

Beyond the Standard Model at LHC Luca Lista INFN - Napoli







- The Standard Model describes fundamental particles and interaction
- The SM is a very well verified theory
- But it does not describe all known phenomena, so can't be considered a "theory of everything"
- Does not include:
 - Gravity
 - Dark matter





- No consistent (=renormalizable) quantum description of Einstein's General Relativity equations
 - Graviton (spin=2)?
- Scale problem: $G_F/G_N \sim 10^{32}$, or, in term of mass scale: $m_{Plank}/m_{EWK} \sim 10^{16}$
- Why so many orders of magnitude?
- Underlying physics reason, or "Anthropic principle"?
- Hides higher space dimensionality?





- Ordinary matter constitutes only 5% of the universe content
 - A small fraction of it makes stars and planets
- A much larger "dark" fraction manifests its presence only via its gravitational effects
 - Galactic rotation curves
- Dark energy is needed in the universe to explain the expansion acceleration





Rotational curve of galaxy M33



Theoretical arguments



- Theoretical arguments suggest physics beyond the SM to guarantee the "hierarchy" of Higgs mass corrections
 - $-\Delta m_{\rm H}^2 \approx k \Lambda^2$
- k is a numerical constant
 - Computable from Feynman loops
- Λ is a cutoff scale (where new physics occurs, could be the Plank scale)
- Higgs physics mass very different from the SM mass parameter via quantum loop corrections
 - "Instability" w.r.t. new physics scale
 - Requires fine tuning of many orders of magnitude
- New particles could run in the loop and provide the proper cancelation without ad hoc fine tuning
 - Supersymmetry?





- New scalar partners can enter in the loop
- Quantum corrections have opposite sign and cancel perfectly, solving
 the hierarchy problem
- The particle spectrum would be duplicated
- As we don't see s-partners with the same mass as ordinary particles, SuSy must be broken



 Super symmetry has an elegant mathematical formulation and also arises from string-inspired models





A new symmetry operator transforms fermions to bosons and vice versa

 $Q|\mathrm{Boson}
angle = |\mathrm{Fermion}
angle,$

$$Q| ext{Fermion}
angle = | ext{Boson}
angle$$

• Special commutation relations

 $egin{aligned} \{Q_lpha,Q_{\dotlpha}^\dagger\} &= -2\sigma^\mu_{lpha\dotlpha}P_\mu, \ \{Q_lpha,Q_eta\} &= 0, & \{Q_{\dotlpha}^\dagger,Q_{\doteta}^\dagger\} &= 0 \ [Q_lpha,P^\mu] &= 0, & [Q_{\dotlpha}^\dagger,P^\mu] &= 0 \end{aligned}$

 Superspace: extensio of 4D space-time with the addition of anticommutating coordinates

$$x^{\mu} \Longrightarrow x^{\mu}, \theta^{\alpha}, \theta^{\dagger}_{\dot{\alpha}} \qquad \hat{Q}_{\alpha} = i \frac{\partial}{\partial \theta^{\alpha}} - (\sigma^{\mu} \theta^{\dagger})_{\alpha} \partial_{\mu} \qquad \stackrel{Q = \text{translation}}{\text{in the superspace!}}$$

Superfield can be decomposed by series expansion in θ (no more than 2nd degree) into ordinary fermion and boson fields + an auxiliary field *F* (Wess-Zumino)

$$\Phi = \phi(y) + \sqrt{2}\theta\psi(y) + \theta\theta F(y)$$





- R-parity conservation?
 - R = (-1)^{3(B L) + 2S}, R=1 for ordinary particles, R=-1 for Susy partners
 - Violation of R-parity would result in most of the models in short proton lifetime
 - The lightest particle with R=-1 (LSP) can't decay (DM candidate!)
- Two (or more...) Higgs doublets (MSSM)
 - a single doublet can't form Susy-invariant terms

 $H_u = (H_u^+ H_u^0), \ H_d = (H_d^0 H_d^-)$

- Ratio of v.e.v: $\, aneta \equiv v_u/v_d$, also related to m_t/m_b
- Higgs bosons mass pattern predicted at tree level (m_{h⁰} < m_Z!), but loop corrections may change the pattern (up to 135 GeV still allowed)





- Susy could be an intermediate step toward a grand unification
- Adding more degrees of freedom would allow the running couplings to meet at a common (GUT) scale







- Higgsinos and gauginos mix states introducing EWK breaking into two charginos and four neutralinos
- If the LSP is the lightest neutralino, would be a good DM candidate

	Names		spin 0	spin 1	/2	$SU(3)_C,SU(2)_L,U(1)_Y$	
	squarks, quarks	Q	$(\widetilde{u}_L \ \widetilde{d}_L)$) $(u_L \ d$	$_L)$	$({f 3},{f 2},{1\over 6})$	
	$(\times 3 \text{ families})$	\overline{u}	\widetilde{u}_R^*	u_R^\dagger		$(\overline{f 3},{f 1},-{2\over 3})$	
		\overline{d}	\widetilde{d}_R^*	d_R^\dagger		$(\overline{3},1,rac{1}{3})$	
	sleptons, leptons		$(\widetilde{\nu} \ \widetilde{e}_L)$	$(\nu \ e_l$;)	$({f 1},{f 2},-{1\over 2})$	
	$(\times 3 \text{ families})$	ē	\widetilde{e}_R^*	e_R^\dagger		(1, 1, 1)	
	Higgs, higgsinos	H_u	$(H_u^+ H_u^+)$	${}^{0}_{u}) \left \begin{array}{cc} (\widetilde{H}^{+}_{u} & \widetilde{H}^{+}_{u}) \right $	\check{I}_{u}^{0})	$({f 1},{f 2},+{1\over 2})$	
		H_d	$(H^0_d \ H^d$	$\left \begin{array}{c} \widetilde{H}_{d}^{0} & \widetilde{H}_{d}^{0} \end{array} \right $	(\tilde{I}_d^-)	$({f 1},{f 2},-{1\over 2})$	
	Names	Names		spin 1	SU	$U(3)_C, \ SU(2)_L, \ U(1)_Y$	
gluino, gluon		n	\widetilde{g}	g		(8, 1, 0)	
	winos, W bosons bino, B boson		$\widetilde{W}^{\pm}~\widetilde{W}^{0}$	$W^{\pm} W^0$		(1,3,0)	
			\widetilde{B}^0	B^0		(1, 1, 0)	

Some models also propose the gravitino as LSP





- Assuming all mass are degenerate at a given (large) scale, the mass parameter pattern may become simplified
 - mSUGRA (supergravity-inspired):
 - m₀: scalar mass
 - m_{1/2}: gaugino mass
 - A₀: trilinear coupling (higgs-sfermion-sfermion), soft-breaking
 - Other schemes have also been proposed





• Mass spectra are not predicted by theory, depend on the model

mSUGRA







- Susy particles produced in pair (R-parity conservation)
- Decay chains via s-particles + ordinaly particles
- LSP escape undetected (\rightarrow MET!)
- Signatures with leptons are easier to detect





• So far no evidence for Susy particles



LHC Physics



• Search for at least three leptons (e, μ , τ) plus MET or transverse hadronic activity H_T = sum of transverse jet E_T



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• \rightarrow Limits can be set in the m₀/m_{1/2} plane



α_{T} variable (multijet)

• In case of a two-jet event:

$$\alpha_{\rm T} = \frac{E_{\rm T}^{j_2}}{M_{\rm T}} , \quad M_{\rm T} = \sqrt{\left(\sum_{i=1}^2 E_{\rm T}^{j_i}\right)^2 - \left(\sum_{i=1}^2 p_x^{j_i}\right)^2 - \left(\sum_{i=1}^2 p_y^{j_i}\right)^2}$$

• Otherwise: cluster jets in order to minimize the E_{T} difference of the two



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 $\tilde{\chi}_1^0$

ã



Razor variable (multijet)



- Heavy → LSP + jets
- Cluster entire event in two "megajets"
- Exploits kinematics differences with proper boost (CMS-SUS-11-008)

$$R \equiv \frac{M_T^R}{M_R}$$
$$M_R \equiv \sqrt{(p_{j_1} + p_{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2}$$
$$M_R = \sqrt{E_T^{miss}(p_T^{j_1} + p_T^{j_2}) - \vec{E}_T^{miss} \cdot (\vec{p}_T^{j_1} + \vec{p}_T^{j_2})}$$



 q_2





Figure 1: Scatter plot in the (M_R , R^2) plane for simulated events: (top left) QCD multijet, (top right) W+jets and $Z(\nu\bar{\nu}+jets)$, (bottom left) $t\bar{t}+jets$, and (bottom right) the SUSY benchmark model LM6 [12] with $M_{\Delta} = 831$ GeV. The yields are normalized to an integrated luminosity of ~ 800 pb⁻¹, except in the QCD multijet case where we use the corresponding generated luminosity. The bin size is (20 GeV × 0.005).









LHC Physics

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- Stop could be the lightest squark due to large mixing effect in the 3rd generation
- Stop can be produced in pairs, decaying in a tt pair plus neutralinos (LSP) with a sizeable cross section



LHC Physics





• Direct limits on stop







• Exact values depend on various assumptions



LHC Physics





		ATLAS SUSV Secretors* 05% CL Lower Limits (Statuce SUSV 2012)
		ATLAS SUST Searches - 95 % CL LOWER LINING (Status, SUST 2012)
	MSUGRA/CMSSM : 0 lep + j's + E _{T miss}	L=5.8 fb ⁻¹ , 8 TeV (ATLAS-CONF-2012-1b9) 1.50 TeV $\widetilde{q} = \widetilde{g}$ mass
hes	MSUGRA/CMSSM : 1 lep + j's + E _{T miss}	L=5.8 (b ⁻¹ , 8 TeV [ATLAS-CONF-2012-104] 1.24 TeV $\tilde{q} = \tilde{g}$ mass $\int L dt = (1.00 - 5.8) (b^{-1})$
arcı	Pheno model : 0 lep + j's + $E_{T miss}$	L=5.8 fb ¹ , 8 TeV [ATLAS-CONF-2012-109] 1.18 TeV [\widetilde{g} mass (m(\widetilde{q}) < 2 TeV, light $\widetilde{\chi}_{0}^{0}$)
Sei	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 (mg) <2 TeV, light $\chi_0^{(2)}$ Is = 7, 8 TeV
ive	Gluino med. $\tilde{\chi}^{\pm}$ ($\tilde{g} \rightarrow q \bar{q} \tilde{\chi}^{\pm}$) : 1 lep + j's + $E_{T.miss}$	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-041] 900 GeV \tilde{g} mass $(m\chi_1^0) < 200 \text{ GeV}, m\chi_2^-) = \frac{1}{2}(m\chi_2^0) + m(\tilde{g})$
Ius	GMSB : 2 lep (OS) + j's + $E_{T,miss}$	L=4.7 fb ⁻¹ , 7 TeV [Preliminary]1.24 TeV \widetilde{g} mass $(tan\beta < 15)$ AILAS
Inc	GMSB: $1-2\tau + 0-1$ lep + j's + E	$ \underline{L=4.7 \text{ fb}^{-1}, 7 \text{ tev} [ATLAS-CONF-2012-112]} 1.20 \text{ tev} \widetilde{g} \text{ mass } (\tan\beta > 20) $
	$GGIM : \gamma \gamma + E$	L=4.8 (b ⁻¹ , 7 TeV [ATLAS-CONF-2012-072] 1.07 TeV
	$\widetilde{g} \rightarrow b \widetilde{p} \widetilde{\chi}$ (virtual b): 0 lep + 1/2 b-j's + $E_{T,miss}$	<u>L=2.1 fb⁻¹, 7 TeV [1203.6193]</u> 900 GeV g mass $(m(\overline{\chi}_1) < 300$ GeV)
ks d	$\widetilde{g} \rightarrow bb\widetilde{\chi}_{\mu}$ (virtual b) : 0 lep + 3 b-j's + $E_{T,miss}$	<u>L=4.7 (b⁻¹, 7 TeV [1207.4686]</u> 1.02 TeV g mass $(m(\chi) < 400 \text{ GeV})$
uar iate	$\sim g \rightarrow bb \chi_1$ (real b) : 0 lep + 3 b-J's + $E_{T,miss}$	$\frac{1.4.7 \text{ fb}^{2}}{7 \text{ TeV} [1207.4686]} \frac{1.00 \text{ TeV}}{9} \text{ g mass}^{0} (m(\chi_{1}) = 60 \text{ GeV})$
sqi	$g \rightarrow tt \chi_{10}$ (virtual t): 1 lep + 1/2 b-J's + $E_{T,miss}$	$ \begin{array}{c} \textbf{L=2.1 fb}, \textbf{7} \text{ Tev} (1203.6193) \end{array} \qquad \begin{array}{c} \textbf{710 GeV} \textbf{G} \\ \textbf{Mass} (m(\chi_{\star}) < 150 \text{ GeV}) \\ \textbf{G} \\ \textbf{Mass} (m(\chi_{\star}) < 150 \text{ GeV}) \\ \textbf{G} \\ \textbf{Mass} \\ \textbf{Mass} (m(\chi_{\star}) < 150 \text{ GeV}) \\ \textbf{G} \\ \textbf{Mass} \\$
en. o m	$g \rightarrow tt \chi$ (Virtual t) : 2 lep (SS) + J'S + $E_{T,miss}$	L=5.416 S Iev Intacs Conv Conv <t< td=""></t<>
d gu	$g \rightarrow tt \chi_1$ (Virtual t): 3 lep + J'S + $E_{T,miss}$	$\mathbf{L} = \mathbf{A}_{1} \cdot \mathbf{M}_{2} \cdot \mathbf{A}_{1} = \mathbf{V}_{1} \mathbf{L} \mathbf{A}_{2} \cdot \mathbf{C} \mathbf{M}_{2} - \mathbf{Z} \mathbf{M}_{2} = \mathbf{M}_{2} \cdot \mathbf{M}_{2} \mathbf{M}_{2} + \mathbf{M}_{2} \mathbf{M}_{2}$
3r gl	$g \rightarrow tt_{\chi_1}$ (virtual t) : 0 lop + 11ulli-j S + $E_{T,miss}$	
	$g \rightarrow ti \chi_1^0$ (virtual i): 0 lep + 3 b-j s + $L_{T,miss}$	$\frac{1}{1} = \frac{1}{1} $
• • • • • • •	$g \rightarrow i \chi_1$ (real i) . 0 lep + 3 b ⁻ 3 + L _{T,miss} bb b $\rightarrow b \chi^0$: 0 lep + 2-b-jets + F	14.1 (h ⁻¹) Top (141 ASCONE-2012-106) 480 GeV b MASS (m ² / ₂) = 150 GeV)
SS UN	bb, $b_1 \rightarrow b_{A_1}$. $b_1 \rightarrow b_2 \rightarrow b_2$ is $\pm E_{T,miss}$	$\frac{1}{147}\frac{1}{167}\frac{1}{7}\frac{1}{164}\frac{1}{164}\frac{1}{166}1$
ctic	\widetilde{t} (very light), $\widetilde{t} \rightarrow \widetilde{v}^{\pm}$: 2 lep + E_{\pm}	L=4.7 fb ⁺ , 7 TeV [CONF-2012-059] 135 GeV \tilde{T} mass $(m\bar{c}_{1}^{0}) = 45$ GeV)
npo	\widetilde{t} (light), $\widetilde{t} \rightarrow b\widetilde{\gamma}^{\pm}$: 1/2 lep + b-iet + E_{\pm}	L=4.7 fb ⁻¹ , 7 TeV [CONF-2012-070] 120-173 GeV t mass $(m(x_1^{-1}) = 45 \text{ GeV})$
эп. prc	\widetilde{t} (heavy), $\widetilde{t} \rightarrow t \widetilde{\gamma}^{0}$: 0 lep + b-iet + E_{T} miss	$L=4.7 \text{ fb}^{-1}, 7 \text{ Tev}[1208.1447]$ 380-465 GeV T mass $(m(\chi^0) = 0)$
l ge ect	\widetilde{t} (heavy), $\widetilde{t} \rightarrow t \widetilde{\chi}^0$: 1 lep + b-jet + E_{τ} miss	L=4.7 fb ⁻¹ , 7 TeV [CONF-2012-073] 230-440 GeV T MASS $(m(\chi)^{-0}) = 0$
3rc dir	$\widetilde{t}\widetilde{t}$ (heavy), $\widetilde{t} \rightarrow t\widetilde{\chi}^0$: 2 lep + b-jet + $E_{T,miss}$	L=4.7 fb ⁻¹ , 7 TeV [CONF-2012-071] 298-305 GeV \tilde{t} mass $(m(\chi^0) = 0)^{-1}$
	\widetilde{t} (GMSB) $Z \rightarrow II$ + b-jet + E_{T}	L=2.1 fb ⁻¹ , 7 TeV [1204.6736] 310 GeV \tilde{t} mass (115 < $m(\tilde{\chi}^0)$ < 230 GeV)
24	$\widetilde{I}_{I}\widetilde{I}_{I},\widetilde{I} \rightarrow I\widetilde{\chi}_{1}^{0}$: 2 lep + $E_{T \text{ miss}}^{\prime,\text{miss}}$	L=4.7 fb ⁻¹ , 7 TeV [CONF-2012-076] 93-180 GeV $1 \text{ mass } (m(\tilde{\chi}^0_{,}) = 0)$
E V lire($\widetilde{\chi}_{1}^{+}\widetilde{\chi}_{1}, \widetilde{\chi}_{1}^{+} \rightarrow \widetilde{Iv}(\widetilde{Iv}) \rightarrow Iv\widetilde{\chi}_{1}^{0}$: 2 lep + $E_{T \text{ miss}}$	L=4.7 fb ⁻¹ , 7 TeV [CONF-2012-076] 120-330 GeV $\widetilde{\chi}^{\pm}_{+}$ mass $(m(\widetilde{\chi}^{0}_{+}) = 0, m(\widetilde{\iota}^{\pm}_{+}) = \frac{1}{2}(m(\widetilde{\chi}^{\pm}_{+}) + m(\widetilde{\chi}^{0}_{+})))$
	$\widetilde{\chi}_{4}^{\pm}\widetilde{\chi}_{2}^{-} \rightarrow 3I(hv)+v+2\widetilde{\chi}_{4}^{0}$: 3 lep + $E_{T,miss}$	
σ	AMSB (direct $\tilde{\chi}_1^{\pm}$ pair prod.) : long-lived $\tilde{\chi}_1^{\pm}$	L=4.7 (b⁻¹, 7 TeV [ATLAS-CONF-2012-111] 210 GeV χ_1^{-} MASS (1 < $\tau(\chi_1^{+}) < 10$ ns)
live cles	Stable g R-hadrons : Full detector	L=4.7 (b ⁻¹ , 7 TeV [ATLAS-CONF-2012-075] 985 GeV g mass
-gr artic	Stable t R-hadrons : Full detector	L=4.7 (b ⁻¹ , 7 TeV [ATLAS-CONF-2012-075] 683 GeV t mass
Гol	Metastable g R-hadrons : Pixel det. only	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-075] 910 GeV g mass (r(g) > 10 ns)
	GMSB : stable ĩ	L=4.7 fb ⁺ , 7 TeV [ATLAS-CONF-2012-075] 310 GeV τ mass (5 < tan β < 20)
~	RPV : nign-mass eµ Bilineer BBV : 1 len + ile + 5	$\begin{array}{c} 1.32 \text{ TeV} \nu_{\chi} \text{ mass} (\lambda_{311}^{-0}-0.10, \lambda_{312}^{-2}-0.05) \\ \end{array}$
Pl	Difficed RFV. Tiep + $JS + E_{T,miss}$	L=1.0 fb $, 7$ TeV [1109.6606] 760 GeV $q = g$ fillass ($c_{T_{LSP}} < 15$ mm)
Щ.	$DCT RFV$. 4 lep + $E_{T,miss}$	$\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ b} , 7 \text{ iev} [\text{a} \text{LAS-CON-2012-035}] $ $\mathbf{L} = 2.1 \text{ iev} [\text{a} LAS-CON-201$
	Hypercolour scalar gluons 4 jets $m \approx m$	$\frac{1}{100} + \frac{1}{100} + \frac{1}$
her	Spin dep WIMP interaction : monoiet + F_{-}	Let ψ_{1} , the talkasoume outside the outside of the outside th
õ s	pin indep. WIMP interaction : monojet $+F_{-}$	
	T,miss	
		10-1 1 10

Mass scale [TeV]

*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.

LHC Physics





- No evidence of Susy particles so far
- No hint of either a second neutral Higgs or charged Higgs
- If Susy exists:
 - either it hides on some special corner of its parameters "phase space"
 - Or it should be less trivial than the assumed MSSM/mSUGRA





 During '20s Kaluza and Klein proposed a model to unify gravity and elecromagnetism by adding fifth space dimension



- If the fifth dimension is "compactified", it would no longer be visibiel
- Byproduct of compactification: the electric charge is quantified!
- The model was abandoned because of difficulties with quantum description, now revisited in more complex contexts

Extra dimensions



- Particles excitation by "curling" around the compactified dimension give raise to a spectrum of new particles
- Search for heavy resonances decaying into pairs of leptons or jets

•
$$m_n^2 = m_0^2 + n^2/R^2$$

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DM candidates could be excitations of a standard particle?





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- Extra dimension could also explain the hierarchy of plank scale vs EWK scale
- Gravity weaker because it propagates in more dimensions
- EWK world = a brane in a higher dimensional space (Arkani-Hamed, Dimopolous, and Dvali (ADD))
 - Gauss law: Planck scale of gravity in four dimensions (M_{Pl}) related to a fundamental Planck scale in 4 + n_{ED} dimensions (M_D) according to the following relation: $M_{Pl}^2 \approx M_D^{2+n_{ED}} \times \mathbb{R}^{n_{ED}}$
- Randall-Sundrum (RS) model (5D) predicts a detectable graviton KK excitation with several possible decays (e.g.: G* → ZZ, ff, ...)



 Signal = excess peaking at Z mass (jj) and G* mass (II + MET)

- BH/string balls may be produced, according to some models, at LHC
- Evaporation (Hawking's radiation) results in emission of SM particle with a "democratic" distribution
- Signature: events with jets and leptons
- No signal found, limits set in the parameter space

CMS: S_T

 S_T = scalar sum of p_T of individual selected objects:

- GUT models (SU(5), SO(10)) and technicolor-composite models predict new bosons that couple to both leptons and quarks
- Produced in pairs via gg fusion or qq annihilation
- Search performed in the 3rd generation: LQ → τb (one tau decys to e or μ, the other to hadrons)

		ATLAS Exotics Searc	ches* - 95% CL Lower I	_imits (Status: LH	CC, Sep 2012)
	Large ED (ADD) : monoiet + E		2 20 To	$M_{(\delta-2)}$	
	Large ED (ADD) : monophoton + $E_{T,miss}$	$L = 1.0 \text{ fb}^{-1}$, 7 TeV [A12A3-CONF-2011-050]	1.93 ToV M_ ($\delta = 2$	
S	Large ED (ADD) : Monophoton $T = T_{miss}$	L=4.9 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-087]	3.29 Tel	M _o (GRW cut-off, NLC	ATLAS
uo	UED : diphoton + E_{T} mise	L=4.8 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-072]	1.41 TeV Compact.	. scale 1/R	Preliminary
ISI	RS1 with $k/M_{\rm Pl} = 0.1$; diphoton, $m_{\rm ell}$	L=4.9 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-087]	2.06 TeV Gra	viton mass	
let	RS1 with $k/M_{\rm Pl} = 0.1$: dilepton, $m_{\rm e}$	L=4.9-5.0 fb ⁻¹ . 7 TeV [1209.2535]	2.16 TeV Gra	aviton mass	• $1 dt = (1.0 - 6.1) \text{ fb}^{-1}$
lin	RS1 with $k/M_{\rm Pl} = 0.1$: ZZ resonance, $m_{\rm HI}$	L=1.0 fb ⁻¹ , 7 TeV [1203.0718]	845 GeV Graviton mass	J	Lut = (1.0 - 0.1) ib
a U	RS1 with $k/M_{\rm Pl} = 0.1$: WW resonance, $m_{T,\rm b,h}$	L=4.7 fb ⁻¹ , 7 TeV [1208.2880]	1.23 Tev Graviton ma	ass	s = 7, 8 TeV
<i>dr</i>	RS with BR(g \rightarrow tt)=0.925 : tt \rightarrow I+jets, m	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-136]	1.9 TeV KK g	luon 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)		
	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, $F_{ij}(m_{ij})$	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-038]	4.11	TEV M_D (δ =6)	
	qqqq contact interaction : $\hat{\chi}(m_{\parallel})$	L=4.8 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-038]		7.8 TeV Λ	
C	qqll CI : ee, $\mu\mu$ combined, \ddot{m}_{μ}	L=1.1-1.2 fb ⁻¹ , 7 TeV [1112.4462]		10.2 TeV A (COP	structive int.)
	uutt CI : SS dilepton + jets + $E_{T, miss}$	L=1.0 fb ⁻¹ , 7 TeV [1202.5520]	1.7 TeV Λ		
	Ζ' (SSM) : <i>m</i> _{ee/μμ}	L=5.9-6.1 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-129]	2.49 TeV	" mass	
	Z' (SSM) : <i>m</i> _{ττ}	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-067]	1.3 TeV Z' mass		
~	W' (SSM) : <i>m</i> _{T,e/µ}	L=4.7 fb ⁻¹ , 7 TeV [1209.4446]	2.55 TeV	N' mass	
_	$W' (\rightarrow tq, g_{B}=1) : m_{tq}$	L=4.7 fb ⁻¹ , 7 TeV [CONF-2012-096] 350 G	v W' mass		
	$W'_{R} (\rightarrow tb, SSM) : m_{tb}$	L=1.0 fb ⁻¹ , 7 TeV [1205.1016]	1.13 TeV W' mass		
	W* : <i>m</i> _{T,e/u}	L=4.7 fb ⁻¹ , 7 TeV [1209.4446]	2.42 TeV	/* mass	
Q	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		
	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		
ks	4 [™] generation : t't'→ WbWb	L=4.7 fb ⁻¹ , 7 TeV [Preliminary]	656 GeV t' mass		
ar	4 th generation : b'b'($I_{5/3} I_{5/3}$) \rightarrow WtWt	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-130]	670 GeV b' (T 5/3) mass		
nb	New quark D^{-1} $D^{-1}D^{$	L=2.0 fb ⁻¹ , 7 TeV [1204.1265] 400	Gev b' mass		
N	Top partner . $T \rightarrow tt + A_0 A_0$ (dilepton, M_{T2})	L=4.7 fb ⁻¹ , 7 TeV [1209.4186]	183 GeV 1 mass ($m(A_0) < 100 \text{ GeV}$	V)	
Ve	Vector-like quark : CC, m _{lvq}	L=4.6 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-137]	1.12 TeV VLQ mass (C	harge -1/3, coupling κ_{qQ} =	$= v/m_{o}$
	Vector-like quark : NC, m	L=4.6 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-137]	1.08 TeV VLQ mass (cl	harge 2/3, coupling $\kappa_{qQ} = 1$	//m _o)
ed	Excited quarks : y-jet resonance, ///	L=2.1 fb ⁻¹ , 7 TeV [1112.3580]	2.46 TeV Q	* mass	
nic	Excited quarks : dijet resonance, m	L=5.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-088]	3.66 1	rev q [*] mass	
Щë	Excited muon : $u_{-\gamma}$ resonance $m_{e_{\gamma}}^{e_{\gamma}}$	L=4.9 fb ⁻¹ , 7 lev [ATLAS-CONF-2012-008]	2.0 TeV E TI	$ass(\Lambda = m(e))$	
	Techni-hadrons (I STC) : dilenton m	L=4.8 fb , 7 lev [ATLAS-CONF-2012-008]	1.9 TeV μ Πα	$dss(\Lambda = m(\mu))$	
	Techni-hadrons (LSTC) : WZ resonance (vIII), m	L=4.5-5.0 ID, 7 IEV [1209.2555]	$p_T (m_T) = m(\pi) + m_T (m_T)$	$m_{\rm T} (m_{\rm T}) = 11 m_{\rm W}$	
er	Major neutr (LBSM no mixing) : 2-len + jets	$L = 1.0 \text{ fb}^{-1}$ 7 TeV [1203.1048]	$p_T mass (m(p_T) = m(n_T) + 15 \text{ Toy}$ N mass	$(m(W_{T}) = 2 \text{ TeV})$	
th	W_{-} (I RSM no mixing) : 2-lep + jets	/=2 1 fb ⁻¹ 7 TeV [1203 5420]	2.4 TeV W	$m_{R} = 2 10 \text{ m}$	
0	$H^{\pm\pm}$ (DY prod., BR($H^{\pm\pm} \rightarrow \mu\mu$)=1) : SS dimuon. m	/=1.6 fb ⁻¹ 7 TeV [1201.1091] 355 G	V H ^{±±} mass	-H	
	Color octet scalar : dijet resonance, $m_{*}^{\mu\mu}$	L=4.8 fb ⁻¹ , 7 TeV [ATLAS-GONF-2012-038]	1.94 TeV Scala	ar resonance mass	
	······				
		10 ⁻¹	1	10	10
				Ν	lass scale [TeV]
*Onl	lv a selection of the available mass limits on new states o	r phenomena shown			

LHC Physics

Luca Lista

- No hint of new physics found at LHC
- Simple Susy model excluded in a large fraction of the parameter space

 — ... though "large fraction" depends on a "metrics" of the parameter space

 The search goes on, improvements are expected with larger data samples and, in next future, with the increase in center-of-mass energy

• A Supersymmetry primer, S. P. Martin, http://arxiv.org/abs/hep-ph/9709356