INSPECTING THE HIGGS FOR NEW WEAKLY INTERACTING PARTICLES

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> Based on: Cheung, Papucci, KZ 1203.5106 Cheung, McDermott, KZ 1302.0314

THE WIMP HAS NOT REVEALED ITSELF UNDERGROUND...

Scattering through the Z boson: ruled out



Next important benchmark: Scattering through the Higgs

 $\sigma_n \sim 10^{-45-46} \ \mathrm{cm}^2$

...IN SPACE...





... OR AT COLLIDERS

		ATLAS SUSY	Searches* - 95% CL Lower Limits (Statu	s: Dec 2012)
NELICEAICNEEM				
MSUGRA/CMSSM MSUGRA/CMSSM	$1:0 \text{ lep + } \text{js + } E_{7,\text{miss}}$	*5.8 fb 1, 8 TeV [ATLAS-CONF-2012-169]	1.60 TeV q = g mass	
Pheno model	$1:0 \text{ lep } + i's + E_{T,miss}$	+5.8 fb ⁻¹ , 8 TeV (ATLAS-CONF-2012-109)	1.18 TeV Q = g mass	ATLAS
Pheno model	1:0 lep + i's + E	=5.8 fb ⁻¹ , 8 TeV (ATLAS-CONF-2012-109)	1.38 TeV 0 mass (m(g) < 2 TeV, light	7) Preliminary
Gluino med. $\tilde{\gamma}^{\pm}$ ($\tilde{q} \rightarrow q \bar{q} \tilde{\gamma}^{\pm}$)): 1 lep + i's + E.	=4.7 fb ⁻¹ , 7 TeV [1208.4688]	900 GeV \tilde{q} mass $(m(\bar{z}^0) < 200 \text{ GeV}, m(\bar{z}^1) =$	(m(z ⁰)+m(q))
GMSB (I NLSP) : 2 le	ep (OS) + i's + E	=4.7 fb ⁻¹ , 7 TeV [1208.4688]	1.24 TeV g mass (tanβ < 15)	
g GMSB (τ NLSP) : 1-2 τ +	0-1 lep + j's + E, miss	=4.7 fb ⁻¹ , 7 TeV [1210.1314]	1.20 TeV g mass (tanβ > 20)	c .
ିଞ୍ଚ GGM (bind	NLSP) : $\gamma\gamma + E_{\gamma mins}^{\gamma mins}$	=4.8 fb ⁻¹ , 7 TeV [1209.0753]	1.07 TeV g mass (m(z) > 50 GeV)	$I dt = (2.1 - 13.0) \text{ fb}^{-1}$
GGM (wino NLS	SP) : γ + lep + E ^r miss	=4.8 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-144]	619 GeV g mass	J 201 (2.1 - 10.0) 10
GGM (higgsino-bino N	LSP): $\gamma + b + E_{T miss}$	=4.8 fb ⁻¹ , 7 TeV [1211.1167]	900 GeV g mass (m(χ) > 220 GeV)	s = 7, 8 TeV
GGM (higgsino NLS	P): Z + jets + E _{7,miss}	=5.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-152]	690 GeV g mass (m(H) > 200 GeV)	
Gravitino LSF	P: 'monojet' + E _{T.miss}	=10.5 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-147]	645 Gev F Scale (m(G) > 10 ⁴ eV)	
g່⇒bbgຶ (virtual_b):0	lep + 3 b-j's + E _{7.miss}	=12.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-145]	1.24 TeV g mass (m(χ) < 200 GeV)	
g→tt x (virtual t) : 2 le	ep (SS) + j's + E _{T,miss}	*5.8 fb", 8 TeV [ATLAS-CONF-2012-105]	850 GeV $g \text{ mass } (m(\overline{\chi}_{\chi}) < 300 \text{ GeV})$	8 TeV results
8 ≥ g→ttχ (virtual t)): 3 lep + j's + E _{7,miss}	=13.0 fb", 8 TeV [ATLAS-CONF-2012-151]	860 GeV g mass (m(\chi) < 300 GeV)	o rev resulta
g j g →ttx (virtual t): 0 le	ep + multi-j's + E _{T miss}	=5.8 fb", 8 TeV [ATLAS-CONF-2012-103]	1.00 TeV g mass (m(x) < 300 GeV)	7 TeV results
$g \rightarrow tt \chi$ (virtual t) : 0	lep + 3 b-j's + E _{T.miss}	=12.8 fb", 8 TeV [ATLAS-CONF-2012-145]	1.15 TeV g mass (m(\chi) < 200 GeV)	
2 ⊆ DD, D, →DX, : 0 le	ep + 2-b-jets + E _{7,miss}	*12.8 fb , 8 TeV [ATLAS-CONF-2012-165]	620 GeV D (mass (m(z)) < 120 GeV)	
E 0 DD, D, →tX	$1 \text{ (S lep + JS + E_{T,miss})}$	=13.0 fb , 6 fev (ATLAS-CONF-2012-151)	$1 \text{ mass } (m(z^0) = 56 \text{ call})$	
$f_{a} = f_{a} = f_{a$	$1 \log + b - j e t + E$	+110 D ⁻¹ 8 TeV (AT) AS CONF-2012-166	160.350 GeV 1 mass (m/2) = 0 GeV m/2 = 150 GeV	
s s tt (medium) t-	$\rightarrow h\bar{\chi}^{\pm}$: 2 lep + E	=13.0 fb ⁻¹ 8 TeV (ATLAS-CONE-2012-100)	160-440 GeV T mass (m/z ²) = 0 GeV m ²) = 10 GeV)	
6 J	1 lep + b-iet + E	=13.0 fb ⁻¹ . 8 TeV (ATLAS-CONF-2012-166)	230-560 GeV t mass (m(x)) = 0)	
E tt. t→t7 : 0/1/2 k	ep (+ b-jets) + E	=4.7 fb ⁻¹ , 7 TeV [1208.1447,1208.2590,1209.418	5) 230-465 GeV t mass $(m(\chi^0) = 0)$	
tt (natural GMSB) : Z	(→II) + b-jet + E	=2.1 fb ⁻¹ , 7 TeV [1204.6736]	310 GeV I mass (115 < m(x) < 230 GeV)	
Ĩ,Ĩ, Ĵ	$ \rightarrow \bar{\chi}_{1}$: 2 lep + E_{χ} miss	=4.7 fb ⁻¹ , 7 TeV [1208.2884] 85-195 0	I mass $(m(\bar{\chi}) = 0)$	
$\geq \tilde{z}$, $\tilde{z}, \tilde{z}, \tilde{z} \rightarrow \tilde{v}(\tilde{v})$	→lvx : 2 lep + E _{T mins} L	=4.7 fb ⁻¹ , 7 TeV [1208.2884]	110-340 GeV $\tilde{\chi}_{\pm}^{\pm}$ mass $(m(\tilde{\chi}_{\pm}^{0}) < 10 \text{ GeV}, m(\tilde{\chi}_{\pm}) = \frac{1}{2}(m(\tilde{\chi}_{\pm}) + m(\tilde{\chi}_{\pm})))$	
$\square \in \overline{\chi}, \overline{\chi}, \rightarrow [v], [v], [v], [v], [v], [v], [v], [v],$	I(vv): 3 lep + E	=13.0 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-154]	550 GeV $\tilde{\chi}_{+}^{\pm}$ mass $(m(\tilde{\chi}_{+}^{\pm}) = m(\tilde{\chi}_{-}^{0}), m(\tilde{\chi}_{+}^{0}) = 0, m(\tilde{\chi})$	is above)
$\chi^{\pm 50}_{,\chi^{-}} \rightarrow W^{4}_{,\chi^{0}}\chi^{0}_{,\chi^{0}}$	$Z^{(1)}\overline{\chi}_{1}^{(2)}$: 3 lep + $E_{T,miss}$	=13.0 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-154]	40-295 GeV $\tilde{\chi}_{+}^{\pm}$ MASS $(m(\tilde{\chi}_{+}^{\pm}) = m(\tilde{\chi}_{-}^{0}), m(\tilde{\chi}_{+}^{0}) = 0$, sleptons decoupled)	
 Direct x[±], påir prod. (A 	AMSB) : long-lived χ_{i}	=4.7 fb ⁻¹ , 7 TeV [1210.2852] 220	GeV $\overline{\chi}_1^*$ mass $(1 < \tau(\overline{\chi}_1) < 10 \text{ ns})$	
Stable g R-hadrons : lov	w β, βγ (full detector) 🛛	=4.7 fb ⁻¹ , 7 TeV [1211.1597]	985 GeV g mass	
등 끝 Stable t R-hadrons : lov	w β, βγ (full detector)	=4.7 fb ⁻¹ , 7 TeV [1211.1597]	683 GeV t mass	
ba	GMSB : stable ₹	=4.7 fb ⁻¹ , 7 TeV [1211.1597]	300 GeV τ mass (5 < tanβ < 20)	
$\chi \rightarrow qq\mu (RPV) : \mu + heat$	avy displaced vertex	=4.4 fb", 7 TeV [1210.7451]	700 GeV q mass (0.3×10" < λ ₂₁₁ < 1.5×10", 1 mm	< ct < 1 m, g decoupled)
LFV : pp→v _s +X	$v_{q} \rightarrow e^{+}\mu$ resonance	=4.6 fb", 7 TeV [Preliminary]	1.61 TeV V_{τ} mass $(\lambda_{311}=0.10, \lambda_{12})$	u ^{=0.05})
LEV : pp->v.+X, v.	$\rightarrow e(\mu) + \tau$ resonance	=4.6 fb", 7 TeV [Preliminary]	1.10 TeV V mass (X ₃₁₁ =0.10, X ₁₂₂₃ =0.0	o)
	num : Alon + E	#4.7 15 . 7 TeV [ATLAS-CONF-2012-140]	$\frac{1.2 \text{ lev}}{7} \text{ q} = \text{g} (11355 (ct_{LSP} < 1 \text{ mm}))$	2.01
$\chi_{\chi_{\mu}\chi_{\mu}\chi_{\mu}}$	$e\mu v = 4 lep + E_{T,miss}$	+13.0 fb ⁻⁴ B T-V (ATLAS-CONF-2012-153)	430 GeV [[[[[[[]] > 500 GeV, m[]] am[]]]]]	2 > 0)
$i_{1}i_{1}, i_{1} \rightarrow i_{1}, \chi_{1} \rightarrow eev_{\mu}$	2 iol reconcer pair	=4.6 fb ⁻¹ .7 TeV (1210.4813)	ese Gev a mass	(A 122 - 0)
Scalar gluon :	2-jet resonance pair	=4.6 fb ⁻¹ , 7 TeV [1210.4826] 10	0-287 GeV SQLUON MASS (incl. limit from 1110,2693)	
WIMP interaction (D5, Dirac x	() : 'monojet' + E	=10.5 fb", 8 TeV (ATLAS-CONF-2012-147)	704 GeV M* \$Cale (m, < 80 GeV, limit of < 687 Ge	V for Q8)
		10 ⁻¹	1	10
*Only a selection of the available mass limits on new states or phenomena shown				

All limits quoted are observed minus 1 or theoretical signal cross section uncertainty.

WHAT NEXT?

- We have the Higgs, and nothing else
- ((Panic. The end of particle physics is nigh.))
- (Bigger detectors, higher energies.)
- Look in new places
- Optimize existing searches
- Get over naturalness addiction
- Use DM as a motivating principle for where to look

INSPECTING THE HIGGS ...

- ... through vacuum stability and DM
- Quartic runs to smaller values via RGEs.



 $b_{\lambda_H}^{(1)} = 12y_b^2\lambda_H - 12y_b^4 - \frac{9}{5}g_1^2\lambda_H - 9g_2^2\lambda_H + \frac{27g_1^4}{100} + \frac{9}{10}g_2^2g_1^2 + \frac{9g_2^4}{4} + 12\lambda_Hy_t^2 + 4\lambda_Hy_\tau^2 + 12\lambda_H^2 - 12y_t^4 - 4y_\tau^4 + 4y_\tau^4 + 4\lambda_Hy_\tau^2 + 12\lambda_Hy_\tau^2 + 12\lambda_Hy_\tau^4 + 4\lambda_Hy_\tau^2 + 12\lambda_Hy_\tau^4 + 4\lambda_Hy_\tau^2 + 12\lambda_Hy_\tau^4 + 4\lambda_Hy_\tau^4 + 4\lambda_Hy_$

 Depending on IR value, quartic can become negative at high scale.

$$\frac{dg}{dt} = \frac{b_g^{(1)}}{(4\pi)^2}$$



В

А

(b)

- ... through vacuum stability and DM
- Don't require absolute stability, only stability on timescales of the order of the age of the universe
- Can compute tunneling probability as a function of length scale of bounc $\Gamma = \max \left[R^{-4} \exp(-16\pi^2/3|\hat{\lambda}_H|) \right] \Big|_{R^{-1}}$

INSPECTING THE HIGGS ...

- ... through vacuum stability and DM
- Suppose we have electroweak DM interacting with the Higgs and nothing else.
- What does that imply about where New Physics must enter?





Bino/Higgsino DM

singlet/doublet fermion: $-\Delta \mathcal{L} = \frac{1}{2}m_S S^2 + m_D D D^c + y_S H S D + y_S^c H^c S D^c$

Wino/Higgsino DM

triplet/doublet fermion: $-\Delta \mathcal{L} = \frac{1}{2}m_T T^2 + m_D D D^c + y_T H T D + y_T^c H^c T D^c$

Important effects on vacuum stability

 $\frac{10^{\circ}}{\Lambda (\text{GeV})} = \frac{10^{12}}{10^{12}} = \frac{10^{14}}{10^{10}} = \frac{10^{10}}{10^{10}} = \frac{10^{12}}{10^{12}} = \frac{10^{14}}{10^{10}} = \frac{10^{10}}{10^{10}} = \frac{10^{12}}{10^{14}} = \frac{10^{14}}{10^{10}} = \frac{10^{14}}{10^{10}$

STABILITY AND DM

Cheung, Papucci, KZ 1203.5106

Metastability bands

STABILITY AND DM

 Direct Detection and Relic Density can probe the couplings

• Relic density in particular can place a "floor" on the size of the couplings to the Higgs











INSPECTING THE HIGGS ...

- ... for new weakly interacting particles through its decay modes
- Plenty of scanning in the literature.



 How do we think about separating which combinations of observables are relevant for which combinations of theoretical parameters?

INSPECTING THE HIGGS

Ellwanger

1112.3458

h

- Embed in specific models, e.g.
 NMSSM
- Boost $h \rightarrow \gamma \gamma$ by depleting total width



INSPECTING THE HIGGS

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- More general question: how to map Higgs physics to new physics from Higgs observations?
- Basic observables:

$$R[\mathcal{O}] = \mathcal{O}/\mathcal{O}_{\mathrm{SM}},$$

 $R_i^j \equiv R[\sigma(jj \to h) \times Br(h \to ii)]$

Mixing and loop effects



TREES AND LOOPS

- Can easily separate tree level effects from loop effects by looking at *ratios* of observables
- Example of a story: Singlet + 2 HDM + new EW states
- Suppose new colored particles will show up elsewhere first

INSPECTING THE HIGGS

Cheung, McDermott, KZ

- Singlet + 2 HDM + new EW states
- Mixing: two angles $h = \sum_{I} P_{I} H_{I} \qquad I = u, d, s$ $P_{I} = (\cos \alpha \cos \gamma, -\sin \alpha \cos \gamma, -\sin \gamma)$
- Singlet mixing and deviation from SM decoupling limit

$$\delta = \alpha - \beta + \pi/2,$$

INSPECTING THE HIGGS

$$h = \sum_{I} P_{I} H_{I}$$
$$P_{I} = (\cos \alpha \cos \gamma, -\sin \alpha \cos \gamma, -\sin \gamma)$$

$$d_t = \cos \gamma \cos \alpha / \sin \beta = \cos \gamma \cos \delta (1 + \tan \delta \cot \beta)$$

$$d_b = -\cos \gamma \sin \alpha / \cos \beta = \cos \gamma \cos \delta (1 - \tan \delta \tan \beta)$$

$$d_V = \cos\gamma\sin(\beta - \alpha) = \cos\gamma\cos\delta$$

Tree:

$$d_{i} = \sum_{I} P_{I} \eta_{I,i}$$
$$\eta_{I,i} = \frac{v}{m_{i}} \frac{\partial m_{i}}{\partial v_{I}},$$



 $\frac{R_b^j}{R_V^j} = \frac{R_\ell^j}{R_V^j} = \frac{|d_b|^2}{|d_V|^2} = (1 - \tan\delta\tan\beta)^2 \qquad \frac{R_i^g}{R_i^V} \simeq |\mathcal{A}_{g,t}(1 + \tan\delta\cot\beta) + \mathcal{A}_{g,b}(1 - \tan\delta\tan\beta)|^2$



 $\frac{R_b^j}{R_V^j} = \frac{R_\ell^j}{R_V^j} = \frac{|d_b|^2}{|d_V|^2} = (1 - \tan\delta\tan\beta)^2 \qquad \frac{R_i^g}{R_i^V} \simeq |\mathcal{A}_{g,t}(1 + \tan\delta\cot\beta) + \mathcal{A}_{g,b}(1 - \tan\delta\tan\beta)|^2$

EXTRACT $\tan\beta$, $\tan\delta$



EXTRACT $\tan\beta$, $\tan\delta$



$\frac{\mathbf{EXTRACT}}{\cos\gamma}$

 $R_i^j \equiv R[\sigma(jj \to h) \times Br(h \to ii)]$



δ

VIRTUAL EFFECTS

 R^j_γ/R^j_V not very sensitive to tree level parameters



Extract virtual EW states



 $\frac{R_{\gamma}^{j}}{R_{V}^{j}} = |1 + \epsilon(\beta) \tan \delta|^{2}$

EXTRACT THE LOOP PARAMETERS





$$\eta_{I,\chi^{\pm}} = \frac{2m_W^2}{\overline{m}^2} \left(-\cos\beta, -\sin\beta, \frac{\lambda M_2}{\sqrt{2}g_2 m_W} \right)$$

$$\left(\overline{m}^{2}\right)^{2} = \left(m_{\chi_{1}^{\pm}}m_{\chi_{2}^{\pm}}\right)^{2} = \det\left(\mathcal{M}_{\chi^{\pm}}^{\dagger}\mathcal{M}_{\chi^{\pm}}\right)$$



SUMMARY

- Traditional probes are closing an increasing fraction of the window for new EW states
- To close (or observe!) the remaining part of the window, need to use complementary probes
- Higgs provides an opportunity through indirect probes -- stability and production / decay
- These can be more effectively utilized by looking at correlations between observables that can be mapped uniquely to a theory

SUMMARY

- Haven't discussed but there are important correlations with direct and indirect detection experiments if these states are connected to the DM (another talk)
- Flavor too
- Multi-pronged approach!