Phenomenology at collider experiments

[Part 3: The Higgs boson]

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Outline

1. Reviewing the Higgs mechanism
2. Higgs boson searches and its properties in the SM
3. Extended Higgs sectors
Reminder: The Higgs mechanism

Masses and gauge invariance

- SM contains gauge and matter fields: spin-1 bosons and spin-$\frac{1}{2}$ fermions
- Massless fields guarantee good features:
  - Gauge invariance under $SU(2)_L \otimes U(1)_Y$
  - Renormalizability of theory
- Could introduce mass terms “by hand”:
  $$\mathcal{L}_m \propto m_A^2 A^\mu A_\mu + m_f (\bar{\Psi}_R \Psi_L + \bar{\Psi}_L \Psi_R)$$
- Violates gauge invariance, since
  - $A^\mu \rightarrow A^\mu + \frac{1}{g} \partial^\mu \theta$, therefore $A^\mu A_\mu$ yields terms $\propto \theta$ after gauge trafo.
  - $\Psi_L$ and $\Psi_R$ transform differently under $SU(2)_L$
    ($\Psi_R$ is singlet = neutral), therefore terms $\propto \theta$ do not cancel.
- This is bad: We love the local gauge principle!
Reminder: The Higgs mechanism

Generating mass from the vacuum expectation value

- Add complex doublet under $SU(2)_L$ (4 d.o.f.), couple it gauge-invariantly with the vectors: $\mathcal{L}_\Phi = (D^\mu \Phi)(D_\mu \Phi)$

- Add interaction term with fermions:
  $$\mathcal{L}_\Phi \Psi = g_f \bar{\Psi}_L \Phi \Psi_R + \text{h.c.}$$
  (need $\Phi$ for down-type fermions and $i\sigma_2 \Phi^*$ for up-types)

- Add potential with non-trivial structure
  (infinite number of equivalent minima needed)

- Pick one minimum and expand around it:
  - One radial and three circular modes
  - Circular modes “gauged away”
    $\rightarrow$ “eaten” by bosons
  - vev (energy of minimum) $\rightarrow$ masses
Reminder: The Higgs mechanism

Fixing the parameters

- From the structure above:
  \[(D_\mu \Phi)^2 \quad \rightarrow \quad \frac{g^2 v^2}{4} W_\mu W^\mu \quad \rightarrow \quad M_W^2 = \frac{g^2 v^2}{4}\]
  \[g_f \bar{\Psi}_L \Phi \Psi_R \quad \rightarrow \quad g_f \frac{v}{\sqrt{2}} \bar{\Psi}_L \Phi \Psi_R \quad \rightarrow \quad m_f = \frac{g_f v}{\sqrt{2}}\]
  \[\lambda (|\Phi|^2 - v^2/2)^2 \quad \rightarrow \quad \lambda v^2 H^2 \quad \rightarrow \quad M_H^2 = 2\lambda v^2\]

- Fixed relation between mass and coupling to (surviving) Higgs scalar.

Therefore, to verify EWSB:

- find \(H\)
- check it's a scalar
- verify coupling \(\propto\) mass
- measure potential through self-interactions
Reminder: The Higgs mechanism

Restoring unitarity of $WW \rightarrow WW$-scattering

(from O. Brein)
Reminder: The Higgs mechanism

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Restoring unitarity of $WW \rightarrow WW$-scattering

(from O.Brein)
Reminder: The Higgs mechanism

(Fixing the parameters)

- Consider $W^+ W^- \rightarrow W^+ W^-$
- Without $H$: violates unitarity at $\approx 1 \text{ TeV}$.
- Therefore: Must add $H$ with $g_{WWH} \propto m_W$.
- Repeat for $WW \rightarrow ZZ \rightarrow g_{ZZH} \propto m_Z$.
- Repeat for $WW \rightarrow f \bar{f} \rightarrow g_{f\bar{f}H} \propto m_f$.
- Test in $WW \rightarrow WWH \rightarrow g_{HHH} \propto m_H^2 / m_W$.
- Test in $WW \rightarrow HHH \rightarrow g_{HHHH} \propto m_H^2 / m_W^2$.
- Once it is there, the functional dependence of the Higgs boson couplings is fixed by the unitarity requirement of the theory.
Tayloring search channels

**Limits on \( m_H \)**
- Unitarity: \(< 1 \text{ TeV} \).
- EW precision tests: \(< 250 \text{ GeV} \).
- LEP searches: \( > 114 \text{ GeV} \).

![Graph showing the limits on \( m_H \)](from LEPEWWG)

**Basic considerations**
- Signal rates defined by triggers: you won’t measure what you don’t see.
- Significance: \( S/\sqrt{B} \) vs. \( S/B \).
- Important: Control systematics. Avoid embarassment.
- Mass resolution for \( m_H \) and decay products: may help to suppress backgrounds
- Any topological help?
Tayloring search channels

Higgs production processes at hadron colliders

Common feature: Couple to heavy objects (top, $W$, $Z$)

Gluon fusion:

Higgs-Strahlung:

Quark-associated:

Weak boson fusion (WBF/VBF):
Tayloring search channels

Higgs production cross sections at hadron colliders

(from M.Spira, hep-ph/9810289)
Tayloring search channels

Higgs decays

- Individual decay channels:

<table>
<thead>
<tr>
<th>decay mode</th>
<th>width $\Gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \to f\bar{f}$</td>
<td>$\frac{G_F M_H}{8\pi \sqrt{2}} \cdot 2m_f^2 N_C \left(1 - \frac{4m_f^2}{m_H^2}\right)^{\frac{3}{2}}$</td>
</tr>
<tr>
<td>$H \to W^+ W^-$</td>
<td>$\frac{G_F M_H}{8\pi \sqrt{2}} \cdot m_H^2 \left(1 - \frac{4m_W^2}{m_H^2} + \frac{12m_W^4}{m_H^4}\right) \left(1 - \frac{4m_W^2}{m_H^2}\right)^{\frac{1}{2}}$</td>
</tr>
<tr>
<td>$H \to ZZ$</td>
<td>$\frac{G_F M_H}{8\pi \sqrt{2}} \cdot m_H^2 \frac{m_W^2}{2m_Z^2} \left(1 - \frac{4m_Z^2}{m_H^2} + \frac{12m_Z^4}{m_H^4}\right) \left(1 - \frac{4m_Z^2}{m_H^2}\right)^{\frac{1}{2}}$</td>
</tr>
<tr>
<td>$H \to \gamma\gamma$</td>
<td>$\frac{G_F M_H}{8\pi \sqrt{2}} \cdot m_H^2 \left(\frac{\alpha}{4\pi}\right)^2 \cdot \left(\frac{4}{3} N_C Q_t^2\right)^2$ (2$m_t &gt; m_H$)</td>
</tr>
<tr>
<td>$H \to gg$</td>
<td>$\frac{G_F M_H}{8\pi \sqrt{2}} \cdot m_H^2 \left(\frac{\alpha_s}{4\pi}\right)^2 \cdot \left(\frac{2}{3}\right)^2$ (2$m_t &gt; m_H$)</td>
</tr>
<tr>
<td>$H \to VV^*$</td>
<td>more complicated, but important for $m_H \lesssim 2m_V$</td>
</tr>
</tbody>
</table>

- $m_H < 2m_W$: Higgs boson quite narrow, $\Gamma_H = \mathcal{O}(\text{MeV})$.
- $m_H > 2m_W$: $H$ becomes obese, $\Gamma_H(m_H = 1\text{TeV}) \approx 0.5$ TeV.
- At large $m_H$: decay into $VV$ dominant, $\Gamma_{H \to WW} : \Gamma_{H \to ZZ} \approx 2 : 1$. 
Tayloring search channels

Higgs decays

Tayloiring search channels

Some typical channels (mostly @ Tevatron)

- $gg \rightarrow H \rightarrow W^+W^- \rightarrow \ell\ell' + E_\perp$: “golden plated”
  No mass peak, but background partially killed with $\angle_{\ell\ell'}$ etc..

- $q\bar{q} \rightarrow ZH \rightarrow \ell\ell b\bar{b}$: only limits on $\sigma$
  Key ingredient: $b$-tagging efficiencies, mass resolution for jets to suppress QCD backgrounds.

- $q\bar{q}' \rightarrow WH \rightarrow \ell\nu b\bar{b}$: like above.

- $q\bar{q}' \rightarrow WH \rightarrow E_\perp + b\bar{b}$: only limits on $\sigma$
  combination of the two above, with $Z \rightarrow \nu\nu$

- $q\bar{q}' \rightarrow W^\pm H \rightarrow W^\pm W^+W^-$: only limits on $\sigma$
  same sign leptons, other $W$ goes hadronically (xsec!).
Tayloring search channels

Some typical channels (mostly @ LHC)

- $gg \rightarrow H \rightarrow ZZ \rightarrow 4\mu, 2e2\mu$: “Golden plated” for $m_H > 140$ GeV. Key ingredients: Mass peak from excellent mass resolution (leptons).
- $gg \rightarrow H \rightarrow W^+W^- \rightarrow \ell\ell' + \not\!E_T$: nearly as good as ZZ but no mass peak. Background killed with $\angle\ell\ell'$ etc.. Very similar to Tevatron analysis with huge stats.
- $gg \rightarrow H \rightarrow \gamma\gamma$: Good for small $m_H \lesssim 120$ GeV. Key ingredient: mass resolution for $\gamma$'s & veto on $\pi^0$'s.
- $WBF \rightarrow H \rightarrow \tau\tau$: Popular mode Key ingredient: QCD-backgrounds killed with rapidity gap
- $WBF \rightarrow H \rightarrow WW$: ditto.
- $WBF \rightarrow H \rightarrow b\bar{b}$: in principle ditto but: Hard to trigger, pure QCD-like objects (jets)
## Tayloring search channels

### Difficult channels (mostly @ LHC)

- **top-associated production and $H \rightarrow b \bar{b}$**: xsec okay, but difficult. Potential show-stopper: backgrounds from $t \bar{t} + \text{jets}$, $W + \text{jets}$, etc., many jets to be reconstructed, combinatorics from $t \bar{t}$-reco . . .

- **top-associated production and $H \rightarrow \gamma \gamma$**: xsec small, difficult.

- **top-associated production and $H \rightarrow \tau \tau$**: xsec okay, but difficult. Potential show-stopper: backgrounds from $t \bar{t} + Z$, $W$, $Z + \text{jets}$, etc., many jets to be reconstructed, combinatoric backgrounds from $t$-reco, find the $\tau$’s (only 1/3 into leptons) . . .

- **Higgs decays into $\mu$**: small BR, could be useful for SUSY.
Remarks on resonance production

Simple “rule of the thump” to calculate xsec

1. Consider processes like $gg \rightarrow H \rightarrow ZZ$ etc.: resonant production.
2. If width small: can cut internal resonant propagator.
3. Two-body decay $R \rightarrow ab$: $\Gamma_{ab} = \frac{|\langle ab | R \rangle|^2}{16\pi m_R}$
4. Resonance production in $cd \rightarrow R$: $\sigma_{cd} = \frac{2\pi}{m_R^2} \frac{|\langle R | cd \rangle|^2}{\pi[(s-m_R^2)^2+\Gamma_R^2 m_R^2]}$
5. Use peak at $s = m_R^2$ (will yield a $\delta$ function)
6. Therefore $\sigma_{ab \rightarrow R \rightarrow cd} = \frac{32\pi}{m_R^2} \text{BR}(R \rightarrow ab) \text{BR}(R \rightarrow cd)$
7. If width not so small: include Breit-Wigner.
8. At hadron colliders: Need to integrate over Bjorken-$x$. 

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Phenomenology at collider experiments [Part 3: The Higgs boson]
Search channel: \( gg \rightarrow H \rightarrow WW \rightarrow \ell\ell'\nu\nu \) @ Tevatron

**Short intro**

(from D0 Note-5757Conf)

- Consider \( ee, e\mu, \) and \( \mu\mu \) final states, each with 2 neutrinos
- Use \( m_H \) in steps of 5 GeV, from 115 to 200 GeV.
- Backgrounds: direct \( WW, WZ, ZZ, t\bar{t}, DY, QCD, W+\)jets
- Main cuts (acceptance and background suppression):
  - lepton isolation etc., \( |\eta_{e,\mu}| < 3, 2. \)
  - \( p_{\perp}^{e,\mu} > 15, 10 \) GeV, \( E_{\perp} > 20 \) GeV (anti-DY)
  - some protection against wrong \( E \)
  - \( M_{\ell\ell} > 15 \) GeV
  - \( \Delta\phi_{\ell\ell'} < 2 \ldots 2.5 \) (channel-dep.):
    - most background like back-to-back, \( H \) likes small.
- Neural network, trained with \( \mathcal{O}(15) \) observables (some shown below)
- Similar analysis for CDF, public page
- Up-to data analysis: 3 fb\(^{-1}\).
Search channel: $gg \rightarrow H \rightarrow WW \rightarrow \ell\ell'\nu\nu$ @ Tevatron

Distributions for signals and backgrounds

(from D0 Note-5757Conf)
Search channel: $q\bar{q}' \rightarrow ZH \rightarrow \ell\ell b\bar{b}$ @ Tevatron

Distributions for signals and backgrounds

(from CDF public homepage, also D0-Note 5570/Conf)

- Use $\ell = e, \mu$, major backgrounds: $Z+$jets, $ZZ$, $WZ$, $WW$, $t\bar{t}$.
- Signal- or background-like? ME method (CDF, 2 fb$^{-1}$).
- Relevant observable: $m_{b\bar{b}}$, need $b$-tagging to kill $jj$-pairs and similar

Finally bound: $\sigma_{\text{signal}} \leq 15 \cdot \sigma_{H(SM)}$ at 95% C.L..

Similar analysis with more data and NN (CDF&D0).
Combined searches @ Tevatron

Collected results from CDF

(from CDF Note-9282)

CDF Run II Preliminary, L=1.9-3.0 fb⁻¹

LEP Excl.

95% CL Limit/SM

100 110 120 130 140 150 160 170 180 190 200

m_H (GeV/c²)

WW 1.9 fb⁻¹ Obs
WW 1.9 fb⁻¹ Exp
H→tt 2.0 fb⁻¹ Obs
H→tt 2.0 fb⁻¹ Exp
ZH→llbb 2.4 fb⁻¹ Obs
ZH→llbb 2.4 fb⁻¹ Exp

WH+ZH→bbMET 2.1 fb⁻¹ Obs
WH+ZH→bbMET 2.1 fb⁻¹ Exp
WH→lbb 2.7 fb⁻¹ Obs
WH→lbb 2.7 fb⁻¹ Exp
H→WW 3.0 fb⁻¹ Obs
H→WW 3.0 fb⁻¹ Exp

Combined Obs
Combined Exp
Combined searches @ Tevatron

Results from Tevatron, 2008

(from D0 Note-5754Conf/and CDF)

Tevatron Run II Preliminary, L=3 fb⁻¹

95% CL Limit/SM

- Expected
- Observed
- ±1σ
- ±2σ

m_H (GeV/c²)

SM

July 30, 2008

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Phenomenology at collider experiments [Part 3: The Higgs boson]
Prospects for Higgs boson searches @ LHC

(from ATLAS-Note Pub-2007-013)

Search channel: $gg \rightarrow H \rightarrow \gamma\gamma$

- Characteristic: Bump on a smooth background
  $\rightarrow$ side-band subtraction
- Tricky issue: Mass resolution of $\gamma\gamma$
  (converted $\gamma$’s, $j(\pi^0) \rightarrow \gamma$ conversions, $\gamma$ direction)
- $\delta m_{\gamma\gamma} \approx 1.5$ GeV.
- $S/\sqrt{B}(30\text{fb}^{-1}) \approx 6$ for $m_H \in [120, 140]$ GeV
Prospects for Higgs boson searches @ LHC

(from CMS-Note Pub-2006-112)

Search channel: \( gg \rightarrow H \rightarrow \gamma\gamma \)

- Characteristic: Bump on a smooth background
  \( \rightarrow \) side-band subtraction
- Main obstacles: converted \( \gamma \)'s, \( j(\pi^0) \rightarrow \gamma \) conversions, \( \gamma \) direction
- After hard work:
  \( \delta m_{\gamma\gamma} \approx 1.5 \) GeV.
- \( S/\sqrt{B}(30 \text{fb}^{-1}) \approx 6 \) for \( m_H \in [120, 140] \) GeV
Characteristics

- At LO: No colour exchange between protons
  - Tag-jets tend to be forward, at low $p_\perp \approx m_H/2$, colour connected with “adjacent” proton remnants
    - → hadronic activity mostly forward
    - (between tag jet and proton rump)
    - → no hadronic activity at center
    - → rapidity gap for signal

- Rapidity gap filled by Higgs boson and its decay products

- Typical backgrounds: $W, Z+\text{jets}, t\bar{t}, W, Z$-pairs, QCD
  - all of them typically have colour exchange between protons
  - → no rapidity gap for background
Weak boson fusion processes: Behaviour of the tag jets

Example: WBF, $H \rightarrow \tau\tau$
Weak boson fusion processes: Rapidity gap

Example: WBF, \( H \rightarrow \tau\tau \)

- Many backgrounds with 3rd jet - typically quite central, i.e. between the hardest two (tag) jets
- Quantify by “Zeppenfeld”-variable: \( \eta_3^* = \eta_3 - \frac{\eta_1 + \eta_2}{2} \)

(from CMS-Note 2006-088)
WBF, $H \rightarrow \tau\tau \rightarrow \ell jE_{T}$

### Results

<table>
<thead>
<tr>
<th>Selection</th>
<th>Cumulative Cross Section [fb] (% from previous step)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>signal samples: $qqH, H \rightarrow \tau\tau \rightarrow \ell jE_{T}$</td>
</tr>
<tr>
<td>$M_{H}=115$</td>
<td>$M_{H}=125$</td>
</tr>
<tr>
<td>production σ</td>
<td>4.65x10^9</td>
</tr>
<tr>
<td>$xBR(H \rightarrow \tau\tau \rightarrow \ell j)$</td>
<td>157.3 (3.4)</td>
</tr>
<tr>
<td>preselection</td>
<td>-</td>
</tr>
<tr>
<td>L1</td>
<td>81.81 (52.0)</td>
</tr>
<tr>
<td>L1 + HLT</td>
<td>41.46 (50.7)</td>
</tr>
<tr>
<td>Lepton ID</td>
<td>39.46 (95.2)</td>
</tr>
<tr>
<td>Lepton pT</td>
<td>39.12 (99.1)</td>
</tr>
<tr>
<td>τ-jet E_{T}</td>
<td>12.70 (32.5)</td>
</tr>
<tr>
<td>τ-jet ID</td>
<td>9.014 (71.0)</td>
</tr>
<tr>
<td>valid mass</td>
<td>6.113 (67.8)</td>
</tr>
<tr>
<td>VBF ID (q_{1}, E_{T})</td>
<td>2.718 (44.4)</td>
</tr>
<tr>
<td>VBF: Δη_{jj}</td>
<td>1.498 (55.1)</td>
</tr>
<tr>
<td>VBF: Δφ_{jj}</td>
<td>1.174 (78.4)</td>
</tr>
<tr>
<td>VBF: M_{jj}</td>
<td>0.771 (65.7)</td>
</tr>
<tr>
<td>M_{T}(E_{T})</td>
<td>0.620 (80.4)</td>
</tr>
<tr>
<td>CIV</td>
<td>0.503 (81.2)</td>
</tr>
<tr>
<td>Events at 30 fb^{-1}</td>
<td>15.1</td>
</tr>
</tbody>
</table>

(from CMS-Note 2006-088)
WBF, $H \rightarrow \tau \tau \rightarrow \ell j E_{\perp}$

Results: $m_H$ and significance

![Graph showing $M_{\tau\tau}$ distribution with Signal, EW+QCD Z+jets, ttbar W+jets, Fit to Signal, Fit Z, Fit to ttbar W+jets, and Sum of fits.]

<table>
<thead>
<tr>
<th>$M_H$ [GeV]</th>
<th>115</th>
<th>125</th>
<th>135</th>
<th>145</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_B$ (30fb$^{-1}$)</td>
<td>10.47</td>
<td>7.79</td>
<td>7.94</td>
<td>3.63</td>
</tr>
<tr>
<td>$N_B$ (30fb$^{-1}$)</td>
<td>3.70</td>
<td>2.21</td>
<td>1.84</td>
<td>1.42</td>
</tr>
<tr>
<td>$S_{\text{CP}}$ at 30fb$^{-1}$ (no uncertainty)</td>
<td>4.04</td>
<td>3.71</td>
<td>3.98</td>
<td>2.19</td>
</tr>
<tr>
<td>$S_{\text{CP}}$ at 30fb$^{-1}$ ($\sigma_B = 7.8%$)</td>
<td>3.97</td>
<td>3.67</td>
<td>3.94</td>
<td>2.18</td>
</tr>
<tr>
<td>$S_{\text{CP}}$ at 60fb$^{-1}$ ($\sigma_B = 5.9%$)</td>
<td>5.67</td>
<td>5.26</td>
<td>5.64</td>
<td>3.19</td>
</tr>
</tbody>
</table>

(from CMS-Note 2006-088)
A new idea: Higgs-Strahlung @ LHC


**Basic idea**

- **ZH and WH production** not really considered up to now
- **Obstacle**: if produced at low mass
  - Good fraction of $\sigma_{\text{prod}}$ out of acceptance
  - Decay products often with too low $p_\perp$
- **Typically**: Huge backgrounds (e.g. $t\bar{t}$ at same scales)
- **So**: Why not try to produce at large $p_\perp$, back-to-back? ($p_\perp > 200$ GeV, $\sigma_{ZH,\text{boosted}} \approx 0.05 \times \sigma_{ZH,\text{tot}}$)
- **Large boosts**: decay products in relatively small cones
- **Kills also backgrounds** such as tops:
  Impossible to have $b\bar{b}$ with large boost in one direction and $W \rightarrow \ell\nu$ in other direction without having massive QCD radiation
- **Added benefit**: For $Z \rightarrow \nu\nu$ massive $E_\perp$. 
A new idea: Higgs-Strahlung @ LHC


Key: Structure of boosted $H \rightarrow b\bar{b}$

- Boosted $H$ will produce a “fat” jet with two $b$’s in it.
- Distance of the two $b$’s in LEGO: $R_{b\bar{b}} \approx \frac{m_H}{p_H^\perp} \frac{1}{\sqrt{z(1-z)}}$
- For resolution use $k_\perp$-like algorithm
- The last two subjets must have $b$-tags, and there must not be a too large mass drop between them ($m_1 > \mu m_2$)
A new idea: Higgs-Strahlung @ LHC


Results: Signal in four regions

\[ ZH \rightarrow \ell \bar{\ell} b \bar{b} \]

![Graph (a)](image)

\[ ZH \rightarrow \nu \bar{\nu} b \bar{b} \]

![Graph (b)](image)

\[ WH \rightarrow \ell \bar{\nu} b \bar{b} \]

![Graph (c)](image)

Combination

![Graph (d)](image)
SM-Higgs boson searches at LHC: upshot

Sensitivities after 30 fb$^{-1}$

Measuring the properties of the Higgs boson

Reminder: Why do we care?

Okay, so we’ve found plenty of evidence for a “bump” in some distributions, i.e. a new particle.

Is this enough to claim victory and for P.Higgs to book flights?

Question: How do we know the bump is the Higgs boson?
Answer: It must be the scalar responsible for mass generation!

Therefore:

1. Is it a scalar, i.e. spin-0 and even CP?
2. Is the coupling to the other fields proportional to their mass?
3. Is this an accident or the result of the potential/self-interactions?

Answers to all three questions may not be available quickly.
Test 1: Spin and CP

Measuring the $H$-spin its decays: $H \rightarrow ZZ$


- Basic idea: polarizations of $Z$ bosons correlated, must be visible.
- Check differential cross sections/distributions of $Z$-decay products.
- For scalar particles, all $Z$ polarizations contribute:
  \[ M_+ \sim \varepsilon_1 \cdot \varepsilon_2 \]
  (including the longitudinal ones which are dominant for large $m_H$).
- For pseudoscalar particles, only the transverse polarisations contribute:
  \[ M_- \sim \epsilon_{\mu\nu\rho\sigma} k_1^\mu k_2^\nu \varepsilon_1^\rho \varepsilon_1^\sigma \sim \vec{k}_1 \cdot (\vec{\varepsilon}_1 \times \vec{\varepsilon}_2) \]
- Will give rise to different distributions.
Test 1: Spin and CP

Measuring the $H$-spin its decays: $H \rightarrow ZZ$


Differential cross sections:

$$\frac{d\Gamma}{d\cos \theta_1 d\cos \theta_2} \sim A_{\theta}^\pm \sin^2 \theta_1 \sin^2 \theta_2 + B_{\theta}^\pm (1 + \cos^2 \theta_1)(1 + \cos^2 \theta_2) + C_{\theta}^\pm \cos \theta_1 \cos \theta_2$$

$$\frac{d\Gamma}{d\phi} \sim A_{\phi}^\pm + B_{\phi}^\pm \cos \phi + C_{\phi}^\pm \cos(2\phi) ,$$

where $\{A, B, C\}_{\phi,\theta}^\pm$ depend on CP state ($\pm$) of the Higgs boson and on $Zf\bar{f}$ couplings and kinematics.
Test 1: Spin and CP

Measuring the $H$-spin its decays: $H \rightarrow ZZ$


- Difference between $M_+$ and $M_-$, persists for the “normality” towers $\rightarrow$ can rule out $0^-, 1^+, 2^-$ etc..
- Can rule out odd spins ($1^-$): missing $A^+_{\theta} = 0$ (Bose symmetry)
- Need other decays for even spins ($2^+$)

(after 300 fb$^{-1}$)
Test 2: Yukawa couplings

Strategy

- Yukawa couplings $\propto$ masses $\rightarrow$ light particles ($u, d, \ldots$) hopeless
- Typically: Extract couplings from total cross section measurements
- As we’ve seen before, this is often more than challenging: lumi/PDF uncertainties, systematics of the process itself, \ldots
- Ratios might be better/more sensitive due to cancellations: but maybe not sensitive to new physics in Higgs sector
Some results
Test 2: Yukawa couplings

Projection: From LHC to ILC

![Graph showing relative error on coupling constants for LHC 300 fb^{-1} and ILC 500 fb^{-1}.]
Test 3: Higgs potential and self-interactions

Or: Why to build the ILC

- It does not seem as if the Higgs potential and the $HHH$ self-interactions are accessible in the SM Higgs-sector at the LHC. Of course, this is different in the MSSM, if $m_{H^0} > 2m_{h^0}$ (resonant production of the heavy Higgs)

- It does seem, however, as if this is accessible in the SM Higgs-sector at the ILC, operating at 500 GeV c.m.-energy.

<table>
<thead>
<tr>
<th>QCD</th>
<th>$HHH$ on</th>
<th>$HHH$ off</th>
</tr>
</thead>
<tbody>
<tr>
<td>yes</td>
<td>$3.096(60) \cdot 10^{-2}$</td>
<td>$6.308(24) \cdot 10^{-3}$</td>
</tr>
<tr>
<td>no</td>
<td>$2.34(12) \cdot 10^{-2}$</td>
<td>$3.704(15) \cdot 10^{-3}$</td>
</tr>
</tbody>
</table>

(from T. Gleisberg et al.,
Non-minimal Higgs sectors

Motivation

- Adding one complex scalar doublet is a minimal version, why not more fields and a more involved theory?
- The SM Higgs-boson is under some stress from data (EW precision wants it lighter than 100 GeV, LEP bound wants it beyond 114 GeV).
- In many attractive models (SUSY, extra dimensions) the Higgs sector becomes larger - either enforced in order to make sure that all particles gain masses in a gauge invariant way (SUSY), or through replica of the original single doublet (ED).
- But: Need to be careful!
  Typically constraints from absence of FCNC at tree-level (charged Higgs should couple $\sim V_{CKM}$, EW precision data ($\Delta\rho$, mass ratios of weak bosons should be respected) etc..
The simplest solution: THDM

**Basic idea**

- The idea behind the THDM is to add another Higgs doublet.
- There are various versions (types) to do that, respecting CP-invariance or adding CP-violation to the theory.
- Full Lagrangian introduces $O(10)$ new parameters.
- Most interesting THDM-II: Interesting in its own right, but mostly because the SUSY-Higgs sector looks like a constrained THDM-II.
- SUSY-Higgs sector described by two new parameters: $m_A^0$ and $\tan \beta$.
- Indirect constraints from rare processes in $K$- and $B$-sector, EW precision data, cosmology.
- Will concentrate on it in the next few slides.
Non-minimal Higgs sectors: THDM/MSSM

Theory setup: upshot

- Two doublets with two vevs: $v_{1,2}$
  \[ v_1^2 + v_2^2 = v^2 \approx (246 \text{GeV})^2, \quad \tan \beta = \frac{v_2}{v_1}. \]

- $H_1$ doublet gives mass to the up-type fermions, $H_2$ for the down-types, both together are responsible for the gauge bosons.

- After EWSB and mixing to mass eigenstates: 
  5 fields ($h^0, H^0, A^0, H^\pm$) as linear combinations of original fields.

- Immediate consequence: \textbf{VVH-couplings reduced w.r.t. the SM}, \textbf{$\bar{f} f H$-coupling altered by $\tan \beta$: $\bar{d}dH$ enhanced, $\bar{u}uH$ reduced.}

- Tree-level mass relations (big loop-corrections, esp. for $m_{h^0}$): 
  \[ m_{H^\pm}^2 = m_{A^0}^2 + m_W^2, \quad m_{H^0}^2 + m_{h^0}^2 = m_{A^0}^2 + m_Z^2. \]

- At tree-level, typically: $m_{h^0} < m_Z$! (after loops: $m_{h^0} < 140$ GeV)
## MSSM Higgs searches

### Searches for $h^0$

- **Typical feature:** decays to vector bosons less dominant.
- **Relevant channels** are: $h^0 \to \gamma\gamma$, $h^0 \to ZZ \to 4\ell$, $t\bar{t}h^0$ with $h^0 \to b\bar{b}$ and WBF with $h^0 \to \tau\bar{\tau}$.
- At small $\tan\beta$, searches very similar to the SM, gluon fusion $gg \to h^0$ a good process.
- At large $\tan\beta$, $gg \to h^0$ enhanced due to $b$-triangle, decays to $\tau$’s gain significance.
- With 100 fb$^{-1}$ they cover nearly the full $m_{A^0}$-$\tan\beta$ plane in each experiment individually (with a hole around $m_{A^0} \in [90, 130]$ GeV)
MSSM Higgs searches

Searches for $H^0/A^0$

- Typical feature: decays to vector bosons less dominant.
- At large $\tan\beta$, $b$-associated production is dominant, the final state $b\bar{b}\tau\bar{\tau}$ covers a good fraction of the parameters space. In addition, decays to $\mu\mu$ benefit from good mass resolution (this does not work for $h^0$ due to the $Z$ nearby).
- At small $\tan\beta$, $A^0 \rightarrow Zh^0$ is a good candidate ($Zh\bar{h}$ absent in the SM): good for $m_{A^0} \in [200\text{GeV}, 2m_t]$
  for $m_{A^0} > 2m_t$, both $A^0$ and $H^0$ decay predominantly into $t\bar{t}$
  \(\longrightarrow\) look for resonances.
Neutral Higgs bosons at Tevatron

Discovery contours
MSSM Higgs searches

Searches for $H^\pm$

- Relevant production processes: $t \to H^+ b$ (small $m_{H^\pm}$), already being studied at the Tevatron:

Set limits on $\text{BR}(H^+ \to cs)$ and $\text{BR}(H^+ \to \tau\nu)$

Limits on charged Higgs mass for
- Leptophobic: $\text{BR}(H^+ \to cs) = 100\%$
- and tauonic: $\text{BR}(H^+ \to \tau\nu) = 100\%$

models
MSSM Higgs searches

**Searches for $H^\pm$**

- Relevant processes $gg \rightarrow tbH^\pm$, pair production and $WH^\pm$-associated production (large $m_{H^\pm}$).
- Relevant decays: $H^\pm \rightarrow \tau\nu$, $H^\pm \rightarrow cs$, $H^\pm \rightarrow tb$, $H^\pm \rightarrow Wh^0$; at larger $\tan\beta$, $\tau\nu$ is a good candidate.
- Interesting case: $gb \rightarrow H^\pm t \rightarrow \tau^\pm + E_T + 2jb$, $\tau \rightarrow \nu + \text{hadrons}$. Then transverse mass of $\tau$-jet and $E_T$ is a good S-B discriminator: Yields a Jacobean peak at $m_{H^\pm}$. 

F. Krauss

Phenomenology at collider experiments [Part 3: The Higgs boson]
MSSM Higgs searches

\[ gb \to H^\pm t \to \tau^\pm + E_T^{\perp} + 2 j b, \quad \tau \to \nu + \text{hadrons} \]

- Tricks & cuts:
  - Only 3 high-\( p_\perp \) jets, one \( b \)-tagged;
  - use hard hadron spectrum from \( H^\pm \) (harder than \( W^+ \))

(cut on 80\% of visible energy reduces \( t\bar{t} \) by 300, signal to 10-20\%)

MSSM-Higgs boson searches at LHC: upshot

Sensitivities in the $m_A$-tan $\beta$ plane

A more exotic solution: Adding extra singlets

Basic idea

- Add a further Higgs singlet $\phi$ (real or complex) + interactions with the SM Higgs-sector through $\mathcal{L} \propto (\Phi^{\dagger} \Phi)(\phi^{*} \phi)$.
  (Note: No renormalisable interactions with the SM gauge sector for $\phi$.)
- Typical result: mixing of the scalar fields to mass eigenstates:
  - Complex $\phi$, no further interactions ("phantom model"): $H_1^0, H_2^0$, massless $A^0$ (goldstone of broken $U(1)$), the latter with potentially large coupling to $H_i^0$.
  - Complex $\phi$ + additional $U(1)$: $A^0$ is eaten by $Z'$.
- Real $\phi$: $H_1^0$ and $H_2^0$

- Consequence: reduced couplings to SM fields - can make life hard.
- Perversion of the above: Many singlets $\rightarrow$ can make $H$ totally invisible due to huge width and small coupling to individual modes.