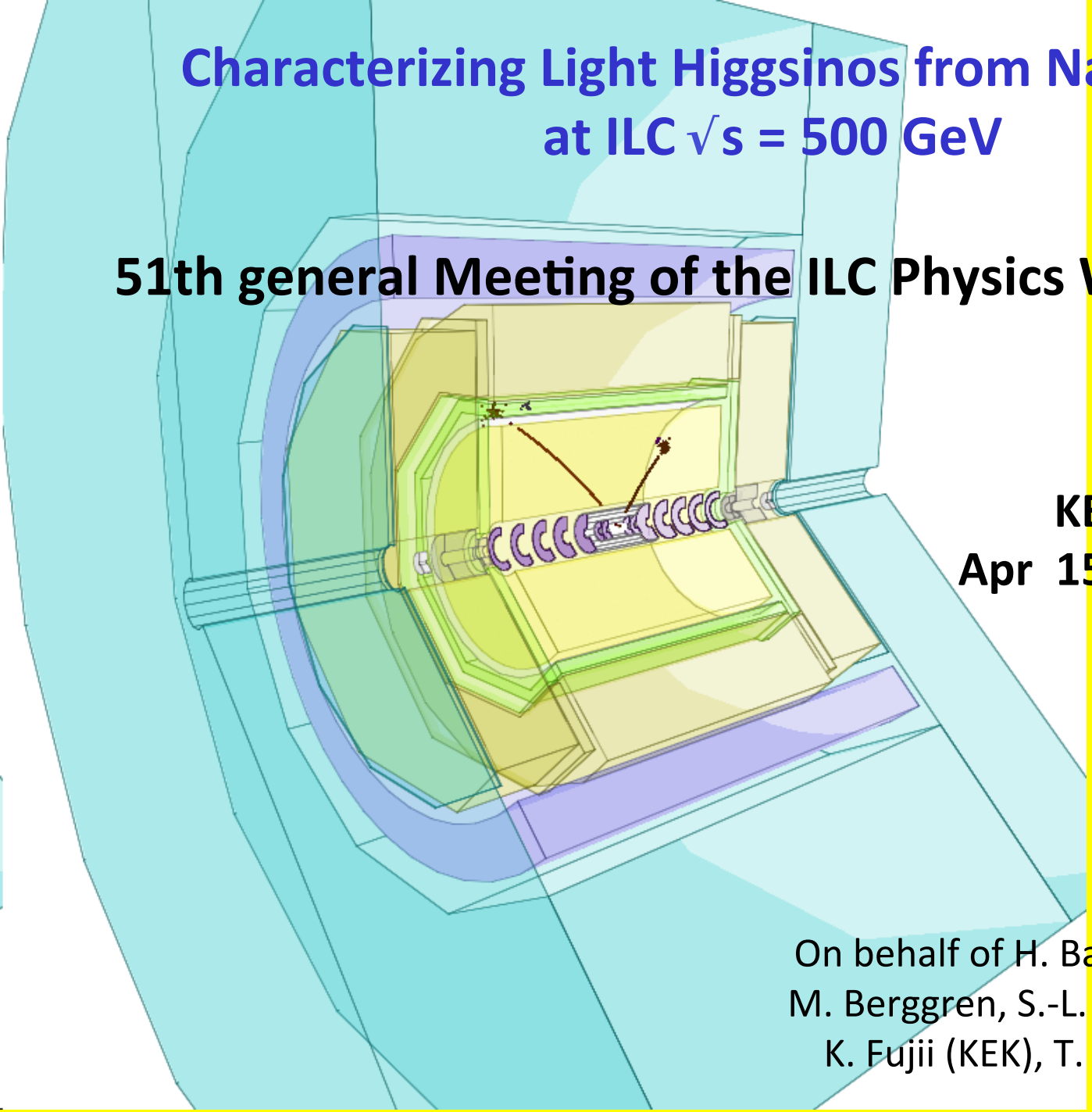
Characterizing Light Higgsinos from Natural SUSY at ILC $\sqrt{s}$ = 500 GeV



51th general Meeting of the ILC Physics Working Group

KEK
Apr 15, 2017

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On behalf of H. Baer (Univ of Oklahoma),
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Outline

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

Motivation for searching light Higgsinos with compressed spectrum

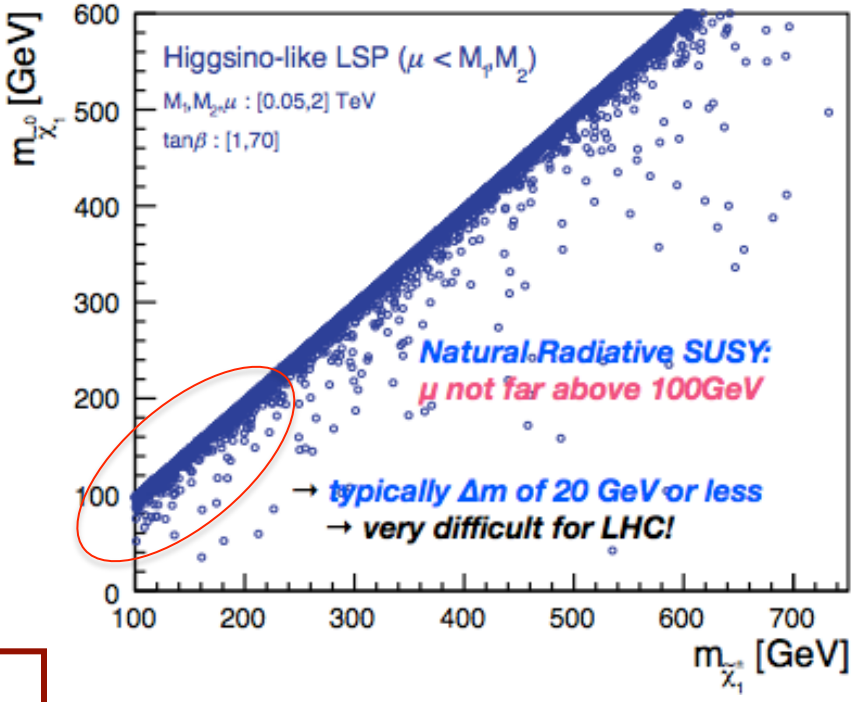
❖ **experimental point of view:**

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"

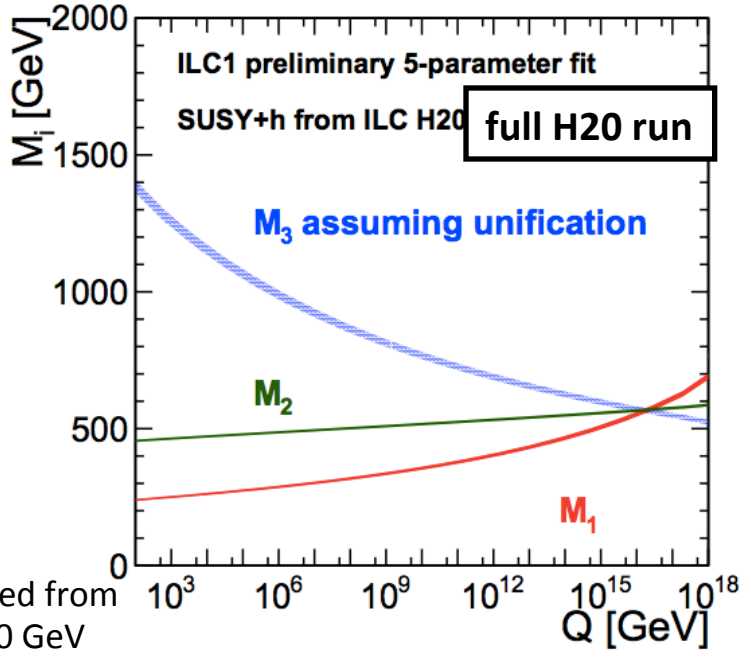
determine SUSY parameters

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 χ^2 fit of to observables**

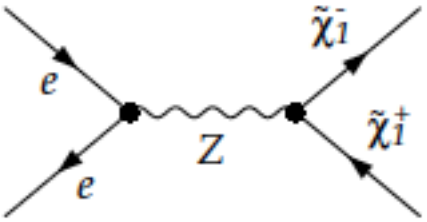
Study required input parameters and precisions;
interplay with Higgs precision measurements



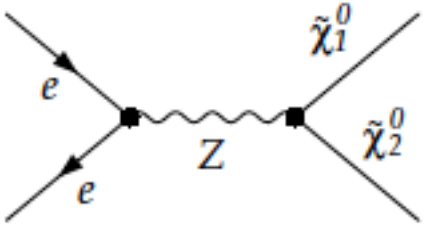
√s = 250, 350, 500 GeV, scaled from full simulation studies at 500 GeV

Benchmarks in this Study

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



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



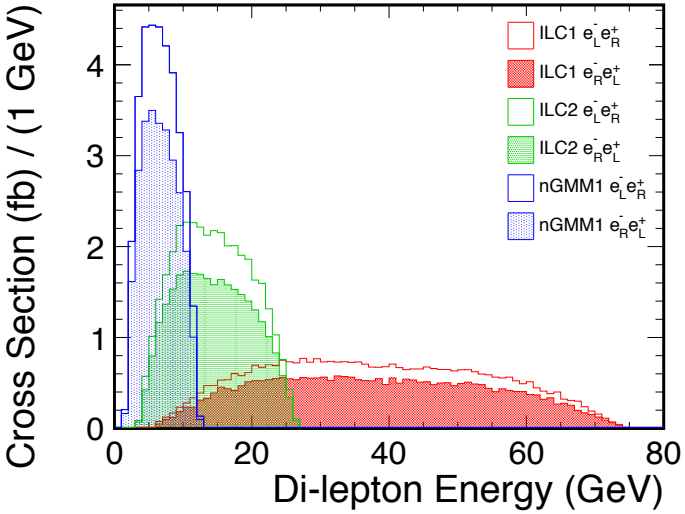
4 light Higgsinos

- **√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

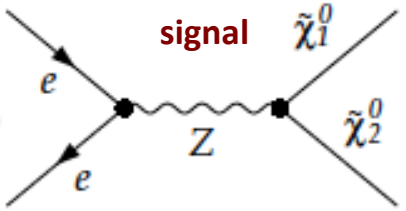
Event Generator: WHIZARD v1.95, DBD setup, TDR beam parameters

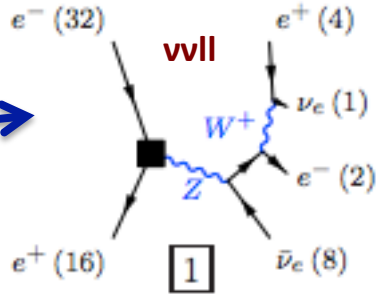
Event Selection

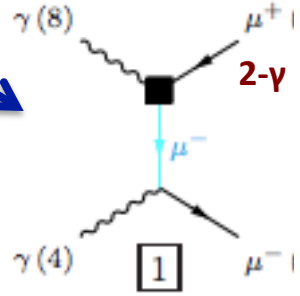
Neutralino mixed production with leptonic decay

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

- Reconstruct **two leptons (ee or μμ)** which originate from Z^* emission in decay of χ_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



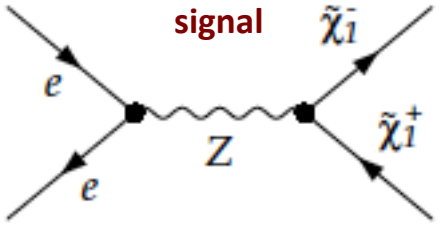




Chargino pair production with semileptonic decay

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

- 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**.

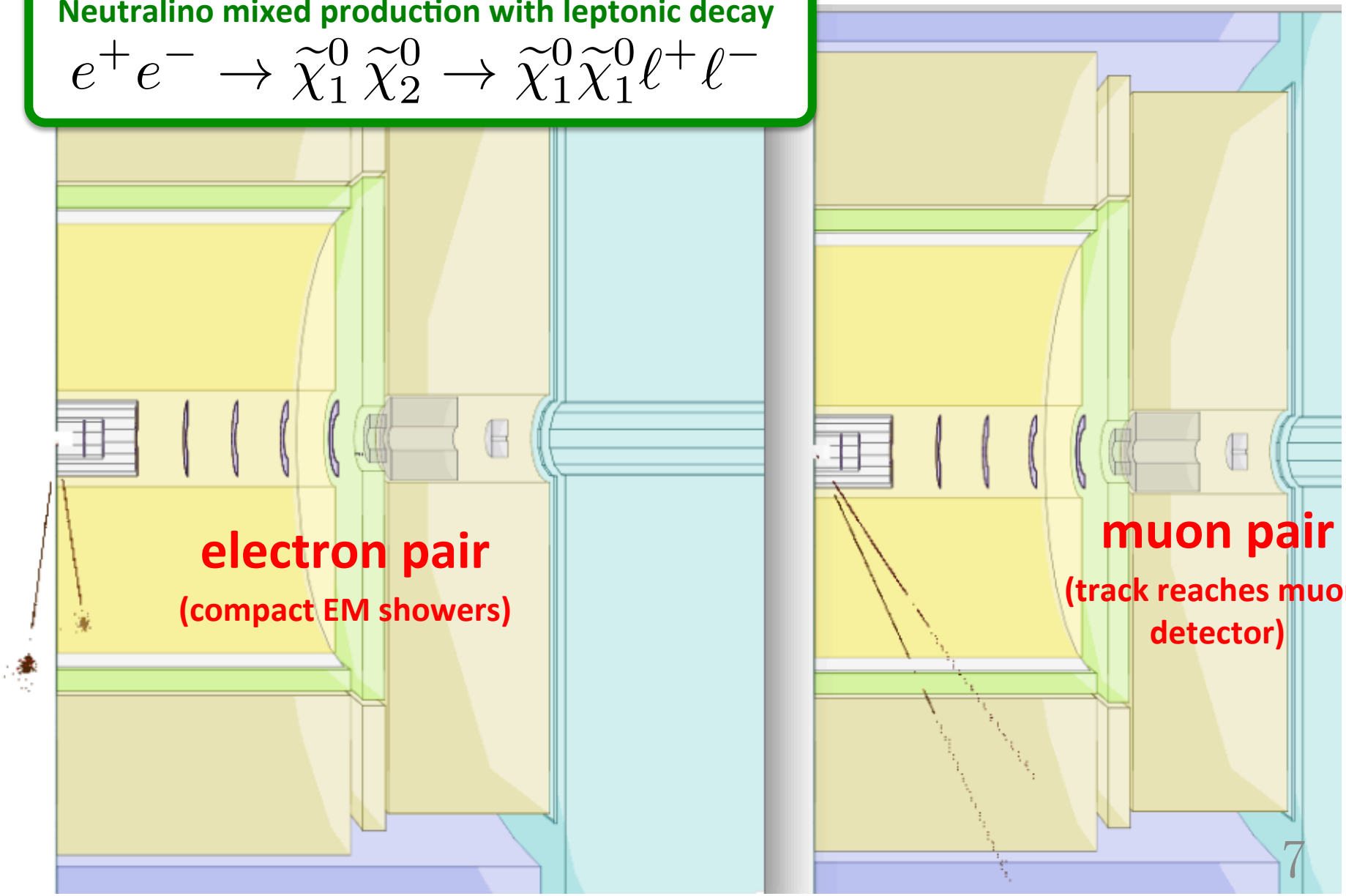


How do these signals look in the detector? (1)

√s =500 GeV

Neutralino mixed production with leptonic decay

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

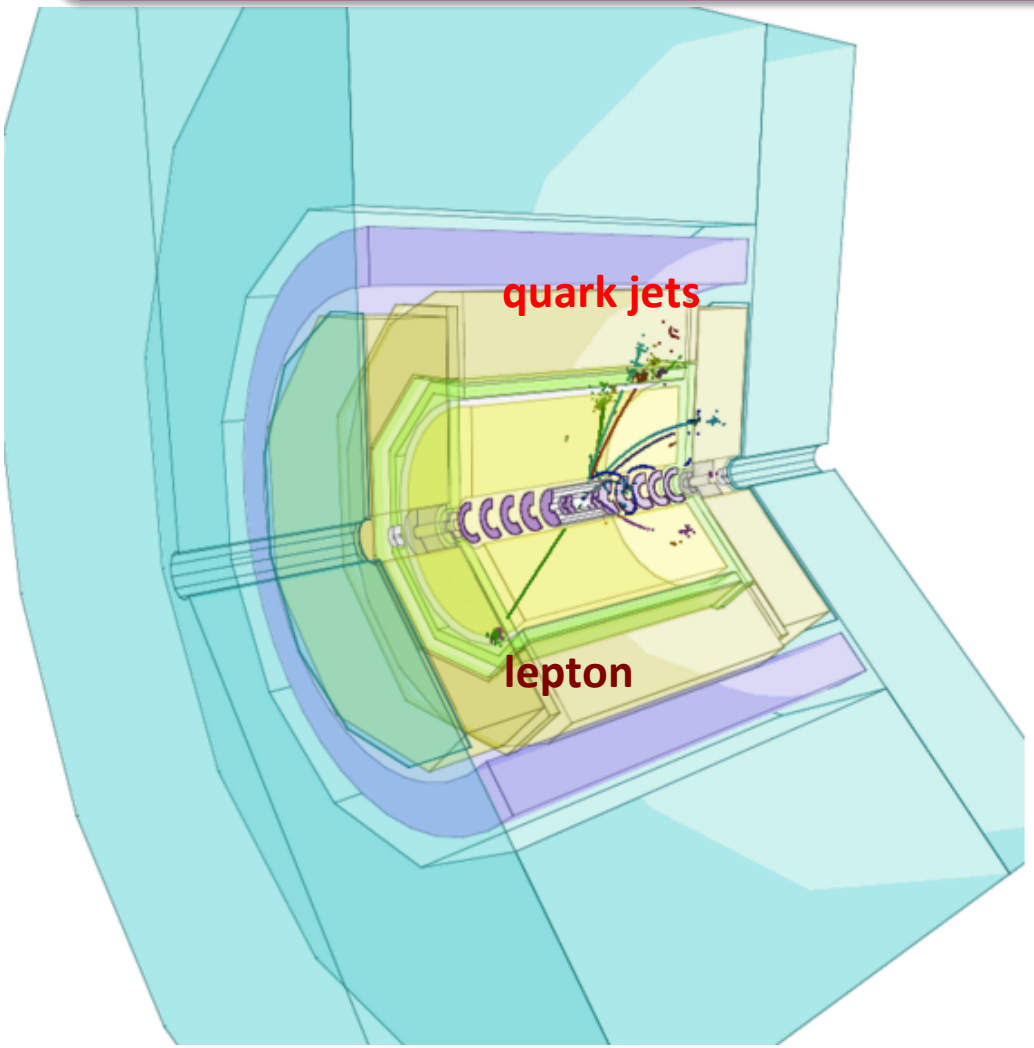


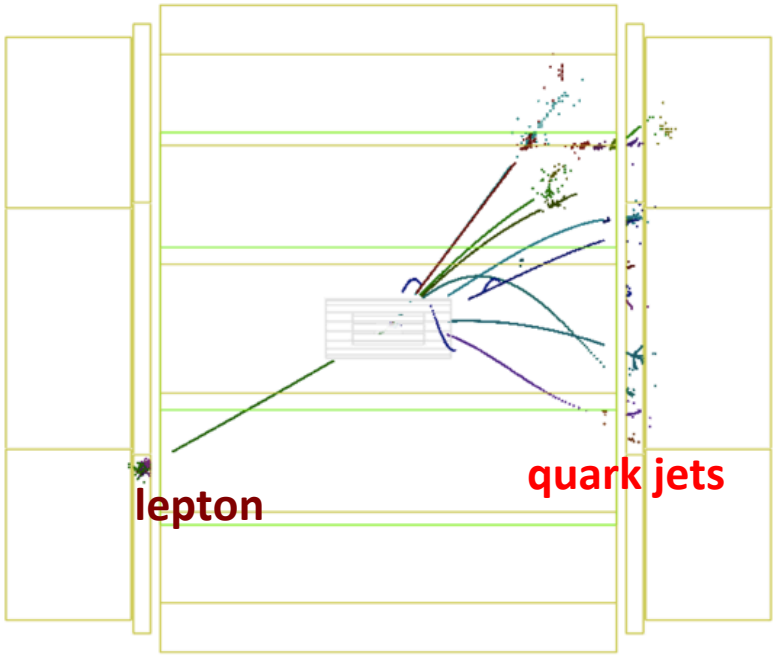
How do these signals look in the detector? (2)

√s =500 GeV

Chargino pair production with semileptonic decay

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



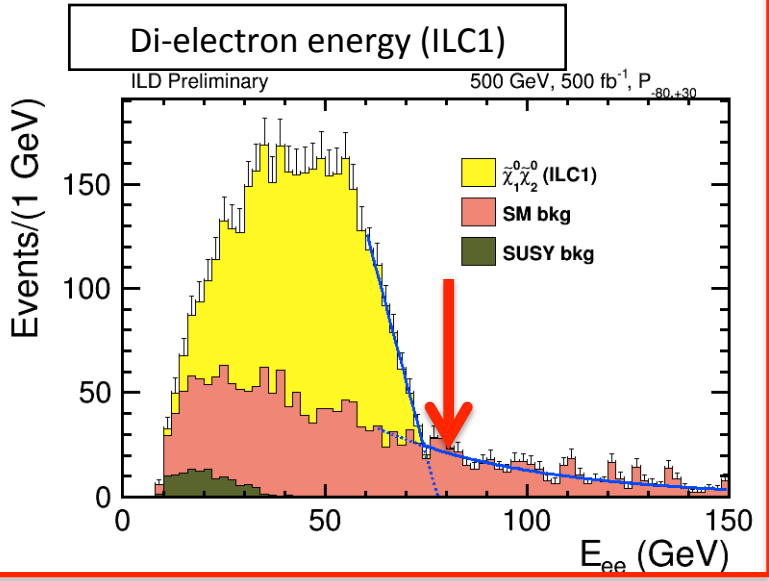


Method to Extract Higgsino Mass and Cross Section

Mass

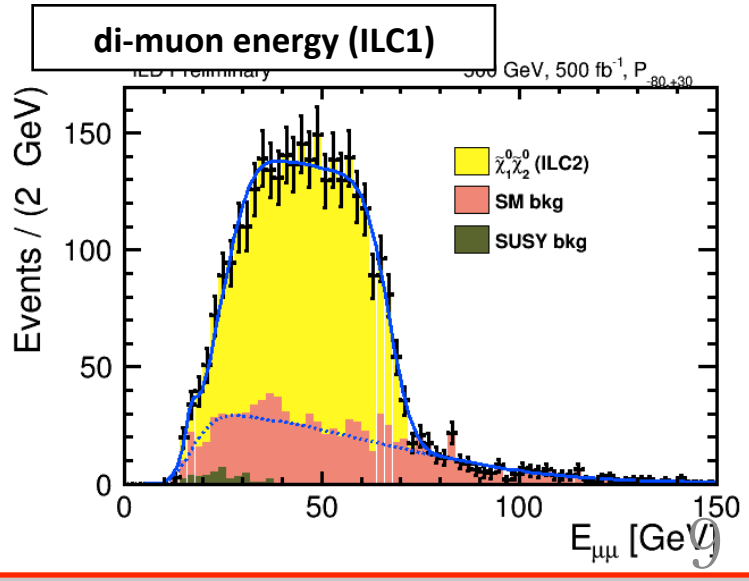
Kinematic edges of E_ll, E_jj, M_ll, M_jj are functions of $\sqrt{s}$ and Higgsino masses

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

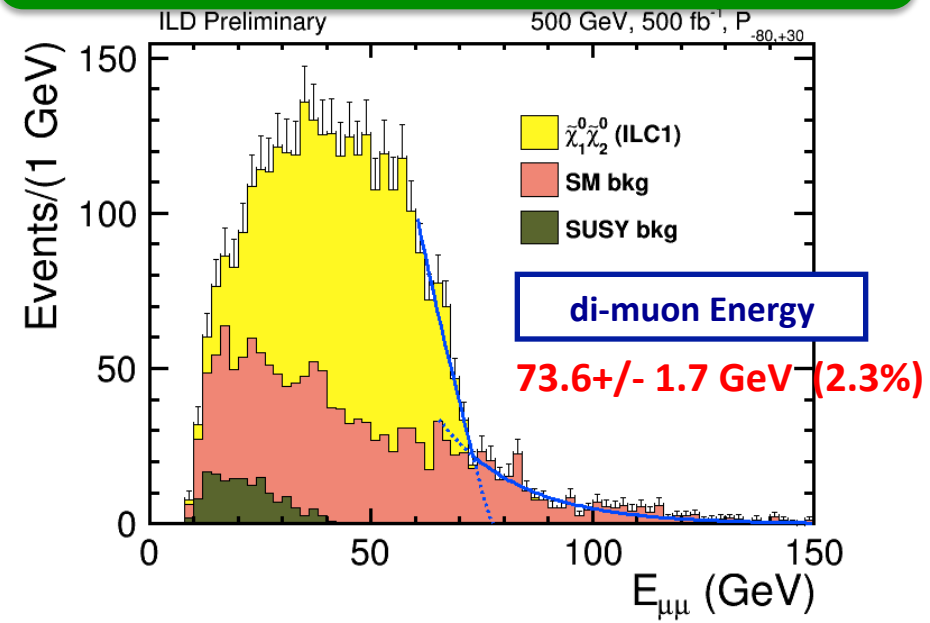
Abstract submitted to Higgs and New Physics session of EPS-HP 2017 conference (July 5-12, 2017)

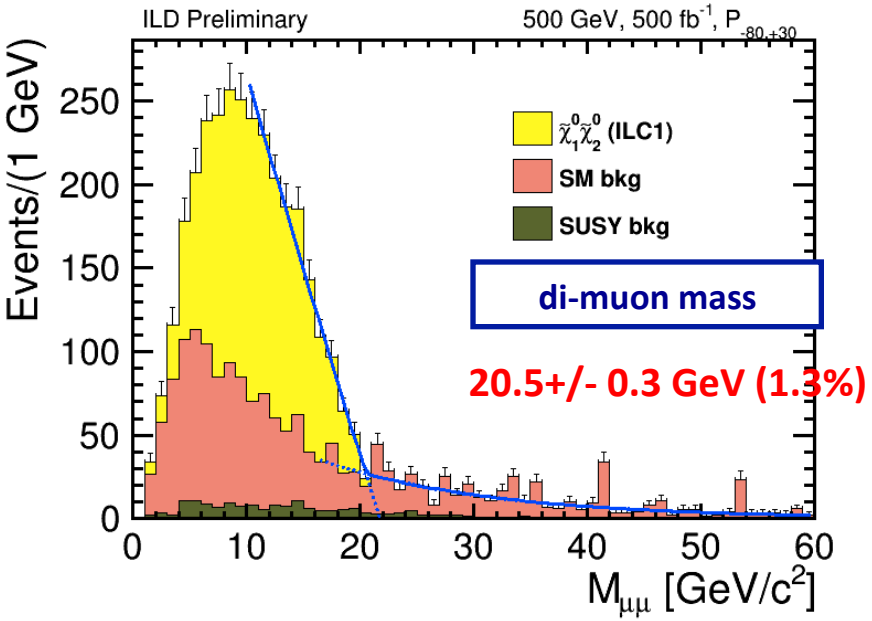
Neutralino mixed production with leptonic decay

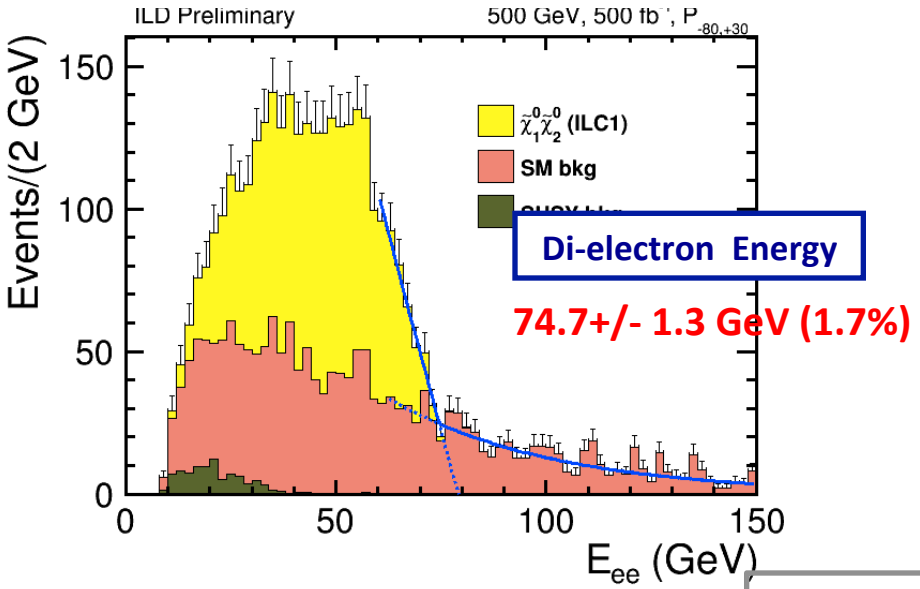
$$e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ell^+ \ell^-$$

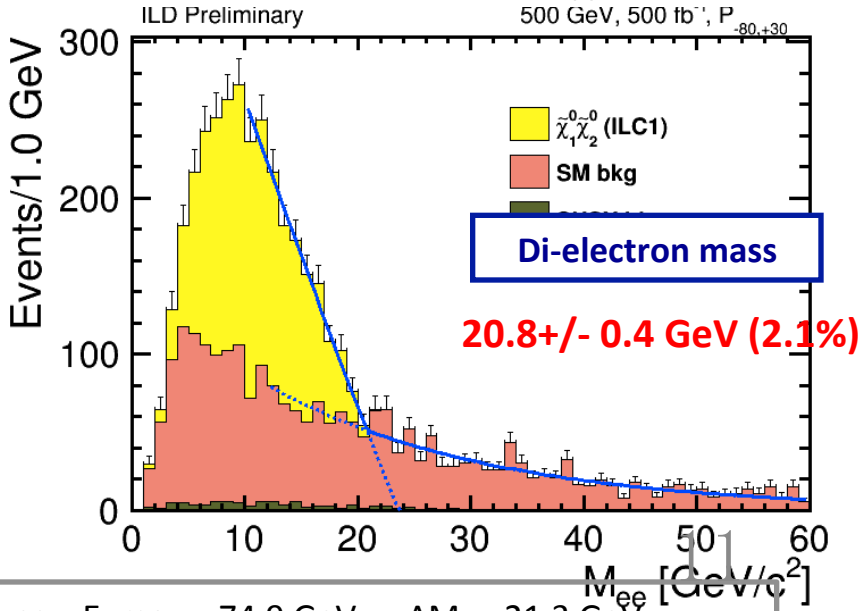
ILC1

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









Theoretical values: E_max = 74.9 GeV ΔM = 21.3 GeV

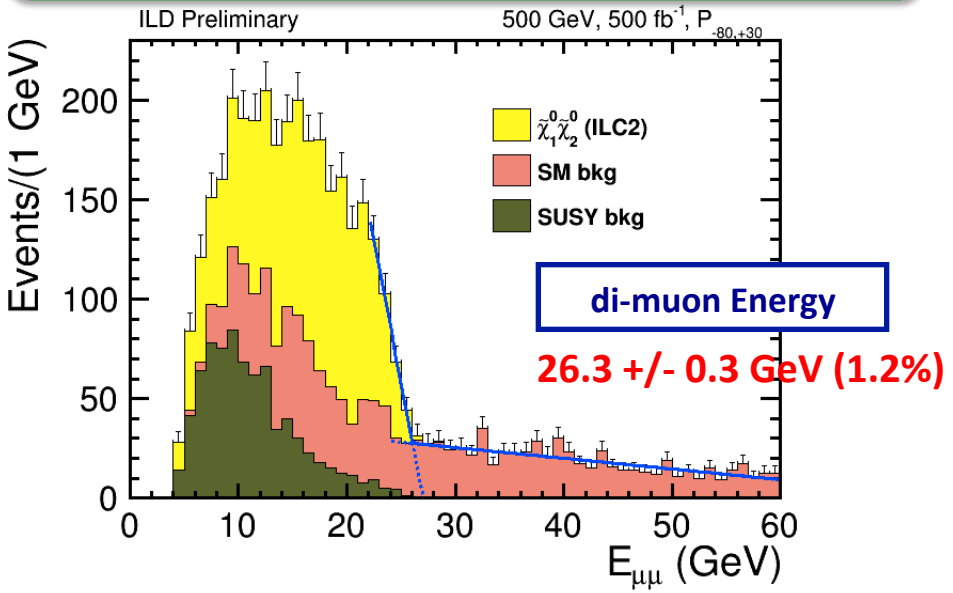
Neutralino mixed production with leptonic decay

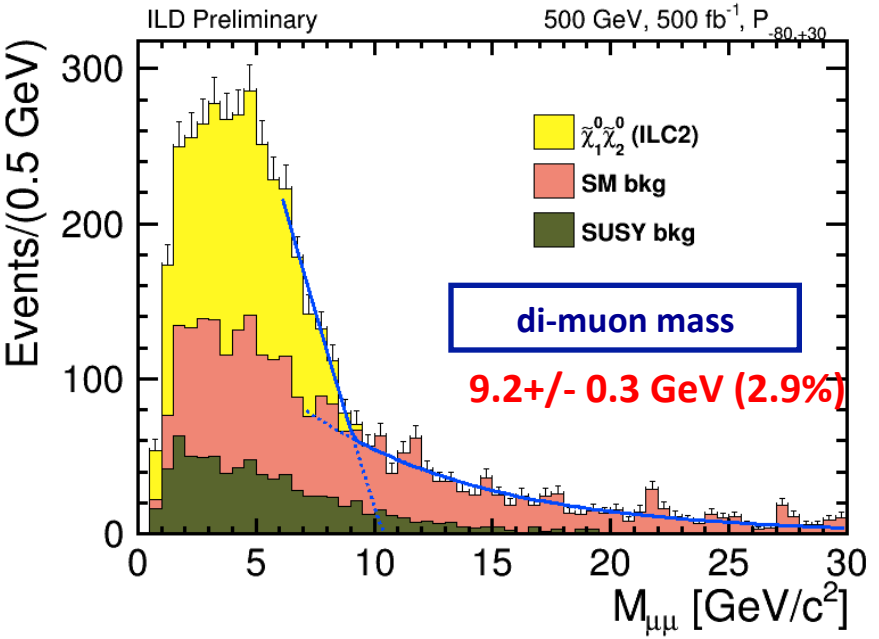
$$e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ell^+ \ell^-$$

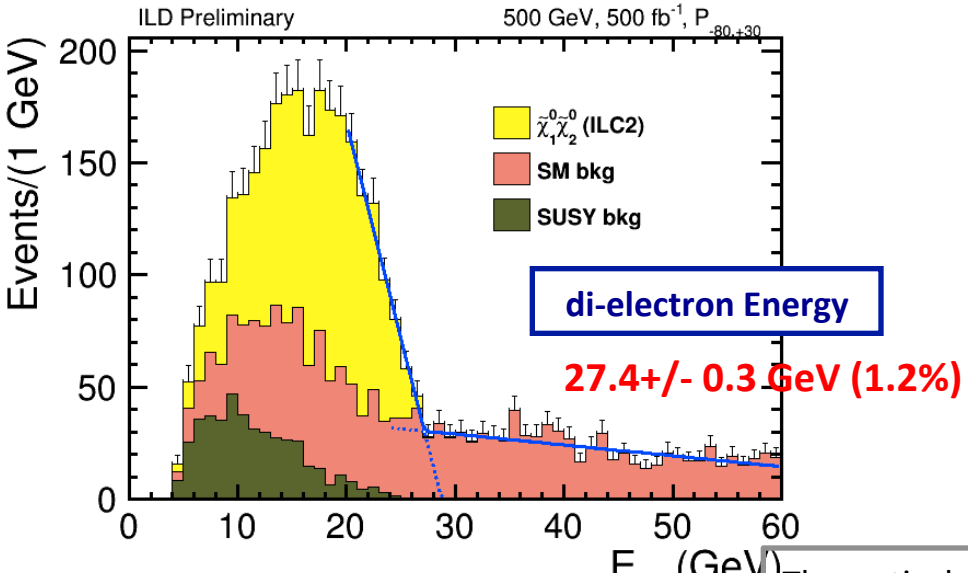
ILC2

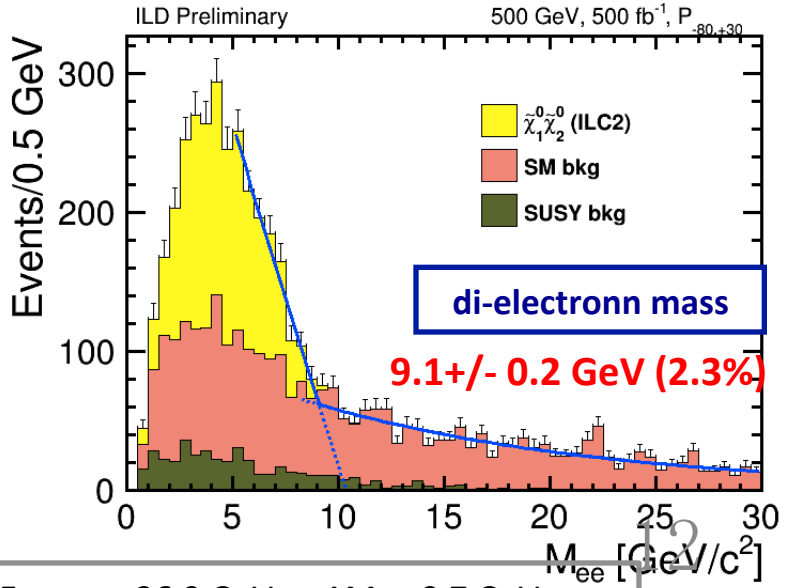
(Pe-, Pe+)=(0.8,0.3) L=500fb-1

ΔM=9.7 GeV









Theoretical values: E_max = 26.9 GeV ΔM = 9.7 GeV

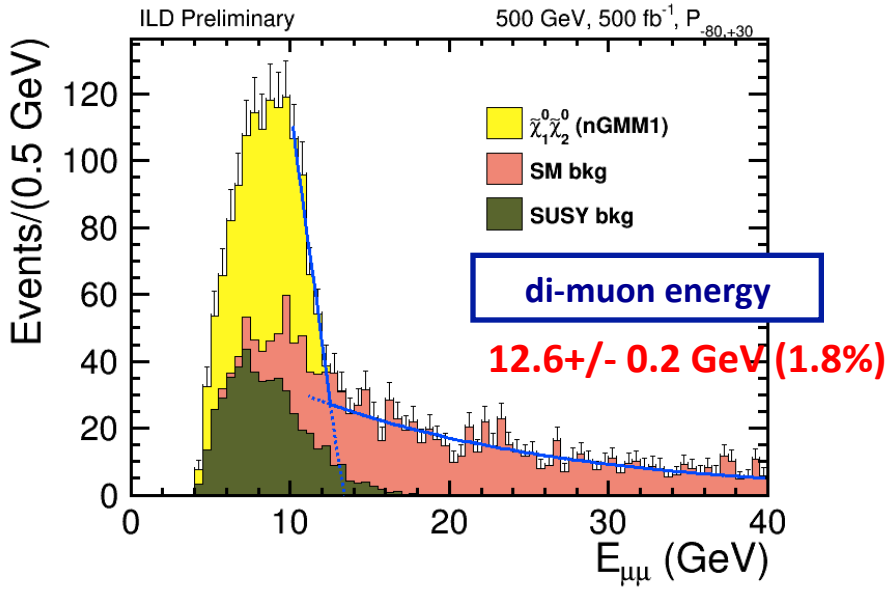
Neutralino mixed production with leptonic decay

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

Mirage

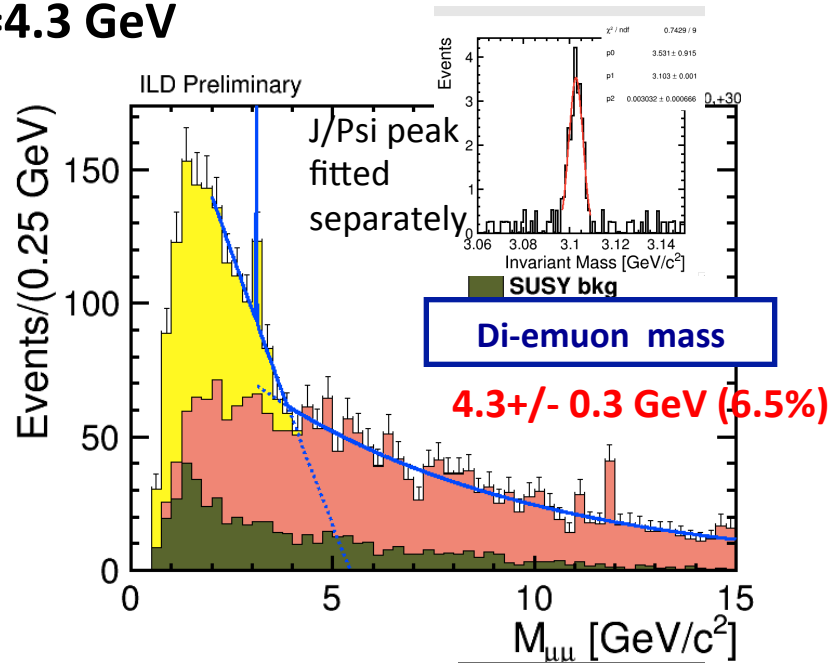
ΔM=4.3 GeV

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



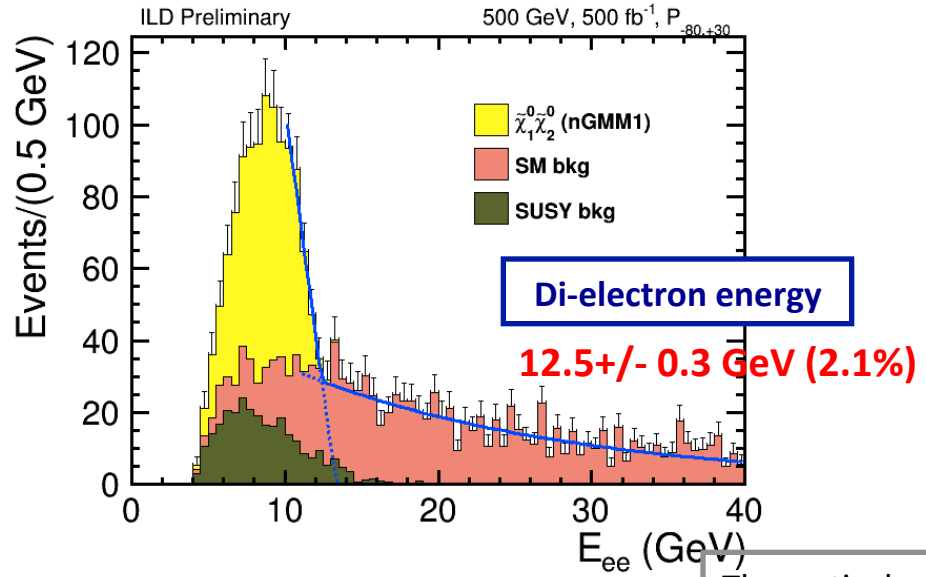
di-muon energy

12.6+/- 0.2 GeV (1.8%)



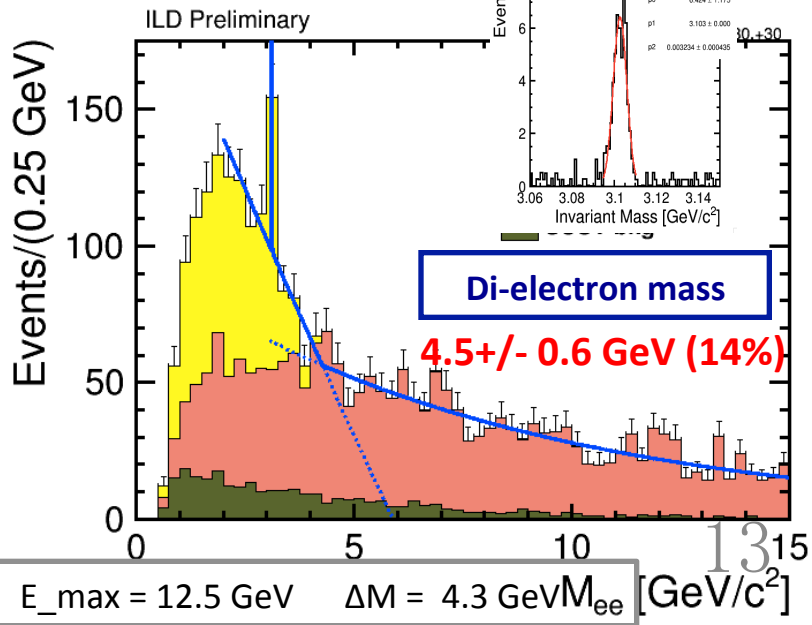
Di-emuon mass

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 χ^2 fit

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

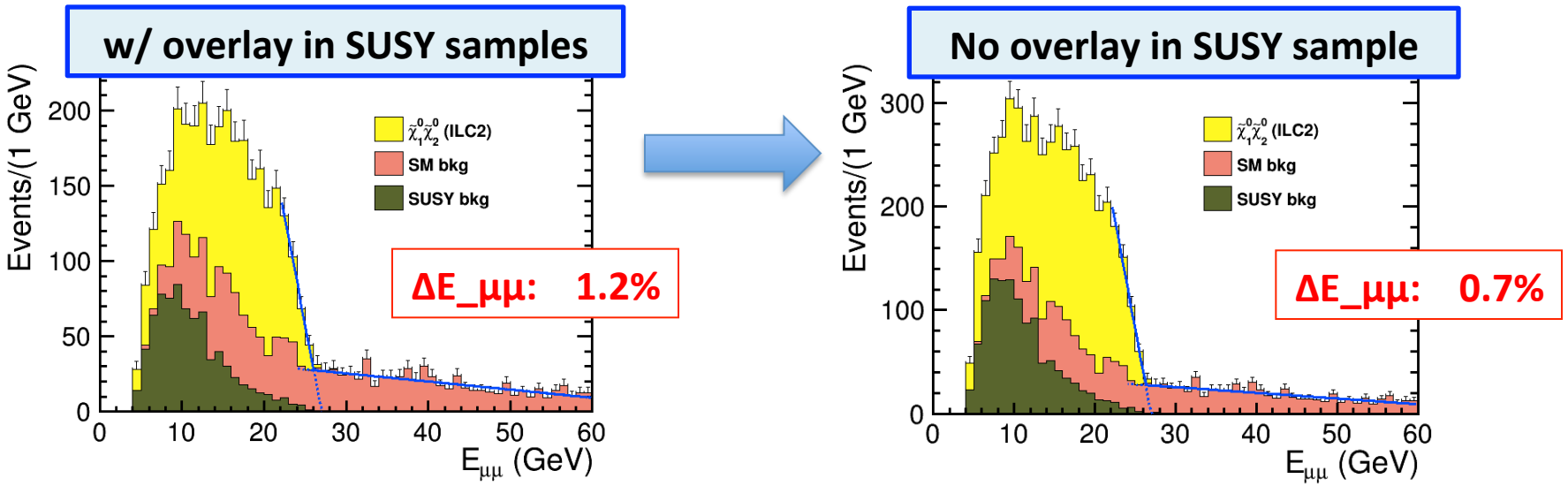
- **Assuming 500 fb^{-1}:** ILC1, ILC2 : 1–2% Mirage: 4–5%
- **Assuming H20 , 1600 fb^{-1}** ILC1, ILC2: better than 1% Mirage: 2–3%

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)



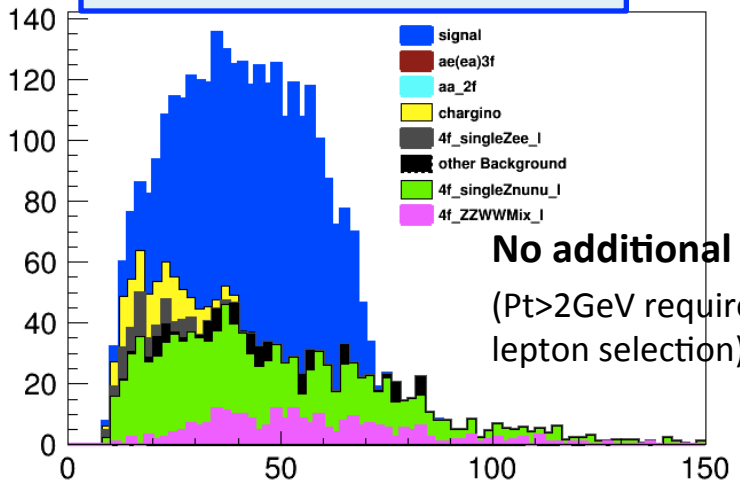
Cross section fit for N1N2 analysis

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

2 sets of cuts

tighter cuts for xsec measurement (minimize SUSY bkg)

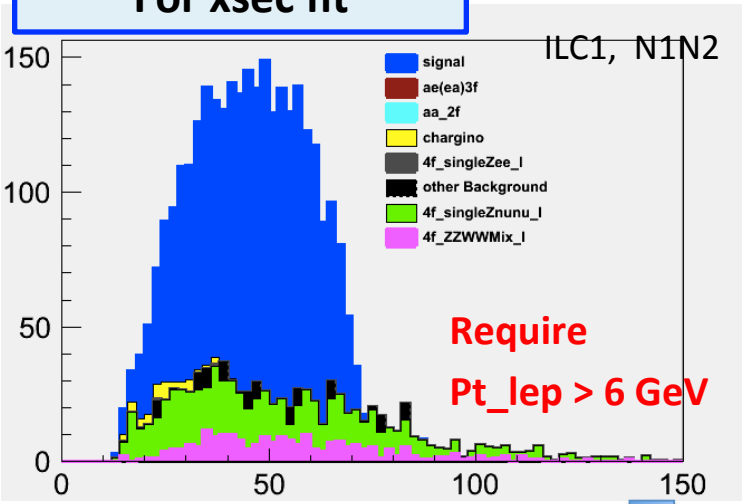
For kinematic edge fit



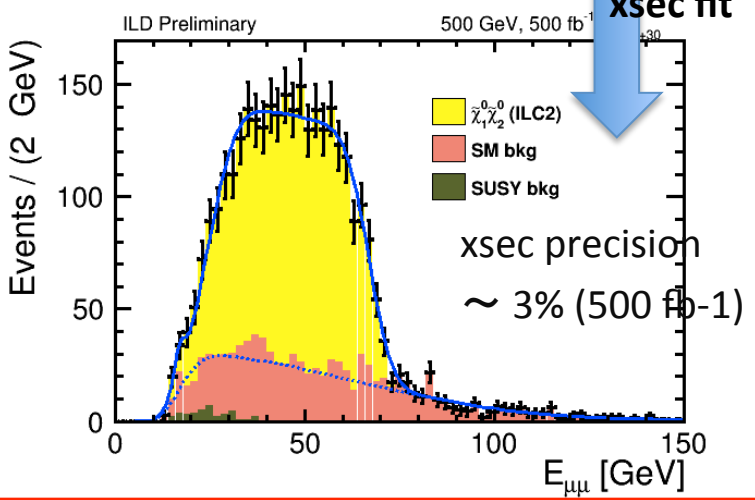
No additional Pt_lep cut

(Pt>2GeV required in isolated lepton selection)

For xsec fit



xsec fit



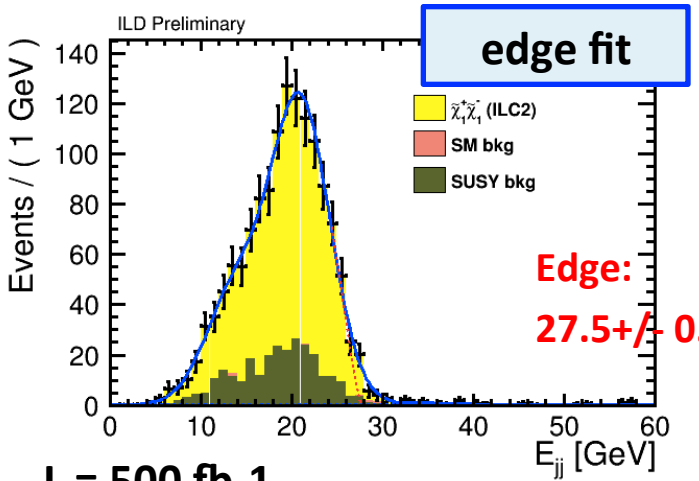
Better than a few % precision for cross section fits assuming L=500 fb-1

Chargino pair production with semileptonic decay

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

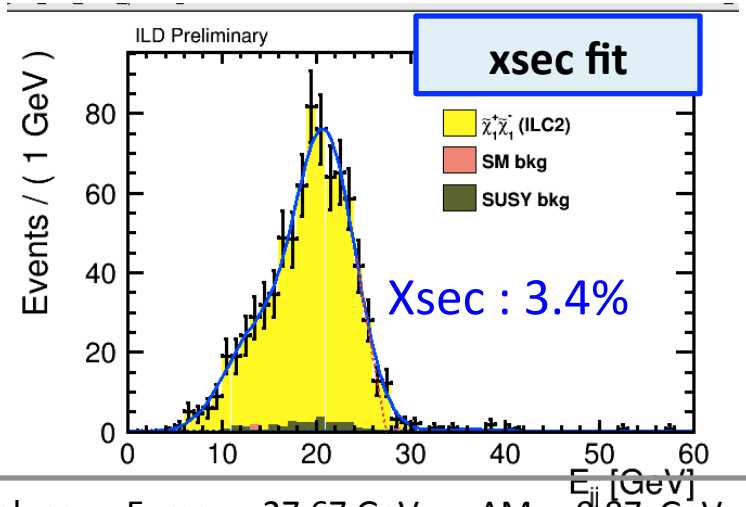
- an almost bkg-free analysis
- kt algorithm optimized to treat beam jets from γγ→hadron bkg

ILC2 ΔM=9.9 GeV



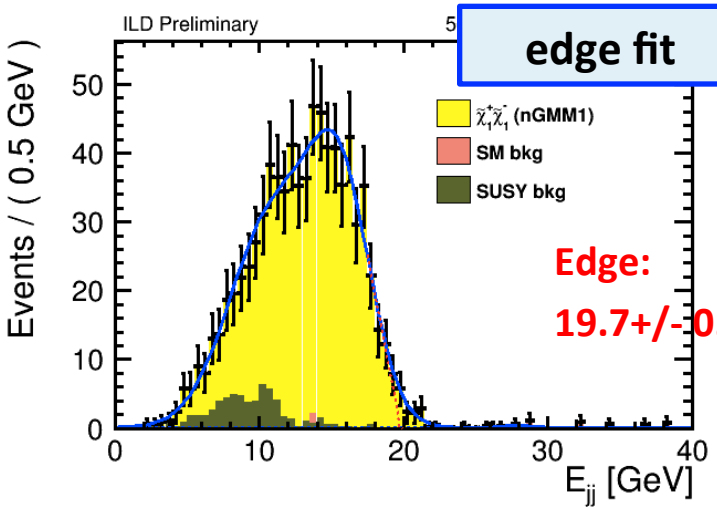
L = 500 fb-1

tighter cuts for xsec fit

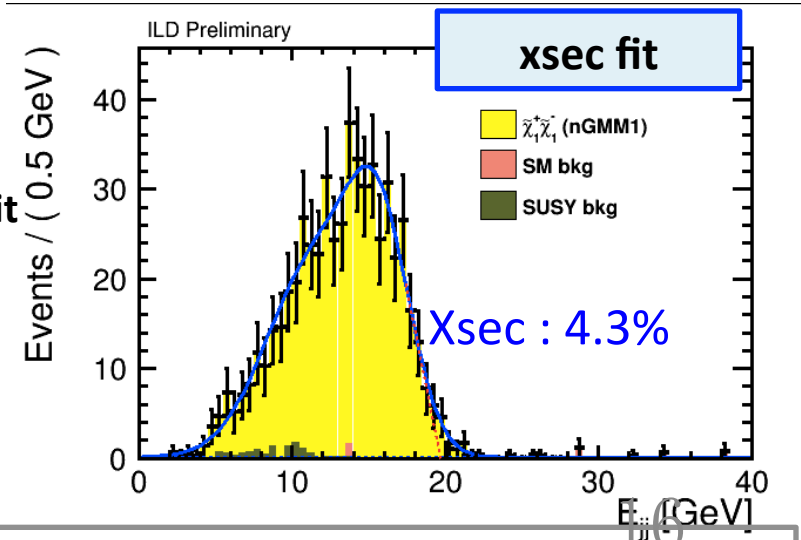


Theoretical values: E_max = 27.67 GeV , ΔM = 9.87 GeV

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)

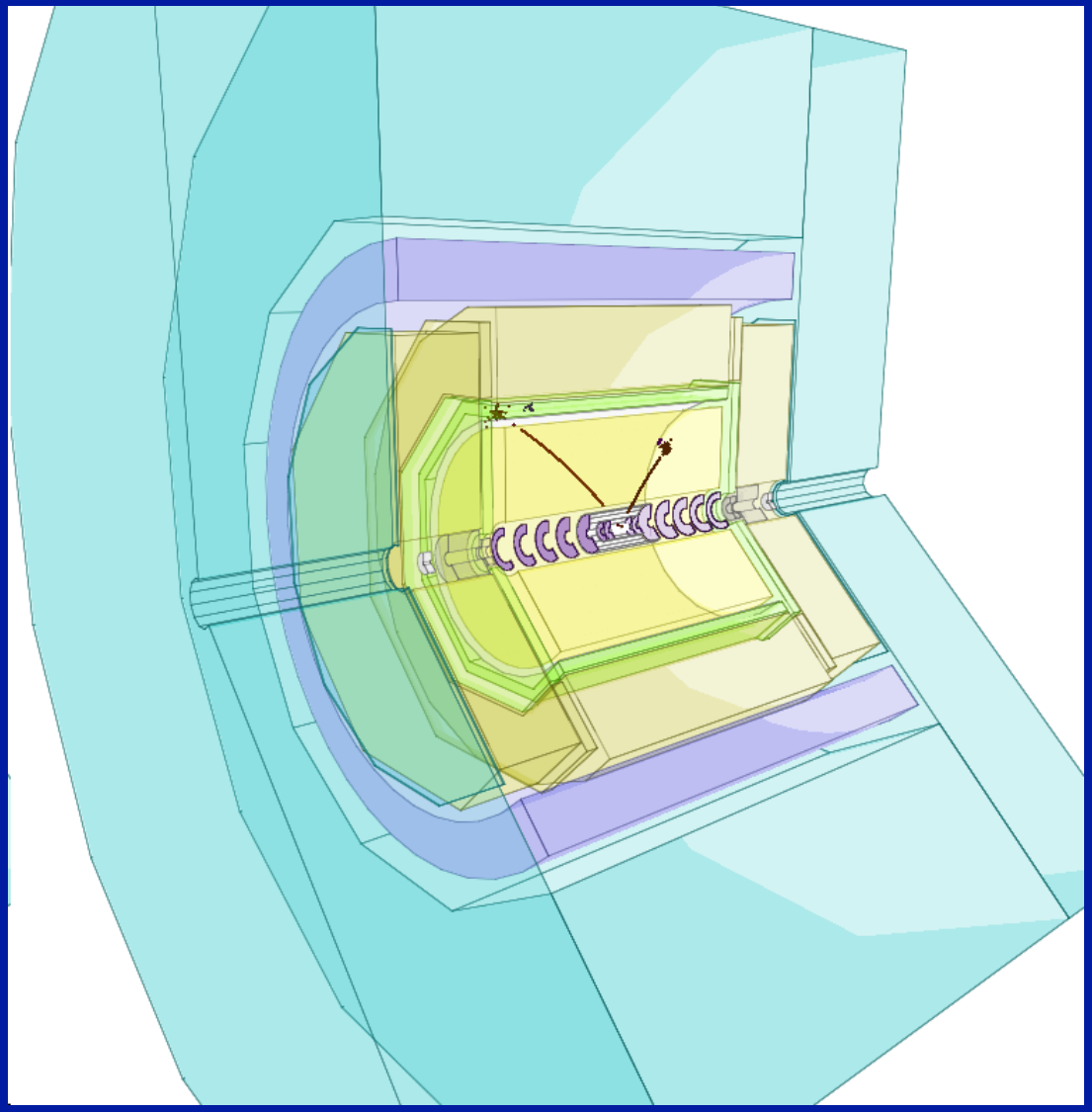
❖ **Consider contribution from Higgsino analysis to staging**

- 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)

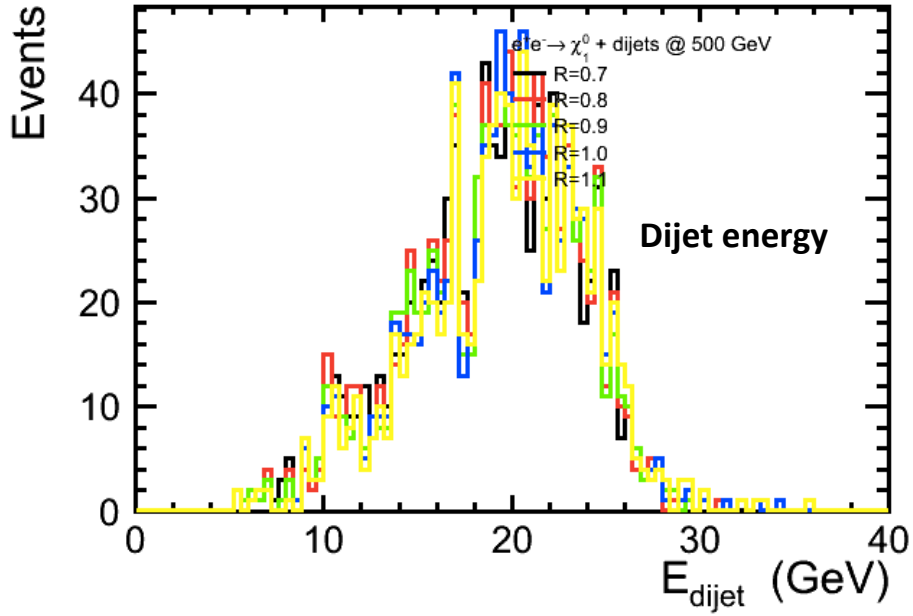
  350 GeV: ILC2(ΔM～10GeV), Mirage (ΔM～5GeV)

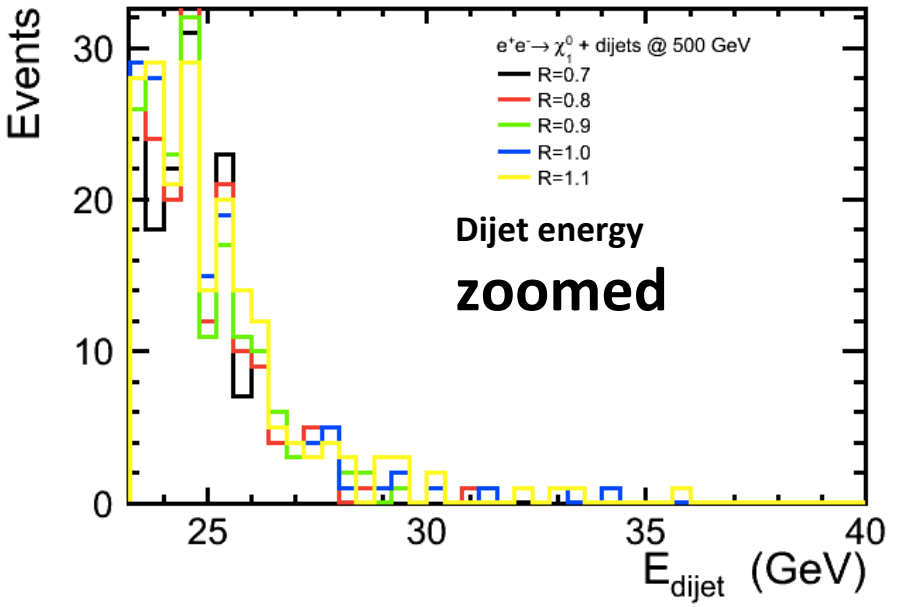
Backup

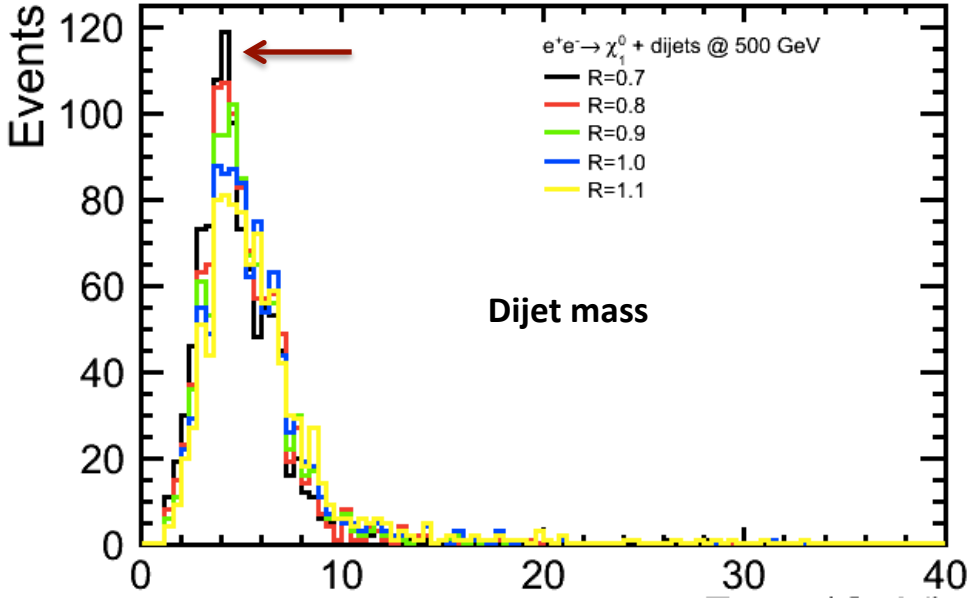


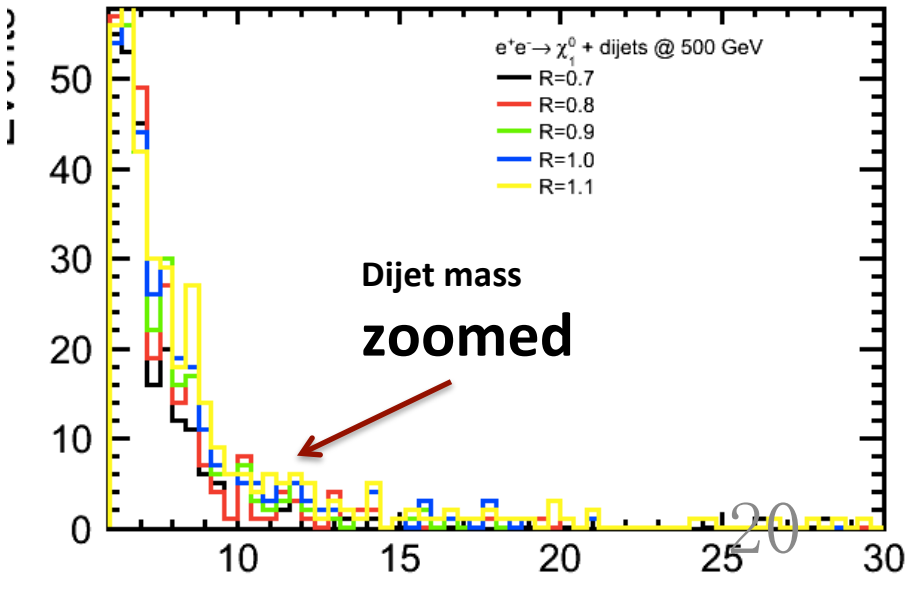
ILC2 : C1C1 left pol, mu tag, v01-16-02 **Compare R= 0.7, 0.8, 0.9, 1.0, 1.1**

All analysis cuts applied





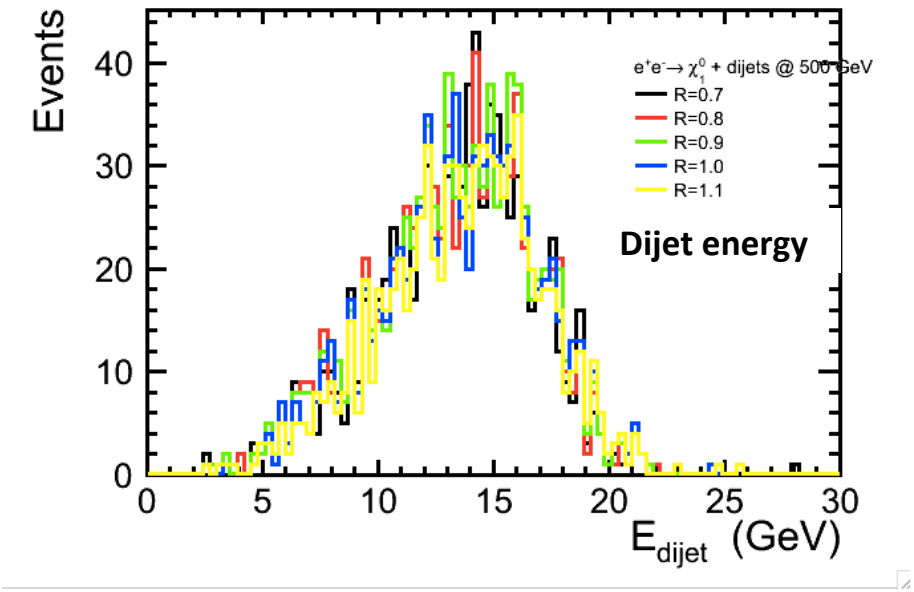


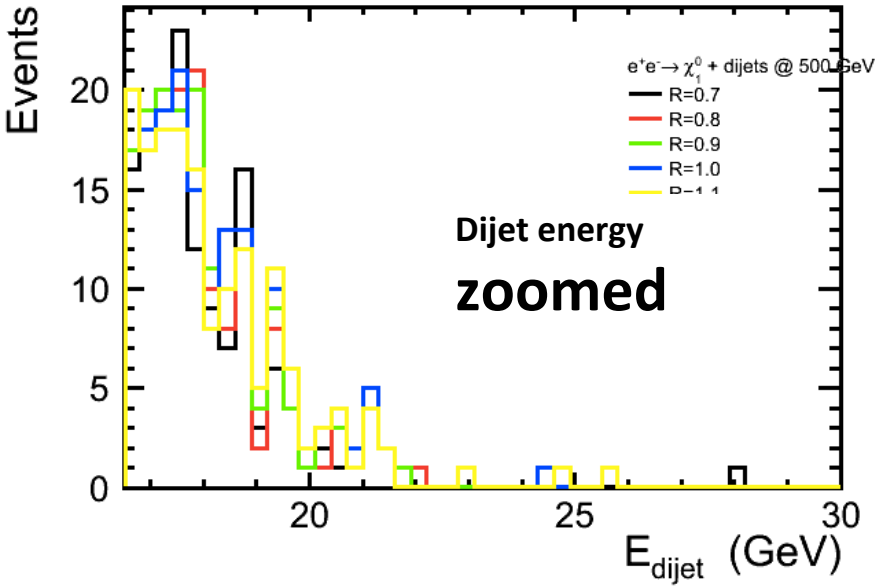


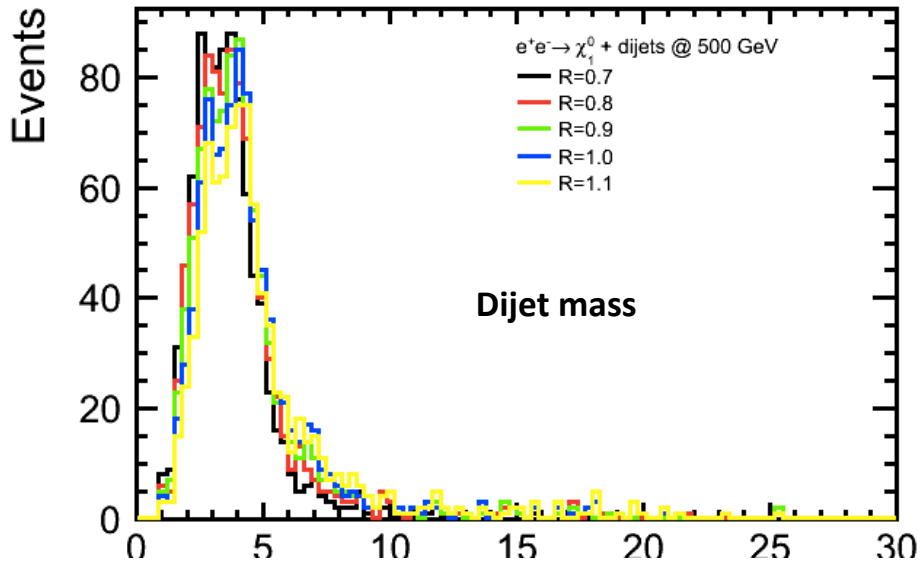
Mirage : C1C1 left pol, mu tag, v01-16-02

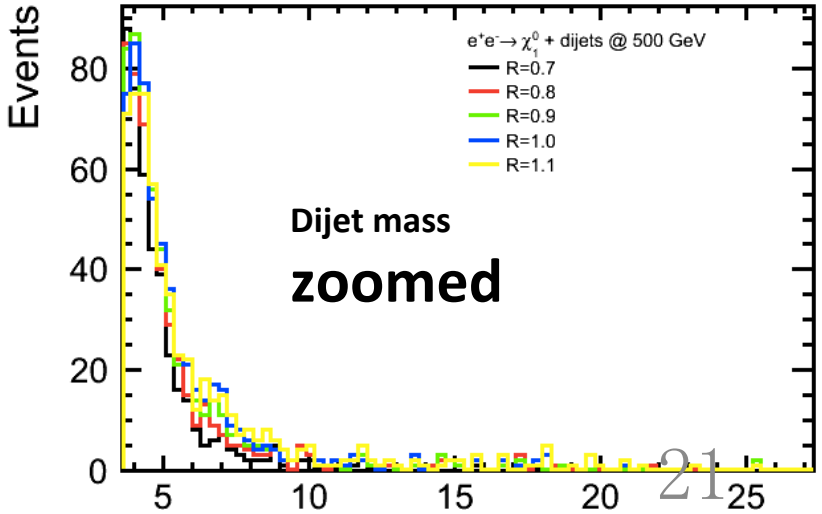
All analysis cuts applied

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

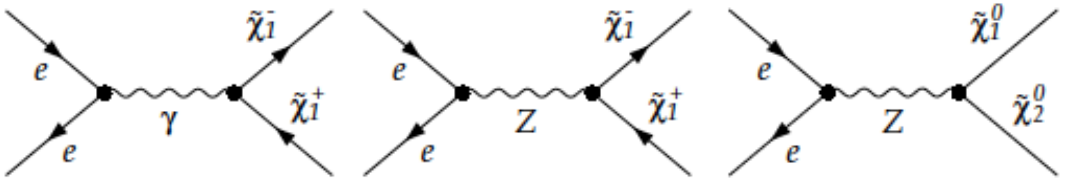








Benchmarks in this Study



√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)

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**

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

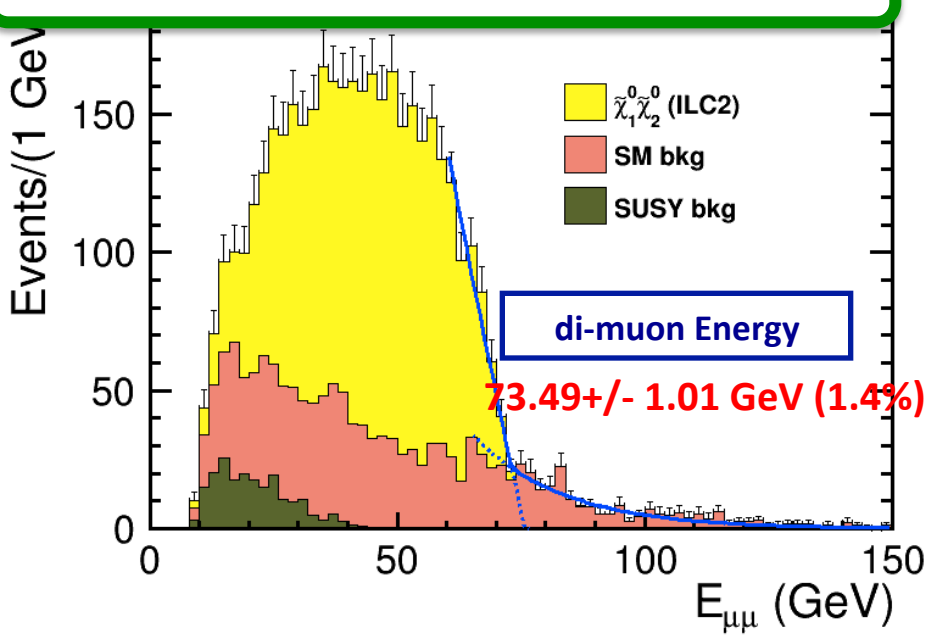
Defined at GUT scale ,
Defined at weak scale **Observables**

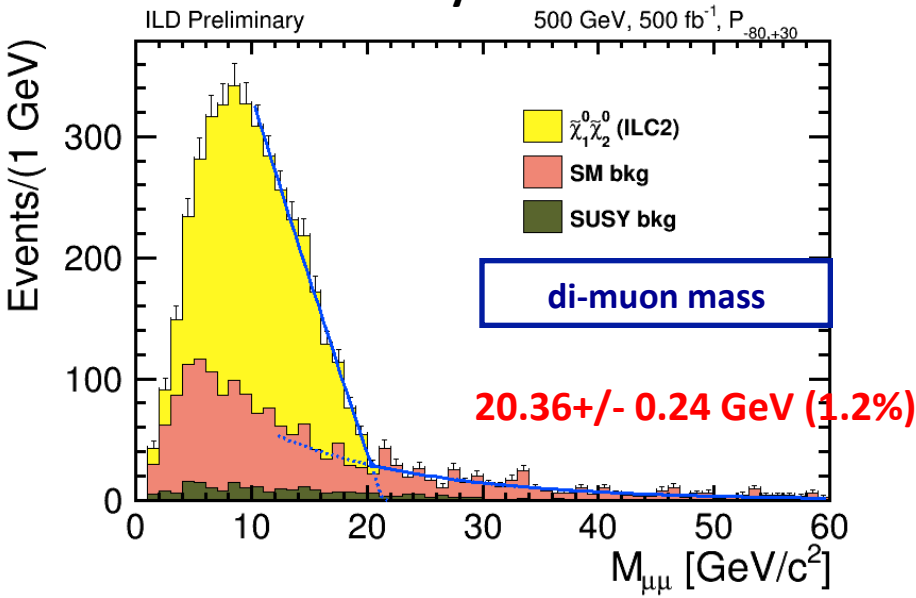
Neutralino mixed production with leptonic decay

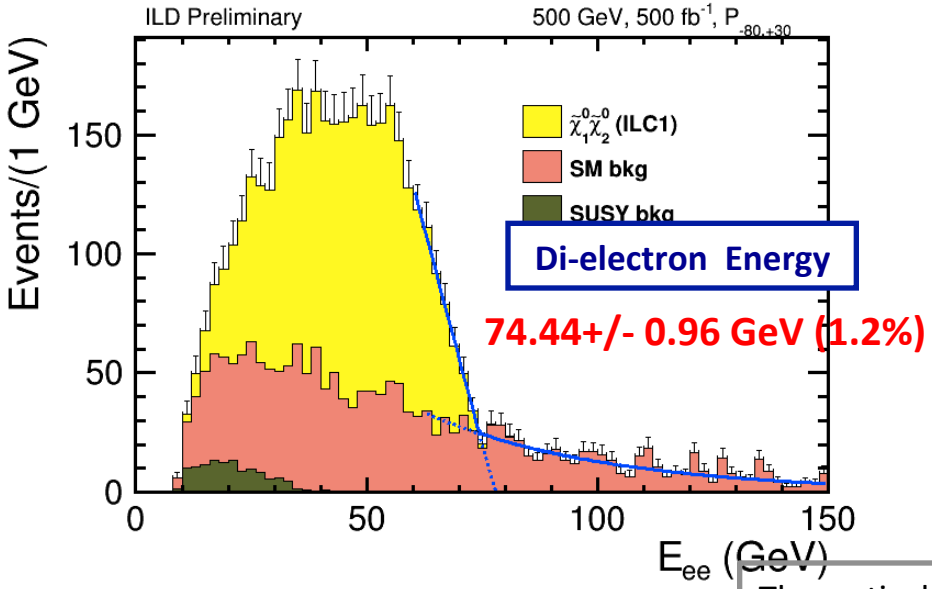
$$e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ell^+ \ell^-$$

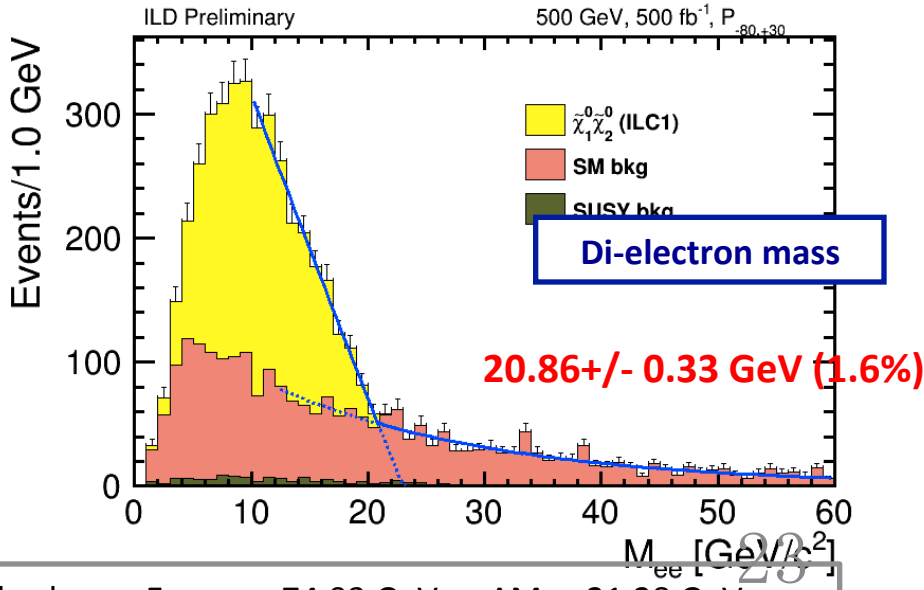
ILC1 @500fb-1 v01-16-02

Without overlay









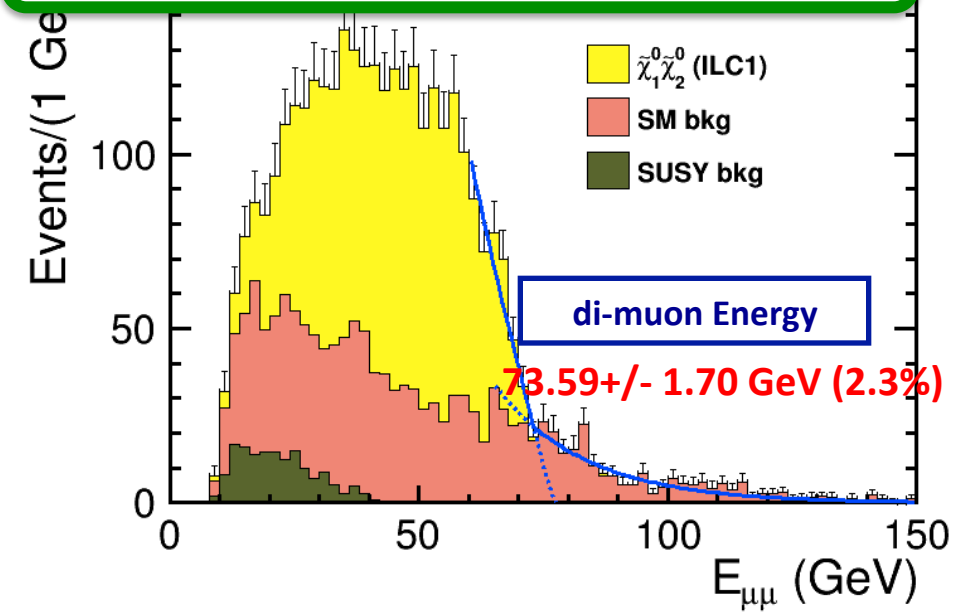
Theoretical values: E_max = 74.93 GeV ΔM = 21.28 GeV

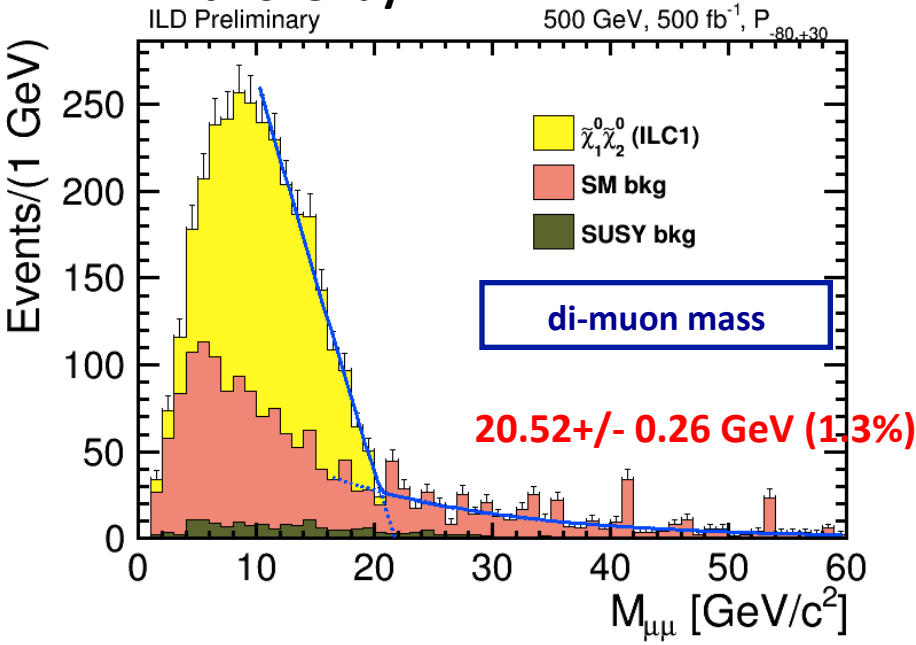
Neutralino mixed production with leptonic decay

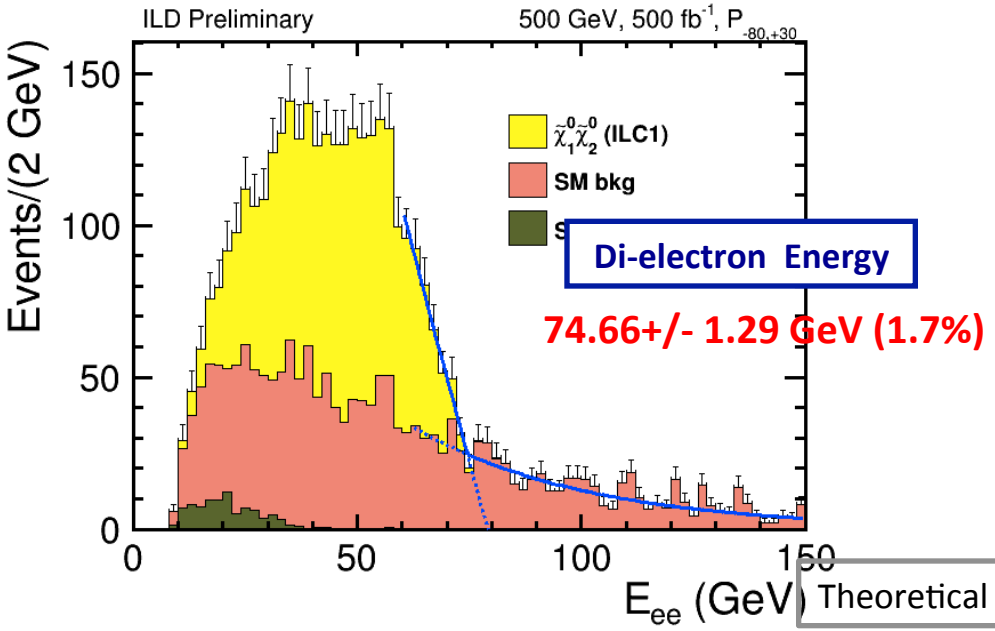
$$e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ell^+ \ell^-$$

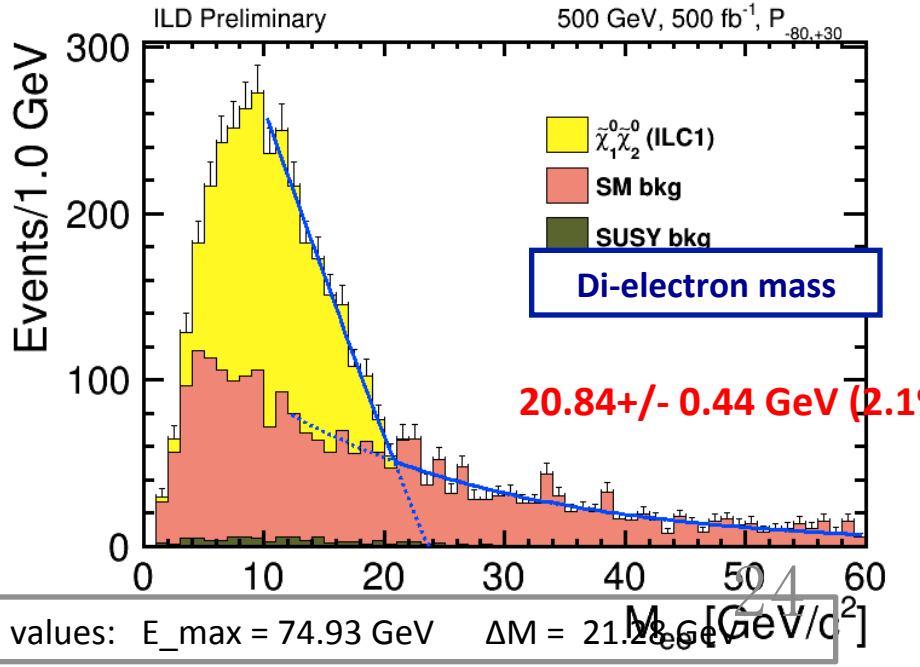
ILC1 @500fb-1 v01-16-02

With overlay









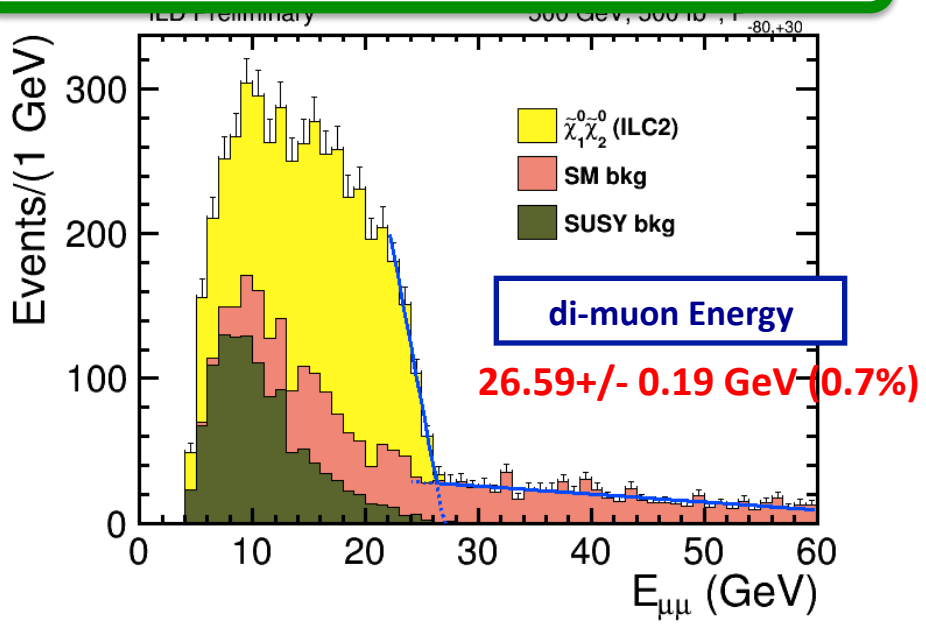
Theoretical values: E_max = 74.93 GeV ΔM = 21.28 GeV

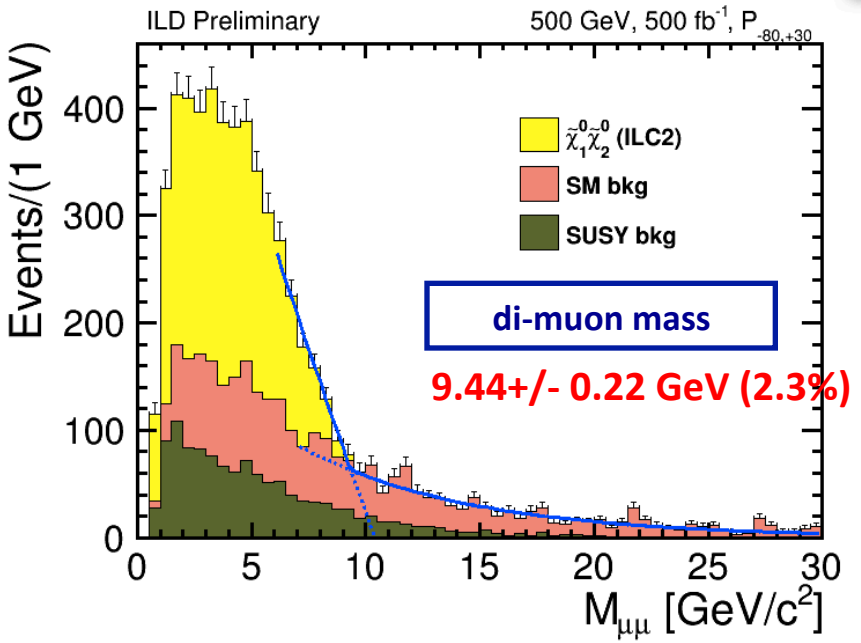
Neutralino mixed production with leptonic decay

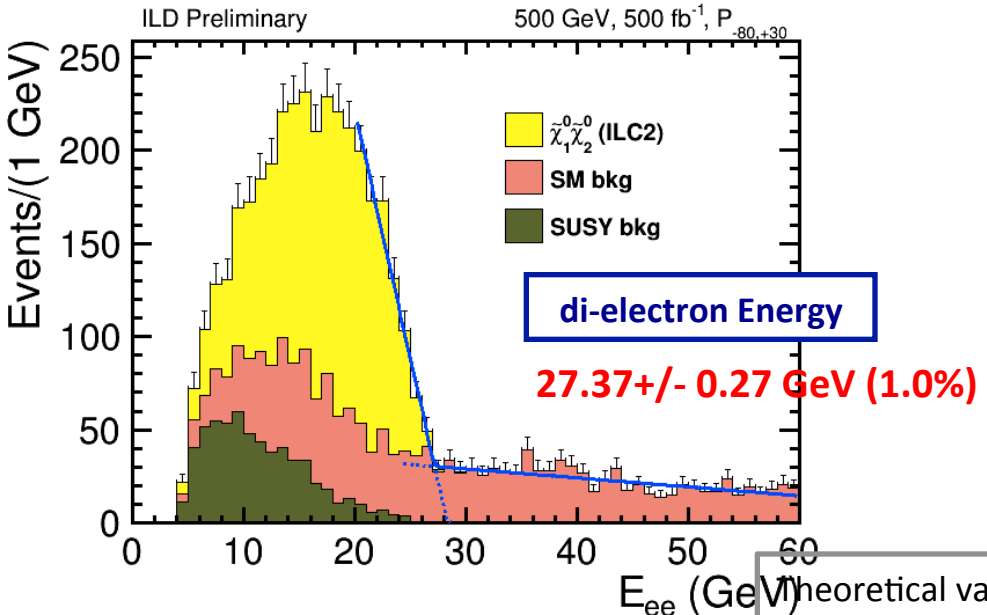
$$e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ell^+ \ell^-$$

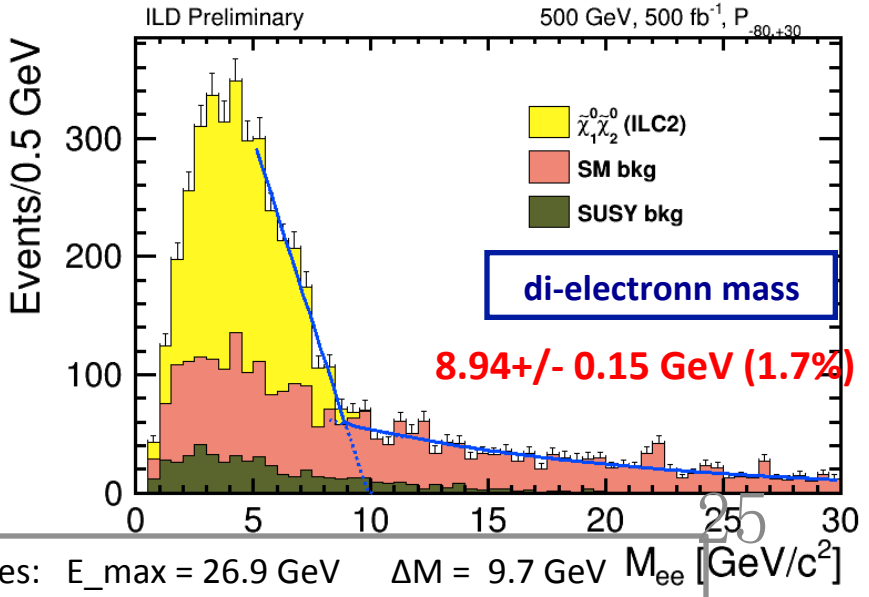
ILC2 @500fb-1 v01-16-02

Without overlay









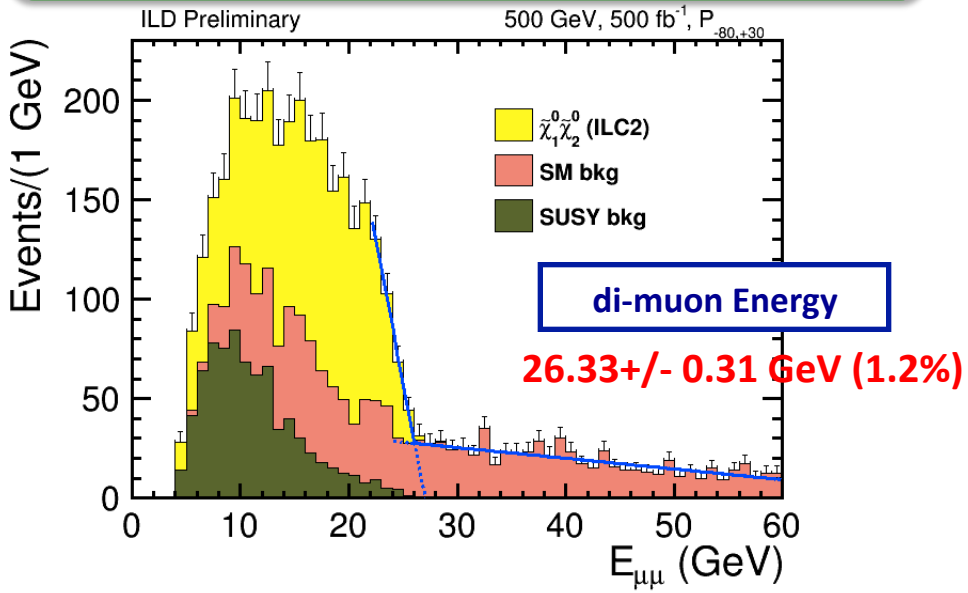
Theoretical values: E_max = 26.9 GeV ΔM = 9.7 GeV

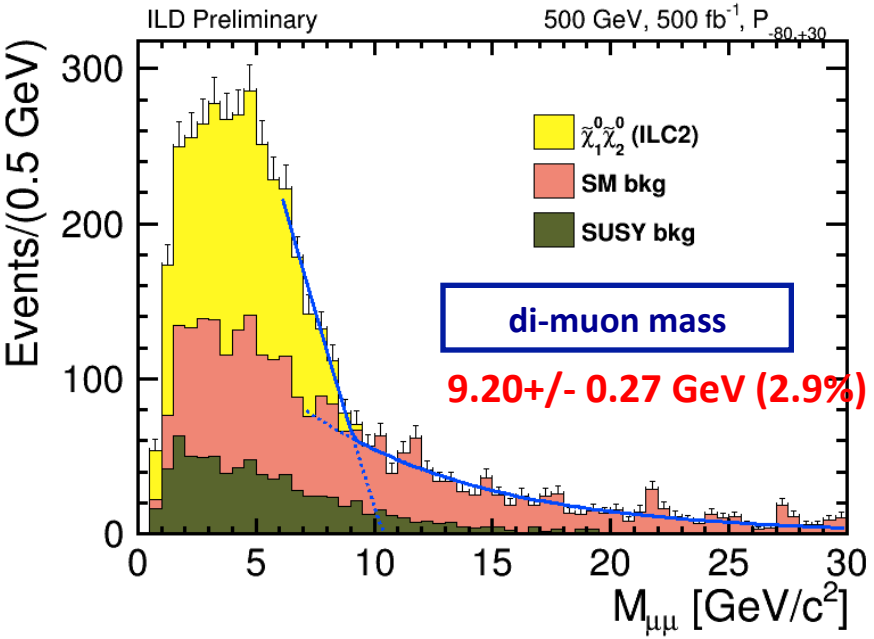
Neutralino mixed production with leptonic decay

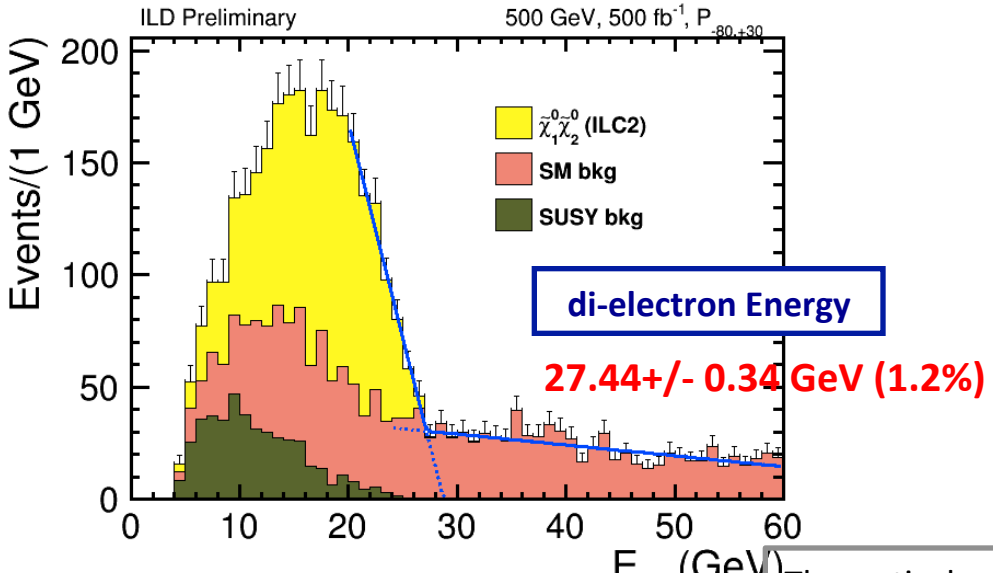
$$e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ell^+ \ell^-$$

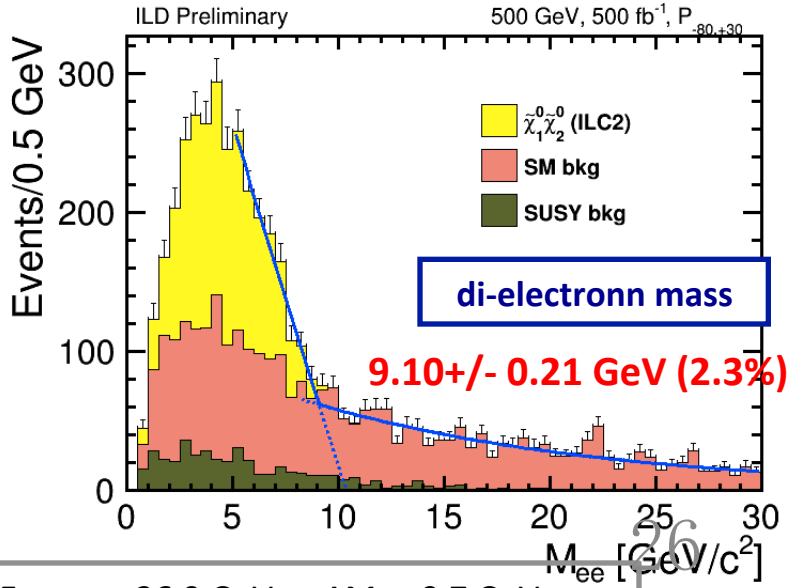
ILC2 @500fb-1 v01-16-02

With overlay









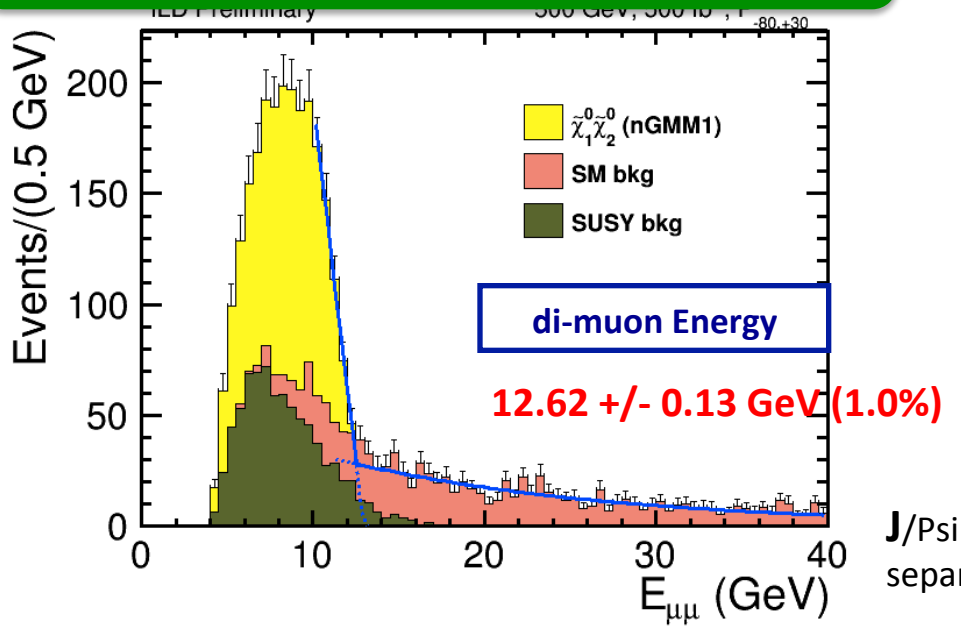
Theoretical values: E_max = 26.9 GeV ΔM = 9.7 GeV

Neutralino mixed production with leptonic decay

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

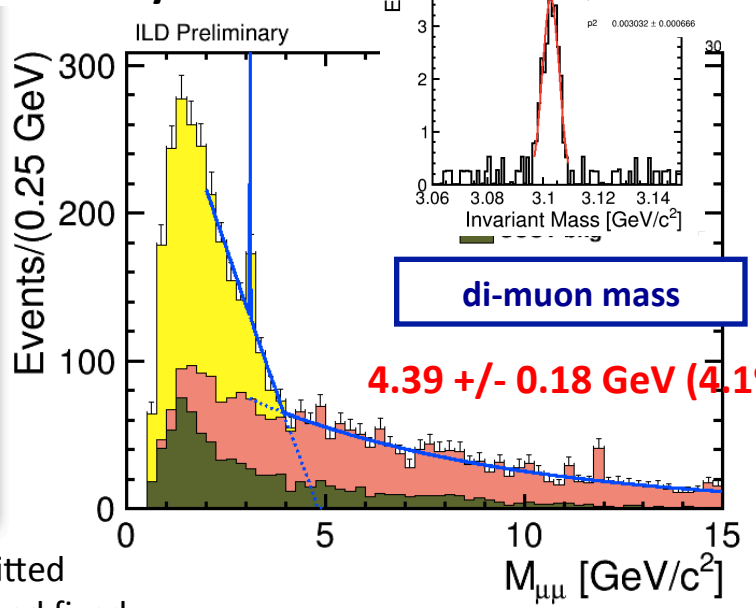
Mirage Mediation @500fb-1

Without overlay



di-muon Energy

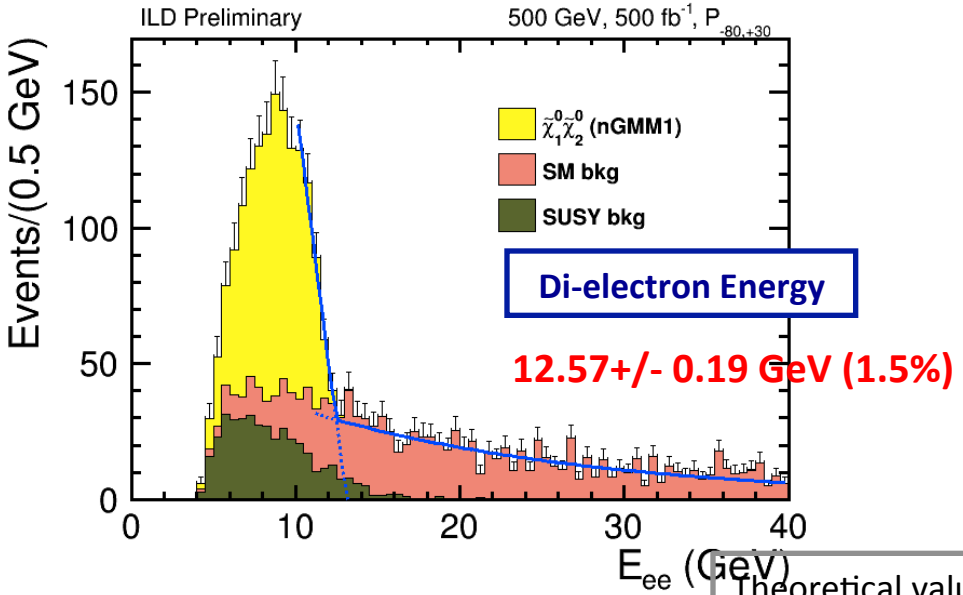
12.62 +/- 0.13 GeV (1.0%)



di-muon mass

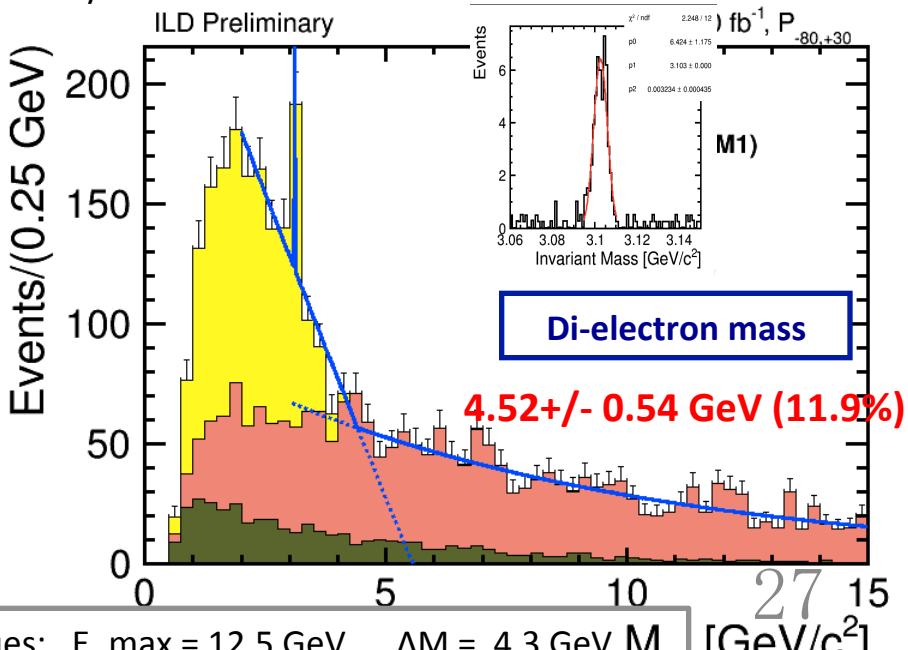
4.39 +/- 0.18 GeV (4.1%)

J/Psi peak fitted separately and fixed



Di-electron Energy

12.57+/- 0.19 GeV (1.5%)



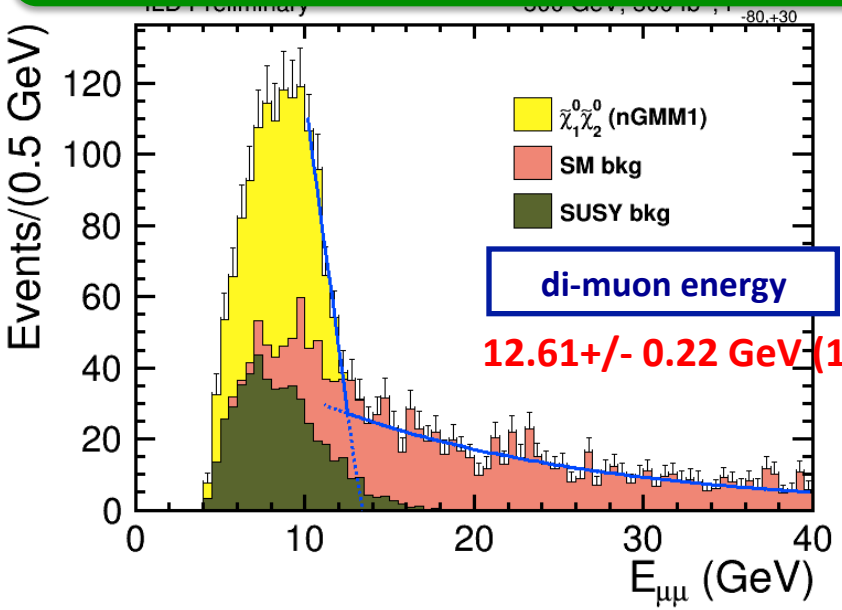
Di-electron mass

4.52+/- 0.54 GeV (11.9%)

Theoretical values: E_max = 12.5 GeV ΔM = 4.3 GeV

Neutralino mixed production with leptonic decay

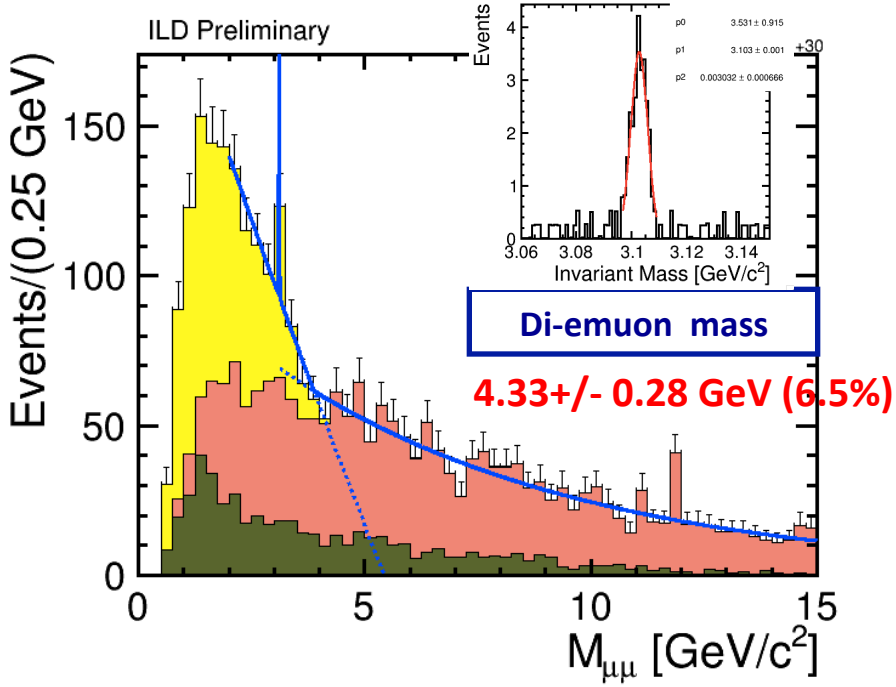
$$e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ell^+ \ell^-$$



di-muon energy

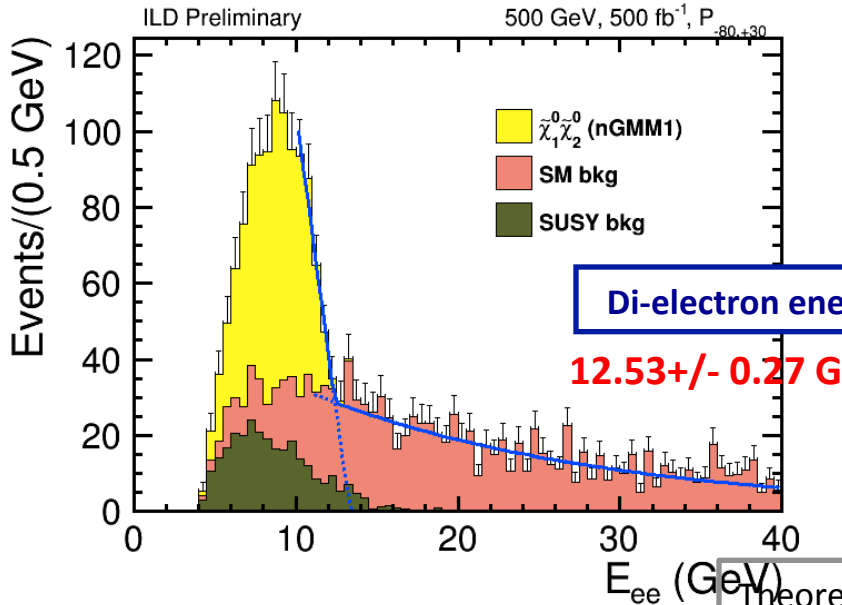
12.61+/- 0.22 GeV (1.8%)

Mirage v01-16-02



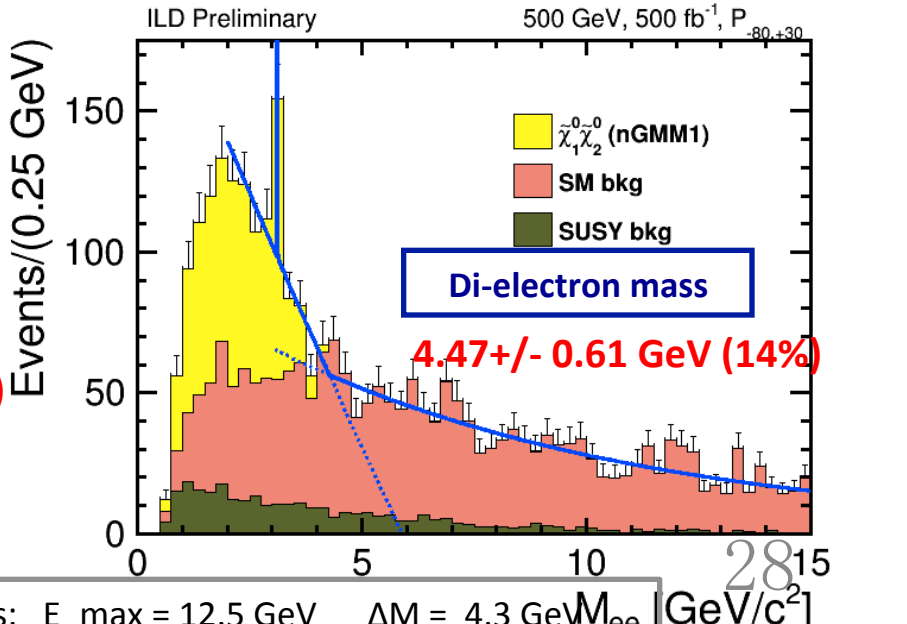
Di-emuon mass

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