Higgs Searches at the LHC

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On behalf of the ATLAS and CMS Collaborations

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XLIIIrd Rencontres de Moriond QCD
The primary objective of the LHC

Elucidate the mechanism responsible for electroweak symmetry breaking

All experimental data to date favors a light Higgs

- SM: $M_H = 87^{+36}_{-27} \text{ GeV}$; $M_H < 160 \text{ GeV} @ 95\% \text{ CL}$
- LEP Direct Limit: $M_H > 114.4 \text{ GeV} @ 95\% \text{ CL}$

\[ \Lambda \] is the scale of new physics beyond the Standard Model

\[ \Delta \chi^2 \]

Vacuum stability

T. Hambye and K. Riesselmann hep-ph/9708416

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Higgs production at the LHC

Vector Boson Fusion

The two “spectator” quarks make for a very distinct final state

<10% unc. NLO

Gluon-gluon Fusion

Large backgrounds for low-mass Higgs searches

10-20% unc. NNLO

Associated Production

~10% unc. NLO

<5% unc. NNLO

Allows for triggering regardless of Higgs decay mode

NLO cross-sections

SM Higgs discovery final states

At low mass ($M_H < 2M_Z$)

- Dominant decay through $bb$; enormous QCD background, suppressed in $ttH$
- $H \rightarrow \tau\tau$ accessible through Vector Boson Fusion (VBF)
- $H \rightarrow WW(*)$ accessible through gluon-gluon fusion and VBF
- $H \rightarrow \gamma\gamma$ has a low BR (decays through top and W loops); but due to excellent $\gamma$/jet separation and $\gamma$ resolution is still very significant
- $H \rightarrow ZZ^* \rightarrow 4l$ also accessible

For higher masses

- $H \rightarrow WW$ and $H \rightarrow ZZ \rightarrow 4l$ final-states

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The ATLAS and CMS Experiments
Designed to search for the Higgs over a wide mass range

Hermetic calorimetry
- Exceptional measurement of missing transverse energy, jets to high eta

Exceptional particle identification
- Muons: Efficiency ~90% Jet Rejection ~10^5
- Electrons: Efficiency ~80% Jet Rejection ~10^5
- Photons: Efficiency ~80% Jet Rejection ~10^3
- b-Jet ID: Efficiency ~60% Light Jet Rejection ~10^2
- Tau ID: Efficiency ~50% Jet Rejection ~10^2

Electron, muon and photon energy and momentum resolution of ~2-3%
Strategy and Start-up

Anticipating the start of the LHC

• Summer 2008
• Few ~100 pb\(^{-1}\) by the year’s end
• Parts of both ATLAS and CMS have already taken cosmic ray data

Understand the detectors…

• Diagnose hot or dead channels
• Tally up dead material
• Tracking detector alignment
• Tune the detector simulations to better match ATLAS and CMS

…do Standard Model measurements

• Examine our standard candles
• Demonstrate the ability to measure Ws, Zs and tops (b-jet identification)

…then search for the Higgs

LHC The first five years?

<table>
<thead>
<tr>
<th>Year</th>
<th>Integrated Luminosity</th>
<th>Cross Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>~100 pb(^{-1})</td>
<td>(10^{31} \text{ – } 10^{32} \text{ cm}^{-2} \text{ s}^{-1})</td>
</tr>
<tr>
<td>2009</td>
<td>~1 fb(^{-1})</td>
<td>(10^{32} \text{ cm}^{-2} \text{ s}^{-1})</td>
</tr>
<tr>
<td>2010</td>
<td>~10 fb(^{-1})</td>
<td>(2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1})</td>
</tr>
<tr>
<td>2011</td>
<td>~30 fb(^{-1})</td>
<td>(2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1})</td>
</tr>
<tr>
<td>2012</td>
<td>~100 fb(^{-1})</td>
<td>(2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1})</td>
</tr>
</tbody>
</table>

1 pb\(^{-1}\) = 3 days at \(10^{31} \text{ cm}^{-2} \text{ s}^{-1}\)

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The “Golden Mode”

- Very clean signal (looking for final states with 4e, 4μ, 2e2μ)
- Excellent mass resolution (1.5 – 2 GeV for $M_H = 130$ GeV)
- Powerful analysis in a wide mass range

Experimental issues:

- Zbb and tt rejection (leptons non-isolated, with activity around the leptons in the calorimeter and tracker; high impact parameter significance)
- $qq \rightarrow ZZ$ known at NLO; $gg \rightarrow ZZ$ is added as 30% of LO $qq \rightarrow ZZ$ (no generator, yet)
$H \rightarrow \gamma \gamma$

Final state produced through W, top and bottom loops

Powerful for low masses
- Significance of $6 - 8\sigma$ with 30 fb$^{-1}$
- Excellent mass resolution ($\sim 1.5 - 2$ GeV)

Experimental issues
- Electromagnetic calorimeter calibration
- Requires excellent $\gamma$/jet separation
- Conversion recovery

Recent developments
- Split events into categories (by jet multiplicity, energy ratios and $\eta$ region)
- Inclusive, 1 and 2-jet analyses; combine to increase significance
- Use of fits and a Likelihood Ratio for discovery, systematics
\( H \rightarrow \gamma\gamma \)

Diphoton background now calculated at NLO
- Agrees with the data from the Tevatron

Backgrounds can be taken from the sidebands…

Inclusive Analysis
H → WW → 2l2ν

Unlike other channels, full mass reconstruction is not possible

- Essentially a counting experiment
- Accurate background estimate is critical

Most significant ~160 GeV

- BR(H→WW) > 95%

Dominant backgrounds

- ttbar (suppressed with a jet veto)
- WW (exploit spin correlations)
Forward Jet Tagging and the Central Jet Veto

We can get the upper-hand in the VBF channels

Forward Jet Tagging
- D. Rainwater, D. Zeppenfeld, et al.

\[ \eta_{j1} \cdot \eta_{j2} < 0 \]

\[ |\Delta \eta_{jj}| > 3.5 - 4 \]

\[ m_{jj} > 500 - 700 \text{ GeV} \]

Central Jet Veto
- V.Barger, K.Cheung and T.Han in PRD 42 3052 (1990)

Veto events with extra jets in the central region

Tagging Jet

Higgs decay products

S. Asai, ATL-PHYS-2003-005
VBF $H \rightarrow \tau\tau$

A very significant channel for low masses
- Important for studying the coupling of Higgs to leptons
- Three final states lepton-lepton, lepton-hadron, hadron-hadron
- Triggers for the fully hadronic mode are under investigation

Mass reconstruction via the collinear approximation
- Approximation breaks down when the two taus are back-to-back
- Mass resolution limited by missing transverse energy ($\sim 8 – 10$ GeV)

Experimental issues:
- Tau tagging (Likelihood, Neural Net methods)
- Z+jets background (especially for low masses)
- $tt$ rejection (b-jet ID and veto for lepton-lepton)
Data-driven control samples are being explored for many backgrounds

- The relative contributions from different jet multiplicities are not known
- Unknowns related to critical analysis cut-specific variables exist

For the dominant background, collect $\text{Z} \rightarrow \mu\mu$ and $\text{Z} \rightarrow \text{ee}$ events from data and use TAUOLA to decay the leptons to taus

In this way we can emulate each of the lepton-lepton, lepton-hadron and hadron-hadron final states

Obtain both the background shape and normalization from data
VBF $H \rightarrow WW \rightarrow l\nu qq$

One of the best channels for intermediate and high Higgs masses

- A VBF analysis reaping the benefits of the CJV and Tagging Jets selection

Event Selection

- VBF tagging jets selection
- Central Jet Veto
- Isolated lepton
- 4 jets
- Large missing transverse energy

Mass reconstruction possible

- Backgrounds: $t\bar{t}$bar, $W$+jets, $WW$+jets
- Exploring data-driven approaches for obtaining background shapes
Luminosity for discovery or exclusion

- ~few 100 pb⁻¹, some exclusion @ 95% CL
- ~1 fb⁻¹, 5σ discovery if $M_H \sim 160 - 170$ GeV
- ~10 fb⁻¹, discovery over a broad mass range
MSSM Higgs at the LHC

Minimal Supersymmetric extension to the SM: \((A, H, h, H^\pm)\)

- As one example here, consider \(A / H / h \rightarrow \mu\mu\)
- Not visible in the SM
- Enhanced in the MSSM by \(\sim \tan^2 \beta\); excellent mass resolution as opposed to \(\tau\tau\)

Direct and associated production

Divide analysis into two uncorrelated channels

Initial event selection:
- Di-muon selection, low event MET, b-tag
- 0 b-jet
- \(\geq 1\) b-jet
  - Acoplanarity, sum \(p_T\) of all jets
MSSM Higgs at the LHC

Combine the 0 and $\geq 1$ b-jet analyses to increase the significance

- A very similar analysis has been explored for the $\tau\tau$ channel

Reconstructed Invariant mass

$\tan\beta$ for a $5\sigma$ Discovery

10 fb$^{-1}$ Alone

10 fb$^{-1}$ Combined

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Conclusions
If it is there, ATLAS and CMS are in a good position to find the Higgs…

• Unless it is discovered first at the Tevatron
• For a SM Higgs ATLAS and CMS need ~1 – 30 fb⁻¹
• How long will it take to get that much integrated luminosity from the LHC?
• How quickly will we understand the detectors?

Post-discovery questions that would need be answered…

• Is it the simple Standard Model Higgs?
• Does it have the expected couplings to various particle types?
• Are there more Higgs particles (à la Supersymmetry)
• Higgs discovery also raises the “hierarchy” problem

ATLAS and CMS are on track to try and answer these questions.
Backup Slides
The ATLAS Experiment
The CMS Experiment
**ttH(H→bb)**

A very complex final state

- Good discovery channel at low masses
- Determination of the Yukawa coupling
- Dominant backgrounds tt+jets production
- Also considering fully-hadronic and dilepton final states

**Experimental issues:**

- b-tagging (efficiency ~$\varepsilon_b^4$)
- Good understanding of background shape at turn-over
MSSM Higgs at the LHC

Summary of CMS reach in $M_A \tan \beta$

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MSSM Higgs with ATLAS

\[ \tan \beta \]

\[ m_A \text{ (GeV)} \]

- $t \rightarrow bH^+$, $H^+ \rightarrow \tau \nu$
- $h \rightarrow \gamma \gamma$ and $Wh/\tau h$, $h \rightarrow \gamma \gamma$
- $tth$, $h \rightarrow bb$
- $H^+ \rightarrow tb$
- $H/A \rightarrow \mu \mu$
- $H/A \rightarrow \tau \tau$
- $gb \rightarrow tH^+$, $H^+ \rightarrow \tau \nu$
- $H \rightarrow ZZ^{(w)} \rightarrow 4$ leptons
- $H \rightarrow hh \rightarrow bb\gamma$
- $A \rightarrow Zh \rightarrow llbb$
- $H/A \rightarrow tt$

ATLAS

$\sqrt{s} dt = 300 \text{ fb}^{-1}$

Maximal mixing

LEP 2000

Trevor Vic
The ATLAS Experiment

Trigger and Data Acquisition System:

• Level-1 is hardware, Level-2 confined to “Regions of Interest”, Event Filter has the ability to access the entire event

High-Level Trigger

Interaction rate
~1 GHz
Bunch crossing rate 40 MHz
LEVEL 1 TRIGGER
< 75 (100) kHz
< 10 μs
Regions of Interest

LEVEL 2 TRIGGER
~ 1 kHz
~10 ms

EVENT FILTER
~ 100 Hz
~1 s

Event builder

CALO MUON TRACKING
Pipeline memories
Derandomizers
Readout drivers (RODs)
Readout buffers (ROBs)

Full-event buffers and processor sub-farms

Data recording
~100 MB/s

Average Event Size ~2 MB
~1 PB/year (petabyte = 10^{15} bytes!)
ATLAS Data-taking Chain
First test of end-to-end data-taking chain took place in September 2007

FLOW OF DATA FROM CERN TIER 0 TO TIER 1 SITES ALL OVER THE WORLD.

For data processing and analysis, the GRID is an absolute necessity.
The Large Hadron Collider

Housed in the former LEP tunnel

- Dipole field at 7 TeV is 8.33 T
- ~350 MJ per beam!
- Ultimately ~2800 bunches
- Vacuum 10^{-13} atm (~6500 m^3 pumped)
- 1232 Dipoles (operate at 1.9 K)
- 858 Quadrupoles
- Typical store lasts ~10 hours
- Can also be used for ion running (Pb)
- Final price tag estimated at 4G EUR
Expected LHC Event Rates

ATLAS with LHC at $\mathcal{L} = 10^{33}$ cm$^{-2}$ s$^{-1}$

<table>
<thead>
<tr>
<th>Process</th>
<th>Events / s</th>
<th>Events in 10 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>W$\rightarrow$ev</td>
<td>15</td>
<td>$10^8$</td>
</tr>
<tr>
<td>Z$\rightarrow$ee</td>
<td>1.5</td>
<td>$10^7$</td>
</tr>
<tr>
<td>ttbar</td>
<td>1</td>
<td>$10^9$</td>
</tr>
<tr>
<td>bbbar</td>
<td>$10^6$</td>
<td>$10^{12}$-$10^{13}$</td>
</tr>
<tr>
<td>H (m=130)</td>
<td>0.02</td>
<td>$10^5$</td>
</tr>
</tbody>
</table>
### VBF $H \rightarrow \tau\tau$

Note: All cross-sections are shown in fb

<table>
<thead>
<tr>
<th>Decay modes</th>
<th>TAUOLA-CLEO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow e\nu_e \nu_\tau$</td>
<td>17.8 %</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu\nu_\mu \nu_\tau$</td>
<td>17.4 %</td>
</tr>
<tr>
<td>$\tau \rightarrow h^\pm neutr.\nu_\tau$</td>
<td>49.5 %</td>
</tr>
<tr>
<td>$\tau \rightarrow \pi^\pm \nu_\tau$</td>
<td>11.1 %</td>
</tr>
<tr>
<td>$\tau \rightarrow \pi^0\pi^\pm \nu_\tau$</td>
<td>25.4 %</td>
</tr>
<tr>
<td>$\tau \rightarrow \pi^0\pi^0\pi^\pm \nu_\tau$</td>
<td>9.19 %</td>
</tr>
<tr>
<td>$\tau \rightarrow \pi^0\pi^0\pi^0\pi^\pm \nu_\tau$</td>
<td>1.08 %</td>
</tr>
<tr>
<td>$\tau \rightarrow K^\pm neutr.\nu_\tau$</td>
<td>1.56 %</td>
</tr>
<tr>
<td>$\tau \rightarrow h^\pm h^\pm h^\pm neutr.\nu_\tau$</td>
<td>14.57 %</td>
</tr>
<tr>
<td>$\tau \rightarrow \pi^\pm \pi^\pm \pi^\pm \nu_\tau$</td>
<td>8.98 %</td>
</tr>
<tr>
<td>$\tau \rightarrow \pi^0\pi^\pm \pi^\pm \nu_\tau$</td>
<td>4.30 %</td>
</tr>
<tr>
<td>$\tau \rightarrow \pi^0\pi^0\pi^\pm \pi^\pm \nu_\tau$</td>
<td>0.50 %</td>
</tr>
<tr>
<td>$\tau \rightarrow \pi^0\pi^0\pi^0\pi^\pm \nu_\tau$</td>
<td>0.11 %</td>
</tr>
<tr>
<td>$\tau \rightarrow K^\pm X^\pm \nu_\tau$</td>
<td>0.90 %</td>
</tr>
<tr>
<td>$\tau \rightarrow (\pi^0)\pi^\pm \pi^\pm \pi^\pm \pi^\pm \nu_\tau$</td>
<td>0.10 %</td>
</tr>
<tr>
<td>other modes with K</td>
<td>1.30 %</td>
</tr>
<tr>
<td>others</td>
<td>0.03 %</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>signal (fb)</th>
<th>$t\bar{t} + jets$</th>
<th>background (fb)</th>
<th>$\gamma^*/Z + jets$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>VV</td>
<td>gg</td>
<td>EW</td>
<td>QCD</td>
<td>EW</td>
</tr>
<tr>
<td>Lepton acceptance</td>
<td>5.55</td>
<td>2014</td>
<td>18.2</td>
<td>669.8</td>
</tr>
<tr>
<td>+ Forward Tagging</td>
<td>1.31</td>
<td>42.0</td>
<td>9.50</td>
<td>0.38</td>
</tr>
<tr>
<td>+ $P_T^{miss}$</td>
<td>0.85</td>
<td>29.2</td>
<td>7.38</td>
<td>0.21</td>
</tr>
<tr>
<td>+ Jet mass</td>
<td>0.76</td>
<td>20.9</td>
<td>7.36</td>
<td>0.11</td>
</tr>
<tr>
<td>+ Jet veto</td>
<td>0.55</td>
<td>2.70</td>
<td>5.74</td>
<td>0.05</td>
</tr>
<tr>
<td>+ Angular cuts</td>
<td>0.40</td>
<td>0.74</td>
<td>1.20</td>
<td>0.04</td>
</tr>
<tr>
<td>+ Tau reconstruction</td>
<td>0.37</td>
<td>0.12</td>
<td>0.28</td>
<td>0.001</td>
</tr>
<tr>
<td>+ Mass window</td>
<td>0.27</td>
<td>0.01</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau \rightarrow e\mu$</td>
<td>0.27</td>
<td>0.01</td>
<td>0.03</td>
<td>0.02</td>
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<tr>
<td>$H \rightarrow \tau\tau \rightarrow e\mu$</td>
<td>0.13</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau \rightarrow \mu\mu$</td>
<td>0.14</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>
Constrained MSSM

- O. Buchmueller et al., arXiv:0707.3447v2 [hep-ph]
- CMSSM: $M_h = 110 \pm 3 \text{ (theo.) GeV}$
- Includes CDM, flavor physics and $a_\mu$ experimental data

\[
\chi^2 / \text{ndf} = 17.34 / 14
\]
Central Jet Veto and Pile-up

Figure 7: (a) Central Jet Veto performance in the presence of varying levels of pileup for signal and background samples. (b) Performance of the $b$-jet tagging as a function of the forward jet $p_T$ in the events, where the $tt$ processes is analyzed.
Impact Parameter

Displaced vertices present in Zbb and $t\bar{t}$

Impact Parameter Significance $\equiv d_0/\sigma_{d_0}$

Transverse impact parameter resolution
$\sim 15 \, \mu m$ for $P_T = 20$ GeV

Transverse primary vertex spread
$\sim 15 \, \mu m$, taken into account

Isolation + Impact Parameter Criteria
$O(10^2)$ Rejection for Zbb
$O(10^3)$ Rejection for $t\bar{t}$
for signal efficiency $O(80\%)$

Effect of pile-up on signal significance $\leq 5\%$
**Mass**

Favoured mass of SM Higgs

$113.5 < m_H < 212$ GeV

In this range $m_H$ can be measured to 0.1% using $\gamma\gamma$ and $4\ell$ channels

Energy scale can be calibrated to 0.1% using $Z\rightarrow e^+e^-$ and $Z\rightarrow \mu^+\mu^-$
Higgs Properties: Width

- **precise measurement of width**
  - $qq\rightarrow qqh, h\rightarrow 2\gamma, WW^{(*)}, 2\tau$ together
  - with $gg\rightarrow WW^{(*)}$ allows indirect measurement of Higgs width

D. Zeppenfeld, R. Kinnunen, A. Nikitenko

- **observation of other Higgs channels:**
  - $Wh$ with $h\rightarrow bb, h\rightarrow \gamma\gamma$
  - $tth$ with $h\rightarrow \gamma\gamma, WW$
  - $qqh$, with $h\rightarrow \mu\mu$ (?)

- **self couplings;** $h\rightarrow hh$ (?)

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Graphs:
- **Indirect measurement**
  - $\frac{\Delta\Gamma_H}{\Gamma_H}$ vs $M_{H^*}$, GeV
  - ATLAS+CMS, 200 fb$^{-1}$

- **Direct measurement**
  - $\frac{\Delta\Gamma_H}{\Gamma_H}$ vs $m_H$ (GeV)
  - ATLAS, 300 fb$^{-1}$
Higgs Properties: Cross-sections

10% of $\sigma$ in intermediate mass region comes from WW fusion
Identified by requiring forward tagging jets and no additional central jets

Errors
Statistical: 5 – 20%
$\gamma\gamma$ and 4$\ell$ well understood
Modes involving fwd jets more difficult to estimate

Corrected $\sigma$ compared with perturbative QCD calculations
Known to NLO for all and NNLO for gg\(\rightarrow\)H processes
Higgs Properties: Couplings and BRs

Use various Higgs production and decay modes
In ratios luminosity uncertainty largely cancels
Assuming 300 fb-1

\[
\frac{\sigma \cdot B(t\bar{t}H + WH \rightarrow \gamma\gamma)}{\sigma \cdot B(t\bar{t}H + WH \rightarrow b\bar{b})} \Rightarrow \frac{BR(H \rightarrow \gamma\gamma)}{BR(H \rightarrow b\bar{b})}
\]

\[
\frac{\sigma \cdot B(H \rightarrow \gamma\gamma)}{\sigma \cdot B(H \rightarrow ZZ^*)} \Rightarrow \frac{BR(H \rightarrow \gamma\gamma)}{BR(H \rightarrow ZZ^*)}
\]

\[
\frac{\sigma \cdot B(t\bar{t}H \rightarrow \gamma\gamma / b\bar{b})}{\sigma \cdot B(WH \rightarrow \gamma\gamma / b\bar{b})} \Rightarrow \frac{g_{Ht\bar{t}}^2}{g_{HWW}^2}
\]

\[
\frac{\sigma \cdot B(H \rightarrow WW^* / W)}{\sigma \cdot B(H \rightarrow ZZ^* / Z)} \Rightarrow \frac{g_{HWW}^2}{g_{HZZ}^2}
\]
Higgs Properties: Branching Ratios

BR cannot be measured directly at the LHC
But possible to infer ratios of couplings from measured rates

<table>
<thead>
<tr>
<th>Measure</th>
<th>Error</th>
<th>$M_H$ range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B(H \to \gamma\gamma) / B(H \to b\bar{b})$</td>
<td>30%</td>
<td>80–120</td>
</tr>
<tr>
<td>$B(H \to \gamma\gamma) / B(H \to ZZ^*)$</td>
<td>15%</td>
<td>125–155</td>
</tr>
<tr>
<td>$\frac{\sigma(t\bar{t}H)}{\sigma(WH)}$</td>
<td>25%</td>
<td>80–130</td>
</tr>
<tr>
<td>$B(H \to WW^{(<em>)}) / B(H \to ZZ^{(</em>)})$</td>
<td>30%</td>
<td>160–180</td>
</tr>
</tbody>
</table>
Azimuthal angle $\phi$ between decay planes in the rest frame of Higgs

$$F(\phi) = 1 + \alpha \cos(\phi) + \beta \cos(2\phi)$$

Polar angle $\theta$ between lepton and the Z momentum in Z rest frame

$$G(\theta) = L \sin^2(\theta) + T(1+\cos^2(\theta)), \quad R=(L-T)/(L+T)$$

$M_{Z^*}$ distribution for $M_H < 2M_Z$, $d\Gamma_H/dM_{Z^*} \sim \beta^n$ near threshold (n=1 in SM)

$$\beta^2=[1-(M_Z+M_{Z^*})^2/M_H^2][1-(M_Z-M_{Z^*})^2/M_H^2]$$

Recent ATLAS fast simulation study on sensitivity to $F(\phi)$ and $G(\theta)$ for exclusion of $0^-, 1^+, 1^-$ for $M_H > 2M_Z$: SN-ATLAS-2003-025