Part 4: Search for the Higgs Boson



4th July 2012 A great day for science / particle physics



Some convincing signals

$H \rightarrow \gamma\gamma$







 $H \to WW \to \ell_V \ell_V$





Updated ATLAS analysis (since 4th July) including the 2012 data

new

33



Evolution of the excess with time



35

Signal strengths in individual channels, mass estimates



Next important steps: - updated ATLAS analyses on tt and bb channels awaited - Determination of parameters of the resonance (mass, spin / CP, couplings)

Part 5: Searches for Physics Beyond the Standard Model

- Most of this will be summarized in the dedicated lecture by Meenakshi Narain
- I will conentrate on a few important SUSY results in the following



5.1 Search for Supersymmetry

 qq, qg or gg in the initial state → production of coloured SUSY particles is dominant, via strong interaction





 Drell-Yan production of sleptons, charginos and neutralinos (lower cross sections)



Cross sections for SUSY production processes



NLO corrections in QCD perturbation theory are known

Decays of heavy SUSY particles \rightarrow long and complex decay chains Invariants in R-parity conserving SUSY: jets, E_T^{miss} (2 LSPs)





An example of a search for E_T^{miss} + jets (1.04 fb⁻¹)

Selection of events with E_T^{miss} + jets

Split the analysis according to jet multiplicities: 2, 3 and 4 jets (different sensitivity for different squark/gluino mass combinations, i.e. in different regions of SUSY parameter space)

Definition of signal regions:



- Three different analyses, depending on squark / gluinos mass relations:
 - (i) dijet analysis small m₀, m(squark) < m(gluino)
 - (ii) 3-jet analysis intermediate m₀ m(squark) \approx m(gluino) $\tilde{q}\,\tilde{g} \rightarrow q\,\tilde{\chi}_1^0 q\,\bar{q}\,\tilde{\chi}_1^0$

 $\tilde{q}\,\bar{\tilde{q}} \rightarrow q\,\tilde{\chi}_1^0 \bar{q}\,\tilde{\chi}_1^0$

(iii) Gluino analysis large m₀, m(squark) > m(gluino) $\tilde{g} \, \tilde{g} \rightarrow q \, \bar{q} \, \tilde{\chi}_1^0 q \, \bar{q} \, \tilde{\chi}_1^0$



An example of a search for E_T^{miss} + jets (1.04 fb⁻¹)

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Definition of signal regions:





Summary on control of backgrounds using data (control regions, very important !!)



- A: Z + jet events, Z \rightarrow ee (to estimate Z $\rightarrow vv$ background, likewise γ + jet events were used)
- B: QCD multijet background (reverse cut on $\Delta \phi$ (jet, E_T^{miss})

- C: W \rightarrow Iv + jet control region (select events with one lepton, 30 < M_T(I,E_T^{miss}) < 100 GeV, no b-jet to suppress top contribution)
- D: top quark control region (same selection as for W events, but require b-tag)



Process	Signal Region					
FIOCESS	> 2_iet	≥ 3-jet	≥ 4-jet,	≥ 4-jet,	High mass	
	≥ 2-jet		$m_{\rm eff} > 500 { m GeV}$	$m_{\rm eff} > 1000 { m ~GeV}$	ingn mass	
Z/γ +jets	$32.5\pm2.6\pm6.8$	$25.8\pm2.6\pm4.9$	$208\pm9\pm37$	$16.2 \pm 2.1 \pm 3.6$	$3.3 \pm 1.0 \pm 1.3$	
W+jets	$26.2\pm3.9\pm6.7$	$22.7\pm3.5\pm5.8$	$367\pm30\pm126$	$12.7 \pm 2.1 \pm 4.7$	$2.2\pm0.9\pm1.2$	
tī+ Single Top	$3.4\pm1.5\pm1.6$	$5.6\pm2.0\pm2.2$	$375\pm37\pm74$	$3.7\pm1.2\pm2.0$	$5.6\pm1.7\pm2.1$	
QCD jets	$0.22 \pm 0.06 \pm 0.24$	$0.92 \pm 0.12 \pm 0.46$	$34 \pm 2 \pm 29$	$0.74 \pm 0.14 \pm 0.51$	$2.10 \pm 0.37 \pm 0.83$	
Total	$62.3 \pm 4.3 \pm 9.2$	$55\pm3.8\pm7.3$	$984 \pm 39 \pm 145$	$33.4\pm2.9\pm6.3$	$13.2\pm1.9\pm2.6$	
Data	58	59	1118	40	18	

Observed and expected event numbers (from Standard Model processes)

dominant backgrounds:

- W/Z + jets
- tt production

Normalized in control regions ! (as explained on the previous slide)









Interpretation of the results in the (m_{gluino}, m_{squark}) -plane as 95% C.L. exclusion limits in a simplified SUSY model:

- $m_{\chi} = 0$
- masses of gluinos and of 1st and 2nd generation squarks as given on plot
- all other SUSY masses are assumed to be decoupled, with masses of 5 TeV

Large area of mass combinations excluded; Limits do not apply to stop / sbottom production

mSUGRA interpretation





 $\tan \beta = 10,$ $A_0 = 0, \ \mu > 0$



mSUGRA interpretation, including 2012 data



 $\tan \beta = 10, \ A_0 = 0, \ \mu > 0$

MSSM/cMSSM interpretation (for equal squark and gluino masses):

L = 5.8 fb⁻¹ at \sqrt{s} = 8 TeV m(squark), m(gluino) > 1500 GeV

Looking for "natural" SUSY

- Search for stops and sbottoms in gluino decays
 - if other squarks are very heavy, gluino will decay into sbottoms and stops with high branching ratio
- Search for stop and sbottom pair production
 to close the loophole that the "gluino is too heavy"



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Direct Stop searches

Heavy stop > m_t : look for hadronic or leptonic top decays with extra E_T^{miss} Light stop <m_t : look for top-like decay via chargino. Signal events contain lower p_T leptons, and subsystem mass below 2m_t $m_t > m_{\bar{t}} > m_{\bar{\chi}_1^{\pm}}$





Combined stop exclusion





Is SUSY dead ?



A. Parker, ICHEP 2012, SUSY summary talk

- Under attack from all sides, but not dead yet.
- The searches leave little room for SUSY inside the reach of the existing data.
- But interpretations within SUSY models rely on many simplifying assumptions, and so care must be taken when making use of the limit plots
- Plausible "natural" scenarios still not ruled out: stop and/or RPV scenarios have few constraints.
- There is no reason to give up hope of finding SUSY at the LHC.

Summary of results on searches for Physics Beyond the Standard Model in ATLAS in ATLAS

		ATLAS Exotics Searches* - 95% CL Lower Limits (Status: ICHEP	2012)
	Large ED (ADD) : monoiet + E	$L_{A,7}$ (h^{-1}) T (h^{-1}) ($h^{$	-1
	Large ED (ADD) : monophoton + F	$L=4.7 \text{ to } , 7 \text{ tev} [\text{ATLAS-CONF-2012-084}] \qquad 3.8 \text{ tev} [M_D(0-2)] $	
	Large ED (ADD) : Monophoton $T L_{T,miss}$	$L = 4.0 \text{ fb}^{-1}$ 7 TeV [ATLAS-CONF-2012-087] 1.7 TeV [ATLAS-CONF-2012-087] 329 TeV M_{\odot} (GRW (LIf-off NLO)	ATLAS
(0)	UFD : diphoton + F_{-}	$L=4.8 \text{ th}^{-1} \text{ TeV} [ATLAS-CONF-2012-07] $ $1.41 \text{ TeV} Compact scale 1/B$	Preliminary
suc	BS1 with $k/M_{\odot} = 0.1$ diphoton m	$L = 4.9 \text{ fb}^{-1}$ 7 TeV [ATLAS-CONF-2012-087]	
nsi	BS1 with $k/M_{\odot} = 0.1$: dilepton $m_{\gamma\gamma}$	1-4 9-5 0 th ⁻¹ 7 TeV IATI AS CONF-2012-0071 2116 TeV Graviton mass	o = o = 1
neı	RS1 with $k/M_{rs1} = 0.1$; ZZ resonance, m_{rs1} and	$L=1.0 \text{ fb}^{-1}$, 7 TeV [1203.0718] 845 GeV Graviton mass	0 - 5.8) to
dii	RS1 with $k/M_{\rm ex} = 0.1$; WW resonance, $m_{\rm T}$	L=4.7 fb ⁻¹ .7 TeV IATLAS-CONF-2012-0681 1.23 TeV Graviton mass	- 7 8 TeV
dra	RS with g /g =-0.20 : tt \rightarrow l+jets, m	L=2.1 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-029] 1.03 TeV KK gluon mass	- 7,0100
ŵ	RS with BR(g \rightarrow tf)=0.925 : tt \rightarrow I+jets, m	L=2.1 fb ⁻¹ , 7 TeV [Preliminary] 1.50 TeV KK gluon mass	
	ADD BH $(M_{TH} / M_{D} = 3)$: SS dimuon, N_{ab} and	$L=1.3 \text{ tb}^{-1}$, 7 TeV [1111.0080] 1.25 TeV M_{\odot} ($\delta=6$)	
	ADD BH $(M_{TH}/M_{p}=3)$: leptons + jets, Σp_{-}	L=1.0 fb ⁻¹ , 7 TeV [1204.4646] 1.5 TeV $M_{\rm O}$ (δ =6)	
	Quantum black hole : dijet, F (m_{μ})	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-038] 4.11 TeV M_{0} (δ =6)	
	qqqq contact interaction : $\chi(m_{\mu})$	L=4.8 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-038] 7.8 TeV Λ	
C	qqll CI : ee, μμ combined, mื	L=1.1-1.2 fb ¹ , 7 TeV [1112.4462] 10.2 TeV A (constructive i	nt.)
	uutt CI : SS dilepton + jets + $E_{T miss}$	L=1.0 fb ⁻¹ , 7 TeV [1202.5520] 1.7 TeV	,
	Z' (SSM) : m _{ee/uu}	L=4.9-5.0 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-007] 2.21 TeV Z' mass	
	Z' (SSM) : m _{rr}	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-067] 1.3 TeV Z' mass	
Ň	W' (SSM) : <i>m</i> _{T.e/u}	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-086] 2.55 TeV W' mass	
	W' (\rightarrow tq, g _p =1) : m_{tq}	L=4.7 fb ⁻¹ , 7 TeV [CONF-2012-096] 350 GeV W' mass	
	$W'_{R} (\rightarrow tb, SSM) : m_{tb}$	L=1.0 fb ⁻¹ , 7 TeV [1205.1016] 1.13 TeV W' Mass	
a	Scalar LQ pairs (β =1) : kin. vars. in eejj, evjj	L=1.0 fb ⁻¹ , 7 TeV [1112.4828] 660 GeV 1 st gen. LQ mass	
L	Scalar LQ pairs (β =1) : kin. vars. in µµjj, µvjj	L=1.0 fb ⁻¹ , 7 TeV [1203.3172] 685 GeV 2 nd gen. LQ mass	
	4^{th} generation : Q $\overline{Q}_{4} \rightarrow W q W q$	L=1.0 fb ⁻¹ , 7 TeV [1202.3389] 350 GeV Q ₄ mass	
ks	4 [™] generation : u₄tī → WbWb	L=1.0 fb ⁻¹ , 7 TeV [1202.3076] 404 GeV U ₄ MASS	
Jar	$4^{"}$ generation : $d_{A}d_{A} \rightarrow WtWt$	L=1.0 fb ⁻¹ , 7 TeV [1202.6540] 480 GeV d ₄ mass	
n dı	New quark b' : bb'→Zb+X, m _{zb}	L=2.0 fb ⁻¹ , 7 TeV [1204.1265] 400 GeV b' mass	
len	$TT_{top partner} \rightarrow tt + A_0A_0 : 2 - lep + jets + E_{T,miss}(M_{T2})$	L=1.0 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-071] 483 GeV T mass ($m(A_0) < 100 \text{ GeV}$)	
<	Vector-like quark : CC, m	$\frac{L=1.0 \text{ fb}^{-1}, 7 \text{ TeV} [1112.5755]}{900 \text{ GeV}} Q \text{ mass (coupling } \kappa_{qQ} = \nu/m_Q)$	
	Vector-like quark : NC,m _{llq}	<u>L=1.0 fb⁻¹, 7 TeV [1112.5755]</u> 760 GeV Q mass (coupling $\kappa_{qQ} = \nu/m_Q$)	
rm.	Excited quarks : γ -jet resonance, m	<u>L=2.1 fb⁻¹, 7 TeV [1112.3580] 2.46 TeV q[*] mass</u>	
. fe	Excited quarks : dijet resonance, m	L=5.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-088] 3.66 TeV q* mass	
xcit	Excited electron : $e-\gamma$ resonance, m	L=4.9 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-023] 2.0 TeV e^* mass ($\Lambda = m(e^*)$)	
<u>Щ</u>	Excited muon : μ - γ resonance, $m_{\mu\gamma}$	L=4.8 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-023] 1.9 TeV μ^* mass ($\Lambda = m(\mu^*)$)	
	Techni-hadrons : dilepton, $m_{ee/\mu\mu}$	<u>L=1.1-1.2 fb⁻¹, 7 TeV [ATLAS-CONF-2011-125]</u> 470 GeV ρ_T / ω_T mass $(m(\rho_T / \omega_T) - m(\pi_T) = 100 \text{ GeV})$	
~		L=1.0 fb ⁻ , 7 TeV [1204.1648] 483 GeV $\rho_{\rm T}$ mass $(m(\rho_{\rm T}) = m(\pi_{\rm T}) + m_{\rm W}, m(a_{\rm T}) = 1.1 m(\rho_{\rm T}))$	
the	Major. neutr. (LRSM, no mixing) : 2-lep + jets	$5 L=2.1 \text{ fb}^{-7}, 7 \text{ Tev} [1203.5420] 1.5 \text{ Tev} \text{ N mass} (m(W_R) = 2 \text{ lev})$	
0	W _R (LKSM, no mixing) : 2-lep + jets	$L=2.1 \text{ fb}', 7 \text{ TeV} [1203.5420] 2.4 \text{ TeV} W_R \text{ mass} (m(N) < 1.4 \text{ GeV})$	
	Γ_{L} (D) prod., $D \cap (\Gamma_{L} \rightarrow \mu\mu) = 1$. 35 diffuori, $m_{\mu\mu}$	L=1.6 fb , 7 TeV [1201.1091] 355 GeV H_ mass	
	Color octet scalar . ujet resonance, mji	1.94 TEV [ATLAS-GUNF-2012-038] 1.94 TEV Scalar resonance mass	
		10^{-1} 1 10	10
*Onl	v a selection of the available mass limits on new states or	nr phenomena shown Mass s	cale[leV]

Summary of the lectures

- After a long way of design, construction, installation, commissioning of both machine and experiments the LHC had an excellent start in 2010
- The performance of the accelerator and the experiments is superb; (In 2012: an integrated luminosity > 12 fb⁻¹ already)
- The Standard Model has been established, all relevant processes measured; In many areas measurements have reached the precision phase
- A new boson has been discovered with a mass around 125/126 GeV; Exiting analyses ahead of us to understand the nature of this new particle
- So far: no deviations from the Standard Model seen, but the LHC potential has by far not yet been fully exploited !

End of lectures





$$\begin{aligned} \mathcal{L}_{\mathrm{TGC}} &= ieg_{1}^{\gamma} (A_{\mu}(\partial_{\mu}W_{-\nu}(\partial_{\nu}W_{-\mu})W_{+\nu} - A_{\mu}(\partial^{\mu}W^{+\nu} - \partial^{\nu}W^{+\mu})W_{-\nu}) \\ &+ ie\kappa_{\gamma}(\partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu})W^{+\mu}W^{-\nu} \\ &+ ie\cot\theta_{W}g_{1}^{Z}Z_{\mu}(\partial_{\mu}W_{-\nu} - \partial_{\nu}W_{-\mu})W_{\nu}^{+} - Z_{\mu}(\partial^{\mu}W^{+\nu} - \partial^{\nu}W^{+\mu})W_{\nu}^{-}) \\ &+ ie\cot\theta_{W}\kappa_{Z}(\partial_{\mu}Z_{\nu} - \partial_{\nu}Z_{\mu})W^{+\mu}W^{-\nu} \\ &+ ie\frac{\lambda_{\gamma}}{M_{W}^{2}}((\partial_{\mu}A_{\rho} - \partial_{\rho}A_{\mu})(\partial^{\rho}W^{+\nu} - \partial_{\nu}W^{+\rho})(\partial_{\nu}W^{-\mu} - \partial_{\mu}W^{-\nu})) \\ &+ ie\cot\theta_{W}\frac{\lambda_{Z}}{M_{W}^{2}}((\partial_{\mu}Z_{\rho} - \partial_{\rho}Z_{\mu})(\partial^{\rho}W^{+\nu} - \partial_{\nu}W^{+\rho})(\partial_{\nu}W^{-\mu} - \partial_{\mu}W^{-\nu})) \end{aligned}$$