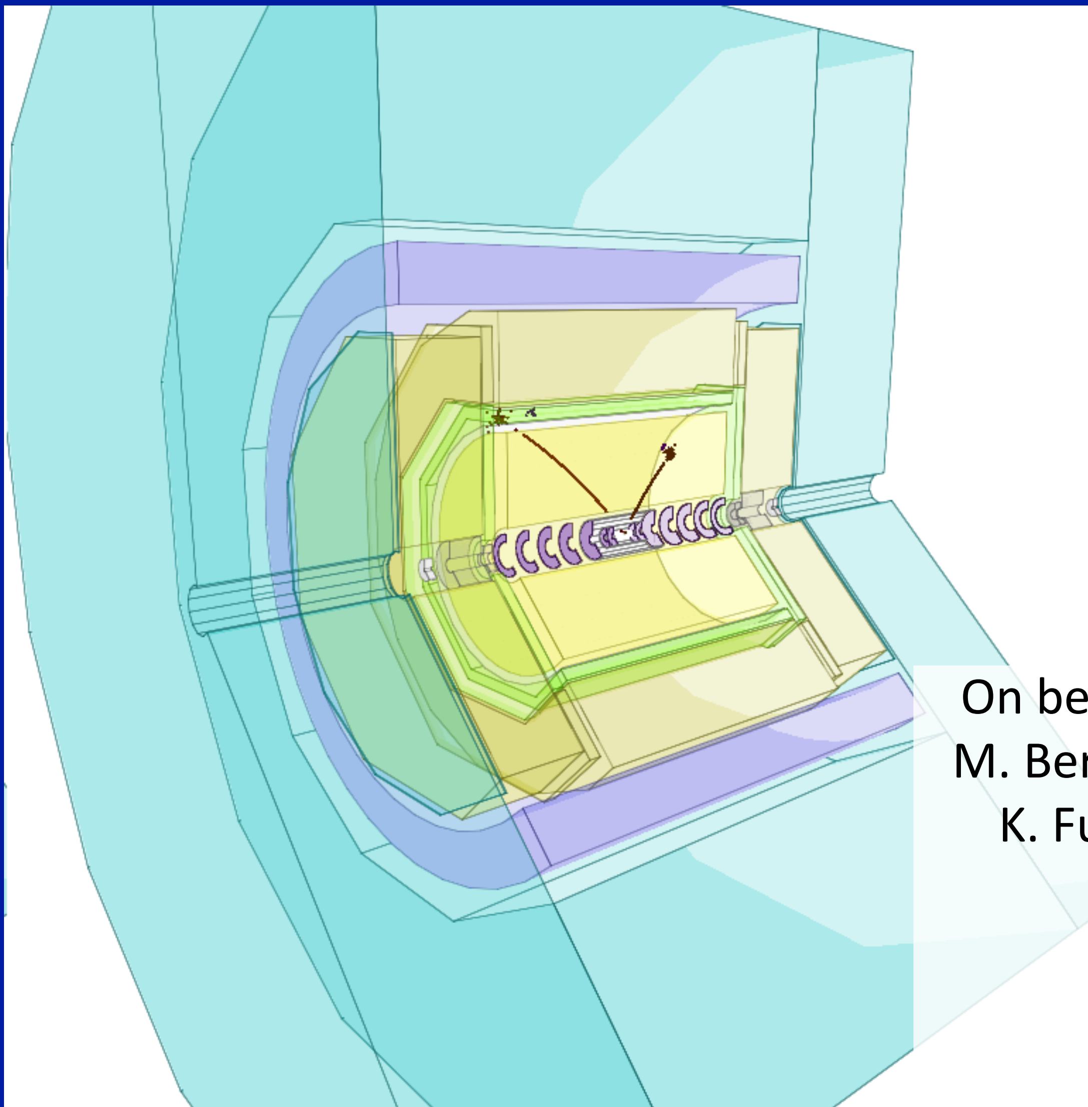
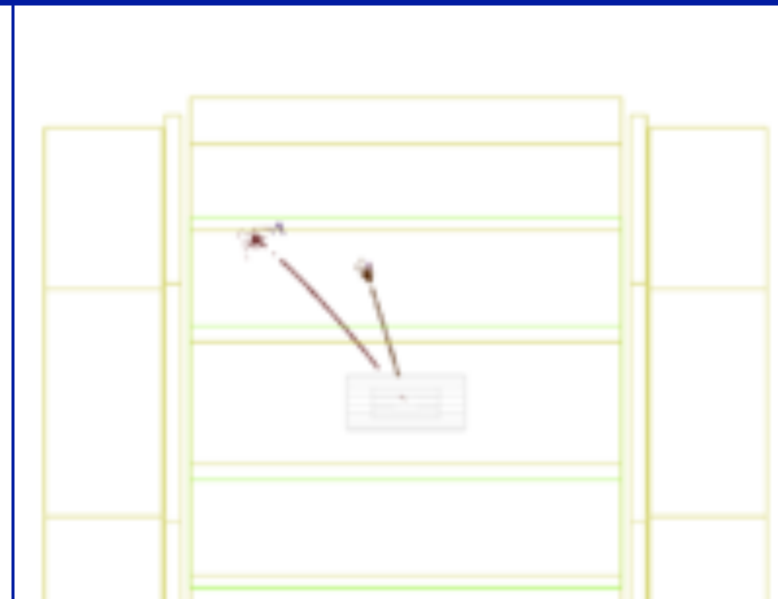
Characterizing Light Higgsinos from Natural SUSY at ILC $\sqrt{s}$ = 500 GeV





Jacqueline Yan (KEK)

On behalf of H. Baer (Univ of Oklahoma), M. Berggren, S.-L. Lehtinen, J. List (DESY), K. Fujii (KEK), T. Tanabe (Univ of Tokyo)

ILD Software and Analysis Meeting

July 13, 2016

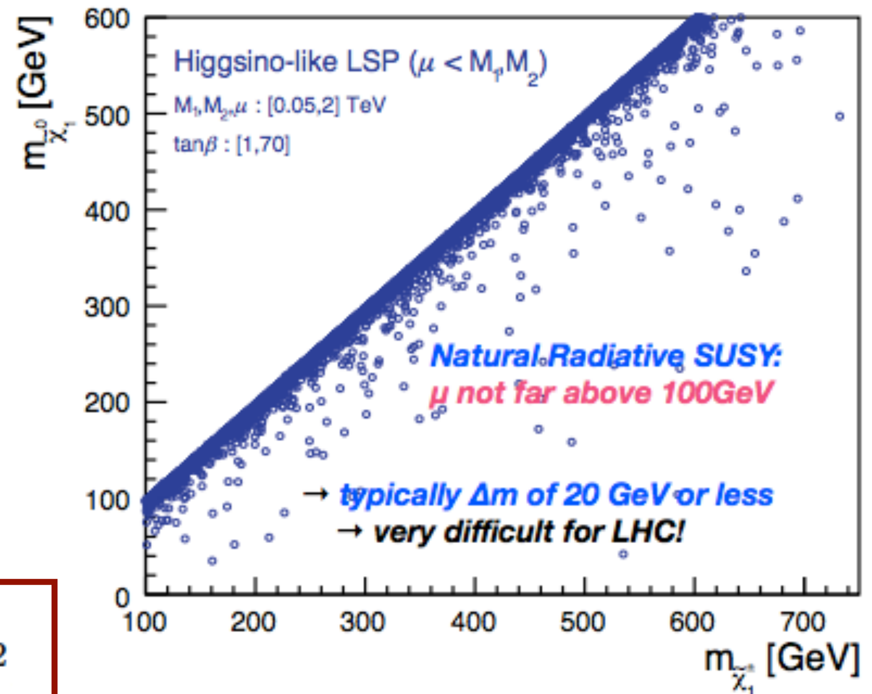
Outline

- Motivation of study
- Event selection
- Extraction of Higgsino mass and cross section
- SUSY parameter determination
- Goals and plans

Motivation for Searching Light Higgsinos with Small ΔM

❖ **From experimental point of view:**

- LHC already excluded large regions with large ΔM = M(NLSP) – M(LSP)
- Remaining region with compressed spectrum
  very small visible energy release,
  near impossible to probe at LHC
  ➔ **ILC is essential**



❖ **From theoretical point of view:**

Compressed Higgsino spectra related to naturalness [e.g. arXiv:1212.2655, arXiv:1404.7510]

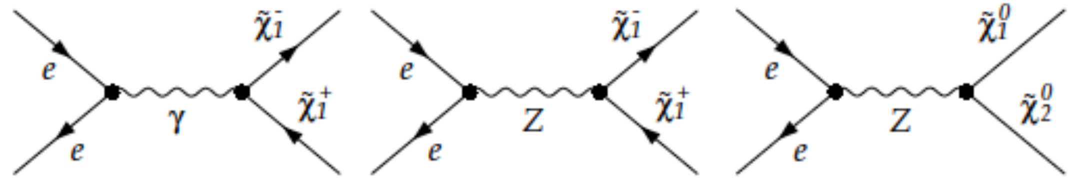
$$\frac{M_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

- To maintain **small electroweak fine tuning ΔEW (<∼3%)**, all contributions on right-hand-side should be comparable to M(Z) ➔ requires **μ ∼ 100–300 GeV**

  top and bottom squarks in the few TeV regime, gluino mass 2−4 TeV,
  1st, 2nd generation squarks and sleptons in the 5−30 TeV regime

- μ feeds mass to both SM (W, Z, h) and SUSY particles (Higgsinos)
- Higgsino masses not too far from masses of W, Z, h (∼100 GeV)

Benchmarks in this Study



RNS model (Radiatively-driven natural SUSY)

- **4 light Higgsinos:** $\tilde{\chi}_1^0$ (LSP) $\tilde{\chi}_2^0$ $\tilde{\chi}_1^+$ $\tilde{\chi}_1^-$

- **ΔM about 10-20 GeV complies with naturalness** (ISR tag not needed)

This study: **$\sqrt{s}$ = 500 GeV**
Full detector simulation

Currently studying ILC1 benchmark

(Pe-, Pe+)	(-1.0,+1.0)	(+1.0,-1.0)
$\sigma(\chi_1^+\chi_1^-)$ [fb]	1800	335
$\sigma(\chi_1^0\chi_2^0)$ [fb]	491	379

BR($\chi_1^+ \rightarrow \chi_1^0 qq'$)	67%
BR($\chi_1^+ \rightarrow \chi_1^0 l\nu$) (l=e,μ)	22%
BR($\chi_2^0 \rightarrow \chi_1^0 qq'$)	58%
BR($\chi_2^0 \rightarrow \chi_1^0 ll$) (l=e,μ)	7.4%

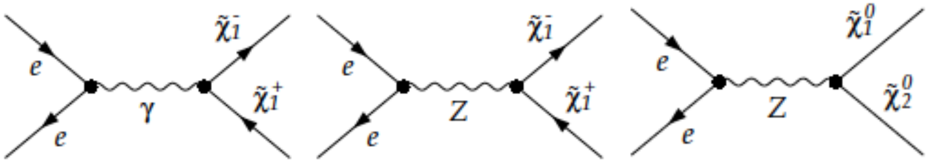
NUHM2 model parameters [arXiv:1404.7510]

Benchmark	ILC1	ILC2
M_0 [GeV]	7025	5000
$M_{1/2}$ [GeV]	568.3	1200
A_0 [GeV]	-10427	-8000
tanβ	10	15
μ [GeV]	115	150
M_A [GeV]	1000	1000
$M(\chi_1^0)$ [GeV]	102.7	148.1
$M(\chi_1^\pm)$ [GeV]	117.3	158.3
$M(\chi_2^0)$ [GeV]	124.0	157.8
$M(\chi_3^0)$ [GeV]	267.0	538.8

Higgs precision measurements useful for parameter determination

Defined at GUT scale
Defined at weak scale
Observables

Goal of Light Higgsino Study



This study

Demonstrate measurement precision of Higgsino masses and production cross sections

- **Study dependence of cross section on beam polarization**
  → Determine mixing ratio
  Higgsino vs. Bino vs. Wino

Masses and cross sections as input

Determine SUSY parameters
e.g. **M_1, M_2, μ, tanβ**

S.-L. Lehtinen et al

Why?

- **To get info about unobserved sparticles**
- **To test GUT-scale models**

How?

- **Global χ^2 fit of to observables**

Study input parameters and required precision for parameter extraction; interplay with Higgs precision measurements

Existing studies

(1) "Tackling light higgsinos at the ILC", M. Berggren et al. [arXiv:1307.3566]
- √s= 500 GeV, ΔM ∼1 GeV → use ISR tag, , Based on full ILD simulation

(2) "Physics at a Higgsino Factory", H. Baer et al. [arXiv:1404.7510]
- √s= 250 (340) GeV for ILC1 (ILC2), ΔM = 10-20 GeV, detector effects based on resolution formula

Ongoing studies

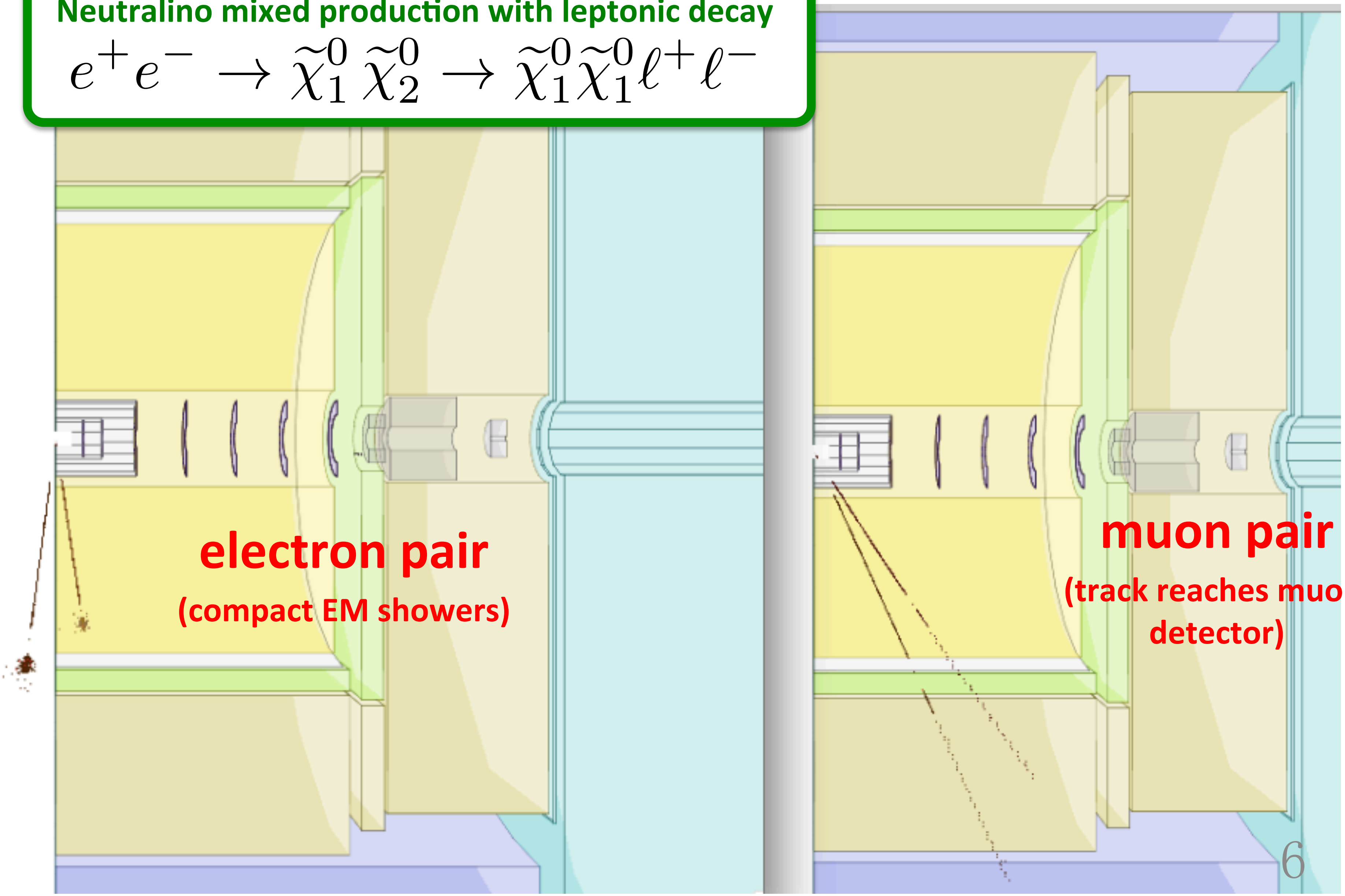
Light Higgsinos with ΔM= 10 – 20 GeV , J. Yan, T. Tanabe et al
√s= 500 GeV, ΔM ∼10-20 GeV , Based on full ILD simulation

How do these signals look in the detector? (1)

√s =500 GeV

Neutralino mixed production with leptonic decay

$$e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ell^+ \ell^-$$

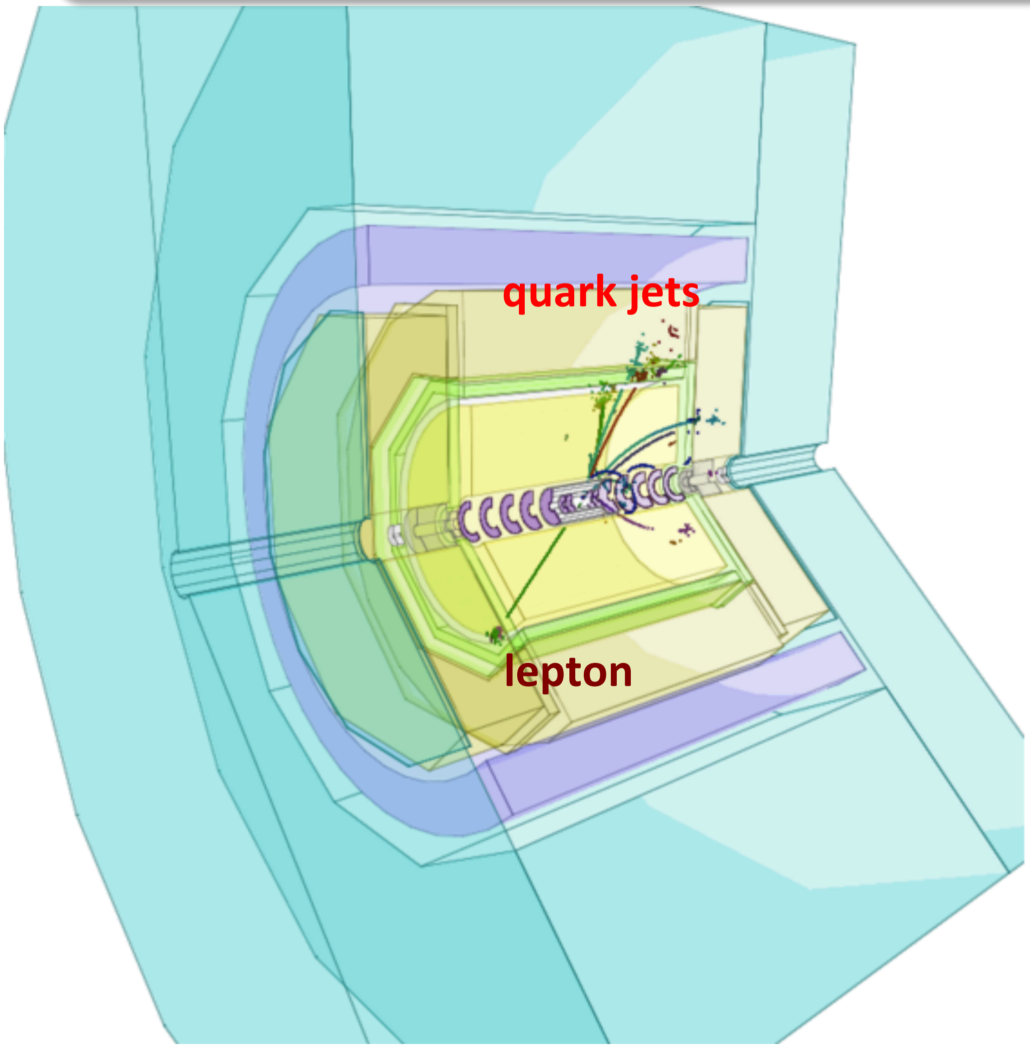


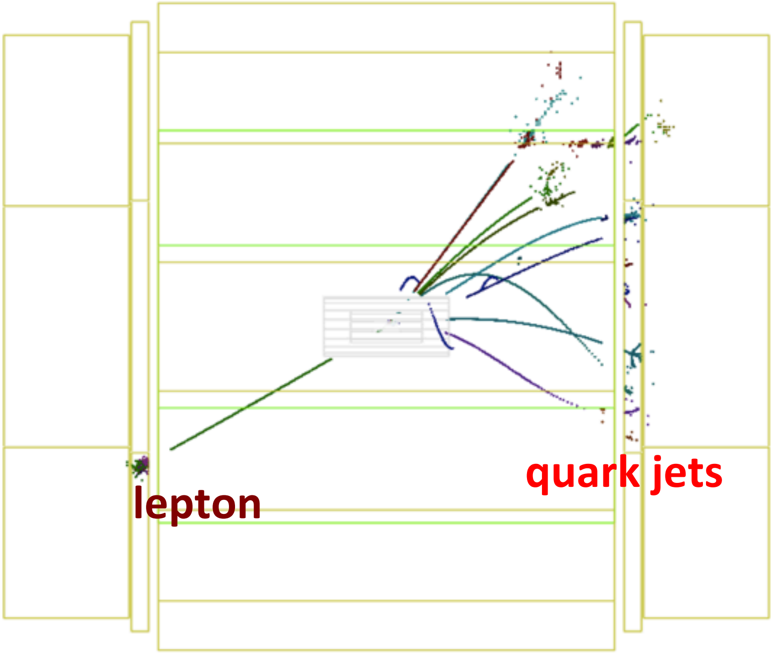
How do these signals look in the detector? (2)

√s =500 GeV

Chargino pair production with semileptonic decay

$$e^+e^- \to \widetilde{\chi}_1^+ \widetilde{\chi}_1^- \to \widetilde{\chi}_1^0 \widetilde{\chi}_1^0 q q' \ell \nu$$



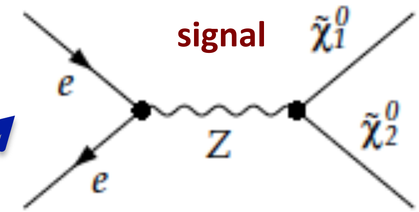


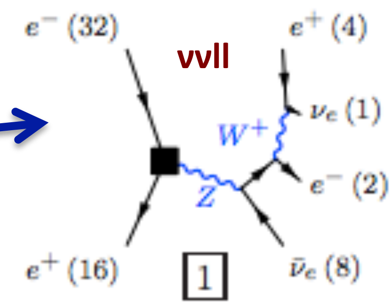
Event Selection

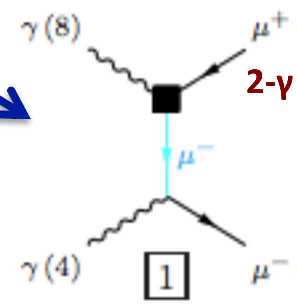
Neutralino mixed production with leptonic decay

$$e^+e^- \to \tilde{\chi}_1^0\,\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0\ell^+\ell^-$$

- Reconstruct **two leptons (ee or μμ) which originate from Z^* emission in decay of χ_2^0 to χ_1^0**
- Major residual bkg. are 4f processes accompanied by large missing energy (vvll)
- 2-γ processes are removed by BeamCal veto, cuts on lepton track p_T, and coplanarity





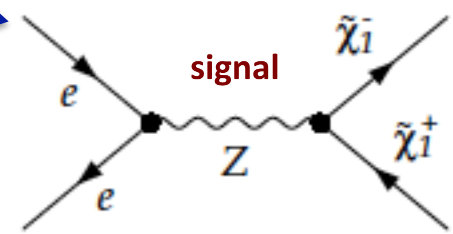


Chargino pair production with semileptonic decay

$$e^+e^- \to \tilde{\chi}_1^+\,\tilde{\chi}_1^- \to \tilde{\chi}_1^0\,\tilde{\chi}_1^0 qq'\ell\nu$$

- Reconstruct **two jets which originate from W^* emission in decay of $\chi_1^\pm$ to χ_1^0**
- Use lepton (e or μ) from the other chargino as tag
- BeamCal veto, cuts on missing p_T, # of tracks, # of leptons, and coplanarity remove almost all bkg.

  (signal significance > 100)



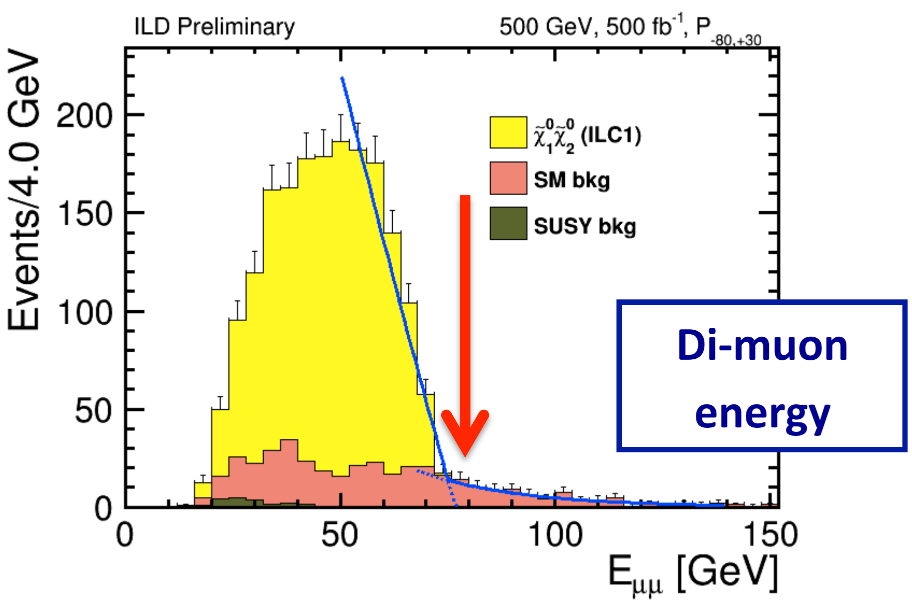
Extraction of Higgsino Mass
[work in progress]

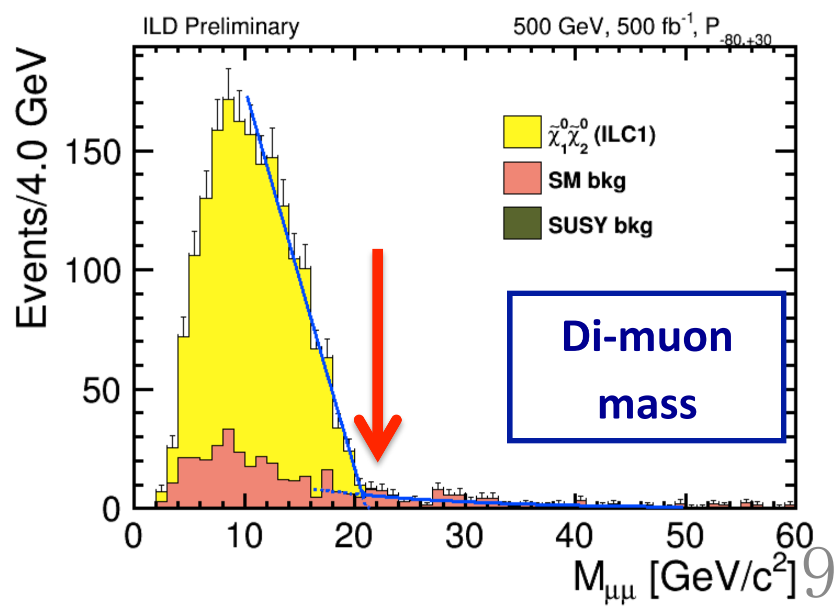
Neutralino mixed production with leptonic decay

$$e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ell^+ \ell^-$$

- The position of the kinematic edges of the dilepton energy (E_{ll}) and invariant mass (M_{ll}) are functions of CM energy and the two neutralino masses.
- The maximum values $E_{ll,max}$ and $M_{ll,max}$ are extracted by a fit to obtain the neutralino masses after correcting for detector/reconstruction effects`

Similar for case of chargino pair production (ll → jj)





Cuts have been designed so as not to destroy upper edge

- Use toy MC (generated from MC data fit) to evaluate statistical uncertainty
- Making progress in kinematic edge extraction

Edge extraction precision ～1 %

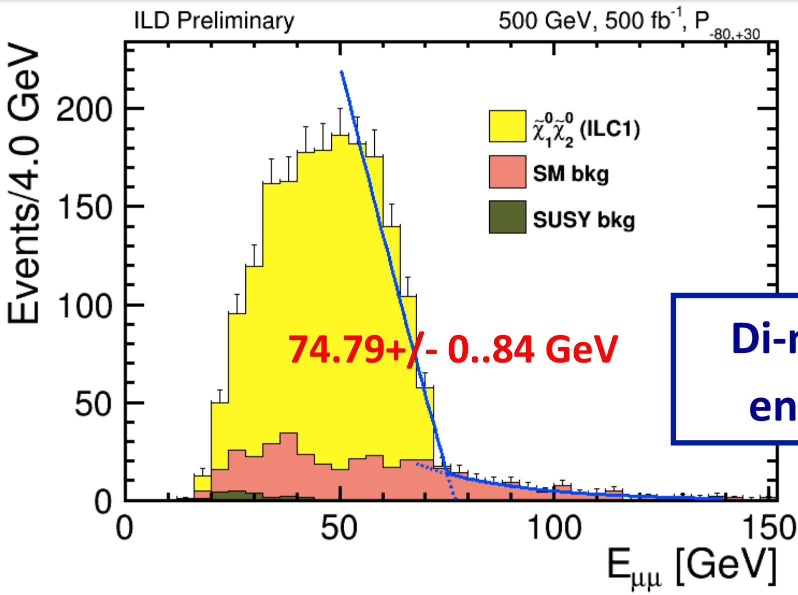
Neutralino mixed production with leptonic decay

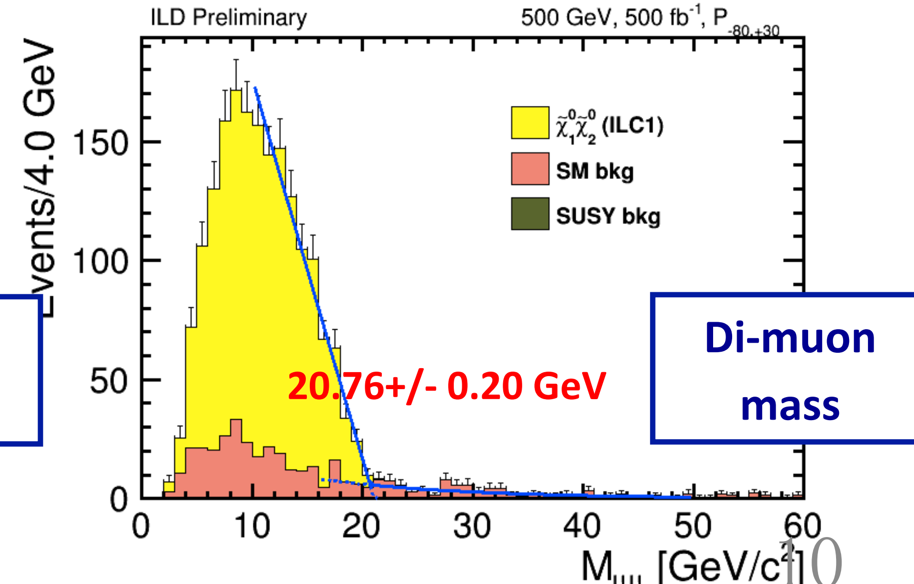
$$e^+e^- \rightarrow \tilde{\chi}_1^0\,\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0\ell^+\ell^-$$

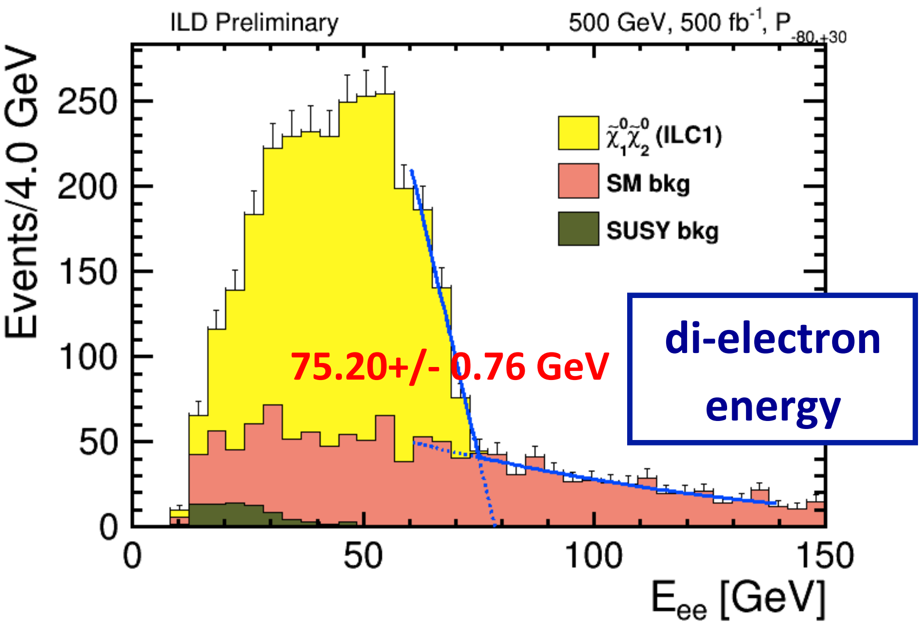
Polarization (Pe-,Pe+) = (-0.8, +0.3)

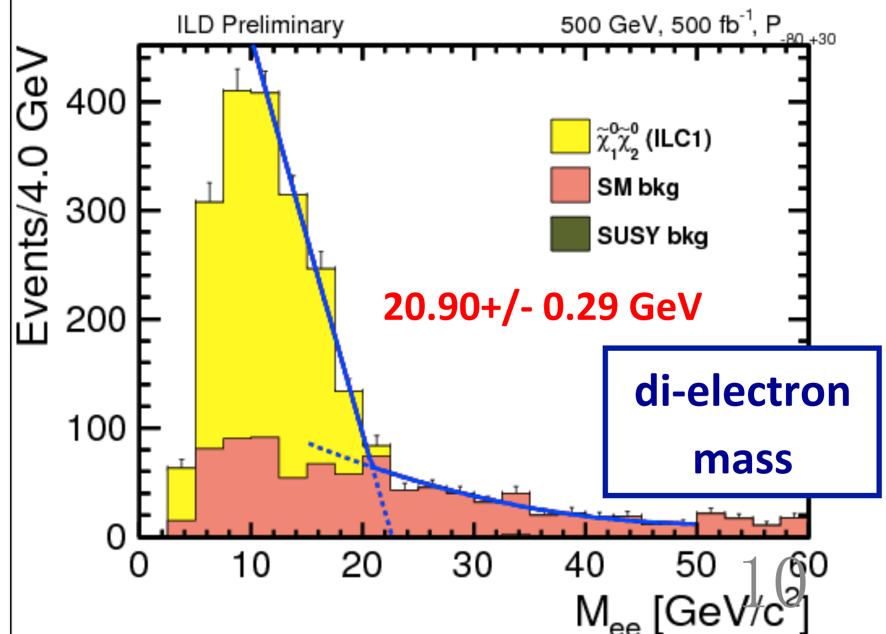
statistical precision 1.0 – 1.5 %

preliminary









Neutralino mixed production with leptonic decay

$$e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ell^+ \ell^-$$

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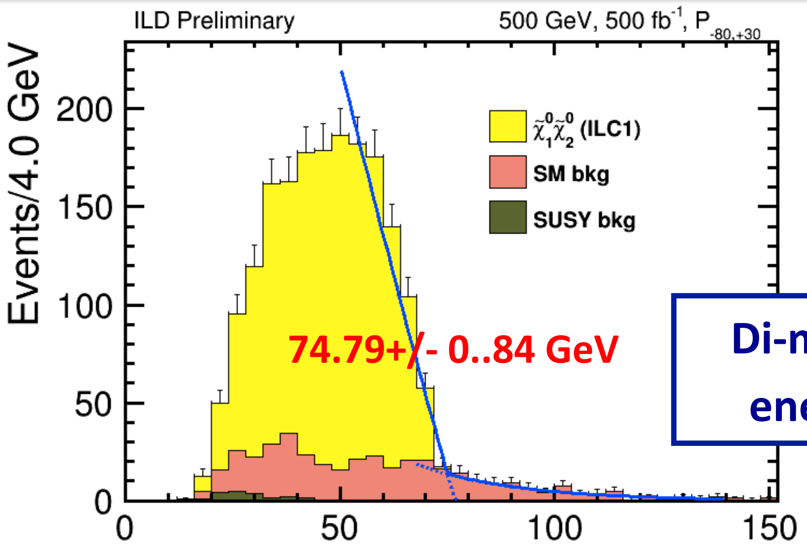
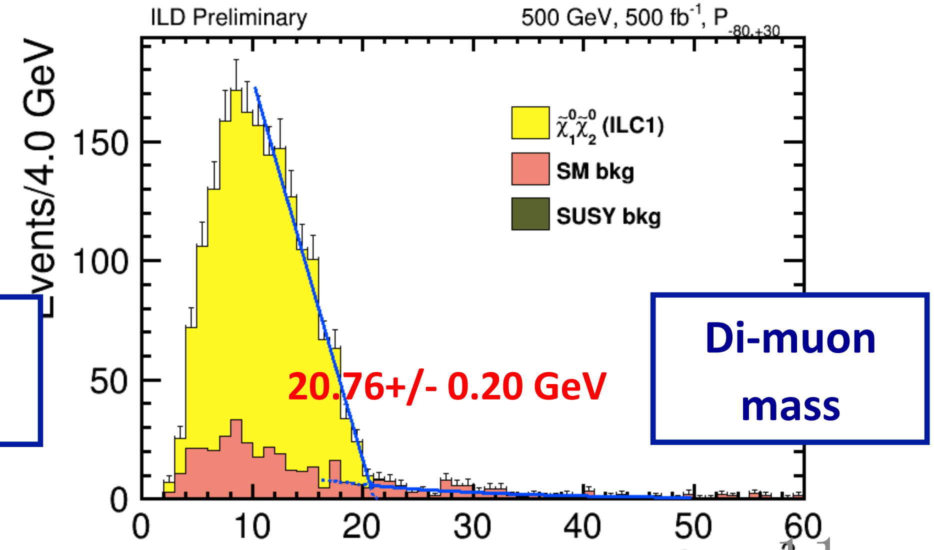
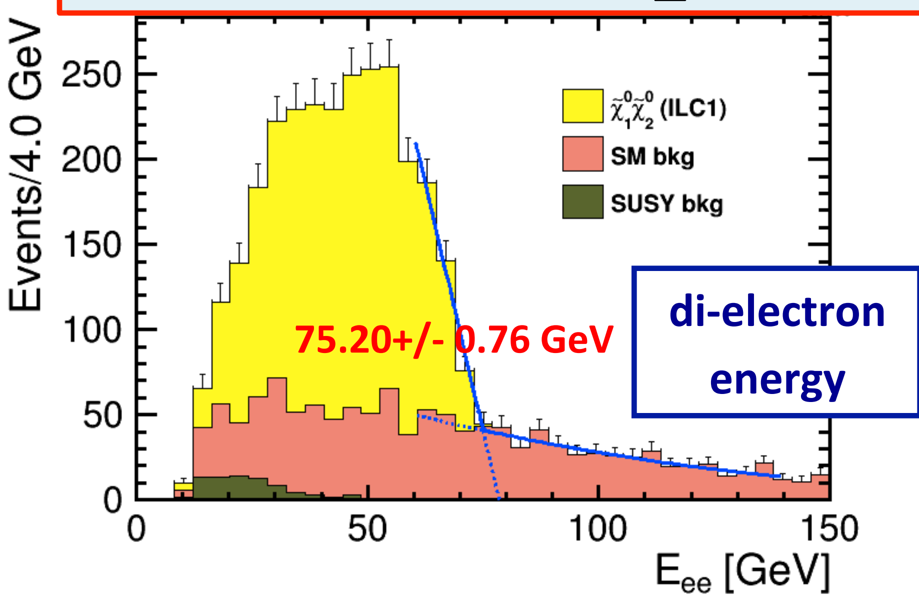
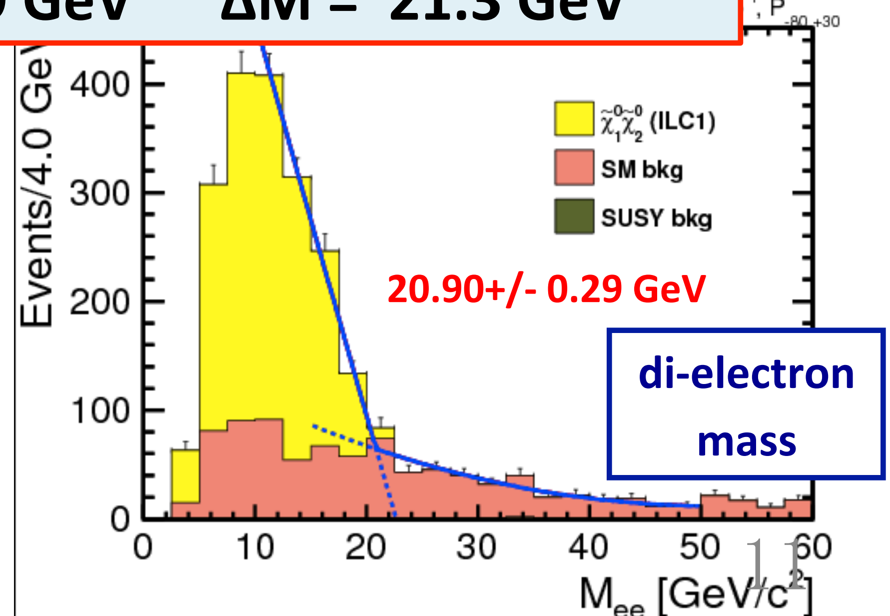




Theoretical values: E_max = 74.9 GeV ΔM = 21.3 GeV

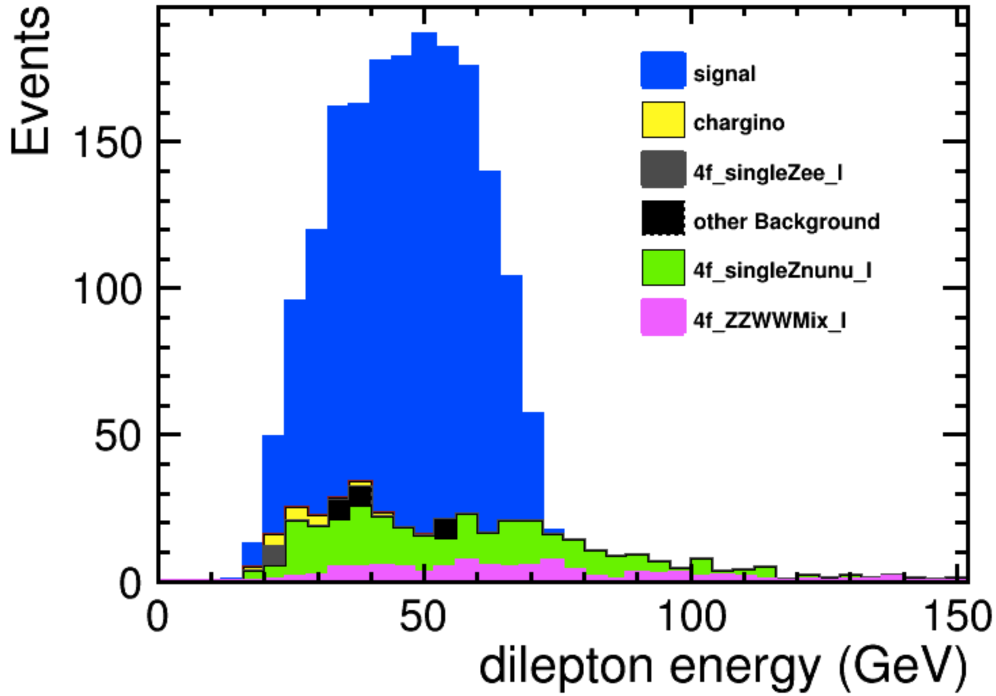




Di-muon energy

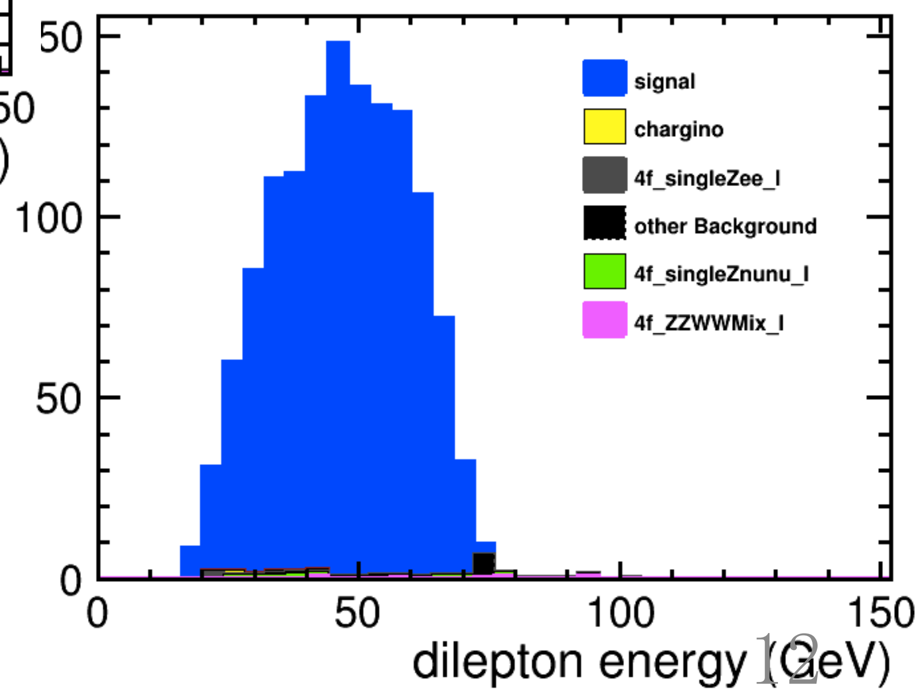
(Pe-,Pe+) = (-0.8, +0.3)

Background is greatly suppressed for right-hand polarization



Di-muon energy

(Pe-,Pe+) = (+0.8, -0.3)



We will study the difference in statistical precisions of edge and cross sections

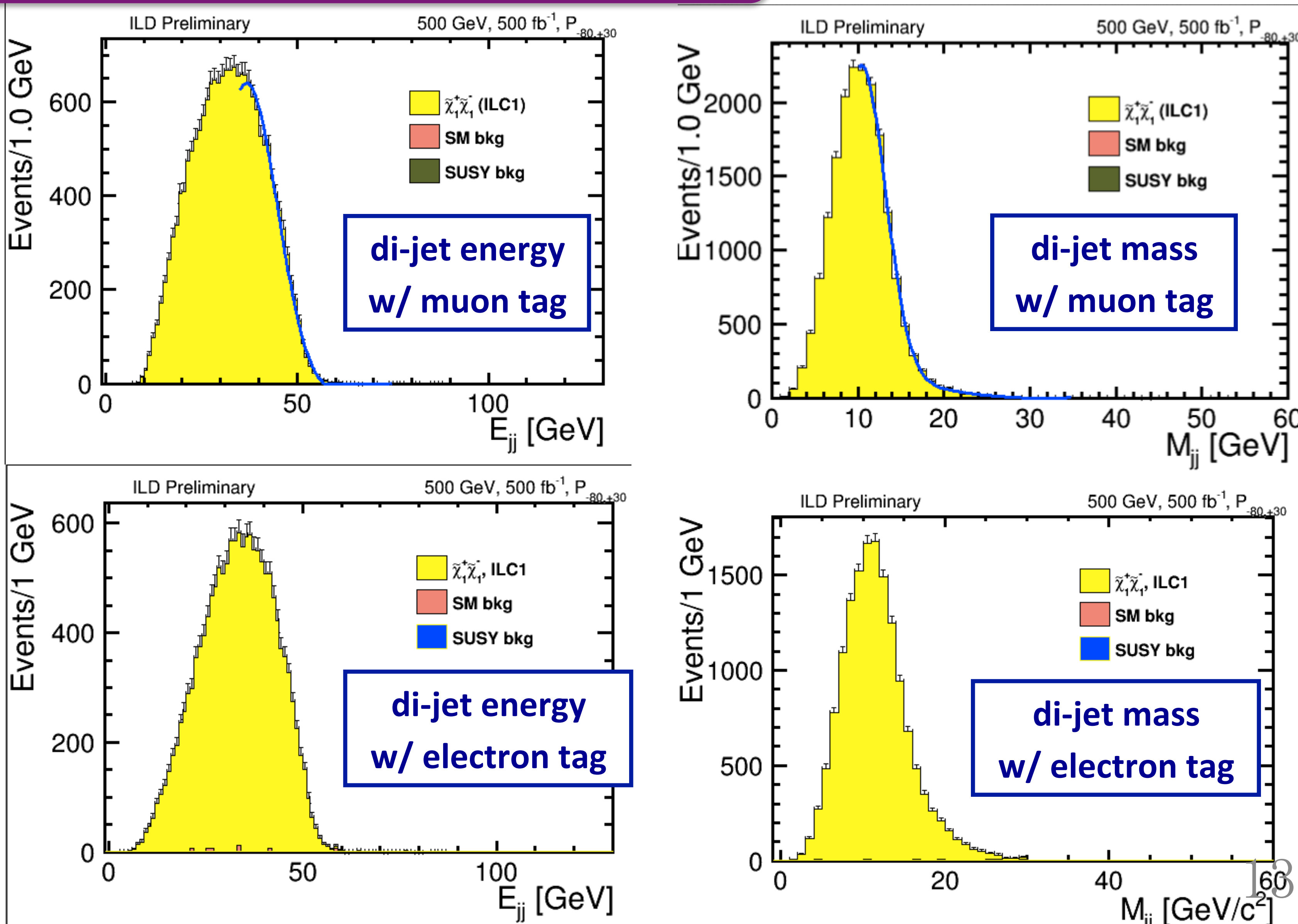
Chargino pair production with semileptonic decay

$$e^+e^- \to \widetilde{\chi}_1^+\,\widetilde{\chi}_1^- \to \widetilde{\chi}_1^0\,\widetilde{\chi}_1^0 qq'\ell\nu$$

Polarization (Pe-,Pe+) = (-0.8, +0.3)

SM and SUSY backgrounds almost fully eliminated

preliminary



Extraction of Cross Section [work in progress]

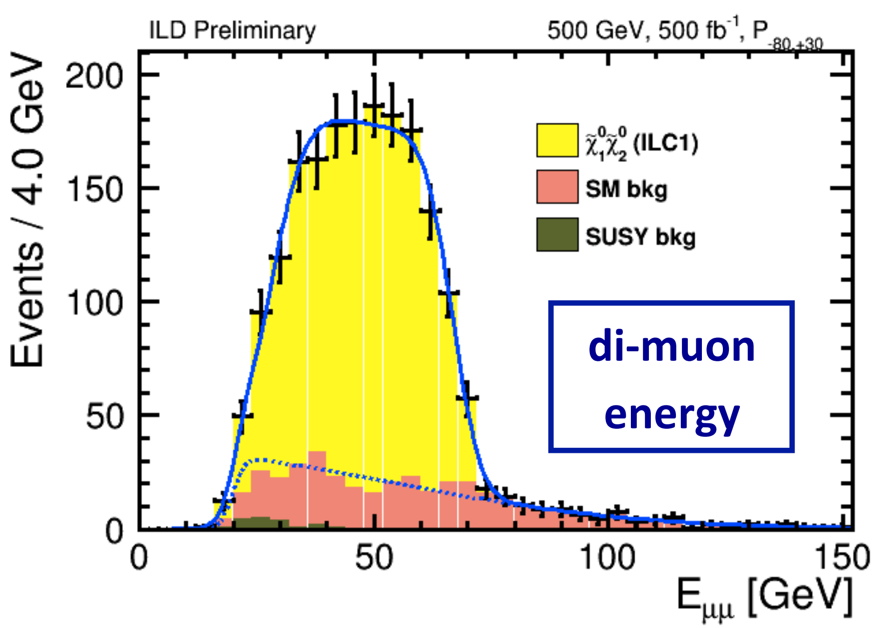
Strategy: Fit overall shape to estimate total number of signal events

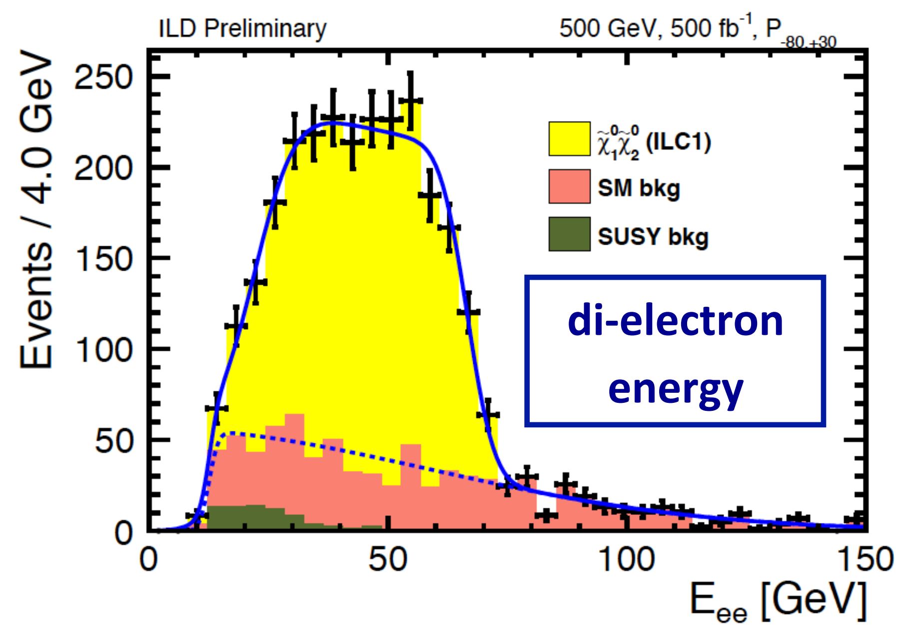
Neutralino mixed production with leptonic decay

$$e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ell^+ \ell^-$$

Δσ / σ = 3 - 5 %

preliminary





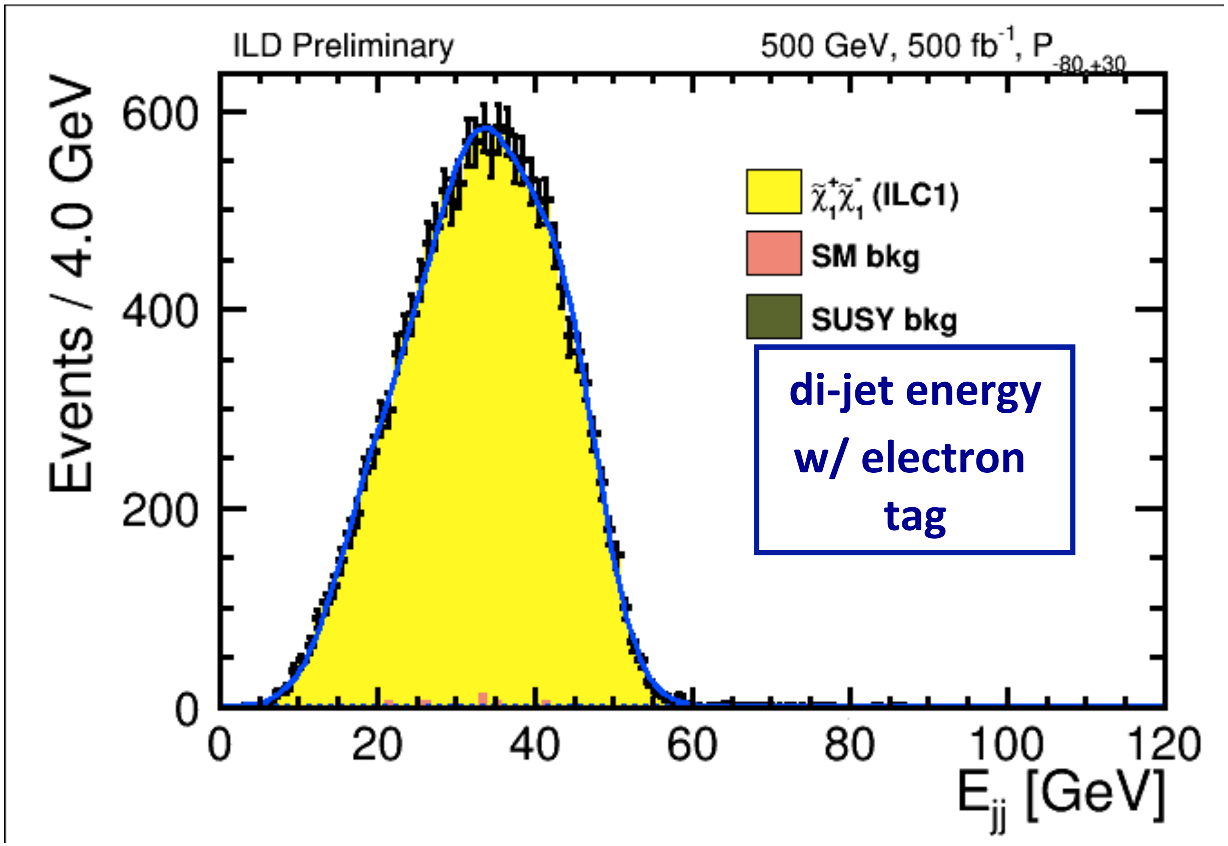
The results of Higgsino mass and cross section become input to the parameter fit to extract SUSY parameters (e.g. Wino and Bino masses, tanβ, etc.)

Extraction of Cross Section [work in progress]

Chargino pair production with semileptonic decay

$$e^+e^- \rightarrow \widetilde{\chi}_1^+ \widetilde{\chi}_1^- \rightarrow \widetilde{\chi}_1^0 \widetilde{\chi}_1^0 q q' \ell \nu$$

Polarization (Pe-,Pe+) = (-0.8, +0.3)



Δσ / σ = 0.8 %

Fit with triple Gaussian

Other channels have similar shapes in the case of chargino

Summary and Plans

Precision measurement of light Higgsinos with small ΔM (10-20 GeV)

- **Motivated by both experiment (complementary to LHC) and theory (naturalness)**

This study: Full ILD detector simulation, L=500 fb-1 at √s = 500 GeV, (Pe-, Pe+) = (-0.8,+0.3),(+0.8, -0.3)

- **Analysis of neutralino mixed production ($\chi_1^0\chi_2^0$) and chargino pair production ($\chi_1^+\chi_1^-$)**
- **Data selection yields good S/B ratio ; almost no background for chargino**
- **Fit kinematic edges to extract Higgsino masses**
- **Fit to overall distribution to extract production cross sections**

in progress

Obtained preliminary results for some channels

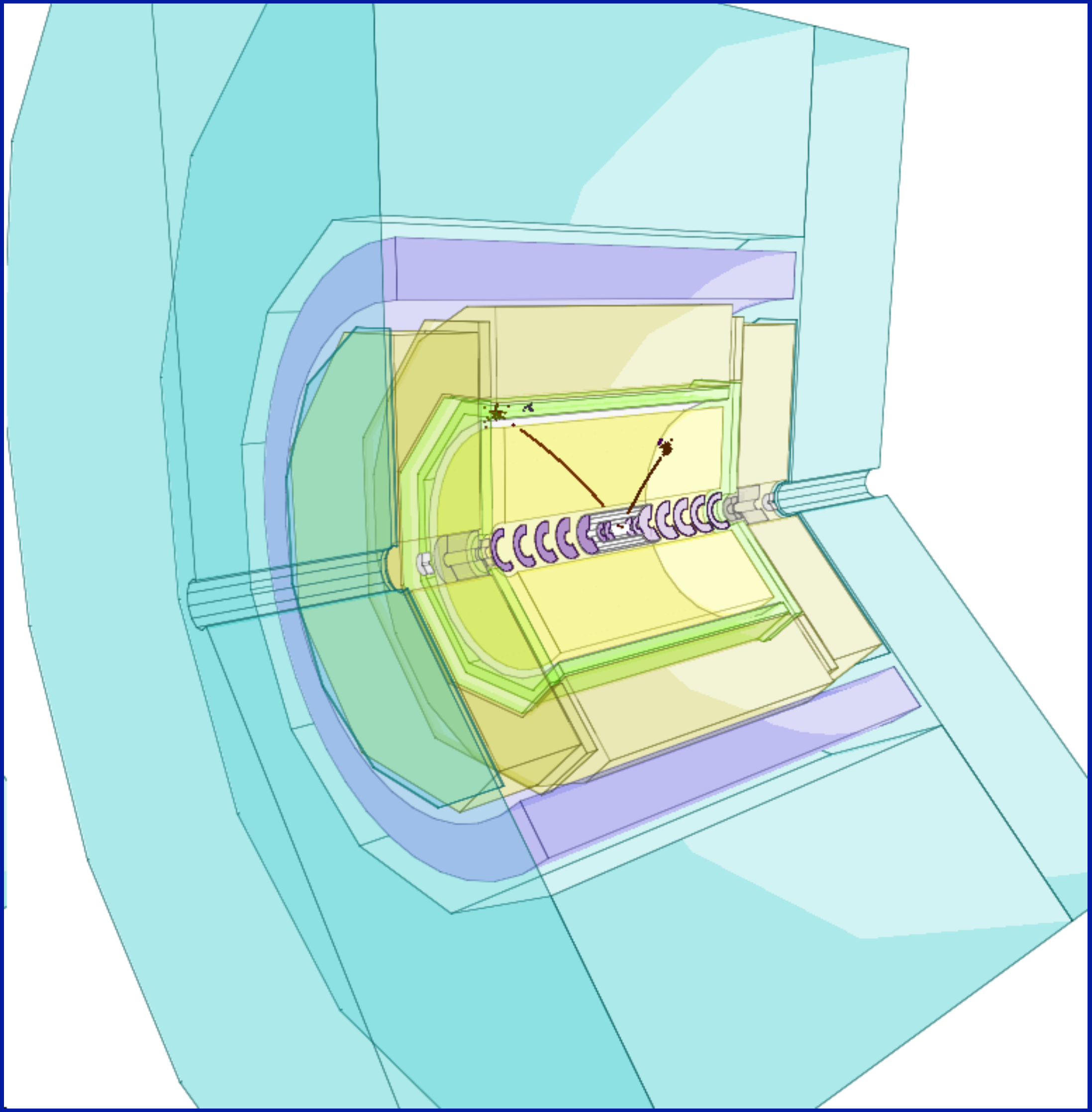
- **For neutralino: Edge precision 1.0 -1.5% , Cross section precision 3-5%**
- **Edge values generally consistent with theoretical values within uncertainty range**
- **For chargino : Cross section precision : 0.8%**
- **Still working on edge extraction : difficulties involving jet energy resolution**

- **Need to implement gamma gamma overlay bkg**
- **Other CM energies and polarizations: precise mass determination, input necessary for theoretical studies, etc…**

results obtained in this study become input to SUSY parameter determination

To test GUT-scale physics and SUSY-breaking mechanism [S.-L. Lehtinen, in progress]

Thank you for listening



Additional Material

Extraction of Higgsino Mass

[work in progress]

Neutralino mixed production with leptonic decay

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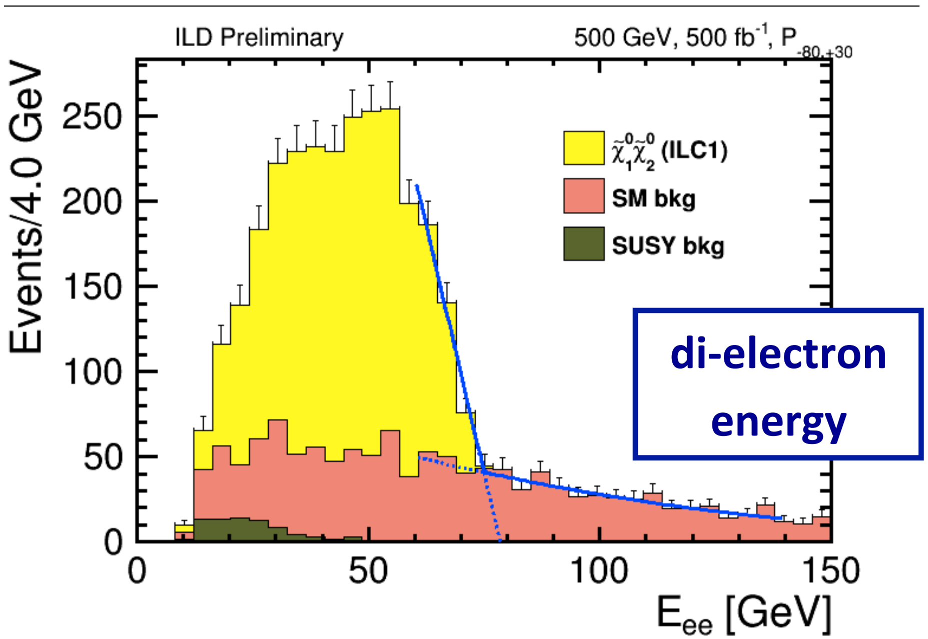
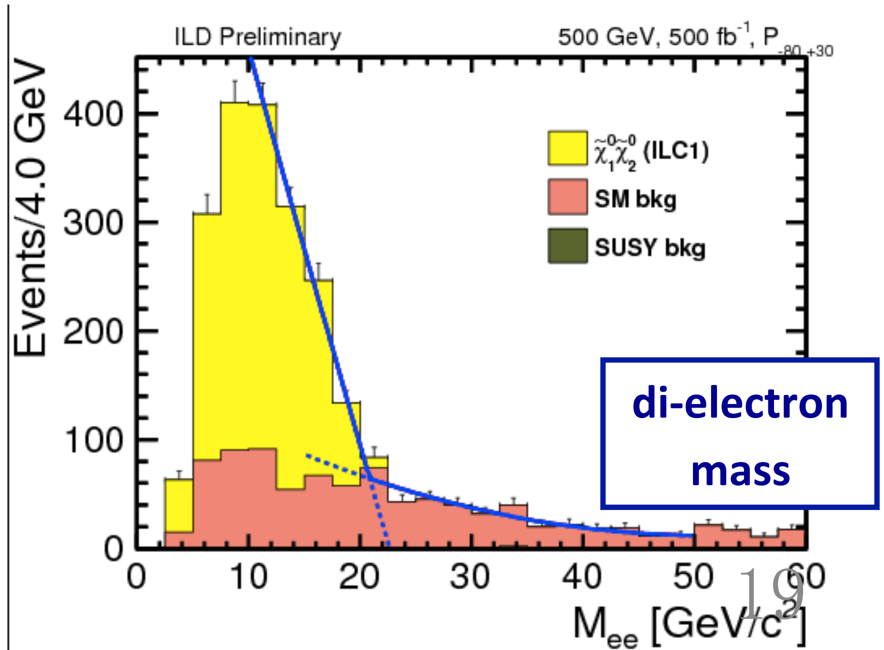
- The position of the kinematic edges of the dilepton energy (E_{ll}) and invariant mass (M_{ll}) are functions of CM energy and the two neutralino masses.
- The maximum values $E_{ll,max}$ and $M_{ll,max}$ are extracted by a fit to obtain the neutralino masses after correcting for detector/reconstruction effects`

Similar for case of chargino pair production (ll → jj)





Cuts have been designed so as not to destroy upper edge

- Use toy MC (generated from MC data fit) to evaluate statistical uncertainty
- Making progress in kinematic edge extraction

Edge extraction precision ～1 %

Fits of NUHM2 Parameters

[S.-L. Lehtinen]

ILC2

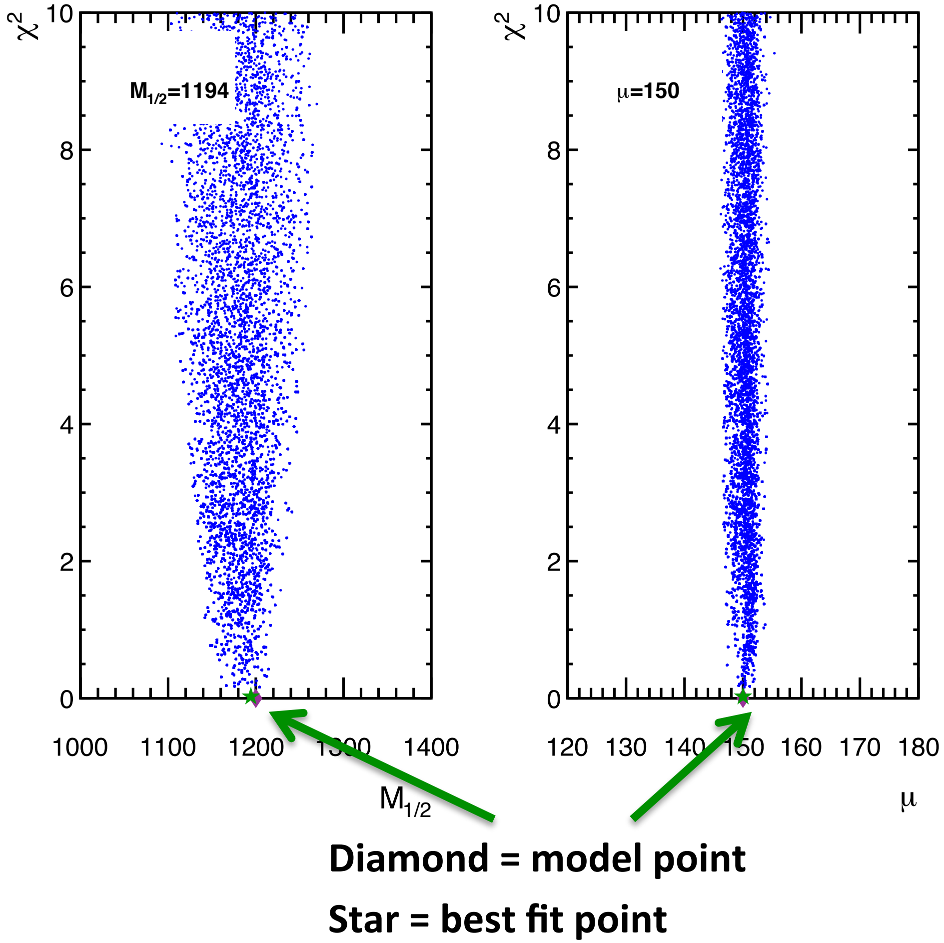
All 6 parameters are simultaneously varied. Initial values are set to be near the model values.

Each blue point corresponds to a set of parameter values. The χ^2 value is computed for each point.

Using the χ_1^0, χ_2^0, $\chi_1^\pm$ masses and production cross sections, **$M_{1/2}$** can be determined.

Adding Higgs mass and BR as measured at the ILC fixes **μ** and possibly constrains other parameters

In addition, if χ_3^0 can be observed in $\chi_2^0\chi_3^0$, $\tan\beta$ can be constrained as well. (ILC1)



Outlook

- **Test gaugino mass unification by fitting weak scale parameters M_1 and M_2**

ILC1

Cross sections (pure beam polarizations)
$\sqrt{s}$=500 GeV with TDR beam parameters

(Pe-, Pe+)	(-1.0,+1.0)	(+1.0,-1.0)
$\sigma(\chi_1^+ \chi_1^-)$ [fb]	1800	335
$\sigma(\chi_1^0 \chi_2^0)$ [fb]	491	379
$\sigma(\chi_2^0 \chi_3^0)$ [fb]	11.0	8.42
$\sigma(\chi_1^0 \chi_1^0)$ [fb]	2.03	1.56
$\sigma(\chi_2^0 \chi_2^0)$ [fb]	0.53	0.41
$\sigma(\chi_1^0 \chi_3^0)$ [fb]	0.28	0.20

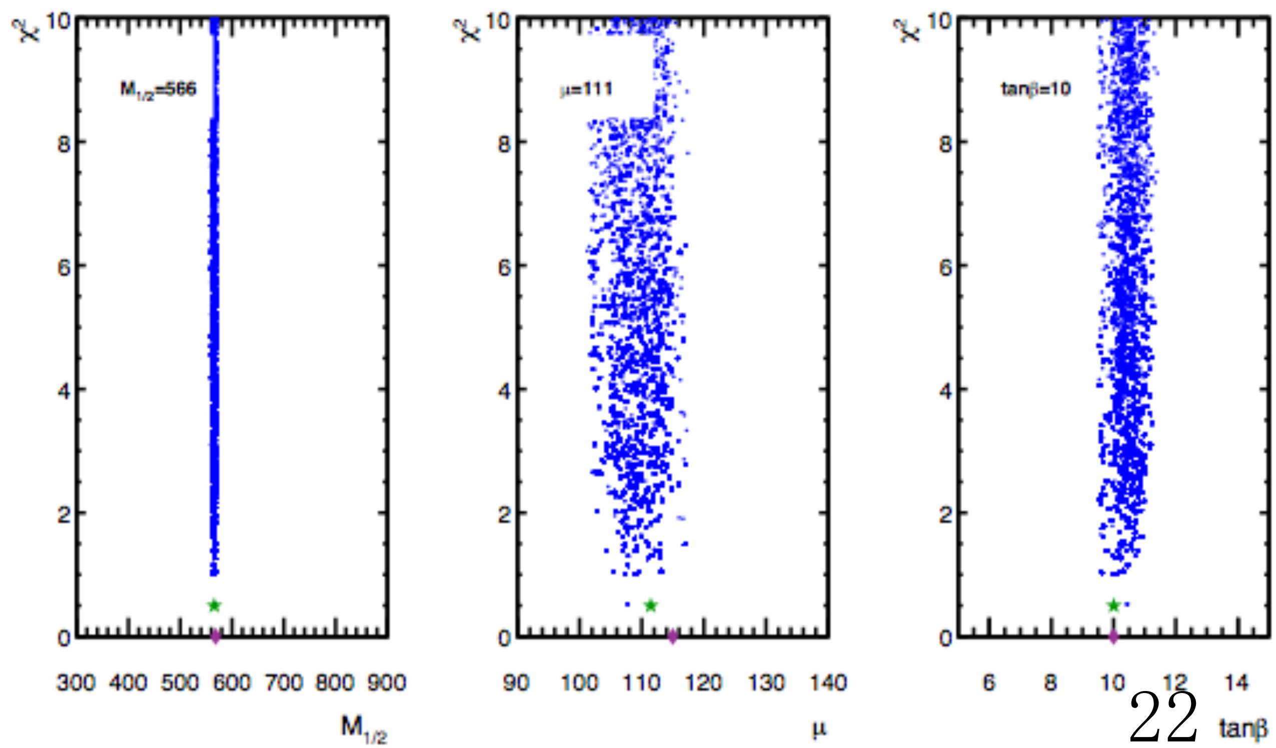
Branching ratios

BR($\chi_1^+ \rightarrow \chi_1^0 qq'$)	67%
BR($\chi_1^+ \rightarrow \chi_1^0 l\nu$) (l=e,μ)	22%
BR($\chi_2^0 \rightarrow \chi_1^0 qq'$)	58%
BR($\chi_2^0 \rightarrow \chi_1^0 ll$) (l=e,μ)	7.4%

[S.-L. Lehtinen]

parameter	scale	ILC1
m_0	GUT	7025
$m_{1/2}$	GUT	568.3
A_0	GUT	-10426.6
$\tan\beta$	weak	10
μ	weak	115
m_A	weak	1000

- $\tan\beta$ constrained if we add χ_3^0 mass and $\chi_1^0\chi_3^0$ production cross section



Cut table N1N2 , μμ (Pe-, Pe+) = (-80,+30)

	sig	bkg	4f_l	aa_2f	ae_3f	SUSY bkg
xsec	300.8	3.00E6	10566.2	2.68E6	261580	1065.2
N_gen	150395	1.50E9	5.28E6	1.34E9	1.31E8	532585
Lep_type nTrack=2	1974	9.1E8	444255	8.9E8	2.2E7	2426
BCAL veto	1950	6.0E6	149871	5.5E6	965354	2411
Pt_lep,1,2	1675	2.0E6	105721	1.4E6	295459	1986
cosθ_lep	1624	1.3E6	56001	910330	167734	1950
coplanarity	1407	48366	5272	3509	33067	22
Evis	1404	14325	2465	2248	4743	22
Emis, cosθmis	1393	1063	929	34	9	19
cosZ, Pt_ll, Minv	1393	545	429	34	9	19

Cut table C1C1 , μtag (Pe-, Pe+) = (-80,+30)

	sig	bkg	4f_l	aa_2f	ae_3f	SUSY bkg
Xsec [fb]	1065.2	3.00E6	10566.2	2.68E6	261580	300.8
N_gen	532585	1.50E9	5.28E6	1.34E9	1.31E8	150395
nLep=1 BCAL veto	57983	1.5E9	443296	1.2E6	860530	1135
Ptmis	38240	2.7E6	377010	465397	519308	964
Jet_coplanarity	26085	1.5E6	86399	83683	109325	531
Jet_cosθ nTrack (per jet) > 1	14612	305870	3066	555	2234	22
cosθjet-lep Evis	14308	3753	791	100	41	0
Emis, cosθmis	14231	83	57	3	0	0
Pt_jj, M_jj	14173	51	31	3	0	0