LHC Phenomenology

Heather Logan
Carleton University

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Outline

Introduction: why we expect new discoveries at the LHC

Higgs constraints and phenomenology

Frameworks for physics beyond the Standard Model I: Supersymmetry

Frameworks for physics beyond the Standard Model II: Composite models

Summary and outlook

The Standard Model is extremely successful so far.

Can't we get by with just the degrees of freedom that we've observed?

- 3 generations of quarks; CKM matrix for flavor physics
- 3 generations of charged leptons
- Neutrinos with mass (might need something new there)
- gluons from SU(3) strong interaction
- photon plus massive $W^{\pm}$ and Z from SU(2) $\times$ U(1)

(Electroweak symmetry is broken, but do we really have to worry about how?)

- (Dark matter?)
- (How to bring gravity into the quantum theory?)

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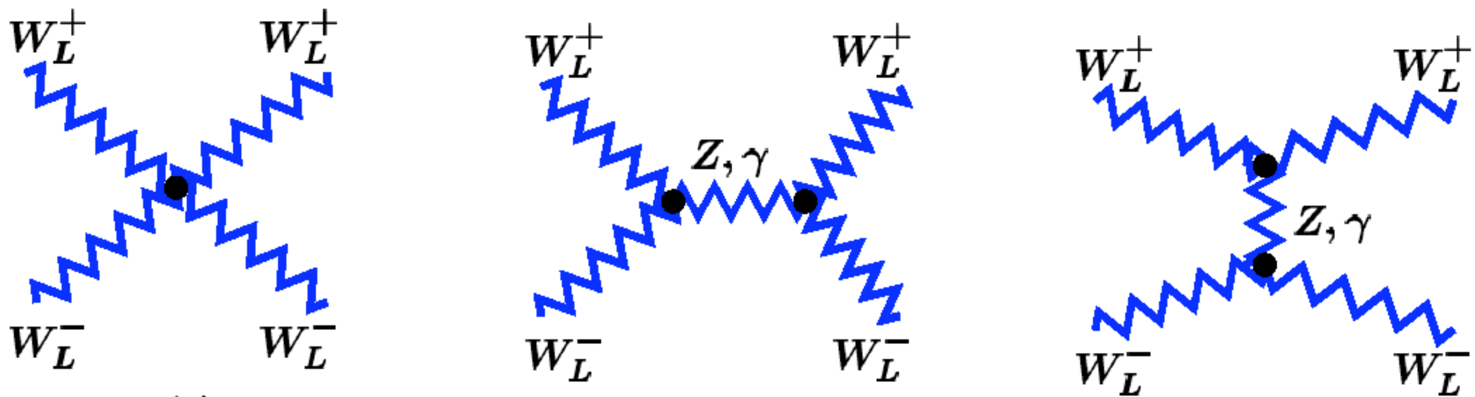
- (How to bring gravity into the quantum theory?)

The answer is no:
the SM without a Higgs is intrinsically incomplete.

Scattering of longitudinally-polarized Ws exposes need for a Higgs*

SU(2) x U(1) @ E^4



(a) (b) (c)

Graphs	$g^2 \frac{E^4}{m_w^4}$
(a)	$-3 + 6\cos\theta + \cos^2\theta$
(b)	$-4\cos\theta$
(c)	$+3 - 2\cos\theta - \cos^2\theta$
Sum	0

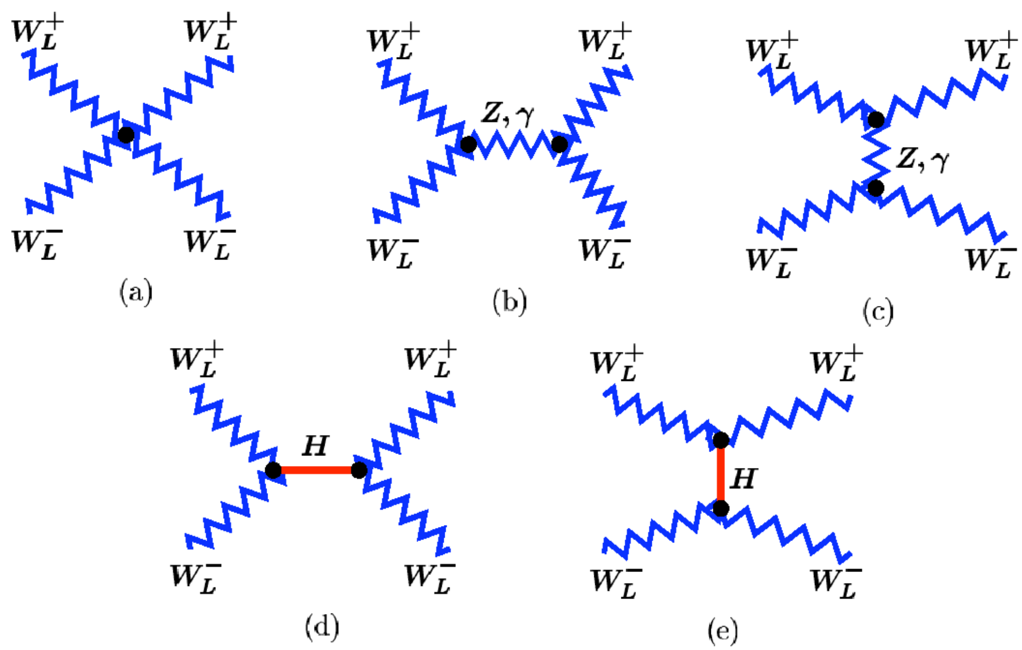
$$\epsilon_L^\mu(k) = \frac{k^\mu}{m_w} + \mathcal{O}\left(\frac{m_w}{E}\right)$$

Graphics from R.S. Chivukula, LHC4ILC 2007

*or something to play its role

Scattering of longitudinally-polarized Ws exposes need for 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 $\Rightarrow \mathcal{O}(E^2) \Rightarrow E < \sqrt{8\pi}v \simeq 1.2\,\mathrm{TeV}$

Graphics from R.S. Chivukula, LHC4ILC 2007

*or something to play its role

Standard Model Higgs mechanism:

Electroweak symmetry broken by an SU(2)-doublet scalar field:

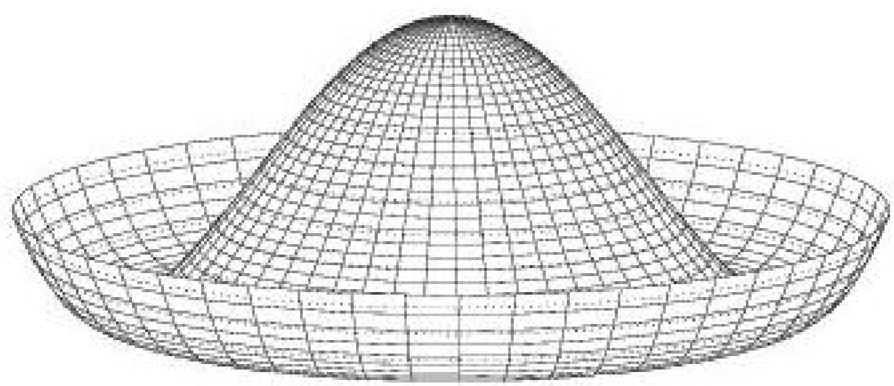
$$H = \begin{pmatrix} G^+ \\ (h+v)/\sqrt{2} + iG^0/\sqrt{2} \end{pmatrix}$$

- G^+ and G^0 are the Goldstone bosons (eaten by W^+ and Z).
- v is the SM Higgs vacuum expectation value (vev),
  $v = 2m_W/g \simeq 246$ GeV.
- h is the SM Higgs field, a physical particle.

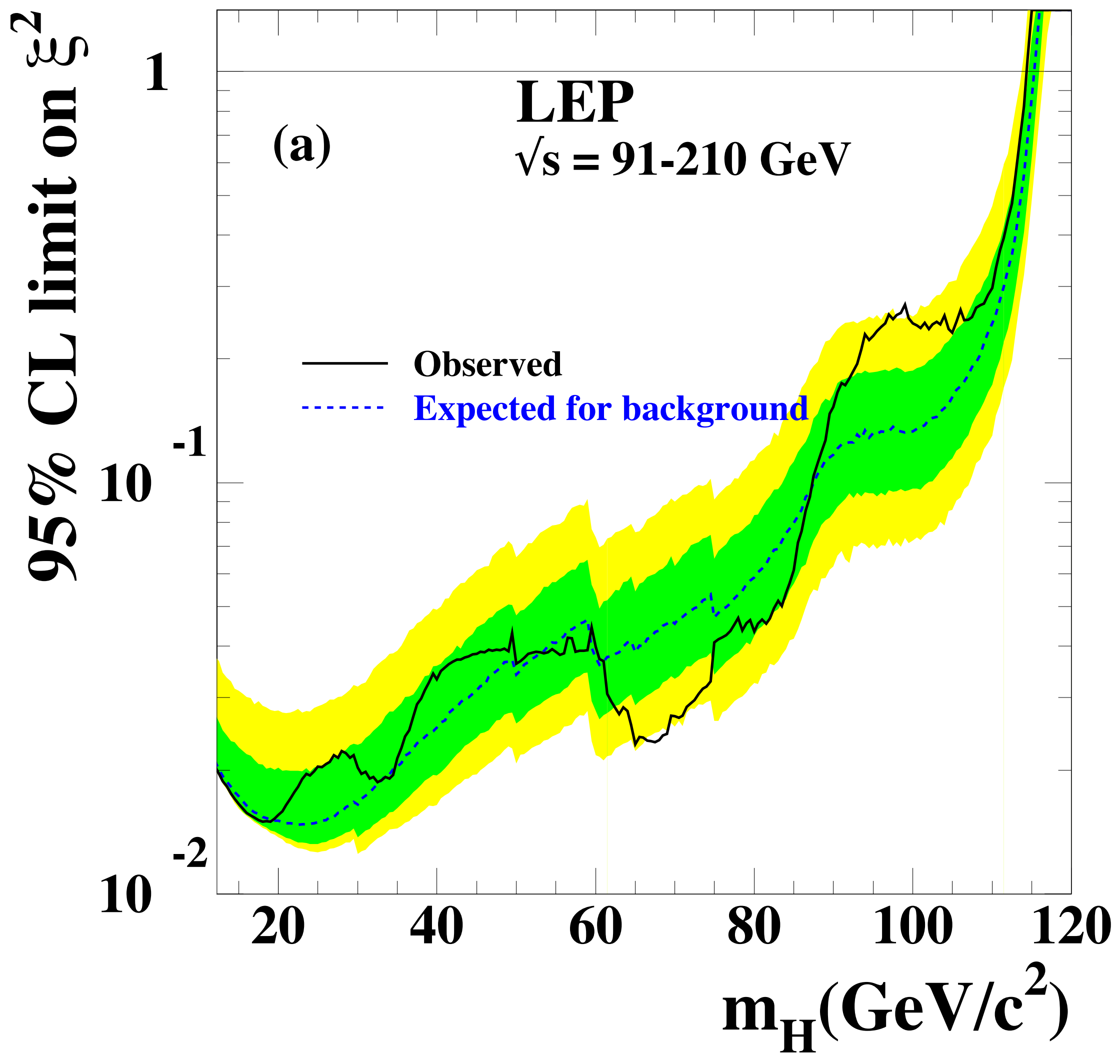
Electroweak symmetry breaking comes from the Higgs potential:

$$V = \mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

where $\lambda \sim \mathcal{O}(1)$
and $\mu^2 \sim -\mathcal{O}(M_{\rm EW}^2)$.
$\Rightarrow v^2 = -\mu^2/\lambda = (246\ \text{GeV})^2$,
$M_h^2 = 2\lambda v^2 = -2\mu^2$.



Direct SM Higgs searches – LEP expts final combination



$e^+e^- \to Z^* \to ZH$

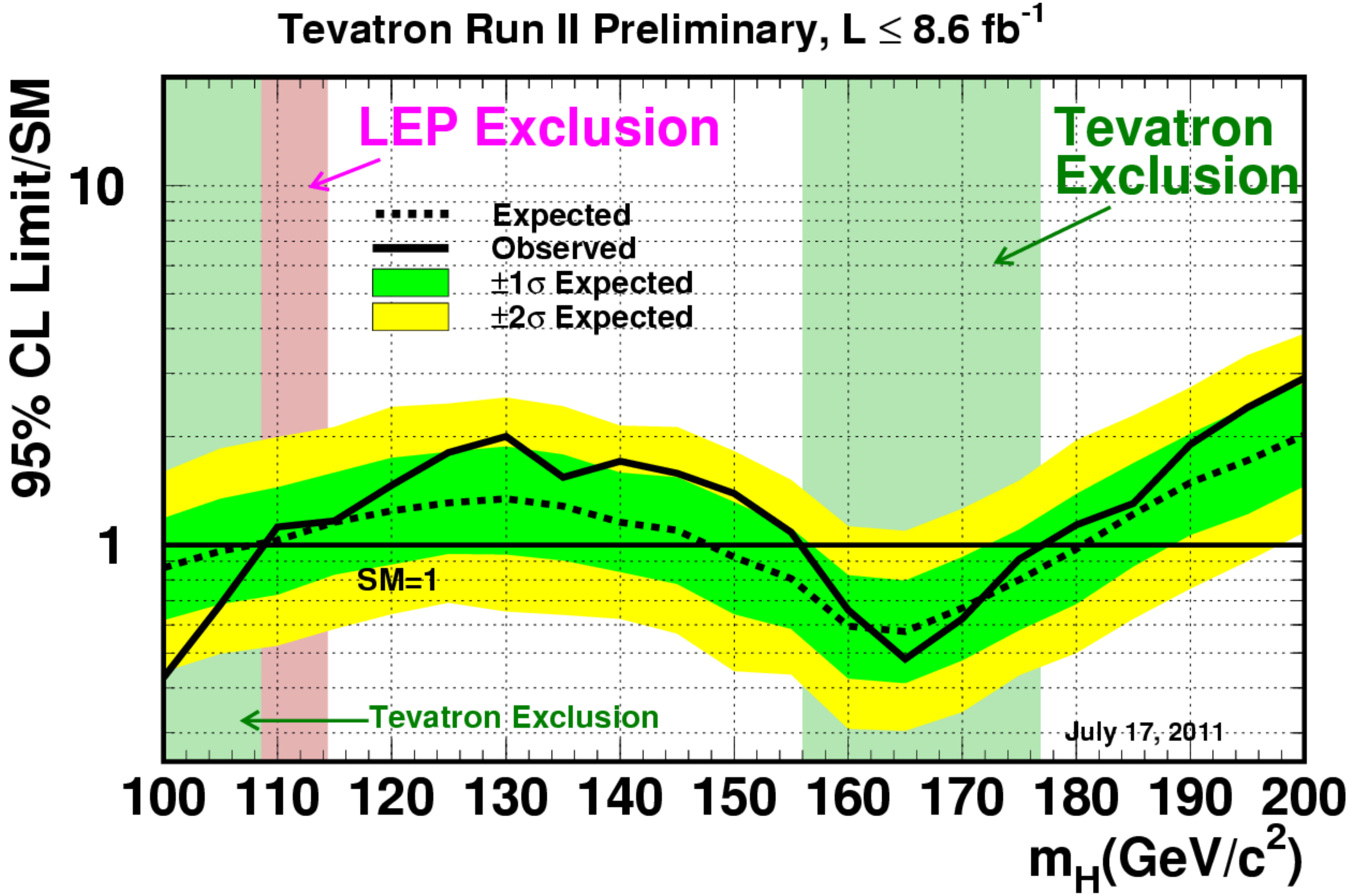
SM Higgs decay BRs assumed

ξ = scaling factor on ZZH relative to SM

SM limit:
$M_H \geq 114.4$ GeV

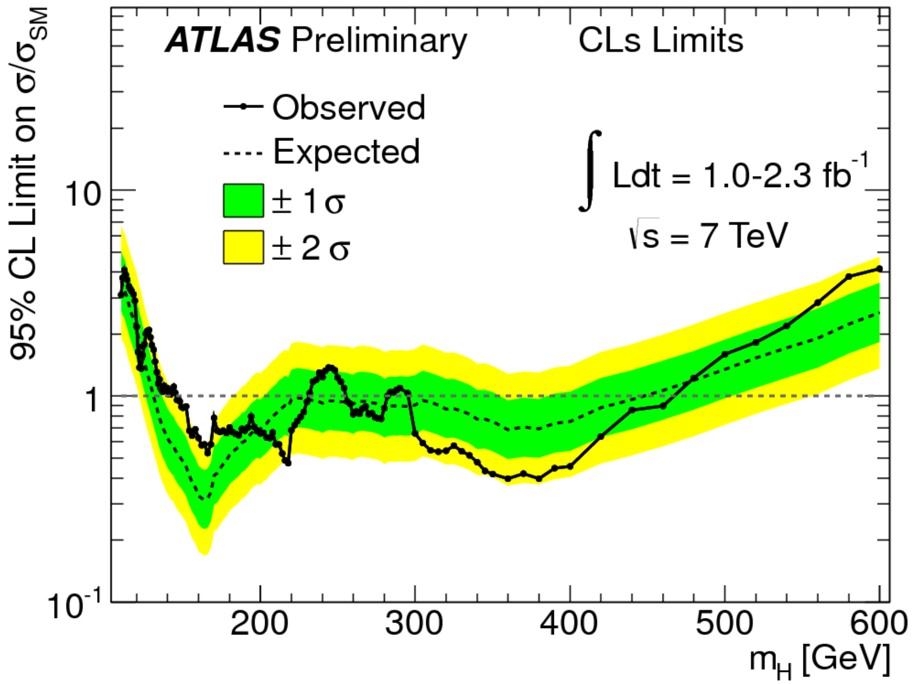
Final LEP combination, Phys. Lett. B565, 61 (2003)

Latest SM Higgs results from Tevatron (EPS-HEP 2011)

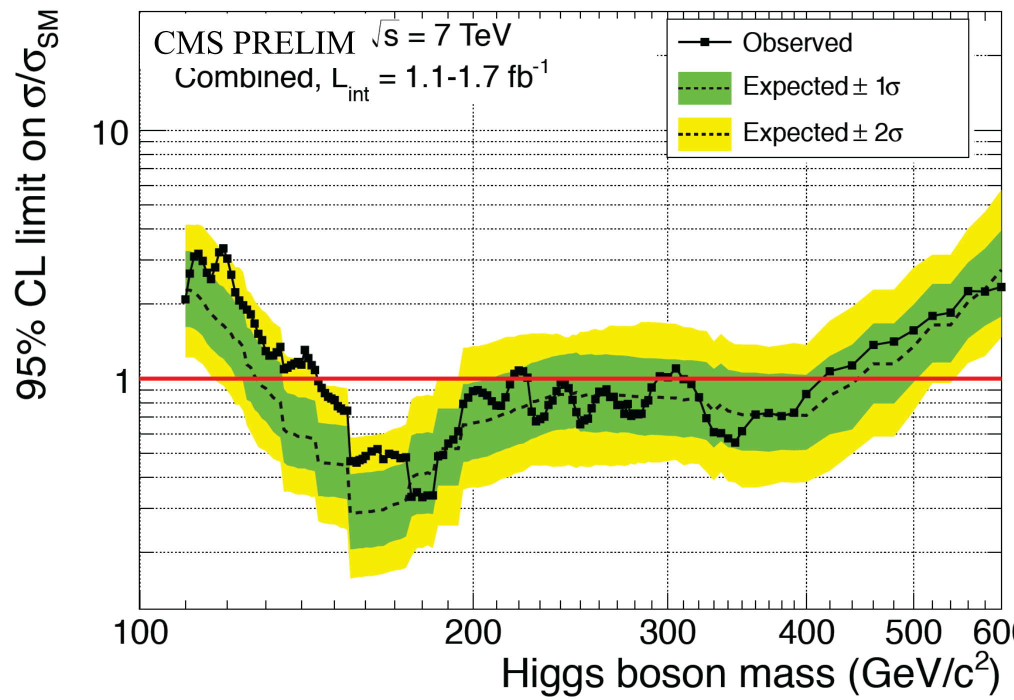


Tevatron combined, arXiv:1107.5518 [hep-ex], shown at EPS-HEP 2011

Latest SM Higgs results from LHC (Lepton-Photon 2011)



ATLAS-CONF-2011-135

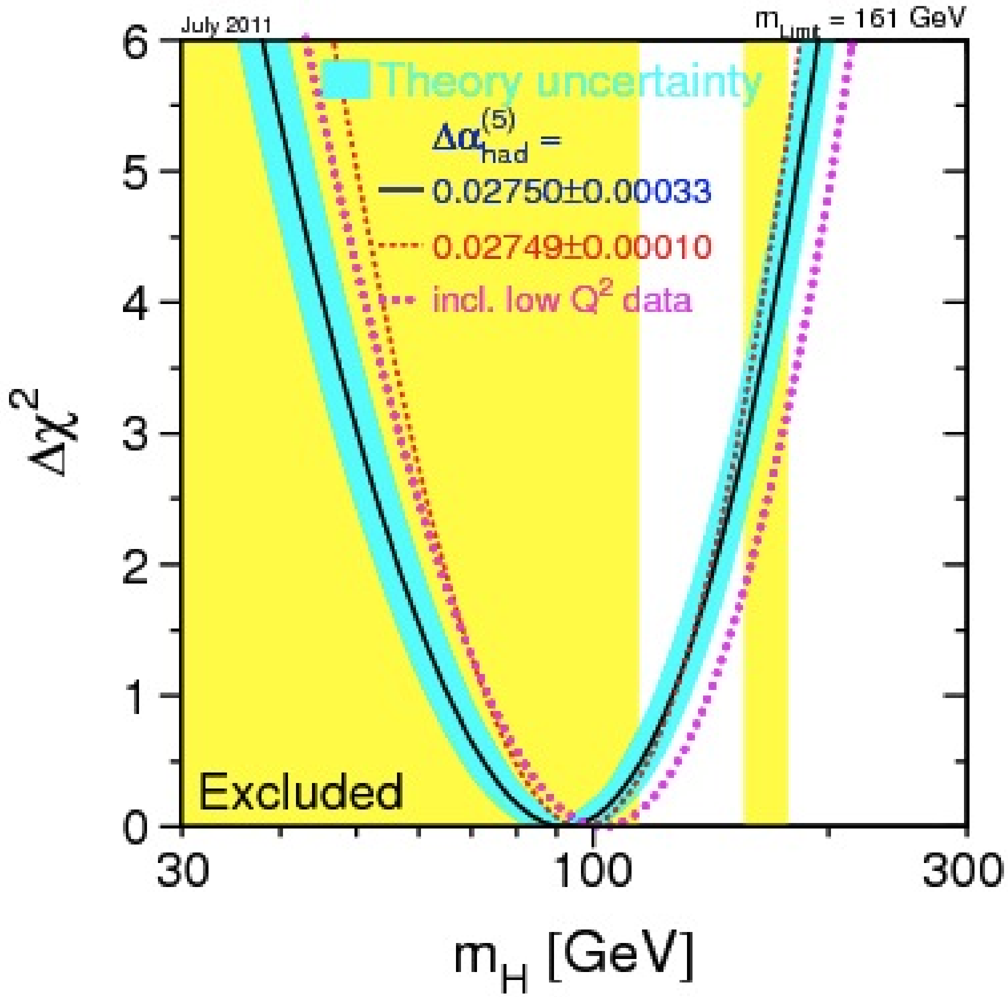


CMS PAS HIG-11-022 (LP2011)

CMS + ATLAS exclude (at 95% CL) all mass regions except: below 145 GeV, 288–296 GeV, and above 464 GeV.

Higgs with suppressed gluon-fusion production coupling and/or suppressed WW, ZZ decay BRs still allowed in the SM-excluded mass regions.

Precision electroweak SM Higgs mass fit (summer 2011)

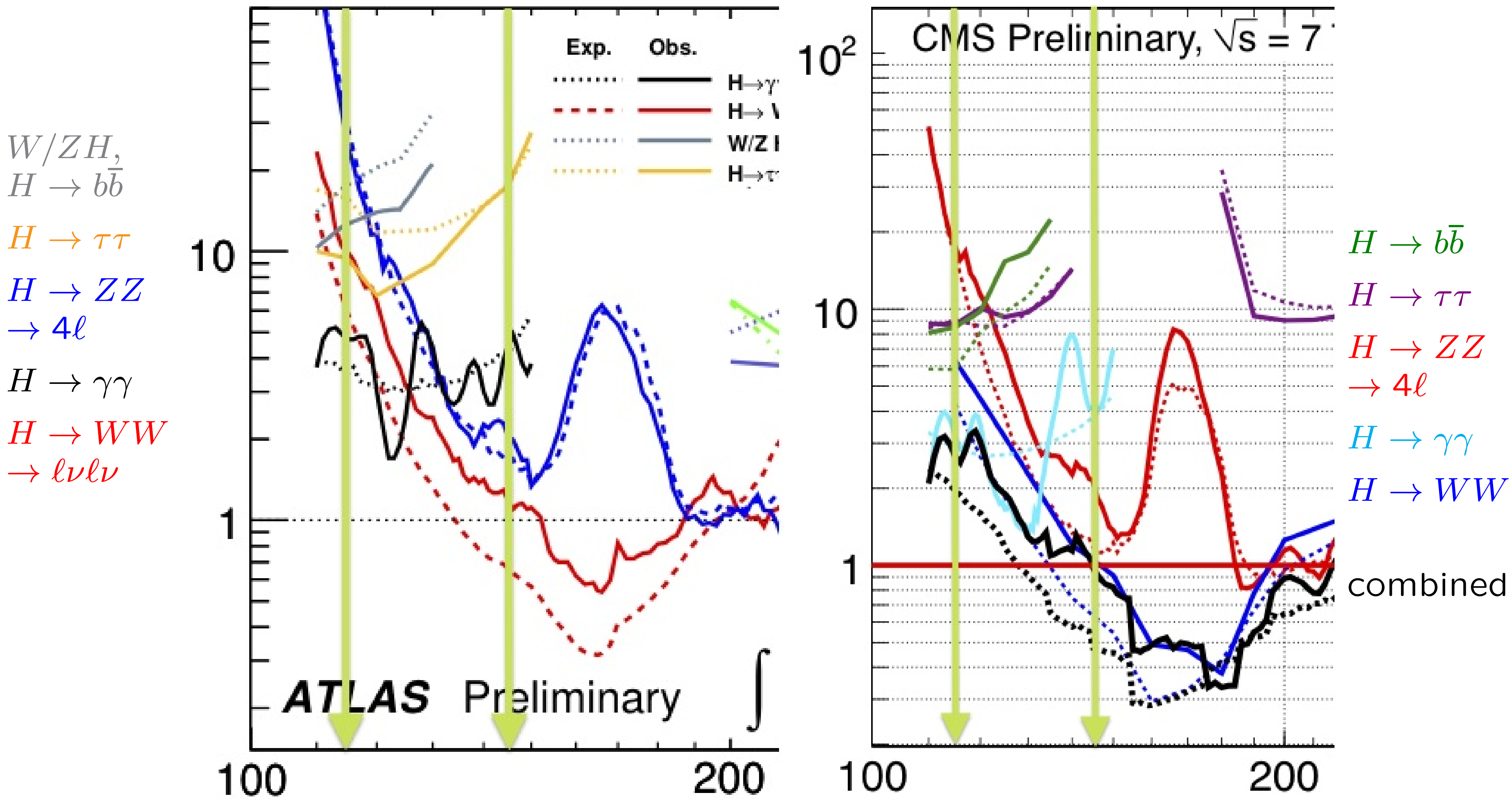


LEP Electroweak Working Group (2011)

Precision EW favors low-mass allowed window, 114.4–145 GeV.

(Fit valid only in SM context; new physics can change preferred mass range.)

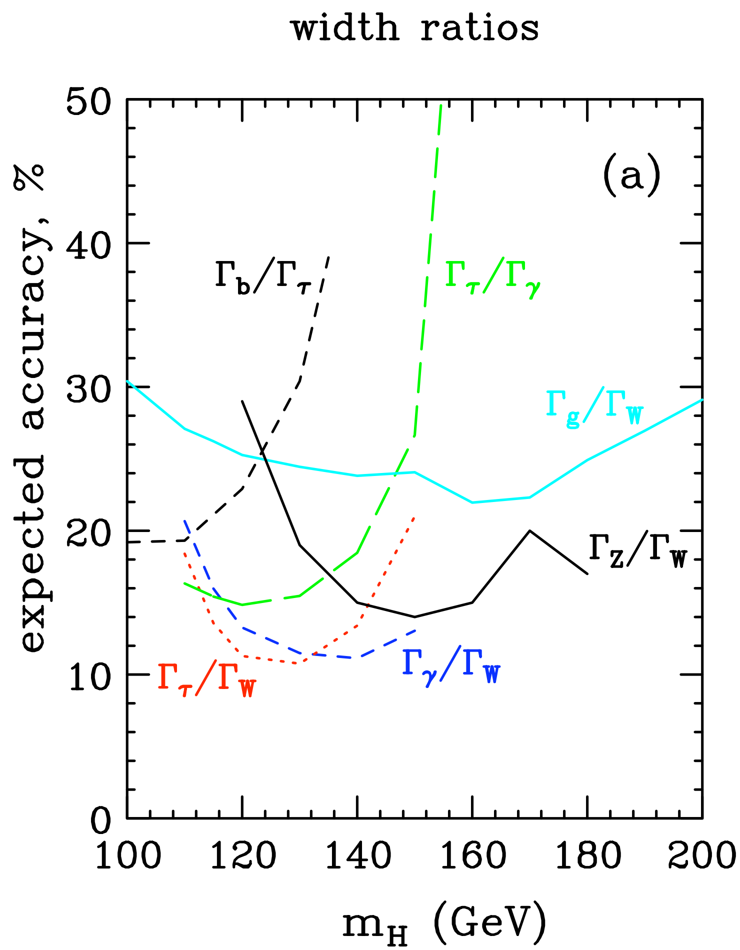
LHC Higgs channels: focus on SM, low-mass range

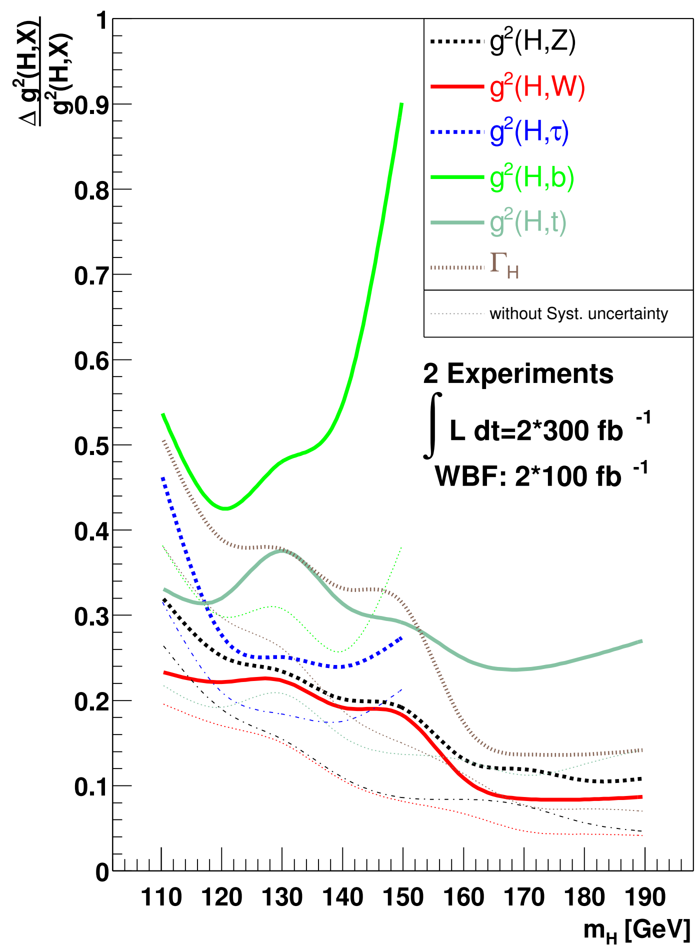


ATLAS-CONF-2011-135 CMS PAS HIG-11-022 (LP2011)

Not yet done: VBF $\to H \to \tau\tau, WW, ZZ, \gamma\gamma$; $ttH, H \to bb, \gamma\gamma, WW$; $WH, H \to \gamma\gamma$

Low-mass range most interesting for extracting Higgs couplings.
- Ratios of rates give ratios of partial widths.
- Add theory assumption: $hWW, hZZ \leq$ SM $\Rightarrow$ fit Higgs coups.



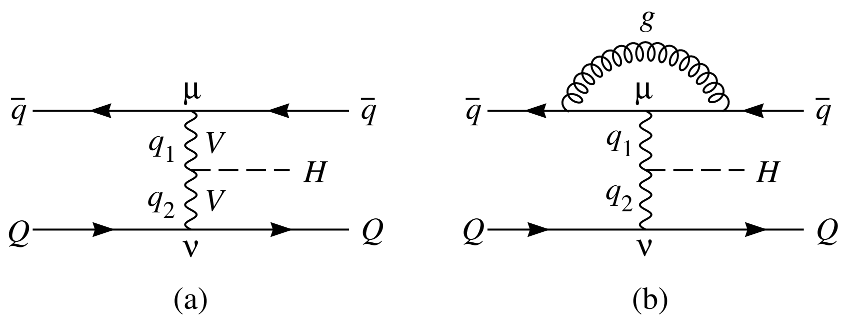


[L] 200 fb^{-1} (except 300 fb^{-1} for $ttH(\to bb)$, $WH(\to bb)$). Zeppenfeld, hep-ph/0203123
[R] Dührssen, Heinemeyer, H.L., Rainwater, Weiglein & Zeppenfeld, hep-ph/0406323

Plus input from Tevatron at low end of mass range?

Measure tensor structure of HVV coupling in VBF:

Most general HVV vertex $T^{\mu\nu}(q_1, q_2)$



$$T^{\mu\nu} = a_1\, g^{\mu\nu} + a_2\, \left(q_1 \cdot q_2\, g^{\mu\nu} - q_1^{\nu} q_2^{\mu}\right) + a_3\, \varepsilon^{\mu\nu\rho\sigma}\, q_{1\rho} q_{2\sigma}$$

The $a_i = a_i(q_1, q_2)$ are scalar form factors

Physical interpretation of terms:

SM Higgs $\mathcal{L}_I \sim H V_\mu V^\mu \longrightarrow a_1$

loop induced couplings for neutral scalar

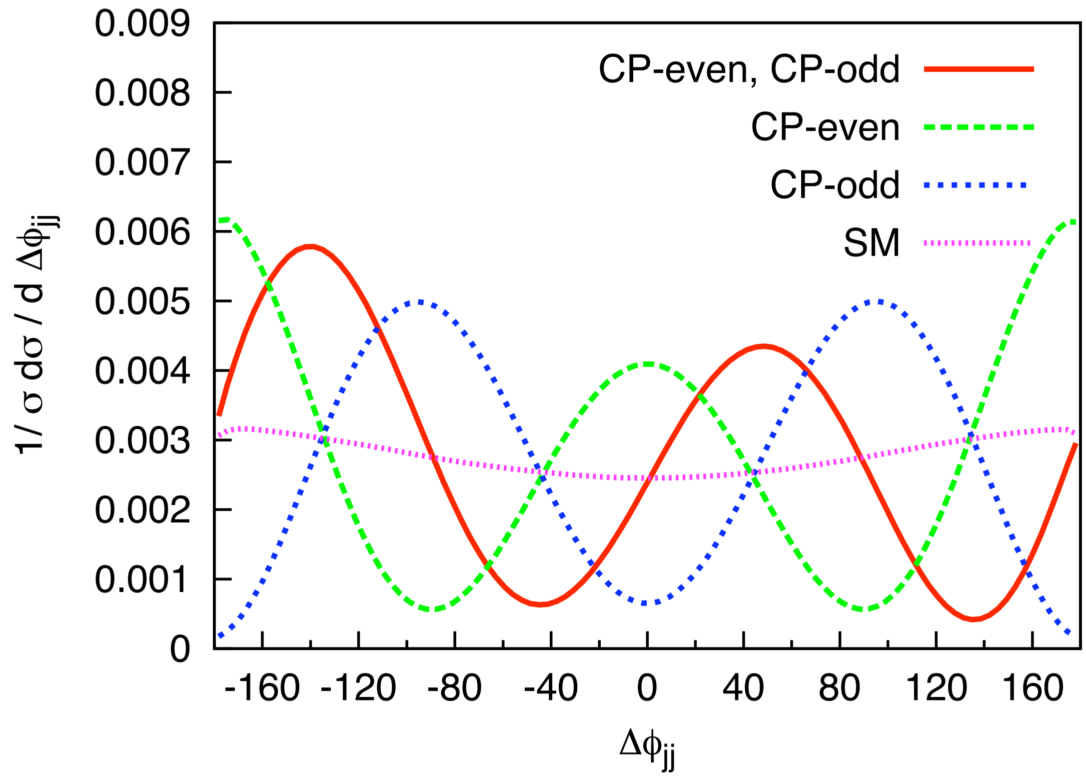
CP even $\mathcal{L}_{eff} \sim H V_{\mu\nu} V^{\mu\nu} \longrightarrow a_2$

CP odd $\mathcal{L}_{eff} \sim H V_{\mu\nu} \tilde{V}^{\mu\nu} \longrightarrow a_3$

Must distinguish a_1, a_2, a_3 experimentally

Slide from D. Zeppenfeld, plenary talk at SUSY'06 conference

HVV vertex structure gives different distributions in jj azimuthal angle $\Delta\phi$:



mixed CP case:
$a_2 = a_3, a_1 = 0$

pure CP-even case:
a_2 only

pure CP odd case:
a_3 only

Figy, Hankele, Klämke, & Zeppenfeld, hep-ph/0609075; plot for $M_H = 120$ GeV

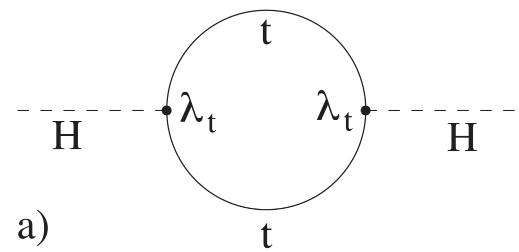
$HV^\mu V_\mu$ structure is "smoking gun" for Higgs mechanism EWSB. Check for CP violation and/or loop-induced $HV^{\mu\nu}V_{\mu\nu}$ structure. Can also use $H \to ZZ, WW$ lepton distributions.

Why expect more than just SM Higgs: The Hierarchy Problem

The Higgs mass-squared parameter μ^2 gets quantum corrections that depend quadratically on the high-scale cutoff of the theory.

Calculate radiative corrections from, e.g., a top quark loop.

$$\mu^2 = \mu_0^2 + \Delta\mu^2$$



For internal momentum p, large compared to m_t and external h momentum:

$$\begin{aligned}
\text{Diagram} &= \int \frac{d^4p}{(2\pi)^4}(-)N_c \mathrm{Tr}\left[i\lambda_t \frac{i}{\not{p}} i\lambda_t \frac{i}{\not{p}}\right] \\
&= -N_c\lambda_t^2 \int \frac{d^4p}{(2\pi)^4} \mathrm{Tr}\left[\frac{1}{p^2}\right] \qquad \mathrm{Tr}\,[1] = 4 \\
&= -\frac{4N_c\lambda_t^2}{(2\pi)^4}\int \frac{d^4p}{p^2}
\end{aligned}$$

Momentum cutoff Λ: Integral diverges like Λ^2.

Full 1-loop calculation gives

$$\Delta\mu^2 = \frac{N_c \lambda_t^2}{16\pi^2}\left[-2\Lambda^2 + 6m_t^2 \ln(\Lambda/m_t) + \cdots\right]$$

We measure $\mu^2 \sim -\mathcal{O}(M_{\rm EW}^2) \sim -(100\ \text{GeV})^2 = -10^4\ \text{GeV}^2$.
Nature sets the bare parameter μ_0^2 at the cutoff scale Λ.
If $\Lambda = M_{\rm Pl} = \frac{1}{\sqrt{8\pi G_N}} \sim 10^{18}$ GeV, then $\Delta\mu^2 \sim -10^{35}\ \text{GeV}^2$!

- Not an inconsistency in the theory.

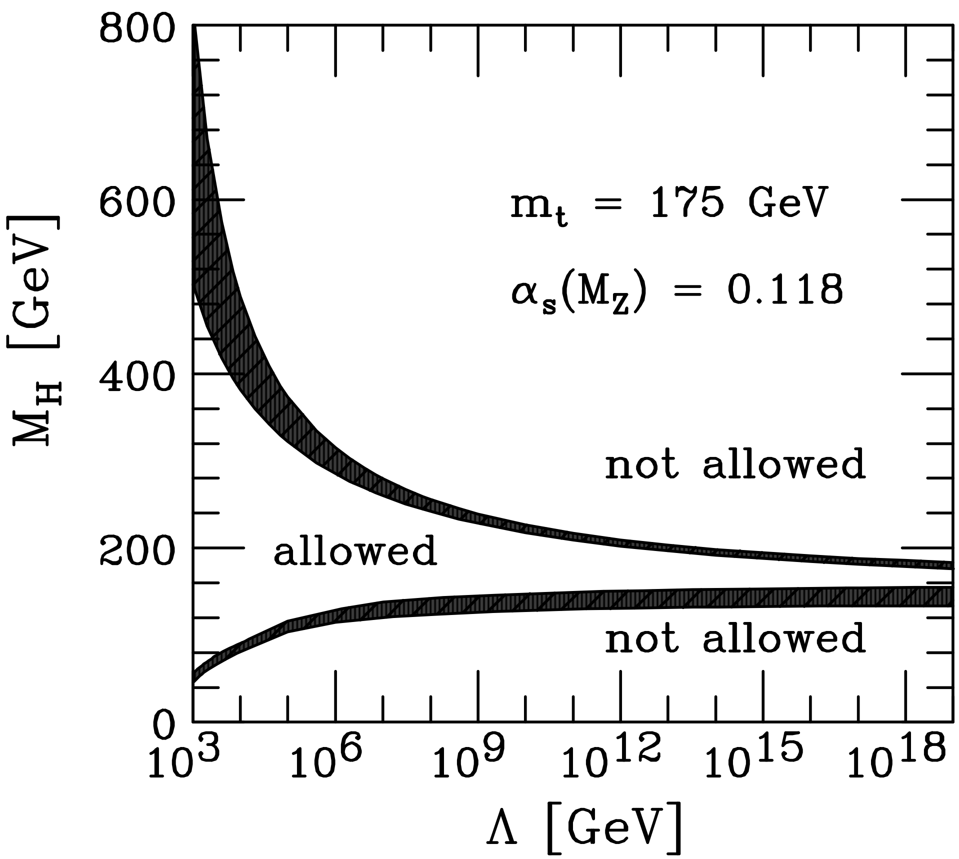
Renormalizable: absorb the divergence into the bare parameter μ_0^2.

- But it is an implausibly huge top-down coincidence that μ_0^2 and $\Delta\mu^2$ cancel to 31 decimal places! Looks horribly fine-tuned.

and not just at one loop – must cancel two-, three-, four-, ... loop contributions

Want $|\Delta\mu^2| \sim (100\ \text{GeV})^2 \;\Rightarrow\; \Lambda \sim 1$ TeV.
Expect New Physics that solves hierarchy problem at TeV scale!

Aside: Can the SM be valid all the way to the Planck scale?



Landau Pole:

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

Vacuum Instability:

Higgs self-coupling too small compared to top Yukawa; runs negative at scale Λ

Hambye & Riesselmann, hep-ph/9708416

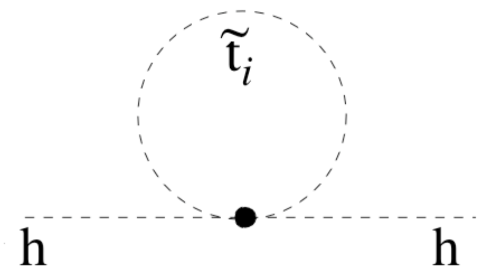
SM Higgs sector is perturbative and stable (but terribly fine-tuned) all the way to the Planck scale for $M_H \simeq$ 134–180 GeV.

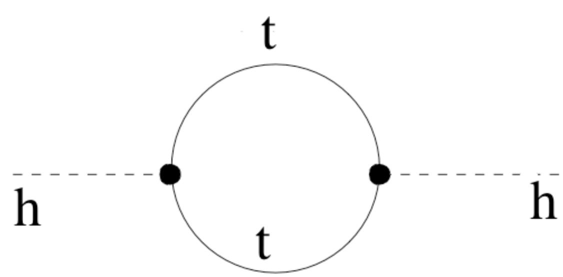
$\exists$ window for $\sim$134–145 GeV. For a nice review see Quigg, arXiv:0905.3187

Smaller top mass $\Rightarrow$ lower bound decreases a little.

Two main classes of solutions to the hierarchy problem:

1) Supersymmetry
SUSY relates μ^2 to a fermion mass, which only runs logarithmically. Guarantees cancellation between SM loop diagrams and SUSY loop diagrams.

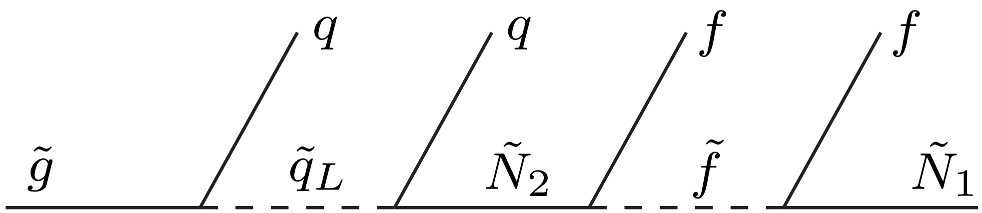




2) Composite Higgs
Higgs is some kind of bound state ("meson") of fundamental fermions, held together by a new force that gets strong at the TeV scale. Above a TeV there are no fundamental scalars, so no hierarchy problem.
[Includes extra-dimension / RS models by AdS/CFT duality.]

Supersymmetry

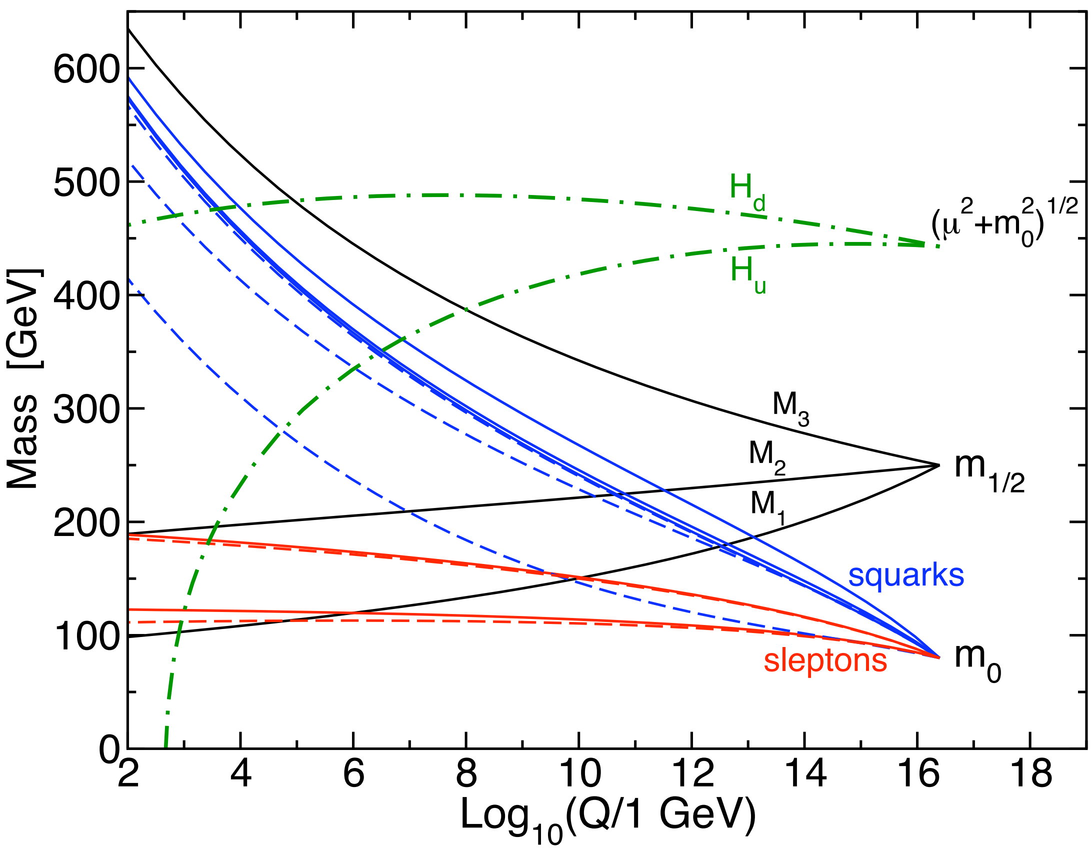
SUSY signals depends hugely on the SUSY mass spectrum: controls cascade decays



Generic features:

- Jets + MET: strong squark and/or gluino production, cascade decays to invisible LSP.
- Leptons + MET: electroweak production of sleptons, gauginos: typically lighter than squarks/gluino due to renormalization-group running.
- 3rd generation + MET: renormalization-group running tends to drive top, bottom squarks lighter than others.
- Photons + MET: SUSY-breaking at an intermediate scale $\Rightarrow$ gravitino is LSP, cascade decays to NLSP (bino).

General features of the SUSY mass spectrum



Martin, hep-ph/9709356

- Squarks start with common mass at high scale to avoid flavour problems

- Run down using RGEs ⇒ coloured particles heavier

- Large Yukawa coupling ($\tilde{t}$; $\tilde{b}$, $\tilde{\tau}$) pulls the mass down

- Left-right mixing large when Yukawa is large ⇒ mass splitting

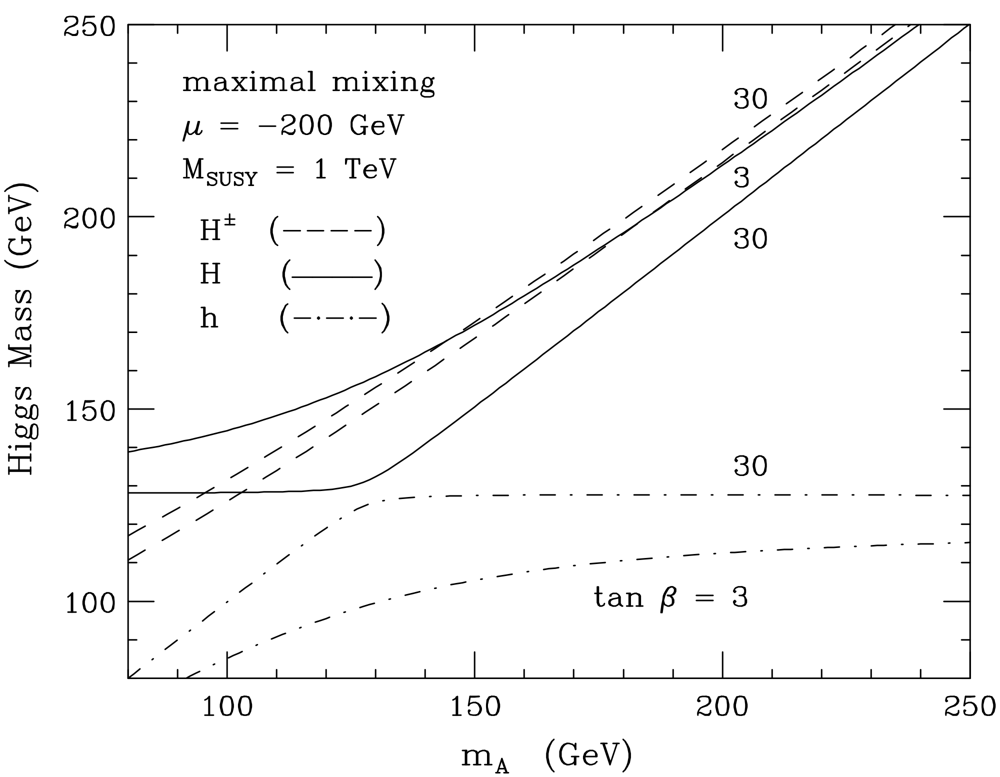
- Heavier stops pull up the h^0 mass, but too-heavy stops reintroduce fine-tuning. 1 TeV stops are nice; 2 TeV I think are a bit stretched.

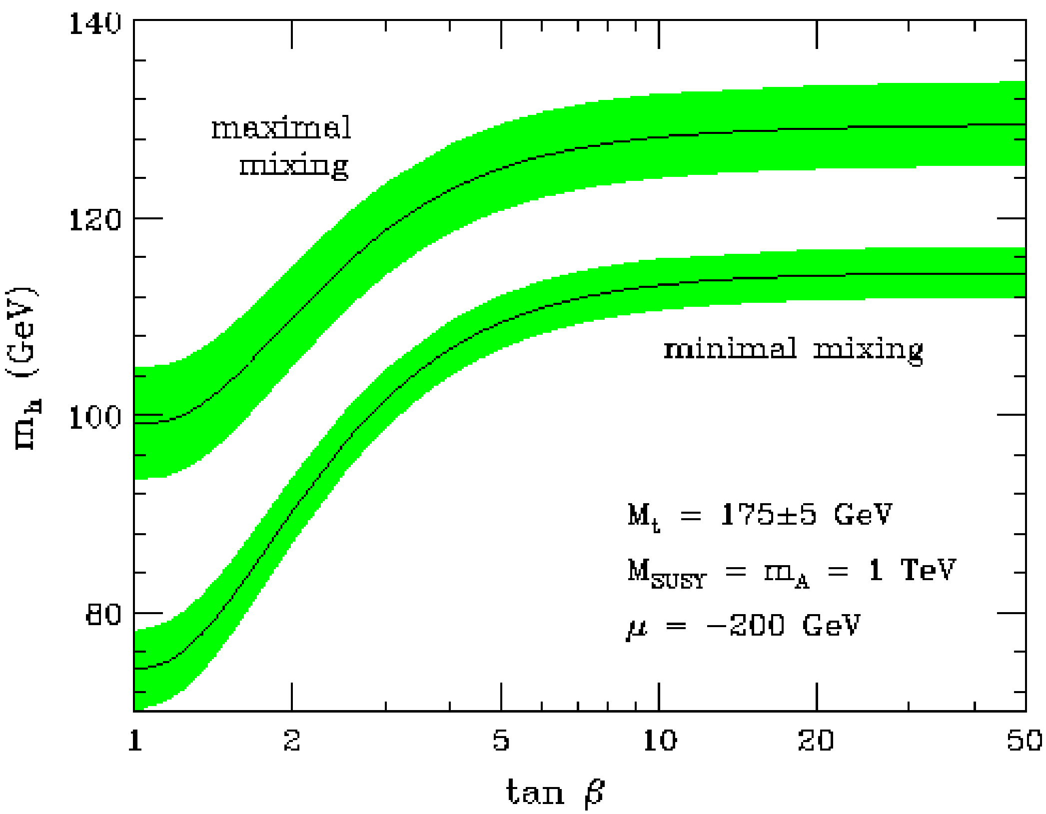
- Gluino mass is an independent parameter from squark masses

- Gluino:Wino:Bino mass ratios fixed by SUSY-breaking mechanism.
* mSUGRA, GMSB: 7 : 2 : 1
* AMSB: 8.3 : 1 : 2.8

Supersymmetry definitely predicts a Higgs boson.
- h^0: tends to be SM-like
- $H^0, A^0, H^\pm$: tend to be degenerate; decays depend on $\tan\beta$

MSSM with top squarks below 1 TeV requires $M_h \lesssim 135$ GeV.



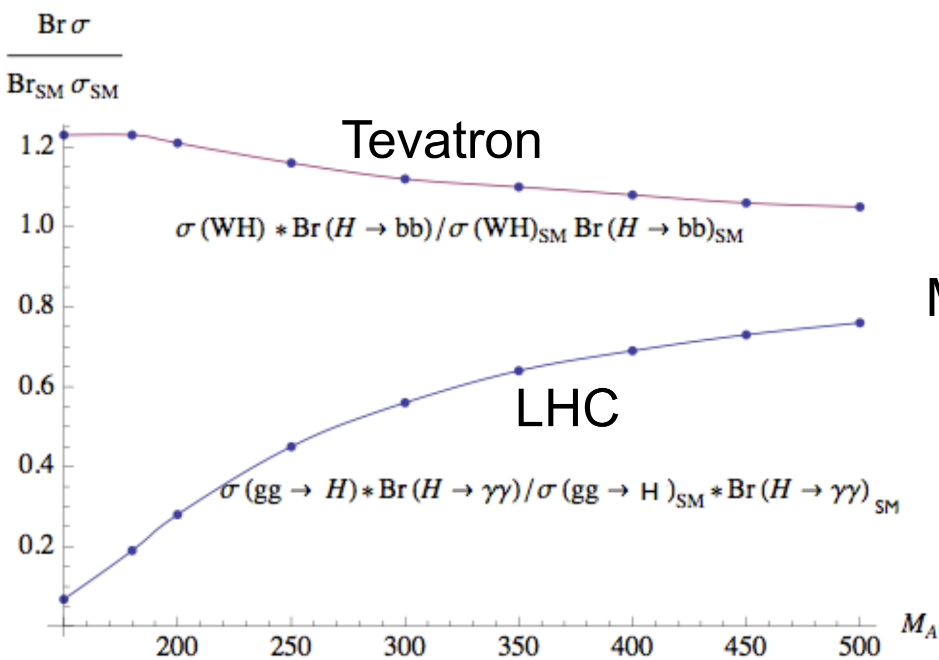


Carena & Haber, hep-ph/0208209

MSSM light-Higgs discovery can be tricky due to mixing and modification of loop-induced couplings by SUSY particles.

M. Carena, talk at Pheno 2011

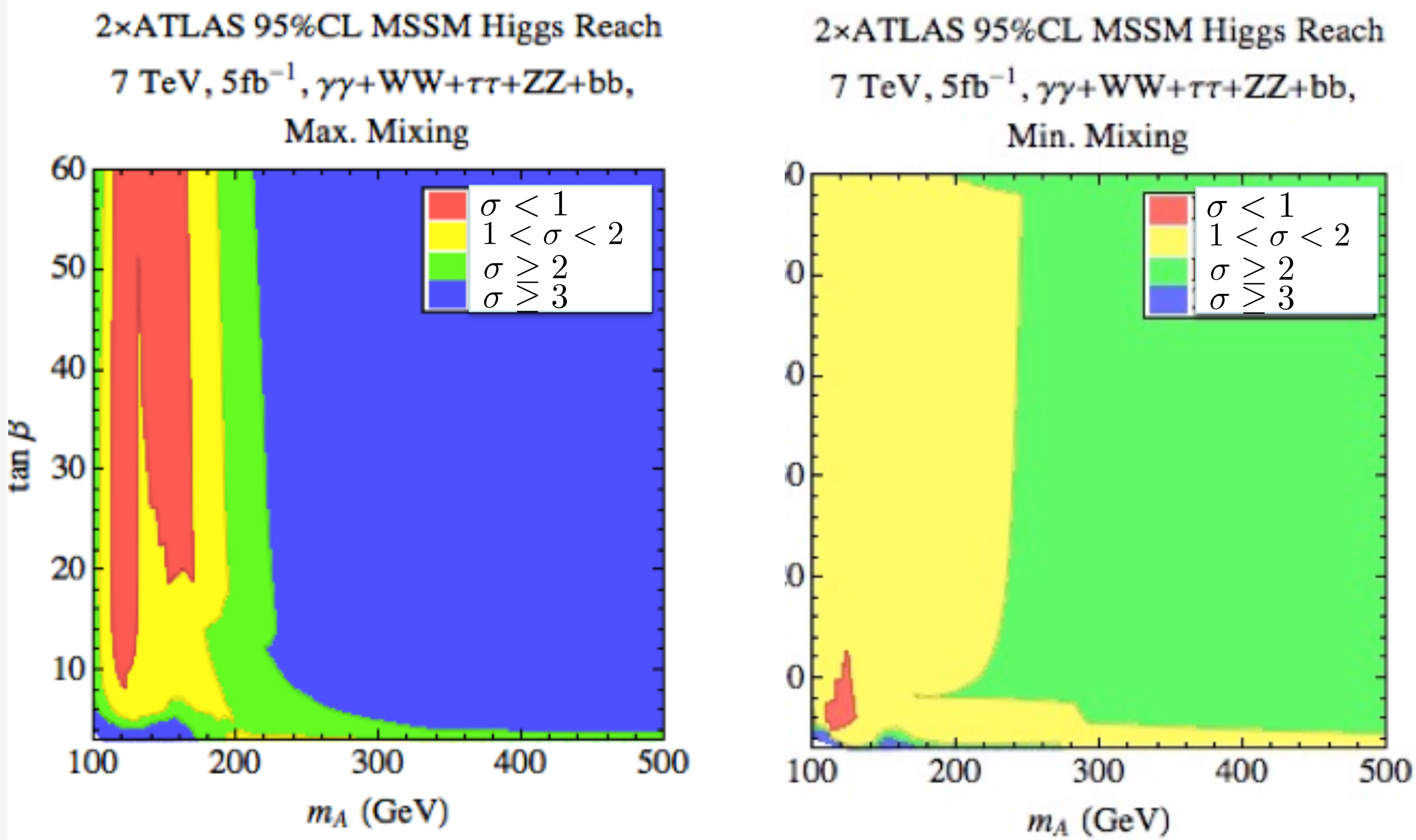
For a large region of parameter space suppression of the $\gamma\gamma$ mode at the LHC



$M_h \sim 115$ -125 GeV

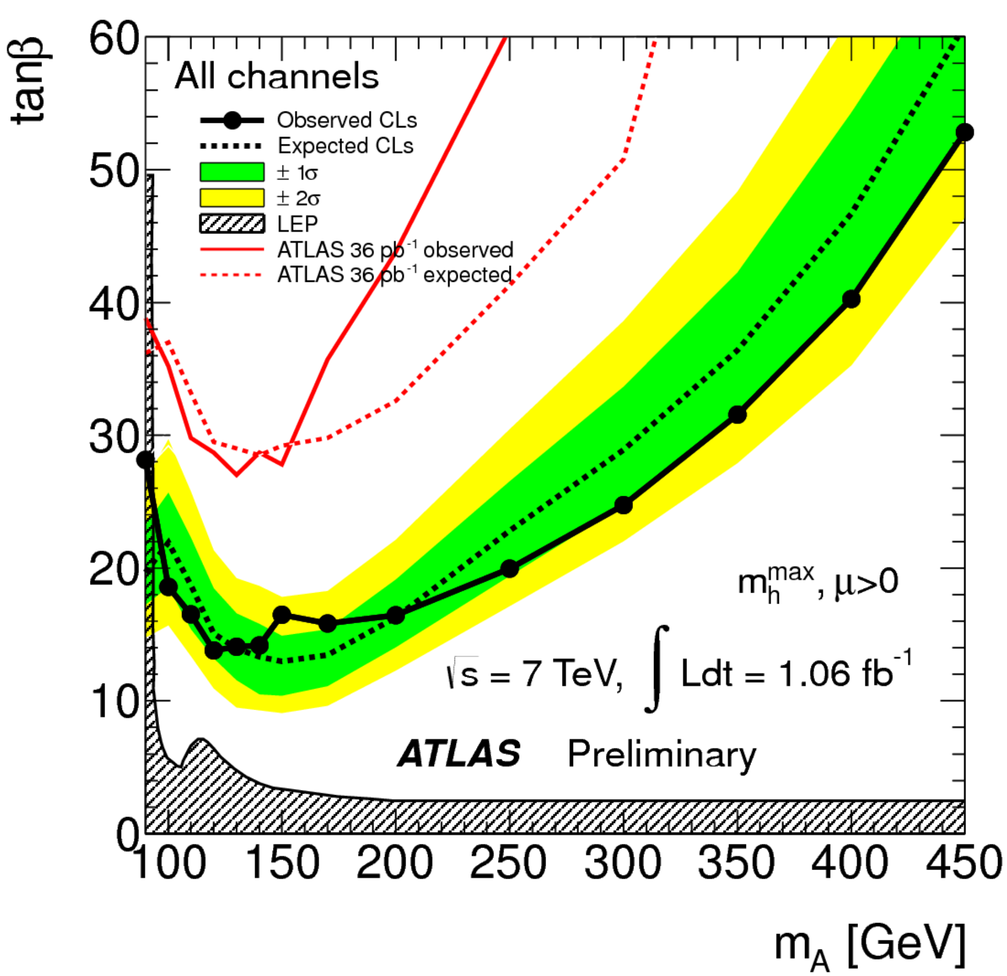
Suppression still sizable for m_A as large as 500 GeV

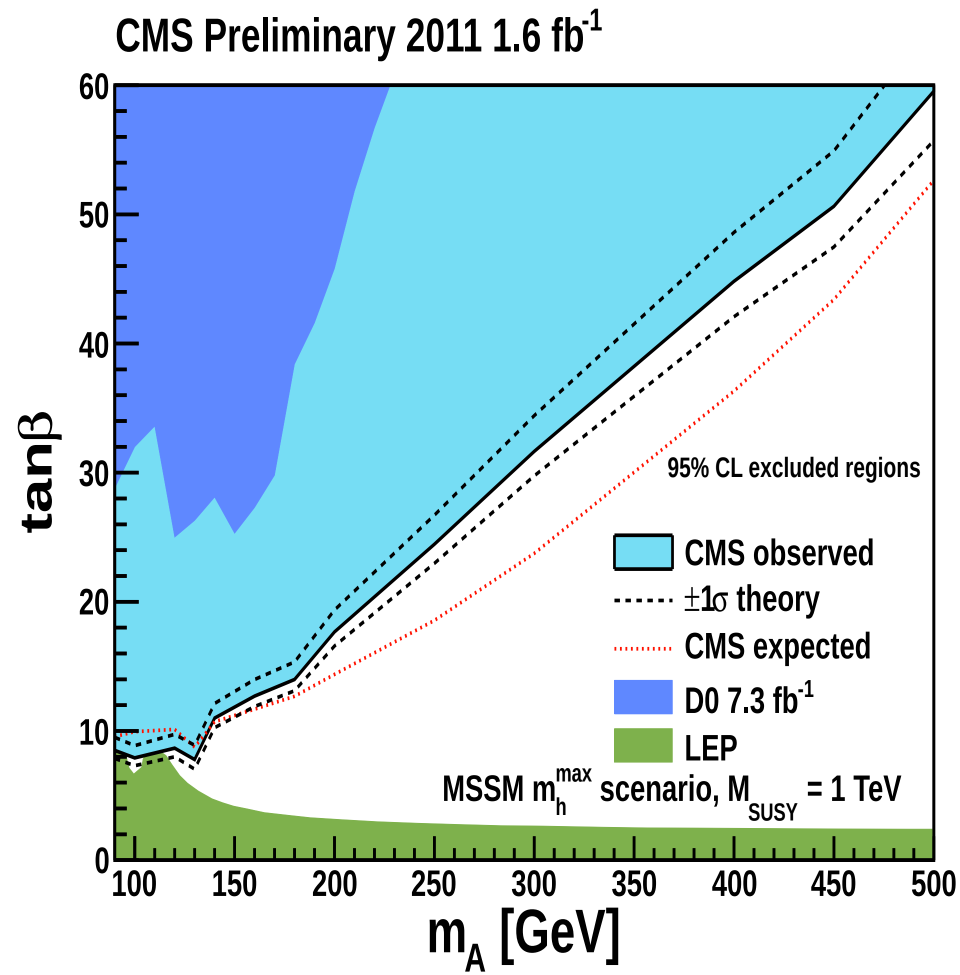
LHC reach for the MSSM SM-like Higgs



Important to improve on early LHC reach in tau tau mode

MSSM Higgses: $\tau\tau$ resonance search (from $A^0/H^0/h^0$)





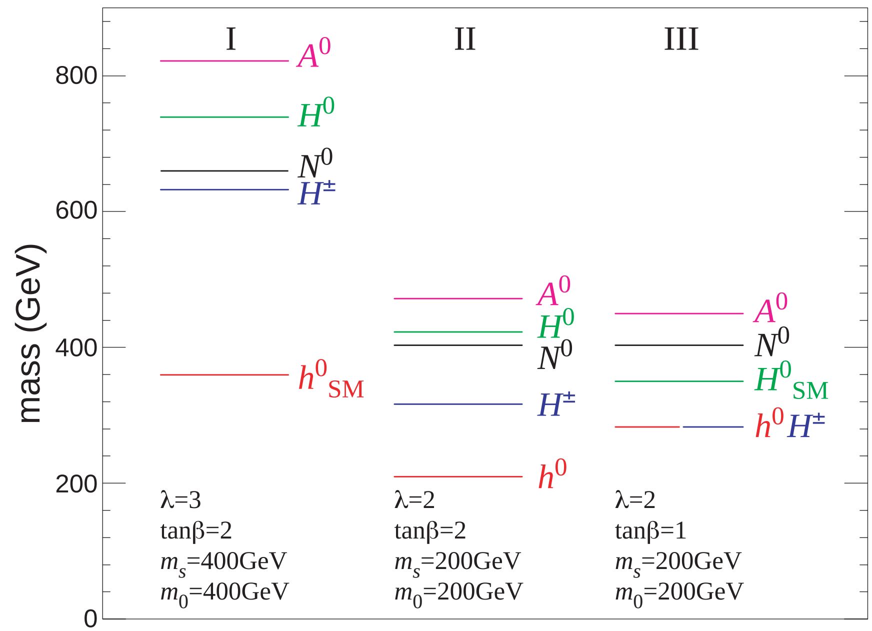
ATLAS-CONF-2011-132 (Lepton-Photon 2011)

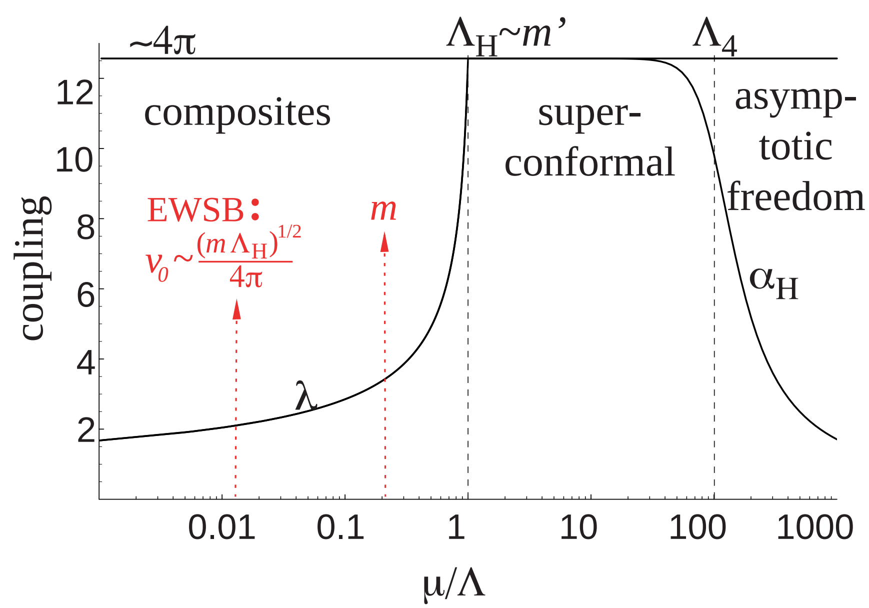
CMS-PAS-HIG-11-020 (yesterday!)

Most of "difficult" light-A^0 region is already excluded.

Is SUSY compatible with a Higgs above 135 GeV?

Yes, but it requires modifications. Options:
- "Hard" or very-low-scale SUSY breaking
- NMSSM (coupling $\lambda S H_u H_d$) with large $\lambda \Rightarrow$ Landau pole
  $\Rightarrow$ Supersymmetric "Fat Higgs" model and variants:
  Higgs $\sim$ 200–450 GeV. (Still viable with mixing, new decay modes)



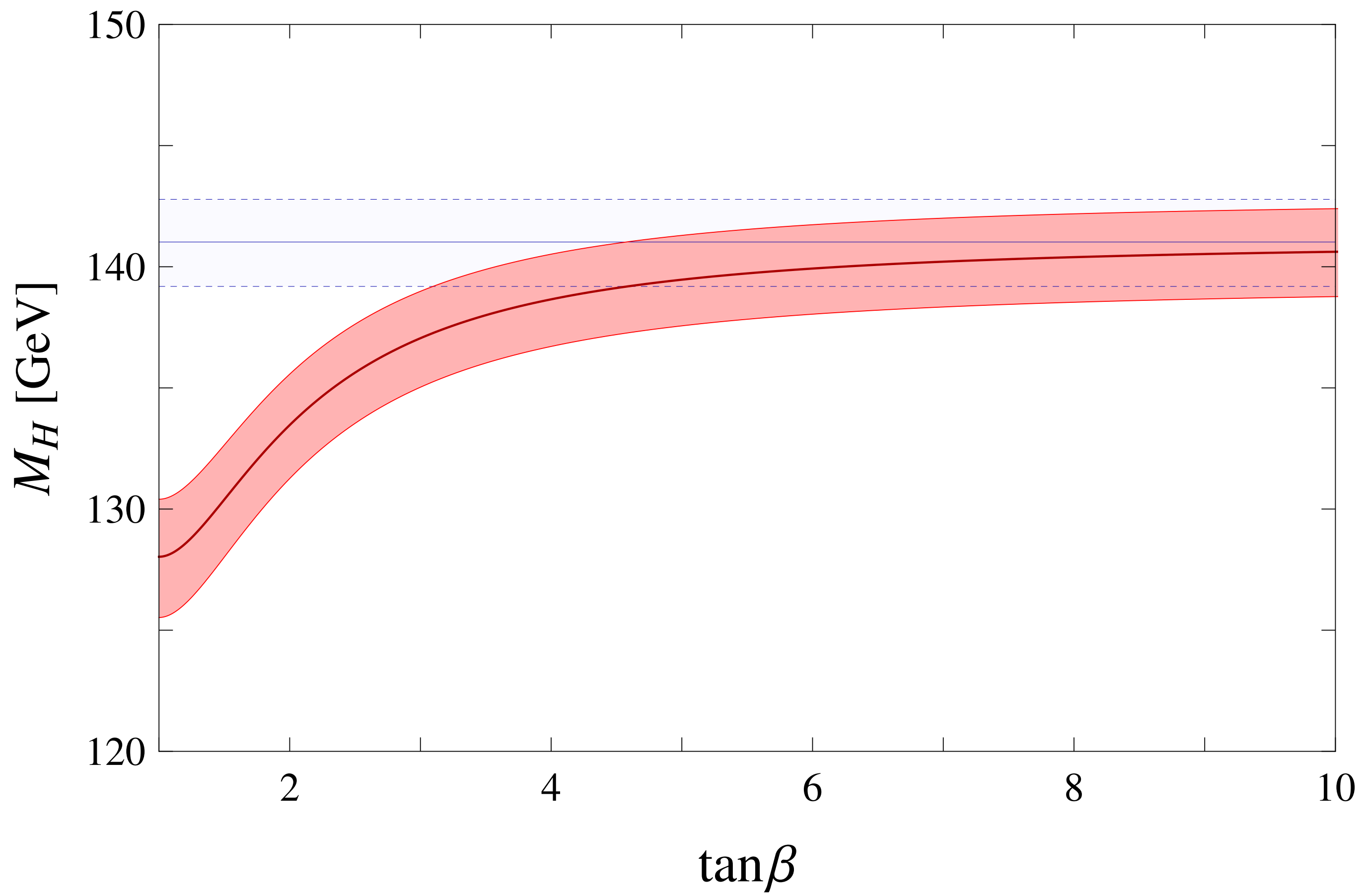


Harnik, Kribs, Larson, Murayama, hep-ph/0311349

- Make the top squarks heavier (reintroduces fine-tuning)

Supersplit Supersymmetry* predicts $128 \pm 2 - 141 \pm 2$ GeV

Fox, Kaplan, Katz, Poppitz, Sanz, Schmaltz, Schwartz & Weiner, hep-ph/0503249

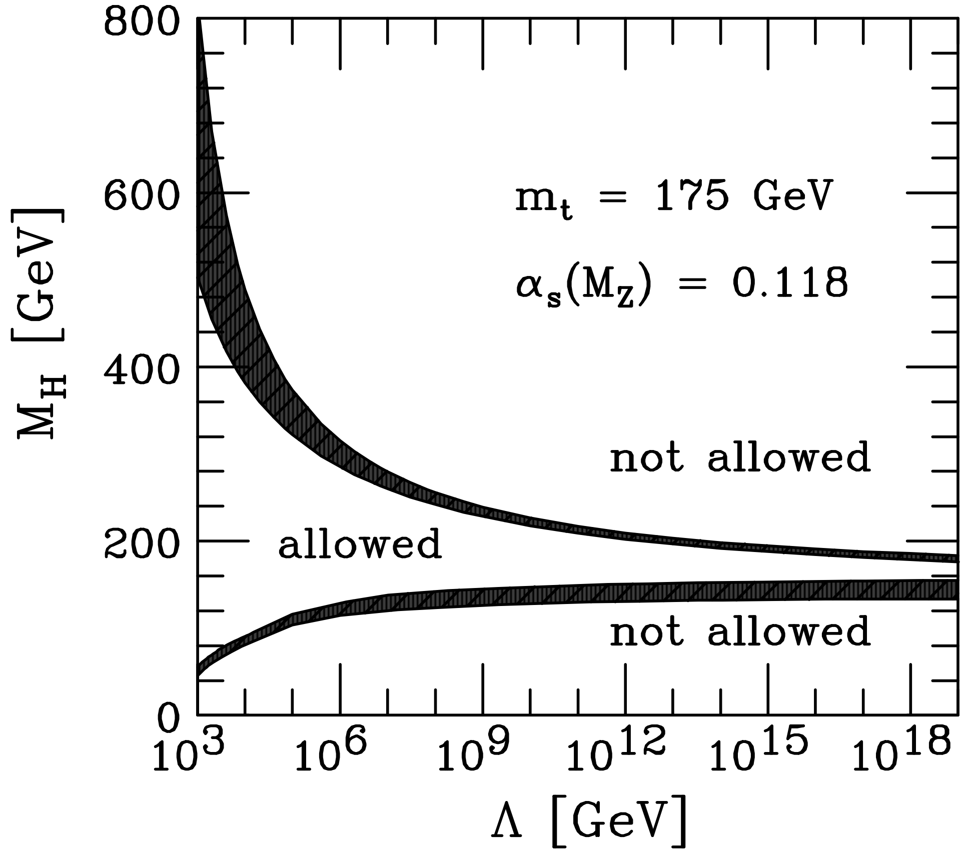


Hall & Nomura, JHEP 1003, 076 (2010)

Plot: $m_t = 173.1$ GeV, $\widetilde{m} = 10^{14}$ GeV; uncert. from Δm_t, $\Delta \alpha_s$.

*more than just the best April Fool's joke in particle physics!

Same as high-cutoff SM with stable, perturbative Higgs potential; GUT boundary condition fixes Higgs quartic at 10^{14-16} GeV.



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Higgs self-coupling too small compared to top Yukawa; runs negative at scale Λ

Hambye & Riesselmann, hep-ph/9708416

∃ window for ∼134–145 GeV.

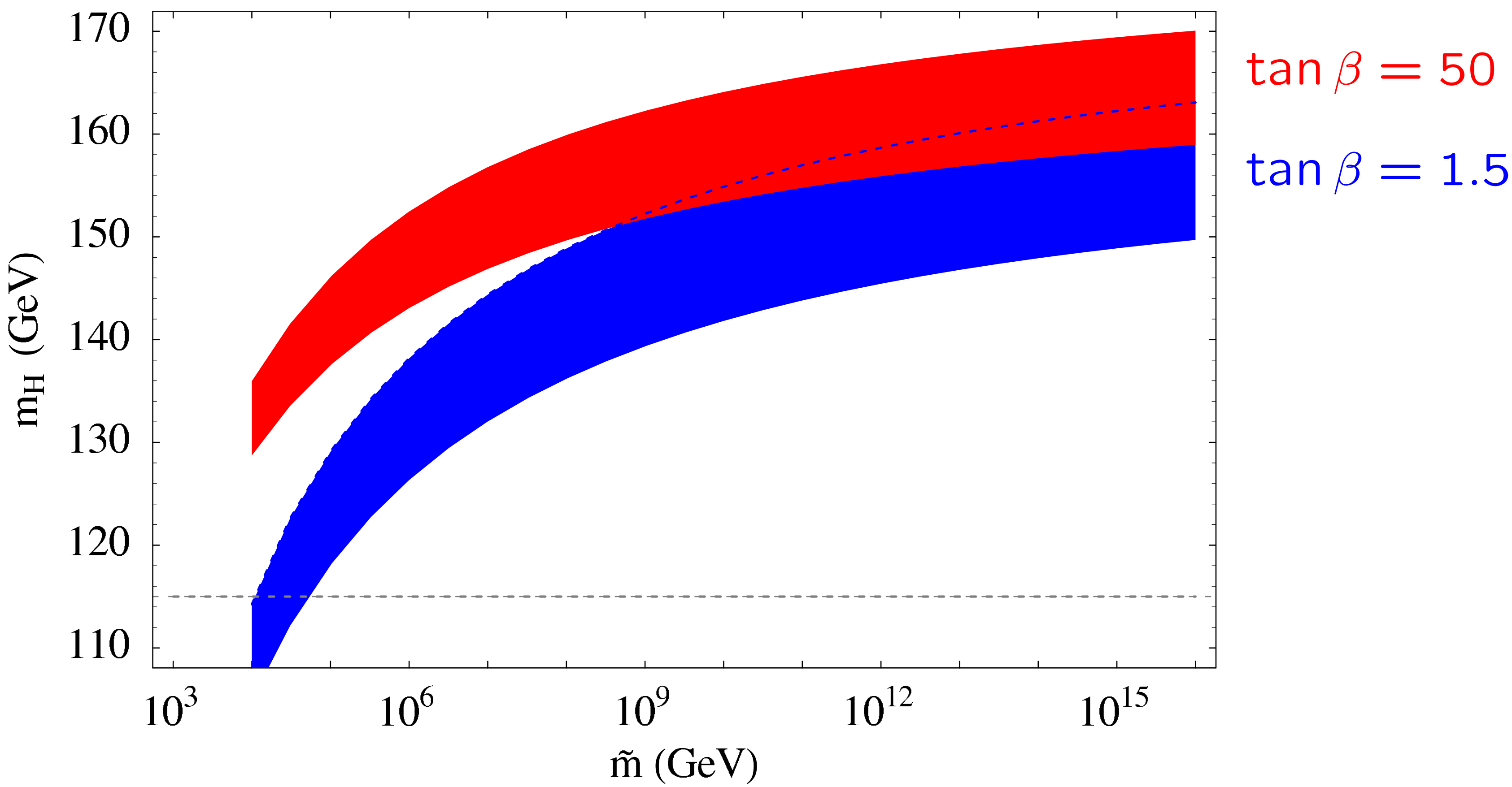
Compare Supersplit SUSY: ∼128–141 GeV

Lower edge of "window" depends sensitively on top mass.

Less extreme: Split Supersymmetry

Preserves gauge coupling unification, dark matter candidate; less fine-tuned.

Gauginos at TeV scale pull up Higgs mass compared to Supersplit



Giudice & Romanino, Nucl. Phys. B699, 65 (2004)

Gluino signatures are key: can have displaced vertices, CHAMPs.

New study: Alves, Izaguirre & Wacker, arXiv:1108.3390

Composite Models

Compositeness models trace EWSB to some new strong dynamics at or above the TeV scale.

Three broad classes of possibilities:

Technicolor (or Higgsless models)

- No Higgs state per se
- Goldstone bosons eaten by W, Z are bound states ("pions") of strongly-coupled dynamics

Composite-Higgs models

- Genuine Higgs (or Higgs-like) particle exists: bound state of strongly-coupled theory

Little Higgs models

- Higgs kept light by an extra layer of global symmetries; allows strong-coupling scale to be pushed higher
- Minimal extra matter content (top-partner, W', Z', ...) near TeV scale

Technicolor

Strongly coupled theory: hard to calculate reliably

Original analyses used QCD measurements $\Rightarrow$ too large effect on precision EW. Technicolor can't be just like QCD.

New understanding:

- Better techniques for strongly-coupled gauge theories
- AdS/CFT correspondence: calculate in 5-dim "dual" theory

"Deconstruct" the 5-dim theory to 4-dim for phenomenologically-useful "Higgsless" model:

- Expect techni-rho spin-1 resonances (W', Z') below TeV scale
  Exchange of these unitarizes WW scattering up to $\sim$1.5 TeV
  resonance decays into WW, WZ
- Can have physical techni-pions depending on global symmetries

Hard to make top quark heavy enough $\Rightarrow$ top-color, etc.

- Expect top-Higgs, top-pions
  Implications from LHC Higgs searches

Top-Higgs

Dedicated (composite) scalar doublet to generate most of top quark mass: common add-on for models of dynamical EWSB.
- topcolor-assisted technicolor
- deconstructed "top triangle" 3-site Moose

Top-Higgs doublet has vev $f = v_{\rm SM} \sin\omega$
(Strong dynamics responsible for most of EWSB: $v_{\rm SM} \cos\omega$)

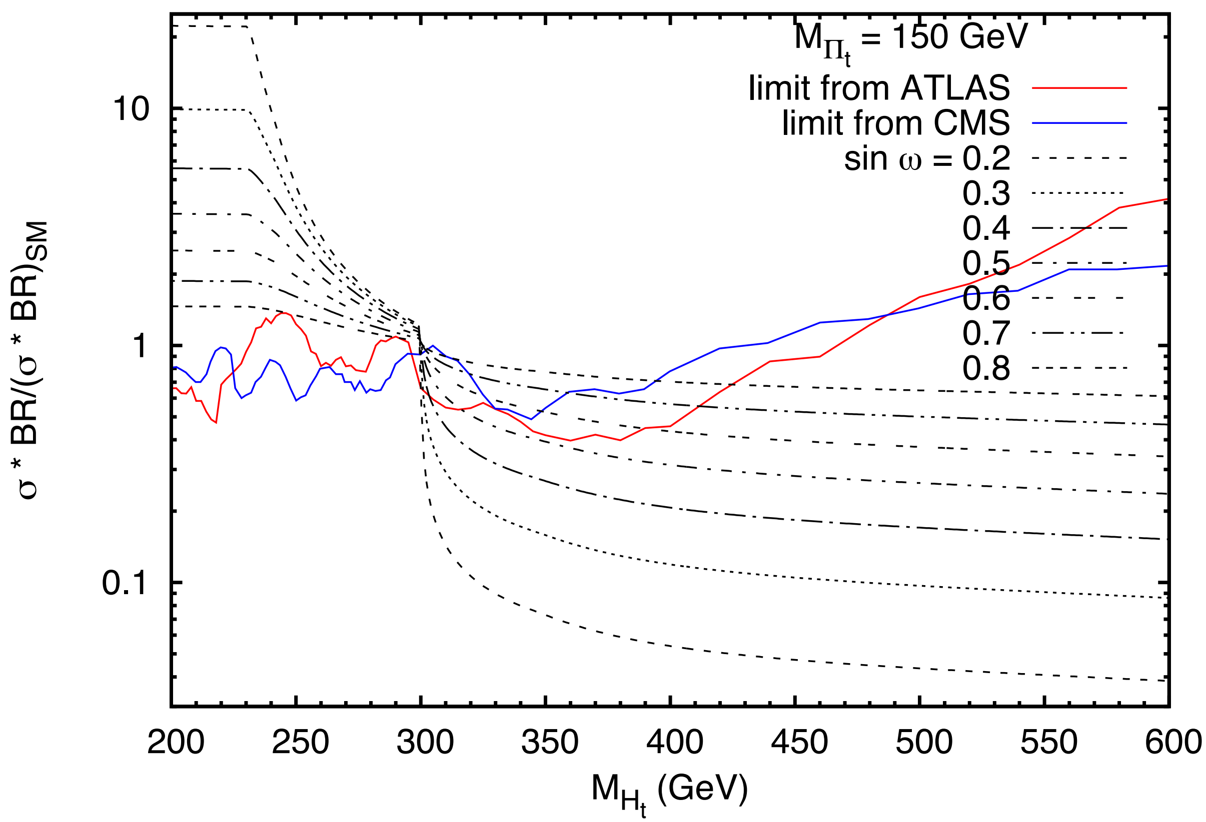
Top-Higgs particle H_t couples only to $t\bar{t}$, WW, ZZ at tree level
- WW, ZZ couplings suppressed $\sim \sin\omega$
- $t\bar{t}$ coupling enhanced $\sim 1/\sin\omega$
- $gg \to H_t$ enhanced $\sim 1/\sin^2\omega$: LHC production enhanced!

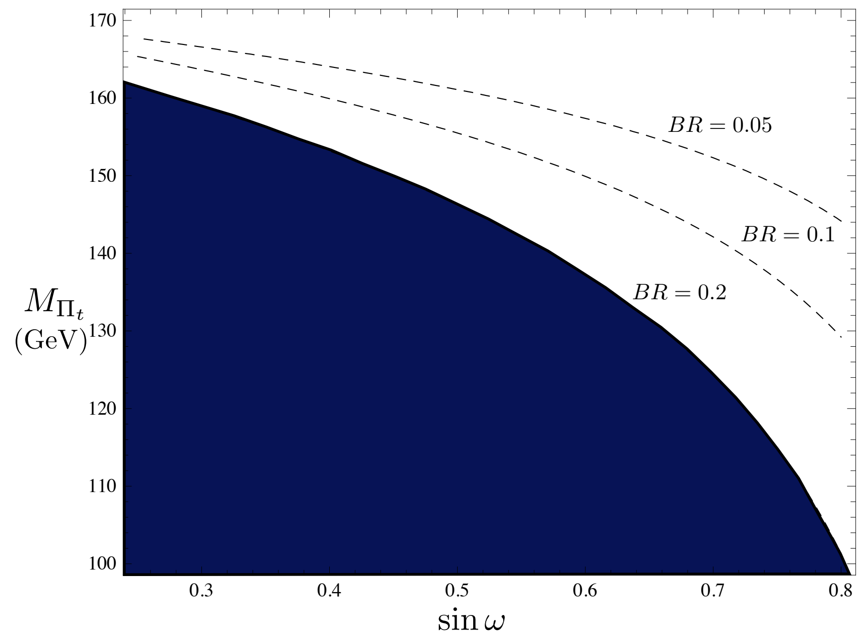
Typical mass is $M_{H_t} \lesssim 2m_t$ for dynamical top mass generation in topcolor-assisted technicolor (TC2)

LHC Higgs search: relevant channels are $gg \to H_t \to WW, ZZ$

BR($H_t \to WW, ZZ$) is suppressed when decays to top-pions ($W^{\pm}\Pi_t^{\mp}$, $Z\Pi_t^0$, $\Pi_t\Pi_t$) are kinematically accessible.

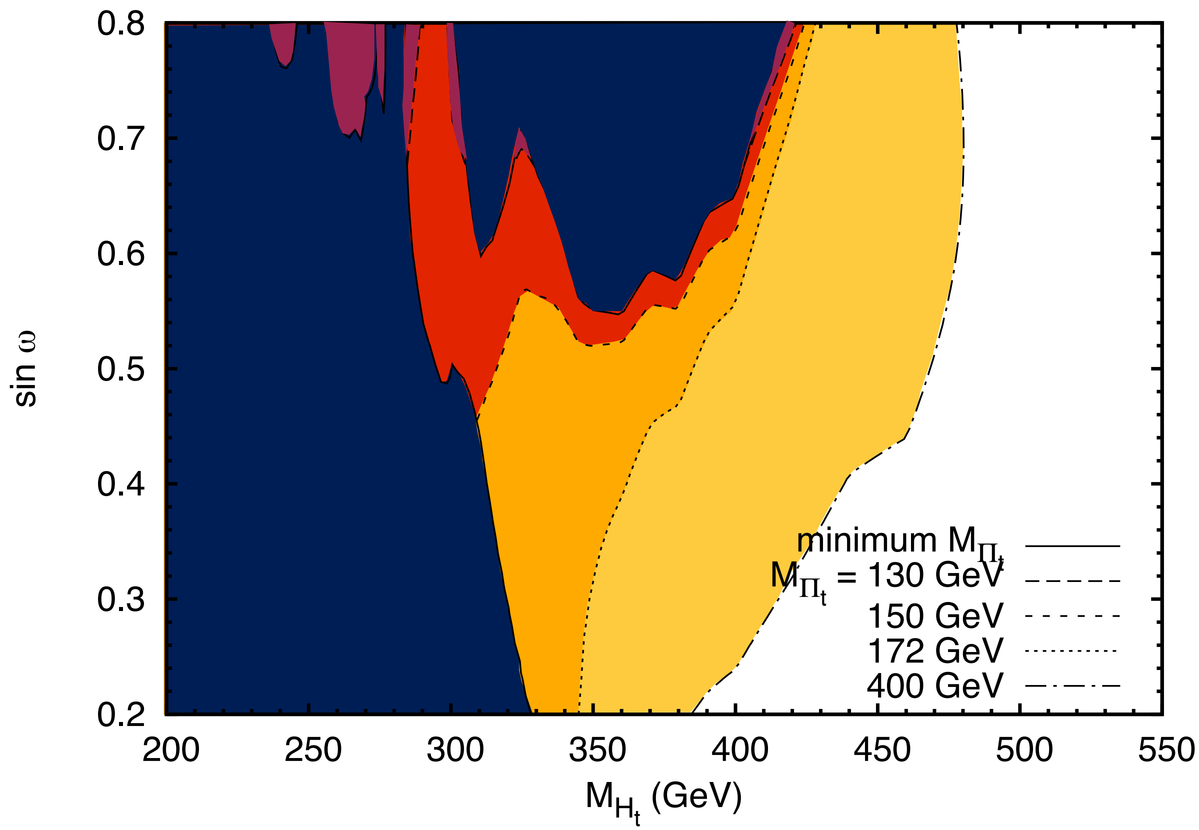
Top-pion mass constrained by exotic top decay limits: $t \to \Pi_t^+ b$.





Chivukula, Simmons, Coleppa, HEL, & Martin, arXiv:1108.4000 (updated with LP11 limits)

Most of the interesting TC2 top-Higgs parameter space has been excluded this summer!



Chivukula, Simmons, Coleppa, HEL, & Martin, arXiv:1108.4000 (updated with LP11 limits)

Other options:

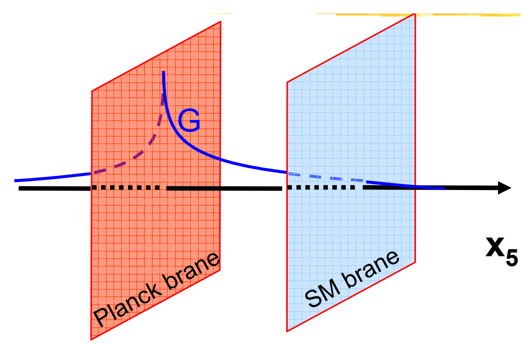
Top seesaw ⇒ much heavier top-Higgs: still viable

Composite Higgs: model based on Randall-Sundrum

Has a physical Higgs state

Higgs lives on or near IR brane: interpreted as composite

Top quark near IR brane: need overlap with Higgs to pick up large enough mass



KK excitations of Z, W, gluon

- Enhanced coupling to right-handed top
- Z', G' decay preferentially to $t\bar{t}$: TeV resonances in top pairs

KK excitations of quarks

- Single production via qW, qZ fusion

  Cross section is larger than for pair production for heavy masses
- Decays back to qW, qZ

Electroweak constraints

Generic models of New Physics tend to be tightly constrained by electroweak precision data.

- New particles contribute to measured SM processes, e.g., $f\bar{f} \to f\bar{f}$.
- New features in SU(2) and top sectors constrained by S, T and R_b.

EW precision constraints generically push $\Lambda_{\rm eff}^{\rm NP}$ well above "natural" TeV scale, especially for strongly coupled new physics: called the "little hierarchy" problem.

Tricks:

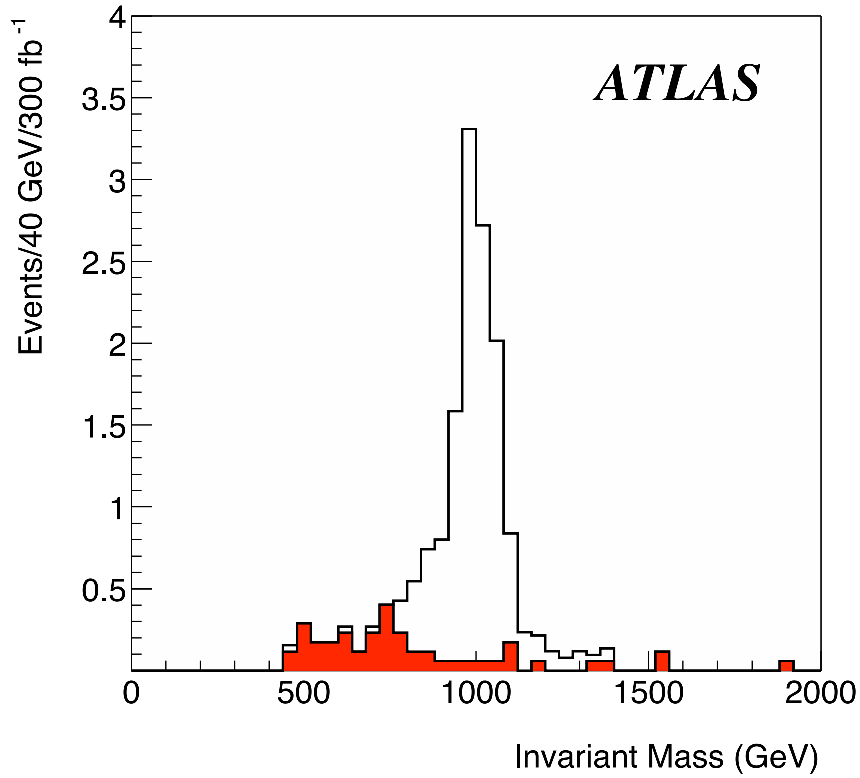
- Little Higgs models: Use global symmetries to kill off 1-loop correction to Higgs mass: push strong dynamics up to ~10 TeV.
- $\Delta\mu^2 \sim (g^2/16\pi^2)^2\Lambda^2$ instead of $(g^2/16\pi^2)\Lambda^2$

- Little Higgs with T-parity: make extra TeV-scale states T-parity odd: produced only in pairs, exchanged only in loops. Escape EW precision constraints; get dark matter candidate.

Little Higgs models

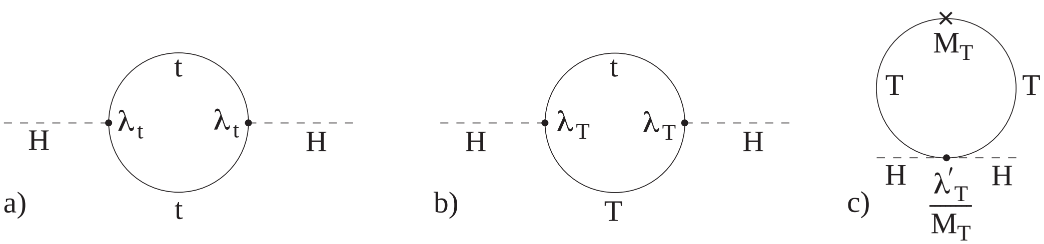
Need "partners" at TeV scale for top, W, Z, Higgs to cancel one-loop μ^2 corrections.

$T \to tZ \to b\ell\nu\ell\ell$



Azuelos et al, hep-ph/0402037

Top partner T:



SU(2)-singlet "vectorlike" quark.

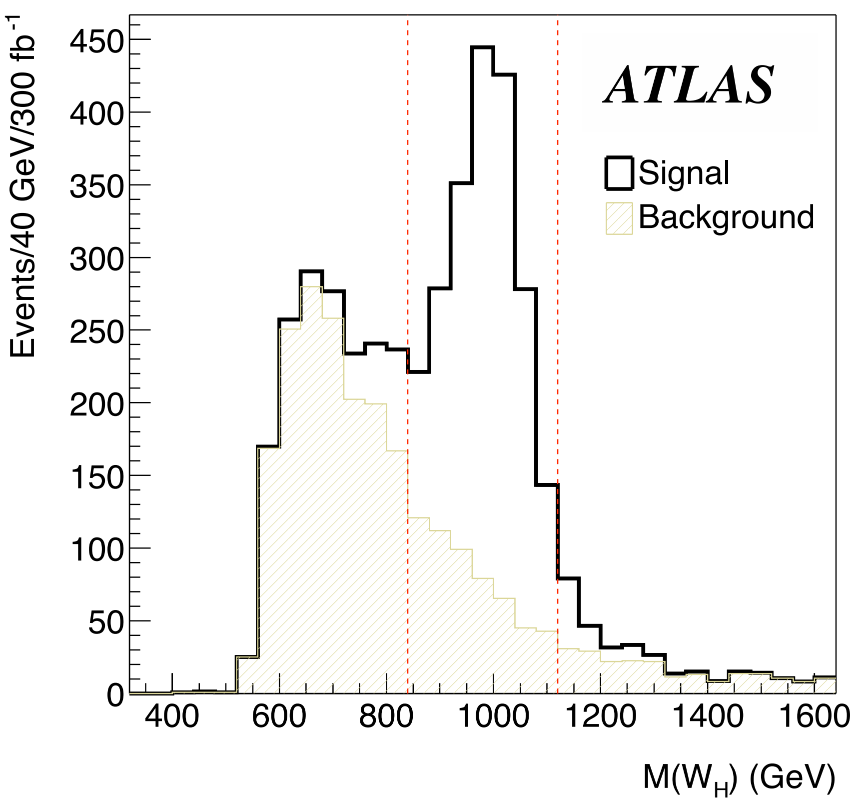
Production: $\bar{T}T$ via QCD, Tj via t-channel W.

Decays: $T \to bW, tZ, tH$.

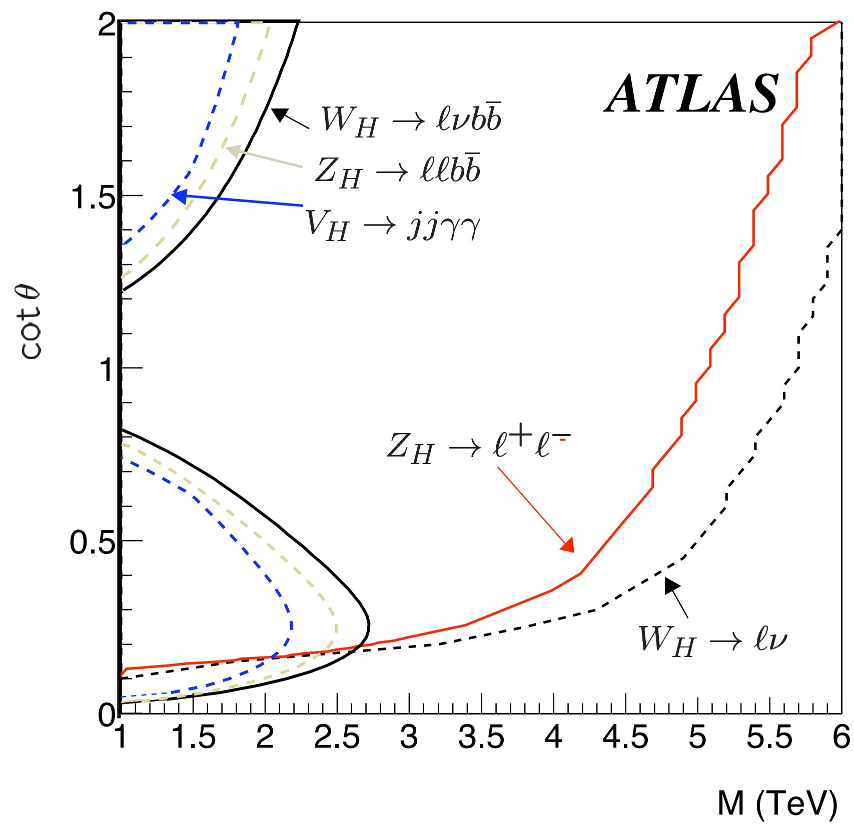
Gauge partners W_H, Z_H (and sometimes B_H):

- Come from SU(2) $\times$ SU(2) $\to$ SU(2)$_L$ breaking
- Couplings to left-handed fermions like SM $W_\mu^{\pm,3}$, with strength $g \cot\theta$
- Extra decays $Z_H \to HZ, WW$; $W_H \to HW, ZW$

$W_H \to WH \to \ell\nu bb$

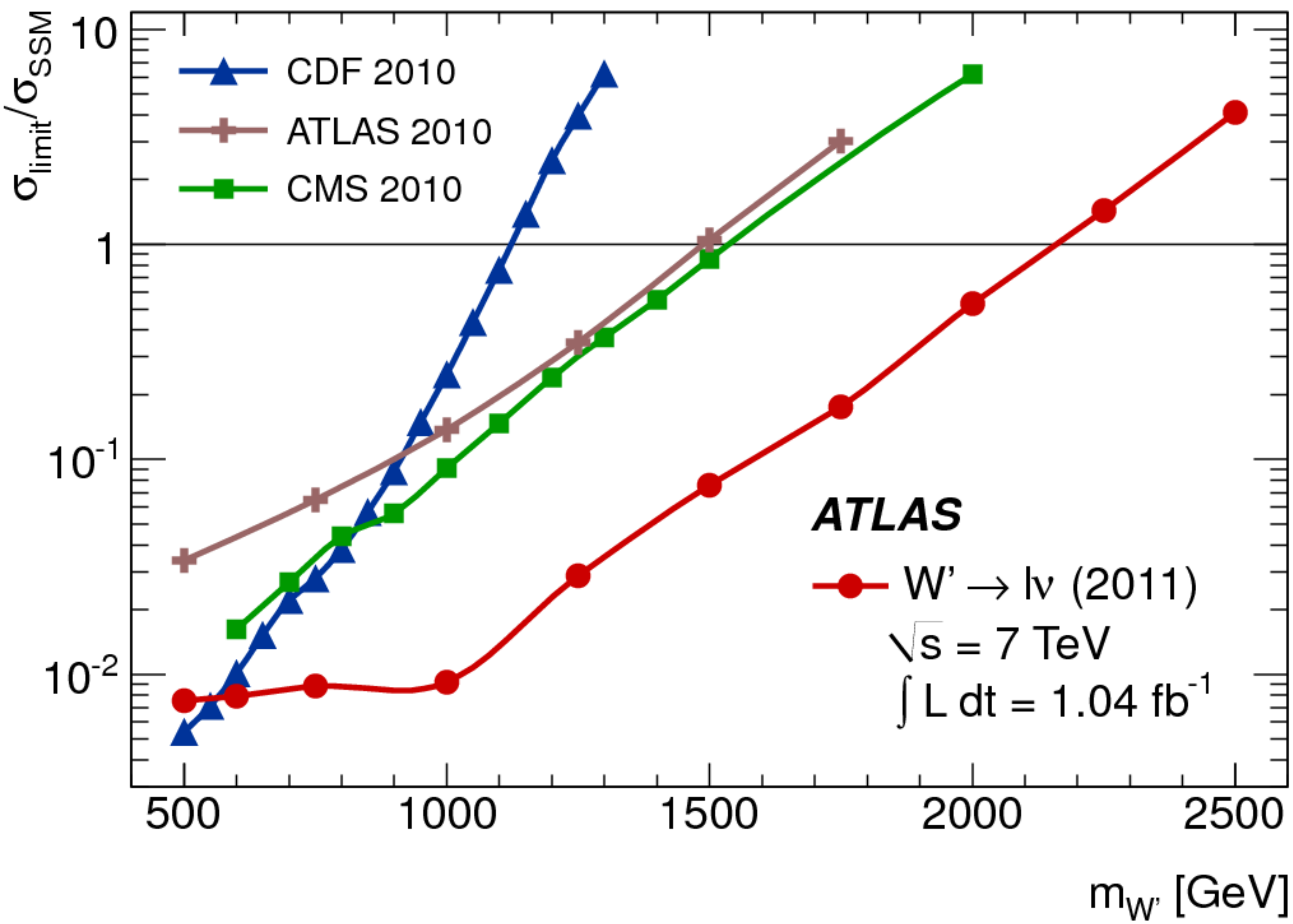


5σ discovery w/ 300 fb^{-1}:



Azuelos et al, hep-ph/0402037

$W' \to \ell\nu$ search:
Probe production coupling strength, decay BRs.



ATLAS, arXiv:1108.1316 [hep-ex]

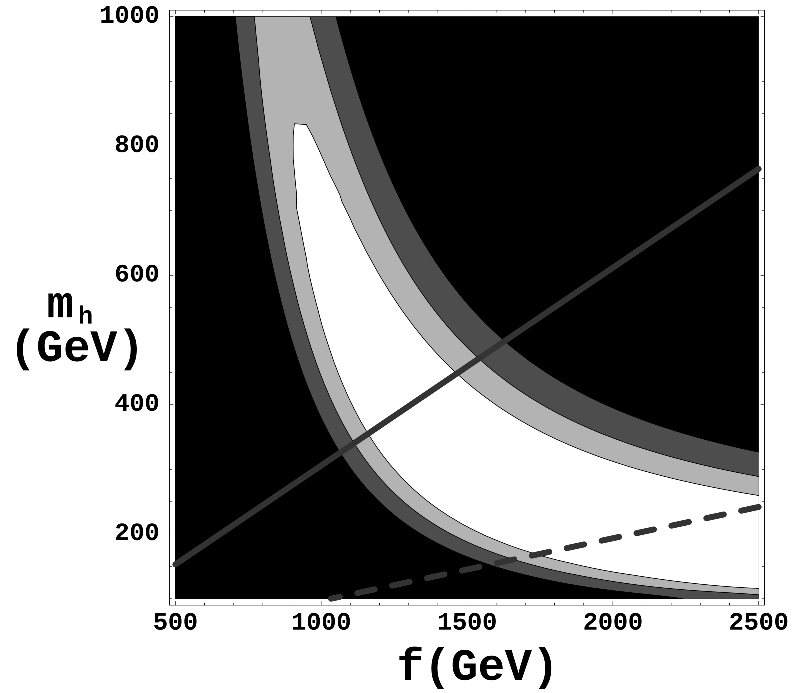
Little Higgs with T-parity

Looser electroweak constraints ⇒ new particles can be lighter
- less fine-tuned

T-parity ⇒ T-odd particles pair-produced, stable “LTP”
- $T \to t$ + invisible
- gauge partner pair signals reminiscent of SUSY

Higgs mass range preferred by precision EW + fine-tuning can be rather heavy.

- very model-dependent statement
- major implications from Higgs search
- needs to be systematically explored



Littlest Higgs with T-parity, Hubisz, Meade, Noble, Perelstein, hep-ph/0506042

Summary and outlook

Early LHC data already having impacts on huge range of models.

- Major task for phenomenologists to incorporate the new LHC exclusions into model "landscape" (fine-tuning, etc.)

None of the major classes of new-physics models is "dead yet"

- but some are starting to be tightly constrained (e.g., TC2).

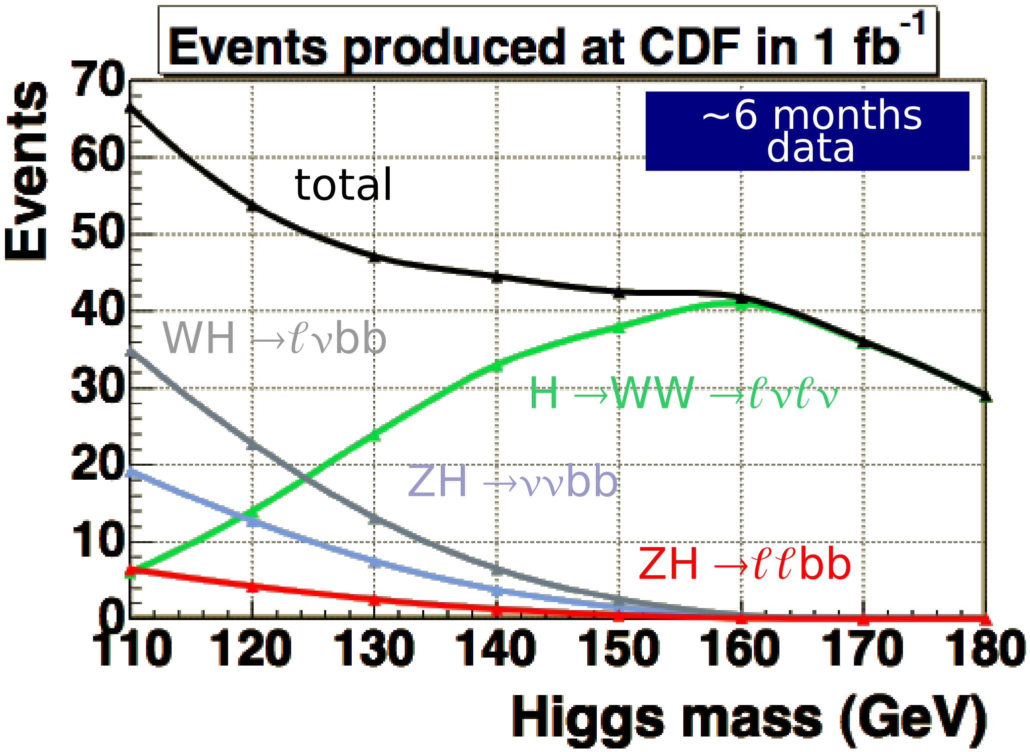
Outcome of Higgs search in 5–10 fb^{-1} will be very important.

We eagerly await experimental input on the dynamics of electroweak symmetry breaking!

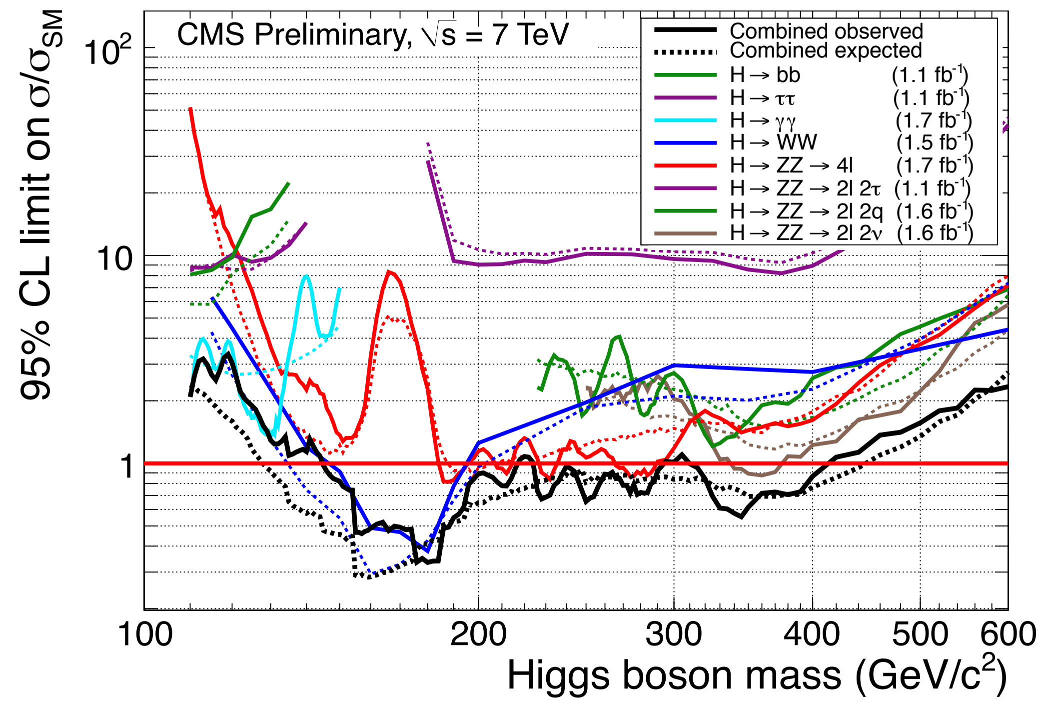
Backup slides

MSSM Higgs search:

Low-mass Tevatron and LHC channels are complementary.



M. Casarsa, talk at PLHC 2011

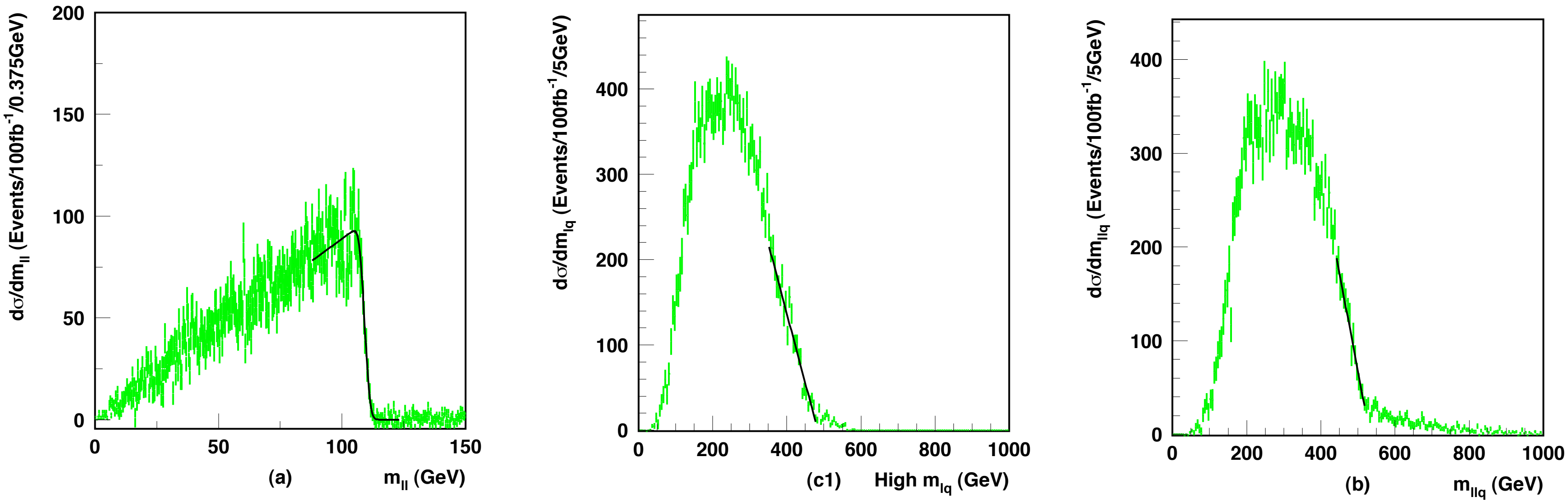


CMS-PAS-HIG-11-022 (LP2011)

Supersymmetry: key measurements

1) Mass spectrum

- Use kinematic edges to get mass differences in decay chain



Paige, hep-ph/0211017

- Exact kinematic relations: "solve" individual decay chains

Kawagoe, Nojiri & Polesello, PRD71, 035008 (2005), Cheng et al., PRL 100, 252001 (2008)

- MT2 ("stransverse mass"), kinks, cusps, $\sqrt{\hat{s}}_{\rm min}$, etc.

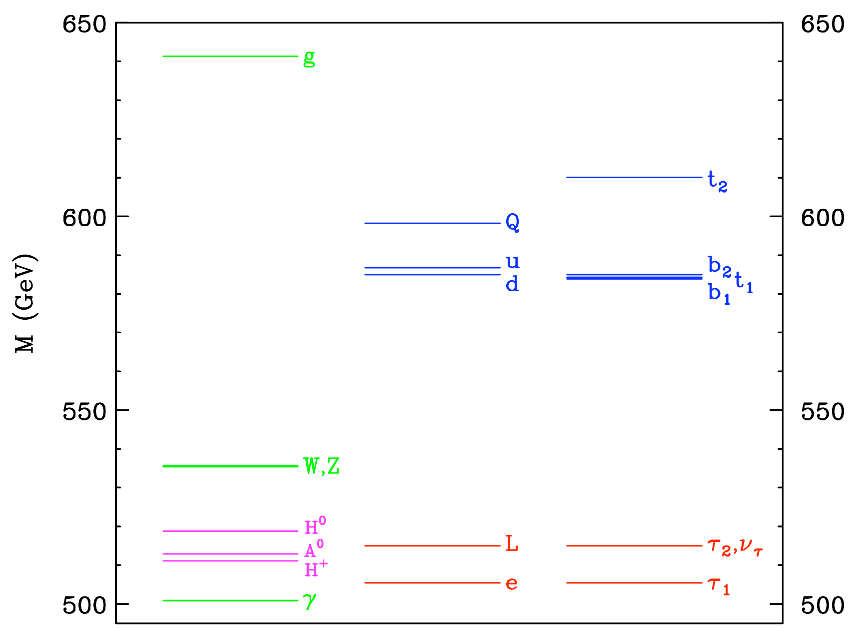
Recent review: Barr et al., arXiv:1105.2977

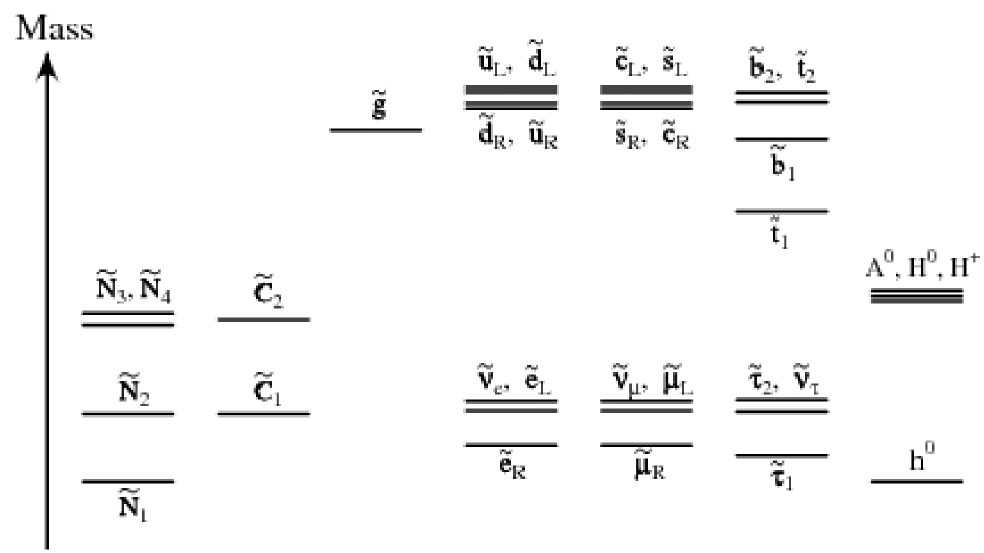
Supersymmetry: key measurements

2) Spin of superpartners

Universal Extra Dimensions can mimic SUSY
Stable "LKP" $\rightarrow$ jets + missing energy signatures.

UED, $L = (500\ \text{GeV})^{-1}$ MSUGRA

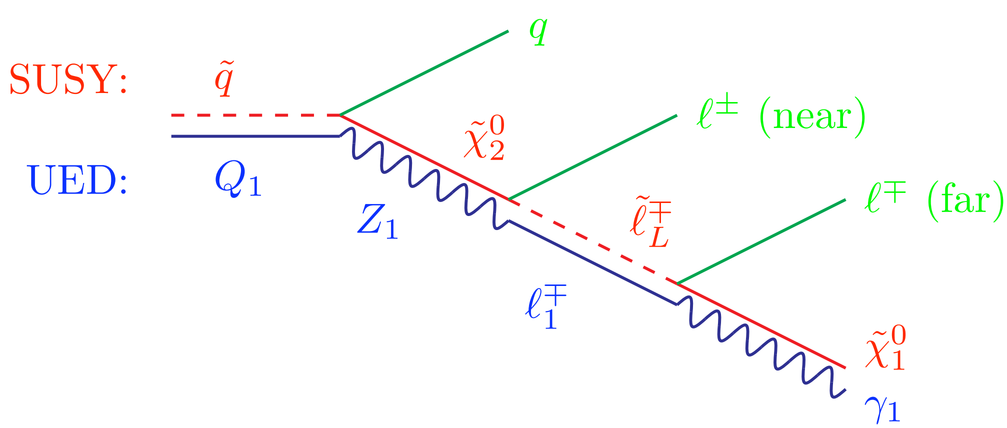


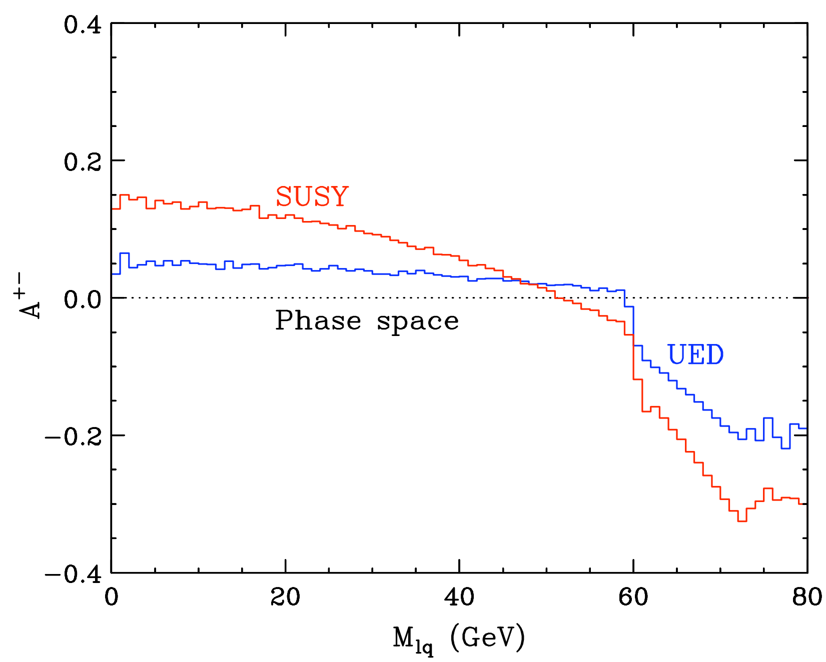


Supersymmetry: key measurements

2) Spin of superpartners

Need to be clever to find distinguishing observables!
Kinematic distributions, etc.



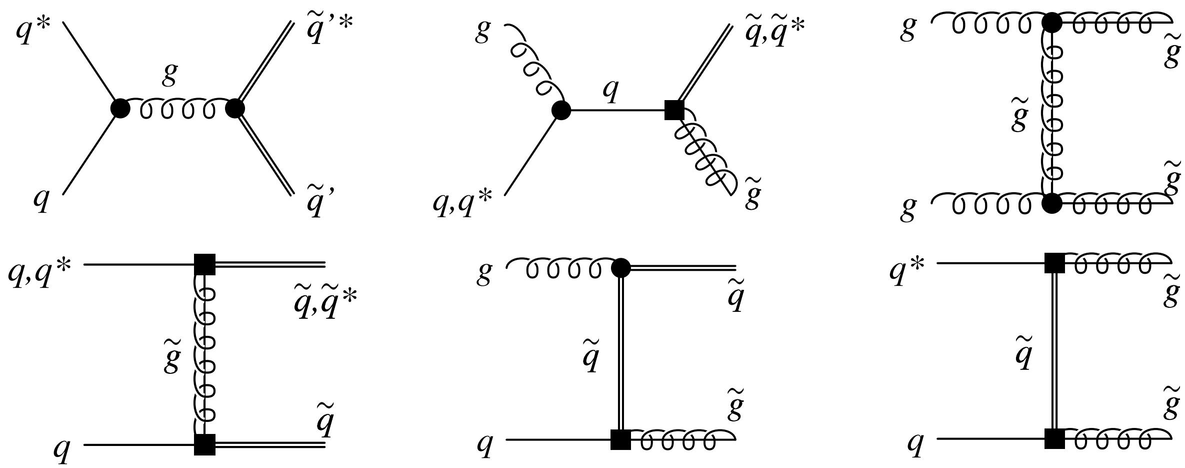


Datta, Kong & Matchev, hep-ph/0509246

Supersymmetry: key measurements

3) Coupling relations

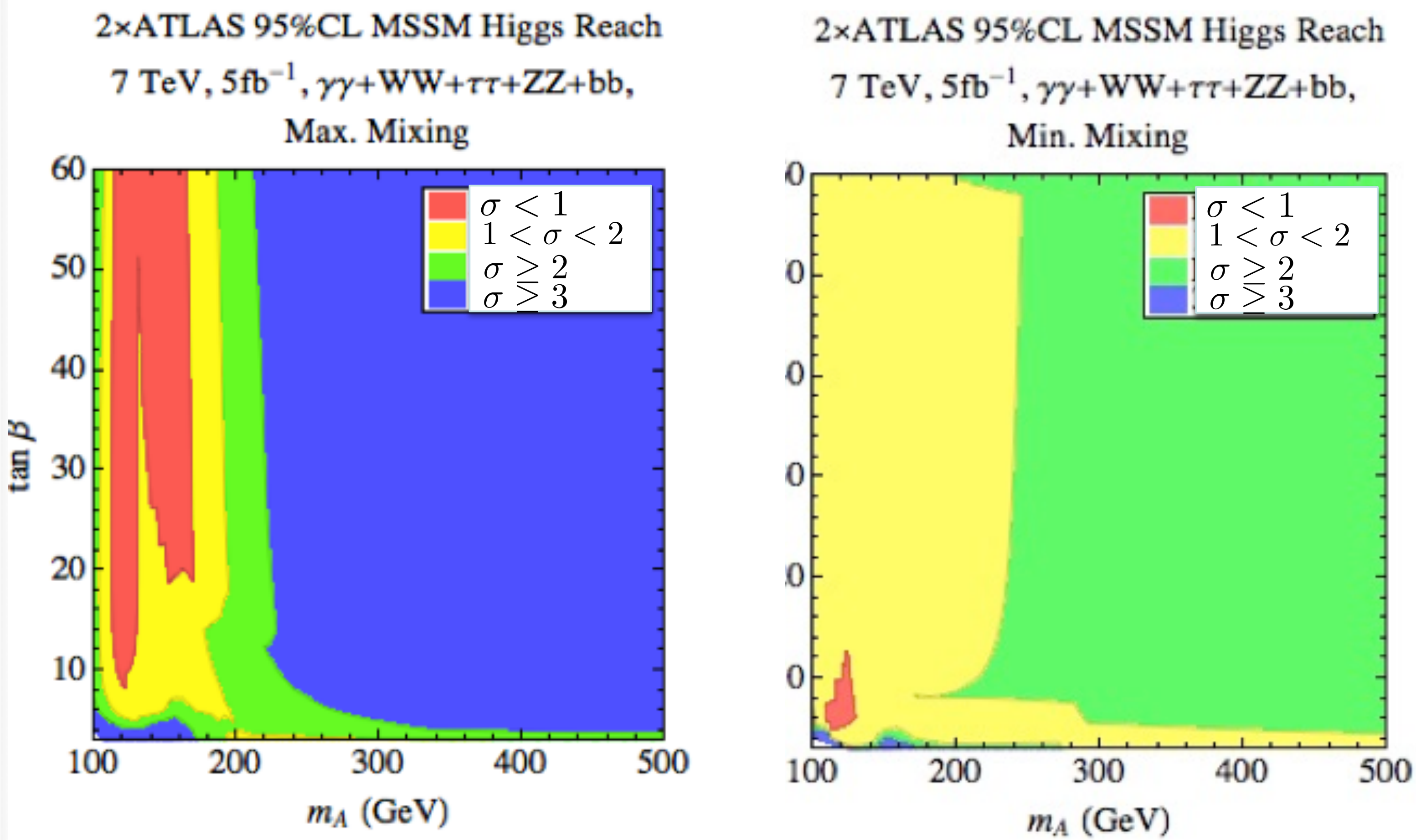
gauge couplings $\leftrightarrow$ gaugino Yukawa couplings



Freitas & Skands, hep-ph/0606121

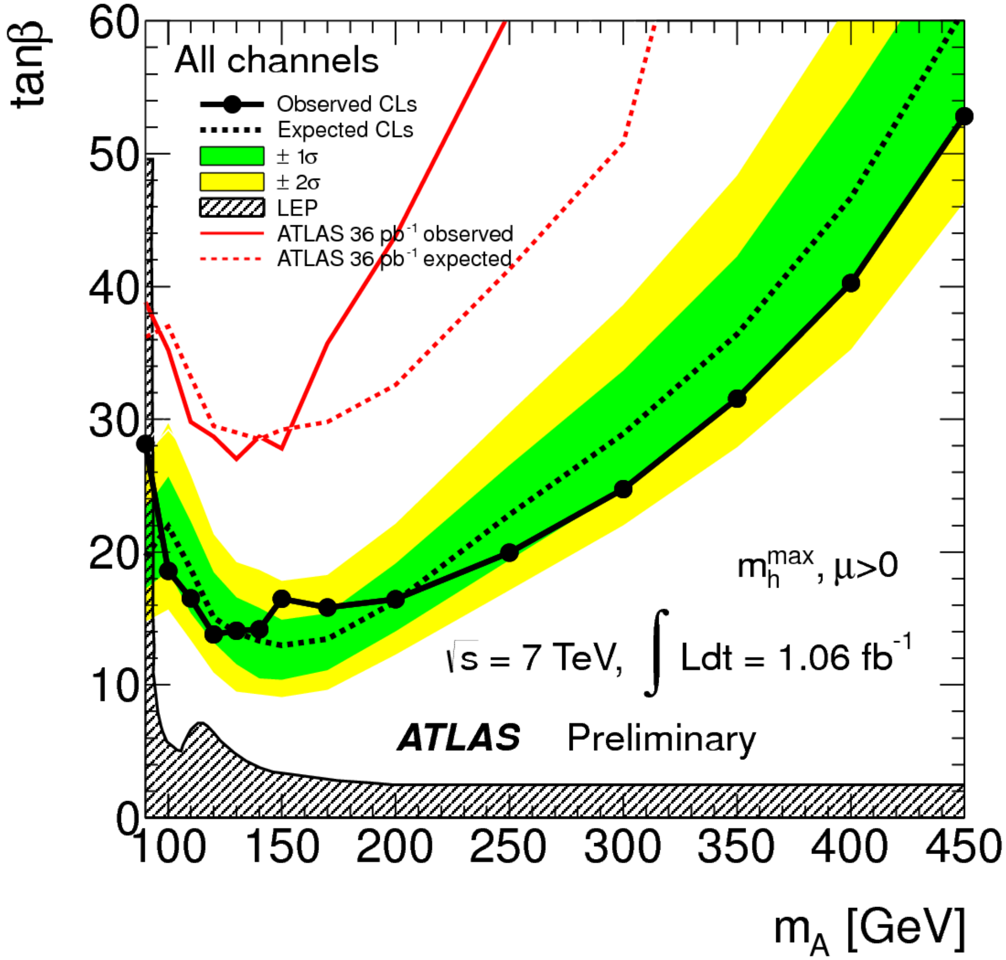
Requires ILC input for squark decay BRs.

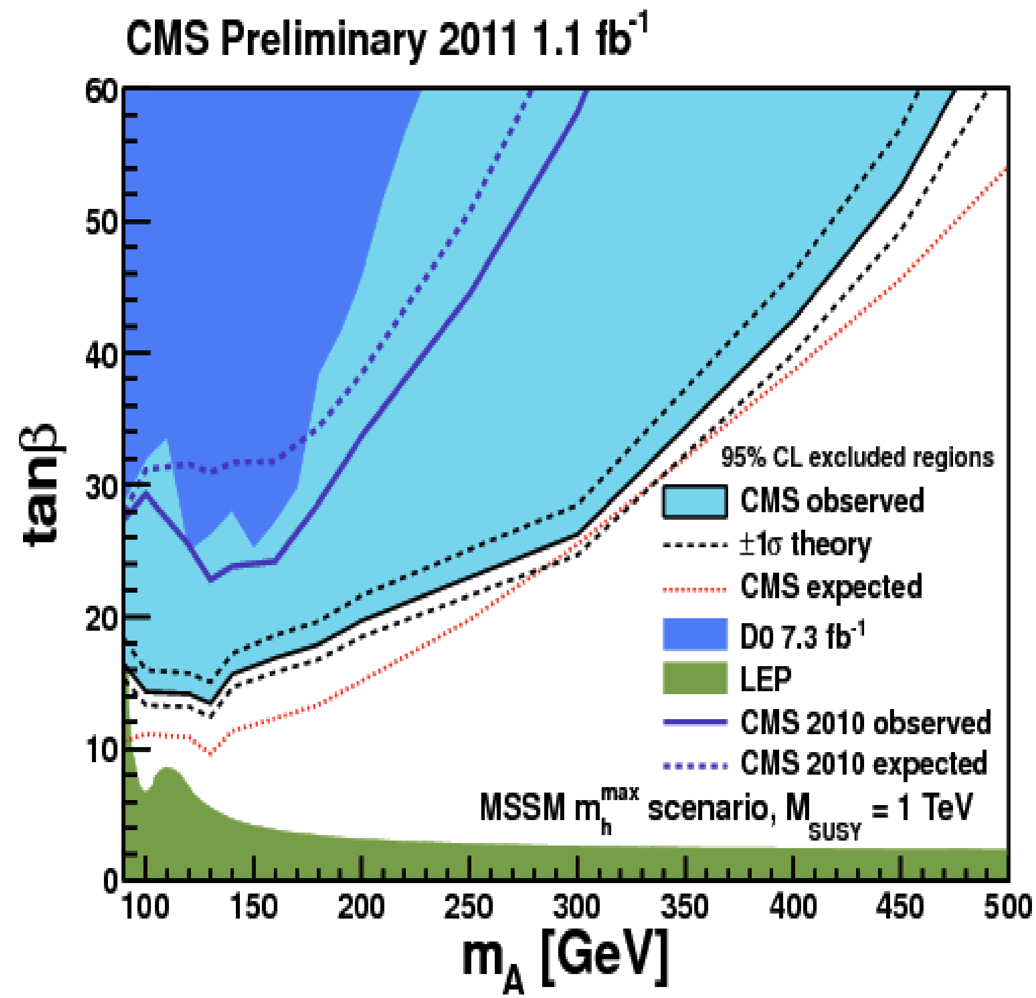
LHC reach for the MSSM SM-like Higgs



Important to improve on early LHC reach in tau tau mode

MSSM Higgses: $\tau\tau$ resonance search (from $A^0/H^0/h^0$)

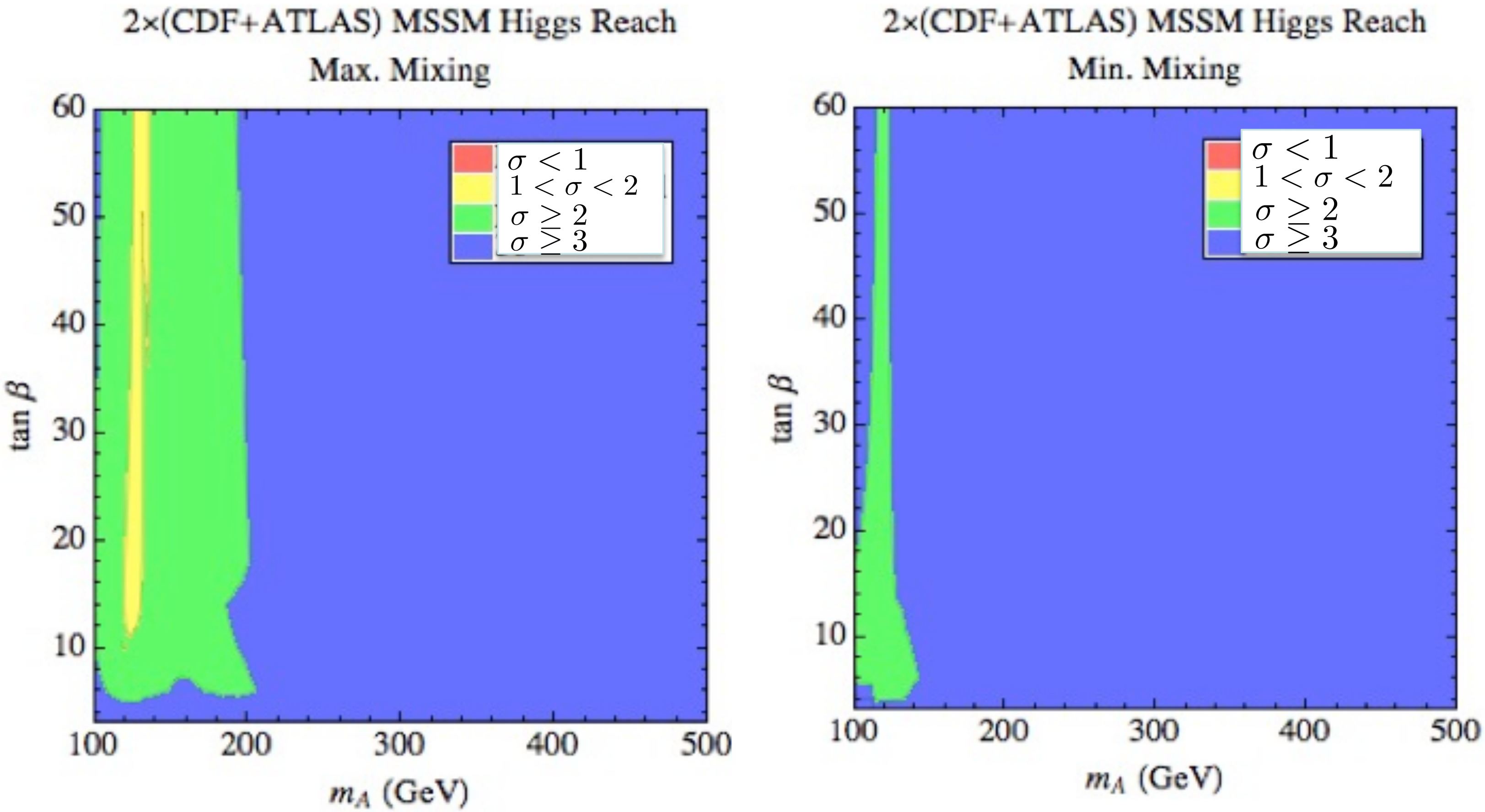




ATLAS-CONF-2011-132 (Lepton-Photon 2011) CMS-PAS-HIG-11-009 (EPS-HEP 2011)

Most of "difficult" light-A^0 region is already excluded.

Tevatron - early LHC combined reach : MSSM SM-like Higgs



3 sigma evidence of the SUSY Higgs responsible for EWSB

$Z' \to \ell\ell$ search: 5-event discovery reach in dimuons Godfrey & Martin, 2011