Discovery scenarios for the first 10 fb^{-1}

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University of Regina – August 13, 2007

This talk: a theorist's overview of possible discovery scenarios in the "early phase" of LHC running, based on the recent workshop:

The workshop also addressed implications for ILC, but I'll focus on just the LHC aspects.

Outline

I'll consider four classes of possible signals at the early phase ($\equiv 10$ fb^{-1}) of the LHC.

1) Only one state, SM-like Higgs boson

2) No Higgs boson detected (yet?)

3) Leptonic resonances and/or multi-gauge-boson signals

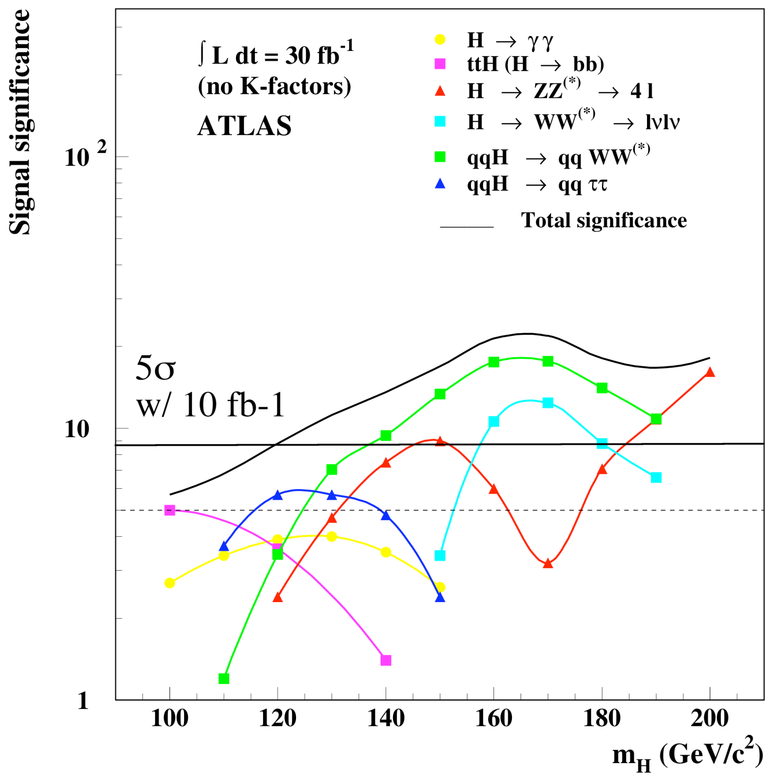
4) Missing energy (+ leptons, jets)

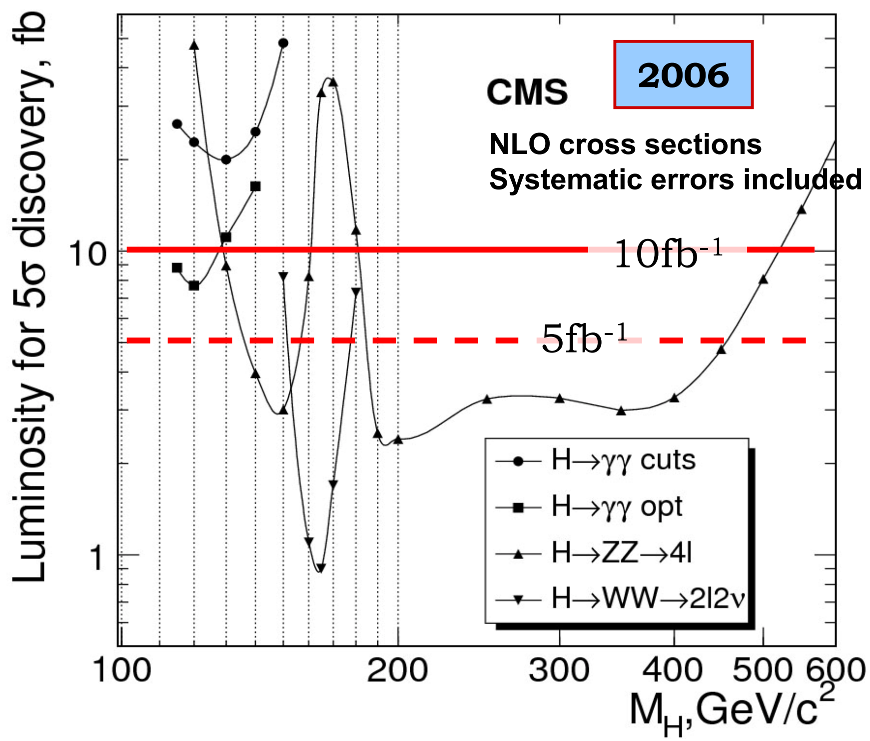
For each of these I'll give:

- Very brief summary of experimental prospects
- Implications for theory

1) Only one state, SM-like Higgs boson

What will we know? – Discovery modes: depend on M_H



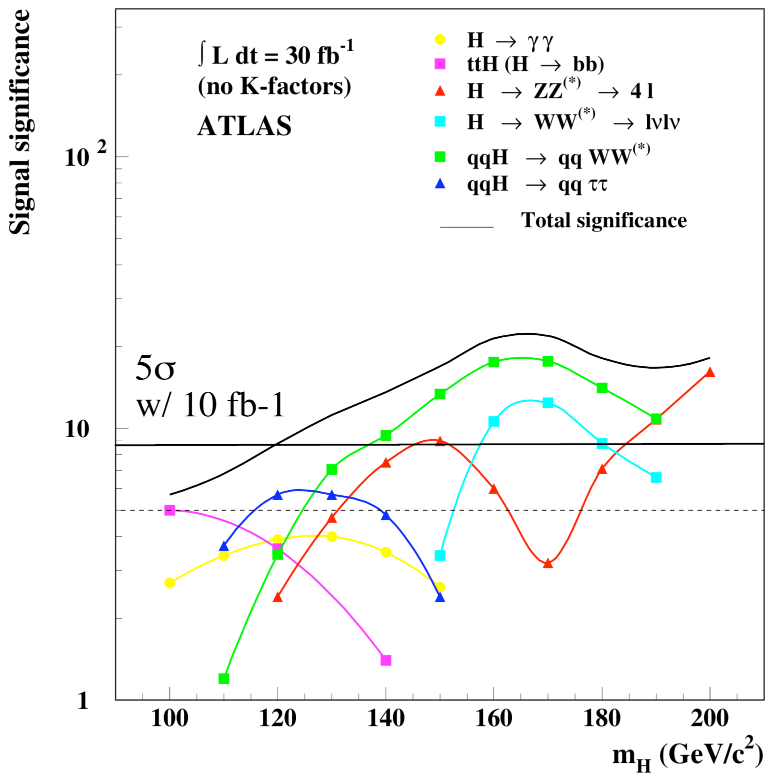


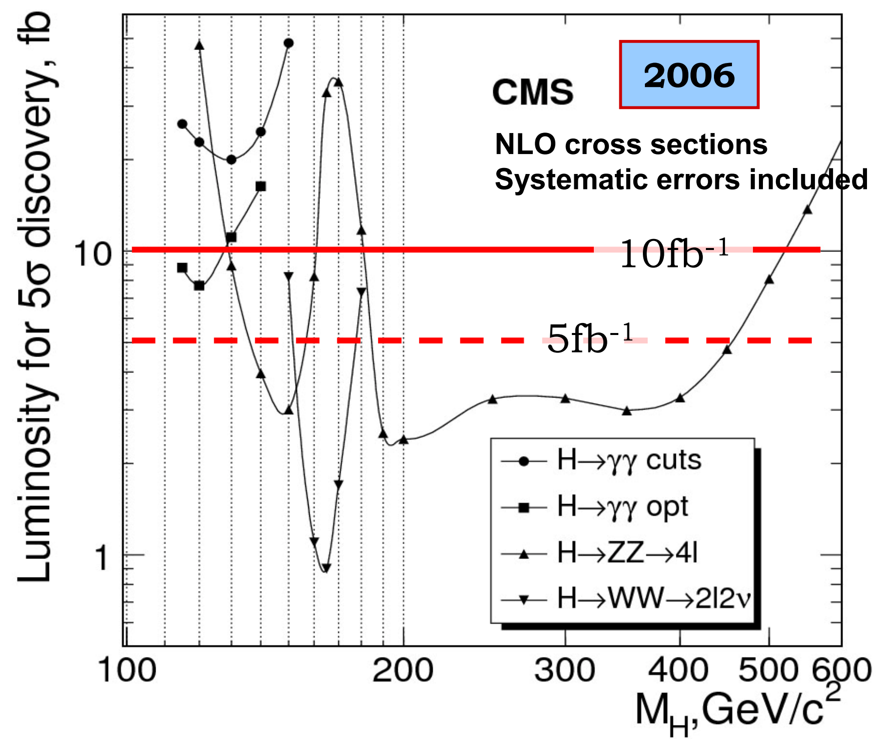
Expt updates:

- $\gamma\gamma$: NLO signal & background; new ATLAS analysis comparable to CMS
- $t\bar{t}H$, $H \to b\bar{b}$ more pessimistic: systematics, BG, full det sim

Theory update: `PROPHECY4F` NLO MC for $H \to WW, ZZ \to 4f$

What will we know? – Discovery modes: depend on M_H





Inclusive $H \to \gamma\gamma$ for 115–130 GeV → good mass meas

WBF → $H \to WW$ for 135–190 GeV

Inclusive $H \to WW \to 2\ell 2\nu$ for 150–180 GeV

Inclusive $H \to ZZ \to 4\ell$ for 130–160, 180+ GeV → good mass meas

Evidence in WBF → $H \to \tau\tau$ for 115–140 GeV

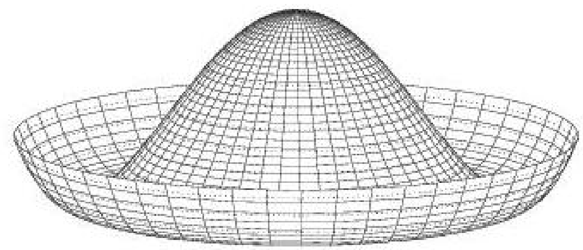
Evidence in $t\bar{t}H(H \to b\bar{b})$ for ∼ 115 GeV

What is a Higgs?

- Scalar particle, CP-even, neutral component of an electroweak doublet.

- Gives mass to the SM particles via the Higgs mechanism

  - It is the excitation along the "radial direction" of the EWSB condensate: $\Phi \sim (v + h)$



The Standard Model Higgs:

One field alone accomplishes EWSB; the Higgs doesn't mix with any other states.

Beyond the Standard Model:

Can have more than one Higgs field. "Higgs-like" state typically a mixture of the vev-carrying doublet and some other scalar field(s).
Typically get additional neutral scalars – CP-odd, etc.
Higgs can be a bound state – composite object.

Does our new state looks like the SM Higgs?

Spin-zero?

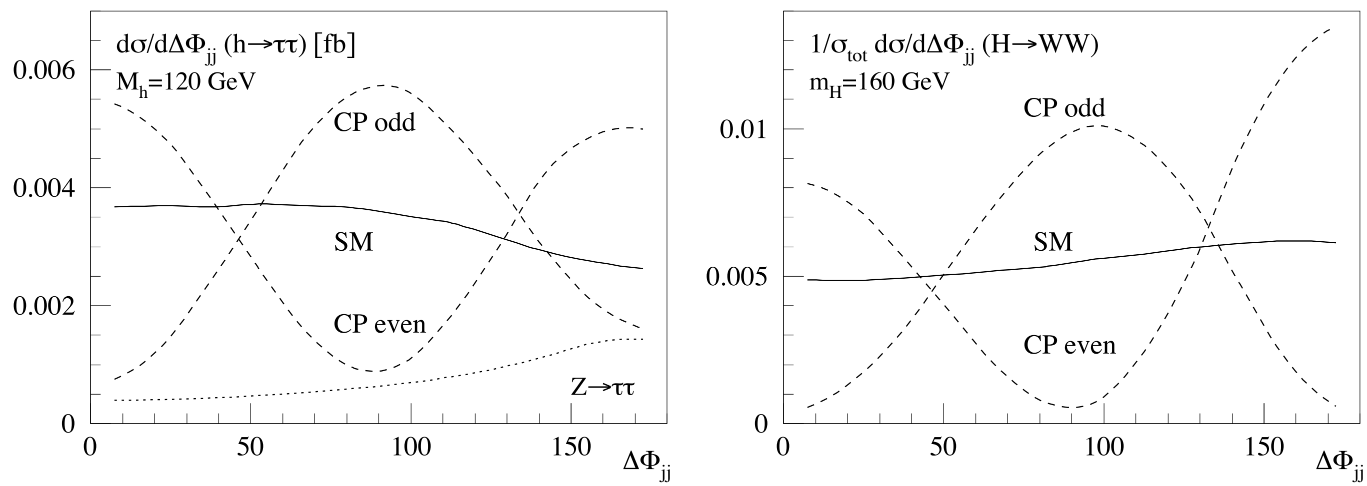
Landau-Yang theorem: $V \not\to \gamma\gamma$.

$H \to WW \to 2\ell 2\nu$, $H \to ZZ \to 4\ell$: VV polarizations give characteristic dist'n of final-state leptons.

CP-even?

WBF production measures vertex structure

SM $g^{\mu\nu}$ vs. CP-even $\Phi W^{\mu\nu} W_{\mu\nu}$ vs. CP-odd $\Phi W^{\mu\nu} \widetilde{W}_{\mu\nu}$



Need about 10x lumi past discovery to bin ϕ_{jj}.

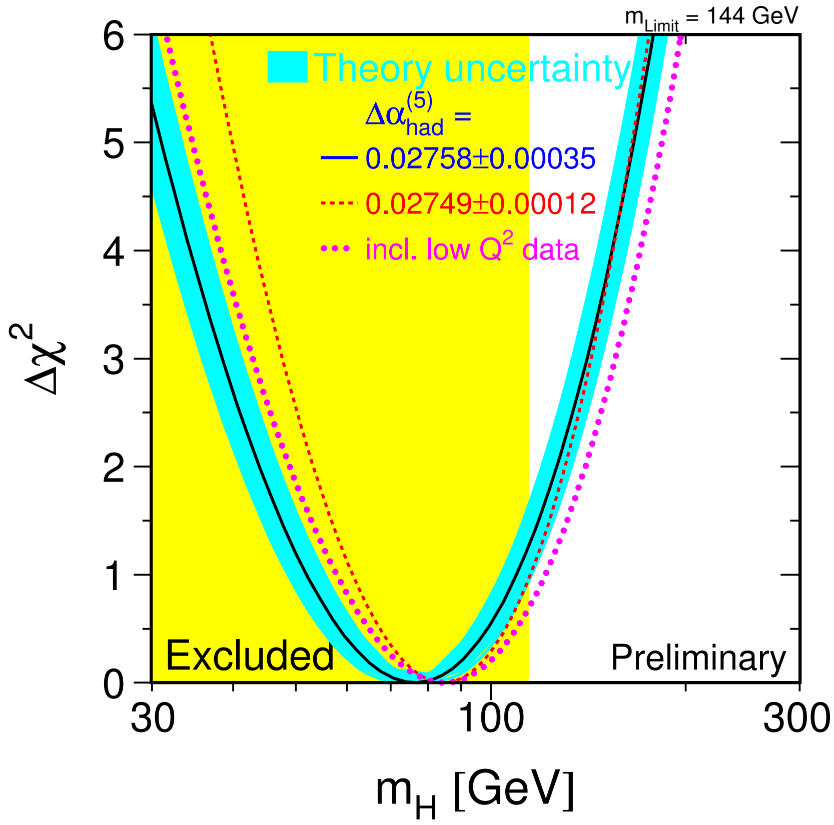
Rates in observed channels consistent with SM Higgs?

Higgs mass:

Check that Higgs mass is consistent with SM electroweak fit.

EW precision fit *within the SM* favors a light Higgs $M_H \lesssim$ 150–200 GeV.

If we discover a SM-like Higgs well above 200 GeV, something BSM is going on.



Winter 2007

There are still a wide variety of BSM possibilities.

SUSY
- MSSM
- NMSSM and other extensions
- Fat Higgs, etc.

Composite Higgs
- Topcolor
- Little Higgs (various models)
- Randall-Sundrum

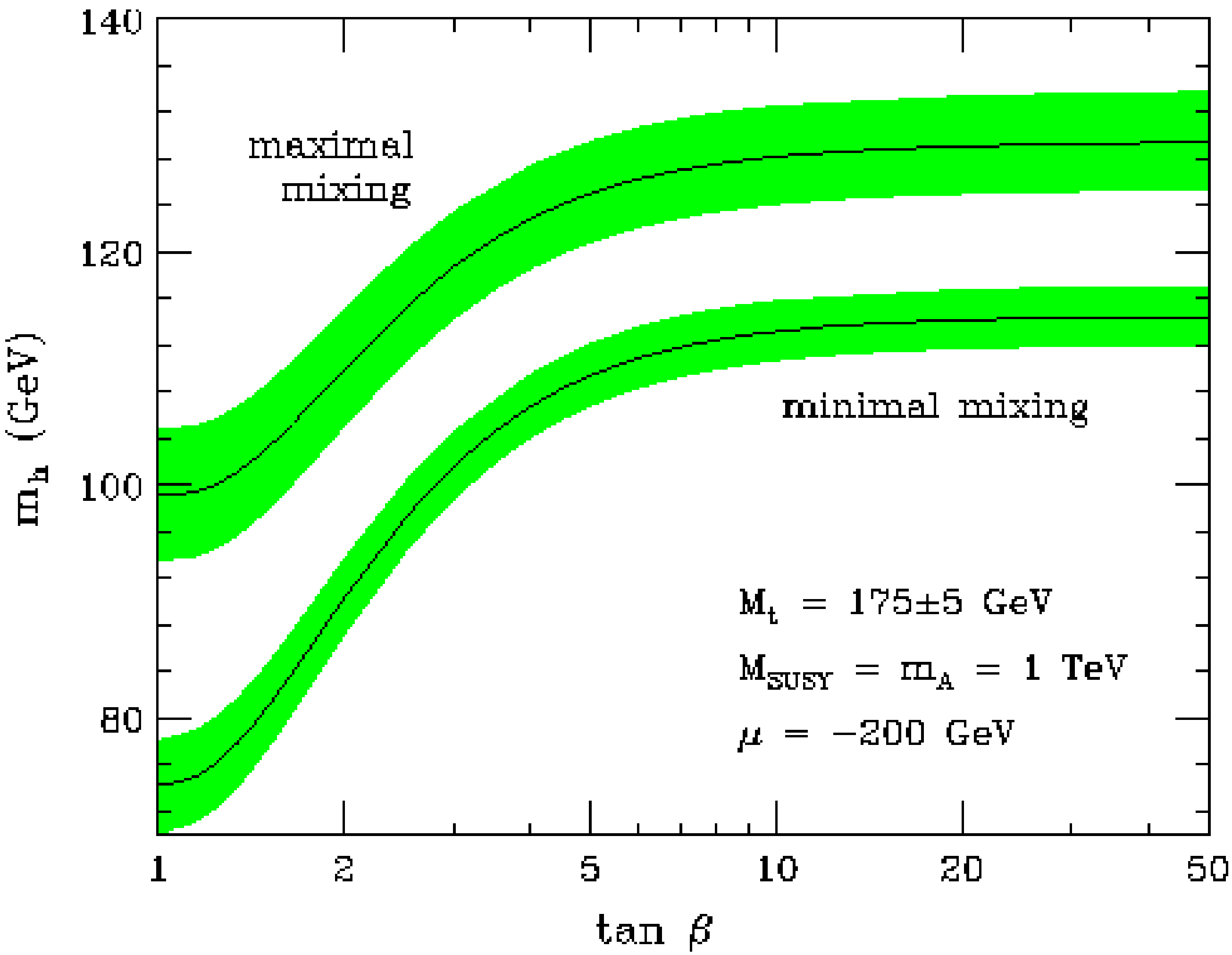
Extra Dimensions
- Large extra dimension(s) / ADD
- Universal extra dimension(s)
- Radion

Generic models with extra scalar multiplets

[Left out: Technicolor, Higgsless models – no SM-like Higgs!]

Higgs mass measurement will favor or disfavor various models.

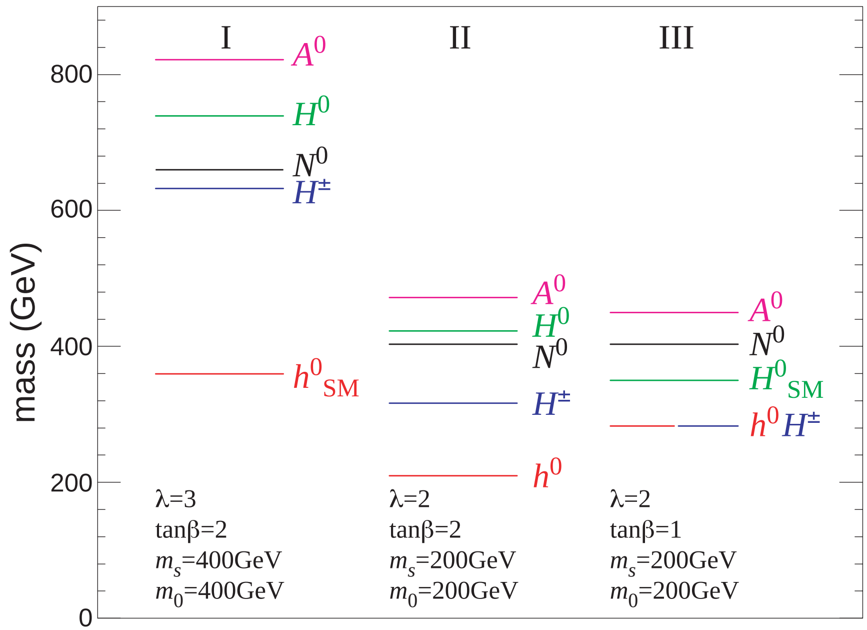
The MSSM is only really viable for $m_h \lesssim 135$ GeV...

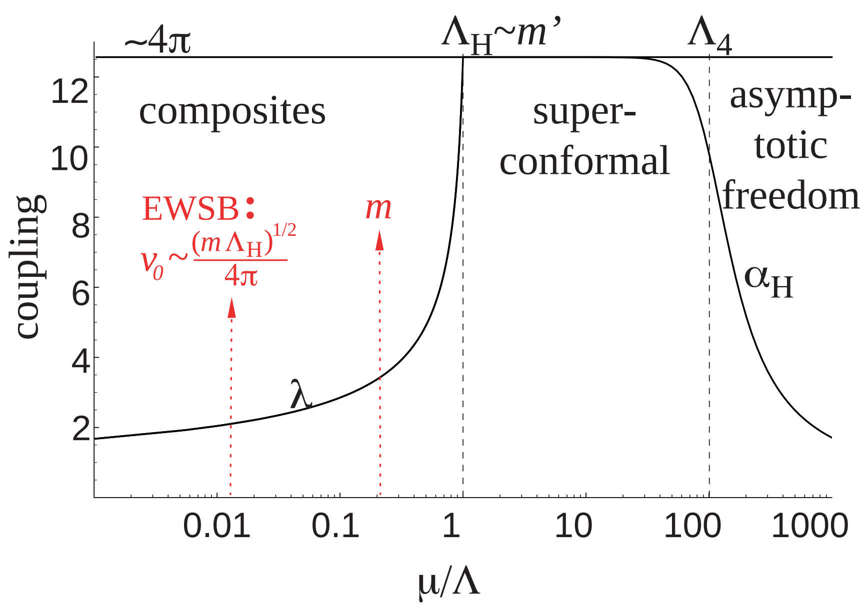


Carena & Haber, hep-ph/0208209

Higgs mass measurement will favor or disfavor various models.

...whereas the supersymmetric "Fat Higgs" model prefers a heavier SM-like Higgs...

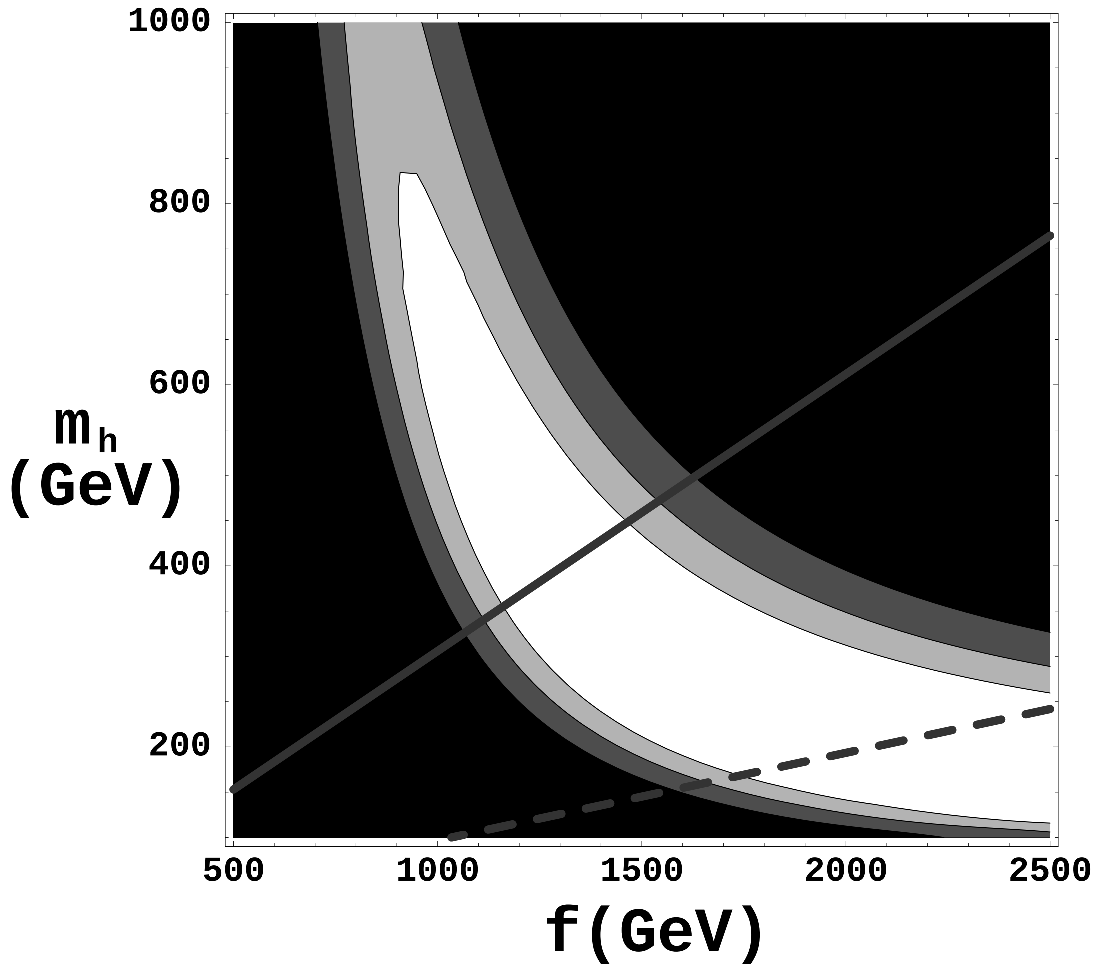




Harnik, Kribs, Larson, Murayama, hep-ph/0311349

Higgs mass measurement will favor or disfavor various models.

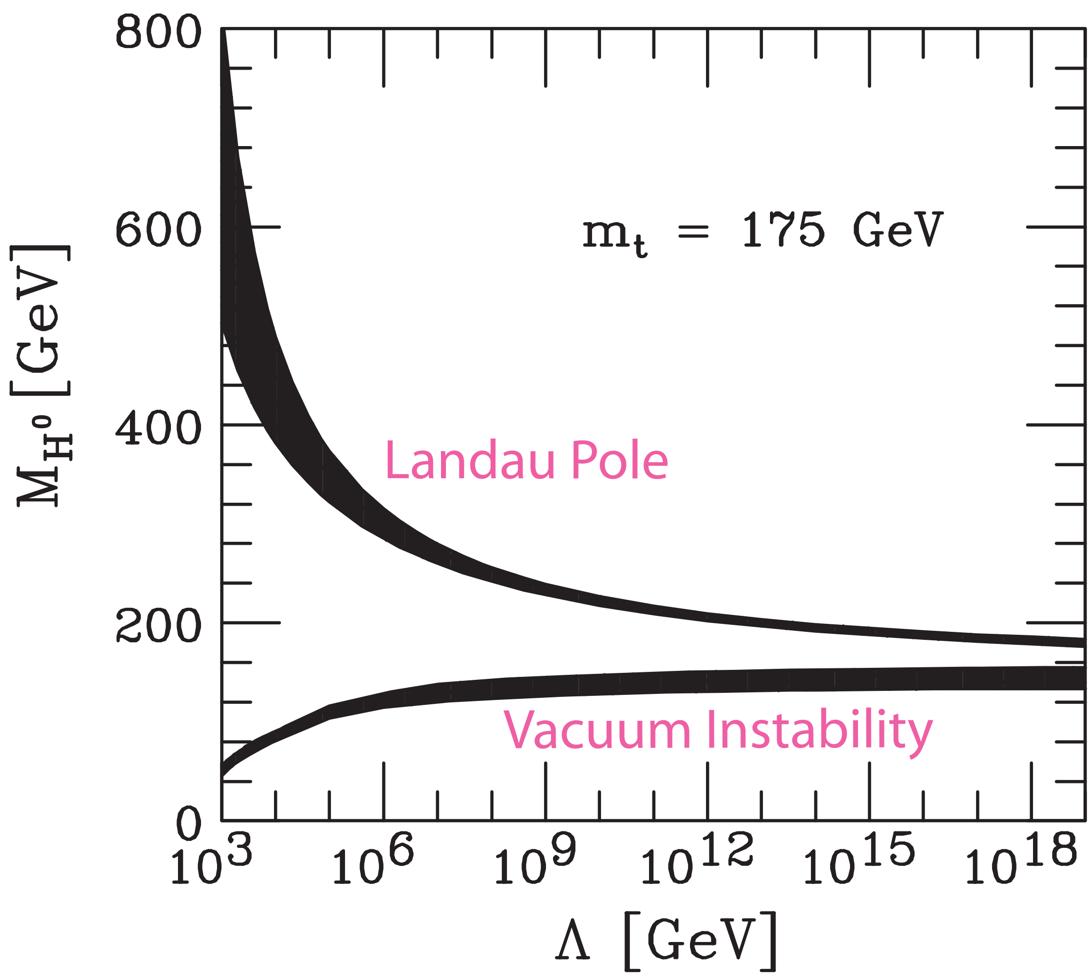
...and Little Higgs w/ T-parity is least fine-tuned for $m_H \gtrsim 350$ GeV.



Hubisz, Meade, Noble, Perelstein, hep-ph/0506042

Higgs mass measurement will favor or disfavor various models.

Even the "Standard Model All the Way Up" is only viable for $140 \lesssim m_H \lesssim 180$ GeV.



Landau Pole:

Higgs self-coupling too large; blows up at scale Λ

Vacuum Instability:

Higgs self-coupling too small; runs negative at scale Λ

[PDG 2002]

Early LHC Higgs data will already slash the parameter space of all the models.

Measurement of the Higgs mass will reduce parameter space dimensionality by one.

Non-observation of additional states would further constrain the parameter space.

More generic constraints

Higgs observation in SM mode(s) rules out overwhelming non-standard decay mode.

- No $h \to aa$ in NMSSM
- No $h \to$ jets (e.g., via very light sbottoms)
- No invisibly-decaying Higgs

5σ discovery $\leftrightarrow$ 20% measurement of relevant rate

- Inclusive $H \to \gamma\gamma$ for 115–130 GeV
- Inclusive $H \to ZZ$ for 130–160 and 180+ GeV
- Inclusive $H \to WW$ for 150–180 GeV
- WBF $\to H \to WW$ for 135–190 GeV

Can establish consistency with Standard Model.

Rate measurement: $\sigma \times$ BR.
BR $\leq 1 \to$ lower bound on σ.
No upper bound on σ: can dial couplings to reproduce observed rates.

The "Higgs Questions": Responsible for EWSB?
Does the new state give rise to the W, Z masses?

Tree-level HWW, HZZ couplings possible only if H carries a vev:

SM: $\mathcal{L} = |\mathcal{D}_\mu H|^2 \longrightarrow (g^2/4)(h+v)^2 W^+ W^- + (g_Z^2/8)(h+v)^2 ZZ$

HWW, HZZ couplings $\sim g^2 v$, times a possible group-theory coefficient from SU(2) multiplets larger than doublets.

$\mathcal{L} = |\mathcal{D}_\mu \Phi|^2 \longrightarrow$
$(g^2/4)[2T(T+1) - Y^2/2](\phi+v)^2 W^+ W^- + (g_Z^2/8) Y^2 (\phi+v)^2 ZZ$

Constraints from ρ parameter can be evaded by monkeying around with representations and vevs. $Q = T^3 + Y/2$

SU(2) doublets only: sum rule $\sum_{\phi_i} g^2_{\phi_i WW} = g^2_{H_{\rm SM} WW}$
Larger multiplets: sum rule violated

Compared to SM HWW, HZZ:
- Can get enhancements from group-theory factors
- Can get suppressions by mixing angles

Constraints from early LHC data:

WBF $\rightarrow H \rightarrow WW$ for 135–190 GeV puts a lower bound on HWW coupling (from production rate, since decay BR $\leq$ 100%)

Small overlap in Inclusive $H \rightarrow WW$ and Inclusive $H \rightarrow ZZ$ for 150–160 GeV: can measure ratio of rates
$\rightarrow$ ratio of HWW and HZZ couplings-squared.

Higher mass: direct measurement of Higgs width bounds the inclusive production coupling: puts a (weak) lower bound on HZZ coupling.
Rate $= \sigma(gg \rightarrow H)\Gamma(H \rightarrow ZZ)/\Gamma_{\text{tot}}$; $\quad \Gamma(H \rightarrow gg) \leq \Gamma_{\text{tot}}$

Rates provide SM check.
But general models will not be very constrained.

The "Higgs Questions": Responsible for fermion masses?

Tree-level fermion masses can come only from a Higgs doublet.

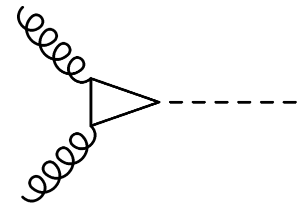
SM: $\mathcal{L} = (y_f/\sqrt{2})(h+v)\bar{f}_R f_L + \text{h.c.}$

Only access to fermion couplings in early LHC data is from:
- nonobservation of fermionic decay modes
- nonobservation of associated production (e.g., bbH)
- observation of inclusive production.
- evidence in WBF $\to H \to \tau\tau$; $t\bar{t}H$ ($H \to b\bar{b}$)?

Inclusive production must come from:
- gluon fusion
- weak boson fusion *
- associated production with W, Z, quark(s) *

* These two can be tagged.

Gluon fusion via loop of colored particles:



- quarks in SM: first window on $t\bar{t}H$.
- extra contributions in BSM (e.g., squarks), constrained by direct new-particle searches.

Can check ratio of Inclusive to WBF cross sections for 135–190 GeV – constrain Hgg vs. HWW couplings.

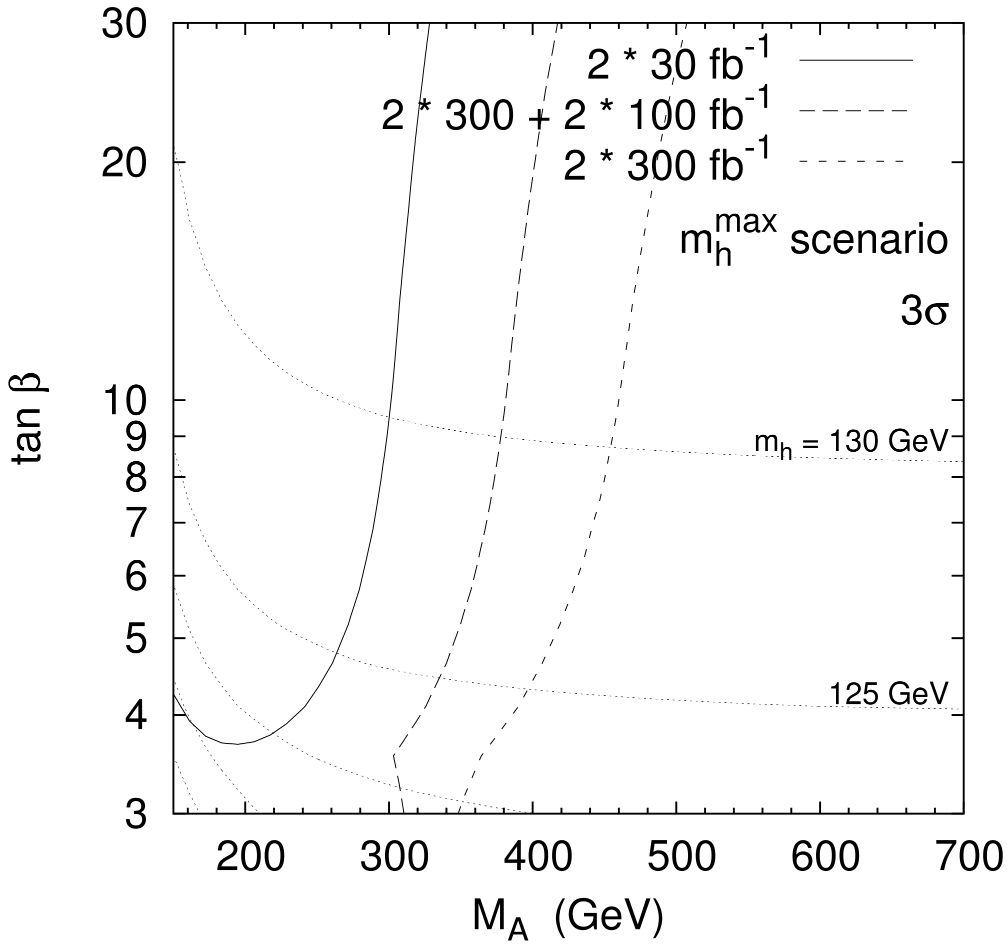
$H \to \gamma\gamma$ decay goes via loop of charged particles:
- SM: W loop dominant, t loop $\sim$ 30% destructive interference.
- Add possible loops of charged, color-neutral BSM particles.
- Rest of amplitude is same as $gg \to H$, but with color factors replaced by charges.

Exception: Radion (g_{55} in RS models; mixes with Higgs)
- Couples to the trace of the stress-energy tensor T^{μ}_{μ}.
- Couples to gg, $\gamma\gamma$ through SM loops AND through the trace anomaly – contributions to the coupling amplitude proportional to SU(3), SU(2), U(1) beta-functions.

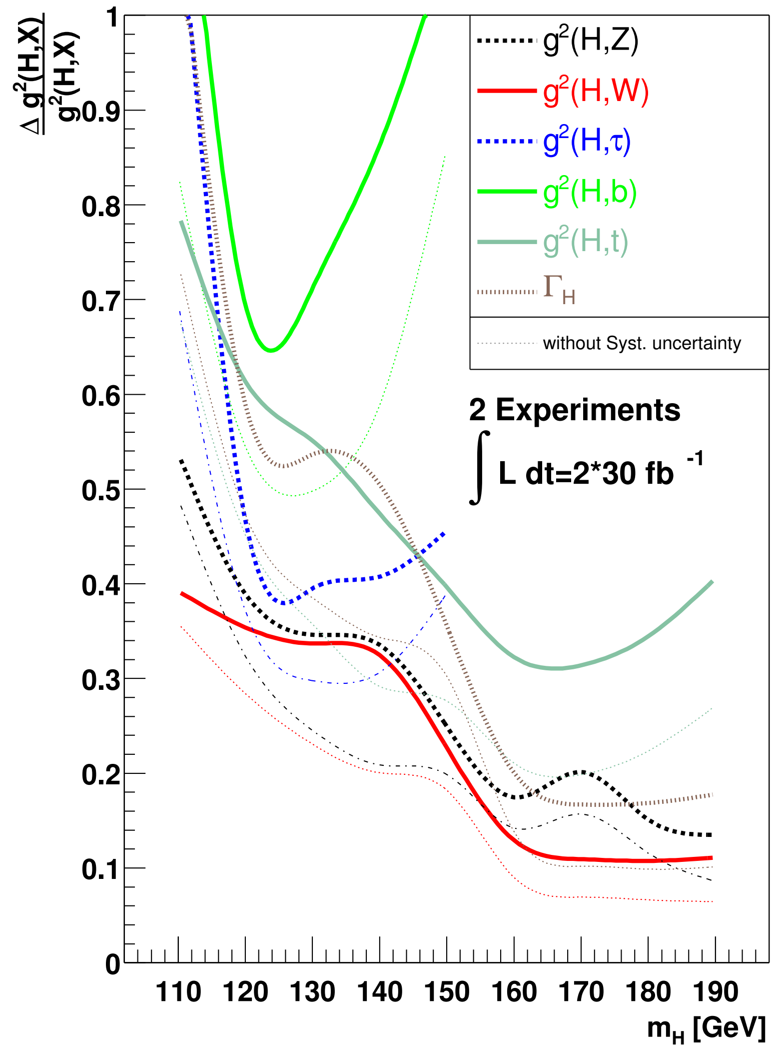
Not enough constraints in LHC Early Phase: can always tune parameters to reproduce SM rates in few observed channels.

Can still constrain models.

Need theory assumption to fit Higgs couplings: $g^2_{\phi VV} \leq g^2_{H_{SM}VV}$



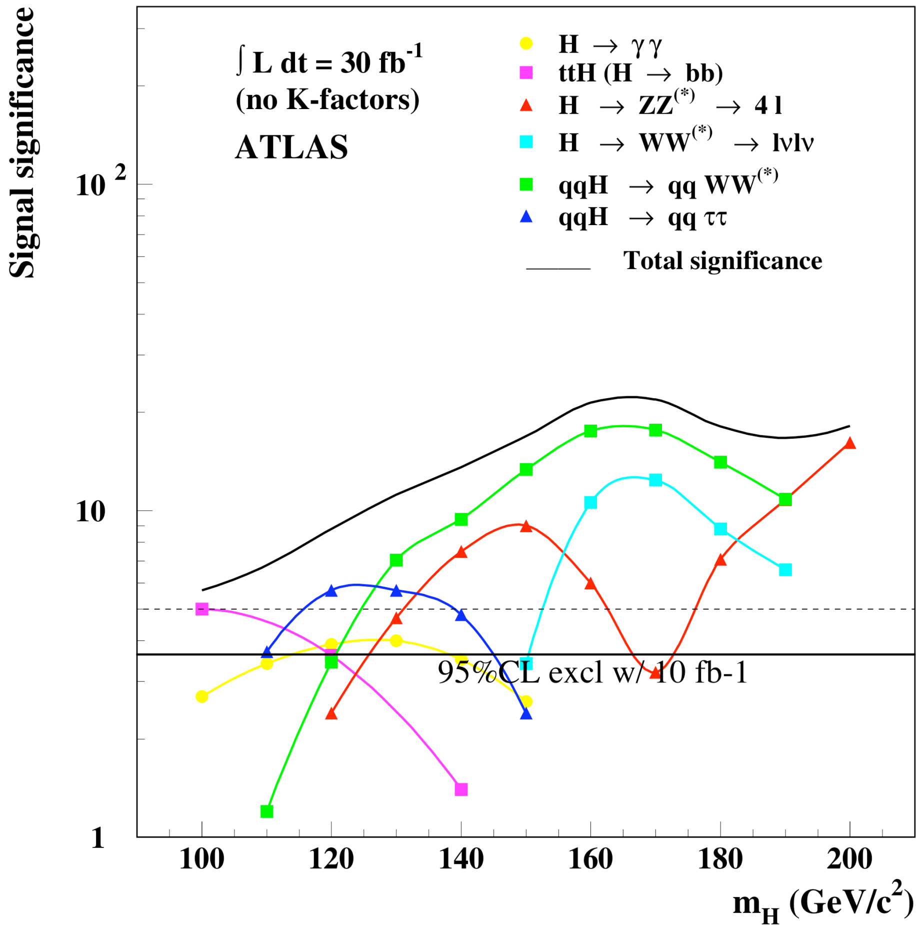
$30\ \text{fb}^{-1} \times 2$ detectors



Dührssen, Heinemeyer, H.L., Rainwater, Weiglein & Zeppenfeld, hep-ph/0406323

2) No Higgs boson detected (yet?)

What will we know? – Discovery modes: depend on M_H



No Higgs with 10 fb^{-1} means the Higgs is not SM-like.

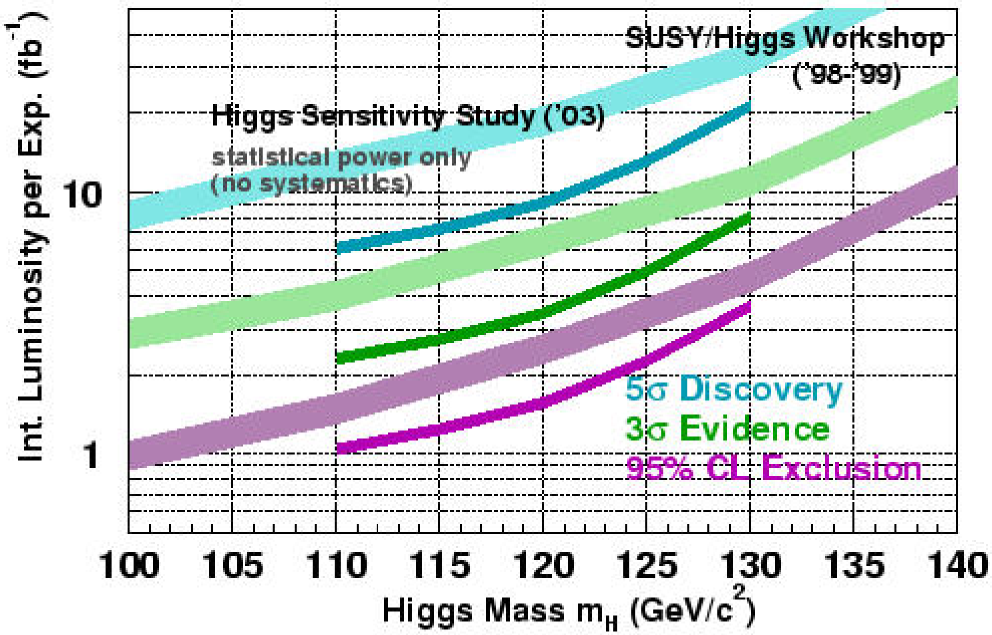
Possibilities:

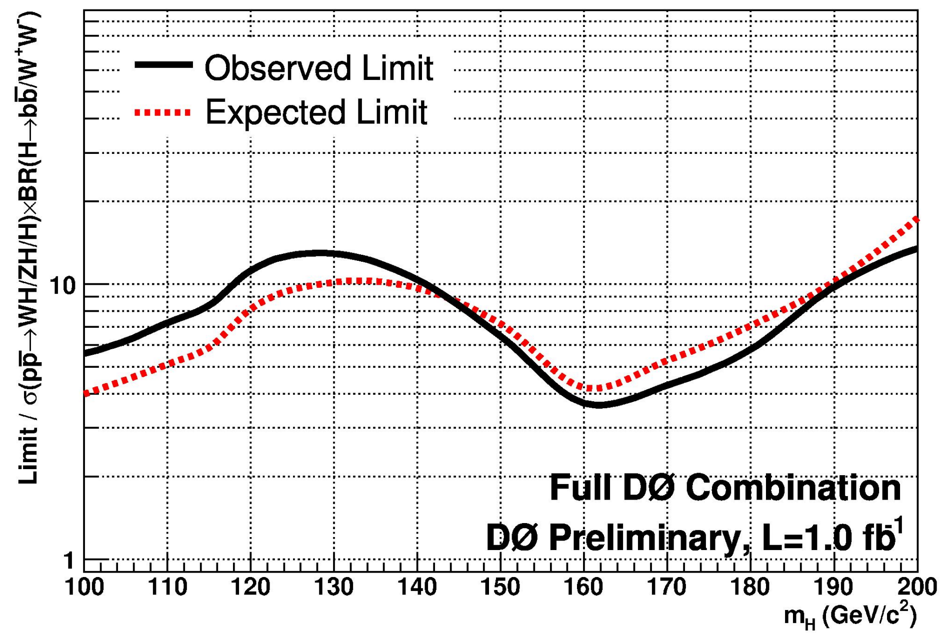
1) There is $\geq$ 1 Higgs, but it escaped detection in first 10 fb^{-1}.

2) There truly is no Higgs boson.

Evade 95%CL exclusion by scaling down SM rates by $\sim$ 6x at 120 GeV.

Tevatron will add exclusion channels at “weak” low-M_H end.





Not quite there yet...

How could a Higgs be missed?

Production cross section could be suppressed.

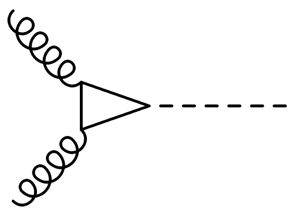
Multi-Higgs-doublet models:

HWW, HZZ couplings shared among more than one state.
Sum rule: $\sum g^2_{H_i VV} = g^2_{H_{SM} VV}$; affects VBF modes.
Hard to suppress all by $\geq$ 6x without lots of mixed doublets.
All those come with pseudoscalars, $H^\pm$

$\Rightarrow$ other signatures.

General extended models:

New particles run in the loop for $gg \to H$:
can suppress gluon fusion modes.



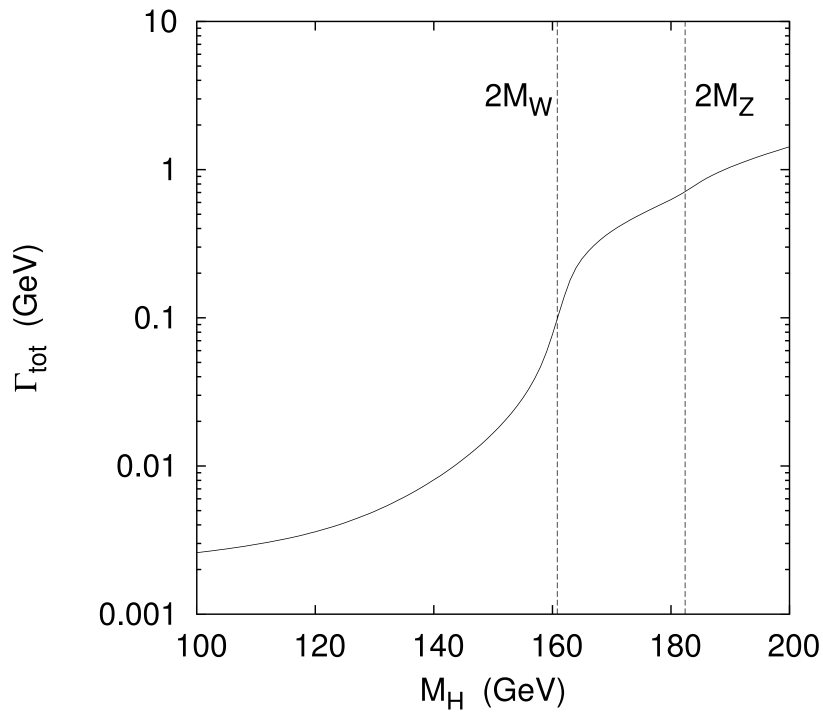
Need relatively light new states to get significant suppression:

$\Rightarrow$ other signatures.

How could a Higgs be missed?

SM Higgs is very narrow below WW threshold:
few MeV $\sim$ tens of MeV

Any new exotic decay mode:
light Higgs BRs very susceptible to suppression.



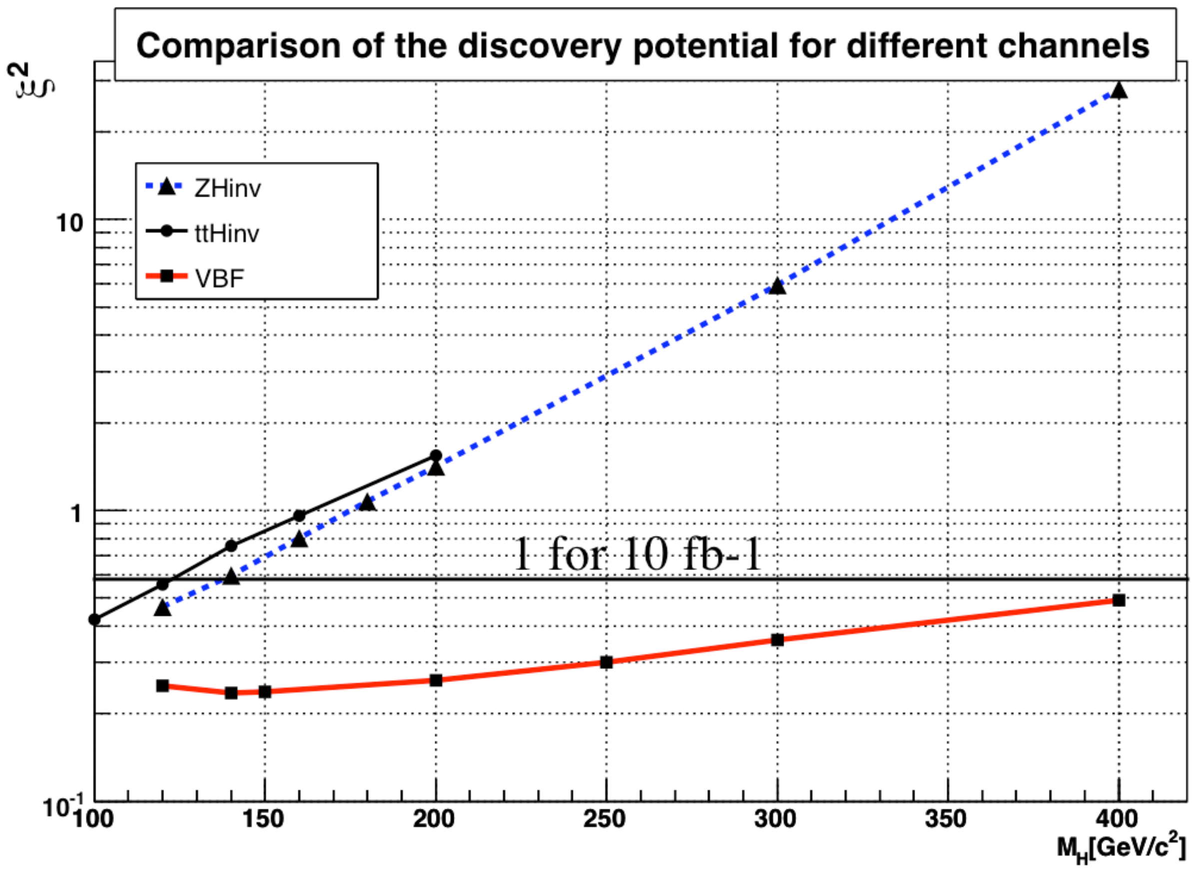
Evade 95%CL exclusion by scaling down SM rates by $\sim$ 6x at 120 GeV:

Doable with new coupling only $\sim$ 2.5–3 x bottom quark Yukawa.

Invisibly-decaying Higgs? H $\rightarrow$ dark matter particles?

Exclusion: strongest limit will be from Vector Boson Fusion.

ξ^2 is a scaling factor: $\sigma \times \mathrm{BR}(H \rightarrow \mathrm{invis}) \equiv \xi^2 \sigma_{\mathrm{SM}}$



ZH_{inv} uses $Z \rightarrow \ell^+\ell^-$

VBF looks very promising, but it's not clear how well those events can be triggered

$t\bar{t}H_{\mathrm{inv}}$ – may be room for improvement?

95% CL exclusion limits with 30 fb^{-1} at LHC [ATL-PHYS-PUB-2006-009]

Theory progress: signal, VBF $\rightarrow Z$, Zjj, Wjj all NLO QCD.

To reduce SM decays by $\sim$ 6x, need BR(inv) $\gtrsim$ 80% $\Rightarrow$ excluded.

Other exotic decays?

Example: MSSM + singlet (=NMSSM)

- Extra singlet $\Rightarrow$ extra scalar, pseudoscalar, and neutralino
- Lightest pseudoscalar a can be very light:
  can have $h \to aa$ as dominant Higgs decay mode.

Question becomes how does a decay.

$M_a > 2m_b$: $a \to b\bar{b}$, $h \to aa \to 4b$

$2m_b > M_a > 2m_\tau$: $a \to \tau\tau$, $h \to aa \to 4\tau$

$2m_\tau > M_a$: $a \to \gamma\gamma$ can be important.

a's highly boosted: can look like *one* photon.

Specialized searches needed.

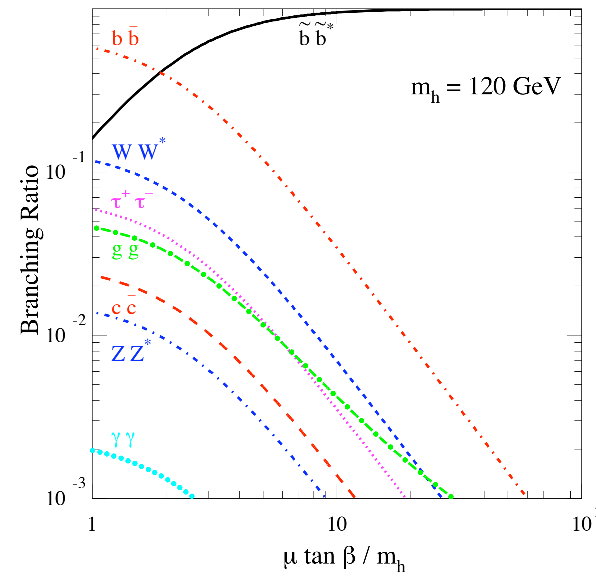
But, have whole SUSY spectrum to look for too.

Other exotic decays?

Example: MSSM with superlight sbottoms & gluinos (5–15 GeV)

Motivated by old $2b$ excess at Tevatron

$\tilde{b}_1$ either long-lived or decays hadronically (R-parity violated)



BR($h \to \tilde{b}_1 \tilde{b}_1^*$) $\sim$ 100%:

looks like $h \to$ jets

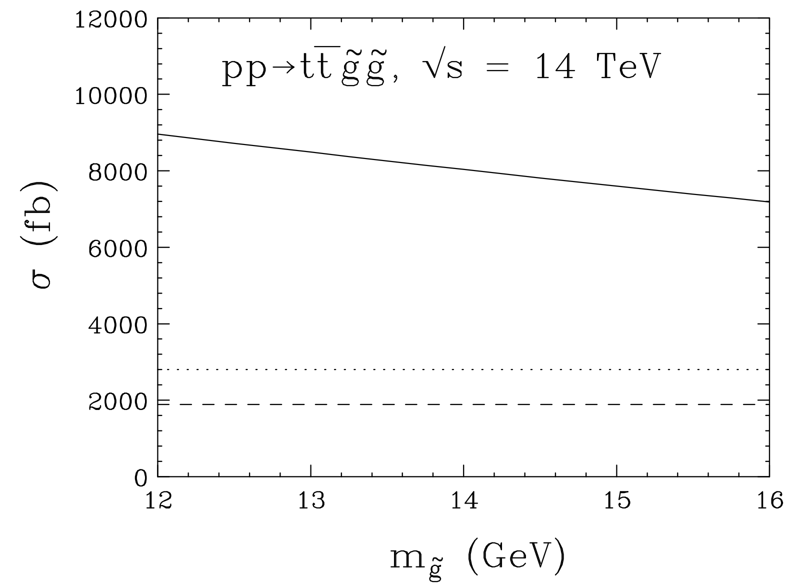
Hopelessly buried in background!

Berger, Chiang, Jiang, Tait, Wagner, hep-ph/0205342

Instead, look for $t\bar{t}b\bar{b}$:

Leibovich & Rainwater, hep-ph/0202174

- Large cross section for $t\bar{t}\tilde{g}\tilde{g}$
- $\tilde{g}$ decays promptly to $b\tilde{b}_1$



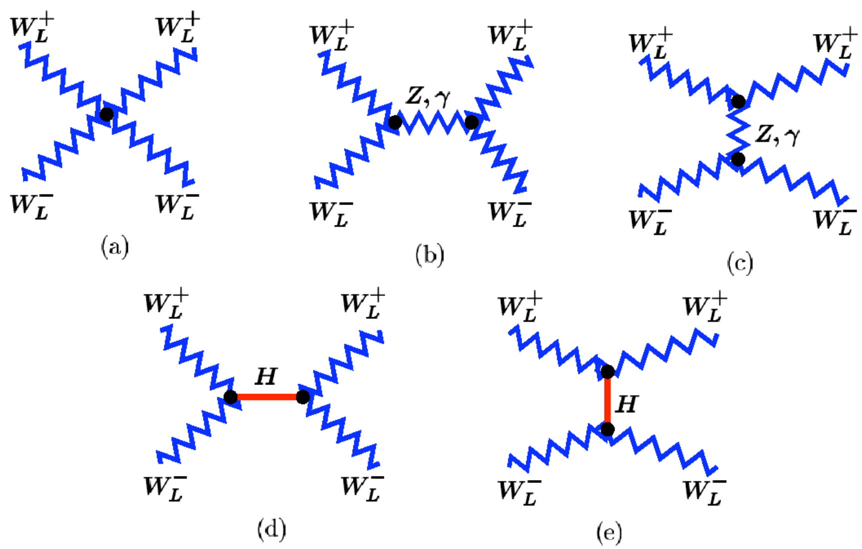
Again, $\exists$ other channels, and have whole SUSY spectrum too.

What if there's really no Higgs?

$\Rightarrow$ Problems with SM unitarity in WW scattering

Why a Higgs?

SU(2) x U(1) @ E^2



Graphs	$g^2 \frac{E^2}{m_w^2}$
(a)	$+2 - 6\cos\theta$
(b)	$-\cos\theta$
(c)	$-\frac{3}{2} + \frac{15}{2}\cos\theta$
(d + e)	$-\frac{1}{2} - \frac{1}{2}\cos\theta$
Sum including (d+e)	**0**

- $\mathcal{O}(E^0) \Rightarrow$ 4d m_H bound: $m_H < \sqrt{16\pi/3}\, v \simeq 1.0$ TeV
- If no Higgs $\Rightarrow \mathcal{O}(E^2) \Rightarrow E < \sqrt{8\pi} v \simeq 1.2\,\mathrm{TeV}$

Chivukula, LHC4ILC 2007

Higgsless models

- Need something to restore unitarity in WW scattering.

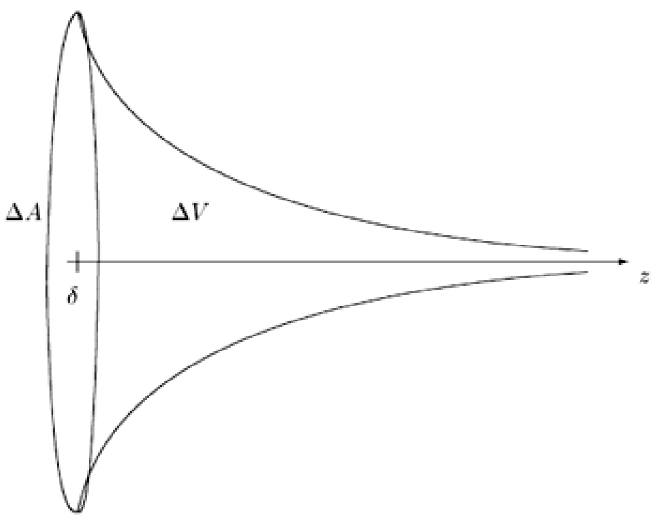
Technicolor: Higgsless since 1976!

Strongly coupled: can't calculate.

AdS/CFT duality:

Conjecture: Equivalence of 5D theory in Anti de Sitter space with 4D Conformal Field Theory

UV



IR

Walking Technicolor

$\Leftrightarrow$

5D Higgsless models

Full 5D theory unnecessarily complicated.

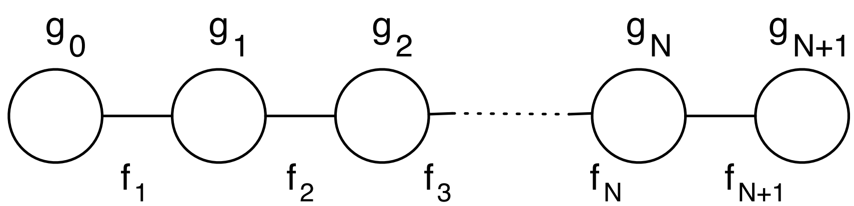
Deconstruction:

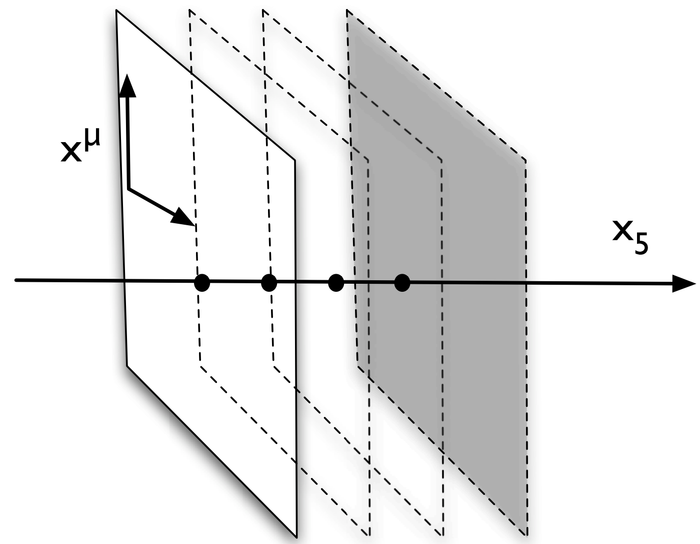
Latticize 5th dimension.

4D gauge group at each site

Nonlinear sigma model link fields

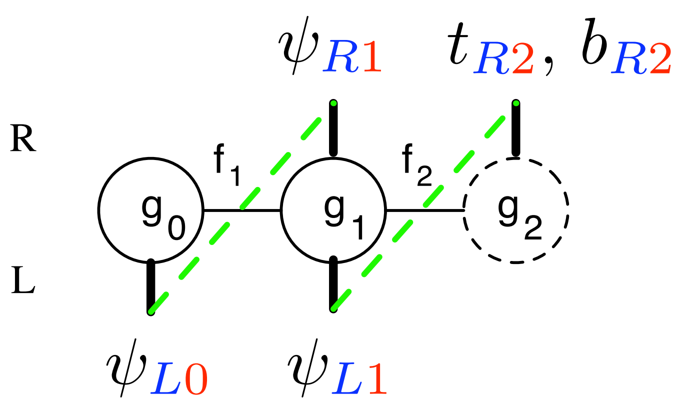
$=$ composite scalars





Simplest viable model: 3-site model

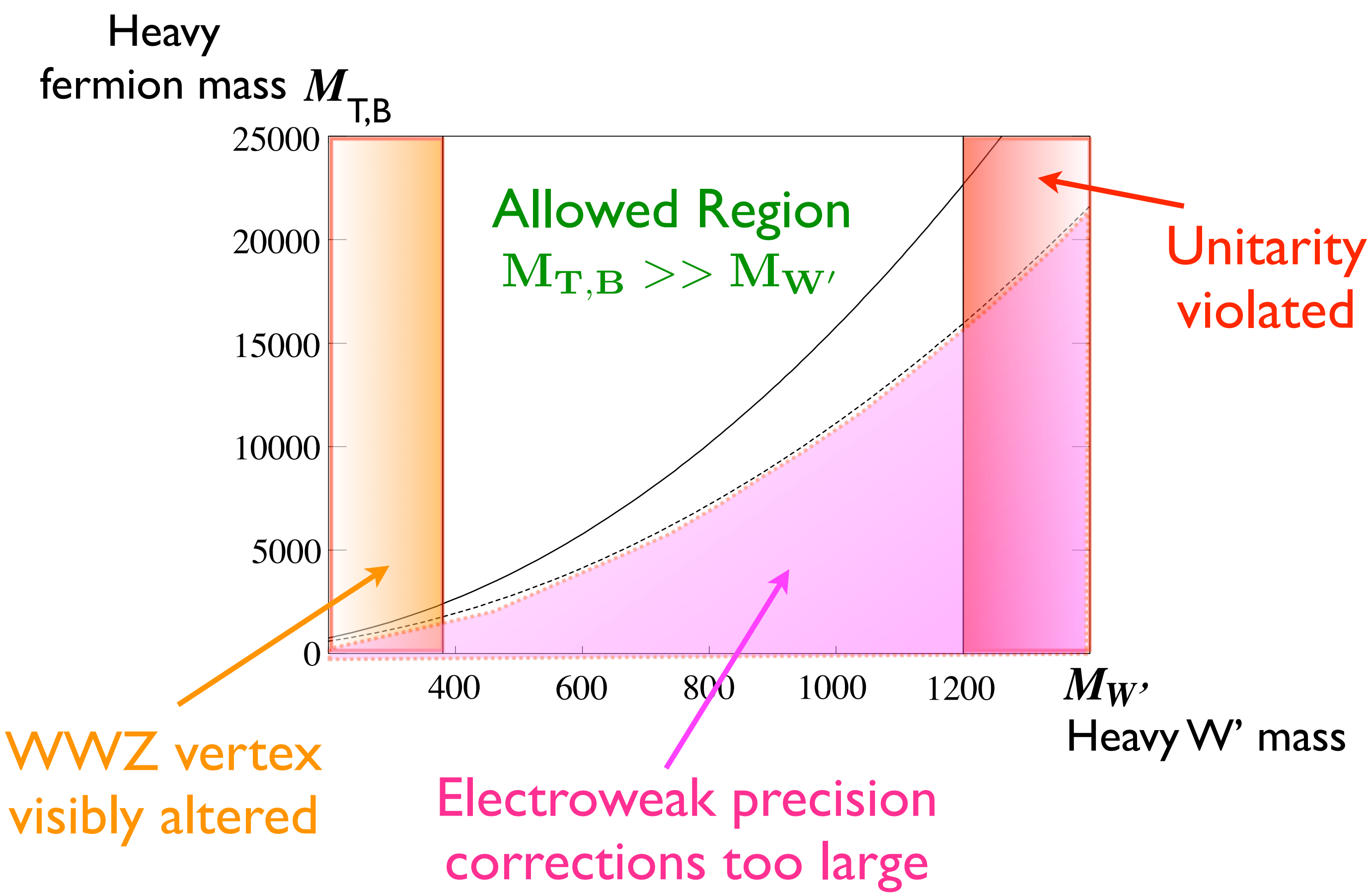
$SU(2) \times SU(2) \times U(1)$ $\qquad g_0,\, g_2 \ll g_1$



γ, Z, Z'
W, W'

$+$ set of heavy fermion partners

W', Z' unitarize VV scattering.
Fermiophobic: limits very loose. Search in WW, WZ fusion!



Chivukula, LHC4ILC 2007

Resonances in WW, WZ scattering. "Dual" to techni-rho.
New channels to search, new signatures.

3) Leptonic resonances
(and/or multi-gauge boson signals)

Dilepton resonance: everyone's favourite new-physics signal

$Z' \rightarrow e^+e^-, \ \mu^+\mu^-$

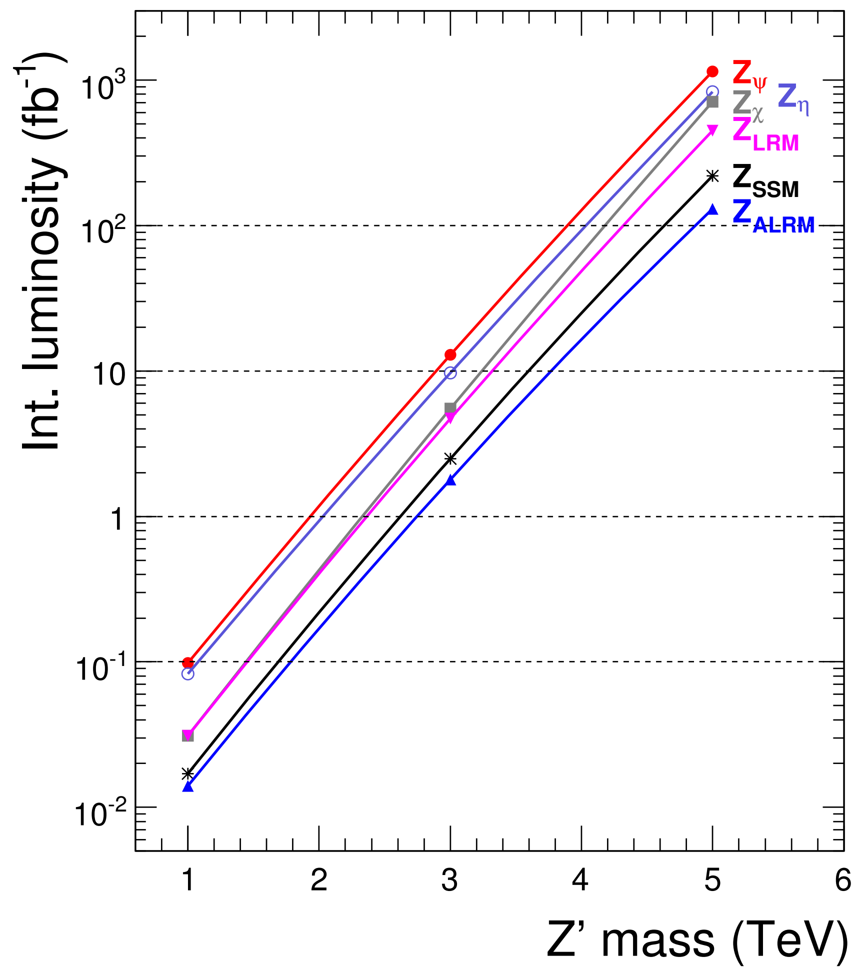
5σ discovery reach:

2–3 TeV with 1 fb^{-1}

3–4 TeV with 10 fb^{-1}

Depends on production couplings

Don't forget $\tau^+\tau^-$



CMS TDR

Many models contain Z'–like object(s)

- Gauge extensions of the SM (of course)

- Little Higgs models

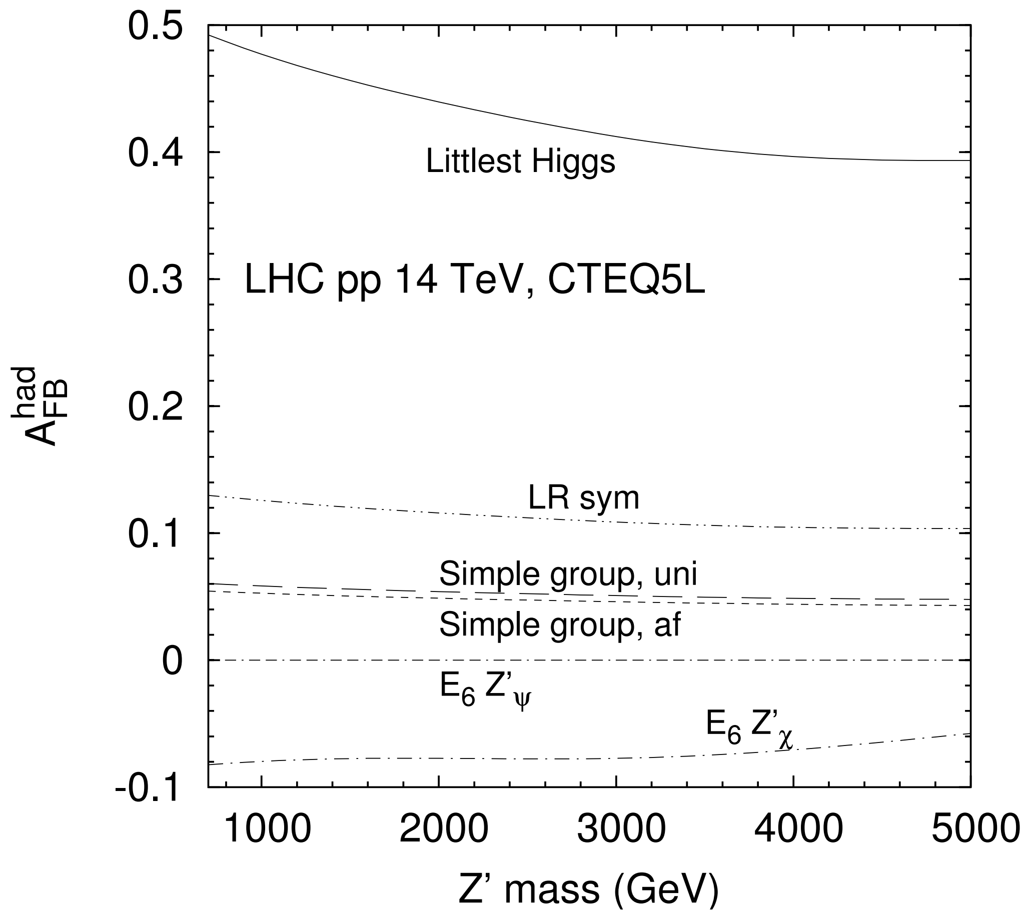
- Extra dimensional models: KK excitations of SM gauge bosons
  - UED
  - RS

- Technicolor: Spin-1 techni-rho, etc

- Higgsless models: heavy gauge bosons ("dual" to TC?)

Construct charge asymmetry: $A_{FB} \sim (g_{Li}^2 - g_{Ri}^2)(g_{Lf}^2 - g_{Rf}^2)$

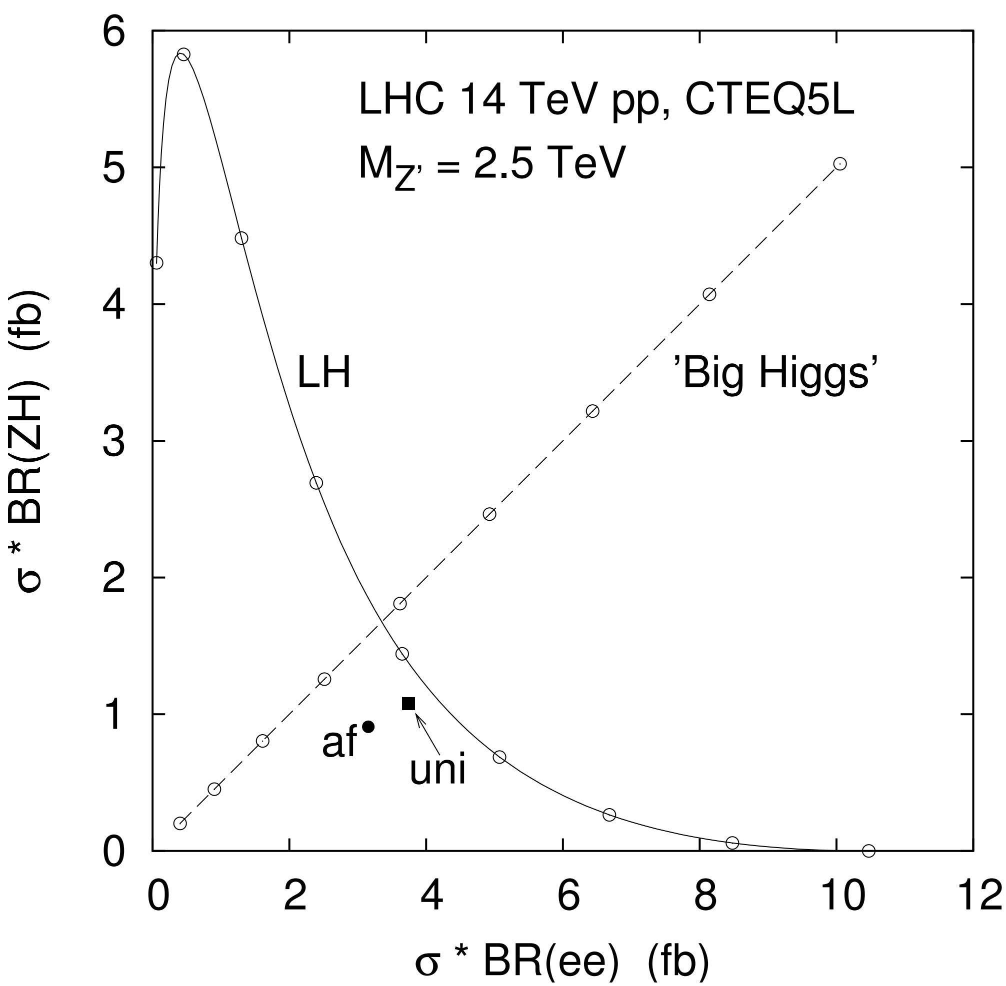
Access to couplings for model discrimination



Han, H.L., Wang hep-ph/0506313

Models with gauge group mixing can have $Z' \to W^+W^-$, ZH
$\Rightarrow$ more couplings to measure

e.g., Little Higgs:



Han, H.L., Wang hep-ph/0506313

Randall-Sundrum model:

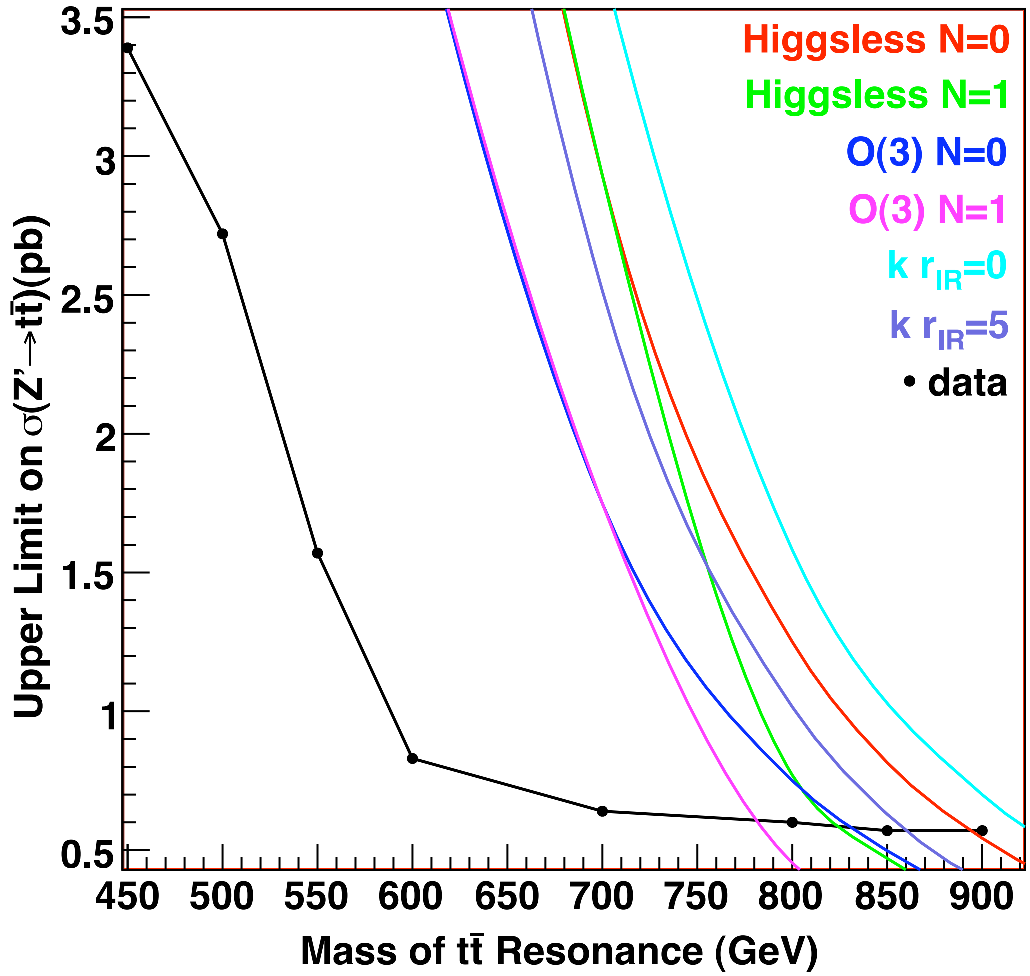
KK gauge excitations couple preferentially to t_R

Have to deal with highly boosted tops

KK gluon $\rightarrow t\bar{t}$ final state

Basic RS model:
BR($g^1 \rightarrow t\bar{t}$) $\sim$ 90%

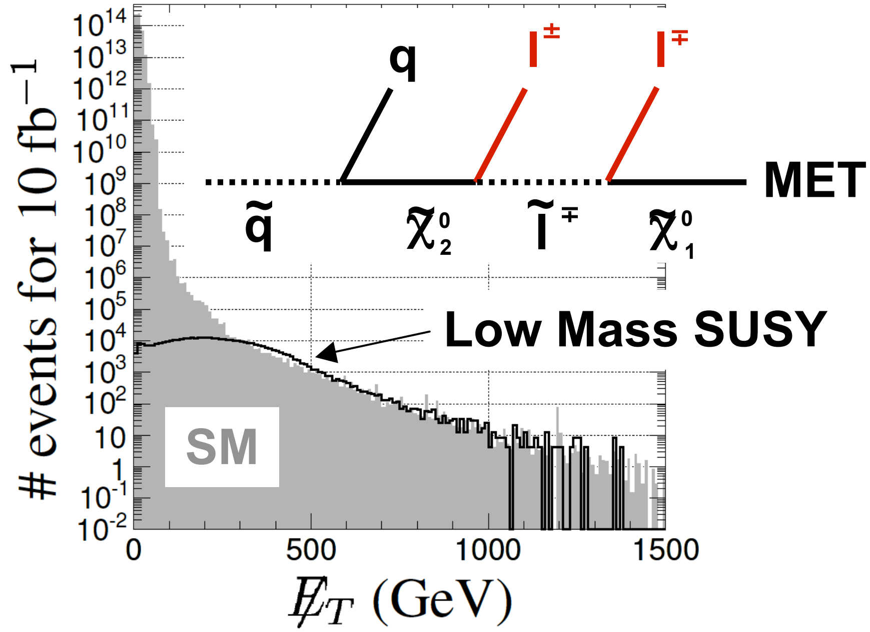
CDF exclusion limits on narrow $t\bar{t}$ resonance (955 pb^{-1}, 2006)



Lillie, Shu, Tait, arXiv:0706.3960

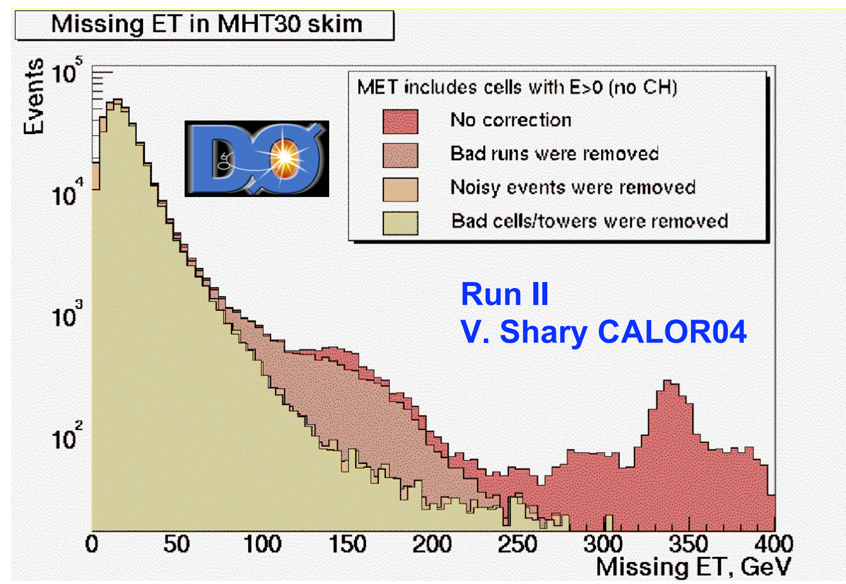
4) Missing energy (+ leptons, jets)

MET is a powerful discriminator for New Physics



Experimental challenge: understanding tails

Difficult part is to convince yourself that there is a real excess!



Interpreting MET signals

Within a BSM model:

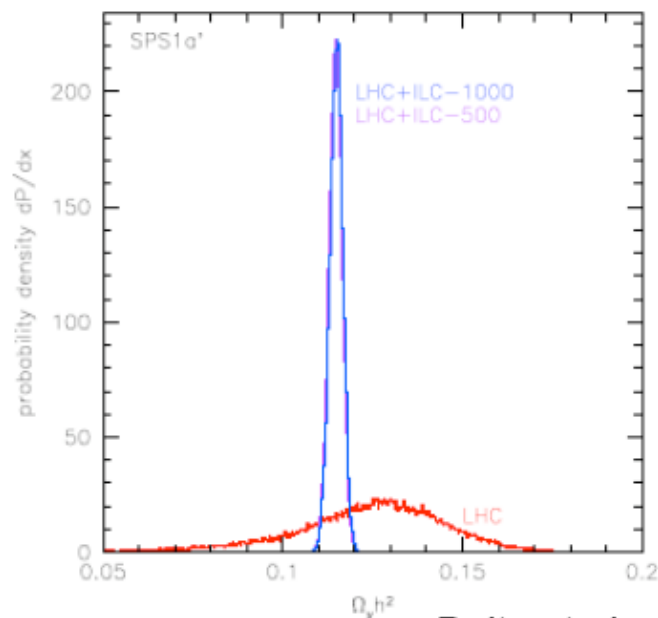
Discovery of new states (e.g., superpartners)

Is missing particle a WIMP?

Enough information to predict relic abundance?

Cosmologically, LHC lacking...

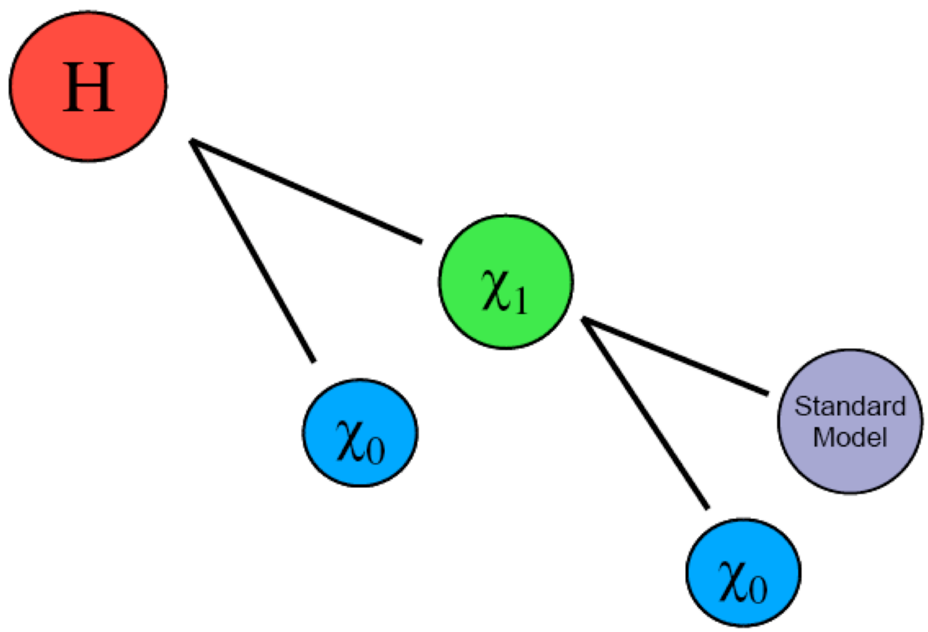
ILC combination ideal



Baltz et.al.

SUSY is best-studied example.

Other possibilities: MSSM + new neutralino χ_0 (NMSSM & other extensions)



Nonstandard decays into neutral states, neutralinos?

Invisible Higgs decay to $2\chi_0$ strongly constrained.

Dominant singlino LSP implies longer cascade chains.

Longer cascades mean more visible energy (jets, leptons) and reduced missing energy.

Effects degrade search, especially with optimized SUSY MET cuts.

T-parity in Little Higgs / composite Higgs models:

Forbids large effects on EW precision observables

Dark matter candidate? Missing energy signature?

? $\rightarrow$ Can define a parity, but is it respected by the dynamics?

Anomalies can break the parity.

Like $\pi^0 \rightarrow \gamma\gamma$ through chiral anomaly: spontaneous breaking of chiral sym.

"Lightest T-odd particle" no longer stable:

can decay through anomaly! $\Rightarrow$ Interesting signatures.

$A_H \rightarrow W^+W^-$, ZZ; decay length $\sim$ μm. Cascade decays to gauge-boson-rich, fully reconstructible final states.

Fairly generic:

Wherever there are fermions, have to worry about anomalies.

Composite Higgs: EWSB broken by fermion condensation.

Weakly coupled: can look a lot like SM Higgs.

Even with just the (composite) Higgs & gauge sectors, need to worry about anomalies in Little Higgs models.

T-parity generally violated:

Lose the DM candidate, lose the MET signal.

Other possibilities:

Other new LSPs, e.g., right-handed sneutrino

Super-WIMP: NLSP (e.g., neutralino) escapes detector, decays later into true LSP (e.g., light gravitino)

R-parity violation into neutrinos: fake Dark Matter signal

Highly displaced vertices from weak R-parity violation

$H \to 2\chi_1 \to 6$ (displaced?) jets

Hidden Valley models (Strassler et al.)

Big challenge to pin down what's really going on.

Summary

I considered four classes of possible signals for the early phase ($\equiv$ 10 fb^{-1}) of LHC:

1) Only one state, SM-like Higgs boson
2) No Higgs boson detected (yet?)
3) Leptonic resonances (and/or multi-gauge-boson signals)
4) Missing energy (+ leptons, jets)

Categories cross into each other.

Early LHC data will open up brand new territory in electroweak symmetry breaking, dark matter, hierarchy problem, ???

New mysteries to solve: data will not come with theory labels!