Measuring Higgs Couplings

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Eugene, 4/2012
Where we stand

Around Moriond 2012

- ATLAS and CMS results published
- official line: ‘exclusion gone wrong’ [in many channels]
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  MSSM one example [tons of papers]
  hypersphere in $m_{t_{L/R}}$, $\tan \beta$, $A_t$, $\mu$, $m_A$ predicting little $[x_t^2/(m_{t_1} m_{t_2}) \gtrsim 1]$
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⇒ but Graham wants technical details [skipping references, wrote the talk on plane]
Where we are going

The model

– assume: we see a scalar $\left[ ZZ \text{ and WBF correlations} \right]$
  it is a narrow resonance
  SM-like D4 structures
  self coupling out of reach $\left[ \text{Baur et al} \right]$

– production & decay combinations

$$
\begin{align*}
gg & \rightarrow H \\
qq & \rightarrow qqH \\
gg & \rightarrow ttH \\
q\bar{q}' & \rightarrow WH \\
\text{plus a little problem}
\end{align*}
$$

$$
\begin{align*}
H & \rightarrow ZZ \\
H & \rightarrow WW \\
H & \rightarrow b\bar{b} \\
H & \rightarrow \tau^+\tau^- \\
H & \rightarrow \gamma\gamma \\
H & \rightarrow Z\gamma \\
\ldots
\end{align*}
$$

signal $\times$ trigger
backgrounds
Gauss/Poisson statistics
systematics
theory errors
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\begin{array}{c}
gg \to H \\
qq \to qqH \\
gg \to t\bar{t}H \\
q\bar{q}' \to WH \\
\text{plus a little problem}
\end{array}
\quad \leftrightarrow \quad
\begin{array}{c}
H \to ZZ \\
H \to WW \\
H \to b\bar{b} \\
H \to \tau^+\tau^- \\
H \to \gamma\gamma \\
H \to Z\gamma \\
\ldots
\end{array}
\]

signal \times \text{trigger}
backgrounds
Gauss/Poisson statistics
systematics
theory errors

Why 125 GeV is just perfect \[\text{[Zeppenfeld et al; Dührssen et al; SFitter 2009]}\]

– parameters: Higgs couplings to \(W, Z, t, b, \tau, g, \gamma\) \[\text{[SM-like D4 operators]}\]

\[
g_{HXX} = g_{HXX}^{SM} (1 + \Delta_X) \quad g_{HWW} > 0
\]

– measurements: \(GF: H \to ZZ, WW, \gamma\gamma\)
  \(WBF: H \to ZZ, WW, \gamma\gamma, \tau\tau\)
  \(VH: H \to b\bar{b}\)
  \(t\bar{t}H: H \to \gamma\gamma, b\bar{b}\)

\[\Rightarrow \text{perfect application for SFitter}\]
Markov chains

**Probability maps**  [statistics questions go to Kyle]

- honest LHC parameters: weak-scale Lagrangean  
  [Higgs, MSSM, dark matter,...]
- likelihood map: data given a model  \( p(d|m) \sim |\mathcal{M}|^2(m) \)
- Bayes’ theorem:  \( p(m|d) = p(d|m) \frac{p(m)}{p(d)} \)  
  \([p(d) \text{ normalization, } p(m) \text{ prejudice}]\)

Markov chains

- problem in grid: huge phase space, find local best points? 
  problem in fit: domain walls, find global best points?
- construct ‘representative’ poll
- classical: representative set of spin states 
  compute average energy on this reduced sample
- BSM or Higgs: map  \( p(d|m) \) of parameter points 
  evaluate whatever you want
- Metropolis-Hastings 
  starting probability  \( p(d|m) \) vs suggested probability  \( p(d|m') \)
  1– accept new point if  \( p(d|m') > p(d|m) \)
  2– or accept with  \( p(d|m')/p(d|m) < 1 \)
SFitter 1: Markov chains

Weighted Markov chains [Lafaye, TP, Rauch, Zerwas; Ferrenberg, Swendsen]

- special situation
  measure of ‘representative’: probability itself
- example with 2 bins, probability 9:1
  10 entries needed for good Markov chain
  2 entries needed if weight kept
- binning with weight would double count
  bin with inverse averaging

\[
P_{\text{bin}}(p \neq 0) = \frac{\text{bincount}}{\sum_{i=1}^{\text{bincount}} p^{-1}}
\]

- good choice for \( O(6) \) dimensions
SFitter 1: Markov chains

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  \]
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Cooling Markov chains  [Lafaye, TP, Rauch, Zerwas]

- zoom in on peak structures  [inspired by simulated annealing]
- modified condition
  Markov chain in 100 partitions, numbered by $j$
  \[
  \frac{p(m')}{p(m)} > r^{100/j} \quad \text{with} \quad c \sim 10, \quad r \in [0, 1] \quad \text{random number}
  \]
- check for parameter coverage with many Markov chains
  ⇒ exclusive likelihood map first result
SFitter 2: Frequentist vs Bayesian

Getting rid of model parameters

- poorly constrained parameters
- uninteresting parameters
- unphysical parameters  [JES part of $m_t$ extraction]

- two ways to marginalize likelihood map

1. integrate over probabilities
   normalization etc mathematically correct
   integration measure unclear
   noise accumulation from irrelevant regions
   classical example: convolution of two Gaussians
SFitter 2: Frequentist vs Bayesian

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1. integrate over probabilities
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   - classical example: convolution of two Gaussians

2. profile likelihood \( \mathcal{L}(\ldots, x_{j-1}, x_{j+1}, \ldots) \equiv \max_{x_j} \mathcal{L}(x_1, \ldots, x_n) \)
   - no integration needed
   - no noise accumulation
   - not normalized, no comparison of structures
   - classical example: best-fit point

- one-dimensional parameter distributions second target
SFitter 3: Error analysis

Sources of uncertainty

- statistical error: Poisson
  systematic error: Gaussian, if measured
  theory error: not Gaussian

- simple argument
  LHC rate 10% off: no problem
  LHC rate 30% off: no problem
  LHC rate 300% off: Standard Model wrong

- theory likelihood flat centrally and zero far away

- profile likelihood construction: RFit \cite{CKMFitter}

\[-2 \log L = \chi^2 = \tilde{\chi}_d^T C^{-1} \tilde{\chi}_d\]

\[
\chi_{d,i} = \begin{cases} 
0 & |d_i - \bar{d}_i| < \sigma_i^{(\text{theo})} \\
\frac{|d_i - \bar{d}_i| - \sigma_i^{(\text{theo})}}{\sigma_i^{(\text{exp})}} & |d_i - \bar{d}_i| > \sigma_i^{(\text{theo})}
\end{cases}
\]
SFitter 3: Error analysis

Sources of uncertainty

– statistical error: Poisson
  systematic error: Gaussian, if measured
  theory error: not Gaussian

– profile likelihood construction: RFit  \[\text{RFit}\] [CKMFitter]
  \[-2 \log L = \chi^2 = \chi_d^T C^{-1} \chi_d\]
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|d_i - \bar{d}_i| - \sigma_i^{(\text{theo})} & |d_i - \bar{d}_i| > \sigma_i^{(\text{theo})} \end{cases} \]

Combination of errors

– Gaussian $\otimes$ Gaussian: half width added in quadrature
  Gaussian/Poisson $\otimes$ flat: RFit scheme
  Gaussian $\otimes$ Poisson: ??

– approximate formula
  \[\frac{1}{\log L_{\text{comb}}} = \frac{1}{\log L_{\text{Gauss}}} + \frac{1}{\log L_{\text{Poisson}}}\]

– modified Minuit gradient fit last step
Higgs couplings

Higgs-sector analysis  [Zeppenfeld et al; Dührssen et al; SFitter 2009; Contino et al]

- light Higgs around 125 GeV: over 10 channels ($\sigma \times BR$)
- measurements: $GF : H \rightarrow ZZ, WW, \gamma\gamma$  [first analyses]
  $WBF : H \rightarrow ZZ, WW, \gamma\gamma, \tau\tau$  [just starting]
  $VH : H \rightarrow b\bar{b}$  [BDRS crucial]
  $t\bar{t}H : H \rightarrow \gamma\gamma, WW, b\bar{b}$...  [useful but later]
- parameters: couplings $W, Z, t, b, \tau, g, \gamma$  [plus Higgs mass]
- hope: cancel uncertainties
  
  $(WBF : H \rightarrow WW)/(WBF : H \rightarrow \tau\tau)$
  $(WBF : H \rightarrow WW)/(GF : H \rightarrow WW)$...
- all wrong because of exclusive $H + n$ jets...  [later]
Higgs Couplings
Tilman Plehn

Where we stand
Where we are going
Markov chains
Errors
SFitter
After Moriond
Hypotheses
To do

Higgs couplings

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  $(WBF : H \rightarrow WW)/(GF : H \rightarrow WW)...$
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Total width

- myths about scaling

\[ N = \sigma BR \propto \frac{g_p^2}{\sqrt{\Gamma_{tot}}} \frac{g_a^2}{\sqrt{\Gamma_{tot}}} \sim \frac{g^4}{g^2 \sum \frac{\Gamma_i(g^2)}{g^2} + \Gamma_{unobs}} \quad g^2 \rightarrow 0 = 0 \]

  gives constraint from \[ \sum \frac{\Gamma_i(g^2)}{g^2} < \Gamma_{tot} \rightarrow \Gamma_H|_{\min} \]

- $WW \rightarrow WW$ unitarity: $g_{WWH} \lesssim g_{WWH}^{SM} \rightarrow \Gamma_H|_{\max}$
- assume in SFitter $\Gamma_{tot} = \sum_{obs} \Gamma_j$ [plus generation universality]
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  [later]

**SFitter ansatz**  [Dührssen, Klute, Lafaye, TP, Rauch, Zerwas]

- couplings measurement \(g_{HXX} = g_{HXX}^{SM} (1 + \Delta X)\)
  D5 couplings \(g_{ggH}, g_{\gamma \gamma H}\) free?
- experimental/theory errors on signal and backgrounds
  ATLAS and CMS both included
- exclusive likelihood map
  individual coupling measurements
- alternative parameters, e.g. coupling ratios?
Basic checks

Marginalization procedures

1– noisy environment preferring profile likelihoods  [no effective couplings, 30 fb$^{-1}$]
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3—but not saving Bayesian statistics  [no effective couplings, 300 fb$^{-1}$]
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1—noisy environment preferring profile likelihoods [no effective couplings, 30 fb$^{-1}$]
2—higher luminosity quantitatively different [no effective couplings, 30 vs 300 fb$^{-1}$]
3—but not saving Bayesian statistics [no effective couplings, 300 fb$^{-1}$]
4—theory errors not dominant for 30 fb$^{-1}$ [with effective couplings, 30 fb$^{-1}$]

⇒ profile likelihood for now
Results after Moriond

**ATLAS and CMS data well documented** [Dührssen, Klute, Lafaye, TP, Rauch, Zerwas]

- **ATLAS**: $\gamma\gamma, Z\ell Z\ell, WW + 0/1$ jets
- **CMS**: $\gamma\gamma + 0/2$ jets, $Z\ell Z\ell, WW + 0/1/2$ jets
- **CMS**: $\tau\tau + 0/1/2$ jets, $bb$ with $W\ell, Z\ell, Z\nu$
- central points on SM values
- everything preliminary
- (7 TeV, 2.1 – 4.9 fb$^{-1}$)
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  (7 TeV, 20 fb$^{-1}$)
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- Central points on SM values
  - Everything preliminary
- (7 TeV, 2.1 – 4.9 fb$^{-1}$)
  - (7 TeV, 20 fb$^{-1}$)
- Different projections 2012-2014

Form factor already constrained
- Gauge boson couplings promising
- Fermion couplings a problem
- D5 operators wide open
- Ratios actually better

- Comments welcome!
- Technical screwups?
- Experimental misunderstandings?
- Proper operator basis?
  - ...
Specific Higgs hypotheses

Status of the Higgs portal

- visible and hidden decays \( [\text{plus } H_2 \rightarrow H_1 H_1 \text{ cascade decays}] \)
  \[
  \Gamma_{1}^{\text{tot}} = \cos^2 \chi \Gamma_{\text{tot}, 1}^{\text{SM}} + \sin^2 \chi \Gamma_{1}^{\text{hid}}
  \]

- constraints on event rate
  \[
  \frac{\sigma[H_1 \rightarrow F]}{\sigma[H_1 \rightarrow F]^{\text{SM}}} = \frac{\cos^2 \chi \Gamma_{1}^{\text{hid}}}{1 + \tan^2 \chi \Gamma_{1}^{\text{hid}} \Gamma_{\text{tot}, 1}^{\text{SM}}} < \mathcal{R}
  \]

- two scenarios: \( m_H = 125, \mathcal{R} \sim 1 \) and \( m_H = 155, \mathcal{R} \sim 0.4 \)

⇒ invisible Higgs needed for final answer
Specific Higgs hypotheses

Status of the Higgs portal

- visible and hidden decays [plus $H_2 \rightarrow H_1 H_1$ cascade decays]
  \[
  \Gamma_{tot,1}^1 = \cos^2 \chi \Gamma_{SM, tot,1}^1 + \sin^2 \chi \Gamma_{hid,1}^1
  \]
- constraints on event rate
  \[
  \frac{\sigma[H_1 \rightarrow F]}{\sigma[H_1 \rightarrow F]_{SM}} = \frac{\cos^2 \chi}{1 + \tan^2 \chi \frac{\Gamma_{hid,1}^1}{\Gamma_{SM, tot,1}^1}} < \mathcal{R}
  \]
  \[\Rightarrow\] invisible Higgs needed for final answer

Strongly interacting Higgs at LHC [Espinosa, Grojean, Mühlleitner; SFitter; Ellis & You]

- pretty much fundamental Higgs
- coupling analysis technically simple
1- all couplings scaled $g \rightarrow g \sqrt{1 - \xi}$
  - one-parameter fit in SFitter
  - (14 TeV, 30 fb$^{-1}$) and 120 GeV Higgs: $\Delta g/g \sim 10\%$
2- gauge couplings $g \rightarrow g \sqrt{1 - \xi}$
  Yukawas $g \rightarrow g(1 - 2\xi)/\sqrt{1 - \xi}$
  - sign change of Yukawas, $g_{\gamma\gamma H}$ correlated
To-do list

Problems in Higgs sector analyses

1– pile-up in Higgs analyses
   nothing I can do

2– channels for $bbH$ and $ttH$ couplings
   Higgs and top tagging: tools in good hands [thank you to Higgs workshop in 2009!]

3– $N^\infty$LO cross section predictions
   maybe I am not German enough

4– analyses not organized by production channels
   count recoil jets instead, jet vetos
To-do list

Higgs searches vs number of recoil jets??  [for Dave and Steve]

– ‘soft’ gluon radiation infinitely likely  [like soft photons]
– many analyses at odds with DGLAP  [hard to predict at fixed order]

⇒ study exclusive $n_{\text{jets}}$ distributions
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Poisson scaling  [Peskin & Schroeder]

- example: photons off hard electron

$$\sigma_n = \frac{\bar{n}^n e^{-\bar{n}}}{n!} \iff R_{(n+1)/n}^{excl} = \frac{\sigma_{n+1}}{\sigma_n} = \frac{\bar{n}}{n+1}$$

1– radiation matrix element $\bar{n}^n$ [abelian fine, non-abelian for leading log and color]
2– phase space factor $1/n!$ [only combinatorics effect, matrix element ordered]
3– normalization factor $e^{-\bar{n}}$
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**Staircase scaling**  [Ellis, Kleiss, Stirling]

- observed since UA2

- same for inclusive and exclusive rates

$$R_{(n+1)/n}^{\text{incl}} = \frac{\sum_{j=n+1}^{\infty} \sigma_j^{\text{excl}}}{\sigma_n^{\text{excl}}} + \sum_{j=n+1}^{\infty} \sigma_j^{\text{excl}} = R_{(n+1)/n}^{\text{excl}} = \text{const}$$
Jet veto

Example: WBF $H \rightarrow \tau\tau$  [Englert, Gerwick, TP, Schichtel, Schumann]

- staircase scaling before WBF cuts  [QCD and e-w processes]
- e-w $Zjj$ production with too many structures

\[ \frac{n!}{(n+1)!} - 1 \]

\[ n!/(n+1)! \]

\[ R(n+1)/n \]
Jet veto

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Understanding a jet veto

- count add’l jets to reduce backgrounds
  $p_T^{\text{veto}} > 20$ GeV $\quad \min y_{1,2} < y^{\text{veto}} < \max y_{1,2}$
- Poisson for QCD processes ['radiation' pattern]
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- count add’l jets to reduce backgrounds
  \[ p_T^{\text{veto}} > 20 \text{ GeV} \quad \min y_{1,2} < y^{\text{veto}} < \max y_{1,2} \]
- Poisson for QCD processes ['radiation' pattern]
- (fairly) staircase for e-w processes [cuts keeping signal]
- $n_{\text{jets}}$ features understood, go from here...

![Graph showing Higgs gluon fusion and Z QCD with jet veto](image)
Outlook

Confirming Higgs@LHC

- hope there were enough details, you can wake up now
- coupling analysis the main LHC goal
- many technical issues
- Higgs tagger vital
- SFitter paper imminent

⇒ case for a 250 GeV linear collider

much of this work was funded by the BMBF Theorie-Verbund which is ideal for hard and relevant LHC work
Pretty colorful pictures

Two-dimensional correlations and effective couplings

1— including effective $g_{Hgg}$
   sign of $g_{Htt}$ fixed by $g_{HWW} > 0$
   correlation of $g_{Hbb}$ and $g_{HWW}$ [loops and width]
   $g_{Hgg}$ accessible
Pretty colorful pictures

**Two-dimensional correlations and effective couplings**

1– including effective $g_{Hgg}$
   *sign of $g_{Htt}$ fixed by $g_{HW\gamma} > 0$*
   *correlation of $g_{Hbb}$ and $g_{HW\gamma}$ [loops and width]*
   $g_{Hgg}$ accessible

2– only effective $g_{H\gamma\gamma}$
   *correlated $g_{Htt}$ and $g_{HW\gamma}$ on both branches*
   $g_{H\gamma\gamma}$ structure more complex
Pretty colorful pictures

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2— only effective $g_{H\gamma\gamma}$
   correlated $g_{Htt}$ and $g_{HWW}$ on both branches
   $g_{H\gamma\gamma}$ structure more complex

3— both effective couplings
   discrete structures getting out of hand
Weak boson fusion and supersymmetry

Higgs analysis beyond the Standard Model

- extension of Higgs analysis to BSM scenarios
- comparison SM-MSSM
  - no-lose: TP, Rainwater, Zeppenfeld
- define hypothesis
  - known particles: known corrections
  - new particles: theory error
- general: heavy additional states at one loop
  - example: MSSM sectors Higgs–weak–strong

Technical questions

- vertex corrections dominant? [Djouadi & Spira]
- which one larger: QCD vs EW? [similar for Standard Model: Ciccolini, Denner, Dittmaier]
- corrections from Higgs sector? [renormalization scheme/higher orders]
- general phase space generator?
- Germans: we can do 52504 diagrams [Hadcalc: automized IR-finite one-loop $2 \rightarrow 3$]

⇒ input for MSSM-Higgs analysis
Weak boson fusion and supersymmetry

Higgs sector corrections

- finite momentum, different masses → Feynman diagrams \[\text{[FeynHiggs]}\]
- consistent self couplings → effective potential \[\text{[SubH]}\]
- check identical limit: effective angle $\alpha_{\text{eff}}$
Weak boson fusion and supersymmetry

Higgs sector corrections

- finite momentum, different masses $\rightarrow$ Feynman diagrams $^{[\text{FeynHiggs}]}$
- consistent self couplings $\rightarrow$ effective potential $^{[\text{SubH}]}$
- check identical limit: effective angle $\alpha_{\text{eff}}$

SUSY corrections

- QCD corrections suppressed:
  - color flow and forward jets $^{[\text{no interference, like SM}]}$
  - mass suppression of one-loop $q_L q_L W$ vertex $^{[1/m_g]}$
  - up-down cancellation in one-loop $d u W h$ vertex $^{[T_3 - Q_s^2 w = -1/3, +5/16]}$
- electroweak corrections as expected

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<th>$\Delta \sigma \sim \mathcal{O}(\alpha)$</th>
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$\Rightarrow$ electroweak corrections dominant
Weak boson fusion and supersymmetry

Higgs sector corrections

- finite momentum, different masses → Feynman diagrams [FeynHiggs]
  consistent self couplings → effective potential [SubH]
- check identical limit: effective angle $\alpha_{\text{eff}}$

SUSY corrections

- SPS1b with variable mass scale $m_{1/2}$
- perfect decoupling at one loop
- typical corrections around 1%
  maximum corrections below 4%
Higgs Couplings
Tilman Plehn

Where we stand
Where we are going
Markov chains
Errors
SFitter
After Moriond
Hypotheses
To do