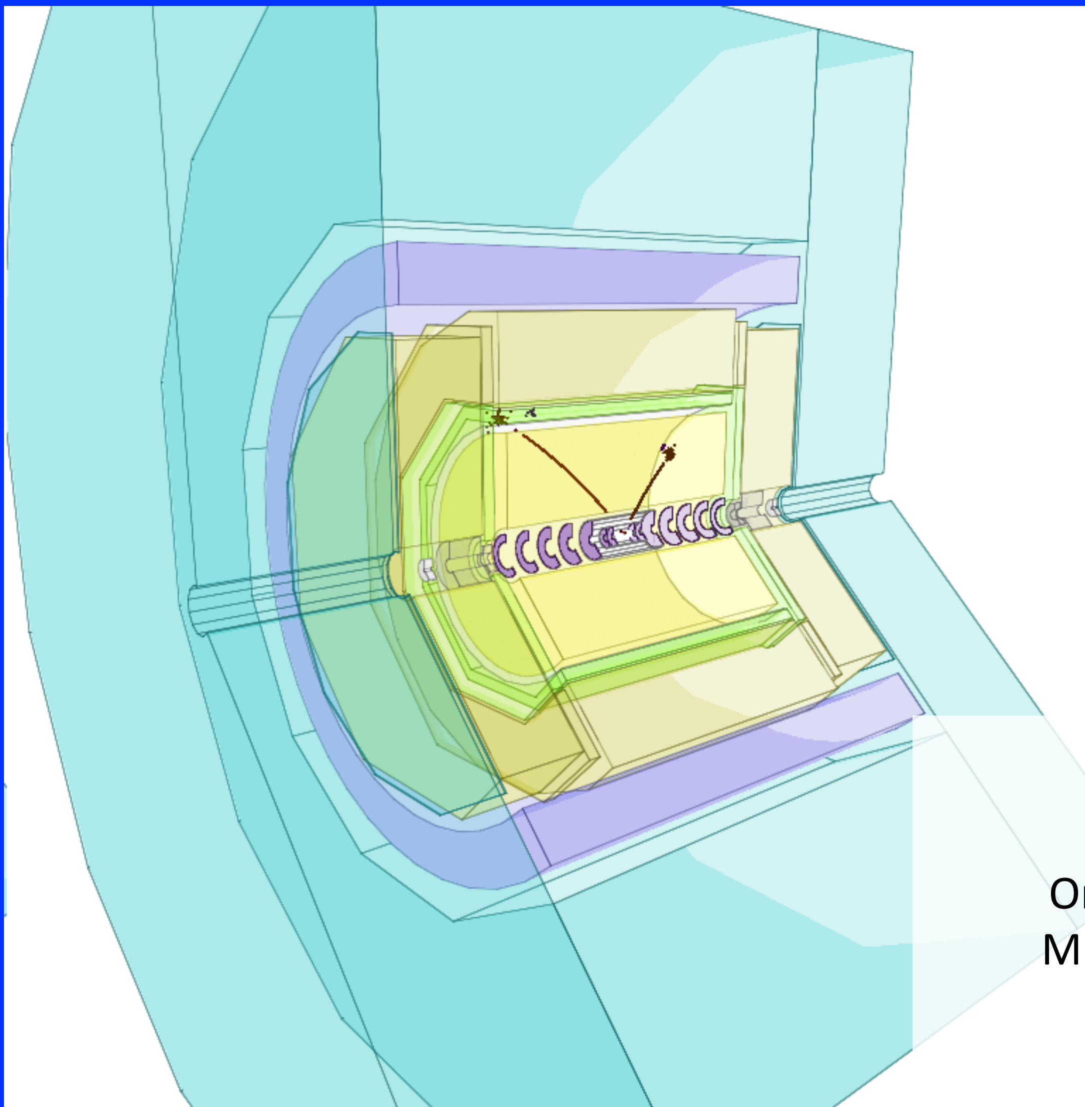
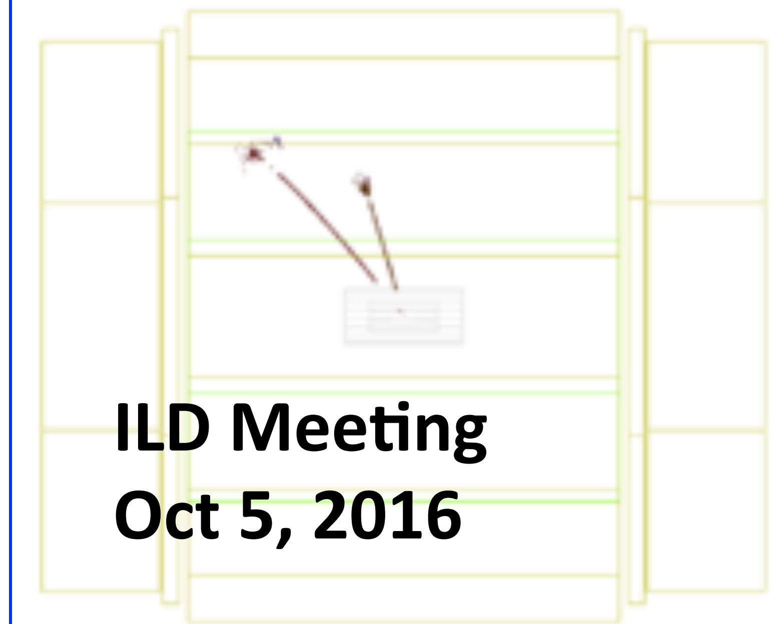
Characterizing Light Higgsinos from Natural SUSY at ILC $\sqrt{s}$ = 500 GeV





ILD Meeting
Oct 5, 2016

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)

Goal of Light Higgsino Study

J. Yan, T. Tanabe, K. Fujii et al

Demonstrate measurement precision of Higgsino masses and production cross sections

Serve as a basis for future discussions of ILC run scenario in the case of new particles being discovered

Results of masses and cross sections (= “observables”) as input

S.-L. Lehtinen (DESY) et al

determine SUSY parameters

e.g. M_1, M_2, μ, $\tan\beta$

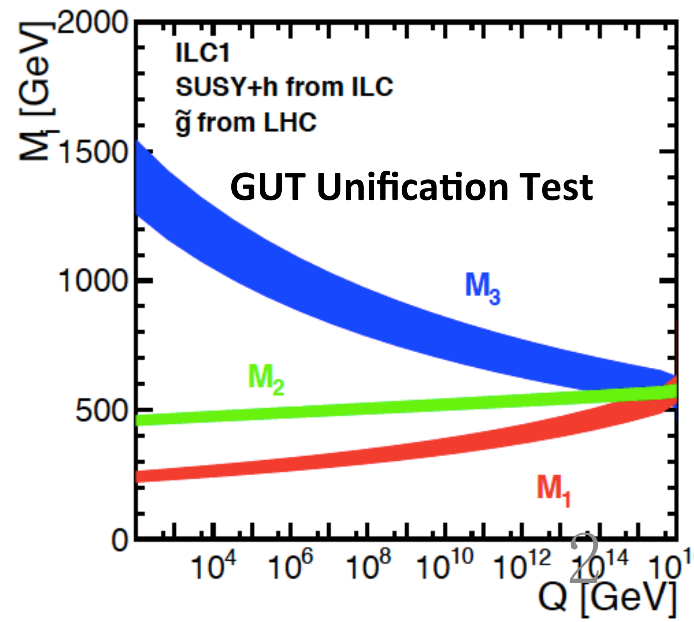
Why?

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

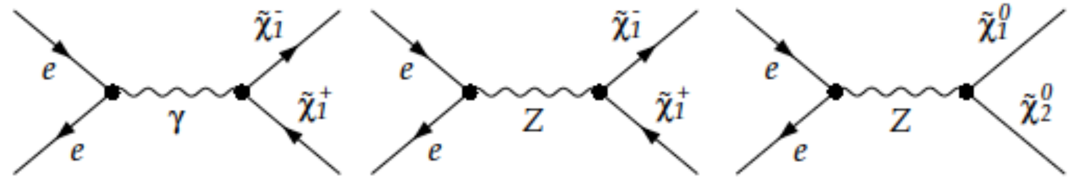
How?

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

Study required input parameters and precisions;
interplay with Higgs precision measurements



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: √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($\chi_1^+ \rightarrow \chi_1^0$ lν) (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

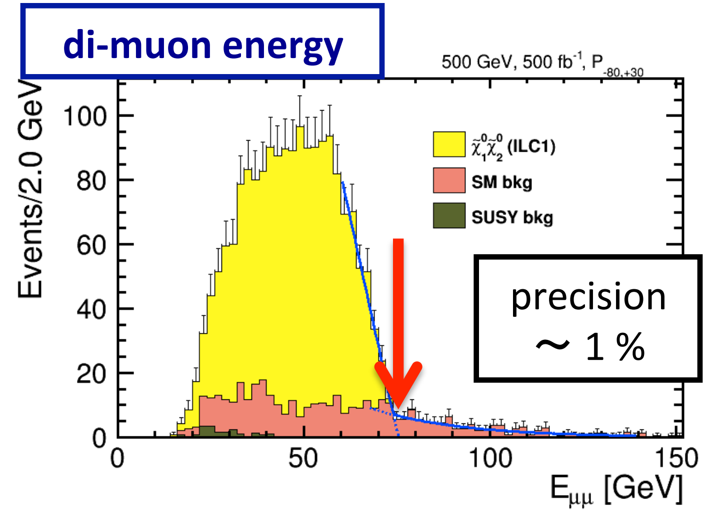
Defined at GUT scale
Defined at weak scale
Observables

Extraction of Higgsino Mass and Cross Section

Mass :

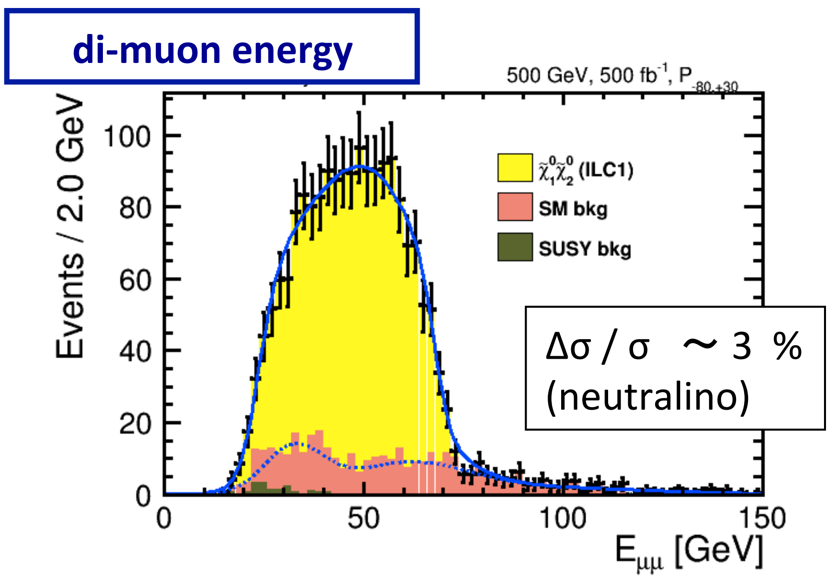
- Kinematic edges of dilepton/dijet energy and invariant mass are functions of $\sqrt{s}$ and Higgsino masses
- Extract kinematic edges by a fit to distributions ➔ calculate masses

(requires correction for detector resolution)



Cross section:

Count number of events under dilepton / dijet energy



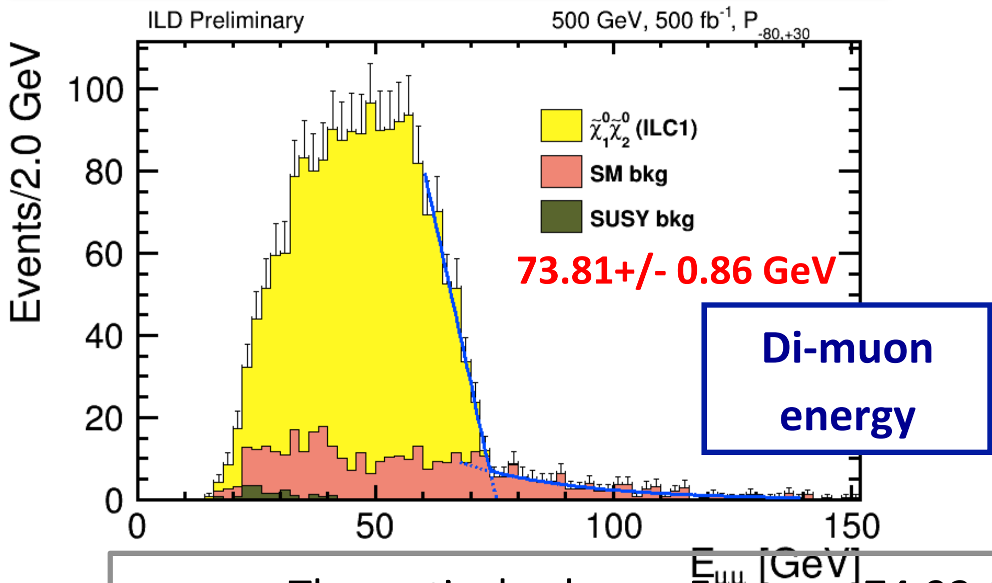
- Use Toy Monte Carlo to obtain mass and cross section precisions

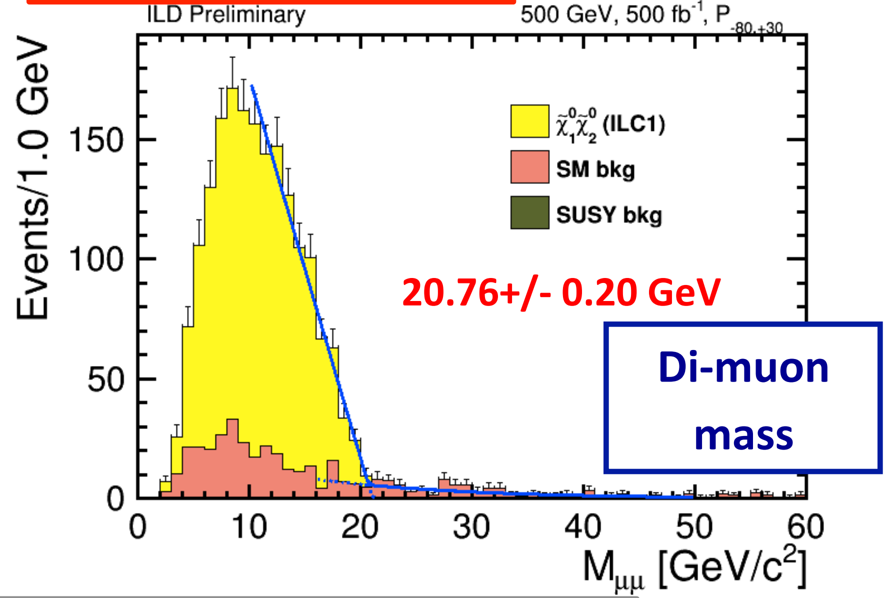
Neutralino mixed production with leptonic decay

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

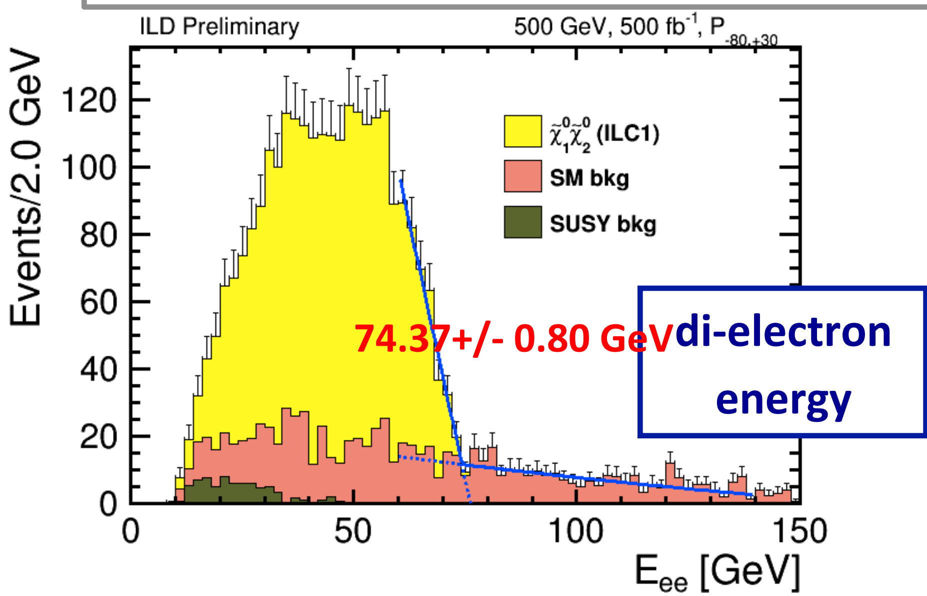
Left Polarization **(Pe-,Pe+) = (-0.8, +0.3)**

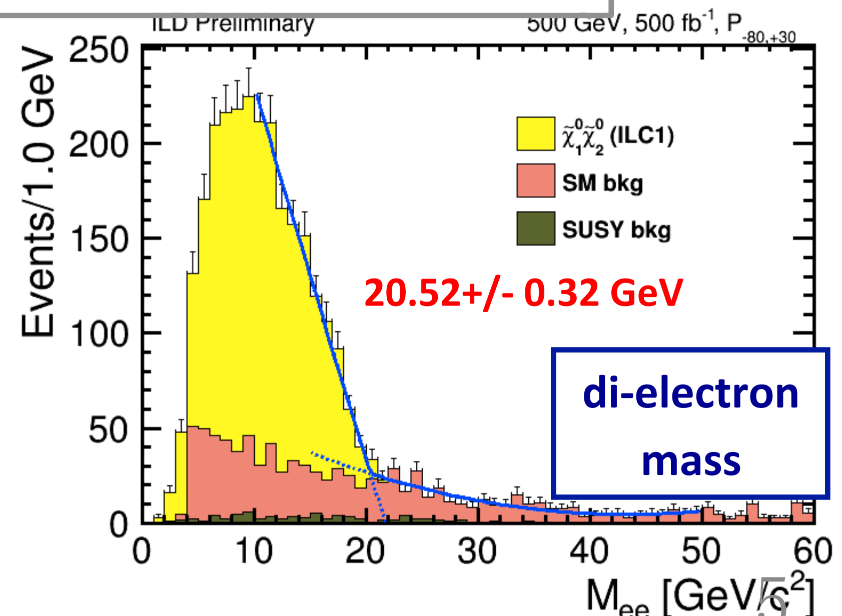
Edge precision ~ 1 %





Theoretical values: E_max = 74.93 GeV ΔM = 21.28 GeV



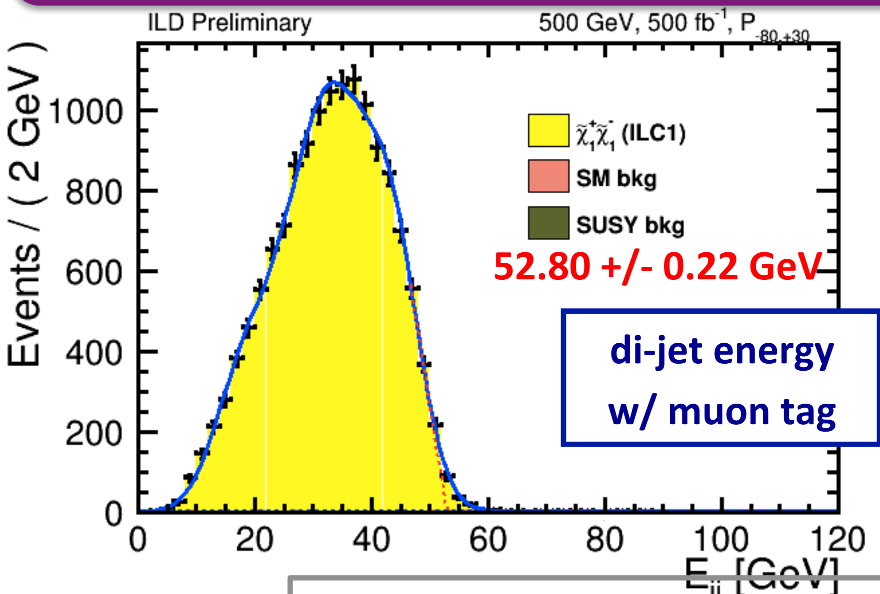


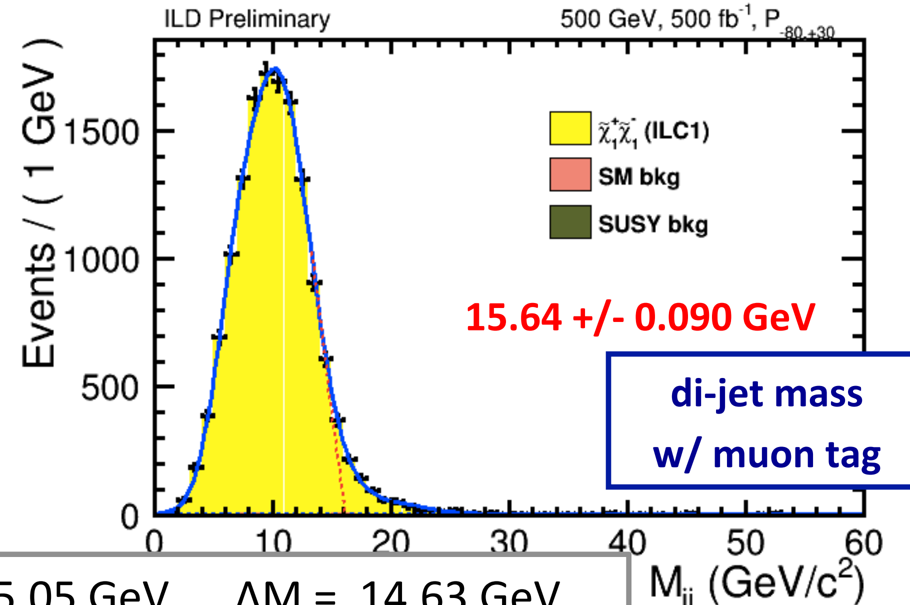
Chargino pair production with semileptonic decay

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

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

Almost all bkg rejected





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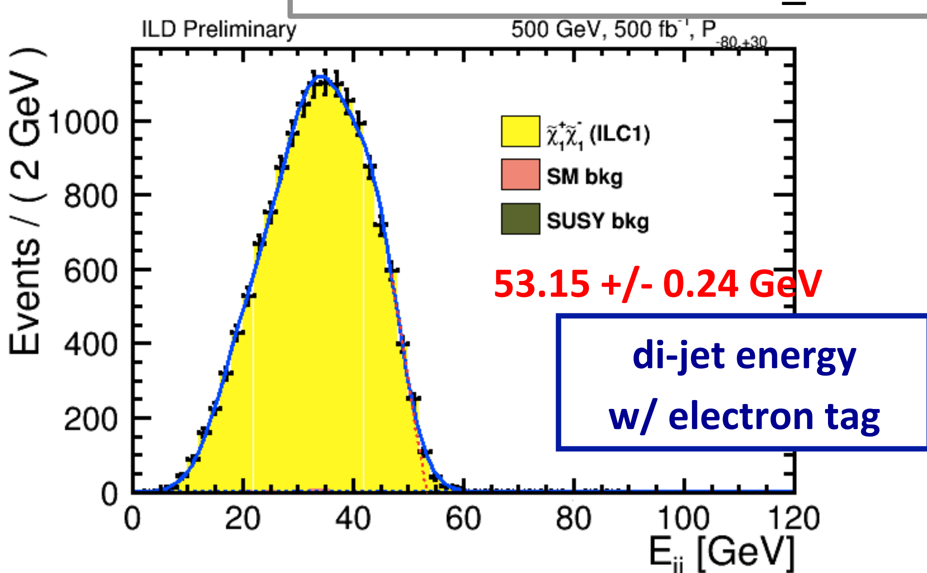
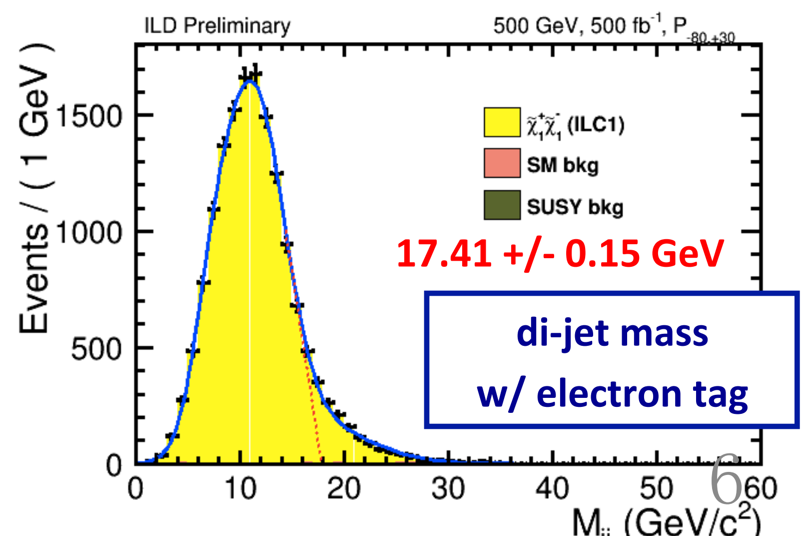
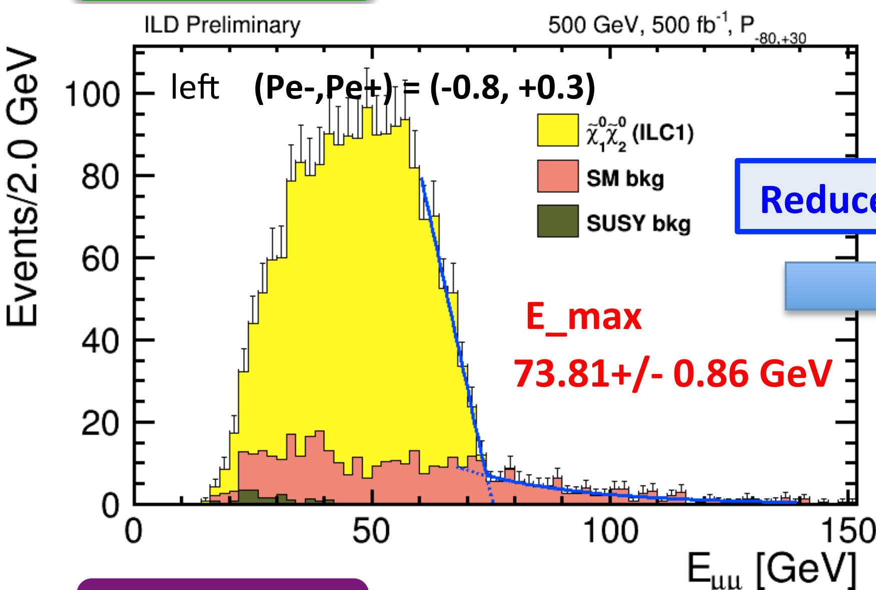


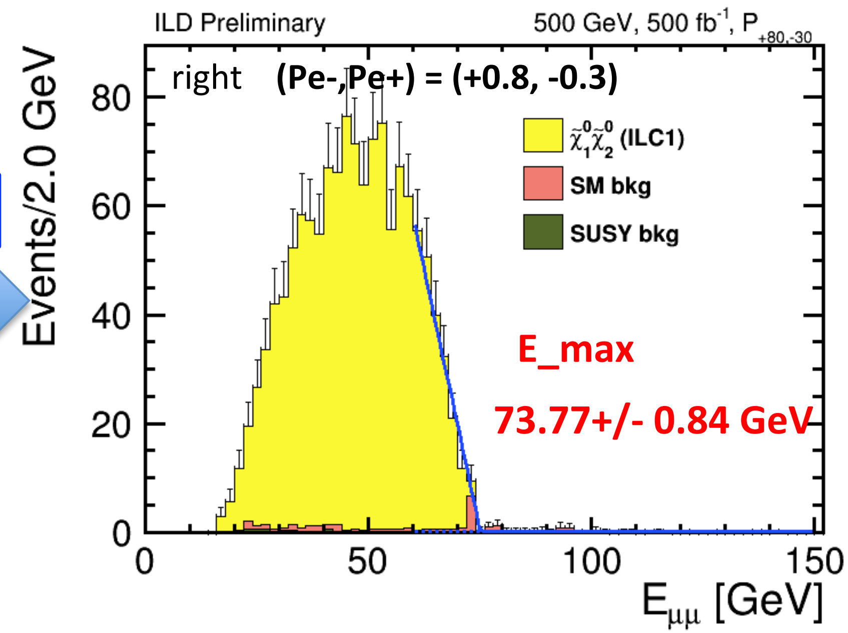


Left polarization vs right polarization

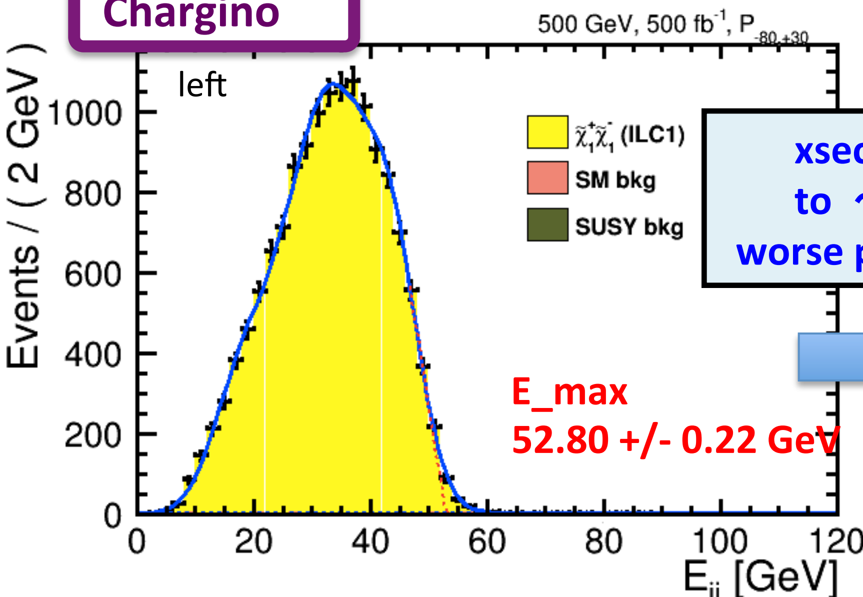
Neutralino



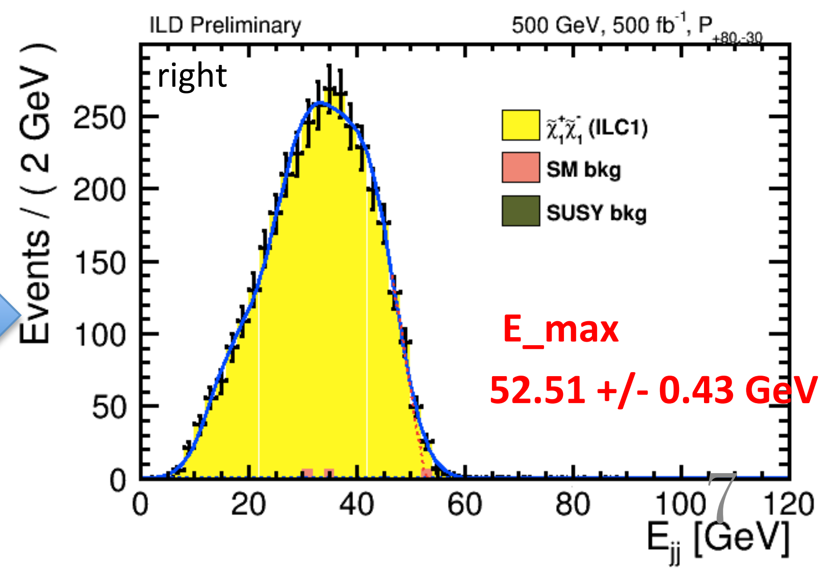
Reduced BKG



Chargino



xsec falls to ~1/5 worse precision



Higgsino Mass Precisions (combined)

apply χ^2 fit to "observables" (kinematic edges)

(Ell_max, Ejj_max, Mll_max, Mjj_max are functions of Higgsino masses)

Neutralino

4 channels (mm, ee, left, right)

N1N2	MN1	ΔMN1/MN1	MN2	ΔMN2/MN2
	102.54	0.758%	123.36	0.688%
H20		0.424%		0.385%

Scale results to H20

For each polarization:

- Default : 500 fb^{-1}
- H20: 1600 fb^{-1}

Chargino

4 channels (m tag, e tag, left, right)

C1C1	MN1	ΔMN1/MN1	MC1	ΔMC1/MC1
	116.60	0.447%	132.79	0.435%
H20		0.250%		0.243%

8 channels (m, e, left, right, N1N2, C1C1)

ALL	MN1	ΔMN1/MN1	MN2	ΔMN2/MN2	MC1	ΔMC1/MC1
	110.56	0.405%	130.90	0.372%	126.09	0.396%
H20		0.226%		0.208%		0.221%

Theoretic values: MN1 = 102.70 GeV MN2 = 123.98 GeV, MC1 = 117.33 GeV

MN1: χ^0_1 mass MN2: χ^0_2 mass MC1: $\chi^\pm_1$ mass

- **combined statistical mass precision ～ 0.2% （H20)**
- Dominated by precision of chargino channel (higher cross section)
- Neutralino results consistent with theoretic values
- Chargino results deviated due to jet energy resolution

H20		0.424%		0.385%

- H20: 1600 fb^{-1}

Chargino

4 channels (m tag, e tag, left, right)

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MN1: χ^0_1 mass MN2: χ^0_2 mass MC1: $\chi^\pm_1$ mass

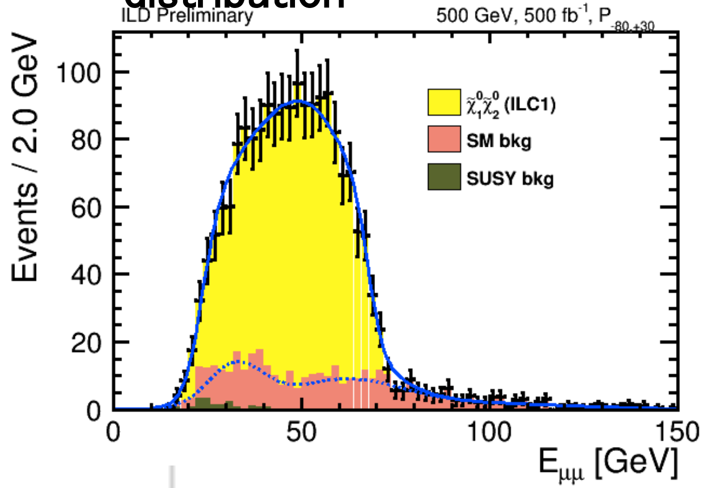
Cross section precisions

- Neutralino (N1N2): 1 –1.5% (H20)

  right polarization has better precision due to suppressed BKG
- Chargino (C1C1) : 0.3–0.7% (H20)

  scales with size of cross section

Count # of events under distribution



N1N2	$\Delta\sigma/\sigma$	C1C1	$\Delta\sigma/\sigma$
left, mumu	3.49%	left, mu-tag	0.85%
left, ee	3.17%	left, e-tag	0.83%
combined	2.35%	combined	0.59%
H20	1.31%	H20	0.33%
N1N2	$\Delta\sigma/\sigma$	C1C1	$\Delta\sigma/\sigma$
right mumu	2.80%	right mu-tag	1.75%
right ee	2.41%	right e-tag	1.71%
combined	1.83%	combined	1.22%
H20	1.02%	H20	0.68%

Summary for Light Higgsino Study

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**

Obtained results for ALL channels

- Mass precision ～ 0.2%
- Cross section precision：

neutralino: 1 – 1.5%

chargino: 0.3 – 0.7%

(from full H20 run, three $\sqrt{s}$)

$$\Delta M_1 = 1.5\%$$
$$\Delta M_2 = 1.0\%$$
$$\Delta M_3 = 11.6\%$$
$$\Delta\mu = 0.1\%$$
$$\Delta \tan\beta = 2.5\%$$

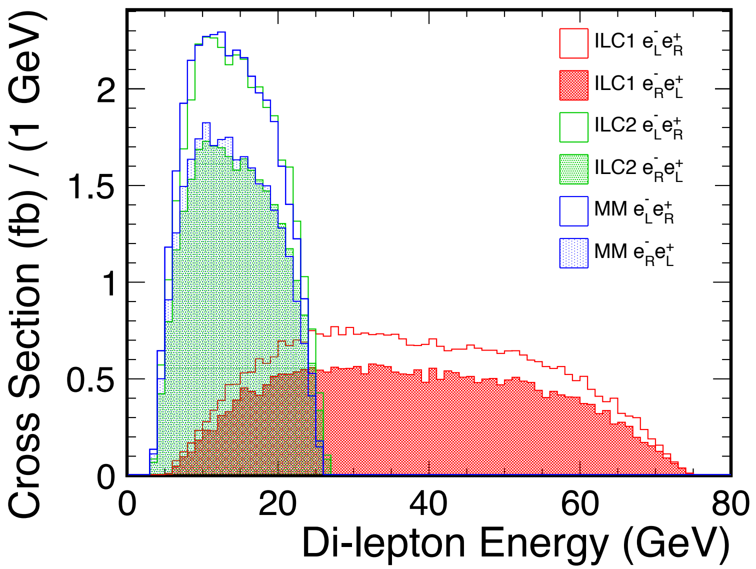
results obtained in this study become input to SUSY parameter determination

To extract other SUSY parameters, test GUT-scale physics and SUSY-breaking mechanism

Plans for Higgsino Studies

- **Analyze more challenging benchmarks with smaller ΔM**
  ➔ compare precision of SUSY parameter extraction
- **Summarize the results of this analysis in document**
- **First draft for section on Higgsino is done**
- **Move towards publication**

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



Event Generator: WHIZARD v1.95 (DBD setup)
Cross sections for √s=500 GeV with TDR beam parameters

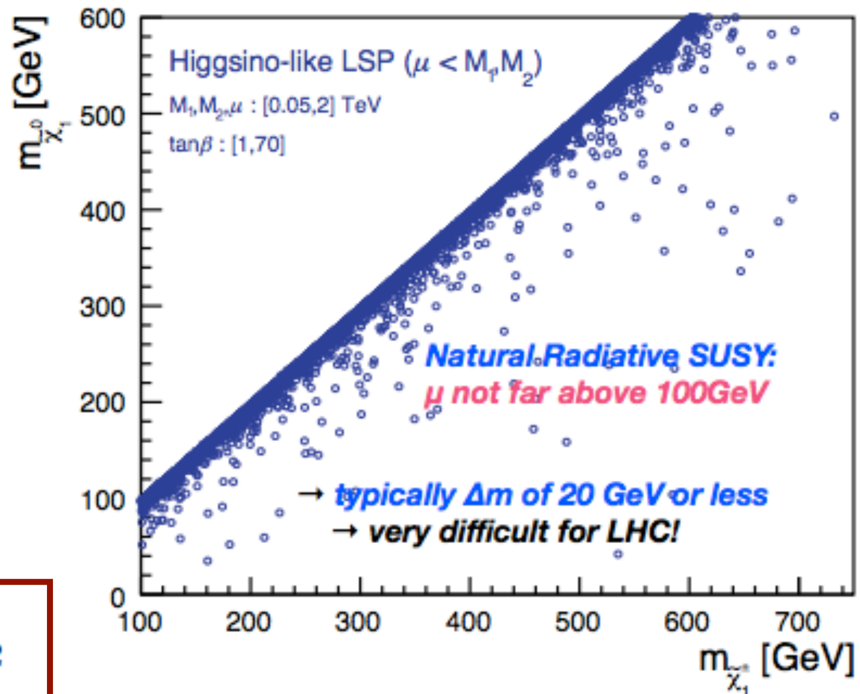
	ILC1	ILC2	mirage12_15
ch1ch1.eL.pR	1799.9 fb	1530.5 fb	1536.6 fb
ch1ch1.eR.pL	334.5 fb	307.2 fb	308.0 fb
neu1neu2.eL.pR	490.9 fb	458.9 fb	460.6 fb
neu1neu2.eR.pL	378.5 fb	353.8 fb	355.1 fb

Additional Material

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)

Motivation for Searching Light Higgsinos with Small ΔM

❖ From experimental point of view:

- LHC already excluded large regions with large $\Delta M = M(NLSP) - M(LSP)$
- Remaining region with compressed spectrum
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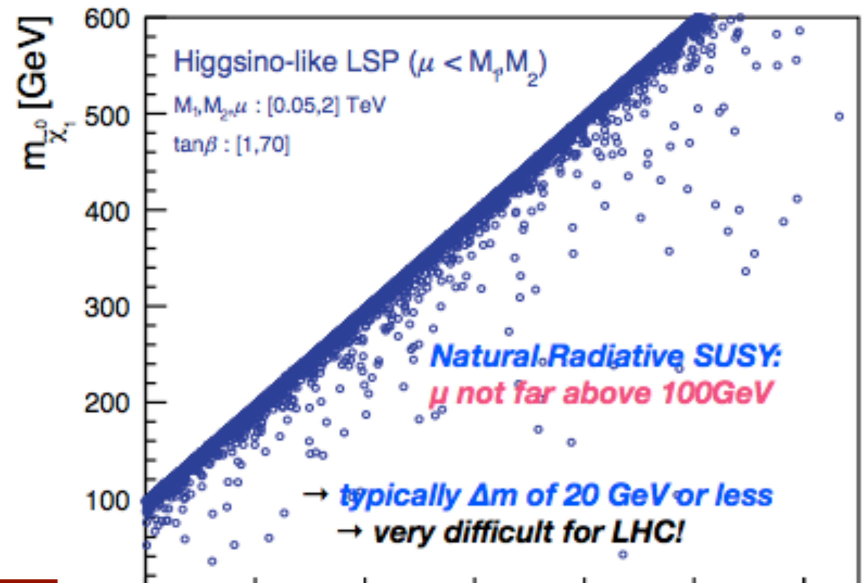


❖ From theoretical point of view:

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

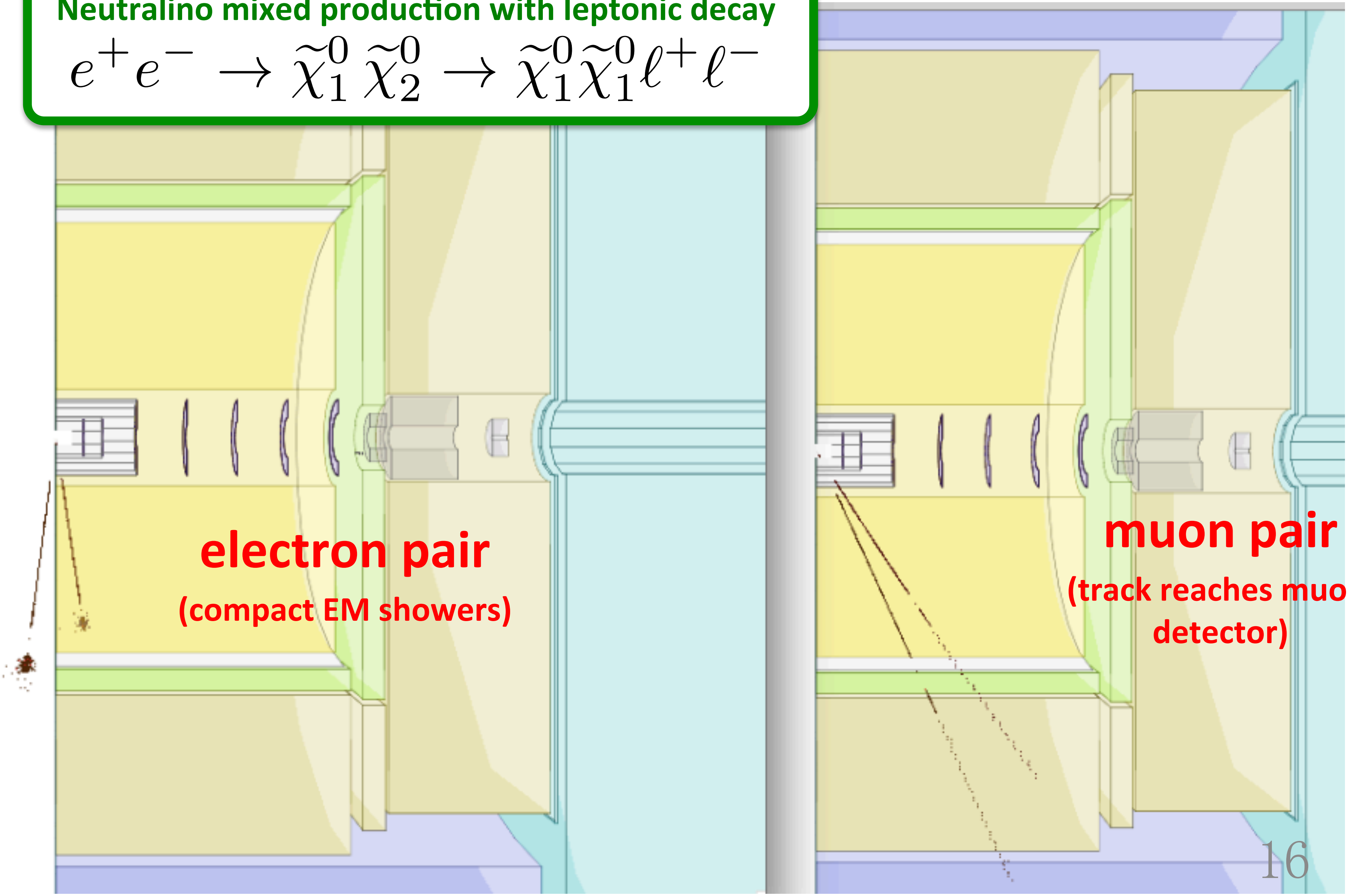
If SUSY particles exist al all,
they may be in a region
only accessible by the ILC (?)

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

√s =500 GeV

Neutralino mixed production with leptonic decay

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

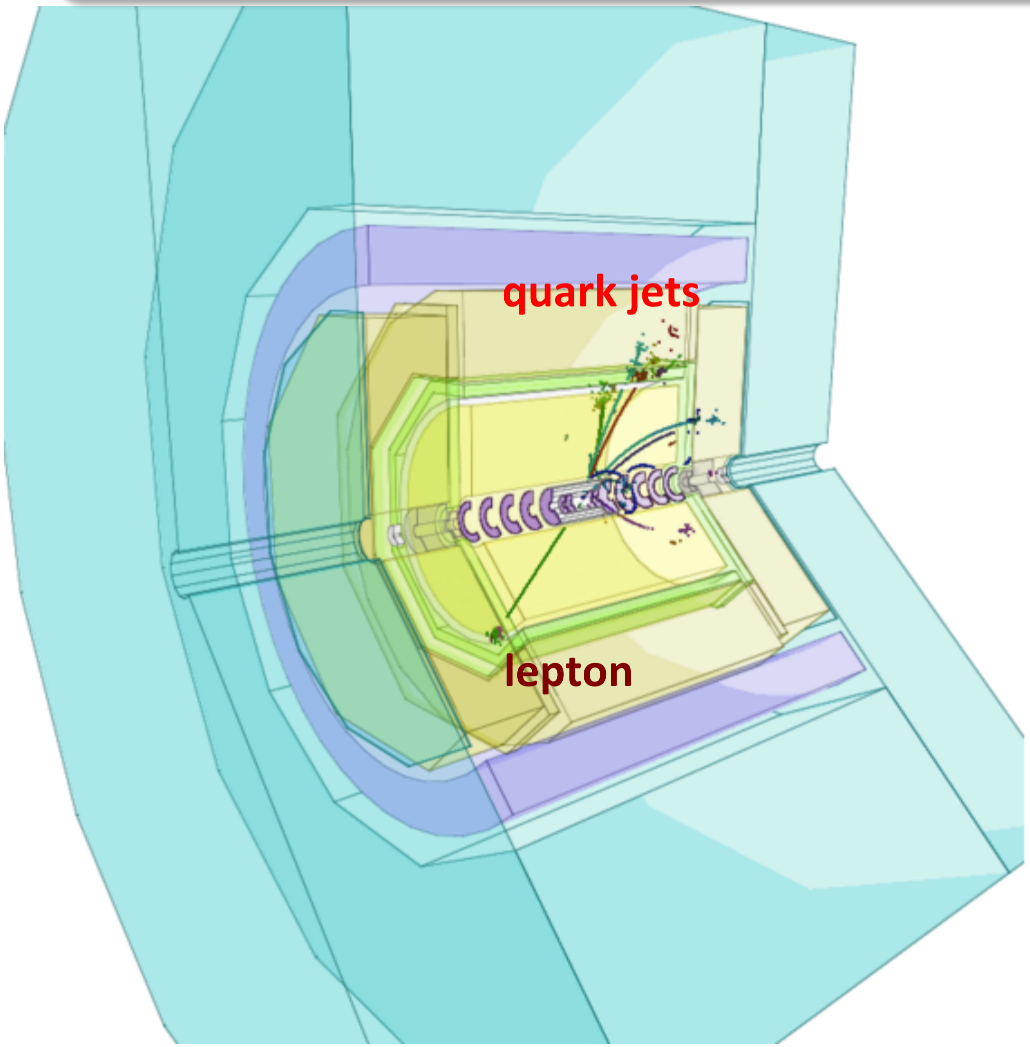


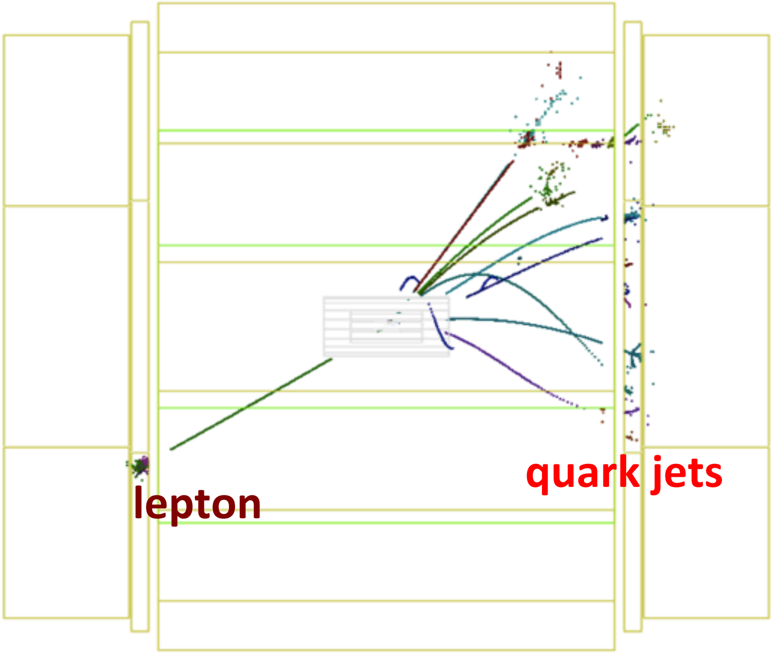
How do these signals look in the detector? (2)

√s =500 GeV

Chargino pair production with semileptonic decay

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



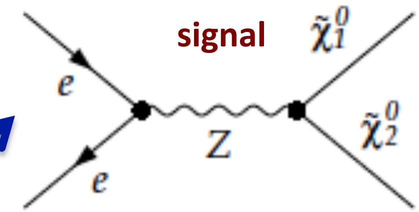


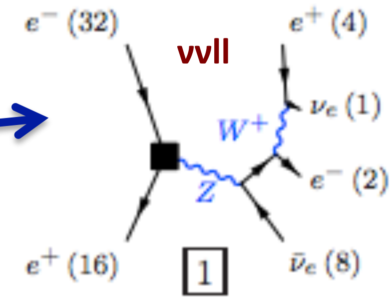
Event Selection

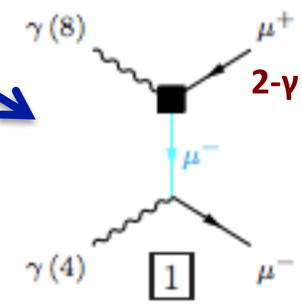
Neutralino mixed production with leptonic decay

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

- 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 (ννll)
- 2-γ processes are removed by BeamCal veto, cuts on lepton track p_T, and coplanarity



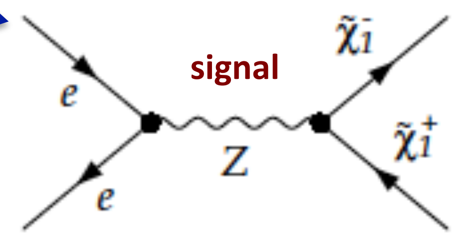




Chargino pair production with semileptonic decay

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

- 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.



Extraction of Higgsino Mass

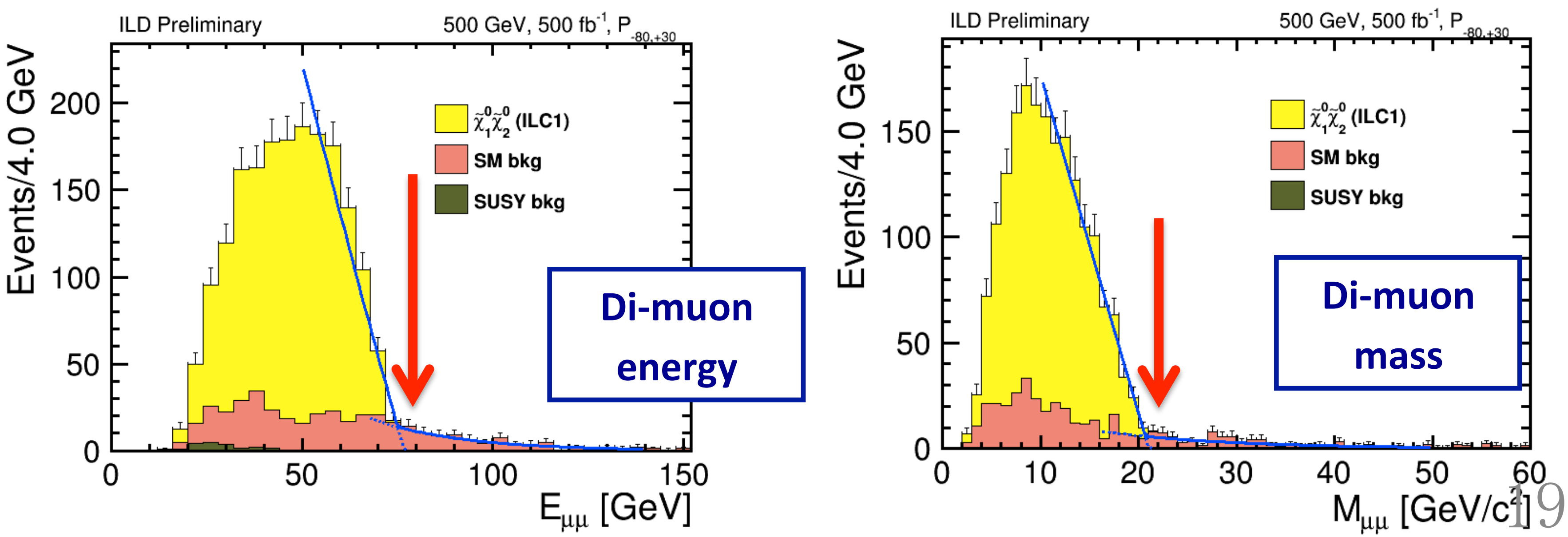
Neutralino mixed production with leptonic decay

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

- 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.
- $E_{ll,max}$ and $M_{ll,max}$ are extracted by a fit to obtain the neutralino masses

  need correction 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

Neutralino mixed production with leptonic decay

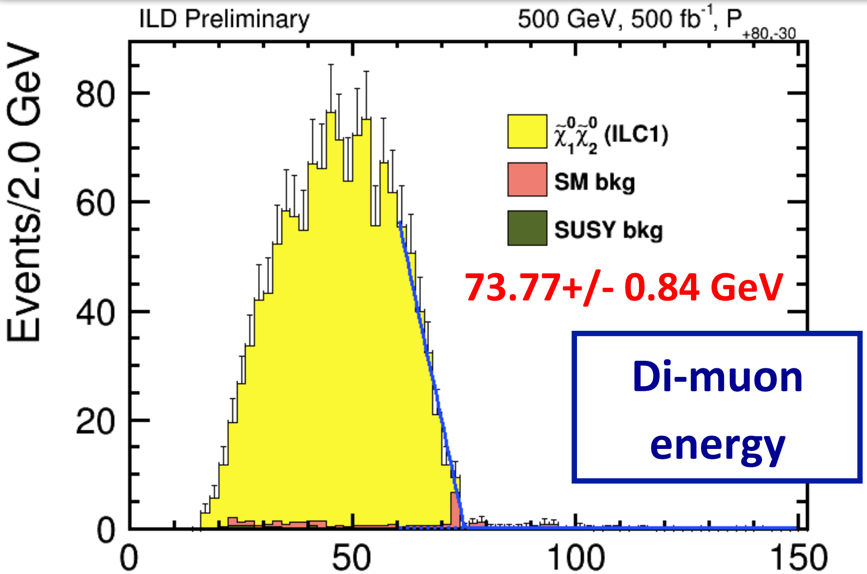
$$e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ell^+ \ell^-$$

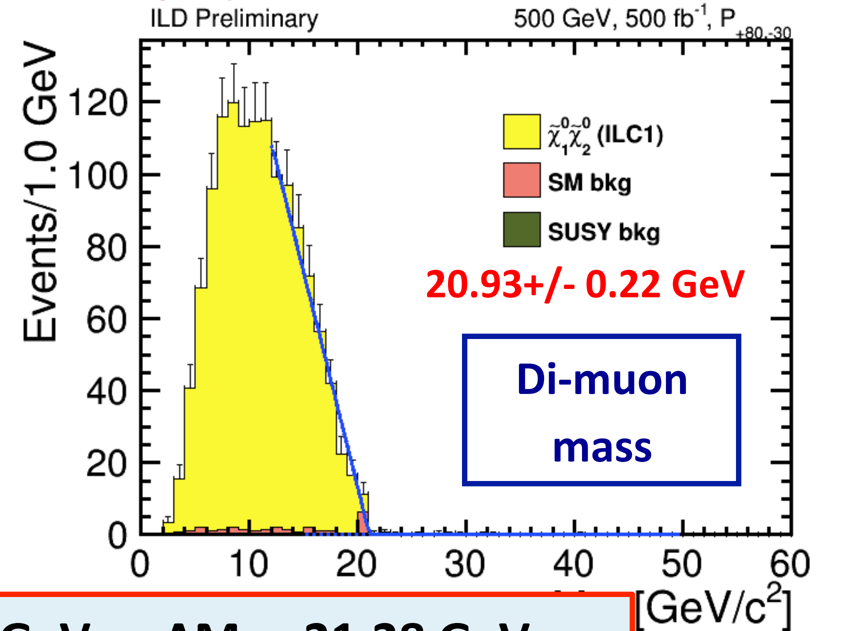
Right Polarization (Pe-,Pe+) = (+0.8, -0.3)

Much less bkg

Precision slightly better

Edge precision < ~ 1 %





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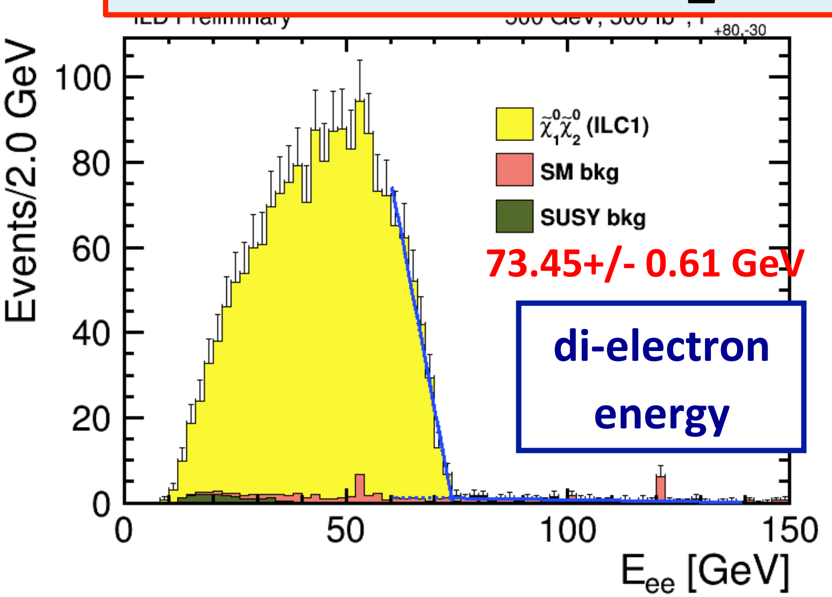

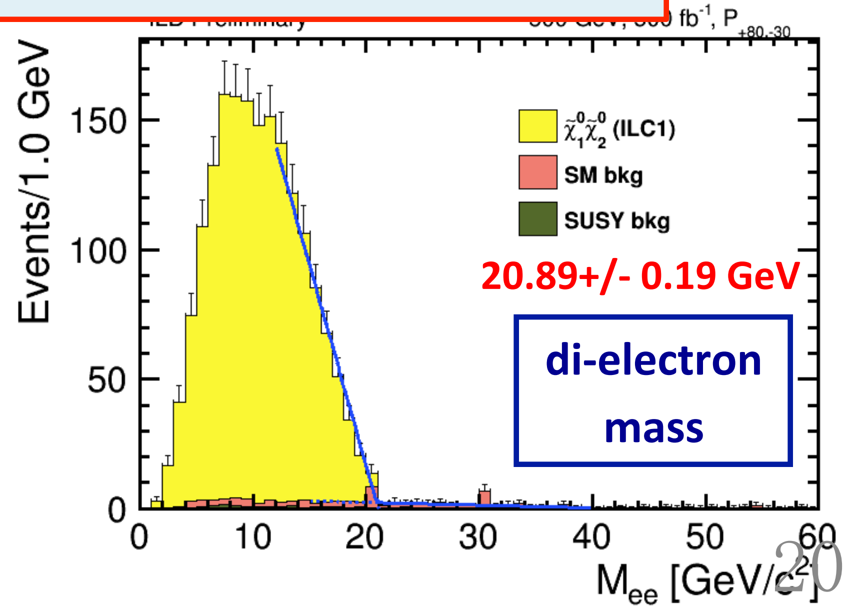

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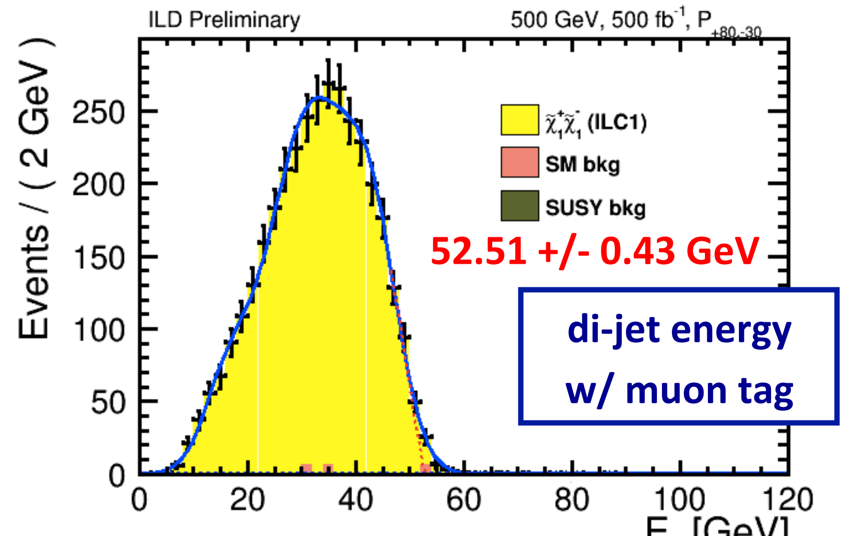
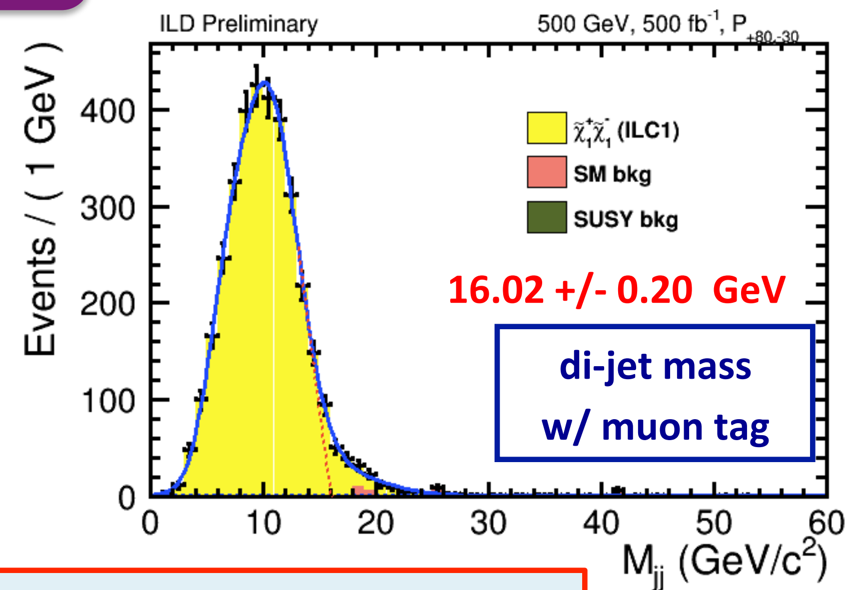
right Polarization (Pe-,Pe+) = (+0.8, -0.3)

Cross section ~ 1/5 of left polarization





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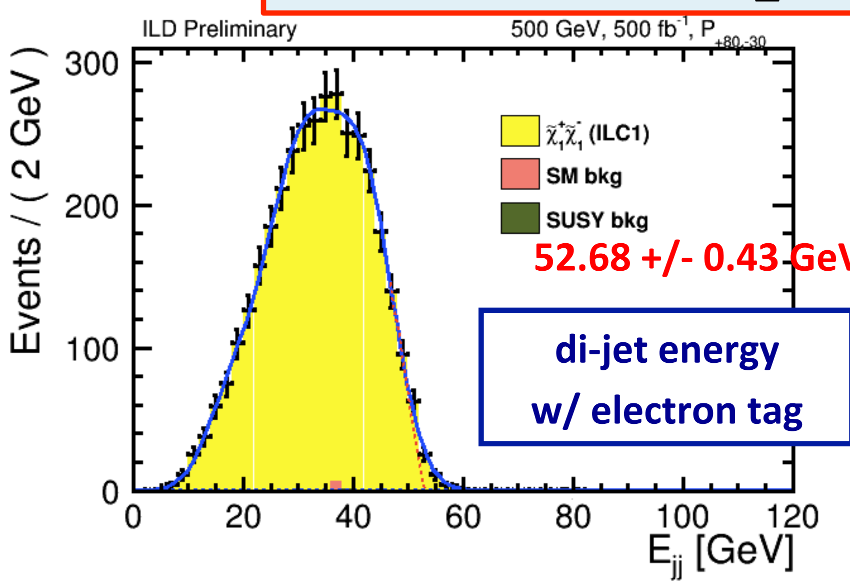
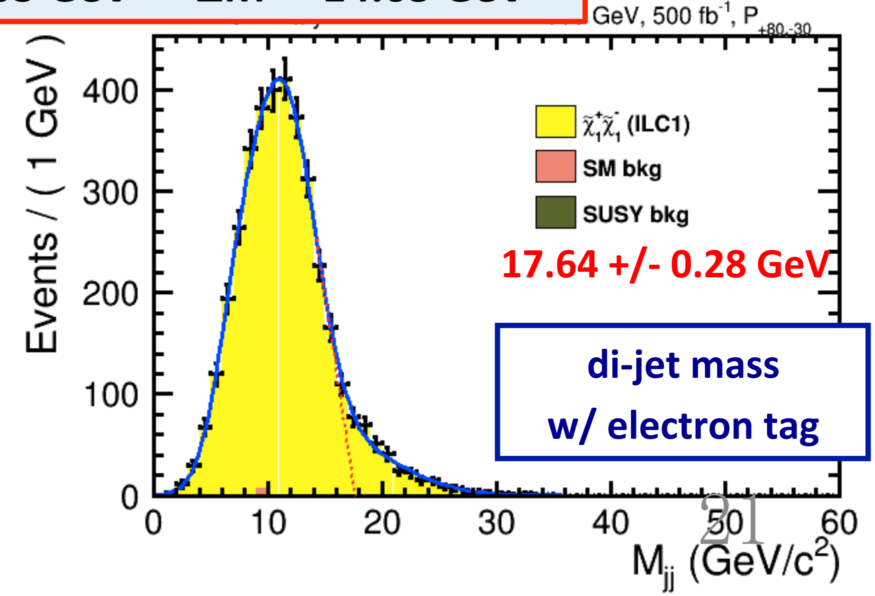
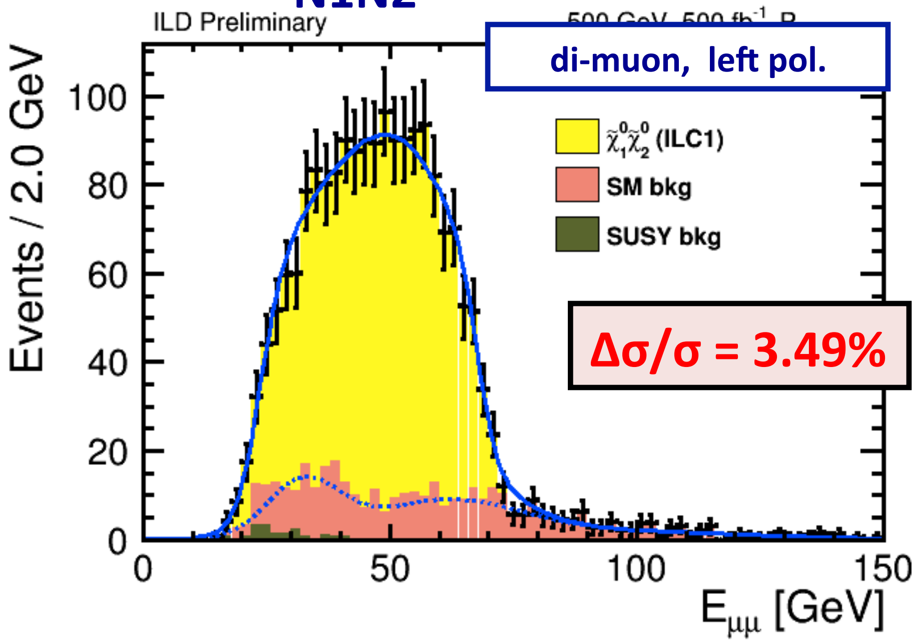


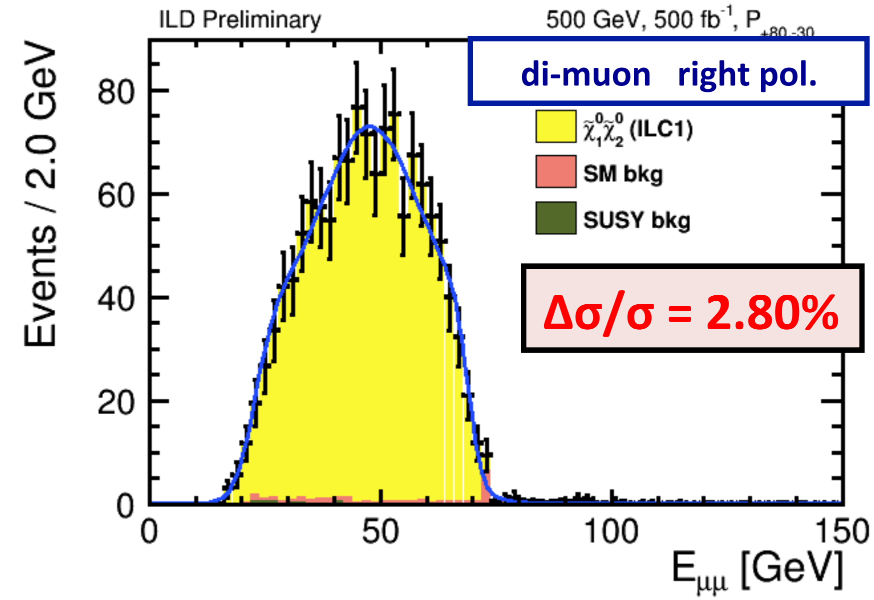


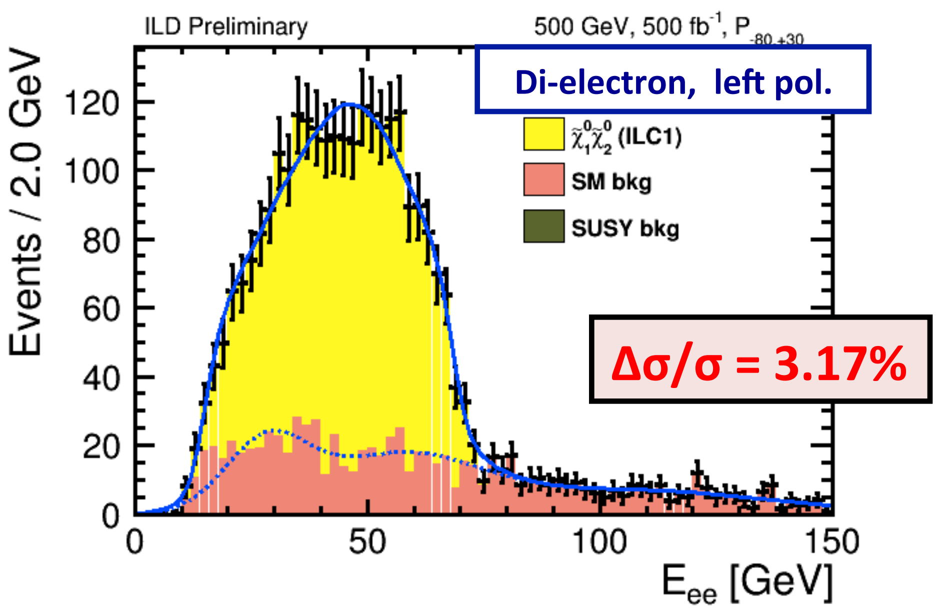
Extraction of Cross Section

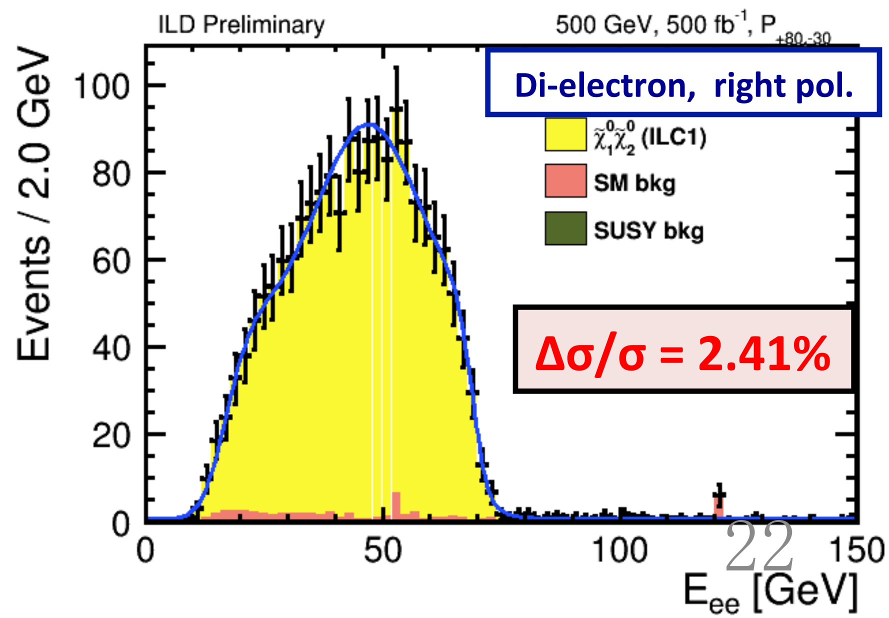
N1N2

Uncertainty of right pol is about 3 / 4 of left pol dependent on statistics (evaluated using Toy MC)



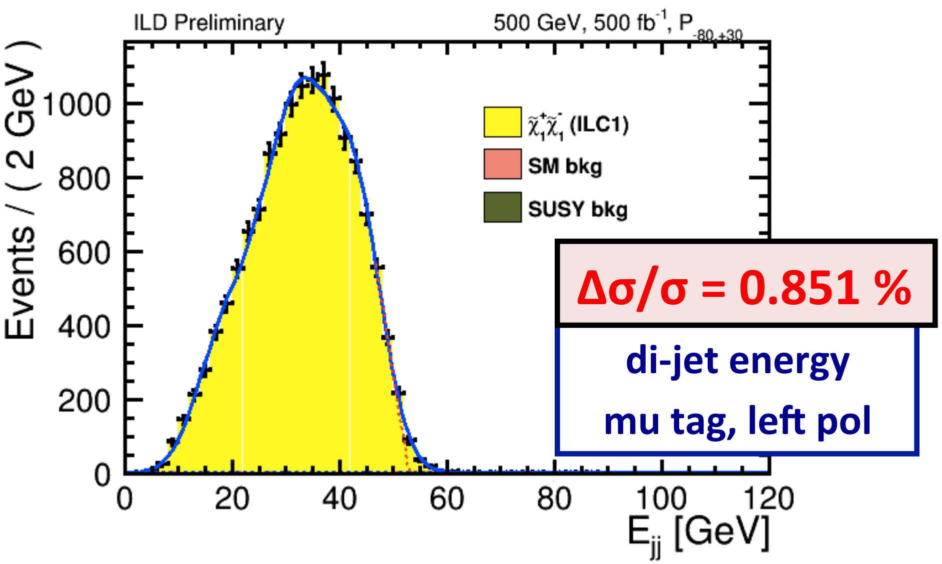


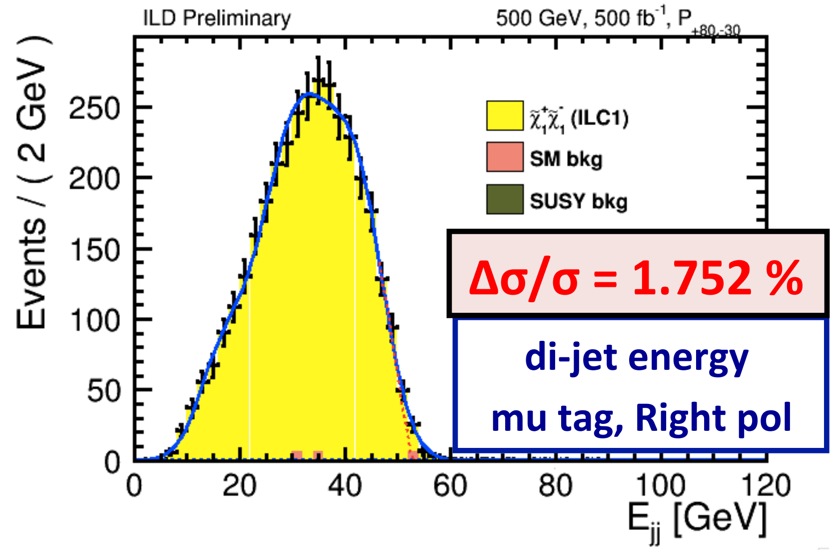


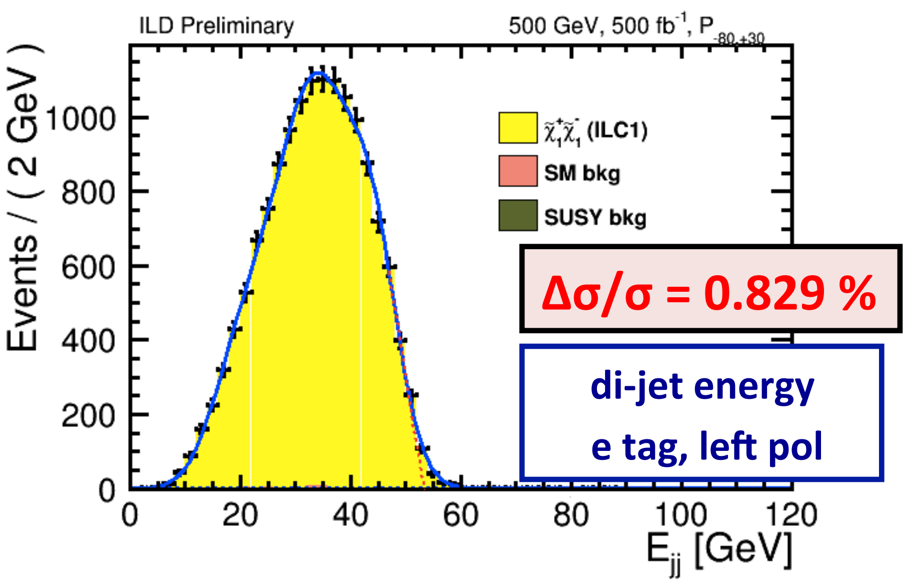


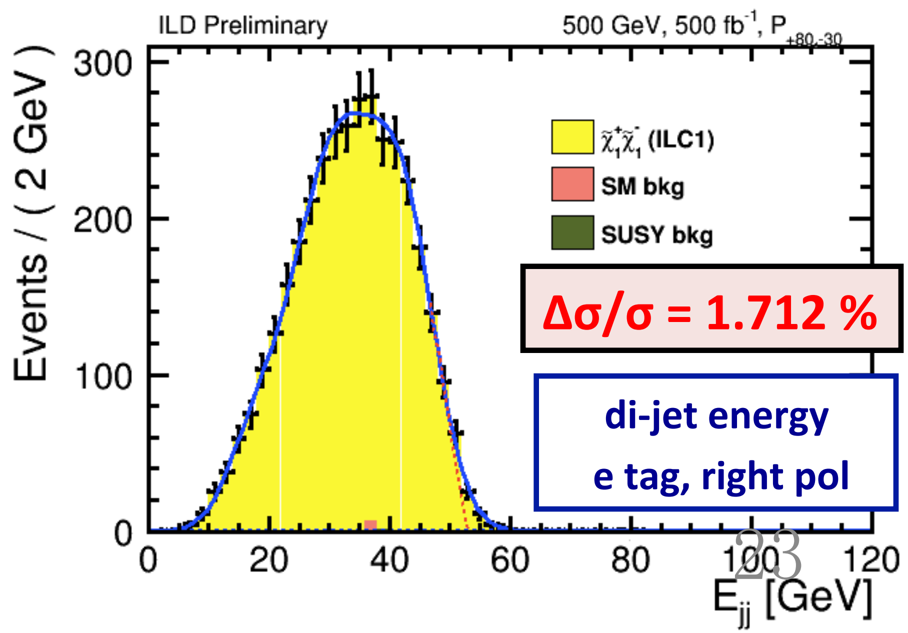
Extraction of Cross Section C1C1

- **Left pol has x2 better precision**
- **dependent on statistics**









Mass Precisions（individual channels）

$\sqrt{s}$ = 500 GeV

L = 500 fb^{-1}

Convert precisions of kinematic edges to those of Higgsino masses

MN1: χ^0_1 mass   MN2: χ^0_2 mass   MC1: $\chi^\pm_1$ mass

Neutralino: 1 – 2%

polarization		MN1	MN2	ΔMN1	ΔMN1/MN1	ΔMN2	ΔMN2/MN2
left	mm	102.26	123.02	1.77	**1.7%**	1.76	**1.4%**
left	ee	100.30	120.81	2.17	**2.2%**	2.15	**1.8%**
right	mm	103.06	123.99	1.82	**1.8%**	1.81	**1.5%**
right	ee	103.41	124.30	1.44	**1.4%**	1.43	**1.1%**

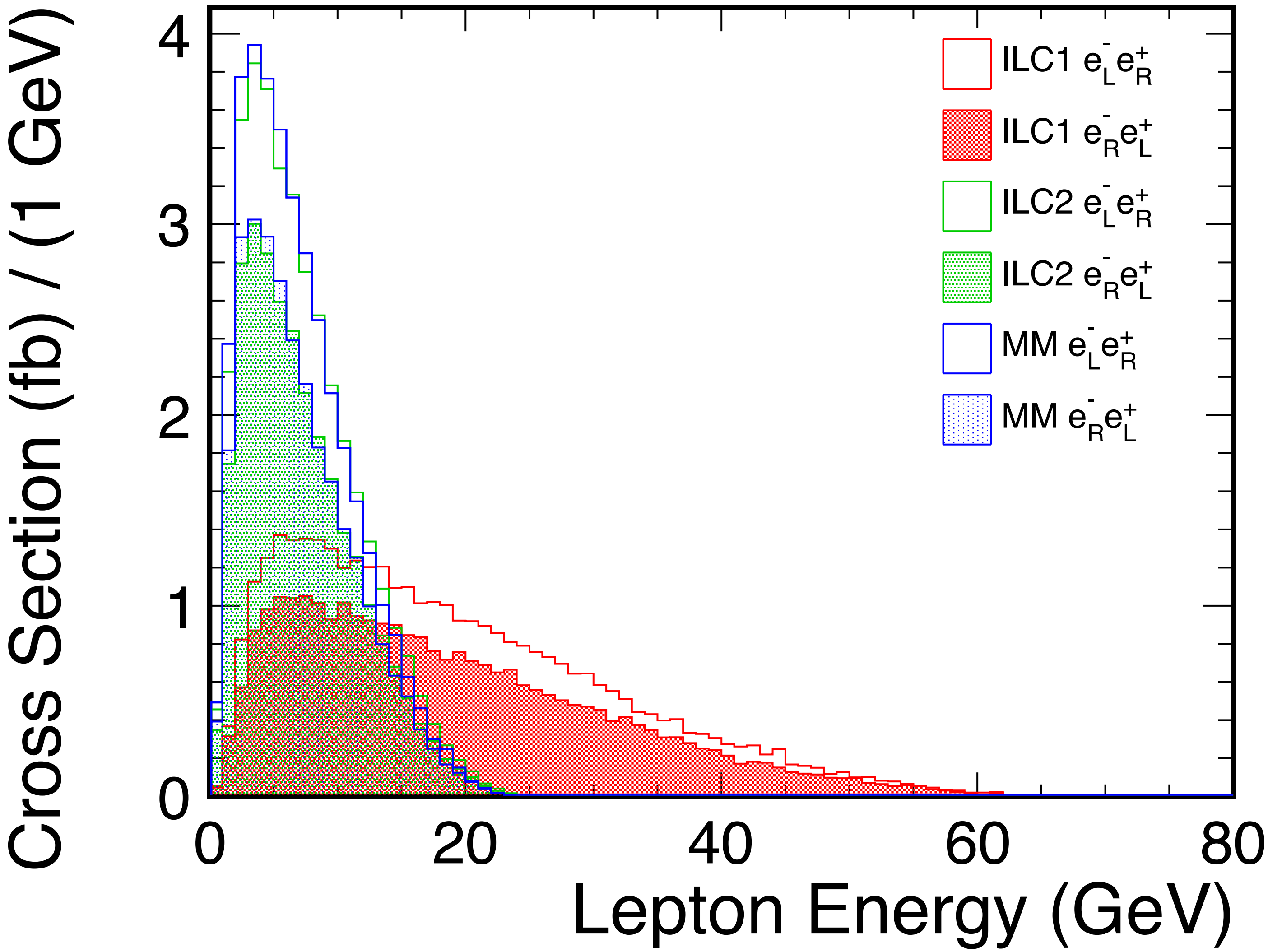
Chargino: left pol is better than 1%

～ 2 times better than right pol

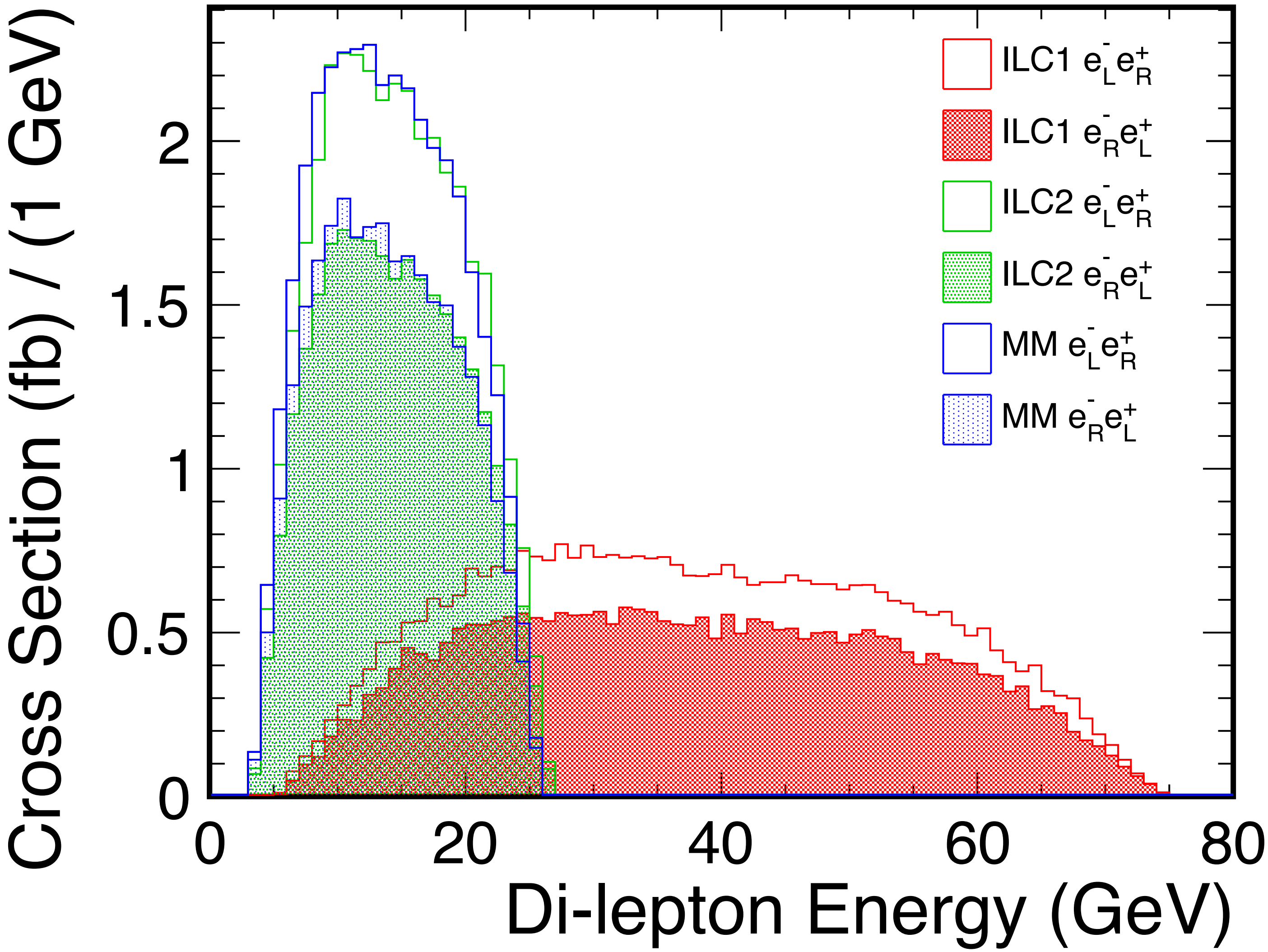
polarzation		MN1	MC1	ΔMN1	ΔMN1/MN1	ΔMC1	ΔMC1/MC1
left	mu tag	113.50	129.14	0.82	**0.7%**	0.82	**0.6%**
left	e tag	122.96	140.37	1.19	**1.0%**	1.18	**0.8%**
right	mu tag	116.42	132.44	1.76	**1.5%**	1.75	**1.3%**
right	e tag	125.34	142.98	2.20	**1.8%**	2.18	**1.5%**

Theoretic values MN1 = 102.70 GeV   MN2 = 123.98 GeV, MC1 = 117.33 GeV

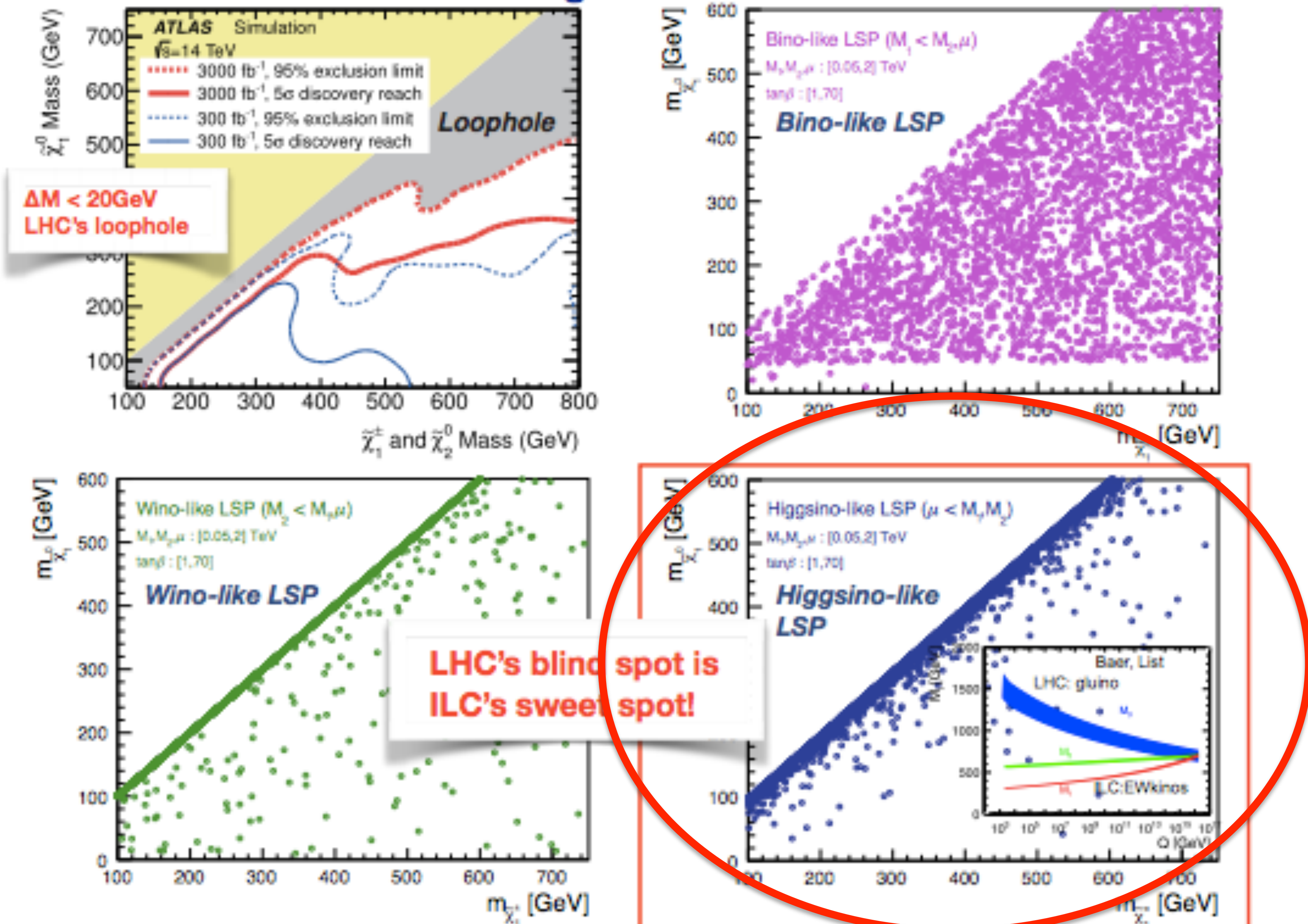
$$e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0, \quad \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-$$



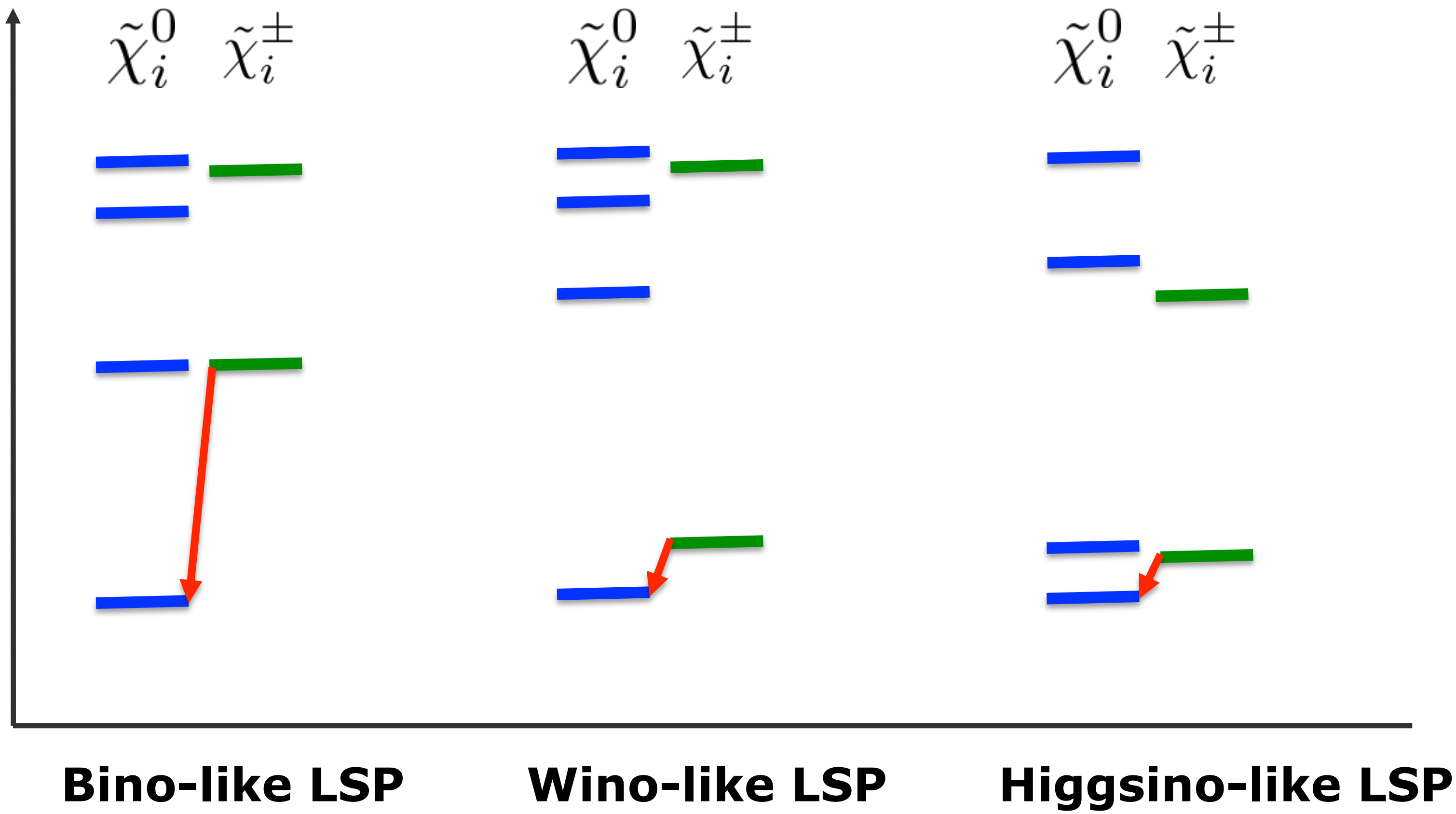
$$e^+e^- \to \widetilde{\chi}_1^0\widetilde{\chi}_2^0, \quad \widetilde{\chi}_2^0 \to \widetilde{\chi}_1^0\ell^+\ell^-$$



Chargino Search



SUSY Electroweak Sector



LSP/NLSP typically degenerate
(depends on mixing)

[S.-L. Lehtinen]

SUSY Parameter Determination

Why?

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

How?

- **Global χ^2 fit of SUSY parameters to observables using Fittino** [hep-ph/0412012]
- **Fit GUT scale (NUHM2) parameters**

Reminder:

Benchmark	ILC2
M_0 [GeV]	5000
$M_{1/2}$ [GeV]	1200
A_0 [GeV]	-8000
tanβ	15
μ [GeV]	150
M_A [GeV]	1000

Defined at GUT scale
Defined at weak scale

Observables and assumed precision for ILC2 benchmark

observable	value	uncertainty
mass $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_1^\pm$	$\sim$ 160 GeV	0.2 GeV
$BR(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 l^+ l^-)$	0.106	0.1
$BR(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 q\bar{q})$	0.590	0.1
$BR(\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 q\bar{q}')$	0.671	0.1
$BR(\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 l\nu_l)$	0.329	0.1
$\sigma(\tilde{\chi}_1^0\tilde{\chi}_2^0)$, 4 polarisations	140 – 300 fb^{-1}	1%
$\sigma(\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp)$, 4 polarisations	200 – 970 fb^{-1}	1%

- Uncertainty to be updated with results from simulation study
- Study required precision that allows for full parameter determination

Fits of NUHM2 Parameters

[S.-L. Lehtinen]

ILC2

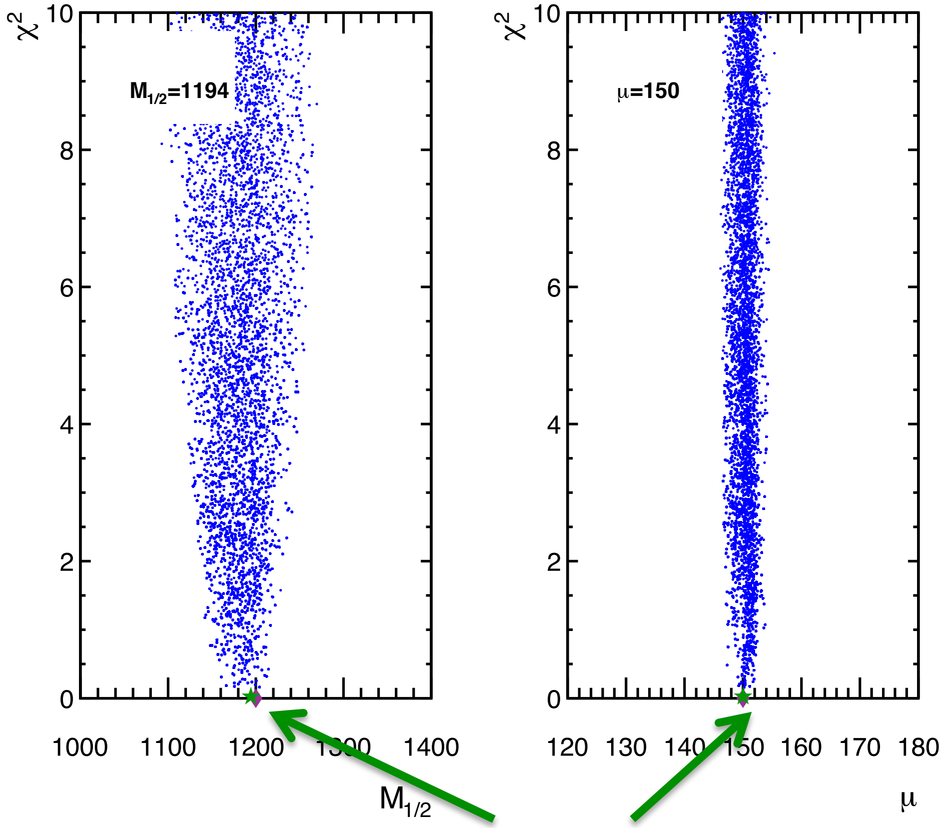
All 6 parameters are simultaneously varied. Initial values are set to be near the model values.

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, $\mathbf{M_{1/2}}$ 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 $\chi_2^0\chi_3^0$, tanβ can be constrained as well. (ILC1)



Diamond = model point

Star = best fit point

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($\chi_1^+ \rightarrow \chi_1^0$ lν) (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%