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Searches for new physics at the LHC: some frustration, but no despair...

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Bundesministerium für Bildung und Forschung

- Summary of beyond the Standard Model searches at the LHC
- Global fits of constrained supersymmetric models
- Where could supersymmetry hide?
- ► Bosonic supersymmetry? Searches for models with extra dimensions
- Summary and conclusions

Summary of BSM searches at the LHC: limits, limits and more limits...



Summary of BSM searches at the LHC: no indications for new physics

	AILAS SUS	Searches [*] - 95% CL Lower Limits (Status:	: Dec 2012)	
NOTOR CONCOL AND TO T				
MSUGRA/CMSSM: 0 lep + j S + E _{T,miss}	L=5.8 fb ', 8 TeV [ATLAS-CONF-2012-109]	1.50 TeV q = g mass		
Dhene model + 0 lep + 1's + E _{T,miss}	L=5.816 ', 8 TeV [ATLAS-CONF-2012-104]	1.24 TeV y=y mass	ATI AS	
Pheno model : 0 lop + i's + E _{T,miss}	L=5.816 , 8 TeV (ATLAS-CONF-2012-109)	1.18 lev grilass (m(q) < 2 lev, light y)	Preliminary	
6 Object and 1 G of the time of the times	LESSIB, STEV [ATLAS-CONF-2012-103]	1.38 lev q ma33 (mg < 2 lev, light z)	-h -m	
Gluino med. χ (g→qqχ). T lep + js + E _{T,miss}	LT4.7 ID , 7 TeV [1200.4000]	900 Gev g mass (mg,) < 200 Gev, mg,) = 2(m	(X)+m(g))	
6 GMSB (I NLSP) : 2 IEP (US) + JS + E GMSP (F NI SP) : 1.2 r + 0.1 Iop + ie + E ^T miss	L=4.715 . 7 TeV [1208.4688]	1.24 lev gillass (tan) < 15)		
GGM (bino NI SP) $\gamma y + F^{T,miss}$	Line, 7 ID , 7 IEV [1210.1314]	1.20 lev g mass (amp > 20)	fun an innert	
GGM (wino NI SP) : v + lep + F ^{T,miss}	L 14.0 ID . 7 TeV [1203.0703]	(mg,) > 50 GeV)	$Lat = (2.1 - 13.0) \text{ fb}^{-1}$	
\leq GGM (higgsing-bing NLSP) $\gamma + b + F^{T,miss}$	1 - 4 9 (b ⁻¹ 7 Tay (1931) 1167)	900 GeV 0 mass (m ⁶⁴) = 220 GeV)	€ - 7 8 TeV	
GGM (biggsing NI SP) : 7 + jets + F	1-5 9 (b ⁻¹ 9 TeV (AT) AS CONE 2012 (51)	600 Golf (mu) - 200 Golf	13 = 7,0100	
Gravitino I SP : 'monoiet' + F	L=10.5 (b) ¹ 8 TeV (ATLAS-CONF-2012-152)	ESC GEV G1/2 SCale (m(R) > 200 GEV)		
	1-12 C 1-12 C 1-12 C 1-12 C 12 C 12 C 12	((a) 200 c ((a) a) 226 m (a) Vat 45 t		
<pre>0 g-bb/ (virtual) : 0 lop + 3 b-j s + E_T,miss 0 dt vitroit (virtual) : 2 lop (SS) + i'e + E</pre>	1=58 (b ⁻¹ 8 TeV (AT) AS(CONE)2012(105)	850 GeV 0 mass (m(x)) < 300 GeV)		
$g \rightarrow u_{T}$ (virtual t) : 2 lop (33) + 1 s + $E_{T,miss}$	1-12 0 10 ⁻¹ 9 Toy (ATL AS CONE 1012 101)	(100 000 ((((((((((((((((8 TeV results	
5 g the (virtual) - 0 loo + multi-re + E	1-5 9 10 ⁻¹ 9 TAV (AT) AS CONE 2012 (201		77.11	
a stra (virtualt) : 0 lop + 2 bits + E	I=12.8 (b) ¹ .8 TeV (AT) AS(CONE/2012/145)	1 15 TeV 0 mass (m(x) < 200 GeV)	7 lev results	
bb b ship 0 lop + 2 b lots + E miss	1-12 C 10 ⁻¹ S TAV (ATL AS CONE 1012-105)	520 GeV b mass (m/c) = 120 GeV)		
S bb b strat : 3 lon + i'e + E	I=13.0 Pt ⁻¹ 8 TeV (ATLAS-CONE-2012-151)	$mass (m(\tilde{x}) = 2m(\tilde{x}))$		
\overline{t} (light) $\overline{t} \rightarrow b\overline{x}^{\pm}$ 1/2 lep (+ b-iet) + F	1-47 (b ⁻¹ 7 TeV (1208 4305 1209 2102167 G	t mass (m(x)) = 55 GeV)		
\tilde{t} (medium) $\tilde{t} \rightarrow b \bar{y}^{\pm}$ 1 lep + b-iet + F_{\pm}	(=13.0 m)1 8 TeV (ATI AS-CONE-2012-186)	160-350 GeV T MASS (m(x)) = 0 GeV m(x)) = 150 GeV)		
S tt (medium), t→by [±] : 2 lep + E.	L=13.0 fb ⁻¹ . 8 TeV [ATLAS-CONF-2012-167]	160-440 GeV \tilde{t} mass $(m(\tilde{y}^{0}) = 0 \text{ GeV}, m(\tilde{t}) \cdot m(\tilde{y}^{0}) = 10 \text{ GeV})$		
6 5 ft t→ty 1 len + h-iet + F	1-13.0 (b)1 & TeV (AT) AS-CONE-2012-1661	230-560 GeV T MASS (m(x) = 0)		
\overline{ft} $\overline{t} \rightarrow t \overline{v}^0 \cdot 0/1/2 \text{ lep } (+ \text{ b-iets}) + F$	L=4.7 fb ⁻¹ , 7 TeV [1208.1447.1208.2590.1209.	1861 230-465 GeV T mass (m(7) = 0)		
tt (natural GMSB) : Z(→II) + b-jet + E	L=2.1 fb ⁻¹ , 7 TeV [1204.6736]	310 GeV t mass (115 < m(x ²) < 230 GeV)		
$[1, 1 \rightarrow]\overline{\gamma}^0$: 2 lep + $E_{\tau}^{T,miss}$	L=4.7 fb ⁻¹ , 7 TeV [1208.2884] 85-19	GeV mass $(m(\tilde{y}^0) = 0)$		
$\geq \tilde{0}$ $\tilde{\gamma}^* \tilde{\gamma} \cdot \tilde{\gamma}^* \rightarrow \tilde{1} v (\tilde{V}) \rightarrow l v \tilde{\gamma}^0 : 2 lep + E_{\tau}$	L=4.7 fb ⁻¹ , 7 TeV [1208.2884]	110-340 GeV $\tilde{\chi}^{\pm}$ Mass $(m(\tilde{\chi}^{0}) < 10 \text{ GeV}, m(\tilde{\chi}) = \frac{1}{2}(m(\tilde{\chi}^{\pm}) + m(\tilde{\chi}^{0})))$		
$\overline{\chi}^{\pm}$ $\overline{\chi}^{\pm}$ $\overline{\chi}^{\pm}$ \rightarrow \overline{I} $\overline{\chi}^{I}$ \overline{I} $(\overline{\chi} \nu)$, $ \overline{\nu} $ $ (\overline{\chi} \nu)$: 3 lep + E_{-}	L=13.0 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-154]	580 GeV $\overline{\chi}^{\pm}$ mass $(m(\overline{\chi}^{\pm}) = m(\overline{\chi}^{0}), m(\overline{\chi}^{0}) = 0, m(\overline{\chi})$ as a	(bove)	
$\tilde{\chi}_{\chi}^{\pm 0} \rightarrow W^* \tilde{\chi}_{\chi}^{0} \tilde{Z}_{\chi}^{+ 0}$: 3 lep + $E_{T,min}$	L=13.0 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-154]	140-295 GeV χ_{\pm}^{\pm} mass $(m(\chi_{\pm}) = m(\chi_{\pm}), m(\chi_{\pm}) = 0$, sleptons decoupled)		
 Direct y pair prod. (AMSB) : long-lived y 	L=4.7 fb ⁻¹ , 7 TeV [1210.2852]	20 GeV χ^{-1}_{1} mass $(1 < \tau(\chi^{-1}) < 10 \text{ ns})$		
Stable ğ R-hadrons : low β, βγ (full detector)	L=4.7 fb ⁻¹ , 7 TeV [1211.1597]	985 GeV g mass		
5 Stable t R-hadrons : low β, βγ (full detector)	L=4.7 fb ⁻¹ , 7 TeV [1211.1597]	683 GeV t mass		
GMSB : stable T	L=4.7 fb ⁻¹ , 7 TeV [1211.1597]	300 GeV $\overline{\tau}$ Mass (5 < tan β < 20)		
$\overline{\chi}^{0} \rightarrow qq\mu$ (RPV) : μ + heavy displaced vertex	L=4.4 fb ⁻¹ , 7 TeV [1210.7451]	700 GeV q mass (0.3×10 ⁶ < λ ₂₁₁ < 1.5×10 ⁶ , 1 mm <	ct < 1 m, g decoupled)	
LFV : pp→v,+X, v,→e+µ resonance	L=4.6 fb ⁻¹ , 7 TeV [Preliminary]	1.61 TeV V mass (λ ₂₁₁ =0.10, λ ₁₂₂ =0	0.05)	
LFV : $pp \rightarrow v_* + X, v_* \rightarrow e(\mu) + \tau$ resonance	L=4.6 fb ⁻¹ , 7 TeV [Preliminary]	1.10 TeV V mass (λ ₂₁₁ =0.10, λ ₃₁₂₀₂ =0.05)		
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 $\vec{q} = \vec{g} \text{ mass } (cr_{LSP} < 1 \text{ mm})$		
$\overline{\chi}, \overline{\chi}, \overline{\chi}, \overline{\chi}, \rightarrow W \overline{\chi}, \overline{\chi}, \rightarrow eev_{\mu}, e\mu v_{\mu} : 4 lep + E_{T,miss}$	L=13.0 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-153]	700 GeV χ_1 mass $(m(\tilde{\chi}_1) > 300 \text{ GeV}, \lambda_{121} \text{ or } \lambda_{122} >$	0)	
$l_{L}l_{L}, l_{L} \rightarrow l\overline{\chi}, \overline{\chi}, \rightarrow eev_{\mu}, e\mu v_{\mu}: 4 lep + E_{T,miss}$	L=13.0 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-153]	430 GeV MASS (m(χ̃) > 100 GeV, m(l̃ ₀)=m(l̃ ₁), λ ₁₂₁ or λ,	₁₂₂ > 0)	
g̃ → qqq : 3-jet resonance pair	L=4.6 fb ⁻¹ , 7 TeV [1210.4813]	666 GeV g mass		
Scalar gluon : 2-jet resonance pair	L=4.6 fb ⁻¹ , 7 TeV [1210.4826]	100-287 GeV Sgluon mass (incl. limit from 1110.2693)		
VIIIII IIIIGIGUUUI (20, DIGC (). IIICIUJCI T L T_TIGG (). IIICIUJCI T L T_TIGG (). IIICIUJCI T L T_TIGG (). IIICIUJCI T L				
	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. Mass scale [TeV]

Summary of BSM searches at the LHC: no indications for new physics

		ATLAS Exotics Searches* - 95% CL Lower Limits (Status: HCP 2012)		
	Lores ED (ADD), managed a E		i _ i _ i _ i _ i _ i _ i _ i _ i	
	Large ED (ADD) - monophotop + E	4.37 TeV [1210.4491] 4.37 TeV [1210.4491] 4.37 TeV [1210.4491]		
\$	Large ED (ADD) : diphoton & dilepton m	Let 7 0 ⁻¹ 7 TeV (1203-025) 1.53 TeV M _D (0-2)	ATLAS	
0	UED : diphoton + E_{-}	1 41 TeV Compact scale R ⁻¹	Preliminary	
SL	S ¹ /Z ED dilepton m.	L=4.9-5.0 (b ⁻¹ , 7 TeV [1209.2535] 4 71 TeV [Mey ~ R ⁻¹		
Jel	RS1 : diphoton & dilepton, m	L=4.7-5.0 fb ¹ , 7 TeV [1210.8389] 2.23 TeV Graviton mass (k/M	s = 0.1)	
rit.	RS1 : ZZ resonance, m	L=1.0 fb ⁻¹ , 7 TeV [1203.0718] 845 GeV Graviton mass (k/M _{p1} = 0.1)	(
a	RS1 : WW resonance, m _{T.blv}	L=4.7 fb ⁻¹ , 7 TeV [1208.2880] 1.23 TeV Graviton mass (k/M _{Pl} = 0.1)	Ldt = (1.0 - 13.0) fb ⁻¹	
xtr	RS $g_{KK} \rightarrow tt$ (BR=0.925) : $tt \rightarrow I+jets$, $m_{theoster}$	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-136] 1.9 TeV g _{xx} mass	- 7 8 ToV	
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 16V	
	ADD BH $(M_{TH}/M_D=3)$: leptons + jets, Σp_T	L=1.0 fb ⁻¹ , 7 TeV [1204.4646] 1.5 TeV M _D (δ=6)		
	Quantum black hole : dijet, F _y (m _{ij})	L=4.7 fb ⁻¹ , 7 TeV [1210.1718] 4.11 TeV $M_D(\delta=6)$		
-	$qqqq$ contact interaction : $\chi(m)$	L=4.8 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-038] 7.8 TeV A		
0	qqll CI: ee & μμ, m	L=4.9-5.0 (b ⁻¹ , 7 TeV [1211.1150] 13.9	Tev A (constructive int.)	
	uutt CI : SS dilepton + jets + E _{T,mise}	L=1.0 fb ⁻¹ , 7 TeV [1202.5520] 1.7 TeV A		
	Z (33W) - M _{aa/µµ}	L=5.9-6.1 16 ; 8 lev [AILAS-CONF-2012-129] 2.49 TeV Z' mass		
	2 (33W) . III _{tt}	1.4 TeV [1210.6604] 1.4 TeV Z IIIIIII MC mpco		
2	$W' (\rightarrow ta, a = 1) : m$	2.55 TEV 17 TAV (1209 6503) 420 GAV W mpss		
	$W_{-} (\rightarrow tb, SSM) : m$	L=1.0 (L ¹ 7 TeV (1205.0525) 450 GEV VV III355		
	W* · m_	1-47 (N ¹ 7 TeV (1209 4446) 2 42 TeV W* (1355		
	Scalar I O pair (8=1) kin vars in eeii evii	L=1.0 (b ⁻¹ , 7 TeV (1112,4828) 660 GeV 1 st gen, LQ mass		
q	Scalar LQ pair (B=1) : kin. vars. in uuii, uvii	L=1.0 fb ⁻¹ , 7 TeV (1203.3172) 685 GeV 2 rd gen, LQ mass		
1	Scalar LQ pair (β=1) : kin. vars. in ττjj, τvjj	L=4.7 fb ⁻¹ , 7 TeV (Preliminary) 538 GeV 3 rd gen. LQ mass		
ŝ	4 th generation : t't'→ WbWb	L=4.7 fb ⁻¹ , 7 TeV [1210.5468] 656 GeV t mass		
A.F.	4 th generation : b'b'(T ₅₀ T ₅₀)→ WtWt	L=4.7 (b ⁻¹ , 7 TeV [ATLAS-CONF-2012-130] 670 GeV b' (T _{en}) mass		
Ing	New quark b' : b'b' \rightarrow Zb+X, m _{2b}	L=2.0 fb ⁻¹ , 7 TeV [1204.1265] 400 GeV b' mass		
>	Top partner : $TT \rightarrow tt + A_0A_0$ (dilepton, M_{T_2})	L=4.7 fb ⁻¹ , 7 TeV [1209.4186] 483 GeV T mass (m(A _n) < 100 GeV)		
10/	Vector-like quark : CC, ming	L=4.6 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-137] 1.12 TeV VLQ mass (charge -1/3, coupli	ng $\kappa_{qQ} = v/m_{Q}$	
.<	Vector-like quark : NC, m _{liq}	L=4.6 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-137] 1.08 TeV VLQ mass (charge 2/3, couplin	$g \kappa_{qQ} = v / m_Q$	
nit.	Excited quarks : y-jet resonance, m	L=2.1 fb ⁻¹ , 7 TeV [1112.3580] 2.46 TeV q* mass		
ЩĘ	Excited quarks : dijet resonance, m	L=13.0 fb", 8 TeV [ATLAS-CONF-2012-148] 3.84 TeV [4" mass		
	Tachni badrone (I STC) - dilanton m	L=13.0 fb ', 8 TeV [ATLAS-CONF-2012-146] 2.2 TeV [1" mass (A = m(1"))		
	Techni-hadrons (LSTC) · WZ resonance (vIII) m	$\frac{1}{1} = \frac{1}{1} = \frac{1}$	(2))	
5	Major poutr (LPSM po mixing) : 2-lop + jote	$L_{10} = 10^{-1} T_{10} (1200 E400)$ $L_{10} = 10^{-1} T_{10} (1200 E400)$ $L_{10} = 10^{-1} T_{10} (1200 E400)$ $L_{10} = 10^{-1} T_{10} (1200 E400)$,P _T))	
2	W . (LRSM, no mixing) : 2-lep + jets	1-21 (b) 7 TeV (1203 5420) 24 TeV (1203 5420) 24 TeV W mass (m(N) < 1	4 TeV)	
ð	H [#] (DY prod., BR(H [#] →II)=1) ; SS ee (µµ), m	1-47.0° ¹ 7 TeV (1210 5070) 409 GeV H ^{±±} mass (limit at 398 GeV for uu)	,	
	H ^{±±} (DY prod., BR(H ^{±±} →eµ)=1) : SS eµ, m	L=4.7 (b ⁻¹ , 7 TeV (1210.5070) 375 GeV H ^{±±} mass		
	Color octet scalar : dijet resonance, m	L=4.8 fb ⁻¹ , 7 TeV [1210.1718] 1.86 TeV Scalar resonance mass		
		10 ⁻¹ 1 1	0 10	
		10	5 10	

*Only a selection of the available mass limits on new states or phenomena shown

Mass scale [TeV]

Summary of BSM searches at the LHC: no indications for new physics

- ▶ coloured SUSY particles probed up to $\mathcal{O}(1.5\,\mathrm{TeV})$
- third generation squarks probed up to $\mathcal{O}(500 \,\mathrm{GeV})$
- electroweak SUSY particles probed up to $\mathcal{O}(300 \,\mathrm{GeV})$
- exotic particles (Z' etc.) probed up to $\mathcal{O}(2 \text{ TeV})$

"probed up to" \neq "excluded": it is important to read the fine print!

► The problem of mass:

What is the origin of particle masses? Is it the Higgs boson? What stabilizes the Higgs mass? What sets the scale of fermion masses?

► The problem of unification:

Is there a simple framework for unifying all particle interactions?

► The problem of flavour:

Why are there so many types of quarks and leptons? What is the origin of CP-violation?

► Cosmological problems:

What is the origin of the baryon-antibaryon asymmetry? What is the nature of dark matter and dark energy?

Why new physics at the LHC?

The naturalness problem: why is $M_{\rm Higgs} \ll M_{\rm Planck}$?



ightarrow need new coloured (top) partners with mass below about 500 GeV

New physics at the LHC?

A dark matter connection?

The new physics should



stabilize the Higgs mass



decouple from EWK physics

A dark matter connection?

The new physics should



stabilize the Higgs mass



decouple from EWK physics

Solution: impose a discrete parity

- \rightarrow all interactions require pairs of new particles;
- ightarrow the lightest new particle is stable and provides a dark matter candidate.

A weakly interacting massive particle (WIMP) with mass $\sim {\cal O}(100)$ GeV provides the correct dark matter relic abundance.

(Alternative DM candidates include the axion, gravitino and axino.)

New physics at the LHC?

New physics models that address

the naturalness problem and the origin of dark matter

generically predict a spectrum of new particles at the TeV-scale with a weakly interacting & stable particle (\leftarrow discrete parity).

A generic LHC new physics signature is thus cascade decays with $E_{\mathrm{T,miss}}$



Supersymmetry is a prime example for this class of models.

A symmetry between fermions and bosons: $Q|\text{boson}\rangle = |\text{fermion}\rangle$ $Q|\text{fermion}\rangle = |\text{boson}\rangle$ with algebra $\{Q_{\alpha}, Q_{\beta}^{\dagger}\} = (\sigma^{\mu})_{\alpha\beta}P_{\mu}$

- SUSY is the unique maximal external symmetry in Nature.
- ▶ Weak-scale SUSY provides a solution to the hierarchy problem.
- SUSY allows for gauge coupling unification, radiative EWSB, and provides dark matter candidates.

To describe SUSY breaking phenomenologically and to preserve the solution to the hierarchy problem one introduces "soft" SUSY breaking terms \rightarrow 124 parameters in the MSSM.

SUSY searches are often interpreted in more specific models, like the constrained MSSM, with a universal scalar mass M_0 , gaugino mass $M_{1/2}$, and trilinear coupling A_0 at $M_{\rm GUT}$, and with tan $\beta = v_2/v_1$ and sign(μ).

The mass spectrum of the CMSSM

The SUSY masses at the weak scale are determined through the RGE:



Thus, in the CMSSM the sparticle masses are strongly correlated.

SUSY searches

SUSY models are constrained through

- ▶ loop-induced effects: rare decays of B mesons, $(g 2)_{\mu}$, ewk observables
- \blacktriangleright astrophysical observations: $\Omega_{\rm DM},$ direct and indirect DM detection limits
- direct sparticle and Higgs boson search limits from colliders:
 LEP and Tevatron bounds and LHC exclusions from jets+E_{Tmiss} searches
- ► the LHC Higgs signal

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Global SUSY fits are trying to address the following questions:

- What is the most probable SUSY parameter space including all low-energy observations, astrophysical constraints and collider data?
- To what extend are the various observations and constraints in mutual agreement?

[see e.g. Mastercode (arXiv:1207.7315), SuperBayes (arXiv:1206.0264), and Fittino (arXiv:12044199), and further references in arXiv:1109.3859]

▶ sparticles and H, A, H^{\pm} beyond the current LHC reach:



▶ branching ratios of the light Higgs *h* close to the SM values:



▶ the branching ration for $B_s \rightarrow \mu\mu$ close to the SM value:

	CMSSM, LHC	C, m _h =126 (GeV
SPRING ZUIZ			
a _μ - a sm _μ	(2.9 \pm 0.8 \pm 0.2)E-9	0.3E-9	
BR(b→ sγ)	(3.55 \pm 0.26 \pm 0.23)E-4	2.88E-4	
BR(B → τν)	(1.67 \pm 0.39)E-4	0.99E-4	
$BR(B_s \rightarrow \mu^+ \mu^-)$	<(4.50 ± 0.30)E-9	3.61E-9	
∆ m _s (ps⁻¹)	$\textbf{17.78} \pm \textbf{0.12} \pm \textbf{5.20}$	20.58	
sin²θ ^l eff	$\textbf{0.23113} \pm \textbf{0.00021}$	0.23138	
m _w (GeV)	$\textbf{80.385} \pm \textbf{0.015} \pm \textbf{0.010}$	80.386	
m _h (GeV)	$\textbf{126.0} \pm \textbf{2.0} \pm \textbf{3.0}$	124.4	
LHC			
Ω _{CDM} h²	$\textbf{0.1123} \pm \textbf{0.0035} \pm \textbf{0.0112}$	0.1112	
σ ^{si} (pb)		2.44E-11	
			0 1 2 3 MeasFit / σ

no dark matter signal in current direct or indirect searches:



- ▶ sparticles and H, A, H^{\pm} beyond the current LHC reach
- ▶ branching ratios of the light Higgs *h* close to the SM values
- \blacktriangleright the branching ration for ${\it B_s} \rightarrow \mu \mu$ close to the SM value
- no dark matter signal in current direct or indirect searches

- ▶ sparticles and H, A, H^{\pm} beyond the current LHC reach \checkmark
- \blacktriangleright branching ratios of the light Higgs h close to the SM values \checkmark
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- \blacktriangleright the branching ration for $B_s
 ightarrow \mu \mu$ close to the SM value \checkmark
- \blacktriangleright no dark matter signal in current direct or indirect searches \checkmark

Future global SUSY fits should

- \blacktriangleright include the measured Higgs couplings in the fits; \checkmark
- calculate the *p*-value using toy fits;
- address more general models, in particular those with a different connection between the coloured and uncoloured sparticle sector;
- ▶ include a larger set of LHC observables and proper combinations thereof.

However,

- ▶ just from exclusions it is hard to constrain a larger set of SUSY parameters;
- we need fast and accurate implementations of the LHC results.

Where could SUSY hide?



Where could SUSY hide?

Compared to the CMSSM, the true SUSY model could have a

split spectrum and thus reduced production cross section:

- "natural" SUSY with light stops;
- "unnatural" SUSY with heavy scalars, Higgsino and gravitino;
- ► light Higgsinos from anomaly mediation or higher-dim. GUTs;
- supersoft SUSY;
- ▶ ...
- different decay pattern:
 - compressed spectrum;
 - R-parity violation;
 - models with gravitino dark matter;
 - stealth SUSY;
 - ...

SUSY models with a compressed mass spectrum could have escaped the standard searches:



[Conley et al.]

If the spectrum is compressed, all momentum is carried by the LSP $% \left({{{\rm{LSP}}} \right)$

 \rightarrow the event is invisible



One can use initial state radiation to search for these events.



[Alwall et al., LeCompte, Martin; Izaguirre et al., Gunion, Mrenna; Drees et al., Carena et al., Belanger et al., Rolbieki, Sakurai; Dreiner, MK, Tattersall,...] We consider three simplified models to capture the extreme scenarios



(a) squark degenerate with LSP ($\Delta m = 1 - 100 \,\text{GeV}$), gluino decoupled;

(b) gluino degenerate with LSP ($\Delta m = 1 - 100 \,\text{GeV}$), squark decoupled;

(c) squark and gluino degenerate with LSP ($\Delta m = 1 - 100 \text{ GeV}$).

It is essential to properly describe the initial state radiation by matching matrix element calculations and parton showers:



- The uncertainty of the parton shower prediction has been estimated by using different shower settings and is very large.
- The MLM and CKKW-L matching schemes give consistent results with a small uncertainty.

Compressed spectra

We have implemented a variety of SUSY and mono-jet searches into the RIVET analysis package and set limits on the three simplified models.

The CMS razor and mono-jet searches provide the best limits:



We find the following limits:

- (a1) stop degenerate with LSP, squarks & gluino decoupled: $m_{\tilde{t}} > 200 \text{ GeV}$
- (a2) squark degenerate with LSP, gluino decoupled: $m_{\tilde{q}} > 340 \text{ GeV}$
 - (b) gluino degenerate with LSP, squark decoupled: $m_{\tilde{g}} > 500 \,\text{GeV}$
 - (c) squark and gluino degenerate with LSP: $m_{\tilde{q}} \approx m_{\tilde{g}} > 650 \, {\rm GeV}$

Consider minimal universal extra dimension model [Appelquist, Cheng, Dobrescu]

- 4D flat space time & one extra dimensions of size R
- ▶ tower of massive Kaluza-Klein partners for all Standard Model particles
- The SM particles and their KK partners have:
 - identical spins
 - identical couplings
- discrete symmetry (KK-parity)
 - \rightarrow lightest KK particle is stable and provides a dark matter candidate
- ▶ predicts jets+ $E_{T miss}$ signatures qualitatively similar to supersymmetry

Bosonic supersymmetry? Searches for models with extra dimensions

Supersymmetry or universal extra dimensions?



Search for resonances from the production and decay of 2nd KK modes:

strong production:



 \otimes decay:



Bosonic supersymmetry? Searches for models with extra dimensions

Production cross sections at the LHC (8 TeV) [Edelhäuser, Flacke, MK]



Bosonic supersymmetry? Searches for models with extra dimensions

Limits from comparison with CMS-PAS-EXO-12-061 [Edelhäuser, Flacke, MK]



 $ightarrow {\it R}^{-1}\gtrsim$ 700 GeV and ${\it M}_{
m KK^{(2)}}\gtrsim$ 1.5 TeV

The LHC7/8 has started to cut heavily into the landscape of new physics at the TeV-scale

- there is no sign of new physics so far;
- canonical searches with jets and MET have pushed limits on squark and gluino masses beyond 1 TeV;
- very constrained models like the CMSSM are by now disfavoured.

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However, the LHC searches need to

- be optimized for and interpreted in a wider class of BSM models;
- focus on third generation and electroweak sparticles;
- be extended to more general and complex scenarios, e.g. compressed spectra.

Unfortunately, the (canonical) BSM searches are running out of steam; it will be crucial to upgrade the LHC energy towards 14 TeV.

The landscape of new physics

... Anthropic big desert up to the Planck scale



The landscape of new physics

... or a natural supersymmetric Garden Eden?



Thank you!