Higgs Bosons at the LHC

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Goals of Higgs Physics

SM Channels

MSSM: H/A and H±

Coupling measurements

QCD Corrections

HVV vertex structure

Conclusions
Goals of Higgs Physics

Higgs Search = search for dynamics of $SU(2) \times U(1)$ breaking

- **Discover the Higgs boson**
- **Measure its couplings** and probe mass generation for gauge bosons and fermions

Fermion masses arise from Yukawa couplings via

$$\Phi^\dagger \rightarrow (0, \frac{v+H}{\sqrt{2}})$$

$$\mathcal{L}_{\text{Yukawa}} = -\Gamma_{d}^{ij} \bar{Q}_{L}^{i} \Phi d_{R}^{j} - \Gamma_{d}^{ij} \bar{d}_{R}^{i} \Phi^{\dagger} Q_{L}^{j} + \ldots = -\Gamma_{d}^{ij} \frac{v+H}{\sqrt{2}} d_{L}^{i} d_{R}^{j} + \ldots$$

$$= - \sum_{f} m_{f} \bar{f} f \left(1 + \frac{H}{v}\right)$$

- Test SM prediction: $\bar{f} f H$ Higgs coupling strength $= m_{f} / v$
- Observation of $H f \bar{f}$ Yukawa coupling is no proof that v.e.v exists
Higgs coupling to gauge bosons

Kinetic energy term of Higgs doublet field:

\[(D^\mu \Phi)^\dagger (D_\mu \Phi) = \frac{1}{2} \partial^\mu H \partial_\mu H + \left( \frac{g v}{2} \right)^2 W^\mu W^-_\mu + \frac{1}{2} \frac{(g^2 + g'^2) v^2}{4} Z^\mu Z_\mu \right) \left( 1 + \frac{H}{v} \right)^2\]

- $W, Z$ mass generation: $m_W^2 = \left( \frac{g v}{2} \right)^2, m_Z^2 = \frac{(g^2 + g'^2) v^2}{4}$

- $WWH$ and $ZZH$ couplings are generated

- Higgs couples proportional to mass: coupling strength $= 2 m_V^2 / v$ within SM

Measurement of $WWH$ and $ZZH$ couplings is essential for identification of $H$ as agent of symmetry breaking: Without a v.e.v. such a trilinear coupling is impossible at tree level
Verify tensor structure of $HVV$ couplings. Loop induced couplings lead to $HV_{\mu \nu} V^{\mu \nu}$ effective coupling and different tensor structure: $g_{\mu \nu} \rightarrow q_1 \cdot q_2 g_{\mu \nu} - q_1 \nu q_2 \mu$
The MSSM Higgs sector

The SM uses the conjugate field $\Phi_c = i\sigma_2 \Phi^*$ to generate down quark and lepton masses. In supersymmetric models this must be an independent field

$$\mathcal{L}_{\text{Yukawa}} = -\Gamma_d \bar{Q}_L \Phi_1 d_R - \Gamma_e \bar{L}_L \Phi_1 e_R + \text{h.c.}$$
$$-\Gamma_u \bar{Q}_L \Phi_2 u_R + \text{h.c.}$$

Two complex Higgs doublet fields $\Phi_1$ and $\Phi_2$ receive mass and v.e.v.s $\nu_1, \nu_2$ from generalized Higgs potential. Mass eigenstates constructed out of these 8 real fields are

**Neutral sector:**
2 CP even Higgs bosons: $h$ and $H$
1 CP odd Higgs boson: $A$
1 Goldstone boson: $\chi_0$

**Charged sector:**
charged Higgs bosons: $H^\pm$
charged Goldstone boson: $\chi^\pm$

Goldstone bosons absorbed as longitudinal degrees of freedom of $Z, W^\pm$. 

Fermions

Two doublet fields mix, two v.e.v’s

\[ v_1 = v \cos \beta, \quad v_2 = v \sin \beta: \]

\[
\mathcal{L}_{\text{Yuk.}} = -\Gamma_b \bar{b}_L \Phi_1^0 b_R - \Gamma_t \bar{t}_L \Phi_2^0 u_R + \text{h.c.}
\]

\[ = -\Gamma_b \bar{b}_L \frac{v_1 + H \cos \alpha - h \sin \alpha + i A \sin \beta}{\sqrt{2}} b_R - \Gamma_t \bar{t}_L \frac{v_2 + H \sin \alpha + h \cos \alpha + i A \cos \beta}{\sqrt{2}} t_R + \ldots \]

Expressed in terms of masses the Yukawa Lagrangian is

\[
\mathcal{L}_{\text{Yuk.}} = -\frac{m_b}{v} \bar{b} \left( v + H \frac{\cos \alpha}{\cos \beta} - h \frac{\sin \alpha}{\cos \beta} - i \gamma_5 A \tan \beta \right) b - \frac{m_t}{v} \bar{t} \left( v + H \frac{\sin \alpha}{\sin \beta} + h \frac{\cos \alpha}{\sin \beta} - i \gamma_5 A \cot \beta \right) t
\]

\[ \Rightarrow \text{coupling factors compared to SM } hff \text{ coupling } -i \frac{m_f}{v} \]

Gauge Bosons

extra coupling factors for \( hVV \) and \( HVV \) couplings as compared to SM

\[ hVV \sim \sin(\beta - \alpha) \quad HVV \sim \cos(\beta - \alpha) \]
$m_H = 91^{+45}_{-32} \text{ GeV}$

Including theory uncertainty

$m_H < 186 \text{ GeV} \ (95\% \ CL)$

Does not include

Direct search limit from LEP

$m_H > 114 \text{ GeV} \ (95\% \ CL)$

Renormalize probability for

$m_H > 114 \text{ GeV} \to 100\%:

$m_H < 219 \text{ GeV} \ (95\% \ CL)$
Higgs boson channels at LHC

Two steps

- **Production** of the Higgs boson
- **Detection** of the decay products of the Higgs boson and identification of the events
Production Modes

Gluon fusion

Weak-Boson Fusion

Higgs Strahlung

$t\bar{t}H$
Total cross sections at the LHC

\[ \sigma(pp \rightarrow H + X) \text{[pb]} \]
\[ \sqrt{s} = 14 \text{ TeV} \]
NLO / NNLO

\[ gg \rightarrow H \text{ (NNLO)} \]
\[ q\bar{q} \rightarrow HW \]
\[ qq \rightarrow Hqq \]
\[ gg/q\bar{q} \rightarrow t\bar{t}H \text{ (NLO)} \]
\[ q\bar{q} \rightarrow HZ \]

[Krämer ('02)]
Higgs decay width and branching fractions within the SM
BR(\(H \rightarrow \gamma\gamma\)) \(\approx 10^{-3}\)

- large backgrounds from \(q\bar{q} \rightarrow \gamma\gamma\) and \(gg \rightarrow \gamma\gamma\)
- but CMS and ATLAS will have excellent photon-energy resolution (order of 1%)
- Look for a narrow \(\gamma\gamma\) invariant mass peak
- extrapolate background into the signal region from sidebands.
\( H \rightarrow ZZ \rightarrow \ell^+\ell^- \ell^+\ell^- \)

✓ invariant mass of the charged leptons fully reconstructed

For \( m_H \approx 0.6–1 \text{ TeV} \), use the “silver-plated” mode \( H \rightarrow ZZ \rightarrow \nu \nu \ell^+\ell^- \)

✓ \( \text{BR}(H \rightarrow \nu \nu \ell^+\ell^-) = 6 \times \text{BR}(H \rightarrow \ell^+\ell^- \ell^+\ell^-) \)

✓ the large missing \( E_T \) allows a measurement of the transverse mass
Exploit $\ell^+\ell^-$ angular correlations

measure the transverse mass with a Jacobian peak at $m_H$

$$m_T = \sqrt{2 \ p_T^{\ell\ell} \ E_T \ (1 - \cos (\Delta \Phi))}$$

background and signal have similar shape $\implies$ must know the background normalization precisely

$H \to WW \to \ell^+\bar{\nu}\ell^--\nu$

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Most measurements can be performed at the LHC with statistical accuracies on the measured cross sections times decay branching ratios, $\sigma \times BR$, of order 10% (sometimes even better).
Characteristics:

- Energetic jets in the forward and backward directions ($p_T > 20$ GeV)
- Higgs decay products between tagging jets
- Little gluon radiation in the central-rapidity region, due to colorless $W/Z$ exchange (central jet veto: no extra jets with $p_T > 20$ GeV and $|\eta| < 2.5$)

$$\eta = \frac{1}{2} \log \frac{1 + \cos \theta}{1 - \cos \theta}$$
Higgs discovery potential

\[ \int L \, dt = 30 \text{ fb}^{-1} \]
(no K-factors)

\[ \frac{S}{\sqrt{B}} \]

ATLAS

- \( H \to \gamma\gamma \)
- \( t\bar{t}H (H \to bb) \)
- \( H \to ZZ^{(*)} \to 4l \)
- \( H \to WW^{(*)} \to l\ell l\ell \)
- \( q\bar{q}H \to q\bar{q} WW^{(*)} \)
- \( q\bar{q}H \to q\bar{q} \tau\tau \)

Total significance
Reach for H/A discovery within MSSM

Enhancement of \( H_{bb} \) and \( A_{bb} \) coupling by factor \( \tan \beta \) compared to SM Higgs

\[ \rightarrow \text{large production cross section for } pp \rightarrow \bar{b}bH/A \]

\[ \rightarrow \text{decay dominated by } H/A \rightarrow \bar{b}b, \tau^+\tau^- \]

5\(\sigma\) discovery contours
Reach for $H^\pm$ discovery within MSSM

- For $m_{H^\pm} > m_t + m_b$ expect $H^\pm \to tb$ decay
- Dominant production process
  \[ gg \to H^\pm tb \]
b-quark has low $p_T$:
  \[ gb \to H^\pm t \] is dominant sub-process
- Main background from $\bar{t}t (+\text{jets})$ production

5σ discovery contours
Statistical and systematic errors at LHC

- **QCD/PDF uncertainties**
  - ±5% for WBF
  - ±20% for gluon fusion

- **luminosity/acceptance uncertainties**
  - ±5%

Assumed errors in fits to couplings:

- Solid: gluon fusion
- Dashed: WBF
- Dotted: ttH

\[ \frac{\Delta \sigma_H}{\sigma_H} = \sqrt{\frac{N_S + N_B}{N_S}} \]

200 fb^{-1} of data
Measuring Higgs couplings at LHC

LHC rates for partonic process \( pp \to H \to xx \) given by \( \sigma(pp \to H) \cdot BR(H \to xx) \)

\[
\sigma(H) \times BR(H \to xx) = \frac{\sigma(H)^{\text{SM}}}{\Gamma_{p}^{\text{SM}}} \cdot \frac{\Gamma_{p} \Gamma_{x}}{\Gamma},
\]

Measure products \( \Gamma_{p} \Gamma_{x}/\Gamma \) for combination of processes (\( \Gamma_{p} = \Gamma(H \to pp) \))

**Problem:** rescaling fit results by common factor \( f \)

\[
\Gamma_{i} \to f \cdot \Gamma_{i}, \quad \Gamma \to f^{2} \Gamma = \sum_{\text{obs}} f \Gamma_{i} + \Gamma_{\text{rest}}
\]

leaves observable rate invariant \( \implies \) no model independent results at LHC

Loose bounds on scaling factor:

\[
f^{2} \Gamma > \sum_{\text{obs}} f \Gamma_{x} \implies f > \sum_{\text{obs}} \frac{\Gamma_{x}}{\Gamma} = \sum_{\text{obs}} BR(H \to xx) (= \mathcal{O}(1))
\]

Total width below experimental resolution of Higgs mass peak (\( \Delta m = 1 \ldots 20 \text{ GeV} \))

\[
f^{2} \Gamma < \Delta m \implies f < \sqrt{\frac{\Delta m}{\Gamma}} < \mathcal{O}(10 - 40)
\]
Fit LHC data within constrained models

- $\frac{g_{H\tau\tau}}{g_{Hbb}} = $ SM value
- $\frac{g_{HWW}}{g_{HZZ}} = $ SM value
- no exotic channels

With 200 fb$^{-1}$ measure partial width with 10–30% errors, couplings with 5–15% errors
Alternative: compare data to predictions of specific models
Example: $m_H^{\text{max}}$ scenario of LEP analyses

Consider modest $m_A$:

- decoupling almost complete for $hWW$ and $h\gamma\gamma$ (effective) vertices
- enhanced $hbb$ and $h\tau\tau$ couplings compared to SM increases total width of $h$

$$\implies$$

- $\approx$ SM rates for $h\rightarrow\tau\tau$ in WBF
- suppressed $h\rightarrow\gamma\gamma$ and $h\rightarrow WW$ rates in WBF
QCD corrections for Higgs production

Measurement of partial widths at 10–20% level or couplings at 5–10% level requires predictions of SM production cross sections at 10% level or better

→ need QCD corrections to production cross sections

Much work in recent years

- $gg\to H$ (all but NLO in $m_t\to\infty$ limit)
  - NLO for finite $m_t$: Graudenz, Spira, Zerwas (1993)
  - NNLL: Catani, de Florian, Grazzini, Nason (2003)

- weak boson fusion
  - total cross section at NLO: Han, Willenbrock (1991)

- $\bar{t}tH$ associated production at NLO: Beenakker et al.; Dawson, Orr, Reina, Wackeroth (2002)

- $\bar{b}bH$ associated production at NLO: Dittmaier, Krämer, Spira; Dawson et al. (2003)
QCD corrections to $gg \rightarrow H$

Huge improvement in recent years

Remaining scale uncertainty below 10%

Uncertainty from gluon pdf $\approx 4 - 7$

What is K-factor for cross section with cuts?

Most problematic: central jet veto against $\bar{t}t$ background for $H \rightarrow WW$ search
NLO QCD corrections to WBF

- Small QCD corrections of order 10%
- Tiny scale dependence of NLO result
  - ±5% for distributions
  - < 2% for \( \sigma_{\text{total}} \)
- K-factor is phase space dependent
- QCD corrections under excellent control
- Need electroweak corrections for 5% uncertainty

\[ m_H = 120 \text{ GeV}, \text{ typical WBF cuts} \]
NLO QCD corrections to $b\bar{b}H$ production

- Discovery channel for $H/A$ in the MSSM at sizeable $\tan \beta$
- NLO corrections known for $\bar{b}bH$ final state
- $b$-quarks at low $p_T$: effective process is $\bar{b}b \rightarrow H$: cross section known at NNLO

Harlander, Kilgore (2003)

scale dependence of inclusive vs. double $b$-tagged cross section
Tensor structure of the $HVV$ coupling

Most general $HVV$ vertex $T^{\mu\nu}(q_1, q_2)$

\[
T^{\mu\nu} = a_1 g^{\mu\nu} + a_2 (q_1 \cdot q_2 g^{\mu\nu} - q_1^\gamma q_2^\mu) + a_3 \varepsilon^{\mu\nu\rho\sigma} q_1^\rho q_2^\sigma
\]

The $a_i = a_i(q_1, q_2)$ are scalar form factors

Physical interpretation of terms:

- **SM Higgs** \( \mathcal{L}_I \sim HV_\mu V^\mu \rightarrow a_1 \)
  - Loop induced couplings for neutral scalar

- **CP even** \( \mathcal{L}_{\text{eff}} \sim HV_{\mu\nu} V^{\mu\nu} \rightarrow a_2 \)

- **CP odd** \( \mathcal{L}_{\text{eff}} \sim HV_{\mu\nu} \tilde{V}^{\mu\nu} \rightarrow a_3 \)
  - Must distinguish $a_1, a_2, a_3$ experimentally
Tell-tale signal for non-SM coupling is azimuthal angle between tagging jets

Dip structure at $90^\circ$ (CP even) or $0/180^\circ$ (CP odd) only depends on tensor structure of $HVV$ vertex. Very little dependence on form factor, LO vs. NLO, Higgs mass etc.
Effective $Hgg$ vertex is induced via top-quark loop

\[ \text{CP – even : } \quad i \frac{m_t}{v} \rightarrow H G^{a}_{\mu \nu} G^{\mu \nu, a} \text{ coupling} \]

\[ \text{CP – odd : } \quad m_t \gamma_5 \rightarrow H G^{a}_{\mu \nu} \tilde{G}^{\mu \nu, a} \text{ coupling} \]

Consider $Hjj$ production via gluon fusion, e.g.

Parton level analysis with relevant backgrounds

(Hankele, Klämke, DZ, hep-ph/0605117)

\[ \rightarrow \text{ Difference visible in } Hjj, H \rightarrow WW \rightarrow l^+ l^- \not{p}_T \text{ events at } m_H \approx 160 \text{ GeV with } 30 \text{ fb}^{-1} \text{ at } 6\sigma \text{ level} \]

Method can be generalized for any Higgs mass. Problem is lower signal rate for $h \rightarrow \tau \tau$ or $h \rightarrow \gamma \gamma$
Summary

- LHC will observe a SM-like Higgs boson in multiple channels, with $5\ldots20\%$ statistical errors
  $\implies$ great source of information on Higgs couplings

- Extraction of couplings at the LHC requires knowledge of NLO QCD corrections for signal and important backgrounds

- Absence of $HVV$ and $AVV$ couplings for the heavy $H/A$ of supersymmetry make their observation more challenging
  $\implies$ Need sizable $\tan\beta$ rate enhancement for discovery

- Higgs boson CP properties from jet-angular correlations in WBF and gluon fusion
\( t\bar{t}H \rightarrow t\bar{t}b\bar{b} \)

- \( h_t = t\bar{t}H \) Yukawa coupling \( \Rightarrow \) measure \( h_t^2 \times BR(H \rightarrow b\bar{b}) \)
- \( \times \) must know the background normalization precisely