Production and Decay of Higgs Bosons
Higgs Channels at the LHC
Analysis of Effective Higgs Couplings
Combining Poisson and Gaussian Errors
Determining Errors on Couplings
Main Higgs-boson production modes:

- **Gluon-Gluon Fusion**

- **Vector-Boson Fusion**

- **Associated Production with a Gauge Boson**

- **Associated Production with Top-Quark–Antiquark Pair**
**Higgs-Boson Decays**

- $H \rightarrow b \bar{b}$
  - Main decay mode ($\sim 90\%$) for light Higgs bosons, as suggested by electroweak precision data
  - Hard to extract from QCD backgrounds
  - Combination with $ttH$ production hard to observe because of combinatorial background (4 bottom quarks in final state)
  - Recent suggestion of $WH/ZH$ production plus jet substructure analysis looks promising
Higgs-Boson Decays

\[ H \rightarrow WW \]

- Main decay mode for heavier Higgs bosons \((m_H \gtrsim 140 \text{ GeV})\)
- Two leptonic decays of the \(W\) allow only reconstruction of transverse mass of the \(WW\) pair
- Gluon and vector-boson fusion relevant even if \(W\)'s are off-shell
- Associated \(WH/ZH\) and \(t\bar{t}H\) production only for heavier Higgs bosons

![Graph showing branching ratios for different Higgs decay modes vs. Higgs boson mass](image-url)
Higgs-Boson Decays

- $H \rightarrow ZZ$
  - “Golden Channel” due to four-lepton final state
  - Combination with gluon and vector-boson fusion production
  - Statistically limited to larger Higgs masses

- $H \rightarrow \tau\tau$
  - Need to reconstruct invariant mass of the two taus
  - Limits production channel to vector-boson fusion
  - One of the discovery channels for light Higgs bosons

![Graph showing branching ratios for Higgs boson decays](image-url)
Higgs-Boson Decays

- \( H \to \gamma\gamma \)
  - Loop-induced coupling by (mainly) \( W \) and \( t \)
  - Only fully reconstructable channel for a light Higgs boson
  - Small branching ratio \((\lesssim 0.2\%\))
  - Promising discovery channel for light Higgs bosons, background can be subtracted via sidebands
  - Higgs mass measurement up to 100 MeV

[CMS-TDR]
Higgs-Boson Decays

Decays not considered in our analysis:

1. \( H \rightarrow Z\gamma \)
   - Similar features to the two-photon channel
   - Reduced branching ratio (phase-space suppression)
   - Additional leptonic branching ratio of the \( Z \)

2. \( H \rightarrow \mu\mu \)
   - Excellent \( \mu\mu \) invariant mass reconstruction
   - Might be observable similar to two-photon decay
   - Combination with vector-boson fusion production mode

3. \( H \rightarrow \text{invisible} \)
   - Important for new physics
   - Best seen in combination with vector-boson fusion
     (Two tagging jets recoiling against missing energy)

4. \( H^* \rightarrow HH, HHH \)
   - Triple Higgs coupling can in principle be seen at the LHC
   - Relies on precision measurement of all other parameters
   - Quartic Higgs coupling not measurable at any considered collider
General Higgs Sector

- Theory: Standard Model plus general Higgs sector
- For Higgs couplings present in the Standard Model \( j = W, Z, t, b, \tau \) replace general couplings by

\[
g_{Hjj} \rightarrow g_{Hjj}(1 + \frac{\Delta_{Hjj}}{g_{Hjj}}) \equiv g_{Hjj}(1 + \delta_{Hjj})
\]

- For loop-induced Higgs couplings \( j = \gamma, g \) replace by

\[
g^{\text{SM}}_{Hjj} \rightarrow g_{Hjj}(1 + \frac{\Delta_{Hjj}}{g_{Hjj}}) \equiv g_{Hjj} + \delta_{Hjj} \cdot g^{\text{SM}}_{Hjj}
\]

where \( g_{Hjj} \): Using general couplings of loop particles

\( g^{\text{SM}}_{Hjj} \): Using Standard Model couplings of loop particles

- Additional free parameters:
  - Higgs boson mass \( m_H \)
  - Top-quark mass \( m_t \)
  - Bottom-quark mass \( m_b \)

- Experimental input:
  ATLAS study on Higgs couplings

[Dührssen, references therein]
Need to scan high-dimensional parameter space

⇒ SFitter

General Higgs couplings from modified version of HDecay

Three scanning techniques:
  - Gradient Minimisation (Minuit)
  - Grid scan
  - Weighted Markov Chain

Output of SFitter:
  - Fully-dimensional log-likelihood map
  - Reduction to plotable one- or two-dimensional distributions via both
    - Bayesian (marginalisation) or
    - Frequentist (profile likelihood) techniques
  - List of best points
Results

LHC data set with $30 \text{ fb}^{-1}$:
Frequentist: True data set

Smeared data set
LHC data set with $30 \text{ fb}^{-1}$:
Frequentist: Smeared data set

Bayesian:

Smeared dataset leads to shifted best-fitting points
Can see expected correlations between Higgs couplings
### Results (2)

List of best points: True data set

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<table>
<thead>
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<td>bb</td>
<td>γγ</td>
<td>gg</td>
<td>m_H</td>
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Smeared data set

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<th>$HZZ$</th>
<th>$Ht\bar{t}$</th>
<th>$Hb\bar{b}$</th>
<th>$H\tau\bar{\tau}$</th>
<th>$H\gamma\gamma$</th>
<th>$Hgg$</th>
<th>$m_H$</th>
<th>$m_b$</th>
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Looking at the $Hb\bar{b}$ coupling:

Channel $ttH, H \rightarrow b\bar{b}$ significantly degraded in performance when including NLO results

Recent jet substructure analysis looks promising

[Butterworth, Davison, Rubin, Salam]
Errors

- Statistical errors on individual channels of Poisson type
- Systematic errors (luminosity, tagging efficiency, . . .) extracted from large event samples ⇒ Gaussian
- Need to combine
  - Poisson $P_P(d, m) = \frac{\exp(-m)m^d}{\Gamma(d+1)}$ and
  - Gaussian $P_G(d, m, \sigma) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(d-m)^2}{2\sigma^2}\right)$ errors
- Mathematically correct way: convolution
- No analytic solution, numerical integration too time-consuming
- ⇒ Approximate formula:

$$\frac{1}{\tilde{\chi}^2} \equiv \frac{1}{-2 \log L} = \sum_i \frac{1}{-2 \log L_i}$$

- Yields exact formula for Gaussian-only (adding errors in quadrature)
- Gives correct result when one error approaches 0 or $\infty$
Errors

Approximate formula for Gauss and Poisson errors:

\[
\frac{1}{\chi^2} = \frac{1}{-2 \log L} = \sum_i \frac{1}{-2 \log L_i}
\]

\[
\rightarrow \frac{1}{-2 \log L_P} + \frac{1}{-2 \log L_G}
\]

\[
= \frac{1}{-2 \log P_P(d, m)/P_P(m, m)} + \frac{\sigma^2}{-2(d - m)^2}
\]

Example: Poisson\((d = 5)\), Gauss\((\sigma = 0.5)\)

\[
\Rightarrow \text{Very good agreement with exact convolution}
\]

\[
\Rightarrow \text{Difference almost always positive} \Rightarrow \text{slight overestimation of Higgs-coupling errors (good!)}
\]
Determination of errors on Higgs couplings:

- Perform 10,000 toy experiments with measurements smeared around correct value
- Minimise each toy experiment
- Plot resulting distribution of parameter points and fit with Gaussian

Results:

<table>
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Determining the Higgs-boson couplings next step after discovery
Important for our understanding of electroweak symmetry breaking

Independent of explicit realisation of new physics (if any):
Standard Model with effective Higgs couplings

Problem of high-dimensional parameter space with correlated measurements
⇒ Dedicated tool: SFitter

Obtain Standard Model couplings for true data
For smeared data result shifted within errors
Observe expected correlations between Higgs couplings
Recently suggested jet substructure analysis can improve result on bottom-quark coupling

Analysis of errors on couplings
Supersymmetric scenario with non-SM couplings