Distinguishing fermiophobic Higgs via associated Higgs plus vector boson production

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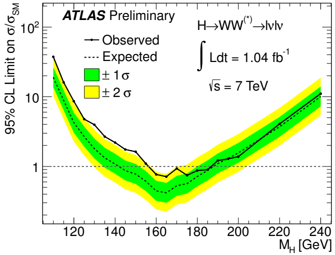
Based on

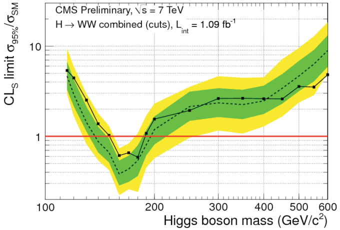
Ed Berger, Z.S., Hao Zhang, arXiv:1203.6645

A hint something is going on in *WW*?

EPS 2011: late July



Strandberg for ATLAS



Kovalskyi for CMS

- Early data from LHC shows too many *WW* events at low invariant mass w.r.t. a Standard Model (SM) Higgs boson.
- CERN says be prepared for SM Higgs to soon be ruled out.
- We start asking whether this could be a Higgs boson. . .

Outline

1. **“Fermiophobic” Higgs vs. Standard Model Higgs**
   - Does the Higgs have to couple to fermions?
   - How would we distinguish fermiophobic from SM Higgs?
2. **Analysis of $HW/HZ \to \gamma\gamma jj$**
   - Isolating a fermiophobic Higgs signal
   - Possible evidence in 7 TeV LHC data
   - Discovery potential at 8 TeV LHC
3. **Conclusions**

Higgs mechanism breaks electroweak symmetry

- Imagine a complex scalar SU(2)$_L$ doublet $\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ w/ $Y = +1/2$

$$\mathcal{L}_{\text{Higgs}} = (D_\mu\phi)^\dagger D^\mu\phi + \mu^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2$$

Higgs mechanism By assigning a non-zero vacuum expectation value $< \phi^\dagger\phi >_0 = v^2/2$, $v = 246$ GeV, the ground state explicitly breaks SU(2)$_L\times$U(1)$_Y$ down to U(1)$_{EM}$

- Recasting ϕ in the language of a nonlinear sigma model

$$\phi \to \tfrac{1}{2}(\sigma + v)\exp[iT^1\theta^1 + iT^2\theta^2 + i(T^3 - Y)\theta^3]\left(\begin{smallmatrix} 0 \\ 1 \end{smallmatrix}\right)$$

  - The 3 θ^i are "eaten" by the W, Z giving them masses $\propto v$.
  - The mass relationships are predictive:
    $M_W = 80.4$ GeV predicts $M_Z = 91$ GeV

- The job of the Higgs Mechanism is to explain gauge boson masses and relationships. It succeeds.

The Higgs boson is the remaining degree of freedom, the σ

- The Higgs boson (σ or H) was just a placeholder here, but it must couple to W and Z ($\mathcal{L} \sim HWW + HZZ$)

Does the Higgs couple to fermions too?

- The original EWSB models of Englert and Brout; Higgs; Guralnik, Hagen and Kibble had no mention of coupling to fermions.
- Later the "Standard Model" incorporated Yukawa interactions as a convenient way to generate Dirac mass terms.

$$\mathcal{L}_{\mathrm{Yukawa}} = -\Gamma_u^{ij}\overline{Q}_L^i \epsilon\phi^* u_R^j - \Gamma_d^{ij}\overline{Q}_L^i \phi d_R^j - \Gamma_e^{ij}\overline{L}_L^i \phi e_R^j + H.c.$$

  $\Gamma_u, \Gamma_d, \Gamma_e$ are 3×3 complex matrices
- Using $M^{ij} = \Gamma^{ij} v/\sqrt{2}$ we have (after EWSB, $\phi \to v/\sqrt{2}$)

$$\mathcal{L}_{\mathrm{Mass}} = -M_u^{ij}\overline{u}_L^i u_R^j - M_d^{ij}\overline{d}_L^i d_R^j - M_e^{ij}\overline{e}_L^i e_R^j + H.c.$$

- These tree-level couplings are not necessary for EWSB.

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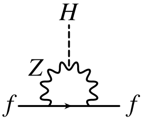
- These tree-level couplings are not necessary for EWSB.

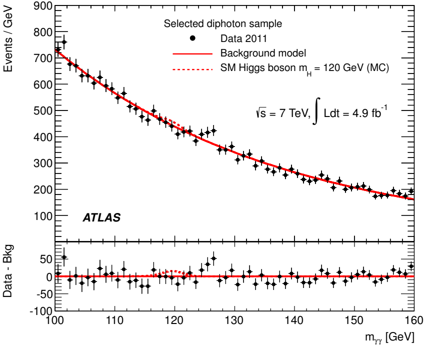
  A "fermiophobic" Higgs boson does not use Yukawa interactions to generate fermion mass.

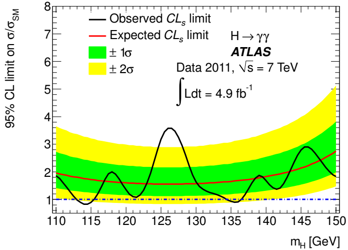
  - You do not completely decouple $H\bar{f}f$, but it is highly suppressed.



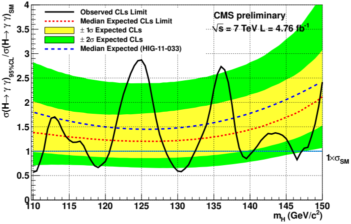
is small

LHC data suggest a Higgs peak at $M_{\gamma\gamma} \sim 125$ GeV



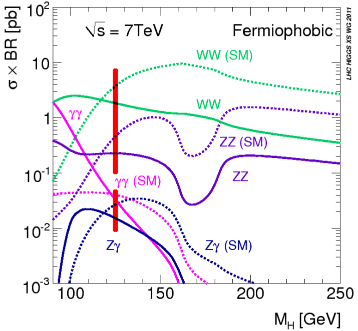


ATLAS, PRL 108, 111803 (12)
CMS, HIG-12-001



- This is an inclusive $\gamma\gamma$ measurement.
- Could this be a fermiophobic Higgs?
- How does Higgs couple to $\gamma\gamma$?

Is the $M_{\gamma\gamma}$ peak SM or fermiophobic (FP) Higgs?



- A miracle occurs!
- $\sigma \times \mathrm{BR}(H \to \gamma\gamma)_{\mathrm{FP}}$
  $\approx \sigma \times \mathrm{BR}(H \to \gamma\gamma)_{\mathrm{SM}}$!
- We expect to see the same number of diphoton events from both SM Higgs and FP Higgs!
- We need something to distinguish SM Higgs from FP Higgs

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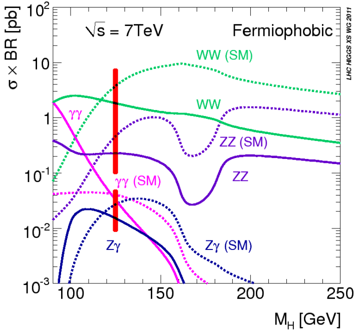

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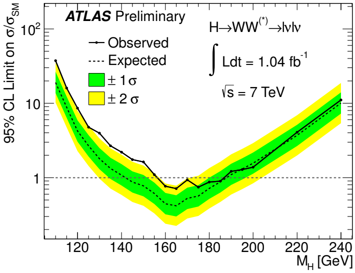
- $\sigma \times \mathrm{BR}(H \to WW/ZZ)_{\mathrm{FP}} \sim 0.5\, \sigma \times \mathrm{BR}(H \to WW/ZZ)_{\mathrm{SM}}$!
- This would explain our original observation and motivation.

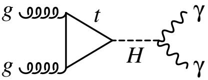
Also shown by Gabrielli, Mele, Raidal, 1202.1796



Discovery requires distinctive final states

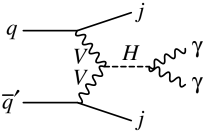
- At LHC, Standard Model Higgs and fermiophobic Higgs have different dominant production mechanisms.

Standard Model



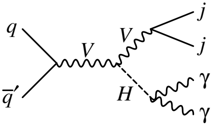
gg-fusion
0% in FP model

SM or FP



Vector boson fusion
58% in FP model

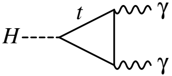
Fermiophobic



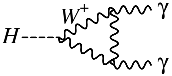
HW/*HZ* assoc.
42% in FP model

- They also decay to $\gamma\gamma$ differently ($\mathrm{BR}(H\to\gamma\gamma)_{\mathrm{FP}} \gg \mathrm{BR}(H\to\gamma\gamma)_{\mathrm{SM}}$)

Standard Model



SM or FP

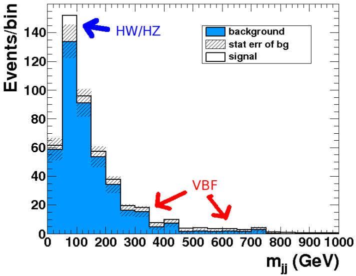


- Fermiophobic Higgs is always produced in association with other particles, while Standard Model Higgs is occasionally (VBF$\sim$ 7%).
- Clearly we should look for the other particles.

Unambiguous distinction is easier with vector bosons

- ATLAS and CMS have concentrated on excluding fermiophobic Higgs by placing limits on the larger VBF cross section.
- We concentrate on discovery and distinction from Standard Model by focusing on observation of the associated vector boson (W or Z).

- VBF is not very distinctive
  - Both SM and FP have VBF rates
  - It is difficult to convince oneself of a broad excess across the tail of the M_{jj} distribution.
- HW/HZ produce a clear peak in the dijet invariant mass M_{jj}.
- We focus on $W/Z \to jj$, rather than $Z \to l^+l^-$ in order to have a large enough event rate.



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   - Discovery potential at 8 TeV LHC

3. Conclusions

Simulating fermiophobic Higgs S and B

- We simulate signal and background shapes by feeding MadEvent $\rightarrow$ PYTHIA $\rightarrow$ PGS.
  - We correct jet energy scales for anti-K_T jets with a fit to the Z pole.
- We first reproduce the inclusive ATLAS diphoton event excess from ATLAS-CONF-2012-019 matching their cuts:
  - $E_{T\gamma_1} > 40$ GeV, $E_{T\gamma_2} > 25$ GeV; $1.52 < |\eta_\gamma| < 2.37$ or $|\eta_\gamma| < 1.37$
  - Isolation and reconstruction efficiencies are applied.
  - We agree with ATLAS efficiencies to $< 1\%$
- To separate the contributions of WH, ZH, and VBF, we model each contribution at NLO (after cuts) using MCFM.
- Backgrounds are predominantly due to $\gamma\gamma + \mathrm{n}j\,(\mathrm{n} \leqslant 2)$
  - We used MLM-matched samples in MadEvent, and fix normalization after cuts to the observed ATLAS diphoton spectrum.
- We also consider $W\gamma\gamma$, $W\gamma j$, Wjj, $Z\gamma\gamma$, $Z\gamma j$, Zjj, but find they contribute less than 1 event after acceptance cuts.

At this point we reproduce the ATLAS diphoton measurement.

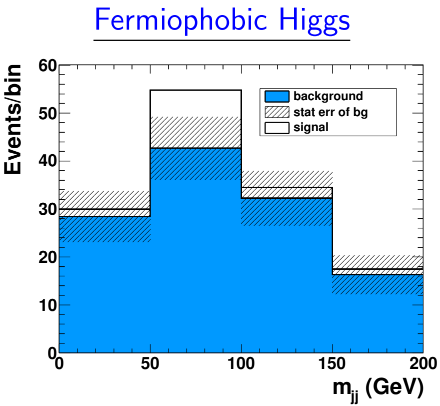
Prediction at 7 TeV ($4.9\ \mathrm{fb}^{-1}$)

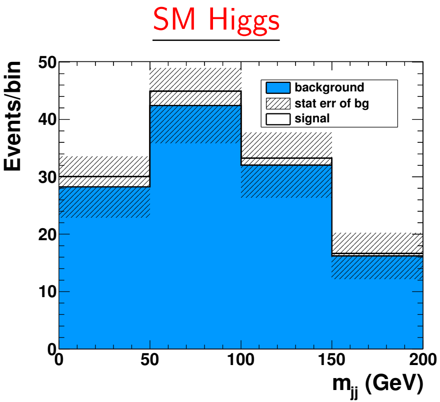
- Jets cuts: $E_{Tj_1} > 40$ GeV, $E_{Tj_2} > 13$ GeV; $|\eta_j| < 4.5$
- To isolate $V \to jj$ we apply cuts tuned to suppress background.

Channel	HW	HZ	VBF	Bkgd.
Incl. $H \to \gamma\gamma + X$	$86.4^{+36.3}_{-30.2}$	$47.6^{+20.0}_{-16.7}$	$188.6^{+79.2}_{-66.0}$	—
ATLAS γ cuts	$36.4^{+15.3}_{-12.7}$	$20.0^{+8.4}_{-7.0}$	$84.0^{+35.3}_{-29.4}$	22349
$\lvert M_{\gamma\gamma} - 125\rvert < 3.8$ GeV	$29.1^{+12.2}_{-10.2}$	$16.3^{+6.8}_{-5.7}$	$68.6^{+28.8}_{-24.0}$	2859
≥ 2 jet acceptance	$14.8^{+6.2}_{-5.2}$	$9.1^{+3.8}_{-3.2}$	$50.9^{+21.4}_{-17.8}$	575
$\Delta\phi_{jj} < 2.8$	$13.3^{+5.6}_{-4.7}$	$8.0^{+3.4}_{-2.8}$	$43.6^{+18.3}_{-15.3}$	447
$\Delta R_{jj} < 3.0$	$12.4^{+5.2}_{-4.4}$	$7.5^{+3.1}_{-2.6}$	$10.1^{+4.3}_{-3.6}$	329
$\lvert\eta_{jj} - \eta_{\gamma\gamma}\rvert < 1.0$	$8.4^{+3.5}_{-2.9}$	$5.0^{+2.1}_{-1.8}$	$4.8^{+2.0}_{-1.7}$	130
$\lvert M_{jj} - 75\rvert < 25$ GeV	$6.7^{+2.8}_{-2.3}$	$3.8^{+1.6}_{-1.3}$	$1.6^{+0.7}_{-0.5}$	42.4

- After jet acceptance, we predict a 3.1σ significance for H+dijet production, with $S/B \sim 1/8$.
- After loose vector boson mass reconstruction, $S/B \sim 1/3.5$; $HW/HZ \to \gamma\gamma\, jj$ existing LHC data (7 TeV): 1.9σ/experiment (2.7σ combined)

$V \rightarrow jj$ mass peak: fermiophobic Higgs vs. SM Higgs

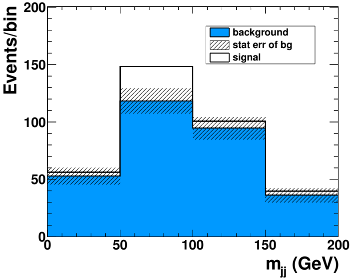




- We expect a clear vector boson mass peak for fermiophobic Higgs.
  - SM Higgs has no discernible signal.
- We expect 1.9σ fermiophobic-SM distinction in 4.9 fb^{-1}/experiment.
  - Combining ATLAS and CMS, you might find 2.7σ evidence.

Expectations for 8 TeV ($10\ \mathrm{fb}^{-1}$)

Fermiophobic Higgs



Cuts are slightly tighter at 8 TeV

Channel	HW	HZ	VBF	Bkgd.
Incl. $H \to \gamma\gamma + X$	217^{+91}_{-76}	152^{+64}_{-53}	510^{+214}_{-179}	—
ATLAS γ cuts	$86.9^{+36.5}_{-30.4}$	$62.4^{+26.2}_{-21.9}$	$223.5^{+93.9}_{-78.2}$	55599
$\lvert M_{\gamma\gamma} - 125\rvert < 3.8$ GeV	$83.3^{+35.0}_{-29.2}$	$59.8^{+25.1}_{-20.9}$	$199.2^{+83.7}_{-69.7}$	7387
≥ 2 jet acceptance	$28.5^{+12.0}_{-10.0}$	$23.1^{+9.7}_{-8.1}$	$111.0^{+46.6}_{-38.8}$	1126
$\Delta\phi_{jj} < 2.5$	$23.5^{+9.9}_{-8.2}$	$18.3^{+7.7}_{-6.4}$	$80.4^{+33.8}_{-28.1}$	658
$\Delta R_{jj} < 3.0$	$22.5^{+9.5}_{-7.9}$	$17.5^{+7.4}_{-6.1}$	$19.8^{+8.3}_{-6.9}$	539
$\lvert\eta_{jj} - \eta_{\gamma\gamma}\rvert < 1.5$	$19.2^{+8.1}_{-6.7}$	$14.9^{+6.3}_{-5.2}$	$13.3^{+5.6}_{-4.7}$	321
$\lvert M_{jj} - 75\rvert < 25$ GeV	$15.3^{+6.4}_{-5.3}$	$11.2^{+4.7}_{-3.9}$	$3.6^{+1.5}_{-1.3}$	118

$S/B \sim 1/3.9$

- We expect fermiophobic Higgs discovery at 8 TeV in $\gamma\gamma + jj$
  - $M_{\gamma\gamma}$ will have a 4.8σ (6.8σ combined) Higgs mass peak after $\Delta\phi_{jj}$ cut
- We can then expect an unambiguous distinction between fermiophobic and SM Higgs.
  - We expect 2.8σ fermiophobic-SM distinction in $10\ \mathrm{fb}^{-1}$/experiment.
  - Combining ATLAS and CMS, you might reach 4σ discovery.

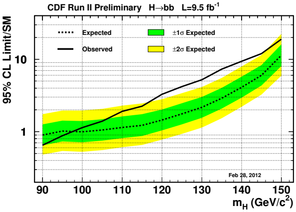
Conclusions

- The Higgs boson is the simplest scalar solution for the Higgs mechanism. The mechanism explains EWSB.
- It is an open question whether the Higgs has a large coupling to fermions.
  - The Higgs mechanism does not require Yukawa couplings.
  - There is so far no compelling experimental evidence.
- Even if the Higgs has suppressed couplings to fermions, there should be a peak in $H \to \gamma\gamma$ in the 8 TeV run ($10\ \mathrm{fb}^{-1}$) with 4.8σ/experiment (6.8σ combined).
- By looking for vector bosons produced in assoc. with $H \to \gamma\gamma$ we can have an unambiguous distinction between a SM Higgs and fermiophobic Higgs.
  - $HW/HZ \to \gamma\gamma\, jj$ existing LHC data (7 TeV): 1.9σ/experiment (2.7σ combined)
  - $HW/HZ \to \gamma\gamma\, jj$ current LHC run (8 TeV, $10\ \mathrm{fb}^{-1}$): 2.8σ/experiment (4σ combined)

THANK YOU

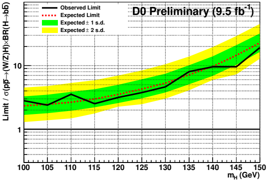
Aside on $H \to b\bar{b}$ data

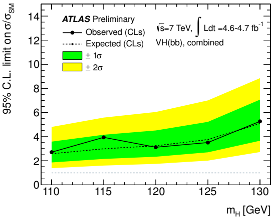
- CDF may see a hint of $H \to b\bar{b}$



- CDF also has excess $b\bar{b}$ events in single-top and $Z+b$-jets
- These excesses may be related, more understanding is needed.

- This is not yet confirmed by DØ, ATLAS, or CMS





DØ Note 6293-CONF, ATLAS-CONF-2012-015

- At this point we are still waiting for a definitive direct observation by the Tevatron or LHC of $H \to b\bar{b}$.