Finding the Higgs boson

Sally Dawson, BNL

XIII Mexican School of Particles and Fields

Lecture 1, Oct, 2008

- Properties of the Higgs boson
- Higgs production at the Tevatron and LHC

Discovery vs spectroscopy

Collider Physics Timeline

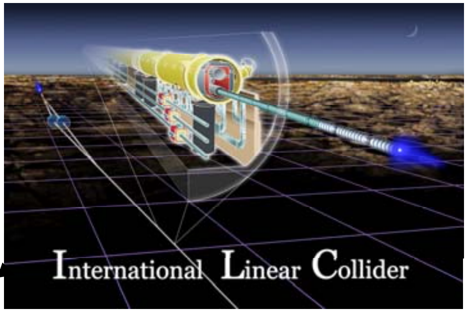
First collisions in Spring, 2009

Tevatron LHC LHC *L* Upgrade ILC

2007 2008 2015

e$^+$e$^-$ @ 500 GeV, earliest possible date, 202x

15+ billion $'s



Planned shut-down in 2010

Large Hadron Collider (LHC)

- proton-proton collider at CERN (2008)
- 14 TeV energy
  - 7 mph slower than the speed of light
  - *cf*. 2 TeV @ Fermilab

    (307 mph slower than the speed of light)
- Typical energy of quarks and gluons 1-2 TeV

Detectors of Unprecedented Scale

- Two large multi-purpose detectors
- CMS is 12,000 tons (2 x's ATLAS)
- ATLAS has 8 times the volume of CMS

Standard Model Synopsis

- Group: $\underbrace{SU(3)}_{\text{QCD}} \times \underbrace{SU(2) \times U(1)}_{\text{Electroweak}}$
- Gauge bosons:
  - SU(3): G_μ^i, i=1…8
  - SU(2): W_μ^i, i=1,2,3
  - U(1): B_μ
- Gauge couplings: g_s, g, g'
- SU(2) Higgs doublet: Φ

$\boxed{\textit{Gauge symmetry forbids gauge boson masses}}$

The Problem of Mass

- Why are the W and Z boson masses non-zero?
- U(1) gauge theory with spin-1gauge field, A_μ

$$L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$F_{\mu\nu} = \partial_\nu A_\mu - \partial_\mu A_\nu$$

- U(1) local gauge invariance:

$$A_\mu(x) \to A_\mu(x) - \partial_\mu \eta(x)$$

The Problem of Masses

- Mass term for A would look like:

$$L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m^2 A_\mu A^\mu$$

- Mass term violates local gauge invariance
- We understand why $M_A = 0$

Gauge invariance is guiding principle

SM Higgs Mechanism

- Standard Model includes complex Higgs SU(2) doublet

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$$

- With SU(2) x U(1) invariant scalar potential

$$V = \mu^2 \Phi^+ \Phi + \lambda(\Phi^+ \Phi)^2$$

- $\mu^2 > 0$, boring….. (Minimum at Φ=0, gauge bosons stay massless)

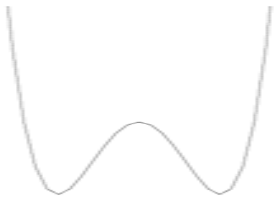
SM Higgs Mechanism

- If $\mu^2 < 0$, then spontaneous symmetry breaking

$$V = \mu^2 \Phi^+ \Phi + \lambda (\Phi^+ \Phi)^2$$

- Minimum of potential at:
  - Choice of minimum breaks gauge symmetry
  - Why is $\mu^2 < 0$?

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$



More on SM Higgs Mechanism

- Couple Φ to SU(2) x U(1) gauge bosons

  (W_i^μ, i=1,2,3; B^μ)

$$L_S = (D^\mu \Phi)^+ (D^\mu \Phi) - V(\Phi)$$

$$D_\mu = \partial_\mu - i\frac{g}{2}\sigma^i W^i{}_\mu - i\frac{g'}{2} B_\mu$$

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}$$

- Gauge boson mass terms from:

$$(D_\mu \Phi)^+ D^\mu \Phi \to \ldots + \frac{1}{8}(0, v)(g W_\mu^a \sigma^a + g' B_\mu)(g W^{b\mu}\sigma^b + g' B^\mu)\begin{pmatrix} 0 \\ v \end{pmatrix} + \ldots$$

$$\to \ldots + \frac{v^2}{8}\left(g^2 (W_\mu^1)^2 + g^2 (W_\mu^2)^2 + (-g W_\mu^3 + g' B_\mu)^2\right) + \ldots$$

Higgs mechanism gives gauge bosons mass

More on SM Higgs Mechanism

- Massive gauge bosons:

$M_W = gv/2$
$M_Z = \sqrt{(g^2+g'^2)}v/2$

$$W_\mu^{\pm} = (W_\mu^1 \mp W_\mu^2)/\sqrt{2}$$
$$Z_\mu^0 = (g W_\mu^3 - g'B_\mu)/\sqrt{(g^2+g'^2)}$$

- Orthogonal combination to Z is massless photon

$$A_\mu^0 = (g' W_\mu^3 + gB_\mu)/\sqrt{(g^2+g'^2)}$$

More on SM Higgs Mechanism

- Weak mixing angle defined

$$\cos\theta_W = \frac{g}{\sqrt{g^2 + g'^2}} \qquad \sin\theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}$$

- $Z = -\sin\theta_W B + \cos\theta_W W^3$
- $A = \cos\theta_W B + \sin\theta_W W^3$

$$\boxed{M_W = M_Z \cos\theta_W}$$

Natural relationship in SM—Provides stringent restriction on Beyond the SM models

Recap

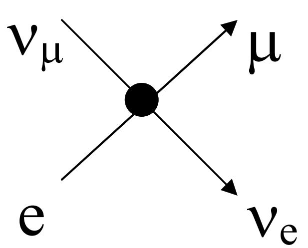
- Generate mass for W,Z using Higgs mechanism
  - Higgs VEV breaks SU(2) x U(1)$\rightarrow$U(1)$_{em}$
  - Single Higgs doublet is minimal case
- Before spontaneous symmetry breaking:
  - Massless W_i, B, Complex Φ
- After spontaneous symmetry breaking:
  - Massive $W^{\pm}$,Z; massless γ; physical Higgs boson H

Exercise: Count degrees of freedom

Muon decay

- Consider $\nu_\mu\, e \rightarrow \mu\, \nu_e$
- Fermi Theory:

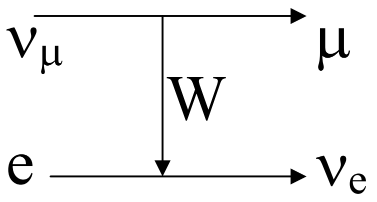
$$-i2\sqrt{2}G_F g_{\mu\nu}\bar{u}_\mu\gamma^\mu\left(\frac{1-\gamma_5}{2}\right)u_{\nu_\mu}\bar{u}_{\nu_e}\gamma^\nu\left(\frac{1-\gamma_5}{2}\right)u_e$$



$$G_F = 1.16637 \times 10^{-5}\ \mathrm{GeV}^{-2}$$

- EW Theory:

$$\frac{ig^2}{2}\frac{1}{k^2-M_W^2}g_{\mu\nu}\bar{u}_\mu\gamma^\mu\left(\frac{1-\gamma_5}{2}\right)u_{\nu_\mu}\bar{u}_{\nu_e}\gamma^\nu\left(\frac{1-\gamma_5}{2}\right)u_e$$



$$\boxed{\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} = \frac{1}{2v^2}}$$

Higgs Parameters

- G_F measured precisely

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W{}^2} = \frac{1}{2v^2}$$

$$\boxed{v^2 = (\sqrt{2}G_F)^{-1} = (246GeV)^2}$$

- Higgs potential has 2 free parameters, μ^2, λ

$$V = \mu^2\Phi^+\Phi + \lambda(\Phi^+\Phi)^2$$

- Trade μ^2, λ for v^2, $M_H{}^2$

$$\boxed{\begin{aligned} v^2 &= -\frac{\mu^2}{2\lambda} \\ M_H{}^2 &= 2v^2\lambda \end{aligned}}$$

$$V = \frac{M_H{}^2}{2}H^2 + \frac{M_H{}^2}{2v}H^3 + \frac{M_H{}^2}{8v^2}H^4$$

  - Large M_H $\rightarrow$strong Higgs self-coupling
  - A priori, Higgs mass can be anything

What about Fermion Masses?

- Fermion mass term:

$$L = m\overline{\Psi}\Psi = m\left(\overline{\Psi}_L \Psi_R + \overline{\Psi}_R \Psi_L\right) \leftarrow$$

Forbidden by SU(2)xU(1) gauge invariance

- Left-handed fermions are SU(2) doublets

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L$$

- Scalar couplings to fermions:

$$L_d = -\lambda_d \overline{Q}_L \Phi d_R + h.c.$$

- Effective Higgs-fermion coupling

$$L_d = -\lambda_d \frac{1}{\sqrt{2}} (\overline{u}_L, \overline{d}_L) \begin{pmatrix} 0 \\ v+H \end{pmatrix} d_R + h.c.$$

$$\boxed{\lambda_d = -\frac{m_d \sqrt{2}}{v}}$$

- Mass term for down quark

Fermion Masses, 2

- M_u from $\Phi_c = i\sigma_2\Phi^*$ (not allowed in SUSY)

$$L = -\lambda_u \overline{Q}_L \Phi_c u_R + hc \qquad \Phi_c = \begin{pmatrix} \overline{\phi}^0 \\ -\phi^- \end{pmatrix} \qquad \boxed{\lambda_u = -\frac{m_u\sqrt{2}}{v}}$$

- For 3 generations, α, β=1,2,3 (flavor indices)

$$\boxed{L_Y = -\frac{(v+H)}{\sqrt{2}}\sum_{\alpha,\beta}\left(\lambda_u^{\alpha\beta}\overline{u}_L^\alpha u_R^\beta + \lambda_d^{\alpha\beta}\overline{d}_L^\alpha d_R^\beta\right) + h.c.}$$

Fermion masses, 3

- Unitary matrices diagonalize mass matrices

$$\boxed{\begin{array}{ll} u_L^{\alpha} = U_u^{\alpha\beta} u_L^{m\beta} & d_L^{\alpha} = U_d^{\alpha\beta} d_L^{m\beta} \\ u_R^{\alpha} = V_u^{\alpha\beta} u_R^{m\beta} & d_R^{\alpha} = V_d^{\alpha\beta} d_R^{m\beta} \end{array}}$$

- Yukawa couplings are ***diagonal*** in mass basis
- Neutral currents remain flavor diagonal
- Not necessarily true in models with extended Higgs sectors

Exercise: Prove this!

Review of Higgs Couplings

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

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

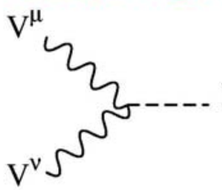
  - Top-Higgs coupling plays special role?
  - No Higgs coupling to neutrinos
- Higgs couples to gauge boson masses

$$L = gM_W W^{+\mu} W_\mu^- H + \frac{gM_Z}{\cos\theta_W} Z^\mu Z_\mu H + ...$$

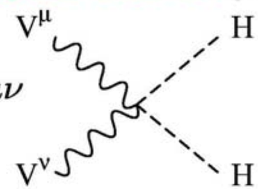
- Only free parameter is Higgs mass!
- Everything is calculable….***testable theory***

Review of Higgs Boson Feynman Rules

- Couplings to EW gauge bosons $(V = W, Z)$:

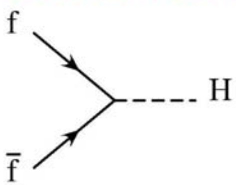


$= 2i\frac{M_V^2}{v} g^{\mu\nu}$



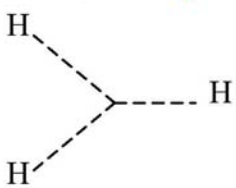
$= 2i\frac{M_V^2}{v^2} g^{\mu\nu}$

- Couplings to fermions $(f = l, q)$:

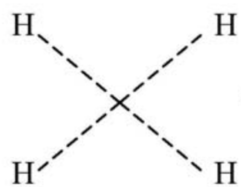


$= -i\frac{m_f}{v}$

- Self-couplings:



$= -3i\frac{M_H^2}{v}$

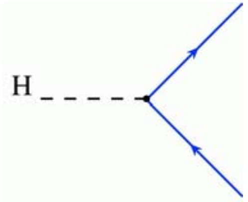


$= -3i\frac{M_H^2}{v^2}$

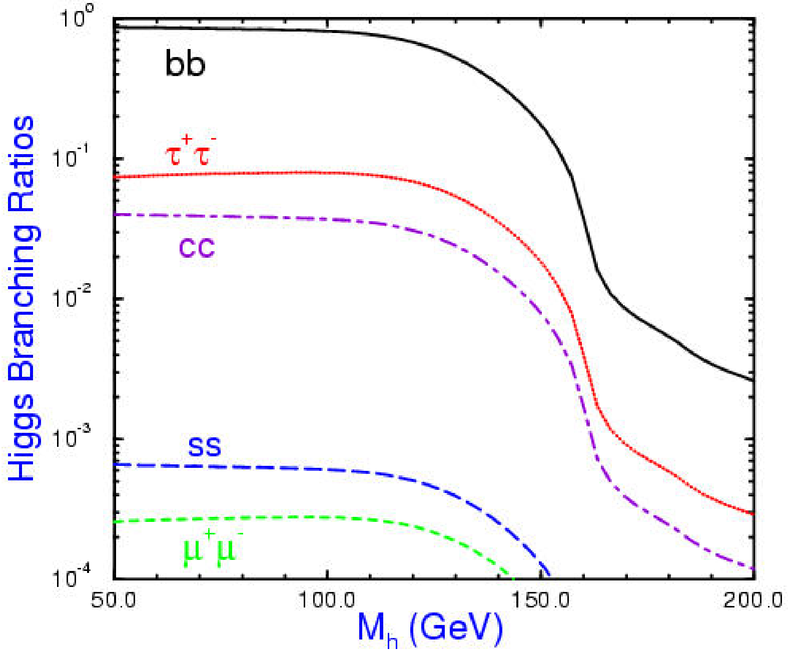
- Higgs couples to heavy particles
- No tree level coupling to photons (γ) or gluons (g)
- $M_H^2 = 2v^2\lambda \Rightarrow$ large M_H is strong coupling regime

Higgs Decays

- $H \rightarrow f\bar{f}$ proportional to m_f^2



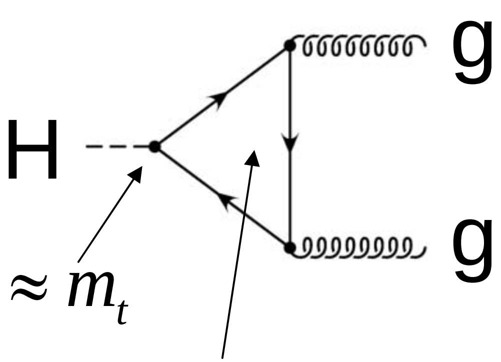
$$\frac{BR(H \rightarrow b\bar{b})}{BR(H \rightarrow \tau^+\tau^-)} \approx N_c \left(\frac{m_b{}^2}{m_\tau{}^2} \right)$$



- Identifying b quarks important for Higgs searches

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

Higgs Decays to Gluons



$$\int \frac{d^4k}{(k+m_t)^3} \approx \frac{1}{m_t}$$

- Top quark contribution most important
- Doesn't decouple for large m_t
- Decoupling theorem doesn't apply to particles which couple to mass (ie Higgs!)
- Decay sensitive to extra generations

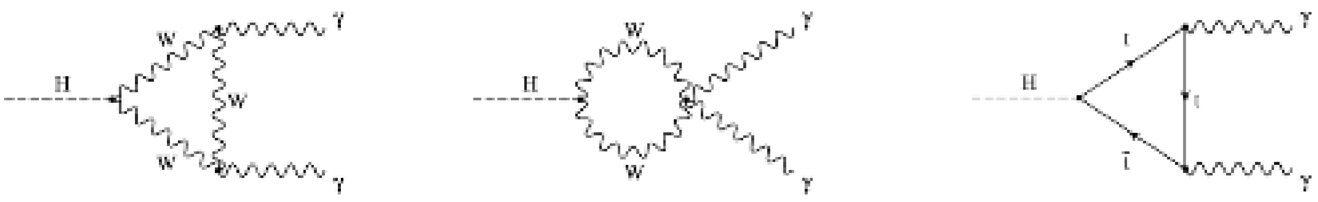
$$\boxed{\Gamma(H \to gg) \approx \frac{\alpha_s^2 \alpha}{72\pi^2 s_\theta^2} \frac{M_H^3}{M_W^2}}$$

Higgs Decays to Photons

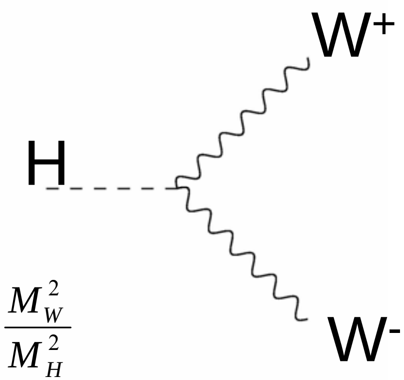
- Dominant contribution is W loops
- Contribution from top is small

$$\boxed{\Gamma(H \to \gamma\gamma) \approx \frac{\alpha^3}{256\pi^2 s_\theta^2}\frac{M_H^3}{M_W^2}\left|7 - \frac{16}{9} + \ldots\right|^2}$$

W top



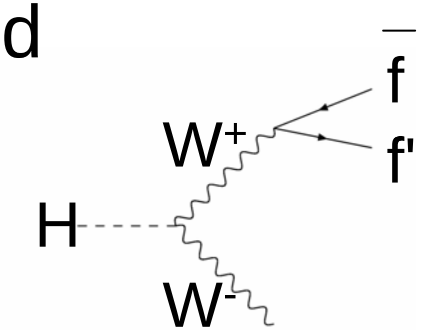
Higgs Decays to W/Z



- Tree level decay

$$\Gamma(H \to W^+W^-) = \frac{\alpha}{16 s_\theta^2} \frac{M_H^3}{M_W^2} \sqrt{1 - x_W} \left(1 - x_W + \frac{3}{4} x_W^2 \right) \qquad x_W = 4 \frac{M_W^2}{M_H^2}$$

- Below threshold, H→WW* with branching ratio W* →ff' implied
- Final state has both transverse and longitudinal polarizations



Higgs Decays to $W^+ W^-$, ZZ

- The action is with longitudinal gauge bosons (since they come from the EWSB)

$$p_V = (E_V, 0, 0, \vec{p}_V)$$
$$\varepsilon_T = \frac{1}{\sqrt{2}}\left(0,1,\pm i,0\right) \qquad \varepsilon_L = \frac{1}{M_V}\left(\left|\vec{p}_V\right|, 0, 0, E_V\right) \to \frac{p_V^\mu}{M_V}$$

- Cross sections involving longitudinal gauge bosons grow with energy
- $H \to W_L^+ W_L^+$

$$A(H \to W_L^+ W_L^-) = g M_W \varepsilon_L \cdot \varepsilon_L \approx g \frac{M_H^2}{M_W}$$

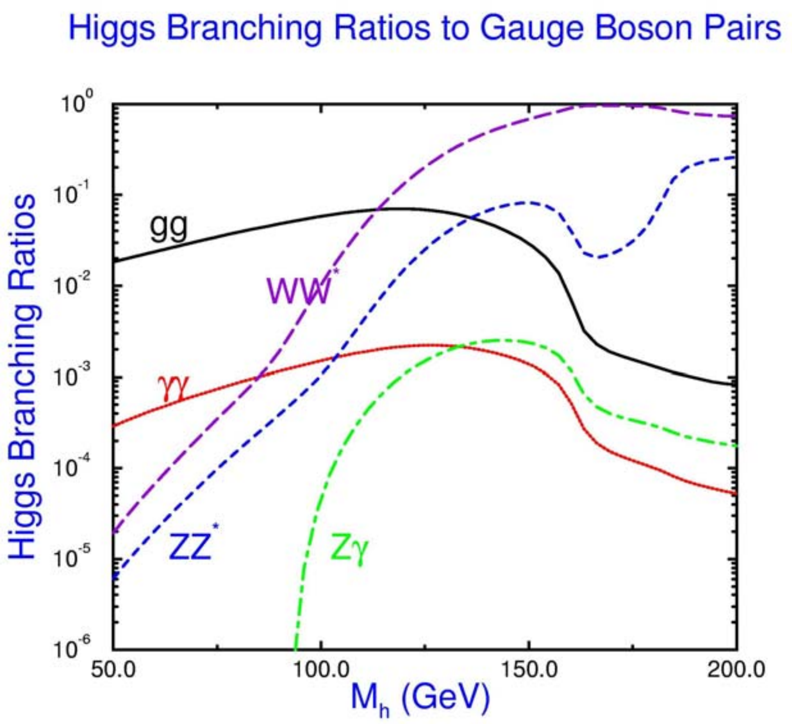
- As Higgs gets heavy, decays are longitudinal

$$\frac{\Gamma(H \to V_T V_T)}{\Gamma(H \to V_L V_L)} = \frac{x_V^2}{2 - x_V^2} \qquad x_W = 4\frac{M_W^2}{M_H^2}$$

$\boxed{\textit{Exercise: Prove this}}$

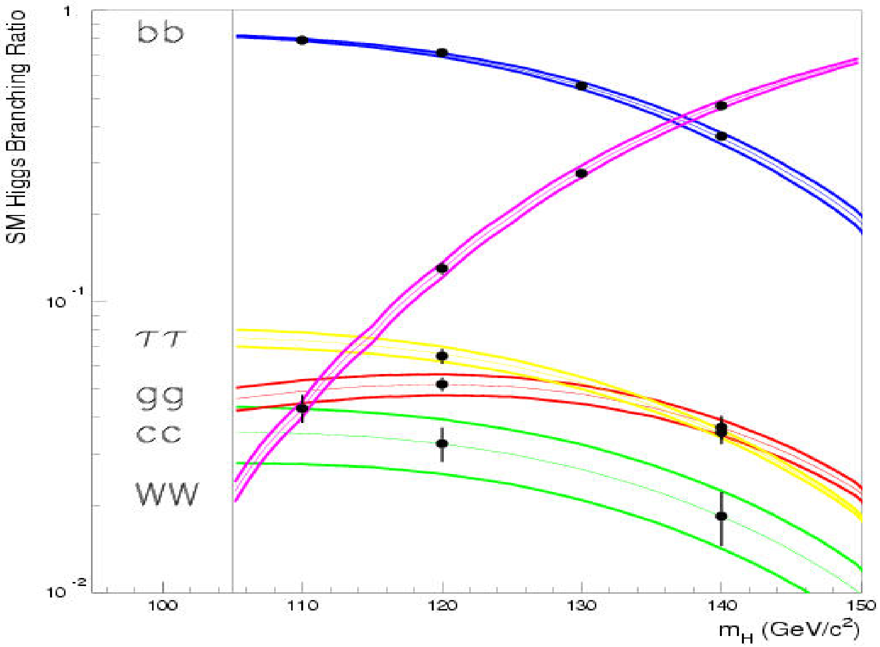
Higgs decays to gauge bosons

- $H \to W^+W^- \to f\bar{f}f\bar{f}$ has sharp threshold at 2 M_W, but large branching ratio even for M_H=130 GeV



For any given M_H, not all decay modes accessible

Status of Theory for Higgs BRs

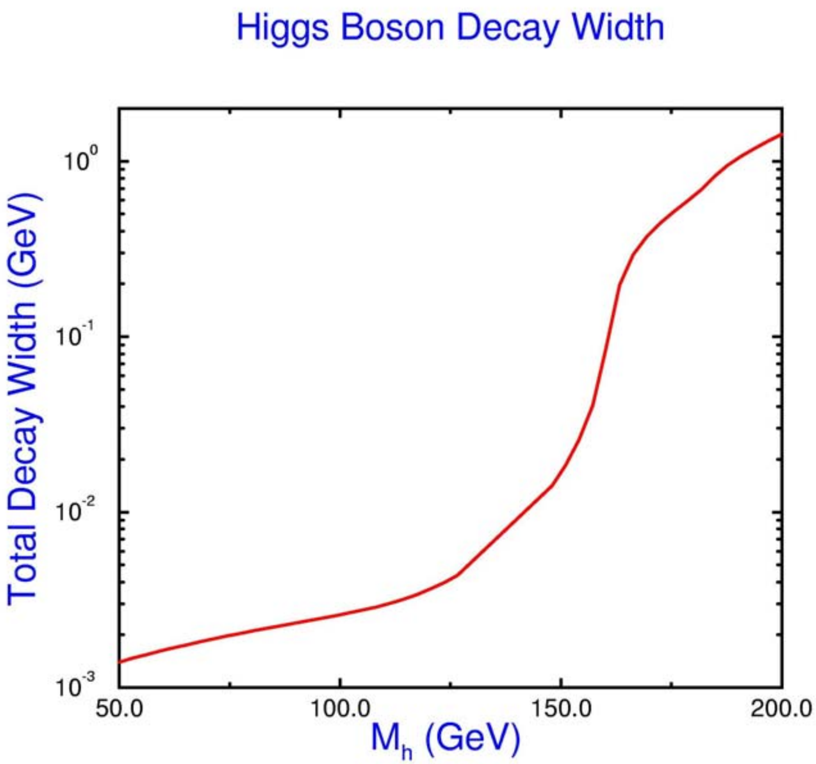


- Bands show theory errors
- Largest source of uncertainty is b quark mass

Data points are e^+e^- at $\sqrt{s}$=350 GeV with L=500 fb^{-1}

Total Higgs Width

- Small M_H, Higgs is narrower than detector resolution
- As M_H becomes large, width also increases
  - No clear resonance
  - For $M_H \sim 1.4$ TeV, $\Gamma_{tot} \sim M_H$

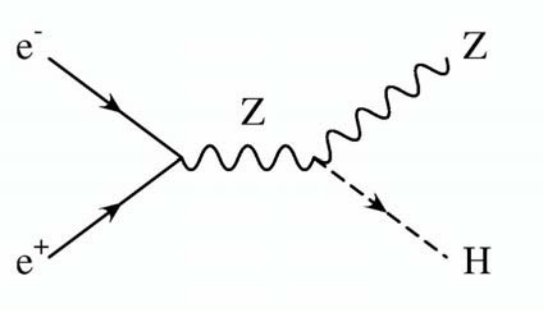


$$\Gamma(H \to W^+W^-) \approx \frac{\alpha}{16\sin^2\theta_W}\frac{M_H^{\,3}}{M_W^{\,2}}$$

$$\approx 330 GeV\left(\frac{M_H}{1TeV}\right)^3$$

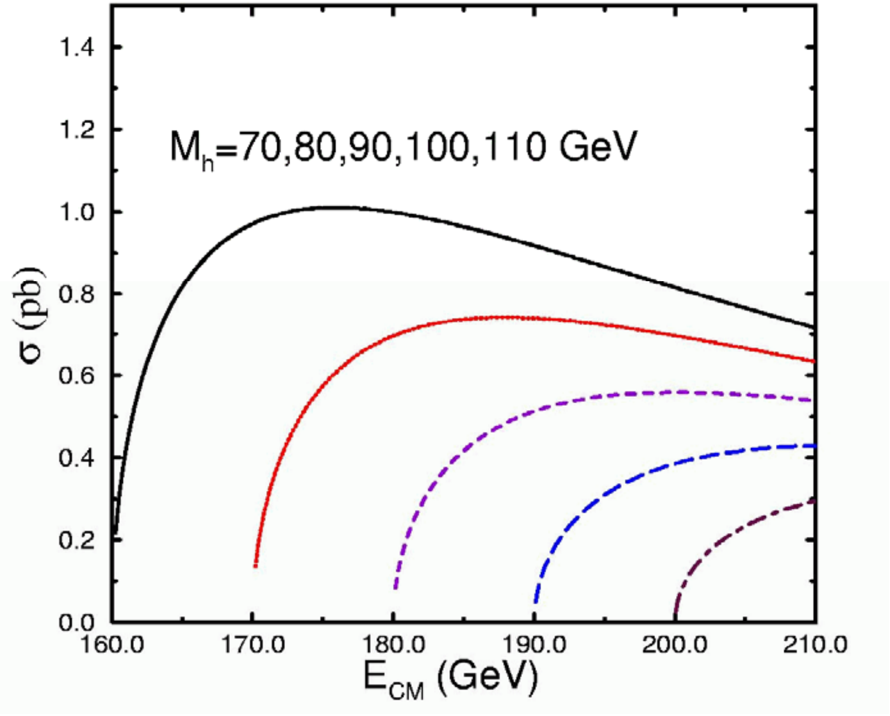
Higgs Searches at LEP2

- LEP2 searched for $e^+e^-\rightarrow ZH$
- Rate turns on rapidly after threshold, peaks just above threshold, $\sigma\sim\beta^3/s$
- Measure recoil mass of Higgs; ***result independent of Higgs decay pattern***
  - $P_{e-}=\sqrt{s}/2(1,0,0,1)$
  - $P_{e+}=\sqrt{s}/2(1,0,0,-1)$
  - $P_Z=(E_Z, p_Z)$
- Momentum conservation:
  - $(P_{e-}+P_{e+}-P_Z)^2=P_H^2=M_H^2$
  - $s-2\sqrt{s}E_Z+M_Z^2= M_H^2$



Higgs Limits From LEP2

$e^+e^- \rightarrow ZH$



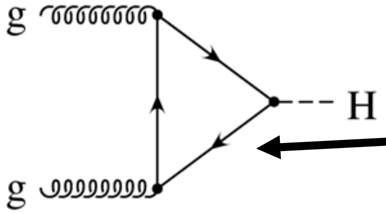
LEP2 limit, M_H > 114.1 GeV

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 Mechanisms in Hadron Colliders

- Gluon fusion
  - Largest rate for all M_H at LHC and Tevatron
  - Gluon-gluon initial state
  - Sensitive to top quark Yukawa λ_t



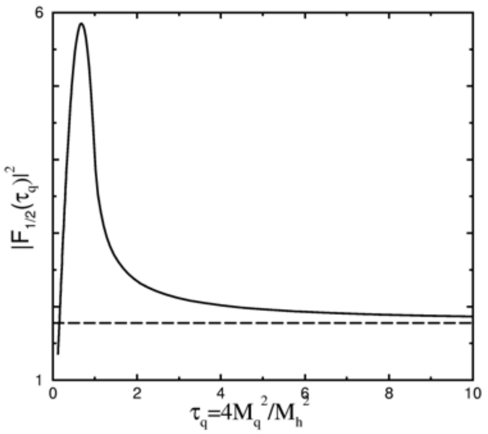
Largest contribution is top loop

In SM, b-quark loops unimportant

Gluon Fusion

- Lowest order cross section:
  - $\tau_q = 4M_q^2/M_H^2$
  - Light Quarks: $F_{1/2} \rightarrow (M_b/M_H)^2 \log(M_b/M_H)$
  - Heavy Quarks: $F_{1/2} \rightarrow -4/3$

$$\boxed{\hat{\sigma}_0(gg \rightarrow H) = \frac{\alpha_s(\mu_R)^2}{1024\pi v^2} \left| \sum_q F_{1/2}(\tau_q) \right|^2 \delta(M_H^{\ 2} - \hat{s})}$$



- Rapid approach to heavy quark limit: Counts number of heavy fermions

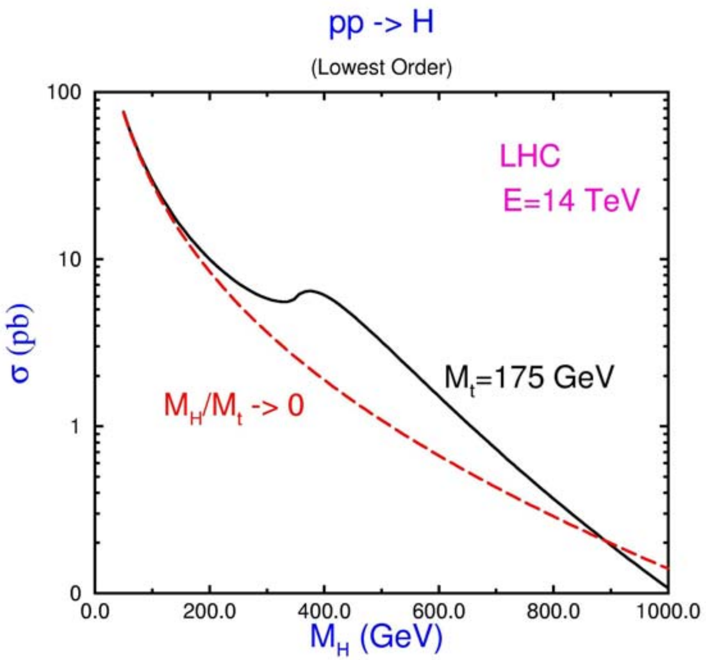
- NLO/NNLO corrections calculated in heavy top limit

Gluon fusion, continued

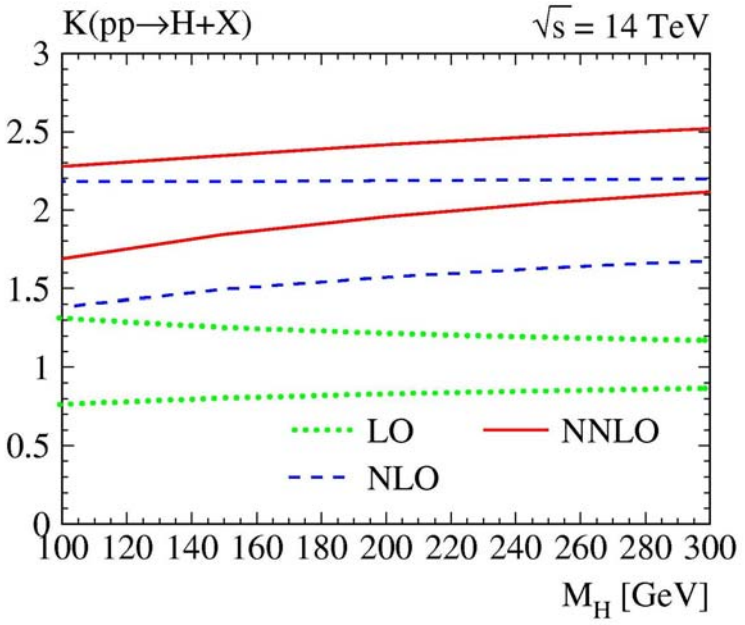
- Integrate parton level cross section with gluon parton distribution functions

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

  - $z = M_H^2/S$, S is hadronic center of mass energy
- Rate depends on μ_R, μ_F



NNLO, $gg \to H$



Rates depend on renormalization scale, $\alpha_s(\mu_R)$, and factorization scale, $g(\mu_F)$

Bands show $.5M_H < \mu < 2\ M_H$

LO and NLO μ dependence bands don't overlap

μ dependence used as estimate of theoretical uncertainty

$$K \equiv \frac{\sigma_{NLO}}{\sigma_{LO}}$$

Higher order corrections computed in large M_t limit

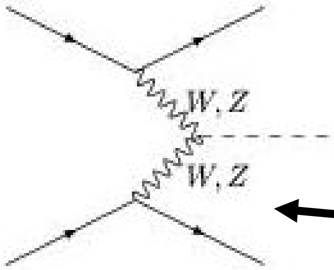
Vector Boson Fusion

- $W^+W^- \rightarrow X$ is a real process: $\sigma_{pp\rightarrow WW\rightarrow X}(s) = \int dz \left.\frac{dL}{dz}\right|_{pp/WW} \sigma_{WW\rightarrow X}(zs)$
- Rate increases at large s: $\sigma \approx (1/M_W^2)\log(s/M_W^2)$
- Integral of cross section over final state phase space has contribution from W boson propagator:

$$\int \frac{d\theta}{(k^2 - M_W{}^2)^2} \approx \int \frac{d\theta}{(2EE'(1-\cos\theta) + M_W{}^2)^2}$$

Peaks at small θ

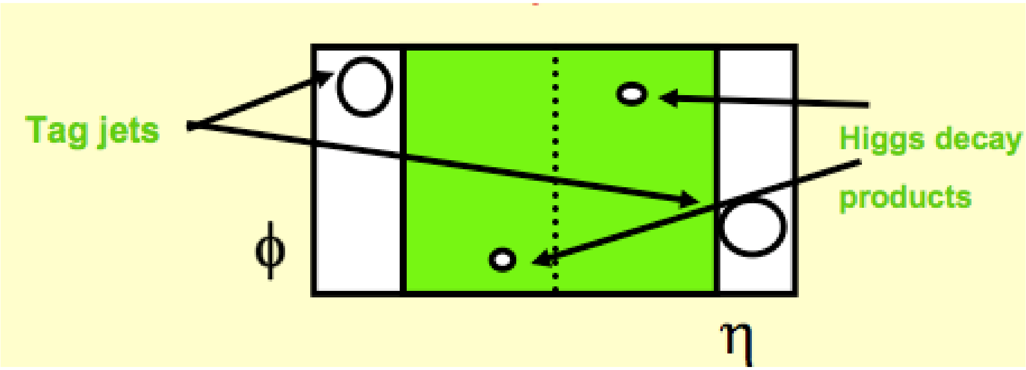
- Outgoing jets are mostly forward and can be tagged



k=W,Z momentum

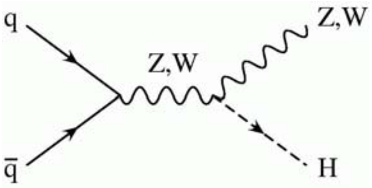
Vector Boson Fusion

- Idea: Tag 2 high-p_T jets with large rapidity gap in between
- No color flow between tagged jets – suppressed hadronic activity in central region



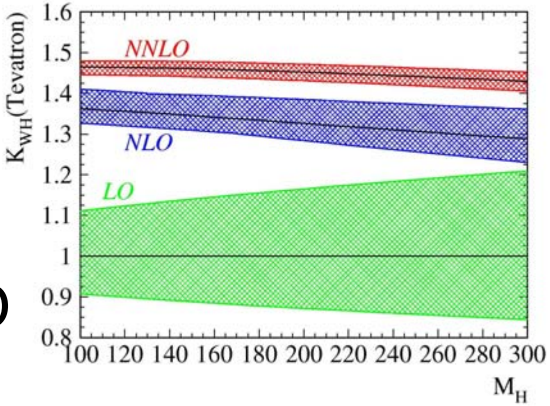
W(Z)-strahlung

- W(Z)-strahlung ($q\bar{q} \rightarrow WH, ZH$) important at Tevatron
  - Same couplings as vector boson fusion
  - Rate proportional to ***weak*** coupling

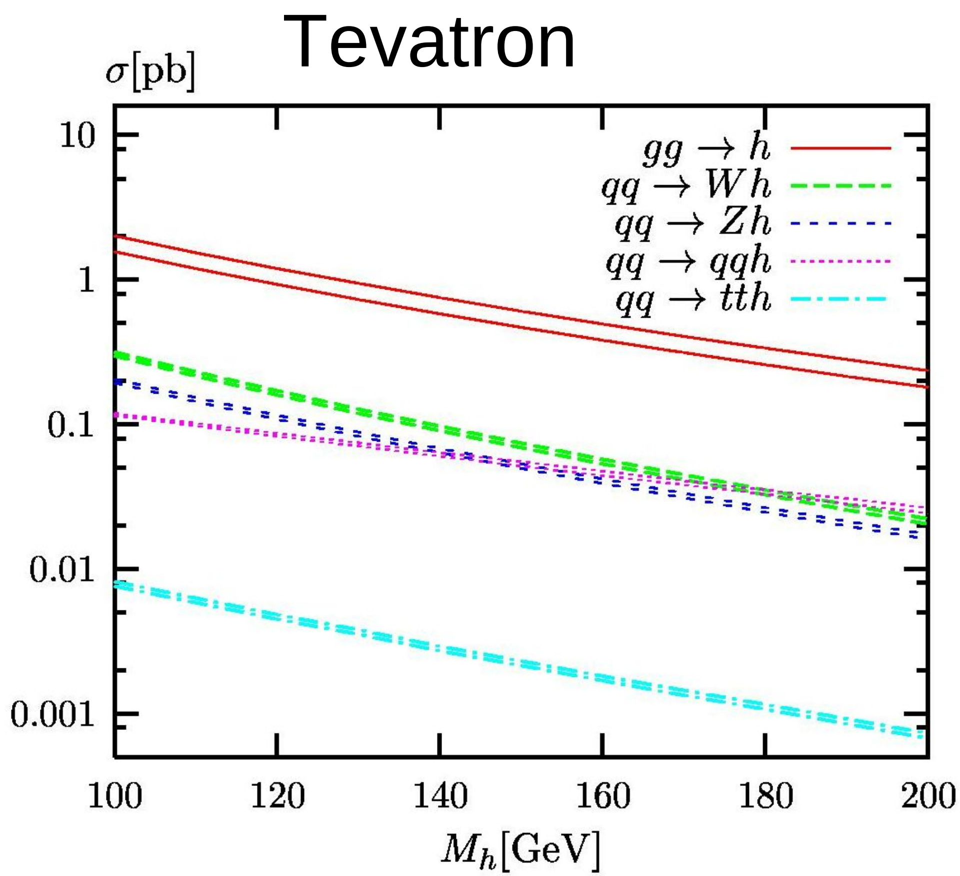


- Theoretically very clean channel
  - NNLO QCD corrections: $K_{QCD} \approx 1.3\text{-}1.4$
  - Electroweak corrections known (-5%)
  - Small scale dependence (3-5%)
  - Small PDF uncertainties

Improved scale dependence at NNLO



Producing the Higgs at the Tevatron



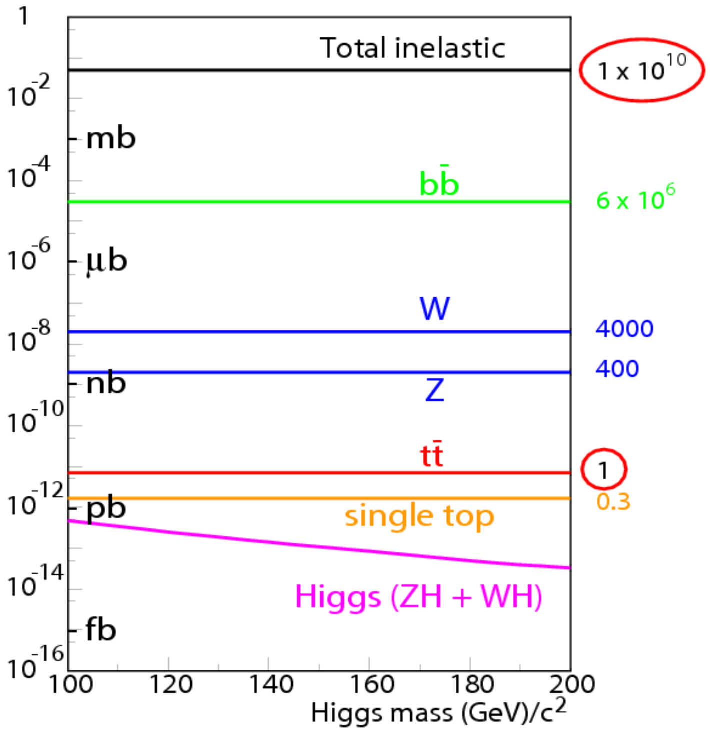
NNLO or NLO rates

$M_H/2 < \mu < M_H/4$

Aside: Tevatron analyses now based on 3 fb^{-1}

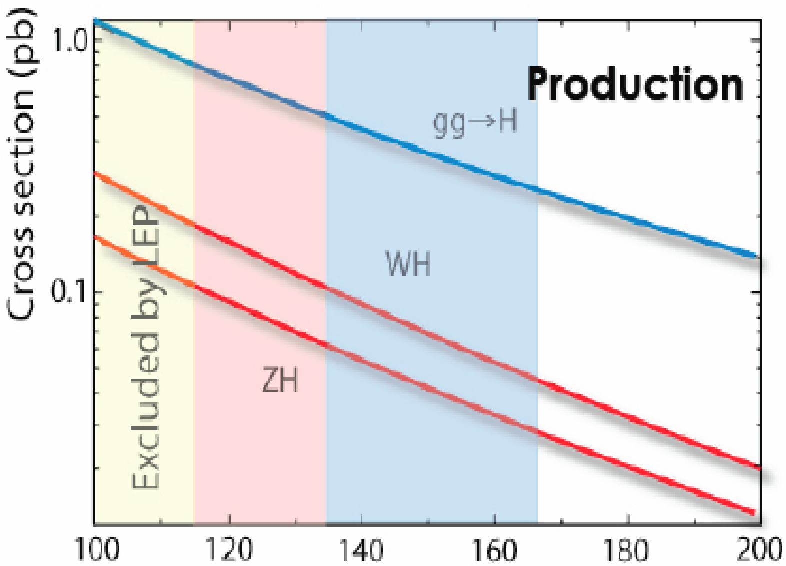
Higgs at the Tevatron

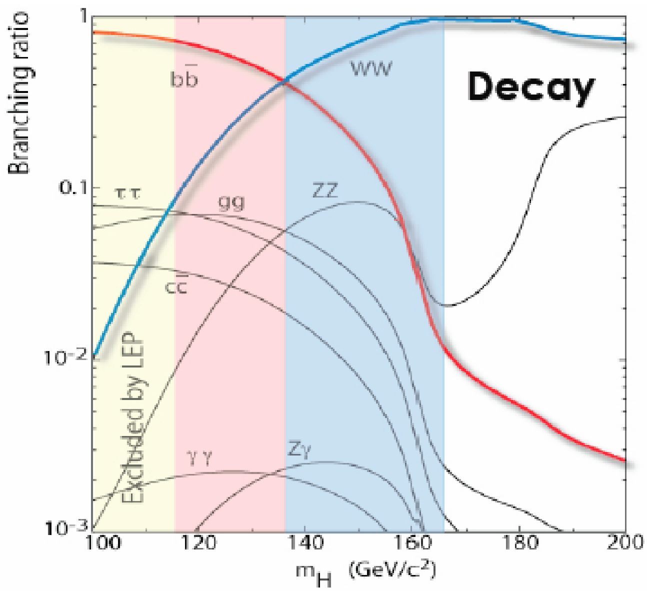
- Largest rate, $gg \rightarrow H$, $H \rightarrow b\bar{b}$, is overwhelmed by background



$\sigma(gg \rightarrow H) \sim 1$ pb << $\sigma(bb)$

Looking for the Higgs at the Tevatron

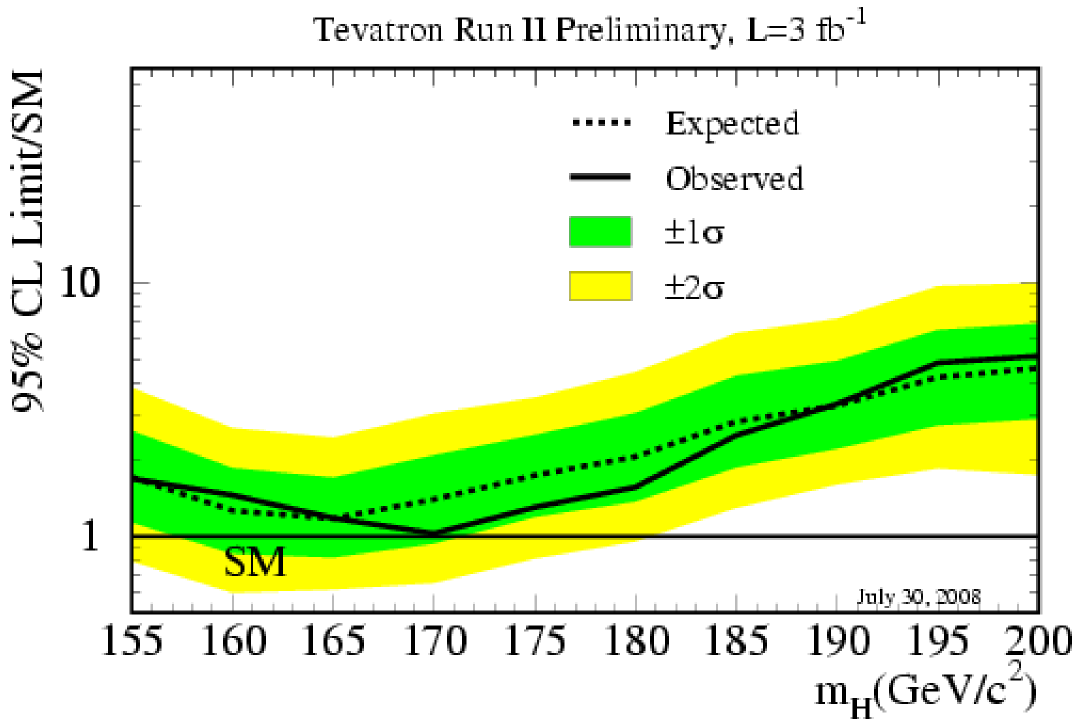




- High mass: Look for $H \rightarrow WW \rightarrow l\nu l\nu$
  Large $gg \rightarrow H$ production rate
- Low Mass: $H \rightarrow bb$, Huge QCD bb background
  Use associated production with W or Z

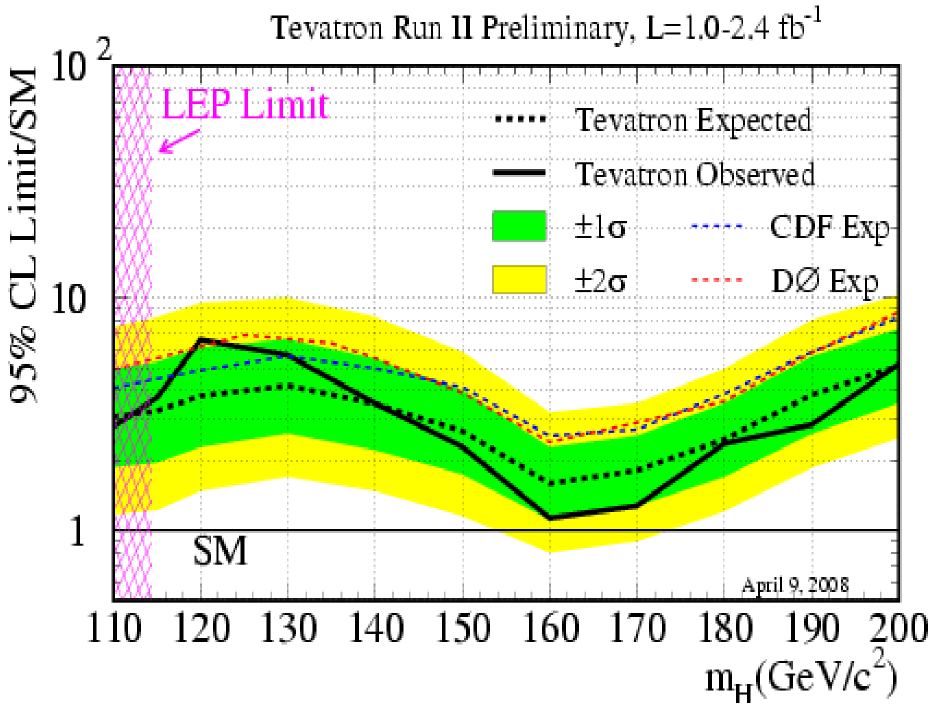
Analyses use more than 70 channels

SM Higgs Searches at Tevatron



95% CL exclusion of SM Higgs at 170 GeV

SM Higgs Searches at Tevatron



Expected sensitivity of CDF/DØ combined with 3 fb^{-1}:

< 3.0xSM @ 115 GeV