Higgs Bosons Beyond the Standard Model

December, 2006

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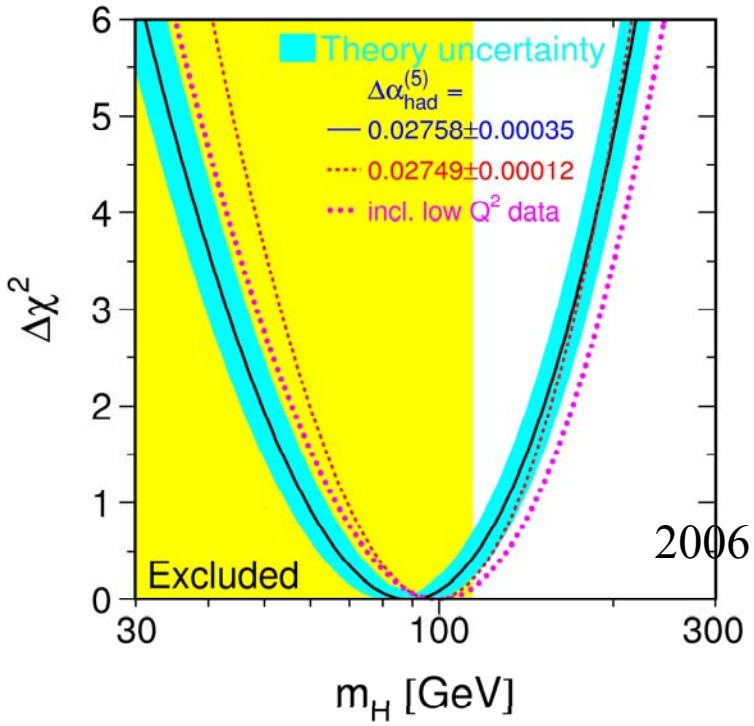
Standard Model Higgs Limits

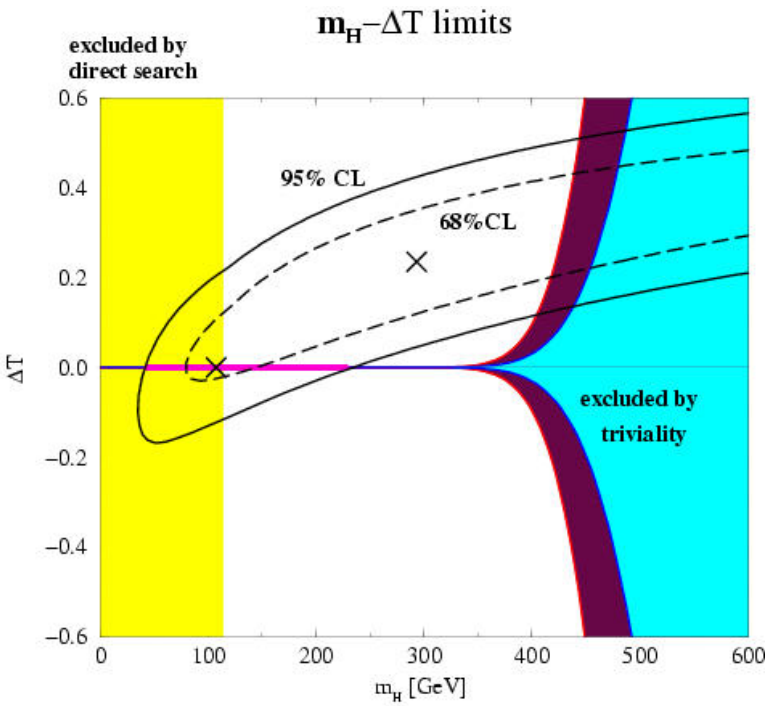


- New from ICHEP 2006:
  - M_t=171.4 ± 2.1 GeV
  - M_h=85^{+39}_{-28} GeV
  - M_h < 166 GeV (one-sided 95% cl)
  - M_h < 199 GeV (Precision measurements plus direct search limit)

These limits ASSUME the Standard Model

Higgs can be heavy with new physics

- Specific examples of heavy Higgs bosons in Little Higgs and Triplet Models
- $M_H \approx$ 450-500 GeV allowed with large isospin violation ($\alpha\Delta T=\rho$)

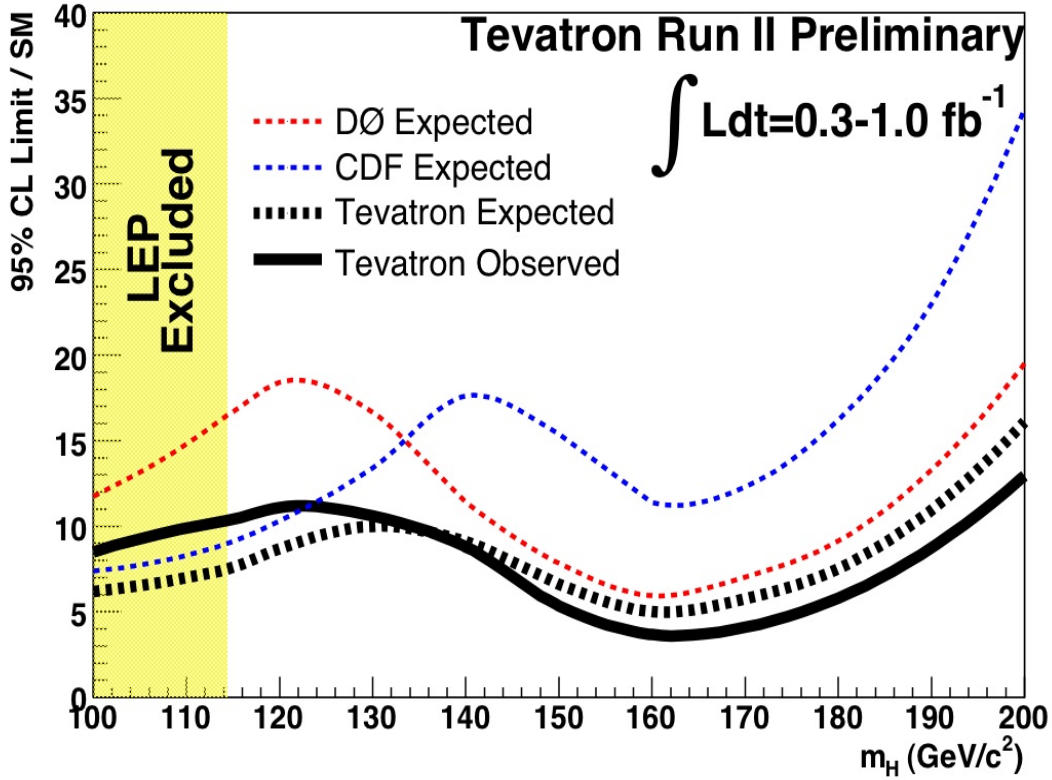


We don't know what the model is which produces the operators which generate large ΔT

Chivukula, Holbling, hep-ph/0110214

Fermilab looks for the Higgs in Many Channels

Discovery possible in theories with enhanced production



- 2006: D0, CDF combined results, New from ICHEP 2006

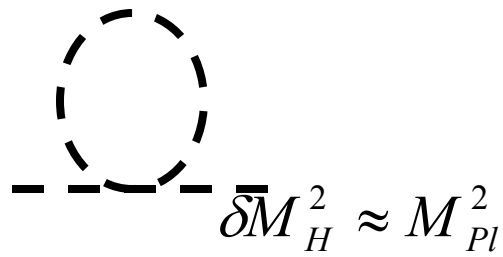
Many Possibilities for BSM Higgs

- Perturbative and weakly coupled
  - Two Higgs doublets
  - MSSM, NMSSM
  - Higgs triplets (gives H^{++} and $H^{+}W^{-}Z$ couplings)
  - Little Higgs models….
- Strongly coupled
  - Technicolor
  - Top-color assisted technicolor

Aside: Can we tell them apart?

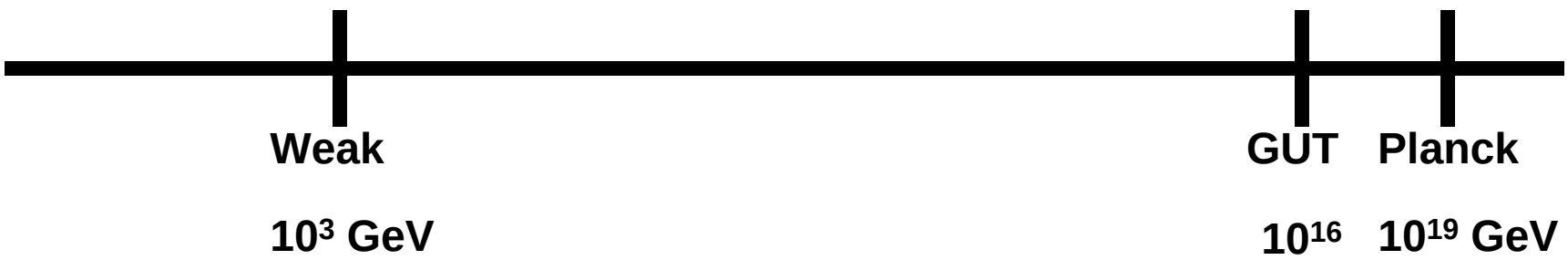
Standard Model isn't Completely Satisfactory

Quantum corrections drag weak scale to Planck scale



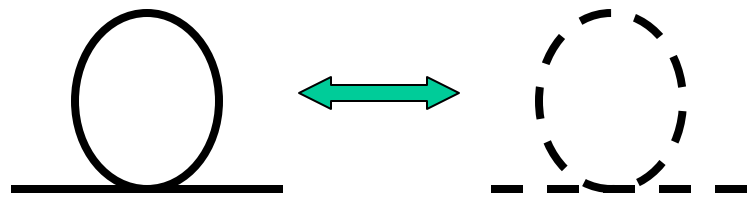
$$\delta M_H^2 \approx M_{Pl}^2$$

Tevatron/LHC Energies



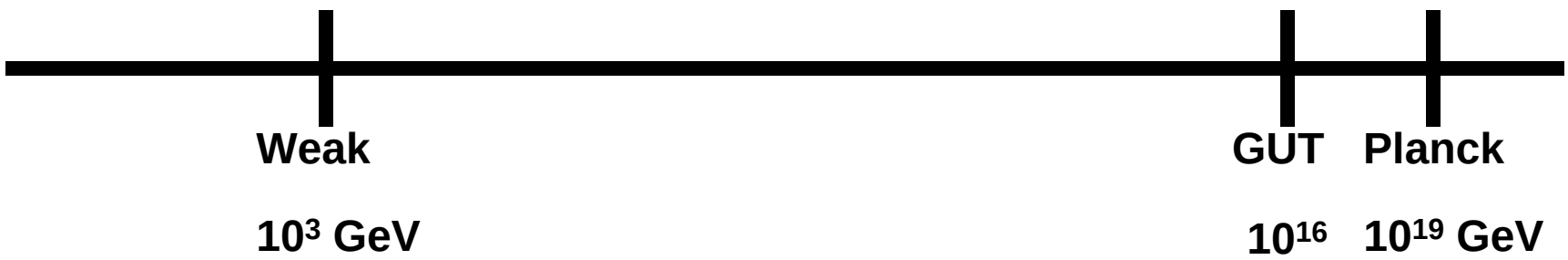
Quantum Corrections and Supersymmetry

$\delta M_H^2 \approx -M_{Pl}^2$



$\delta M_H^2 \approx M_{Pl}^2$

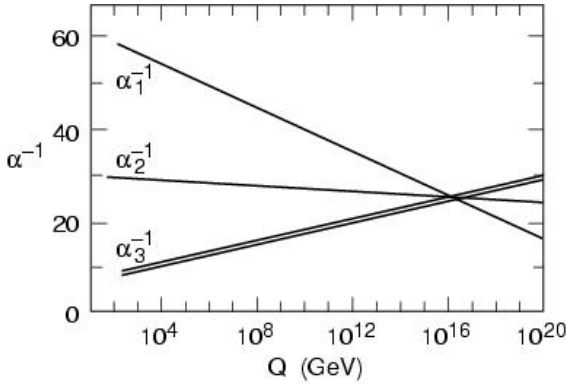
Tevatron/LHC Energies

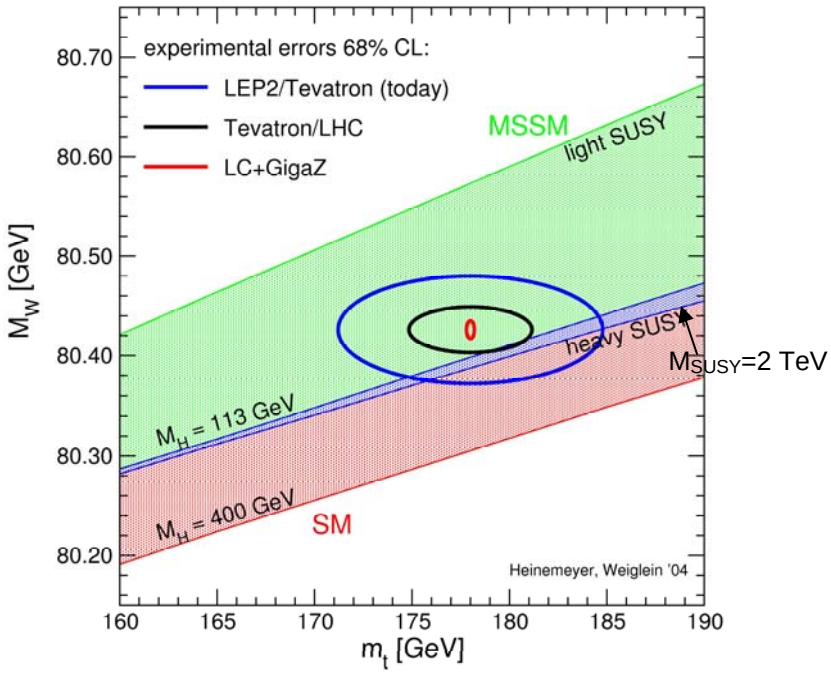


Quantum corrections cancel order by order in perturbation theory

Supersymmetry (MSSM version)

- Many positive aspects
  - Gauge coupling unification
  - Dark Matter candidate (LSP)
  - Predicts light Higgs boson
    - $M_H < 140$ GeV
  - Agrees with precision EW measurements





Heinemeyer, Hollik, Weiglein, hep-ph/0412214

Two Higgs Doublets and the MSSM: Our Favorite Beyond the SM Examples

- Begin with 2 Higgs doublet models (Φ_1, Φ_2) with CP conservation (real VEVs)
- 5 physical Higgs particles: h, H, A, $H^{\pm}$
- Models classified by how Φ_1, Φ_2 couple to fermions
- VEVS described by $\tan\beta = v_2/v_1$
  - M_W gives $v_{SM}^2 = v_1^2 + v_2^2$
- Higgs sector described by α, $\tan\beta$, Higgs potential parameters

$$h = \sqrt{2}\left(-\left[\mathrm{Re}\,\Phi_1^0 - v_1\right]\sin\alpha + \left[\mathrm{Re}\,\Phi_2^0 - v_2\right]\cos\alpha\right)$$
$$H = \sqrt{2}\left(\left[\mathrm{Re}\,\Phi_1^0 - v_1\right]\cos\alpha + \left[\mathrm{Re}\,\Phi_2^0 - v_2\right]\sin\alpha\right)$$

Constrained Potential in MSSM

– Tree level potential has 2 free parameters

$$V = m_1^2 H_1 H_1^+ + m_2^2 H_2 H_2^+ - m_{12}^2 (\varepsilon_{ab} H_1^a H_2^b + h.c.) + \left(\frac{g'^2 + g^2}{8}\right)\left(H_1 H_1^+ - H_2 H_2^+\right)^2 + \left(\frac{g^2}{2}\right)\left|H_1 H_2^+\right|^2$$

Gauge Couplings

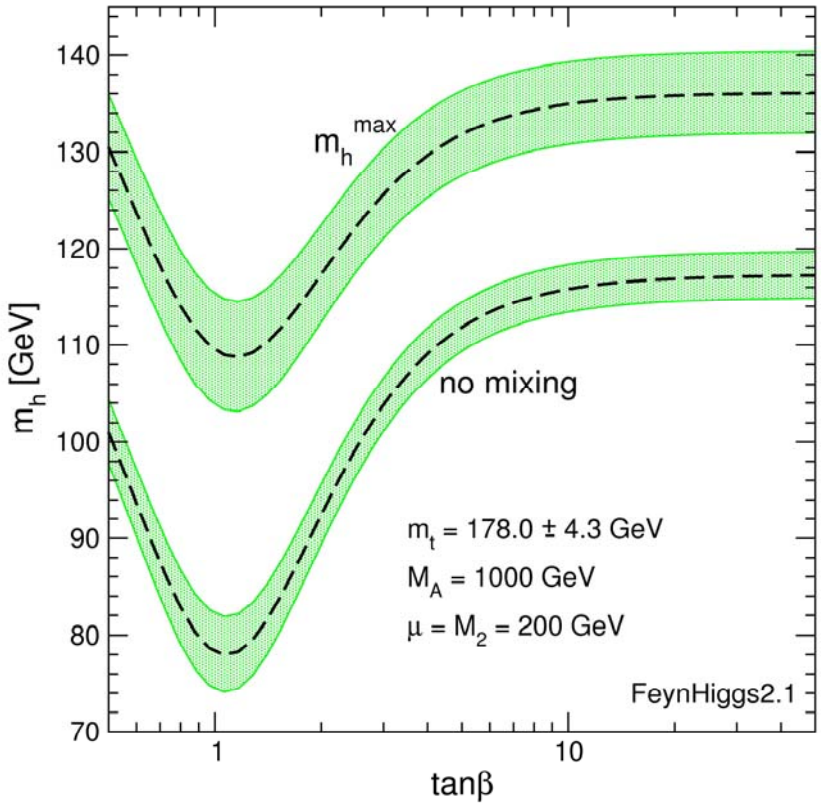
– Typically pick M_A, tan β as parameters

– Predict M_h, M_H, $M_{H\pm}$, all couplings

– Large corrections $O(G_F m_t^2)$ to predictions

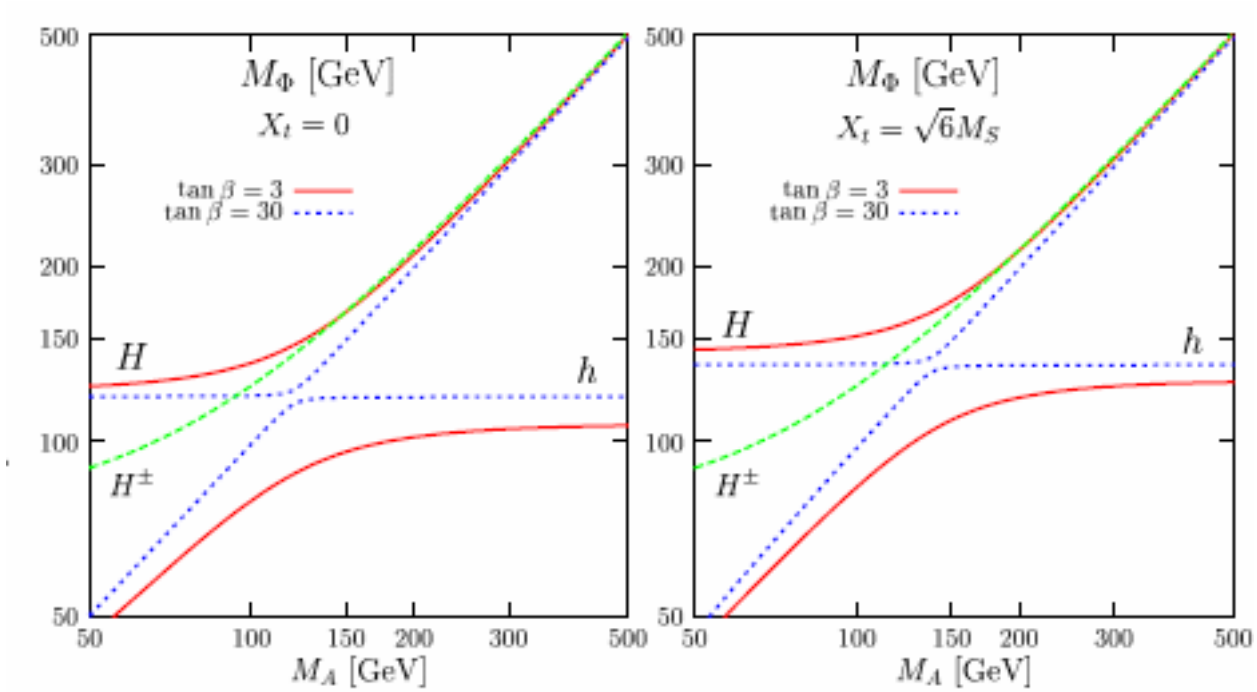
$$M_h^2 = \frac{1}{2}\left(M_A^2 + M_Z^2 - \sqrt{\left(M_A^2 + M_Z^2\right)^2 + 4M_A^2 M_Z^2 \sin^2 2\beta}\right) + \frac{3\sin^2\beta Y_t^2 m_t^2}{8\pi^2}\left(\ln\left[\frac{M_S^2}{m_t^2}\right] + \frac{X_t^2}{M_S^2}\left[1 - \frac{X_t^2}{12M_S^2}\right]\right)$$

Upper bound on M_h



Higgs Masses in MSSM

$$M_{H^\pm}^2 = M_A^2 + M_W^2$$



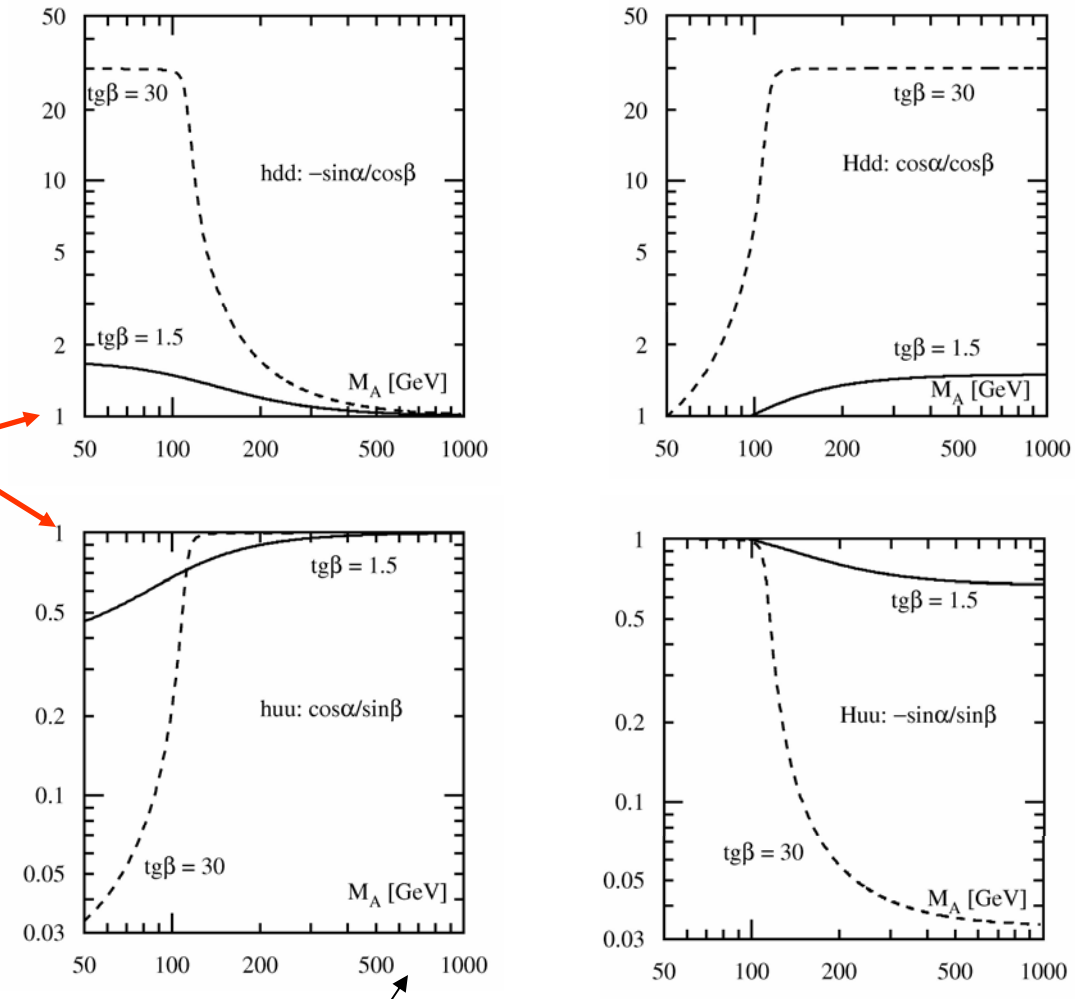
MSSM Couplings

Φ	$g_{\Phi uu}$	$g_{\Phi dd}$	$g_{\Phi VV}$	$g_{\Phi ZA}$
h	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\sin(\beta-\alpha)$	$\frac{1}{2}\cos(\beta-\alpha)$
H	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\cos(\beta-\alpha)$	$\frac{1}{2}\sin(\beta-\alpha)$
A	$i\gamma_5\cot\beta$	$-i\gamma_5\cot\beta$	0	0

- Couplings given in terms of α, β
- Can be very different from SM

Higgs Couplings different in MSSM

Lightest Neutral Higgs **Heavier Neutral Higgs**



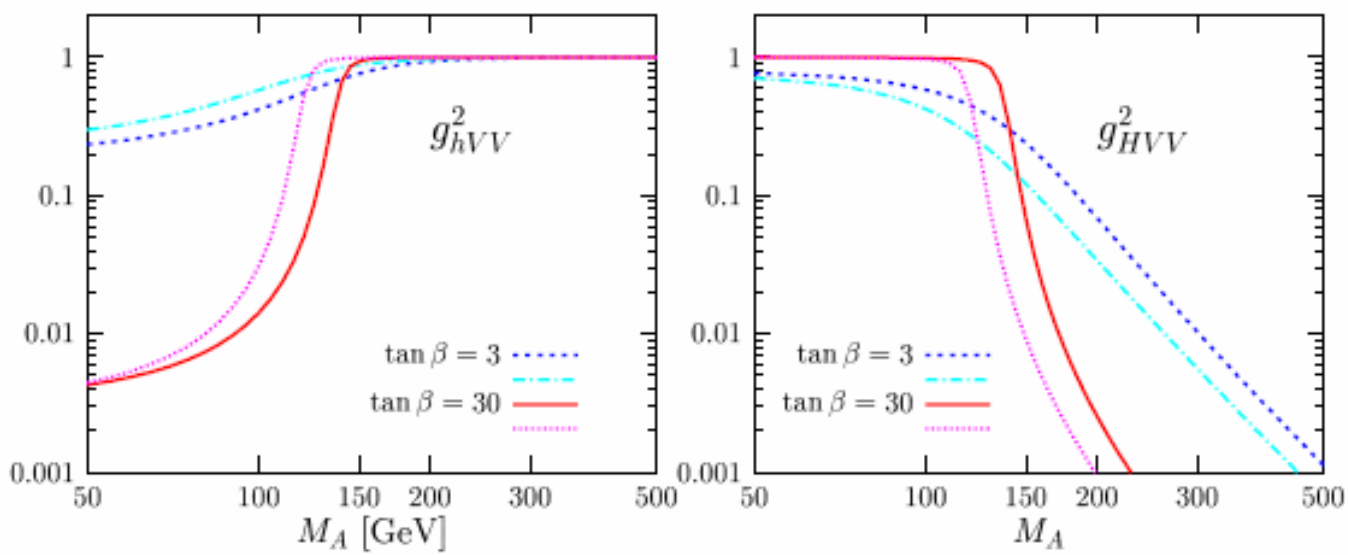
SM

Decoupling limit

- Couplings to d, s, b enhanced at large tan β
- Couplings to u, c, t suppressed at large tan β

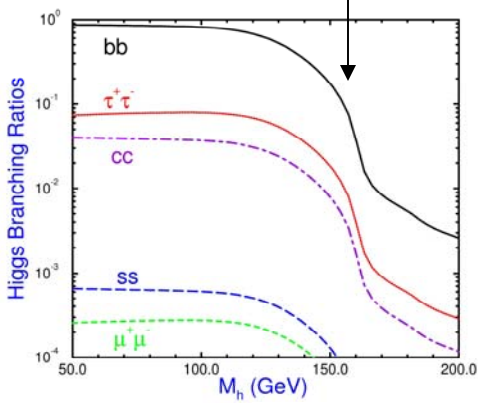
Gauge Coupling Constants

- $g_{hVV}^2 + g_{HVV}^2 = g_{hVV}^2(SM)$
- Vector boson fusion and Wh production always suppressed in MSSM



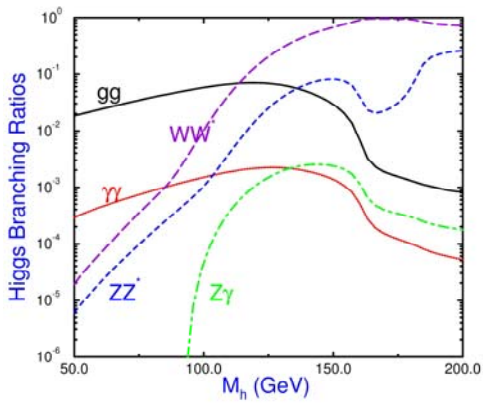
Higgs Decays affected at large tan β

- SM: Higgs branching rates to bb and $\tau^+\tau^-$ turn off as rate to W^+W^- turns on (M_h > 160 GeV)



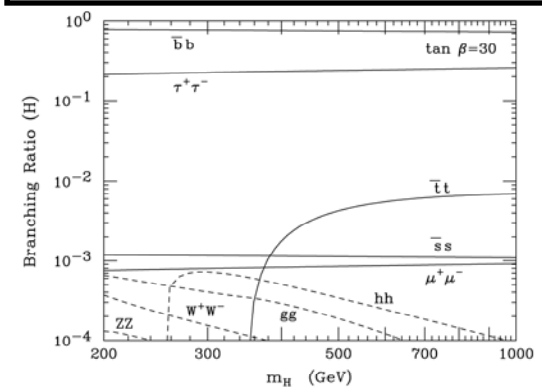
Rate to bb and $\tau^+\tau^-$ almost constant in MSSM

SM

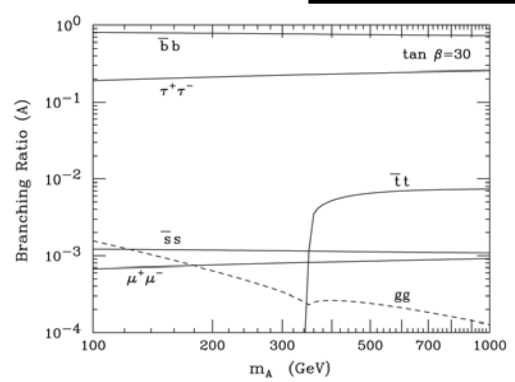


•MSSM: At large tan β, rates to bb and $\tau^+\tau^-$ stay large

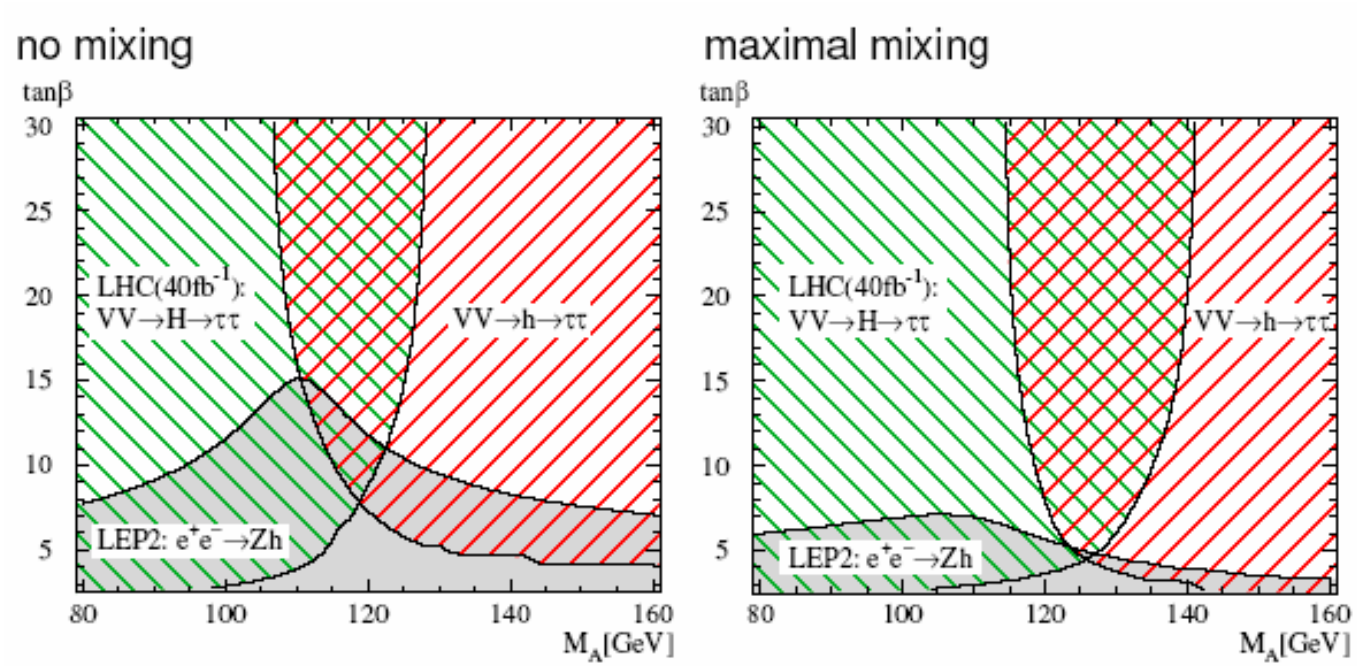
Heavy H^0 MSSM BRs

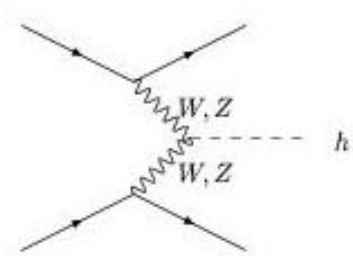


A^0 MSSM BRs



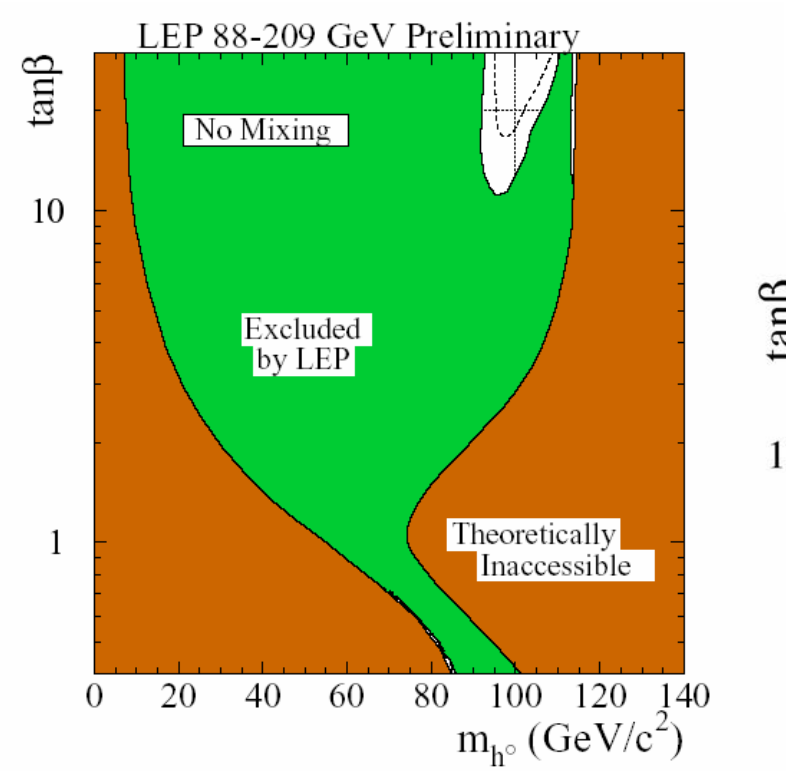
LHC can find h or H in weak boson fusion

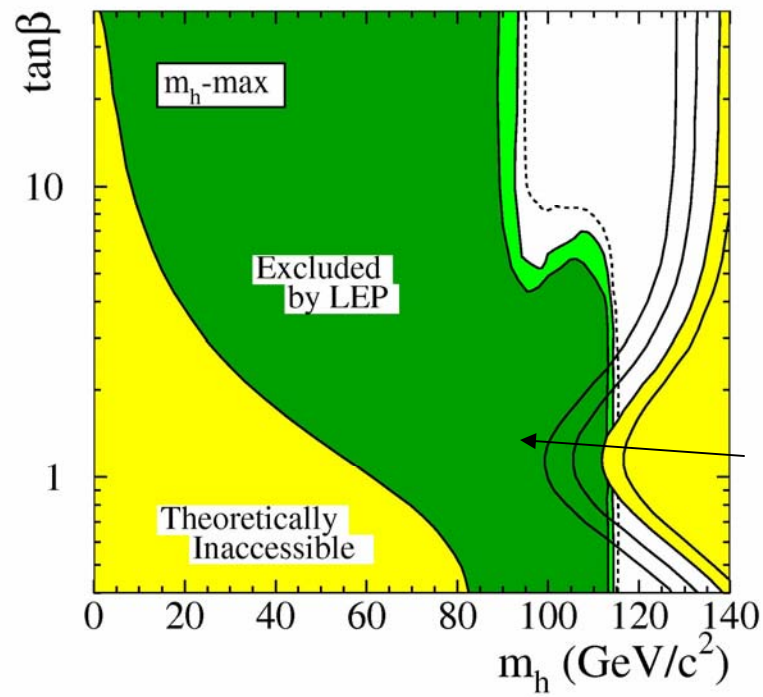




Decays to $\tau^+\tau^-$ needed

LEP MSSM Higgs Bound

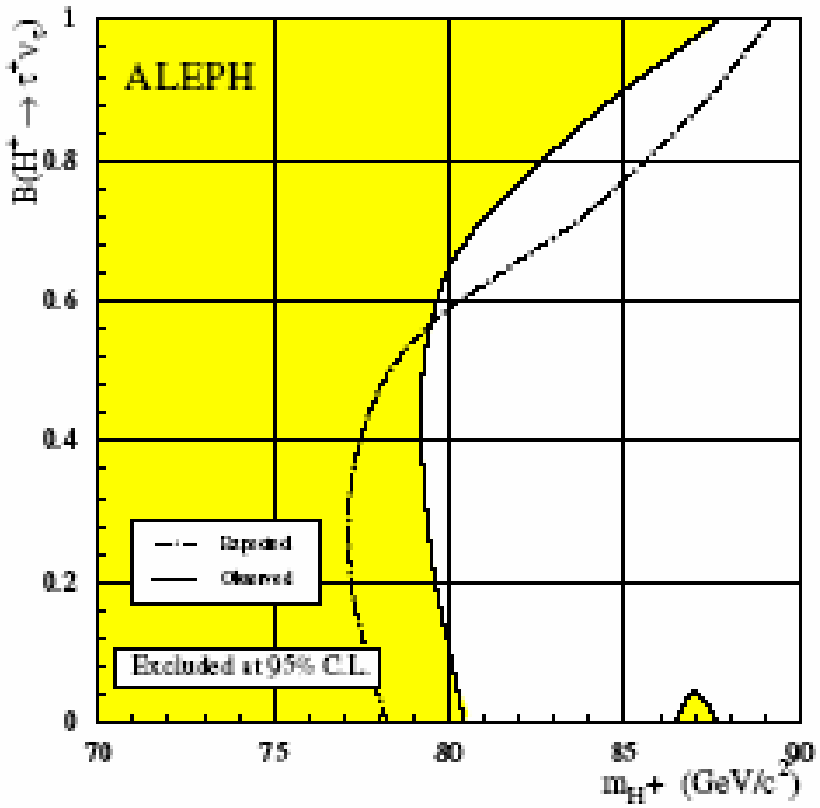




M_t=169.3,174.3, 179.3, 183 GeV

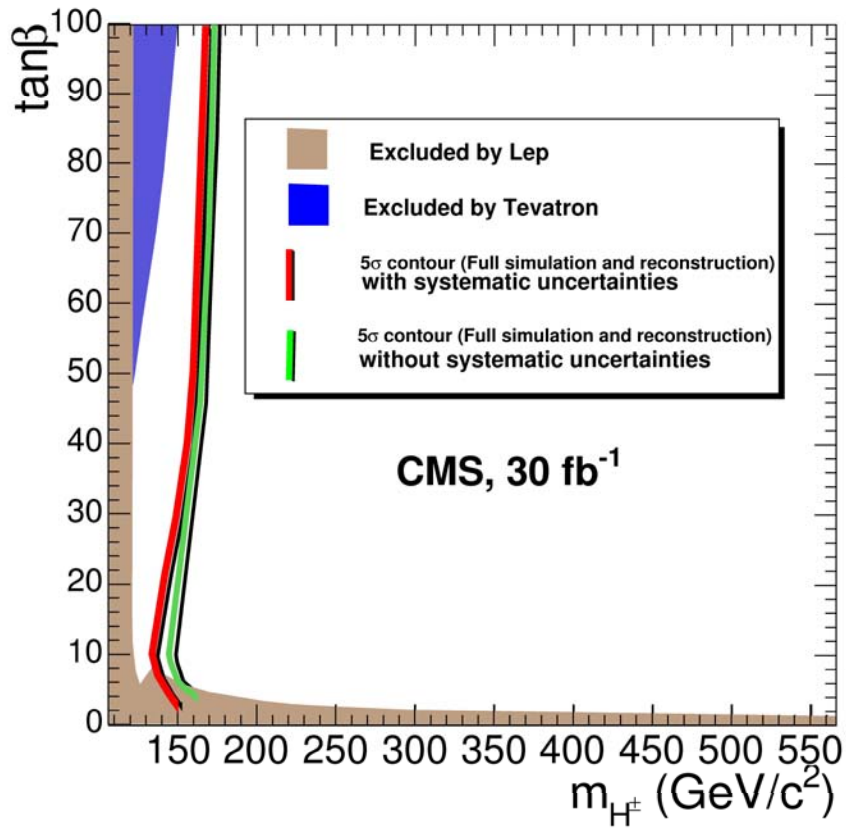
Bound on Charged Higgs

- Fairly model independent

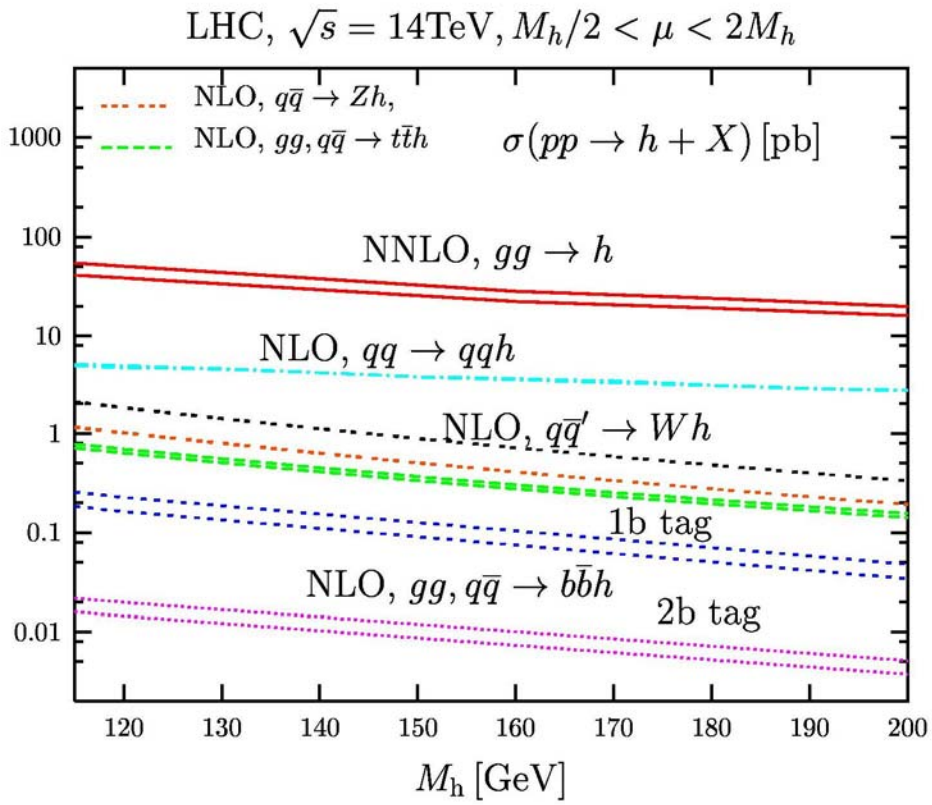


Can We find the H^+ at the LHC?

- Concentrate on $M_{H^+} < M_t - m_b$ region
  - Charged Higgs in this region would imply a light h
- Look for $H^+ \rightarrow \tau\nu$



SM Production Mechanisms at LHC



Bands show scale dependence

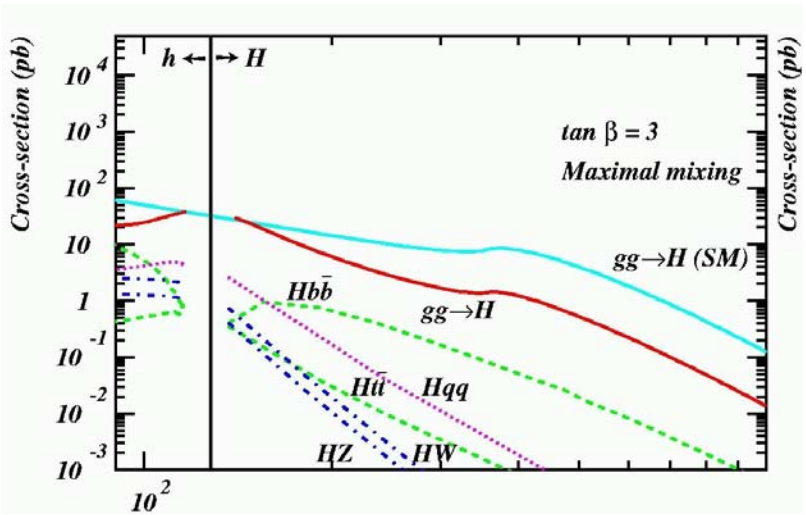
All important channels calculated to NLO or NNLO

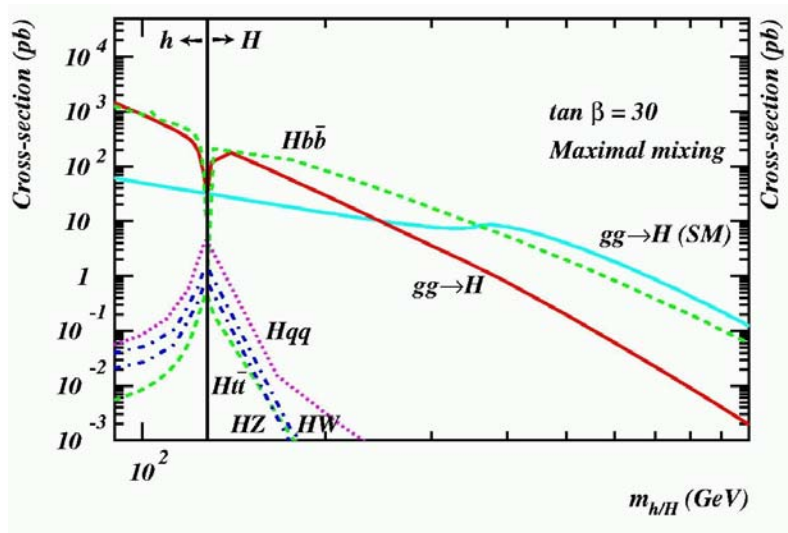
Production with b's very small in SM

Production of SUSY Higgs Bosons

- For large tan β, dominant production mechanism is with b's
- bbh can be 10x's SM Higgs rate in SUSY for large tan β

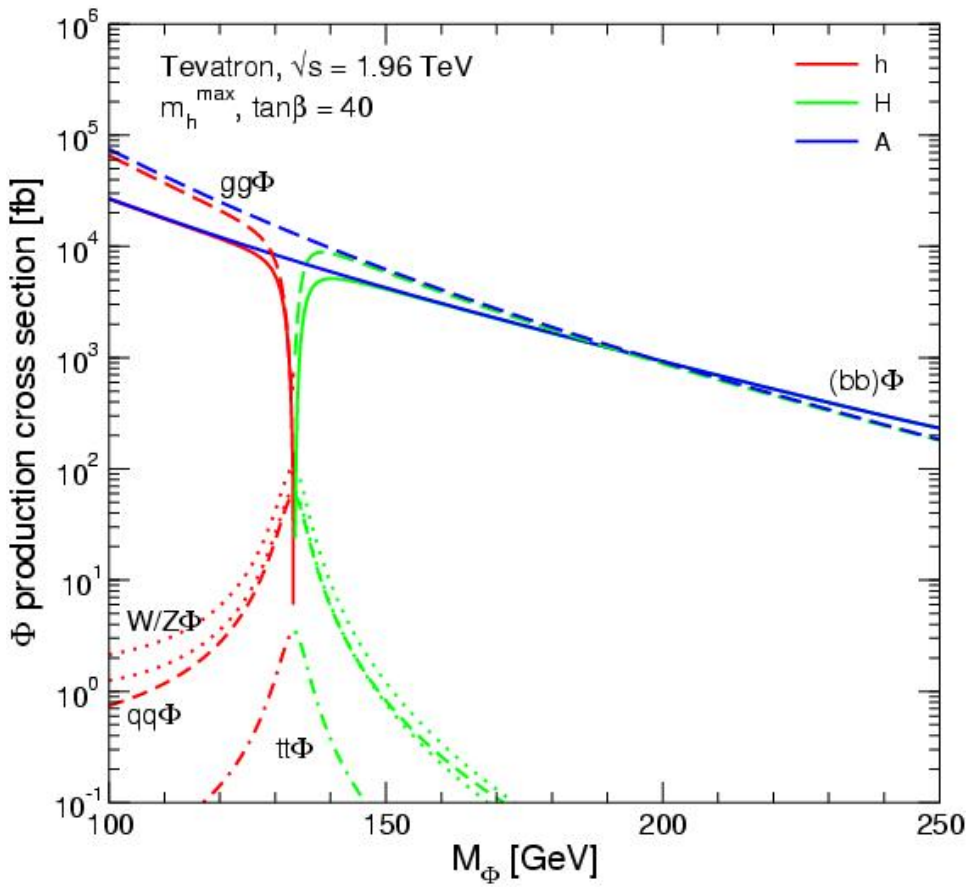
LHC



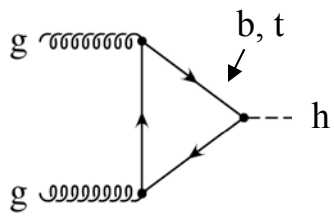


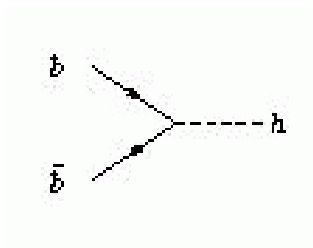
SUSY Higgs are produced with b's!

SUSY Rates at the Tevatron

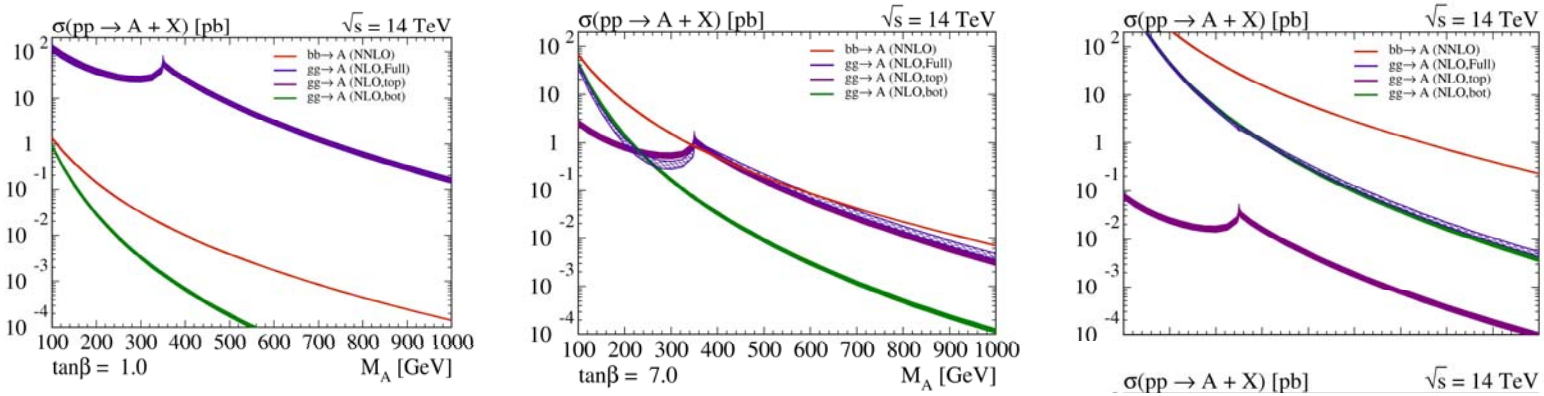


Large tan β Changes Relative Importance of Production Modes





$$\sigma_{gg} = c_1 \cot^2\beta + c_2 \frac{m_b^2}{M_h^2} + c_3 \frac{m_b^4}{M_h^4} \tan^2\beta \qquad \sigma_{bb} = \frac{m_b^2}{M_h^2} \tan^2\beta$$

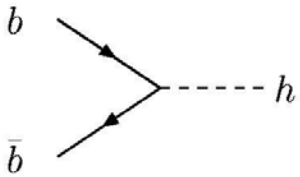


Kilgore

tanβ ≥ 7, $b\bar{b}$ production mode dominates

Counting Rules with b PDFs:

Reordering of perturbation expansion



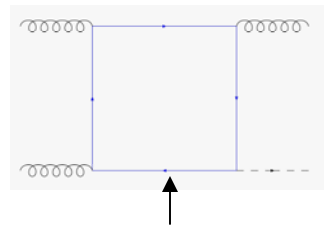
$(\alpha_s \ln(M_h^2/m_b^2))^2 \approx .4$

$\alpha_s^2 \ln(M_h^2/m_b^2) \approx .06$

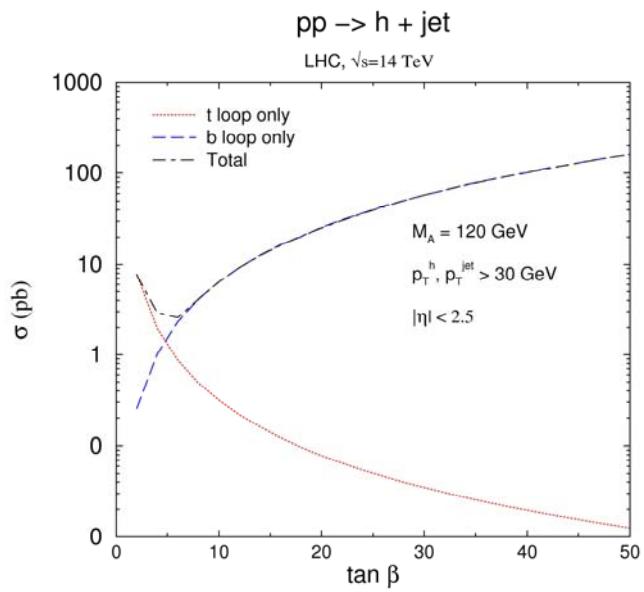
$\alpha_s^2 \approx .01$

New Modes important

- New channels can play a role: Higgs plus jet
- Large tan β, b quarks dominate



b, t

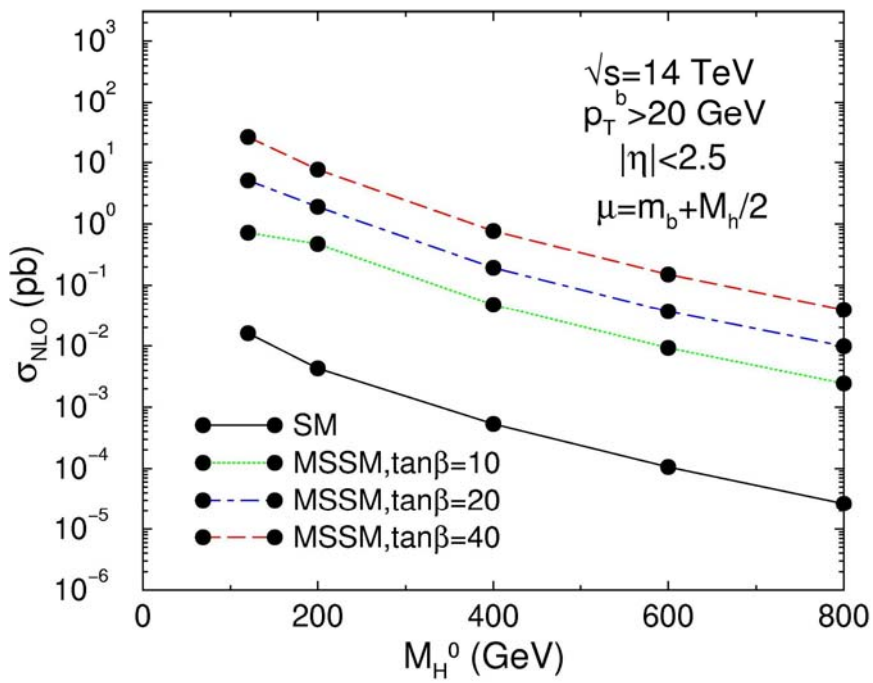


Note huge enhancement at large tan β

$pp \to b\bar{b}H$

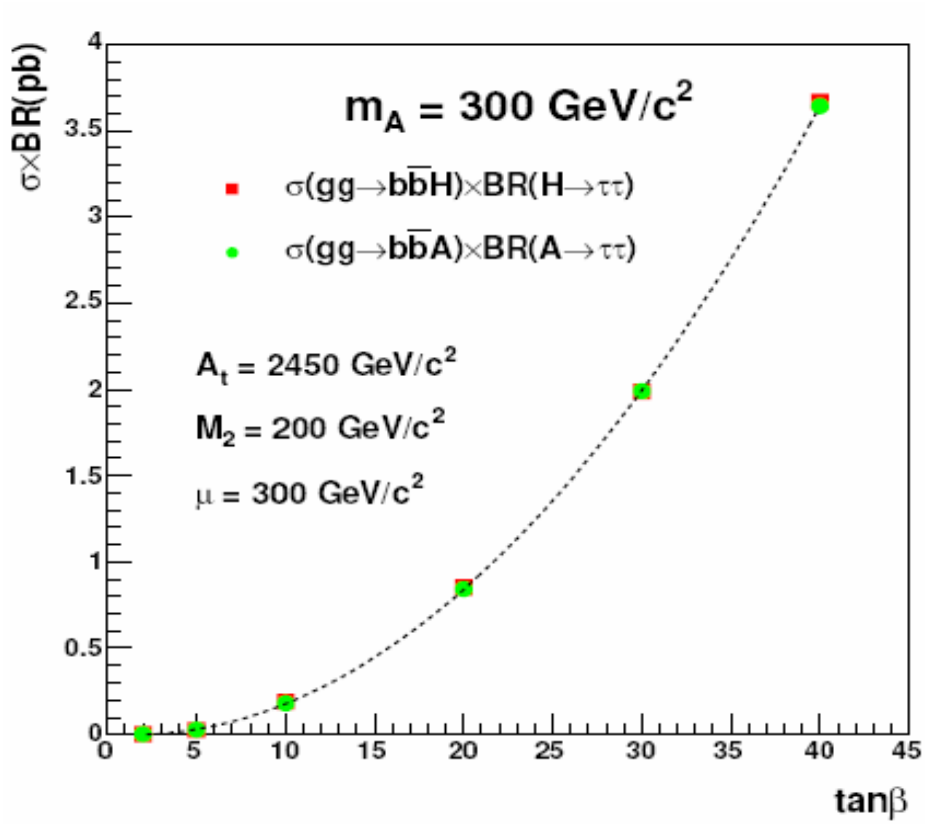
Enhancement in MSSM

Note log scale!



Can observe heavy MSSM scalar Higgs boson

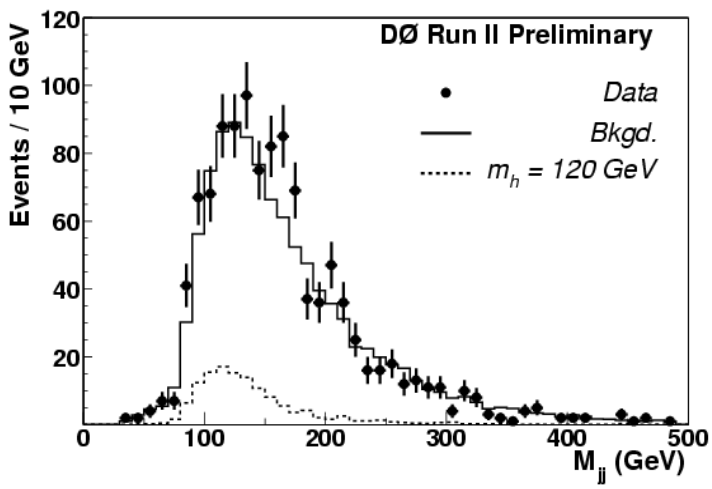
Large BRs to τ's for SUSY Higgs



Can we use this to measure tan β?

bh production at NLO

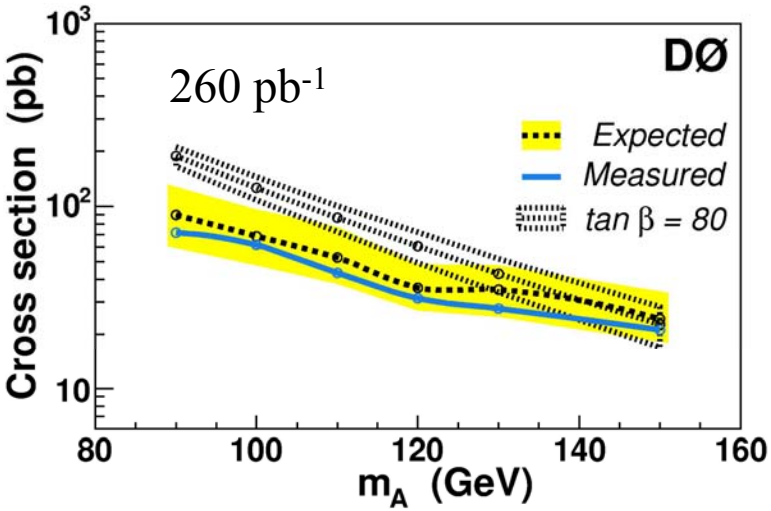
- Larger rate than 2-b tag process
- Extra b tag and Higgs transverse momentum improve detection efficiency from 0-b tag process (bb→h)
- Require at least 3 b-tagged jets
- Look for excess in di-jet mass



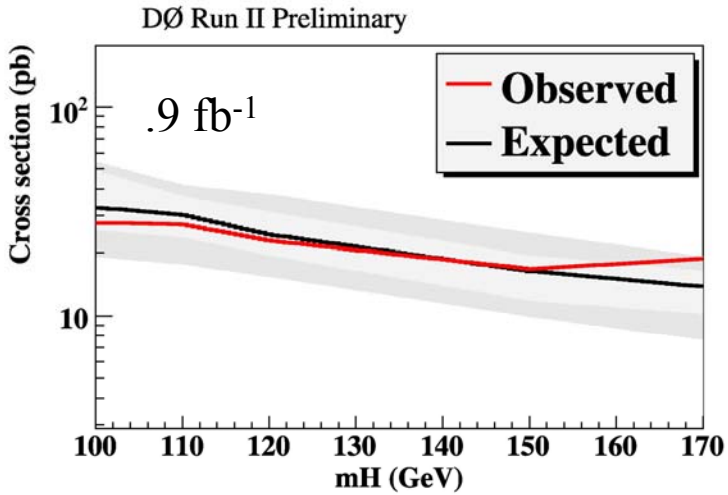
- Look for signal in invariant mass spectrum from two leading b-jets
- Main background is QCD b-jets
- Signal acceptance 0.2-1.5%

New bh, h→bb limit

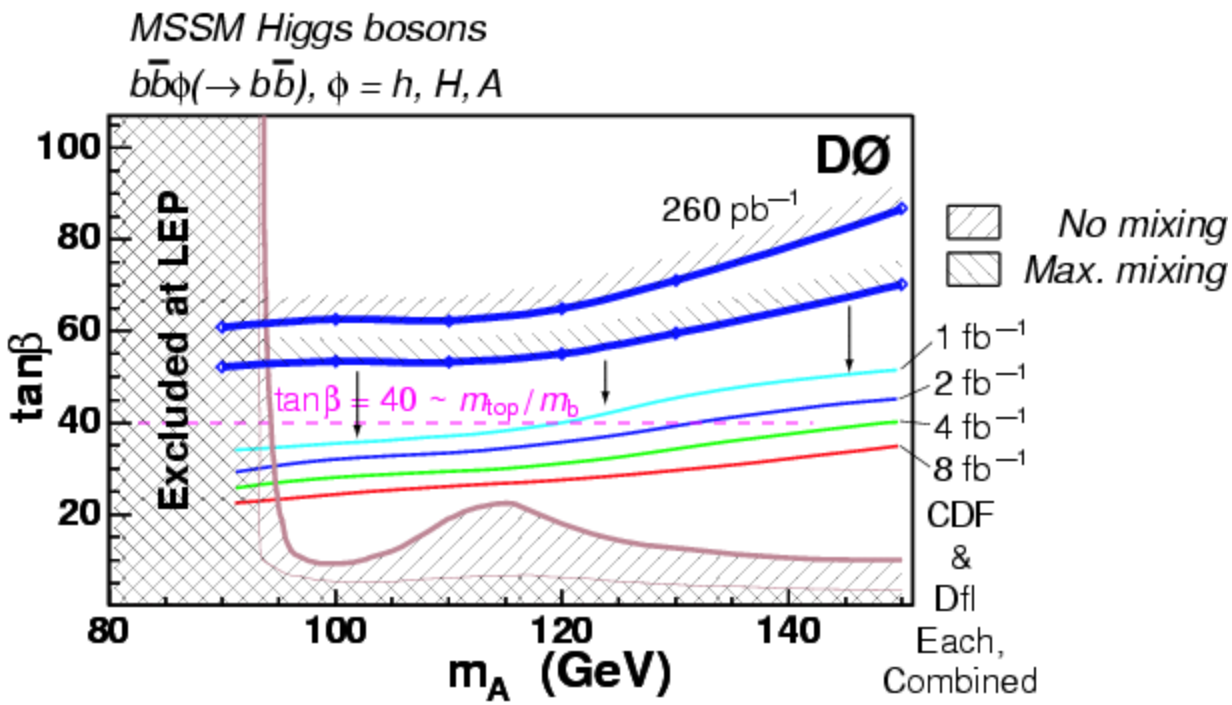
D0 search: tag 3 b's



ICHEP, 2006

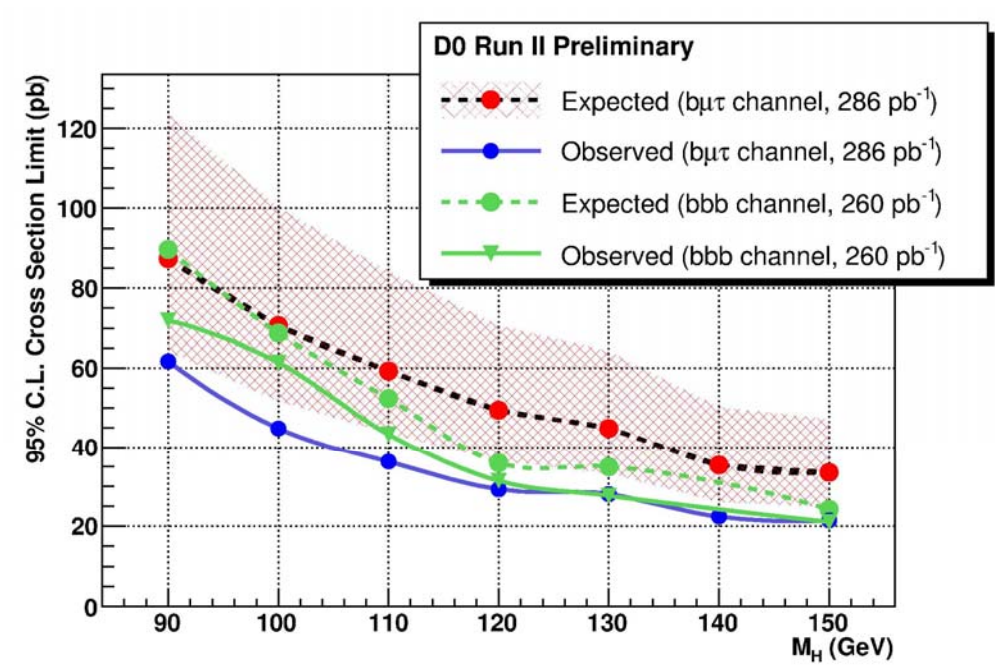


Limit on MSSM from bh, h→bb



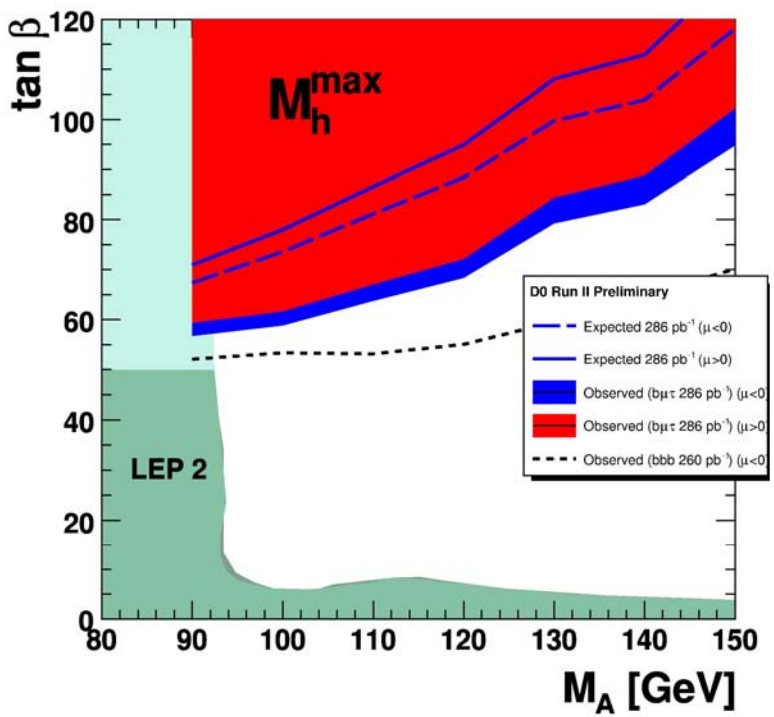
bh Production: $h \rightarrow \tau^+ \tau^-$

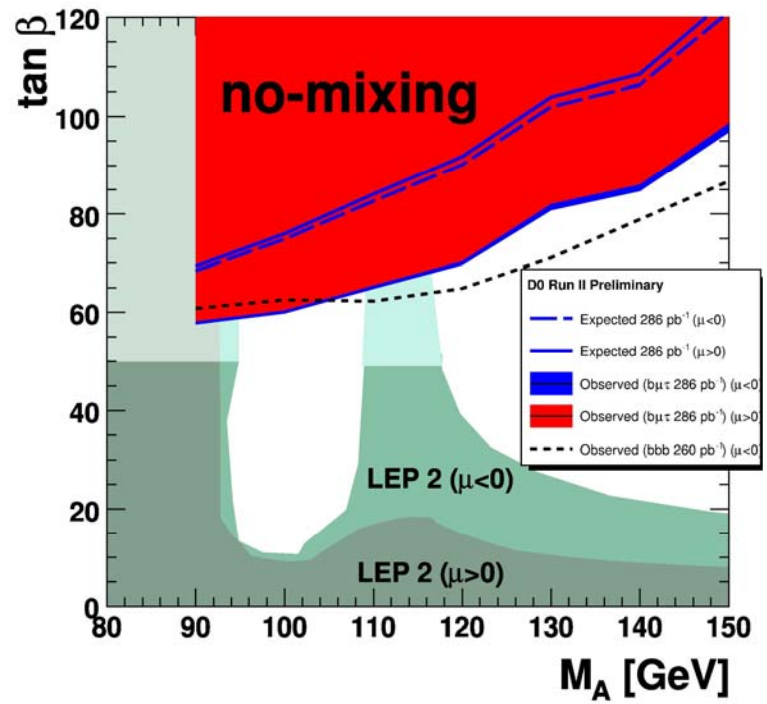
- Smaller branching ratio than h→bb, but clean signal



MSSM limits from bh, $h \to \tau^+ \tau^-$

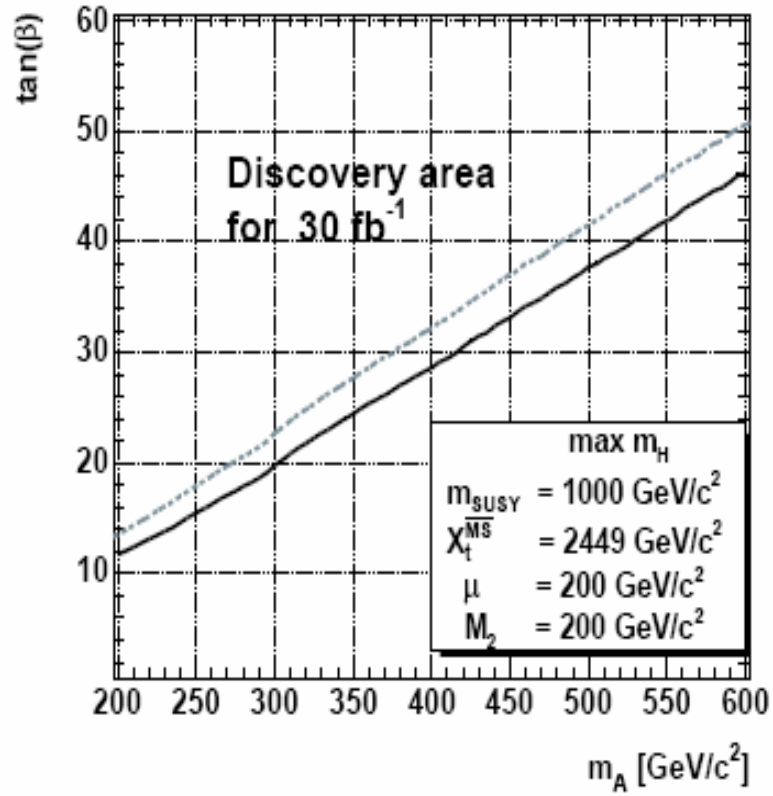
D0, 340 pb^{-1}, ICHEP 2006





b Higgs expectations at the LHC from bbh, $h \rightarrow \tau^+ \tau^-$

At least 1 b jet tagged

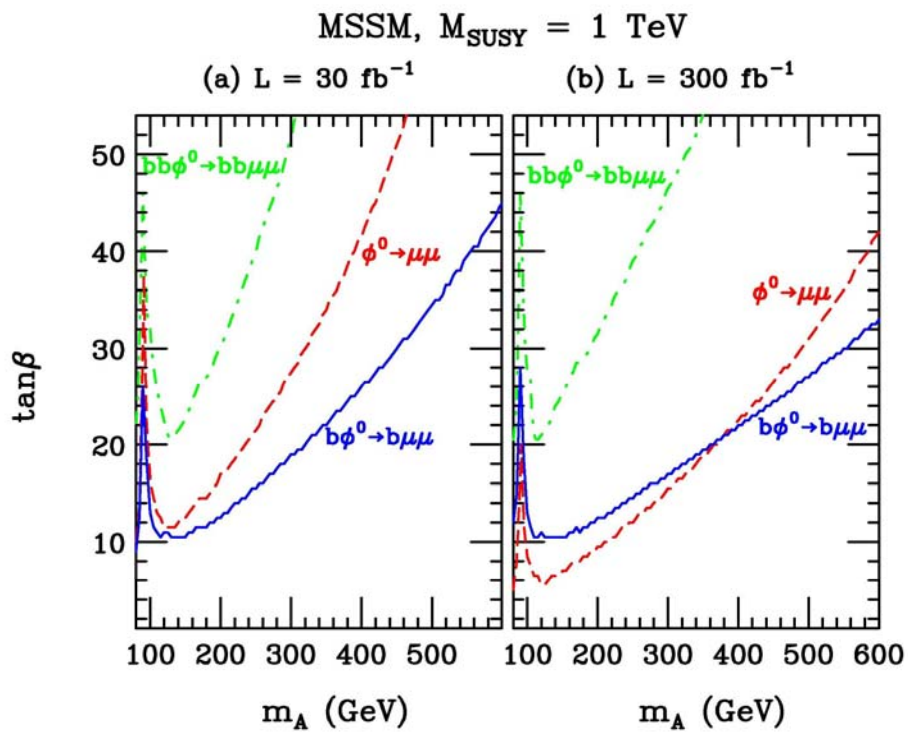


CMS Physics TDR, 2006

$b\bar{b} \to h$ in MSSM

Can you use decay $h \to \mu^+ \mu^-$?

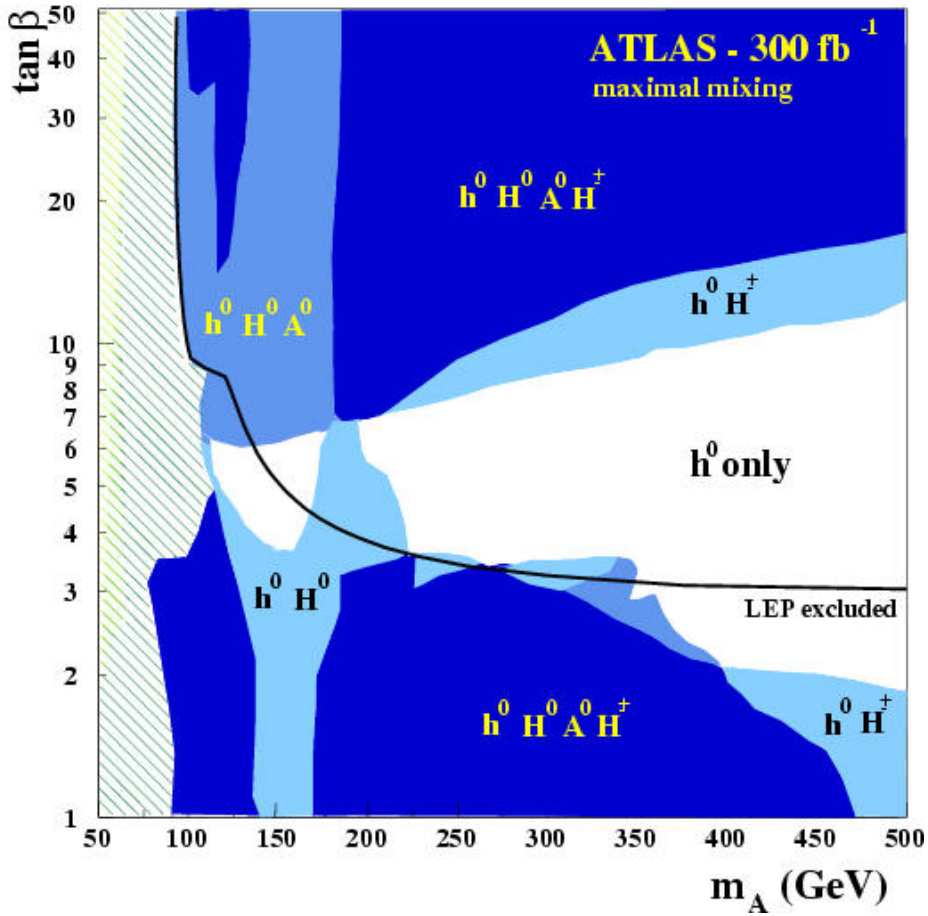
5σ discovery region



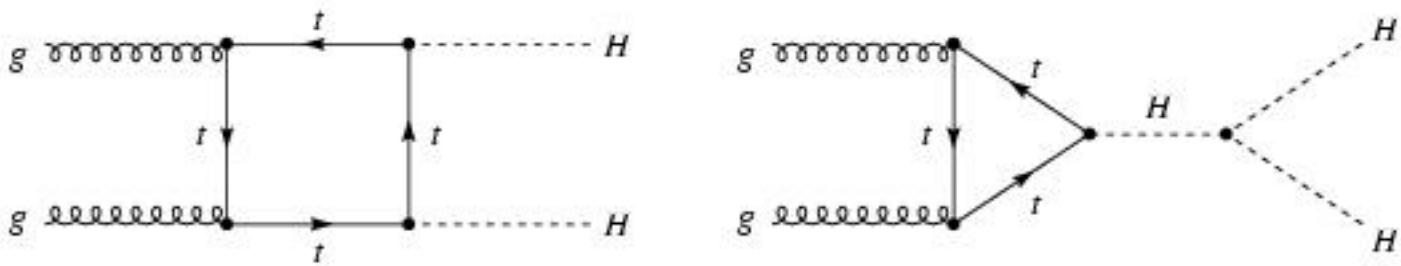
Best channel is bh production

Dawson, Dicus, Kao, Malhotra, hep-ph/0402172

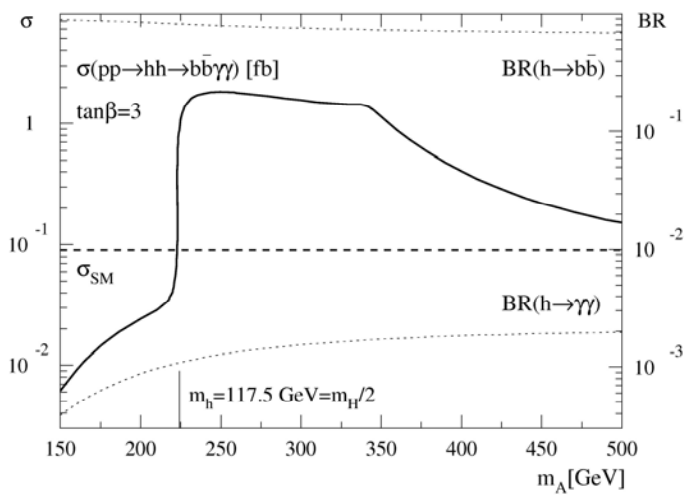
Need to see Multiple Higgs



Reconstructing the Higgs potential



- λ_3 requires 2 Higgs production
- Depressing story unless you are in resonance regime: $H \to hh$



Baur, Plehn, Rainwater, hep-ph/0310056

Modifying the MSSM: NMSSM

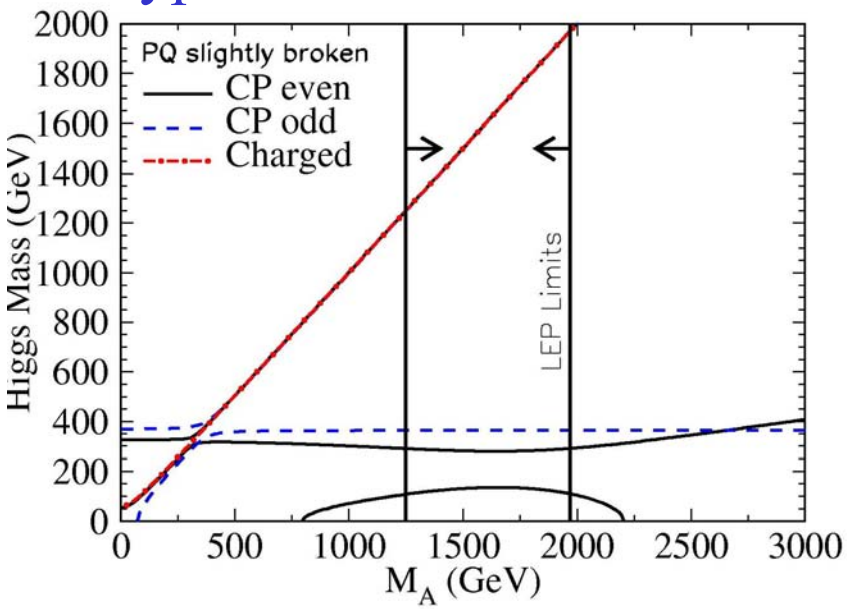
- Simplest modification of MSSM: add Higgs singlet S
- Superpotential $W = \lambda H_1 H_2 S + \frac{\kappa}{3} S^3$
  - $\lambda \langle S \rangle H_1 H_2$ naturally generates $\mu H_1 H_2$ term
- At tree level, lightest Higgs mass bound becomes:

$$M_H^{\ 2} \leq M_Z^{\ 2} \cos^2 2\beta + v^2 \lambda^{\ 2} \sin^2 2\beta$$

- Assume couplings perturbative to M_{GUT}
  - $M_H < 150$ GeV with singlet Higgs
- Phenomenology very different from MSSM

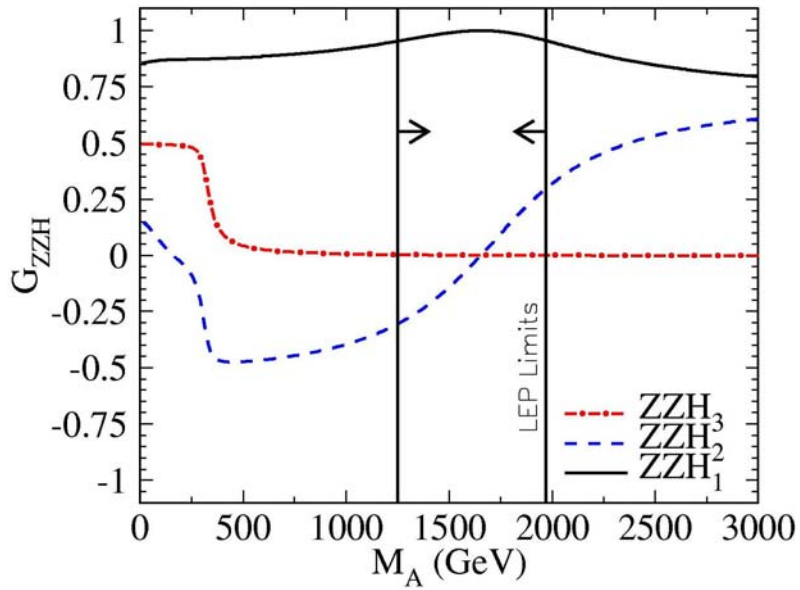
NMSSM Higgs Mass Spectrum

Typical Scenario:



ZZH couplings suppressed

(Evade LEP bounds on M_H)



- Spectrum of light Higgs: 2 light scalars, 1 light pseudoscalar
- Heavy, roughly degenerate H_3, A_2, $H^{\pm}$

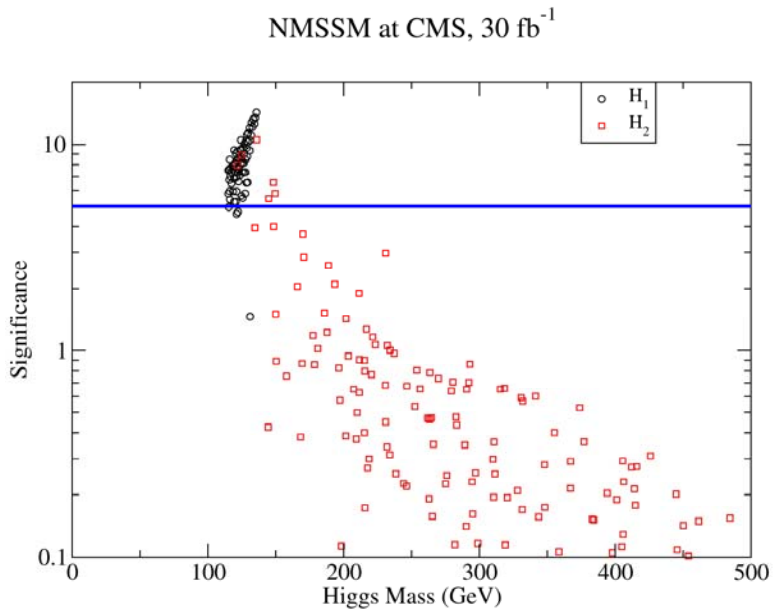
New Decays:

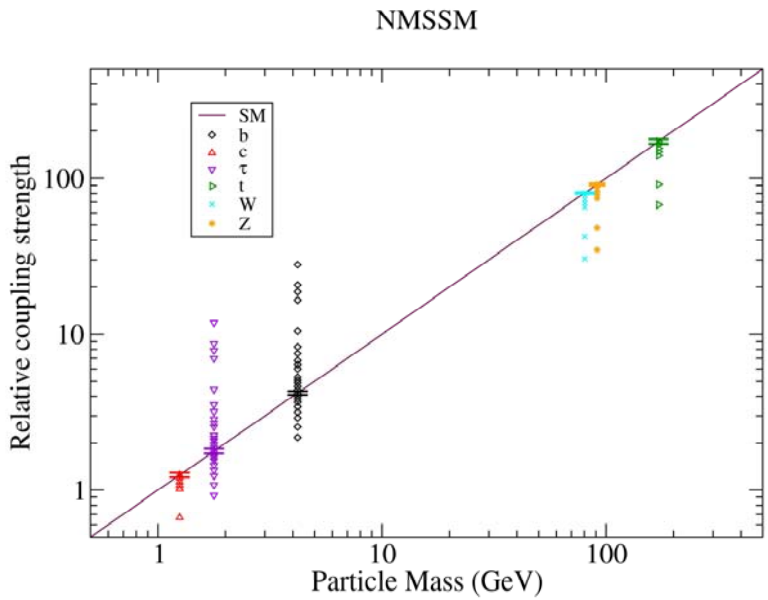
$A_1 \rightarrow H_1 H_1$, $H_2 \rightarrow A_1 A_1$

Very different from MSSM!

NMSSM Discovery

- Discovery of lightest H_1 straightforward; heavier H_2 difficult
- Higgs couplings can be very different than SM





Barger, Langacker, Shaughnessy, hep-ph/0611239

A More Complicated Higgs Sector

- The Higgs boson properties are sensitive to additional scalar particles
- Add a single real scalar *S* to the standard model
- *S* carries no charges and couples to nothing except the Higgs, through the potential

$$V(H,S) = -\mu^2|H|^2 + \lambda|H|^4 + \eta S^2 H^2 + m_s^2 S^2 + \kappa S^4$$

If <S> = 0, the H decay could be invisible

$$V(H,S) = -\mu^2|H|^2 + \lambda|H|^4 + \eta S^2 H^2 + m_s^2 S^2 + \kappa S^4$$

Suppose $\langle H\rangle = v/\sqrt{2}$, $\langle S\rangle = 0$,

$$S^2H^2 \rightarrow (v+h)^2S^2 = v^2S^2 + 2vhSS + hhSS$$

$h \rightarrow SS$ (if $m_h > 2\, m_S$) with a width $\sim h^2v^2 / m_h$.

This can be larger than decays to bottom quarks.

S is stable (S → -S symmetry). h→hSS is invisible

Not hard to hide the Higgs

If <S> not 0, Physical Higgs is Mixture of H, S

$$V(H,S) = -\mu^2|H|^2 + \lambda|H|^4 + \eta S^2 H^2 + m_s^2 S^2 + \kappa S^4$$

$$\phi_1 = h\cos\gamma + s\sin\gamma \; ; \phi_2 = s\cos\gamma - h\sin\gamma$$

- φ_1, φ_2 decay to usual Higgs final states, via their *h* component
- Production rates/branching ratios suppressed from SM

If $m_1 > 2\, m_2$, new decay channel:

$\phi_1 \rightarrow \phi_2\, \phi_2 \rightarrow$ (bb)(bb), (bb)($\tau^+\tau^-$), ($\tau^+\tau^-$)($\tau^+\tau^-$)

Another Possibility: Little Higgs

- Global Symmetry, G (SU(5))
  - Broken to subgroup H (SO(5)) at scale $4\pi f$
- Higgs is Goldstone Boson of broken symmetry
  - Effective theory below symmetry breaking scale
- Gauged subgroups of G ($[SU(2)xU(1)]^2$) contain SM
- Higgs gets mass at 2 loops (naturally light)
- Freedom to arrange couplings of 1st 2 generations of fermions (their quadratic divergences small)

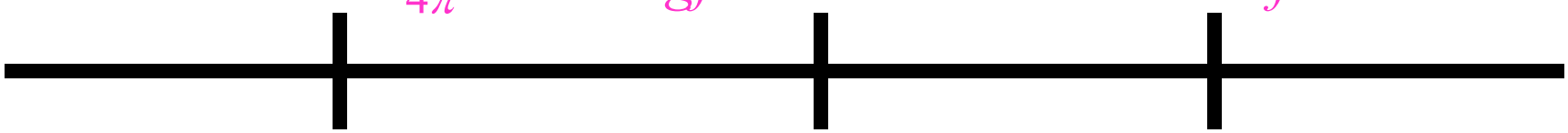
Solving the Little Hierarchy Problem with Little Higgs Models

←Weak Coupling | Strong Coupling→

$$\Lambda_{weak} = \frac{g^2 f}{4\pi}$$

$$gf = 1-3\ TeV$$

$$\Lambda = 4\pi f$$



Weak

10^3 GeV

Quadratic divergences cancelled by new states

10 TeV

Higgs gets mass at 2-loops

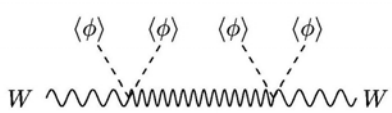
Higgs is pseudo Goldstone boson from global symmetry breaking at Λ

Littlest Higgs Model

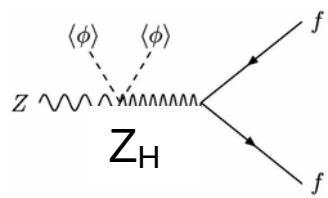
- Quadratic contributions to Higgs mass cancelled at one-loop by new states
  - $W, Z, B \leftrightarrow W_H, Z_H, A_H$
  - $t \leftrightarrow T$
  - $H \leftrightarrow \phi$
- Cancellation between states with same spin statistics
  - Naturalness requires $f \sim$ few TeV
- Symmetries only allow Higgs mass at 2-loops
  - $\delta M_H^2 \sim (g^2/16\pi^2)^2 \Lambda^2$
  - Allows scale to be raised to $\Lambda \sim 10$ TeV

Little Higgs Models and Precision EW Measurements

- Mixing of SM gauge bosons with heavy gauge bosons of little Higgs models gives strong constraints on scale, f > 1- 4 TeV



W_H



Z_H

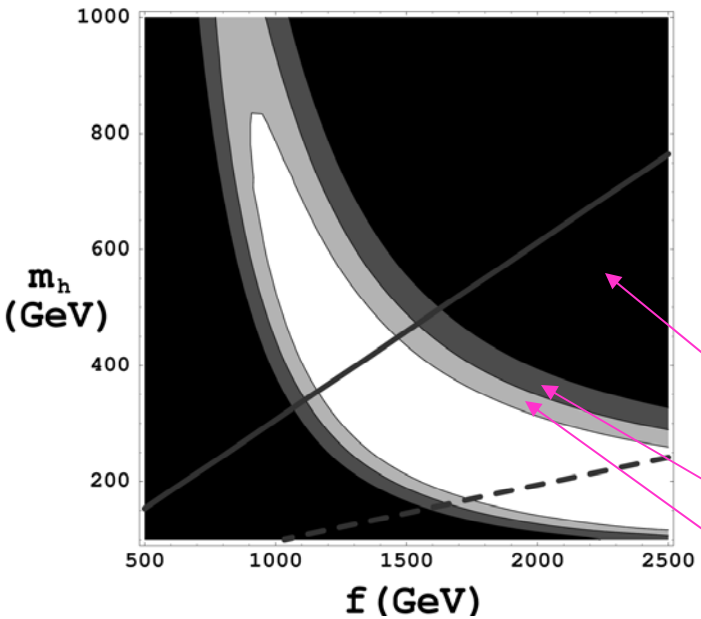
- Introduce symmetry (T parity) so new particles must be produced in pairs
  - Eliminates tree level constraints
  - Scale can be lower, f ~ 500 GeV
  - Lightest neutral gauge boson, A_H, could be dark matter candidate

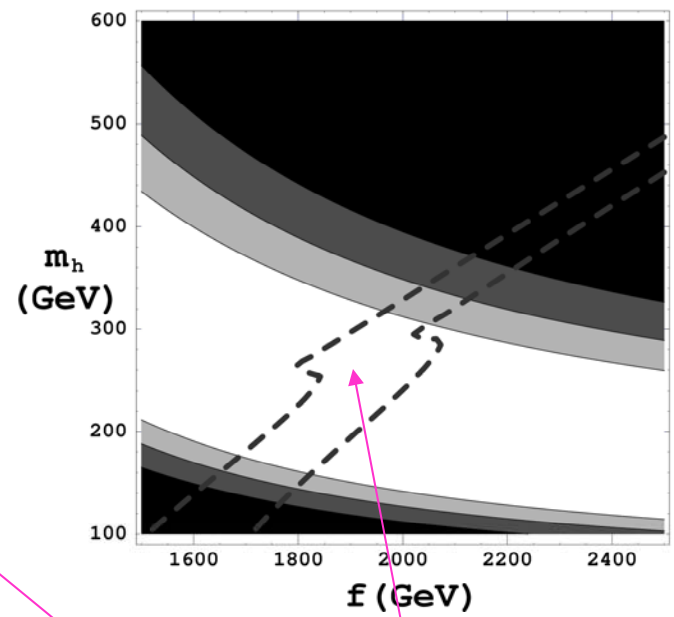
H.Cheng and I. Low, hep-ph/0409025, J. Hubisz and P. Meade, hep-ph/0411264

New Phenomenology with T parity

•Heavy Higgs allowed

•Lightest T-odd particle is dark matter candidate





Excluded at 95%, 99%, 99.9% CL

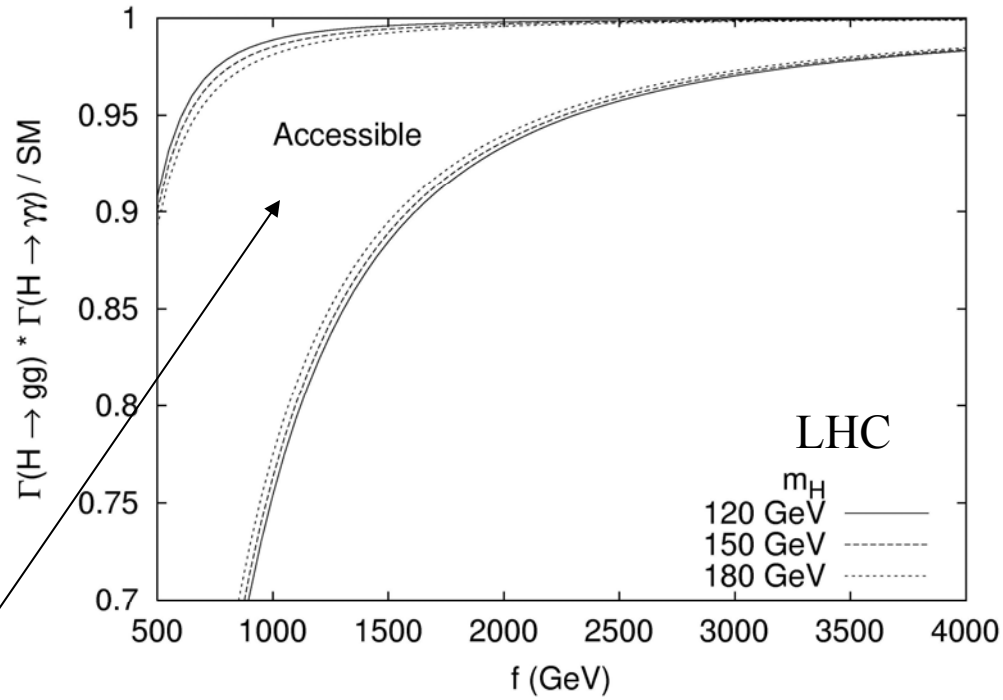
Relic density of lightest T-odd particle is within 2σ of WMAP central value

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

Higgs production & decay in Little Higgs Models

- Higgs rate could be reduced by ≈25%

$gg \to h \to \gamma\gamma$



This is theoretically allowed region

Han, Logan, McElrath, Wang, hep-ph/0302188

Conclusions

- MANY POSSIBILITIES!
- Don’t let common lore deceive us
  - Must measure Higgs production and decay rates
  - There may be surprises