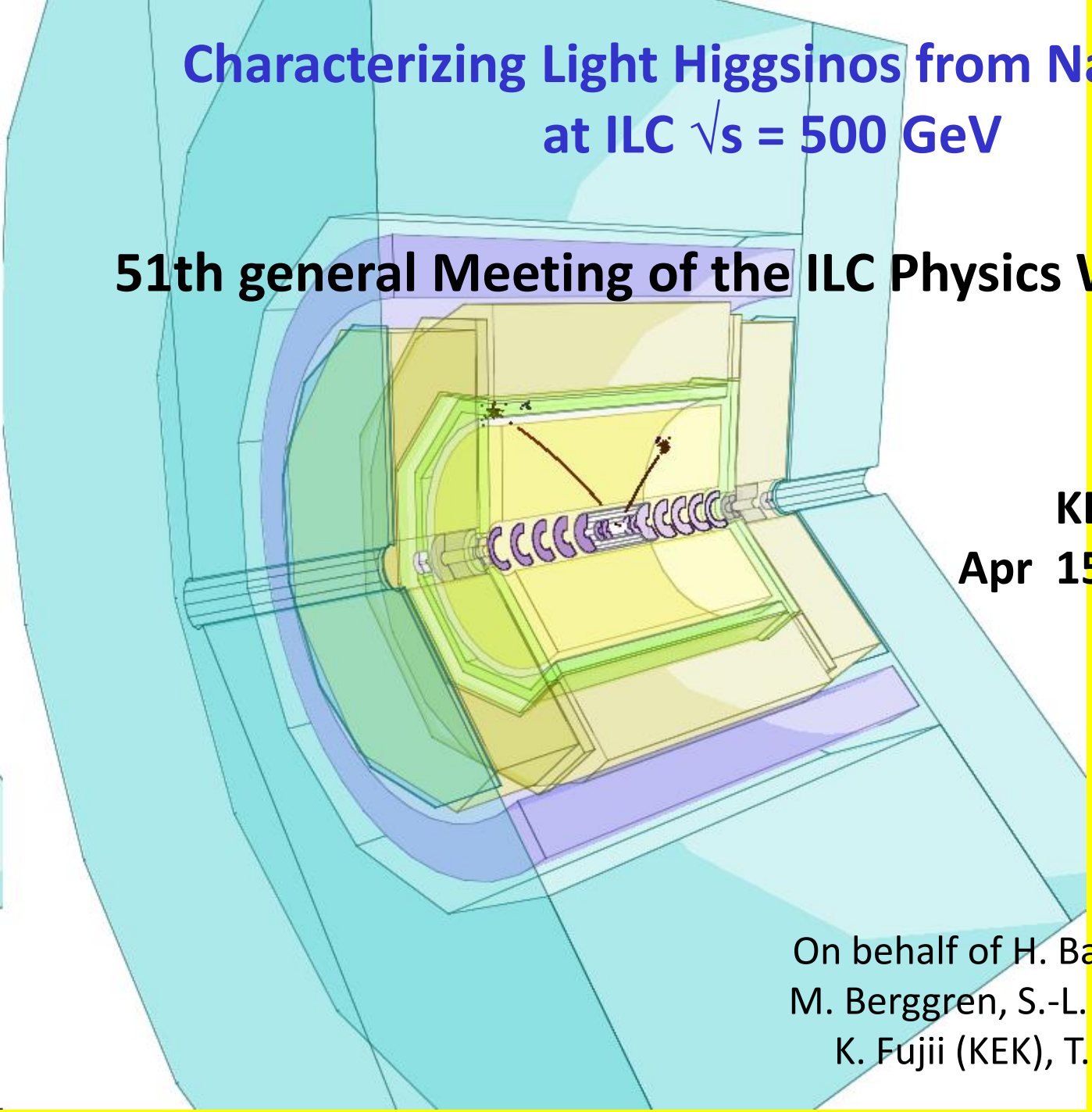
# Characterizing Light Higgsinos from Natural SUSY at ILC $\sqrt{s}$ = 500 GeV

## 51th general Meeting of the ILC Physics Working Group



**KEK**

**Apr 15, 2017**


**Jacqueline Yan (KEK)**

On behalf of H. Baer (Univ of Oklahoma),
M. Berggren, S.-L. Lehtinen, J. List (DESY),
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# Outline

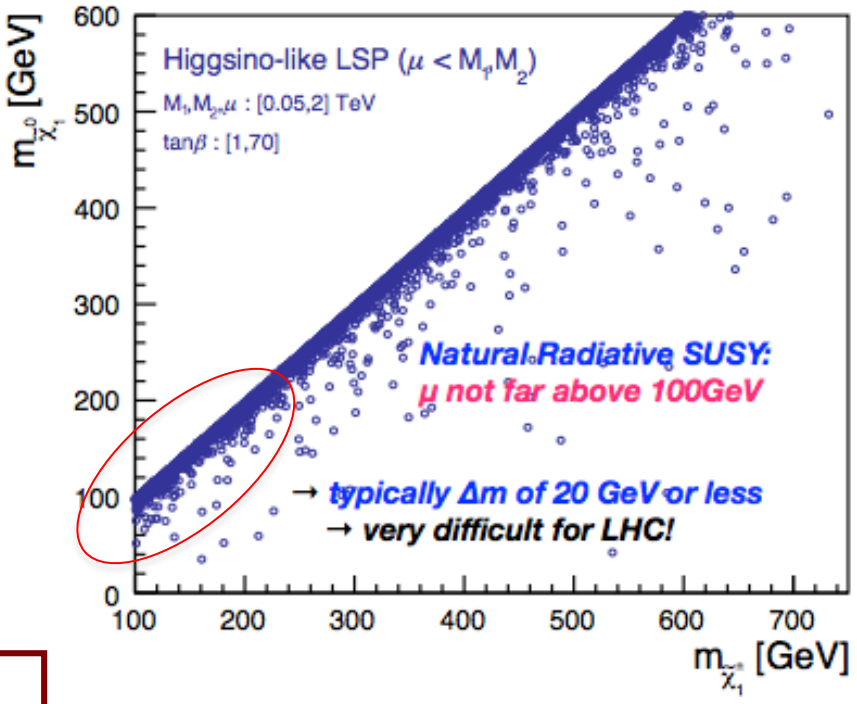
- Motivation of study
- Analysis method
- Current study results
- Goals and Plans

# Motivation for searching light Higgsinos with compressed spectrum

❖ **experimental point of view:**

LHC already excluded wide regions with large ΔM while sensitivity falls rapidly for ΔM < 20 GeV with very small visible energy release,

➔ **no problem for ILC environment**




❖ **theoretical point of view:**

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

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

- maintaining small electroweak fine tuning ΔEW (<∼3%) requires **μ ~ 100–300 GeV**
- **Higgsino masses not too far from masses of W, Z, h (∼100 GeV)**

top and bottom squarks : few TeV, gluino mass: 2–4 TeV, 1st, 2nd generation squarks and sleptons : 5–30 TeV

**ILC is expected to either discover or exclude natural SUSY**

This full ILD simulation-based study demonstrates ILC's potential in discovery and precision measurement of

**4 light Higgsinos within reach of ILC √s >= 250 GeV,**
**ΔM 4 – 21 GeV, just beyond reach of HL-LHC**

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

**using precise measurements of masses and cross as "input"**

## determine SUSY parameters

e.g. $M_1$, $M_2$, μ, tanβ

S. Lehtinen (DESY) et al

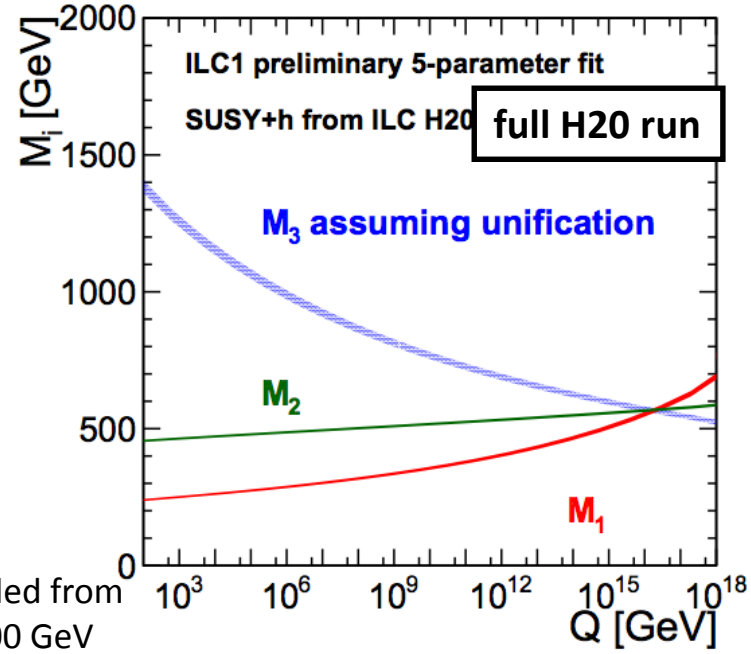
***Why?***

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

***How?***

- **Global $\chi^2$ fit of to observables**

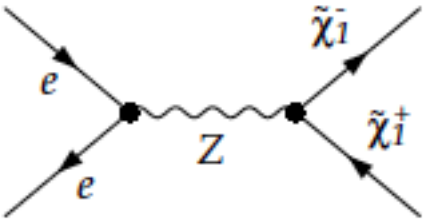
**Study required input parameters and precisions;**
interplay with Higgs precision measurements



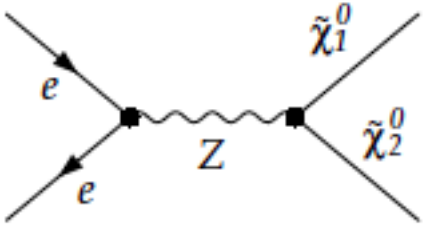

√s = 250, 350, 500 GeV, scaled from full simulation studies at 500 GeV

# Benchmarks in this Study

**Charginos ($\chi_1^+\chi_1^-$)**




**Neutralinos ($\chi_1^0\chi_2^0$)**



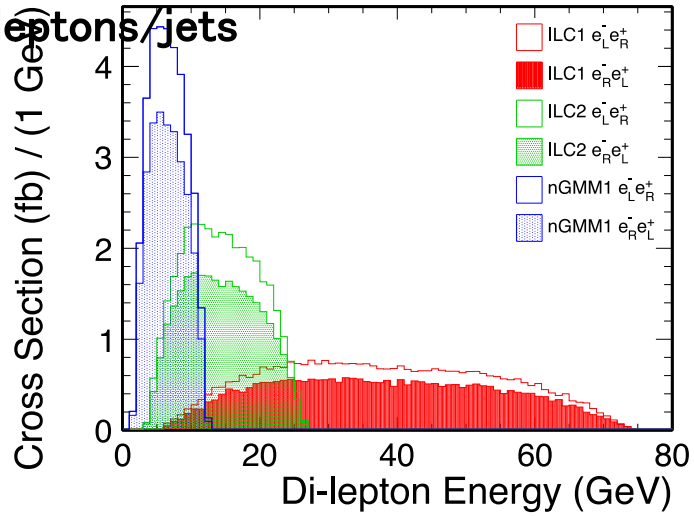

## 4 light Higgsinos

- **√s = 500 GeV**
- full ILD detector simulation

**ΔM complies with naturalness** (no use of ISR tag)

| Unit: GeV | ILC1 | ILC2 | nGMM1 |
|---|---|---|---|
| M(N1) | 102.7 | 148.1 | 151.4 |
| M(N2) | 124.0 | 157.8 | 155.8 |
| **ΔM(N2,N1)** | **21.3** | **9.7** | **4.4** |
| M(C1) | 117.3 | 158.3 | 158.7 |
| **ΔM(C1,N1)** | **14.6** | **10.2** | **7.3** |

**Good precision achievable even for challenging ΔM with soft leptons/jets**




| Process (Pe-,Pe+) | ILC1 | ILC2 | nGMM1 |
|---|---|---|---|
| C1C1 (-1,+1) | 1799.9 | 1530.5 | 1520.6 |
| C1C1 (+1,-1) | 334.5 | 307.2 | 309.5 |
| N1N2 (-1,+1) | 490.9 | 458.9 | 463.5 |
| N1N2 (+1,-1) | 378.5 | 353.8 | 357.3 |

Cross sections for $\sqrt{s}$ = 500 GeV
Similar for all benchmarks

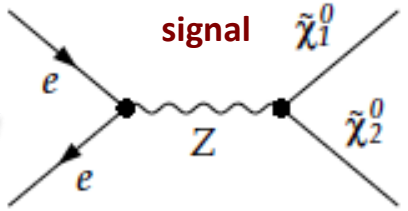
Event Generator: WHIZARD v1.95, DBD setup, TDR beam parameters

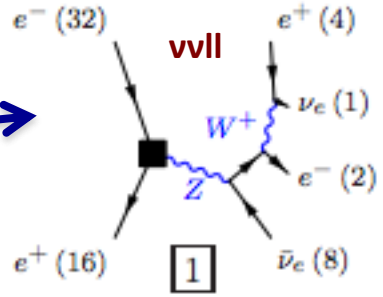
# Event Selection

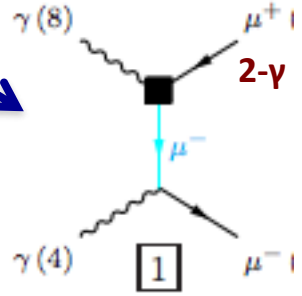
**Neutralino mixed production with leptonic decay**

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

- Reconstruct **two leptons (ee or μμ)** which originate from $Z^*$ emission in decay of $\chi_2^0$
- **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



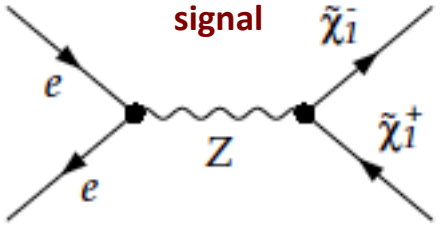




**Chargino pair production with semileptonic decay**

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

- Reconstruct **two jets** which originate from $W^*$ emission in decay of $\chi_1^{\pm}$
- **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**.

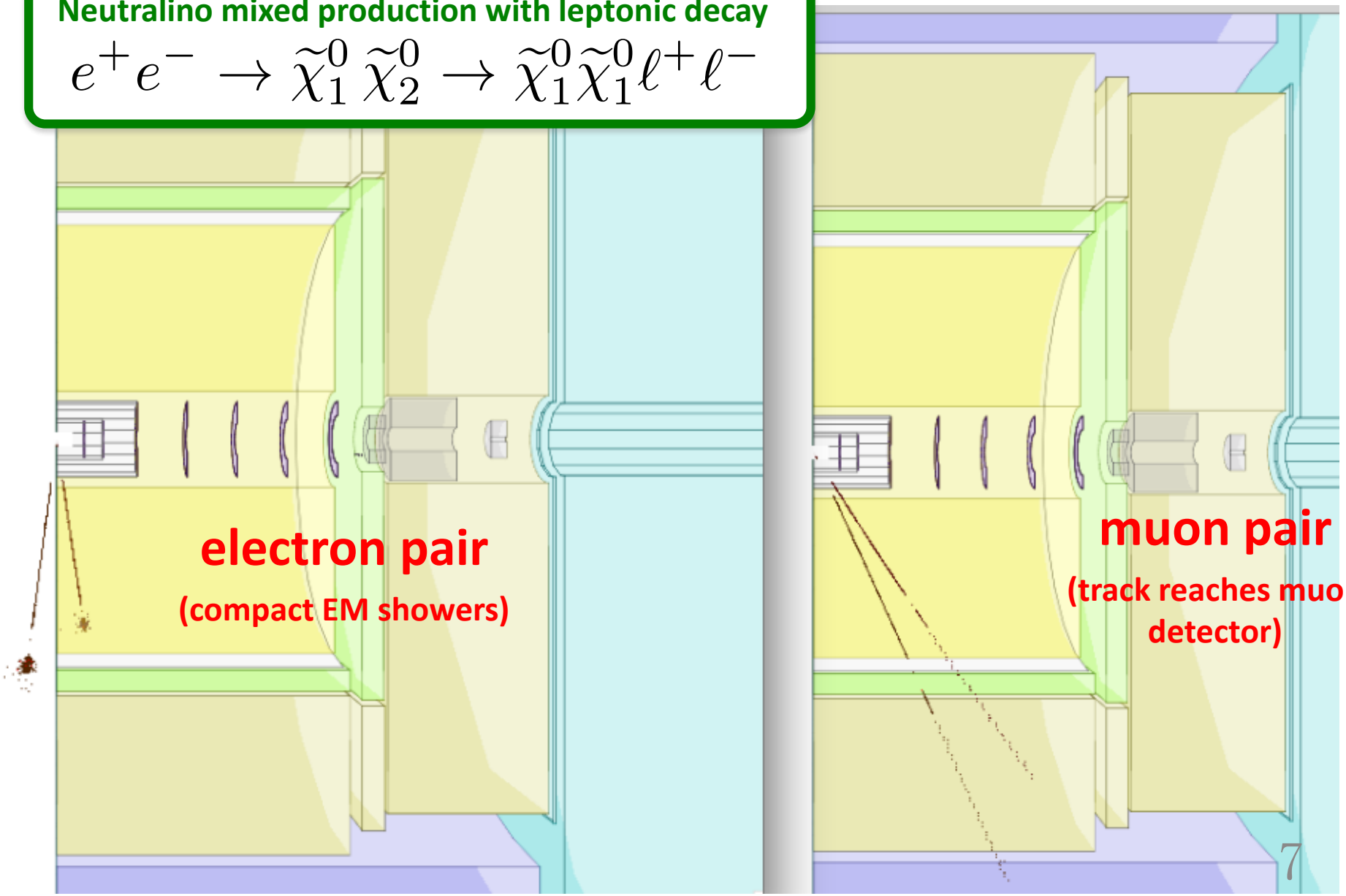


# How do these signals look in the detector? (1)

√s =500 GeV

**Neutralino mixed production with leptonic decay**

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

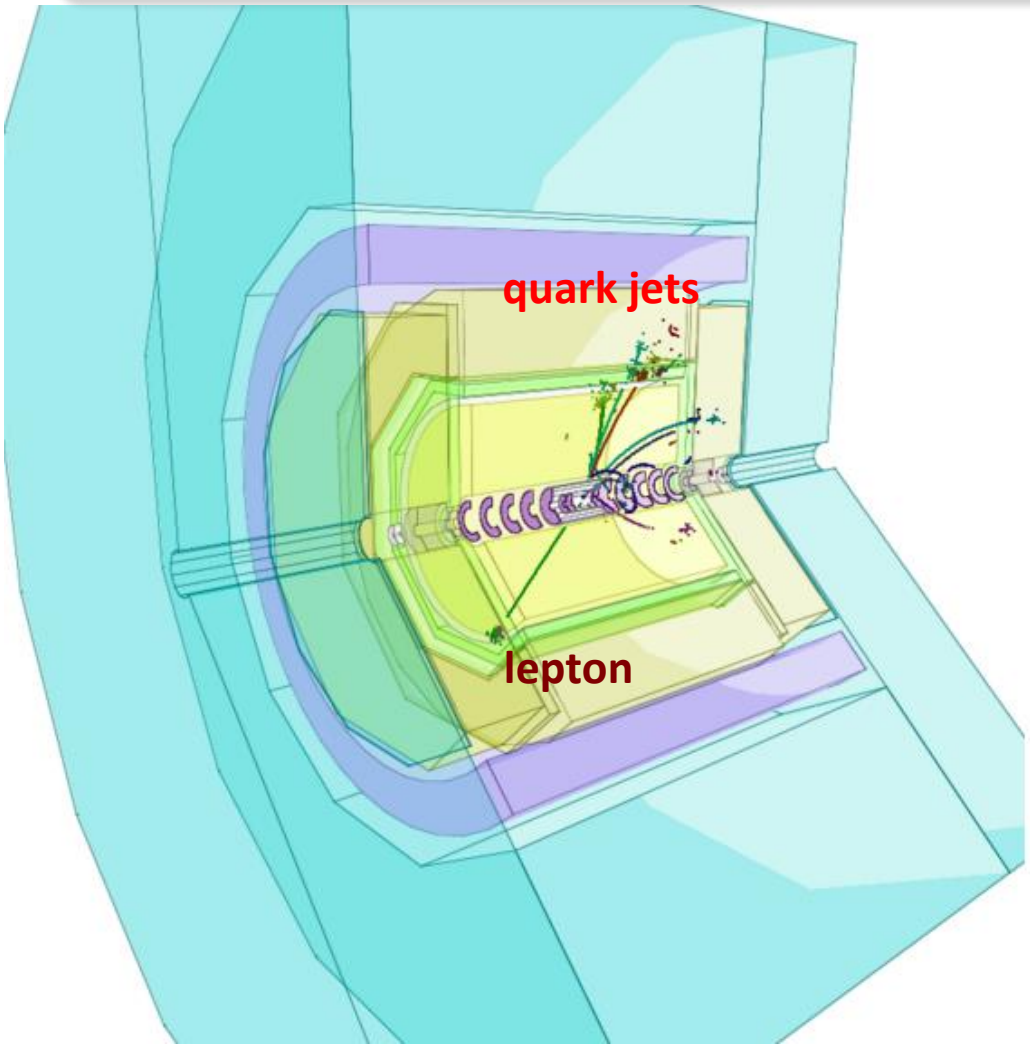


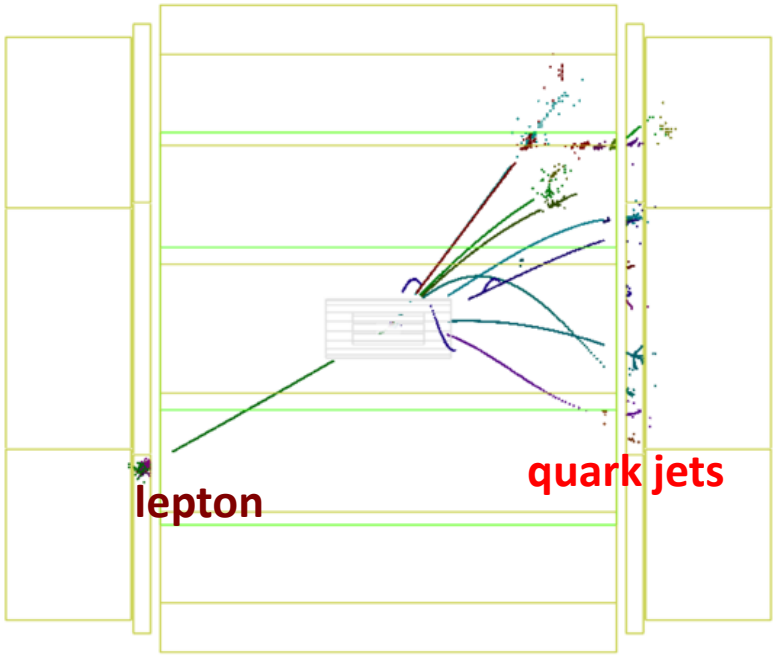
# How do these signals look in the detector? (2)

√s =500 GeV

**Chargino pair production with semileptonic decay**

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



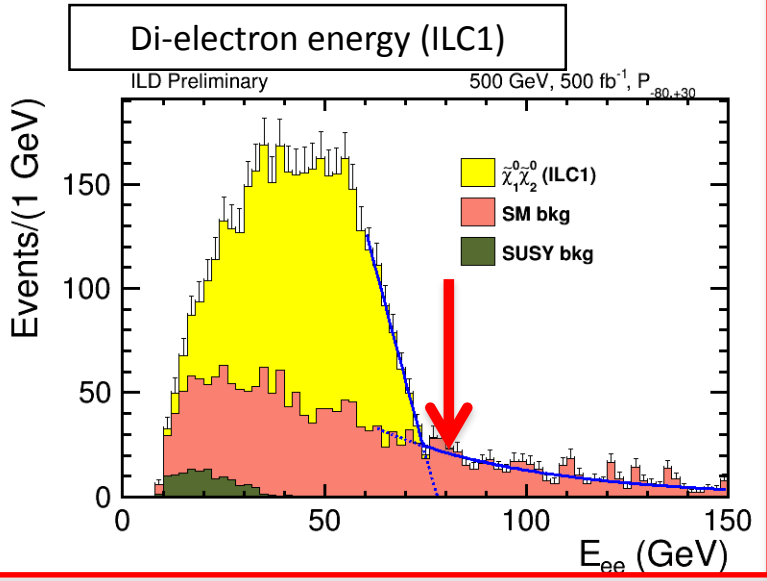



# Method to Extract Higgsino Mass and Cross Section

## Mass

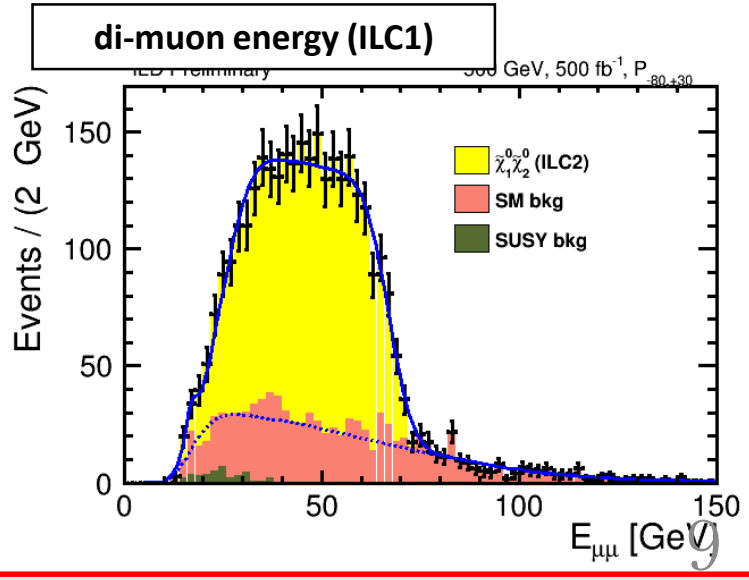
Kinematic edges of E_ll, E_jj, M_ll, M_jj are functions of $\sqrt{s}$ and Higgsino masses

**Extract edges** by a fit to distributions, then calculate Higgsino mass




## Cross section

**Count number of events** under E_ll, E_jj spectra




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

# Status of Higgsino Study

**currently finalizing results and** working on paper

Advances after LCWS 2016 :

Did analysis for benchmark with smallest ΔM (< 5GeV)

Optimized signal selection and cuts

- to further **improve significance**
- to **converge to a common set of analysis method** for all benchmarks

*some preliminary set of results will be shown today*

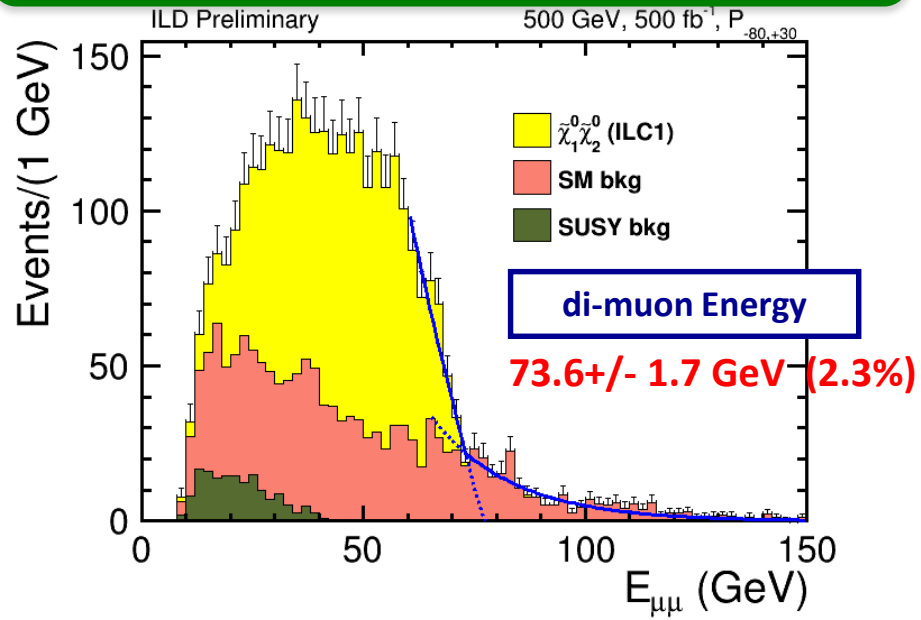
Abstract submitted to Higgs and New Physics session of EPS-HP 2017 conference (July 5-12, 2017)

**Neutralino mixed production with leptonic decay**

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

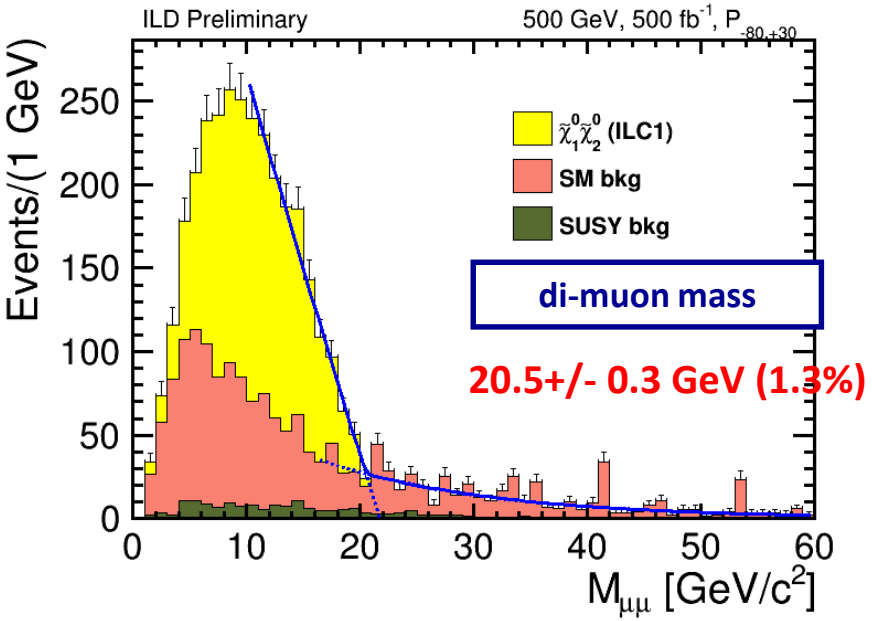
# ILC1

**ΔM=21 GeV** **(Pe-, Pe+)=(0.8,0.3)** **L=500fb-1**



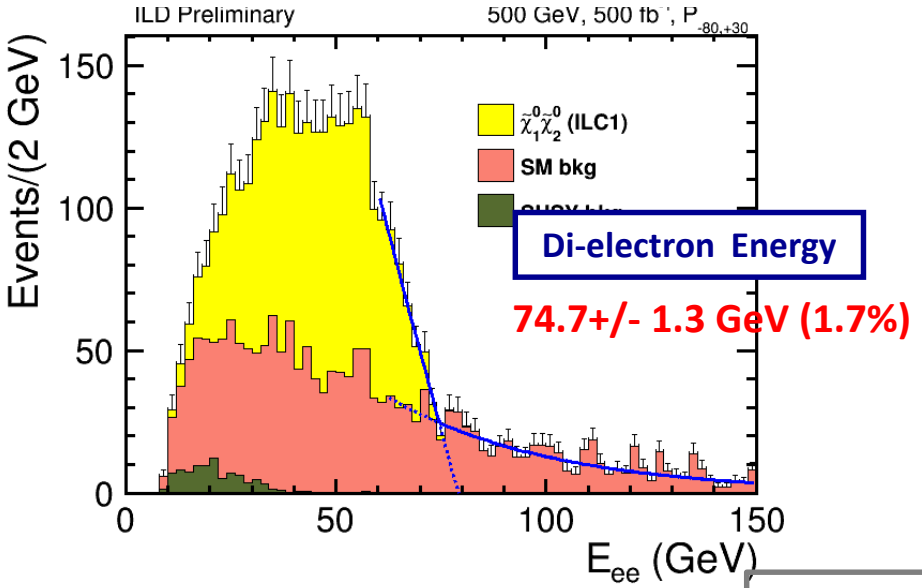

**di-muon Energy**

**73.6+/- 1.7 GeV (2.3%)**



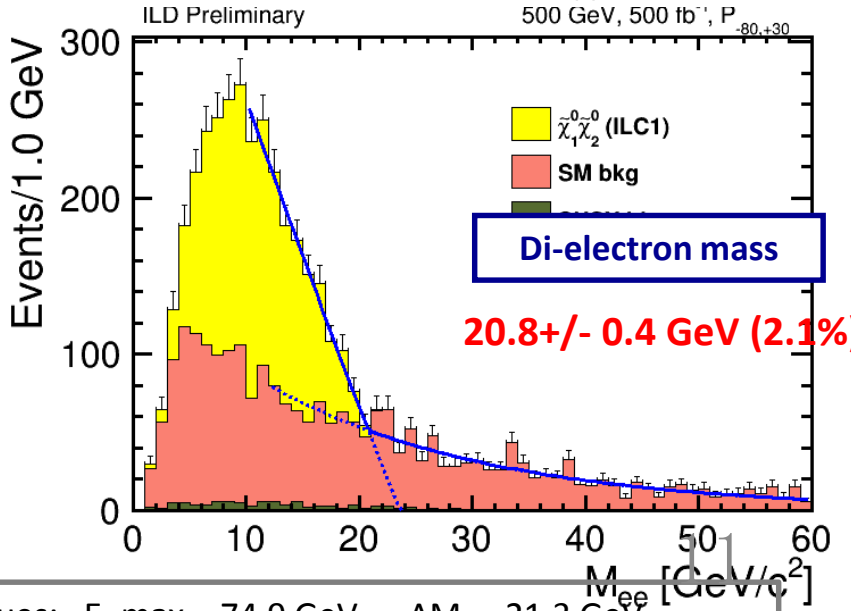

**di-muon mass**

**20.5+/- 0.3 GeV (1.3%)**




**Di-electron Energy**

**74.7+/- 1.3 GeV (1.7%)**




**Di-electron mass**

**20.8+/- 0.4 GeV (2.1%)**

Theoretical values: E_max = 74.9 GeV ΔM = 21.3 GeV

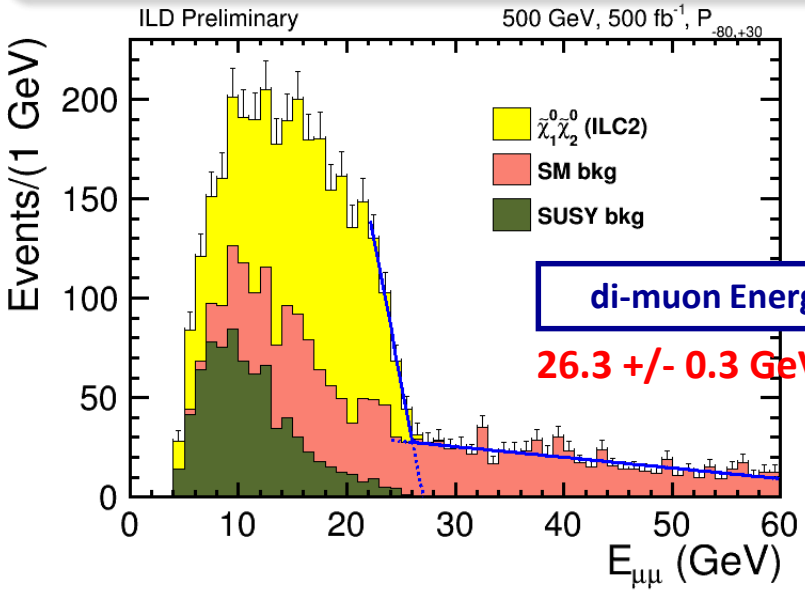
**Neutralino mixed production with leptonic decay**

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

# ILC2

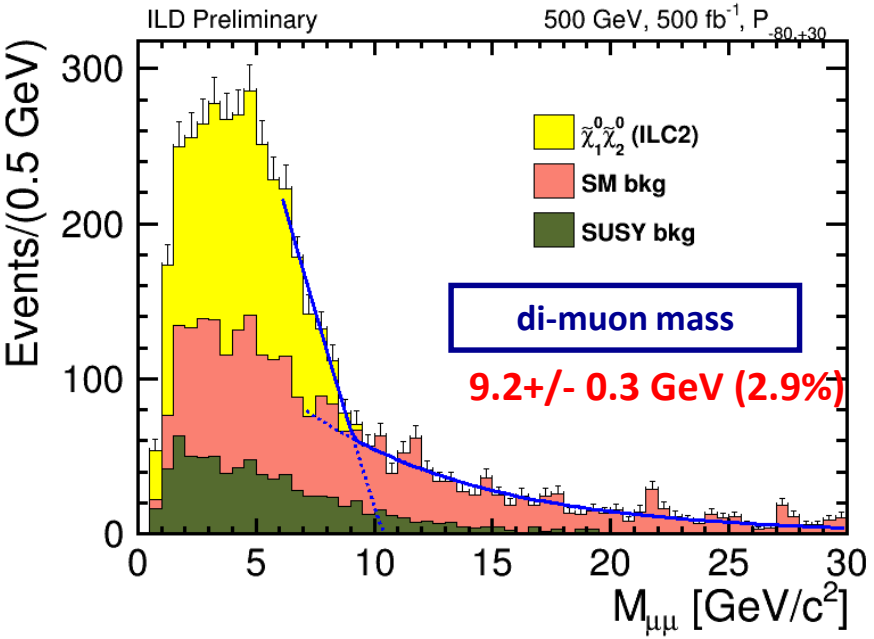
(Pe-, Pe+)=(0.8,0.3) L=500fb-1

**ΔM=9.7 GeV**



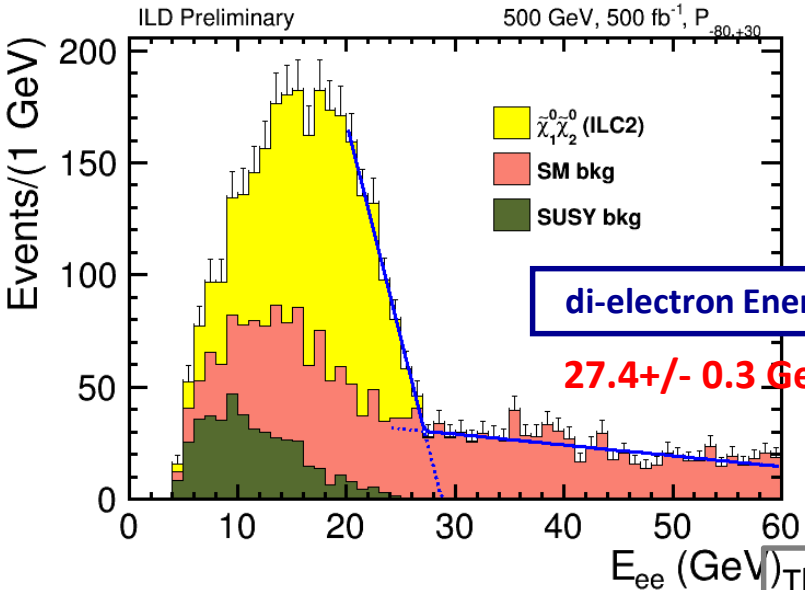

**di-muon Energy**

**26.3 +/- 0.3 GeV (1.2%)**



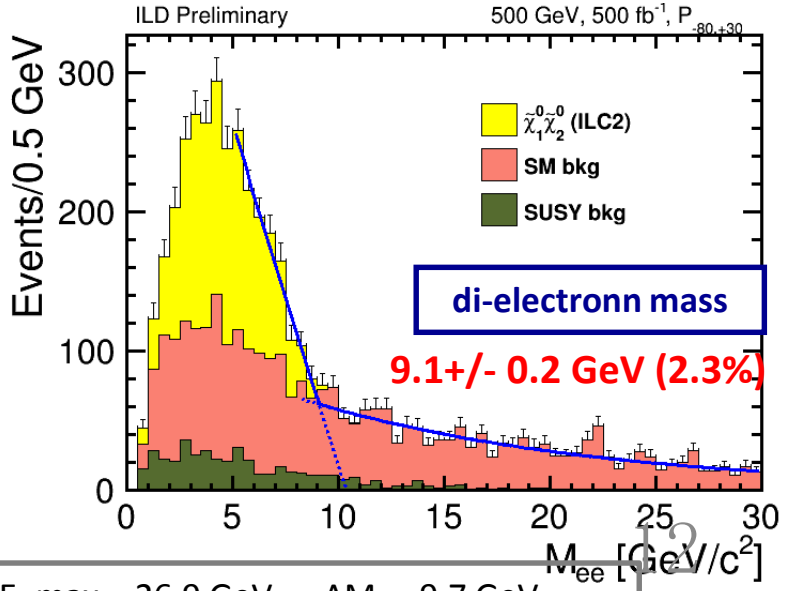

**di-muon mass**

**9.2+/- 0.3 GeV (2.9%)**




**di-electron Energy**

**27.4+/- 0.3 GeV (1.2%)**




**di-electronn mass**

**9.1+/- 0.2 GeV (2.3%)**

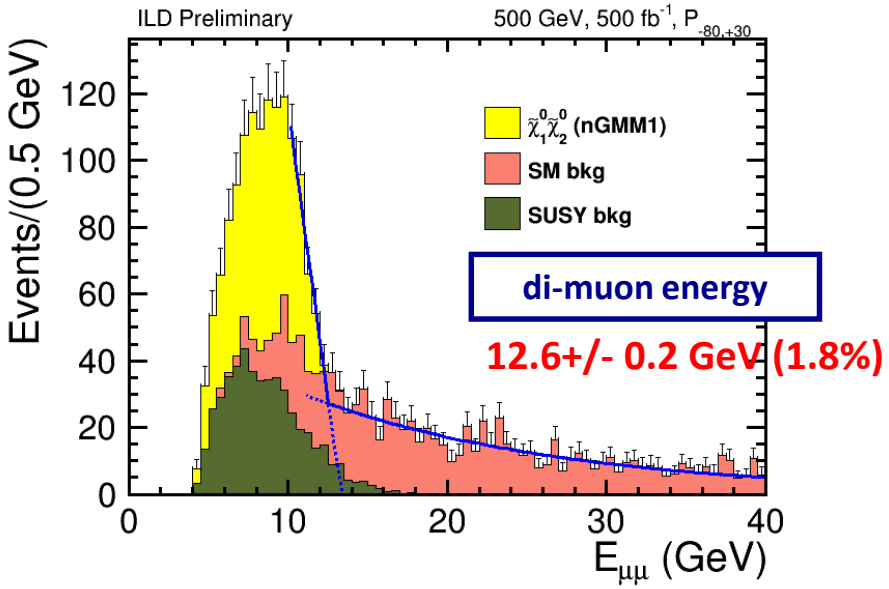
Theoretical values: E_max = 26.9 GeV ΔM = 9.7 GeV

# Mirage

**Neutralino mixed production with leptonic decay**

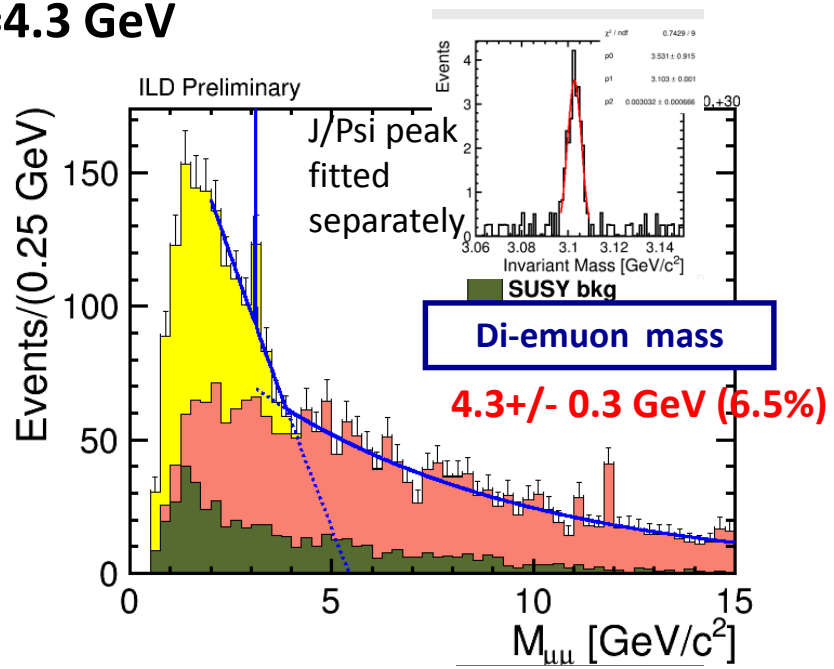
$$e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ell^+ \ell^-$$

**ΔM=4.3 GeV** **(Pe-, Pe+)=(0.8,0.3)** **L=500fb-1**



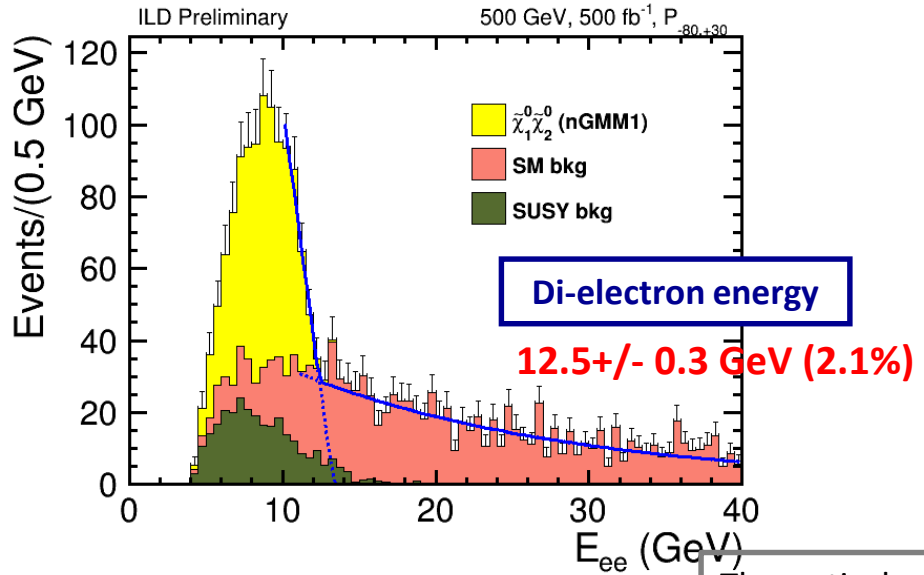

**di-muon energy**

**12.6+/- 0.2 GeV (1.8%)**



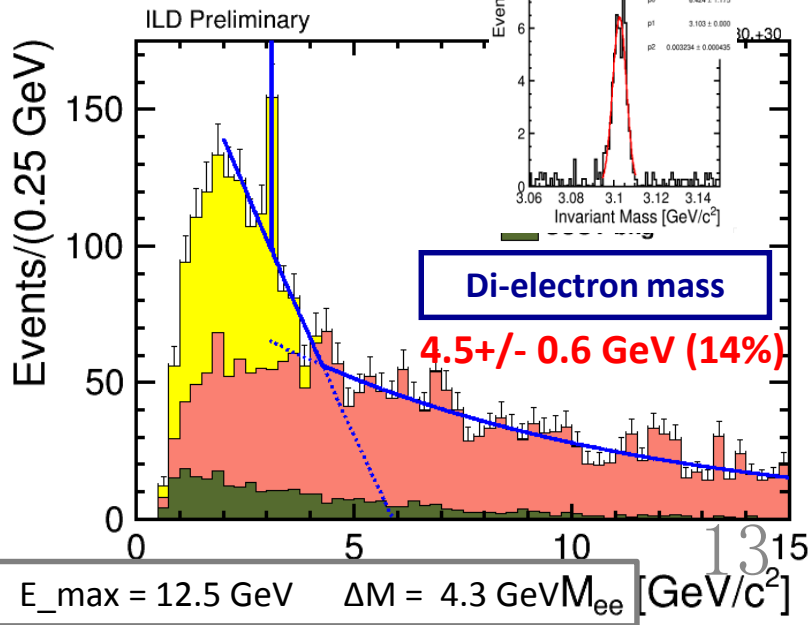

**Di-emuon mass**

**4.3+/- 0.3 GeV (6.5%)**




**Di-electron energy**

**12.5+/- 0.3 GeV (2.1%)**




**Di-electron mass**

**4.5+/- 0.6 GeV (14%)**

Theoretical values: E_max = 12.5 GeV ΔM = 4.3 GeV

# Higgsino Mass Precisions for N1N2 analysis

**Combine "observables" (fitted edges) of multiple channels and apply $\chi^2$ fit**

From left polarization results of neutralino analysis （similar for chargino channel ）

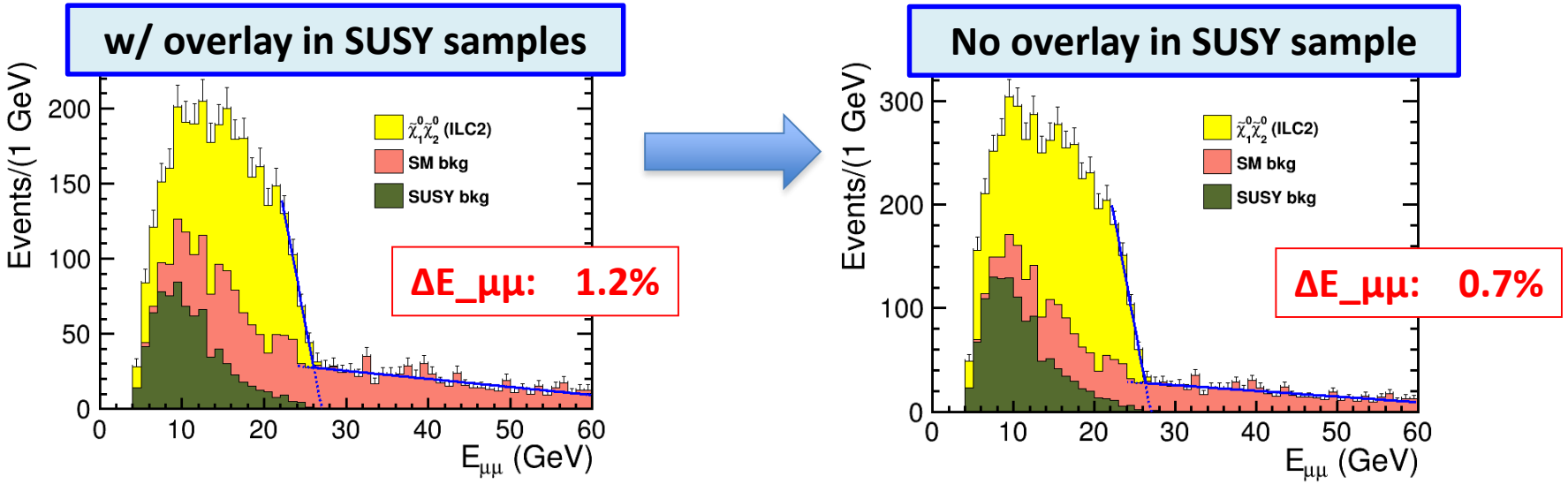
- **Assuming 500 fb$^{-1}$:** ILC1, ILC2 : 1–2% Mirage: 4–5%
- **Assuming H20 , 1600 fb$^{-1}$** ILC1, ILC2: better than 1% Mirage: 2–3%

Statistical precisions expected to improve up to a factor of 2 by adding right polarization and chargino analysis results (soon to come)

※ Precisions slightly better for right hand polarization (lower SM bkg)

**Precision should improve by 1.5 – 2 X by treatment of γγ→hadron bkg**

(analysis also carried out for case of "no overlay" in Higgsino signal)



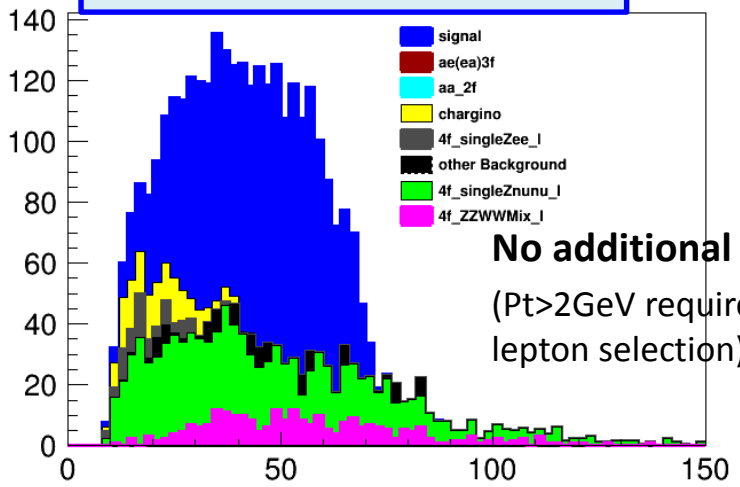
# Cross section fit for N1N2 analysis

loose cuts for
"discovery" (works for any model)
& edge fit (maximize significance)

2 sets of cuts

**tighter cuts for xsec measurement (minimize SUSY bkg)**

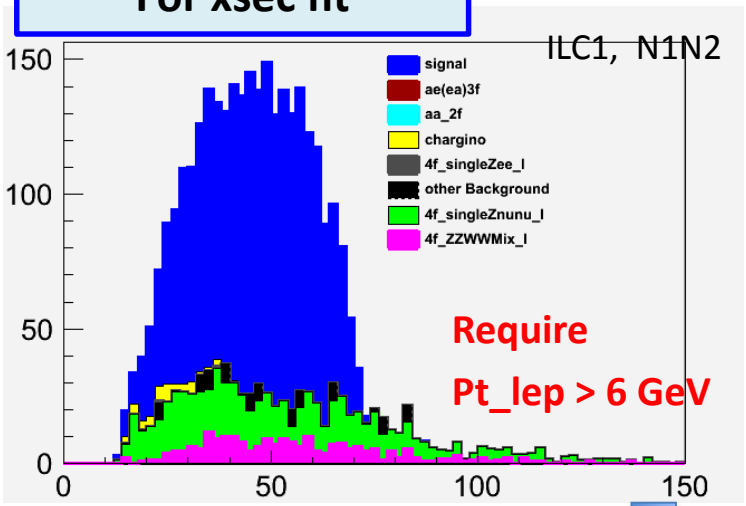
**For kinematic edge fit**



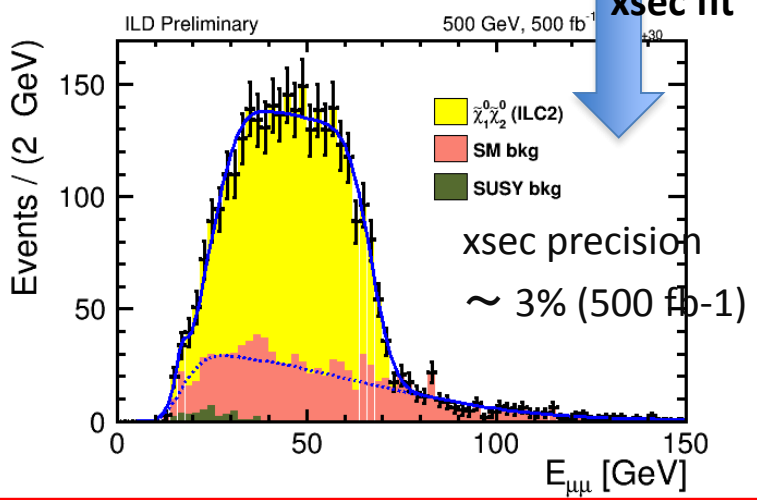

**No additional Pt_lep cut**

(Pt>2GeV required in isolated lepton selection)

**For xsec fit**




**xsec fit**



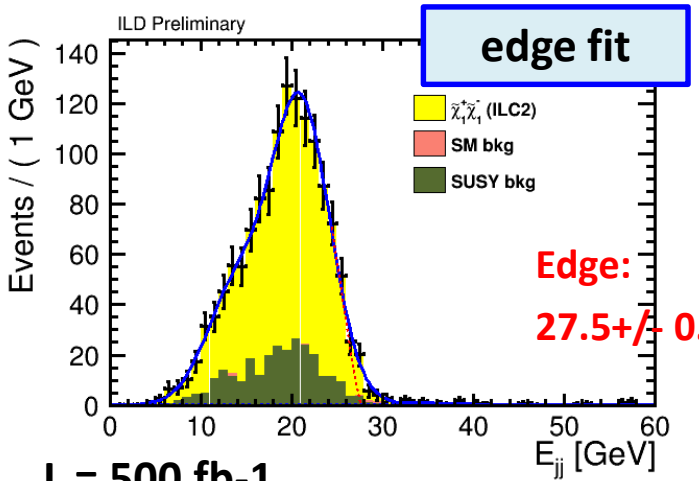

**Better than a few % precision for cross section fits assuming L=500 fb-1**

## Chargino pair production with semileptonic decay

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

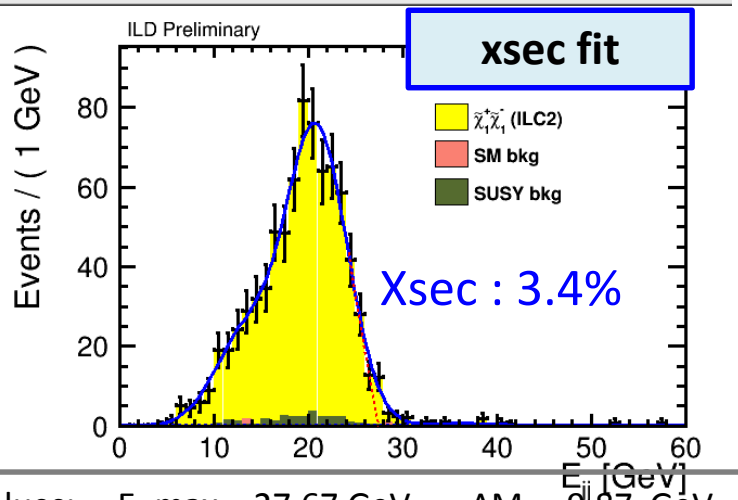
- an almost bkg-free analysis
- kt algorithm optimized to treat beam jets from γγ→hadron bkg

## ILC2 ΔM=9.9 GeV



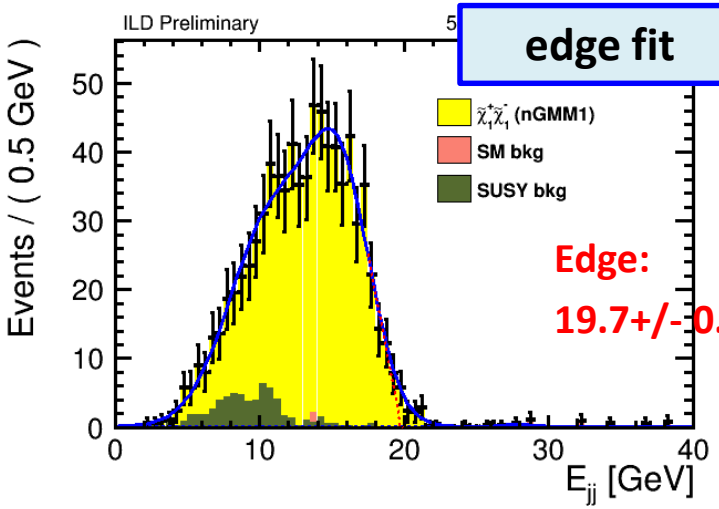

L = 500 fb-1

tighter cuts for xsec fit

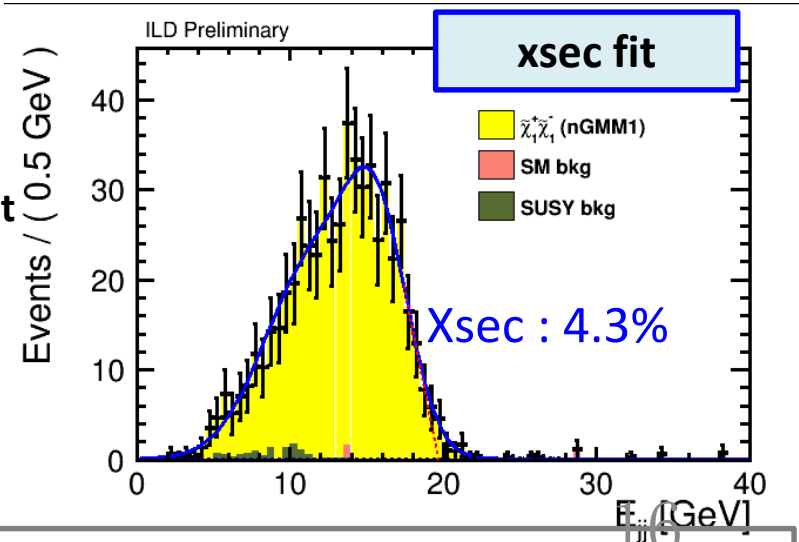



Theoretical values: E_max = 27.67 GeV , ΔM = 9.87 GeV

## Mirage ΔM=7.3 GeV




tighter cuts for xsec fit




Theoretical values: E_max = 19.92 GeV ΔM = 7.3 GeV

# Summary

- Higgsinos in Natural SUSY framework **well motivated theoretically and experimentally**
- This study demonstrates **measurement precision at ILC for Higgsinos with small ΔM (4-21 GeV) , just beyond reach of HL-LHC**

  at √s = 500 GeV, based on full ILD simulation

Currently obtainable statistical precisions

assume H20 scenario, 1600 $fb^{-1}$

Mass:

From left polarization results of neutralino analysis（similar for chargino channel ）

**ILC1, ILC2: better than 1%** **Mirage: 2−3%**

expected to improve further by adding results of chargino and right polarization

Cross section: **better than few %**

# Plans

❖ **Finalize results and prepare publication**

❖ **Talk at EPS-HEP 2017** in July 5-12, Venice (abstract submitted)

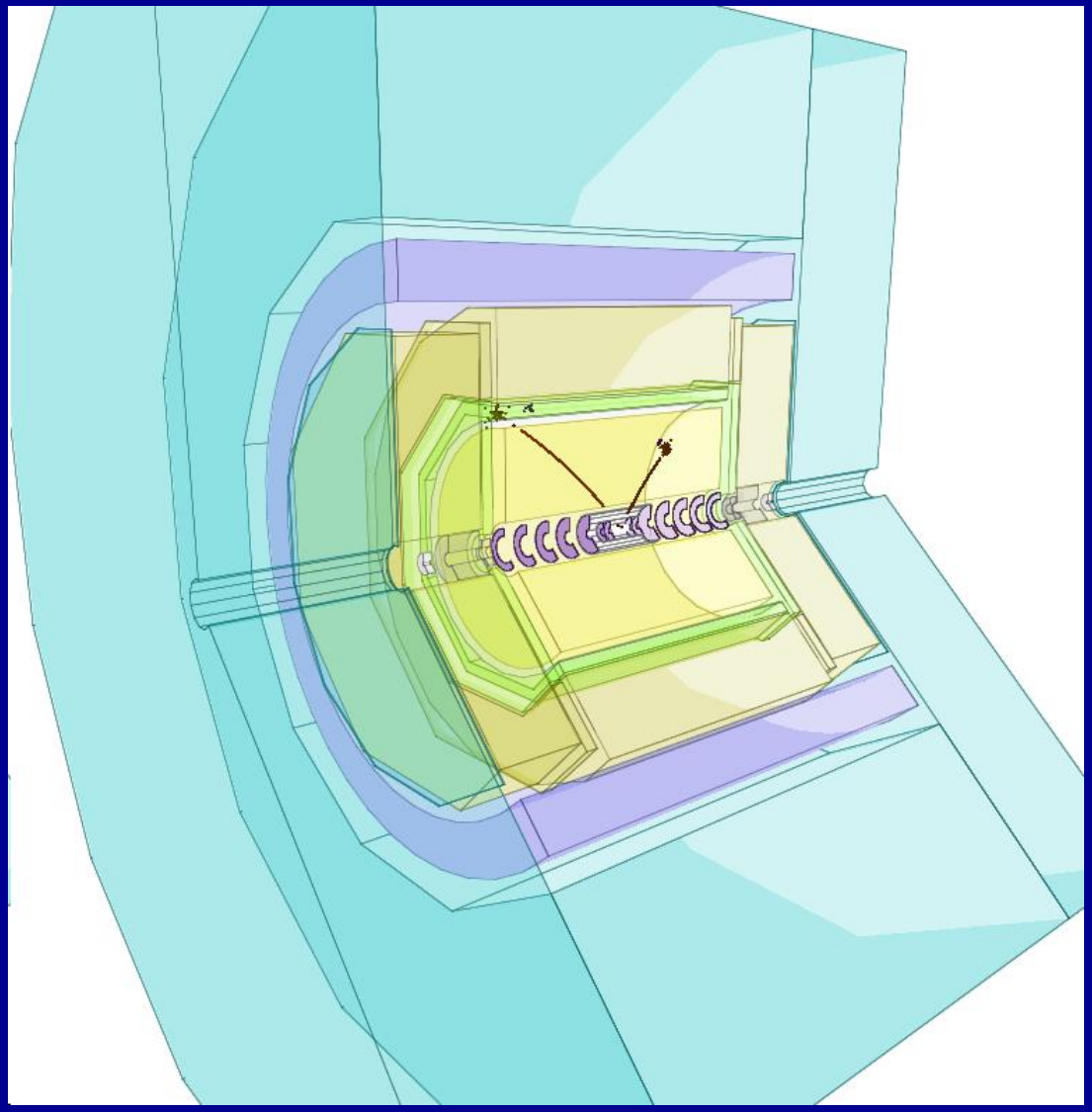
❖ **Consider contribution from Higgsino analysis to staging**

- Results at 500 GeV provide basis for extrapolation to 250, 350 GeV
- Direct full ILD simulation studies at 250, 350 GeV

  250 GeV: ILC1(ΔM～20 GeV)

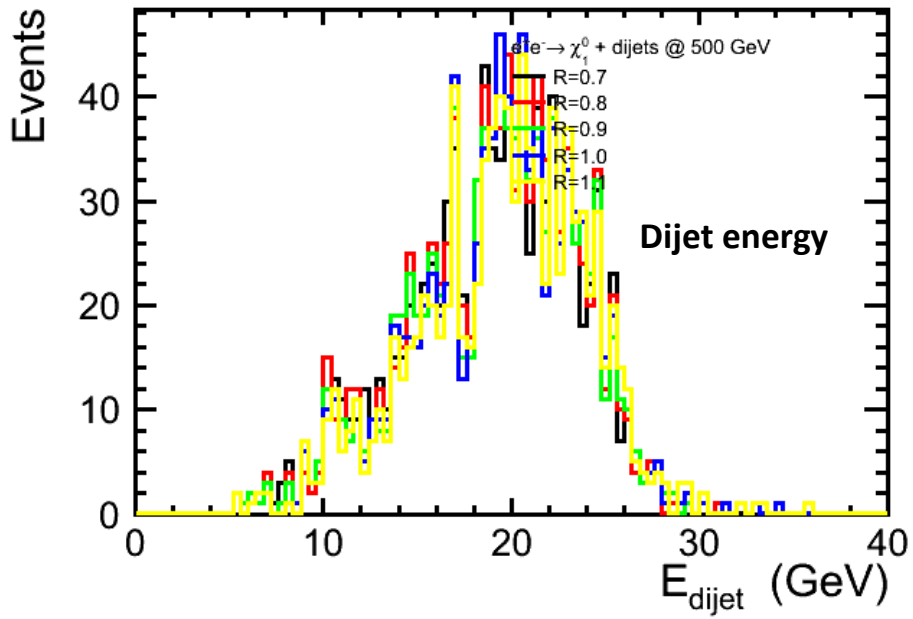
  350 GeV: ILC2(ΔM～10GeV), Mirage (ΔM～5GeV)

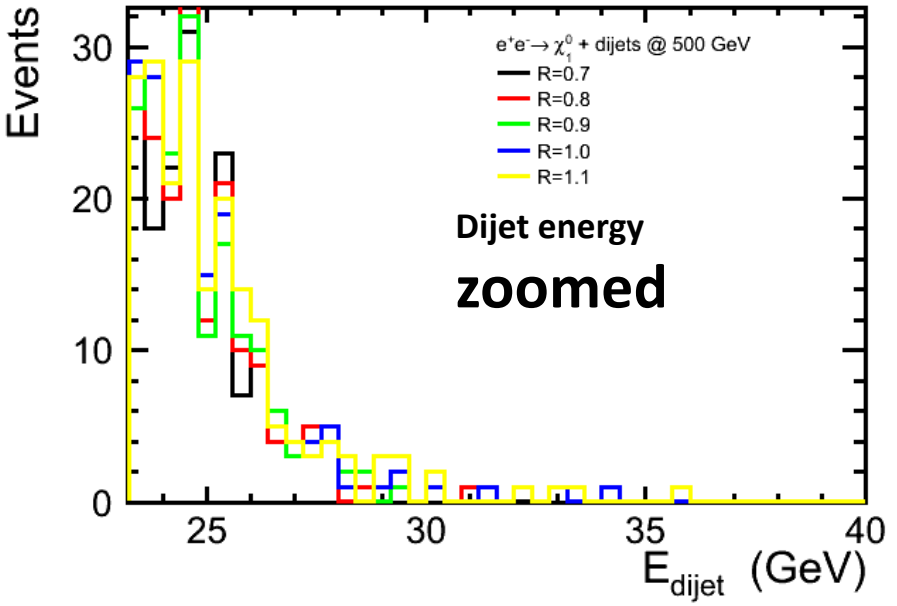
# Backup

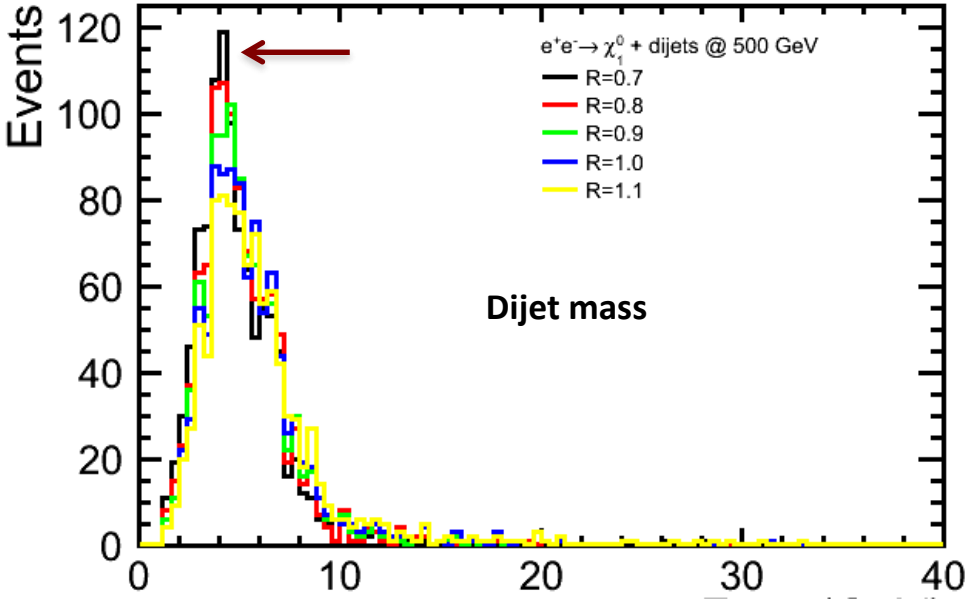


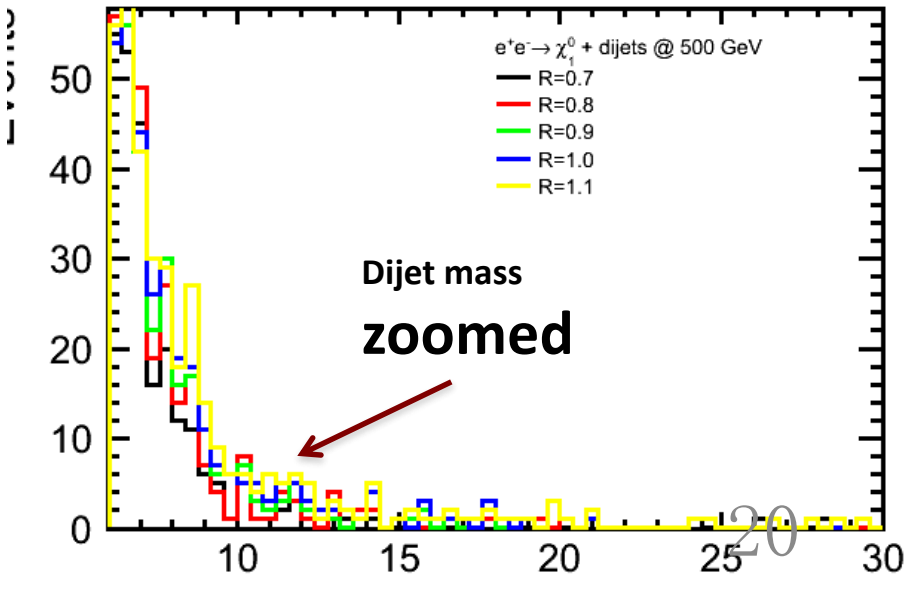
**ILC2 : C1C1 left pol, mu tag, v01-16-02** **Compare R= 0.7, 0.8, 0.9, 1.0, 1.1**

**All analysis cuts applied**



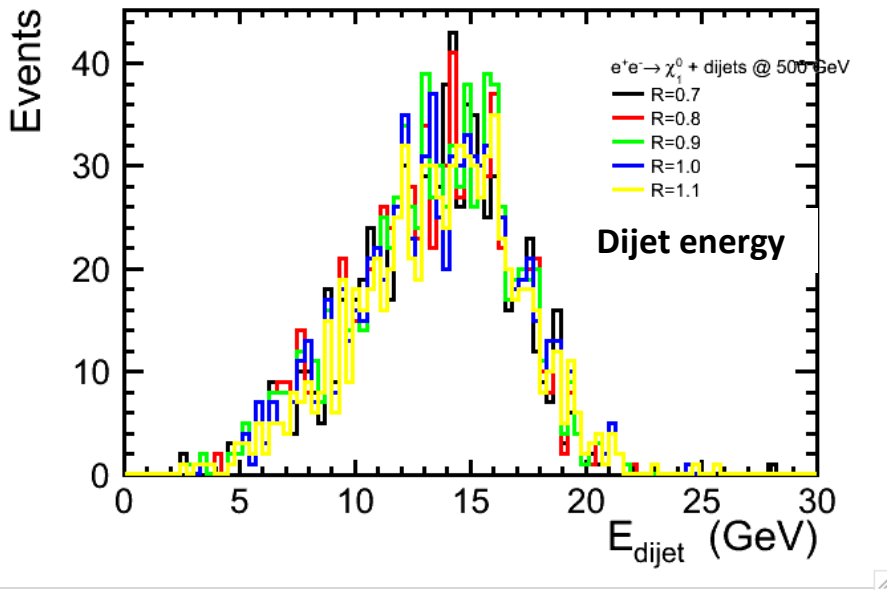



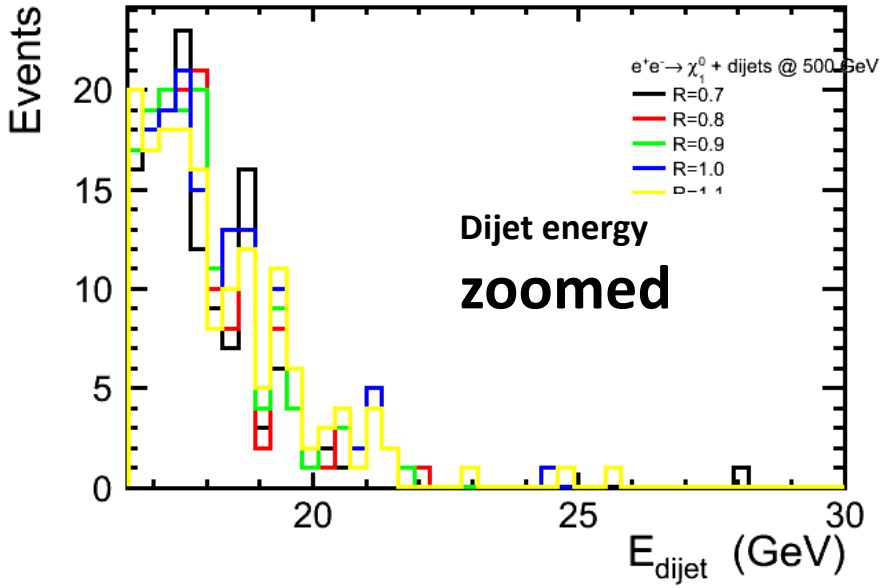



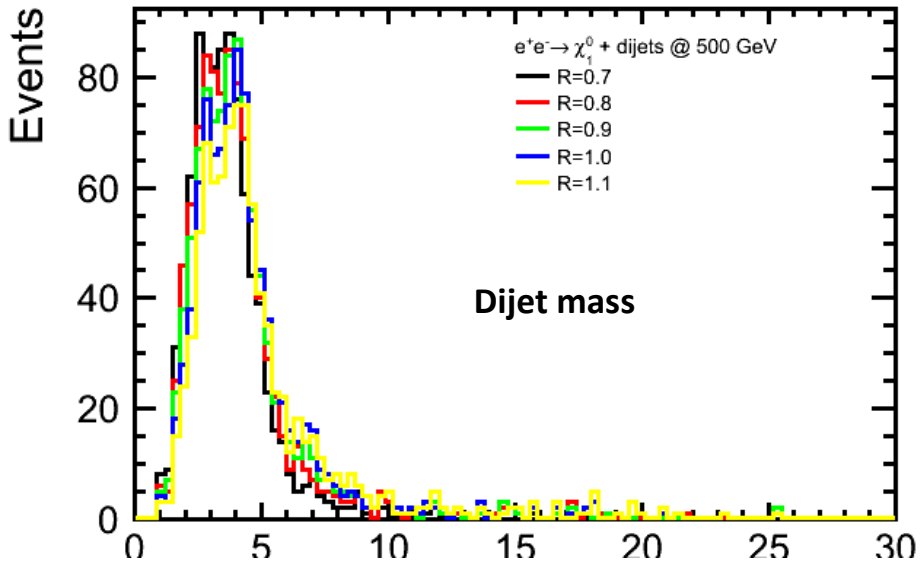
**Mirage : C1C1 left pol, mu tag, v01-16-02**

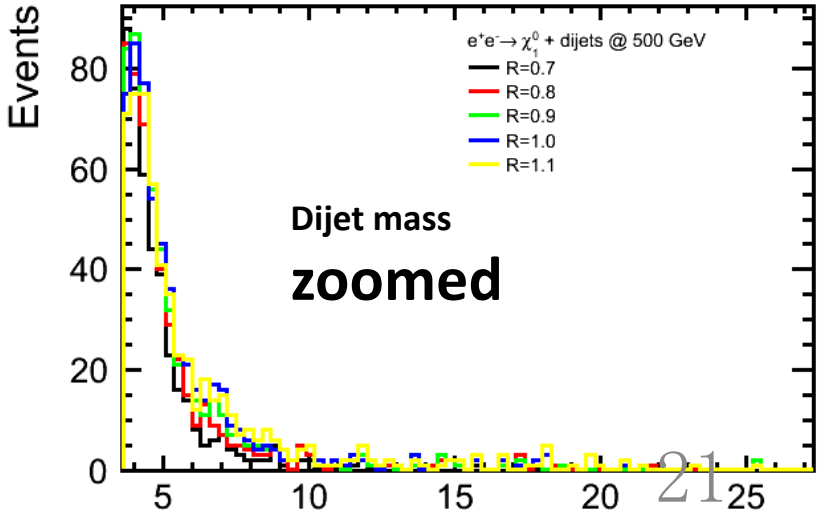
**All analysis cuts applied**

**Compare R= 0.7, 0.8, 0.9, 1.0, 1.1**

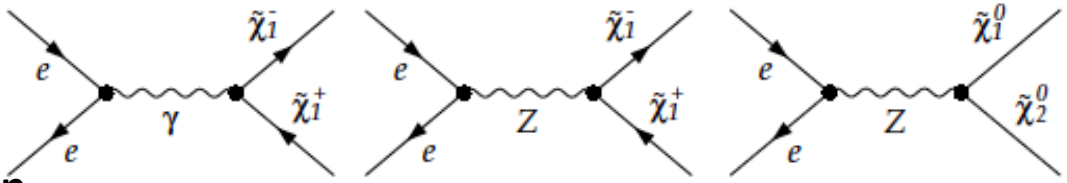


# Benchmarks in this Study




**√s = 500 GeV, full ILD detector simulation**

**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 complies with naturalness** (no need for ISR tag )

**Benchmarks with smaller ΔM are drawing attention** ,
as ILC1 is (almost) excluded by LHC

- ILC1 (and some ILC2) results shown at LCWS2016 and https://arxiv.org/pdf/1702.05333.pdf
- Recently, Progress made in ILC2 and Mirage Mediation (nGMM1) (ΔM as small as 4.5 GeV)

More detailed status on another page

**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 |
| **$\Delta M(N_2,N_1)$** | **21.3** | **9.7** |
| $M(\chi_2^0)$ [GeV] | 124.0 | 157.8 |
| **$\Delta M(C_1,N_1)$** | **14.6** | **10.2** |

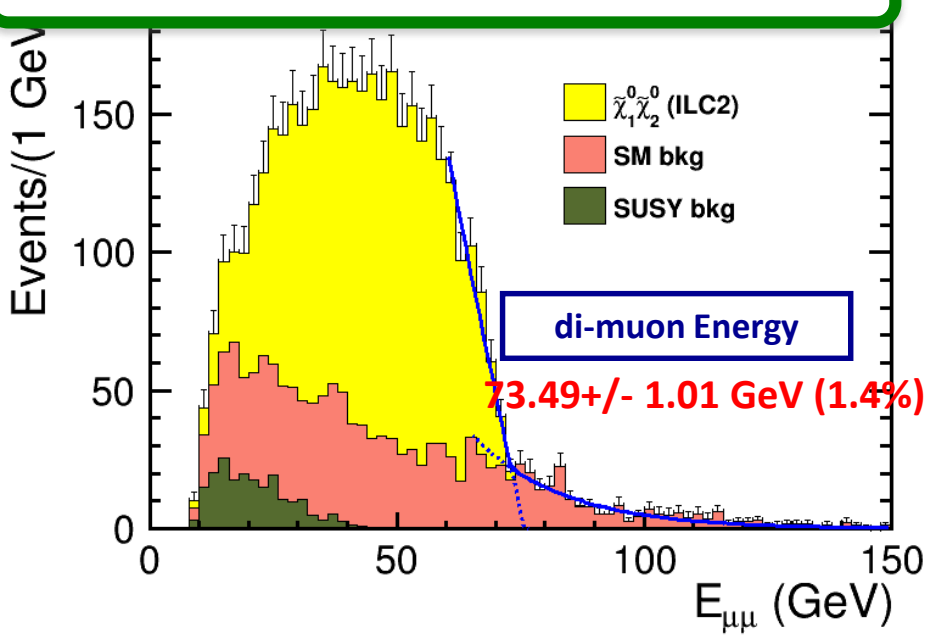
**Defined at GUT scale ,**
**Defined at weak scale Observables**

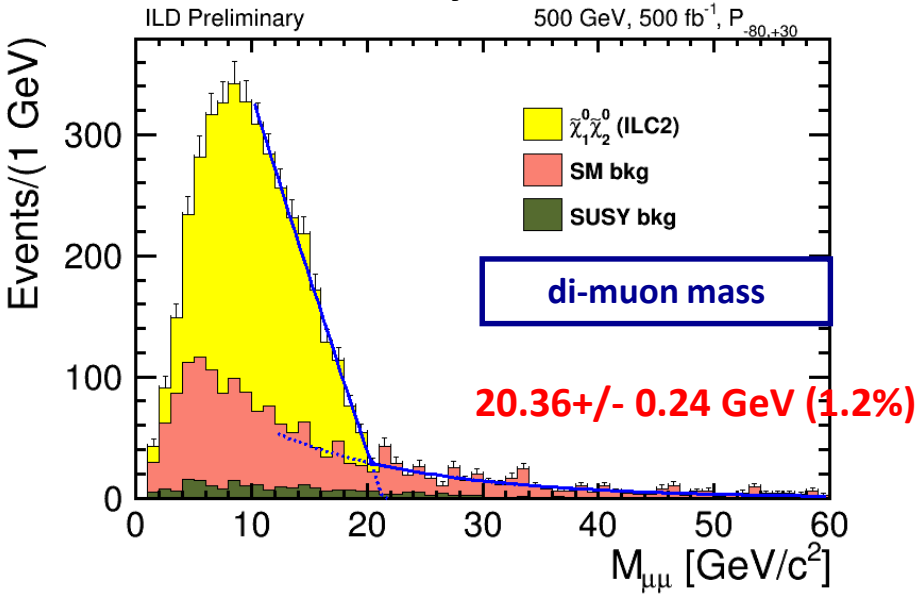
## Neutralino mixed production with leptonic decay

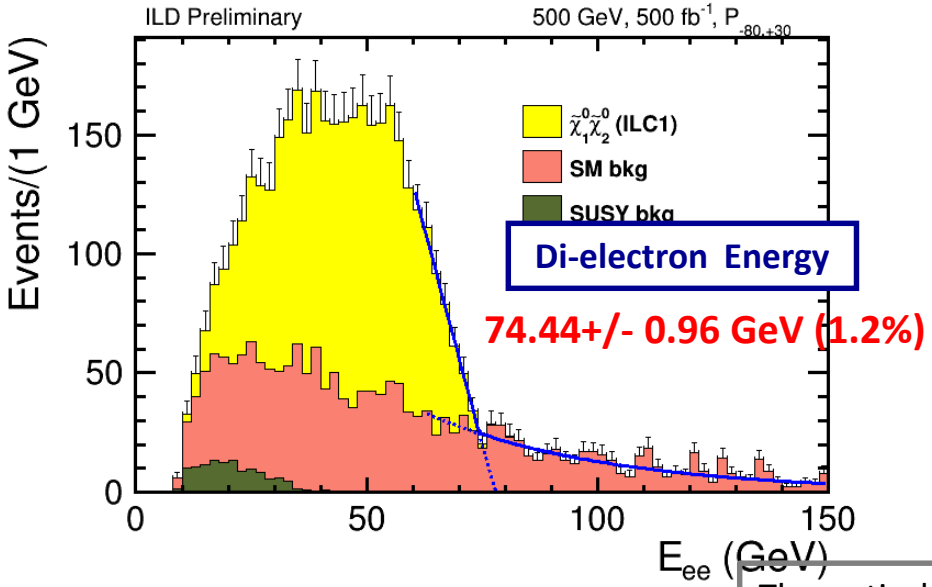
$$e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ell^+ \ell^-$$

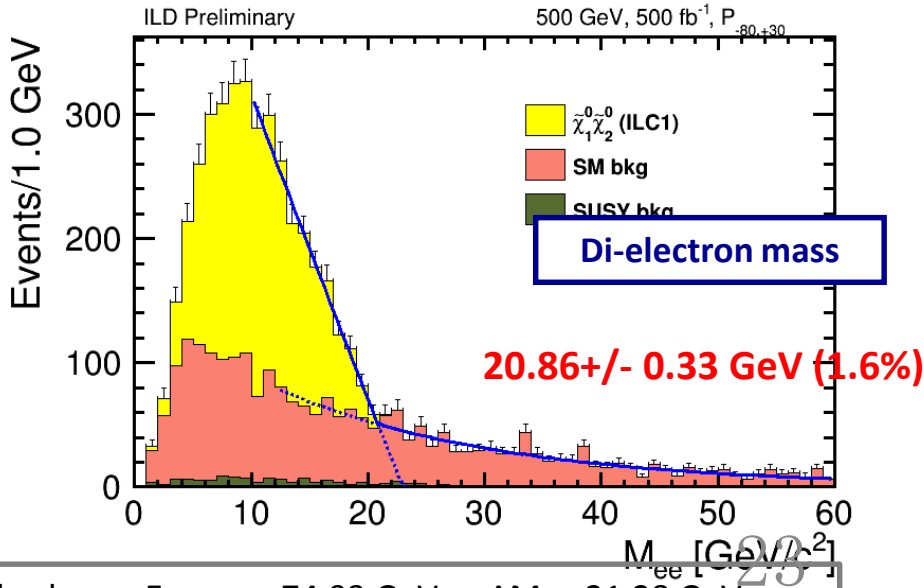
**ILC1 @500fb-1** v01-16-02

**Without overlay**



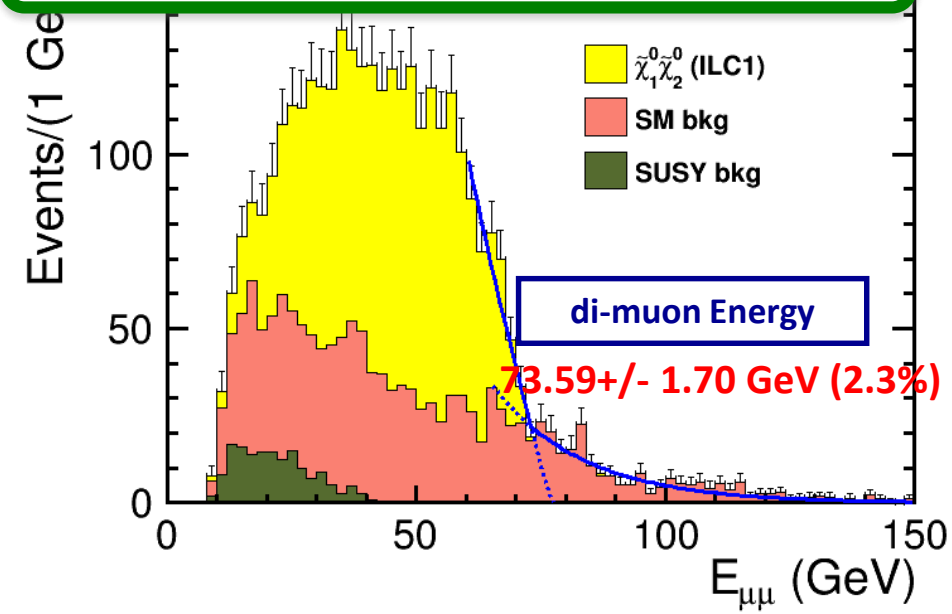

Theoretical values: E_max = 74.93 GeV ΔM = 21.28 GeV

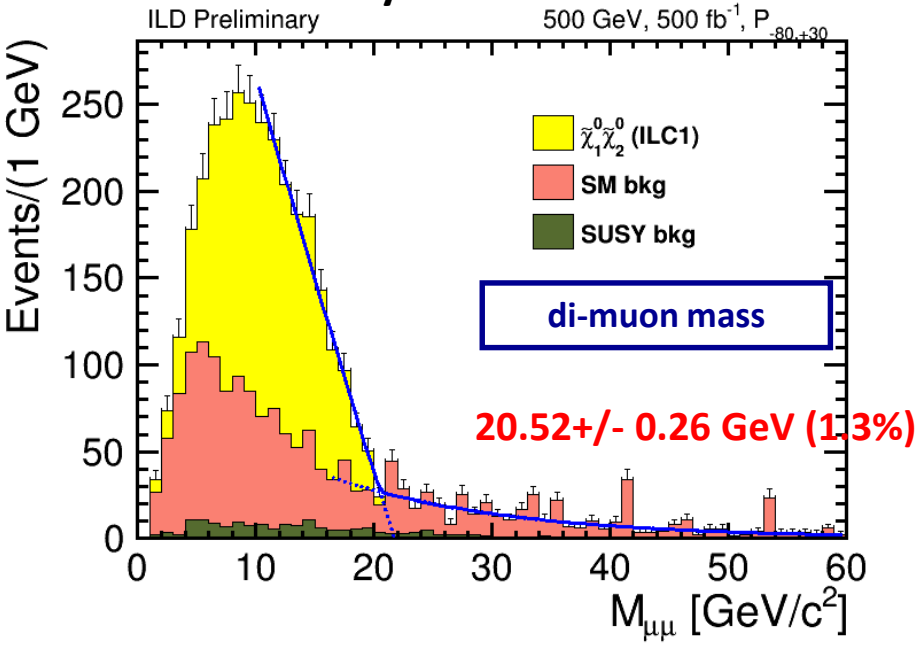
## Neutralino mixed production with leptonic decay

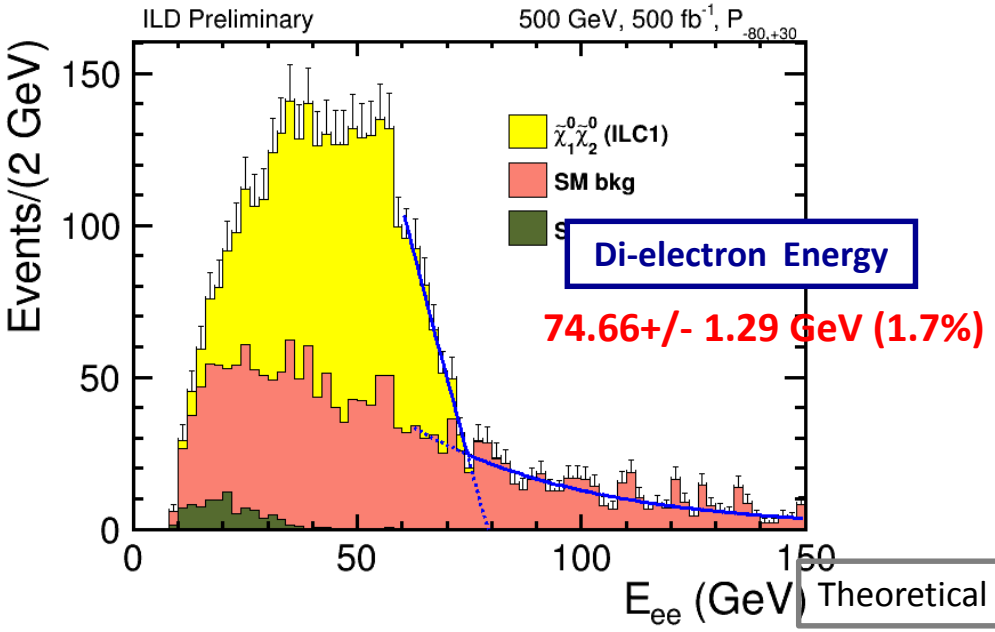
$$e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ell^+ \ell^-$$

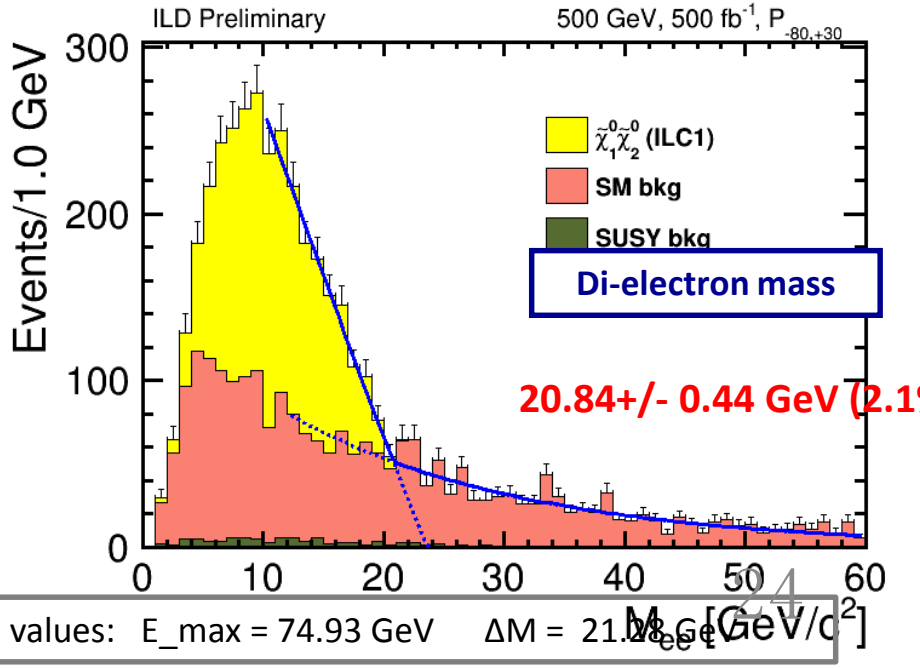
**ILC1 @500fb-1** v01-16-02

**With overlay**



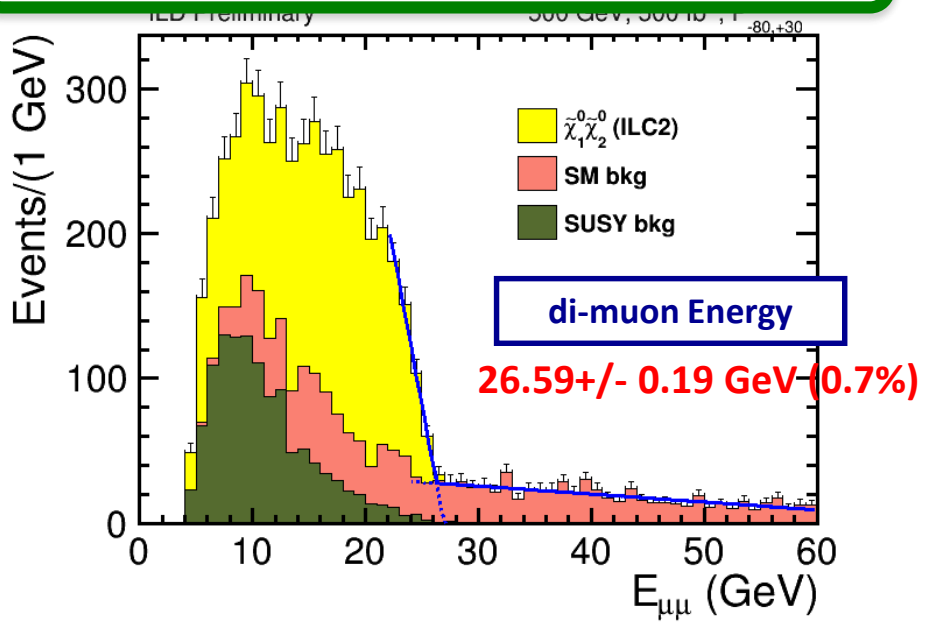

Theoretical values: E_max = 74.93 GeV ΔM = 21.28 GeV

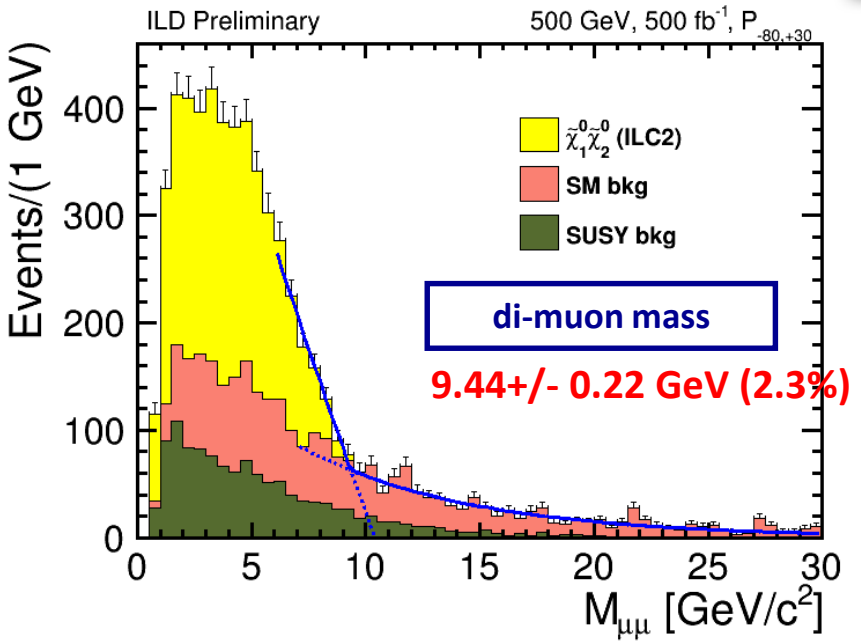
## Neutralino mixed production with leptonic decay

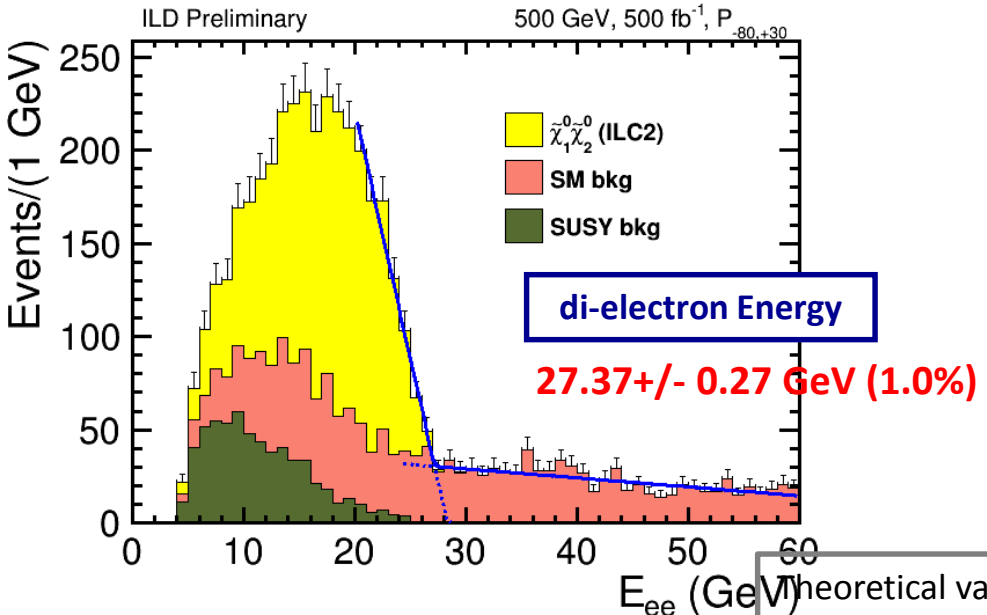
$$e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ell^+ \ell^-$$

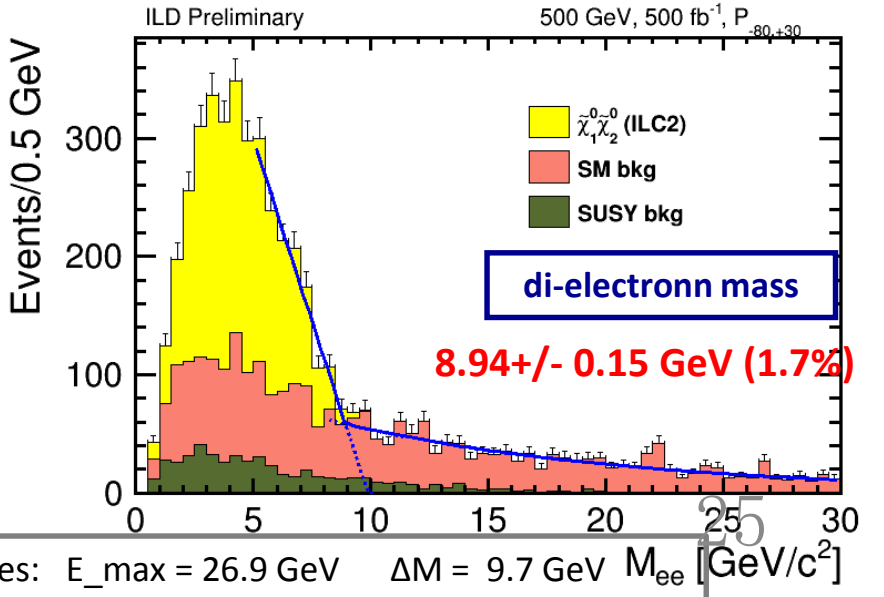
**ILC2 @500fb-1** v01-16-02

**Without overlay**



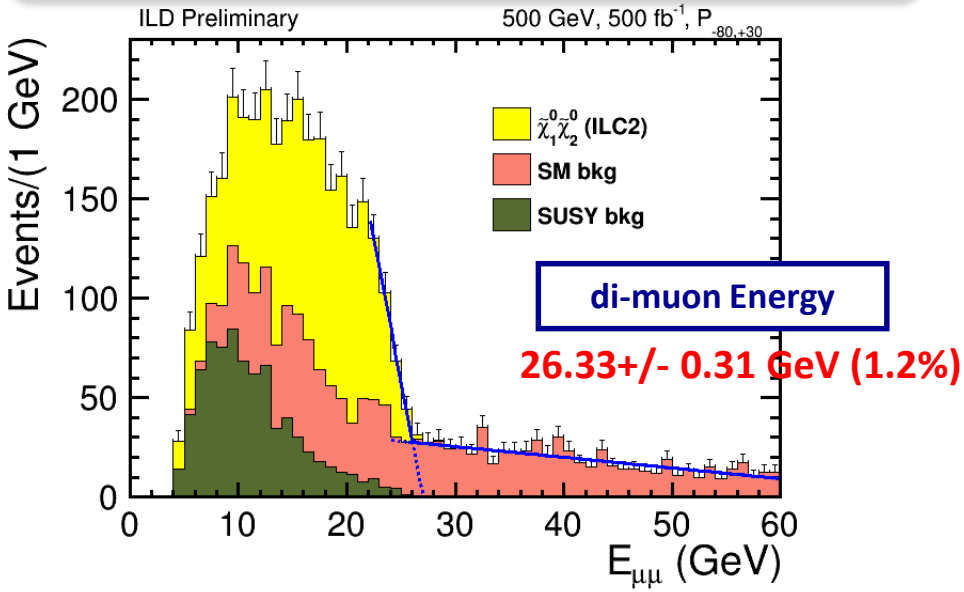

Theoretical values: E_max = 26.9 GeV ΔM = 9.7 GeV

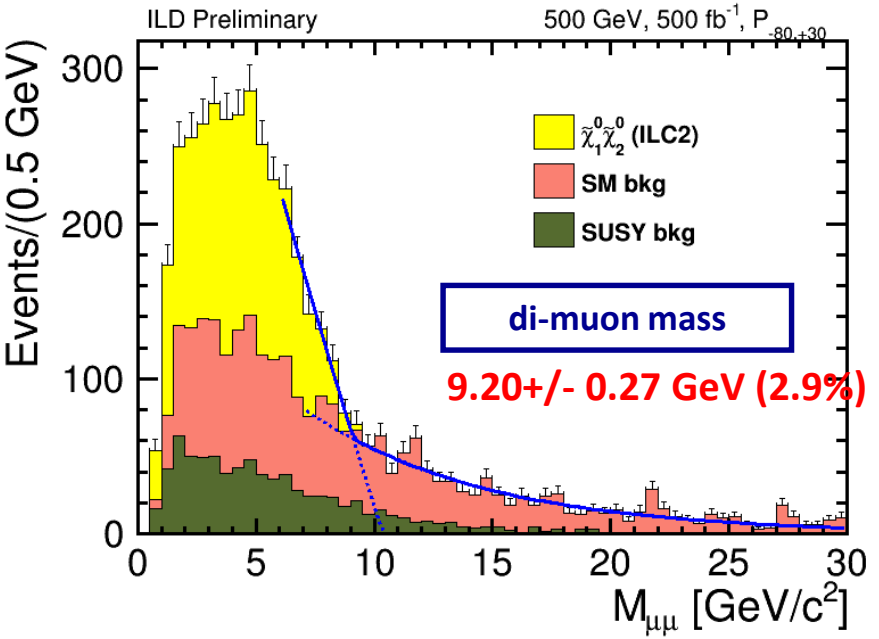
## Neutralino mixed production with leptonic decay

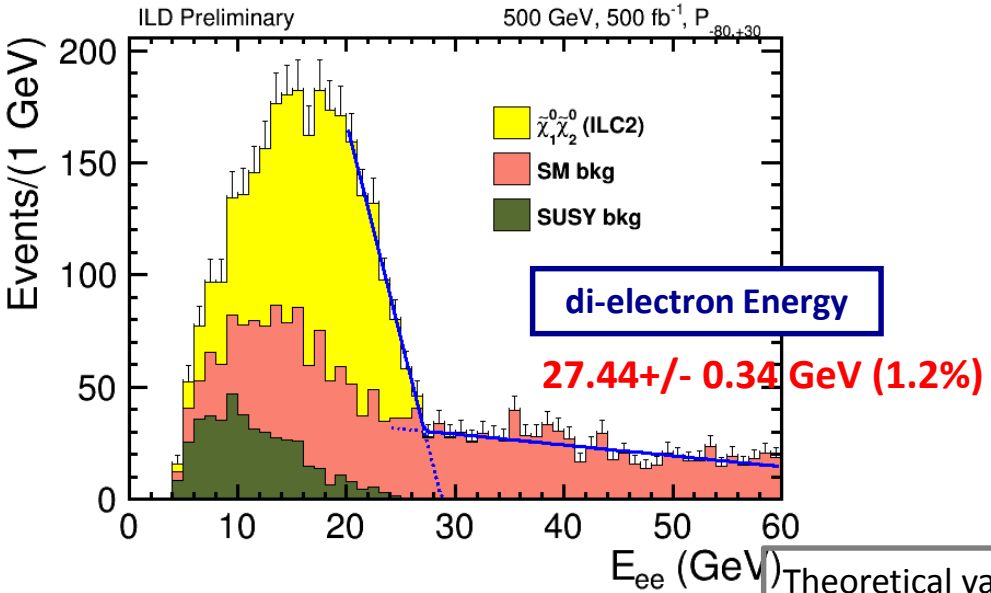
$$e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ell^+ \ell^-$$

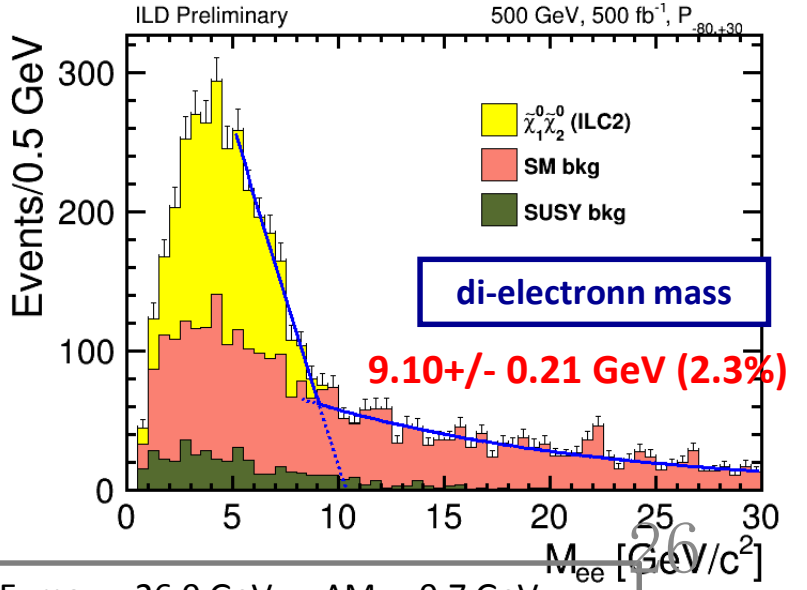
**ILC2 @500fb-1** v01-16-02

**With overlay**




Theoretical values: E_max = 26.9 GeV ΔM = 9.7 GeV

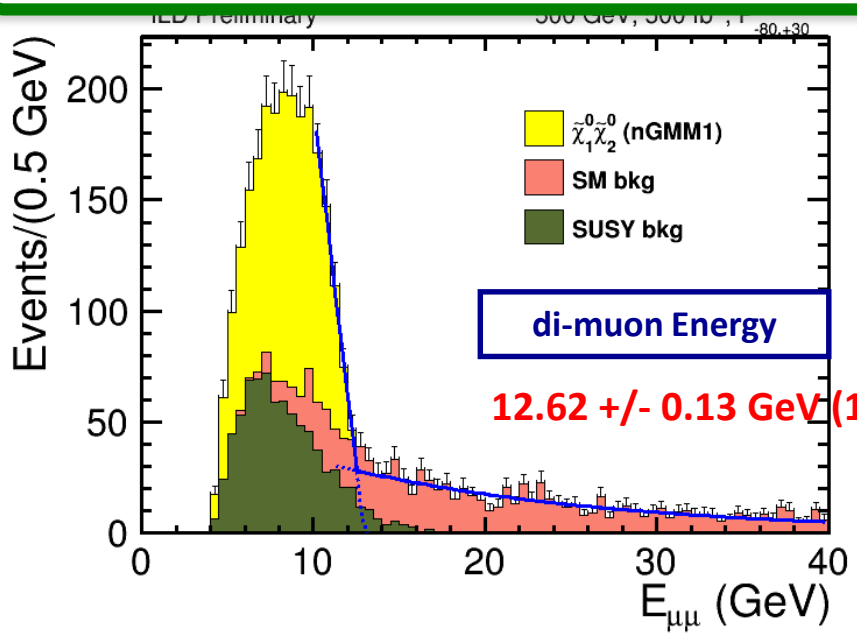
## Neutralino mixed production with leptonic decay

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

## Mirage Mediation @500fb-1

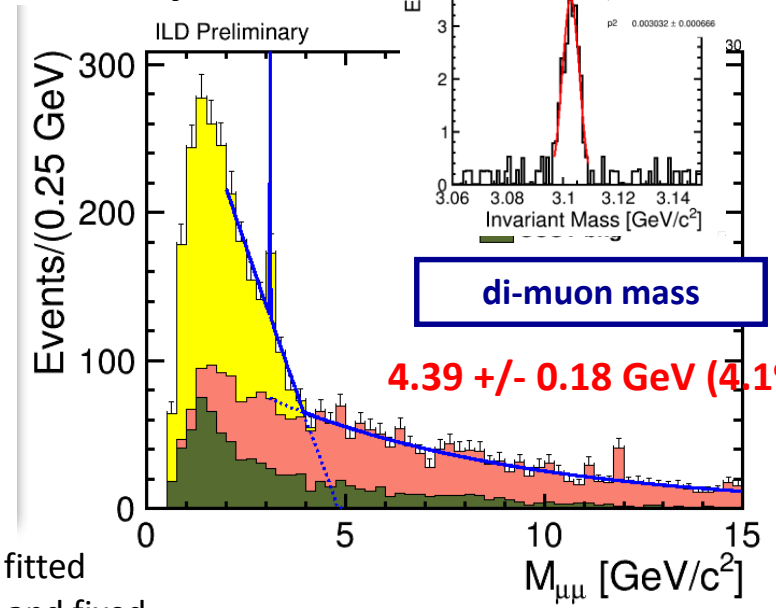
v01-16-02

### Without overlay




di-muon Energy

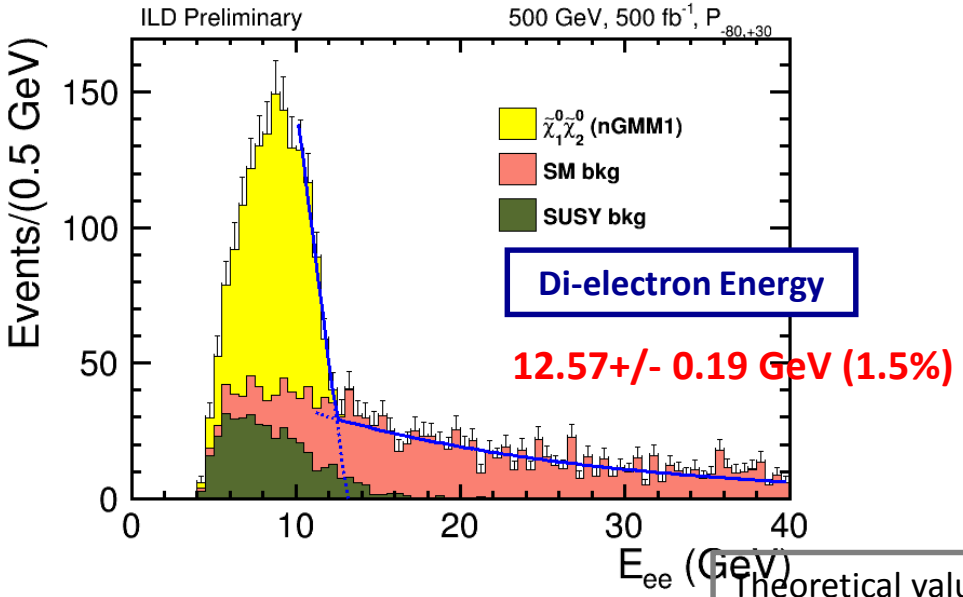
12.62 +/- 0.13 GeV (1.0%)




di-muon mass

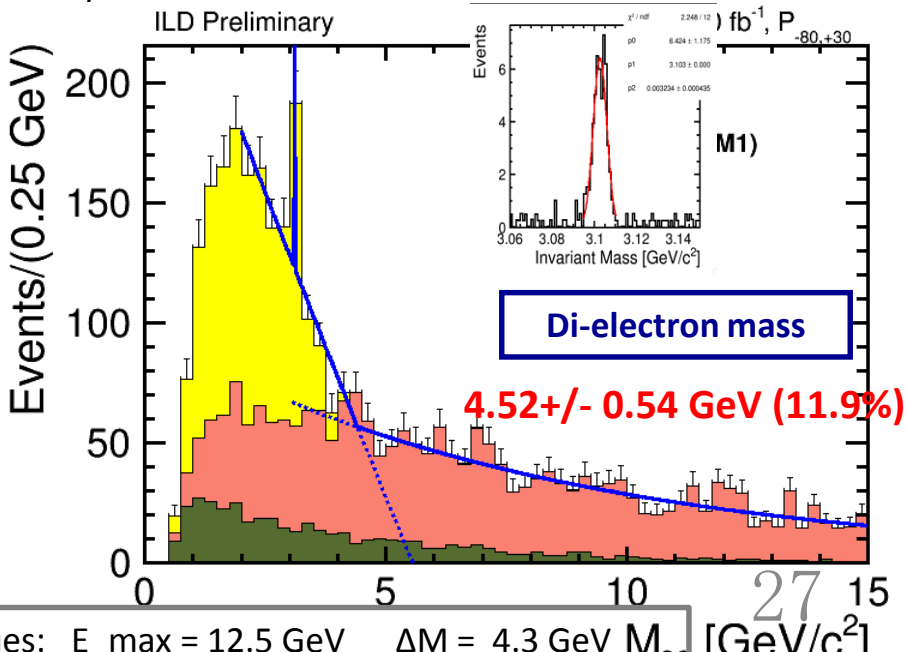
4.39 +/- 0.18 GeV (4.1%)

J/Psi peak fitted separately and fixed




Di-electron Energy

12.57+/- 0.19 GeV (1.5%)



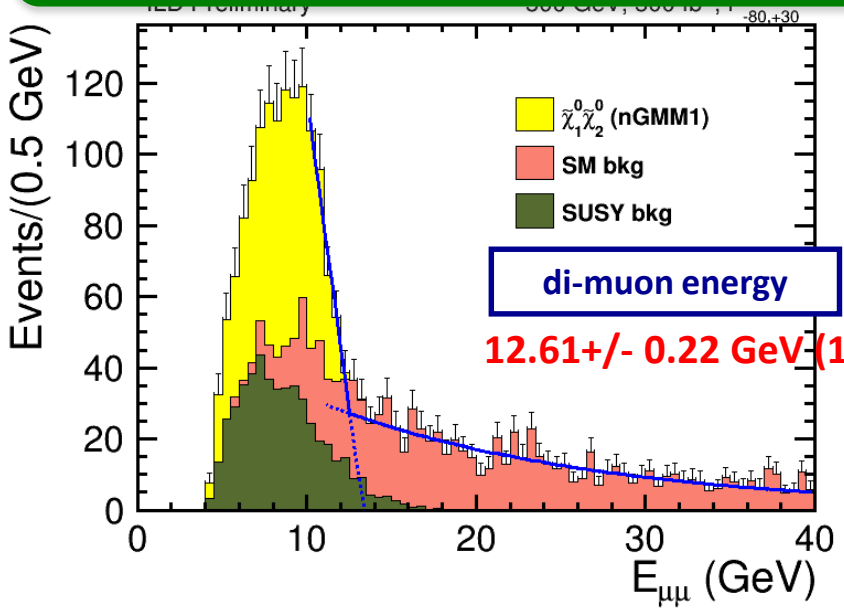

Di-electron mass

4.52+/- 0.54 GeV (11.9%)

Theoretical values: E_max = 12.5 GeV ΔM = 4.3 GeV

## Neutralino mixed production with leptonic decay

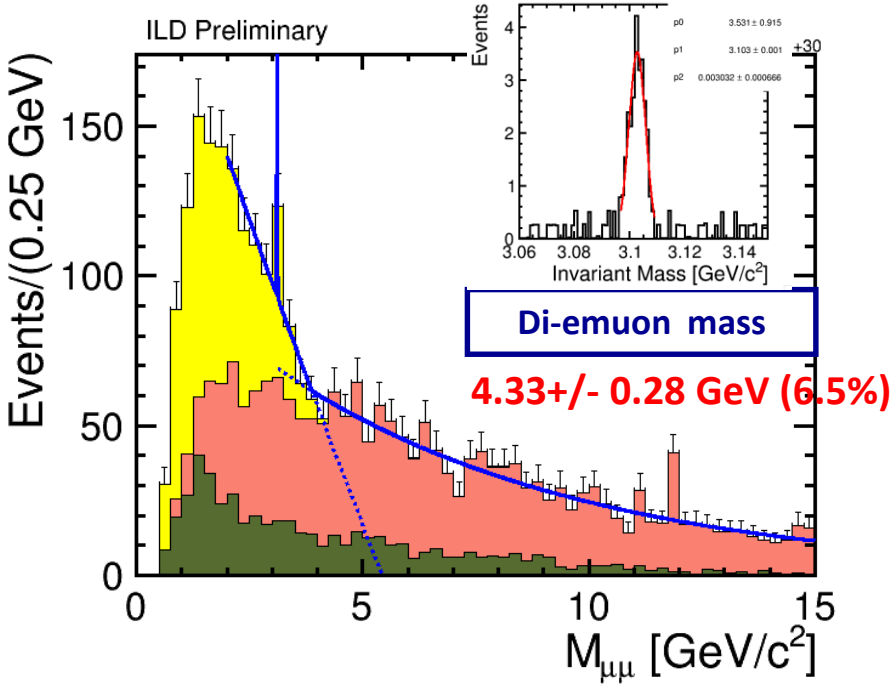
$$e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ell^+ \ell^-$$




**di-muon energy**

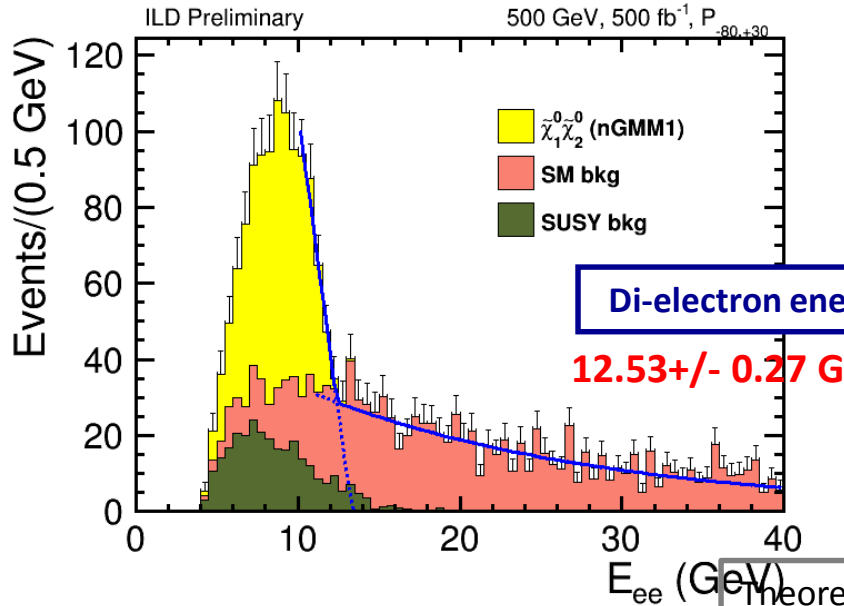
**12.61+/- 0.22 GeV (1.8%)**

**Mirage** v01-16-02



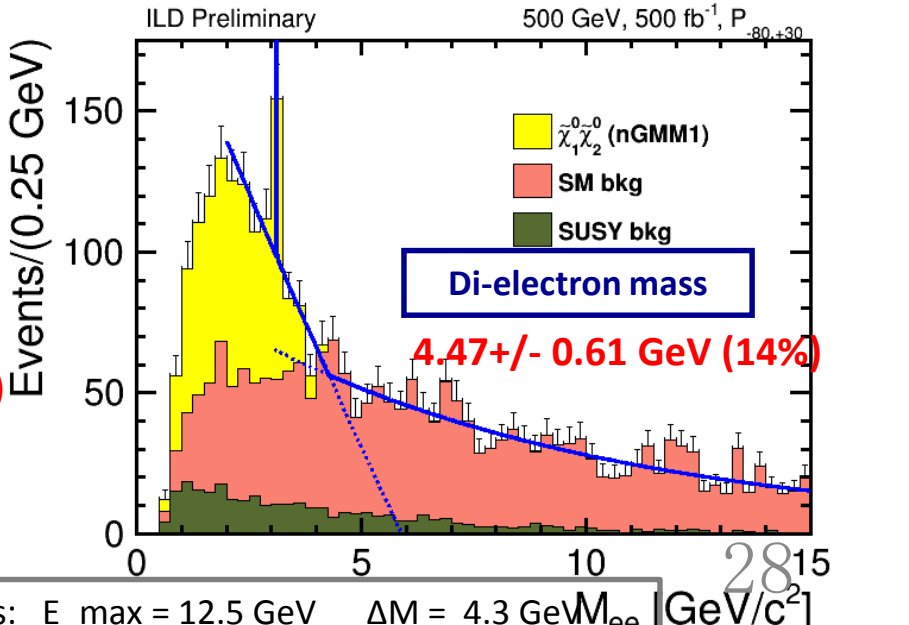

**Di-emuon mass**

**4.33+/- 0.28 GeV (6.5%)**




**Di-electron energy**

**12.53+/- 0.27 GeV (2.1%)**




**Di-electron mass**

**4.47+/- 0.61 GeV (14%)**

Theoretical values: E_max = 12.5 GeV ΔM = 4.3 GeV

## Cuts for ILC2 N1N2

- lepton type (μμ or ee) : the two leptonic channels of N1N2 analysis
- nTrack = 2 : number of charged tracks
- no hit in BeamCal : veto γγ2f BG
- Pt_lep1,2 > 2 GeV and |cosθlep1,2| < 0.95:
- Coplanarity < 1.0 rad : angle between leptons in x-y plane
- Evis – Eγmax < 40 GeV : visible energy (very small for signal)
- Emis > 300 GeV : missing energy (very large for signal)
- |cosθmissing| < 0.98 : θ of missing energy events
- |cosθZ| < 0.98 : Z* production angle
- Pt_dl < 80 GeV : transverse momentum of dilepton
- Minv<20 GeV : dilepton invariant mass: determines ΔM

last of all observe distributions of Minv and dilepton energy (E_dl)

Kinematic edge is a function of Higgsino mass and ΔM