#### **TitleTheory II:**

#### **BSM physics: direct production and indirect sensitivity**

- Why is the SM not sufficient?
- Prospects for SUSY
- Dark Matter Searches
- What about the excess at 750 GeV at the LHC?
- Conclusions



#### Let's start the BSM snooker now ....

# Open questions:

- Particle discovered with m<sub>H</sub>~125 GeV Higgs@SM?
  - The discovered signal is so far compatible with a SM-like Higgs, but a variety of interpretations is possible, corresponding to very different underlying physics
  - We still need precision measurements of couplings, potential, CP properties,...
- In addition

The SM does not contain

- Unification
- Dark matter
- Baryon/Antibaryon Asymmetry
- Neutrino masses
- Gravity

**Cosmo constant** 

Extreme fine tuning



- The SM offers no satisfying answers to those open issues
- Compelling solutions via `Beyond Standard Model' Physics?

#### **Experimental hints for physics beyond the SM?**

- Currently several flavour anomalies:
   > b-> c τ v<sub>τ</sub>, b-> s l- l+, b→sµµ,... : always 2-4 σ level
- Excess at 750 GeV at the LHC:

> not yet established, but already well studied ....

• Whole Neutrino sector;  $\theta_{13}$  rather large...

Obviously, there is BSM around, but there is no consistent picture or experimental hints where to look.

Many different models have been analyzed

> with more or less physics potential for solving the open questions ....

But what's the status? Which interpretations are possible? What are the technical requirements that might be essential for resolving the puzzle,....let's start

# Status physics

guaranteed physics!

well

motivated

W. Chou,

**EPS15** 

- Current physics case for e+e-:
  - Higgs precision physics
  - Top precision physics
  - Light electroweak particles/DM searches
  - BSM detection in general, complementary to LHC
- HEP-e+e-: ILC, CLIC or CepC or Fcc-ee
  - ILC, √s=90-500 (1000) GeV, 163 MW, 31 km, polarized beams, t≥2032
  - CLIC: √s=500 GeV,1.5, 3 TeV 560 MW, 48 km, polarized beams,t≥2035 P. Burrows
  - CepC: √s=240 GeV, 500 MW, 54 km, polarization unclear, t≥2028
  - FCC-ee: √s=350 GeV, 500 MW, 100km, no polarization at 350, t≥2035?
- My guess: only one project has a chance,...if at all

### **Current Status**

- So far: Higgs boson mH=125 GeV behaves SM-like.....
   > no deviations so far within current experimental accuracy
- No new particles found so far: do we live in a decoupling limit?
   Interpretation: Any BSM must contain a light SM-like scalar particle; fundamental or composite?

> puts strong constraints on all BSM models!

- Two possibilities within general 2HDM:
  - Decoupling limit: all but one scalar particle are heavy, m<sub>H</sub>~m<sub>A</sub>~m<sub>H+</sub>»v and m<sub>h</sub>~m<sub>hSM</sub>
  - Alignment limit: either h or H is completely aligned with v, i.e. h~h<sub>SM</sub> but H, A, H<sup>+</sup> not necessarily heavy
- No clear situation, no preferred direction to BSM:
  - Iooking for 'needle in haystack'
- Strategy: case studies, and need to be prepared for the unknown !

#### **Complements of the Standard Model**



# Comparison: pp and e+e- collisions



Characteristics of pp collider composite particles collide E(CM) < 2 E(beam)strong interaction in initial state `no' polarization applicable LHC:  $\sqrt{s} = 14TeV$ , used  $\hat{s} = x_1x_2s$  few TeV small fraction of events analyzed multiple triggers superposition with spectator jets

#### Large potential for direct discovery

e⁺• •e⁻

and of the e +e-(γe, γ γ) collider Pointlike particles collide Known E(CM) = 2 E(beam) well defined initial state polarized initial e- and e+ beams

B-fac ~ O(10)GeV,ILC~90-500GeV , 1 TeV, tunable CepC~240, FCC-ee~350, CLIC~0.5, 1.5, 3 TeV most events in detector analyzed no triggers required clean +fully reconstructable events

Large potential for discovery also via high precision

### **Current experimental result from LHC (CMS)**



#### High mass limits, but how generic?

#### **Current experimental result from LHC (ATLAS)**

#### ATLAS SUSY Searches\* - 95% CL Lower Limits

#### ATLAS Preliminary

0.0	Model	$e, \mu, \tau, \gamma$	Jets	$E_{\mathrm{T}}^{\mathrm{miss}}$	∫£ dt[fb	Mass limit	$\sqrt{s} = 7, 8 \text{ TeV}$ $\sqrt{s} = 13 \text{ TeV}$	Reference
Inclusive Searches	$\begin{array}{l} MSUGRA/CMSSM \\ \tilde{q}\tilde{q}, \tilde{q} \rightarrow q \tilde{\chi}_{1}^{0} \\ \tilde{q}\tilde{q}, \tilde{q} \rightarrow q \tilde{\chi}_{1}^{0} (compressed) \\ \tilde{q}\tilde{q}, \tilde{q} \rightarrow q \ell (\ell \ell / \ell \nu / \nu \nu) \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q \tilde{q} \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q \tilde{\chi}_{1}^{0} \rightarrow q q W^{\pm} \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q \tilde{\chi}_{1}^{0} \rightarrow q q W^{\pm} \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q (\ell \ell / \ell \nu / \nu \nu) \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q (W L \ell \nu / \nu \nu) \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q (W L \ell \nu / \nu \nu) \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q (W L \ell \nu / \nu \nu) \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q (W L \ell \nu / \nu \nu) \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q (W L \ell \nu / \nu \nu) \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q (W L \ell \nu / \nu \nu) \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q (W L \ell \nu / \nu \nu) \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q (W L \ell \nu / \nu \nu) \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q (W L \ell \nu / \nu \nu) \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q (W L \ell \nu / \nu \nu) \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q (W L \ell \nu / \nu \nu) \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q (W L \ell \nu / \nu \nu) \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q (W L \ell \nu / \nu \nu) \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q (W L \ell \nu / \nu \nu) \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q (W L \ell \nu / \nu \nu) \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q (W L \ell \nu / \nu \nu) \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q (W L \ell \nu / \nu \nu) \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q (W L \ell \nu / \nu \nu) \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q (W L \ell \nu / \nu \nu) \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q (W L \ell \nu / \nu \nu) \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q (W L \ell \nu / \nu \nu) \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q (W L \ell \nu / \nu \nu) \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q (W L \ell \nu / \nu \nu) \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q (W L \ell \nu / \nu \nu) \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q (W L \ell \nu \eta) $	$\begin{array}{c} 0.3 \ e, \mu/1-2 \ \tau \\ 0 \\ mono-jet \\ 2 \ e, \mu \ (off-Z) \\ 0 \\ 1 \ e, \mu \\ 2 \ e, \mu \\ 0 \\ 1-2 \ \tau + 0-1 \ \ell \\ 2 \ \gamma \\ \gamma \\ 2 \ e, \mu \ (Z) \\ 0 \end{array}$	2-10 jets/3 b 2-6 jets 1-3 jets 2 jets 2-6 jets 2-6 jets 2-6 jets 0-3 jets 7-10 jets 0-2 jets 2 jets 2 jets 2 jets 2 jets 2 mono-jet	Yes Yes Yes Yes Yes Yes Yes Yes Yes Yes	20.3 3.2 20.3 3.2 3.3 20 3.2 20.3 20.3 2	\$\vec{q}\$,\$\vec{x}\$       980 GeV         \$\vec{q}\$       610 GeV         \$\vec{q}\$       610 GeV         \$\vec{q}\$       820 GeV         \$\vec{x}\$       \$\vec{x}\$         \$\vec{x}\$ <td><math display="block">\begin{array}{c c} \textbf{1.85 TeV} &amp; \textbf{m}(\tilde{q})=\textbf{m}(\tilde{g}) \\ &amp; \textbf{m}(\tilde{k}_{1}^{0})=0 \ \text{GeV}, \ \textbf{m}(1^{st} \ \text{gen}, \tilde{q})=\textbf{m}(2^{sd} \ \text{gen}, \tilde{q}) \\ &amp; \textbf{m}(\tilde{q})-\textbf{m}(\tilde{k}_{1}^{0})=0 \ \text{GeV} \\ &amp; \textbf{m}(\tilde{k}_{1}^{0})=0 \ \text{GeV} \\ \textbf{1.52 TeV} &amp; \textbf{m}(\tilde{k}_{1}^{0})=0 \ \text{GeV} \\ \textbf{1.6 TeV} &amp; \textbf{m}(\tilde{k}_{1}^{0})=3 \ \text{GeV}, \ \textbf{m}(\tilde{k}^{\pm})=0.5(\textbf{m}(\tilde{k}_{1}^{0})+\textbf{m}(\tilde{g})) \\ \textbf{1.38 TeV} &amp; \textbf{m}(\tilde{k}_{1}^{0})=3 \ \text{GeV} \\ \textbf{1.4 TeV} &amp; \textbf{m}(\tilde{k}_{1}^{0})=100 \ \text{GeV} \\ \textbf{1.63 TeV} &amp; \textbf{ta}(\beta&gt;20 \\ \textbf{1.34 TeV} &amp; \textbf{c}\tau(\text{NLSP})&lt;0.1 \ \text{mm} \\ \textbf{1.37 TeV} &amp; \textbf{m}(\tilde{k}_{1}^{0})&lt;950 \ \text{GeV}, \ \textbf{c}\tau(\text{NLSP})&lt;0.1 \ \text{mm}, \mu&lt;0 \\ \textbf{1.3 TeV} &amp; \textbf{m}(\tilde{k}_{1}^{0})&lt;850 \ \text{GeV}, \ \textbf{c}\tau(\text{NLSP})&lt;0.1 \ \text{mm}, \mu&gt;0 \\ &amp; \textbf{m}(\tilde{k}_{1}^{0})&lt;850 \ \text{GeV}, \ \textbf{c}\tau(\text{NLSP})&lt;0.1 \ \text{mm}, \mu&gt;0 \\ &amp; \textbf{m}(\tilde{k}_{1}^{0})&lt;810 \ \text{GeV} \\ &amp; \textbf{m}(\tilde{k}_{1}^{0})=1.8 \times 10^{-4} \ \text{eV}, \ \textbf{m}(\tilde{q})=\textbf{m}(\tilde{q})=1.5 \ \text{TeV} \end{array}</math></td> <td>1507.05525 ATLAS-CONF-2015-062 <i>To appear</i> 1503.03290 ATLAS-CONF-2015-062 ATLAS-CONF-2015-076 1501.03555 1602.06194 1407.0603 1507.05493 1507.05493 1507.05493 1503.03290 1502.01518</td>	$\begin{array}{c c} \textbf{1.85 TeV} & \textbf{m}(\tilde{q})=\textbf{m}(\tilde{g}) \\ & \textbf{m}(\tilde{k}_{1}^{0})=0 \ \text{GeV}, \ \textbf{m}(1^{st} \ \text{gen}, \tilde{q})=\textbf{m}(2^{sd} \ \text{gen}, \tilde{q}) \\ & \textbf{m}(\tilde{q})-\textbf{m}(\tilde{k}_{1}^{0})=0 \ \text{GeV} \\ & \textbf{m}(\tilde{k}_{1}^{0})=0 \ \text{GeV} \\ \textbf{1.52 TeV} & \textbf{m}(\tilde{k}_{1}^{0})=0 \ \text{GeV} \\ \textbf{1.6 TeV} & \textbf{m}(\tilde{k}_{1}^{0})=3 \ \text{GeV}, \ \textbf{m}(\tilde{k}^{\pm})=0.5(\textbf{m}(\tilde{k}_{1}^{0})+\textbf{m}(\tilde{g})) \\ \textbf{1.38 TeV} & \textbf{m}(\tilde{k}_{1}^{0})=3 \ \text{GeV} \\ \textbf{1.4 TeV} & \textbf{m}(\tilde{k}_{1}^{0})=100 \ \text{GeV} \\ \textbf{1.63 TeV} & \textbf{ta}(\beta>20 \\ \textbf{1.34 TeV} & \textbf{c}\tau(\text{NLSP})<0.1 \ \text{mm} \\ \textbf{1.37 TeV} & \textbf{m}(\tilde{k}_{1}^{0})<950 \ \text{GeV}, \ \textbf{c}\tau(\text{NLSP})<0.1 \ \text{mm}, \mu<0 \\ \textbf{1.3 TeV} & \textbf{m}(\tilde{k}_{1}^{0})<850 \ \text{GeV}, \ \textbf{c}\tau(\text{NLSP})<0.1 \ \text{mm}, \mu>0 \\ & \textbf{m}(\tilde{k}_{1}^{0})<850 \ \text{GeV}, \ \textbf{c}\tau(\text{NLSP})<0.1 \ \text{mm}, \mu>0 \\ & \textbf{m}(\tilde{k}_{1}^{0})<810 \ \text{GeV} \\ & \textbf{m}(\tilde{k}_{1}^{0})=1.8 \times 10^{-4} \ \text{eV}, \ \textbf{m}(\tilde{q})=\textbf{m}(\tilde{q})=1.5 \ \text{TeV} \end{array}$	1507.05525 ATLAS-CONF-2015-062 <i>To appear</i> 1503.03290 ATLAS-CONF-2015-062 ATLAS-CONF-2015-076 1501.03555 1602.06194 1407.0603 1507.05493 1507.05493 1507.05493 1503.03290 1502.01518
3 <sup>rd</sup> gen. <u>§</u> med.	$\begin{array}{l} \tilde{g}\tilde{g},  \tilde{g} \rightarrow b \tilde{b} \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g},  \tilde{g} \rightarrow t \tilde{\ell} \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g},  \tilde{g} \rightarrow b \tilde{\ell} \tilde{\chi}_{1}^{+} \end{array}$	0 0-1 <i>e</i> ,μ 0-1 <i>e</i> ,μ	3 b 3 b 3 b	Yes Yes Yes	3.3 3.3 20.1	ie ie ie	1.78 TeV $m(\tilde{\chi}_1^0) < 800 \text{ GeV}$ 1.76 TeV $m(\tilde{\chi}_1^0) = 0 \text{ GeV}$ 1.37 TeV $m(\tilde{\chi}_1^0) < 300 \text{ GeV}$	ATLAS-CONF-2015-067 To appear 1407.0600
3 <sup>nl</sup> gen. squarks direct production	$ \begin{split} & \tilde{b}_{1}\tilde{b}_{1}, \tilde{b}_{1} \to b\tilde{\chi}_{1}^{0} \\ & \tilde{b}_{1}\tilde{b}_{1}, \tilde{b}_{1} \to t\tilde{\chi}_{1}^{0} \\ & \tilde{r}_{1}\tilde{r}_{1}, \tilde{r}_{1} \to b\tilde{\chi}_{1}^{1} \\ & \tilde{r}_{1}\tilde{r}_{1}, \tilde{r}_{1} \to Wb\tilde{\chi}_{1}^{0} \text{ or } t\tilde{\chi}_{1}^{0} \\ & \tilde{r}_{1}\tilde{r}_{1}, \tilde{r}_{1} \to c\tilde{\chi}_{1}^{0} \\ & \tilde{r}_{1}\tilde{r}_{1}(\text{natural GMSB}) \\ & \tilde{r}_{2}\tilde{r}_{2}, \tilde{r}_{2} \to \tilde{r}_{1} + Z \\ & \tilde{r}_{2}\tilde{r}_{2}, \tilde{r}_{2} \to \tilde{r}_{1} + h \end{split} $	0 2 $e, \mu$ (SS) 1-2 $e, \mu$ 0-2 $e, \mu$ 0 m 2 $e, \mu$ (Z) 3 $e, \mu$ (Z) 1 $e, \mu$	2 b 0-3 b 1-2 b 0-2 jets/1-2 l nono-jet/c-ta 1 b 1 b 6 jets + 2 b	Yes Yes Yes Yes g Yes Yes Yes Yes	3.2 3.2 4.7/20.3 20.3 20.3 20.3 20.3 20.3 20.3	b1         840 GeV           b1         325-540 GeV           c1117-170 GeV         200-500 GeV           c11         90-198 GeV         205-715 GeV           c1         90-245 GeV         745-785           c1         150-600 GeV         745-785           c1         150-600 GeV         745-785           c1         320-620 GeV         320-620 GeV	$\begin{array}{c} m(\tilde{\xi}_{1}^{0}){<}100~\text{GeV} \\ m(\tilde{\xi}_{1}^{0}){=}50~\text{GeV}, m(\tilde{\xi}_{1}^{1}){=}~m(\tilde{\xi}_{1}^{0}){+}100~\text{GeV} \\ m(\tilde{\xi}_{1}^{0}){=}2m(\tilde{\xi}_{1}^{0}), m(\tilde{\xi}_{1}^{0}){=}55~\text{GeV} \\ \textbf{GeV} & m(\tilde{\chi}_{1}^{0}){=}1~\text{GeV} \\ m(\tilde{\chi}_{1}^{0}){-}m(\tilde{\chi}_{1}^{0}){<}85~\text{GeV} \\ m(\tilde{\chi}_{1}^{0}){-}150~\text{GeV} \\ m(\tilde{\chi}_{1}^{0}){<}200~\text{GeV} \\ m(\tilde{\chi}_{1}^{0}){=}0~\text{GeV} \\ \end{array}$	ATLAS-CONF-2015-066 1602.09058 1209.2102, 1407.0583 08616, ATLAS-CONF-2016-00 1407.0608 1403.5222 1403.5222 1506.08616
EW direct	$ \begin{array}{l} \tilde{\ell}_{LR} \tilde{\ell}_{LR}, \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}_{1}^{-}, \tilde{\chi}_{1}^{+} \rightarrow \tilde{\tau} \nu(\tau \tilde{\nu}) \\ \tilde{\chi}_{1}^{+} \tilde{\chi}_{2}^{0} \rightarrow \ell_{L} \nu \tilde{\ell}_{L} \ell(\tilde{\nu}\nu), \ell \tilde{\nu} \tilde{\ell}_{L} \ell(\tilde{\nu}\nu) \\ \tilde{\chi}_{1}^{+} \tilde{\chi}_{2}^{0} \rightarrow W \tilde{\chi}_{1}^{0} Z \tilde{\chi}_{1}^{0} \\ \tilde{\chi}_{1}^{+} \tilde{\chi}_{2}^{0} \rightarrow W \tilde{\chi}_{1}^{0} \tilde{\chi}_{1}^{0}, h \rightarrow b \tilde{b} / W W / \tau \tau \\ \tilde{\chi}_{2}^{0} \tilde{\chi}_{3}, \tilde{\chi}_{23}^{0} \rightarrow \tilde{\ell}_{R} \ell \\ \text{GGM (wino NLSP) weak prod.} \end{array} $	2 e,μ 2 e,μ 2 τ 3 e,μ 2-3 e,μ /γγ e,μ,γ 4 e,μ 1 e,μ + γ	0 0 0-2 jets 0-2 <i>b</i> 0	Yes Yes Yes Yes Yes Yes Yes	20.3 20.3 20.3 20.3 20.3 20.3 20.3 20.3		$\begin{split} & m(\tilde{\chi}_{1}^{0}){=}0 \text{ GeV} \\ & m(\tilde{\chi}_{1}^{0}){=}0 \text{ GeV}, m(\tilde{\ell}, \tilde{\nu}){=}0.5(m(\tilde{\ell}_{1}^{\pi}){+}m(\tilde{\ell}_{1}^{0})) \\ & m(\tilde{\chi}_{1}^{0}){=}0 \text{ GeV}, m(\tilde{\ell}, \tilde{\nu}){=}0.5(m(\tilde{\ell}_{1}^{\pi}){+}m(\tilde{\ell}_{1}^{0})) \\ & m(\tilde{\ell}_{1}^{\pi}){=}m(\tilde{\ell}_{2}^{0}), m(\tilde{\ell}_{1}^{0}){=}0, m(\tilde{\ell}, \tilde{\nu}){=}0.5(m(\tilde{\ell}_{1}^{\pi}){+}m(\tilde{\ell}_{1}^{0})) \\ & m(\tilde{\chi}_{1}^{\pi}){=}m(\tilde{\chi}_{2}^{0}), m(\tilde{\chi}_{1}^{0}){=}0, \text{ sleptons decoupled} \\ & m(\tilde{\chi}_{1}^{\pi}){=}m(\tilde{\chi}_{2}^{0}), m(\tilde{\ell}_{1}^{0}){=}0, m(\tilde{\ell}, \tilde{\nu}){=}0.5(m(\tilde{\ell}_{2}^{0}){+}m(\tilde{\ell}_{1}^{0})) \\ & cr{<}1 \text{ mm} \end{split}$	1403.5294 1403.5294 1407.0350 1402.7029 1403.5294, 1402.7029 1501.07110 1405.5086 1507.05493
Long-lived particles	Direct $\tilde{\chi}_{1}^{*}\tilde{\chi}_{1}^{-}$ prod., long-lived $\tilde{\chi}_{1}^{*}$ Direct $\tilde{\chi}_{1}^{*}\tilde{\chi}_{1}^{-}$ prod., long-lived $\tilde{\chi}_{1}^{*}$ Stable, stopped $\tilde{g}$ R-hadron Metastable $\tilde{g}$ R-hadron GMSB, stable $\tilde{\tau}, \tilde{\chi}_{1}^{0} \rightarrow \tilde{\tau}(\tilde{e}, \tilde{\mu}) + \tau(e_{1}, \tilde{\mu}) + \tau(e_{1}, \tilde{\mu}) + \tau(e_{2}, \tilde{\mu}$	Disapp. trk dE/dx trk 0 dE/dx trk $(\mu)$ $1-2\mu$ $2\gamma$ displ. $ee/e\mu/\mu$ displ. vtx + jet	1 jet  1-5 jets - - - τ ts - ts -	Yes Yes - Yes - Yes -	20.3 18.4 27.9 3.2 19.1 20.3 20.3 20.3	$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	$ \begin{array}{c} m(\tilde{k}_{1}^{z}) - m(\tilde{k}_{1}^{0}) \sim 160 \text{ MeV}, \ r(\tilde{k}_{1}^{z}) = 0.2 \text{ ns} \\ m(\tilde{k}_{1}^{z}) - m(\tilde{k}_{1}^{0}) \sim 160 \text{ MeV}, \ r(\tilde{k}_{1}^{z}) < 15 \text{ ns} \\ m(\tilde{k}_{1}^{0}) = 100 \text{ GeV}, \ 10 \ \mu s < r(\tilde{g}) < 1000 \text{ s} \\ m(\tilde{k}_{1}^{0}) = 100 \text{ GeV}, \ r > 10 \text{ ns} \\ 10 \cdot \tan\beta < 50 \\ 1 < r(\tilde{k}_{1}^{0}) < 3 \text{ ns}, \text{SPS8 model} \\ 7 < cr(\tilde{k}_{1}^{0}) < 740 \text{ mm}, \ m(\tilde{g}) = 1.3 \text{ TeV} \\ 6 < cr(\tilde{k}_{1}^{0}) < 480 \text{ mm}, \ m(\tilde{g}) = 1.1 \text{ TeV} \end{array} $	1310.3675 1506.05332 1310.6584 <i>To appear</i> 1411.6795 1409.5542 1504.05162 1504.05162
RPV	$ \begin{array}{l} LFV pp \rightarrow \tilde{v}_{\tau} + X, \tilde{v}_{\tau} \rightarrow e\mu/e\tau/\mu\tau \\ Bilinear \ RPV \ CMSSM \\ \tilde{\chi}_{1}^{+}\tilde{\chi}_{1}^{-}, \tilde{\chi}_{1}^{+} \rightarrow W \tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow ee\tilde{v}_{\mu}, e\mu\tilde{v}_{e} \\ \tilde{\chi}_{1}^{+}\tilde{\chi}_{1}^{-}, \tilde{\chi}_{1}^{+} \rightarrow W \tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow \tau\tau\tilde{v}_{e}, e\tau\tilde{v}_{\tau} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow qqq \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\bar{q} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow qqq \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow t_{1}t, \tilde{t}_{1} \rightarrow bs \\ \tilde{t}_{1}\tilde{t}_{1}, \tilde{t}_{1} \rightarrow b\ell \end{array} $	$e\mu, e\tau, \mu\tau \\ 2 e, \mu (SS) \\ 4 e, \mu \\ 3 e, \mu + \tau \\ 0 \\ 2 e, \mu (SS) \\ 0 \\ 2 e, \mu \\ $	- 0-3 b - 6-7 jets 6-7 jets 0-3 b 2 jets + 2 b 2 b	Yes Yes Yes Yes Yes	20.3 20.3 20.3 20.3 20.3 20.3 20.3 20.3	\$\vec{v}_r\$           \$\vec{q}\$, \$\vec{g}\$           \$\vec{x}_1\$         760 GeV           \$\vec{x}_1\$         450 GeV           \$\vec{g}\$         917 GeV           \$\vec{g}\$         980 GeV           \$\vec{g}\$         980 GeV           \$\vec{g}\$         880 GeV           \$\vec{t}_1\$         320 GeV           \$\vec{t}_1\$         0.4-1.0 TeV	<b>1.7 TeV</b> <b>1.45 TeV</b> <b>1.45 TeV</b> <b>1.45 TeV</b> $m(\tilde{q})=m(\tilde{g}), c\tau_{LSP}<1 \text{ mm}$ $m(\tilde{\chi}_{1}^{0})>0.2\times m(\tilde{\chi}_{1}^{0}), \lambda_{121}\neq 0$ $m(\tilde{\chi}_{1}^{0})>0.2\times m(\tilde{\chi}_{1}^{0}), \lambda_{133}\neq 0$ BR(t)=BR(b)=BR(c)=0% $m(\tilde{\chi}_{1}^{0})=600 \text{ GeV}$ $BR(\tilde{t}_{1}\rightarrow be/\mu)>20\%$	1503.04430 1404.2500 1405.5086 1405.5086 1502.05686 1502.05686 1404.2500 1601.07453 ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde{c} \rightarrow c \tilde{\chi}_1^0$	0	2 c	Yes	20.3	č 510 GeV	m( $\tilde{x}_{1}^{0}$ )<200 GeV	1501.01325
*Onl	ly a selection of the availab	le mass limi	its on new	,	1	0 <sup>-1</sup>	1 Mass scale [TeV]	•

#### All simplified models!

#### SUSY as one of the best studied examples.... what does it tell us for e+e- machines?

### **BSM Example: Supersymmetry**

- Idea:
  - New SUSY particles change energy dependence of interactions



- Unification possible!
- SUSY provides candidate for dark matter
- SUSY predicts even 5 Higgs particles ..... so stay tuned!
- SUSY provides new sources for CP violation

>But no specific SUSY hints so far at LHC ..... dead already? Is this a bug or a feature? ....What do the experimental results really tell us?

KET Workshop@ Munich, May 2/3 2016

### **Example for physics beyond the Standard Model**

#### Symmetry between fermions and bosons



'The search for SUSY is one of the biggest adventures in present-day physics.' Ed Witten (1999)

- SUSY structure: same gauge structure, SM ↔ SUSY same coupling, different spin
   >> discovering SUSY requires proving such a structure!
- Caveat: due to SUSY breaking 105 new free parameters are imposed
   Strong assumptions on breaking mechanism lead to models of only ~5 parameters

# SUSY breaking schemes

Strongly constrained models, but still respect **SUSY structure!** 



- SUGRA: mediating interactions are gravitational
- --- GMSB: mediating interactions are ordinary electroweak and QCD gauge interactions
- AMSB: SUSY breaking happens on a different brane in a higher-dimensional theory
- Feature of schemes: lead to 'characteristic' mass spectra

> But these are strong assumptions....!

also

### Impact of model assumptions

Often used models:

- Constrained models: very restrictive in mass spectra
  - > exclusion limits only valid in the specific parameter point
  - **≻**not transferable to full parameter regions

> but: if new particles found within these analyses still the model structure testable!

- Simplified models: strong assumptions on masses and branching ratios
  - > do not respect the structure of actual BSM models ......'auxiliary tool' for setting limits
  - ➤exclusion limits correspond to ``best case" scenarios

realistic models can be tested with simplified-model limits; constraints in general much weaker

MSSM with 18 parameters: respects the model structure, more general mass hierarchies

- >> no CP-phases,....ok, but phenomenologically a good starting point !
- >however: sampling of parameter random scans is of limited validity

•

Caution!!!



**MSSM** with 18 parameters: respects the model structure, more general mass hierarchies

> no CP-phases,....ok, but phenomenologically a good starting point !

>however: sampling of parameter random scans are of limited validity

>depend on the resolution of the scan but in nature only one parameter point will be realized, iff.....

So, stay tuned, SUSY@LHC is still highly motivated: do further hints from nature exist?

## **Any arguments for light SUSY?**

• Minimization of 1-loop Higgs Potential:

$$\frac{M_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u) \tan^2 \beta}{\tan^2 \beta - 1} - \mu^2 \simeq -(m_{H_u}^2 + \Sigma_u^u) - \mu^2$$

- To keep EWFT ~ 3%:
  - rather small µ (~200 GeV) required
  - 'naturalness'
  - Several 'natural' scenarios: light stops and light higgsinos,...
  - degenerate masses ~200 GeV range expected not excluded by LHC!
- Consistent with results from low energy, (g-2)<sub>μ</sub>
  - Favours also rather low SUSY masses in electroweak sector

$$\delta \boldsymbol{a}_{\mu}(\mathrm{N.P.}) = \mathcal{O}(\boldsymbol{C}) \left(\frac{\boldsymbol{m}_{\mu}}{\boldsymbol{M}}\right)^{2}, \quad \boldsymbol{C} = \frac{\delta \boldsymbol{m}_{\mu}(\mathrm{N.P.})}{\boldsymbol{m}_{\mu}}$$

Required experimental features: ISR technique, precise mass measurements, powerful detector magnets for resolution ...

#### E.g. light but mass-degenerate new particles: 'light higgsinos'

- Theoretically easily embedded in hybrid gauge-gravity mediated models
- Higgsino masses ~160 GeV range with typically  $\Delta m(\chi \pm \chi_0)$ ~1 GeV
- Leads to experimental challenges: many  $\pi$ 's, soft  $\gamma$ ,  $\mathbf{E}_{miss}$  from decay
- Solution: apply ISR and use recoil mass:  $\Delta m_{res}(x_{x\pm}) < 1 \text{ GeV}$  'mono-photon'

#### E.g. revealing the underlying structure of the model:

- determine chiral quantum properties of new particles
- prove the coupling structure
- prove the spin structure of the model
- Solution: apply polarized e<sup>±</sup>-beams and precise angle distributions+cross sections
- E.g. handling of a large number of new model parameters:
- test the CP properties of new particles
- determine fundamental parameters without imposing the breaking scheme
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- measure masses of the light higgsinos
- measure cross section (X<sup>0</sup><sub>1</sub> X<sup>0</sup><sub>2</sub>)~ O(%) with polarized beams
- > determine ∆µ~ 4 %
- > infer M<sub>1</sub>,M<sub>2</sub> even in TeV range depending on tanβ

# Would be an absolute nightmare scenario for LHC on its own!!!



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Determination of chiral quantum properties of new particles

New particles are carry quantum numbers ≫have to be proven experimentally Here: scalar particles are associated to chiral quantum numbers

#### Beam polarization is 'chirality analyzer'

- based on measurement of masses and polarized cross sections
- unique identification of associated chiral quantum !

Experimental verification of such quantum properties not possible at LHC!



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Determination of the coupling structure of the model

Choi, S.Y. et al

#### 0.2 ----**Example here:** P.=-0.9, P.+ =+0.6 0.15 Equivalence of electroweak Yukawa couplings gwino, gbino 0.1 with SU(2) and U(1) gauge couplings g,g' 0.05 $Y_L=g_{wino}/g$ , $Y_R=g_{bino}/g'$ 500 fb 0 Contour plots of measured P<sub>e</sub> =+0.9, P<sub>e</sub>+ =>0.6 -0.05 100 fb<sup>-1</sup> polarized cross sections allow the test at %-level, depending on -0.1 luminosity and polarization -0.15Similar studies for coloured Yukawas exist via determination of gq,gg,qq at LHC, -0.04-0.03 -0.02 -0.01 0.02 0.01 0.03 0.040.05 0 however with larger uncertainties. Y, -1 If accomplished by LC 5-10% level achievable.

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#### • Proving the spin structure of the model

Smuon pair production in SUSY and an UED model: clear separation possible via both

- > thresholds excitation curves, requires tunable energy: p-wave character obvious
- > precise measurement of production angle distributions: sin<sup>2</sup>θ-dependence unique sign for spin

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Determination of fundamental mixing angles

can be converted in fundamental parameters

# Based on measurements of the light charginos only

- masses+polarized cross sections
- different cms energies



**Model-independent** parameter determination: very challenging at LHC !

#### E.g. handling of a large number of new model parameters:

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Choi, S.Y. et al



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### Dark matter (DM) aspects

- Most compelling reason for BSM is evidence for dark matter:
  - rather flat rotation curves of galaxy in the halo of DM
  - gravitational lensing point also to gravitational potentials from DM
  - total matter and baryon density from cosmic microwave background: Ωh<sup>2</sup>=0.1196±0.0031
- Constraints from direct searches
  - DM scattering off nuclei
  - two classes: spin-dependent  $\sigma_{SD}$ , spin-independent  $\sigma_{SI}$ 
    - $> \sigma_{SI}$  gets contributions from H, Z,new coloured F/S
    - $> \sigma_{SD}$  gets contributions Z, new coloured F/S
  - several experiments: excess compatible with m<sub>DM</sub>~5-30 GeV
     in conflict with XENON LUX
    - > in conflict with XENON, LUX,...
- Constraints from indirect searches
  - very important for testing the WIMP paradigm
    - ➢Fermi-LAT sensitive to few tens of GeV
    - ➢ forecast: O(100GeV) within decade of data
    - >caveat: based on assumptions on astrophysical foregrounds
    - >active field: remember discussion about ~130 GeV  $\gamma$ -ray line



### Dark matter (DM) prospects

- Candidates —should be stable or long-lived— for DM:
- If weakly interacting: chance to produce DM at collider: SM
  - SM candidates practically excluded, i.e. not sufficient:
     > baryons and neutrinos (Ω<sub>v</sub>h<sup>2</sup>=0.004)
  - SUSY candidates: LSP (R-parity conserv.) X<sup>0</sup>1
    - >pp  $\rightarrow X^{0}_{1}X^{0}_{1}\gamma$  or  $X^{0}_{1}X^{0}_{1}j$

> e+e-  $\rightarrow X^{0}_{1}X^{0}_{1}\gamma$ 

#### ➤ precise MET and polarized beams important

- Universal extra dimensions: lightest KK-odd particle
  - > i.g. a vector particle B<sub>1</sub> with mass n/R

> important Higgs mass and couplings: limit on R

- Higgs portal models, i.e. 'Higgs connects DM sector to SM':
  - >> S with <S>=0 or vector field  $X_{\mu}$ , and Majorana fermion  $\chi$
  - > imposing Z<sub>2</sub>-parity: Higgs responsible for DM annihilation+elastic scattering of DM

> important Higgs invisible width!

- Extended scalar sector, e.g. the inert doublet model:
  - > DM either S or P, low (<60GeV), intermediate and heavy mass region (>500GeV)
  - > crucial invisible Higgs decays, modified Hyy-rate





#### Dark matter (DM) prospects at e+e- colliders

- Resolving the mystery of DM
  - E.g. SUSY candidates: LSP ~ X<sup>0</sup><sub>1</sub>
     if no hints for new particles at LHC, but √s<sub>ee</sub>>m<sub>X01</sub>
     > e+e- →X<sup>0</sup><sub>1</sub>X<sup>0</sup><sub>1</sub>y very promising!
    - > signal is high energy  $\gamma$  only
    - > background e+e-  $\rightarrow$ vv $\gamma$
    - beam polarization essential to reduce background and enhance the signal
    - > exploit energy spectrum: precise  $m_{DM}$ ,  $\sigma_{DM}$



Bartels et al.

• If  $m_{DM} < m_{h/2}$ 

Invisible Higgs width provides unique opportunity

- > essential for  $\sigma_{SI}$  in models dominated via Higgs exchange
- > requires precise determination of BR(H $\rightarrow$ invisible) and T<sub>invis</sub>

#### Dark matter (DM) prospects at e+e- colliders

- Resolving the mystery of DM
  - E.g. SUSY candidates: LSP ~ X<sup>0</sup><sub>1</sub>
     if no hints for new particles at LHC, but √s<sub>ee</sub>>m<sub>X01</sub>
    - > different approach: parametrize DM interactions
      - via effective operators
    - >SM+DM: heavy mediators only
    - > still e+e-  $\rightarrow X^{0}_{1}X^{0}_{1}\gamma$  very promising!
    - > signal is high energy  $\gamma$  only
    - > background e+e-  $\rightarrow$ vv $\gamma$
  - In some parts of the parameter space:

bounds from LC (SI DM <10 GeV, SD DM <100): unique opportunity



Dreiner et al.

#### Determination of DM (and co-produced particles) properties

>precise mass measurements of X's, e.g. via threshold scans in associated production

- >measurements of mass splittings via endpoints
- > measurement of mixing character of DM and test of  $\Delta(\Omega h^2)$ ~10%

### Implications of 750 GeV events in yy channel

#### What's the status?



#### KET Workshop@ Munich, May 2/3 2016

Gudrid Moortgat-Pick/Uni Hamburg

### Implications of 750 GeV events in yy channel

#### What's the status?



### CMS: invariant mass spectra at 13 TeV

2.7 fb<sup>-1</sup> (13 TeV, 3.8T) 0.6 fb<sup>-1</sup> (13 TeV, 0T) CMS Preliminary **CMS** Preliminary Events / ( 20 GeV ) 1 1 Events / ( 20 GeV ) EBEB **EBEB** Data Data Fit model Fit model 10<sup>2</sup> ±1σ ±1σ ±2σ **10**╞ ±2σ 10╞ (data-fit)/ $\sigma_{stat}$ (data-fit)/ $\sigma_{stat}$ 400 600 800 1200 1400 1600 400 600 800 1000 1000 1200 1400 1600 m<sub>y y</sub> (GeV) m<sub>y y</sub> (GeV)

#### CMS collaboration, Moriond'16

#### **CMS: two events categories**

- both photons in ECAL barrel
- one photon in ECAL barrel, one photon in ECAL endcap

What's the status?

#### Implications of 750 GeV events in yy channel

What can be done at e+e- colliders if, iff, iff-f,.....that's a true signal?

- Is it a new resonance at 750 GeV?
  - ➤ either spin 0 (most cases) or spin 2
  - but in generic models (SUSY, 2HDM) not easy to get only enhancement in γγ finale state and nowhere else
  - > extra F/S needed in loops, in that case also contributions to WW, ZZ, Zy expected,.....so stay tuned
  - But what if width is large?
     Maybe it's a new strong interaction?
     Could be reflected in Higgs couplings
  - But what if final state is not 2 photons? Could happen in the (plain) NMSSM !





Could be very collimated γ

Depends on mass and coupling of a

### **Implications of 750 GeV events in γγ channel More possibilities?**

• Could it be a parent resonance ?



> If there is a real signal, there should be more new physics!

• 2016 data@LHC will tell us more, but in case the signal gets stronger:

a ~1TeV LC could provide the γγ-option for precise analysis of that state
 potentially precise measurements of additional states

Nothing known yet, data 2016 will reveal this mystery, ... maybe more mysteries will show up in the next years:

> But the bonus options at the LC γγ-, eγ-collision should technically not be precluded! Keep such a flexibility!

### Conclusions

- BSM is well motivated, too many open questions in the SM
  - > lots of models on the market
  - > but 'no clue' which model is most likely to be realized in nature
- Current results at LHC do not point to a specific scale for BSM
  - > caution: not guaranteed that new scale is ever known!
  - but one should not wait any longer: physics case is well established ... !
- Any BSM has new features/structure
  - chiral structure, spin, coupling properties have to be experimentally analyzed and tested
  - > direct and indirect test of BSM go hand-in-hand
  - > e+e- machines offer variable tools and high flexibility
  - > tuneable precise energy, polarized beams, ' $4\pi$  detector', bonus options (GigaZ,  $\gamma\gamma$ , e $\gamma$ )
- LC offers highest flexibility.....technical design should not preclude options
   well prepared for the 'Known' but also for the 'Unknown' !

#### LHC + LC mandatory to resolve the BSM snooker !





# Very special event just ahead!

# Don't forget to reserve in time!

Helmholtz Alliance
PHYSICS AT THE TERASCALE



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An introduction to the physics of linear colliders

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#### Frauenchiemsee, Germany

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Contact: anacen@desy.de



# Free Parameters in the MSSM

- mass matrices are 3 x 3 hermitian
  - $\longrightarrow$   $m_Q^2$ ,  $m_u^2$ ,  $m_d^2$ ,  $m_L^2$ ,  $m_e^2$ : 45 parameters
- gaugino masses  $M_1, M_2, M_3$  are complex numbers: 6
- trilinear couplings a, a, a are 3 x 3 complex matrices: 54
- bilinear coupling b is 2 x 2 matrix: 4
- Higgs masses m<sup>2</sup><sub>Hu</sub>, m<sup>2</sup><sub>Hd</sub>: 2
  - altogether 111 parameter ???

Symmetries (lepton + baryon number, Peccei-Quinn, R symmetry) lead to'rotations':

-4 non-trivial field redifinitions

-2 in the Higgs sector (since minimal model only 2 parameters in the Higgs sector)

remain 105 free new parameters in the MSSM!