

Part III: Beyond the Standard model

Motivation, BSM Higgs Searches, SUSY Searches & Exotica

Why do we need physics Beyond the Standard model?

Dark matter problem

The rotation velocity of stars in galaxies differs a lot from the expectation! The expectation is based on the mass density of the luminous matter. \rightarrow There must be a huge mass around the galaxies that we don't see.

Another evidence: Graviational lensing.



Observed first by V. Rubin around 1970

WMAP 74% Dark Energy on! 22% Dark Matter 4% Atoms

The standard modell does not offer any **candidate for the dark matter**:

- must be electrically neutral (otherwise we would see it)
- must be massive
- must be stable

Neutrinos? Probably not, they are too fast \rightarrow cannot form lasting structures

Btw, another solution to this is a ² modification of gravity.

Why do we need physics Beyond the Standard model?

Fine-tuning problem

The vaccuum expectation values sets the weak energy scale \rightarrow about the mass we would expect for the Higgs boson.

In the pertubative calculation, the Higgs mass receives large radiative corrections up to the cut-off scale Λ , where the SM breaks (eg. the GUT scale, or the Planck scale)



 \rightarrow observale Higgs m ~ Λ \rightarrow This contradicts the EW precision fits!

Theorists can handle this by introducing counter-terms (renormalization), but these terms have to be extremly fine-tuned in the theory to cancel the divergences:

$$\mathcal{O}(\text{fine tuning}) \approx \frac{\mathcal{O}(EW^2)}{\mathcal{O}(\Lambda^2)} \approx 10^{-26} \longrightarrow \text{This is neither natural nor convincing.}$$

Why do we need physics Beyond the Standard model?

Other open questions (a few of them)

 Why is the electrical charge of the proton identical to that of the electron? If it was not true, atoms would not be stable. Protons and electrons are very different objects, but are they maybe two sides of the same medal (a new symmetry)? → This is subject to grand unified theories (uniting strong and electroweak interactions)

More generally, the SM does not explain particle quantum numbers (and, why are there 3 fermion generations, and 3 colors)

 There are at least 19 free parameters of the SM (forgetting about neutrinos) (9 fermion masses, 3 CKM parameters + 1 weak CP violating phase, 1 strong CP violating phase, three coupling constants, two weak boson masses

Is it possible to calculate them from first principles?

• A bit more crazy: What about gravity? It's a part of our world, can we make it a part of a unified theory as well?

→ The SM agrees well with all experimental data from accelerators, but it is theoretically unsatisfactory

The most-favored extension of the Standard Model: Supersymmetry (SUSY)

SUSY is also part of GUT, string theory, some extra-dimensional models, ...

SUSY is the symmetry transforming bosons into fermions and vice versa:

 $Q|Boson\rangle \propto |Fermion\rangle$ $Q|Fermion\rangle \propto |Boson\rangle$

This predicts a new class of partner particles (in analogy to anti-particles):



The most-favored extension of the Standard Model: Supersymmetry (SUSY)

To increase the confusion...

The SUSY fields mix and then form the **observable SUSY particles**:

Name	Spin	<i>R</i> -parity	Interaction e.s.	Mass e.s.
Higgs bosons	0	+1	H_u, H_d	h^0, H^0, A^0, H^\pm
Squarks	0	-1	$\tilde{Q}_{1,2,3}, \ \tilde{u}^c, \tilde{c}^c, \tilde{t}^c, \ \tilde{d}^c, \tilde{s}^c, \tilde{b}^c$	$\tilde{u}_{1,2,3,4,5,6}, \ \tilde{d}_{1,2,3,4,5,6}$
Sleptons	0	-1	$\tilde{L}_{1,2,3}, \ \tilde{e}^c, \tilde{\mu}^c, \tilde{\tau}^c$	$\tilde{\ell}_{1,2,3,4,5,6}, \ \tilde{\nu}_{1,2,3}$
Neutralinos	$\frac{1}{2}$	-1	$\tilde{B}^0, \tilde{W}^0, \tilde{H}^0_u, \tilde{H}^0_d$	$\chi^{0}_{1,2,3,4}$
Charginos	$\frac{1}{2}$	-1	$\tilde{W}^{\pm}, \tilde{H}_u^+, \tilde{H}_d^-$	$\chi^{\pm}_{1,2}$
Gluinos	$\frac{1}{2}$	-1	${ ilde g}$	\widetilde{g}
Gravitino	$\frac{1}{2}, \frac{3}{2}$	-1	$ ilde{G}$	$ ilde{G}$

Come back to the Higgses in a few slides...

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Sleptons	0	-1		$\tilde{L}_{1,2,3}, \ \tilde{e}^c, \tilde{\mu}^c, \tilde{\tau}^c$	$\tilde{\ell}_{1,2,3,4,5,6}, \ \tilde{\nu}_{1,2,3}$
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Charginos	$\frac{1}{2}$	-1		$\tilde{W}^{\pm}, \tilde{H}_{u}^{+}, \tilde{H}_{d}^{-}$	$\chi^{\pm}_{1,2}$
Gluinos	$\frac{1}{2}$	-1		${ ilde g}$	\tilde{g}
Gravitino	$\frac{1}{2}, \frac{3}{2}$	-1		$ ilde{G}$	$ ilde{G}$

Come back to the Higgses in a few slides...

So, where are the SUSY particles?

Fact: No SUSY particle has ever been observed *(I will present a few searches later on)* eg. a boson of 511 keV (the "selectron") would have probably not escaped our detectors...

 \rightarrow The SUSY mass scale is higher, SUSY particles are heavier than SM particles. The mass scale is expected to be around 1 TeV.

SUSY is a broken symmetry (it's imperfect). We don't know anything about the breaking mechanism \rightarrow Our ignorance is parametrized in about 100 new parameters

So, why is SUSY a good theory?

1. It solves the Fine-tuning problem:

The sfermion loops cancel the divergent fermion loops:

$$\delta m^2 \approx \mathcal{O}(\alpha) \cdot |m_{\tilde{f}}^2 - m_f^2| \approx \mathcal{O}(10^{-2}) \cdot m_{SUSY}^2$$

The Higgs mass stays small. This works if $m_{SUSY} \sim 1$ TeV.



So, why is SUSY a good theory? (continued...)

2. It stages a possible dark matter candidate:

The lightest neutral SUSY particle (the neutralino χ^0) might be stable. If it is stable it would be a dark matter candidate.

It is stable if R-parity is conserved: $R = (-1)^{2s+3B+L}$ Parti

Particles: +1 Sparticles: -1

Conservation of R-parity is elegant because it tells that SUSY particles can only be produced in pairs.

3. It facilitates a grand unification:



The running coupling constants unite at some large energy,

This does not happen in the SM.

However, some theorists argue that this is not always true and that it depends on the details of the SUSY theory eg. breaking parameters

In the SM we introduced one Higgs doublet, now we need two:



Down-type: u,d,s, charged leptons

$$\Phi = \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix} \to H_u = \begin{pmatrix} h_u^+ \\ h_u^0 \end{pmatrix}, \ H_d = \begin{pmatrix} h_d^0 \\ h_d^- \end{pmatrix}$$

 H_u couples to up-type fermions H_d couples to down-type fermions

 \rightarrow Two vev's: v_u, v_d

In the SM we had 4 degrees of freedom, now we have 8. 3 of them are absorbed as masses into the Z and W^{\pm} bosons, 5 remain.



On tree level, the whole Higgs sector can be described with just 2 parameters:

$$\mathbf{m}_{A}$$
 Coupling parameter $\mathbf{tan}\beta = v_{u} / v_{d}$

Remarkable: The mass of the lighest Higgs is constrained

 $m_h < m_Z \cos 2\beta + \Delta$ - SUSY enters

 Δ is a term for radiative corrections from stop loops, details are model-dependent. Usually it is assumed that $m_h \leq 130 \text{ GeV}$

(130 GeV is quite large already, lesser would be more appreciated by theorists)



How do $h/A/H/H^{\pm}$ relate to the SM Higgs?

• "Decoupling limit" m_A >> m_z

h is SM-like (not exactly identical), H/A/H $^{\pm}$ are very heavy

• "Anti-decoupling limit" $m_A \approx m_z$, tan β large

H is the SM Higgs, h/A/H^{\pm} are light

• "intermediate-coupling regime" $m_{A} \ge m_{7}$, moderate $tan\beta$

Neither SUSY Higgs is SM-like

In the MSSM, the couplings of Higgs bosons to other particles are different to those in the SM. \rightarrow Modified cross sections and branching ratios \rightarrow Different search channels

In particular: The coupling to down-type fermions is enhanced, depending on tan β .

 \rightarrow Larger probability for decay into $\tau\tau$ and $\mu\mu$, and also to $b\overline{b}$.

The decay to $H \rightarrow VV$ (V=Z/W) is supressed, and $A \rightarrow VV$ is not allowed



ightarrow THAT's WHY WE NEED TO MEASURE COUPLINGS OF THE NEW PARTICLE at 125 GeV

What can we learn from a Higgs at 125 GeV?

Let's assume the new particle is a SUSY Higgs. It's mass depends on SUSY:

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m_h < m_Z \cos 2\beta + \Delta
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 Δ is mostly influenced by the stop sector. Important parameters:



 $M_s = \sqrt{(m_{t1} * m_{t2})}$ (SUSY mass scale, stop mass) X_t=A_t-μcotβ (stop mixing parameter)

For that plot other parameters fixed:

 $\mu = M_2 = 200 \text{ GeV}, \quad m_{\tilde{g}} = 0.8 M_S,$ $m_A = 500 \text{ GeV}, \quad \tan \beta = 10$

Plot: Pietro Slavich (LPTHE Paris) using Feynhiggs

What can we learn from a Higgs at 125 GeV?

Consider the "Phenomenological MSSM" (pMSSM)

No special assumptions of SUSY breaking, but SUSY parameter range simplified and reduced to 22 parameters (pMSSM details: arXiv:1109.3859v3)

Result of a parameter scan: (arXiv:1112.3028v3)



No experimental data taken into acount except for m_{μ} .

 Each point represents one set of parameter values that give the correct (observed) Higgs mass.

Scan range:

$$\begin{split} 1 &\leq \tan \beta \leq 60 \;,\; 50 \;\, {\rm GeV} \leq M_A \leq 3 \;\, {\rm TeV} \;,\; -9 \;\, {\rm TeV} \leq A_f \leq 9 \;\, {\rm TeV} \;, \\ 50 \;\, {\rm GeV} \leq m_{\tilde{f}_r} \;, m_{\tilde{f}_{P}} \;, M_3 \leq 3 \;\, {\rm TeV} \;,\; 50 \;\, {\rm GeV} \leq M_1, M_2, |\mu| \leq 1.5 \;\, {\rm TeV} \end{split}$$

What can we learn from a Higgs at 125 GeV?

Another paper does a scan in pMSSM with 7 free parameters: arXiv:1211.1955v1

This scan takes also into account the signal strengths of Higgs searches in ATLAS & CMS + low energy observables (eg. $b \rightarrow s\gamma$, g-2) and quantifies the agreement of data and model:



Each point represents one model which would be allowed, color quantifies the fit quality.

 \rightarrow The new particle could either be h or H, both options are possible. If it is H, than 16 h/A would be light. If it was h, than H/A would be heavy.

Search for BSM Higgs at the LHC

(selection)

$h/A/H \to \mu \mu$

This decay has a branching ratio of only 0.04%, but similar to $H \rightarrow \gamma \gamma$ it is a clear final state and the background can be estimated with a fit to the dimuon mass.

Analysis is split into b-tagged category (sensitive to b-associated Higgs) and b-vetoed category (sensitive to gluon fusion production).



$h/A/H \to \tau\tau$

Again, analysis split into b-tagged and b-vetoed categories. Leplep, lephad and hadhad channels considered. Just like in the SM search, $Z \rightarrow \tau \tau$ is the dominant background.





CMS vs ATLAS:



Searches for BSM Higgs: Charged MSSM Higgs

Charged Higgs production depends on charged Higgs mass:





If $m_{H} < m_{t}$:

 $t \to H^{\scriptscriptstyle +} b$

(H^{\pm} produced in top decay)

Dominant decay: $H^+ \rightarrow \tau v$

(dominant for $tan\beta > 3$)

If $m_{H} > m_{t}$: gb \rightarrow tH⁺ (or gg \rightarrow tbH) (H[±] produced in gluon-bottom fusion)

Dominant decays: $H^{+} \rightarrow \tau b$ and $H^{+} \rightarrow \tau v$

Searches for BSM Higgs: Charged MSSM Higgs

ATLAS search for tt \rightarrow **bbWH**⁺ with H⁺ $\rightarrow \tau v$ Assuming BR(H⁺ $\rightarrow \tau v$) = 100%

Leptonic and hadronic tau decays considered, W decay to leptons or quarks.



 \rightarrow No excess observed!

In the MSSM, the Higgs potential parameter μ has the dimension of a mass and in order that the theory works, it must have a value of 0.1-1 TeV. \rightarrow We would like to get rid of a-priori assumptions on parameters

Introduce a new Higgs singlet superfield S in addition to the MSSM Higgs doubletts:

$$\widehat{S}, \ \widehat{H}_d = \left(\begin{array}{c} \widehat{H}_d^0 \\ \widehat{H}_d^- \end{array} \right), \ \widehat{H}_u = \left(\begin{array}{c} \widehat{H}_u^+ \\ \widehat{H}_u^0 \end{array} \right)$$

 \rightarrow (Even) more Higgs bosons observable (now there are 7):



For more information, here are two reviews on the NMSSM:

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arXiv:0910.1785 [hep-ph]
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www.physics.gla.ac.uk/~dmiller/doc/nmssm_review.ps

ATLAS Search for Higgs decay to low-mass pseudoscalar a^o (100-400 MeV)

If a⁰ mass below $3^*\pi^0$ mass, then the dominant decay is $a^0 \rightarrow \gamma \gamma$

Consider the decay $H \rightarrow a^0 a^0 \rightarrow \gamma \gamma + \gamma \gamma$ H does not need to be specified further, the aim is to set a limit on its cross section

The a₀ are extremely forward \rightarrow Each $\gamma\gamma$ pair appear as one cluster

 \rightarrow The experimental difficulty of this analysis was to refine the photon ID



CMS Search for a light pseudo-scalor $a^0 \rightarrow \mu\mu$



Could be produced with very large cross sections eg. tan β =30 σ =10⁶ pb, or tan β =2 σ =10⁴ pb

→ even if decay a → $\mu\mu$ is rare, large signal expected. → Look for a dimuon resonance!

Overwhelming backgrounds from $Y \to \mu \mu$ resonances \to Cut them out from the search region



26

CMS Search for a light pseudo-scalor $a^0 \rightarrow \mu\mu$



Direct search for Supersymmetry with ATLAS (selection)



ATLAS-CONF-2012-145

ATLAS search for gluino pairs, eg. in final states with \geq 3 b-jets and MET



LSP is long-lived. \tilde{t}_1 and \tilde{b}_1 are light and are produced with a high rate.

Discriminating variables:

- Large MET
- large m_{eff}
- >=4 or 6 jets of with at least 3 are b-jets
- large pT of the b-jets

Remember: $t \rightarrow Wb$ with almost 100%. So there are many true b-jets in the final state.

effective mass m_{eff} is scalar sum of MET and p_{T} of all (or selected number of) jets.

ATLAS-CONF-2012-145

ATLAS search for gluino pairs in final states with \geq 3 b-jets and MET



- Dominant background: tops
- Background control validated on signal-free control regions.
- 30 No excess observed, need more data to set limits on high mass LSPs

ATLAS search for gluino pairs: Summary of Results

Interpretation in a simplified model where \tilde{t}_1 is lightest squark but

 $m_{ ilde{g}} < m_{ ilde{t}_1}$ and BR=100% for $ilde{g}
ightarrow t \overline{t} ilde{\chi}_1^0$



 \rightarrow No excess observed, but stringent limits set!

ATLAS-CONF-2012-166

ATLAS search for direct stop pairs in final states with one lepton, jets and MET

Stop pair production:





Stop pair decay:



1.
$$\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^{\pm}$$

with $\tilde{\chi}_1^{\pm} \rightarrow W^{(*)} + \tilde{\chi}_1^0$

2.
$$\tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0$$

with $t \rightarrow bW$

Both decays have similar final states (W's, b-jets, leptons, MET) but different kinematics 32

ATLAS search for direct stop pairs in final states with one lepton, jets and MET

Neutralinos escape direct detection \rightarrow they manifest as missing energy The heavier the stops and neutralinos, the more MET can be expected:



ATLAS search for direct stop pairs in final states with one lepton, jets and MET



Better than MET would be to reconstruct the stop mass, but this is very difficult when dealing with cascade decays and two massive neutral particles in the final state.

Variable used: am_{T_2} .

Useful to supress top background!

This is a generalized transverse mass inspired from W mass meaurement:

arXiv:hep-ph/9906349v1

SUSY signal extends to larger values of aM_{T_2} than the top background.

ATLAS search for stop pairs: Summary of Results



 \rightarrow No excess observed, but stringent limits set!

ATLAS generic search for squarks and gluinos in final states with MET and jets

Interprete in constrained MSSM model with assumptions on SUSY breaking parameters

Example signal region with MET > 160 GeV and 5 jets:



arXiv:1109.3859v3 "Constrained MSSM' (cMSSM):

Reduce ~100 SUSY parameters to a few

 \rightarrow Specific model: **mSUGRA**

mSUGRA is minimal Supergravity model where gravity breaks SUSY. Gaugino masses, sfermion masses, scalar masses unify at GUT scale.

Parameters:

- M_o scalar mass
- $M_{_{1/2}}$ gaugino mass
- A₀ trilinear coupling
- tanβ
- μ Higgsino mass parameter

36

ATLAS generic search for squarks and gluinos in final states with MET and jets



 \rightarrow No excess observed, but stringent limits set!

ATLAS SUSY Searches* - 95% CL Lower Limits (Status: Dec 2012)

		10 ⁻¹	1	10
	T,niss	L=10.5 fb , 8 lev [A1LAS-CONF-2012-147]	704 GeV IVI \$Calle (m _{\chi} < 80 GeV, limit of < 687 Ge	
WIM	Scalar gluon : 2-jet resonance pair P interaction (D5, Dirac γ) : 'monoiet' + F	L=4.6 fb ⁻¹ , 7 TeV [1210.4826]	00-287 GeV Sgluon mass (incl. limit from 1110.2693)	(for D0)
	$g \rightarrow qqq$: 3-jet resonance pair	L=4.6 fb ⁻¹ , 7 TeV [1210.4813]	666 GeV g mass	
	$ l_{L}, l_{L} \rightarrow \tilde{\chi}_{1}, \tilde{\chi}_{1} \rightarrow eev_{\mu}, e\muv_{\mu} > 4 lep + E_{T.miss}$	L=13.0 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-153]	430 GeV I mass $(m(\bar{\chi}_1^u) > 100 \text{ GeV}, m(l_e)=m(l_\mu)=m(l_t), \lambda_{121} \text{ or}$	r λ ₁₂₂ > 0)
2	$\tilde{\chi}_{1}^{\dagger}\tilde{\chi}_{1}^{\dagger}\tilde{\chi}_{1}^{\dagger} \rightarrow W\tilde{\chi}_{0}^{\dagger}, \tilde{\chi}_{0}^{\bullet} \rightarrow eev_{\mu}, e\muv_{\mu}: 4 lep + E_{T.miss}$	L=13.0 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-153]	700 GeV χ_1 mass $(m(\chi_1) > 300 \text{ GeV}, \lambda_{121} \text{ or } \lambda_{122})$	₂ > 0)
2	Bilinear RPV CMSSM : 1 lep + 7 j's + $E_{T,miss}$	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-140]	1.2 TeV $q = g \text{ mass} (c\tau_{LSP} < 1 \text{ mm})$	
	LFV : pp $\rightarrow \tilde{v}_{\tau} + X$, $\tilde{v}_{\tau} \rightarrow e(\mu) + \tau$ resonance	L=4.6 fb ⁻¹ , 7 TeV [Preliminary]	1.10 TeV V_{χ} mass $(\lambda_{311}^{*}=0.10, \lambda_{1(2)33}^{*}=0.05)$	5)
	LFV : pp→ντ̃,+X, ν̃,→e+μ resonance	L=4.6 fb ⁻¹ , 7 TeV [Preliminary]	1.61 TeV V_{τ} mass $(\lambda_{311}^{*}=0.10, \lambda_{13})$	₂ =0.05)
-	$\tilde{\chi}_1^{\circ} \rightarrow qq\mu \text{ (RPV) : } \mu + heavy displaced vertex$	L=4.4 fb ⁻¹ , 7 TeV [1210.7451]	700 GeV q mass (0.3×10 ⁻⁵ < λ ₂₁₁ < 1.5×10 ⁻⁵ , 1 mm	< ct < 1 m,g decoupled)
D a	GMSB : stable $\bar{\tau}$	L=4.7 fb ⁻¹ , 7 TeV [1211.1597]	300 GeV τ MASS (5 < tanβ < 20)	
-bit	Stable t R-hadrons : low β , $\beta\gamma$ (full detector)	L=4.7 fb ⁻¹ , 7 TeV [1211.1597]	683 GeV t mass	
live Sles	Stable \tilde{g} R-hadrons : low β , $\beta\gamma$ (full detector)	L=4.7 fb ⁻¹ , 7 TeV [1211.1597]	985 GeV g mass	
0 0	Direct χ_1^- pâir prod. (AMSB) : long-lived χ_1^-	L=4.7 fb ⁻¹ , 7 TeV [1210.2852] 22	20 GeV χ_1^- MASS $(1 < \tau(\chi_1^-) < 10 \text{ ns})$	
	$\chi_1 \chi_2 \rightarrow W^{*} \chi_1 Z^{*} \chi_1 : 3 \text{ lep } + E_{T, \text{miss}}$	L=13.0 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-154]	140-295 GeV χ_1^- mass $(m(\chi_1^+) = m(\chi_2), m(\chi_1^-) = 0$, sleptons decoupled)	
山谷	$\overline{\chi}_1 \overline{\chi}_2 \rightarrow v (\overline{v}v), \overline{v} (\overline{v}v) : 3 \text{ lep } + E_{T,\text{miss}}$	L=13.0 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-154]	580 GeV $\overline{\chi}_1^+$ mass $(m(\overline{\chi}_1^+) = m(\overline{\chi}_2^0), m(\overline{\chi}_1^0) = 0, m(\overline{l}, \overline{v})$ as	s above)
90	$\overline{\chi}_{1}\overline{\chi}_{1}, \overline{\chi}_{1} \rightarrow lv(l\overline{v}) \rightarrow lv\overline{\chi}_{1}$: 2 lep + $E_{T,miss}$	L=4.7 fb ⁻¹ , 7 TeV [1208.2884]	110-340 GeV χ_1^- Mass $(m(\chi_1^u) < 10 \text{ GeV}, m(\bar{l}, \bar{v}) = \frac{1}{2}(m(\chi_1^+) + m(\chi_2^-)))$	
*	$I_{L}I_{L}, I \rightarrow I \tilde{\chi}_{0} : 2 \text{ lep } + E_{T, \text{miss}}$	L=4.7 fb ⁻¹ , 7 TeV [1208.2884] 85-195	GeV I mass $(m(\bar{\chi}_1^u) = 0)$	
	tt (natural GMSB) : $Z(\rightarrow II) + b$ -jet + E	L=2.1 fb ⁻¹ , 7 TeV [1204.6736]	310 GeV t mass (115 < $m(\chi_1)$ < 230 GeV)	
di g	tt, t \rightarrow t χ : 0/1/2 lep (+ b-jets) + $E_{T,miss}$	L=4.7 fb ⁻¹ , 7 TeV [1208.1447,1208.2590,1209.41	186] 230-465 GeV t mass $(m(\chi_1) = 0)$	
d g	\sim tt, t \rightarrow t χ_1 : 1 lep + b-jet + $E_{T,miss}$	L=13.0 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-166]	230-560 GeV t mass $(m(\chi_1) = 0)$	
en.	tt (medium) t $\rightarrow b\overline{\chi}_1^+$: 2 lep + $E_{T,miss}$	L=13.0 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-167]	160-440 GeV t mass $(m(\chi_1) = 0 \text{ GeV}, m(t) - m(\chi_1) = 10 \text{ GeV})$	
S D	tt (medium), t \rightarrow b $\overline{\chi}_{1}^{+}$, 1 lep + b-jet + $E_{T,miss}$	L=13.0 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-166]	160-350 GeV t mass $(m(\chi_1) = 0 \text{ GeV}, m(\chi_1) = 150 \text{ GeV})$	
nct	\underline{tt} (light), $t \rightarrow \underline{b} \overline{\chi}_{1}^{+}$: 1/2'lep (+ b-jet) + $E_{T,\text{miss}}$	L=4.7 fb ⁻¹ , 7 TeV [1208.4305, 1209.2102]67 Ge	\mathbf{v} tmass $(m(\tilde{\chi}_1) = 55 \text{ GeV})$	
No.	\overline{z} bb, b' $\rightarrow t\overline{\chi}^{\pm}$: 3 lep + j's + $E_{T,miss}$	L=13.0 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-151]	405 GeV b mass $(m(\bar{\chi}_1^{\pm}) = 2m(\bar{\chi}_1^{\mu}))$	
\$ 0	bb, $b_1 \rightarrow b \tilde{\chi}_1$: 0 lep + 2-b-jets + $E_{T,miss}$	L=12.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-165]	620 GeV b mass $(m(\bar{\chi}_1^u) < 120 \text{ GeV})$	
<u>ო</u> თ	$g \rightarrow tt \chi_1$ (virtual t) : 0 lep + 3 b-j's + $E_{T,miss}$	L=12.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-145]	1.15 TeV g mass (m(χ_1) < 200 GeV)	
E E	$g \rightarrow tt \chi_{1}$ (virtual t).; 0 lep + multi-j's + $E_{T,miss}$	L=5.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-103]	1.00 TeV g mass $(m(\chi_1) \leq 300 \text{ GeV})$	7 TeV results
ge ng	$g \rightarrow tt \chi_1$ (virtual t) : 3 lep + j's + $E_{T,miss}$	L=13.0 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-151]	860 GeV g mass $(m(\chi_1) \leq 300 \text{ GeV})$	o lev lesuits
n. S	$g \rightarrow tt \chi_1$ (virtual t) : 2 Jep (SS) + j's + $E_{T,miss}$	L=5.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-105]	850 GeV g mass $(m(\chi_{h}) < 300 \text{ GeV})$	P. ToV regults
ġ ġ	$g \rightarrow b \overline{b} \overline{\chi}_{n}$ (virtual b) : 0 lep + 3 b-j's + $E_{T,miss}$	L=12.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-145]	1.24 TeV g mass (m(χ̃) < 200 GeV)	
	Gravitino LSP : 'monojet' + E _{T.miss}	L=10.5 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-147]	645 GeV F [™] scale (m(G) > 10 ⁴ eV)	
	GGM (higgsino NLSP) : Z + jets + $E_{T,miss}$	L=5.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-152]	690 GeV $g_{\mu\nu}^{\text{mass}}$ (m(H) > 200 GeV)	
	GGM (higgsino-bino NLSP) : $\gamma + b + E_{T miss}^{\gamma}$	L=4.8 fb ⁻¹ , 7 TeV [1211.1167]	900 GeV $g \text{ mass}(m(\bar{\chi}_1^0) > 220 \text{ GeV})$	s = 7, 8 TeV
101	GGM (wino NLSP) : γ + lep + $E_{T \text{ miss}}^{\gamma}$	L=4.8 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-144]	619 GeV g mass	J_4(2.1 10.0)10
USI	GGM (bino NLSP) : $\gamma\gamma + E_T$ mise	L=4.8 fb ⁻¹ , 7 TeV [1209.0753]	1.07 TeV g mass (m(χ ⁰) > 50 GeV)	$Ldt = (2.1 - 13.0) \text{ fb}^{-1}$
A9	GMSB ($\overline{\tau}$ NLSP) : 1-2 τ + 0-1 lep + j's + \overline{E}_{τ}	L=4.7 fb ⁻¹ , 7 TeV [1210.1314]	1.20 TeV g mass (tanβ > 20)	C
Se	GMSB (I NLSP) : 2 lep (OS) + i's + ET miss	L=4.7 fb ⁻¹ , 7 TeV [1208.4688]	1.24 TeV g mass (tanβ < 15)	
arc	Gluino med, $\tilde{\chi}^{\pm}(\tilde{g} \rightarrow q\bar{q}\tilde{\chi}^{\pm})$: 1 lep + j's + E_{τ} miss	L=4.7 fb ⁻¹ , 7 TeV [1208.4688]	900 GeV \tilde{g} mass $(m(\chi^0) < 200 \text{ GeV}, m(\chi^\pm) = 1$	$(m(\overline{\chi}^0)+m(\widetilde{g}))$
he	Pheno model : 0 lep + j's + $E_{T miss}$	L=5.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-109]	1.38 TeV q mass (m(g) < 2 TeV, light	⁻⁰ , Preliminary
60	Pheno model : 0 lep + j's + $E_{T miss}$	L=5.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-109]	1.18 TeV \tilde{g} mass $(m(\tilde{q}) < 2$ TeV, light χ^0)	ATLAS
	MSUGRA/CMSSM : 1 lep + j's + ET mice	L=5.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-104]	1.24 TeV $\vec{q} = \vec{q}$ mass	
	MSUGRA/CMSSM : 0 lep + i's + ET mer	L=5.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-109]	1.50 TeV g = g mass	

*Only a selection of the available mass limits on new states or phenomena shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty. Mass scale [TeV]

Exotics (selection)



Search for New Phenomena in the Dijet Mass

Testing the SM up to the highest energies at LHC.

ATLAS-CONF-2012-148

Aim: Look for excited quarks $q^* \rightarrow qg$ (ie. quark sub-structure) by probing dijet mass.

The SM dijet mass comes from non-resonant QCD dijet production.



Search strategy:

Look for bumbs in the dijet mass!

Background estimated from a fit to the dijet mass:

$$f(x) = p_1(1-x)^{p_2} x^{p_3 + p_4 \ln x}$$

Significance does not contain systematic uncertainties.

BumpHunter algorithm (arXiv:1101.039@)

Search for New Phenomena in the Dijet Mass

Cross section limits on excited quarks:

Bkg subtracted data vs. prediction:



Highest dijet mass event: $m_{ii} = 4.69$ TeV. MET = 47 GeV.



Search for Microscopic Black Holes

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CMS-PAS-EXO-12-009
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ADD (Arkani-Hamed, Dimopoulos, Dvali) model: n large, flat extradimensions.

New physics mass scale $\,M_D^{n+2} \propto M_{\rm Pl}^2 R^{-n}$

With M_{n} Planck scale (10¹⁹ GeV), and R size of the extra dimensions



Search strategy:

The black hole evaporates and a large amount of particles are produced

→ look for large MET, events with high jet mulitplicty, large scalar sum of E_{τ} (S_{τ} variable)

Main background: QCD multi-jet events

Search for Microscopic Black Holes

Model independent limit:

 $\sigma(S_T > S_T^{min}) \times A (pb)$ Excluded M^{min} (TeV) CMS Preliminary \sqrt{s} = 8 TeV, 3.7 fb⁻¹ CMS Preliminary \sqrt{s} = 8 TeV, 3.7 fb⁻¹ f) 6 Multiplicity, $N \ge 8$ Observed Expected $\pm 1\sigma$ n = 6 Expected $\pm 2\sigma$ 5.5 Observed, 2011 data Expected, 2011 data n = 4 n = 2 10⁻² 2012, 3.7 fb⁻¹, 8 TeV 4.5 BlackMax 10⁻³ Nonrotating ----- Rotating 2011, 4.7 fb⁻¹, 7 TeV Rotating (mass and angular momentum loss) 2.5 3 3.5 10-4 4.5 M_D (TeV) 3000 4000 1.5 2 2000 5000 4 S_{τ}^{min} (GeV)

 \rightarrow No excess observed!

Limits on BH masses for specific models:

Search for Microscopic Black Holes



Exotic Higgs Searches: Doubly-charged Higgs

CMS Search for $\Phi^{\!\pm\!\pm}\!\rightarrow$ 2I

CMS PAS HIG-12-005

In the SM : One Higgs doublet In the MSSM: Two Higgs doublets In the NMSSM: Two Higgs doublets + one singlet

Even more exotic: One Higgs triplet

Production/decay of doubly-charged Higgs:

Dilepton mass spectrum:



 \rightarrow look for same charge leptons!

CMS Preliminary $\sqrt{s} = 7$ TeV, $\int \mathcal{L}$ =4.6 fb⁻¹



Exotic Higgs Searches: Doubly-charged Higgs

 $\mathsf{BR}(\Phi^{\pm\pm} \to e^{\pm}e^{\pm}) = 100\%$ CMS Preliminary $\sqrt{s} = 7$ TeV, $\int \mathcal{L} = 4.6$ fb⁻¹



 \rightarrow No excess observed!

Search for excited electrons and muons



Is the lepton a composite particle?

⊢ Event signature: two leptons and a photon

Look for $\mathbf{q}\overline{\mathbf{q}} \rightarrow \mathbf{II}^* \rightarrow \mathbf{II}\gamma$ in ee γ and $\mu\mu\gamma$ final states

Since no signs of compositensess found previously, compositness scale Λ must be large.

 $p_{_{T}}(\gamma) > 30 \text{ GeV}$





Search for excited electrons and muons

Limits are set on the excited electron and excited muon mass as a function of the compositeness scale Λ .

Excited electron:

Excited muon:



 \rightarrow No excess observed!

Search for dark matter and extra dimenions with monojets

Graviton + mono-jet production:



Graviton is precited in models with large extra dimensions (ADD models).

Graviton cross section is then large, it is not confined to the 4D brane where the SM lives.



Wimp-pair production:



Wimp: Massive, interacting massive particle \rightarrow Dark matter candidate.

Wimps and gravitons do not interact with the detector, but leave MET.

Search for dark matter and extradimenions with monojets

arXiv:1206.5663v1

Limits on wimp-nucleon scattering cross section:

ADD mass scale parameter:



 $M_D^{n+2} \propto M_{\rm Pl}^2 R^{-n}$

Better limits than direct searches for $m_{\chi} < 3$ GeV.

Search for dark matter and extradimenions with monojets



ATLAS Exotics Searches* - 95% CL Lower Limits (Status: HCP 2012)

	Large ED (ADD) : monojet + $E_{T,miss}$	L=4.7 fb ⁻¹ , 7 TeV [1210.4491]		4.37 TeV M _D (δ=2)	
	Large ED (ADD) : monophoton + E _{T,miss}	L=4.6 fb ⁻¹ , 7 TeV [1209.4625]	1.93 TeV M	_ρ (δ=2)	ATLAS
ns	Large ED (ADD) : diphoton & dilepton, m _{yy / II}	L=4.7 fb ⁻¹ , 7 TeV [1211.1150]		4.18 TeV M_{S} (HLZ δ =3, NLO)	Broliminany
9.	UED : diphoton + E _{T,miss}	L=4.8 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-072]	1.41 TeV Compa	ct. scale R ⁻¹	Freinnary
ns	S ¹ /Z ₂ ED : dilepton, m _{il}	L=4.9-5.0 fb ⁻¹ , 7 TeV [1209.2535]		4.71 TeV M _{KK} ~ R ⁻¹	
e	RS1 : diphoton & dilepton, myr/	L=4.7-5.0 fb ⁻¹ , 7 TeV [1210.8389]	2.23 TeV	Graviton mass (k/M _{PI} = 0.1)	
i	RS1 : ZZ resonance, m	L=1.0 fb ⁻¹ , 7 TeV [1203.0718]	845 Gev Graviton mass	$(k/M_{\rm Pl} = 0.1)$	
ð	RS1 : WW resonance, m _{T,ww}	L=4.7 fb ⁻¹ , 7 TeV [1208.2880]	1.23 TeV Graviton	mass $(k/M_{\rm Pl} = 0.1)$ Lo	$dt = (1.0 - 13.0) \text{ fb}^{-1}$
(tr	RS $g_{KK} \rightarrow tt$ (BR=0.925) : $tt \rightarrow l+jets$, $m_{theoreted}$	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-136]	1.9 TeV g _{kk}	mass	
ш	ADD BH $(M_{TH}/M_D=3)$: SS dimuon, $N_{ch, part}$	L=1.3 fb ⁻¹ , 7 TeV [1111.0080]	1.25 TeV M _D (δ=6)		s = 7, 8 lev
	ADD BH $(M_{TH}/M_{D}=3)$: leptons + jets, Σp_{T}	L=1.0 fb ⁻¹ , 7 TeV [1204.4646]	1.5 TeV Μ _D (δ	=6)	
	Quantum black hole : dijet, F _v (m _{ii})	L=4.7 fb ⁻¹ , 7 TeV [1210.1718]	4	1.11 TeV $M_D(\delta=6)$	
	qqqq contact interaction : X(m)	L=4.8 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-038]		7.8 TeV A	
ō	qqll CI:ee & μμ, m_	L=4.9-5.0 fb ⁻¹ , 7 TeV [1211.1150]		13.9 TeV A	(constructive int.)
0	uutt CI : SS dilepton + jets + ET miss	L=1.0 fb ⁻¹ , 7 TeV [1202.5520]	1.7 TeV Λ		
	Z' (SSM) : m _{ed/m}	L=5.9-6.1 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-129]	2.49 TeV	Z' mass	
	Z' (SSM) : m	L=4.7 fb ⁻¹ , 7 TeV [1210.6604]	1.4 TeV Z' mass	5	
-	W' (SSM) : m _{T-1}	L=4.7 fb ⁻¹ , 7 TeV [1209.4446]	2.55 TeV	W' mass	
\geq	W' $(\rightarrow tq, q_{-}=1)$: m_{train}	/ =4.7 fb ⁻¹ .7 TeV [1209.6593]	430 GeV W' mass		
	W'_{P} (\rightarrow tb, SSM) : m_{u}	L=1.0 fb ⁻¹ , 7 TeV [1205.1016]	1 13 TeV W' mass		
	W* : m	L=4.7 fb ⁻¹ , 7 TeV [1209.4446]	2.42 TeV	W* mass	
	Scalar I O pair (B=1) kin vars in eeii evii	L=1.0 fb ⁻¹ , 7 TeV [1112.4828]	660 GeV 1 st gen. LQ mass		
Q	Scalar I Q pair $(\beta = 1)$ kin vars in uui uvi	/=1.0 fb ⁻¹ 7 TeV [1203.3172]	685 GeV 2 nd gen 1 Q mass		
	Scalar Q pair (B=1) kin vars in ttii tvii	L=4.7 fb ⁻¹ , 7 TeV [Preliminary]	538 GeV 3 rd gen I Q mass		
\$	Δ th generation : t't'→ WbWb	L=4.7 fb ⁻¹ . 7 TeV [1210.5468]	656 GeV t' mass		
ž	4^{th} generation : b'b'($T_{}T_{5/2}$) \rightarrow WtWt	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-130]	670 GeV b' (T) mass		
na	New quark b' : b' $\vec{b}^3 \rightarrow \vec{Z}b+X, m_{-}$	L=2.0 fb ⁻¹ , 7 TeV [1204.1265] 4	00 GeV b' mass		
9	Top partner : TT \rightarrow tt + A ₂ A ₂ (dilepton, M ^{2b})	L=4.7 fb ⁻¹ , 7 TeV [1209.4186]	483 GeV T mass $(m(A)) < 100 G$	ieV)	
Ň	Vector-like guark : CC. m.	L=4.6 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-137]	1 12 TeV VLQ mass	(charge -1/3, coupling $\kappa_{\infty} =$	v/m_)
Š	Vector-like quark : NC. m	/ =4.6 fb ⁻¹ 7 TeV [ATLAS-CONE-2012-137]	1.08 TeV VI Q mass	(charge 2/3, coupling $\kappa_{-n} = v$	/m_)
	Excited guarks : γ-jet resonance, m	/ =2 1 fb ⁻¹ 7 TeV [1112 3580]	2.46 TeV	d* mass	Q/
ij E	Excited quarks dijet resonance m	/=13.0 fb ⁻¹ .8 TeV [ATLAS_CONE_2012_148]	2.40 100	84 TeV 0* mass	
Щæ	Excited lepton : I-y resonance, m	/=13.0 fb ⁻¹ 8 TeV [ATLAS_CONE.2012.146]	2.2 TeV	* mass $(\Lambda = m(l^*))$	
	Techni-hadrons (LSTC) : dilepton m	1=49.50 fb ⁻¹ 7 TeV (1209 2525)	850 GeV o /w mass (m	$(\alpha / \omega) - m(\pi) = M$	
	Techni-hadrons (LSTC) : WZ resonance (vIII), m	L=4.0 m ⁻¹ 7 TeV [1203.2000]	482 GeV α mass $(m(\alpha)) = m(\pi)$	$+m_{W}(2) = 11m_{(2)}$	
-	Major noutr (LDSM, no mixing) : 2 lon + jots	1=2.1 fb ⁻¹ 7 TeV [1203.5420]	465 GEV PT Mass (m(pT) = m(nT)	$(m(W_{1}) = 2 \text{ TeV})$	
he	W_ (LRSM, no mixing) : 2-lep + jets	1 = 2.1 fb ⁻¹ 7 ToV [1203.5420]	2.4 ToV	W_{-} mass $(m(N) < 1.4 \text{ TeV})$	
đ	$H^{\pm}(DY \text{ prod} BR(H^{\pm} \rightarrow II)=1)$: SS ee (IIII) m	L=4.7 fb ⁻¹ .7 ToV [1240.5070]	09 GeV H ^{±±} mass (limit at 398 Ge	V for uu)	
0	H^{\pm} (DY prod BR($H^{\pm} \rightarrow e\mu$)=1) · SS $e\mu m^{\pm}$	L=4.7 fb ⁻¹ 7 ToV (1210.5070) 27	S Gev H ^{±±} mass	(10) μμ)	
	Color octet scalar : dijet resonance m	L=4.7 ID , 7 TeV [1210.3070] 31	A DE TAV	alar resonance mass	
	color otter scalar . ujet resonalice, m		1.86 TEV 3C		
		40-1	4	40	402
		10	1	10	10-
				M	ass scale [TeV]

Summary

- The LHC found a Higgs-like particle!!
- Apart from that, all measurements match the predictions of the Standard Model...
 But to watch out for: Enhanced H → γγ signal strength.
- Is the Higgs-like particle a SUSY Higgs? It is possible! But no direct traces of SUSY have been found.
- ATLAS and CMS look for other interesting signs of new physics, but nothing found so far