Implications of the Higgs Discovery for BSM Searches

Roni Harnik,
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My to-do list

* LHC Run 1:
  * A Higgs was discovered!
  * No other new physics was found.

* My job in this talk is to tell cosmo (and HEP) people:
  What does this mean for future BSM searches?
  What is the state of mind of HEP?

  This is a subjective BSM theorist’s perspective.

* (Also to provide pre-dinner entertainment by showing cute pictures of my kids).
The Higgs

* The Higgs is at the core of the standard model.

* The Higgs field condenses (gets a vev), giving mass to the fundamental particles in the SM.

* The LHC experiments managed to disturb this field, excite the vacuum (make a Higgs boson), and watch the excitation decay.

* An amazing achievement!
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Outline

So, where does this point BSM searches?

A Higgs was found.

- A new particle!
- Lets explore it.
- What are its properties?
- How does it couple?

No other NP.

- Naturalness?
- Where is SUSY?
- Is nature tuned?

(these the two parts of the talk)
Both high energy physicists and cosmologist are driven by a child-like curiosity.

Higgs:
A new particle = A new toy!
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**Higgs:**
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A New Toy

* You get a new toy. Never seen anything like it. You are curious. What do kids do?

1. Get really excited.

2. Ask questions.
   Play with it. Explore.
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   Fermilab, July 4th 2012, 3AM

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   Play with it. Explore.

   Hold it in your hand. take it apart & put it back together.
   Taste it. Push its buttons.
Playing with the Higgs

* We ask many naive questions about the Higgs:
  - Is it a scalar?
  - What does it couple to?
  - Couplings in agreement with SM?
  - Do its couplings violate flavor?
  - Do they violate CP?
  - Does it decay to BSM states?
  - ....
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- ....

the SM has definite answers to these questions.
Any deviation from these is a discovery of new physics.
Higgs Couplings

* SM predict all Higgs couplings.
* Observed rates of production+decay are SM-like, w/ room for 30-100% modifications.
Flavor and Higgs

* In the SM, the Higgs gives mass to fermions.

* Any flavor violating coupling of Higgs to Fermions is New Physics.

* There are many possible probes of this: LHC, rare muon decays, EDM searches.

See talk by Crivellin for an example of FV Higgs.
Flavor and Higgs

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\[ \langle h \rangle \xrightarrow{\text{mass}} f_i \quad ? \quad h \xrightarrow{\text{coupling}} f_i \]

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See talk by Crivellin for an example of FV Higgs.
Flavor and Higgs

Flavor violation in $\tau-\mu$: LHC.

- $\tau \to 3\mu$ (approx.)
- $(g-2)_{\mu}$
- EDM

Our LHC limit (ATLAS 7 TeV, 4.7 fb$^{-1}$)

$|Y_{\tau\mu}|$

$|Y_{\mu\tau}|$
Flavor and Higgs

Flavor violation in $\tau$-$\mu$: LHC.

![Graph showing flavor violation in $\tau$-$\mu$](image)

- $\tau \rightarrow 3 \mu$ (approx.)
- $\text{Our LHC limit (ATLAS 7 TeV, 4.7 fb}^{-1})$
- $\text{my guess for upcoming limits.}$
Flavor and Higgs

Flavor violation in $\tau$-$\mu$: $\tau \rightarrow 3\mu$ (approx.)

Our LHC limit
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my guess for upcoming limits.

Flavor violation in $\mu$-$e$: Low energy probes.

$\text{BR}(H \rightarrow \mu e) = 0.99 \times 10^{-12}$
Flavor and Higgs

Flavor violation in $\mu$-$e$: Low energy probes.

Most of HEP is taking part in constraining the Higgs:

<table>
<thead>
<tr>
<th>Leptons</th>
<th>Probe</th>
<th>d-quarks</th>
<th>Probe</th>
<th>u-quarks</th>
<th>Probe</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$-$e$</td>
<td>muons</td>
<td>$s$-$d$</td>
<td>K-K</td>
<td>$c$-$u$</td>
<td>D-D</td>
</tr>
<tr>
<td>$\tau$-$e$</td>
<td>eEDM*</td>
<td>$b$-$d$</td>
<td>B-B</td>
<td>$t$-$u$</td>
<td>nEDM*</td>
</tr>
<tr>
<td>$\tau$-$\mu$</td>
<td>LHC</td>
<td>$b$-$s$</td>
<td>$B_s$-$B_s$</td>
<td>$t$-$c$</td>
<td>LHC / D-D</td>
</tr>
</tbody>
</table>

my guess for upcoming limits.
The Golden Channel

* The decay $h \rightarrow 4\ell$ was vitally important in discovering the Higgs. Determining its mass.

![Graph showing the decay $H \rightarrow ZZ^* \rightarrow 4\ell$](graph.png)

**ATLAS**

$H \rightarrow ZZ^* \rightarrow 4\ell$

- $\sqrt{s} = 7$ TeV, $\int d\tau = 4.6$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV, $\int d\tau = 20.7$ fb$^{-1}$

- Very clean.
- Many things to measure.
- Let's play!
Golden Channel

* $h \to 4\ell$ is Dominated by the SM coupling $h Z^\mu Z_\mu$ (which gives the Z its mass!). From now on this is background.

* Sub-dominant contributions from loop induced couplings to $ZZ$ and $Z\gamma$ and $\gamma\gamma$ (a.k.a signal!):

\[
\begin{align*}
h Z^\mu Z^\nu \\
h F^\mu Z^\nu \\
h F^\mu F^\nu
\end{align*}
\]
CP and Higgs

* Baryogenesis: need new CP violating physics.
* Could this new CPV infect Higgs couplings?
* Example: Higgs coupling to photons

\[ h F_{\mu\nu} F^{\mu\nu} \quad h F_{\mu\nu} \tilde{F}^{\mu\nu} \]

\[ E^2 - B^2 = \text{CP even} \quad E \cdot B = \text{CP odd} \]

Together, they violate CP.
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Together, they violate CP.

Each of the loop induced couplings in the previous slide can be CP even or odd.
**CP Violating Higgs**

* These interactions can be probed by interference effects in $h \to 4\ell$:

$$\text{Rate}_{(h\to 4\ell)} \propto \left| A_{hZ\mu Z\mu} + A_{\gamma\gamma} + \tilde{A}_{\gamma\gamma} + \ldots \right|^2$$

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\[
\text{Rate}(h \rightarrow 4\ell) \propto \begin{vmatrix}
\text{large} & \text{small} & \text{small} & \text{small} \\
A_{hZ^\mu Z^\mu} + A_{\gamma\gamma} + \tilde{A}_{\gamma\gamma} + \ldots
\end{vmatrix}^2
\]

large x small = not too small?

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large $\times$ small $=$ not too small?

* LHC is most sensitive to $\gamma\gamma$!

It is most different from $ZZ$ “background”. (see backup slide)

* LHC can be sensitive to SM value of $\gamma\gamma$ coupling and probe its CP structure (experimentalist, please incorporate this...).

CP Violating Higgs


The figure shows a plot of $h F_{\mu\nu} F^{\mu\nu}$ vs $\tilde{h} F_{\mu\nu} \tilde{F}^{\mu\nu}$, where $h$ and $\tilde{h}$ are the Higgs boson and its CP conjugate, respectively. The plot includes different regions corresponding to various kinds of constraints:

- **Golden channel fits**
- **Electric dipole moment**
- **$H \rightarrow \gamma\gamma$**
- **Standard model**

The pink circle represents the expected sensitivity achieved in the golden channel or in other indirect approaches without making model dependent assumptions. This makes the golden channel the unique method capable of determining these properties in the near future.

The turquoise circle corresponds to the projected sensitivity which will be achieved in the golden channel while the pink ring indicates the projected final LHC luminosity of roughly corresponds to the 'true' point defined in Eq.(8) for the overall sign of the Higgs photon coupling.

Of course the results we have presented in this study assume an $e^+e^-$ collider with a luminosity of $N=12800$ events. This makes the golden channel the unique method capable of determining these properties in the near future and we encourage experimentalists at the LHC to carry out this measurement.

Necessary to complete this study.

We thank Ian Low, Joe Lykken, Y. Chen, RH, R. Vega-Morales, in preparation

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We leave a detailed study of all of these effects we neglected including production, background, and NLO effects for values approximating those predicted by the Standard Model. We have demonstrated qualitatively that the CP nature of the Higgs boson to gauge boson pairs $ZZ$, $WW$, and $ZZZ$.

The conclusion that the LHC has excellent prospects for the CP nature of the Higgs boson to gauge boson pairs $ZZ$, $WW$, and $ZZZ$.

We have neglected including production, background, and NLO effects which do not become important until we begin to reach the level necessary to establish the CP properties of the Higgs boson to gauge boson pairs $ZZ$, $WW$, and $ZZZ$.

further details can be found in our previous publications.

Specifically we find that with $\epsilon_{\mu\nu}^{\,\,\mu\nu}$, we have

$\epsilon_{\mu\nu}^{\,\,\mu\nu}$

Thus they do not qualitatively change the results presented here and in particular be able to determine the overall sign of the Higgs photon coupling.

The results for the CP properties of the Higgs boson to gauge boson pairs $ZZ$, $WW$, and $ZZZ$. Thus they do not qualitatively change the results presented here and in particular be able to determine the overall sign of the Higgs photon coupling.

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Higgs Decays to DM

* The Higgs exists. DM exists.
* Maybe Higgs mediates SM-DM interaction?
Higgs Decays to DM

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Limits on $Z^+$ h invisible:

A robust link within this model.

See related talks by: Eno, Worm (Cosmo), Meridiani & Swiezewska
Naturalness
the Weird Higgs

* Higgs is the first fundamental scalar we see.
  (Did we see evidence for another last week w/ BICEP?)

* In the SM its potential is exquisitely tuned.
  (So maybe we are not surprise they are rare in nature).

* Finding a scalar w/o new physics is puzzling!
  Assume NP at $M_{pl}$:

$$M_H^2 =$$
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\[
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  Assume NP at $M_{pl}$:  
  
  $M_H^2 = 3.2734594296342905438674964732159643$  
  
  $= 10^{-32} \text{ (in planck units)}$  
  
  “bare mass”  
  
  quantum corrections, e.g.
Symmetry & Partners

* We would prefer to see a milder cancelation.

\[ M_H^2 \sim 10 - 9 = 1 \text{ (in units of } \sim 100 \text{ GeV squared)} \]
Top Partner Searches

* This morning alone, we saw $N$ different searches for top partners and related particles. Talks by Yamanaka, Sekmen, Eno, Hry'Ova, Cooke, Olivito

* Summary: Limits. No discovery :-(

* e.g. stops are generically above 700 GeV.
So,
Where is everybody?

A few possibilities:
• We are a tad tuned...
• Top partners are hiding
• We are very tuned. Missing something big.
A Tad Tuned: An Analogy

(1 cannot guarantee historical accuracy...)

* In the early 90’s cosmologist knew about the dipole in the CMB.

* Limits on the quadrupole were advancing...hmm
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Today we know:

![Image of COBE data](image)

![Graph of angular power spectrum](graph)
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Today we know:

Message: Push ahead!
Onward to 14 TeV!
Partners Hiding

* OK. May be the stops are here?

* There are many stealth stop scenarios. A good challenge for our experimental friends.

stops look like tops.
top production at NNLO can be important.
(Talk by Fiedler)
Un-Colored Partners

* The last frontier for naturalness:
  Maybe the top partners do not carry color?

* Example: Twin Higgs (Chacko, Goh, RH)-

\[(\text{SM}) \times (\text{mirror SM})\]
Un-Colored Partners

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* Even in this model - Higgs couplings will be modified
  (say at 10-20%), and \( h_{\text{inv}} \). Will not hide forever!
Conclusion

* LHC found a SM-like Higgs.
* Nothing else.
* We are curious! asking (and will hopefully answer) some naive and profound questions.
* Thinking of the future:
As Advertised:
Deleted Scenes.
Higgs couplings to $\tau e$

* $\tau e$ is similar to $\tau \mu$.... but:
Higgs couplings to $\tau e$

* $\tau e$ is similar to $\tau \mu$... but:

Electron EDM is interesting here!

**Figure 3:** Diagram leading to muonium–antimuonium oscillations.

**Figure 4:** A diagram contributing to the anomalous magnetic moment $g_2$ of the muon through FV couplings of the Higgs to $\tau \mu$.

where "$X$ and $\#X$ are the spin orientations of particle $X$. We can work in the non-relativistic limit here. For a contact interaction, the spatial wave function of muonium, $\psi = \exp(-r/a_M)/[\pi a_M^3]^{1/2}$ only needs to be evaluated at the origin. (Here $r$ is the electron–antimuon distance and $a_M = (m_e + m_\mu)/((m_e m_\mu)^{1/2}$ is the muonium Bohr radius.)

The resulting mass splitting between the two mass eigenstates of the mixed $M$–$\bar{M}$ system is [34],

$$M = 2 |M_{\bar{M}M}| = |Y_{\mu e} + Y_{e\mu}^\ast|^{2} \pi a_M^3 m_e^2 \hbar,$$

(19)

and the time-integrated conversion probability is

$$P(M \to \bar{M}) = \int_0^\infty dt \mu \sin^2(\mu t) e^{-\mu t} = \frac{2}{\mu^2 + 4}.$$ 

(20)

The bound from the MACS experiment [33] then translates into

$$|Y_{\mu e} + Y_{e\mu}^\ast| < 0.079.$$

D. Constraints from magnetic dipole moments

The CP conserving and CP violating parts of the diagram in Fig. 4 generate magnetic and electric dipole moments of the muon, respectively. Since the experimental value of the electron EDM:
A Dedicated Search

* A CMS-like VBF analysis: 

Looks promising!

**Figure 10:** Signal and background rates for $h \rightarrow \tau_{\text{had}} \tau_{\mu}$ events in a CMS-like search (see text) as a function of the reconstructed $\mu - \tau$ invariant mass $m_{\mu \tau}$ for a vector boson fusion-enriched event sample. In the left panel the transverse mass cut $m_{T}(\mu, p_{\text{miss}})$ < 40 GeV is included, while in the right panel it is omitted. The QCD multijet background and the small $t \bar{t}$ background, are not included. The value chosen for $q_{Y}^{2}$ is well within the region allowed by other searches for flavor violation in the $\mu - \tau$ system (see Sec. III).

**Figure 11:** The muon transverse mass distribution for the backgrounds and for the $\tau_{\text{had}} \rightarrow \mu$ signal.

CMS-like.

CMS-like w/o $m_{T}$ cut.
(May be worth while, depending on what other BG’s do)
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Golden Channel Sensitivity