Exploring Supersymmetry in Future e^+e^- Colliders

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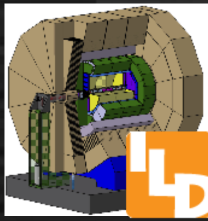
on behalf of ILD, SiD, CLICpd groups



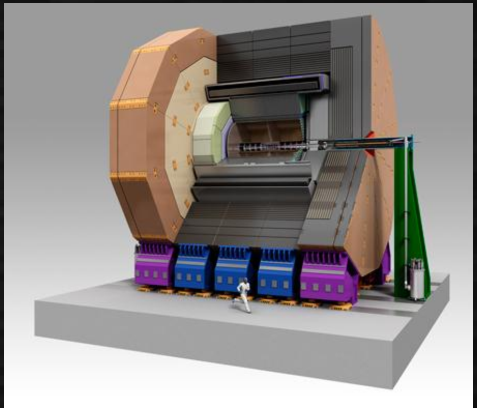
LC detector concepts

international linear collider

Compact Linear Collider

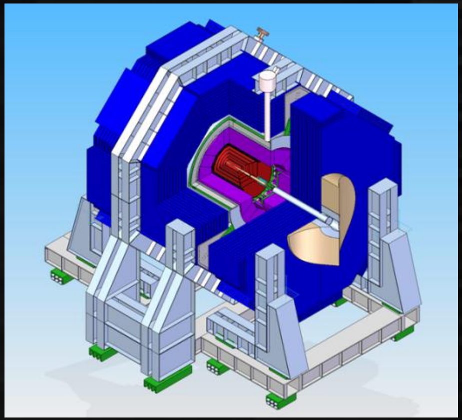
√s: 0.25 – 1 TeV (first stage: 0.5 TeV)

√s: 0.5 – 3 TeV



ILD concept

- Silicon vertex & intermediate tracker
- Time projection chamber
- Finely segmented CAL
- 3.5T magnetic field



SiD concept

- Silicon vertex
- Silicon tracker
- Finely segmented CAL
- 5T magnetic field

Adapt ILC detectors for higher energy initial studies (CLIC_ILD & CLIC_SID)

- Larger inner radius of VTX first layer
- Larger HCAL
- Stronger magnetic field (CLIC_ILD only: 4T)

Common Simulation Framework

ILD framework

- Mokka MC simulator (g4-based)
- Marlin C++-based reconstruction framework
  - Digitization
  - Tracking, PFA, flavor tagging

SiD framework

- slic MC simulator (g4-based)
- org.lcsim Java-based reconstruction framework
  - Digitization, Tracking, PFA
- Flavor tagging in Marlin

Common features:

- Geant4-based full simulation
- Realistic detector geometry (incl. gaps, electronics, etc.)
- Common persistency (LCIO) compatible data format
- Common generator samples of SM bkg. and signals

CLIC application

- Use adapted geometry: CLIC_ILD & CLIC_SID
- Overlaying $\gamma\gamma$ to hadron background (severe in multi-TeV env.)

SUSY in LC

mass

Colored sector

- Naturally heavy in light of LHC data
- May be accessible in a multi-TeV LC
- For some parameters low energy squarks still alive

Slepton sector

- Light sleptons still alive
- Long-lived stau also accessible in LC

Gaugino sector

- Should be light
- Direct production is difficult in hadron colliders
- Many properties are accessible in LC
  "Window to SUSY world"

Higgs (light/heavy)

- Structure of Higgs doublet can be accessible in TeV LC
- Precision study of light Higgs also gives constraints on SUSY

Gravitino

SUSY in LC

mass

Colored sector

- Naturally heavy in light of LHC data
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  "Window to SUSY world"

Higgs (light/heavy)

Not covered in this talk:
See F. Simon's presentation in Higgs session

Gravitino

Virtually no model-independent constraints by LHC
in gaugino sector

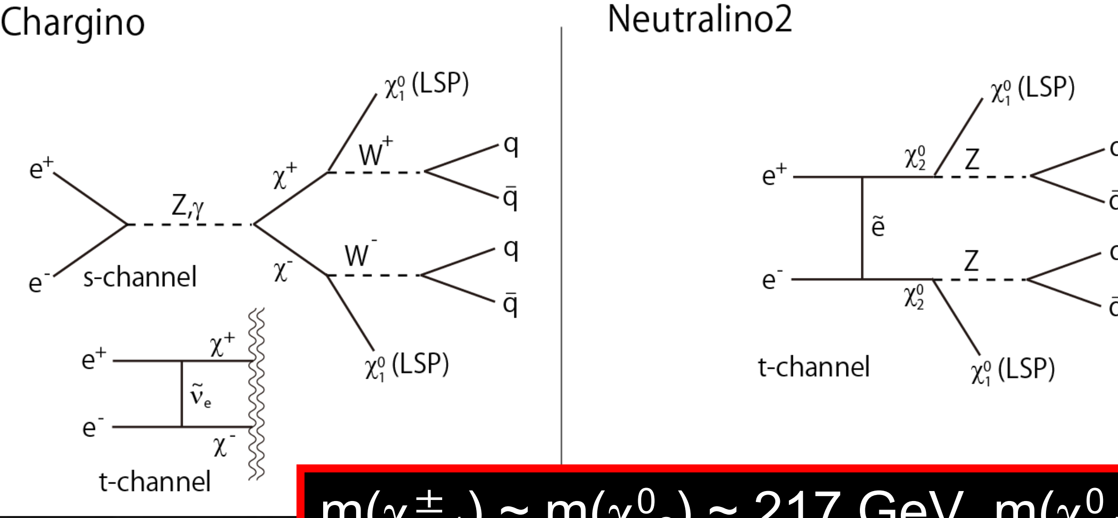
Part of following studies may use benchmark points which are already excluded, but they are easily applicable for parameters with too heavy colored sector to be seen in LHC.

Gaugino sector

- Chargino/Neutralino mass fit
- Spin determination
- WIMP + ISR
- Neutralino decay (RPV)

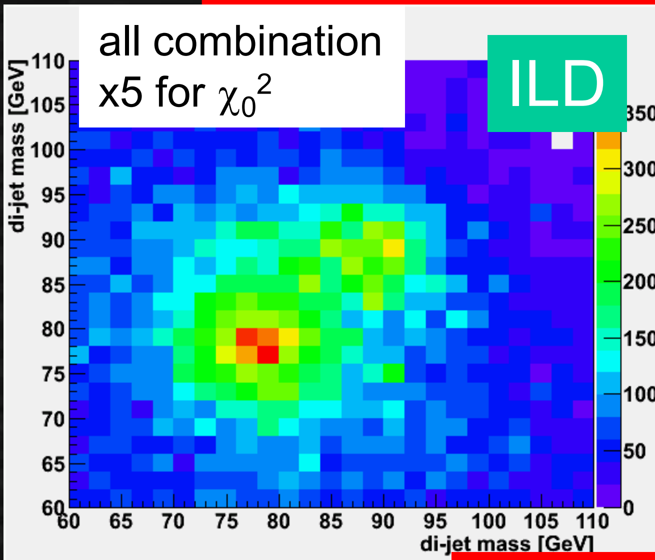
Chargino/Neutralino study

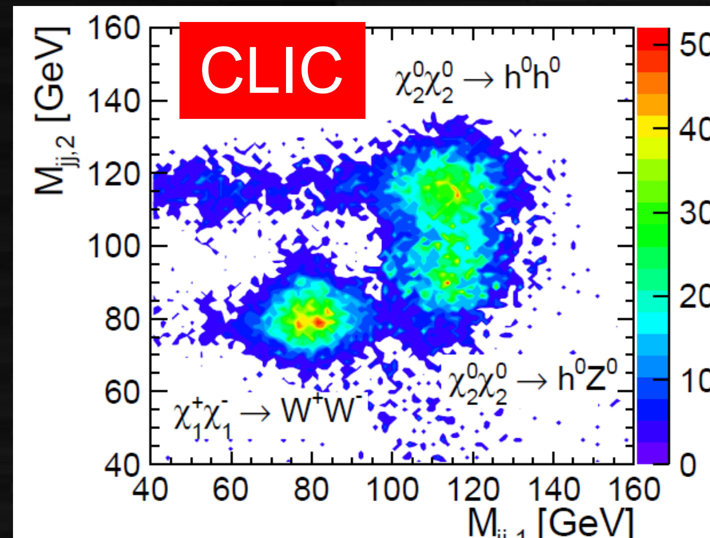
J.List, TS (ILD)
Y.Li, A. Nomerotski (SiD)
T. Barklow, A. Munnich,
P. Roloff (CLIC)



- Detector benchmark (ILC LoI, CLIC CDR) for W/Z/H separation in particle flow
- Mass & cross section measurement

$m(\chi^{\pm}_1) \sim m(\chi^0_2) \sim 217$ GeV, $m(\chi^0_1) \sim 116$ GeV (ILD, SiD 500 GeV)
$m(\chi^{\pm}_1) \sim m(\chi^0_2) \sim 643$ GeV, $m(\chi^0_1) \sim 340$ GeV (CLIC 3TeV)



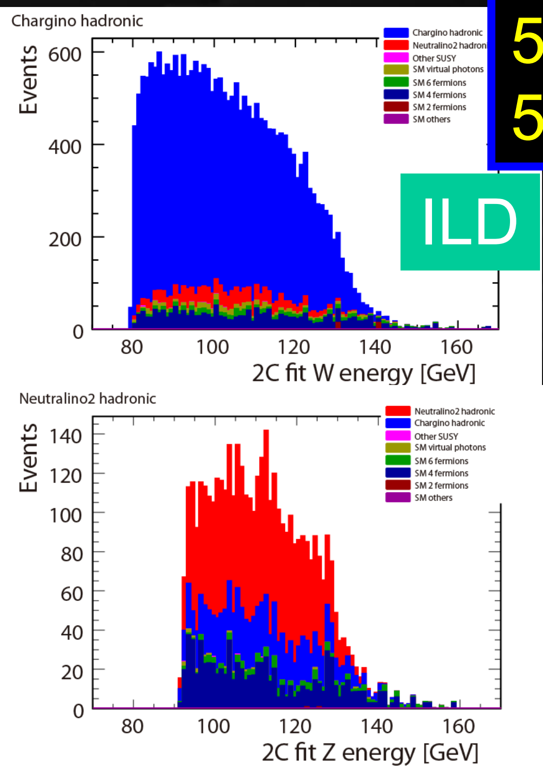


1~3% cross section accuracy can be obtained.

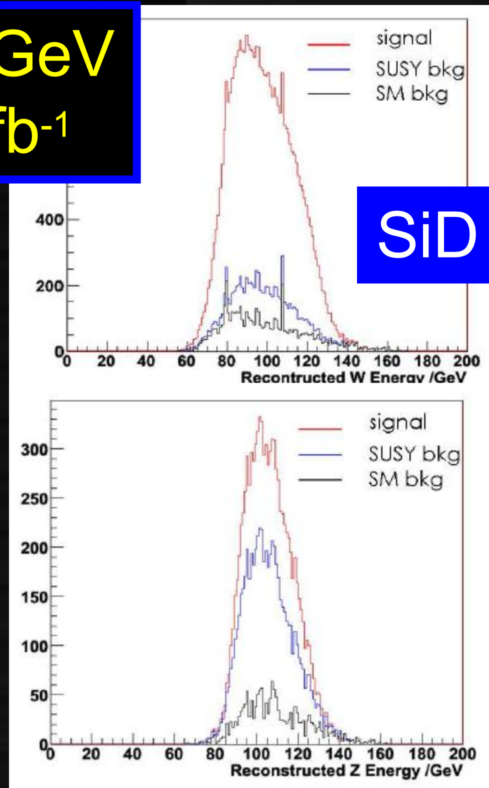
Chargino/Neutralino mass fit

500 GeV
500 fb^{-1}

ILD

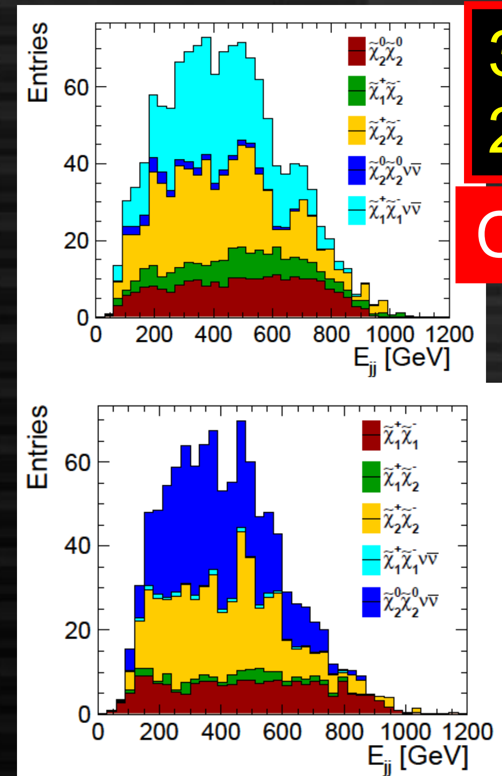


SiD



3 TeV
2 ab^{-1}

CLIC

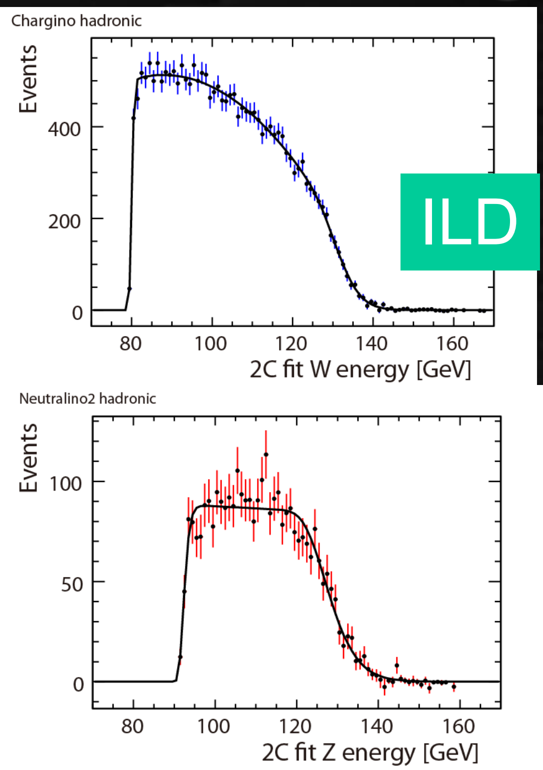


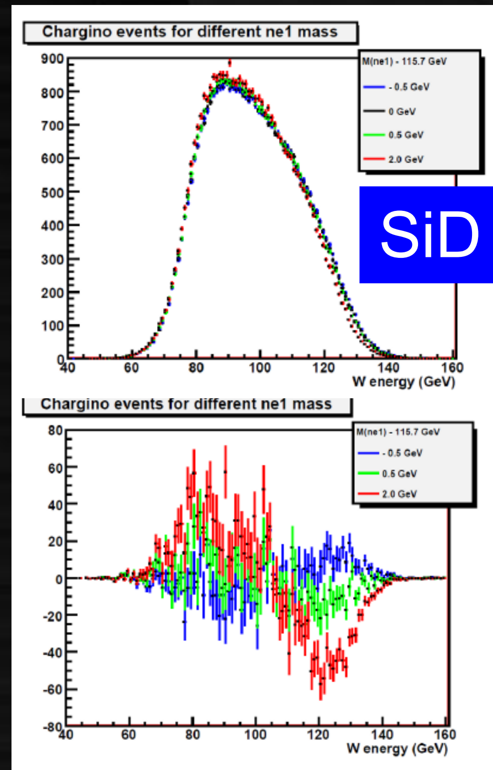
fit -> edge -> mass | template -> χ^2 | both (template & fit)

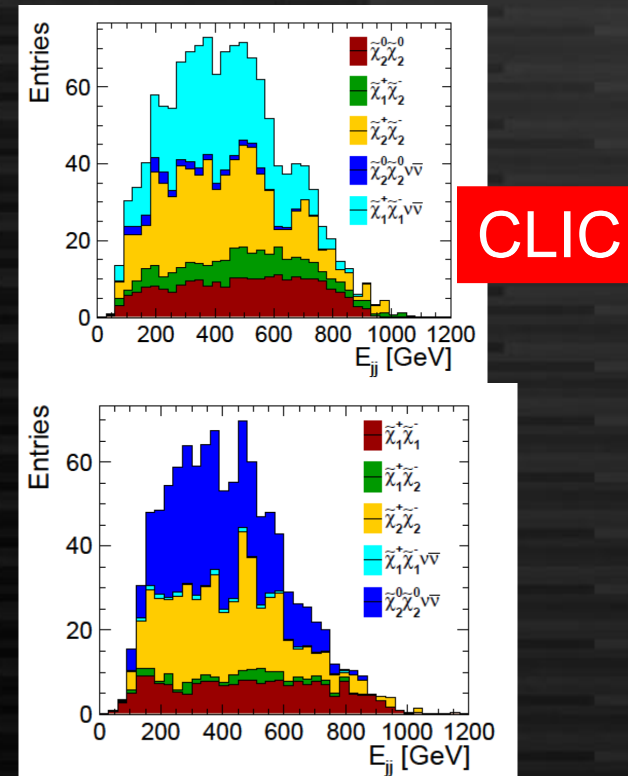
	ILD(fit)	SiD(template)	CLIC(tmpl.)	CLIC(fit)
$\Delta m(\chi^{\pm}_1)$	1.4%	0.2%	1.0%	1.1%
$\Delta m(\chi^0_2)$	0.5%	0.5%	1.1%	1.5%
$\Delta m(\chi^0_1)$	0.7%	0.1%	0.9%	0.9%

ILD: with correlation; SiD: without correlation

Chargino/Neutralino mass fit







fit -> edge -> mass template -> χ^2 both (template & fit)

	ILD(fit)	SiD(template)	CLIC(tmpl.)	CLIC(fit)
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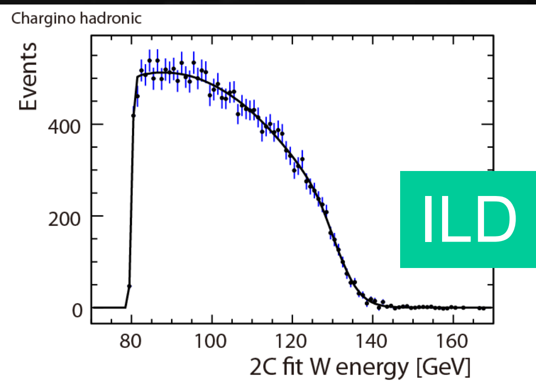
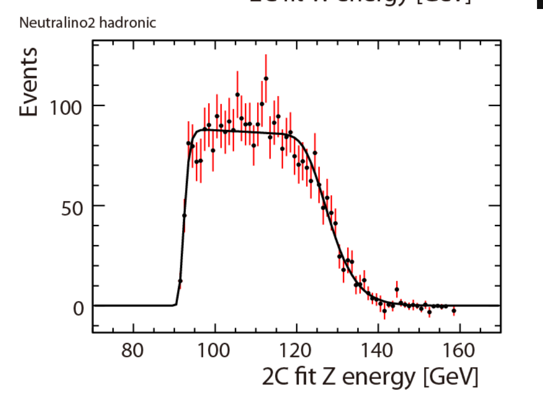
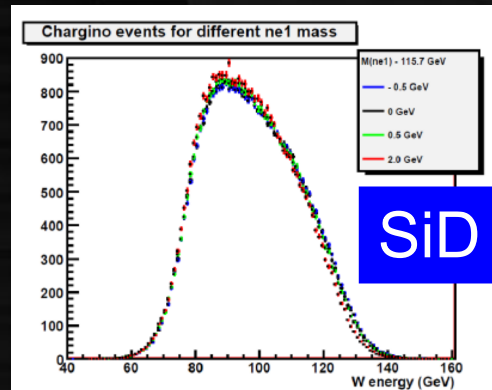
with correlation

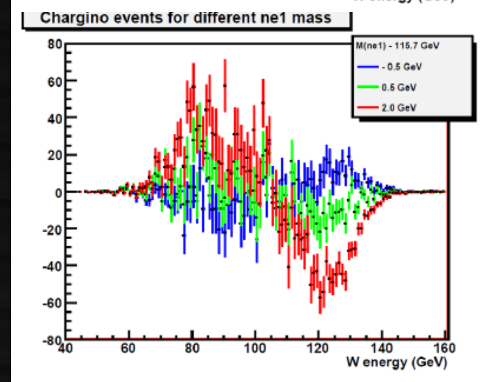
without correlation

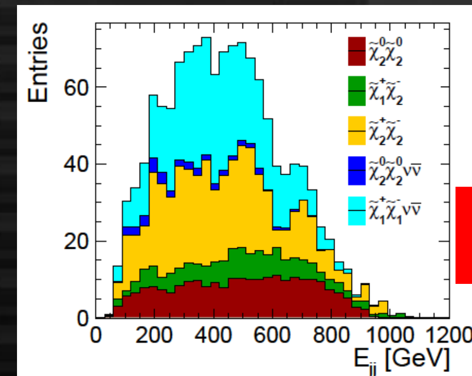
Chargino/Neutralino mass fit

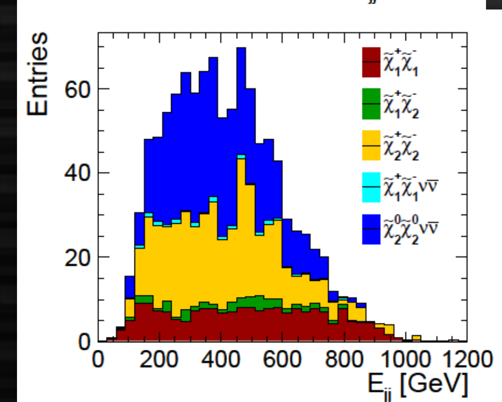












fit -> edge -> mass

template -> χ^2

both (template & fit)

	ILD(fit)	SiD(template)	CLIC(tmpl.)	CLIC(fit)

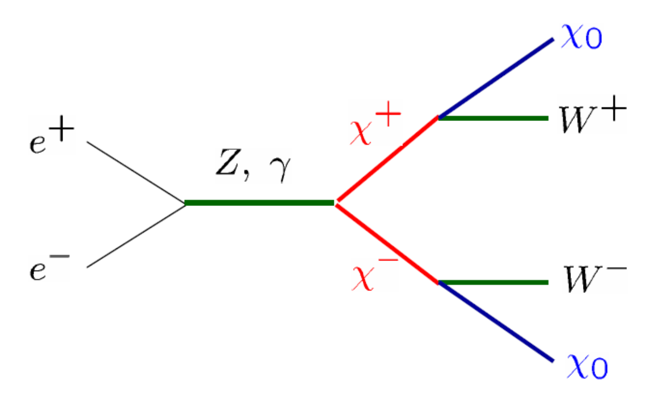
~1 % mass resolution is obtained.

Spin determination

500 GeV
500 fb^{-1}

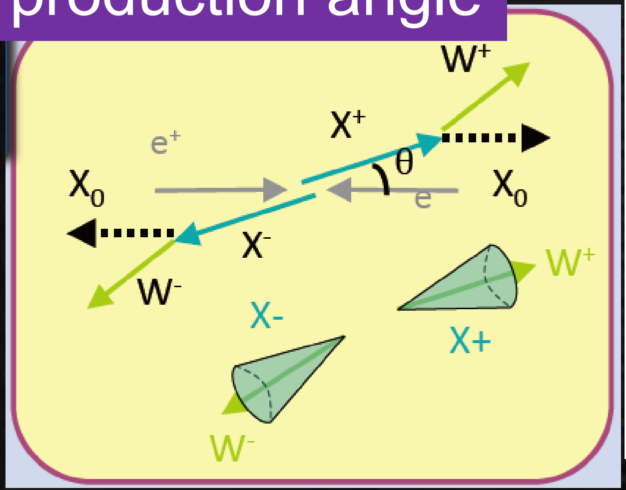
M. Asano,
T. Saito, TS et al.
(ILD)

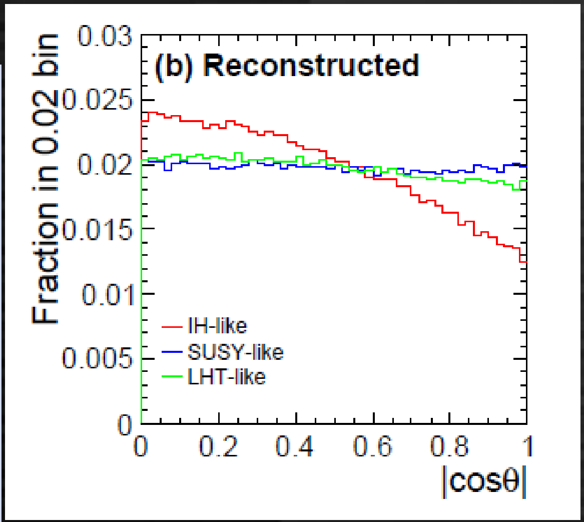
m($\chi^{\pm}$) ~ 232 GeV, m(χ^0) ~ 44 GeV, σ = 40 fb



Obtaining $\chi^{\pm}$ spin by production angle and threshold scan

production angle

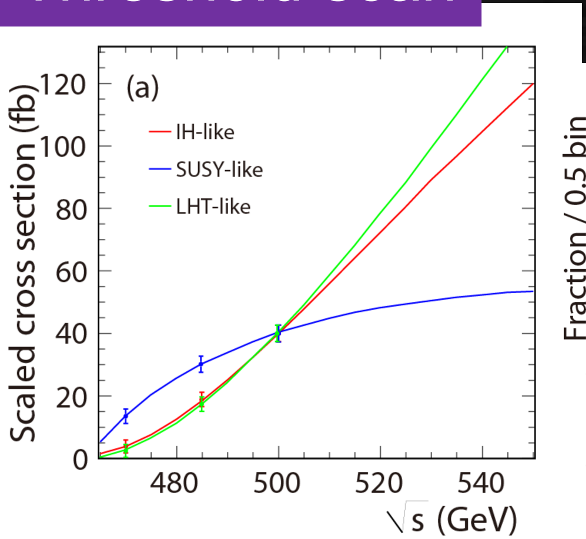


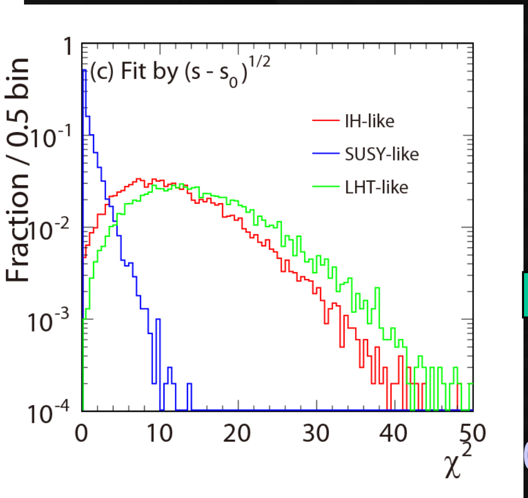


Template fit using 2D distribution of two solutions

→ scalar $\chi^{\pm}$ can be separated with > 4.9 σ

Threshold scan





→ fermion (SUSY) $\chi^{\pm}$ can be well separated with 3 x 50 fb^{-1} statistics

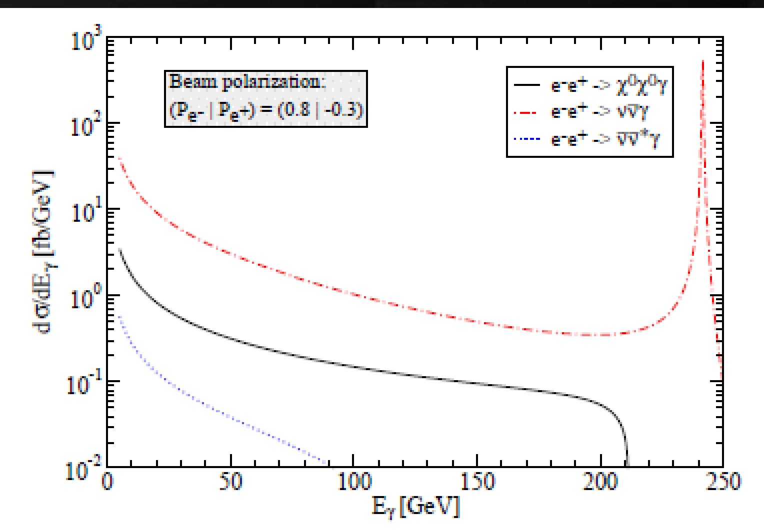
WIMP-pair production w/ ISR

500 GeV
500 fb^{-1}

$m(\chi^0_1)$ ~ 100 GeV case

C. Bartels, O. Kittel, J. List et al. (ILD)

σ ~ 60 fb in (Pe^-, Pe^+) = (0.8, -0.3)



Template fit for mass determination

$\pm$ stat.	$\pm$ sys.	($\delta E \pm \delta\mathcal{L}$)	(total) [GeV]	(P_{e-}; P_{e+})
± 2.65	± 0.09	± 2.20	(3.44)	(0.8; 0.0)
± 2.07	± 0.09	± 2.20	(3.02)	(0.8; −0.3)
± 1.70	± 0.09	± 2.20	(2.79)	(0.8; −0.6)

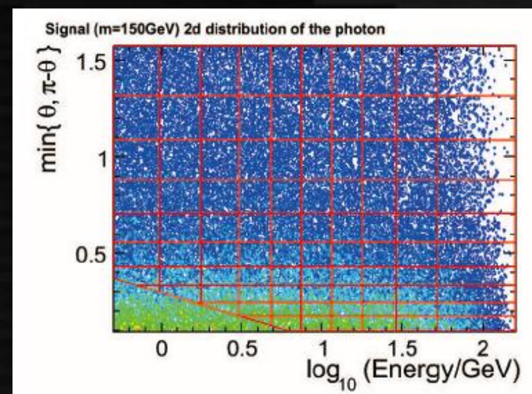
$\Delta m(\chi^0_1)$ ~ 3-4 %

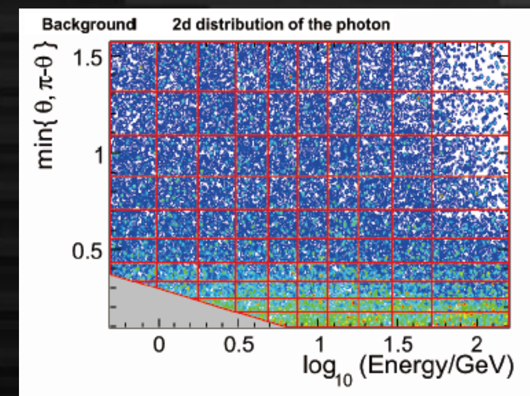
$m(\chi^0_1)$ ~ 150, 200 GeV case

K. Murase, T. Tanabe, TS et al. (ILD)

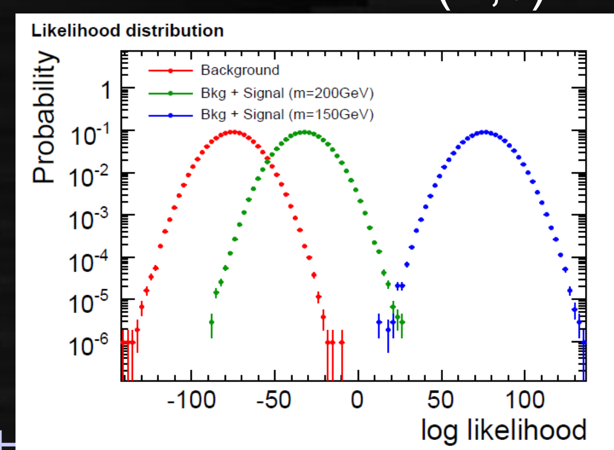
σ ~ 30 fb in (Pe^-, Pe^+) = (0.8, -0.3) (150)

σ ~ 11 fb in (Pe^-, Pe^+) = (0.8, -0.3) (200)





2D distribution of (E,θ) -> likelihood



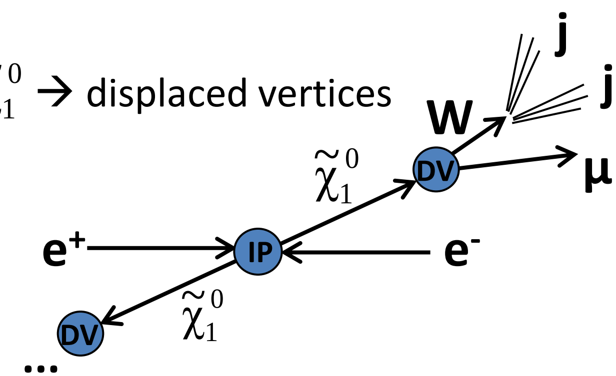
$m(\chi^0_1)$ = 200 GeV can be seen in 3.1 σ

500 GeV
500 fb^{-1}

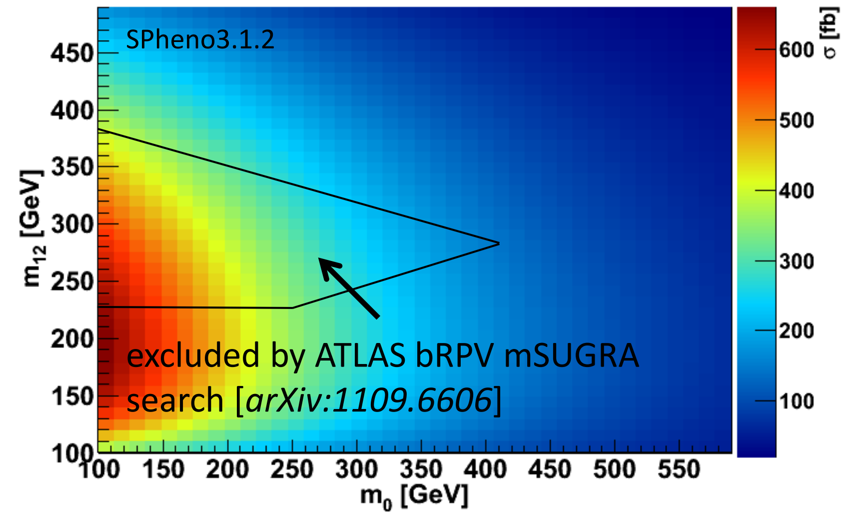
Bilinear R-Parity violating SUSY

Motivated by
- neutrino masses/mixing [*arXiv:hep-ph/0011248*]
- cosmology (gravition DM) [*arXiv:1007.5007*]

Signal signature
- $\tilde{\chi}_1^0 \rightarrow W + l$
- lifetime of $\tilde{\chi}_1^0 \rightarrow$ displaced vertices



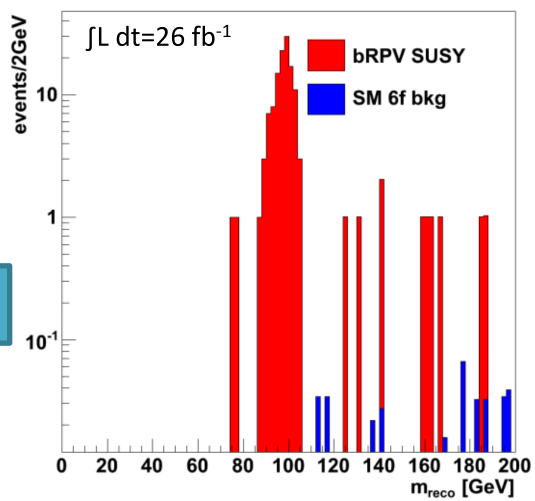
Production cross section of neutralino pairs @ ILC



Full ILD simulation

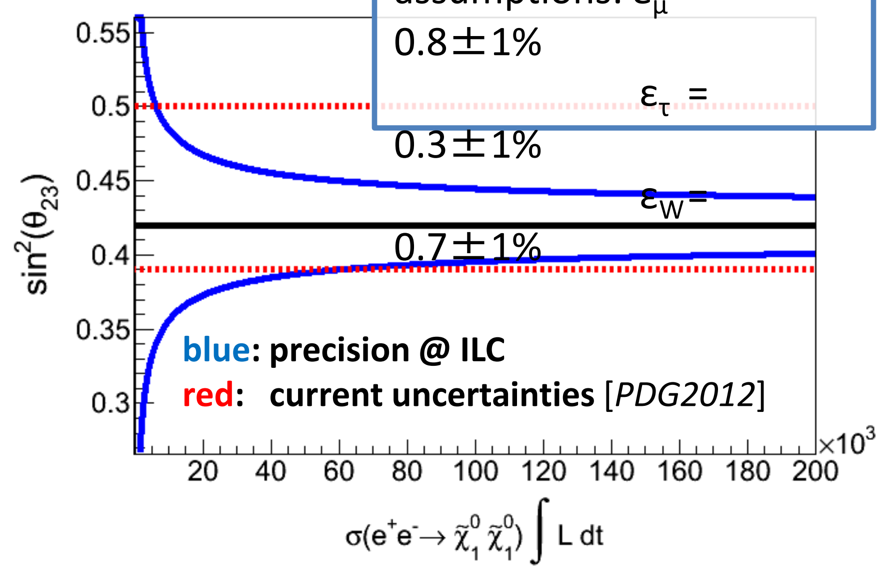
- search for 2W+2l
- no assumptions on neutralino mass or lifetime

background free



Measurement of neutrino mixing

assumptions: ε_μ = 0.8±1%
ε_τ = 0.3±1%
ε_W = 0.7±1%



Model-independent constraints by LHC are also very weak in slepton sector

Slepton sector

- smuon/stau (500 GeV)
- selectron/smuon/sneutrino (3 TeV)
- stau (1.5 TeV)
- Long-lived stau (500 GeV)

Light smuon/stau

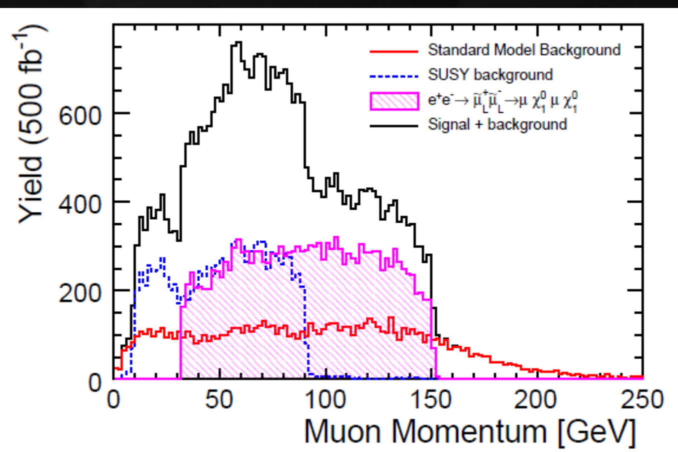
500 GeV
500 fb^{-1}

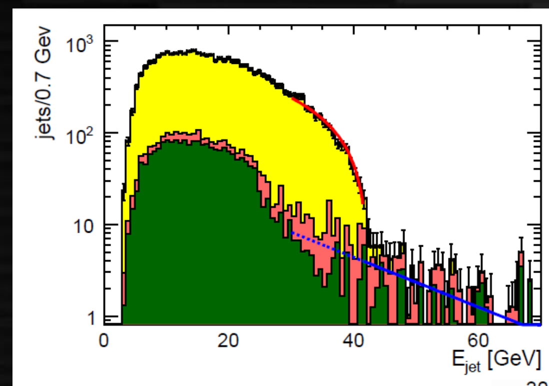
smuon P. Bechtle, N. D'Ascenzo, E. Garutti(ILD)

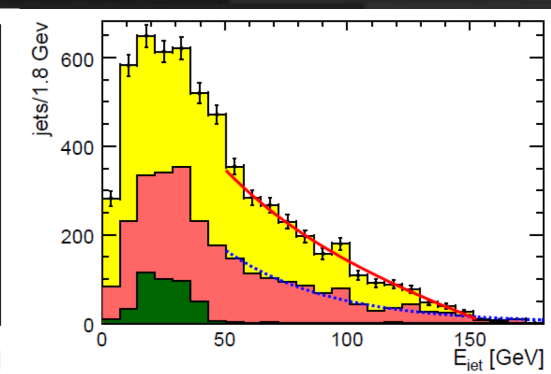
stau P. Bechtle, M.Baggren, J.List,, P. schade, O. Stempel(ILD)

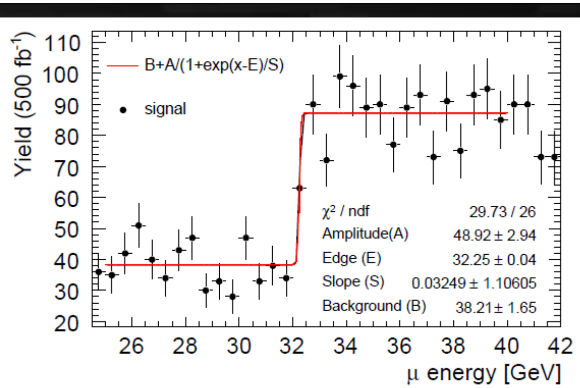
m(smuL) = 184 GeV, m(χ^0_1) = 98 GeV, 54.32fb

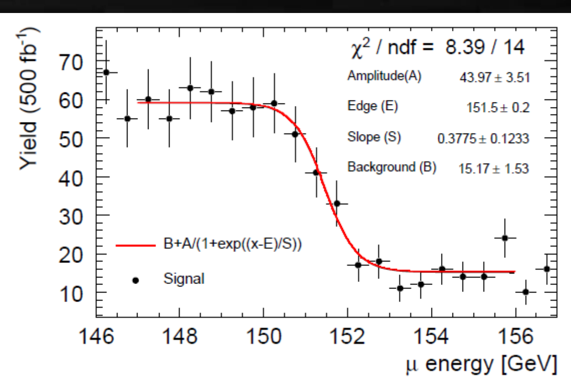
m(stau1) = 108 GeV, fb
m(stau2) = 195 GeV, fb

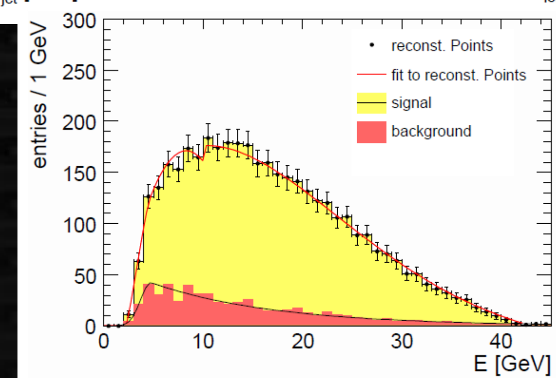












Δm(χ^0_1) : 1.1%
Δm(smuL): 0.2%
Δσ: 2.5%

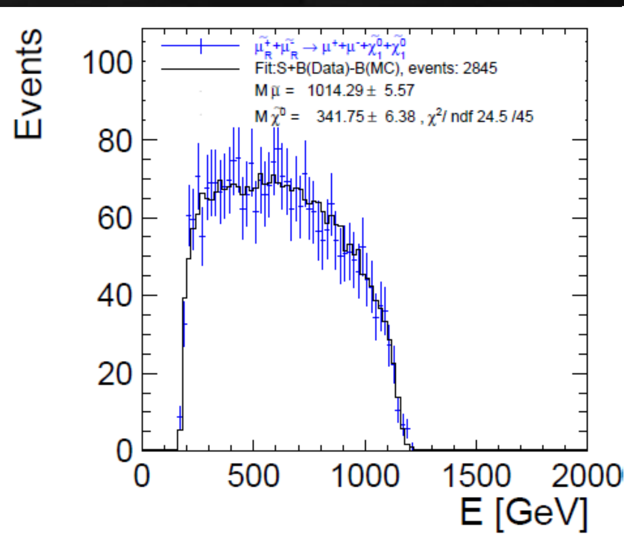
Δm(stau1): 1.1Δm(χ^0_1) GeV
Δm(stau2): +11-5 + 18Δm(χ^0_1) GeV
ΔP: 9% (π) 5% (ρ)

Heavy Sleptons

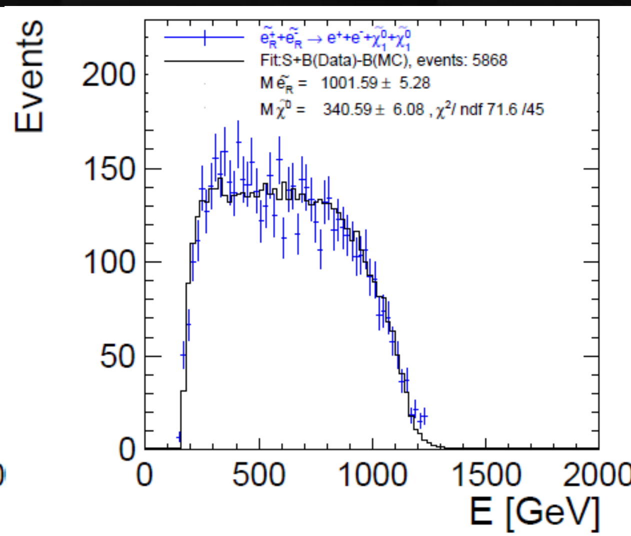
3 TeV
2 ab^{-1}

M. Battaglia, J-J.Blaising,
J. Marshall, J. Nardulli,
M. Thomson, A. Sailer, E van der Kraaij (CLIC)

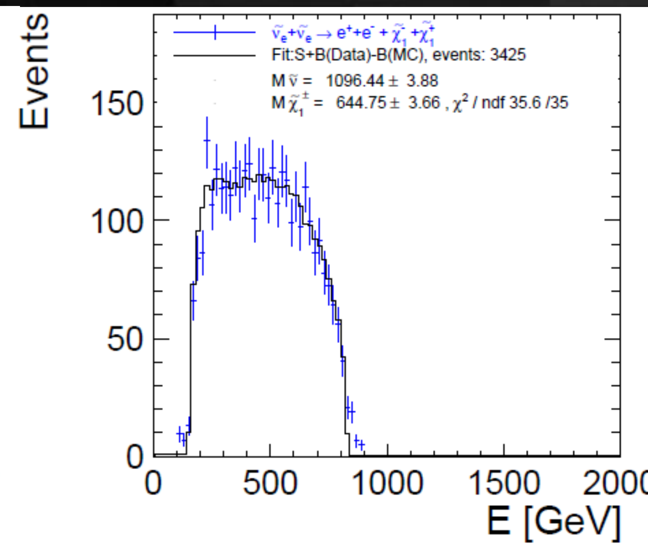
Process	Decay Mode	σ fb	$m_{\tilde{\ell}}$ GeV	$m_{\tilde{\chi}_1^0}$ or $m_{\tilde{\chi}_1^\pm}$ GeV
$e^+e^- \to \tilde{\mu}_R^+\tilde{\mu}_R^-$	$\mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	0.71 ± 0.02	1014.3 ± 5.6	341.8 ± 6.4
$e^+e^- \to \tilde{e}_R^+\tilde{e}_R^-$	$e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	6.20 ± 0.05	1001.6 ± 5.3	340.6 ± 6.1
$e^+e^- \to \tilde{e}_L^+\tilde{e}_L^-$	$e^+e^-\tilde{\chi}_2^0\tilde{\chi}_2^0$	2.77 ± 0.20		
$e^+e^- \to \tilde{\nu}_e\tilde{\nu}_e$	$e^+e^-\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$	13.24 ± 0.32	1096.4 ± 3.9	644.8 ± 3.7



(a) $e^+e^- \to \tilde{\mu}_R^+\tilde{\mu}_R^-$



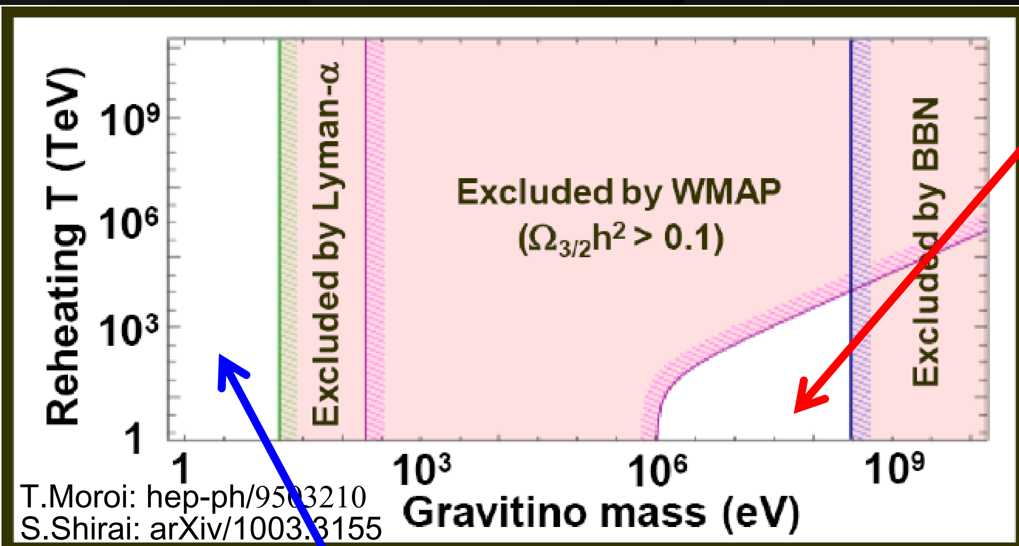
(b) $e^+e^- \to \tilde{e}_R^+\tilde{e}_R^-$



(c) $e^+e^- \to \tilde{\nu}_e\tilde{\nu}_e$

Long-lived stau

500 GeV
500 fb^{-1}



stopping stau

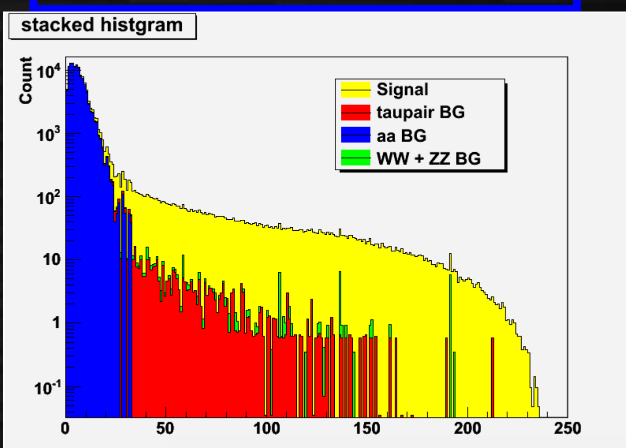
W. Yamaura,
K. Kotera et al. (ILD)

for m(stau) = 150 GeV,

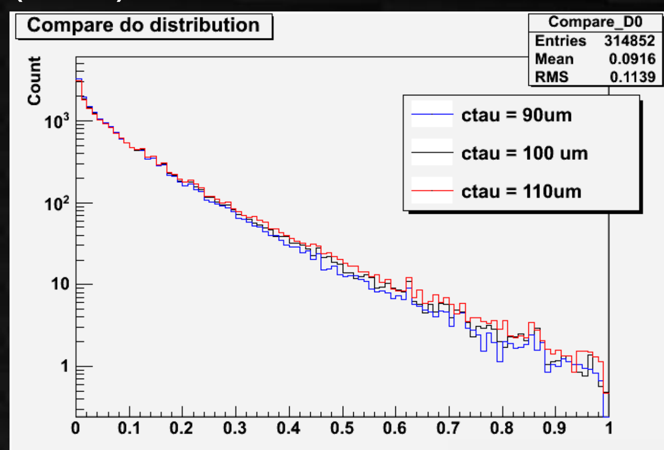
- m(stau) can be determined by dE/dx at TPC and TOF -> ~1.4% resolution
- gravitino life can be measured by tuning sqrt(s) for staus to be stopped at HCAL ~ 2.4%

decaying stau (VLG)
$c\tau$ ~ 0.1-10 mm

R. Katayama, T. Tanabe, TS et al. (ILD)
m(stau) = 120 GeV, σ = 136 fb



Track energy [GeV]



d0 [mm]

Δm(stau) : 1.4%
$\Delta\tau$(stau) : 2.1%

Δm(gravitino) : 4%

Colored sector

- squark (3 TeV)
- degenerate sbottom (500 GeV)

Light-flavor Squarks

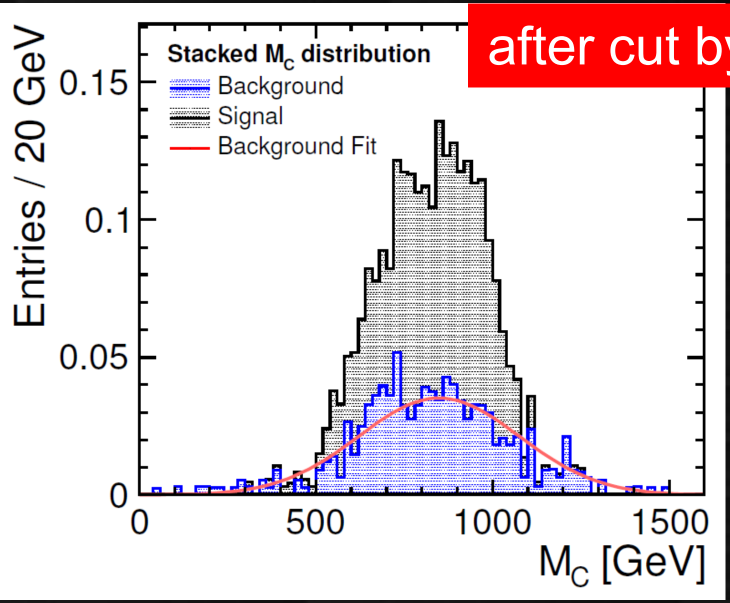
3 TeV
2 ab^{-1}

L. Waeste,
F.Simon (CLIC)

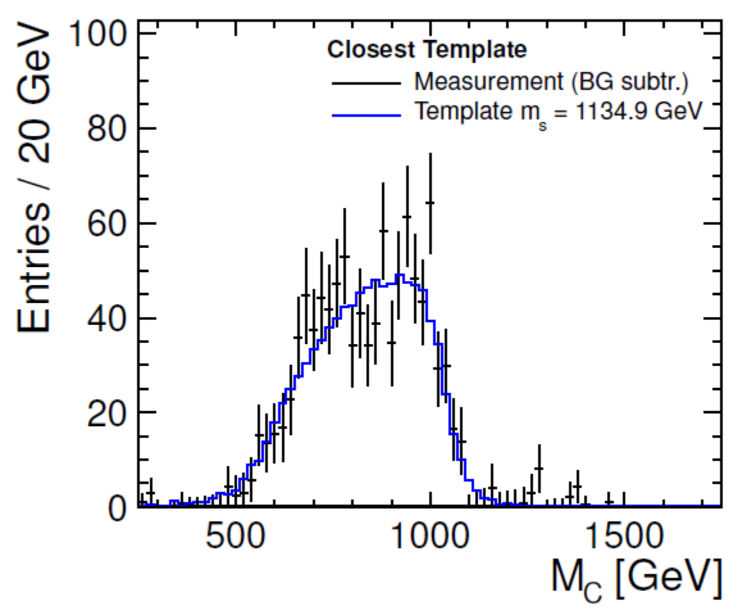
$m_{\tilde{u}_R}, m_{\tilde{c}_R}$	$m_{\tilde{d}_R}, m_{\tilde{s}_R}$	m_χ	combined cross section
1125.7 GeV	1116.1 GeV	328.3 GeV	1.47 fb

$$M_C = \sqrt{(E_{q,1}+E_{q,2})^2 - (\vec{p}_{q,1}-\vec{p}_{q,2})^2}$$
$$= \sqrt{2(E_1E_2+\vec{p}_1\cdot\vec{p}_2)},$$

M_C: independent of the CM energy



after cut by BDT



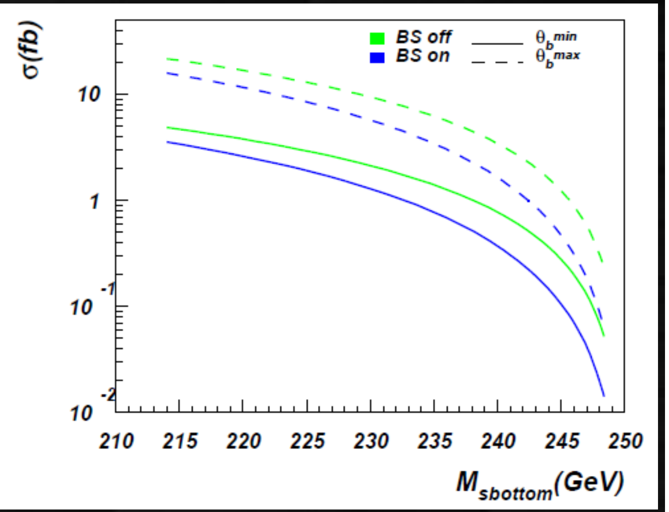
Δm(squark) : 0.5%
$\Delta\sigma$: 4.9%

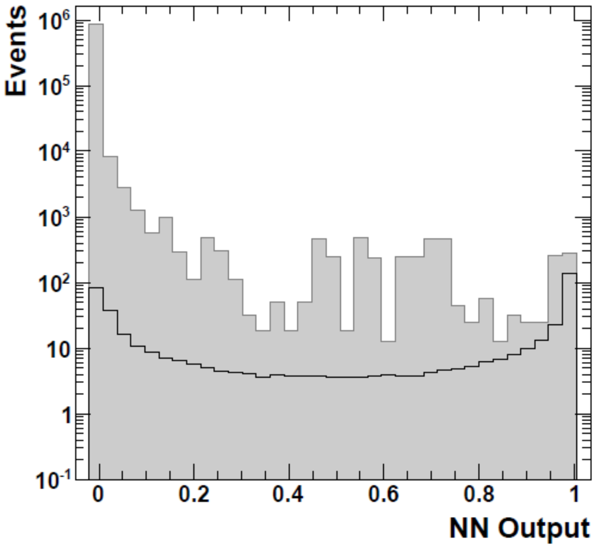
Sbottom co-annihilation

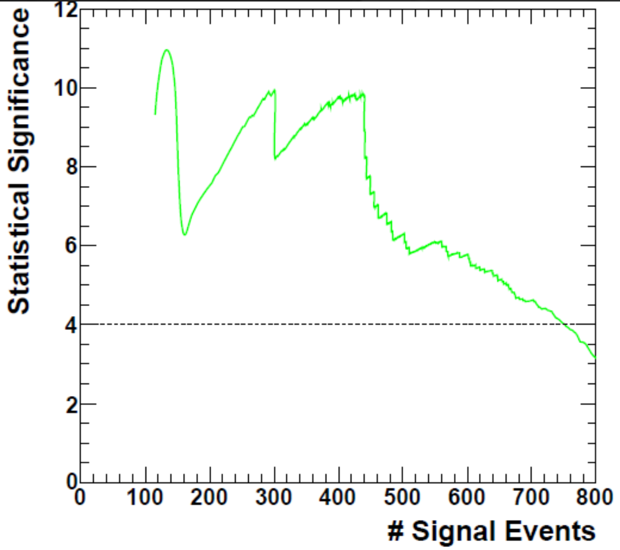
500 GeV
$500\ fb^{-1}$

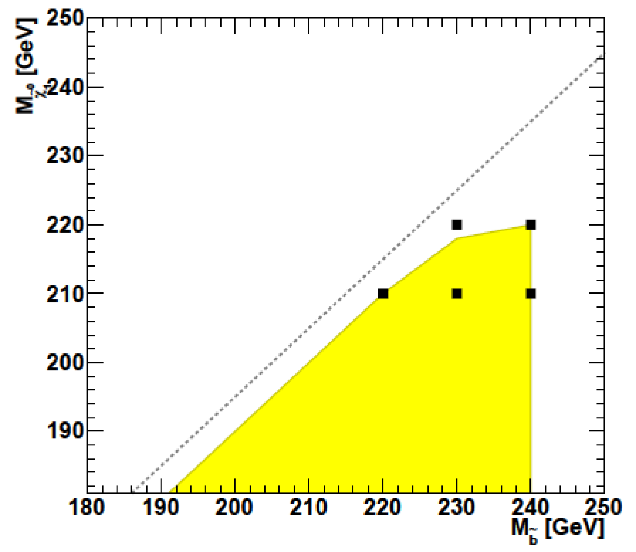
A. Belyaev,
T. Lastovisca,
A. Nomerotski,
G L-Medin (SiD)

Sbottom-neutralino co-annihilation: small mass difference between sbottom and χ_1^0, difficult to discover in LHC









with σ of $\theta_b$min
m(sbottom), m(χ_1^0) = (230,210), (240,210), (240,220), (220,210): > 3 σ separation
(230,220) : 2 σ separation

Summary

- Still a lot of room to explore SUSY with LC!
  - In case of “discovery” at LHC:
    many properties of SUSY can be revealed
  - In case of “non-discovery” at LHC:
    many possibilities of SUSY to be revealed
- Many realistic full simulation have been performed & ongoing
- ILD, SiD and CLICpd groups are in very close cooperation to realize one linear collider