SUSY Models

ATLAS and CMS results

Summary & Outlook

# SUSY with tau final states Models and Current Searches

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Geilo, Dec 17th 2012

ATLAS and CMS results

Summary & Outlook

# Cold Dark Matter and SUSY

- Cold Dark Matter: distribution of additional mass in the universe,
  - ▷ electrically neutral ("dark")
  - $\triangleright~$  not black holes or massive neutrinos
- Many SUSY models have candidate particle for Cold Dark Matter

(their lightest stable particle, LSP)



- SUSY models are constrained from various sides:
  - Measurements
     SM observables, rare decays
  - Searches
    - no superpartner observed yet
  - Discovery of Higgs-like boson
  - Cosmological
- Strongly restrict viable models/parameter space
- Interest in final states with tau leptons

# SUSY with tau final states

### Third-generation final states favoured by many models

Left-right mixing in SUSY

$$M_{\tilde{f}}^2 = \begin{pmatrix} m_{\tilde{f}_L}^2 & -\boldsymbol{m_f} \left( A_f + \mu \tan \beta \right) \\ -\boldsymbol{m_f} \left( A_f + \mu \tan \beta \right) & m_{\tilde{f}_R}^2 \end{pmatrix}$$

leads to lighter sfermion masses in 3rd generation

- RGE in MSSM, mSUGRA
- $\begin{tabular}{ll} $$ $\tilde{\tau}$ is NLSP in relevant $$ GMSB parameter range $$ $$
- Cosmological constraints



• RGE for 3rd gen

$$\frac{dm_{\tilde{t},\tilde{b}}^2}{dt} = \frac{1}{16\pi^2} |y_{t,b}|^2 \left(m_{H_{u,d}}^2 + m_{Q_3}^2 + m_{\tilde{t}_R,\tilde{b}_R}^2\right) + \dots$$
  
$$t = \log\left(Q\right)$$

# Gravity-mediated models (CMSSM/mSUGRA)

phenomenology

- SUSY-breaking model assumes hidden sector which couples to SM only through gravity
- assume universality of gaugino & sfermion masses at high scale
- leads small set of free par.

• R-parity is conserved

• experimental constraints leave small allowed parameter region



O. Buchmüller et al, arxiv:1207.7315

See also talk by J. Lindroos

# Gravity-mediated models and taus

- $\bullet\,$  In CMSSM/mSUGRA the  $\tilde{\tau}$  is often the lightest sfermion
- $\bullet\,$  at small  $M_0$  exists region where  $\tilde{\tau}$  and LSP are almost mass degenerate
- $\Rightarrow$  large co-annihilation cross-section in this region:  $\tilde{\chi}^0 \tilde{\tau}_1 \rightarrow \tau \gamma$
- This region is favoured by cosmological constraints: agreement with observed relic density  $\Omega_{\rm CDM}h^2 \sim 0.12$  from WMAP (without co-annihiliation the predicted  $\Omega_{\rm CDM}h^2$  is too high)



# Gauge-mediated SUSY-Breaking

- SSB is transmitted to the SM world via messenger fields
- No scalar mass parameter  $M_0$
- free parameters
  - $\Lambda$ : scale
- $M_{\rm mes}$ : messenger mass scale
  - $N_5$ : nr of equivalent messengers
- $\tan\beta$ : ratio of VEVs
- $\mathit{C}_{\mathrm{grav}}$ : Gravitino mass ratio
- $sign(\mu)$ : sign of mass parameter for Higgsino superfield mixing
  - NLSP is either  $\tilde{\chi}_1^0$ ,  $\tilde{\tau}_1$  or  $\tilde{e}_R/\tilde{\mu}_R$
  - LSP is the gravitino  $\widetilde{G}$



S. Martin - illustration

- typical  $M_{\text{mes}} = 250 \text{ GeV}$ ,  $N_5 = 3$ , sign=+,  $C_{\text{grav}} = 1$ .
- between 2 and 4  $\tau$  in final state  $\tilde{\chi}^0_1 \rightarrow \tilde{\tau}^+ \tau^- \rightarrow \tau^+ \tau^- \widetilde{G}$  .

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# Other models

#### Model-independent search:

 ad-hoc model of strong gluino pair production with decay chain to LSP



- gluino and LSP masses are free parameters
- decay through *X˜*<sup>0</sup> or *X˜*<sup>±</sup> with fixed mass (<sup>1</sup>/<sub>2</sub>m<sub>*˜*g</sub>)
- used in CMS interpretation under the name "T5taunu" and "T3tauh"

#### **R-Parity violating models:**

- lightest SUSY particle can decay
- additional symmetries needed to prevent proton decay
- However, existence of DM not argument against RPV SUSY:
  - ▷ very small *R* coupling to LSP
     ▷ gravitino DM

merits dedicated talk

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# **Experimental signatures**

#### final states with

- typically  $\geq 2$  taus are produced, Second  $\tau$  could be soft if  $\Delta M(\tilde{\tau}_1, \tilde{\chi}_1^0) \lesssim 5 \text{ GeV}$
- low efficiency and high  $p_{\rm T}$  threshold for identification: signatures with 1 and 2 taus
- jets +  $E_{\rm T}^{\rm miss}$  triggers (easier to trigger than  $\tau$ )



### $Tau+Jets+MissingE_{\tau}$ signals

- Quantities sensitive to high masses of SUSY process
- Transverse scalar sum  $H_{\rm T} = \sum p_{\rm T}^{\tau} + \sum p_{\rm T}^{\rm jet}$





No excess of data events above SM backgrounds

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# CMSSM limits from tau final states

### • For $\tan \beta = 40$ , $A_0 = 500 \text{ GeV}$ , $\mu > 0$

- High sensitivity in co-annihilation region
- $\label{eq:mgluino} m_{\rm gluino} < 1.15 \, {\rm TeV} \\ {\rm for} \ M_0 < 400 \, {\rm GeV}$
- CMS-PAS SUS-12-004

#### one tau



#### at least two tau



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# **ATLAS GMSB Limits with taus**



see talk by Ø. Dale arxiv:1210.1314, 1208.4688 [hep-ex]

#### Limits on free model parameters

- $\Lambda < 50 \dots 60$  TeV excluded at 95% CL over almost entire allowed  $\tan \beta$  region
- results from τ and di-lepton analyses: comparable limits, complementary regions

ATLAS and CMS results

### Tau results as part of ATLAS SUSY Searches

	ATLAS SUSY S	Searches* - 95% CL Lower Limits (Status:	Dec 2012)
NEUCEDA (CHECH LO IN LES CE			
MSUGRA/CMSSM : 0 lep + j's + E <sub>T,miss</sub>	L=5.8 fb , 8 TeV [ATLAS-CONF-2012-709]	1.50 TeV q = g mass	•
MOUGRA/OMOOM . Tiep + Js + E <sub>T,miss</sub>	LISS ID ', 8 TeV [ATLAS-CONF-2012-104]	1.24 TeV g = g mass	171 15
Pheno model : U lep + J s + E <sub>T,miss</sub>	L=5.8 fb", 8 TeV [ATLAS-CONF-2012-103]	1.18 TeV g mass (m(q) < 2 TeV, light χ <sub>1</sub> )	Brolimicon
Pheno model : U lep + J s + E <sub>T,miss</sub>	L=5.8 fb , 8 TeV [ATLAS-CONF-2012-103]	1.38 TeV q mass (m(g) < 2 TeV, light χ.)	Pieninary
Gluino med. χ (g→qqχ): 1 lep + js + E <sub>T miss</sub>	L=4.7 fb , 7 TeV [1208.4688]	900 GeV g mass $(m(\chi) < 200 \text{ GeV}, m(\chi') = \frac{1}{2}(m_0)$	( )+m(g))
6 GMSB (INLSP) : 2 lep (OS) + 1S + E CMSP (#NILSP) : 1.2 r + 0.4 lop + 1S + E T,miss	Lo4.7 fb ', 7 TeV [1208.4688]	1.24 TeV 9 ITIdISS (tan/r < 15)	
GIGM (bino NI SP) : wy + E	Lo4.7 fb ', 7 TeV [1210.1314]	1.20 TeV g (TIASS (tan)/ > 20)	[
GGM (wino NI SP) : v + lep + F <sup>T,miss</sup>	Lo4.8 fb , 7 TeV [1209.0753]	1.07 lev g mass (m(χ,) > 50 GeV)	$Ldt = (2.1 - 13.0) \text{ fb}^{-1}$
GCM (biggsing bing NI SP) w + b + E <sup>T,miss</sup>	LING ID , 7 TEV [ATEAS-CONF-2012-164]	era dev grindss	·
COM (higgshio billo filed) 7 - j rb r 2 Timis	LI4.010 ,7 16V [1211.1167]	900 Gev g (11855 (m(x ) > 220 Gev)	IS = 7, 8 IEV
GGW (higgsho NLOP) . 2 + jets + E <sub>T,miss</sub>	L=5.8 fb ', 8 TeV [ATLAS-CONP-2012-152]	GOUGEV GITTASS (M(H) S 200 GEV)	
Graviuno LSP - monojet + ET,min	L=10.5 fb , 8 TeV [ATLAS-CONF-2012-147]	545 Gev F SCALE (M(G) > 10 eV)	
G → DDY (VIRUAID): 0 lep + 3 D-JS + E <sub>T,miss</sub>	LITZETE , E TEV (KILKS-CONF-2012-145)	1.24 TeV g (mass (m(2,) < 200 GeV)	
g g yrux (virtualt) : 2 lop (35) + 15 + E <sub>T,miss</sub>	1-13-05 <sup>-1</sup> 8 Tev (ATLAS CONF-2012-105)	90 GeV (mm255 (mm2) < 300 GeV)	8 TeV results
G G G G G G G G G G G G G G G G G G G	LITSOID , & TEV (KICKS-CONF-2012-151)	G (10) (10) (10) (10) (10) (10) (10) (10)	
g g g→tty (virtuart) to tep + multi-js + E <sub>T,miss</sub>	LISSIS , STEV (ATLAS-CONF-2012-103)	1 15 TeV 0 TRASS (m(2) < 300 GeV)	7 TeV results
g→uz, tvirtual() : 0 lop + 3 b-is + ET_miss	Lata etc." a Terristi se conte ana resi	620 GeV b mass (m <sup>2</sup> ) = 120 GeV	
2 5 bb b stort 2 lop + in + E	Lata 64 <sup>-4</sup> a Tev (ATLAS CONF 2012 (61)	(05 GeV b mass (m <sup>27</sup> ) = 2 m <sup>27</sup> )	
10,0,→(7, 3 lep + ] S + E <sub>T,miss</sub>	Let 7.0 <sup>-1</sup> 7 TeV (1978 4905 1970 210367 0-11	t mass (m <sup>2</sup> ) = 50 (m)	
ff (medium) T-by <sup>±</sup> : 1 len + biet + F	Lata ALT & Tay INTI AS COME 2012 1881	160.250 GeV T mpss (m <sup>20</sup> ) = 0.0eV (m <sup>20</sup> ) = 150.0eV)	
$\vec{T}$ $\vec{T}$ $(medium)^{T}$ $\vec{T} \rightarrow b\vec{x}^{\pm}$ $(2 \text{ len } + \vec{F})^{miss}$	Land the " a Tex (AT) AS COME 2012 107	100 500 COLT ( TIMOSO (m()) = 0 Col( m(), m(-)) = 10 Col()	
6 5 ft t_sty : 1 len + hiet + F	Land the " a Tex (AT) AS COME 2012 (48)	210.500 GeV T (110.55 (m <sup>2</sup> ) = 0	
T T-sty 0/1/2 len (+ h.iets) + F	I =4.7 fb <sup>-1</sup> 7 TeV [1208 1447 1208 2500 1209 418	$230.465 \text{ GeV} \pm 0.355 \text{ (m/s^2)} = 0)$	
ft (natural GMSB) ; Z(→II) + b-iet + E <sup>T</sup> miss	L=2.1 fb <sup>-1</sup> , 7 TeV (1204.6736)	310 GeV T MASS (115 c m/r) c 230 GeV)	
1.1 July 2 lon + F	L=4.7 fb <sup>-1</sup> , 7 TeV (1208.2884) 85,195 (1	ev [mass (m(x)) = 0)	
$\geq 9$ $\vec{y}^* \vec{y} \cdot \vec{y}^* \rightarrow i v (i \vec{v}) \rightarrow i v \vec{y} \cdot 2 \text{ len } + F$	L=4.7 fb <sup>-1</sup> , 7 TeV [1208.2884]	110.340 GeV 7 mass (mg) = 10 GeV m(v) = 1(mg) + m(v))	
$\overrightarrow{P} = \overrightarrow{V} \xrightarrow{V_1} \overrightarrow{V} \xrightarrow{V_1} \overrightarrow{V} \xrightarrow{V_2} \overrightarrow{V} \overrightarrow{V} \xrightarrow{V_2} \overrightarrow{V} \overrightarrow{V} \overrightarrow{V} \overrightarrow{V} \overrightarrow{V} \overrightarrow{V} \overrightarrow{V} V$	( =13.0 fb <sup>-1</sup> 8 TeV (ATLAS, CONF, 2012, 154)	580 GeV $\vec{y}^{\pm}$ mass $(m(\vec{y}) = m\vec{y}^{0}) m(\vec{y}) = 0$ m( $\vec{y}$ ) as ab	(sup)
$M_{1}^{+}2 \xrightarrow{\pm}{} W_{-}^{+} W_{-}^{+} \xrightarrow{0}{} T_{-}^{+} \xrightarrow{0}{} 3 \log \pm E_{-}^{+}$	L=13.0 fb <sup>-1</sup> , 8 TeV (ATLAS-CONF-2012-154) 14	0.295 GeV $\overline{\gamma}^{2}$ mass $(m(\overline{\gamma}^{2}) = m(\overline{\gamma}^{2}), m(\overline{\gamma}^{2}) = 0$ , sleptons decoupled)	,
<ul> <li>Direct v pair prod (AMSB) : long-lived v</li> </ul>	L=4.7 fb <sup>-1</sup> , 7 TeV (1210.2852) 220	$rav \overline{y}^{\pm}$ mass $(1 < t(\overline{y}^{\pm}) < 10 \text{ ns})$	
Stable & R-hadrons : low 8. By (full detector)	L=4.7 fb <sup>-1</sup> , 7 TeV [1211.1597]	985 GeV g mass	
Stable t R-badrops : low 8 By (full detector)	L=4.7 fb <sup>-1</sup> , 7 TeV (1211,1527)	683 GeV t mass	
GMSB : stable 7	L=4.7 fb <sup>-1</sup> , 7 TeV [1211.1597]	300 GeV τ mass (5 < tanβ < 20)	
¬¬¬¬¬¬¬¬¬¬¬¬¬¬¬¬¬¬¬¬¬¬¬¬¬¬¬¬¬¬¬¬¬¬¬¬	L=4.4 fb <sup>-1</sup> , 7 TeV [1210.7451]	700 GeV 9 mass (0.3<10 <sup>4</sup> < λ <sub>ma</sub> < 1.5<10 <sup>4</sup> , 1 mm < ct	< 1 m,g decoupled)
LFV : pp→v +X, v →e+u resonance	L=4.6 fb <sup>-1</sup> , 7 TeV [Preliminary]	1.61 TeV V, MASS (λ <sub>107</sub> =0.10, λ <sub>110</sub> =0.	05)
LFV : $pp \rightarrow \bar{y} + X, \bar{y} \rightarrow e(u) + \tau$ resonance	L=4.6 fb <sup>-1</sup> , 7 TeV [Preliminary]	1.10 TeV V, MASS (λ <sub>11</sub> =0.10, λ <sub>12000</sub> =0.05)	
Bilinear RPV CMSSM : 1 lep + 7 j's + E <sub>T miss</sub>	L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-140]	1.2 TeV q = g mass (cr, co < 1 mm)	
$\tilde{C} = \tilde{\chi}^* \tilde{\chi}, \tilde{\chi}^* \rightarrow W \tilde{\chi}^0, \tilde{\chi}^0 \rightarrow eev_{1,e}\mu v_{1,e} : 4 lep + E_{\chi_{max}}$	L=13.0 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2012-153]	700 GeV χ mass (m(χ) > 300 GeV, λ <sub>100</sub> or λ <sub>100</sub> > 0	
$11.1 \rightarrow 17, 7 \rightarrow eev.euv$ ; $4 lep + E_{v}$	L=13.6 fs <sup>-1</sup> , 8 TeV (ATLAS-CONF-2012-153) 430 GeV I mass (m(x)) > 100 GeV/m(L)=m(L)=m(L), tay (0, 7), 102 > 0)		
a→ agg : 3-iet resonance pair	L=4.6 fb <sup>-1</sup> , 7 TeV [1210.4813]	666 GeV g mass	
Scalar gluon : 2-jet resonance pair	L=4.6 fb <sup>-1</sup> , 7 TeV [1210.4826] 10	-287 GeV Sgluon mass (incl. limit from 1110.2693)	
WIMP interaction (D5, Dirac χ) : 'monojet' + E	L=10.5 fb <sup>-1</sup> , 8 TeV [ATLAS-CONF-2012;447]	704 GeV M* scale (mg < 80 GeV, limit of < 687 GeV to	r (28)
	10 <sup>-1</sup>	1	10

\*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. Mass scale [TeV]

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# CMS GMSB Limits with taus



- Figure shows exclusion limits as function of gluino mass
- Gluino mass < 860 GeV is excluded at 95% CL

ATLAS and CMS results

### **CMS** Razor

#### Razor variable:

- Captures kinematics of the generic process of pair production of two heavy particles.
- Event forced into dijet signature
- $M_R$  characterizes the presence of a heavy particle mass scale

$$M_R \!=\! \sqrt{\left(p^{\text{jet1}}\!+\!p^{\text{jet2}}\right)^2 - \left(p_z^{\text{jet1}}\!+\!p_z^{\text{jet2}}\right)^2}$$

• Razor 
$$R = \frac{\sqrt{E_{\mathrm{T}}^{\mathrm{miss}}\left(p_{T}^{\mathrm{jet1}} + p_{T}^{\mathrm{jet2}}\right) - E_{\mathrm{T}}^{\mathrm{miss}}\left(\vec{p}_{T}^{\mathrm{jet1}} + \vec{p}_{T}^{\mathrm{jet2}}\right)}{M_{R}}}$$



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### CMS Razor II

#### Model-indep. interpretation

- Interpretation in simplified models
- $\tilde{\chi}^{\pm}$  and  $\tilde{\chi}^{0}$  decaying to  $\tau$ s
- limit set on gluino mass



# Summary

- Motivations for finding SUSY in tau final states: from theory itself but also from DM density
- Another motivation: ability to distinguish a tau-enriched SUSY signal from that of a general multi-lepton signal
- ATLAS & CMS tau ID performs well

SUSY Models

W. Liebig

- Several analyses and model-(in)dependent interpretations
- Translated to gluino mass, data requires  $m_{\tilde{g}} > 1.15 \dots 1.25$  TeV
- ATLAS & CMS public results currently from 7 TeV data. Expect results from 22 fb<sup>-1</sup> @ 8 TeV data next year!

# SUSY searches at the LHC 2015-2022

- Increase in mass scale reach from high collision energy ( 14 TeV) and high lumi (  $3000 \text{ fb}^{-1}$ )
- If SUSY is discovered: subsequent determination of model parameters should allow prediction of relic density with precision similar to WMAP with  $\sim$ 30 fb<sup>-1</sup> (for mSUGRA, Arnowitt et al, PRL 100 231802 (2008))
- if SUSY is not discovered: increasing difference between SM mass scale and remaining allowed regions for SUSY masses
   ⇒ *little hierarchy problem.*