HIGGS HUNTER’S DIGEST

UC DAVIS: JOINT THEORY SEMINAR
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Based on arXiv:1202.3415 with A. Azatov and R. Contino;
arXiv:1205.xxxx with A. Azatov, S. Chang, and N. Craig

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Outline

Part I: Setup
1. What do we know from the LHC?
2. How can we use this if we have BSM in mind?

Part II: Application
1. (Minimal) Composite Higgs
2. (Minimal) SUSY

Part III: Conclusions (as we go...)
1. Utility of indirect information from constraining couplings
   \[
   \text{Naturalness} \propto (\text{couplings} \neq \text{SM})
   \]
2. Great opportunity for theory/experiment collaboration...
3. ...as *required* to really get the most from this machine!
PART ONE
What do we know (thanks to the LHC)?

Given background, signal, and observed events: construct likelihood:

\[ P(n|n_{\text{obs}}) = \frac{n^{n_{\text{obs}}} e^{-n}}{n_{\text{obs}}!} \times \pi(n) \]

\[ \xrightarrow{\text{A.L.}} \quad \exp \left[ -\frac{(n - n_{\text{obs}})^2}{2n_{\text{obs}}} \right] \times \pi(n) \]
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\[ n = n_B + \mu n_{S}^{\text{SM}} \Rightarrow P(\mu) = \pi(\mu) \times \exp \left[ -\frac{(n_B + \mu n_{S} - n_{\text{obs}})^2}{2n_{\text{obs}}} \right] \]
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integrated fraction \( \tilde{\alpha} \).

\[ \tilde{\mu} \]
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\( \hat{\mu} \): upper bound on signal strength modifier at \( \text{CL} = \alpha \).

**Two versions:**
1. Expected (background only hypothesis)
2. Observed (compared to data)
What do we know (thanks to the LHC)?

Given background, signal, and observed events: construct likelihood:

\[
P(n|n_{\text{obs}}) = \frac{n^{n_{\text{obs}}}}{n_{\text{obs}}!} e^{-n} \times \pi(n)
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\text{A.L. } \Rightarrow \exp \left[ \frac{-(n - n_{\text{obs}})^2}{2n_{\text{obs}}} \right] \times \pi(n)
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\[\tilde{\mu}: \text{upper bound on signal strength modifier at } CL = \alpha.\]

Two versions:
1. Expected (background only hypothesis)
2. Observed (compared to data)
What do we know (thanks to the LHC)?

Answer:
We know the amount by which we can rescale production/branching -- all in the same proportions -- and still be consistent with observation.

Said another way, we know what’s going on in a one-dimensional parameter space: adequate in some cases, but in several others we’d like to push this information a bit further...

How do we proceed?
PART TWO
A simplified theory input: “The non-panacean Higgs”

The theory we know has to be augmented (unitarity, renorm’ability):

Three massive vectors, triplet of approximate SU(2)

\[ U = \exp \left[ 2i \tau_a \pi_a(x)/v \right] \]

\[ \mapsto L U R^\dagger \]

described at leading order:

\[ \Delta \mathcal{L} = \frac{v^2}{4} \text{tr} \left[ (D_\mu U)^\dagger (D^\mu U) \right] - \frac{v}{\sqrt{2}} \psi_i^c U^\dagger \times \lambda_{ij} \psi_j + \text{h.c.} \]
A simplified theory input: “The non-panacean Higgs”

The theory we **know** has to be **augmented** (unitarity, renorm’ability):

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U = \exp \left[ 2i\tau_a \pi_a(x)/v \right]
\]

\[\mapsto LUR^\dagger\]

described at leading order:

\[
\Delta L = \frac{v^2}{4} \text{tr} \left[ (D_\mu U)^\dagger (D^\mu U) \right] \times \left( 1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots \right)
\]

\[ - \frac{v}{\sqrt{2}} \psi_i^c U^\dagger \times \lambda_{ij} \psi_j + \text{h.c.} \times \left( 1 + c\frac{h}{v} + \ldots \right)\]

Assumption: the (custodial singlet) ‘Higgs’ might not be single-handedly responsible for unitarization, etc.

OTHER NEW PHYSICS enters at potentially low scales

Cases to consider here: Compositeness, SUSY
A simplified theory input: “The non-panacean Higgs”

The theory we know has to be augmented (unitarity, renorm’ability):
Three massive vectors, triplet of approximate SU(2)

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\[ \Rightarrow LU R^\dagger \]

described at leading order:

\[ \Delta \mathcal{L} = \frac{v^2}{4} \text{tr} \left[ (D_\mu U)^\dagger (D^\mu U) \right] \times \left( 1 + 2 \frac{a}{v} + b \frac{h^2}{v^2} + \ldots \right) \]
\[ - \frac{v}{\sqrt{2}} \psi_i^c U^\dagger \times \lambda_{ij} \psi_j + \text{h.c.} \times \left( 1 + \frac{c}{v} + \ldots \right) \]

FOCUSING ON THESE GUYS

Cases to consider here: Compositeness, SUSY
First case:
Composite Higgs*

*Yukawa rescaling ("c") = flavor-universal
Moving on: Comparison to Likelihood

Now just map theory parameters to $\mu$ and compare to $P(\mu) \ldots$
Moving on: Comparison to Likelihood

Now just map theory parameters to $\mu$ and compare to $P(\mu)$ ...

... that we need to determine for ourselves at this point
Moving on: Comparison to RECONSTRUCTED Likelihood

(Three variables, only two constraints: we need to be slightly clever)

Assume asymptotic limit, i.e. Poisson $\rightarrow$ Gaussian:

$$P(n_B + \mu n_S | n_{\text{obs}}) = \pi(\mu) \times \exp \left[ -\frac{(n_B + \mu n_S - n_{\text{obs}})^2}{2n_{\text{obs}}} \right]$$
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$$\Rightarrow \tilde{\mu}_{\exp}^{95\%} = 1.96 \times \frac{\sqrt{n_B}}{n_S}$$
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For observed exclusion, use a simple rewriting:

\[
P(n_B + \mu n_S | n_{\text{obs}}) = \pi(\mu) \times \exp \left[ -\frac{1}{2} \left( \mu \frac{n_S}{\sqrt{n_B}} \frac{\sqrt{n_B}}{\sqrt{n_{\text{obs}}}} + \delta \right)^2 \right]; \quad \delta \equiv \frac{n_B - n_{\text{obs}}}{\sqrt{n_{\text{obs}}}}
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Now make the assumption \( \frac{n_{\text{obs}} - n_B}{n_{\text{obs}}} \ll 1 \)
Moving on: Comparison to RECONSTRUCTED Likelihood

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Now make the assumption \( \frac{n_{\text{obs}} - n_B}{n_{\text{obs}}} \ll 1 \)
Moving on: Comparison to **RECONSTRUCTED** Likelihood

\[ P(\mu) = N \times \exp \left[ -\frac{1}{2} \left( \frac{1.96 \times \mu}{\tilde{\mu}_{\text{exp}}^{(95\%)} + \delta} \right)^2 \right] \]
Moving on: Comparison to RECONSTRUCTED Likelihood

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Solve for remaining parameter using observed exclusion limit:

\[ 0.95 = \int_{0}^{\tilde{\mu}_{\text{obs}}^{(95\%)} } d\mu P(\mu) \]
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RECAP:
- Expected exclusion tells us about s/b
- Observed tells us delta, completes determination of (AL) likelihood
- Good news: can be done over whole mass range, not just at ‘peaks’ where information on best fit is available
Status report for unpopular mass points

CMS Exclusions \([\sqrt{s} = 7 \text{ TeV}; \leq 4.8 \text{ fb}^{-1}]\)
Status report for the Higgs at 125(?)(!)
SM looks fine
SM looks fine

ATLAS seems to disfavor the SM: how should we take this?
SM looks fine.

ATLAS seems to disfavor the SM: how should we take this?

Not very seriously.
Stay tuned...
Take Caution: **Need Exclusive** Searching and Reporting

**ALL INCLUSIVE vs. ALL EXCLUSIVE** subchannels:

![CMS Likelihoods [≤ 4.8 fb⁻¹ @ 7 TeV]: All Inclusive](image1)

![CMS Likelihoods [≤ 4.8 fb⁻¹ @ 7 TeV]: All Exclusive](image2)
Second case: SUSY
First: U and D Yukawas differ (Type-II 2HDM)

I want *two* Higgses

Me too!!

Holomorphy

Anomaly-cancellation
First: U and D Yukawas differ (Type-II 2HDM)

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\[ H_u = 2_{1/2}, \quad H_d = 2_{-1/2}, \quad \frac{\langle \text{Re} H_u^0 \rangle}{\langle \text{Re} H_d^0 \rangle} \equiv \tan \beta \]

\[
\begin{pmatrix} h \\ H \end{pmatrix} = \sqrt{2} \begin{pmatrix} -\sin \alpha & \cos \alpha \\ \cos \alpha & \sin \alpha \end{pmatrix} \begin{pmatrix} \text{Re} H_d^0 \\ \text{Re} H_u^0 \end{pmatrix}
\]
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\]

\[
c_u \equiv g_{hQ_u^c} / \text{SM} = \frac{\cos \alpha}{\sin \beta}
\]

\[
c_d \equiv g_{hQ_d^c} / \text{SM} = \frac{-\sin \alpha}{\cos \beta}
\]

\[
a \equiv \text{gauge/SM} = \sin(\beta - \alpha)
\]
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\[
\begin{pmatrix}
  h \\
  H
\end{pmatrix} = \sqrt{2} \begin{pmatrix}
  -\sin \alpha & \cos \alpha \\
  \cos \alpha & \sin \alpha
\end{pmatrix} \begin{pmatrix}
  \text{Re} H_d^0 \\
  \text{Re} H_u^0
\end{pmatrix}
\]

\[
c_u \equiv \frac{g_h Q_u e}{\text{SM}} = \frac{\cos \alpha}{\sin \beta}
\]

\[
c_d \equiv \frac{g_h Q_d e}{\text{SM}} = \frac{-\sin \alpha}{\cos \beta}
\]

\[ a \equiv \text{gauge}/\text{SM} = \sin(\beta - \alpha) \]

What is the data telling us about this space?
First look: *The* space of the MSSM Higgs

CMS Combined Likelihoods [4.9 fb⁻¹ @ 7 TeV]

- $m_h = 125$ GeV
- 68% CL
- 80% CL
- Decoupling Limit
First look: *The* space of the MSSM Higgs

Decoupling:

\[ H^0, H^\pm, A^0 \to \infty; \]
\[ \Rightarrow a, c_u, c_d \to 1 \]

Supported here by couplings, but also by Higgs mass!

\[ m_h \to m_Z \text{ as } m_{A^0} \to \infty \]
First look: *The* space of the MSSM Higgs

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\[ m_h \rightarrow m_Z \quad \text{as} \quad m_{A^0} \rightarrow \infty \]

- Peak likelihood lies very close to the deoupling limit contour
- Consistency of this requires ALL couplings to revert to SM
- To check this, we can examine a 3D space...
FIRST: What does the accessible space of Yukawas look like?

**Yukawa Couplings: General Type–II 2HDM**

- **Shaded:**
  - General
  - $\tan \beta > 1$
  - $\tan \beta > 2.5$

- **Legend:**
  - "Up–Suppressed"
  - "Down–Suppressed"
The *very constrained* quartic structure of the MSSM (all coming from D terms) forbids it from entering the down-suppressed region whenever tan beta > 1.
Status...

We can construct the likelihood in the full 3D space, then project the gauge direction onto the 2D Yukawa plane:
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While gauge coupling currently prefers decoupling (couplings = SM), fermions seem to sing a slightly different tune: inaccessible for MSSM!
How does the MSSM fare?

\[ \Delta V_{\text{generic}} = \lambda_1 |H_u|^4 + \lambda_2 |H_d|^4 - 2\lambda_3 |H_u|^2 |H_d|^2 \]

(+ non-minimal terms)

MSSM for neutral CP-even fields: \( \lambda_{1,2,3} = \frac{1}{8}(g^2 + g'^2) \)

with potentially lifesaving quantum corrections to \( \lambda_1 \), but for “down-suppression” we need

\[ v_u^2 \times (\lambda_1 + \lambda_3) < v_d^2 \times (\lambda_2 + \lambda_3) \]

i.e. big quantum-level correction to \( \lambda_{2,3} \) when \( \tan \beta > 1 \)

Natural thing to consider: new non-minimal dynamics -- new fields or compositeness...
Down-Suppression from New Perturbative Dynamics

\[ v_u^2 \times (\lambda_1 + \lambda_3) < v_d^2 \times (\lambda_2 + \lambda_3) \]

I. Singlets (e.g. NMSSM)

II. Doublets (Superconformal TC = “The Seiberg Higgs”)

III. Triplets
Down-Suppression from New Perturbative Dynamics

\[ v_u^2 \times (\lambda_1 + \lambda_3) < v_d^2 \times (\lambda_2 + \lambda_3) \]

I. Singlets (e.g. NMSSM)

\[ \Delta W = \lambda S H_u H_d + \kappa S^3 \quad \Rightarrow \quad \delta \lambda_3 = -|\lambda|^2 \]

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\[ \Delta W = \lambda_u H_u O_d + \lambda_d H_d O_u \]

\[ \Rightarrow \Delta L \sim \frac{\lambda_u, d \Lambda^3}{16\pi^2} H_{u,d}; \quad v_{u,d} \sim \frac{\lambda_u, d \Lambda^3}{16\pi^2 m^2_{H_{u,d}}} \]

\{ \text{Tadpoles} \Rightarrow \beta \]

\{ \text{Masses} \Rightarrow \alpha \]

\{ \text{INDEPENDENT ANGLES!} \]

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Down-Suppression from New Perturbative Dynamics

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\[ \Delta W = \lambda_u H_u \mathcal{O}_d + \lambda_d H_d \mathcal{O}_u \]

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\[ \text{Tadpoles } \Rightarrow \beta \]
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III. Triplets

\[ \Delta W = \lambda_T T H_u H_u + \lambda_{\bar{T}} \bar{T} H_d H_d \Rightarrow \delta \lambda_{1,2} = |\lambda_{T,\bar{T}}|^2 \]
Down-Suppression from New Perturbative Dynamics

\[ v_u^2 \times (\lambda_1 + \lambda_3) < v_d^2 \times (\lambda_2 + \lambda_3) \]

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\[ \Delta W = \lambda_T T H_u H_u + \lambda_{\bar{T}} \bar{T} H_d H_d \quad \Rightarrow \quad \delta \lambda_{1,2} = |\lambda_{T,\bar{T}}|^2 \]
Conclusions

I. (preliminary) Composite Higgs: Fairly SM-like couplings indicate strong dynamics at a high scale (so for instance would need large N for light resonances)

II. (preliminary) SUSY: Some hints of non-minimality so far; non-SM couplings indicate that some new states could show up soon...

III. Generally: Couplings provide crucial indirect hints and consistency checks for BSM physics...
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III. Generally: Couplings provide crucial indirect *hints* and *consistency checks* for BSM physics...

If spectra make headlines, couplings will be the fact checkers:

Each piece of the puzzle is important for consistency of the emerging picture; ultimately more data are needed, but we should be well-prepared to fully analyze every bit that we can!
Backups
How well does this method do?

One possible check: the total combination

![Graph showing the comparison of different combinations for CMS @ 7 TeV, ≤ 4.8 fb⁻¹: Official Combination, Gaussian, and Inverse Quadrature. The x-axis represents m_h (GeV) ranging from 120 to 600, and the y-axis represents a value ranging from 0.2 to 2.0. The graph highlights the differences and similarities between the three methods.]
How well does this method do?

One possible check: the total combination

- ACCURATE WITHIN 10% BELOW 300 GeV; within 20% at high masses

- Compare to “naive graphical analysis” (adding in inverse quadrature) which errs by 40% or more

- Looks good: let’s apply the method and run with it
Before moving on:
A closer look at “signal strength modifier”

We want to compare number of observed signal events in SM units:
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\[ n_S^{(i)} = \left( \int dt \mathcal{L} \right) \times \sum_p \sigma_p^{(i)} \times \zeta_{p,i} \times \text{BR}(h \to i) \]

\[ \Rightarrow \mu = \frac{\sum_p \sigma_p^{(i)} \times \zeta_{p,i} \times \text{BR}(h \to i)}{\left[ \sum_p \sigma_p^{(i)} \times \zeta_{p,i} \times \text{BR}(h \to i) \right]_{\text{SM}}} \]
Before moving on:
A closer look at “signal strength modifier”

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\[ \Rightarrow \mu = \frac{\sum_p \sigma^{(i)}_p \times \zeta_{p,i} \times \text{BR}(h \rightarrow i)}{\sum_p \sigma^{(i)}_p \times \zeta_{p,i} \times \text{BR}(h \rightarrow i)} \]

Efficiencies not always provided, so unknown to theorists
Best we can do: assume that \( \zeta_{p,i} = \zeta_i \forall p \).\(^\dagger\)

\(^\dagger\) Safely justified for SM and SM-like (\(a = c\)), but not in general.
Before moving on:
A closer look at “signal strength modifier”

We want to compare number of observed signal events in SM units:

\[
\begin{align*}
\mu = & \left( \int dt \mathcal{L} \right) \times \sum_p \sigma_p^{(i)} \times \zeta_{p,i} \times \text{BR}(h \to i) \\
\Rightarrow \quad \mu = & \frac{\sum_p \sigma_p^{(i)} \times \zeta_{p,i} \times \text{BR}(h \to i)}{\left[ \sum_p \sigma_p^{(i)} \times \zeta_{p,i} \times \text{BR}(h \to i) \right]_{\text{SM}}} 
\end{align*}
\]

Efficiencies not always provided, so unknown to theorists
Best we can do: assume that \( \zeta_{p,i} = \zeta_i \forall p \).†

\[
\mu \rightarrow \frac{\sum_p \sigma_p^{(i)} \times \text{BR}(h \to i)}{\left[ \sum_p \sigma_p^{(i)} \times \text{BR}(h \to i) \right]_{\text{SM}}}
\]

This can be related purely to theory, but it’s only approximate

EFFICIENCIES NEEDED

† Safely justified for SM and SM-like \((a = c)\), but not in general.
Status report for the Higgs at 125(?)(!)

Five channels for a light Higgs:

1. $WW$  
2. $\gamma\gamma$  
3. $ZZ$  
4. $\tau\tau$  
5. $bb$
Status report for the Higgs at 125(?)(!)

Five channels for a light Higgs:

1. $WW$  2. $\gamma\gamma$  3. $ZZ$  4. $\tau\tau$  5. $bb$

1, 2. Zero Jet, same/opposite flavor lepton

3, 4. One Jet, same/opposite flavor lepton

5. Two Jets

\{ Inclusive \}

\{ VBF \}
Status report for the Higgs at 125(?)(!)

Five channels for a light Higgs:

1. $WW$
2. $\gamma\gamma$
3. $ZZ$
4. $\tau\tau$
5. $bb$

1. Both in barrel, $\min(R9) > 0.94$
2. Both in barrel, $\min(R9) < 0.94$
3. $\geq$ One in endcap, $\min(R9) > 0.94$
4. $\geq$ One in endcap, $\min(R9) < 0.94$
5. Dijet tag

Photon candidates with high values of $R_9$ are mostly unconverted and have less background than those with lower values. Photon candidates in the barrel have less background than those in the endcap. For this reason it has been found useful to divide photon candidates into four categories and apply a different selection in each category, using more stringent requirements in categories with higher background and worse resolution.
Status report for the Higgs at 125(?)(!)

Five channels for a light Higgs:

1. $WW$  
2. $\gamma\gamma$  
3. $ZZ$  
4. $\tau\tau$  
5. $bb$

Inclusive

$VBF + GF + "Boosted"$
(combined limit given; event numbers for one mass)

Associated Production
Take Caution: **Need Exclusive** Searching and Reporting

About the displayed CMS results:
- All WW subchannels treated individually
- Others (except bb) treated inclusively
- Can do better for gamma gamma exactly at peak

---

**Different method:**
Fit each band with appropriate distribution (approx. Gaussian)
Take Caution: Need Exclusive Searching and Reporting

About the displayed CMS results:
- All WW subchannels treated individually
- Others (except bb) treated inclusively
- Can do better for gamma gamma exactly at peak
Take Caution: Need Exclusive Searching and Reporting

About the displayed CMS results:
- All WW subchannels treated individually
- Others (except bb) treated inclusively
- Can do better for gamma gamma exactly at peak

Total likelihood given by product of all
Take Caution: **Need Exclusive** Searching and Reporting

Side-by-side comparison of INCLUSIVE results:

(There *are* real differences, but we see a distinctive -- qualitative -- similarity here)
Final Point: The **Need** for **Exclusive** Searching and Reporting

Now treat *gamma gamma* subchannels:
Final Point: The **Need** for **Exclusive** Searching and Reporting

Now treat **gamma gamma** subchannels:

**CMS Likelihoods [≤ 4.8 fb⁻¹ @ 7 TeV]: All Inclusive**

**CMS Likelihoods [≤ 4.8 fb⁻¹ @ 7 TeV]: γγ Exclusive**
Final Point: The **Need** for **Exclusive** Searching and Reporting

Now treat **gamma gamma** subchannels:

near $c = 0$ line,  $R \sim a^2$  

Excess in dijet fit with gauge coupling
Final Point: The **Need** for **Exclusive** Searching and Reporting

**WW** subchannels:
Final Point: The **Need** for **Exclusive** Searching and Reporting

**WW** subchannels:
Final Point: The **Need** for **Exclusive** Searching and Reporting

**WW** subchannels:

Note VBF cuts deeper in this case:
signal deficit in this subchannel
BG $\sim 11$, obs. $\sim 8$