Higgs Boson Discovery Open Questions

Summary: BSM/Cosmology Sessions

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on behalf of the BSM/Cosmology Conveners

19 15. November 2013 Linear Collider Workshop, Tokyo Introdction

Searches for New Physics BSM Searches at the Linear Collider Conclusion Higgs Boson Discovery Open Questions

ATLAS, $H \rightarrow \gamma \gamma$

 $\textbf{CMS}, \ \textbf{H} \rightarrow \textbf{ZZ} \rightarrow \textbf{4I}$



• Discovery of $\sim 126 \,\text{GeV}$ SM like Higgs boson \Rightarrow SM is complete!



Higgs Boson Discovery Open Questions

Open Questions

- No candidate for dark matter in SM
- What is dark energy?

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- Source of Baryon asymmetry?
- Cause for inflation in the early universe?





Higgs Boson Discovery Open Questions

Open Questions

- No candidate for dark matter in SM
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- Source of Baryon asymmetry?
- Cause for inflation in the early universe?





- Hierarchy problem
- Neutrino masses
- Unification of couplings?
- Measurement of g-2

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SUSY Searches at the LHC Is SUSY already excluded?

SUSY Searches at the LHC



- Search for simplified SUSY models: dominant cascade assuming 100% BR
- Models described by masses and cross sections
- 95% exclusion limits

D. Teyssier - LHC results and prospects: Beyond the Standard Model

SUSY Searches at the LHC Is SUSY already excluded?

SUSY Searches at the LHC

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: SUSY 2013

ATLAS Preliminary

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

	Model	e, μ, τ, γ	Jets	E_{T}^{miss}	∫£ dt[ft	⁻¹] Mass limit	Reference
Inclusive Searches	$\begin{array}{l} \text{MSUGRA/CMSSM} \\ \text{MSUGRA/CMSSM} \\ \text{MSUGRA/CMSSM} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q \tilde{g}^{1} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q \tilde{\chi}_{1}^{0} \\ q q W^{\pm} \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q (\ell/\ell/\gamma/m) \tilde{\chi}_{1}^{0} \\ \text{GMSB} (\tilde{\ell} \text{ NLSP}) \\ \text{GMSB} (\tilde{\ell} \text{ NLSP}) \\ \text{GGM (bino NLSP)} \\ \text{GGM (vino NLSP)} \\ \text{GGM (hiog Sino-bino NLSP)} \\ \text{GGM (hiogsino NLSP)} \\ \text{Gravitino LSP} \\ \text{Gravitino LSP} \end{array}$	$\begin{array}{c} 0 \\ 1 \ e, \mu \\ 0 \\ 0 \\ 1 \ e, \mu \\ 2 \ e, \mu \\ 2 \ e, \mu \\ 1 - 2 \ \tau \\ 2 \ \gamma \\ 1 \ e, \mu + \gamma \\ \gamma \\ 2 \ e, \mu (Z) \\ 0 \end{array}$	2-6 jets 3-6 jets 7-10 jets 2-6 jets 2-6 jets 3-6 jets 0-3 jets 0-2 jets 1 b 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 4.7 20.7 4.8 4.8 4.8 4.8 5.8 10.5	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	TLAS-CONF-2013-047 TLAS-CONF-2013-062 1308.1841 TLAS-CONF-2013-047 TLAS-CONF-2013-047 TLAS-CONF-2013-089 1208.4688 TLAS-CONF-2013-089 1208.4688 TLAS-CONF-2013-026 1209.0753 TLAS-CONF-2012-144 1211.1167 TLAS-CONF-2012-152 TLAS-CONF-2012-152
3 rd gen. ẽ med.	$\begin{array}{l} \tilde{g} \rightarrow b \bar{b} \tilde{\chi}_{1}^{0} \\ \tilde{g} \rightarrow t \bar{t} \tilde{\chi}_{1}^{0} \\ \tilde{g} \rightarrow t \bar{t} \tilde{\chi}_{1}^{1} \\ \tilde{g} \rightarrow b \bar{t} \tilde{\chi}_{1}^{1} \end{array}$	0 0 0-1 <i>e</i> , μ 0-1 <i>e</i> , μ	3 b 7-10 jets 3 b 3 b	Yes Yes Yes Yes	20.1 20.3 20.1 20.1	8 1.2 TeV m(ξ ²)<600 GeV AT 8 1.1 Tt V m(ξ ²)<600 GeV AT 1.1 Tt V m(ξ ²)<350 GeV 1.24 TeV m(ξ ²)<400 GeV AT 3 TeV m(ξ ²)<400 GeV AT	TLAS-CONF-2013-061 1308.1841 TLAS-CONF-2013-061 TLAS-CONF-2013-061
3 rd gen. squarks direct production	$ \begin{array}{l} \tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow \tilde{b}_1^{V_1} \\ \tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow \tilde{b}_1^{T_1} \\ \tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow \tilde{b}_1^{T_1} \\ \tilde{\tau}_1 \tilde{t}_1 ([ight]), \tilde{t}_1 \rightarrow \tilde{b}_1^{T_1} \\ \tilde{\tau}_1 \tilde{\tau}_1 ([ight]), \tilde{t}_1 \rightarrow \tilde{b}_1^{V_1} \\ \tilde{\tau}_1 \tilde{\tau}_1 ([neadym]), \tilde{t}_1 \rightarrow \tilde{b}_1^{V_1} \\ \tilde{\tau}_1 \tilde{\tau}_1 ([neadym]), \tilde{t}_1 \rightarrow \tilde{b}_1^{V_1} \\ \tilde{\tau}_1 \tilde{\tau}_1 ([neadym]), \tilde{t}_1 \rightarrow \tilde{b}_1^{V_1} \\ \tilde{\tau}_1 \tilde{\tau}_1 \tilde{\tau}_1 \tilde{\tau}_1 \tilde{\tau}_1 \rightarrow \tilde{b}_1^{V_1} \\ \tilde{\tau}_1 \tilde{\tau}_1 \tilde{\tau}_1 \tilde{\tau}_1 \tilde{\tau}_1 \rightarrow \tilde{b}_1^{V_1} \\ \tilde{\tau}_1 \tilde{\tau}_1 ([neadym]), \tilde{t}_1 \rightarrow \tilde{b}_1^{V_1} \\ \tilde{\tau}_1 \tilde{\tau}_1 ([natural GMSB)) \\ \tilde{\tau}_1 \tilde{\tau}_1 \tilde{\tau}_1 \rightarrow \tilde{c}_1^{V_1} \\ \tilde{\tau}_1 \tilde{\tau}_1, \tilde{\tau}_1 \rightarrow \tilde{t}_1 - \tilde{t}_1 - \tilde{t}_1 \\ \tilde{\tau}_1 \tilde{\tau}_1 \tilde{\tau}_1 = \tilde{t}_1 - \tilde{t}_1 - \tilde{t}_1 \\ \tilde{\tau}_1 \tilde{\tau}_1 \tilde{\tau}_1 = \tilde{t}_1 - \tilde{t}_1 - \tilde{t}_1 \\ \tilde{t}_1 \tilde{\tau}_1 = \tilde{t}_1 - \tilde{t}_1 - \tilde{t}_1 \\ \tilde{t}_1 \tilde{\tau}_1 = \tilde{t}_1 - \tilde{t}_1 - \tilde{t}_1 \\ \tilde{t}_1 \tilde{\tau}_1 = \tilde{t}_1 - \tilde{t}_1 - \tilde{t}_1 \\ \tilde{t}_1 \tilde{\tau}_1 = \tilde{t}_1 - \tilde{t}_1 - \tilde{t}_1 \\ \tilde{t}_1 \tilde{\tau}_1 = \tilde{t}_1 - \tilde{t}_1 - \tilde{t}_1 \\ \tilde{t}_1 \tilde{\tau}_1 = \tilde{t}_1 - \tilde{t}_1 - \tilde{t}_1 - \tilde{t}_1 \\ \tilde{t}_1 = \tilde{t}_1 - \tilde{t}_1 - \tilde{t}_1 - \tilde{t}_1 \\ \tilde{t}_1 = \tilde{t}_1 - \tilde{t}_1 - \tilde{t}_1 - \tilde{t}_1 \\ \tilde{t}_1 = \tilde{t}_1 - \tilde{t}_1 - \tilde{t}_1 \\ \tilde{t}_1$	$\begin{array}{c} 0 \\ 2 \ e, \mu \ (\text{SS}) \\ 1 - 2 \ e, \mu \\ 2 \ e, \mu \\ 2 \ e, \mu \\ 0 \\ 1 \ e, \mu \\ 0 \\ 1 \ e, \mu \\ 0 \\ 3 \ e, \mu \ (Z) \end{array}$	2 b 0-3 b 1-2 b 0-2 jets 2 jets 2 b 1 b 2 b ono-jet/c-t 1 b 1 b	Yes Yes Yes Yes Yes Yes Yes Yes Yes Yes	20.1 20.7 4.7 20.3 20.3 20.1 20.7 20.5 20.3 20.7 20.7	$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	1308.2631 TLAS-CONF-2013-007 1208.4305, 1209.2102 TLAS-CONF-2013-048 TLAS-CONF-2013-065 1308.2631 TLAS-CONF-2013-027 TLAS-CONF-2013-028 TLAS-CONF-2013-025
EW direct	$ \begin{array}{l} \tilde{\ell}_{L,R}\tilde{\ell}_{L,R},\tilde{\ell} \rightarrow \ell \tilde{\chi}_{1}^{0} \\ \tilde{\chi}_{1}^{+}\tilde{\chi}_{1}^{-},\tilde{\chi}_{1}^{+} \rightarrow \tilde{\ell}\nu(\ell \tilde{\nu}) \\ \tilde{\chi}_{1}^{+}\tilde{\chi}_{2}^{-},\tilde{\chi}_{1}^{+} \rightarrow \tilde{\ell}\nu(\ell \tilde{\nu}) \\ \tilde{\chi}_{1}^{+}\tilde{\chi}_{2}^{0} \rightarrow \tilde{\ell}_{1}\nu \tilde{\ell}(\ell(\tilde{\nu}\nu), \ell \tilde{\nu} \tilde{\ell}_{L}\ell(\tilde{\nu}\nu)) \\ \tilde{\chi}_{1}^{+}\tilde{\chi}_{2}^{0} \rightarrow \tilde{\mathcal{M}}_{2}^{+} \ell \tilde{\chi}_{1}^{0} \\ \tilde{\chi}_{1}^{+}\tilde{\chi}_{2}^{0} \rightarrow \tilde{\mathcal{M}}_{2}^{+} \ell \tilde{\chi}_{1}^{0} \\ \tilde{\chi}_{1}^{+}\tilde{\chi}_{2}^{0} \rightarrow \tilde{\mathcal{M}}_{2}^{+} \ell \tilde{\chi}_{1}^{0} \\ \end{array} $	2 e, μ 2 e, μ 2 τ 3 e, μ 3 e, μ 1 e, μ	0 0 - 0 2 <i>b</i>	Yes Yes Yes Yes Yes Yes	20.3 20.3 20.7 20.7 20.7 20.7 20.3	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	TLAS-CONF-2013-049 TLAS-CONF-2013-049 TLAS-CONF-2013-028 TLAS-CONF-2013-035 TLAS-CONF-2013-035 TLAS-CONF-2013-093
Long-lived particles	Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^+$ Stable, stopped \tilde{g} R-hadron GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{e}, \tilde{\mu}) + \tau(GMSB, \tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}, long-lived \tilde{\chi}_1^0$ $\tilde{q}\tilde{q}, \tilde{\chi}_1^0 \rightarrow qq\mu$ (RPV)	Disapp. trk 0 e, μ) 1-2 μ 2 γ 1 μ , displ. vtx	1 jet 1-5 jets - - -	Yes Yes - Yes -	20.3 22.9 15.9 4.7 20.3	χ ¹ 270 GeV m(k ⁷ ₁)-m(k ⁹ ₁)=160 MeV, τ(k ⁷ ₁)=0.2 ns Ai ğ 832 GeV m(k ⁷ ₁)-m(k ⁹ ₁)=160 MeV, τ(k ⁷ ₁)=0.2 ns Ai χ ⁰ 475 GeV m(k ⁷ ₁)-m0 GeV, 10 μs-τ(ğ)<100 s	TLAS-CONF-2013-069 TLAS-CONF-2013-057 TLAS-CONF-2013-058 1304.6310 TLAS-CONF-2013-092
RPV	$ \begin{array}{l} LFV \ pp \rightarrow \tilde{v}_{\tau} + X, \ \tilde{v}_{\tau} \rightarrow e + \mu \\ LFV \ pp \rightarrow \tilde{v}_{\tau} + X, \ \tilde{v}_{\tau} \rightarrow e(\mu) + \tau \\ Bilinear \ RPV \ CMSSM \\ \tilde{x}_1^+ \tilde{x}_1^-, \ \tilde{x}_1^+ \rightarrow W \tilde{x}_1^0, \ \tilde{x}_1^0 \rightarrow e \tilde{v}_{\mu}, e \mu \tilde{u} \\ \tilde{x}_1^+ \tilde{x}_1^-, \ \tilde{x}_1^+ \rightarrow W \tilde{x}_1^0, \ \tilde{x}_1^0 \rightarrow e \tilde{v}_{\mu}, e \mu \tilde{u} \\ \tilde{x}_1^+ \tilde{x}_1, \ \tilde{x}_1^+ \rightarrow W \tilde{x}_1^0, \ \tilde{x}_1^+ \rightarrow \tau \tilde{v}_e, e \tau \tilde{v} \\ \tilde{g} \rightarrow q q \\ \tilde{g} \rightarrow \tilde{t}_1 t, \ \tilde{t}_1 \rightarrow b s \end{array} $	$\begin{array}{c} 2 \ e, \mu \\ 1 \ e, \mu + \tau \\ 1 \ e, \mu \\ \tau \end{array} \\ \begin{array}{c} 3 \ e, \mu + \tau \\ 0 \\ 2 \ e, \mu (SS) \end{array}$	- 7 jets - 6-7 jets 0-3 b	Yes Yes Yes Yes	4.6 4.6 4.7 20.7 20.7 20.3 20.7	Fr 1.61 TeV $\lambda_{311}^{\prime}=0.10, \lambda_{132}=0.05$ Fr 1.1 Tv $\lambda_{311}^{\prime}=0.10, \lambda_{132}=0.05$ G. & 1.2 TeV $\kappa_{311}^{\prime}=0.10, \lambda_{123}=0.05$ J. Z TeV $\kappa_{311}^{\prime}=0.10, \lambda_{123}=0.05$ J. Z TeV m($\lambda_{110}^{\prime}=0.05, \lambda_{121}=0.05$ J. Z TeV m($\lambda_{110}^{\prime}=0.05, \lambda_{121}=0.05$ J. Z TeV m($\lambda_{110}^{\prime}=0.05, \lambda_{121}=0.05$ J. Z TeV m($\lambda_{110}^{\prime}=0.06V, \lambda_{121}=0.05$ J. Z TeV m($\lambda_{110}^{\prime}=0.06V, \lambda_{121}=0.05$ J. Z S BR(h)=	1212.1272 1212.1272 TLAS-CONF-2012-140 TLAS-CONF-2013-036 TLAS-CONF-2013-036 TLAS-CONF-2013-036 TLAS-CONF-2013-091
Other	Scalar gluon pair, sgluon $\rightarrow q\bar{q}$ Scalar gluon pair, sgluon $\rightarrow t\bar{t}$ WIMP interaction (D5, Dirac χ)	0 2 <i>e</i> ,μ (SS) 0	4 jets 1 <i>b</i> mono-jet	- Yes Yes	4.6 14.3 10.5	sgluon 100-287 GeV incl. limit from 1110.2693 AT sgluon 800 GeV m(χ)<80 GeV, limit of <687 GeV for D8	1210.4826 TLAS-CONF-2013-051 TLAS-CONF-2012-147
	√s = 7 TeV full data	vs = 8 TeV	full	8 TeV data		10 ⁻¹ Mass scale [TeV]	

⇒ **D. Teyssier** - LHC results and prospects: Beyond the Standard Model

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SUSY Searches at the LHC Is SUSY already excluded?

Is SUSY already Excluded at ILC Energies?

- Need to investigate realistic decay chains (BR \neq 1)
- Include for example: $\tilde{\chi}_2^0 \rightarrow h \tilde{\chi}_1^0$ (weak bounds)



 \Rightarrow **S. Heinemeyer** - Does the LHC exclude SUSY particles at the ILC?

• Controlling systematic uncertainties is crucial and might lead to low sensitivity even for LHC at 14 TeV and $300\,{\rm fb}^{-1}$

 \Rightarrow **D. Krücker** - Non-Simplified SUSY:A Stau-Coannihilation model at LHC and ILC

BSM Models Accessible at the LC What is the Expected SUSY Reach for the LC? Measuring BSM Parameters at the LC

BSM Models Accessible at the LC

• Anomaly in g - 2 explained by Gaugino contribution

 $\Rightarrow M. Endo - Reconstructing SUSY Contribu$ tion to Muon g-2 at ILC $<math display="block">\Rightarrow N. Yokozaki - A practical GMSB model for$ explaining the muon g-2 with gauge couplingunification

• NR charged Wino pairs produced will annihilate before decay

 \Rightarrow K. Ichikawa - Threshold Production for Wino Dark Matter at a LC



- Split Stop $(m\tilde{t}_1, m\tilde{b}_1 \ll m_{\tilde{t}_2}, m_{\tilde{b}_2})$ can avoid detection at LHC with $300 \, {\rm fb}^{-1} \rightarrow {\rm discovery}$ at LC
- ⇒ **T. Kon** Signatures at One-loop Order of Split Stops Scenarios using GRACE/SUSY

BSM Models Accessible at the LC What is the Expected SUSY Reach for the LC? Measuring BSM Parameters at the LC

What is the Expected SUSY Reach for the LC?

- 10M points in (almost) unconstrained pMSSM to estimate SUSY reach (19 parameters)
- $\bullet\,$ Sizable fraction of models remains out of reach even for $3\,{\rm ab}^{-1}$ LHC
- LC can rule out most models by measuring Higgs BR



- Direct and indirect DM searches help to constrain pMSSM parameter space if LHC finds nothing
- Require LC to measure model parameters



BSM Models Accessible at the LC What is the Expected SUSY Reach for the LC? Measuring BSM Parameters at the LC

Measuring BSM Parameters at the LC



BSM Models Accessible at the LC What is the Expected SUSY Reach for the LC? Measuring BSM Parameters at the LC

Measuring BSM Parameters at the LC

particle	Mass(GeV)	accuracy							
A _H	81.9	1.3%							
W _H	369	0.20%							
Z _H	368	0.56%							
e _H	410	0.46%							
V _H	400	0.10%							
\Rightarrow E. Kato - Little Higgs with T-									
parity measurements at the ILC									



BSM Models Accessible at the LC What is the Expected SUSY Reach for the LC? Measuring BSM Parameters at the LC

Is SUSY the right Theory?

• Fine tuning in an effective theory does not imply fine-tuning of the fundamental theorie





 Only need to give up naturalness if there are no light higgsinos

 \Rightarrow H. Baer - How conventional measures overestimate EW finetuning in SUSY theory, and why this implies we must build ILC





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BSM Models Accessible at the LC What is the Expected SUSY Reach for the LC? Measuring BSM Parameters at the LC

Separating Different SUSY Models

- Need renormalization of the full cMSSM to determine correct BR
- NLO corrections on cross sections of up to 20%

⇒ S. Heinemeyer - Higgs and DM Production
via SUSY Decays at the LC

- Distinguish Majorana (MSSM) from Dirac (MRSSM) sparticles
- Gluinos accessible at LHC \rightarrow need ILC for neutralinos

 \Rightarrow **S. Y. Choi** - Probing the nature of neutralinos at the ILC

- M_1 , M_2 and μ determined from precise measurements (tree level)
- Inclusion of NLO corrections allows access to $m_{\tilde{t}}$ and $\cos \theta_t$
- \Rightarrow J. Kalinowski Determining SUSY parameters from chargino production: including NLO corrections
 - Using polarized beams to distinguish MSSM from NMSSM

 \Rightarrow **S. Porto** - How to distinguish NMSSM and MSSM?

Still many open questions ⇒ the SM is not the end of the story Read the fine print when interpreting LHC exclusion limits! The Higgs discovery allows new ways to constrain physics beyond the Standard Model

 \Rightarrow the linear collider is the ideal tool to explore this new territory