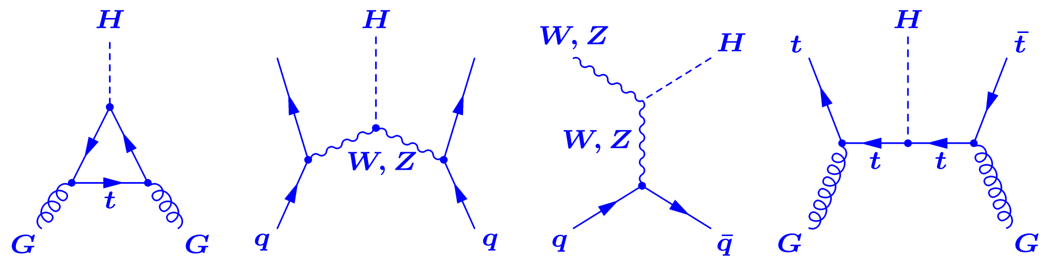
Electroweak Theory, SSB, and the Higgs: Lecture 4

- Higgs production at colliders

  - pp (LHC) and $\bar{p}p$ (Tevatron)



    – Gluon fusion (dominant at LHC, Tevatron) (probes $\bar{t}tH$ vertex)

    – Vector-boson fusion (forward jet tagging)

    – Higgstrahlung (W, Z tagging)

    – Associated $t\bar{t}H$

  - e^-e^+

    – Associated Z production (Higgstrahlung),
    $e^-e^+ \to Z \to ZH$
    (lower energy, e.g., LEP) ($H \to ZZ^*$ allows absolute width determination)

    – W fusion, $e^-e^+ \to \nu_e W^- W^+ \bar{\nu}_e \to \nu_e \bar{\nu}_e H$ (higher energy)
    (σ scales as $\ln(s/M_H^2)$ rather than $1/s$)

- Higgs decays

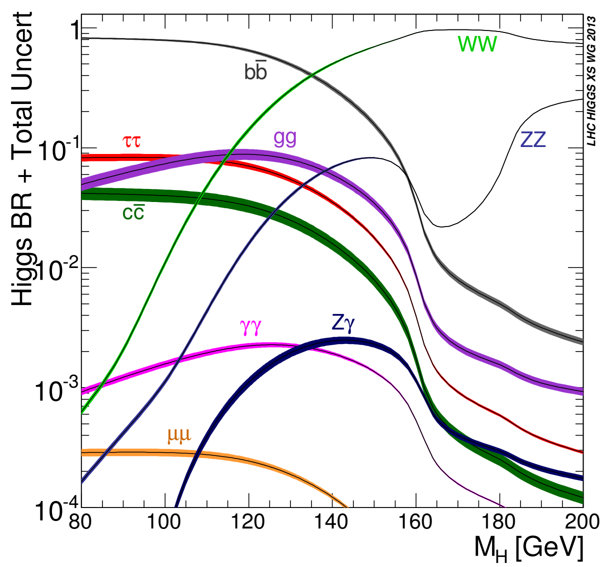
  - Large M_H: $H \to W^+W^-$ and $H \to ZZ$ dominate

    – Golden mode: ($H \to ZZ \to 4\ell$) (suppressed by the low leptonic branching ratios)

    – $H \to WW \to q\bar{q}\ell\nu$ and $H \to ZZ \to q\bar{q}\ell\bar{\ell}$ therefore critical

  - 135 GeV$< M_H < 2M_W \sim 161$ GeV: virtual WW^*; also ZZ^*, $\bar{b}b$

- Lower M_H: $\bar{b}b$ dominates
  - Difficult at hadron collider (QCD backgrounds); need associated forward jets, W, Z, or t
  - Cleanest: $H \to \gamma\gamma$ (loop level), $H \to ZZ^* \to 4\ell$
  - GG, $\tau^+\tau^-$, and $c\bar{c}$ also have significant branching ratios
- Very small width expected for light Higgs:
  (~ 4 MeV for $M_H = 125$ MeV)



$$\Gamma(H \to f\bar{f}) = C_f \frac{G_F m_f^2}{4\sqrt{2}\pi} \beta_f^3 M_H$$

($\beta_f = (1 - 4m_f^2/M_H^2)^{1/2}$ is fermion velocity; $C_f = 1$ (leptons) or 3 (quarks) is color factor)

$$\Gamma(H \to VV^\dagger) = \delta_V \frac{G_F}{16\sqrt{2}\pi}(1-x_V)^{1/2}\left(1 - x_V + \frac{3}{4}x_V^2\right) M_H^3, \qquad \text{(on-shell)}$$

($\delta_W = 2$, $\delta_Z = 1$, $x_V = 4M_V^2/M_H^2$)

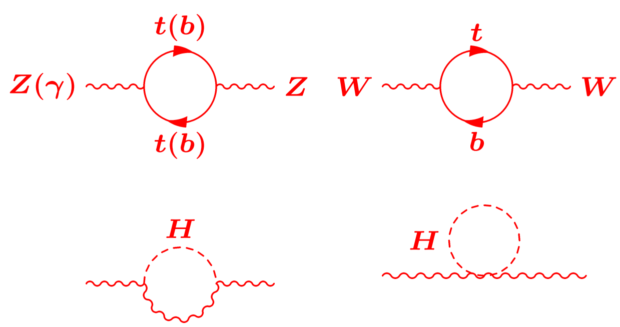
$$\Gamma(H \to GG) \sim \frac{G_F \alpha_s^2 M_H^3}{36\sqrt{2}\pi^3}$$

(t loop, for $M_H \ll 2m_t$; large QCD correction)

$$\Gamma(H \to \gamma\gamma) \sim \frac{G_F \alpha^2 M_H^3}{128\sqrt{2}\pi^3} \left| -7 + \frac{4}{3} C_t q_t^2 \right|^2$$

(W and t loops (cancellation), for $M_H \ll 2M_W$)

- Precision Electroweak Constraints
  - Affects M_W/M_Z and relation to $\sin^2\theta_W$ from vertices
  - $68 < M_H < 155$ GeV at 90% cl; central value: $M_H = 99^{+28}_{-23}$ GeV



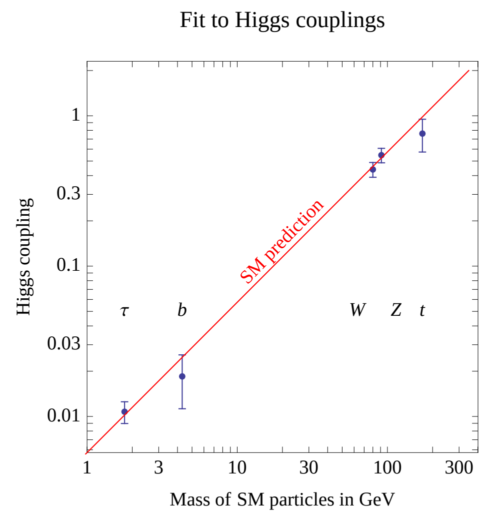
- Direct Searches at Colliders
  - LEP: Higgstrahlung, $e^-e^+ \to Z \to Z^* H$ or $e^-e^+ \to Z^* \to ZH$
    - $M_H < 114.4$ GeV at 95% (hint around 115 GeV)
  - Tevatron (CDF and D0)
    - Initially: excluded $\sim (160 - 170)$ GeV (from $H \to W^+W^-$)
    - Later: $b\bar{b}$, W^+W^-, ZZ, $\tau^-\tau^+$, and $\gamma\gamma$
    - Excluded $90 - 109$ and $149 - 182$ GeV
    - Broad excess from 115-140 GeV (mainly $Vb\bar{b}$)
    - Consistent with SM Higgs at 125 GeV at $\sim 3.0\sigma$ (local significance)

- LHC (ATLAS, CMS)
  - By 12/2011, excluded < 116 and $127 - 600$ GeV
  - Excesses in $\gamma\gamma$ and 4ℓ, $\ell = e^\pm$ or $\mu^\pm$
  - Summer 2012: $> 5\sigma$ discoveries of a Higgs-like particle of mass $\sim (125 - 126)$ GeV
  - Most important: $\gamma\gamma$ and $ZZ^* \to 4\ell$
  - $\Gamma_H < 6.9$ GeV from lineshape (resolution) (SM: 4 MeV)
  - Recent CMS: ($\Gamma_H < 22$ MeV comparing ZZ on H pole and above)
  - Evidence: $H \to WW^* \to \ell\nu\ell\nu$, $H \to \tau^-\tau^+$, $VH \to Vb\bar{b}$
  - Upper limits on $\mu^-\mu^+$, $Z\gamma$, "invisible"
  - Some separation of production mechanisms (+ branching ratios $\Rightarrow$ separation of couplings)
  - $J^{PC} = 0^{++}$ (expected for SM Higgs) established or strongly supported (e.g., $H \to ZZ^* \to 4\ell$ distributions, $H \to \gamma\gamma$), excluding some alternatives

$$H\bar{\psi}\psi,\ HV_\mu V^\mu \text{ (or } HV_{\mu\nu}V^{\mu\nu}) \qquad (H = 0^{++})$$

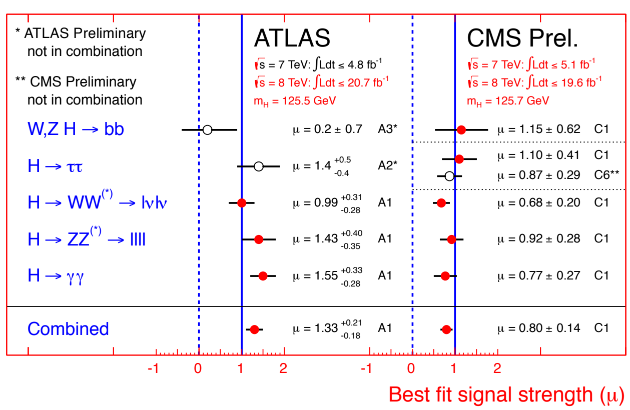
$$P\bar{\psi}\gamma^5\psi,\ PV_{\mu\nu}\tilde{V}^{\mu\nu},\ \text{where } \tilde{V}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}V_{\rho\sigma} \qquad (P = 0^{-+})$$

- Implications
  - Observed state is either the SM Higgs, or something very similar
  - Couplings proportional to a power of mass (to $h_f \equiv m_f/\nu$ for fermion f; to $h_V \equiv 2M_V^2/\nu$ for $V = W, Z$)



($\sqrt{2}h_f$ or $\sqrt{h_V/\nu}$ vs. mass; Giardano et al., 1303.3570)

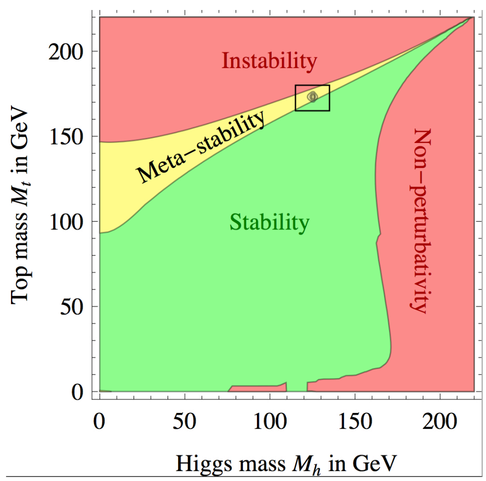
  - However, still significant uncertainties in couplings (20-40%) $\Rightarrow$ considerable room for new physics
  - Need precise measurements from LHC (higher $E, \mathcal{L}$) and possible future Higgs factories (e.g., ILC)



(Ratio of observed rate to SM expectation; PDG online update)

- Typical deviations in extended models $\sim (1-10)\%$
- Future LHC: $(5-10)\%$
- LHC can only measure $\sigma B_i = \sigma\Gamma(H \to i)/\Gamma_H$
- ILC (at 250 GeV): absolute $\Gamma(H \to ZZ)$ from $e^-e^+ \to Z^* \to ZH$ with Z-tagging; other absolute $\Gamma(H \to i)$ and Γ_H from branching ratios
- ILC (at 500-1000 GeV): WW fusion dominates; precise couplings, including (direct) $t\bar{t}H$ and HHH, many at 1%
- CLIC; TLEP, Chinese study (possible first stage of pp collider)

- M_H on borderline between SM (large M_H) and MSSM (small M_H) expectations
- Metastable vacuum for new physics scale $\gtrsim 10^{11}$ GeV



(Degrassi et al., 1205.6497)