbation theory) in light of the broken electroweak symmetry.
- For a theorist, the Higgs (as a fundamental scalar) tells us that something is missing in the Standard Model. In the very least, we can see the description in terms of the SM degrees of freedom may break down at some finite energy scale.

(It tells us to build models...)

Expectations from Precision Data

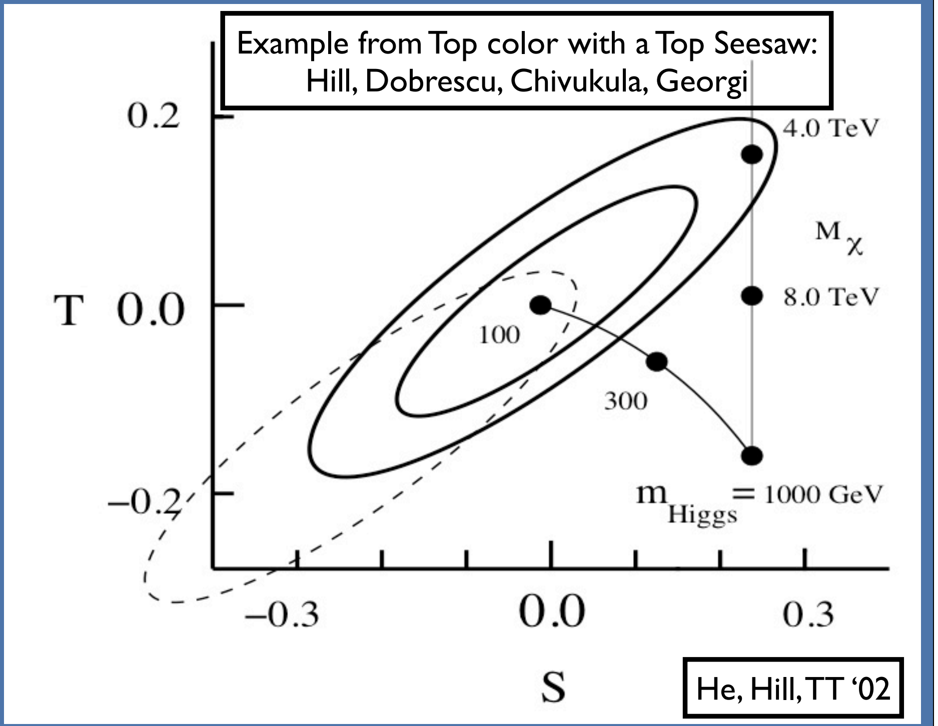






New Physics and m_H

- The LEP/SLD data, combined with the top mass from the Tevatron, is a triumph of precision physics.
- But we should take the m_H limits with a grain of salt. That fit works when the Standard Model is the whole story. Most of us think it isn't.
- Examples include: new quarks and/or leptons, an extended Higgs sector, Z's, RS EW resonances, new strong dynamics, and (even!) super-partners!



Seeing a heavy SM Higgs would already tell us something...

The Higgs and New Physics

- The Higgs is also potentially a bridge to physics beyond the Standard Model.
- Solutions of the hierarchy problem necessarily involve coupling to the Higgs. Examples like twin Higgs and cousins in model space illustrate the fact that solutions to the hierarchy problem can be sequestered to some degree into the Higgs sector.
- Higgs may be our only way to access some models...

A Higgs Portal?

- The Higgs as a fundamental scalar is also somewhat unique - $\Phi^\dagger \Phi$ is one of two dimension 2 SM gauge singlets I can form.
- This operator is potentially part of the lowest dimension interactions between the SM and a hidden sector, and thus the most relevant interaction at low energies.

$$\frac{1}{\Lambda^n} \underbrace{\left(\Phi^\dagger \Phi\right)}_{\text{Higgs}} \underbrace{\mathcal{O}^d}_{\text{Hidden sector operator}} \qquad n = d - 2$$

The Trans-TeV Higgs

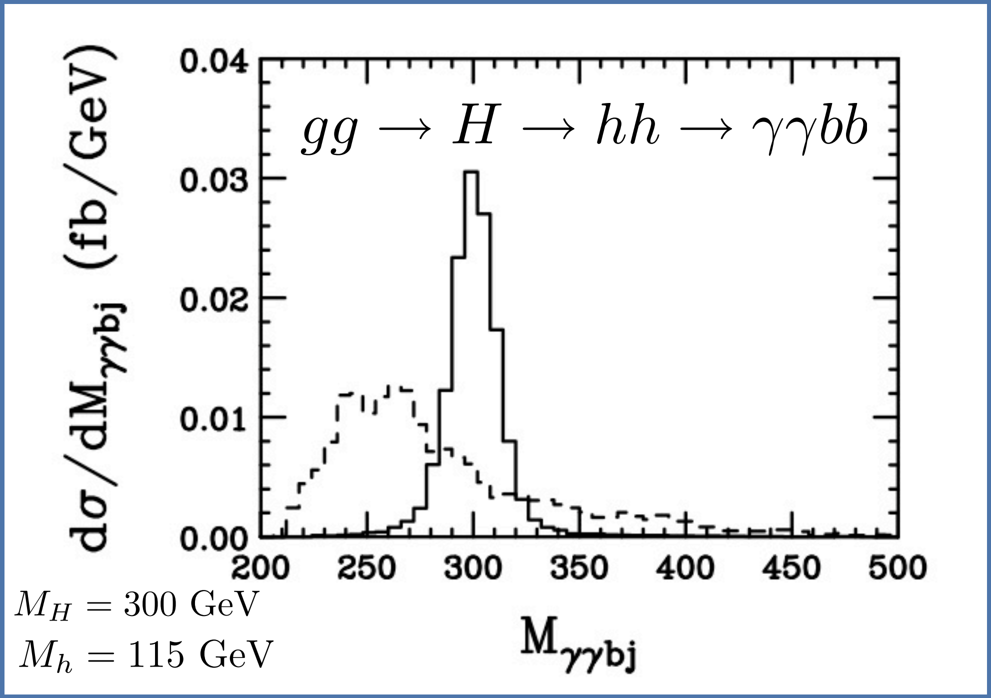
- One example has a (SM) singlet Higgs which couples to the SM through a mixed Higgs-singlet quartic:

Schabinger, Wells '05

$$\left(\Phi^\dagger \Phi\right)\left(S^\dagger S\right)$$

- If the singlet gets a VEV, this term mixes it with the SM Higgs.

- Models which maintain perturbative unitarity can have TeV scalars which decay predominantly into pairs of lighter Higgses.

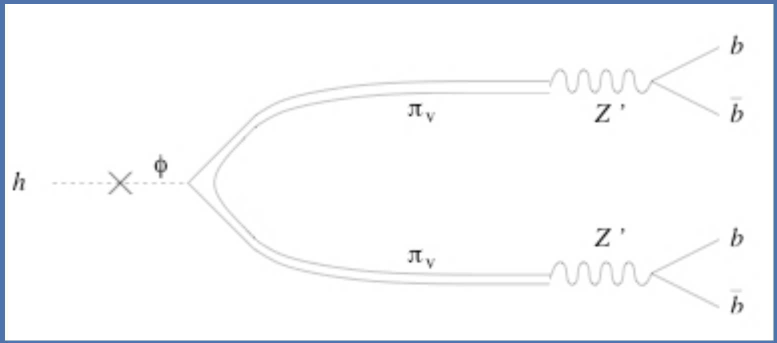


Bowen, Cui, Wells '07

Higgs into a Hidden Valley

- Another option could have a heavy Higgs which decays predominantly (through mixing as before) into fields that live in a 'hidden valley' consisting of a non-Abelian gauge theory described by "v-hadron" states below its confinement scale.

Strassler, Zurek '05



- These v-hadrons could decay through a higher dimensional operator back into SM fields. If the scale of those operators is high, the life-time of the v-hadrons can be long, leading to the novel Higgs signatures of displaced vertices!

More Higgs Doublets?

- Even without a sequestered sector, we can ask for an extension of the SM Higgs sector. The fact that we haven't seen a Higgs means we really don't know whether we should expect a minimal picture.
  - Some theories (like the MSSM) naturally demand two or more!
- Even the simple addition of another Higgs doublet can lead to very interesting phenomena:
  - Only one set of would-be Goldstone bosons are needed to give mass to the Ws and Z. Two Higgs doublets contain three physical neutral scalars and two charged scalars.

2HDM

- The addition of the extra doublet allows a lot more freedom in the couplings.
- The VEV can be shared among the doublets. In a two doublet case with VEVs v_1 and v_2:

$$M_W^2 = g^2 \left(v_1^2 + v_2^2\right) \qquad m_f = y_1^f v_1 + y_2^f v_2$$

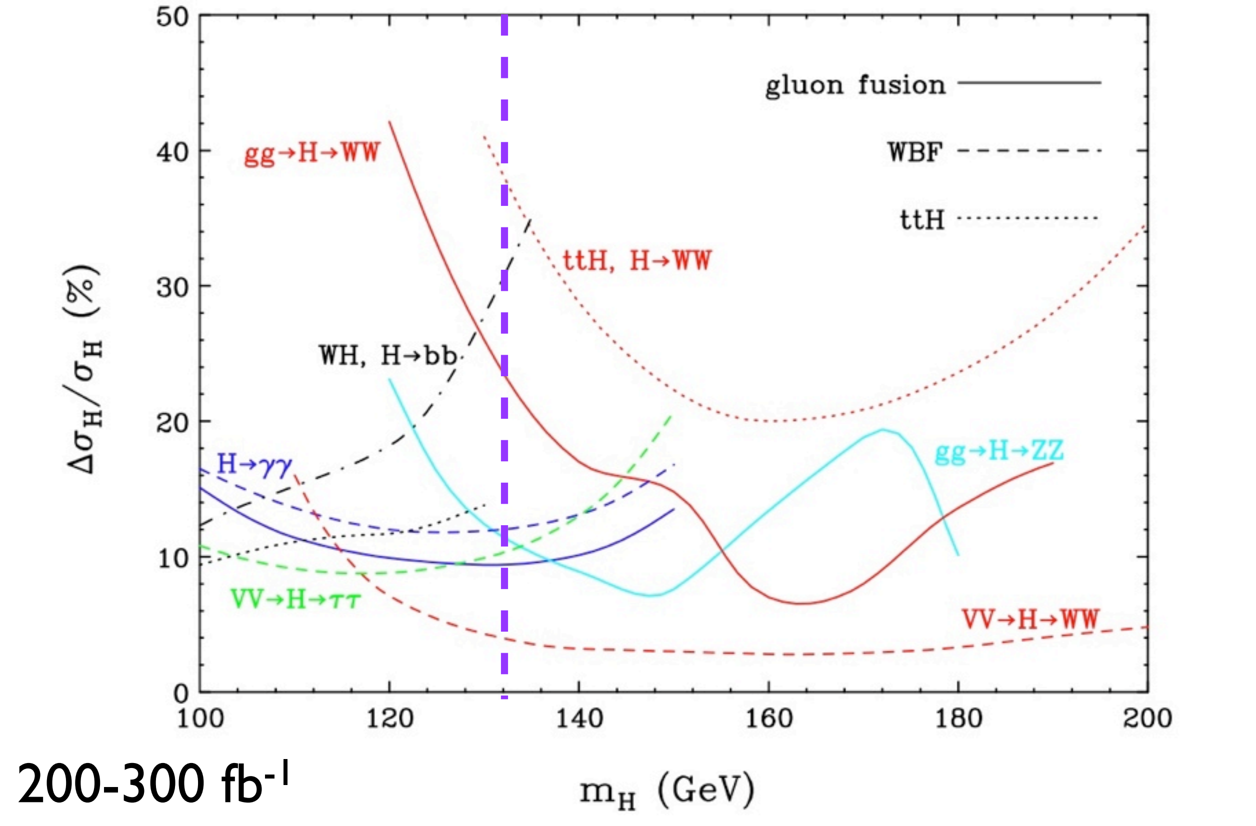
  - The couplings to gauge bosons can be smaller than expected.
  - The couplings to fermions can be enhanced or depressed.
  - The mismatch between masses and couplings can lead to flavor-changing neutral currents mediated by Higgses.

SM Higgs: Parameters

- In the SM, all of the couplings are fixed in terms of masses we have already measured except for the quartic λ, which controls the self-interactions and Higgs mass.
- So in the Standard Model, the only thing left to measure is the Higgs mass, and any property of the SM Higgs can be determined once the mass is known.

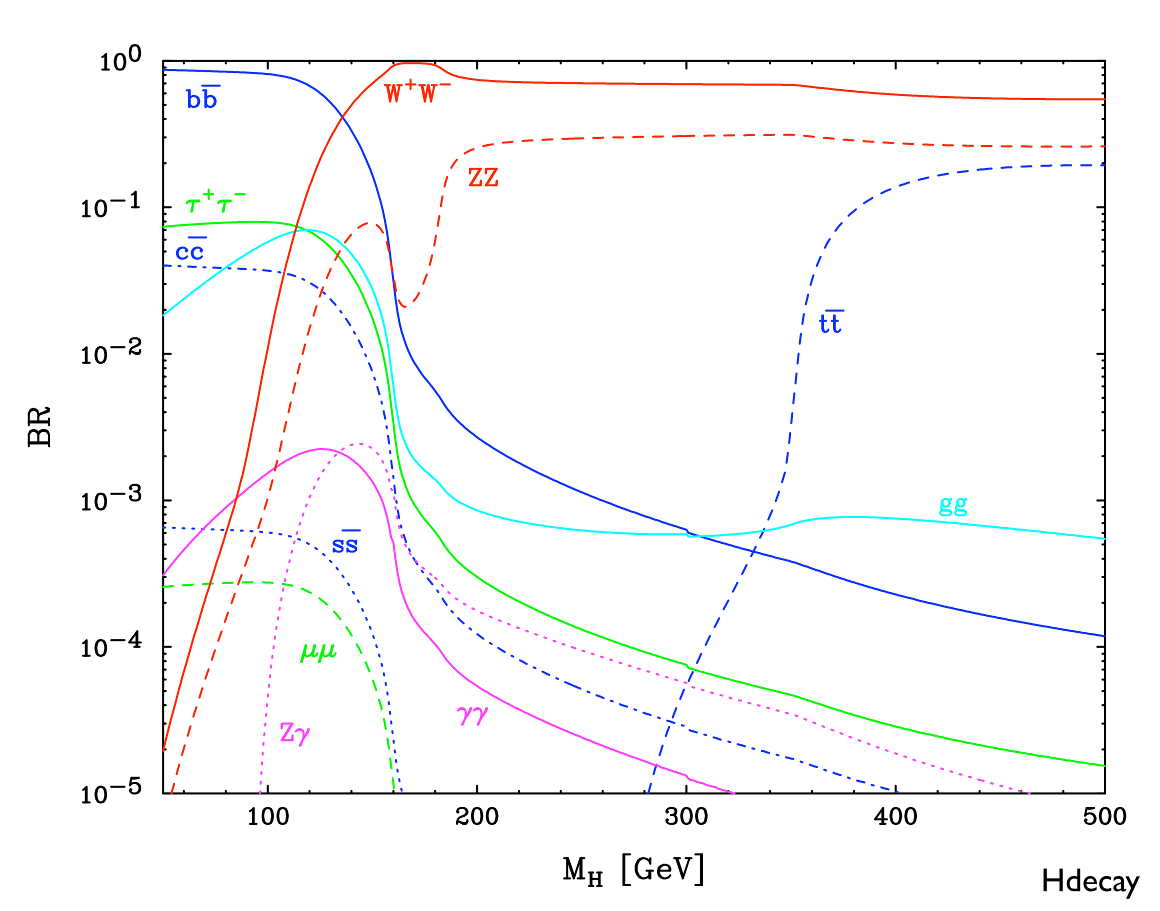
  (It would be nice to verify the self-coupling/mass relation too). Baur, Plehn, Rainwater '04
- Lets take a closer look at the SM Higgs - our expectations for what it looks like determine the ways we search for it at the LHC, and what the properties we would like to measure. What the Higgs can tell us will rest on what we can measure and how those properties might be related to something unexpected or interesting!

Measuring Couplings?



Zeppenfeld '02

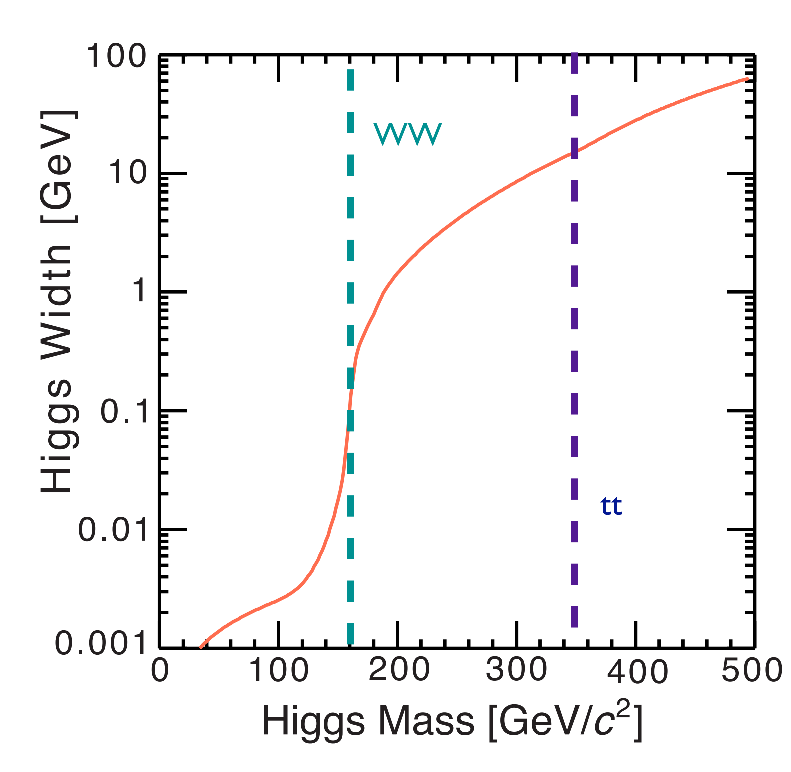
Branching Ratios



- The general rule for Higgs decays is that the Higgs will decay into the heaviest thing available for a given mass.
- The exception is top pairs, which don't manage to dominate WW/ZZ pairs.

Higgs to bottom quarks

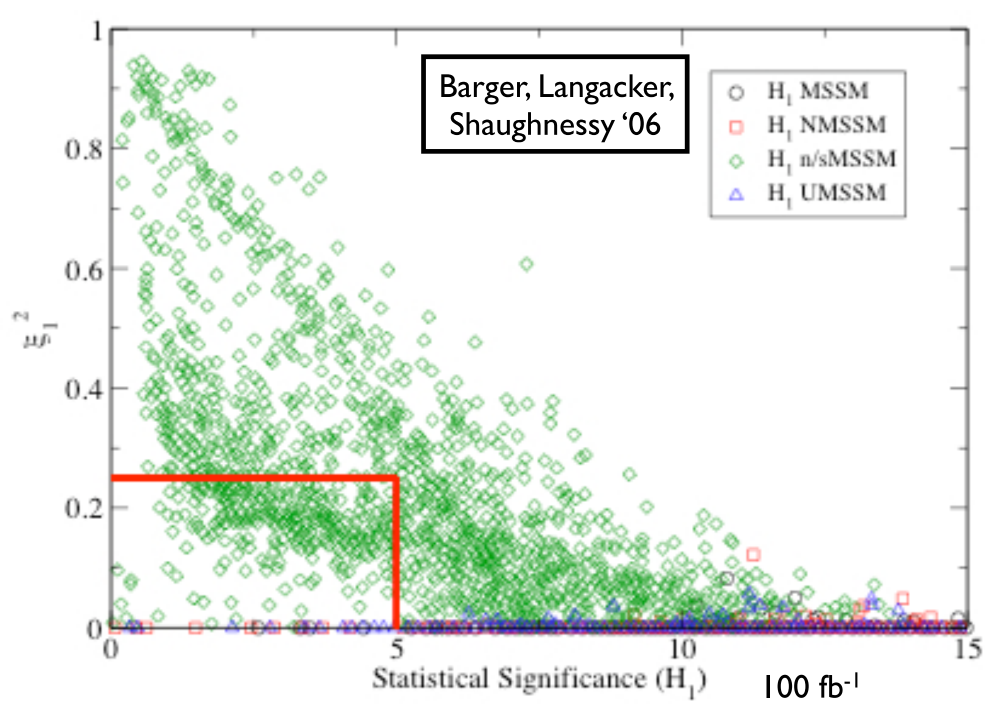
- For a low mass Higgs, the dominant decay mode is into bottom quarks.
- In the SM, the coupling to bottom is very small - the Higgs decays into bottom only because its the only thing kinematically available.
- As a result, the partial width into bottom is very small.
- New physics could easily overwhelm this, and dominate in Higgs decays.



H Decay to Neutralini

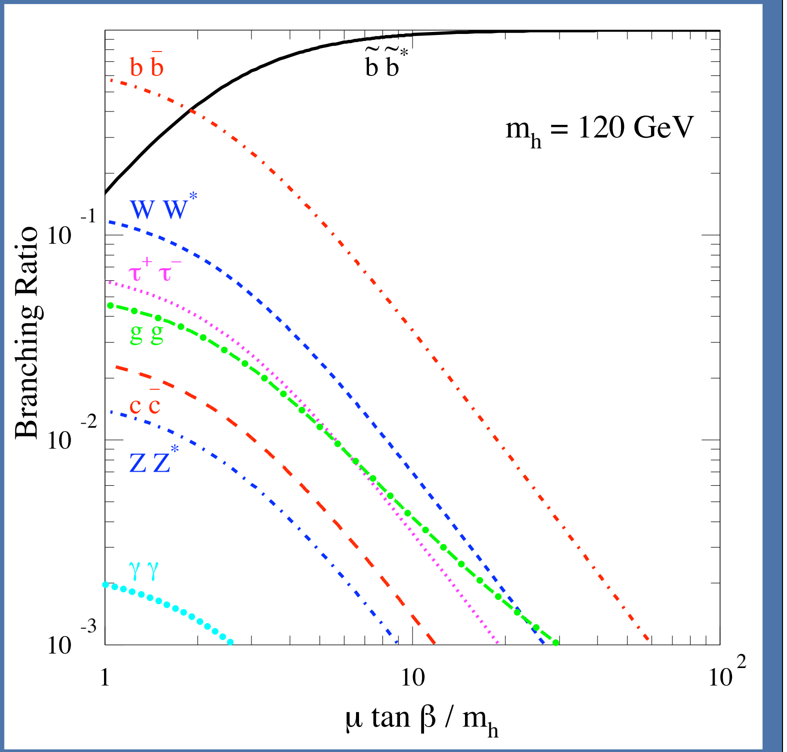
- If the lightest neutralino is light enough, the Higgs could decay into it. Assuming R-parity is conserved, this is an invisible decay mode for the Higgs. Eboli, Zeppenfeld, '00 Datta, Konar, Mukhopadhyaya, '01
- It has been proposed to search for such a Higgs using weak boson fusion. The idea is that the rapidity gap of the associated jets provides something to tag on.
- An invisible decay becomes much more likely with an extra singlet.

$$\xi_i^2 = BF(H_i \to invisible)\frac{\sigma_{WBF}}{\sigma_{WBF}^{SM}}$$



Higgs to Dijets

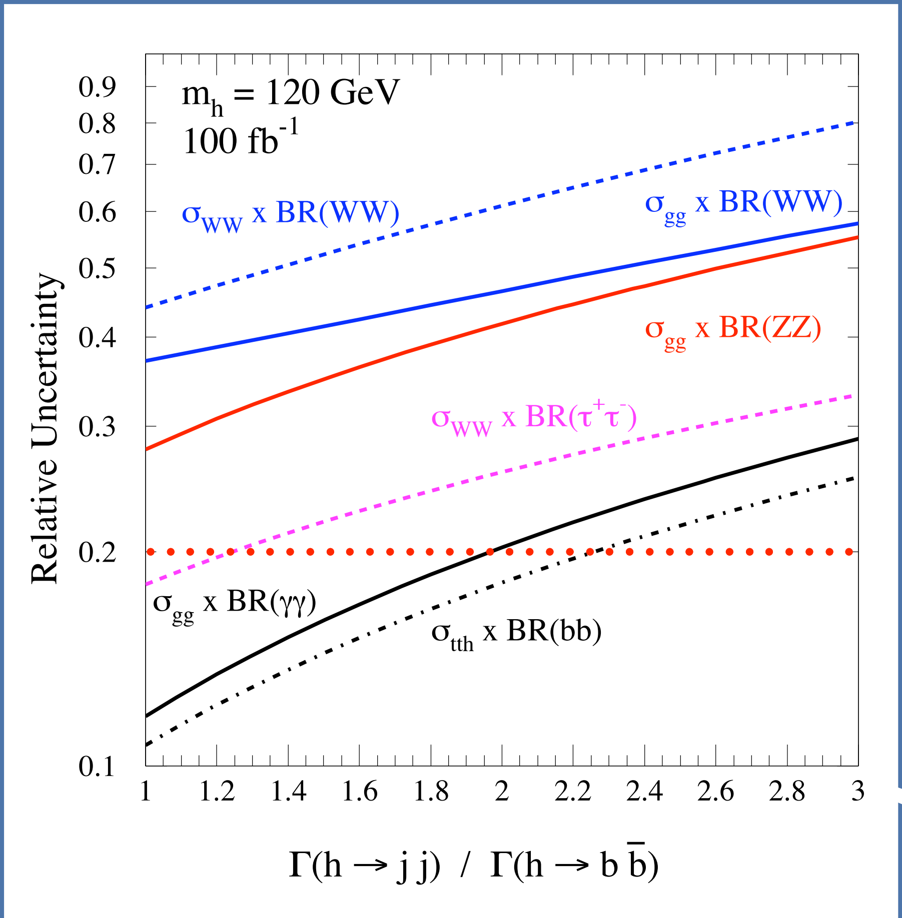
- An option is a Higgs decaying into light sbottoms which themselves decay through R-parity (B-) violating interactions into collimated quarks, looking like a single jet.
- If they are light enough for the Higgs to decay into them, the BR is controlled by ($\mu \tan\beta / m_h$).
- Note that this is even true in the "decoupling" (large M_A) regime! The sbottom is not a SM particle and its Higgs coupling doesn't asymptote to a SM quantity.



Berger, Chiang, Jiang, Tait, Wagner
PRDD66, 095001 (2002)

H to Dijets at LHC

- A decay into dijets is really tough at the LHC.
- The QCD background swamps any channel we can imagine looking for the Higgs decaying into jets.
- At the same time, the BRs into more friendly decay modes is suppressed.
- Once the partial width is enhanced by a factor of a few, the LHC probably cannot discover the Higgs.



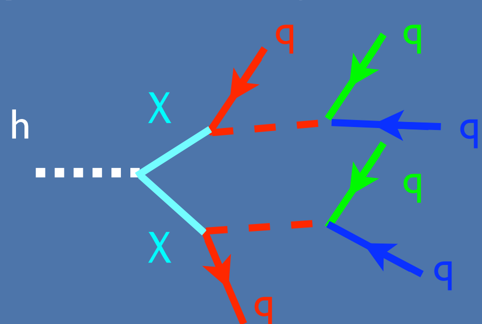
(Maybe look at WW scattering?)

Higgs to More Jets

- Another R-parity violating option allows the Higgs to decay into heavier super-partners which then decay into SM particles.

LSP	LLE	LQD	UDD
χ_0	4τ+2ν	4b/4c+2ν, 2b+2c+2ν, 2b+2c+2τ,3b+c+τ+ν, b+3c+τ+ν	2b+2c+2q
g	-	4b/4c+2ν, 2b+2c+2ν, 2b+2c+2τ,3b+c+τ+ν, b+3c+τ+ν	2b+2c+2q
b	-	2b+2ν, 2c+2τ, b+c+ν+τ	2c+2q
τ	2τ+2ν	2b+2c	-

- A variety of possible LSP's and RPV couplings lead to an array of signals. Many contain large numbers of moderately hard SM particles.



Carpenter, Kaplan, Rhee '08
(and see Linda's slides from the parallels!)

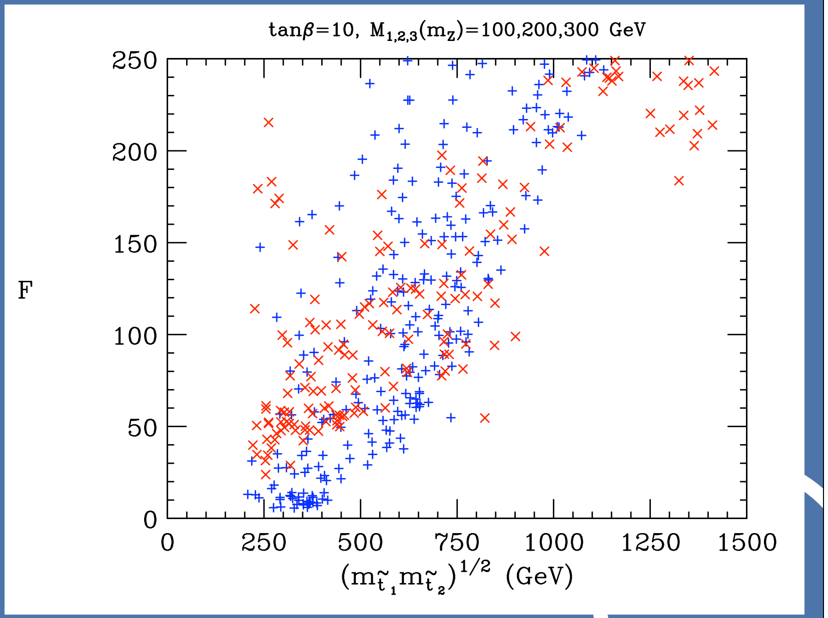
Higgs to Singlets

- In models with scalar singlets, the Higgs can decay into pairs of pseudoscalars.
- The pseudoscalar a can pick up (reduced) couplings to the SM through mixing with the Higgs itself.
- In that case, the decays depend on the a mass:
  - $m_a > 2\, m_b$:   a to bb
  - $2\, m_b > m_a > 2\, m_\tau$:   a to $\tau\tau$
  - $m_a < 2\, m_\tau$:   a to $\gamma\gamma$?
- In the NMSSM, models with h to aa can suffer from much less fine-tuning.

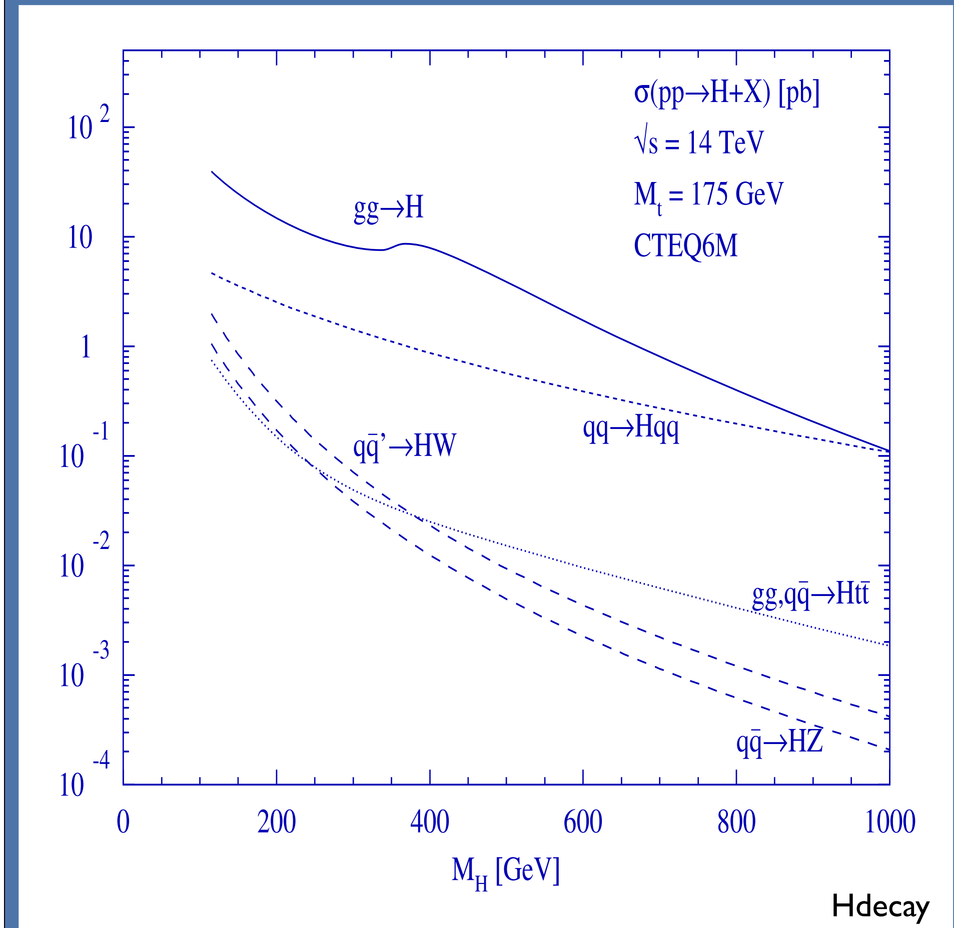
Dobrescu, Landsberg, Matchev
PRD63, 075003 (2001)

Dermisek, Gunion PRL95, 041801 (2005)

+: BR(H->ττττ) > 0.9
x: mH > 114 GeV



Production

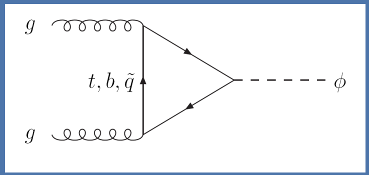


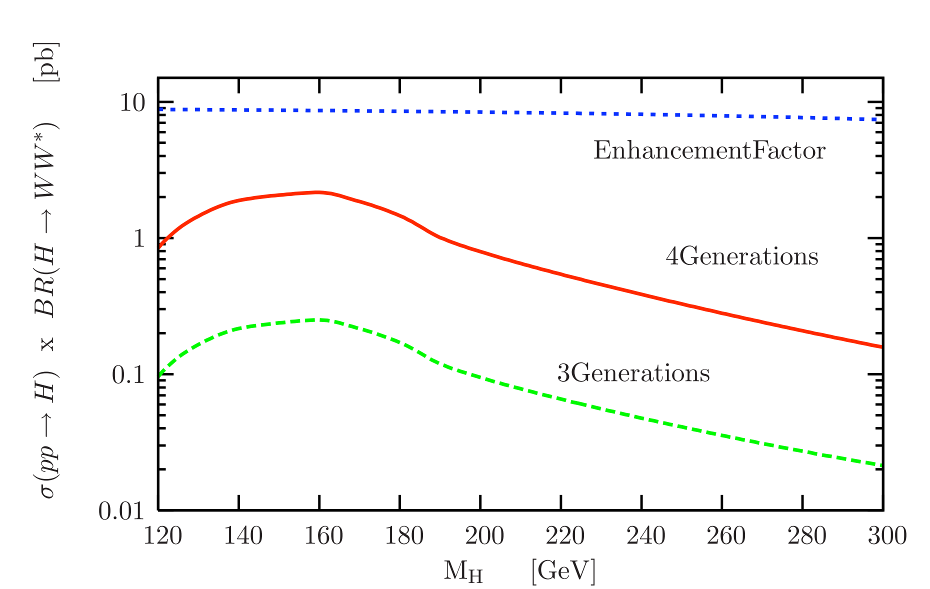
- The dominant production mechanism is gluon fusion, mediated in the SM by a loop of top quarks.
- Next larger is weak boson fusion (WBF).
- Unlike at Tevatron, the associated production with W or Z are not usually very important modes.

Gluon Fusion to Higgs

- The dominant production is through gluon fusion, because of the larger gluon PDFs at smallish x.
- That's already pretty exciting, because that process receives its leading contribution at one loop - which means there is a lot of room for new physics to contribute significantly!
- For example, a chiral fourth family for allowed masses could raise this rate by a factor of nine or so!

Gunio, McKay, Pois '96





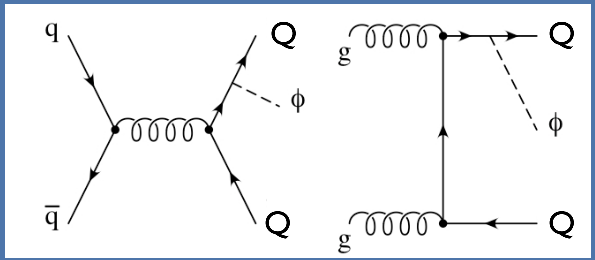
Kribs, Plehn, Spannowsky, TT '07

Weak Boson Fusion

- Weak boson fusion is an important LHC Higgs discovery mode, and also an important test of the Higgs as the agent of EWSB.
- The W-W-H vertex is a consequence of the fact that the Higgs is the agent of electroweak symmetry-breaking. It violates the usual "matter-matter-gauge" (really matter-matter-gauge-gauge) structure of gauge interactions by inserting the Higgs VEV on one of the matter lines to give a "matter-gauge-gauge" interaction.
- In a multi-Higgs doublet model, the rate can be reduced because the VEV is shared among several different scalars.

Higgs with Heavy Quarks

- We can radiate a Higgs from a heavy quark such as top or bottom.
- Production with top looks harder and harder at the LHC in the SM. Maybe by the end of the LHC we can use it for a measurement of the top Yukawa coupling.
- It also allows for novel discovery modes. An observable Higgs + bottom quarks rate would be a clear sign that the Higgs isn't SM-like, and would argue for more Higgs doublets.

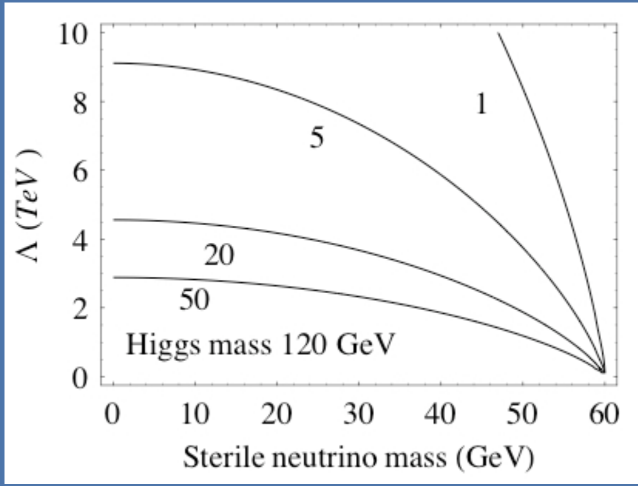


Neutrino Masses?

- The Higgs is also responsible for neutrino masses!
- This is obvious for a Dirac neutrino. It's also true for Majorana masses. The seesaw argues for natural neutrino masses with a heavy Majorana mass and large Yukawa couplings.
- But the Majorana mass doesn't need to be at a high scale. It may be accessible in Higgs decays.
- Since we don't really understand the small Yukawas in (i.e.) the charged leptons, it is easy to imagine deviations from the canonical seesaw.

$$\frac{b_{IJ}}{\Lambda} L_I L_J H H$$

$$\frac{c_{IJ}}{\Lambda} N_I N_J H^\dagger H$$



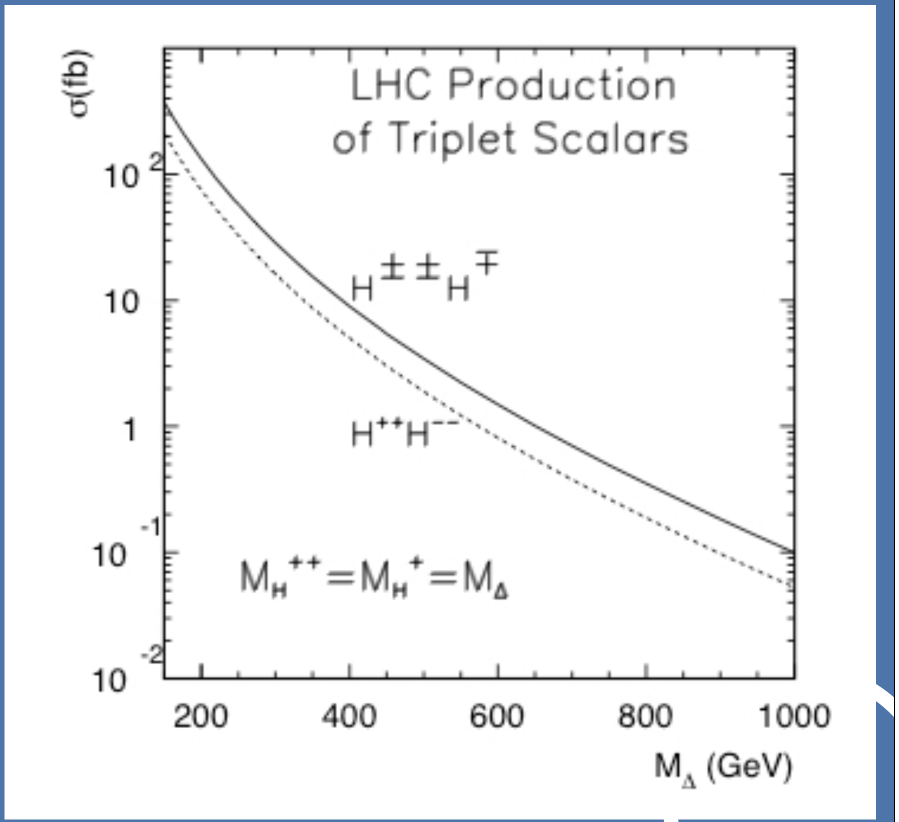
Contours of
Γ(h -> NN) / Γ(h->bb)

Graesser, '07

Triplet Higgses

- Beyond the right-handed neutrino, one can induce neutrino masses by including an EW triplet Higgs carrying hypercharge.
- It can be produced as pairs of $H^{++}H^{--}$ or through a W boson into i.e. $H^{++}H^{-}$.
- Decays into two like-sign leptons can produce a very distinct signature!

Perez, Han, Huang, Li, Wang '08



SUSY Higgs Mass

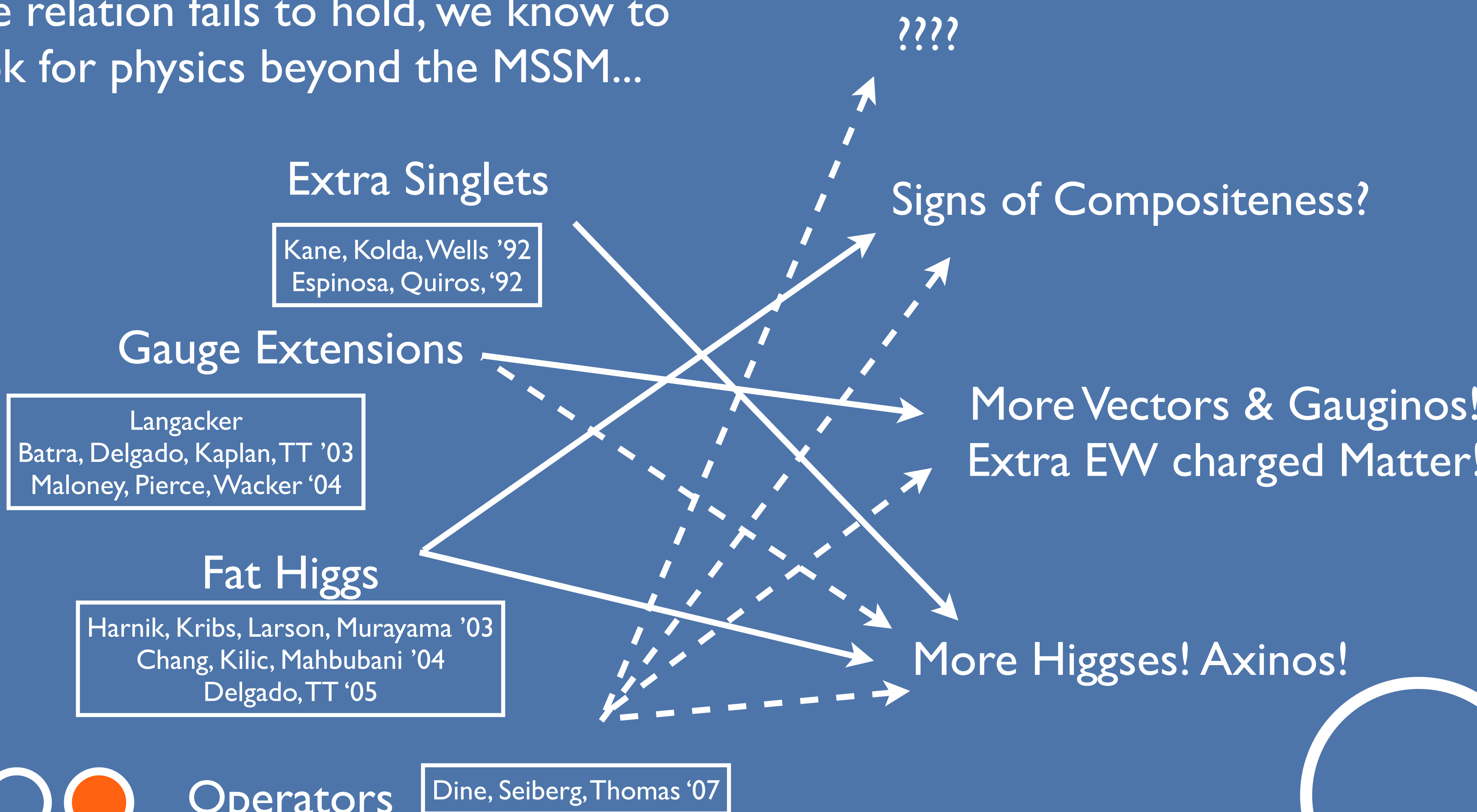
- In the MSSM, the Higgs quartic is related by supersymmetry to the EW gauge couplings.
- There are further large corrections from supersymmetry breaking through the top/stop loops.

$$m_h^2 = (g_1^2 + g_2^2) v^2 \cos^2 2\beta + \frac{3 m_t^4}{8\pi^2 v^2} \left[\log \frac{m_{\tilde{t}}^2}{m_t^2} + \text{mixing} \right] + \ldots$$

- Even if we see evidence of supersymmetric partners, verifying the MSSM mass relation tells us something about whether the MSSM is a good low energy description!

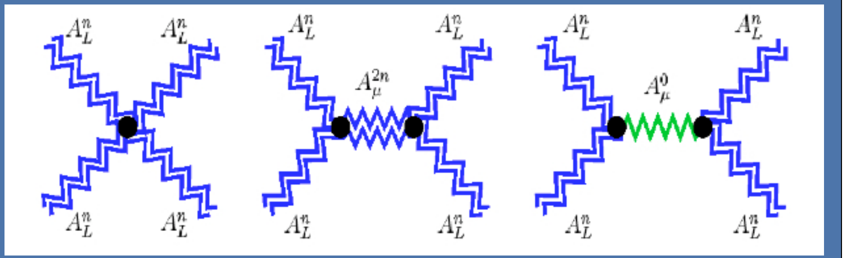
Beyond the MSSM?!

If the relation fails to hold, we know to look for physics beyond the MSSM...



No Higgs at All?

- We could find no Higgs! WW scattering could be unitarized by vectors particles such as a Tecnirho or the KK modes of a Higgsless theory.



- Much of the work on such theories lives in warped space...

Cacciapaglia, Csaki, Grojean, Hubisz, Pilo, Marandella, Murayama, Shirman, Terning '04-'06

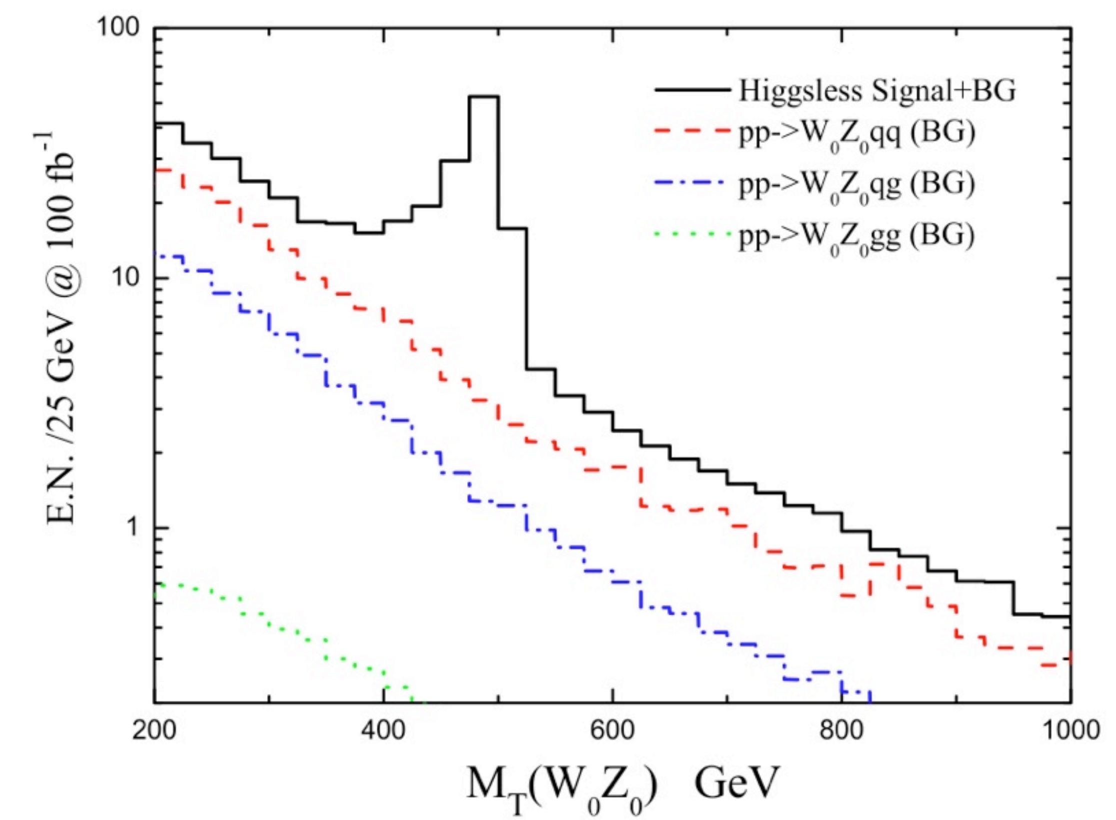
- But one can also deconstruct into a "three site moose model".

Belyaev, Chivukula, Coleppa, DiChiara, He, Kuang, Kurachi, Matsuzaki, Pukhov, Qi, Simmons, Tanabashi, Zhang '06-'07
(Talks by Simmons and Coleppa on Monday)

- Either way, consistency demands small couplings of the new vectors to light fermions.

Higgsless W' Signal

- Despite the weak couplings to light fermions, one can search for the new resonances either in WBF or produced in association with a light electroweak boson.



Outlook

- A Higgs boson can tell us a lot!
- The basic properties we want to understand are the role it plays in electroweak symmetry-breaking and whether it is responsible for unitarizing WW scattering.
- What we know about the SM Higgs picture argues for new physics, and it is easy to believe the Higgs is our best hope for a "portal" into a hidden sector.

Outlook

- The LHC can discover a SM Higgs produced through many process, and in many decay modes. Putting these together can verify the SM picture, or provide a clue as to how the SM is breaking down.
- Even the mass of the Higgs is interesting, perhaps allowing us to use the precision EW data to guess the form of new physics, or to test 'how minimal' the MSSM has turned out to be!

And most of all....

Discovering the Higgs will make people happy!