Finding the Higgs boson

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FNAL LHC School, Lecture 2

- ✍Properties of the Higgs boson
  - Theoretical uncertainties & motivations for precision measurements
- ✍Higgs production at the Tevatron and LHC

Who needs a Higgs?

- Gives masses to W, Z, and fermions in gauge invariant fashion
- Unitarizes VV? VV scattering
  - (More in Lecture 3)
- Makes precision electroweak data consistent

But….

- Higgs mechanism doesn't explain masses or flavor structure
  - It accommodates them
- Higgs mass is quadratically sensitive to physics at high scales
  - (More in Lecture 3)
- Higgs potential stable only for certain Higgs masses
  - (More in Lecture 3)

Review of Higgs Couplings

- Higgs couples to fermion mass
  - Largest coupling is to heaviest fermion

$$L = -\frac{m_f}{v}\bar{f}fh = -\frac{m_f}{v}\left(\bar{f}_L f_R + \bar{f}_R f_L\right)h$$

v=246 GeV

  - Top-Higgs coupling plays special role?
  - No Higgs coupling to neutrinos

Review of Higgs Couplings

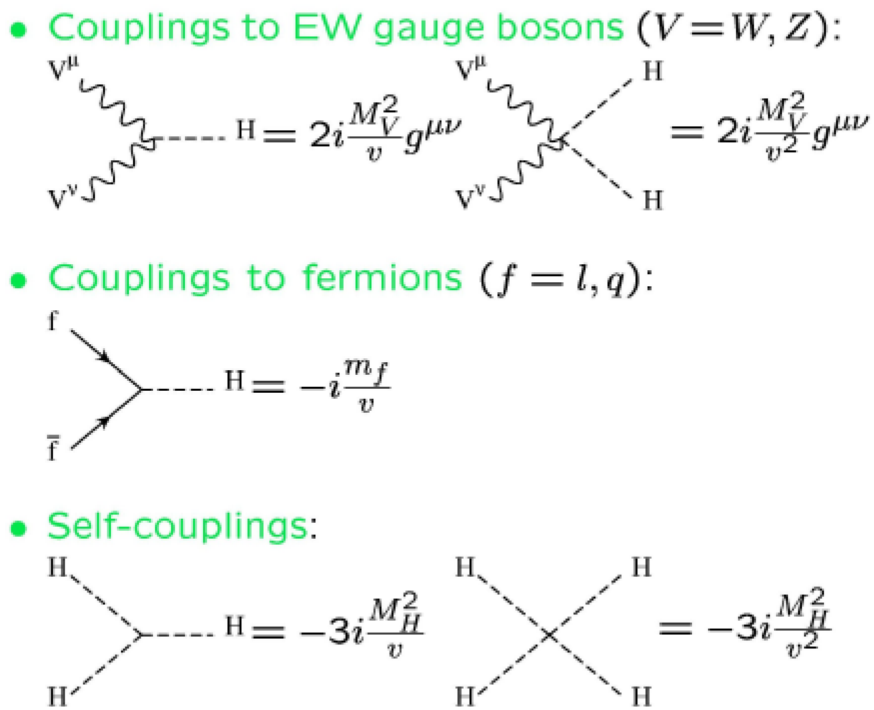
- Higgs couples to gauge boson masses

$$L ? gM_W W^{??} W_?^{\;?} h ? \frac{gM_Z}{\cos ?_W} Z^? Z_? h ? ....$$

- Only free parameter is Higgs mass!
- Everything is calculable….***testable theory***

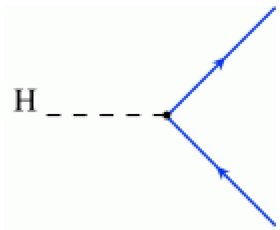
$$g^2 ? \frac{G_F}{\sqrt{2}} 8M_W^2 ? \frac{e^2}{\sin^2 ?_W} ? \frac{4??}{\sin^2 ?_W}$$

Review of Higgs Boson Feynman Rules



- Higgs couples to heavy particles
- No tree level coupling to gluons (g) or photons (?)
- $M_h^2=2v^2$? ? large M_h is strong coupling regime

Higgs Decays



$$?(h ? f\bar{f}) ? \frac{N_c G_F m_f^2 M_h}{4\sqrt{2}?} ?^3$$

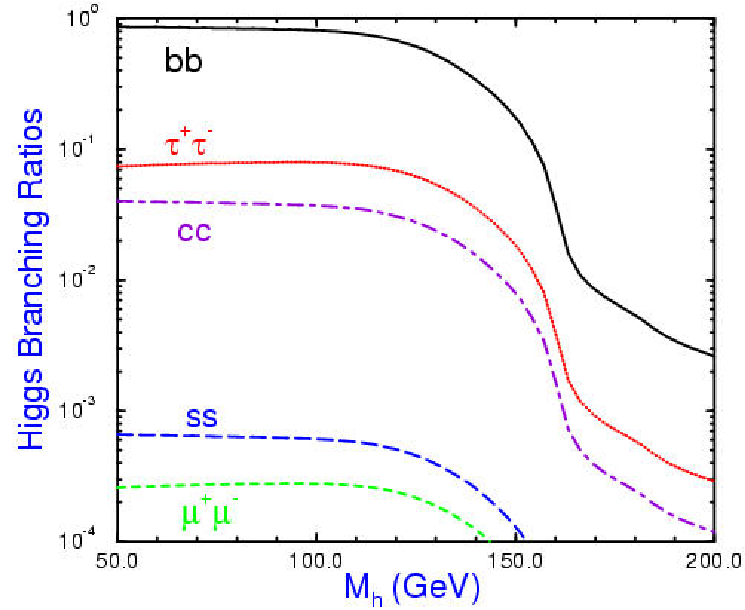
$$?_f ? \sqrt{1 ? \frac{4m_f^2}{M_h^2}}$$

- h? ff proportional to m_f^2

$$\frac{BR(h ? b\bar{b})}{BR(h ? \bar{?}^? ?^?)} ? N_c ?\frac{m_b^2}{m_?^2}?? \frac{?_b}{?_?}?^3$$

- $?^3$ typical of scalar

  (pseudo-scalar decay ??)

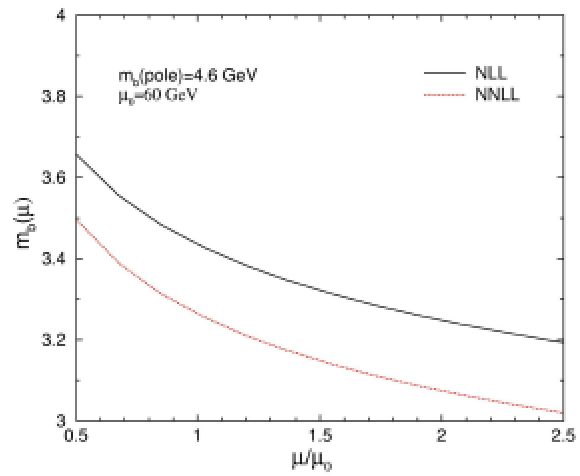


For $M_h<2M_W$, decays to $b\bar{b}$ most important

QCD Corrections to $h \to Q\bar{Q}$

- Tree level: $\Gamma(h \to Q\bar{Q})_{tree} = \frac{3 G_F M_h}{4\sqrt{2}\pi} M_Q{}^2 \beta_Q{}^3$
- Add QCD: $\Gamma(h \to Q\bar{Q})_{QCD} = \frac{3 G_F M_h}{4\sqrt{2}\pi} \overline{m}_Q{}^2(M_h) \beta_Q{}^3 \left\{ 1 + 5.67 \frac{\alpha_s(M_h)}{\pi} + \ldots \right\}$
- Large logs absorbed into running $\overline{\text{MS}}$ mass:

$$m_b(\mu^2) = m_b(m_b{}^2) \left\{ \frac{\alpha_s(m_b^2)}{\alpha_s(\mu^2)} \right\}^{-12/23}$$



Higgs Decays to Gauge Bosons

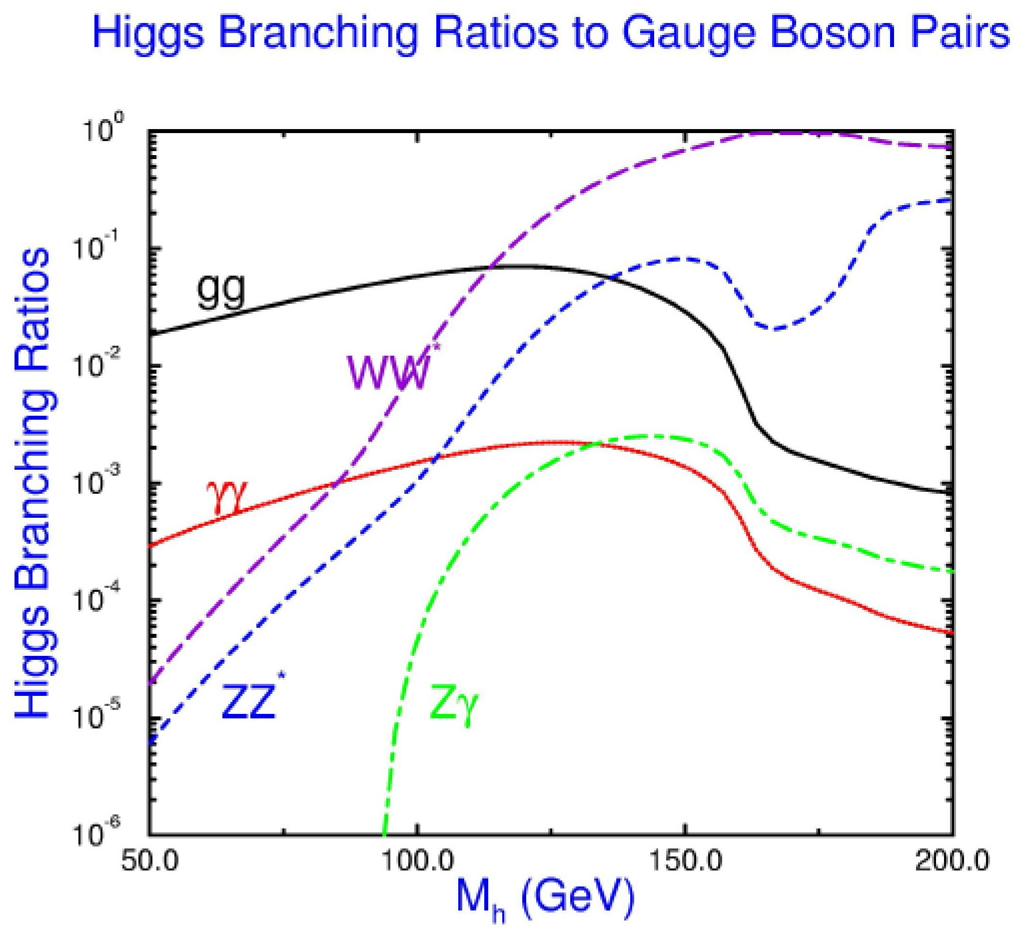
- h ? gg sensitive to top loops
  - Remember no coupling at tree level
- h ? ?? sensitive to W loops, only small contribution from top loops
- h ? W^+W^- ? ffff has sharp threshold at 2 M_W, but large branching ratio even for M_h=130 GeV

$$?(h ? VV) ? \frac{G_F M_h^3}{8\sqrt{2}?} ?_V ? (..)$$

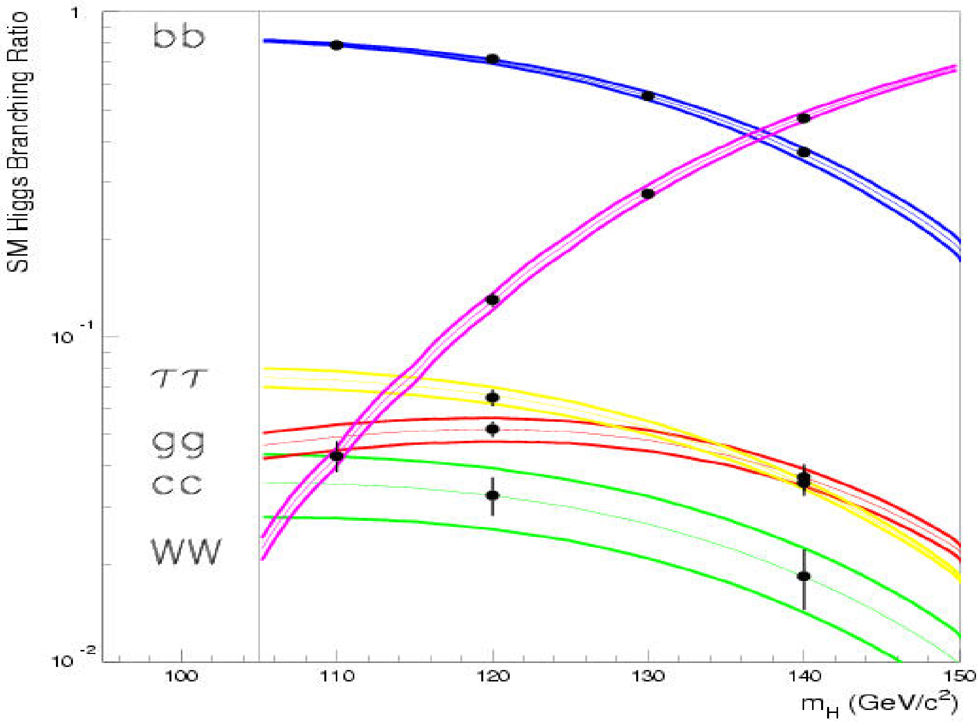
$$?_{W,Z} ? 2,1$$

Cubic in M_h, so for heavy Higgs, decays to vector boson dominate

Decays to Gauge Bosons



Status of Theory for Higgs BRs



Data points are e^+e^- ILC at ?s=350 GeV with L=500 fb^{-1}

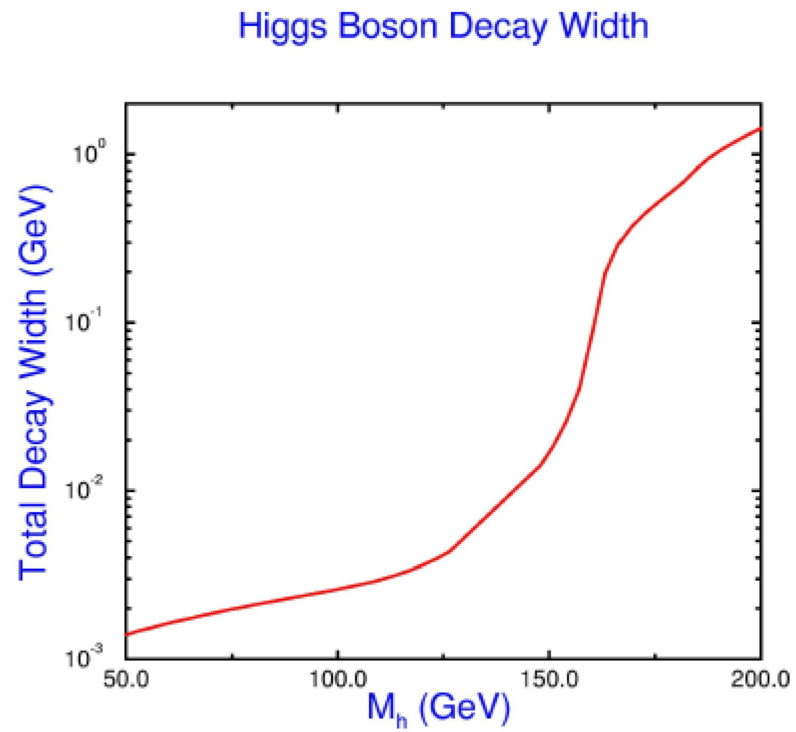
- Bands show theory errors
- Largest source of uncertainty is b quark mass

Total Higgs Width

- Total width sensitive function of M_h
- Small M_h, Higgs is narrower than detector resolution
- As M_h becomes large, width also increases
  - No clear resonance
  - For M_h ?1.4 TeV, $?_{tot}$?M_h

$$?(h ?\ W^? W^?) ? \frac{?}{16 \sin^2 ?_W} \frac{M_h^{\ 3}}{M_W^{\ 2}}$$

$$? 330 GeV ? \frac{M_h}{1 TeV} ?^3$$



- *Higgs branching ratios easily computed with HDECAY program to NLO*
- *http://mspira.home.cern.ch/mspira/proglist.html*

Higgs Searches at LEP2

- LEP2 searched for e^+e^-? Zh
- Rate turns on rapidly after threshold, peaks just above threshold, ???^{3}/s
- Measure recoil mass of Higgs; ***result independent of Higgs decay pattern***

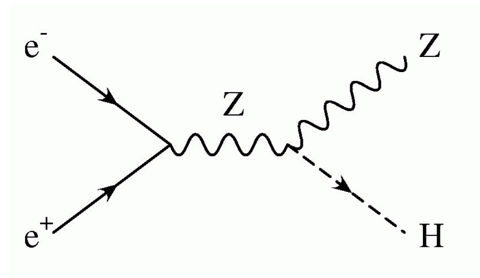
  P_{e-}=?s/2(1,0,0,1)

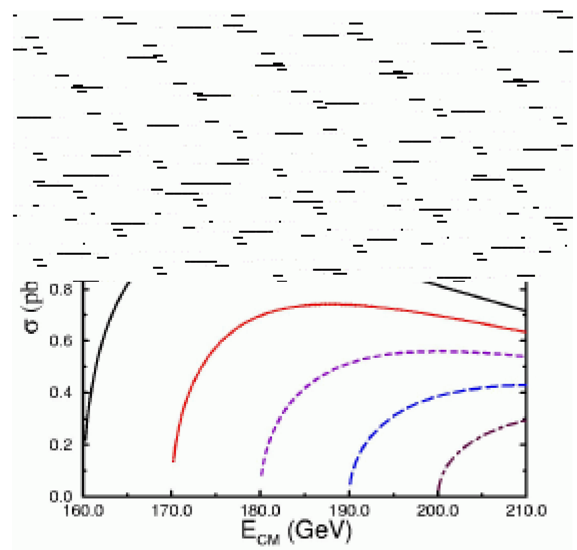
  P_{e+}=?s/2(1,0,0,-1)

  $P_Z=(E_Z, \vec{p}_Z)$
- Momentum conservation:

  $(P_{e-}+P_{e+}-P_Z)^2=P_h^2=M_h^2$

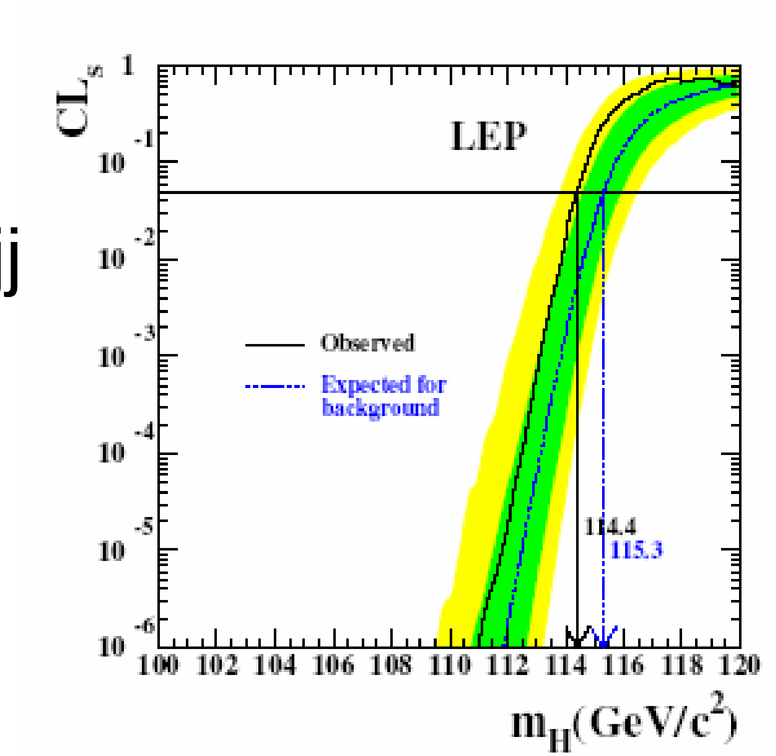
  s-2 ?s $E_Z+M_Z^2= M_h^2$
- LEP2 limit, ***M_h > 114.1 GeV***





Higgs at LEP2

- Higgs decays predominantly to $b\bar{b}$
- LEP-2 searched in many channels
  - $b\bar{b}jj$, $b\bar{b}l^+l^-$, $b\bar{b}$??, ?$^+$?jj, jjjj
- Z branching ratios
  - e^+e^- (3.3%)
  - $b\bar{b}$ (15%)
  - ?? (20%) invisible
  - jj (the rest)



Higgs production at Hadron Colliders

- Many possible production mechanisms; Importance depends on:
  - Size of production cross section
  - Size of branching ratios to observable channels
  - Size of background
- Importance varies with Higgs mass
- Need to see more than one channel to establish Higgs properties and verify that it is a Higgs boson

Production in Hadron Colliders

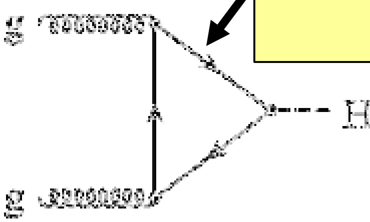
- Gluon fusion
  - Largest rate for all M_h at LHC
  - Gluon-gluon initial state
  - Sensitive to top quark Yukawa $?_t$
- Lowest order cross section:

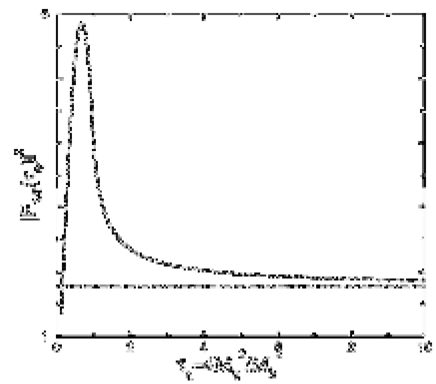
$$?_0(gg ? h) ? \frac{?_s(?_R)^2}{1024?v^2}\left|? _q F_{1/2}(?_q)\right|^2 ?(M_h^2 ? \hat{s})$$

  - $?_q=4M_q^2/M_h^2$
  - Light Quarks: $F_{1/2}?$ $(M_b/M_h)^2\log(M_b/M_h)$
  - Heavy Quarks: $F_{1/2}$? -4/3

In SM, b-quark loops unimportant

Largest contribution is top loop





Rapid approach to heavy quark limit

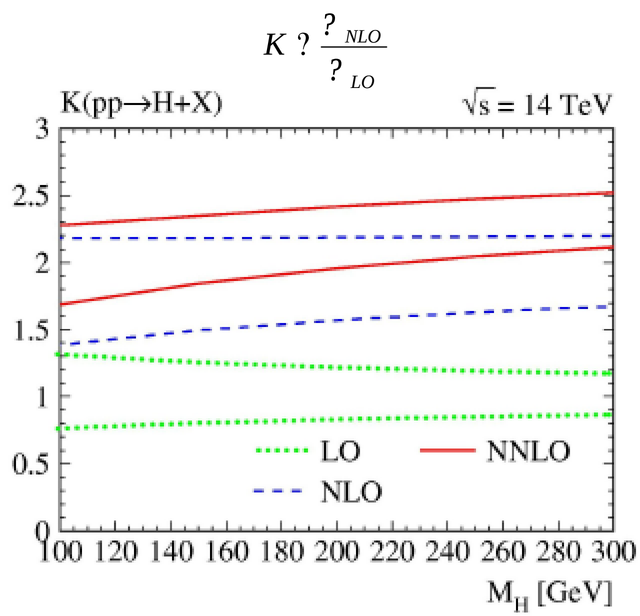
Gluon fusion, continued

- Integrate parton level cross section with gluon parton distribution functions

$$\sigma_0(pp \to h) = \hat{\sigma}_0 z \int_z^1 \frac{dx}{x} g(x, \mu_F) g(\frac{z}{x}, \mu_F)$$

  - $z = M_h^2/S$, S is hadronic center of mass energy
- Rate depends on μ_R, μ_F
- Rate for gluon fusion independent of M_t for $M_t >> M_h$
  - Counts number of heavy fermions

NNLO, gg? h



Rates depend on renormalization scale, $?_s(?_R)$, and factorization scale, $g(?_F)$

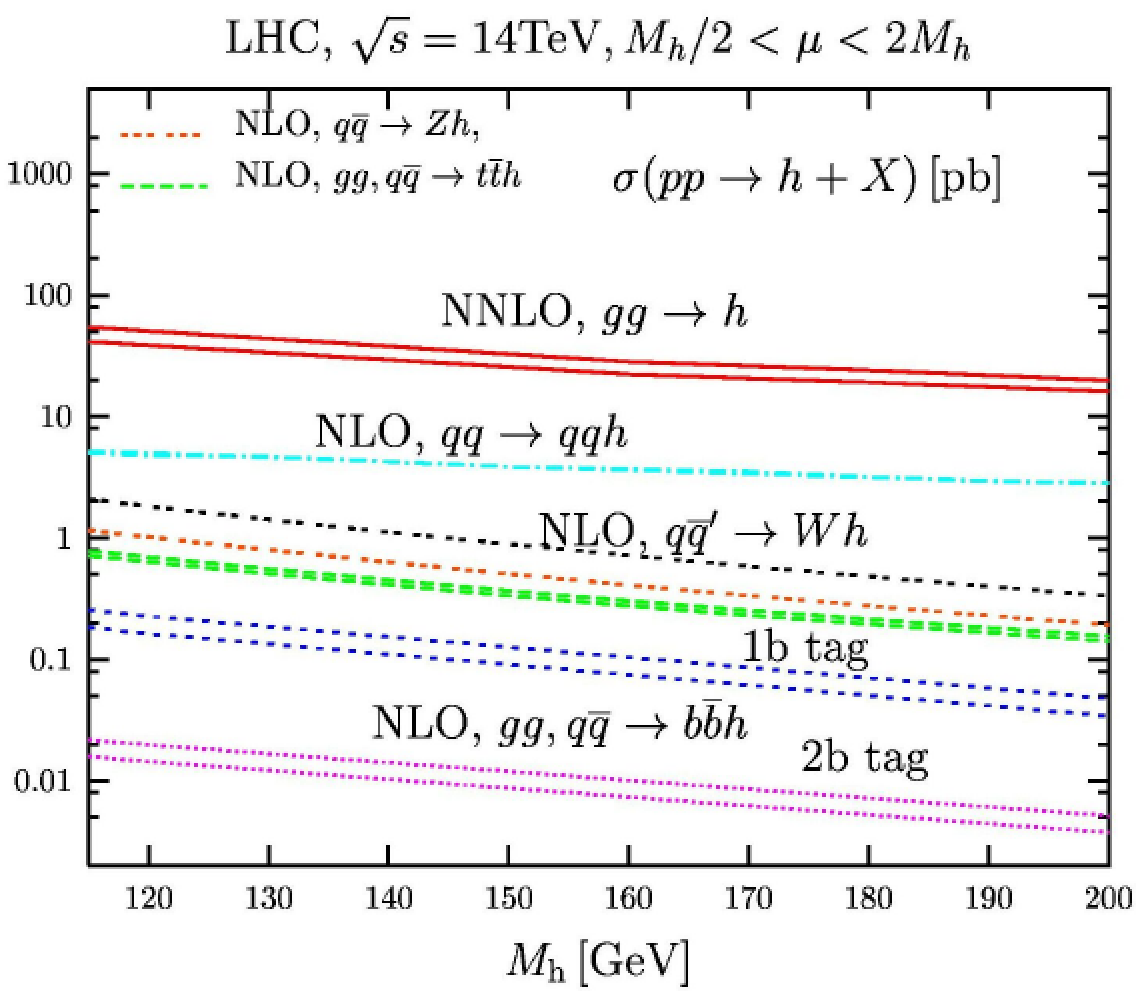
Bands show .5M_h < ?< 2 M_h

LO and NLO ? dependence bands don't overlap

? Dependence used as estimate of theoretical uncertainty

NLO&NNLO results allow improved estimates of theoretical uncertainties

Higgs production at the LHC



Vector Boson Fusion

- W^+W^- ? X is a real process:

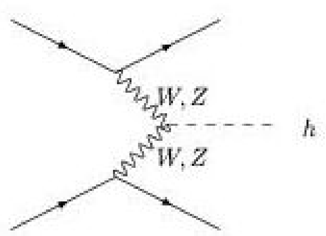
$$? _{pp?\ WW?\ X}(s)\ ?\ ?dz \frac{dL}{dz}\bigg|_{pp/WW}\ ?_{WW?\ X}(zs)$$

- Rate increases at large s: ? ? $(1/M_W^2)\log(s/M_W^2)$
- Integral of cross section over final state phase space has contribution from W boson propagator:

$$?\frac{d?}{(k^2\ ?\ M_W{}^2)^2}\ ?\ ?\frac{d?}{(2EE'(1\ ?\ \cos ?)\ ?\ M_W{}^2)^2}$$

Peaks at small ?

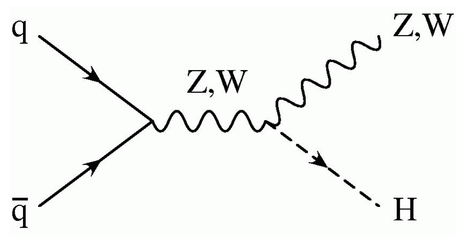
- Outgoing jets are mostly forward and can be tagged



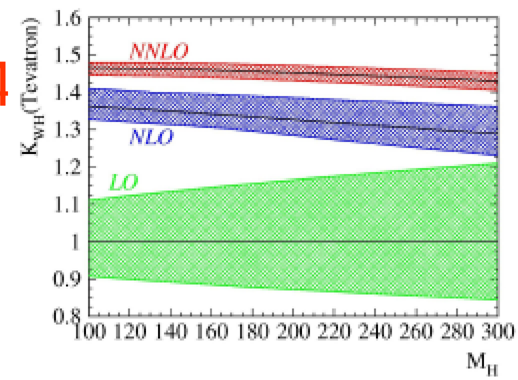
Idea: Look for h decaying to several different channels

Ratio of decay rates will have smaller systematic errors

W(Z)-strahlung



- W(Z)-strahlung ($q\bar{q}$? Wh, Zh) important at Tevatron
  - Same couplings as vector boson fusion
  - Rate proportional to ***weak*** coupling
  - Below 130-140 GeV, look for $q\bar{q}$? Vh, h ? $b\bar{b}$
  - For M_h>140 GeV, look for h? W^+W^-
- Theoretically very clean channel
  - NNLO QCD corrections: K_{QCD}?1.3-1.4
  - Electroweak corrections known (-5%)
  - Small scale dependence (3-5%)
  - Small PDF uncertainties

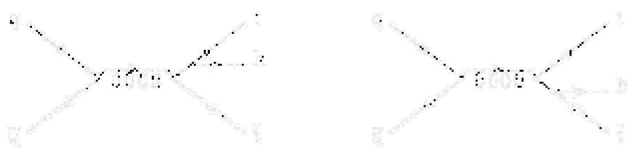


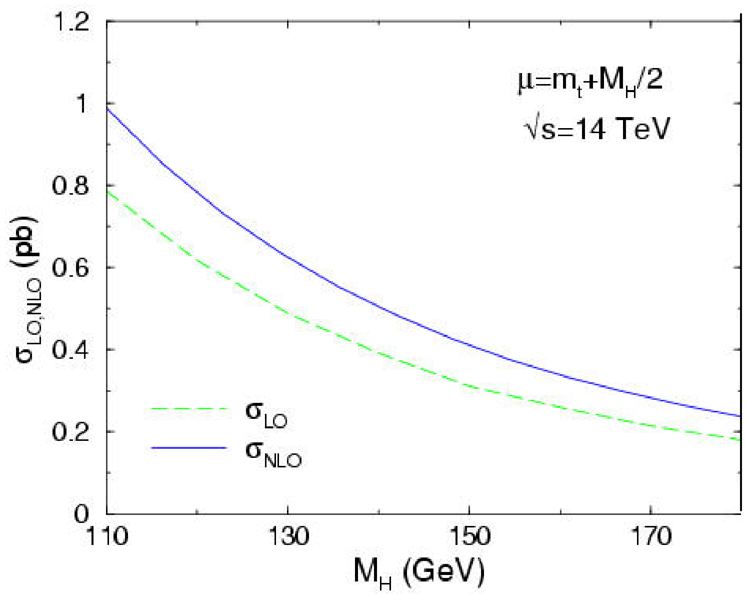
$t\bar{t}h$ Production

•$t\bar{t}h$ production unique channel to measure top quark Yukawa coupling

–h? tt never important

•bbh small in SM, but can be enhanced in SUSY models with large tan ?



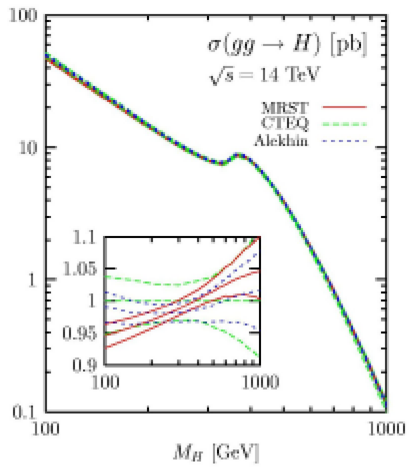


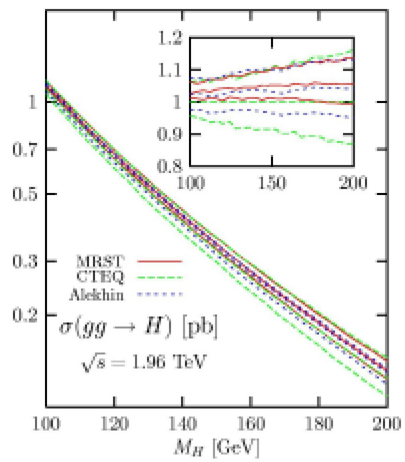
✍ Large QCD effects

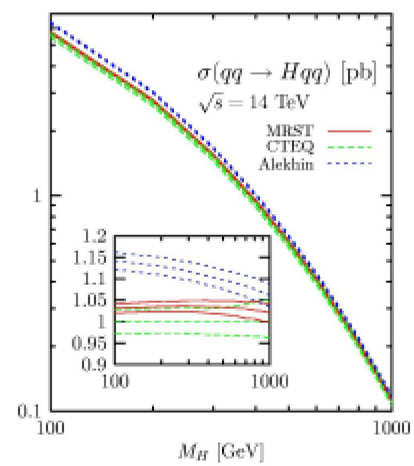
Higher order corrections

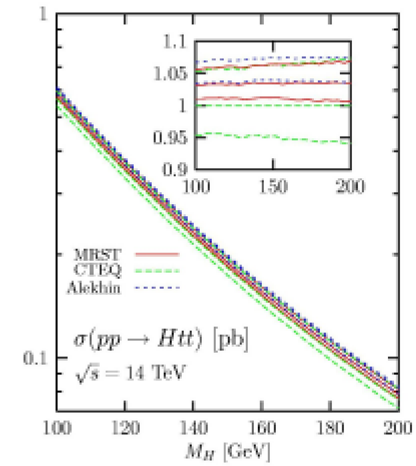
- QCD effects can be large
- Leading order cross sections have large uncertainties due to:
  - Renormalization/factorization scale dependence
  - Uncertainties from parton distribution functions (PDFs)
- Important modes have large QCD backgrounds
  - Often backgrounds only known to leading order

PDF uncertainties









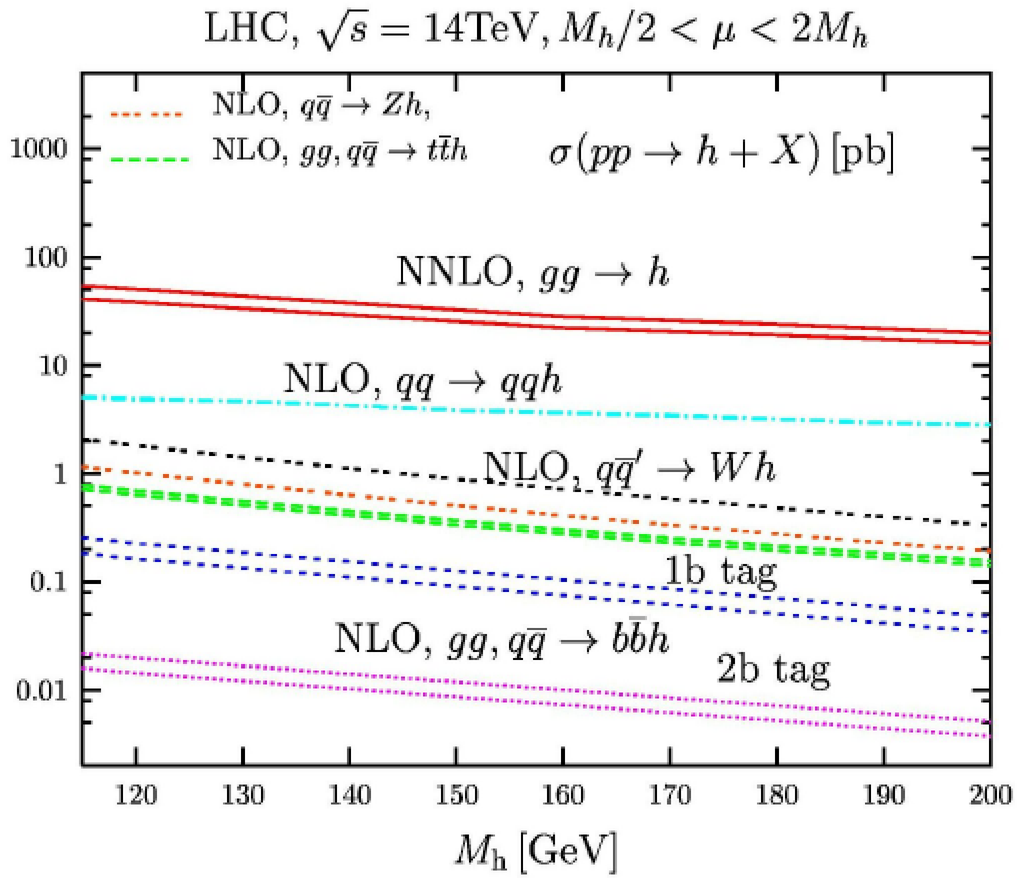
NLO PDFs with NLO cross sections!

Smaller PDF uncertainties in vector boson fusion ($\overline{q}q$ initial channel)

CTEQ6m: 40 PDFs for uncertainty studies

http://user.pa.msu.edu/wkt/cteq/cteq6pdf.html

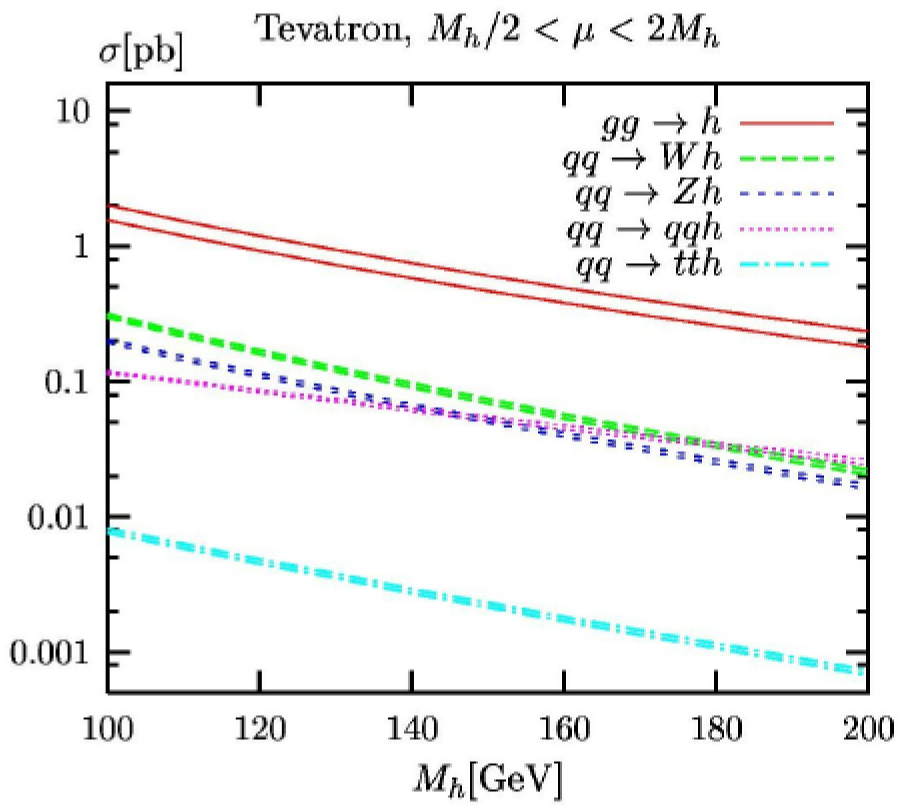
Production mechanisms at LHC



Bands show scale dependence

All important channels calculated to NLO or NNLO

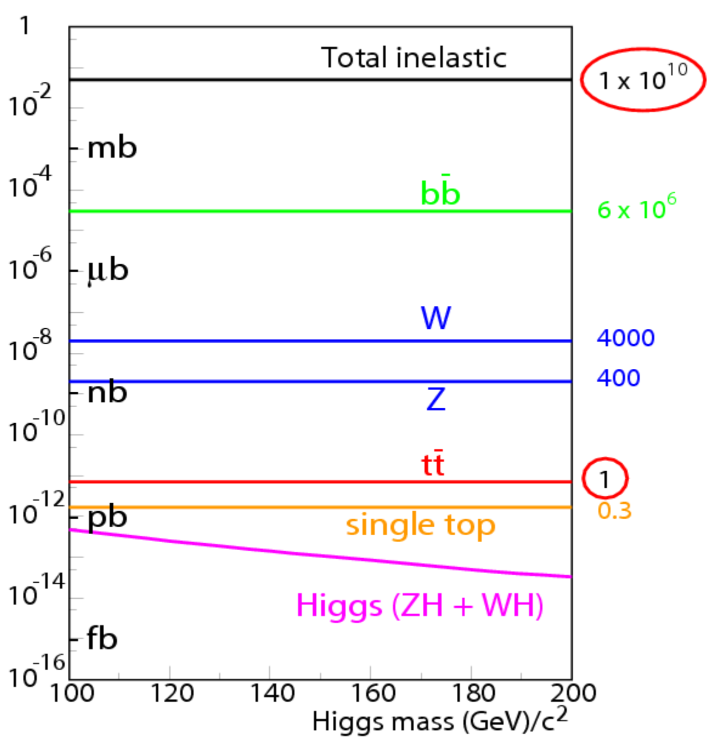
Comparison of rates at Tevatron



- Luminosity goals for Tevatron: 6-8 fb^{-1}
- Higgs very, very hard at Tevatron

Higgs at the Tevatron

- Largest rate, gg? h, h ? b$\bar{b}$, is overwhelmed by background



? (gg? h)? 1 pb << ? (bb)

Higgs at the Tevatron

- Wh, Zh production important for M_h<140 GeV, $h \to b\bar{b}$
  - Background from $Wb\bar{b}$, $Zb\bar{b}$
  - One of the few examples where both signal and background known to NLO

Wh, Zh and background in MCFM Monte Carlo to NLO

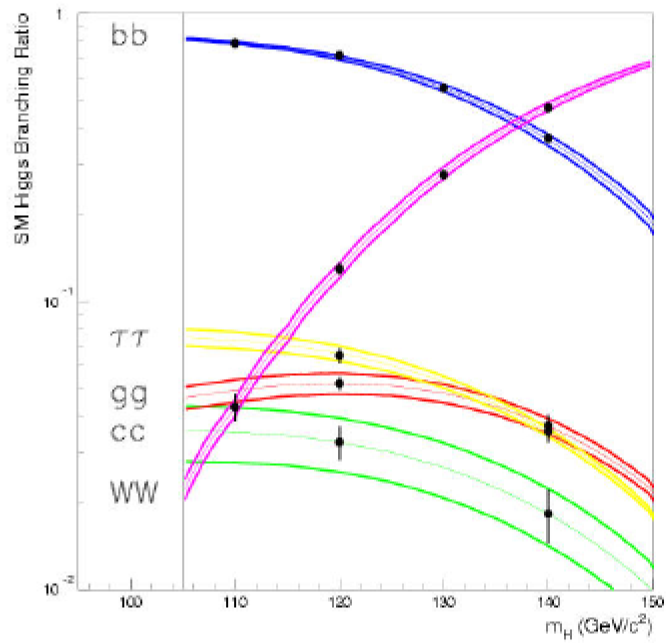
http:mcfm.fnal.gov

Search channels at Tevatron

✍For heavier Higgs, look for h? W^+W^-

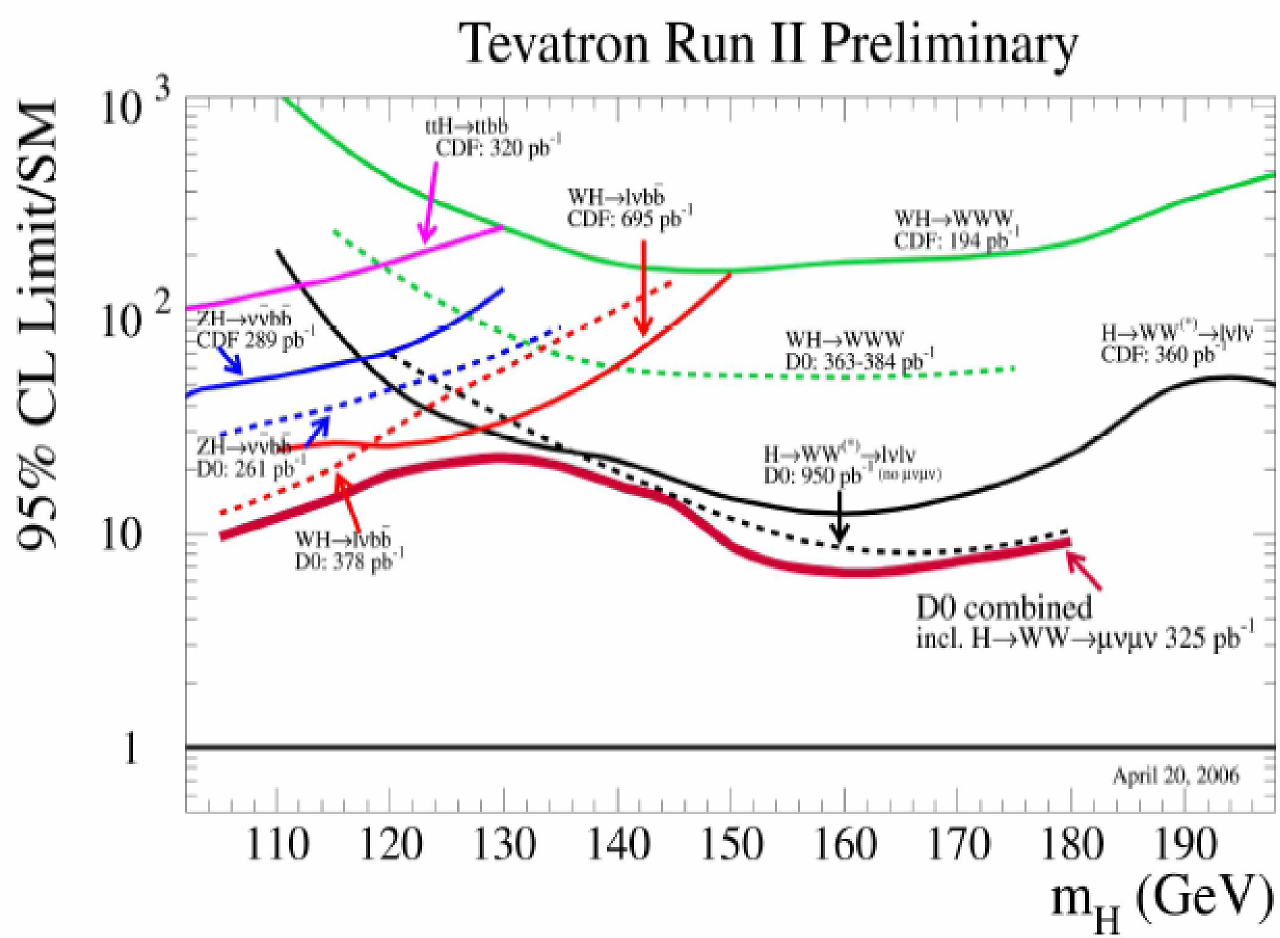
✍Searches for gg? h ? W^+W^- (dileptons)

✍And Wh ? $W^?W^+W^-$ (2 and 3 leptons)

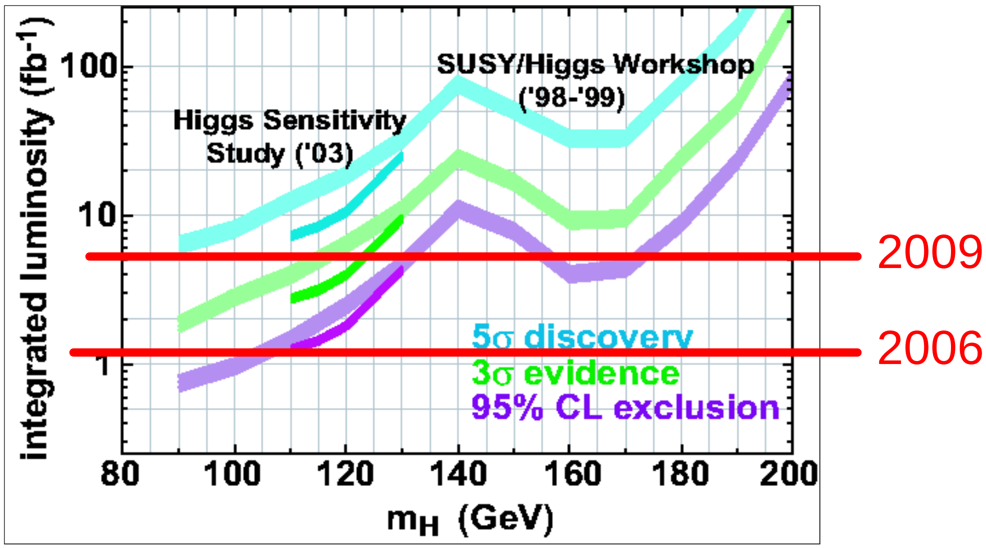


Requiring leptons reduces backgrounds

Tevatron Higgs Searches



Can the Tevatron discover the Higgs?



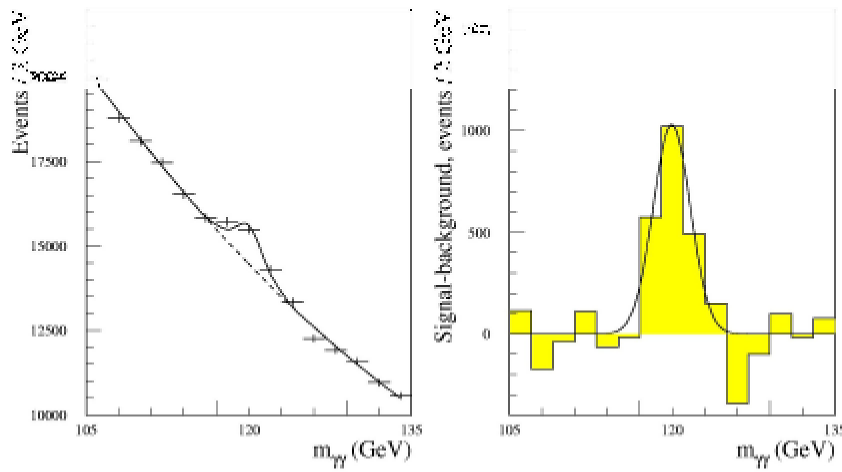
This relies on statistical combination of multiple weak channels

Search Channels at the LHC

gg? h? b$\bar{b}$ has huge QCD bkd:
Must use rare decay modes of h

- ***gg? h? ??***
  - Small BR (10^{-3} – 10^{-4})
  - Only measurable for M_h < 140 GeV
- Largest Background: QCD continuum production of ??
- Also from ?-jet production, with jet faking ?, or fragmenting to $?^0$
- Fit background from sidebands of data

M_h=120 GeV; L=100 fb^{-1}



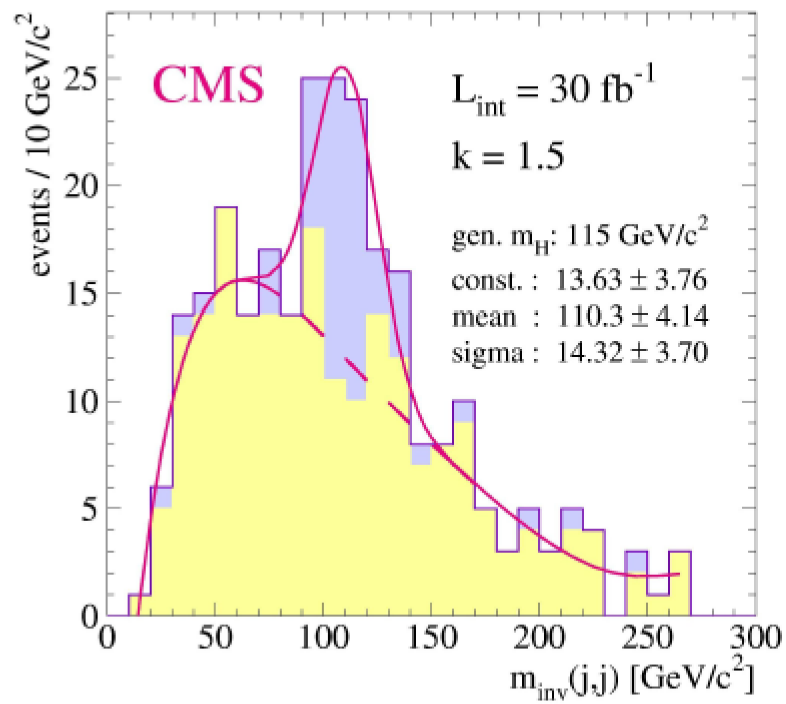
S/?B = 2.8 to 4.3 ?

•Gives 1% mass measurement

$t\bar{t}h$ at the LHC

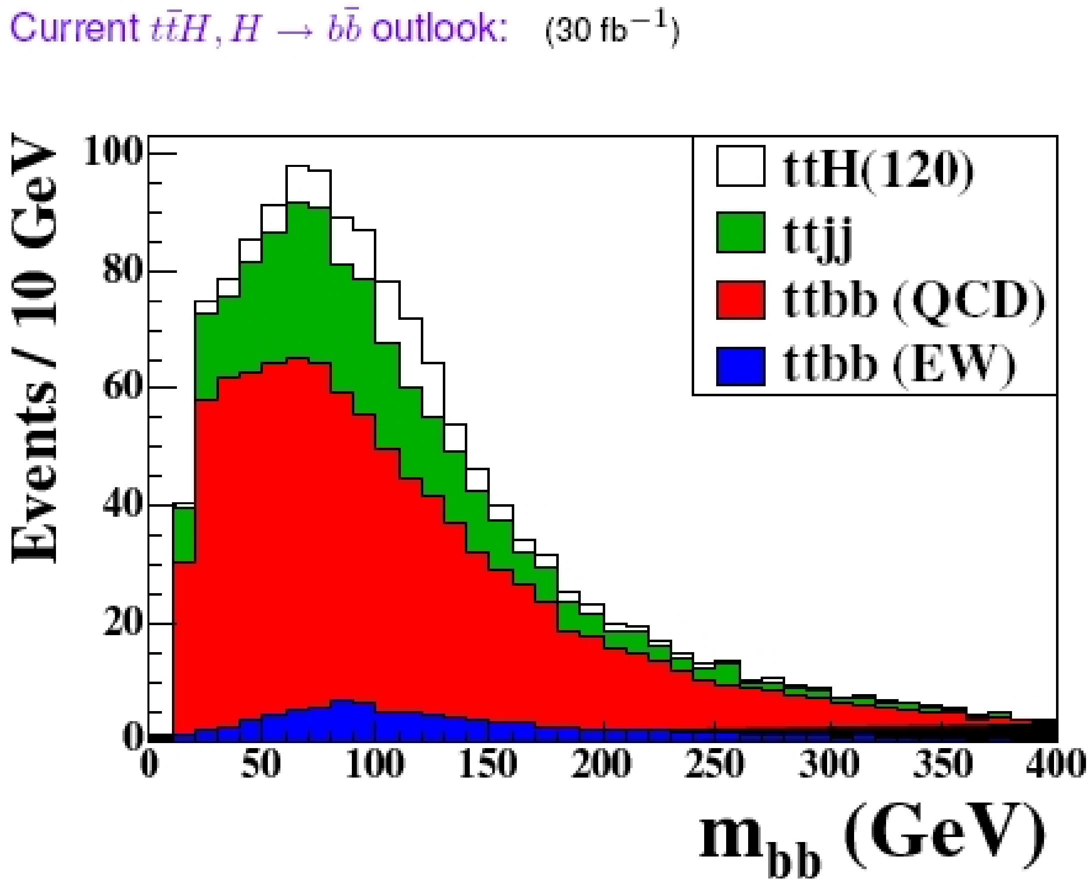
- gg? tt̄h ? tt̄bb̄
- Spectacular signal
  - t ? Wb
  - Look for 4 b jets, 2 jets, 1 lepton

Unique way to measure top quark Yukawa coupling



Early studies looked promising

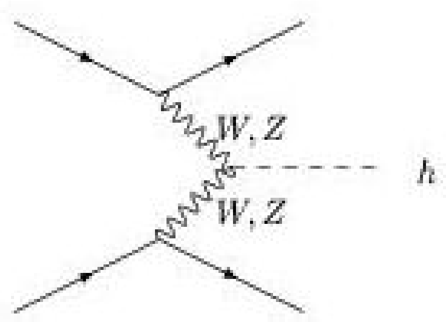
BUT…Large QCD background to tth

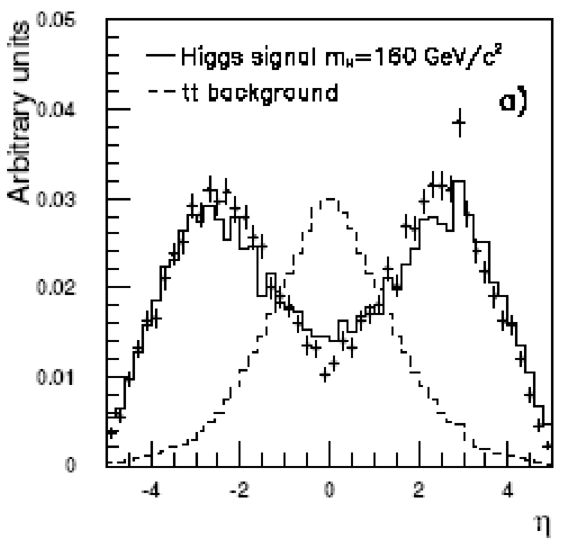


S/B=1/6 for M_h=120 GeV

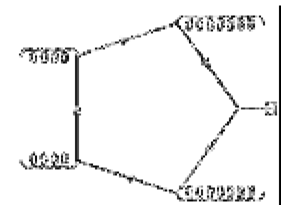
Vector Boson Fusion

- Outgoing jets are mostly forward and can be tagged
- Vector boson fusion and QCD background look different





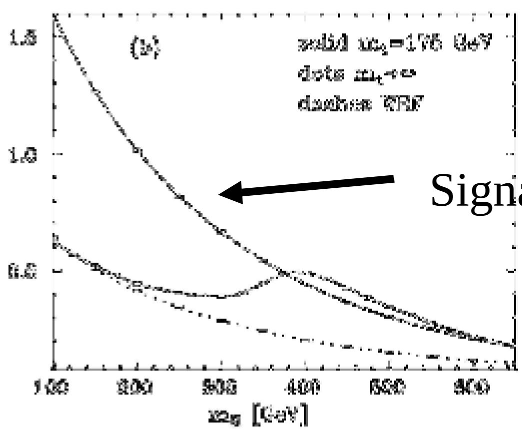
Vector Boson Fusion



- Identify signal with forward jet tagging and central jet veto
- Large Higgs + 2 jet background from gg? ggh
- Kinematic cuts effective at identifying signal

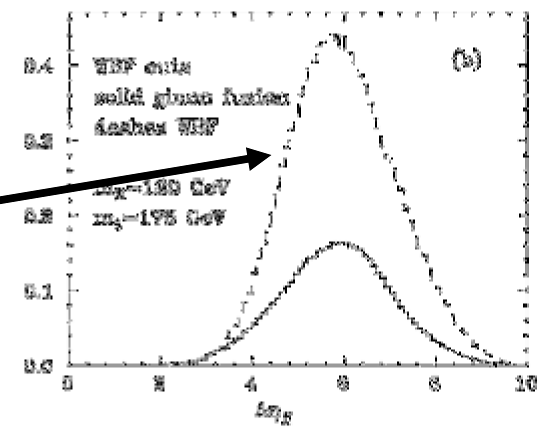
Higgs + 2 jet Production

?



Signal from WBF after cuts

Rapidity between outgoing jets



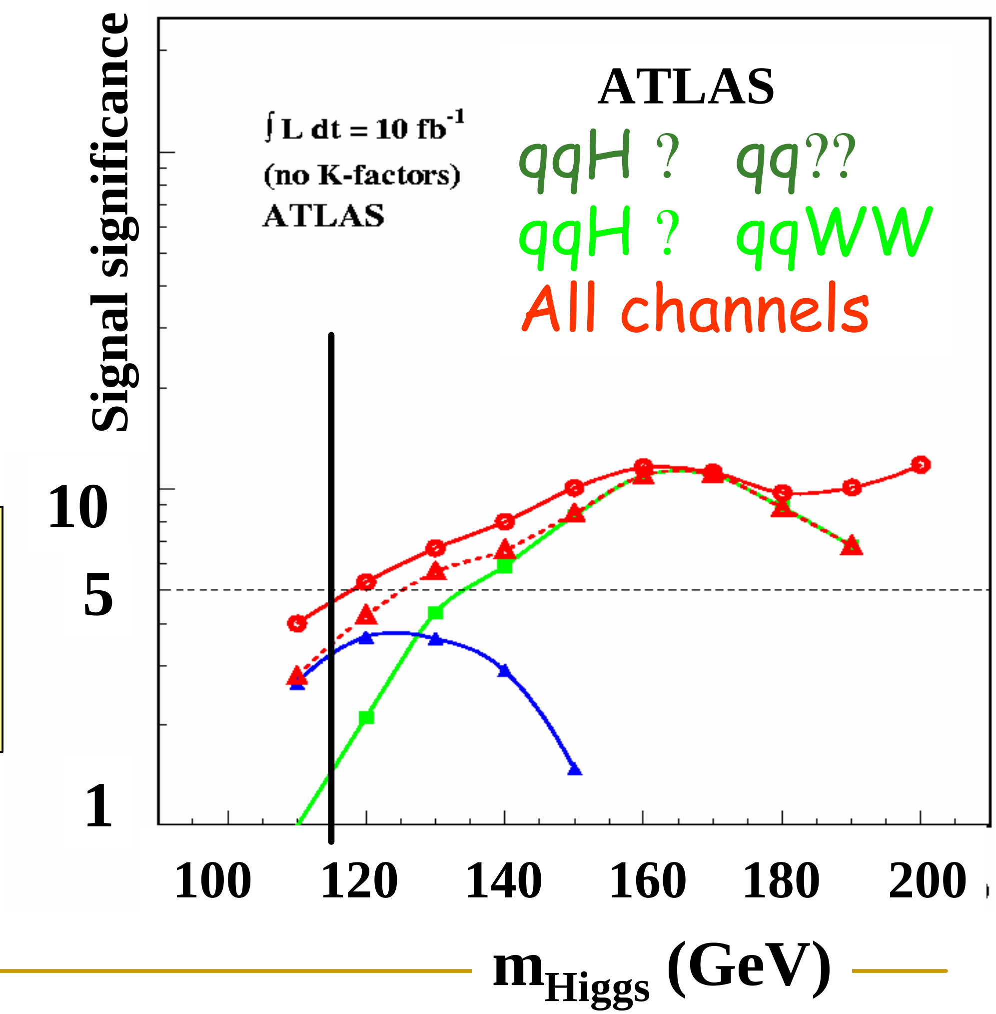
Vector Boson Fusion for light Higgs

✍For M_h = 115 GeV combined significance ~ 5?

Vector boson fusion effective for measuring Higgs couplings

✍Proportional to g_{WWh} and g_{ZZh}

✍Often assume they are in SU(2) ratio: $g_{WWh//}g_{ZZh=}\cos^2?_W$



Vector Boson Fusion for Heavy Higgs

200 GeV < M_h < 600 GeV:

- discovery in h ? ZZ ? $l^+l^- l^+l^-$

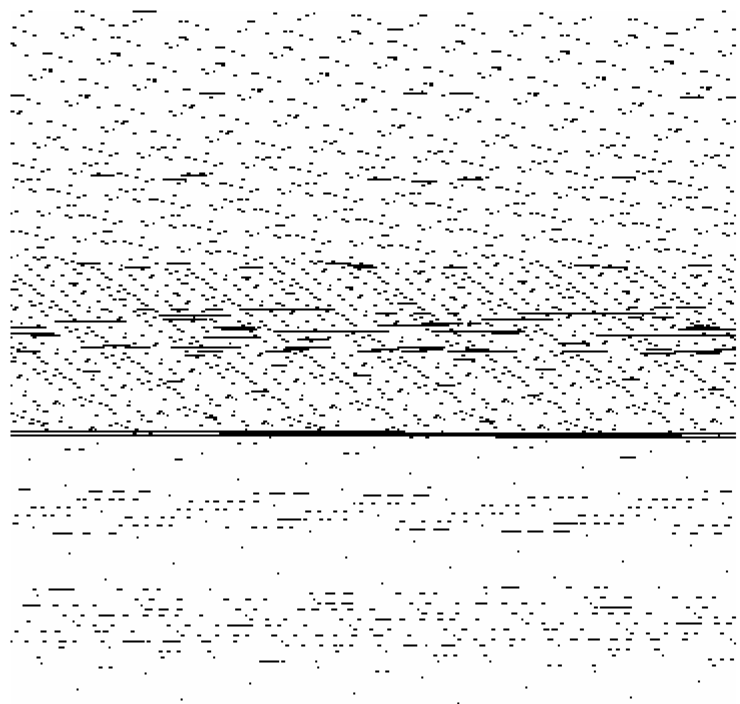
Gold-plated

•Background smaller than signal

•Higgs width larger than experimental resolution (M_h > 300 GeV)

- confirmation in h ? ZZ ? l^+l^- jj channel

h ? ZZ ? $l^+l^- l^+l^-$



M_h > 600 GeV:

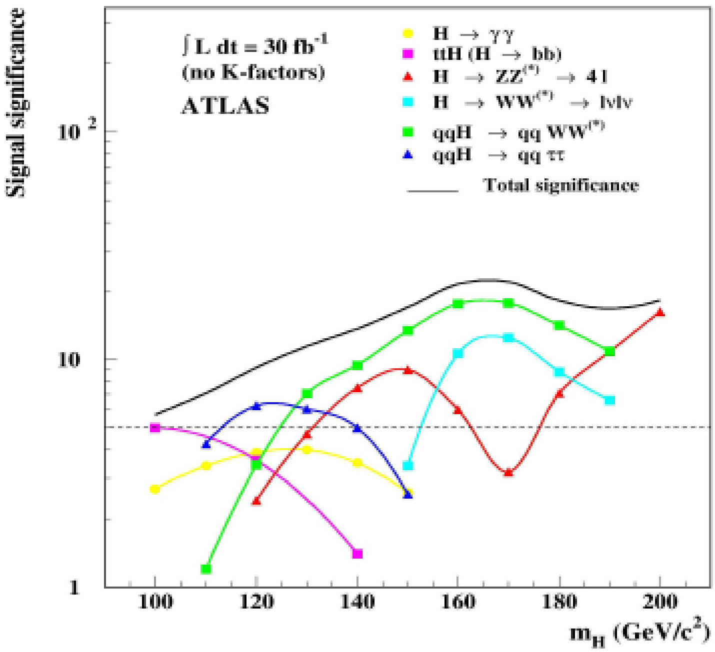
4 lepton channel statistically limited

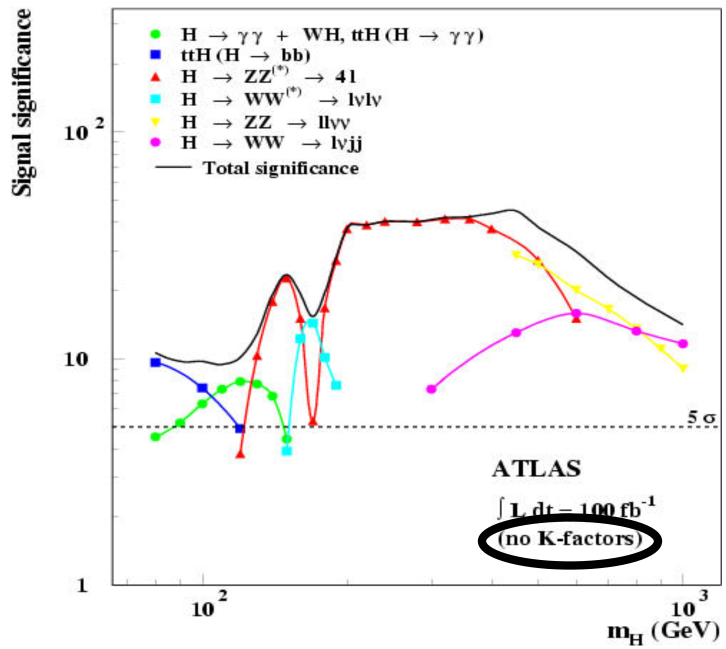
h ? ZZ ? l^+l^- ??

h ? ZZ ? l^+l^- jj , h ? WW ? l ?jj

-150 times larger BR than 4l channel

If there is a light SM Higgs, we'll find it at the LHC





No holes in M_h coverage

If we find a "Higgs-like" object, what then?

- We need to:
  - Measure Higgs couplings to fermions & gauge bosons
  - Measure Higgs spin/parity
  - Reconstruct Higgs potential
  - Is it the SM Higgs?
- Reminder: Many models have other signatures:
  - New gauge bosons (little Higgs)
  - Other new resonances (Extra D)
  - Scalar triplets (little Higgs, NMSSM)
  - Colored scalars (MSSM)
  - etc

Is it a Higgs?

- How do we know what we've found?
- Measure couplings to fermions & gauge bosons

$$\frac{?(h?\ \ b\overline{b})}{?(h?\ \ ?^{?}?^{?})} ? 3\frac{m_b^{\ 2}}{m_?^{\ 2}}$$

- Measure spin/parity

$$J^{PC} ? 0^{??}$$

- Measure self interactions

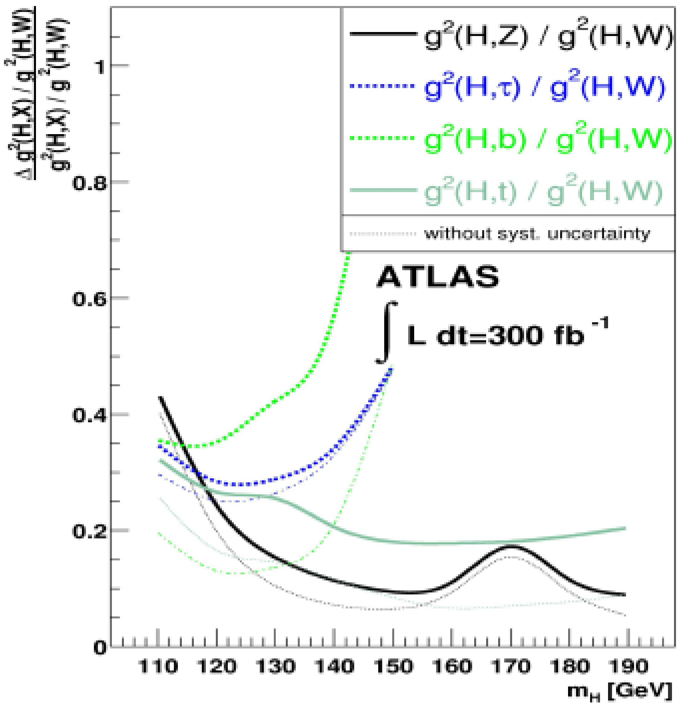
$$V ? \frac{M_h^{\ 2}}{2} h^2 ? \frac{M_h^{\ 2}}{2v} h^3 ? \frac{M_h^{\ 2}}{8v^2} h^4$$

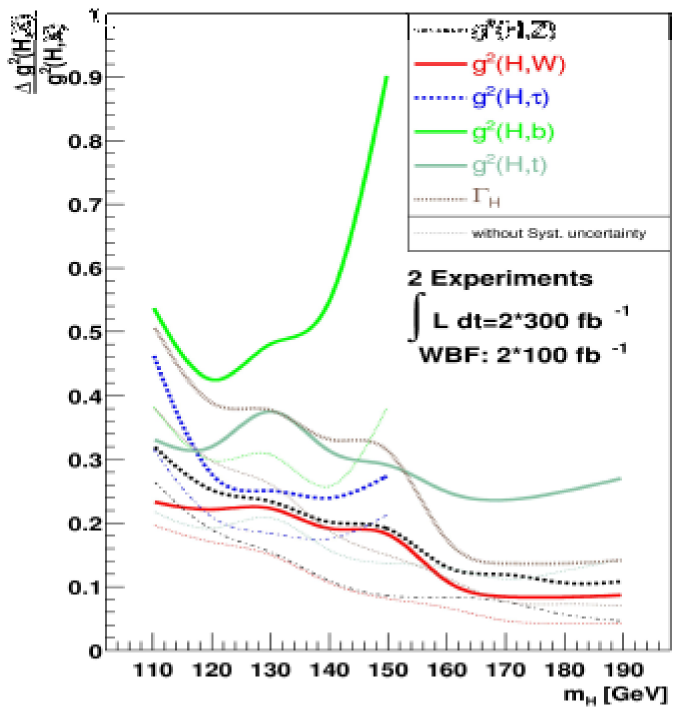
Very hard at hadron collider

Absolute measurements of Higgs couplings

✍Ratios of couplings more precisely measured than absolute couplings

✍10-40% measurements of most couplings

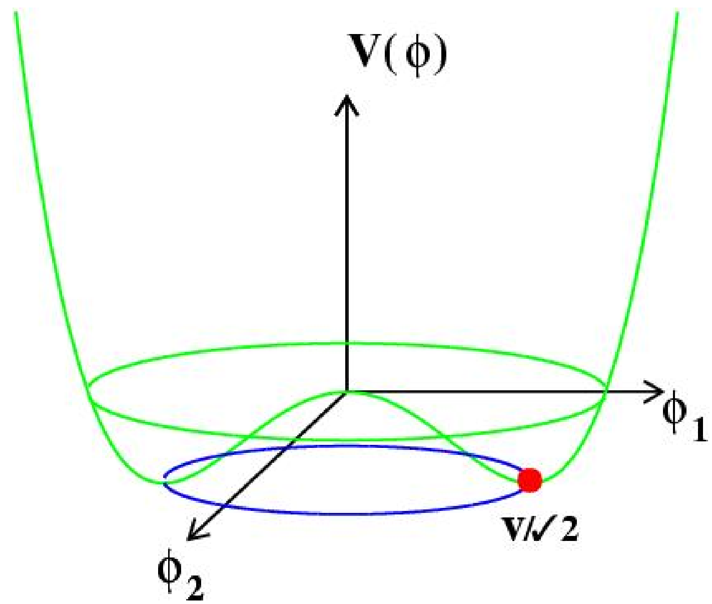




Can we reconstruct the Higgs potential?

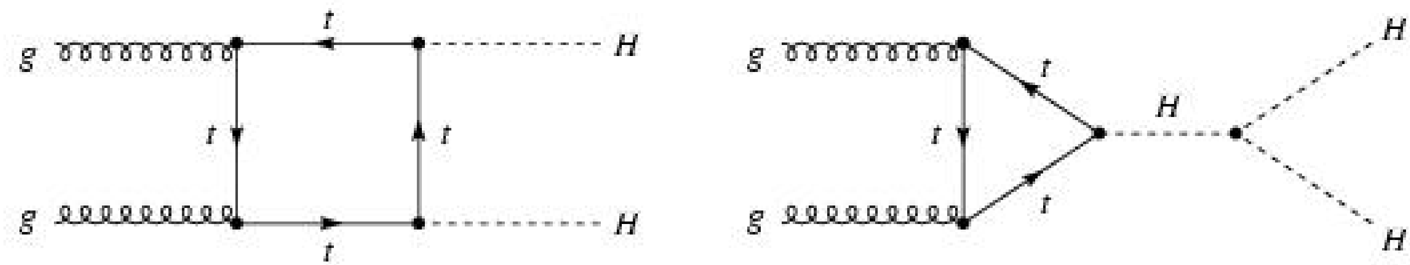
$$V ? \frac{M_h^{\ 2}}{2} h^2 ? ?_3 v h^3 ? \frac{?_4}{4} h^4$$

$$\boxed{SM : ?_3 ? ?_4 ? \frac{M_h^{\ 2}}{2v^2}}$$



- Fundamental test of model!
- We have no idea how to measure $?_4$

Reconstructing the Higgs potential



- ?$_3$ requires 2 Higgs production
- M_h<140 GeV, h? $b\bar{b}b\bar{b}$
- Overwhelming QCD background
- Easier at higher M_h

Can determine whether ?$_3$=0 at 95% cl with 300 fb^{-1} for 150<M_h<200 GeV

Higgs measurements test model!

- Supersymmetric models are our favorite comparison
- SUSY Higgs sector
  - At least 2 Higgs doublets
    - SM masses from

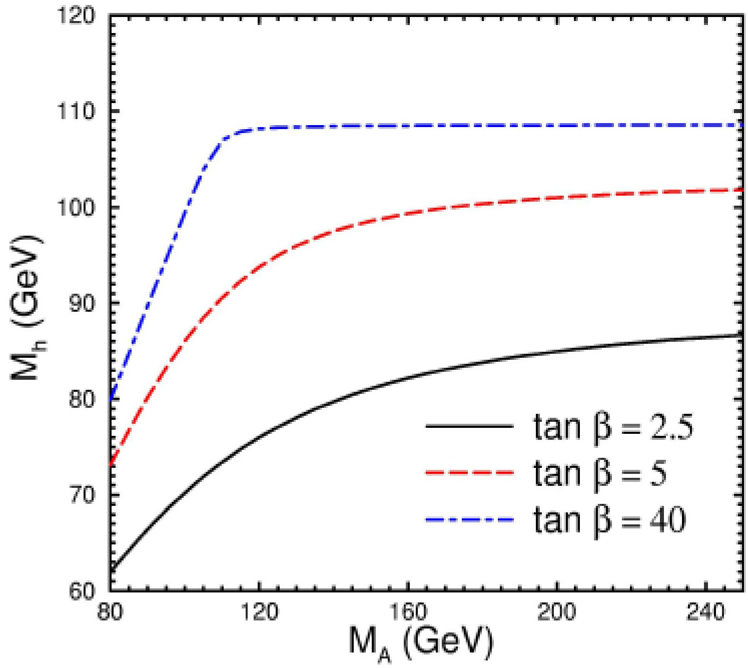
$$L ? ? g_d \overline{Q}_L ? d_R ? g_u \overline{Q}_L ?^c u_R ? h.c.$$

    - $?^c$ term not allowed in SUSY models: Need second Higgs doublet with opposite hypercharge
  - 5 physical Higgs: $h^0, H^0, A^0, H^{\pm}$

SUSY Higgs

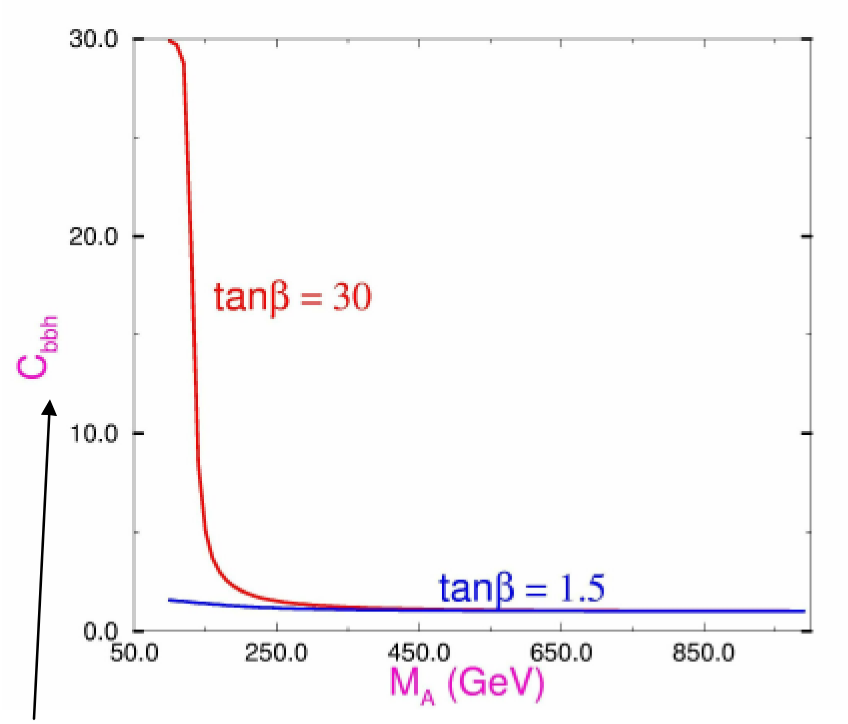
- General 2 Higgs doublet potential has 6 couplings and a phase
- SUSY Higgs potential has only 2 couplings
- Take these to be ***M_A* and tan?**
  - At tree level Higgs couplings, neutral and charged Higgs masses are predicted
  - Lightest Higgs mass has upper limit

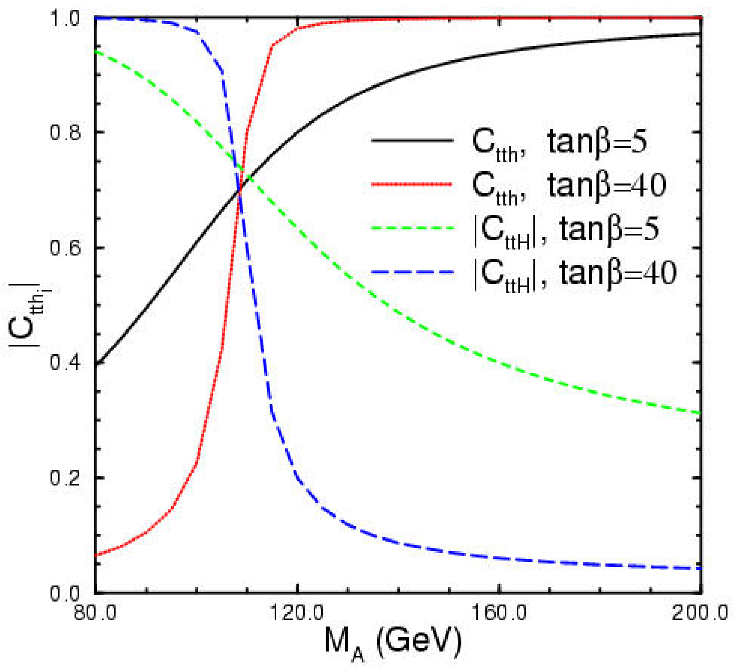
Upper Limit on Higgs Mass in SUSY Models



Can tune parameters, but always have upper limit below M_h?130 GeV

Higgs Couplings very different from SM in SUSY Models

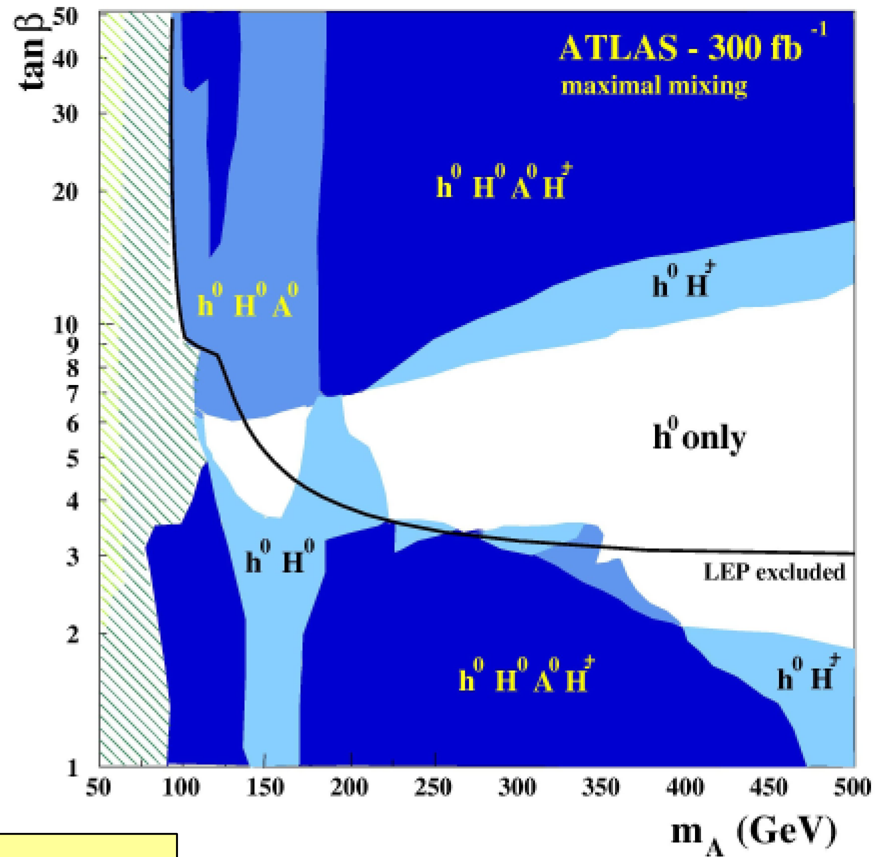




Ratio of h coupling to b's in SUSY model to that of SM

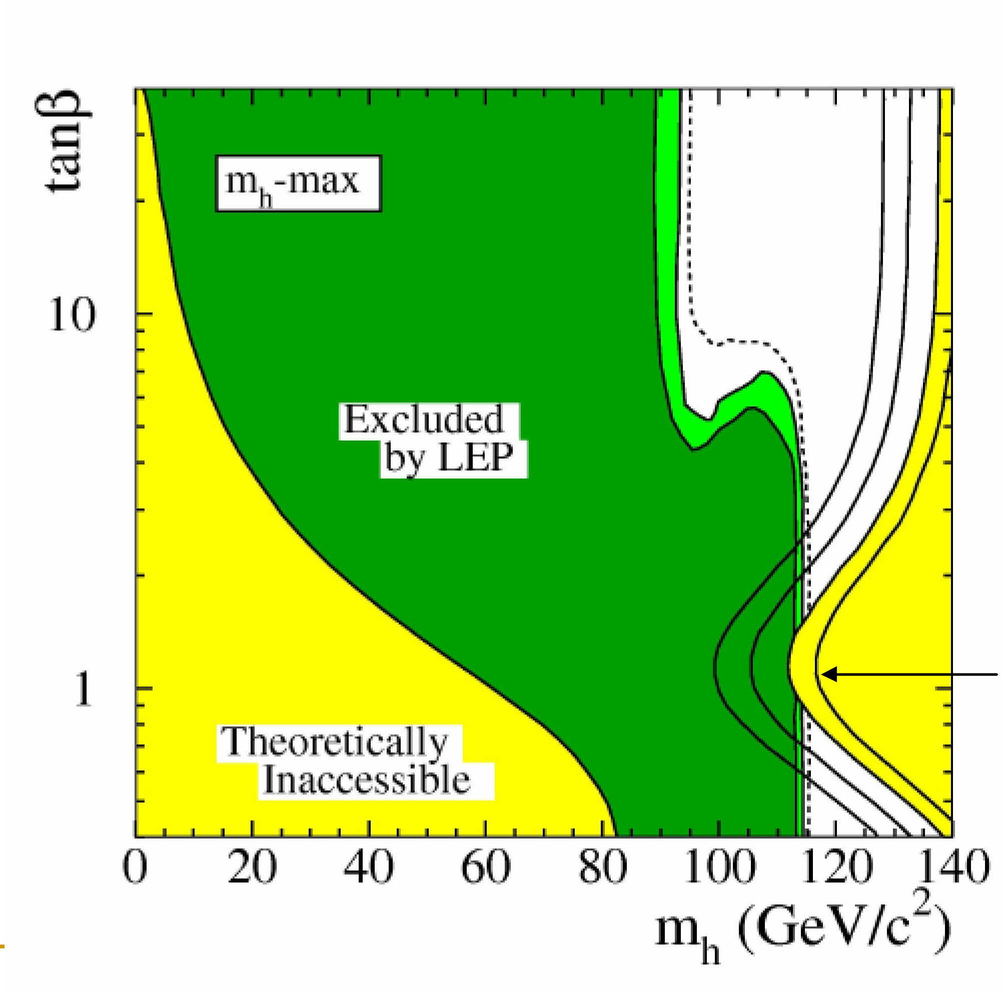
MSSM discovery

- For large fraction of M_A-tan? space, more than one Higgs boson is observable
- For M_A? ?, MSSM becomes SM-like
- Plot shows regions where Higgs particles can be observed with > 5?



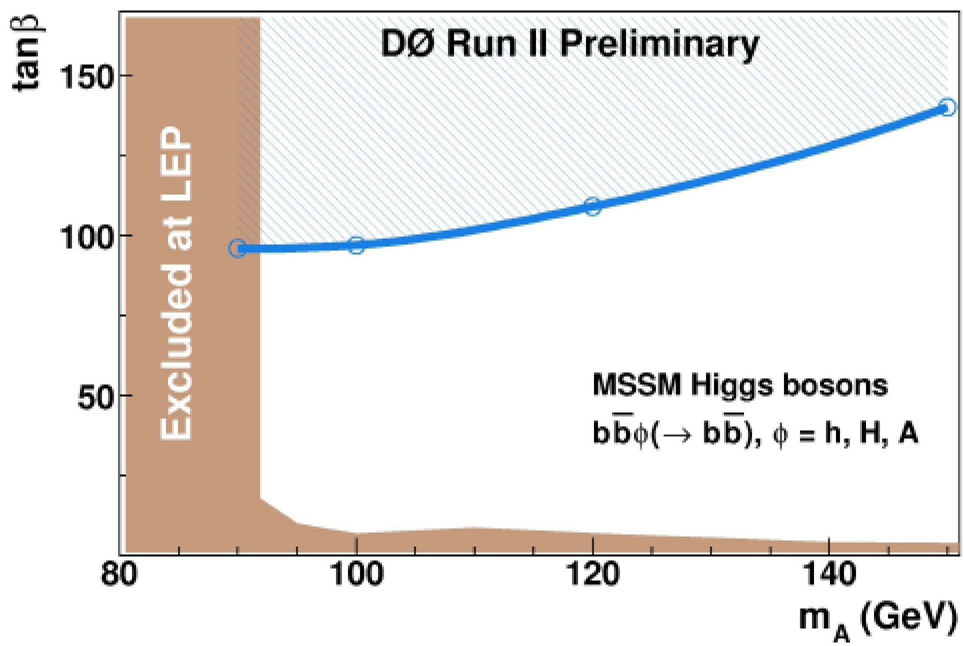
Need to observe multiple Higgs bosons and measure their couplings

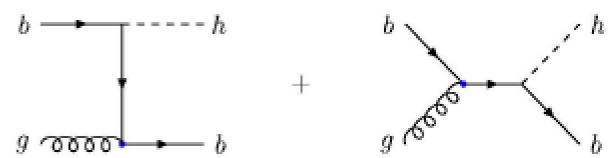
Limits on SUSY Higgs from LEP



M_t=169.3,174.3, 179.3, 183 GeV

New Discovery Channels in SUSY





Conclusion

The Higgs boson is the final missing link in the SM