Higgs Production at the Tevatron and the LHC: The Big Picture

S. Dawson, BNL

January, 2007

Question???

- Question: Why is the Higgs so important?
  - [6 talks at this meeting!]
- Answer: Discovering (or definitively excluding) the Higgs will fundamentally change our understanding
  - It’s a win-win combination
  - Single Higgs boson may or may not be Standard Model-like
  - There may be many new particles associated with the symmetry breaking
  - Higgs sector probes a large variety of new phenomena

Standard Model is Incomplete Without Something like a Higgs boson

- Requires physical, scalar particle, h, with unknown mass
  - M_h is ***ONLY*** unknown parameter of EW sector
- Observables predicted in terms of:
  - M_Z=91.1875 ± .0021 GeV
  - G_F=1.16639(1) x 10^{-5} GeV^{-2}
  - α=1/137.0359895(61)
  - M_h
- Higgs and top quark masses enter into quantum corrections
  - $\approx M_t^2$, log (M_h)

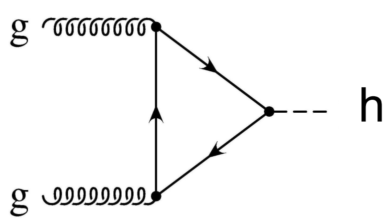
Everything is calculable….***testable theory***

Review of Higgs Couplings

- Higgs couples to fermion mass

$$L_{Yukawa} = -\lambda_d Q_L \Phi d_R + hc$$
$$= -\lambda_d \left(\frac{v+h}{\sqrt{2}} \right) \bar{d} d \;\rightarrow\; -\frac{m_d}{v} \bar{d} d h$$

  - $m_f = \lambda_f v/\sqrt{2}$
  - Yukawa ffh coupling doesn't vanish for v=0
  - Measuring Yukawa coupling doesn't prove VEV exists!



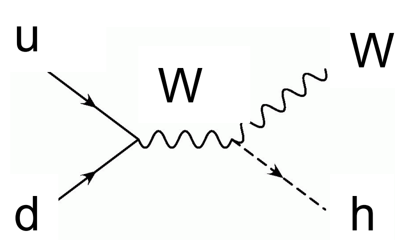
Largest production mechanism at LHC

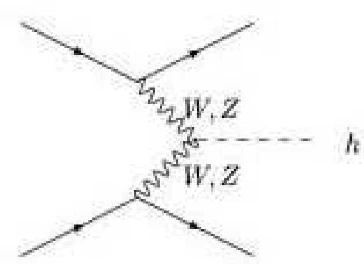
Gauge Higgs Couplings

- Higgs couples to gauge boson masses

$$\left(D_\mu \Phi\right)^+ \left(D_\mu \Phi\right) \to \left(\frac{gv}{2}\right)^2 W^{+\mu} W_\mu^- \left(1 + \frac{h}{v}\right) + \ldots.$$

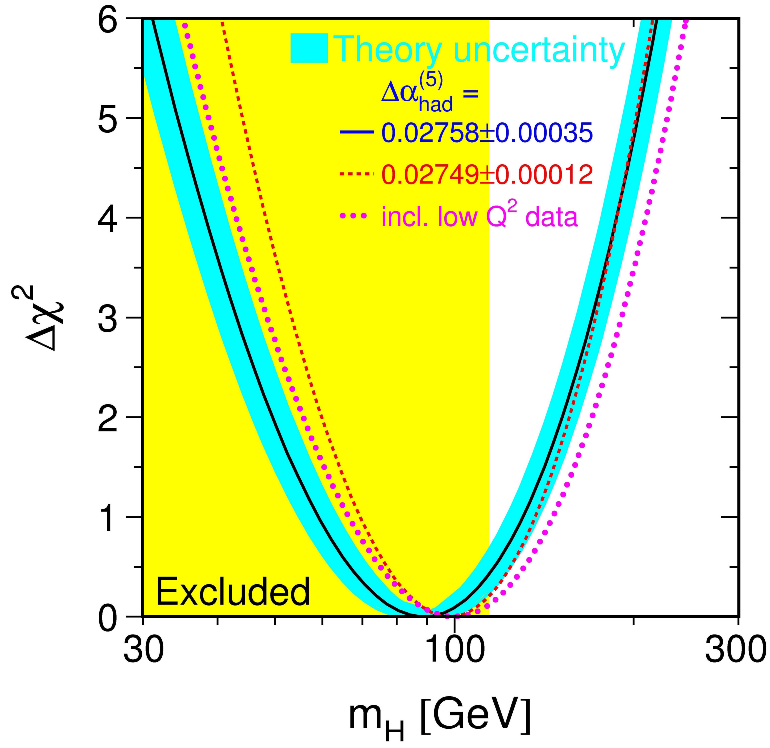
- WWh coupling vanishes for v=0! Tests the connection of M_W to non-zero VEV





In the Standard Model, the Higgs is light

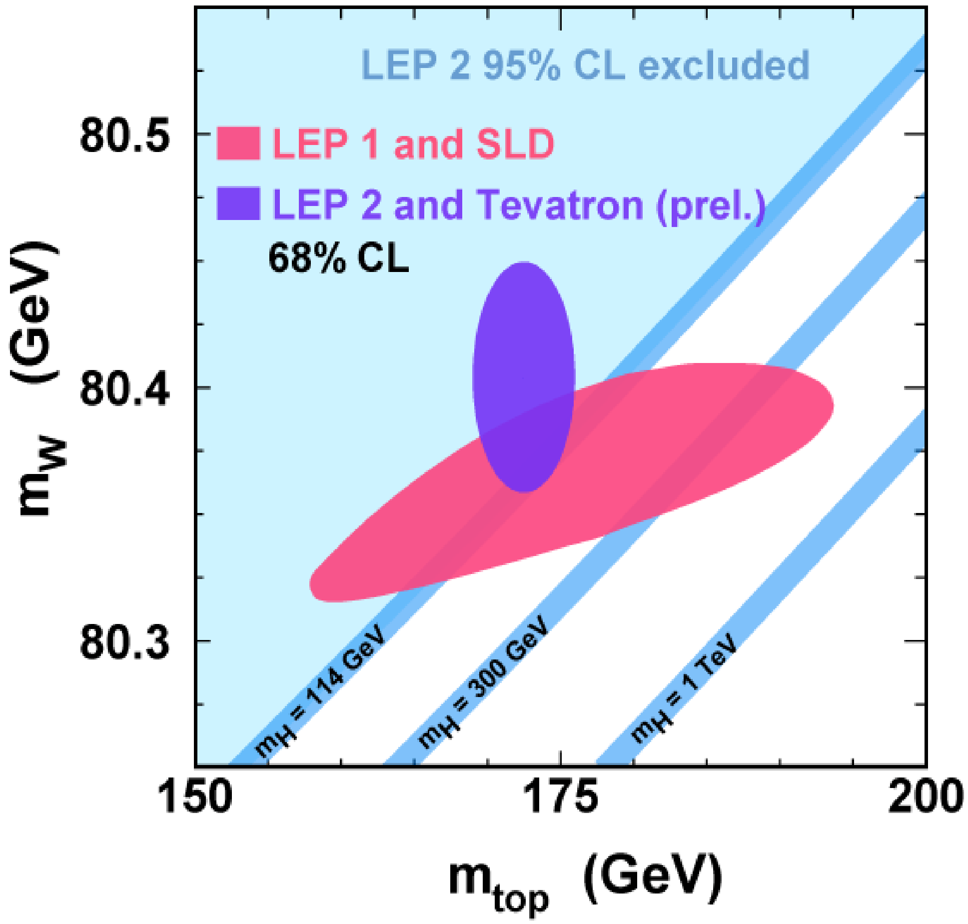
- M_h < 166 GeV (precision measurements)
  - [One sided 95% cl upper limit]
- M_h < 199 GeV if direct search (yellow band) included
- Limits have moved around with top quark mass
  - [M_t=172.5 ± 2.3 GeV in plot]



New from ICHEP, 2006

Quantum Corrections Sensitive to Higgs Mass

- Direct observation of W boson and top quark (blue)
- Inferred values from precision measurements (pink)



New from ICHEP, 2006

Understanding Higgs Limit

$$M_W(GeV) = 80.364 - 0.0579\ln\left(\frac{M_h}{100\ GeV}\right) - 0.008\ln^2\left(\frac{M_h}{100\ GeV}\right)$$
$$-0.5098\left(\frac{\Delta\alpha_{had}^{(5)}(M_Z)}{0.02761} - 1\right) + 0.525\left[\left(\frac{M_t}{172\ GeV}\right)^2 - 1\right]$$
$$-0.085\left(\frac{\alpha_s(M_Z)}{0.118} - 1\right)$$

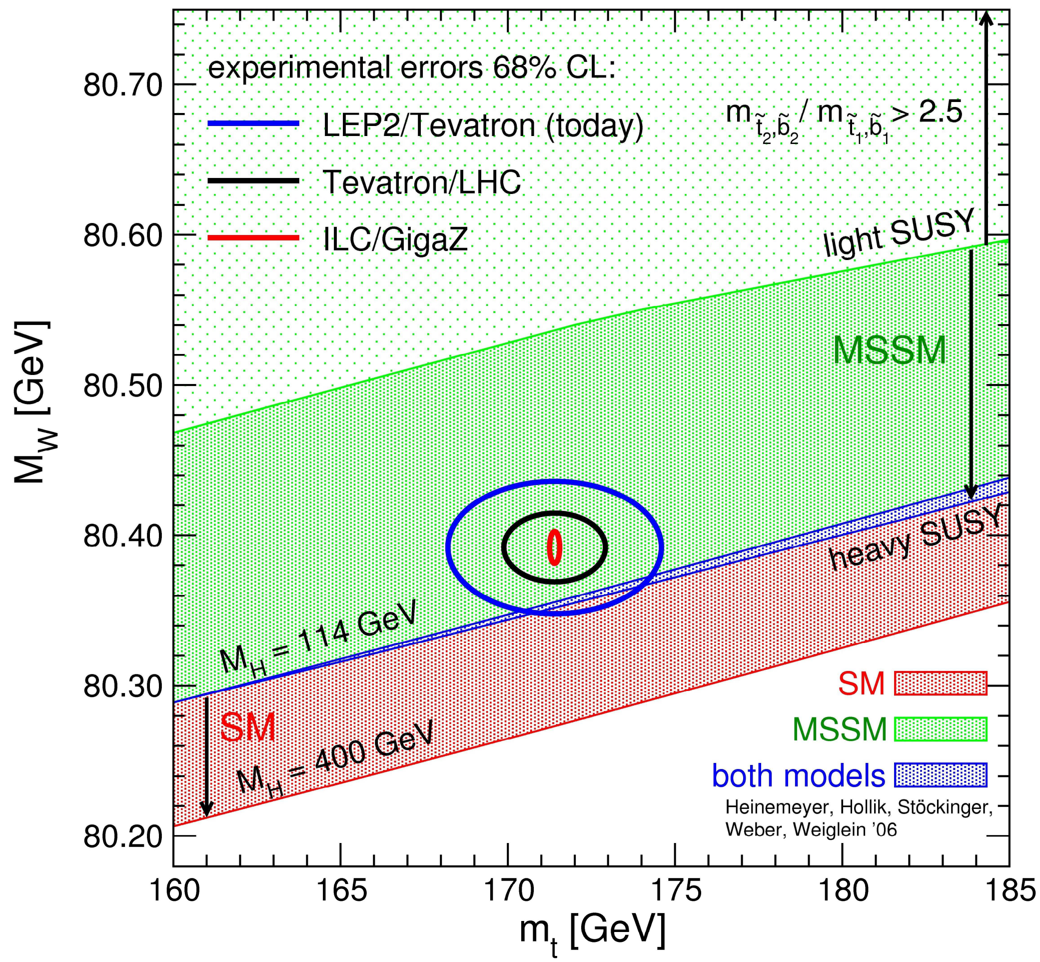
M_W(experiment)=80.392 ± 0.029 GeV*

Increasing M_h moves M_W further from experimental value

* Average of Tevatron and LEP2 values

SM Isn't the Only theory That Fits Precision Measurements

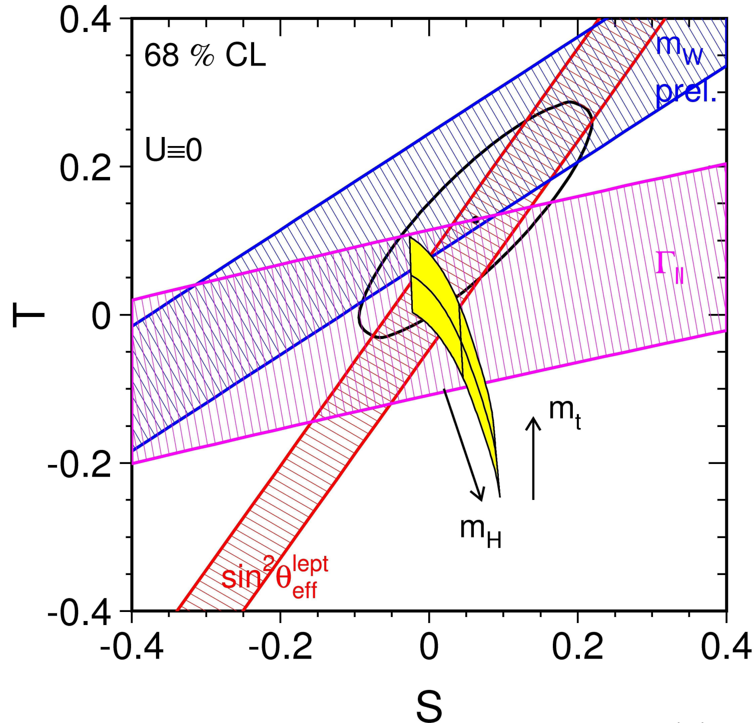
- Slight preference for MSSM



Heinemeyer et al, hep-ph/0611372

SM isn't only theory that can fit precision measurements

- Heavy Higgs allowed with large ΔT (αΔT=Δρ)
- Straightforward to construct such models



Peskin and Wells, hep-ph/0101342

Standard Model is Effective Low Energy Theory

- We don't know what's happening at high energy
- Effective theory approach:

$$L \approx L_{SM} + \sum_i f_i \frac{O_i}{\Lambda^2} + \ldots$$

- Compute deviations from SM due to new operators and compare with experimental data

$$O_{BW} = -\frac{gg'}{2} \Phi^+ B_{\mu\nu} W^{\mu\nu} \Phi$$

$$O_{\Phi,1} = \left[(D_\mu \Phi)^+ \Phi \right] \left[(D_\mu \Phi)\ \Phi^+ \right]$$

LHC job is to probe physics which generates these operators

$$\alpha S = -e^2 \frac{v^2}{\Lambda^2} f_{BW}$$

$$\alpha T = -\frac{v^2}{2\Lambda^2} f_{\Phi,1}$$

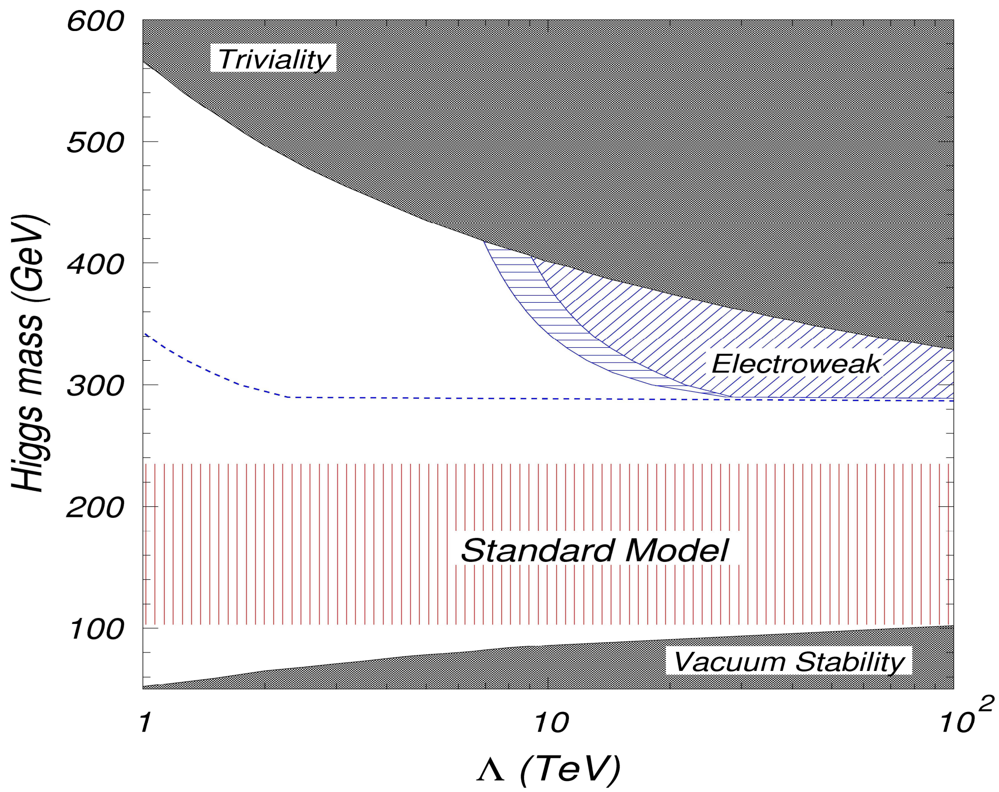
⇒ $\Lambda > 5\ TeV$

Suppose the LHC finds a Higgs….

- The SM predicts production/decay rates
  - We need to understand the uncertainty on these predictions
- Spin/parity
  - Is it a scalar or a pseudoscalar?
- Higgs can't be heavier than $\approx$ 200 GeV in minimal SM
- Minimal SM has no extra scalar particles
  - Spectroscopy of new states in non-minimal models crucial

Do I care about the Higgs Mass?

Range of validity of SM



Kolda & Murayama, hep-ph/0003170

Is it the Higgs?

- Measure couplings to fermions & gauge bosons

$$\frac{\Gamma(h \rightarrow b\bar{b})}{\Gamma(h \rightarrow \tau^+\tau^-)} \approx 3\frac{m_b{}^2}{m_\tau{}^2}$$

- Measure spin/parity

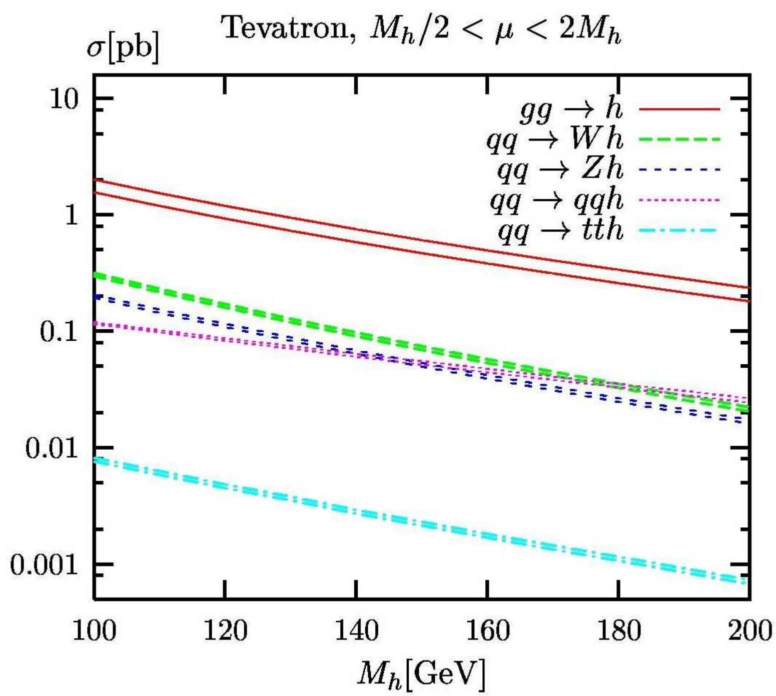
$$J^{PC} = 0^{++}$$

- Measure self interactions

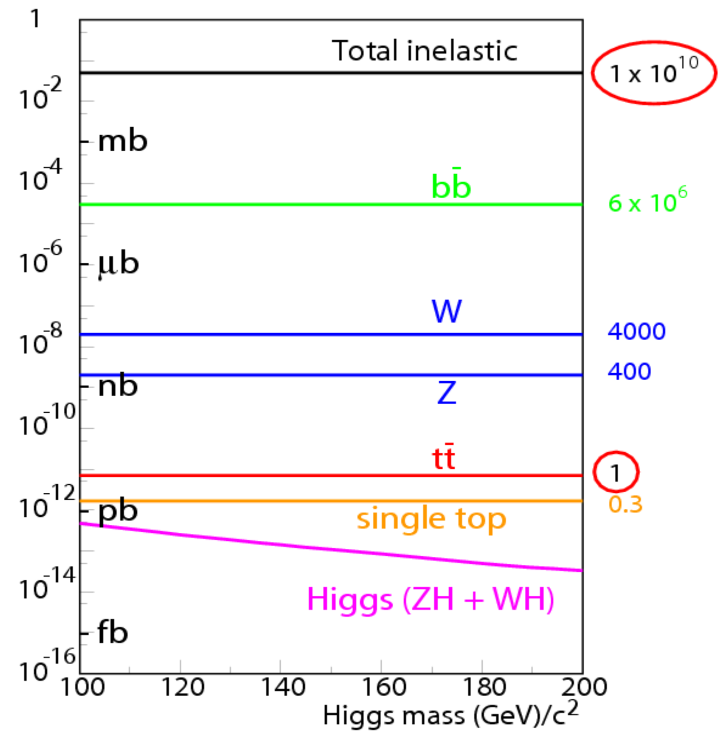
$$V = \frac{M_h{}^2}{2}h^2 + \frac{M_h{}^2}{2v}h^3 + \frac{M_h{}^2}{8v^2}h^4$$

← Need good ideas here!

Higgs at the Tevatron

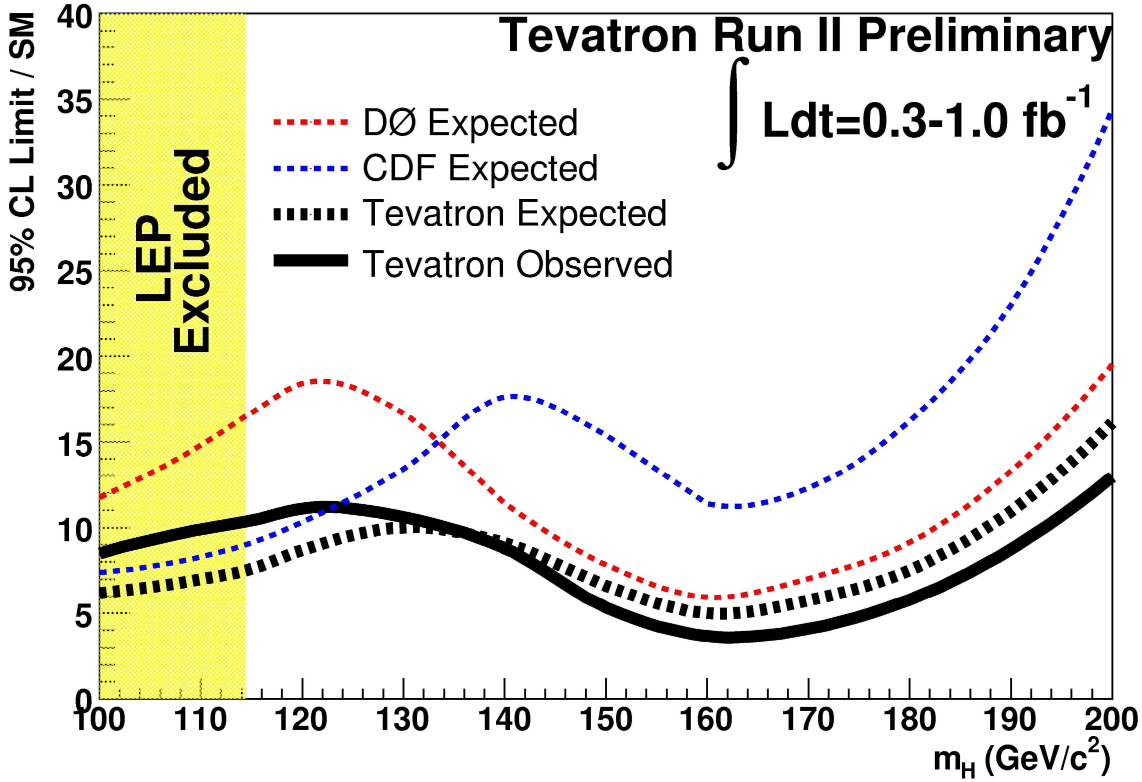


NNLO or NLO rates



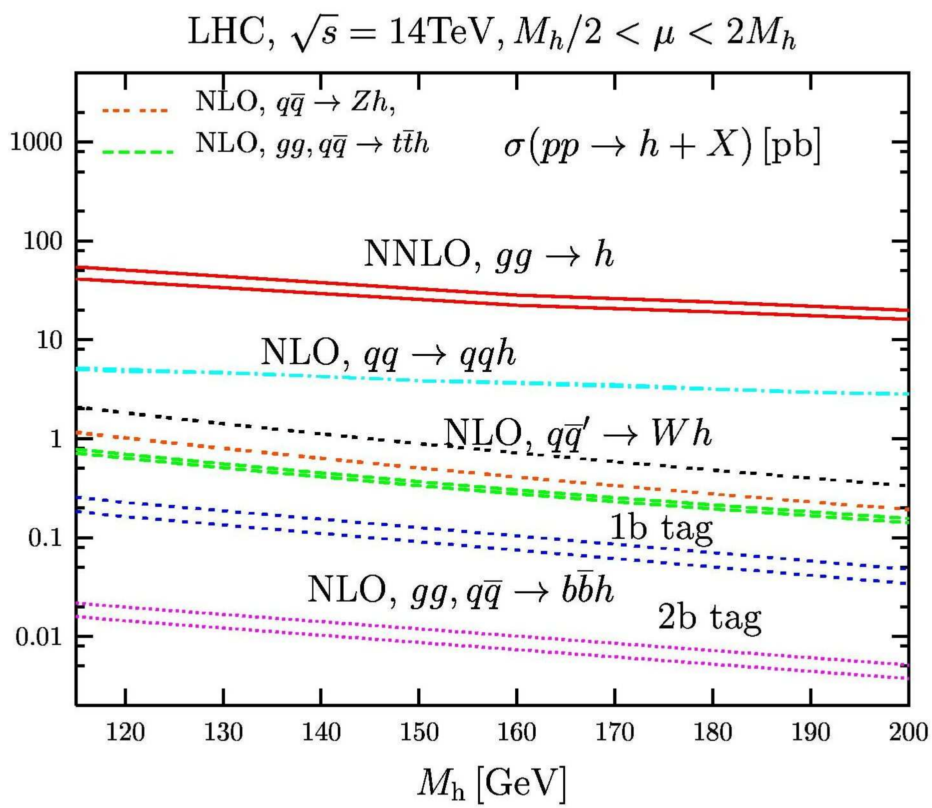
$\sigma(gg \to h) \sim 1$ pb << $\sigma(bb)$

SM Higgs Limits from the Tevatron



Tevatron can find Higgs with enhanced production rate

SM Production Mechanisms at LHC



•Bands show scale dependence

•All important channels calculated to NLO or NNLO

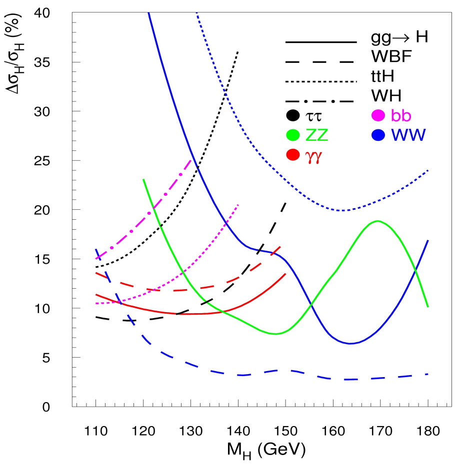
•Relatively small uncertainties from scale dependence

Production with b's very small in SM

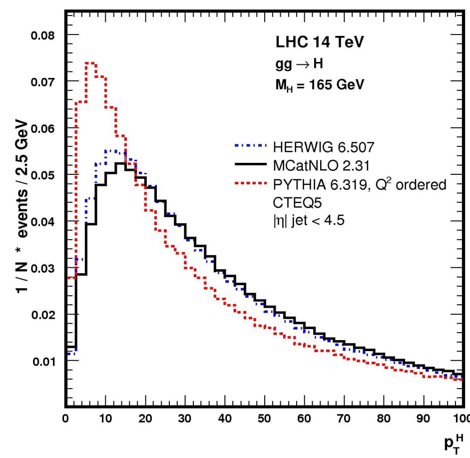
Progress in understanding uncertainties

- Many sources of uncertainties in predictions
- Must have a good handle on them before we can draw inferences about new physics

NLO rates*



Higgs p_T spectrum

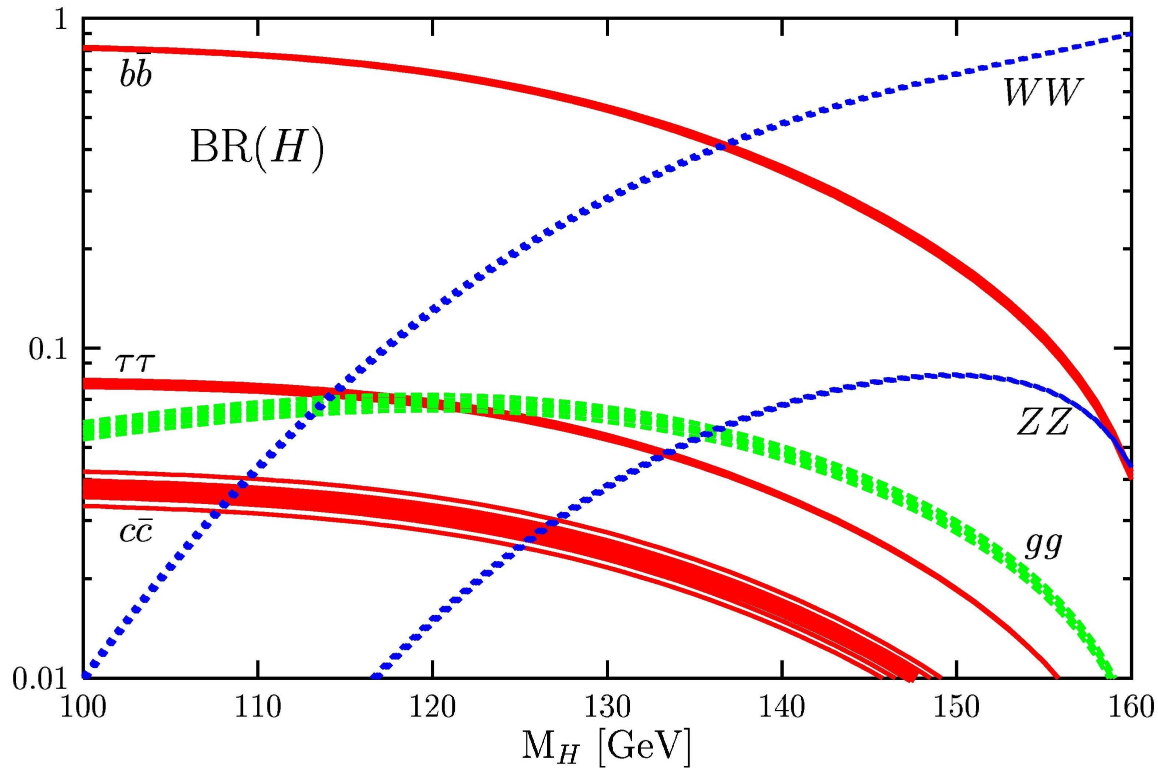


Belyaev & Reina, hep-ph/025270

* 30 fb^{-1} gg→h, h →WW; 300 fb^{-1} tth, h →WW, Wh, h →bb; all others 200 fb^{-1}

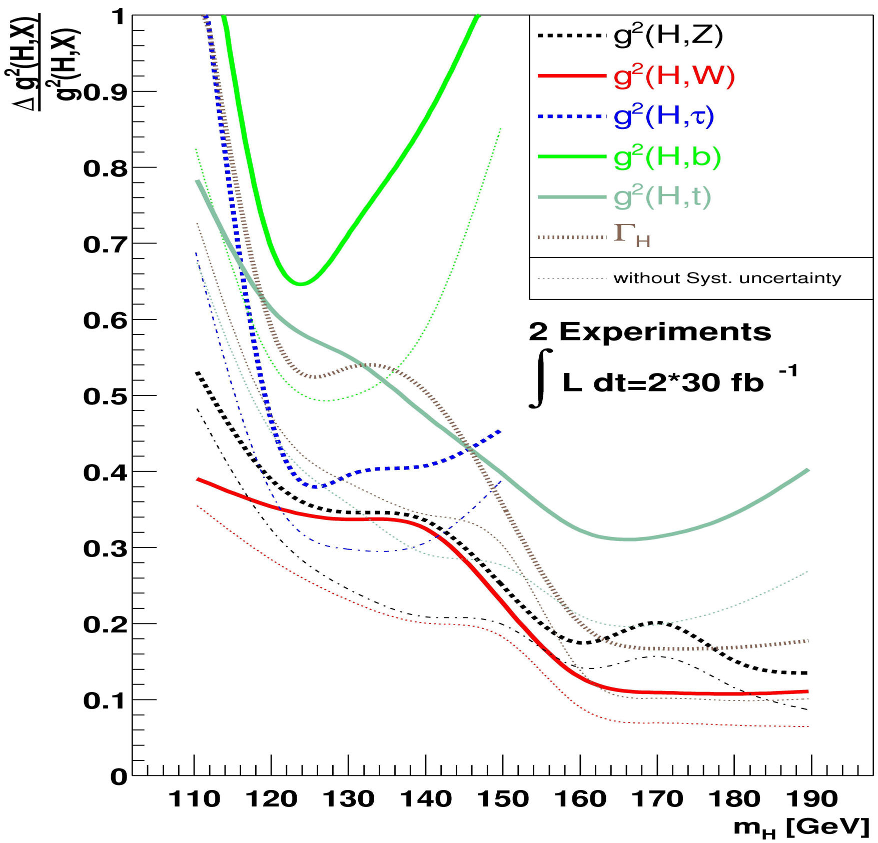
Precision Measurements of Higgs Couplings

- Bands are theory uncertainty
  - Largest uncertainty from $m_b = 4.88 \pm .07$ GeV



Djouadi, hep-ph/0503172

Higgs Couplings Difficult to Measure at LHC

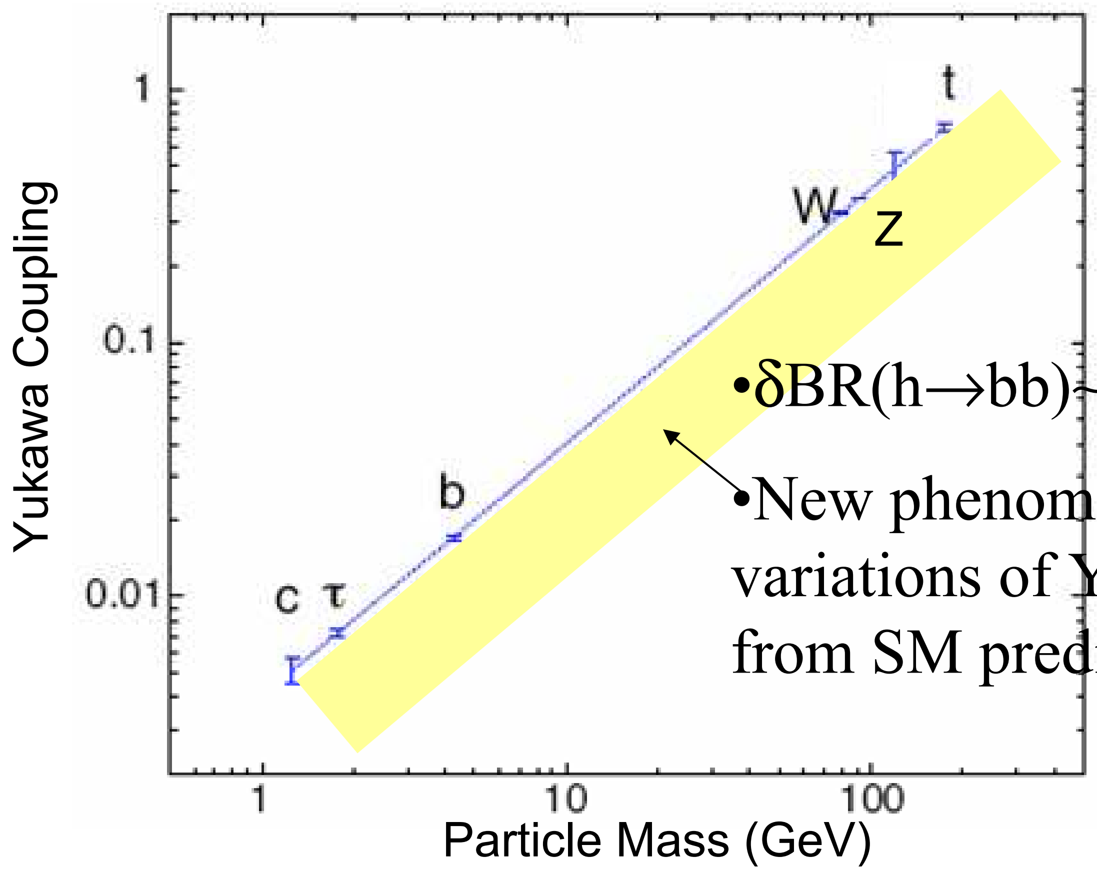


Ratios of couplings easier

Extraction of couplings requires understanding NLO QCD corrections for signal & background

Logan, hep-ph/0409026

ILC Goal: Precision Measurements of Yukawa Couplings

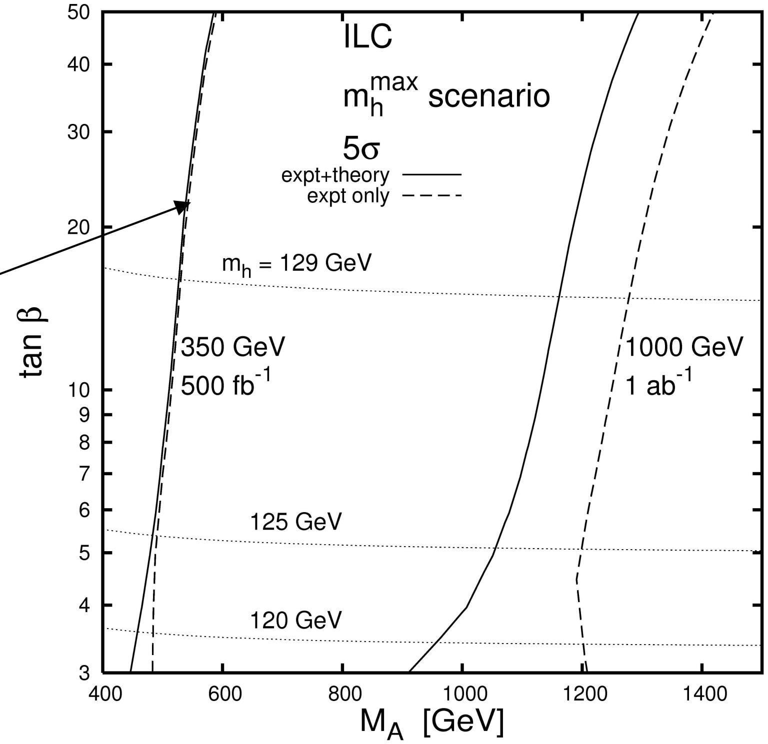


- $\delta BR(h \to bb) \sim 2\%$ with $L=500\ fb^{-1}$
- New phenomena can cause variations of Yukawa couplings from SM predictions

Can this sensitivity probe novel phenomena?

Limits on New Physics from Higgs BRs

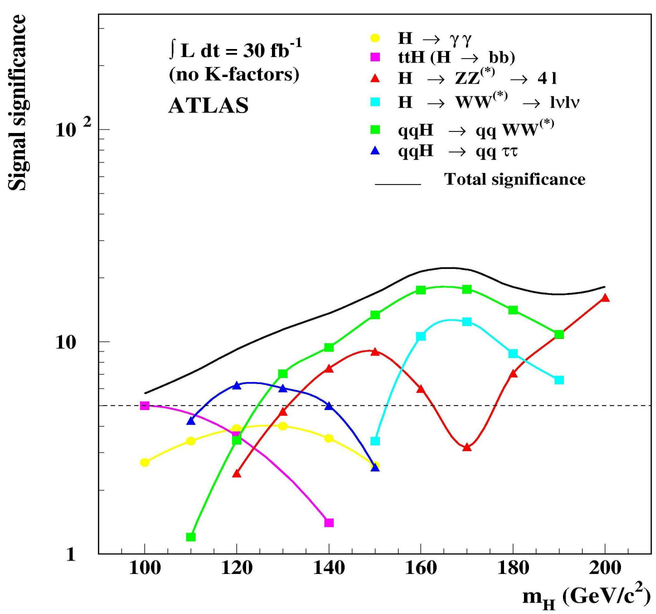
To the left of curves, ILC can distinguish SM h from MSSM h in m_h^{max} scenario

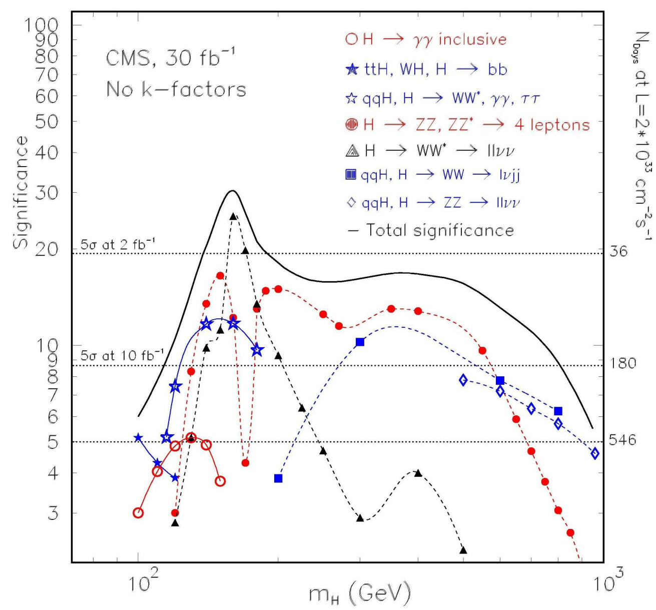


Droll & Logan, hep-ph/0612317

Claim: LHC Can Discover SM Higgs Regardless of Mass

- Tricky if production/branching ratios are highly suppressed
- Can’t directly measure all couplings

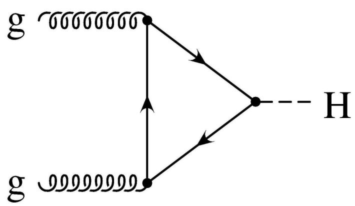




Production can be very different from SM

- Example #1: Generalized operators
  - Dimension 6 operator:

$$L_{6g} = \frac{f_g}{\Lambda^2} \Phi^+ \Phi G_{\mu\nu}{}^a G^{\mu\nu a}$$



  - Expand around vacuum: $\phi^0 \to \frac{(h+v)}{\sqrt{2}}$
  - Generate interaction

$$L_{6g} = \frac{f_g v}{\Lambda^2} h G_{\mu\nu}{}^a G^{\mu\nu a}$$

  - For heavy top quark, the SM hGG interaction is well approximated by

$$L_{6g} = \frac{\alpha_s}{12\pi v}\left(1 + \frac{11\alpha_s}{4\pi}\right) h G_{\mu\nu}{}^a G^{\mu\nu a}$$

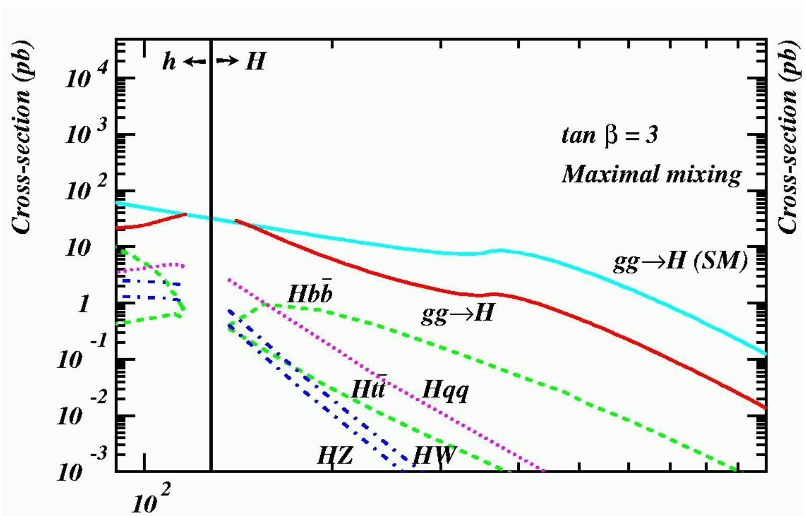
  - New operator is just arbitrary enhancement or suppression of gg→h production rate

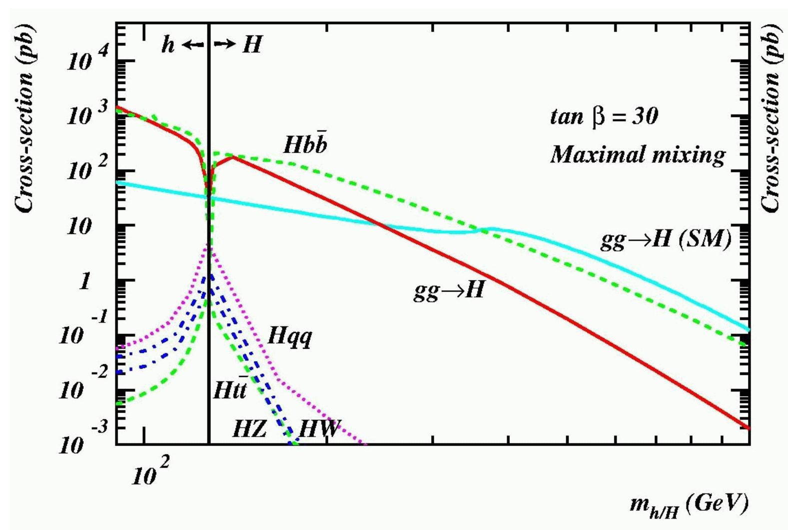
$$\sigma \to \sigma_{SM}\left(1 + \frac{36\pi}{\alpha_s} f_g \left(\frac{v}{\Lambda}\right)^2\right)$$

eg. Manohar and Wise, hep-ph/0601212

Higgs Production can be enhanced

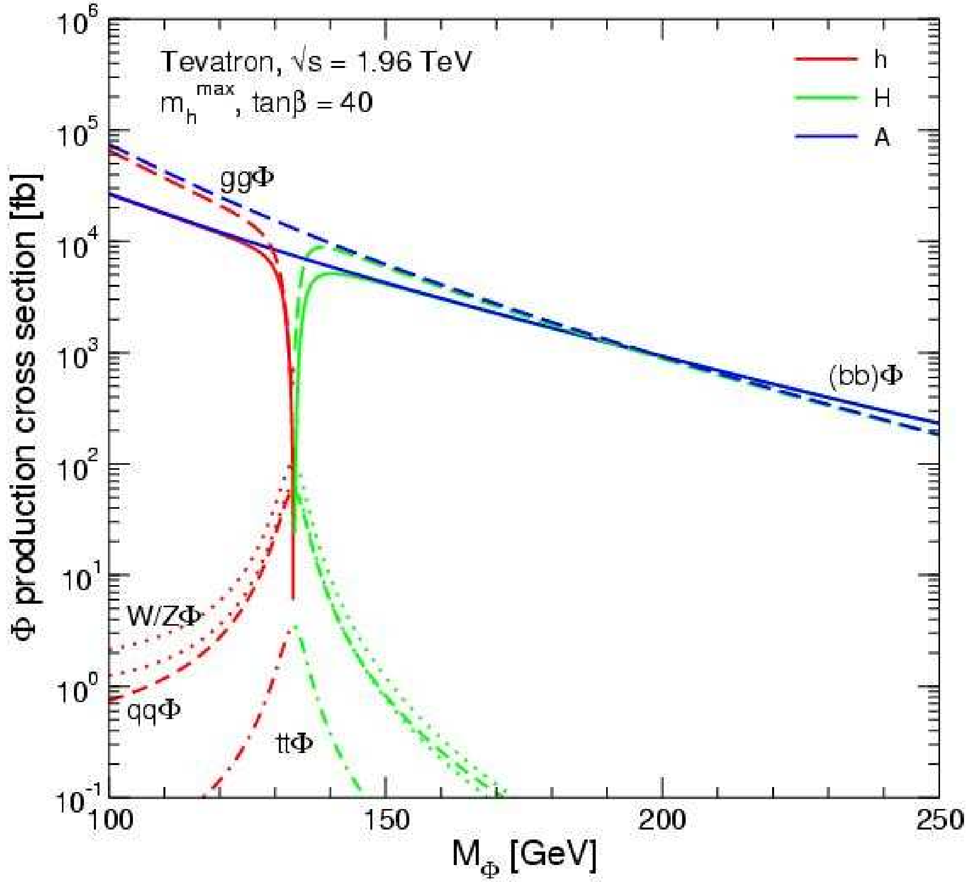
- Example #2: MSSM
- For large tan β, dominant production mechanism is with b's
- bbh can be 10x's SM Higgs rate in SUSY for large tan β





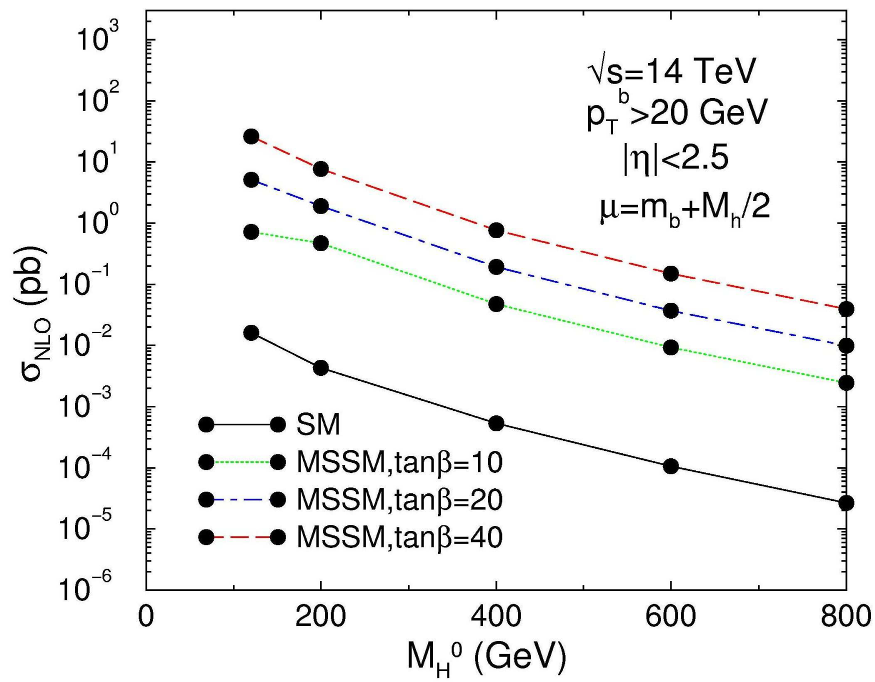
SUSY Higgs are produced with b's!

SUSY Rates at the Tevatron



Enhancement in MSSM: $pp \rightarrow b\bar{b}H$

Note log scale!



Can observe heavy MSSM scalar Higgs boson

* Tevatron has significant limits on bh production

Higgs Production can be suppressed

- Example #3
  - Add a single real scalar *S* to the standard model
  - *S* carries no charge and couples to nothing except the Higgs, through the potential

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

  - Physical particles are linear combination of h, s

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

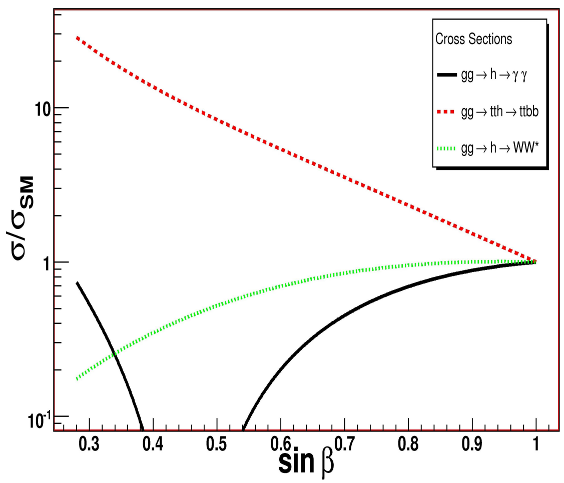
  - Higgs branching ratios are $BR_{SM} \cdot \sin^2\gamma$
  - If $m_1 > 2\, m_2$, new decay channel:

$$\varphi_1 \rightarrow \varphi_2\, \varphi_2 \rightarrow \quad (bb)(bb),\ (bb)(\tau^+\tau^-),\ (\tau^+\tau^-)(\tau^+\tau^-)$$

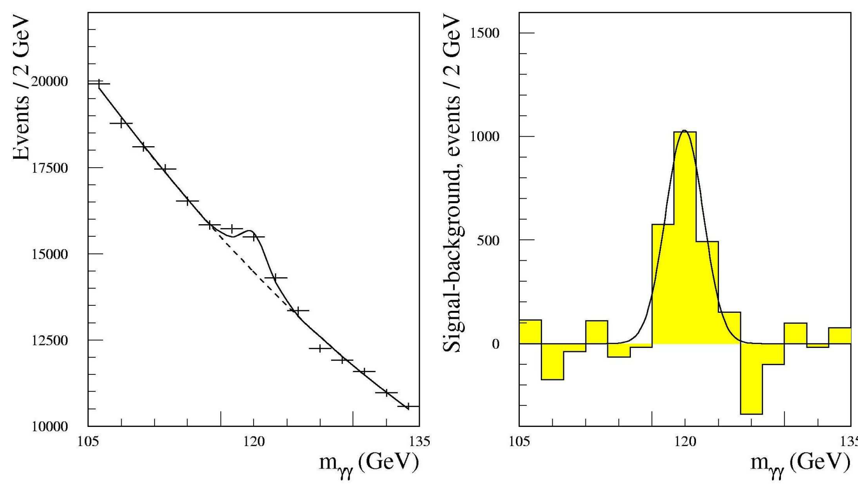
Not Hard to Construct Models With Suppressed $h\to\gamma\gamma$ Rate

- 2 Higgs doublet model where only Φ_1 couples to fermions ($\tan\beta = v_1/v_2$)

2HD, M_h=140 GeV



SM: $h\to\gamma\gamma$



- Little Higgs models, models with radion/Higgs mixing also tend to have suppressed $h\to\gamma\gamma$ rate

Phalen, Thomas, Wells, hep-ph/0612219

Is *the* Higgs a Scalar?

- Weak boson fusion sensitive to tensor structure of HVV coupling
  - Alternative structures from higher dimension operators

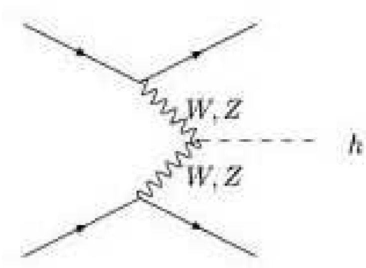
$$T^{\mu\nu} = c_1 g^{\mu\nu} + c_2\left(p_1 \cdot p_2 g^{\mu\nu} - p_1{}^{\mu} p_2{}^{\nu}\right) + c_3 \varepsilon^{\mu\nu\alpha\beta} p_{1\alpha} p_{2\beta}$$

SM

CP even

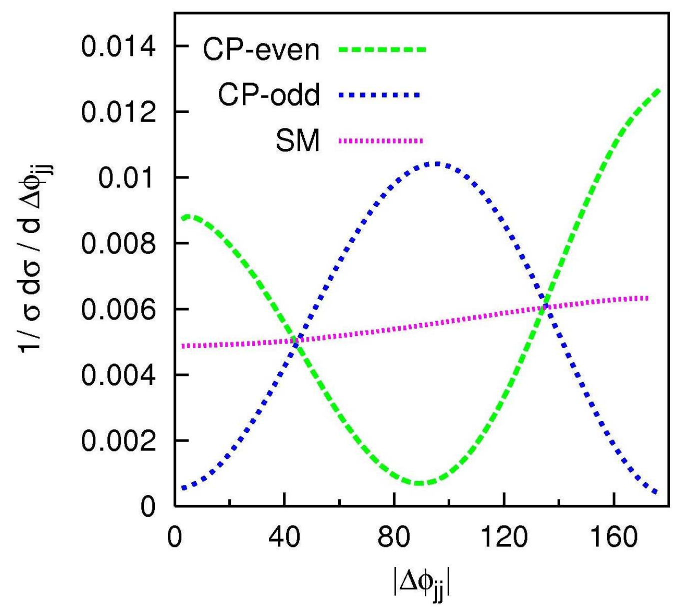
CP odd

Loop induced



Need to Measure CP of Higgs

– Azimuthal angle between tagged jets sensitive to c_2, c_3
– Structure of dips only depends on hVV vertex tensor structure (little dependence on higher order QCD/M_h/etc)



Not so pretty if admixture of CP even/odd

Figy, Hankele, Klamke, Zeppenfeld, hep-ph/0609075

Conclusion

- Expect the unexpected
  - Prejudice is dangerous!
  - Theorists can construct models with enhanced or suppressed Higgs production rates and with or without SM-like branching ratios
- We need to measure:
  - σBR for as many production/decay chains as possible
  - Spin/parity
  - Spectroscopy of new particles associated with symmetry breaking