# Split SUSY at LHC and a 100 TeV collider

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1503.03099



### Status of Supersymmetry

A	LAS SUSY Sea	arches	* - 9	5%	CLL	wer Limits A	TLAS Preliminar
010	Model	$e, \mu, \tau, \gamma$	Jets	$E_{\rm T}^{\rm miss}$	∫£ dr[ft	) Mass limit	Reference
_	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	1.7 TeV m(g)=m(g)	1405.7875
	$\bar{q}\bar{q}, \bar{q} \rightarrow q\bar{\xi}_{1}^{0}$	0	2-6 jets	Yes	20.3	850 GeV m(l <sup>2</sup> )=0 GeV, m(1 <sup>e</sup> gen. q́)+m(2 <sup>od</sup> gen	.cp 1405.7875
8	$\tilde{q}\tilde{q}\gamma, \tilde{q} \rightarrow q\tilde{t}_{\perp}^{0}$ (compressed)	1γ	0-1 jet	Yes	20.3	250 GeV m(i):=m(c)	1411.1559
5	$\tilde{x}\tilde{y}, \tilde{x} \rightarrow q\tilde{q}\tilde{k}_{1}^{0}$	0	2-6 jets	Yes	20.3	1.33 TeV m(?)=0 GeV	1405.7875
2	$\hat{x}\hat{y}, \hat{x} \rightarrow qq\hat{x}_{1}^{*} \rightarrow qqW^{*}\hat{x}_{1}^{*}$	1 e, µ	3-6 jets	Yes	20		20 1501.03555
ŝ	$\hat{\chi}\hat{\chi}, \hat{\chi} \rightarrow qq(\ell\ell/\ell\nu/\nu\nu)\hat{x}_1$	$2 e, \mu$	0-3 jets	-	20	2 1.32 TeV m(?)-0 GeV	1501.03555
8	GMSB (/ NLSP)	1-2 + 0-1 2	0-2 jets	Yes	20.3	1.6 TeV tang >20	1407.0603
100	GGM (bino NLSP)	2γ		Yes	20.3	2 1.28 TeV m((*)>50 GeV	ATLAS-CONF-2014-001
10	GGM (wino NLSP)	$1 e, \mu + \gamma$		Yes	4.8	2 619 GeV m((1)>50 GeV	ATLAS-CONF-2012-144
-	GGM (higgsine-bine NLSP)	y	16	Yes	4.8	2 900 GeV m((*)>220 GeV	1211.1167
	GGM (higgsino NLSP)	$2 e, \mu (Z)$	0-3 jets	Yes	5.8	e 600 GeV m(NLSP)>200 GeV	ATLAS-CONF-2012-152
_	Gravitino LSP	0	mono-je	t Yes	20.3	#1/2 scale 865 GeV m(G)>1.8 × 10 * eV, m(g)=m(j)=1.5	W 1502.01518
SC'	$\bar{g} \rightarrow b\bar{b}\bar{t}_{1}^{0}$	0	3 b 7-10 jets	Yes	20.1	1.25 TeV m(r)+400 GeV	1407.0600
95	g-+441	0-1 6 4	3.6	- res Ves	20.3		1407 0600
in in	g→bili	0-1 e.µ	36	Yes	20.1	1.3 TeV m(t <sup>2</sup> )~300 GeV	1407.0600
	$\bar{b}_1\bar{b}_1, \bar{b}_1 \rightarrow b\bar{t}_1^0$	0	2 b	Yes	20.1	i, 100-620 GeV mt/2)>90 GeV	1308.2631
S S	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow t \tilde{t}_1^{\pm}$	2 e. µ (SS)	0-3 h	Yes	20.3	5, 275-440 GeV m(i) -2 m(i)	1404.2500
89	$I_1I_2, I_1 \rightarrow bK_1^n$	1-2 c. µ	1-2 b	Yes	4.7	110-167 GeV 230-460 GeV m(i <sup>+</sup> <sub>1</sub> ) = 2m(i <sup>+</sup> <sub>1</sub> ) = 2m(i <sup>+</sup> <sub>1</sub> ) = 55 GeV	1209.2102, 1407.0583
80	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wh\tilde{t}_1^0 \text{ or } \tilde{t}_1^0$	2 c.µ	0-2 jets	Yes	20.3	, 90-191 GeV 215-530 GeV mc(2)-1 GeV	1403.4853, 1412.4742
3 <sup>rd</sup> gen.	$\tilde{h}\tilde{h}_{1}, \tilde{h} \rightarrow d\tilde{K}_{1}^{0}$	0-1 e. µ	1-2 b	Yes	20	1, 210-640 GeV m0[*]=1 GeV	1407.0583,1406.1122
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow c \tilde{K}_1^0$	0 m	nono-jet/c-	tag Yes	20.3	i, 90-240 GeV m(i) = ((i) = (35 GeV	1407.0608
	i <sub>1</sub> i <sub>1</sub> (natural GMSB)	$2 e, \mu(Z)$	1.6	Yes	20.3	150-580 GeV mol_)-150 GeV	1403.5222
	$\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	$3 e, \mu (Z)$	1 b	Yes	20.3	l <sub>2</sub> 290-600 GeV m(l <sup>2</sup> <sub>1</sub> )-200 GeV	1403.5222
_	$\tilde{l}_{L,R}\tilde{l}_{L,R}, \tilde{l} \rightarrow t\tilde{\chi}_1^0$	2 e.µ	0	Yes	20.3	90-325 GeV m(it)=0 GeV	1403.5294
EW direct	$\hat{X}_{1}^{*}\hat{X}_{1}^{-}, \hat{X}_{1}^{*} \rightarrow \hat{\ell}\nu(\ell\bar{\nu})$	2 e.µ	0	Yes	20.3	f <sup>*</sup> <sub>1</sub> 140-465 GeV m(l <sup>*</sup> <sub>1</sub> )=0 GeV, m(l <sup>*</sup> <sub>1</sub> )=0.5(m(l <sup>*</sup> <sub>1</sub> )=n(l <sup>*</sup> <sub>1</sub> )	D 1403.5294
	$\hat{X}_{1}^{*}\hat{X}_{1}^{-}, \hat{X}_{1}^{*} \rightarrow \tilde{T}r(T\bar{v})$	2 7		Yes	20.3	i <sup>a</sup> 100-350 GeV m(i <sup>a</sup> <sub>1</sub> )=0 GeV, m(i <sup>a</sup> <sub>1</sub> )=0.5(m(i <sup>a</sup> <sub>1</sub> )+m(i <sup>a</sup>	1407.0350
	$\hat{\chi}_1^* \hat{\chi}_2^0 \rightarrow \hat{\ell}_L v \hat{\ell}_L t (\bar{\nu} \nu), t \bar{\nu} \hat{\ell}_L t (\bar{\nu} \nu)$	3 e.µ	0	Yes	20.3		1402.7029
	$\tilde{\chi}_1^s \tilde{\chi}_2^0 \rightarrow W \tilde{\chi}_1^0 Z \tilde{\chi}_1^0$	2-3 e. µ	0-2 jets	Yes	20.3	r <sup>*</sup> <sub>1</sub> . K <sup>*</sup> <sub>1</sub> 420 GeV m(r <sup>*</sup> <sub>1</sub> )-m(r <sup>*</sup> <sub>1</sub> )-m(r <sup>*</sup> <sub>1</sub> )-0, sleptons dec	upled 1403.5294, 1402.7029
	$\hat{\chi}_{1}^{*}\hat{\chi}_{2}^{0} \rightarrow W \hat{\chi}_{1}^{0}h \hat{\chi}_{1}^{0}, h \rightarrow b\bar{b}/WW/\tau\tau/$	γγ e.μ.γ	0-2 b	Yes	20.3	r <sup>1</sup> <sub>1</sub> . x <sup>2</sup> <sub>1</sub> 250 GeV m(t <sup>2</sup> <sub>1</sub> )-m(t <sup>2</sup> <sub>1</sub> ), m(t <sup>2</sup> <sub>1</sub> )=0, sleptons dec	upled 1501.07110
_	$\tilde{\chi}_2^0 \tilde{\ell}_3^0, \tilde{\chi}_{2,3}^0 \rightarrow \tilde{\ell}_R \ell$	4 e.µ	0	Yes	20.3	f <sup>*</sup> <sub>2,3</sub> 620 GeV m(t <sup>*</sup> <sub>1</sub> )=m(t <sup>*</sup> <sub>1</sub> )=0, m(t <sup>*</sup> <sub>1</sub> )=0, 5(m(t <sup>*</sup> <sub>1</sub> )=m(t <sup>*</sup> ))=0.5(m(t <sup>*</sup> <sub>1</sub> )=m(t <sup>*</sup> ))=0.5(m(t <sup>*</sup> <sub>1</sub> )=0.5(m(t <sup>*</sup> <sub>1</sub> )=m(t <sup>*</sup> ))=0.5(m(t <sup>*</sup> <sub>1</sub> )=0.5(m(t <sup>*</sup> <sub>1</sub> )=0.5(m(t <sup>*</sup> ))=0.5(m(t <sup>*</sup> ))=0	1405.5086
'n	Direct $\hat{x}_1^* \hat{x}_1^-$ prod., long-lived $\hat{x}_1^*$	Disapp. trk	1 jet	Yes	20.3	m(ξ <sup>*</sup> <sub>1</sub> )-m(ξ <sup>*</sup> <sub>1</sub> )=160 MeV, π(ξ <sup>*</sup> <sub>1</sub> )=0.2 m	1310.3675
8 8	Stable, stopped g H-hadron	0	1-5 jets	Yes	27.9	832 GeV m(l <sup>2</sup> )=100 GeV, 10 µ8 <r(g)<1000 s<="" td=""><td>1310.6584</td></r(g)<1000>	1310.6584
옷을	Stable g H-hadron	brk.		-	19.1	e 1.27 TeV	1411.6795
Š.Š.	GMSB, stable $\uparrow, \chi_1 \rightarrow \uparrow(\tilde{e}, \tilde{\mu}) + \tau(e, \tilde{\mu})$	.μ) 1-2 μ			19.1	537 GeV To-sany-so	1411.6795
24	GMSB, $\mathcal{X}_1 \rightarrow \mathcal{Y}G$ , long-lived $\mathcal{X}_1$	2 9		Yes	20.3	435 GeV 2 <rr(t)<3 model<="" ns,="" sp58="" td=""><td>1409.5542</td></rr(t)<3>	1409.5542
_	ĝĝ, X <sub>1</sub> →ggr (RPV)	1 µ, displ. vo			20.3	1.0 lev 1.5 <rr<156 br(µ)="1," m(r_1)="10&lt;/td" mm,=""><td>8GeV AILAS-CONF-2013-092</td></rr<156>	8GeV AILAS-CONF-2013-092
	LFV $pp \rightarrow \tilde{v}_r + X_r \tilde{v}_r \rightarrow e + \mu$	2 e.µ	-		4.6	1.61 TeV X <sub>111</sub> =0.10, X <sub>111</sub> =0.05	1212.1272
	DEnersy DBU Checchi	24.000	0.0.1	Mar.	4.0		1212.12/2
2	ctor ct wol chosen	A c (33)	0.3.0	Tes	20.3	1.35 TET mighting, (Tapel int	1404.2900
R	$x_1x_1, x_1 \rightarrow wx_1, x_1 \rightarrow ver_\mu, e\mu r_e$ $c^+c^-c^+ \rightarrow wc^0c^0$	36445		Yes	20.3	m(r_j)=0.2xm(r_j), J <sub>121</sub> +0	1405.0086
	$\mathcal{X}_{1}\mathcal{X}_{1}, \mathcal{X}_{1} \rightarrow W\mathcal{X}_{1}, \mathcal{X}_{1} \rightarrow TTV_{\ell}, dTV_{\ell}$	34.µ+1	6-7 inte	Tes	20.3	m(r):>0.200000 m(r):>0.2000000	ATLAS COME 2012 001
	$\bar{g} \rightarrow \bar{\ell}_1 t, \bar{\ell}_1 \rightarrow bs$	2 e, µ (SS)	0-3 b	Yes	20.3	850 GeV	1404.250
Other	Scalar charm, $\tilde{c} \rightarrow c \tilde{t}_1^0$	0	2 c	Yes	20.3	₹ 490 GeV m(₹1)-200 GeV	1501.01325
	$\sqrt{s} = 7 \text{ TeV}$	√s = 8 TeV	50-	8 TeV			
	full data	artial data	full	data	1	Mass scale [7	eV]

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

#### gluino searches

#### stop searches





 $m_{\tilde{g}} \gtrsim 1.4 \text{TeV}$ 

 $m_{\tilde{t}} \gtrsim 700 {
m GeV}$ 

#### What does it mean for naturalness?

'natural SUSY' (stop,gluino,higgsino) Papucci, Ruderman,Weiler '11

$$\begin{aligned} stop \\ \delta m_h^2 &= -\frac{3}{8\pi^2} y_t^2 \left( m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2 \right) \log\left(\frac{\Lambda}{\text{TeV}}\right) \\ \sqrt{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2} &\lesssim 600 \text{GeV}\left(\frac{\Delta^{-1}}{20\%}\right)^{-1/2} \end{aligned}$$

gluino

$$\delta m_h^2 = -\frac{2}{\pi^2} y_t^2 \left(\frac{\alpha_s}{\pi}\right) M_3^2 \log^2\left(\frac{\Lambda}{\text{TeV}}\right)$$

$$M_3 \lesssim 900 \text{ GeV} \sin \beta \left(\frac{\Delta^{-1}}{20\%}\right)^{-1/2}$$

125 Gev Higgs : prefers heavy stops

$$\delta m_h^2 = \frac{3G_F}{\sqrt{2}\pi^2} m_t^4 \log\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right)$$

~ 1-10 TeV stop depending on A-term

More complete models generally yield %-level fine-tuning



NMSSM, split generation, low-scale mediation, Dirac gaugino, and R-parity breaking are generically tuned.

Arvanitaki, Baryakhtar, Huang, Tiburg, Villadoro '13

Better model building might save the day

Scherk-Schwartz SUSY breaking

**Compressed** spectrum

Stealth supersymmetry

Twin Higgs

Dimopoulos, March-Russell '14 LeComte, Martin '11 Dimopoulos, March-Russell, Scoville '14

Fan, Reece, Ruderman '11

Chacko, Goh, Harnik '05 Craig, Howe '13



In the MSSM gauginos are Majorana

 $M\lambda\lambda$ 

 $F_X \theta^2 \underbrace{d^2 \theta} W_\alpha W^\alpha$ 

Can be Dirac if new superfields are added



N=2 supersymmetry

extra-dimension

Supersoft SUSY breaking

 $D'\theta_{\alpha}$  D-term brea  $\int d^{2}\theta W_{\alpha}' W_{i}^{\alpha} \Phi_{i}$ D-term breaking

Dirac gauginos do not feed into scalar masses through renormalization

$$m^{2} = \frac{C_{i}\left(r\right)\alpha_{i}m_{i}^{2}}{\pi}\log\left(\frac{\delta^{2}}{m_{i}^{2}}\right)$$

#### They can be naturally heavier than scalars LHC will have a harder time seeing the gluino... M. Heikinheimo, M. Kellerstein, V. Sanz '12 Kribs, Martin '12

...and squarks



#### Squark production



Frugiuele, T.G., Kumar, Ponton

### R-symmetry

With Dirac gaugino: possible to impose an U(1) R-symmetry

#### $M_D\lambda\Psi$

Kribs, Poppitz, Weiner '02

• Bounds from FCNC are weaker: off diagonal  $m_{ij}$ 

 $R[Q, U^{c}, D^{c}, L, E^{c}] = 1$   $R[H_{u}, H_{d}] = 0$ 



### Higgs mass

Tree-level:

Reduced quartic, usual of Dirac gauginos



No help (at tree-level) from

 $\lambda_T H_u T(R_d) + \lambda_S H_u S(R_d)$ 

don't get a vev (In the limit of exact R-symmetry)

But do help in models without an R-symmetry

Benakli, Goodsell, Staub 1211.0552

#### Loop-level

Usual stop correction (but A-terms are 0)



Similar loop from the triplet



$$V_{\rm CW} \sim \frac{1}{16\pi^2} \left( \underbrace{5\lambda_T^4}_{5\lambda_T^2} \log \frac{m_T^2}{M_2^2} + 3\lambda_t^4 \log \frac{m_{\tilde{t}}^2}{m_t^2} \right)$$

$$\downarrow$$
Very sensitive to  $\lambda_T$ 

....but so are electroweak precision measurements

#### allowed by EWPT



Bertuzzo, Frugiuele, T.G., Ponton

## Arkani-Hamed, Dimopoulos

Naturalness might not be a good guide SUSY might still be relevant

- Dark matter
- Gauge coupling unification
- 'UV' reasons

Gauginos and scalars might not be at the same mass scale

natural in for example anomaly mediation

#### Prediction for the Higgs mass

The Higgs quartic coupling is predicted at a high scale:

$$\lambda(m_{\text{scalar}}) = \frac{1}{4}(g^2 + g'^2)\cos^2\beta$$
 tree-level

> Bagnaschi, Giudice,Slavich,Strumia '14



#### Split-SUSY

Bagnaschi, Giudice,Slavich,Strumia '14

#### Arvanitaki, Craig, Dimopoulos, Villadoro '12

#### Mini-split in anomaly mediation

scalar masses are generated by gravity mediation

$$\int d^4\theta \frac{X^{\dagger} X Q^{\dagger} Q}{M_{pl}^2}$$

$$m^2 = m_{3/2}^2$$

but the gaugino masses are generated by AMSB

$$M_i = \frac{b_i}{16\pi^2} g_i^2 m_{3/2}$$



#### term generated through Giudice-Masiero

conformal compensator  $\int d^4\theta \phi^\dagger \phi H_u H_d$ 

$$\mu \sim \frac{B_{\mu}}{\mu} \sim m_{3/2}$$

Heavy Higgsino

### Similar spectrum could also arise in gauge mediation

Arvanitaki, Craig, Dimopoulos, Villadoro '12 Buican, Meade, Seiberg, Shih '09  $W = M_R \left( \phi_1 \bar{\phi_1} + \phi_2 \bar{\phi_2} \right) + X \phi_1 \phi_2$ 

$$M_i \sim \frac{g_i^2}{16\pi^2} \frac{M}{M_R} \frac{F^3}{M_R^3} = \frac{g_i^2}{16\pi^2} \Lambda$$

We take the scalars at  $\sim \Lambda$ 

Gaugino spectrum  
(deflected AMSB)  

$$M_{\tilde{B}} = M_1 \left[ 1 + \frac{C_{\mu}}{11} + \cdots \right]$$
  
 $M_{\tilde{W}} = M_2 \left[ 1 + C_{\mu} + \cdots \right]$   
 $M_{\tilde{g}} = M_3 \left[ 1 + \cdots \right]$   
 $M_{\tilde{g}} = M_3 \left[ 1 + \cdots \right]$   
 $M_i = \frac{\beta_i}{g_i} m_{3/2}$   $C_{\mu} = \frac{\mu}{m_{3/2}} \frac{m_A^2 \sin^2 \beta}{m_A^2 - \mu^2} \ln \frac{m_A^2}{\mu^2}$ 

#### AMSB Gaugino spectrum

Beauchesne, Earl, T.G. '15



Similar expressions for gauge mediation

$$M_{\tilde{B}} = M_1 \left[ 1 + \frac{3C'_{\mu}}{5} + \cdots \right]$$

$$M_{\tilde{W}} = M_2 \left[ 1 + C'_{\mu} + \cdots \right]$$

 $M_{\tilde{g}} = M_3 \left[ 1 + \cdots \right]$ 

$$M_{i} = \frac{g_{i}^{2}}{16\pi^{2}}\Lambda \qquad C'_{\mu} = \frac{\mu}{\Lambda}\frac{m_{A}^{2}\sin^{2}\beta}{m_{A}^{2}-\mu^{2}}\ln\frac{m_{A}^{2}}{\mu^{2}}$$

### Similar expressions for gauge mediation



### Assume that gluino decay to 3rd generation quarks



Electroweakino decays  $\tilde{W^0} \rightarrow \tilde{B}h$  bino LSP  $\tilde{W^+} \rightarrow W^+\tilde{B}$  $\tilde{B} \rightarrow \tilde{W^0}h$  wino LSP

 $\tilde{W^+} \to W^0 + \text{soft}$ 

#### Parameter space

parameters of the model:  $m_{3/2}$   $\mu$   $\tan\beta$   $m_{\rm scalar}$ choose:  $m_{\rm scalar} \sim m_{3/2}$ 

set  $\tan \beta$  to reproduce the Higgs mass results in term of

 $C_{\mu}$  and  $m_{3/2}$ 

#### Recasting LHC bounds

Gaugino spectrum and branching ratios are obtained as a function of  $m_{3/2}$  and  $C_{\mu}$ .

we simulate the signal using MadGraph-Pythia-Delphes and recast LHC searches

> ATLAS multi-leptons+b-jets ATLAS 0-1 lepton+b-jets CMS high jets multiplicity CMS 2 OS leptons+jets



Beauchesne, Earl, T.G. '15

#### Gauge mediation



LHC 14 prospects

looked at 2 sets of cuts

#### same-sign dilepton

cohen et al. 1311.6480

- SSDL
- 2 b-jets or more
- 6 jets or more
- $H_T > 700 \text{GeV}$
- $E_T^{\text{miss}} > 250 \text{GeV}$

8 signal regions High missing energy CMS-PAS-FTR-13-014

- 1 lepton
- 6 jets or more
- 1 b-jet
- $H_T > 500 \text{GeV}$
- $E_T^{\text{miss}} + P_T^{\text{lep}} > 450 \text{GeV}$

4 signal regions

#### AMSB (discovery) at LHC 14

 $M_{ ilde W}$  contours



### GMSB (discovery) at LHC 14 $M_{\tilde{B}}$ contours



#### Prospect for a 100 TeV collider

#### same-sign dilepton

cohen et al. 1311.6480

- SSDL
- 3 b-jets or more
- 7 jets or more
- $H_T > 3000 \text{GeV}$
- $E_T^{\text{miss}} > 800 \text{GeV}$

8 signal regions High missing energy

adapted from Jung, Wells '13

- 2 jets with  $p_T > 0.1 M_{\text{eff}}$
- no lepton
- $E_T^{\text{miss}} > 0.2 M_{\text{eff}}$
- $M_{\rm eff} > 15 {\rm TeV}$
- 3 or more b-jest

5 signal regions

#### AMSB at a 100 TeV collider ( $3ab^{-1}$ )



#### GMSB at a 100 TeV collider



#### Dark matter

#### If the LSP is a wino: need $M_{\tilde{W}} \sim 2.7 { m TeV}$ 100 TeV collider





 $C_{\mu}$ 

#### Gauge couplings unification

#### modified by heavy Higgsino, but seems to work

