### Supersymmetry

A phenomenological Introduction

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"One day, all of these will be supersymmetric phenomenology papers."

## Some words about Renormalization

### Renormalization

- eliminate things which act on a scale irrelevant to the question (fast degrees of freedom)
  - $\Rightarrow$  effective description
- e.g. in molecular physics: no physics of quarks

#### **Dimensional Analysis**

• Three important parameters in P.P.: Energy, Length, Time

• By setting 
$$\hbar = c = 1$$
 we get:  
 $[m] = [E] = [P] = \frac{1}{[I]} = \frac{1}{[m]} = \frac{1}{[length]}$ 

## Scalar Quantum Field Theory

### A scalar Field $\Phi$

$$\mathscr{L} = (\partial_{\mu}\Phi)^{2} + V(\Phi)$$
, Dimension of  $\Phi$ ?  
Quantity of interest: action  $S = \int \mathscr{L} d^{4}x$   
 $[S] = 1 \Rightarrow [\mathscr{L}] = [I]^{-4} \Rightarrow [\Phi] = [I]^{-1}$ 

#### Concept of Propagators



### Renormalization of mass



Other processes that contribute to -----:

$$\frac{\lambda}{|x-y|^2} \propto \frac{\lambda}{\delta^2}$$
$$\frac{\lambda}{\delta^2}$$
$$\frac{\lambda^2}{\delta^2} = \frac{\lambda^2}{\delta^2}$$

### Renormalization of mass

$$\Rightarrow m_{exp}^2 \propto m_0^2 + rac{\lambda}{\delta^2} + rac{\lambda^2}{\delta^2} + \cdots$$

• In SM: Higgs-Boson parameter *m<sub>exp</sub>* is of order 100 GeV

Scale at which SM breaks (probably) down: Plank length I<sub>P</sub>

$$I_P=\sqrt{rac{\hbar G}{c^3}}\simeq 1.6 imes 10^{-35}$$
m; often used as Cut-off parameter A

- unpleasant Fine-Tuning necessary (over 34 digits):
   bare mass m<sub>0</sub> has to compensate the radiative corrections
- Hierarchy problem of the contributions to the Higgs mass

### Renormalization of mass for Fermions and Bosons

Mass term for Fermions:  $\mathscr{L} \propto m \bar{\Psi} \Psi$  L —  $\star$  R

further contributions have also to flip Helicity  $R \xrightarrow{} R \xrightarrow{} R$ 

$$\Rightarrow m_{exp} = m_0 + e^2 m_0 + e^4 m_0 + \cdots$$

Corrections are small and not dependent on a scale same observation holds for Bosons ⇒ Chiral Symmetry acts as protection mechanism

## Similar for (scalar) Higgs-Boson possible?



- Yes, just add symmetry that links fermions to bosons and vv
- Cancellation of the loops due to their different statistics
- Assumption: except Spin, all quantum numbers are equal
   ⇒ Supersymmetry (SUSY)

## Short Repetition of Symmetries in Physics

### continuous Symmetries

- lead to a conserved quantity via the Noether theorem
- time invariance  $\Leftrightarrow$  energy conservation
- spatial invariance ⇔ momentum conservation
- rotation invariance ⇔ angular momentum conservation
- gauge invariance ⇔ conservation of electric charge

### discrete Symmetries

- describe non continuous changes of a system
- time reversal
- spatial inversion (parity)
- charge conjugation

## **SUSY Basics**

#### Lorentz and Poincare groups

• Lorentz group contains rotations and boosts:

$$[J_i, J_j] = i\epsilon_{ijk}J_k, \quad [K_i, K_j] = -i\epsilon_{ijk}J_k, \quad [J_i, K_j] = i\epsilon_{ijk}K_j$$

• Poincare enlarges Lorentz group by adding translations:

$$[P_{\mu}, P_{\nu}] = 0, [J_i, P_j] = i\epsilon_{ijk}P_k, [J_i, P_0] = 0, [K_i, P_{j/0}] = -iP_{0/j},$$

#### Coleman-Mandula theorem

- How to extend space-time symmetries beyond Poincare group?
- Theorem: Symmetry group G ≃ Poincare group × internal symmetries; think of a symmetry V then [V, H] = 0
- Loophole: Use of anticommutators

## The Supersymmetry algebra (schematic)

### Supercharges Q and $Q^{\dagger}$

• Relate boson- and fermionic states by a supersymmetry transformation:

 $Q | Fermion 
angle = | Boson 
angle, \quad Q | Boson 
angle = | Fermion 
angle$ 

- $\bullet\,$  That means Q shifts the spin of the particle by 1/2:  $Q\,|J\rangle = |J\pm 1/2\rangle$
- Implementation by a set of (anti)commutators:  $\left\{Q_{\alpha}, Q_{\dot{\alpha}}^{\dagger}\right\} = -2\sigma_{\alpha\dot{\alpha}}^{\mu}P_{\mu}, \quad \left\{Q_{\alpha}, Q_{\beta}\right\} = \left\{Q_{\dot{\alpha}}^{\dagger}, Q_{\dot{\beta}}^{\dagger}\right\} = 0, \text{ and } \left[P^{\mu}, Q_{\alpha}\right] = \left[P^{\mu}, Q_{\dot{\alpha}}^{\dagger}\right]$

• Now: Superspace  $(x^{\mu}, \theta_{\alpha}, \bar{\theta}_{\dot{\alpha}})$ , Superfields

• Grassmann coordinate  $\theta$ :  $x^2 = 0 \Leftrightarrow x = \theta$ 

## The Supersymmetric Lagrangians

#### massless, non-interacting Wess-Zumino model

• Weyl fermion  $\psi$ , complex scalar field  $\phi$ 

• 
$$\mathscr{L} = \partial_{\mu} \Phi^* \partial^{\mu} \Phi + i \psi^{\dagger} \bar{\tau}^{\mu} \partial_{\mu} \psi$$

• implement infinitesimal transformation by

$$\delta\phi = \epsilon\psi \quad \delta\phi^* = \epsilon^{\dagger}\psi^{\dagger} \quad \delta\psi_{\alpha} = -i(\sigma^{\mu}\epsilon^{\dagger})_{\alpha}\partial_{\mu}\phi \quad \delta\psi^{\dagger}_{\dot{\alpha}} = i(\epsilon\sigma^{\mu})_{\dot{\alpha}}\partial_{\mu}\phi^*$$

• this leads the action invariant under a transformation:

$$\delta S = \int d^4 x (\delta \mathscr{L}_{fermion} + \delta \mathscr{L}_{scalar}) = 0$$

#### Interactions

- add interaction terms with auxiliary fields
- Choice of Superpotential W basically sets up the model of SUSY

# The Minimal Supersymmetric Standard Model (MSSM)

### Higgs doublets

- In order to give mass to all matter, 2 Higgs doublets with different hypercharge Y are needed
- doublets couple by a term  $\mu \bar{H} H$  in W
  - $\Rightarrow$  2 vacuum expectation values  $v_u, v_d$

• paramater 
$$\tan\beta:=rac{v_u}{_d}$$
, with  $v^2=v_u^2+v_d^2=rac{1}{\sqrt{2}G_F}pprox(246{
m GeV})^2$ 

### Supermultiplets

• Particles are arranged in 3 Supermultiplets:

chiral 
$$\begin{pmatrix} \frac{1}{2} \\ 0 \end{pmatrix}$$
 gauge  $\begin{pmatrix} 1 \\ \frac{1}{2} \end{pmatrix}$  gravitation  $\begin{pmatrix} 2 \\ \frac{3}{2} \end{pmatrix}$ 

• In unbroken SUSY the superpartners have same quantum numbers as their counterparts in the SM

## Particle Content of the MSSM

#### General

- 2 scalar Higgs doublets: 8 3 = 5 dof which result in  $h^0, H^0, A^0, H^{\pm}$
- SUSY fermions mix to 2 chargino pairs  $\chi_1^{\pm} \chi_2^{\pm}$ and 4 neutralinos  $\chi_1^0 \chi_2^0 \chi_3^0 \chi_4^0$



## **R-Parity**

### A New Quantum Number

- Superpotential of the MSSM is not unique
- could be extended by terms that violate baryon (B) or lepton number (L) conservation
- $\bullet$  Decay of proton would be possible in theory (lifetime  $> 2 \times 10^{29}$  years)

 $\Rightarrow$  new quantum number:  $R = (-)^{3B+L+2s}$  with spin s

Consequences:

R = 1 for particles and R = (-1) for sparticles

The lightest sparticle (LSP) is stable

 $\Rightarrow$  if uncharged, candidate for Dark Matter

In accelerator experiments sparticles are produced in pairs

## SUSY breaking

### Need for a broken Symmetry

- No detection of superpartners with same mass :  $m_f < m_{ ilde{f}}$ 
  - $\Rightarrow$  Introduction of symmetry breaking:  $\mathscr{L} = \mathscr{L}_{SUSY} + \mathscr{L}_{soft}$
- Additional 106 parameters (to the 18 of the SM)

### Mechanism of SUSY breaking

- The mechanism is not known
- shifted to a hidden sector
- Weakness of the MSSM



## Mechanisms for breaking

### Gravity mediated (SUGRA)

- spontanous symmetrybreaking of a local SUSY
  - $\Rightarrow$  emerging massles Goldstino is absorbed by Gravitino  $ilde{G}$
- very heavy  $\tilde{G}$  sets the mass scale for sparticles
- Neutralino is the LSP

### Gauge mediated (GMSB)

- mediation by gauge bosons and fields of the SM
  - $\Rightarrow \tilde{G}$  will get very light

Gravitino is the LSP

 $\Rightarrow$  Mass scale of SUSY particles depends on breaking mechanism

## Experimental Search for SUSY — Approaches

### Top-down

- choose model of SUSY breaking
- Assume GUT scale parameters:
  - $m_0, m_{\frac{1}{2}}$ : scalar & gaugino mass
  - $A_0$ : trilinear Higgs- $\tilde{f}$ - $\tilde{f}$  coupling
  - $\tan \beta$ : ratio of Higgs vev
  - sign $(\mu)$ : sign of Higgs parameter



### Bottom-up

- Assume mass for SUSY particles
- Simplified models



## Experimental Search for SUSY at LHC

### General considerations

- SUSY phenomenology varies highly within parameter space
  - $\Rightarrow$  search based on very general signatures
- proton-proton collisions produce gluinos and squarks
- decay cascades lead to high  $p_T$  jets and leptons
- If R-parity is conserved: stable LSP's
  - $\Rightarrow$  high missing transverse Energy  $\not\!\!\! {\cal E}_{\cal T}$



## **Dilepton Searches**

### Simplifying Assumptions

- Neutralino  $\tilde{\chi}_1^{\rm 0}$  is the LSP
- SUSY particles decay promptly
- electroweak production of  $\tilde{\chi}_1^+\tilde{\chi}_1^-$
- only one s channel considered:

 $q\bar{q} \rightarrow Z/\gamma \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$ 

- $\sigma$  shrinks with increasing mass
- final-state leptons:

same flavour(SF):  $e^+e^-$  or  $\mu^+\mu^$ different flavour(DF):  $e^{\pm}\mu^{\mp}$ 

• same BR for every generation



## **Dilepton Searches**

#### Background

- Background: whole SM
- dominant BG processes:  $t\bar{t}$ , single top and diboson production
- estimated with Monte-Carlo Simulations

### Signal

- Event selection: 2 OS signal leptons are required
- Signal region(SR): Require high  $m_{T2}$ -mass:

$$m_{T2} \equiv \min_{\mathbf{p}_{1}'+\mathbf{p}_{2}'=\mathbf{p}_{T}'} \left[ \max\{m_{T}^{2}(\mathbf{p}_{TI'},\mathbf{p}_{1}'), m_{T}^{2}(\mathbf{p}_{TI'},\mathbf{p}_{2}')\} \right]$$

- 3 SR that require  $m_{T2}$  > 90 GeV, 120 GeV, 150 GeV, respectively
- in SF: invariant mass  $m_{II}$  must be at least 10 GeV away from Z-mass

### Results I — Comparison with SM



### Results II — Exclusions



 $\Rightarrow \tilde{\chi}_1^{\pm}$ -masses between 140 GeV and 465 GeV are excluded at 95% CL

### Results III — Overall SUSY reach summary

#### ATLAS SUSY Searches\* - 95% CL Lower Limits

Status: Moriond 2014

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ATLAS Preliminary
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 $\int \mathcal{L} dt = (4.6 - 22.9) \text{ fb}^{-1}$   $\sqrt{s} = 7, 8 \text{ TeV}$ 

		Model	$e, \mu, \tau, \gamma$	Jets	$E_{\rm T}^{\rm miss}$	∫£ dt[fl	-1) Mass limit	Reference
	Inclusive Searches	$ \begin{split} & MSUSDRACMSSM \\ & MSUSDRACMSSM \\ & MSUSDRACMSSM \\ & MSUSDRACMSSM \\ & \tilde{g}_{11}^{-1} \rightarrow q_{11}^{-1} \\ & \tilde{g}_{12}^{-1} \rightarrow q_{11}^{-1} \\ & \tilde{g}_{22}^{-1} \rightarrow q_{11}^{-1} \qquad \\ & \tilde{g}_{22}^{-1} \rightarrow q_{11}^{-1} + g_{12}^{-1} \\ & \tilde{g}_{22}^{-1} \rightarrow q_{11}^{-1} + g_{12}^{-1} \\ & \tilde{g}_{22}^{-1} \rightarrow q_{12}^{-1} + g_{12}^{-1} \\ & \tilde{g}_{22}^{-1} \rightarrow q_{22}^{-1} + g_{12}^{-1} + g_{12}^{-1} \\ & \tilde{g}_{22}^{-1} \rightarrow q_{22}^{-1} + g_{22}^{-1} + g_{22}^{-1} \\ & \tilde{g}_{22}^{-1} \rightarrow q_{22}^{-1} + g_{22}^{-1} + g_{22}^{-1} \\ & \tilde{g}_{22}^{-1} \rightarrow q_{22}^{-1} + g_{22}^{-1} + g_{22}^{-1} \\ & \tilde{g}_{22}^{-1} \rightarrow q_{22}^{-1} + g_{22}^{-1} + g_{22}^{-1} + g_{22}^{-1} \\ & \tilde{g}_{22}^{-1} \rightarrow q_{22}^{-1} + g_{22}^{-1} + g_{22}^{-1} + g_{22}^{-1} \\ & \tilde{g}_{22}^{-1} \rightarrow q_{22}^{-1} + g_{22}^{-1} + g_{22}^{-1} + g_{22}^{-1} + g_{22}^{-1} \\ & \tilde{g}_{22}^{-1} \rightarrow q_{22}^{-1} + g_{22}^{-1} + g_{22}^{-1} + g_{22}^{-1} + g_{22}^{-1} \\ & \tilde{g}_{22}^{-1} \rightarrow g_{22}^{-1} + g_{22}^{-1} + g_{22}^{-1} + g_{22}^{-1} + g_{22}^{-1} \\ & \tilde{g}_{22}^{-1} \rightarrow g_{22}^{-1} + g_{22}^{-1} + g_{22}^{-1} + g_{22}^{-1} + g_{22}^{-1} \\ & \tilde{g}_{22}^{-1} \rightarrow g_{22}^{-1} + g_{22}^{-1} + g_{22}^{-1} + g_{22}^{-1} + g_{22}^{-1} \\ & \tilde{g}_{22}^{-1} \rightarrow g_{22}^{-1} + g_{22}^{-1} + g_{22}^{-1} + g_{22}^{-1} + g_{22}^{-1} + g_{22}^{-1} \\ & \tilde{g}_{22}^{-1} \rightarrow g_{22}^{-1} + $	$\begin{array}{c} 0 \\ 1  e, \mu \\ 0 \\ 0 \\ 1  e, \mu \\ 2  e, \mu \\ 1 \cdot 2  \tau \\ 2  \gamma \\ 1  e, \mu + \gamma \\ \gamma \\ 2  e, \mu (Z) \\ 0 \end{array}$	2-6 jets 3-6 jets 7-10 jets 2-6 jets 3-6 jets 3-6 jets 0-3 jets 0-3 jets mono-jet	Yes Yes Yes Yes Yes Yes Yes Yes Yes Yes	20.3 20.3 20.3 20.3 20.3 20.3 20.3 20.3	54 5760 (1994) 5 (1994) 6 (1994) 6 (1994) 6 (1994) 7 (1994)	RTLAS-CONF-2013-047 RTLAS-CONF-2013-062 1308:1841 RTLAS-CONF-2013-047 RTLAS-CONF-2013-047 RTLAS-CONF-2013-062 1208.4688 RTLAS-CONF-2012-014-001 RTLAS-CONF-2012-144 1211.1167 RTLAS-CONF-2012-147 RTLAS-CONF-2012-147
100	g med.	$\tilde{s} \rightarrow b \tilde{b} \tilde{\chi}_1^0$ $\tilde{s} \rightarrow b \tilde{\chi}_1^0$ $\tilde{s} \rightarrow b \tilde{\chi}_1^-$ $\tilde{s} \rightarrow b \tilde{\chi}_1^+$	0 0 0-1 e,µ 0-1 e,µ	3 b 7-10 jets 3 b 3 b	Yes Yes Yes Yes	20.1 20.3 20.1 20.1	2 1.2 TeV m( <sup>2</sup> ), 450 GeV 2 11 TeV m( <sup>2</sup> ), 430 GeV 2 13 TeV m( <sup>2</sup> ), 430 GeV 4 13 TeV m( <sup>2</sup> ), 430 GeV 5 13 TeV m( <sup>2</sup> ), 430 GeV	ATLAS-CONF-2013-061 1308-1841 ATLAS-CONF-2013-061 ATLAS-CONF-2013-061
	3" gen. squarks direct production	$\begin{array}{l} b_1 b_1, \ b_1 \rightarrow b k_1^{(2)} \\ b_1 b_1, \ b_1 \rightarrow b k_1^{(2)} \\ b_1 b_1, \ b_1 \rightarrow b k_1^{(2)} \\ f_1 (lght), \ f_1 \rightarrow b k_1^{(2)} \\ f_1 f_1 (lght), \ f_1 \rightarrow b k_1 \\ f_1 f_1 (modum), \ f_1 \rightarrow b k_1 \\$	0 2 e, µ (SS) 1-2 e, µ 2 e, µ 0 1 e, µ 0 0 m 2 e, µ (Z) 3 e, µ (Z)	2 b 0-3 b 1-2 b 0-2 jets 2 b 1 b 2 b 1 c 1 b 2 b 1 c 1 b 1 b 1 b 1 b	Yes Yes Yes Yes Yes Yes Yes tag Yes Yes Yes	20.1 20.7 4.7 20.3 20.3 20.1 20.7 20.5 20.3 20.3 20.3	λ         196435 GeV         m( <sup>2</sup> )/sec0           λ         101870 GeV         m( <sup>2</sup> )/sec0           λ         101870 GeV         m( <sup>2</sup> )/sec0           λ         102810 GeV         m( <sup>2</sup> )/sec0           λ         102810 GeV         m( <sup>2</sup> )/sec0           λ         103800 GeV         m( <sup>2</sup> )/sec0           λ         105800 GeV         m( <sup>2</sup> )/sec0           λ         105800 GeV         m( <sup>2</sup> )/sec0           λ         305800 GeV         m( <sup>2</sup> )/sec0	1308.2631 RTLAS-CONF-2013.007 1208.4305, 1209.2102 1403.4653 1403.4653 1308.2631 RTLAS-CONF-2013.027 RTLAS-CONF-2013.024 RTLAS-CONF-2013.068 1403.5222
	direct	$\begin{array}{c} \tilde{t}_{\underline{i},\underline{k}}\tilde{t}_{\underline{i},\underline{k}},\tilde{t} \rightarrow \tilde{t}\tilde{t}(\tilde{r}) \\ \tilde{\chi}_{1}^{*}\tilde{\chi}_{1}^{*},\tilde{\chi}_{1}^{*} \rightarrow \tilde{t}r(\tilde{r}) \\ \tilde{\chi}_{1}^{*}\tilde{\chi}_{1}^{*},\tilde{\chi}_{1}^{*} \rightarrow \tilde{t}r(\tilde{r}) \\ \tilde{\chi}_{1}^{*}\tilde{\chi}_{2}^{*} \rightarrow \tilde{t}_{1}\tilde{\tau}(\tilde{r}) \\ \tilde{\chi}_{1}^{*}\tilde{\chi}_{2}^{*} \rightarrow \tilde{W}_{1}\tilde{t}(\tilde{r}) \\ \end{array}$	2 e, µ 2 e, µ 2 τ 3 e, µ 2 3 e, µ 1 e, µ	0 0 0 0 2 b	Yes Yes Yes Yes Yes	20.3 20.3 20.7 20.3 20.3 20.3	1 19333 GAV ロビー (1) - (1) - (2) -	1403.5294 1403.5294 ATLAS-CONF-2013-028 1402.7029 1403.5294, 1402.7029 ATLAS-CONF-2013-093
	parficies	Direct $\tilde{\chi}_{1}^{+}\tilde{\chi}_{1}^{-}$ prod., long-lived $\tilde{\chi}_{1}^{+}$ Stable, stopped $\tilde{g}$ R-hadron GMSB, stable $\tilde{\tau}, \tilde{\chi}_{1}^{0} \rightarrow \tilde{\tau}(\tilde{e}, \tilde{\mu}) + \tilde{\tau}(e, GMSB, \tilde{\chi}_{1}^{-} \rightarrow \gamma \tilde{G}, \log - \tilde{v}ed \tilde{\chi}_{1}^{-}$ $\tilde{q}\tilde{q}, \tilde{\chi}_{1}^{-} \rightarrow qgr$ (RPV)	Disapp. trk 0 (µ) 1.2 µ 2 γ 1 µ, displ. vb	1 jet 1-5 jets	Yes Yes Yes	20.3 22.9 15.9 4.7 20.3	1         270 GeV         m( <sup>2</sup> / <sub>1</sub> ) +m( <sup>2</sup> / <sub>1</sub> ) +160 MeV, π( <sup>2</sup> / <sub>1</sub> ) +0.2 m           8	ATLAS-CONF-2013-069 ATLAS-CONF-2013-057 ATLAS-CONF-2013-058 1304.8310 ATLAS-CONF-2013-092
	ЧЧ	$\begin{array}{l} LFV p_{P} {\rightarrow} \tilde{v}_{\tau} + X, \tilde{v}_{\tau} {\rightarrow} e + \mu \\ LFV p_{P} {\rightarrow} \tilde{v}_{\tau} + X, \tilde{v}_{\tau} {\rightarrow} e(\mu) + \tau \\ Blinear RPV CMSSM \\ \tilde{\lambda}_{11}^{+} \tilde{\lambda}_{11}^{-}, \tilde{\lambda}_{11}^{+} {\rightarrow} W \tilde{\lambda}_{11}^{0} \tilde{\lambda}_{11}^{0} {\rightarrow} e \tilde{v}_{\mu}, e \mu \tilde{v}_{\tau} \\ \tilde{\lambda}_{11}^{+} \tilde{\lambda}_{11}^{-}, \tilde{\lambda}_{11}^{+} {\rightarrow} W \tilde{\lambda}_{11}^{-} \tilde{\lambda}_{11}^{+} {\rightarrow} \tau \tau \tilde{v}_{\tau}, e \tau \tilde{v}_{\tau} \\ \tilde{g} {\rightarrow} \eta q \\ \tilde{g} {\rightarrow} \eta t, t_{1} {\rightarrow} bs \end{array}$	$\begin{array}{c} 2e,\mu\\ 1e,\mu+\tau\\ 1e,\mu\\ 4e,\mu\\ 3e,\mu+\tau\\ 0\\ 2e,\mu(\mathrm{SS}) \end{array}$	7 jets 6-7 jets 0-3 b	' Yes Yes Yes ' Yes	4.6 4.6 20.7 20.7 20.3 20.7	Test Test Test Test Test Test Test Test	1212.1272 1212.1272 RTLAS-CONF-2012-140 RTLAS-CONF-2013-036 RTLAS-CONF-2013-031 RTLAS-CONF-2013-037 RTLAS-CONF-2013-007
	Other	Scalar gluon pair, sgluon $\rightarrow q\bar{q}$ Scalar gluon pair, sgluon $\rightarrow d$ WIMP interaction (D5, Dirac $\chi$ )	2 e, µ (SS) 0	4 jets 2 b mono-jet	Yes Yes	4.6 14.3 10.5	splann 100-287 GeV incl. limt from 1110-2803 splann 350-800 GeV incl. limt from 1110-2803 Mr seale 774 GeV m(t)-580 GeV, limt of-687 GeV for DB	1210.4826 ATLAS-CONF-2013-051 ATLAS-CONF-2012-147
		$\sqrt{s} = 7 \text{ TeV}$ full data	$\sqrt{s} = 8$ TeV artial data	$\sqrt{s} = full$	8 TeV data		10 <sup>-1</sup> 1 Mass scale [TeV]	

\*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1 or theoretical signal cross section uncertainty.