Higgs Overview

UK HEP Forum – Cosener’s House, 20/9/2010
LHC data taking at high energy started in 2010
First results presented this summer at
• ICHEP 2010, 22-28 July
• Higgs Hunting, 29-30 July

In this talk I will review recent Higgs developments and projections for the near future:
• Introduction: SM Higgs production and decay
• SM Higgs searches at the TeVatron
• Theoretical interlude
• LHC: operations at 7 TeV
• SM Higgs sensitivity (and MSSM Higgs, too)
• Conclusions
Main decays used in Higgs searches:

- $m_H < 140$ GeV: $bb$, $\tau\tau$, and $\gamma\gamma$
- $m_H > 140$ GeV: $WW$ dominates, with $ZZ$ a distant 2nd
SM Higgs production

Gluon fusion (GF)
Dominant production mode

Vector boson fusion (VBF)
Characteristic “tag jets” signature

Higgsstrahlung
Associated production with a pair of top-quarks
HIGGS HUNTING AT THE TEVATRON
Higgs at the TeVatron

Overall search strategy

Low Higgs mass
- \( H \rightarrow bb \) decay dominates (…can’t use GF)
- \( pp \rightarrow WH,ZH \rightarrow ℓνbb, ννbb, ℓℓbb \)
- Main backgrounds are \( W+\text{jets}, Z+\text{jets} \)

High Higgs mass
- \( H \rightarrow WW \) is main decay (→ leptons!)
- \( gg \rightarrow H \rightarrow WW \) most important (\( m_H > 125 \) GeV)

Analysis of most channels is divided into sub-channels for improved s/b
But in practice have expanded list of searches: “no channel too small”

$H \rightarrow \tau \tau$, $H \rightarrow \gamma \gamma$ also included

D0 even includes $t\bar{t}(H \rightarrow b\bar{b})$!
Higgs at the TeVatron

- Excluded at 95% CL
  - $158 < m_H < 175$ GeV (4x previous exclusion)
  - In the absence of signal: expect $156 < m_H < 173$ GeV
  - At $m_H=115$ GeV: $1.5 \times \sigma_{SM}$ Higgs
- Approved to end 2011. Request 3 more years (“Run III”)
THEORETICAL INPUTS
Theoretical input to searches

SM Higgs limits are not purely experimental… eg input of $\sigma_{SM\,Higgs}$ (line at R=“1”)

- “Predictions for Higgs production at TeVatron and associated uncertainties” (Baglio & Djouadi, [hep-ph] 1003.4266, 1009.1363)
- Bottom line: authors estimate unctty. in $\sigma(gg\rightarrow H)$ (~40%) is twice as large as what was used in latest TeVatron combination
- Main issues:
  - Uncertainty from scales $\mu_R, \mu_F$ (variation not large enough?)
  - PDF uncertainties, and incorporation of uncertainties on both $\alpha_S^{th} + \alpha_S^{exp}$
  - how to combine above errors
- Over the Summer, work has been done by both sides to discuss + address issues… but debate still rages on
- LHC 7 TeV is also being given the “Baglio & Djouadi treatment” ($\Delta\sigma/\sigma \approx -25\% \leftrightarrow +30\%$)
Theoretical input to searches

Theoretical inputs (event generators, PDFs, cross-sections for signals and backgrounds, Higgs BRs, etc) are crucial to searches. It is vital that theorists and experimentalists work together on this.

LHC Higgs “Cross Section” Working Group

Meetings: April 2010 (Freiburg), July 2010 (CERN), November 2010 (Bari)

https://twiki.cern.ch/twiki/bin/view/LHCPHysics
LHC Higgs Cross Section Working Group

Preparatory workshop in Torino Nov. 23-24, 2009
Inauguration workshop in Freiburg April 12-13, 2010

Task: SM and MSSM Higgs Cross Section and BRs
Compute and agree on cross sections and Brs
Use the same Standard Model input parameters
Strategy on uncertainties (scale, $a_s$, PDF, etc.)
Monte Carlo at NLO for the signal
Define pseudo-observables
Cross sections of background SM processes

Beyond SM and MSSM?
Other SUSY scenario NMMSM,
Invisible Higgs, Higgsless, etc.
LHC
LHC operations in 2010

LHC operations: impressive so far

2010
• Start of 7 TeV pp collisions: end of March
• \( L = 10^{27}, 10^{28}, 10^{29}, 10^{30}, 10^{31} \) cm\(^{-2}\)s\(^{-1}\)
• Already attained max p/bunch: \( 10^{11} \)
• Late August: collided 36 x 36 bunches (delivering \(~0.5 /\text{pb/day}\) )
• Target: \( 10^{32} \) cm\(^{-2}\)s\(^{-1}\) < end of year

ATLAS + CMS
• data collection and detector commissioning going impressively well
• each experiment now has \(~3.5 /\text{pb}\) of high quality data

2011: aim for \( L_{\text{int}} \geq 1 /\text{fb/\text{expmt}} \)
2012: shutdown
2013: collisions at 14 TeV
LHC production cross-sections

Rediscovering the Standard Model

SM processes (pb)

SM Higgs (fb !)

“Done”…

Next…

Next year …??
Detector commissioning going very well (and rapidly) on all fronts: tracking, calorimetry, particle id, jets, missing $E_T$, b-tagging.
Clearly, the 7 TeV LHC should be a significant step up in Higgs sensitivity.

Parton luminosities for $gg/qq \rightarrow X$

For $M_X > 140$ GeV, the $gg$ luminosity is $> 15$ times larger at LHC:
good news for $gg \rightarrow H \rightarrow WW/ZZ$.

In addition, dominant backgrounds are produced via $qq$.

$gg \rightarrow H \rightarrow WW/ZZ$

$qq \rightarrow WW/ZZ$
Projected Higgs exclusion sensitivity for 1/fb of data at 7 TeV LHC

- **Method used by ATLAS + CMS:**
  - No new analyses developed for $\sqrt{s} = 7$ TeV
  - Instead rely on full simulation studies at $\sqrt{s} = 10/14$ TeV and rescale signal and background cross-sections to $\sqrt{s} = 7$ TeV.
  - ATLAS uses GF NLO; CMS uses GF NNLO (~30% higher)
  - Acceptances, efficiencies unchanged (verified to be the same – or even slightly higher – at 7 TeV)
  - Errors rescaled/re-evaluated for 7 TeV and 1/fb
  - 10/14 TeV studies optimised for discovery, instead of exclusion: room for improvement
  - Limit setting (incorporating uncertainties) using profile likelihood method (ATLAS) and $\text{CL}_S$ method (CMS)

- **References:** ATL-PHYS-PUB-2010-009, CMS NOTE 2010/008
Effect of 10/14 TeV $\rightarrow$ 7 TeV

Some signal and background cross-sections as function of $\sqrt{s}$, normalised to $\sqrt{s}=10$ TeV.

Cross sections depend strongly on $\sqrt{s}$...:
- e.g., from 10 $\rightarrow$ 7 TeV
  - GF + VBF signals ($m_H=160$ GeV) drop to 50%
  - $tt$, WW and W backgrounds drop to 30-60%
LHC Higgs search strategy

- $H \rightarrow \gamma\gamma$
- $qq(H \rightarrow \tau\tau)\,$
- $tt(H \rightarrow bb)\,$
- $W/Z(H \rightarrow bb)\,$
- $H \rightarrow WW \rightarrow \ell\ell \nu\nu$
- $H \rightarrowＺＺ \rightarrow \ell\ell \nu\nu$
- $H \rightarrow ZZ \rightarrow \ell\ell \ bb/qq$
very clear signature
excellent mass resolution: CMS 0.7% - ATLAS 1.1%
→ narrow di-photon resonance

BUT
low signal yield: \(B(H \rightarrow \gamma\gamma) \sim 10^{-3}\)
high background rate (\(\gamma\gamma, \gamma j\))

NEED
excellent ECAL calibration
high \(\gamma\) identification efficiency
\(\gamma\) conversion recovery
\(\gamma/jet\) discrimination
Ratio of 95% CL upper limit on $\sigma \times B(H \rightarrow \gamma \gamma)$ and the SM rate

- No exclusion with this channel stand-alone
- Limits are better than current $H \rightarrow \gamma \gamma$ TeVatron limits (~ 20 x SM)
**H → WW → ℓνℓν**

**Powerful channel:** $H \rightarrow WW$ has largest BR around $m_H \sim 2m_W$

- di-lepton signature (include $ee + e\mu + \mu\mu$) and missing $E_T$
- ATLAS analyses $H+0/1/2$jets (GF+VBF)
- CMS uses a multivariate method
- backgrounds are $WW$, top ($tt$, single $t$, $Wt$), and $W+jets$
- no Higgs mass peak, due to $\nu$s!
  - systematics very important
  - detailed understanding of backgrounds is absolutely key: use sophisticated treatment of control regions; data-driven estimates

**References:** ATL-PHYS-PUB-2010-005 (10 TeV); CMS PAS HIG-08/006 (14 TeV)
Explore azimuthal di-lepton correlation, due to resonant scalar decay.

\[ H \rightarrow WW \rightarrow \ell\nu \ell\nu \]

Determining background in signal region (ATLAS)

CMS NN output
$H \rightarrow WW \rightarrow \ell \nu \ell \nu$

Ratio of 95% CL upper limit on $\sigma \times B(H \rightarrow WW \rightarrow \ell \nu \ell \nu)$ and the SM rate

ATLAS
- sensitivity to SM starts with $L = 250 \, \text{pb}$
- with $L = 500 \, \text{pb}$ would exclude same range as ICHEP 2010 TeVatron combination
- $145 < m_H < 180 \, \text{GeV}$ excluded ($L = 1 \, \text{fb}$)

CMS ($L = 1 \, \text{fb}$)
- $150 < m_H < 185 \, \text{GeV}$ excluded
- discovery sensitivity (significance $> 4.5\sigma$): $160 < m_H < 170 \, \text{GeV}$
Very clear signature, low bgd: effective over a wide $m_H$ range

- Four isolated high $p_T$ leptons (4e, 4μ, 2e2μ)
- Reconstruct narrow 4ℓ mass peak ($m_Z$ constraint helps)

BUT
- low signal yield: $B(H\rightarrow ZZ) \times B^2(Z\rightarrow \ell\ell) < 10^{-3}$
- backgrounds: $ZZ(*)$ dominates; Z+jets, tt, Zbb

NEED
- high efficiency e/ reconstruction
- excellent lepton E and p resolution

References: ATLAS CERN-OPEN-2008-020 (14 TeV); CMS PAS HIG-08/003 (14 TeV)
Z mass constraint:
improvement in mass resolution (10-20%)

Impact parameter significance:
rejecting leptons from semi-leptonic B-decays

14 TeV, 1 /fb
Ratio of 95% CL upper limit on $\sigma \times B(H \rightarrow ZZ \rightarrow \ell \ell \ell \ell)$ and the SM rate

- No stand-alone exclusion
- But competitive sensitivity ($< 4 \times$ SM) in wide $m_H$ region: 200 – 400 GeV
LHC 7 TeV combined results

95% CL upper bounds on cross-section (normalised wrt SM Higgs cross-section)
for 1/fb, and $H \rightarrow \gamma\gamma$ + $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ + $H \rightarrow ZZ \rightarrow 4\ell$

$135 < m_H < 188$ GeV

$145 < m_H < 190$ GeV

- Both experiments combined (2 x CMS): $140 < m_H < 200$ GeV (95% CL excl.)
- Both experiments combined should exceed 5$\sigma$ discovery potential for 160 – 170 GeV
- For low $m_H$ will need more channels ($H \rightarrow bb$, $\tau\tau$), and higher $\sqrt{s}$
Subjets structure for Higgs search?

At the LHC: production of EW-scale particles (W,Z,H,t→jets) >> threshold
→ highly boosted/collimated decay products, with measurable subjet structure;
→ can be used to differentiate from QCD jets

Apply subjet analysis technique to WH+ZH (H→bb) at the LHC
• select events with very high $p_T$ H and W,Z decay products
• cluster H decay products into a single fat jet
• iteratively decompose into subjets while checking for consistency with bbg
• two hardest subjets must b-tag
• subjets are “filtered” (cleanup contamination from underlying event)
• selected subjets are then used to reconstruct $m_H$: much improved mass resolution

Subjets as Higgs search tool

LHC

(WH→ℓν bb + ZH→ℓℓ bb + ZH→νν bb)

Combined particle-level result

- Note excellent Z peak for calibration
- 5.9 σ; potentially very competitive
- bb branching information critical for extracting Higgs properties
  - Studies within ATLAS are promising (14 TeV, ~4σ).
  - 7 TeV nearly public.
HIGGS BEYOND THE SM
MSSM: $H^+ \rightarrow c\bar{s}$, $\tau\nu$

**ATLAS**
- Light charged higgs ($m_{H^+} < m_{top}$) can appear from top quark decay.

**$H^+ \rightarrow c\bar{s}$ in semi-leptonic $t\bar{t}$ events**
- Lepton + MET + 4jets (with 2 b-tag)
- Reconstruct $m_{H^+}$ with 2 untagged jet
- Main background: $t\bar{t}$bar (95%)
- Improve dijet mass resolution with leptonic $W$, top mass constraint

**$H^+ \rightarrow \tau\nu$ in di-lepton $t\bar{t}$ events**
- Use leptonic tau decay mode
- Two leptons + MET + 2 b-jets
- Main background: $t\bar{t}$bar (90%)
- Look for excess close to -1 in helicity angle $\cos\theta_\tau^*$

**Better upper limit on branching ratio compared to current Tevatron results**
MSSM Higgs \( pp \rightarrow bb\phi; \phi \rightarrow \tau\tau \)

CMS

14 TeV

- Isolated pairs of \((\tau_{had}\tau_{\mu}), (\tau_{had}\tau_{e}), (\tau_{\mu}\tau_{e})\)
- With MET, 1 tagged bjet, veto extra jets
- Build \(\tau\tau\)-mass using collinear approx
- Count events in sliding \(\tau\tau\)-mass window
- Dominant backgrounds: \(t\bar{t}, Z+b\bar{b}\) & \(Z+c\bar{c}\)
  -- assessed from data
Conclusions and Outlook

- **TeVatron Higgs:**
  - pushing on, with an impressive list of sophisticated searches
  - extended running for 3 more years proposed (“Run III”)

- **LHC:**
  - machine and detectors operating extremely well
  - off to a good start! …but some major milestones still ahead of us

- **LHC initial sensitivity to Higgs: expected early in 2011**

This time next year we may have some real Higgs candidates… not just simulation!

Truly higgsciting times ahead!!
TeVatron Higgs projections

Projections (based on 2 x CDF):

End 2011, 10 /fb
2.4σ expected across whole range
3σ at m_H=115 GeV

End 2014 (Run III), 16 /fb
3σ expected across whole range
4σ at m_H=115 GeV
Rescaling effect on $H \rightarrow ZZ \rightarrow \ell\ell\ell\ell$

Acceptance of signal and irreducible ZZ background agree to within 2%
Fully simulated detector

- Included trigger, real ATLAS b-tagging algorithm, detailed tracking & calorimeter
- Also include Wt background omitted from initial study.
- Also included study of Wbb ME vs Wg->Wbb
- Slight degradation w.r.t particle level, but still very promising
Scale uncertainty

Higher orders (HO) guessed with $\mu_R, \mu_F$
variation around central $\mu_0 = m_H$

$$\frac{m_H}{\kappa} \leq \mu_R, \mu_F \leq \kappa m_H$$

Small HO $\Rightarrow \kappa = 2$ enough (ex. $q\bar{q} \rightarrow HV$)

Large HO in $gg \rightarrow H$ ($K_{HO} \simeq 3$)
guess scale domain from $\sigma_{NLO}$:
NLO band catches $\sigma_{NNLO}$
$\Rightarrow \kappa = 3$ needed (at least) according to our
criterium

NNLO $gg \rightarrow H$: $\simeq 20\%$ scale variation

($\neq 10\%$ assumed by CDF/D0)
PDF and $\alpha_s^{\text{exp}+\text{th}}$ errors

Different sets of PDFs on the market
⇒ different errors on individual PDF
+ different central values
All have $\sim 5 - 7\%$ error, but central ABKM is 25\% smaller than MSTW/CTEQ!

Add PDF+$\alpha_s^{\text{exp}}$ correlated error
(MSTW dedicated set)
⇒ $\alpha_s(M_Z) = 0.1171 \pm 0.0034$ (90\%CL) error
Add $\Delta^{\text{th}}\alpha_s = 0.002$ error with central fixed-$\alpha_s$
MSTW PDF sets
⇒ ABKM is now consistent with MSTW/CTEQ

$\sim 20\%$ final error $\geq 5\%$ PDF alone