# Exploring Natural Supersymmetry

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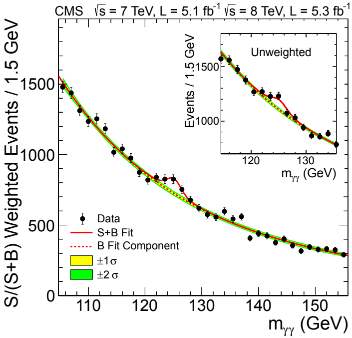
DESY, Hamburg

LCWS 2012, Arlington / TX

# LHC found a Higgs-like boson...

- if it *is* an elementary scalar, what does stabilize its mass?
- in the Standard Model: fine-tuning of parameters — to 32 digits!
- biggest contribution to Higgs mass: top-quark loops



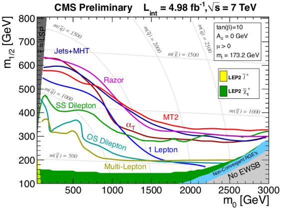

## low energy SUSY

- loops with SUSY partners cancel particle loops $\sim (M_F^2 - M_B^2)$
- remember: this is main motivation for low energy SUSY!
- which SUSY particles *have* to be light to make cancellation work well enough? $\rightarrow$ natural SUSY!

# ...but only limits otherwise - mostly on cMSSM:

## cMSSM

- guiding principle: *mass* unification at the GUT scale
- tight relations between masses at electroweak scale
- Higgsino mass $\mu$ fixed via other parameters

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- mass splitting between generations can be large
- $\mu$ independent parameter: $\rightarrow$ what is it's "natural value"?

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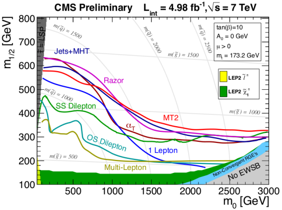


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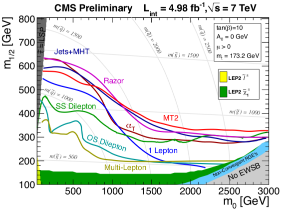


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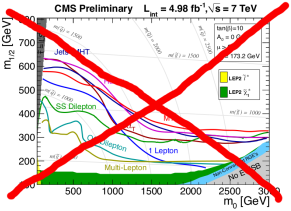

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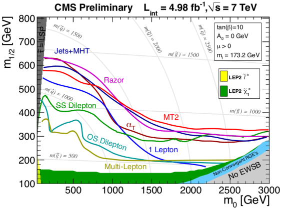


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# Natural SUSY spectrum

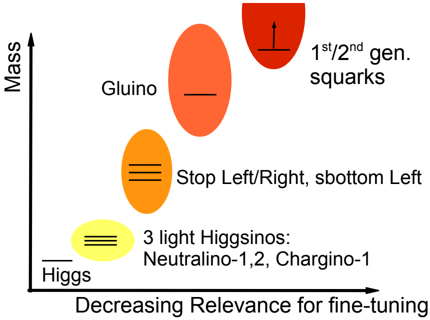
- Higgsino mass $\mu$ directly related to $Z$ mass:

$$m_Z^2 = 2\frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - 2\mu^2 \,.$$

- at least $\mu$ should be small to avoid large cancellations, i.e. fine-tuning
$\Rightarrow$ 3 light Higgsinos $\lesssim$200 GeV, with small mass splitting $\Delta m \lesssim$10 GeV

## other SUSY partners

- a sub- or few TeV spectrum of 3rd gen squarks $\tilde{t}_1$, $\tilde{t}_2$ and $\tilde{b}_1$,
- an intermediate scale gluino $m_{\tilde{g}} \lesssim$ 3-4 TeV
- multi-TeV 1st / 2nd gen. scalars $m_{\tilde{q},\tilde{\ell}} \sim 10 - 50$ TeV



# Experimental Consequences

## 1st / 2nd gen. quarks very heavy:

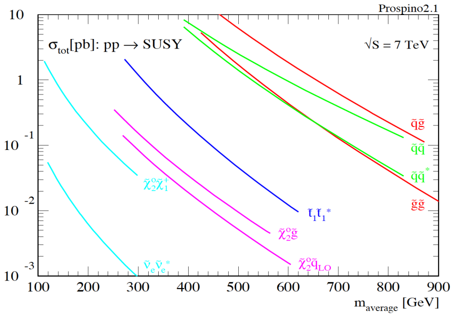
- don't contribute to production $\rightarrow$ reduced cross-section
- gluinos will decay via $\tilde{t}_{L/R}t$ and $\tilde{b}_{L/R}b \rightarrow$ long cascades

## sleptons very heavy:

- absent from decay chains
- reduced BRs to leptons: $\Rightarrow$ *only* from $t$, $Z$ or $W^{\pm}$ decays

## Higgsinos:

- $\tilde{\chi}^{\pm}$ decay products very soft



# Outline

## What do we know and what can we expect to learn about

- Gluinos
- Stops
- Higgsinos

## Parameter Determination

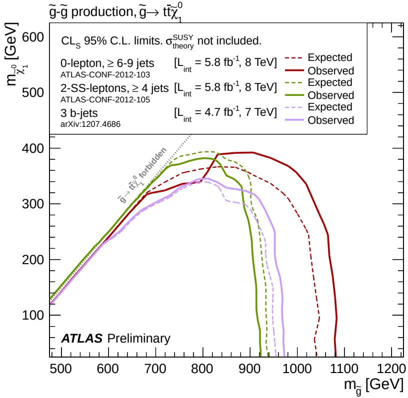
## Impact on Linear Collider Design

## Further Signatures

# Gluinos at the LHC

## Current situation

- some simplified model searches, e.g. for $\tilde{g} \to t\bar{t}\tilde{\chi}^0_1$, apply for certain decay modes
- currently reach to $M_{\tilde{g}} \simeq 1$ TeV for $m_{\tilde{\chi}^0_1} \lesssim 400$ GeV
- and if channel is kinematically open

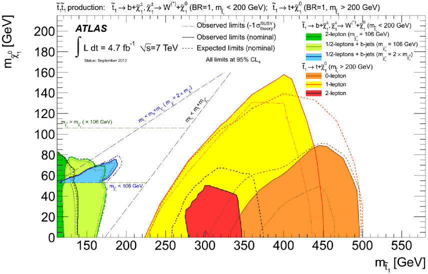



⇒ Very good prospects for the LHC to find natural gluinos with more data, more energy and suitable analyses!

# Stops at the LHC

## independently of gluino mass: direct $\tilde{t}$ pair production

- $\tilde{t}_1 \to t\tilde{\chi}^0_1$: if mass difference $> m_t$
- else $\tilde{t}_1 \to b\tilde{\chi}^\pm_1$ or $\tilde{t}_1 \to c\tilde{\chi}^0_1$: $\to$ difficult!
- small higsino mass splitting: blue/green limits don't apply
- $m_{\tilde{\chi}} \gtrsim 160$ GeV: no restriction for $m_{\tilde{t}}$
- very difficult: $M_{\tilde{t}} \sim m_t$: knowledge of SM $t\bar{t}$ cross-section?




$\Rightarrow$ Very good prospects for discovery at the LHC with more data, more energy and dedicated analyses.

$\to$ *Why not* $m_{\tilde{t}} < 250$ *GeV?*

Difficult regions — can all loop holes be closed if no discovery?

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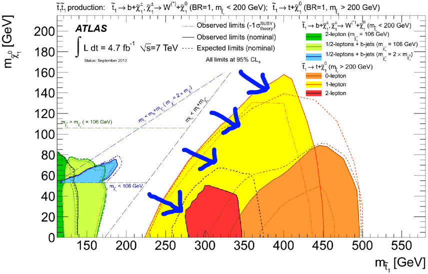


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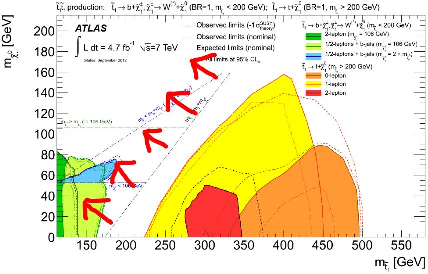


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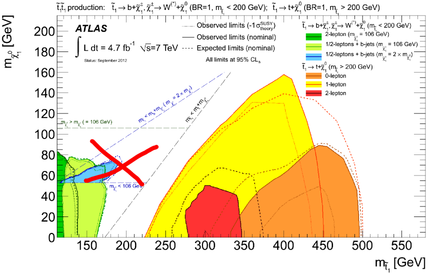


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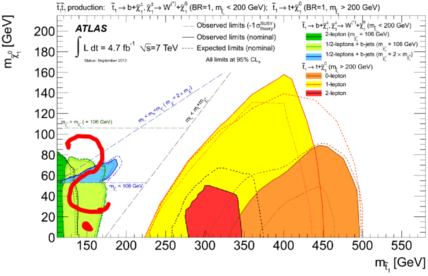


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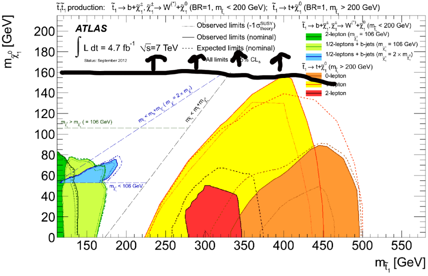


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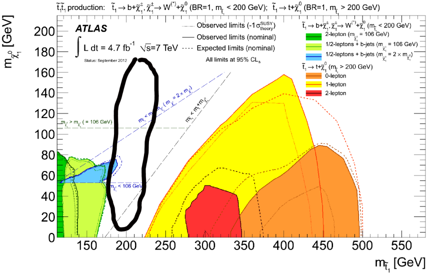


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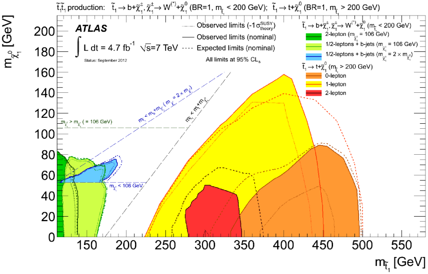


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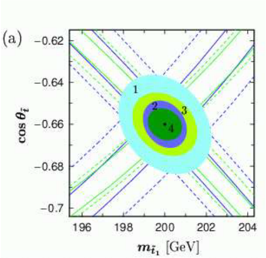
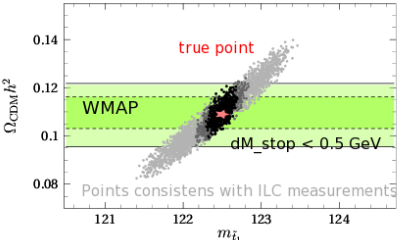
# ...and at a Linear Collider? [Eur. Phys. J. direct C **2** (2000) 7], [JHEP09 (2008) 076]

- even in "difficult cases" it jumps into your face:
  e.g. $5\sigma$ discovery for $M_{\tilde{t}_1} = 122.5$ GeV, $\tilde{t}_1 \to c\tilde{\chi}_1^0$ with $0.22\ \mathrm{fb}^{-1}$ (!)
- mass measurement to $\lesssim 1$ GeV both $\tilde{t}_1 \to c\tilde{\chi}_1^0$ and $\tilde{t}_1 \to b\tilde{\chi}_1^\pm$
- mixing angle from polarised cross-sections: $\delta \cos\theta_{\tilde{t}} \lesssim 0.01$



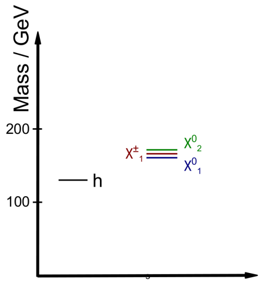

mixing angle and mass determination for different beam polarisations

[POWER report]



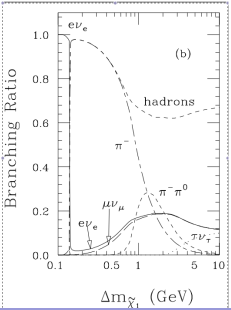

dark matter relic density determination in $t$-coannihilation scenario ($\Delta M(\tilde{t}_1, \tilde{\chi}_1^0) = 30$ GeV)

# Higgsinos in Natural SUSY




## Mass spectrum

- Higgsinos $\tilde{\chi}^0_1$, $\tilde{\chi}^0_2$, $\tilde{\chi}^\pm_1$ close to $\mu$, i.e. $\lesssim 200$ GeV
- nearly degenerate: $\Delta M \lesssim 10$ GeV ... few 100 MeV



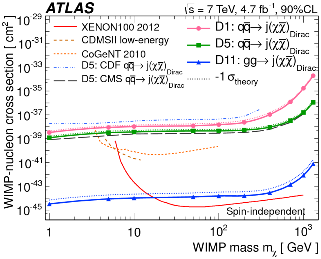

## Branching ratios

- will depend crucially on mass differences
- for small mass differences ($\lesssim 3$ GeV) need to calcualte directly $\tilde{\chi} \to \mathrm{hadrons}\,\tilde{\chi}^0_1$
- $\tilde{\chi}^\pm_1$: for $\Delta m = m_\tau \simeq \tau$ decays!
- $\tilde{\chi}^0_2$: radiative loop decay BR$(\tilde{\chi}^0_2 \to \tilde{\chi}^0_1\gamma) \simeq 25...75\%$

# Higgsinos at the LHC

- will all look like $\not{E}_{\mathrm{t,miss}}$ , thus indistinguishable
- direct production: $\rightarrow$ mono-jet / -photon searches
- Higgsinos: $Z$-exchange, Majorana
- but Higgsino cross-section than contact interactions assumed in WIMP interpretations
- irreducible background from $Z \rightarrow \nu\bar{\nu} \rightarrow$ very challenging:

[plot J.Hajer *et al*]



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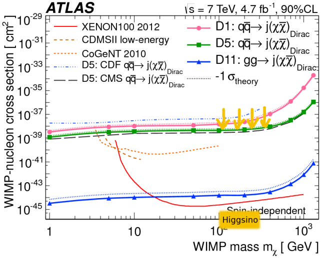

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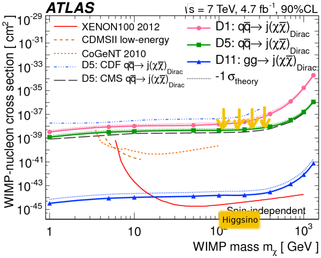
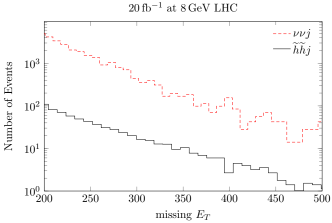


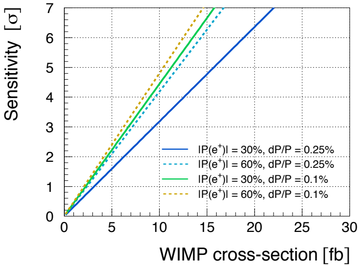
# Higgsinos at the Linear Collider

## Production

- $e^+e^- \to Z \to \tilde{\chi}^0_2\tilde{\chi}^0_1/\tilde{\chi}^+_1\tilde{\chi}^-_1$
- unpolarised cross-sections: **several 100 fb**
- beautiful beam polarisation dependence

## "No-loose" approach [arXiv:1206.6639]

- mono-photon search: treat all higgsinos as missing energy à la LHC
- discover cross-sections down to 10 fb
- measure polarised x-sections to $\mathcal{O}(10\%)$
- measure $M_\chi$ to $\mathcal{O}(1)$ GeV
- distinguish *s*- and *p*-wave production

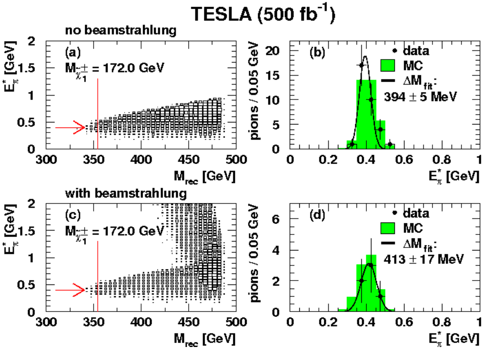


# TESLA Study: $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 \pi^\pm$ in AMSB

## Results for $M_{\tilde{\chi}_1^\pm} = 172$ GeV, $\Delta M = 0.4$ GeV:

[PhD thesis C. Hensel, Hamburg, 2002]

- uncertainty on $M_{\tilde{\chi}_1^\pm} = 1$ GeV
- uncertainty on $\Delta M = 17$ MeV
- including beamstrahlung / pair background
- main difference to Higgsino scenario: $\tilde{\chi}_2^0$ at higher mass




$\Rightarrow$ first thing to check for Higgsinos: $\tilde{\chi}_1^\pm$ vs $\tilde{\chi}_2^0$ separation!

# Ongoing new Higgsino Study

## Experimental setting

- ILC TDR $\sqrt{s} = 500$ GeV
- $\int \mathcal{L} dt = 500$ fb$^{-1}$
- $P(e^+, e^-) = (+30\%, -80\%)$: not optimal → conservative!
- ILD detector; fast simulation SGV (signal) full sim. Mokka+Marlin (SM)

## Benchmark point [JHEP **1107** (2011) 010]

- $\mu = 166$ GeV
- $M_1 = 1.7$ TeV, $M_2 = 4.4$ TeV
- cosmology compatible

## Masses

- $M_{\tilde{\chi}_1^0} = 166.6$ GeV
- $M_{\tilde{\chi}_1^\pm} = 167.4$ GeV
- $M_{\tilde{\chi}_2^0} = 167.6$ GeV
- $m_h = 127$ GeV

## Decay Modes

- $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 W^{\pm *}$: very similar to $\tau$ decays!
- $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 \gamma$: BR = 75%

# Analysis Strategy

## Consider $\tilde{\chi}_1^+\tilde{\chi}_1^-\gamma_{\mathrm{ISR}}$ and $\tilde{\chi}_2^0\tilde{\chi}_1^0\gamma_{\mathrm{ISR}}$:

- suppress $\gamma^*\gamma^* \to f\bar{f}$
- infer $M_{\tilde{\chi}_1^\pm}$ and $(M_{\tilde{\chi}_2^0} + M_{\tilde{\chi}_1^0})/2$ from recoil against ISR

## Separate $\tilde{\chi}_1^+\tilde{\chi}_1^-$ vs $\tilde{\chi}_2^0\tilde{\chi}_1^0$ by exclusive decay modes:

- $\tilde{\chi}_1^+\tilde{\chi}_1^- \to e/\mu\nu + \mathrm{hadrons} + 2\tilde{\chi}_1^0$: BR $\simeq$ 50%
- $\tilde{\chi}_2^0\tilde{\chi}_1^0 \to \gamma + 2\tilde{\chi}_1^0$: BR $\simeq$ 75%

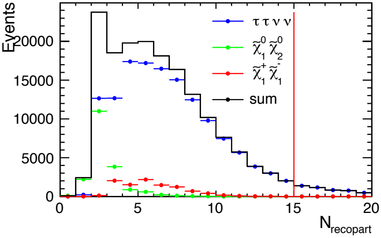
## Boost decay products into $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ restframe

$$E^*_{\mathrm{decay}} = \frac{(\sqrt{s} - E_{\mathrm{ISR}})E_{\mathrm{decay}} - \vec{p}_{\mathrm{decay}} \cdot \vec{p}_{\mathrm{ISR}}}{2M_{\tilde{\chi}^\pm}}$$

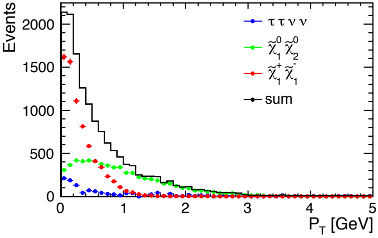
- cut on $E^*_{\mathrm{decay}}$ separates $\tilde{\chi}_1^+\tilde{\chi}_1^-$ vs SM processes like e.g. $\tau^+\tau^-\nu\bar{\nu}$
- determine mass difference $E^*_{\mathrm{decay}} = \Delta M$

# Higgsino look & feel

## Number of reconstructed particles




## Transverse momentum of decay products

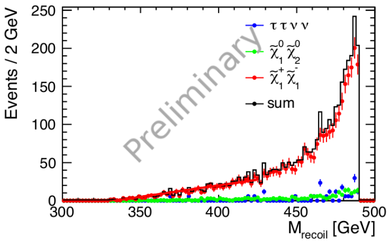



[NB: at different selection stages]

# Mass Measurements

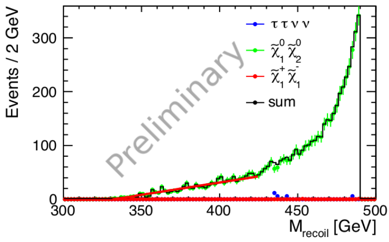
## Chargino mass reconstruction

- select only $e/\mu+$ hadrons




## Neutralino mass reconstruction

- select only radiative decaya




## chargino – neutralino separation works well

- $\Rightarrow$ expect resolution for mass difference similar to AMSB study
- resolution on recoil mass $< 1$ GeV

# Polarised cross-sections, ex $P(e^+, e^-) = (+30\%, -80\%)$

Preliminary!

## Charginos: semi-leptonic events

- efficiency $\times$ BR $= 42\%$
- purity $= 85\%$
- $\delta\sigma/\sigma = \pm 2\%$(stat.)

## Neutralinos: radiative events

- efficiency $\times$ BR $= 78\%$
- purity $= 98\%$
- $\delta\sigma/\sigma = \pm 1\%$ (stat.)

assumes BRs to be calculable and no systematics yet!

- for $P(e^+, e^-) = (-30\%, +80\%)$:
  signal increases, background decreases $\rightarrow$systematics?

# Parameter Determination — with Higgsinos only

## with conservative assumptions:

- $\delta M_{\tilde{\chi}_1^0} = \pm 1$ GeV
- error on mass difference: 20 MeV
- $\delta\sigma = \pm 10\%$ at $\sqrt{s} = 350$ GeV and $\sqrt{s} = 500$ GeV

## achieve:

- $\mu$: [165 GeV, 168 GeV] – input 166 GeV
- $M_1$: [1.5 TeV, 2.0 TeV] – input 1.7 TeV
- $M_2$: [3.9 TeV, 5.3 TeV] – input 4.4 TeV

$\Rightarrow$ can prove Higgsino nature, measure $\mu$ to $\pm 1\%$
$\Rightarrow$ $M_{1,2}$ to $\pm 20\%$, can predict heavier states (LHC, LC upgrades)
[more details: talk by K. Rolbiecki in SUSY, Wed, 11:40]

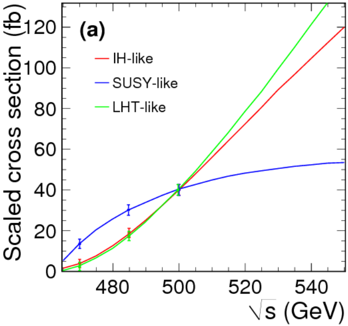
# Test SUSY's core predictions:

## inos = fermions

- shape of production threshold
- or equivalently shape of ISR photon energy spectrum near endpoint
- production angle?

## couplings are the same as in SM

- measure masses *and* cross-sections
- prove consistency
- even higher correlation between mass and cross-section: near threshold!

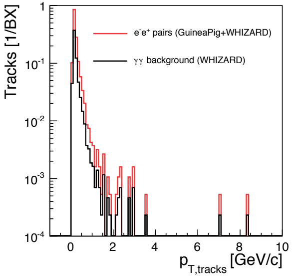



[Phys. Rev. D **84** (2011) 115003]

# Re-evaluate

## impact of $e^+e^-$ pairs

- reduces efficiency of $e$ veto in BeamCal
- backscatter from QD0 / BeamCal surface, fake tracks
- increased with RDR $\rightarrow$ TDR machine parameters




## impact of parasitic soft $\gamma\gamma$ interactions in the same bunch:

- low $p_t$ hadrons create extra activity, mostly in forward region
- has been studied with ILC-RDR ($\sqrt{s} = 500$ GeV)
- RDR $\rightarrow$ TDR: no. of overlay events grew by factor of $\sim 2.5$

# Requirements for Higgsinos Studies

## fragile signature → not trivial even at LC

- high polarisation, also at “low” energies (e.g. 350 GeV)
- efficient $e$ veto in BeamCal → moderate pair background
- clean events → moderate soft $\gamma\gamma$ parasitic interactions
- important: flexibility to adjust background conditions, e.g. increase number of bunches per train and lower bunch lumi

## CLIC

- 0.5 ns bunch spacing → whole bunch train piles up in detector
- even more interactions per BX
- impact on “fragile” final states ?

# Lifetime

## very small $\Delta m$:

- phase space suppression $\rightarrow$ long lifetime
- examples:
  - $M_{\tilde{\chi}_2^0} = 167.6$ GeV, $\Delta M = 1.0$ GeV $\Rightarrow c\tau^* = 72\ \mu$m
  - $M_{\tilde{\chi}_1^\pm} = 167.4$ GeV, $\Delta M = 0.8$ GeV $\Rightarrow c\tau^* = 750\ \mu$m
- visibility?
  - $\tilde{\chi}_2^0$: $\sim$ 75% to single photon $\rightarrow$ look at pair conversions?
  - $\tilde{\chi}_1^\pm$: $\sim$ 100% to charged, mostly 1-prong $\rightarrow$ impact parameter, but also 3-prong $\rightarrow$ vertexing
- interesting study!

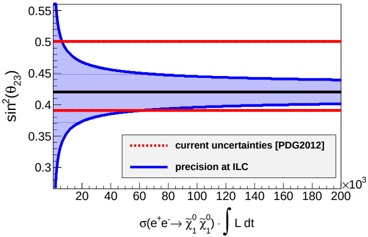
# Bilinear $R$-parity violation

## motivated by

- gravitino = viable decaying Dark Matter candidate [arXiv:1007.5007]
- could also be responsible for LFV in neutrino sector [arXiv:1106.2921]
- decay $\tilde{\chi}_1^0 \to l^\pm W^\pm$
- could allow detection at the LHC [arXiv:1107.0926,arXiv:1206.3605]

## ILC study [B. Vormwald, KILC12]:

- measure neutralino BR's $\tilde{\chi}_1^0 \to \mu^\pm/\tau^\pm W^\pm$
- almost background-free signature
- test compatibility with $\tan\theta_{23}$



# Conclusions I

- Natural SUSY: guided by minimized fine-tuning
- lightest SUSY particles:
  - Higgsinos $\lesssim$200 GeV
  - 3rd gen. squarks $\lesssim$1 TeV
  - gluino $\lesssim$3...4 TeV
- LHC only starts to probe this parameter space
- very good prospects for LHC to find gluino
- good prospects for LHC to find $\tilde{t}_1$
  - but: difficult regions for low $m_{\tilde{t}}$, $\tilde{t}_1 \to c\tilde{\chi}_1^0/btwpm_1$
  - piece of cake for LC
  - why not $m_{\tilde{t}_1} < 250$ GeV?

# Conclusions II

- Higgsinos at the LHC:
  - probably not distinguishable
  - direct production very difficult
- Higgsinos at the ILC:
  - can be studied with percent level precision → SUSY parameter determination!
  - fragile signature → flexibility to minimize machine backgrounds
  - just starting to explore the possibilities!

Maybe ILC will not only be a Higgs factory —
but also a *Higgsino* factory!

# Credits

Many thanks to all people who helped to prepare this talk:

- Mikael Berggren
- Katja Krüger
- Benno List
- Gudi Moortgat-Pick
- Hale Sert
- Georg Weiglein