SEARCHING FOR THE HIGGS BOSON

THE LARGE HADRON COLLIDER, CERN...

OKAY, MOMENT OF TRUTH.

THE LARGE HADRON COLLIDER, CERN...

DO YOU SEE THE HIGGS BOSON?

NOPE.

DO YOU SEE THE HIGGS BOSON?

Huh.

WELL, THEN.

UNTIL THE THEORISTS GET BACK TO US, WANNA TRY HITTING PIGEONS WITH THE PROTON STREAM?

ALREADY ON IT. COOL! I JUST GAVE A HELICOPTER CANCER.

xkcd.com

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Outline

✦ Quick review of the SM and the Higgs mechanism
✦ Constraining the Higgs: theoretical constraints and electroweak precision
✦ A phenomenological profile: decays of the Higgs boson
✦ Production mechanisms at $e^+e^-$ and hadron colliders
✦ A case study in QCD: gluon-fusion production
✦ Searches at the Tevatron and the LHC

 Mostly SM, but will try to mention possible deviations
Success of the Standard Model
Building a gauge theory

- Guiding principle in construction of SM is gauge symmetry
- Pick a gauge group
- Assign matter fields (fermions, scalars) to a representation of the gauge group, e.g., the fundamental N-component vector for SU(N)
- To make the matter Lagrangian gauge invariant, replace $\partial_\mu \rightarrow D_\mu$

\[
\mathcal{L} = -\frac{1}{2} \text{Tr} [F_{\mu\nu} F^{\mu\nu}] + \mathcal{L}_{\text{matter}} (\Psi, D_\mu \Psi)
\]

gives Feynman rules for gauge self-interactions
governs gauge-matter interactions
The Standard Model

* Gauge group: \( SU(3)_C \times SU(2)_L \times U(1)_Y \) (8 gluons; eventually photon, \( W^\pm, Z \))

* Three generations of fermionic matter

|        | \( SU(3)_C \) | \( SU(2)_L \) | \( U(1)_Y \) |
|--------|---------------|---------------|---------------|
| \( Q_L \) | 3            | 2             | \( 1/6 \)     |
| \( u_R \) | 3            | 1             | \( 2/3 \)     |
| \( d_R \) | 3            | 1             | \( -1/3 \)    |

\[
Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad u_R, \quad d_R
\]

|        | \( SU(3)_C \) | \( SU(2)_L \) | \( U(1)_Y \) |
|--------|---------------|---------------|---------------|
| \( L_L \) | 1            | 2             | \( -1/2 \)    |
| \( e_R \) | 1            | 1             | \( -1 \)      |

* Electric charge: \( Q = T_3 + Y \)
Problems with mass

The Lagrangian of the SM:

\[
\mathcal{L}_{gauge+ferm} = -\frac{1}{4} U(1)_Y \frac{B_{\mu\nu} B^{\mu\nu}}{m^2} - \frac{1}{4} SU(2)_L \frac{W^a_{\mu\nu} W^a_{\mu\nu}}{m^2} - \frac{1}{4} SU(3)_C \frac{G^a_{\mu\nu} G^a_{\mu\nu}}{m^2}
\]

\[
+ \sum_{f} i \bar{f} D f
\]

\[
f = Q_L, u_R, d_R, L_L, e_R
\]

We know the \( W^\pm, Z \) bosons have mass, but this is not allowed by gauge symmetry

\[
\mathcal{L}^{SU(2)}_{mass} = \frac{1}{2} m^2 W^a_{\mu} W^a_{\mu} \Rightarrow \Delta \mathcal{L}^{SU(2)}_{mass} \neq 0 \text{ under G.T.}
\]

Similarly, fermion mass terms are not allowed by \( SU(2)_L \) or \( U(1)_Y \)

\[
\mathcal{L}^{ferm}_{mass} = -m \left[ \bar{f}_R f_L + \bar{f}_L f_R \right]
\]

transforms as \( SU(2)_L \) doublet, \( \sum Y \neq 0 \)
Spontaneous symmetry breaking

- The solution: Lagrangian is symmetric, ground state isn’t ⇒ spontaneous symmetry breaking
- Complex scalar transforming as \((1,2,1/2)\) under \(SU(3)_C \times SU(2)_L \times U(1)_Y\)

\[
\mathcal{L}_{Higgs} = (D^\mu H)^\dagger D^\mu H - \lambda \left( H^\dagger H - \frac{v^2}{2} \right)^2
\]

\[
H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}
\]

\[
D^\mu = \partial^\mu - ig W^\mu_a \sigma^a \frac{1}{2} - ig' B^\mu \frac{1}{2}
\]

Vacuum expectation value: \(< H > = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}\)

Expand around vev: \(H = \begin{pmatrix} \phi^+ \\ v + \frac{h}{\sqrt{2}} + i \chi \end{pmatrix}\)

(\(\varphi^*, \chi\) can be removed by G.T., set to zero)
The Higgs mechanism

\* Work out the kinetic part of Higgs Lagrangian

\[
D_\mu H = \frac{1}{\sqrt{2}} \left( \begin{array}{c} 0 \\ \partial_\mu h \end{array} \right) - \frac{i}{2} \left[ v + h \right] \left( \begin{array}{c} \sqrt{2} g W^+_\mu \\ \sqrt{g^2 + g'^2} Z_\mu \end{array} \right)
\]

\[
(D^\mu H) ^\dagger D_\mu H = \frac{1}{2} \partial_\mu h \partial^\mu h + \left( 1 + \frac{h}{v} \right)^2 \left( \begin{array}{c} \frac{g^2 v^2}{4} \frac{W^+ + W^-}{M^2_W} + \frac{1}{2} \frac{(g^2 + g'^2) v^2}{4} \frac{Z_\mu Z^\mu}{M^2_Z} \end{array} \right)
\]

\[
Z_\mu = c_W W^3_\mu - s_W B_\mu, \ A_\mu = s_W W^3_\mu + c_W B_\mu, \ W^\pm_\mu = \frac{W^1_\mu \mp iW^2_\mu}{\sqrt{2}}
\]

\[
c_W = \frac{g}{\sqrt{g^2 + g'^2}}, \ s_W = \frac{g'}{\sqrt{g^2 + g'^2}}
\]

\* \( W^\pm, Z \) acquire mass by “eating” \( \varphi^+, \chi \)

Prediction: \( \rho = \frac{M^2_W}{M^2_Z c_W^2} = 1 \)

(tree-level; more later)
Fermion masses

* Yukawa interactions with Higgs doublets give fermions mass

\[ \mathcal{L}_{Yuk} = -\lambda_d \bar{Q}_L H d_R - \lambda_u \bar{Q}_L (i\sigma_2 H^*) u_R - \lambda_e \bar{L}_L H e_R + \text{h.c.} \]

\[ \Rightarrow - \left(1 + \frac{h}{v}\right) \sum_{f=u,d,e} m_f \bar{f}f \quad \text{with} \quad m_f = \frac{\lambda_f v}{\sqrt{2}} \]

(matrix in generation space, implicitly diagonalized at price of \( V_{CKM} \) in charged currents)

* Sum of all pieces so far give the SM Lagrangian:

\[ \mathcal{L}_{SM} = \mathcal{L}_{gauge+ferm} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yuk} \]

* The single Higgs doublet is just the simplest way to break \( SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM} \); EWSB could be more intricate. But this is the benchmark to compare other theories against.
Feynman rules

Work out the experimental predictions with Feynman rules:

\[ = -i \frac{m_f}{v} \]

\[ = 2i \frac{M_W^2}{v^2} g_{\mu\nu} \]

\[ = 2i \frac{M_W^2}{v^2} g_{\mu\nu} \]

\[ = 2i \frac{M_Z^2}{v} g_{\mu\nu} \]

From muon decay,
\[ v^2 = \frac{1}{(G_F\sqrt{2})} \Rightarrow v \approx 246 \text{ GeV} \]

Only scalars with vevs have linear HVV couplings

Test the consequences of the Higgs mechanism
Unitarity of S-matrix

Conservation of probability in QFT:

\[ S^\dagger S = 1 \implies \sigma = \frac{1}{s} \text{Im} \{ \mathcal{M}(\theta = 0) \} \]

\( \text{forward scattering} \)

Decompose into Legendre polynomials

\[ \mathcal{M} = 16\pi \sum_{l=0}^{\infty} (2l + 1) P_l(c_\theta) a_l \]

\[ a_l = \frac{1}{32\pi} \int_{-1}^{1} dc_\theta P_l(c_\theta) \mathcal{M} \]

\[ \Rightarrow \sigma = \frac{16}{s} \sum_{l=0}^{\infty} (2l + 1) |a_l|^2 \]

\[ \Rightarrow |a_L|^2 = \text{Im}(a_l) \]

\[ \Rightarrow \text{Re}(a_l) \leq 1/2 \]
WW scattering

- Longitudinal modes: \[ \varepsilon_L = \left( \frac{p}{M}, 0, 0, \frac{E}{M} \right) \] (boost from \((0,0,0,1)\))

\[
a_0(W_L W_L \rightarrow W_L W_L) \rightarrow -\frac{s}{32\pi v^2}
\]

\[
a_0(W_L W_L \rightarrow W_L W_L) \rightarrow -\frac{M_H^2}{8\pi v^2}
\]

- Probability not conserved without Higgs; with, \(M_H < 900 \) GeV (perturbative argument)
Theoretical constraints

* Landau pole of $\lambda h^4$ coupling

\[ \lambda(Q) = \frac{M_H^2}{2v^2} \left( \frac{1}{1 - \frac{3}{4\pi^2} \frac{M_H^2}{v^2} \ln \frac{Q}{v}} \right) \]

(large $\lambda$ limit)

Breaks down at some $Q$
For validity up to $Q=\Lambda$ ($\lambda<\infty$),
upper bound on $M_H$

* Shape of Higgs potential: $\lambda>0 \Rightarrow$ lower bound on $M_H$

$\lambda(Q) = \lambda_0 - \frac{3y_t^4}{8\pi^2} \ln \frac{Q}{Q_0} - \frac{9y_t^2}{16\pi^2} \ln \frac{Q}{Q_0}$

(small $\lambda$ limit)

Validity of SM to high scales restricts allowed $M_H$
Electroweak precision

- Can experimentally probe properties of the Higgs directly (try to produce at a collider) or indirectly (through quantum effects)
- LEP+SLC: millions of $e^+e^-\rightarrow Z \rightarrow ff$, high-precision measurements of SM electroweak parameters $\Rightarrow$ effect of Higgs?
- Study one-loop predictions of SM
- Basic idea in renormalizable theory: fix most precisely known quantities, calculation others in terms of them

\[
\begin{align*}
G_F &= 1.166367(5) \times 10^{-5} \text{ GeV}^{-2} \ (\text{muon decay}) \\
\alpha^{-1} &= 137.035999679(94) \ (\text{low-energy experiments}) \\
M_Z &= 91.1875(21) \ (\text{LEP})
\end{align*}
\]

- Example: we’ll outline prediction for $M_W$
Muon decay

Muon-decay at tree-level:

\[ \frac{G_F}{\sqrt{2}} = \frac{e^2}{8 M_W^2 s_W^2} \quad (m_{e,\mu} = 0) \]

\[ s_W^2 = 1 - \frac{M_W^2}{M_Z^2} \quad \text{(on-shell scheme)} \]

\[ \Rightarrow \frac{G_F}{\sqrt{2}} = \frac{\pi \alpha}{2 M_W^2 (1 - M_W^2/M_Z^2)} \]

\[ \Rightarrow M_W^2 = \frac{M_Z^2}{2} \left\{ 1 + \left[ 1 - \frac{2 \sqrt{2} \pi \alpha (1 - \Delta r)}{G_F M_Z^2} \right]^{1/2} \right\} \]

\[ \approx 80.94 \text{ GeV} \quad \Rightarrow \text{experiment gets 80.4 GeV!} \]

Keep only leading corrections (m_t, M_H, running of \(\alpha\); others defined as ‘small’)

\[ \frac{G_F}{\sqrt{2}} = \frac{e^2}{8 M_W^2 s_W^2} (1 + \Delta r) \]

\[ \Rightarrow M_W^2 = \frac{M_Z^2}{2} \left\{ 1 + \left[ 1 - \frac{2 \sqrt{2} \pi \alpha (1 + \Delta r)}{G_F M_Z^2} \right]^{1/2} \right\} \]
Δρ and non-decoupling

Δr receives important contribution from gauge-boson self-energies

\[
\Delta r = \Delta \alpha - \frac{c_W^2}{s_W^2} \Delta \rho
\]

\[
\Delta \rho = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2}
\]

quadratic in \( m_t \)

Exercise: Derive these

\[
\Delta \rho_{\text{ferm}} = \frac{3 G_F m_t^2}{8 \pi^2 \sqrt{2}} + \text{subleading terms}
\]

\[
\Delta \rho_{\text{Higgs}} = -\frac{3 G_F M_Z^2 s_W^2}{4 \pi^2 \sqrt{2}} \ln \frac{M_H}{M_Z} + \text{subleading terms}
\]

logarithmic in \( M_H \)

Decoupling theorem holds only if dimensionful parameters made large

\[
m_t = \frac{\lambda_t v}{\sqrt{2}} \Rightarrow m_t \to \infty, \ v \text{ fixed} \Rightarrow \lambda_t \to \infty
\]

\[
M_H^2 = 2 \lambda v^2 \Rightarrow M_H \to \infty, \ v \text{ fixed} \Rightarrow \lambda \to \infty
\]
Bounding the Higgs mass

Logarithmic dependence on $M_H$ allows $M_W$ to bound it (but very sensitive to the top-quark mass)

$M_W = 80.399 \pm 0.025$ GeV (world average)

(Refinements needed for real comparison to data; important $\ln(m_t)$ and other terms; see PDG and refs within)

$M_W^{tree} = 80.94$ GeV $\Rightarrow M_W^{1-loop} = 80.39$ GeV ($M_H = 120$ GeV)
Global EW fit

* Do the same for large set of LEP-SLC measurements

http://lepewwg.web.cern.ch/LEPEWWG/

SM Higgs mass: $M_H < 160$ GeV from EW precision measurements
S, T, and hiding a heavy Higgs

★ How robust are these bounds? Consider corrections that are *oblique*: affect only gauge boson propagators

\[
\alpha T = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2} = \Delta \rho
\]

\[
\frac{\alpha}{4s_W^2c_W^2} S = \frac{\Pi_{ZZ}(M_Z^2)}{M_Z^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2}
\]

(Not a complete basis, but these are often the most important ones)

★ Calculate for reference \(M_H\), propagate through all EW parameters

Example: 4th generation
(Kribs et al., 0706.3718)

\[
\Delta \rho_{\text{new}} = \frac{3G_F \Delta m_{\text{ferm}}^2}{8\pi^2\sqrt{2}} - \frac{3G_F M_Z^2 s_W^2}{4\pi^2\sqrt{2}} \ln \frac{M_H}{M_H^{\text{ref}}}
\]

⇒ increase \(M_H\), cancel with \(\Delta m\)

Need direct searches!
Decays of the Higgs boson
Since \( g_{Hxx} \sim m_x \), Higgs tends to decay to heaviest kinematically accessible states (with many important caveats...)

Tree-level decays to various massive final states:

\[
\Gamma_{qq} = N_c \frac{G_F}{4\sqrt{2}\pi} M_H m_j^2 \left(1 - \frac{4m_j^2}{M_H^2}\right)^{3/2}, \quad \Gamma_{ll} = \frac{G_f}{4\sqrt{2}\pi} M_H m_j^3 \left(1 - \frac{4m_j^2}{M_H^2}\right)^{3/2}
\]

\[
\Gamma_{VV} = \frac{G_F}{8\sqrt{2}\pi n_V} M_H^3 \left(1 - 4x\right)^{1/2} \left(1 - 4x + 12x^3\right) \text{ with } x = \frac{M_V^2}{M_H^2}, n_W = 1, n_Z = 2
\]

Threshold structure depends on spin, CP (\(3/2 \rightarrow 1/2\) for CP-odd A)

Note \( \Gamma_{ff} \sim M_H \), while \( \Gamma_{VV} \sim (M_H)^3 \) \(\Rightarrow\) when W, Z channels open, Higgs becomes very broad

For light Higgs (\( M_H \leq 130 \text{ GeV} \)), expect \( bb, \tau\tau, cc \) to be important
Equivalence theorem

∗ Growth of VV width comes from longitudinal gauge modes

\[
\mathcal{A}(h \rightarrow W_L^+ W_L^-) = 2 \frac{M_W^2}{v} \epsilon^+_L \epsilon^-_L, \quad \epsilon^\pm_L = \frac{E}{M_W} (\pm \beta_W, \bar{0}, 1)
\]

\[
\mathcal{A}(h \rightarrow W_L^+ W_L^-) \rightarrow - \frac{M_H^2}{v} + \mathcal{O} \left( \frac{M_V^2}{M_H^2} \right)
\]

\[
\Gamma_{WW} = \frac{1}{16\pi M_H} |\mathcal{A}|^2 \rightarrow \frac{G_F M_H^3}{8\pi \sqrt{2}} + \mathcal{O} \left( \frac{M_V^2}{M_H^2} \right)
\]

∗ In the high energy limit, longitudinal mode interactions equivalent to those of eaten scalar ⇒ Goldstone boson equivalence theorem.

Exercise: Work out from $L_{\text{Higgs}}$
Three-body decays

Since $M_{W,Z} \gg m_b, c, \tau$, $H \rightarrow VV^* \rightarrow Vff$ important for $M_H < 2M_W, Z$

\[ \Gamma_{Wff} = \frac{3G_F^2 M_W^4}{16\pi^3} M_H \left\{ \frac{3(1 - 8x + 20x^2)}{\sqrt{4x - 1}} \arccos \left( \frac{3x - 1}{2x^{3/2}} \right) - \frac{1 - x}{2x} (2 - 13x + 47x^2) - \frac{3}{2} (1 - 6x + 4x^2) \ln x \right\} \]

\[ x = \frac{M_W^2}{M_H^2} \]

Important mode even down at $M_H \approx 130$ GeV since $f = e, \mu$

![Graph showing the function $F$]
Loop-induced H→gg

* Can we leverage the large Htt, HVV couplings at low $M_H$?
* Two important cases: $h→gg$ (production more important), $h→γγ$

\[
\Gamma_{gg} = \frac{G_F q_s^2 M_H^3}{36\pi^3 \sqrt{2}} \left| \frac{3}{4} \sum_Q \mathcal{F}_{1/2}(\tau_Q) \right|^2 \\
\mathcal{F}_{1/2}(\tau) = \frac{2}{\tau^2} [\tau + (\tau - 1)f(\tau)]
\]

\[
f(\tau) = \begin{cases} 
\arcsin^2 \sqrt{\tau} & \tau \leq 1 \\
-\frac{1}{4} \left[ \ln \frac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}} - i\pi \right]^2 & \tau > 1
\end{cases}
\]

\[
\tau \to 0 \Rightarrow \mathcal{F}_{1/2} \to \frac{4}{3}
\]

\[
\tau \to \infty \Rightarrow \mathcal{F}_{1/2} \to -\frac{2m_Q^2}{M_H^2} \ln \frac{M_H^2}{m_Q^2}
\]

- Independent of $m_f$ when $m_f \to \infty \Rightarrow$ true for any heavy fermion that gets its mass from Higgs

Exercise: Derive $m_t \to \infty$ result from direct integration
Loop-induced $H \rightarrow \gamma \gamma$

\* Crucial for low-mass Higgs search at LHC

\[
\Gamma_{\gamma\gamma} = \frac{G_F \alpha^2 M_H^3}{128 \pi^3 \sqrt{2}} \left| \sum_f N_c Q_f^2 \mathcal{F}_{1/2}(\tau_f) + \mathcal{F}_1(\tau_W) \right|^2
\]

\[
\mathcal{F}_1(\tau) = -\frac{1}{\tau^2} \left[ 2\tau^2 + 3\tau + 3(2\tau - 1)f(\tau) \right]
\]

$\tau \rightarrow 0 \Rightarrow \mathcal{F}_1 \rightarrow -7$  
W contribution larger than top-quark, they interfere destructively
Putting it all together

Most important channels:
\( M_H \leq 130 \text{ GeV} \): bb, \( \tau\tau \), \( \gamma\gamma \) (clean signature)
\( M_H \geq 130 \text{ GeV} \): WW, ZZ
(boundaries are rough)
Refinement: low-energy theorems

- Can exactly calculate QCD corrections to $h \rightarrow gg, \gamma \gamma$ (two-loop diagrams plus real radiation for $gg$ decay) \cite{Djouadi, Spira, Zerwas early 1990s}
- Useful, illuminating alternative approach for $2m_t > M_H$

Diagrammatically, clear that Higgs interaction comes from derivatives of the top part of the gluon self-energy:

$$
\mathcal{M}(hgg) \underset{p_H \rightarrow 0}{=} \frac{m_t}{v} \frac{\partial}{\partial m_t} \mathcal{M}(gg)
$$

Generates both diagrams in the $M_H \rightarrow 0$ limit
Effective Lagrangian

* Integrate out top quark to produce effective Lagrangian

\[ \mathcal{L} = -\frac{1}{4} G_{\mu\nu}^a G_{a}^{\mu\nu} + \mathcal{L}_{\text{top}} \]

\[ \Rightarrow G_{\mu}^{a' \mu} = \zeta_3 G_{\mu}^a \]

\[ \Rightarrow \mathcal{L}_{\text{EFT}} = -\frac{\zeta_3}{4} G_{\mu\nu}^a G_{a}^{\mu\nu} \]

* Can generate hgg amplitudes from derivatives of gg amplitudes:

\[ \mathcal{L}_{\text{EFT}}^{hgg} = -\frac{m_t}{4v} \left( \frac{\partial}{\partial m_t} \Pi_t(0) \right) h G_{\mu\nu}^{a'} G_{a}^{\mu\nu} \]

\[ \Rightarrow \Pi_t(0) = \frac{\alpha_s}{6\pi} \left[ \frac{\mu^2}{m_t^2} \right]^\epsilon \Gamma(1 + \epsilon) \]

\[ \Rightarrow \mathcal{L}_{\text{EFT}}^{hgg} = \frac{\alpha_s}{12\pi} \frac{h}{v} G_{\mu\nu}^{a'} G_{a}^{\mu\nu} \]
Decay in the EFT

- Reduces 2-loop calculation $\Rightarrow$ 1-loop; separates $m_t$ dependence

- Systematically improvable to all orders in $\alpha_s$

$$\mathcal{L}_{EFT}^{hgg} = -C_1 \frac{h}{v} G_{\mu\nu}^a G_{\mu\nu}^a$$

$$C_1 = -\frac{1}{12} \frac{\alpha_s}{\pi} \left\{ 1 + \frac{\alpha_s}{\pi} \left( \frac{11}{4} - \frac{1}{6} \ln \frac{\mu^2}{m_t^2} \right) + \ldots \right\}$$

Correction to $h \to$ light hadrons:

- (must include qq at higher orders)

$$K = 1 + 17.9167 a_s' + 152.5(a_s')^2 + 381.5(a_s')^3$$

Large!

- Can do same for $h \to \gamma\gamma$ decay, for W contribution also

For references and subtleties, see Chetyrkin et al. hep-ph/9708255, Kniehl, Spira hep-ph/9504378

Baikov, Chetyrkin hep-ph/0604194
**Decays beyond the SM**

- **NMSSM**: decays to light CP-odd scalar can produce final states $h \rightarrow aa \rightarrow bb\tau\tau, \tau\tau\tau\tau, \tau\tau\gamma\gamma, ...$

- **Extended scalar sectors**: decays to stable scalars (dark matter) can make Higgs invisible decaying

| $m_{h_1}/m_{a_1}$ (GeV) | Branching Ratios | $n_{\text{obs}}/n_{\text{exp}}$ units of 1σ | $s_{95}$ | $N_{\text{LHC}}^{LHC}$ |
|--------------------------|-------------------|------------------------------------------|--------|-----------------|
| $h_1 \rightarrow b\bar{b}$ | 0.062             | 2.25/1.72                                | 2.79   | 1.2             |
| $h_1 \rightarrow a_1a_1$ | 0.926             | 1.98/1.88                                | 2.40   | 1.5             |
| $a_1 \rightarrow \tau\tau$ | 0.852             | 2.26/2.78                                | 1.31   | 2.5             |
| $h_1 \rightarrow aa \rightarrow ss$ | 0.000             | 1.44/2.08                                | 1.58   | 1.6             |
| $h_1 \rightarrow aa \rightarrow \tau\tau\tau\tau$ | 0.923             | 1.80/3.12                                | 1.03   | 3.3             |
| $h_1 \rightarrow aa \rightarrow \tau\tau\gamma\gamma$ | 0.832             | 1.79/3.03                                | 1.07   | 3.6             |
| $h_1 \rightarrow aa \rightarrow \tau\tau\tau\tau\gamma$ | 0.095             | 1.64/2.46                                | 1.24   | 2.4             |
| $h_1 \rightarrow aa \rightarrow \tau\tau\tau\tau\gamma\gamma$ | 0.887             | 1.11/1.52                                | 2.74   | 1.2             |

Dermisek, Gunion hep-ph/0510322

$\mathcal{L}_S = \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{1}{2} m_S S^2 - \frac{k}{2} |H|^2 S^2 - \frac{h}{4!} S^4$

**h→SS decays can dominate**

Burgess, Pospelov, ter Veldhuis NPB 619 (2001); Davoudiasl et al. hep-ph/0405097

Many deviations, some drastic, from SM predictions possible!
Producing the Higgs boson
Hadron collider basics

The basic picture of hadronic collisions: factorize long and short time processes

time scale: \( \tau_{\text{proton}} \sim \frac{1}{\Lambda_{\text{QCD}}} \)

\[
\sigma_{h_1 h_2 \rightarrow X} = \int d x_1 d x_2 \left\{ f_{h_1 / i}(x_1; \mu_F^2) f_{h_2 / j}(x_2; \mu_F^2) \right\} \sigma_{ij \rightarrow X}(x_1, x_2, \mu_F^2, \{q_k\}) + \mathcal{O} \left( \frac{\Lambda_{\text{QCD}}}{Q} \right)^n
\]

factorization scale

partonic cross section

power corrections
Parton distribution functions

$x \sim \frac{M_H}{\sqrt{s}}$

Lots of gluons, at LHC especially
Higgs at hadron colliders

- Clearly want to use large gluon luminosity; W, Z assisted production another option

Can’t do LEP search, $\sqrt{s}$ not fixed at hadron machine

Any hadron collider search must confront backgrounds
Overview of Higgs cross sections

- Gluon-fusion dominant at both colliders; WH next at Tevatron, WBF at LHC

- SUSY: $g_{bbh} \sim \tan^2 \beta$; becomes dominant at $\tan \beta \sim 10$

- Plan: discuss WBF and gluon-fusion properties (some tricky/interesting aspects), then move on to searches at Tevatron/LHC
Weak boson fusion: effective W/Z

* Important throughout large region of Higgs mass and in many decay modes; forward jets give experimental handle
* First approximation: inclusive cross section for $M_H \gg M_W, Z$

\[
\frac{1}{(p_1 - p_3)^2 - M_V^2} \Rightarrow \text{peaked at } p_1 \cdot p_3 = 0
\]

\[
\tau_{q \rightarrow V} \sim 1/M_V
\]

\[
\tau_{VV \rightarrow h} \sim 1/M_H \ll \tau_{q \rightarrow V}
\]

* Should be able to factorize, think of V as a parton in q

\[
\sigma_{qq \rightarrow VV \rightarrow h} = \int d\tau_1 d\tau_2 f_{q/V_1}(\tau_1) f_{q/V_2}(\tau_2) \sigma_{VV \rightarrow h}
\]
Can derive when $M_{V}\ll \sqrt{s}$ (small angle scattering dominated)

\[\sigma_{q_{1}q_{2}\rightarrow VV\rightarrow h} = \int_{2M_{V}/\sqrt{s}}^{1} dz_{1} \int_{2M_{V}/\sqrt{s}}^{1} dz_{2} f_{q/V_{L}}(z_{1}) f_{q/V_{L}}(z_{2}) \sigma_{V_{L}V_{L}\rightarrow h}(z_{1}z_{2}\hat{s})\]

\[\sigma_{V_{L}V_{L}\rightarrow h}(x) = \frac{\pi}{36} g^{2}_{HVV} \frac{x}{M_{V}^{2}} \delta(x - M_{H}^{2})\]

\[f_{q/V_{L}}(z) = \frac{g_{v}^{2} + g_{a}^{2}}{4\pi^{2}} \frac{1 - z}{z}\]

Angular momentum cons. prevents emission of transverse boson with forward quark: \[\bar{u}^{\pm}(p\hat{z}) \not\equiv u^{\pm}(p'\hat{z}) \Rightarrow \text{Set } \not\equiv = \gamma^{1,2} \Rightarrow \xi^{\dagger}_{\pm} \sigma^{1,2} \xi_{\pm} = 0\]

Good channel to study strong EWSB

Dawson 1984; Chanowitz, Gaillard 1985
Kinematics of WBF

* Two energetic ($p_T \sim 40$ GeV) jets with large rapidity separation

Forward tagging jets

Central-jet veto

Extra gluon emission suppressed; impose central jet veto

$$\mathcal{M}(q_1 q_2 \rightarrow q_3 q_4 h + g) \propto \mathcal{M}(q_1 q_2 \rightarrow q_3 q_4 h) \, T^a \left\{ \frac{p_3 \cdot \epsilon_g^a}{p_3 \cdot p_g} + \frac{p_4 \cdot \epsilon_g^a}{p_4 \cdot p_g} - \frac{p_1 \cdot \epsilon_g^a}{p_1 \cdot p_g} - \frac{p_2 \cdot \epsilon_g^a}{p_2 \cdot p_g} \right\}$$

$$\rightarrow 0 \text{ since } p_1 \parallel p_3, \ p_2 \parallel p_4$$

Exercise: Derive this

Rainwater, Zeppenfeld hep-ph/9906218 and many others... check refs+citations
Gluon fusion production

* Largest mode at Tevatron and LHC; through top-quark loops

\[ \sigma_{gg\to h}^{LO} = \frac{G_F \alpha_s^2}{288 \pi \sqrt{2}} \left| \frac{3}{4} \sum Q \mathcal{F}_{1/2}(\tau_Q) \right|^2 \delta(1 - z) \]

\[ \tau_Q = \frac{M_H^2}{4 m_Q^2} \quad z = \frac{M_H^2}{\hat{s}} \]

* NLO QCD corrections require 2-loop virtual, 1-loop real-virtual

Can reach \( K_{NLO} = \sigma_{NLO}/\sigma_{LO} \approx 2 \) at LHC, 3 at Tevatron; why so large?

Djouadi, Graudenz, Spira, Zerwas PLB 264 (1991), hep-ph/9504378
Study carefully in the EFT with Hgg vertex

\[ \sigma_{ij} = \sigma_0 \left\{ G_{ij}^{(0)} + \frac{\alpha_s}{\pi} G_{ij}^{(1)} + O(\alpha_s^2) \right\} \]

\[ \mathcal{L}_{EFT} = \frac{1}{12} \frac{\alpha_s}{\pi} \left[ 1 + \frac{11}{4} \frac{\alpha_s}{\pi} + O(\alpha_s^2) \right] \]

NLO receives contributions from 5 pieces: virtual diagrams, real-radiation, ultraviolet renormalization, PDF renormalization correction to EFT coefficient

- Everything in \( d=4-2\epsilon \) dimensions; gluon has \( d-2 \) polarization states
- Scaleless integrals vanish
- Coupling constant gets dimensions: \( g \rightarrow g \mu^\epsilon \)
- Feynman gauge
- Only gg initial-state (others smaller, simpler)

Notes:

\[ \int d^d k \frac{1}{k^2} \sim \frac{1}{\epsilon_{UV}} - \frac{1}{\epsilon_{IR}} \rightarrow 0 \]

J. Collins, *Renormalization*
Gluon-fusion: virtual

Virtual:

\[
\begin{align*}
\text{Leading soft+collinear singularity; emitting} \\
\text{gluons from gluons gives color factor } C_A=3
\end{align*}
\]

UV renormalization: counterterm for \( \alpha_s \) at leading order

**Full d-dimensional LO**

\[
\begin{align*}
\text{First term in beta-function} & \\
& = \frac{\alpha_s \Gamma(1+\epsilon)}{\pi (4\pi)^{-\epsilon}} \left( \frac{\mu^2}{\hat{s}} \right)^\epsilon \left\{ -1 + \frac{N_F}{3} \right\} \left[ \frac{1}{\epsilon} + 1 \right] \delta(1-z)
\end{align*}
\]

Number of light fermions
Gluon-fusion: real radiation

\[ \text{Exercise: Derive the phase space} \]

\[ |\tilde{M}|^2 = 48 \alpha_s \left\{ \frac{(1-2\epsilon)}{(1-\epsilon)^2} \frac{M_H^8}{s^4 + \hat{t}^4 + \hat{u}^4} + \frac{\epsilon}{2(1-\epsilon)^2} \frac{(M_H^4 + s^2 + \hat{t}^2 + \hat{u}^2)^2}{s\hat{t}\hat{u}} \right\} \]

\[ \Rightarrow (1-z)^{-1-2\epsilon} \lambda^{-1-\epsilon} (1-\lambda)^{-1-\epsilon} \]

\( \lambda: \) collinear

\( z: \) soft

\[ \text{Phase space} \quad : \quad \frac{1}{2\hat{s}} \int \frac{d^d p_g}{(2\pi)^d} \frac{d^d p_H}{(2\pi)^d} (2\pi)^d \delta(p_g^2) (2\pi)^d \delta(p_H^2 - M_H^2) (2\pi)^d \delta^{(d)}(p_1 + p_1 - p_g - p_H) \]

\[ = \frac{1}{16\pi \hat{s}} \frac{s^{-\epsilon}}{(4\pi)^{-\epsilon} \Gamma(1-\epsilon)} (1-z)^{1-2\epsilon} \int_0^1 d\lambda \lambda^{-\epsilon} (1-\lambda)^{-\epsilon} \]

\[ \Rightarrow \hat{t} = (p_1 - p_g)^2 = -\hat{s}(1-z)\lambda, \quad \hat{u} = (p_2 - p_g)^2 = -\hat{s}(1-z)(1-\lambda) \]
Real radiation and plus dists.

* Extract singularities using plus distribution expansion

\[
\lambda^{-1-\epsilon} = -\frac{1}{\epsilon} \delta(\lambda) + \frac{1}{|\lambda|_+} - \epsilon \left[ \frac{\ln \lambda}{\lambda} \right]_+ + \mathcal{O}(\epsilon^2), \quad \text{etc.}
\]

\[
\int_0^1 dx f(x)[g(x)]_+ = \int_0^1 dx [f(x) - f(0)] g(x)
\]

\[
\Rightarrow \quad \frac{\alpha_s}{\pi} \frac{\Gamma(1 + \epsilon)}{(4\pi)^{-\epsilon}} \left( \frac{\mu^2}{\hat{s}} \right)^{\epsilon} \left\{ \begin{array}{l}
\text{cancels virtual poles} \\
\left[ \frac{3}{\epsilon^2} + \frac{3}{\epsilon} \right] \delta(1-z) - \frac{6}{\epsilon} \frac{1}{[1-z]_+} + \frac{6z(z^2 - z + 2)}{\epsilon} \\
(3 - \pi^2) \delta(1-z) - \frac{6}{[1-z]_+} + 12 \left[ \frac{\ln (1-z)}{1-z} \right]_+ - \frac{6(z^2 - z + 1)^2 \ln z}{1-z}
\end{array} \right.
\]

\[
- 12z(z^2 - z + 2) \ln(1-z) - \frac{11}{2} + \frac{57z}{2} - \frac{45z^2}{2} + \frac{23z^3}{2}
\]
PDF renormalization: counterterm for initial-state collinear singularities.

\[
\begin{align*}
\text{Altarelli-Parisi splitting function} & = \frac{\alpha_s \Gamma(1 + \epsilon)}{\pi} \frac{1}{(4\pi)^{-\epsilon}} \frac{1}{\epsilon} G_{gg}^{(0), q} \delta(1 - z) \\
& = \frac{\alpha_s \Gamma(1 + \epsilon)}{\pi} \frac{1}{(4\pi)^{-\epsilon}} \left\{ \left( \frac{11}{2} - \frac{N_F}{3} \right) \delta(1 - z) + \frac{6}{[1 - z]^+} - 6z(z^2 - z + 2) \right\} \left[ \frac{1}{\epsilon} + 1 \right]
\end{align*}
\]

Coefficient correction: 
\[
\frac{\alpha_s}{\pi} \left( \frac{11}{2} \right) \delta(1 - z)
\]

Can check that \((\mu^2/s)^\epsilon\) terms give \(\ln(\mu^2/s)\) upon expansion \(\Rightarrow\) combined with scale dependence of \(\alpha_s\) (implicit so far) and PDFs give estimate of theoretical uncertainty (can also get these logs from renormalization group considerations).
Final result

Final result for NLO correction:

\[
G_{gg}^{(1)} = \left( \frac{11}{2} + \pi^2 \right) \delta(1-z) + 12 \left[ \frac{\ln(1-z)}{1-z} \right] + 12z(-z + z^2 + 2)\ln(1-z)
\]

\[
-6\frac{(z^2 + 1 - z)^2}{1-z} \ln(z) - \frac{11}{2} (1-z)^3
\]

What is the source of the \( \pi^2 \)? Since \( 1/\epsilon^2 \) poles cancel, can change that \( \Gamma(1+\epsilon) \) normalizing the real, virtual can be exchanged for something that differs at \( O(\epsilon^2) \) ⇒ shuffles terms between R, V

\[
\Gamma(1+\epsilon) \rightarrow \frac{1}{\Gamma^2(1-\epsilon)\Gamma(1+\epsilon)} \Gamma^2(1-\epsilon)\Gamma^2(1+\epsilon) = N \left( 1 + \frac{\pi^2}{3} \epsilon^2 + O(\epsilon^4) \right)
\]

Real: \( N \left( 1 + \frac{\pi^2}{3} \epsilon^2 \right) \left( \frac{3}{\epsilon^2} - \pi^2 + \ldots \right) \delta(1-z) = N \left( \frac{3}{\epsilon^2} + \ldots \right) \)

Virtual: \( N \left( 1 + \frac{\pi^2}{3} \epsilon^2 \right) \left( -\frac{3}{\epsilon^2} + 2\pi^2 + \ldots \right) \delta(1-z) = N \left( -\frac{3}{\epsilon^2} + \pi^2 + \ldots \right) \)

Completely from analytic continuation: \( 6(-\mu^2/s)^\epsilon = (\mu^2/s)^\epsilon \times (6+\pi^2+\text{imaginary parts}+...) \)

From \( C_A=3 \) color, \( 2\times\text{Re}(M_0M_1^*) \)
Threshold logs and PDFs

- Logarithm is associated with soft radiation; is $z \to 1$ region enhanced?

- Begin with hadronic cross section in following form ($\tau = M^2/s$, $z = M^2/x_1x_2s$)

  $$\sigma_{had} = \tau \int_{\tau}^{1} dz \frac{\sigma(z)}{z} \mathcal{L}\left(\frac{\tau}{z}\right), \quad \mathcal{L}(y) = \int_{y}^{1} dx \frac{y}{x} f_1(x)f_2(y/x)$$

Assume $f_i \sim x^a(1-x)^b$; plot $L$ for various $\tau$, $b$ (‘$a$’ less important)

Look for peak near $z \approx 1$

Clear importance for $\tau \approx 1$; rapid fall-off of large-$z$ PDFs

$$\int_{0}^{1} dx \left[ \frac{\ln^n(1-x)}{1-x} \right]_{+}^{\theta(x-x_{cut})} = -\frac{1}{n+1} \ln^{n+1}(1-x_{cut})$$
Threshold logs and PDFs

* Shape of PDFs near 1 important for small $\tau$; large exponents in $(1-z)^b$ can enhance region where logs are large

A numerical question regarding how dominant the logarithmic terms are in the perturbative expansion; for Higgs, both plus dist. and $\delta(1-z)$ give large corrections (discussions in Kramer, Laenen, Spira hep-ph/9611272, Catani et al. hep-ph/0306211, Ahrens, Becher, Neubert, Yang 0809.4283)
Effective theory validity

* Clearly want to go beyond NLO, but the 3-loop massive computations in the full theory are intractable

$$\sigma_{NLO}^{\text{approx}} = \left( \frac{\sigma_{NLO}^{\text{EFT}}}{\sigma_{LO}^{\text{EFT}}} \right) \sigma_{QCD}^{LO}$$

% level or better for $M_H < 2m_t$, even gets >90% of correction above

Soft, collinear gluons do not resolve top-quark loop (e.g., soft gluons are eikonal $\times$ tree)
Kramer, Laenen, Spira; Marzani et al. 0801.2544

* Use EFT to go to NNLO

$$\sigma_{NNLO}^{\text{approx}} = \left( \frac{\sigma_{NNLO}^{\text{EFT}}}{\sigma_{LO}^{\text{EFT}}} \right) \sigma_{QCD}^{LO}$$

Harlander, 2009 Zurich Higgs workshop
Inclusive Higgs at NNLO

Full calculation at NNLO in the EFT and resummation of logarithms

Virtual-virtual

Real-virtual

Real-real

Harlander, Kilgore '02; Anastasiou, Melnikov ‘02; Ravindran, Smith van Neerven ‘03

Recent asymptotic expansion of sub-leading 1/m_t terms at NNLO indicates they are small
Low-\(p_T\) resummation

\* One more issue with result; go back and look at real radiation

\[
p_T^2 = \frac{\hat{t}\hat{u}}{\hat{s}} = \hat{s}(1-z)^2\lambda(1-\lambda)
\]

\[\Rightarrow |\tilde{M}|^2 \times PS \sim (p_T^2)^{-1-\epsilon}\]

Fine if \(p_T\) integrated, but what if experiment selects low \(p_T\)?

\[
\int_0^{p_T^{max}} (p_T^2)^{-1-\epsilon} \rightarrow \ln \frac{M_H}{p_T^{max}} \gg 1 \text{ for } M_H \gg p_T^{max}
\]

\* If low \(p_T\) selected, need resummation of \(\ln(M_H/p_T)\) terms

(Collins, Söper, Sterman ‘85; Berger, Qiu hep-ph/0210135; Bozzi et al. hep-ph/0302104; Balazs, Yuan and others)

Can show \[
\frac{d\sigma}{dY dp_T^2} \approx \left( \frac{d\sigma}{dY} \right)_{LO} \exp \left( -\frac{3\alpha_s}{2\pi} \ln^2 s/p_T^2 \right)
\]

(J. Owens, CTEQ SS 2000)

Systematically improvable beyond this leading approximation
Searches at the Tevatron and LHC
Tevatron analysis overview

* Inclusive gg→h→bb not feasible at low masses
* WBF only slightly adds to analyses designed for other channels
Combined exclusion limit

- No observation, so collaborations report 95% C.L. exclusion by combining many possible channels

Cross section excluded, normalized to SM

At high mass, all sensitivity from \( H \rightarrow WW \)

Most sensitive: \( Wh \rightarrow lvbb \)
**Wh → lνbb analysis**

Basic acceptance cuts:
- $p_T^l > 20$ GeV
- $E_T > 20$ GeV
- 2-3 jets, 1-2 b-tags
- $p_T^j > 20$ GeV

```
``Estimating the background contribution after applying the event selection to the WH candidate sample is an elaborate process````

W+jets: normalization from data; heavy-flavor fraction from ALPGEN for shape (tree-level)+data for norm.;
Do also uses NLO to check

Combined theory +experiment error

---

| Process      | 1 tag     | 2 tags     |
|--------------|-----------|------------|
| All Pretag Cands. | 50644.0 ± 0.0 | 57174.0 ± 0.0 |
| WW           | 56.2 ± 6.2 | 0.4 ± 0.1  |
| WZ           | 23.0 ± 1.7 | 4.8 ± 0.5  |
| ZZ           | 0.8 ± 0.1  | 0.2 ± 0.0  |
| TopLJ        | 121.3 ± 17.1 | 23.8 ± 3.9 |
| TopDid       | 48.8 ± 6.8  | 14.1 ± 2.3 |
| STopT        | 64.0 ± 9.3  | 1.8 ± 0.3  |
| STopS        | 40.6 ± 5.7  | 12.8 ± 2.1 |
| Z+jets       | 37.4 ± 5.5  | 2.1 ± 0.3  |
| Total MC     | 392.0 ± 35.0 | 59.9 ± 7.5  |
| Wbb          | 538.7 ± 162.5 | 70.3 ± 22.5 |
| Wcc/Wc       | 489.1 ± 150.9 | 6.8 ± 2.3  |
| Total HF     | 1027.8 ± 312.3 | 77.1 ± 24.7 |
| Mistags      | 458.0 ± 57.9  | 2.2 ± 0.6  |
| Non-W        | 135.5 ± 54.2  | 9.0 ± 3.6  |
| Total Prediction | 2013.3 ± 324.1 | 148.2 ± 26.1 |

```
``From CDF, after event selection````

CDF Note 9463; PRL 100 041801 (2008); Do Note 5828-CONF; PRL 102 051803 (2009)
Low-mass limits and projections

* Analysis improvements expected: better dijet mass resolution, increased acceptance

| Analysis       | Lum (fb⁻¹) | Higgs Events | Exp. Limit | Obs. Limit |
|----------------|------------|--------------|------------|------------|
| CDF NN+ME+BDT  | 2.7        | 8.4          | 4.8        | 5.8        |
| DØ ME+NN new   | 2.7        | 13.3         | 6.7        | 6.4        |

Results at m_H = 115 GeV: 95%CL Limits/SM

from M. Herndon, LoopFest 2009

Likely to have exclusion, possibility of 3σ at low mass (depends on Nature...)

CDF Run II Preliminary, m_H=115 GeV
Basic acceptance cuts (CDF):

- $p_T^1 > 20$ GeV
- $p_T^2 > 10$ GeV
- $E_T > 15 - 25$ GeV (for various final states)
- Look separately at 0,1,2+ jet bins

| Channel          | ee pre-selection | ee final  | $\mu\tau$ pre-selection | $\mu\tau$ final |
|------------------|------------------|-----------|--------------------------|-----------------|
| $Z \rightarrow ee$ | 218695 ± 704    | 108 ± 14  | 280.6 ± 3.3              | 0.0^{+0.3}_{-0.0} |
| $Z \rightarrow \mu\mu$ | -              | -         | 274.6 ± 0.9              | 5.8 ± 0.1       |
| $Z \rightarrow \tau\tau$ | 1135 ± 16      | 1.4 ± 0.5 | 3260 ± 3                | 7.3 ± 0.1       |
| $t\bar{t}$        | 131.4 ± 1.4     | 39.9 ± 0.8| 272.0 ± 0.3              | 82.5 ± 0.2      |
| $W$+jets          | 241 ± 5         | 98 ± 3    | 183 ± 4                  | 78.6 ± 2.8      |
| $WW$              | 172.2 ± 2.6     | 66.8 ± 1.6| 421.2 ± 0.1              | 154.7 ± 0.1     |
| $WZ$              | 112.5 ± 0.2     | 9.6 ± 0.06 | 20.5 ± 0.1               | 6.6 ± 0.1       |
| $ZZ$              | 98.2 ± 0.2      | 7.68 ± 0.07| 5.3 ± 0.1                | 0.60 ± 0.01     |
| Multijet          | 1351 ± 55       | 1.7^{+2.0}_{-1.7} | 279 ± 168            | 1.1^{+9.6}_{-1.1} |

Table: From Do

$tt$: affects 2-jet bin; taken from NLO calculations
$W$+jets: jet fakes lepton; from data-driven methods
$WW$: taken from NLO calculation
Kinematic discriminants

A primary handle for 0-jet bin: $\Delta \varphi_{ll}$
Spin correlation: leptons in same direction
High-mass exclusion

- Combine CDF+D0 exclusion limits: $160 \leq M_H \leq 170$ GeV at 95% CL

These are some of the largest systematics in the analysis; detailed QCD study crucial to perform this search!

Solidly exclude SM at 165 GeV
LHC physics overview

* Qualitative change; gluons now overwhelm scattering rate
LHC summary: low fb$^{-1}$

* Will reproduce expected Tevatron exclusion with 1 fb$^{-1}$
LHC summary: high fb^{-1}

* Entire mass range covered, much with multiple modes

\[ h \rightarrow \gamma\gamma, \text{ WBF } h \rightarrow \tau\tau \text{ cover low mass range} \]

\[ M_H > 200 \text{ GeV}: \text{ only few fb}^{-1} \]

\[ M_H < 120 \text{ GeV}: 20-30 \text{ fb}^{-1} \]

\[ h \rightarrow Z\bar{Z} \rightarrow 4l \text{ assures discovery over entire high-mass range} \]

\[ h \rightarrow WW \rightarrow l\nu l\nu \text{ again important at LHC} \]
h→ZZ→l₁l₁l₂l₂

- Trigger: one $p_T > 20 - 25$ GeV or two $p_T > 10 - 15$ GeV leptons
- Reconstruct: at least one $Z \rightarrow ll$ decay

Irreducible backgrounds:

- Formally NNLO, but enhanced by gg luminosity

Reducible: $t\bar{t} \rightarrow ll\nu\nu\bar{b}b$, Zbb with semi-leptonic b-decay
Trigger: 1-2 photons; Reconstruct: $p_T > 40$ GeV, $p_T > 25$ GeV
Excellent EM calorimeter resolution; calibrate with $Z \to ee$

Huge $\pi^0 \to \gamma \gamma$ background; measure from sideband

Additional handles with jets; consider $\gamma \gamma + j, 2j$

$f_0: 20-30$ fb$^{-1}$ for $M_{H_1} < 140$ GeV

Abdullin et al., hep-ph/9805341

Nisati, KITP '08
Two tagging jets: $E_T > 40$ GeV, $\eta_{jj} > 4$, $M_{jj} > 500-1000$ GeV
Higgs decay products between tagging jets; central-jet veto
$\tau\tau \to ll, lh$ modes possible

Central-jet veto a concern at high luminosities

Collinear approximation for $\tau$'s (highly boosted):

Data-driven techniques to control $Z\to\tau\tau$ line-shape

Mellado, CTEQ summer school ‘07
Global analysis of couplings

* Observe Higgs in many modes: gluon-fusion, WBF, W/Z+h (not discovery at LHC, but after $M_H$ known) Butterworth et al., 0802.2470

$$\sigma_p \times BR(h \rightarrow xx) = \frac{\sigma_p}{\Gamma_p}_{SM} \times \frac{\Gamma_p \Gamma_x}{\Gamma} \text{ measure}$$

Scaling degeneracy if total width unknown:

$$\Gamma_i \rightarrow f \Gamma_i, \Gamma \rightarrow f^2 \Gamma$$

Mild assumption: $g_{hVV}^2 < 1.05 \times g_{hVV,SM}^2$

Allows any # of scalar doublets, new particles in loops, small contributions of scalar triplets

$\Rightarrow$ Assumption+VBF measurement of $(\Gamma_V)^2/\Gamma$ breaks degeneracy

Duhrssen et al. hep-ph/0406323, Lafaye et al. 0904.3866
Measuring the Higgs potential

Form of SM Higgs potential makes definite predictions

\[ V(H) = \lambda \left( H^\dagger H - \frac{v^2}{2} \right)^2 \]

\[ g_{hhh} = \frac{3 M_H^2}{v} \]

Probe in \( gg \rightarrow hh \rightarrow W^+W^-W'^+W'^- \rightarrow l^+l'^- + 4j + \text{missing } p_T \)

(one possible final state)

super-LHC luminosity upgrade required

Baur, Plehn, Rainwater hep-ph/0211224
Conclusions

- We must find a Higgs boson or something else which consistently breaks EW symmetry
- Phenomenology of Higgs intricate and highly dependent on its mass; detailed experimental program needed to find it
- Very sensitive to quantum effects; better have a good handle on QCD!
- Tevatron beginning to reach into allowed SM mass region; LHC will pick up the search later this year
- Potential to determine whether the Higgs is SM or not with LHC measurements