Higgs physics at LHC

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(CERN)
Physics@LHC, Cracow, July 06

A non exhaustive review…
• Introduction
  – Constraints on $M_H$
  – SM Higgs production at LHC and Higgs decays
  – Experimental conditions
• SM Higgs searches
  – Few selected channels
  – Overall sensitivity
• Higgs boson properties
  – Mass and Width
  – Spin, CP
  – Couplings
  – Self coupling
• MSSM Higgs searches
  – (short) introduction
  – Application of SM channels
  – $H/A \rightarrow \tau\tau$ and charged Higgs
  – Overall sensitivity
  – NMSSM
• Conclusions
  Not covered: Higgs in more exotic models (little Higgs, extra dimensions,...)
Introduction

What the LHC should tell us:
• What is the mechanism responsible for the EW symmetry breaking?
• The SM Higgs boson (only piece of SM not observed today) or something else?
• The answer should be at $E < \sim \text{TeV}$
• Is there new physics at the same $E$ scale to solve some of the problems of the SM? Supersymmetry or …

What (we think) we know about $M_H$:
• Consistency of the theory
  o Triviality
  o Vacuum stability
• Indirect constraints (EW radiative corrections)
  o $M_H < 186 \text{ GeV} \,@\, 95\%\, \text{CL}$ (EW fit Moriond06)
• Direct limit (LEP): $M_H > 114.4 \text{ GeV}$

Riesselmann, hep-ph/9711456
• Concentrate on “low” mass SM Higgs boson, mostly $M_H<200$ GeV
  – Favored by radiative corrections
  – Susy needs a “light” Higgs boson
  – Search in mass range ~200-600 GeV is “easier” in “golden” 4-leptons mode (although becoming statistics limited at high mass)
• If no light Higgs found, will need to look at WW scattering at high mass:
  – Difficult, requires large integrated luminosity
  – Should anyway be done also if a “light Higgs” is found, to check that it regularizes WW scattering.
    – *Not discussed further here*
Higgs production @ LHC

$gg \rightarrow H$ via top loop

Vector Boson Fusion

Associated production with top

WH,ZH production

All processes are computed at NLO or NLLO for the total rate. Higgs production distribution ($d\sigma/dp_t$) also available at NLO/NNLL

Many progresses in the recent years in QCD computations

*see review talk of R.Harlander and review hep-ph/0503172 by A.Djouadi*

Typical uncertainties on cross-section

- $gg$ 10-20% (NNLO)
- VBF ~ 5% (NLO)
- WH,ZH < 5% (NNLO)
- $ttH$ 10-20% (NLO)
Higgs decay

Higgs → f-fbar
(~mf**2)

Higgs → WW(*), ZZ(*)

H → γγ

All the relevant BR known with few % accuracy
(NLO computations)
• $gg \rightarrow H$: dominant production, large QCD corrections, $H$ “often” produced associated with a “hard” jet ($ZZ^*, WW^*, \gamma \gamma$ decays)
• $qq \rightarrow Hqq$ ($WW, ZZ$ fusion “VBF”). Specific signature allowing better background rejection ($\tau \tau, WW^*, \gamma \gamma$ decays, also $bb$ ??)
• $ttH$ production, Lepton from top allows to trigger ($bb$ decay, also $\tau \tau, WW^*$ for coupling measurements, $\gamma \gamma$ at high lumi.)
• $WH, ZH$ production: $\gamma \gamma$, $WW^*$ at high lumi.
Experimental conditions

• Proton-Proton collisions @ 14 TeV

• Luminosity:
  – First run in 2007 at 900 GeV
  – First run @ 14 TeV in 2008, luminosity increasing to reach
    ~10^{33} cm^{-2}s^{-1} “low luminosity” phase
    => ~ 30 fb^{-1} between 2008 and 2010/2011
  – ~10^{34} cm^{-2}s^{-1} “high luminosity” phase
    => ~300 fb^{-1} by 2014/2015

• Pile-up: ~ 2 (low luminosity) to 20 (high luminosity) pp interactions (“minimum bias”) per bunch crossing (every 25 ns)

• Trigger to go from 40 MHz interaction rate to ~200Hz to disk for offline analysis
Order of magnitude of main processes

- $10^9$/s
- $10^2$/s
- $0.1$/s

$\sigma$ (in elastic)

- b quark production
- QCD jet, $E_t > 100$ GeV
- Quark and gluons in final state $\rightarrow$ high energy « isolated » $e$ and $\mu$
- $W$ and $Z$
- top
- Higgs mass = 120 GeV

Note: Tevatron run 1
$\sigma$(top) ~ 5pb
$\sigma$(tot) ~ 60 mb

Event rate @ $10^{34}$ cm$^{-2}$ s$^{-1}$
CMS and ATLAS

- **Powerful e/photon/muon/tau/b-jet identification**  
  *(cf talk by Anna Kaczmarska this afternoon)*  
  - Rjet \( \sim \) few \( 10^3 \) for \( \text{eff(photons)} \sim 80\% \)  
  - Rjet \( \sim 10^5 \) for \( \text{eff(electrons)} \sim 80\% \)  
  - R(light flavor jets) \( \sim 100 \) for \( \text{eff(b-jets)} \sim 60\% \)  
  - R(jet) \( \sim \) few \( 10^2 \) for \( \text{eff(tau to hadrons)} \sim 50 \% \)

- **Very good energy measurement of e/photon and muons**  
  - \( \sim 1 - 2 \% \) for elec \( \text{pt} \sim 25\text{-}50 \text{ GeV} \)

- **Jets and Transverse missing momentum**
SM Higgs Searches

• Benchmark channels for detector performances
  – $H \rightarrow \gamma\gamma$ (old channel, new variations)
  – $H \rightarrow 4l$
• “counting experiment” channels
  – $H \rightarrow WW^{(*)}$
• Vector Boson fusion production channels
  – $H \rightarrow \tau\tau, \ WW^{(*)}$
\[ H \rightarrow \gamma\gamma \]

- Narrow peak over “smooth” background
- Key points:
  - Good mass resolution (Intrinsic width is negligible) => Energy resolution of e.m. calorimeter + primary vertex determination
  - Good photon identification: To reduce jet background below true photon background
    - Very fine segmentation (ATLAS) to allow photon/\pi^0 separation event by event
    - Isolation cuts
    - Recovery of conversions:
      - ~30% of photons convert in tracker

(CMS ECAL TDR)

✓ Computation agrees with Tevatron data
✓ Allows to use also NLO for signal
✓ Resbos program for NLO normalization of S and B + resummation effects

- Different strong points for CMS (Energy resolution) and ATLAS (fine segmentation, photon angle measurement). Overall, sensitivity is similar if using same input cross-sections.
- Inclusive channel is still one of the most powerful at low mass (~6-8 sigmas for 30 fb⁻¹)
- Several possibilities to divide events according to production mode (H+0J vs H+1Jet, VBF production, associated production, etc..) Can further increase the discovery potential
• Simple cut based analysis: count events in mass window after kinematical cuts

• “Optimized” analysis:
  – CMS: Add kinematic information and photon isolation (help to distinguish reducible background from direct photons)
  – ATLAS: Add Pt(photon pair), angular distribution in likelihood
  – Typically ~30-40% improvement in significance
  – Systematic error from fitting background rate ~ 10-15% effect (*ATLAS study*)

**Significance (m=130GeV) for 30fb⁻¹**

**CMS (all using NLO rates)**
- TDR new “cut” new “optimized”
  - 7.5  6.0  8.2
- ECAL TDR new: better NLO bkg computation, fake estimation, more conversions.

**ATLAS (stat. errors only)**
- TDR(LO) new NLO “cut” +likelihood
  - 3.9  6.3  8.7

Exact level of background will only be known from data…

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H→γγ in associated production

ttH final state:
for 100 fb⁻¹:
~7 signal events, 3.5 sigmas

Background: t-tbar events with radiated photons, W+4j+photons.

Can also consider WH, ZH (lepton-gamma-gamma) final states, and H produced with VBF process (H+2 jets final state)

=> Combining all channels should increase discovery potential
**H \rightarrow 4\text{leptons}**

Rely on good e/muon identification and energy resolution  
(mass resolution ~1.5-2 GeV)

Irreducible background: ZZ(*) -> 4l  
q qbar annihilation known at NLO  
add ~20% to account for gg->ZZ

Reducible backgrounds:  
Zbb -> 4 leptons  
t \bar{t} -> 4 leptons (also non resonant)  
Reduced by isolation cuts + anti impact parameters  
Typical rejection ~ 100 for Zbb => rejected one order of magnitude below ZZ

Clean but low statistics (especially < 130 GeV and ~170 GeV)

*Cf talk by P.Meridiani this afternoon*
In gluon fusion production
Main interest is near $M_H \sim 160$ GeV:
- BR($H \rightarrow WW$) >95%, other decay modes are suppressed
Look at dilepton final state ($ee, \mu\mu$ and $e\mu$)
Backgrounds:
- $t\bar{t}$ production: rejected by jet-veto
- $WW$ continuum: Use spin correlation to distinguish signal from background
Difficulty:
- Counting experiment, essentially no mass reconstruction and no mass peak
- Rely on accurate estimate of background rate
- Strategy: Use control region(s) to estimate background(s) and extrapolate to signal region
New developments:
- Include $gg \rightarrow WW$ continuum contribution: Small increase in background but shape more similar to signal
- Include both $t\bar{t}$ and single top backgrounds @ NLO (Les Houches 2005)
Selection (CMS note 2006-047):
2 leptons $\eta<2$, $30<p_T^{\max}<55$ GeV, $p_T^{\min}>25$ GeV
$E_{\text{tmiss}}>50$ GeV
No jet $E_T^{\text{raw}}>15$ GeV
$\Delta \phi <45^\circ$, $12<M_{ll}<40$ GeV

Systematic uncertainty on total bkg $\sim 13\%$ (normalized in control samples for $t \bar{t}$ and $qq \rightarrow WW$, relies on MC for single top and $gg \rightarrow WW$)
Will need detailed studies with data

*cf talk by A-S. Giolo-Nicollerat*
VBF Higgs production

- Forward tagging jets
  - $P_t \sim M_W/2$
  - Large separation in $\eta$
- No jet radiation in central region

Signal: no color flow between tagging jets

Most backgrounds: strong "acceleration" of color charge between tagging jets => radiation

Atlas-sn-2003-024
Test Case: Z+2 jets production (« Zeppenfeld » plot)

- Two processes QCD and EW (VBF)
- Apply « VBF » cuts to two jets (large $\Delta \eta$, Pt cut)
- Use existing Z+3j matrix elements to compute rate of events with two « tagging » jets + one central jets (i.e. the rate of events which would be vetoed)

Can expect to reject $\sim 70\%$ of QCD processes

But this is hard to predict accurately (parton shower programs don’t always give the correct answer, sensitivity to underlying events, etc.). Being studied with Alpgen/Sherpa. Need data to understand this better.

Rainwater et al hep-ph/9605444
Jet veto also sensitive to pile-up effects

For the time being, consider VBF channels only in the “low” luminosity regime
VBF $H \rightarrow \tau\tau$

- **Typical selection:**
  - 2 tagging jets
  - Higgs decay products in central region between tagging jets
  - Jet veto
  - Lepton-lepton or lepton-hadron final state for tau decays
  - Use missing transverse momentum + collinear approximation of tau decays to reconstruct invariant mass of tau pair
  - Resolution limited by missing pt resolution: ~10 GeV-13 GeV

- **Main background:**
  - $Z \rightarrow \tau\tau + 2$ jets. Dangerous for low $M_H$
Control samples

Z→ττ + jet signal with 30 fb⁻¹
~1000 signal events with S/B ~ 6
Check mass reconstruction

J. Campbell, R.K. Ellis, D. Rainwater
hep-ph/0308195

W/Z+nJ+X NLO predictions at LHC
with cuts:

- p_{T} > 15 GeV
- |η| < 2.4
- p_{T} > 20 GeV
- |η| < 4.5
- DR_j > 0.4
- DR_jj > 0.2

<table>
<thead>
<tr>
<th>process</th>
<th>σ_{LO}</th>
<th>σ_{NLO}</th>
</tr>
</thead>
<tbody>
<tr>
<td>e⁺e⁻ + X</td>
<td>5670</td>
<td>6780+290⁻130</td>
</tr>
<tr>
<td>e⁻ν_e + X</td>
<td>3970</td>
<td>4830+210⁻90</td>
</tr>
<tr>
<td>e⁺e⁻ + X</td>
<td>803</td>
<td>915 ± 31</td>
</tr>
<tr>
<td>e⁺ν_e, j + X</td>
<td>1660</td>
<td>1880+60⁻50</td>
</tr>
<tr>
<td>e⁻ν_e, j + X</td>
<td>1220</td>
<td>1420 ± 40</td>
</tr>
<tr>
<td>e⁺e⁻, j + X</td>
<td>248</td>
<td>288+8⁻7</td>
</tr>
<tr>
<td>e⁺ν_e, jj + X</td>
<td>773</td>
<td>669+10⁻18</td>
</tr>
<tr>
<td>e⁻ν_e, jj + X</td>
<td>558</td>
<td>491+9⁻7</td>
</tr>
<tr>
<td>e⁺e⁻, jj + X</td>
<td>116</td>
<td>105+1⁻5</td>
</tr>
</tbody>
</table>

Z+ jet rates (ee,μμ): control sample for Z+jets
background, signal free
SM Higgs Discovery potential

- note difference between LO and NLO cross-sections
- For $M_H \sim 115$ GeV, several channels can be combined
- In principle, already good discovery potential with $10 \text{ fb}^{-1}$

Provided detector performances and background systematics are under control
Each channel has different sensitivity to background systematics:

Example: \( \text{ttH}(H \rightarrow bb) \) vs \( H \rightarrow 4l \)

(ATLAS phys TDR 100 fb\(^{-1}\))

Background shape?

\( \text{ttbb} \) and \( \text{ttjj} \) @ NLO (dream?)
Background systematics and how to normalize bkg from data

<table>
<thead>
<tr>
<th>Channel</th>
<th>Main background</th>
<th>S/B</th>
<th>Bkg. sys for 5s</th>
<th>Proposed technique/comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-&gt;γγ</td>
<td>Irreduc. γγ</td>
<td>3-5%</td>
<td>0.8%</td>
<td>Side-bands (bkg shape not known a priori)</td>
</tr>
<tr>
<td></td>
<td>Reducible qγ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ttH H-&gt;bb</td>
<td>ttbb</td>
<td>30%</td>
<td>6%</td>
<td>Mass side-bands Anti b-tagged ttjj ev.</td>
</tr>
<tr>
<td>H-&gt;ZZ*-&gt; 4 lep</td>
<td>ZZ-&gt;4l</td>
<td>300-600%</td>
<td>60%</td>
<td>Mass side-bands Stat Err &lt;30% 30fb⁻¹</td>
</tr>
<tr>
<td></td>
<td>Reducible tt, Zbb</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H-&gt;WW*-&gt;llνν</td>
<td>WW*, tW</td>
<td>30-150%</td>
<td>6-30%</td>
<td>No mass peak Bkg control region and extrapolation</td>
</tr>
<tr>
<td>VBF channels</td>
<td>Rejection QCD/EW</td>
<td>Study forward jet tag and central jet veto</td>
<td>Use EW ZZ and WW QCD Z/W + jets</td>
<td></td>
</tr>
<tr>
<td>In general</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VFB H-&gt;WW</td>
<td>tt, WW, Wt</td>
<td>50-200%</td>
<td>10%</td>
<td>Study Z,W,WW and tt plus jets</td>
</tr>
<tr>
<td>VBF H-&gt;ττ</td>
<td>Zjj, tt</td>
<td>50-200%</td>
<td>10-40%</td>
<td>Mass side-bands Beware of resolution tails</td>
</tr>
</tbody>
</table>
Higgs boson properties

- Mass, Width
- Spin, CP (SM 0⁺⁺)
- Couplings to other bosons and to fermions
- Higgs auto-coupling
Higgs mass measurement

- Relatively easy from $H \rightarrow \gamma \gamma$ or 4leptons. The channel $H \rightarrow \tau \tau$ can also contribute at low luminosity.

$\Gamma(H)$ only directly accessible for $m>200$ GeV
Spin, CP

Observation of $gg \to H$ or $H \to \gamma\gamma$ excludes spin 1

For $M_H > 200$ GeV, study spin/CP from $H \to ZZ \to 4l$

CP Properties of HWW coupling can be studied from VBF processes

cf talk by M. Bluj
Couplings

Concentrate on “low” $M_H$

First step:
Assume spin 0
⇒ Measure $\sigma \cdot$BR in different channels

Uncertainties:
Selection efficiencies
Background subtraction
(Luminosity for absolute cross-sections)

Second step:
Assume only H
⇒ Ratio of BR
Third step:
- No new particles in loop,
- No strong coupling to light fermions
⇒ Express all rates and BR as a function of 5 couplings $g_W, g_Z, g_{\text{top}}, g_b, g_\tau$

Example:
$\sigma_{\text{VBF}}$: $a_{\text{WF}} g_W^2 + a_{\text{ZF}} g_Z^2$
$\text{BR}(\gamma\gamma)$: $(b_1 g_W^2 - b_2 g_{\text{top}}^2)/\Gamma_H$

« Absolute » scale not measurable:
Measure $g_Z/g_W, g_{\text{top}}/g_W, g_\tau/g_W$ and $g_W/\sqrt{\Gamma_H}$

If more assumptions (like $g_W < g_W^{\text{SM}}$), can get absolute couplings

Most difficult: b Yukawa coupling
VBF $HW\rightarrow l b b$ feasibility?
Auto-coupling

From Higgs potential: trilinear coupling

Look at Higgs pair production
Small x-sec, ~ 20fb (before BR!)

\[ \frac{-3 i g m_H^2}{2m_w} \]

From Higgs potential:
trilinear coupling

\[ \lambda / \lambda_{SM} \]

m_H = 170 GeV

Parton level study
Baur, Plehn, Rainwater hep-ph/0211224
Still to be confirmed by more detailed exp.
Studies including bkg systematics
MSSM Higgs searches

- 2 Higgs doublets
- 5 physical states after EW symmetry breaking $h, H, A, H^\pm$ ($h, H$ CP=+1, $A$ CP=-1)
- 2 parameters at tree level
  - Usually use $M_A$ and $\tan(\beta)$
  - $M_h < M_Z$ at tree level
- Large radiative corrections
  - Introduce dependence on other Susy parameters
  - Increase upper bound on $M_h \sim 135$ GeV
- Define few scenario (Carena et al, hep-ph/0202167)
  - “$M_h^{\text{max}}$, gluophobic” (minimizes effective ggh vertex), no-mixing, small $\alpha_{\text{eff}}$ (reduces hbb)
- CP violating scenario are also investigated (not discussed here)
MSSM Higgs Searches

• Apply SM searches
  – Rescale cross-section and BR
    • $\sigma(gg\rightarrow h) = \frac{\sigma_{SM} \Gamma(h\rightarrow gg)_{MSSM}}{\Gamma(h\rightarrow gg)_{SM}}$
    • $\sigma(VBF\rightarrow h) = \sigma_{SM} \sin^2(\alpha-\beta)$
  – Mostly relevant for h searches when it is SM like (also for H at low $M_A$)

• Direct searches of H/A $\rightarrow$ SM particles
  – Degenerate in mass in most of parameter space
  – Cross-section $gg\rightarrow bb$ H/A $\sim \tan^2(\beta)$ $\Rightarrow$ explore large $\tan(\beta)$
    • Final state $H/A \rightarrow \tau\tau$ (BR $\sim 10\%$) or $\mu\mu$ (BR $\sim 3.10^{-4}$)
    • Can tag or not the “soft” b produced in association with Higgs
      • $H/A \rightarrow bb$ challenging (trigger)

• Direct searches of $H^\pm$
  – $gg\rightarrow t\bar{b} H^\pm$ production followed by $H^\pm\rightarrow \tau\nu$ or $tb$
  – Produced in top decays if mass $< $ top mass

• Searches of Susy $\rightarrow$ h (not discussed here)
  or Higgs $\rightarrow$ Susy ($\rightarrow 4$leptons+$E_{Tmiss}$, $\rightarrow$invisible, …)
Application of SM Higgs searches

VBF $H, h \rightarrow \tau \tau$ with 30 fb$^{-1}$ (ATLAS)

Difficult channel: tagging jet, $E_{T \text{miss}}$ resolution, tau identification

$H, h \rightarrow \gamma \gamma$ with 300 fb$^{-1}$ (ATLAS)
H,A \rightarrow \tau\tau \text{ searches (CMS example)}

Lepton-Lepton, Lepton-hadron and hadron-hadron final states
Mass reconstruction with collinear approximation (Etmiss resolution)
Can tag or not soft-b's
Main backgrounds:
Z/Drell-Yan, ttbar, W+jets
QCD (for hadron-hadron final state, need powerful tau identification)
H, A → µµ searches (CMS example)

Discovery reach at “low” MA, high tan(β)
“intense” coupling regime where h, H, A are ~degenerate
(cannot resolve the different contributions)
Charged Higgs

\[ gg \rightarrow \bar{t} b H^\pm, \quad H^\pm \rightarrow \tau \nu \quad (BR \sim 20\%) \]

t can be on shell or off shell

Final state: hadronic tau, 3 jets, Etmiss

Backgrounds: t-\bar{t}, W-t production

Can also consider \( gg \rightarrow t b H^+ \), \( H^+ \rightarrow t b \): difficult combinatoric issues
MSSM Summary for 300 fb$^{-1}$ (ATLAS) no H->Susy
If $\tan(\beta) \sim 10$, $M_A > 200$ GeV, only $h$ is seen
Can we observe deviation in coupling measurements?

$M.\text{Duehrssen et al, hep-ph/0407190}$

(5 sigmas effect up to 300 GeV)
Example of H→SUSY

\[ H \rightarrow \chi \chi \rightarrow 4 \text{ lepton} + \text{Etmiss} \]

Nice experimental signature
Can cover intermediate tan(\(\beta\)), \(M_A\)
SUSY parameters dependent

Example for mSUGRA
\[ m_0 = 50, m_{1/2} = 150, A_0 = 0, \tan(\beta) = 5, \mu > 0 \]

\(H\rightarrow\text{invisible also considered}\) (in some non-minimal SUSY models or more exotics models)
(cf M. Heldmann talk this afternoon)

Visible mass

Events / 20 GeV/c\(^2\)

\[ m_{\text{miss}} \text{ (GeV/c}^2\text{)} \]

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NMSSM

- Add one singlet
- 7 states $h_1, h_2, h_3, a_1, a_2, h^+$
- $h_i \rightarrow a_j a_j$ possible
- Possible delicate point (Ellwanger et al hep-ph/0305109)
  $m(h_1)=115$ GeV, $m(a_1)=56$ GeV,
  $\text{BR}(h_1 \rightarrow a_1 a_1) = 98\%$  $\text{BR}(a_1 \rightarrow b \bar{b}) = 92\%$  $\text{BR}(a_1 \rightarrow \tau \bar{\tau})=8\%$

Difficult. Tau and b-identification are again critical
Conclusions

• Many SM Higgs channels have been studied in details
  – Already good sensitivity to SM Higgs with $\sim 10 \text{ fb}^{-1}$
  – Provided detector performances and backgrounds are under control. Only data will tell

• Detailed Higgs studies will require more statistics (as well as WW scattering at high energy)

• MSSM Higgs sector covered
  – But could observe only $h$ “SM like”

• Stay open to more complicated scenario
From prospects to reality…
… expect very different talks in two years from now

Many thanks for A. Nikitenko for providing the CMS results