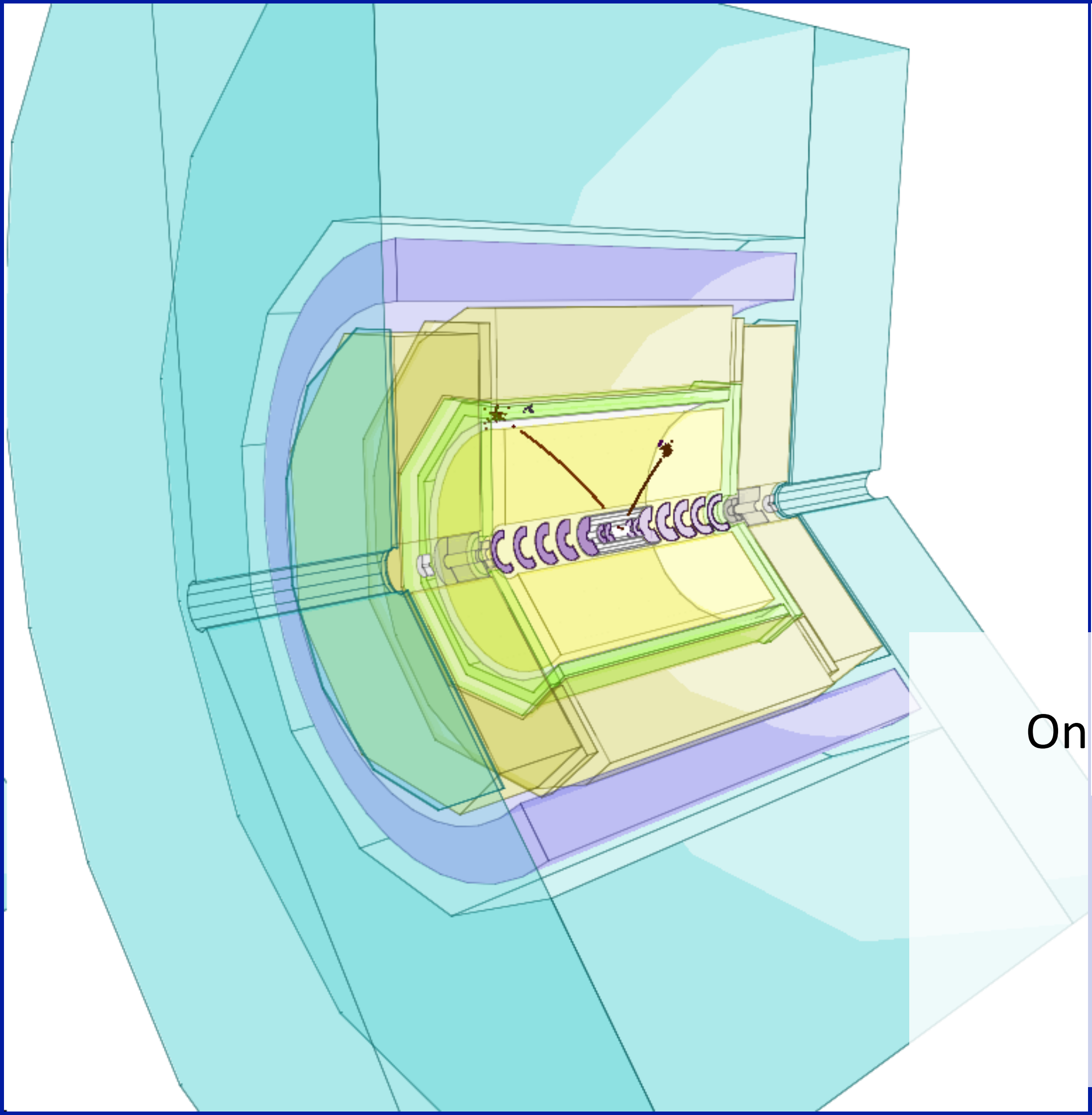
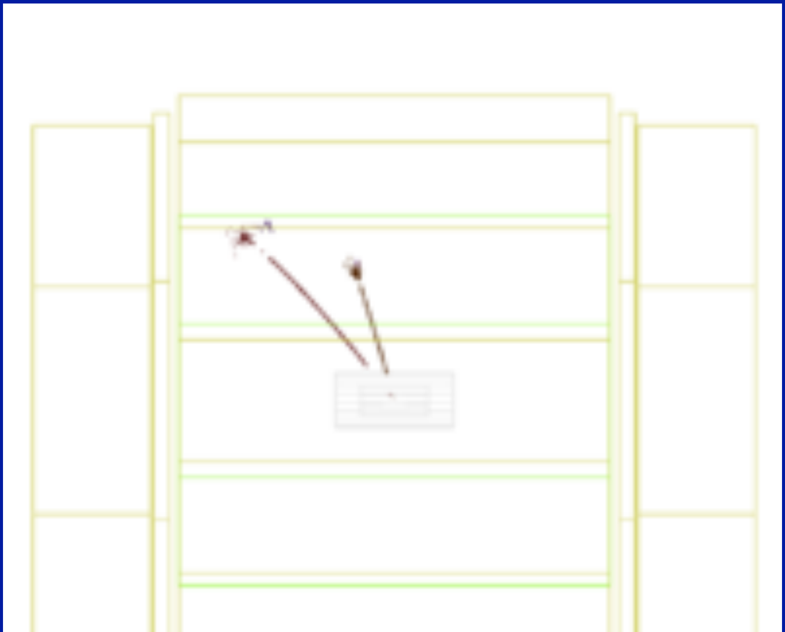
Characterizing Light Higgsinos from Natural SUSY at ILC √s = 500 GeV





Jacqueline Yan (KEK)
On behalf of the ILD BSM study group

ILD Software and Analysis Meeting

Aug 10, 2016

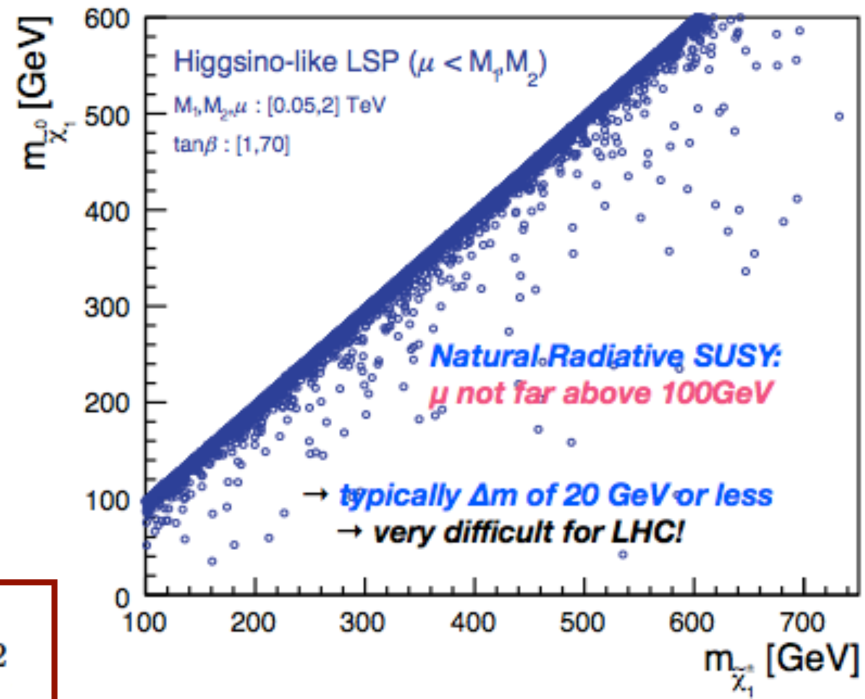
Outline

- ◆ **Update on edge and xsec extraction**
  - now using new full sim samples
  - Edge extraction has been done for all N1N2 channels , both polarizations
  - Cross section extraction has been improved
- ◆ **Observe effect of cuts , using MC truth info**
- ◆ **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]

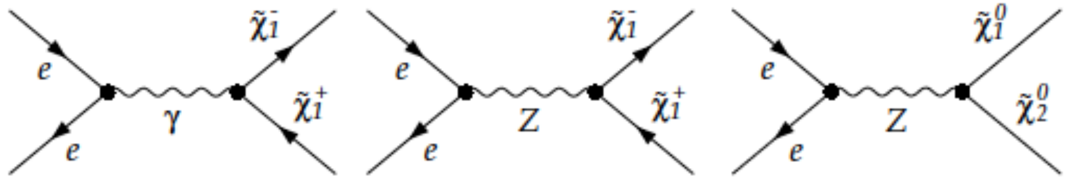
$$\frac{M_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

- 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: **√s = 500 GeV, assume L = 500 fb-1**
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

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

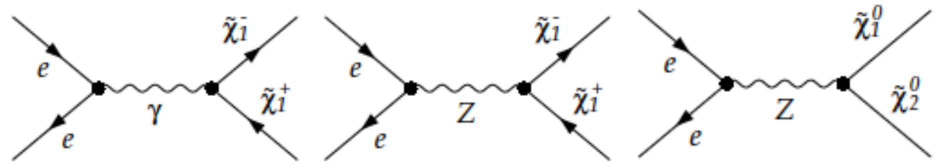
NUHM2 model parameters [arXiv:1404.7510]

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

Extraction of Higgsino Mass

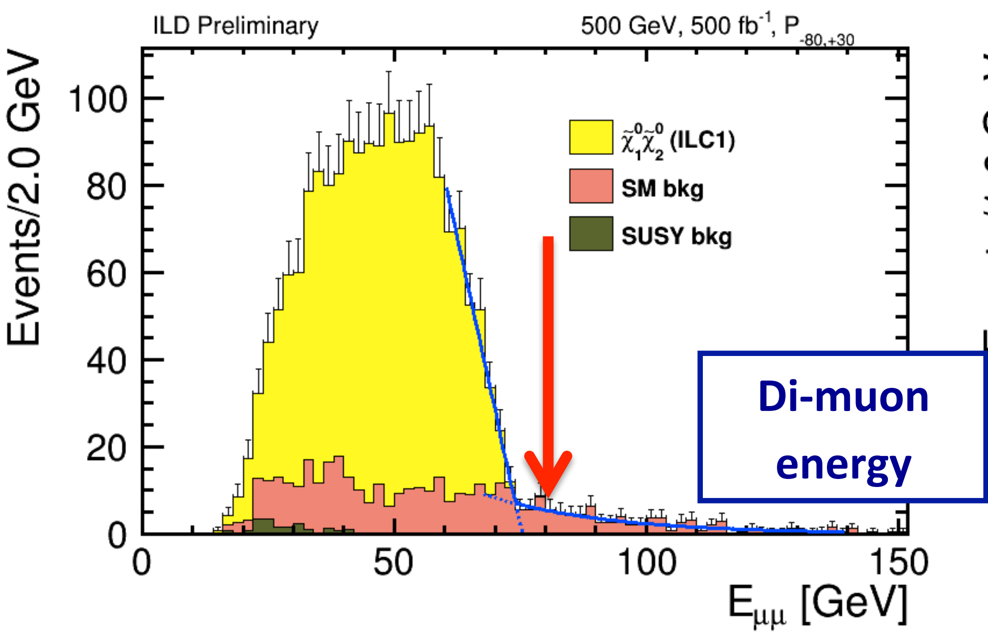
[work in progress] *Almost getting there*

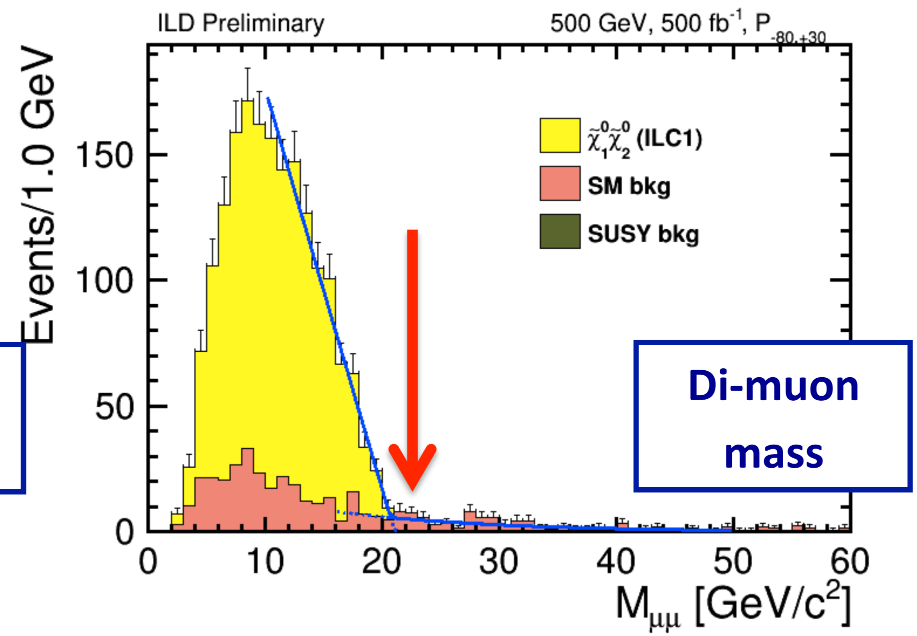
Neutralino mixed production with leptonic decay

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

- 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)





Edge precision ~ 1 %

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

What has been changed since last time (July 13)

Optimized method for extraction of edge and cross section

- **Modeling of complex signal and bkg distributions (energy , invariant mass)**
- **Bin width, fitting range**

Still fine tuning in aim of better precision

e.g. Loosen cuts for edge extraction, tighter cuts for cross section extraction (?)

Now using full simulation bkg samples

(thanks to Miyamoto-san and others in the software group)

Took a while to check the samples and interpret difference between SGV

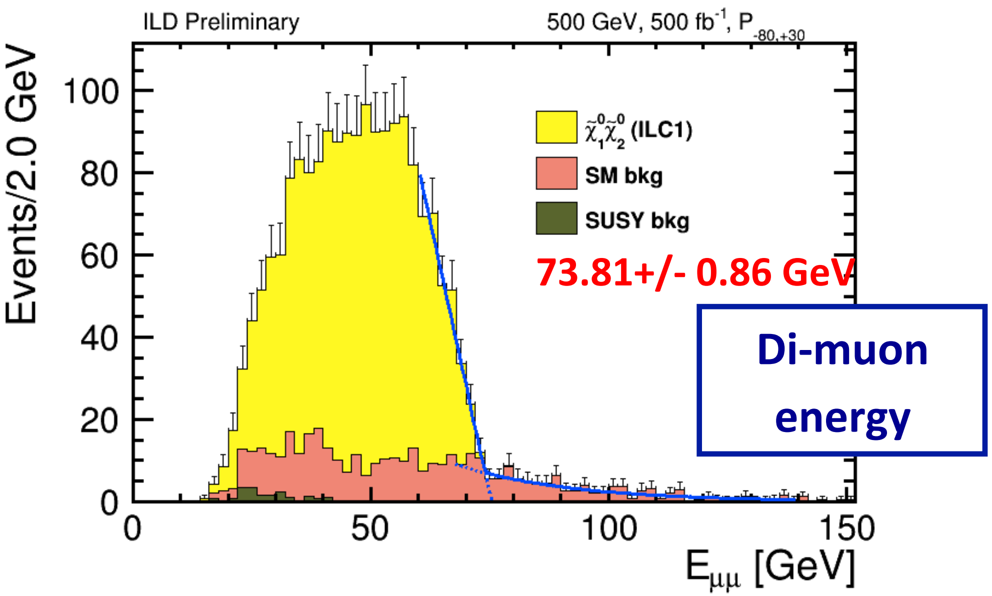
Analysis has been done (partially) for right-handed polarization as well.

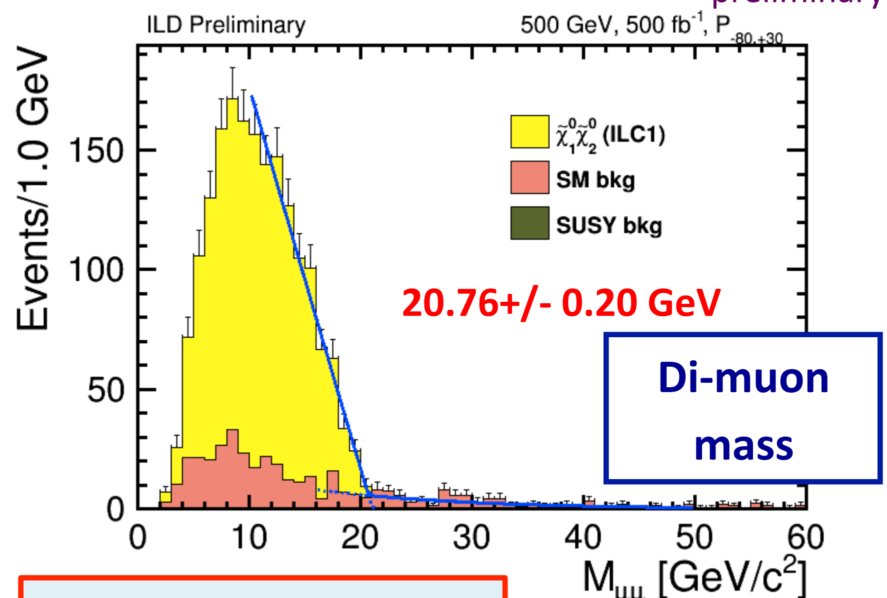
Neutralino mixed production with leptonic decay

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

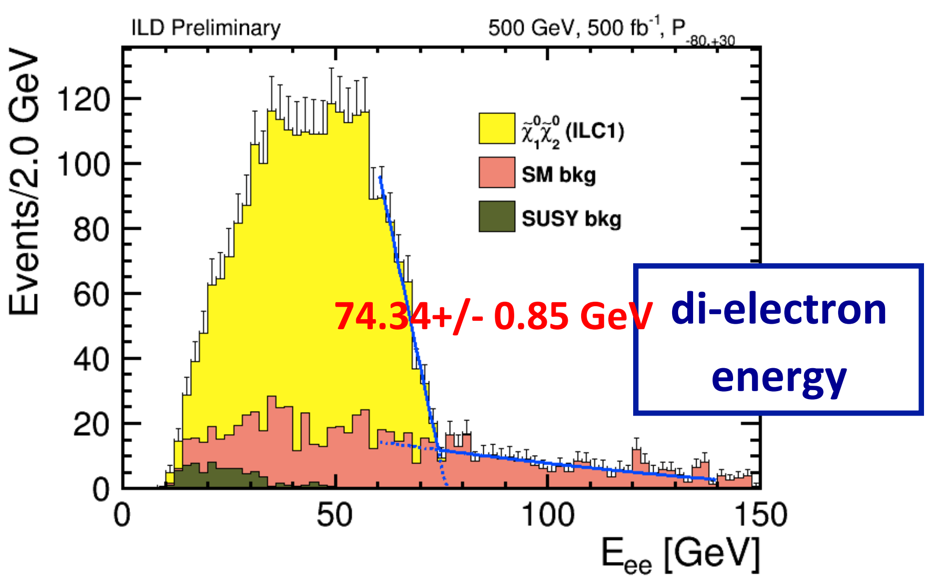
Polarization (Pe-,Pe+) = (-0.8, +0.3)

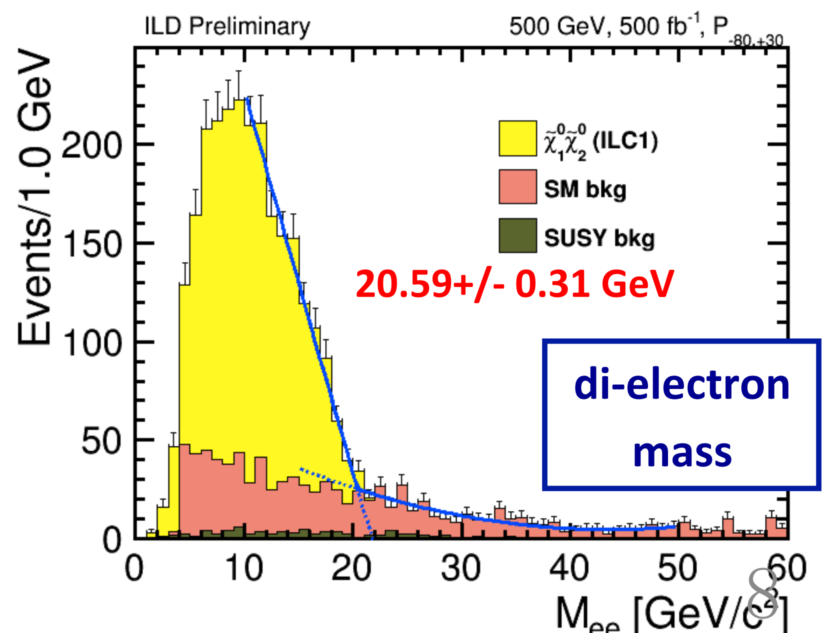
preliminary





Edge precision ～ 1 %





Neutralino mixed production with leptonic decay

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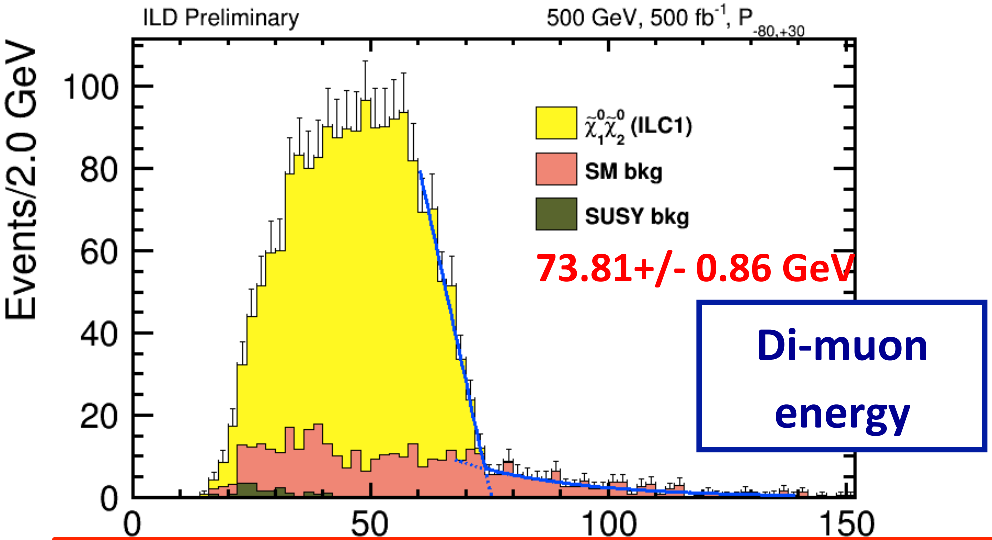
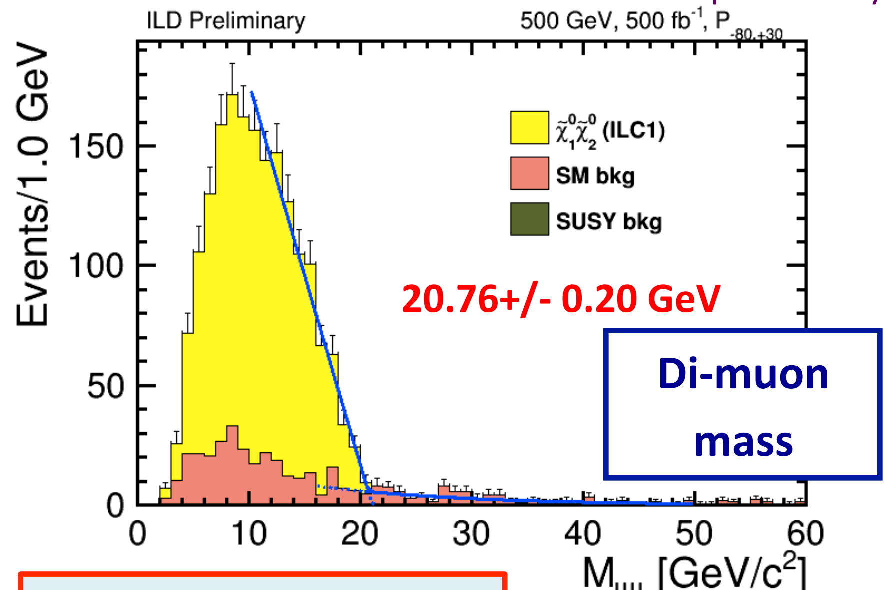
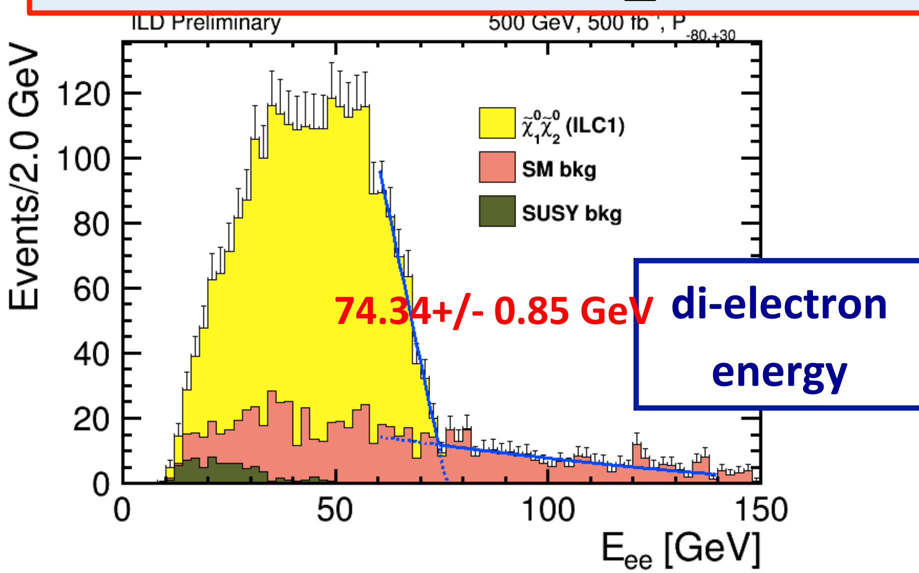
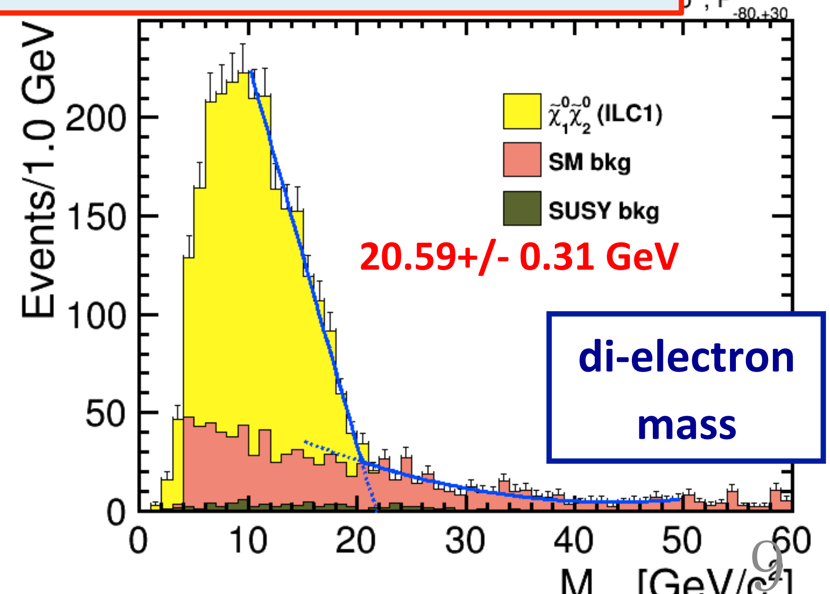




Theoretical values: E_max = 74.9 GeV ΔM = 21.3 GeV





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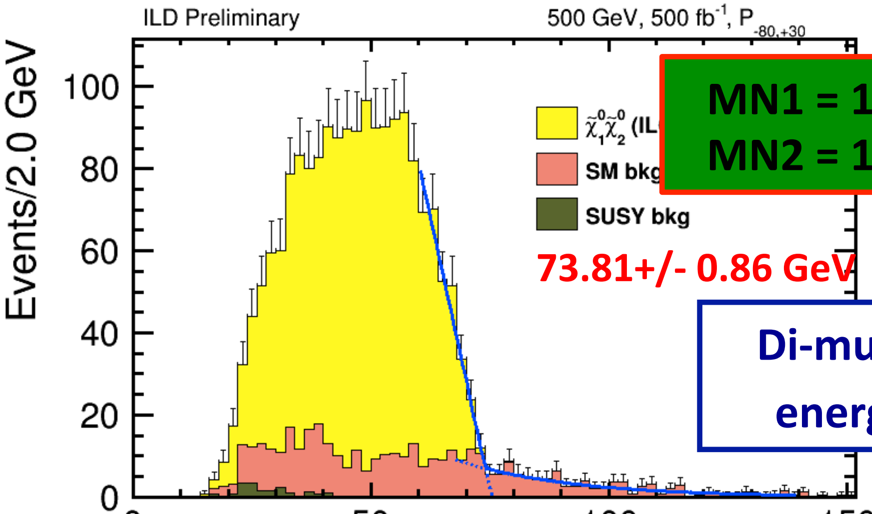
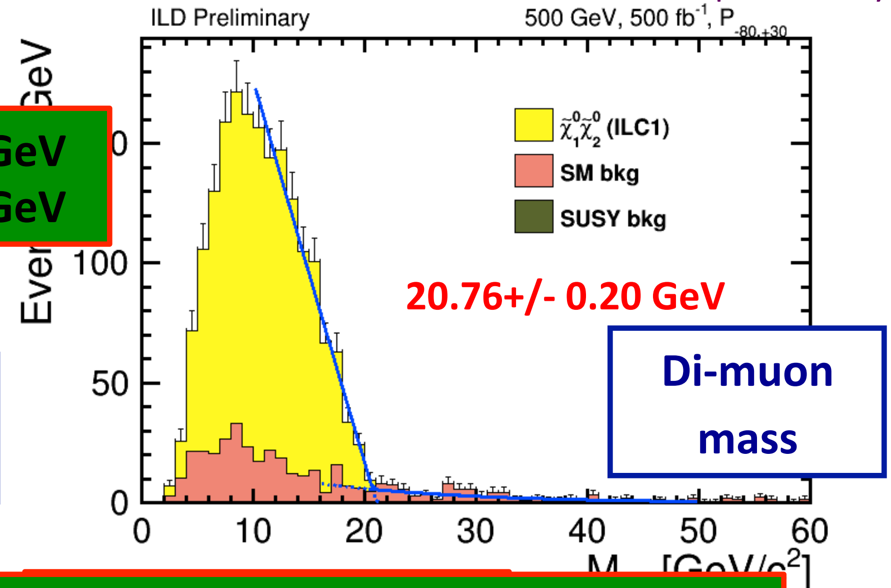
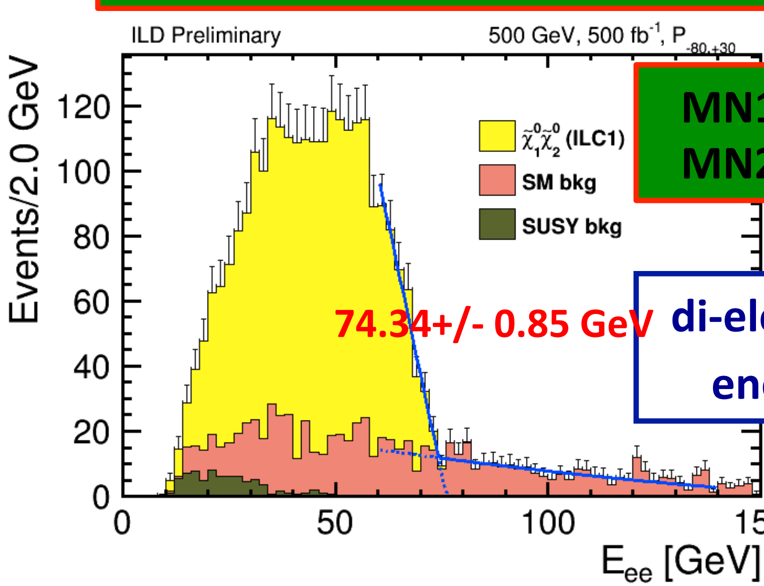


MN1 = 102.3 GeV
MN2 = 123.0 GeV



Theoretical values: MN1 = 102.7 GeV MN2 = 124.0 GeV



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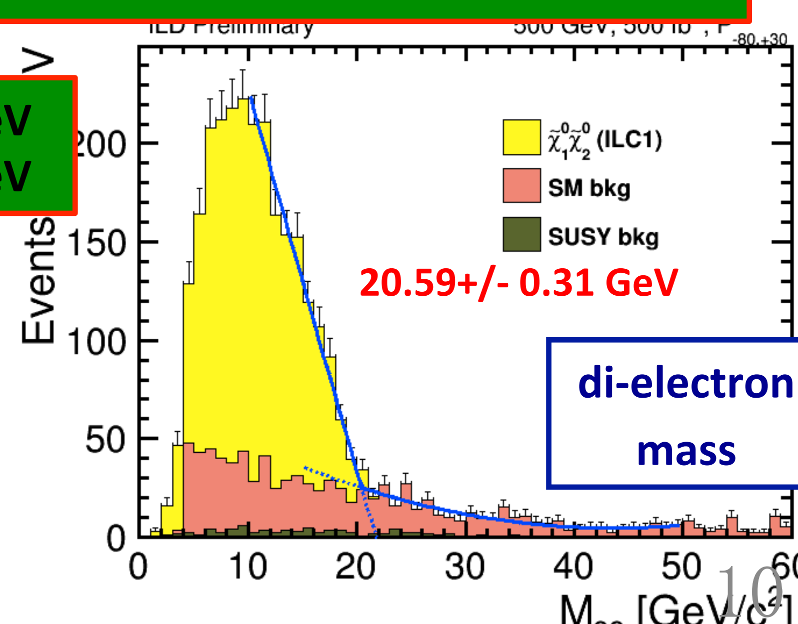


Neutralino mixed production with leptonic decay

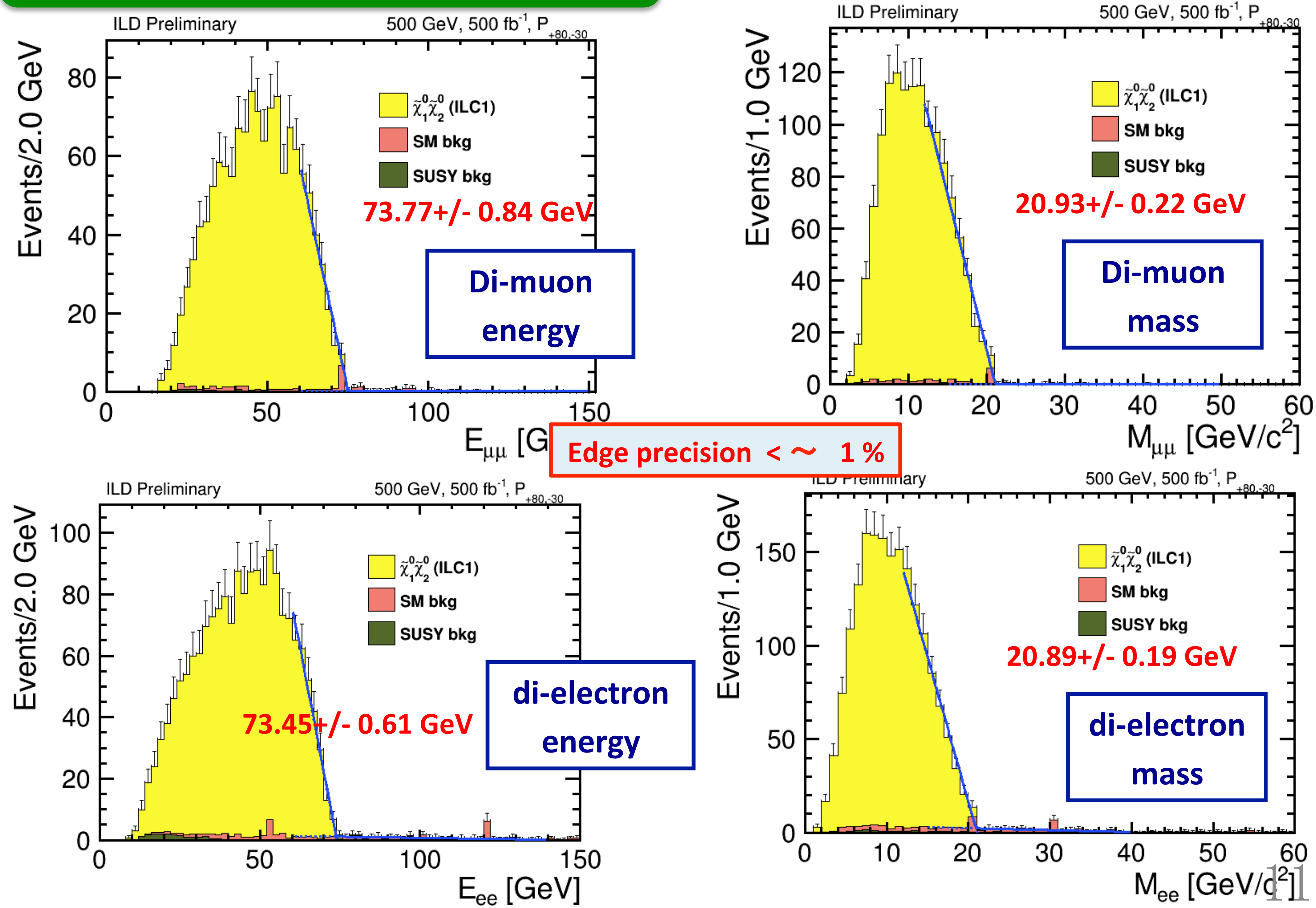
$$e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ell^+ \ell^-$$

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

Much less bkg

Precision slightly better (?)

preliminary



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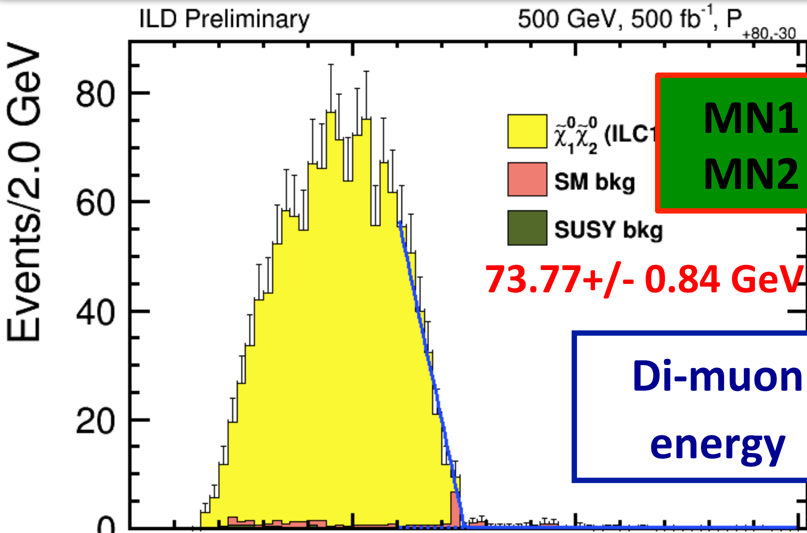
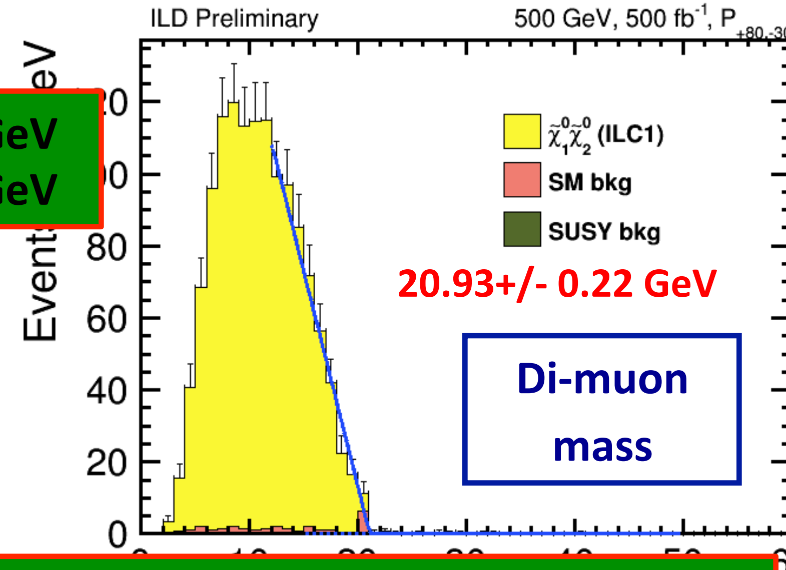


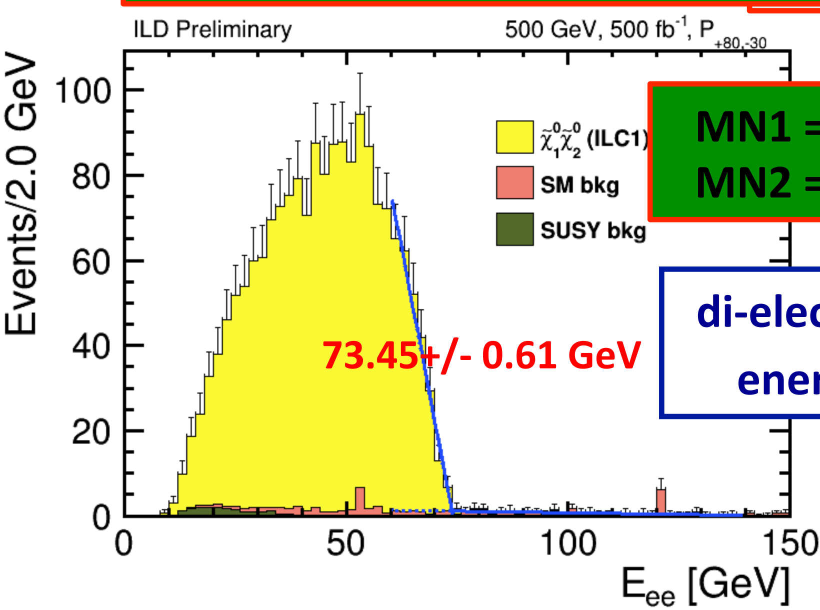
MN1 = 103.1 GeV
MN2 = 124.0 GeV

Di-muon energy



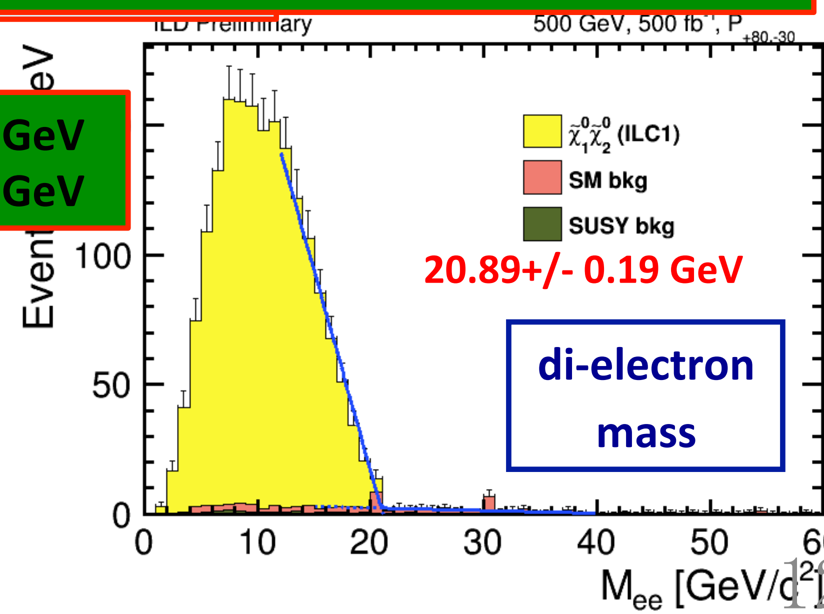
Di-muon mass

Theoretical values: MN1 = 102.7 GeV MN2 = 124.0 GeV



MN1 = 103.4 GeV
MN2 = 124.3 GeV

di-electron energy



di-electron mass

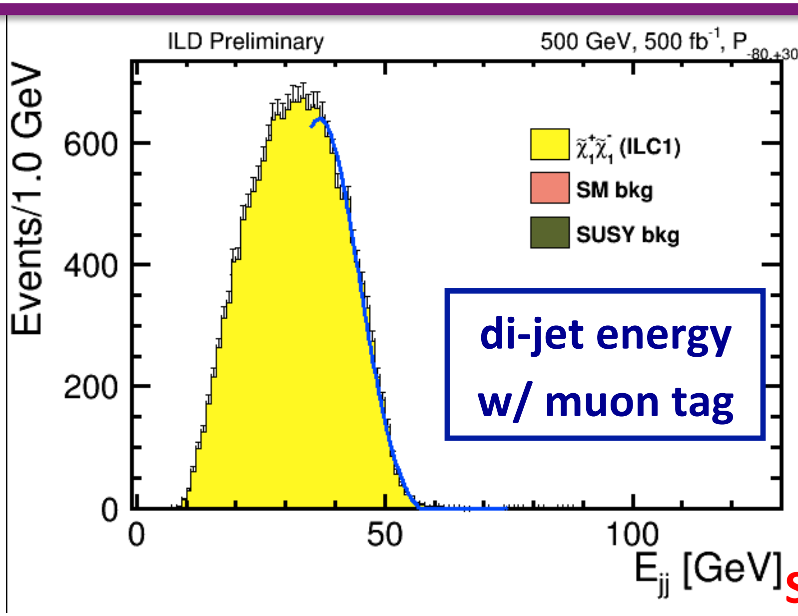
Chargino pair production with semileptonic decay

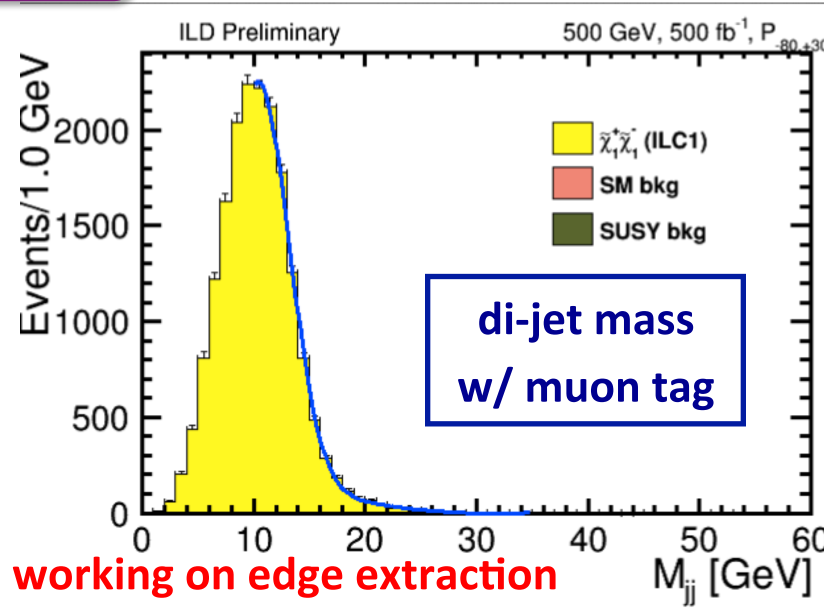
$$e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 qq'\ell\nu$$

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

SM and SUSY backgrounds almost fully eliminated

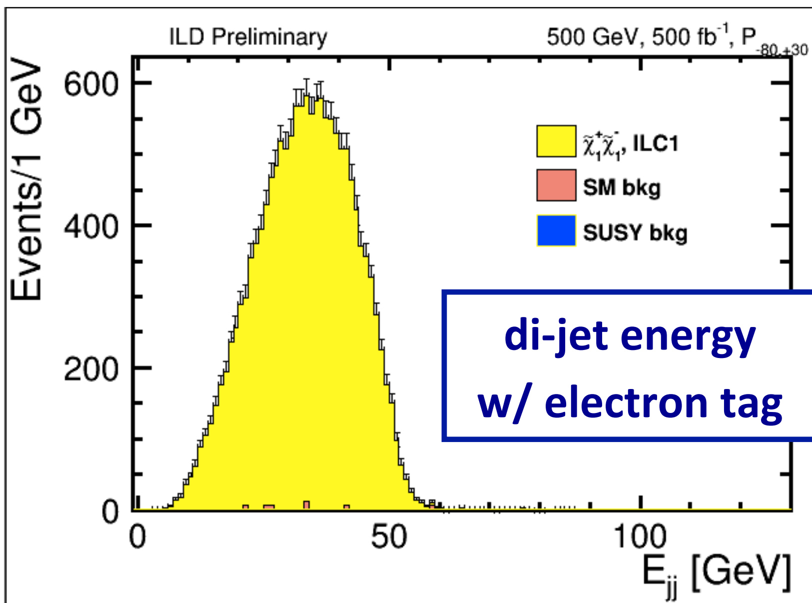
preliminary

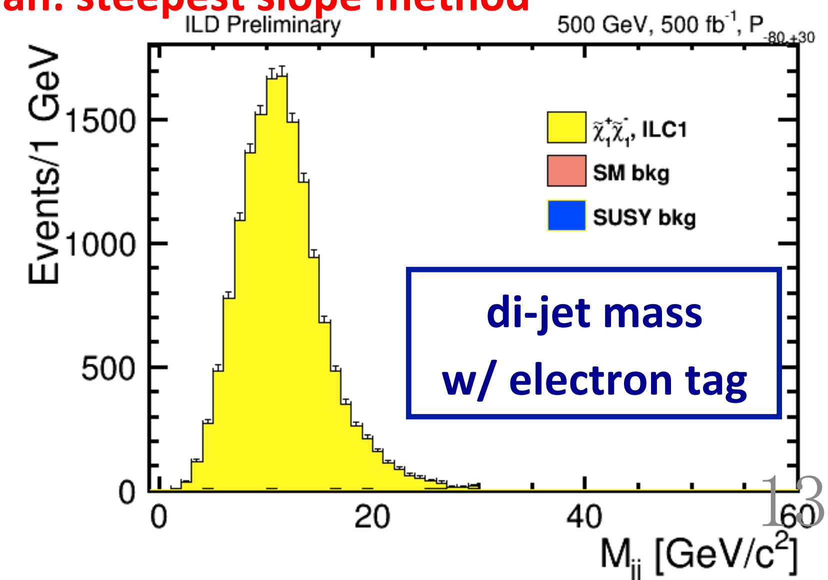




Still working on edge extraction

Plan: steepest slope method





Extraction of Cross Section [work in progress]

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

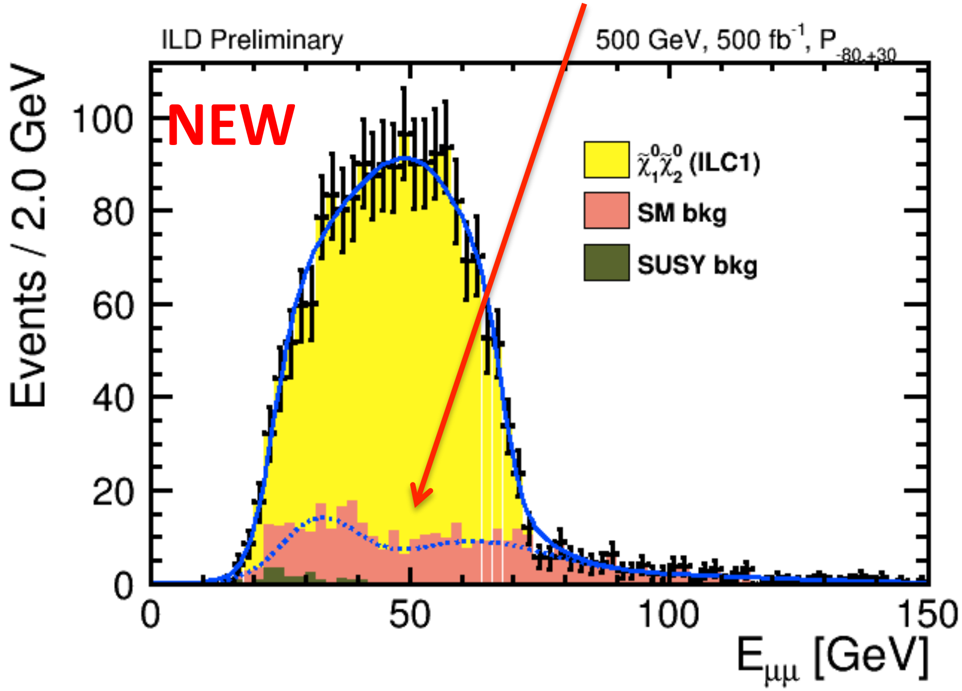
Δσ/σ = 3.4%

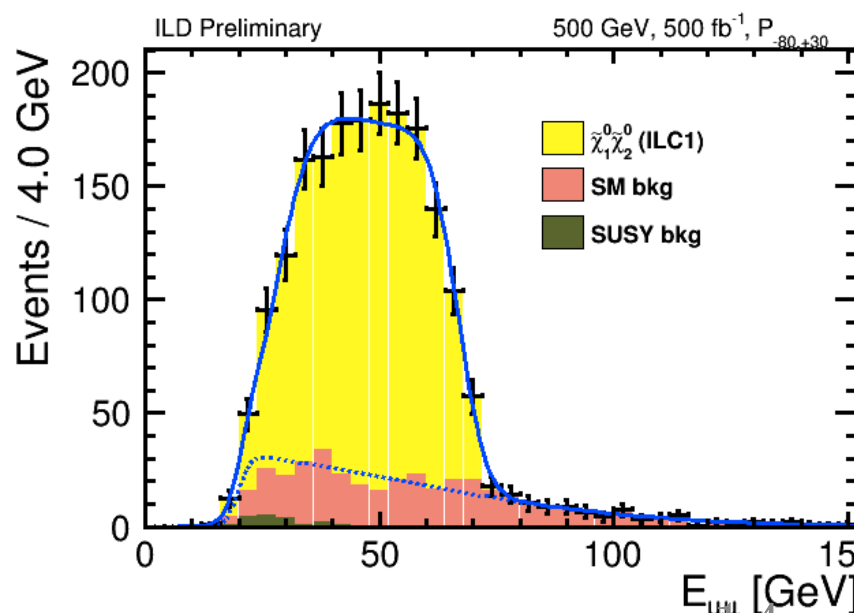
Neutralino mixed production with leptonic decay

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

Better modeling of bkg shape
→ improve cross section precision

OLD
(reported at ILD meeting on 7/13)





di-muon energy, left pol.

Extraction of Cross Section [work in progress]

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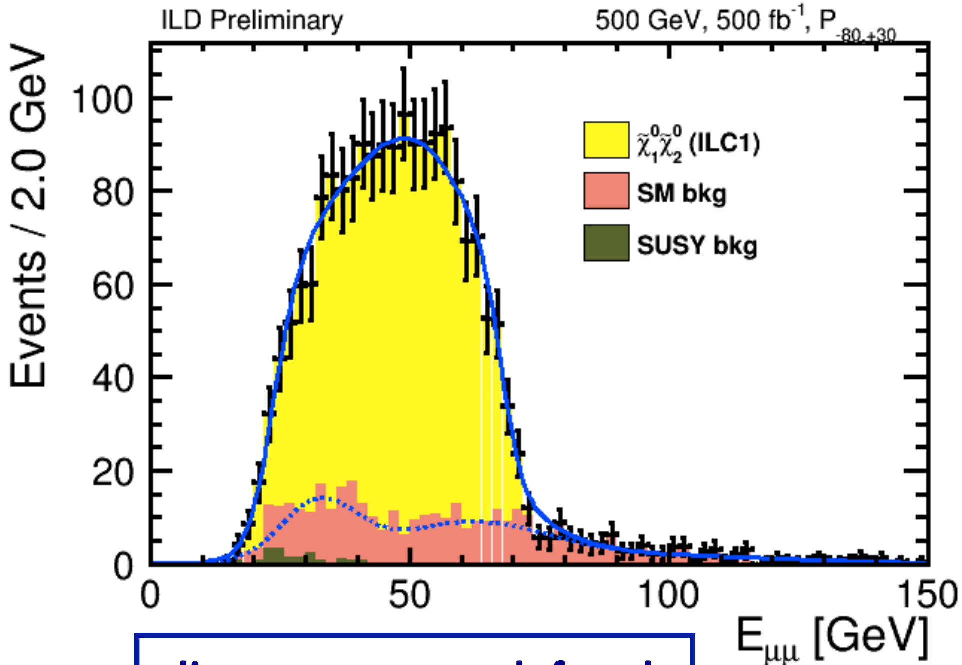
Neutralino mixed production with leptonic decay

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

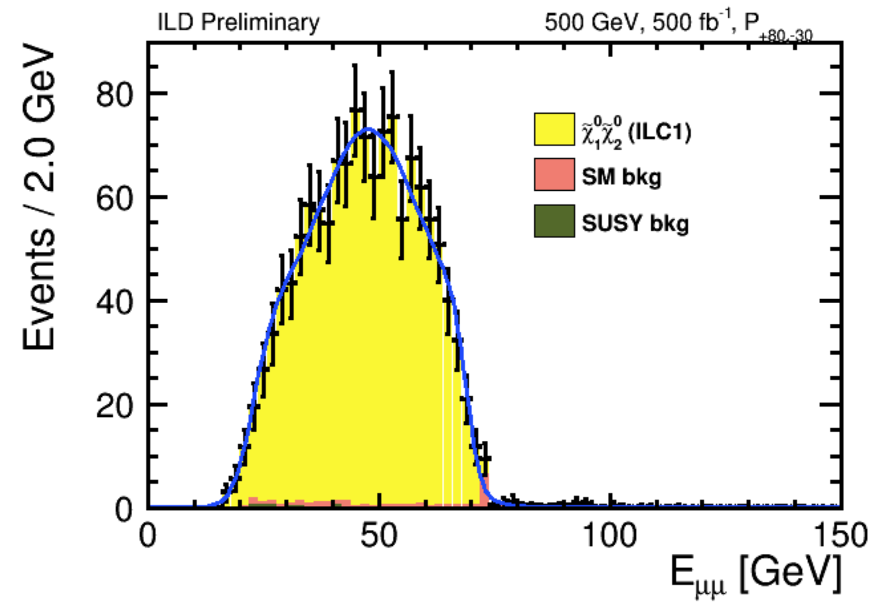
Now began evaluation of cross section for right hand pol also

$\Delta\sigma/\sigma$ = 3.4%



di-muon energy, left pol.

$\Delta\sigma/\sigma$ = 2.8%



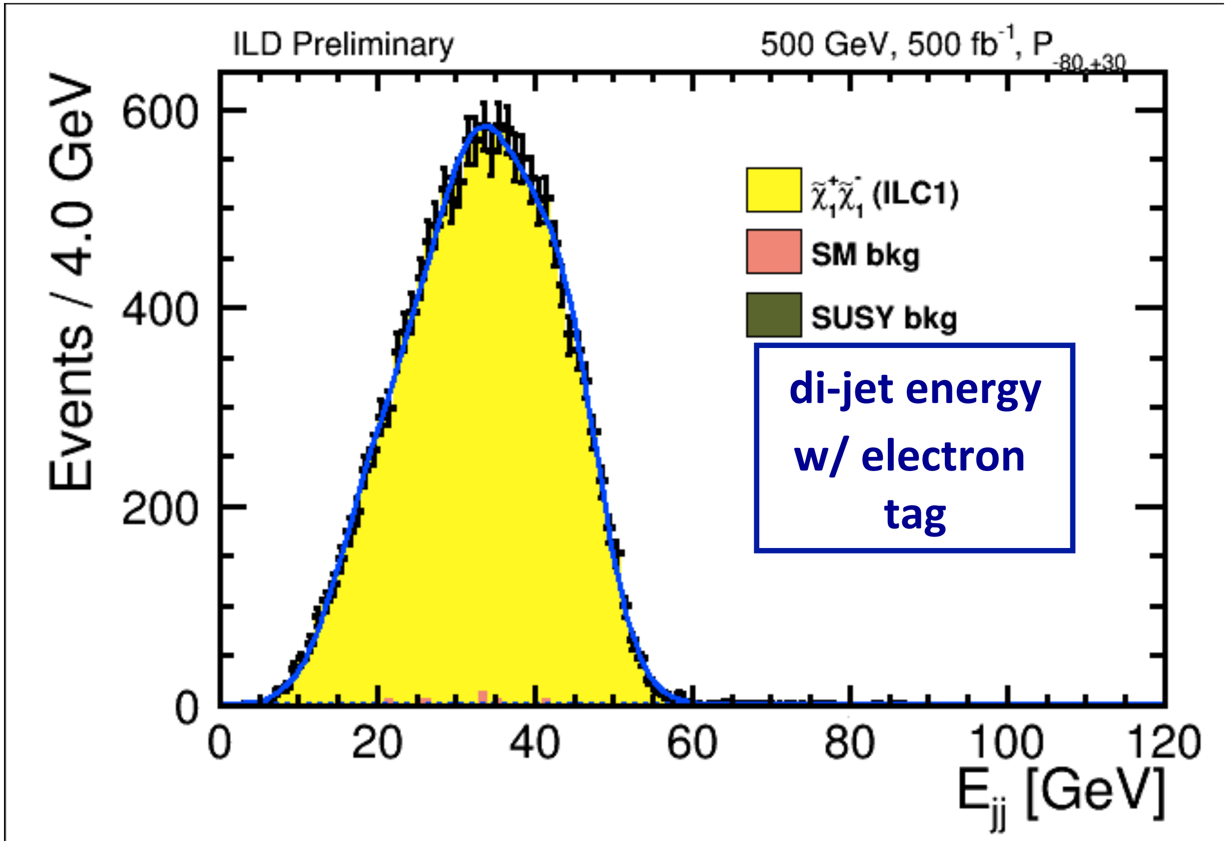
di-muon energy, right pol.

Extraction of Cross Section [work in progress]

Chargino pair production with semileptonic decay

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

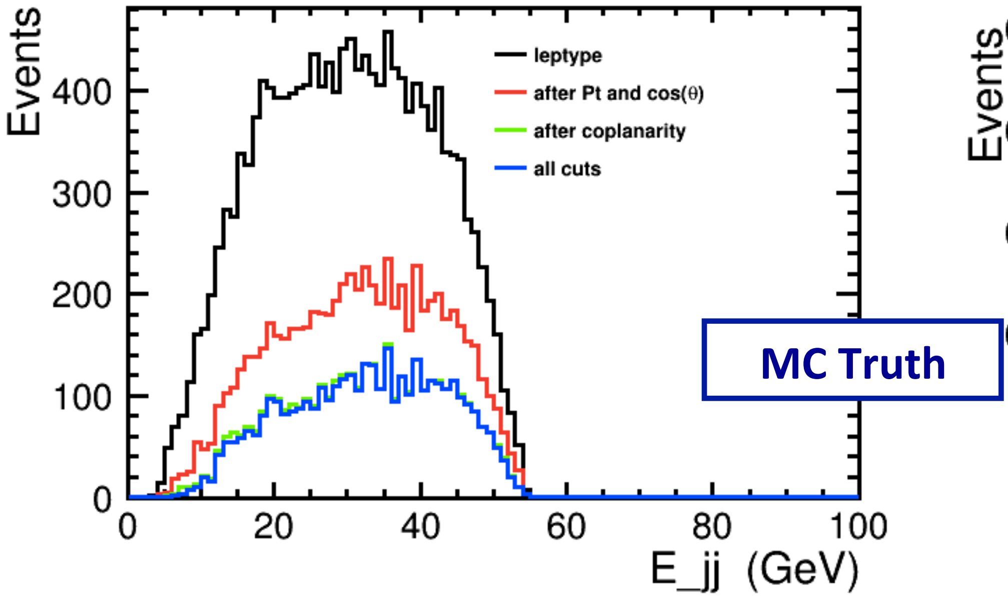
Polarization (Pe-,Pe+) = (-0.8, +0.3)

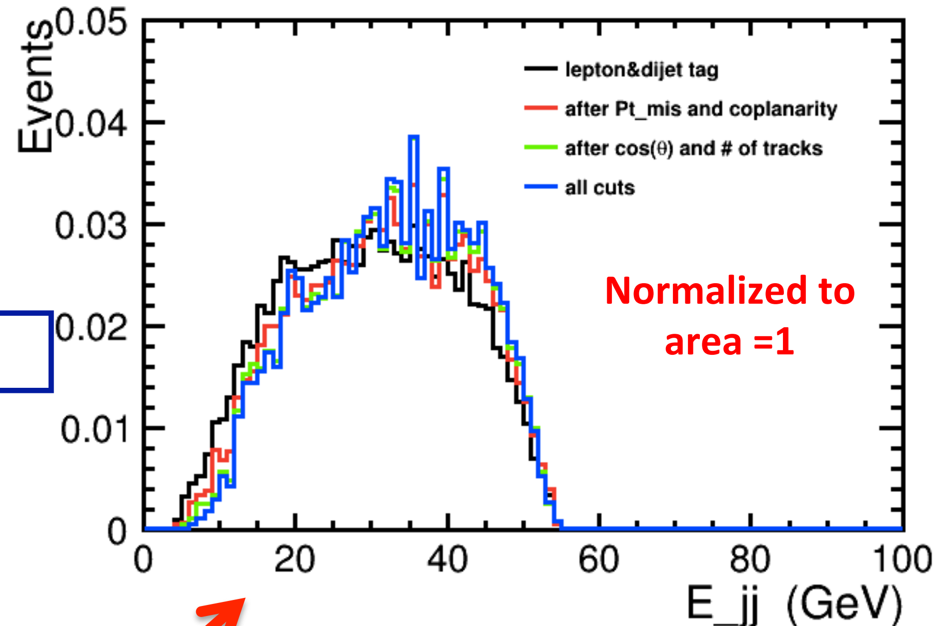


Δσ/σ = 0.8 %

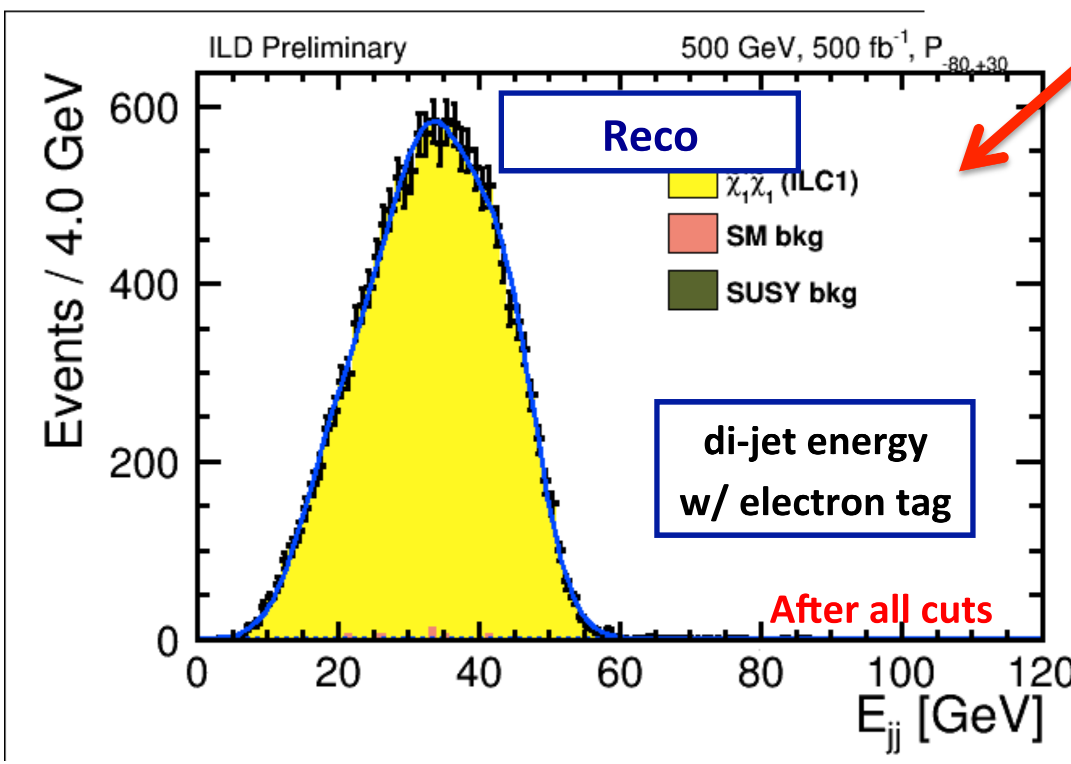
Fit with triple Gaussian

Other channels have similar shapes in the case of chargino





Looks SAME



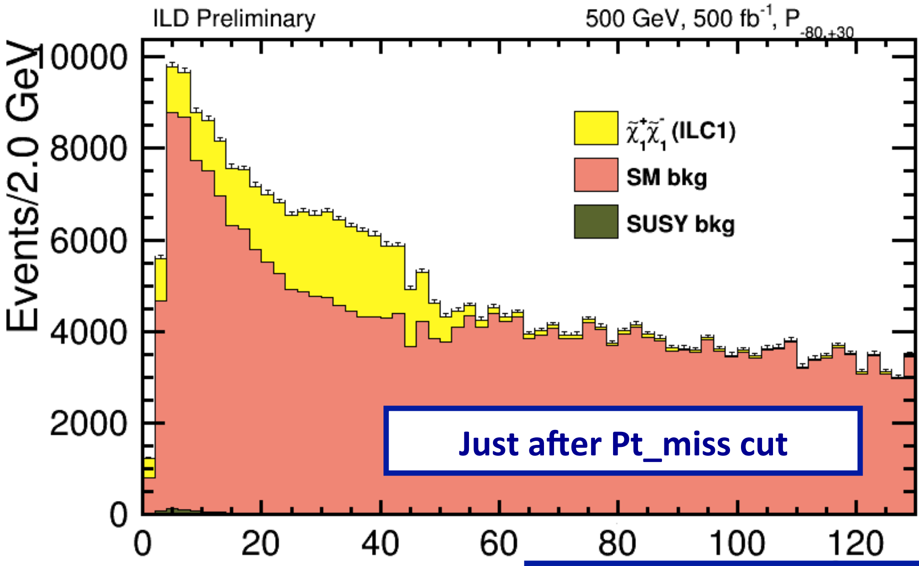
Change in distribution of Di-jet energy with respect to cuts (SIGNAL)

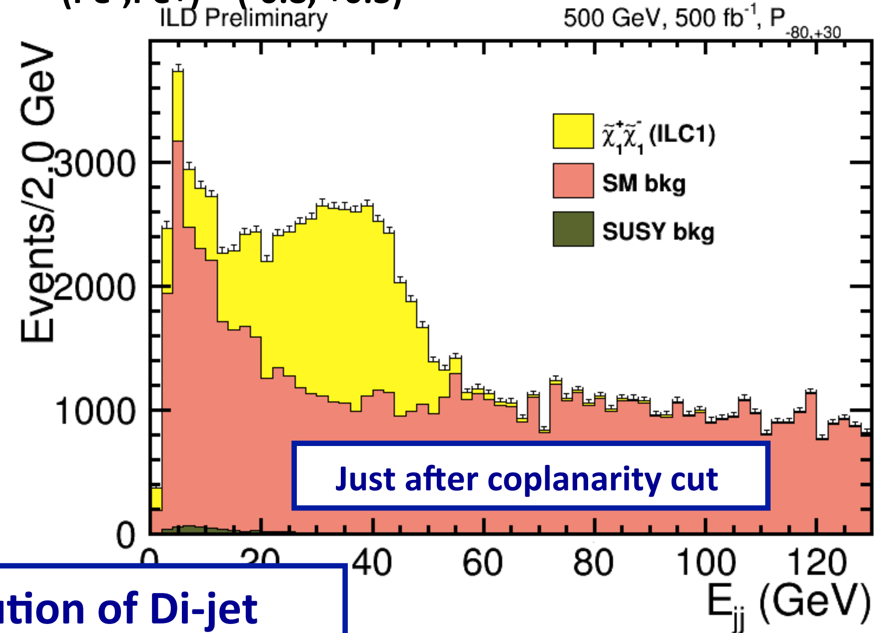
Cuts applied on Reconstructed variables

Chargino pair production with semileptonic decay

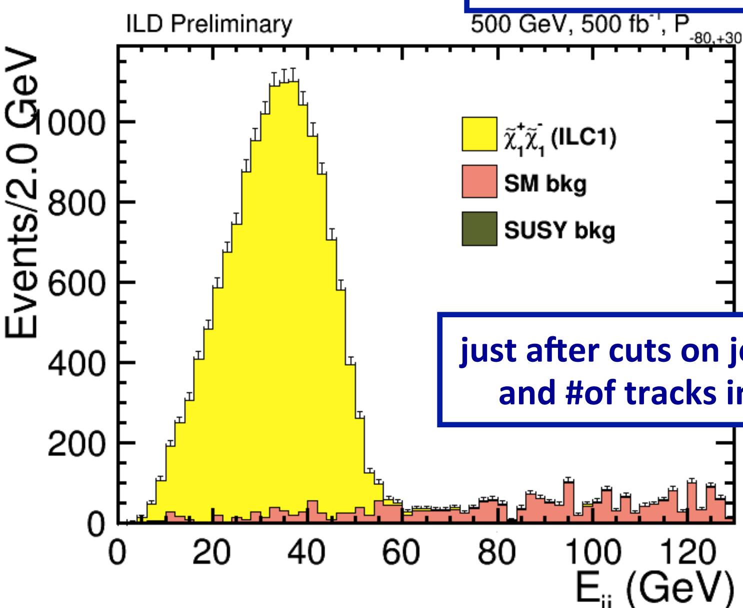
$$e^+e^- \to \tilde{\chi}_1^+\,\tilde{\chi}_1^- \to \tilde{\chi}_1^0\,\tilde{\chi}_1^0 qq'\ell\nu$$

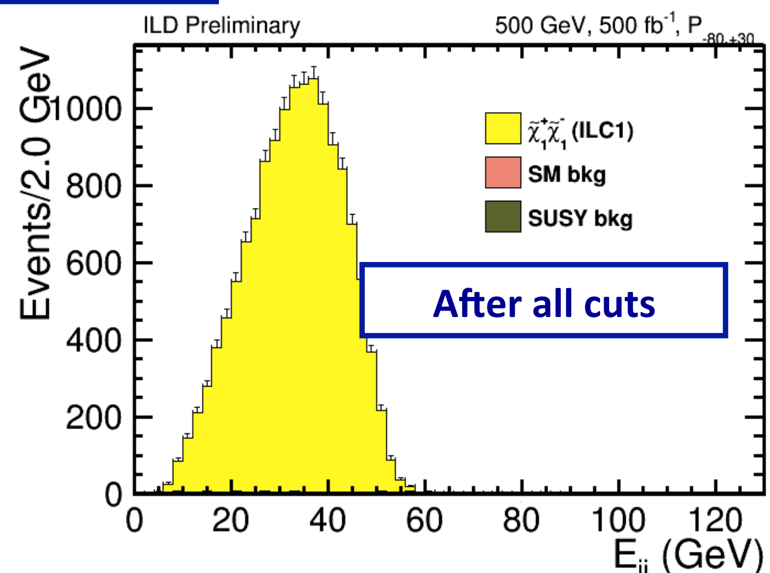
(Pe-,Pe+) = (-0.8, +0.3)





Change in distribution of Di-jet energy with respect to cuts (BKG)





Summary

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

- Motivated by both experiment (complementary to LHC) and theory (naturalness)
- Analysis of neutralino mixed production ($\chi_1^0 \chi_2^0$) and chargino pair production ($\chi_1^+ \chi_1^-$)
- Full ILD detector simulation, L=500 fb-1 at √s = 500 GeV, (Pe-, Pe+) = (-0.8,+0.3),(+0.8, -0.3)
- Data selection yields good S/B ratio ; almost no bkg for chargino
- Fit kinematic edges to extract Higgsino masses
- Fit to overall distribution to extract production cross sections

in progress

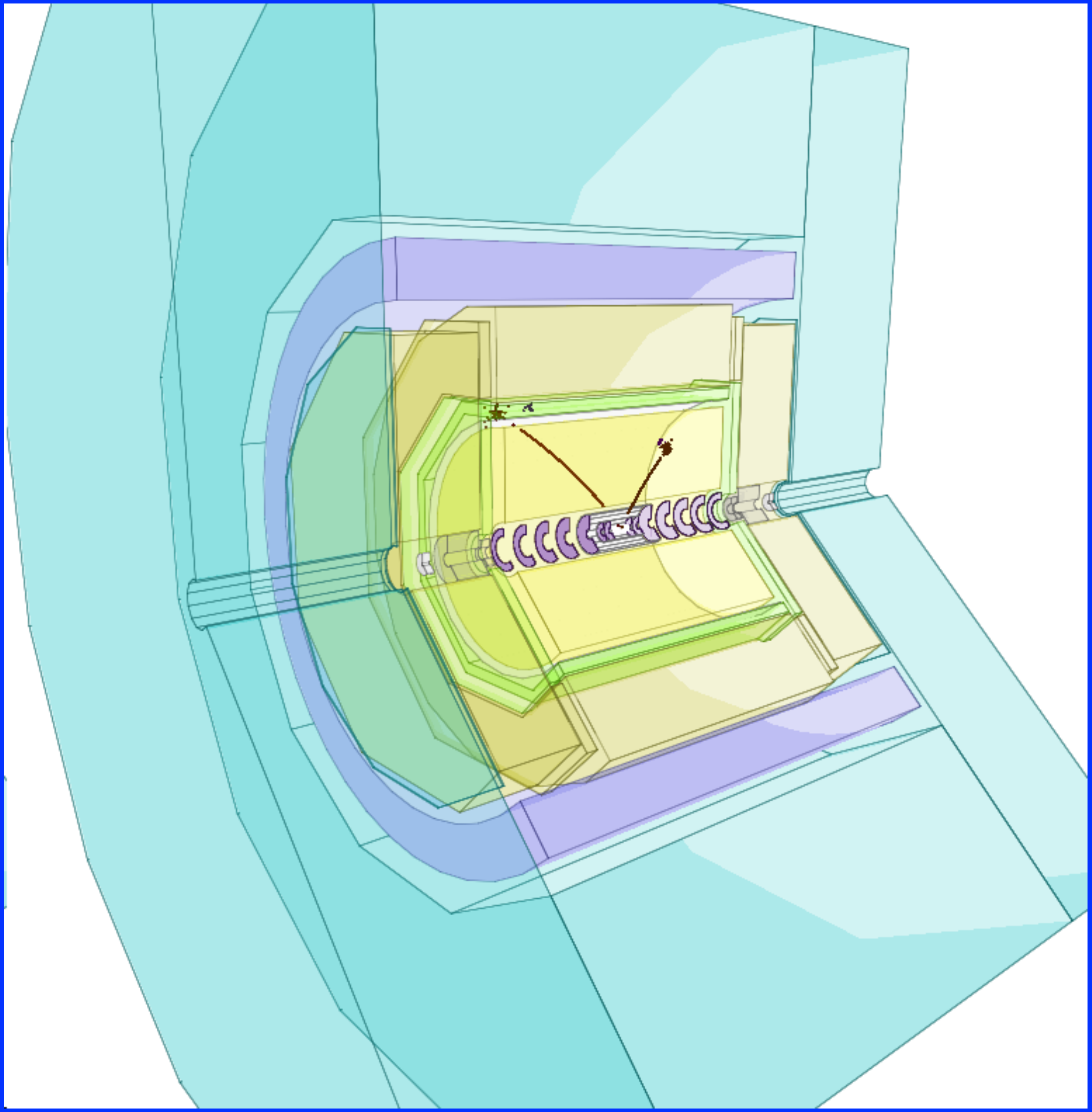
preliminary results for most channels

- Neutralino: Edge precision ~% , Cross section precision 3-4 % for left pol, 2.8% for right pol
- Edge values not far from theoretical values, need some correction for detector effects
- Chargino : Cross section precision : 0.8%, Still working on edge extraction

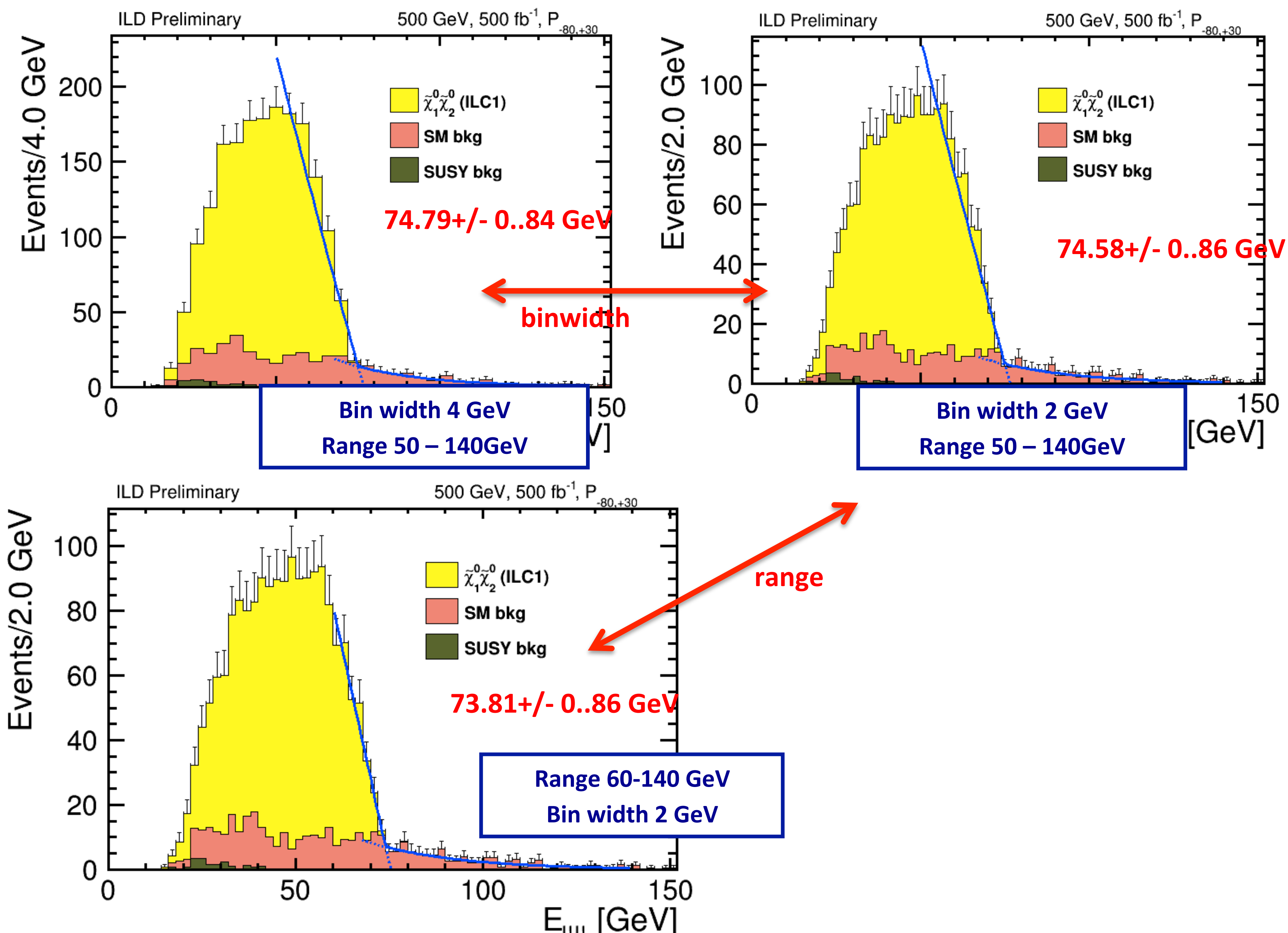
Plans

- Converge current analysis to a full set of results (chargino edge, propagation to Higgsino masses)
  → input to document which includes ILC new physics discovery potential
- Need to implement gamma gamma overlay bkg
- Other CM energies and polarizations: input for studies on SUSY parameter determination

Thank you for listening

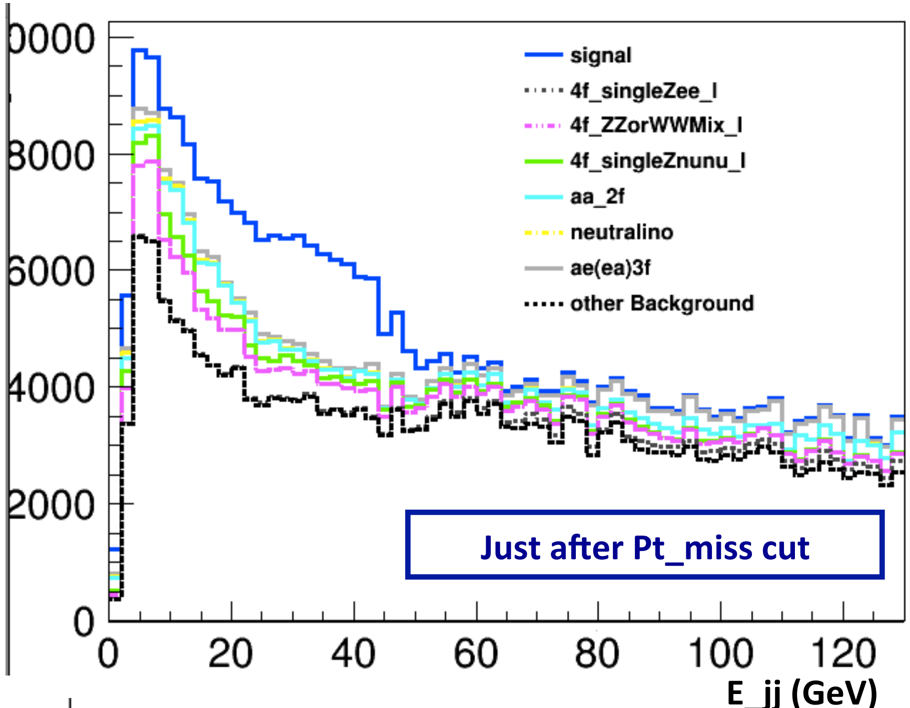


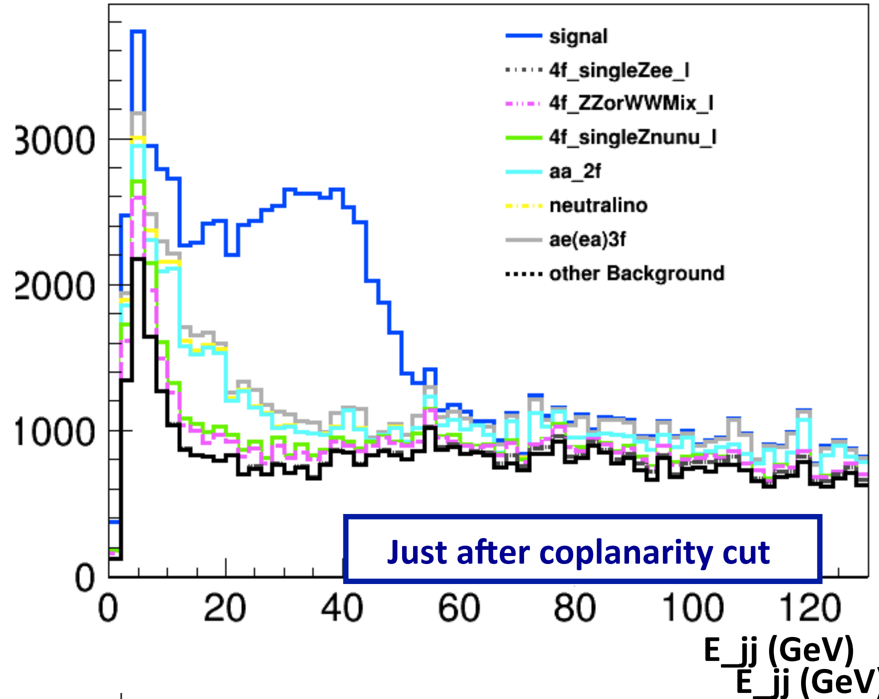
Additional Material

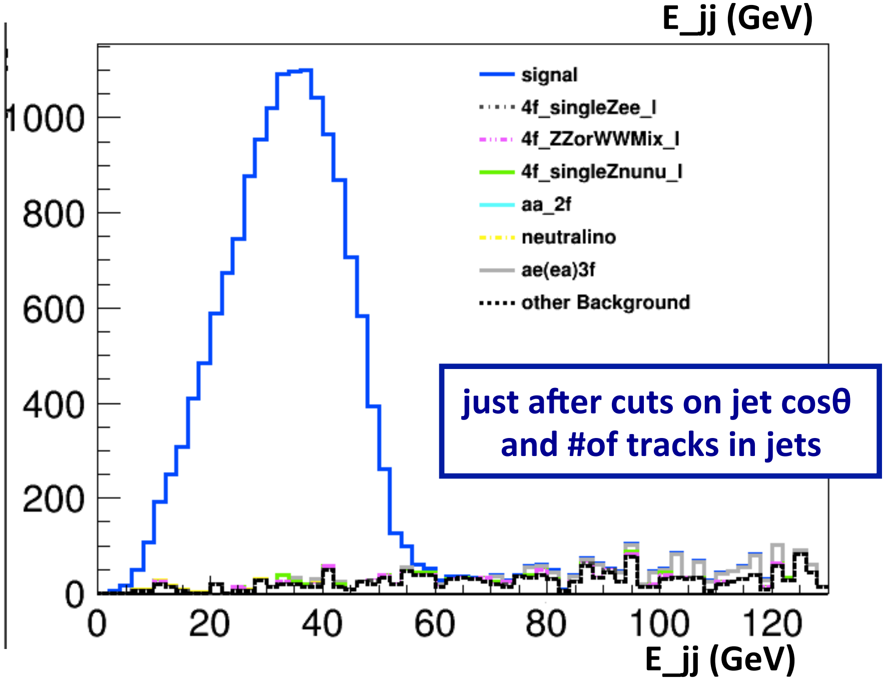

ILD Preliminary
500 GeV, 500 fb-1, P-80,+30
Events/4.0 GeV
χ̃10χ̃20 (ILC1)
SM bkg
SUSY bkg
74.79+/- 0..84 GeV
Bin width 4 GeV
Range 50 – 140GeV
binwidth
ILD Preliminary
500 GeV, 500 fb-1, P-80,+30
Events/2.0 GeV
χ̃10χ̃20 (ILC1)
SM bkg
SUSY bkg
74.58+/- 0..86 GeV
Bin width 2 GeV
Range 50 – 140GeV
[GeV]
range
ILD Preliminary
500 GeV, 500 fb-1, P-80,+30
Events/2.0 GeV
χ̃10χ̃20 (ILC1)
SM bkg
SUSY bkg
73.81+/- 0..86 GeV
Range 60-140 GeV
Bin width 2 GeV
Eμμ [GeV]

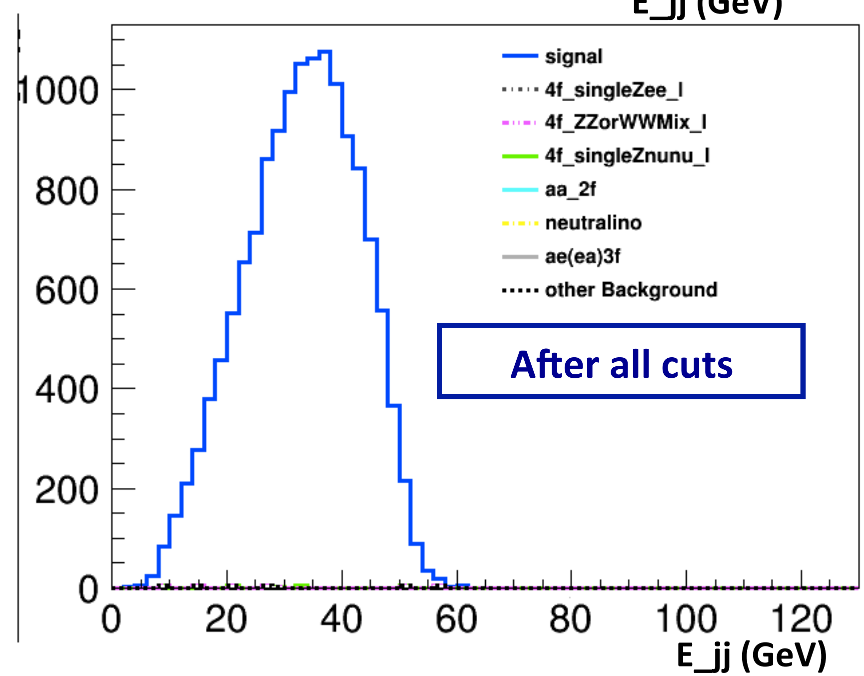
$$e^+e^- \to \widetilde{\chi}_1^+ \widetilde{\chi}_1^- \to \widetilde{\chi}_1^0 \widetilde{\chi}_1^0 qq'\ell\nu$$

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



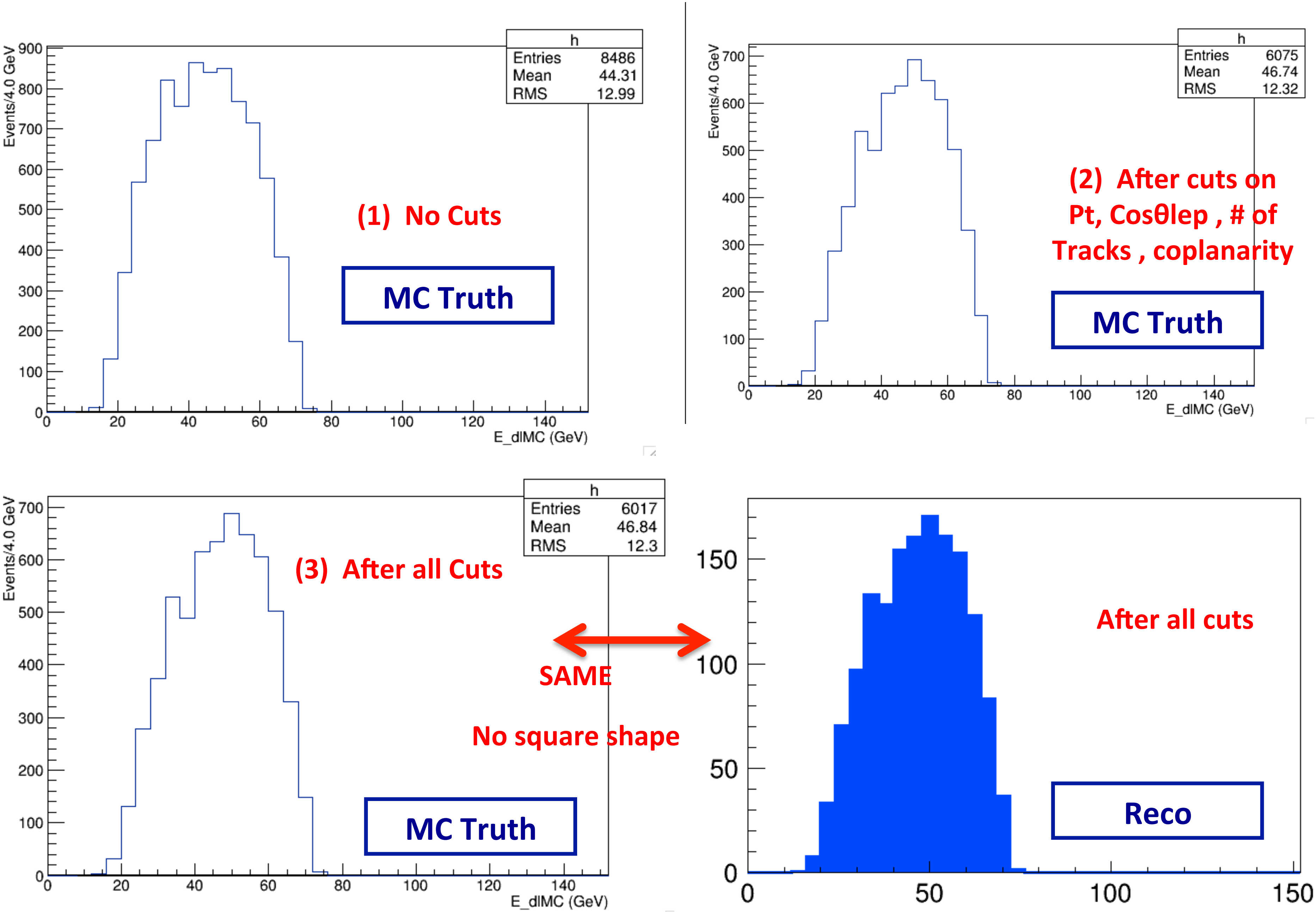


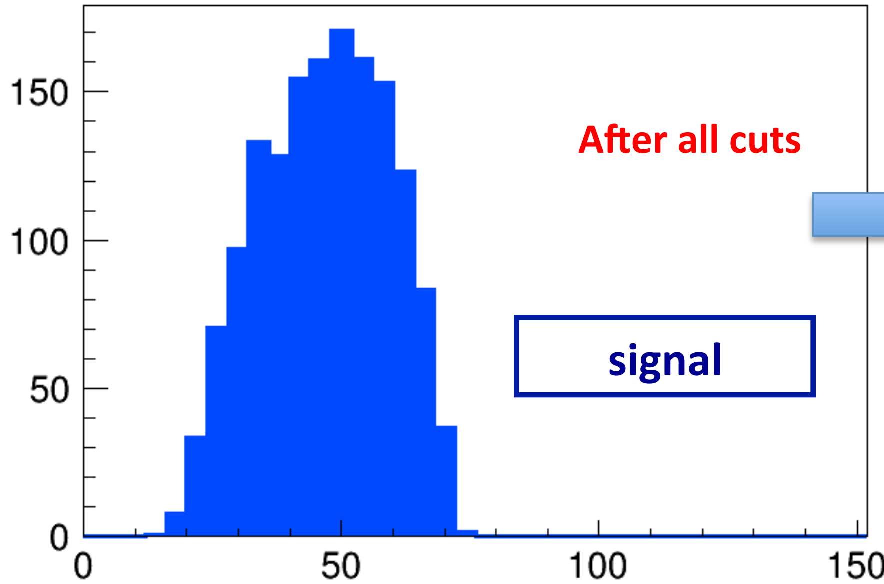




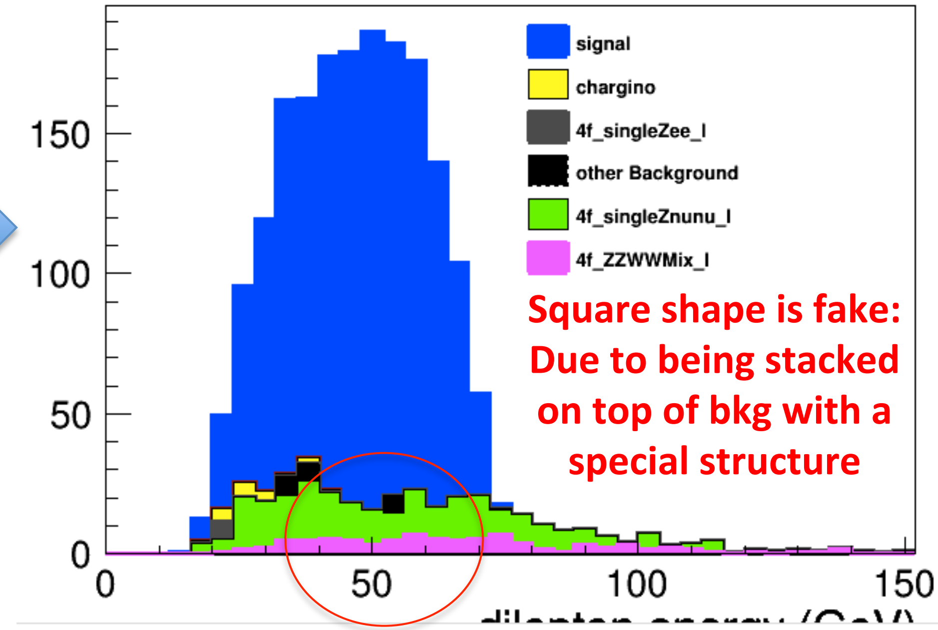
di-muon energy

Cuts applied on Reconstructed variables

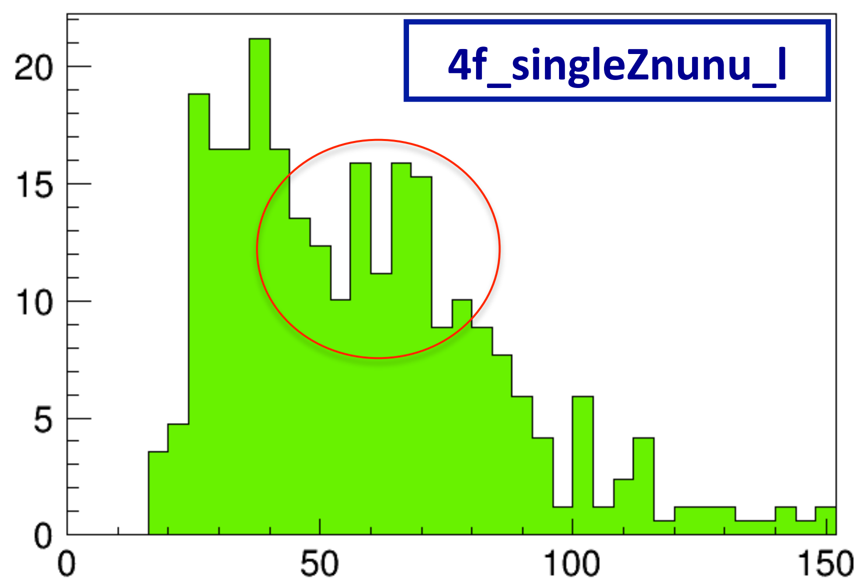




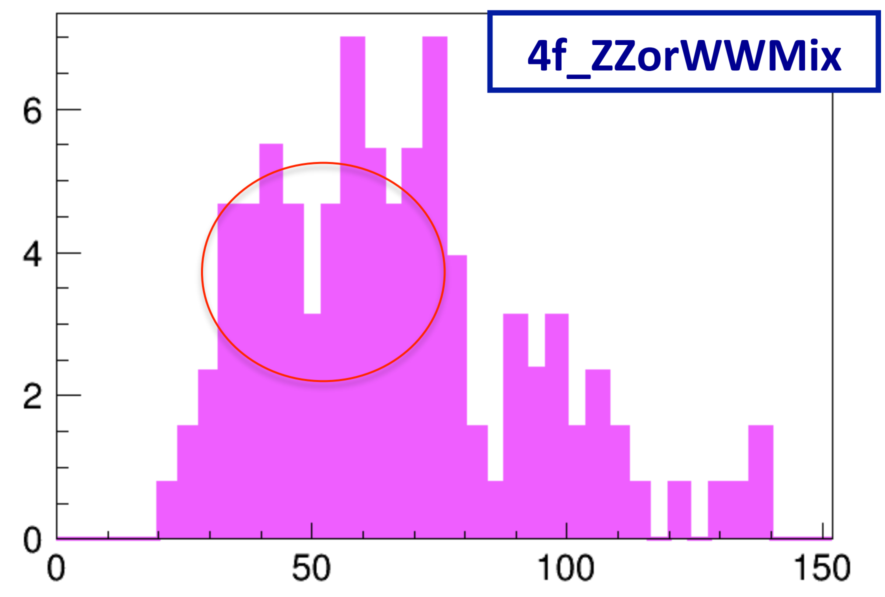
After all cuts
signal
0
50
100
150



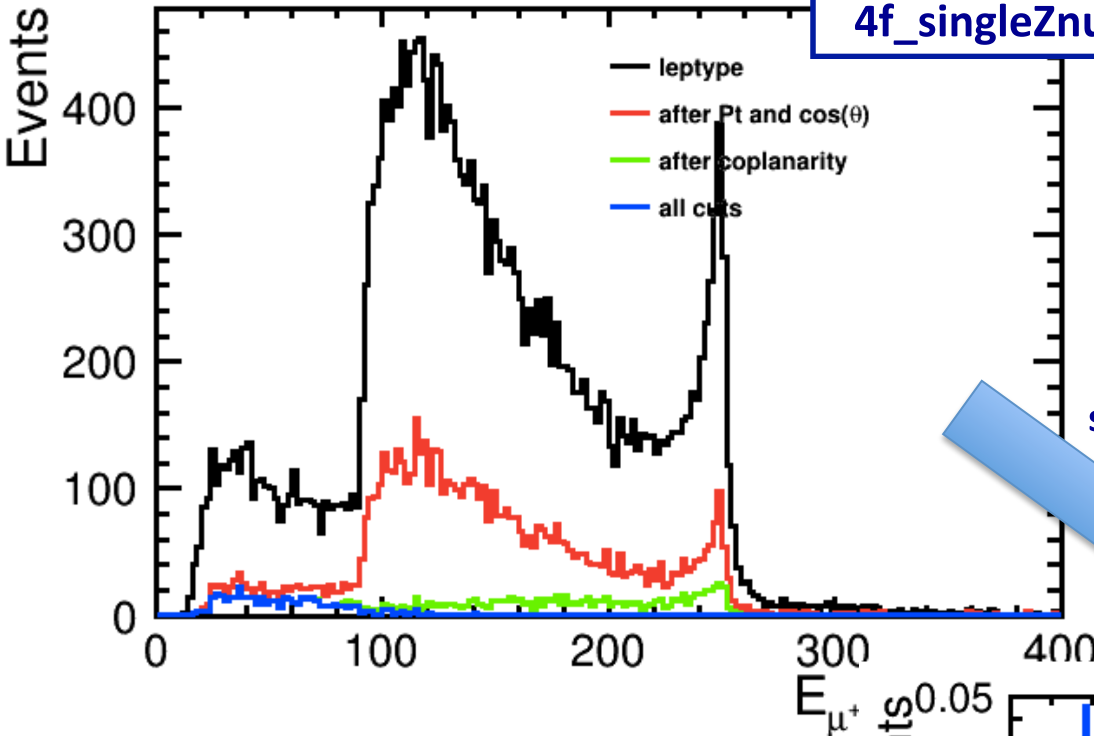
signal
chargino
4f_singleZee_l
other Background
4f_singleZnunu_l
4f_ZZWWMix_l
Square shape is fake:
Due to being stacked
on top of bkg with a
special structure
0
50
100
150



4f_singleZnunu_l
0
5
10
15
20
50
100
150

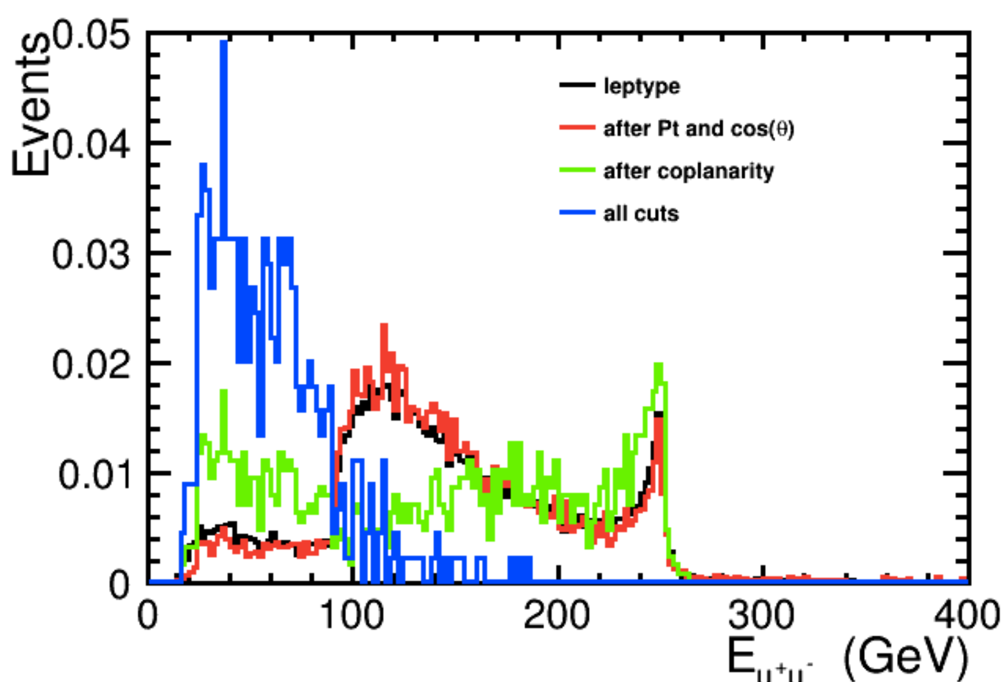


4f_ZZorWWMix
0
2
4
6
50
100
150



4f_singleZnunu_l

Scaled to area=1 in order to compare shape of distrubution



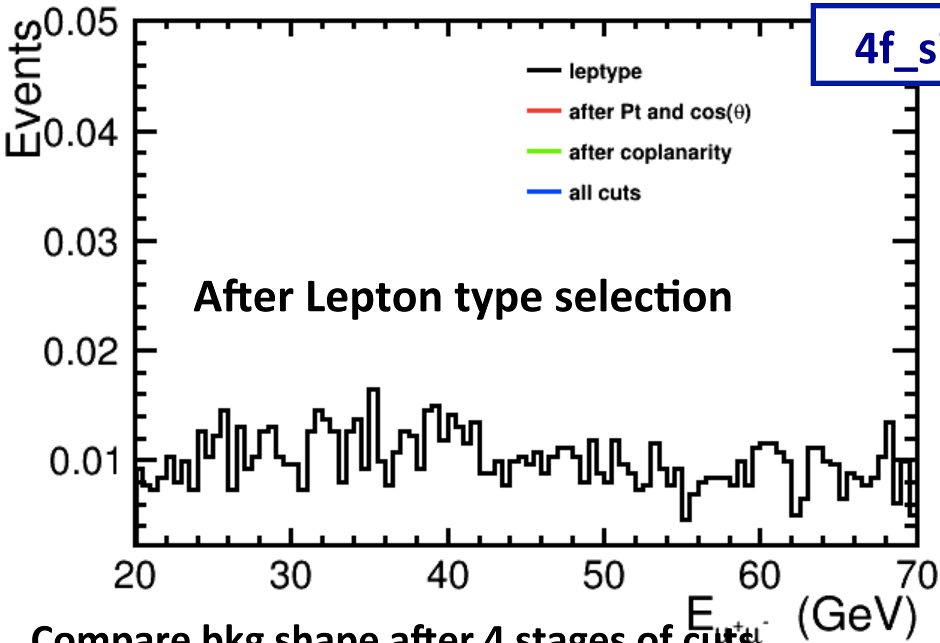
Compare bkg shape after 4 stages of cuts

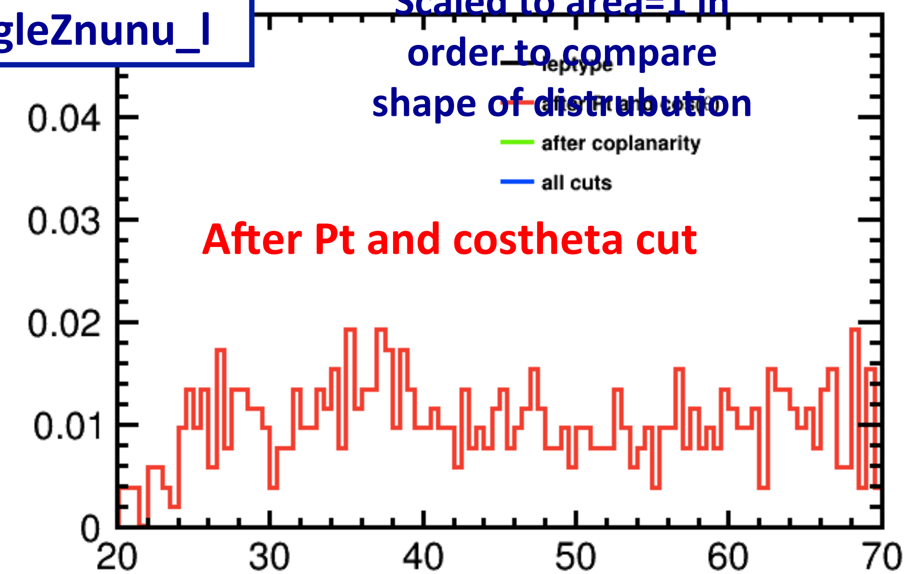
- **After Lepton type selection**
- **After Pt and costheta cut**
- **After Coplanarity cut**
- **After all cuts**

Dip around 50 GeV seems apparent after coplanarity cut

4f_singleZnunu_l

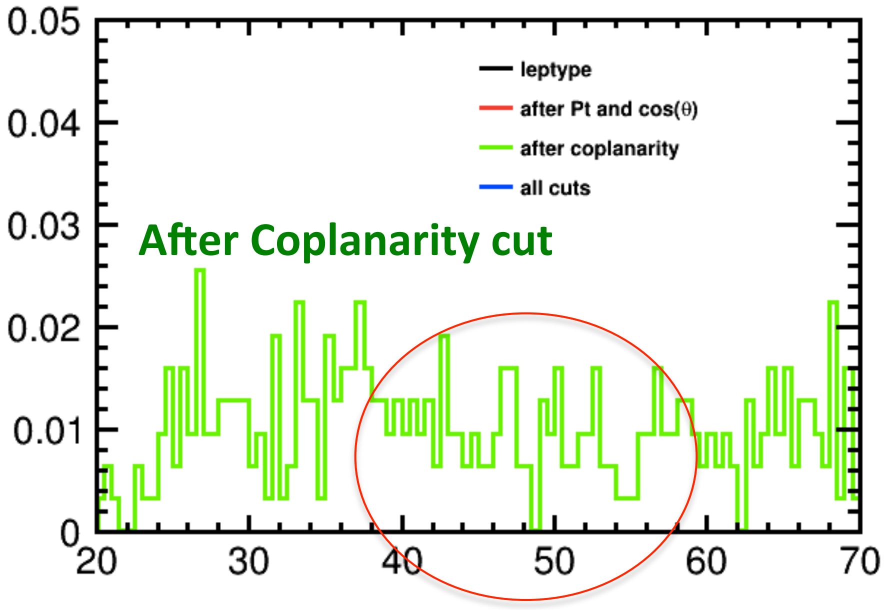
Scaled to area=1 in order to compare shape of distrubution

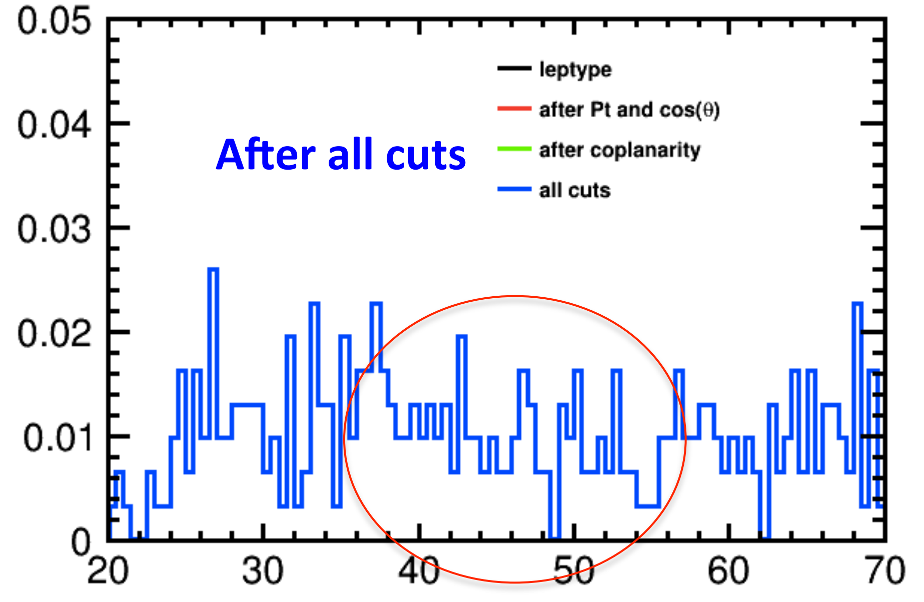




Compare bkg shape after 4 stages of cuts

Dip around 50 GeV seems apparent after coplanarity cut

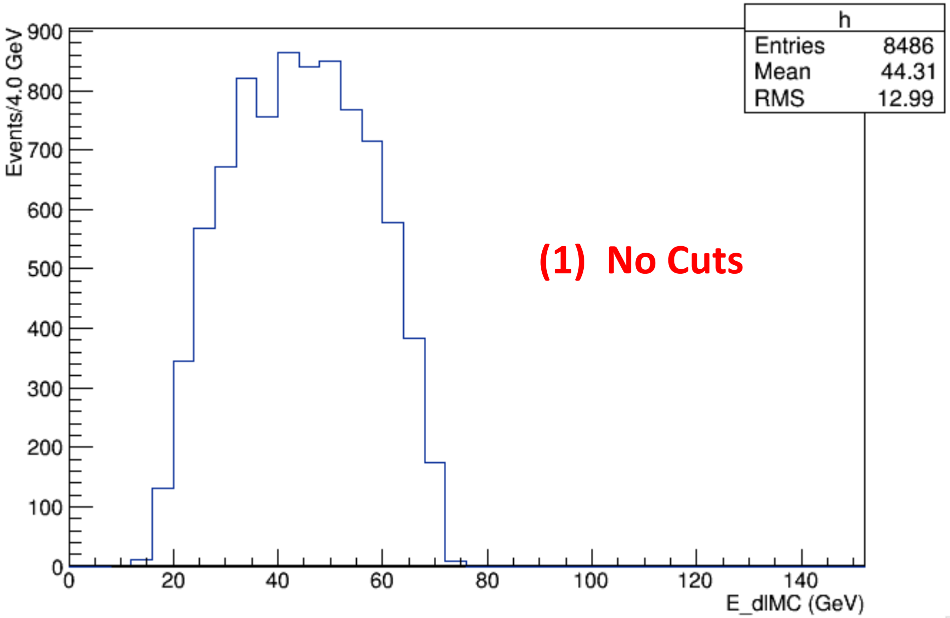


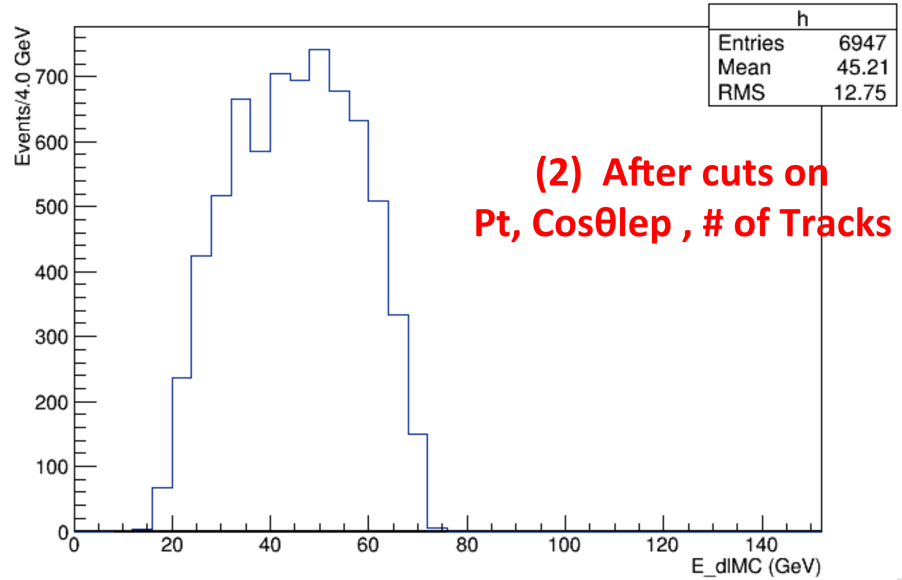


MC Truth of di-muon energy

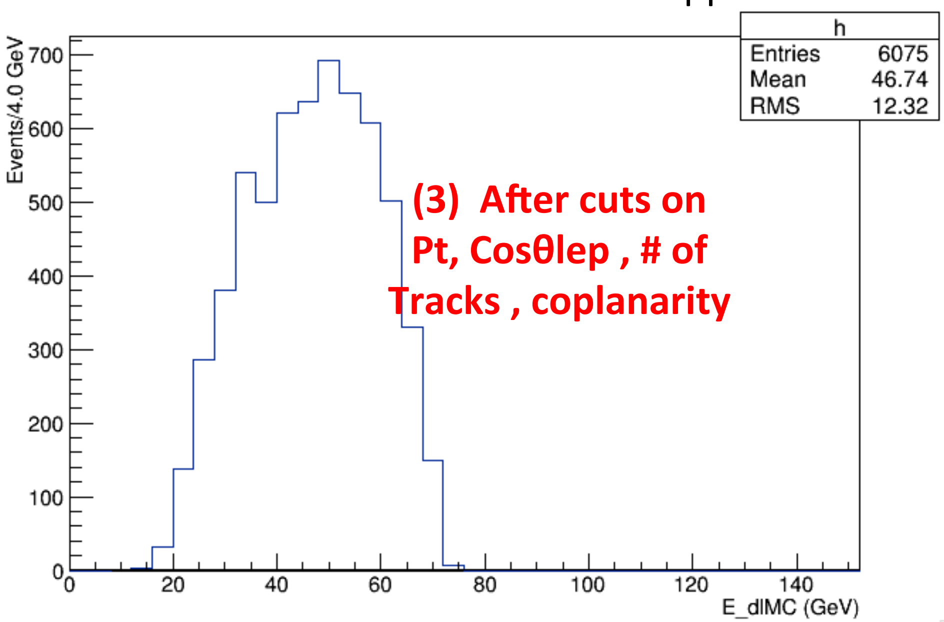
Polarization (Pe-,Pe+) = (-0.8, +0.3)

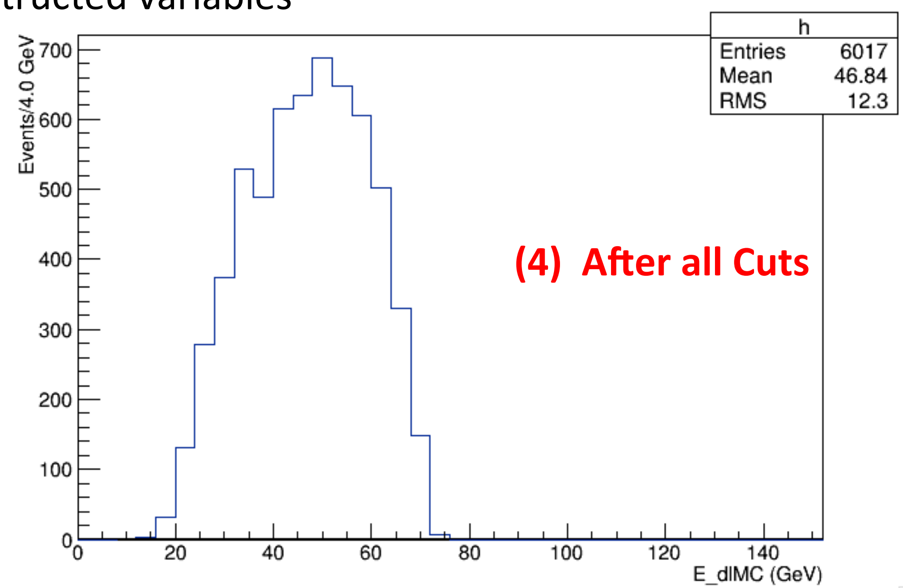
Bin width : 4 GeV





Cuts applied on Reconstructed variables

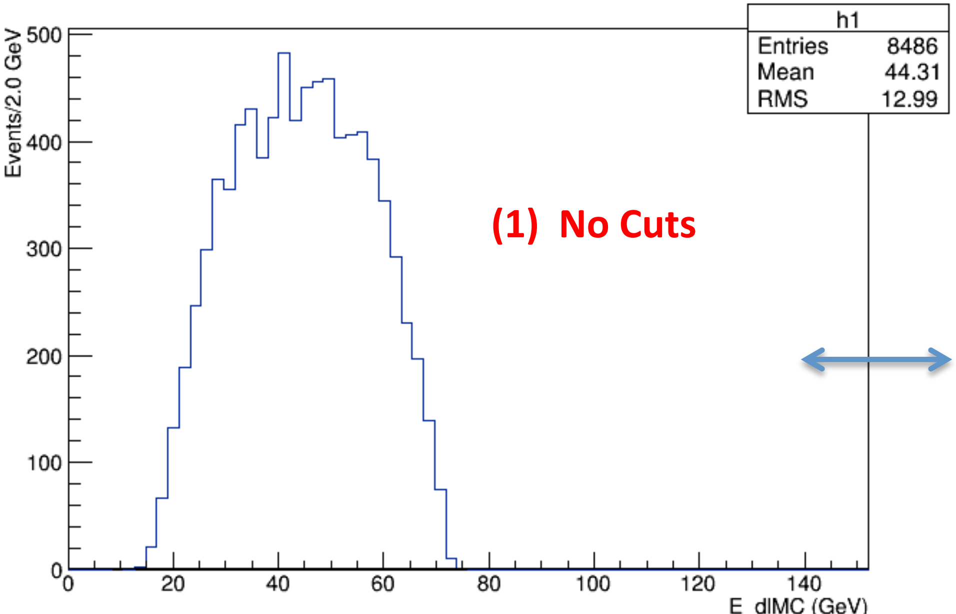


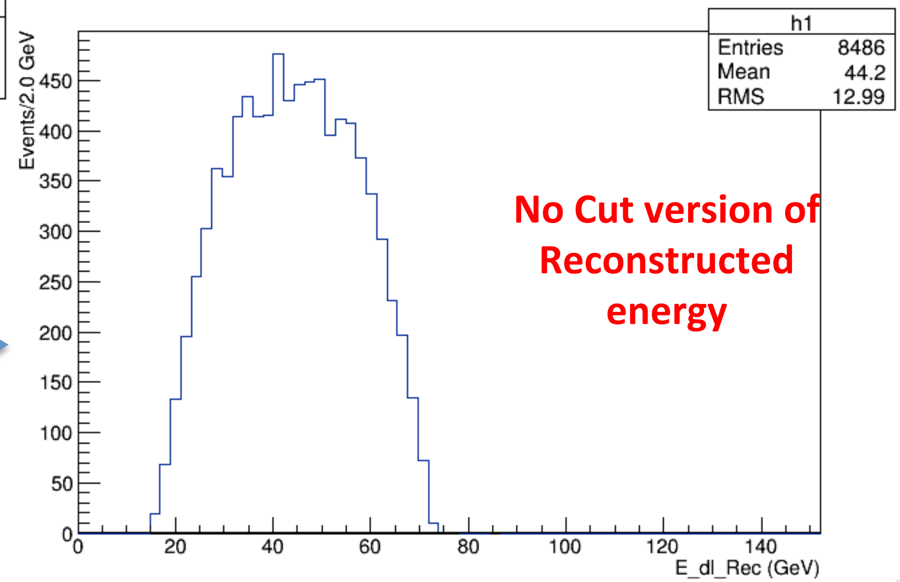


MC Truth of di-muon energy

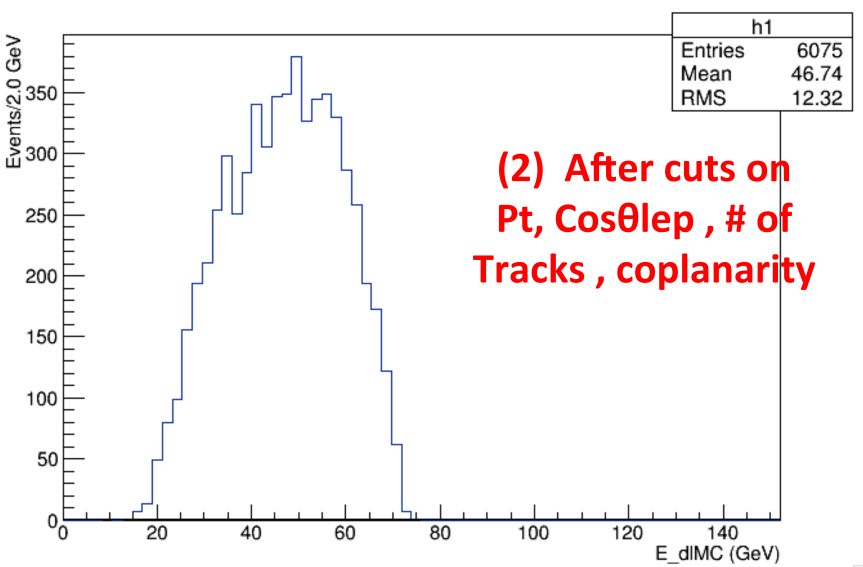
Polarization (Pe-,Pe+) = (-0.8, +0.3)

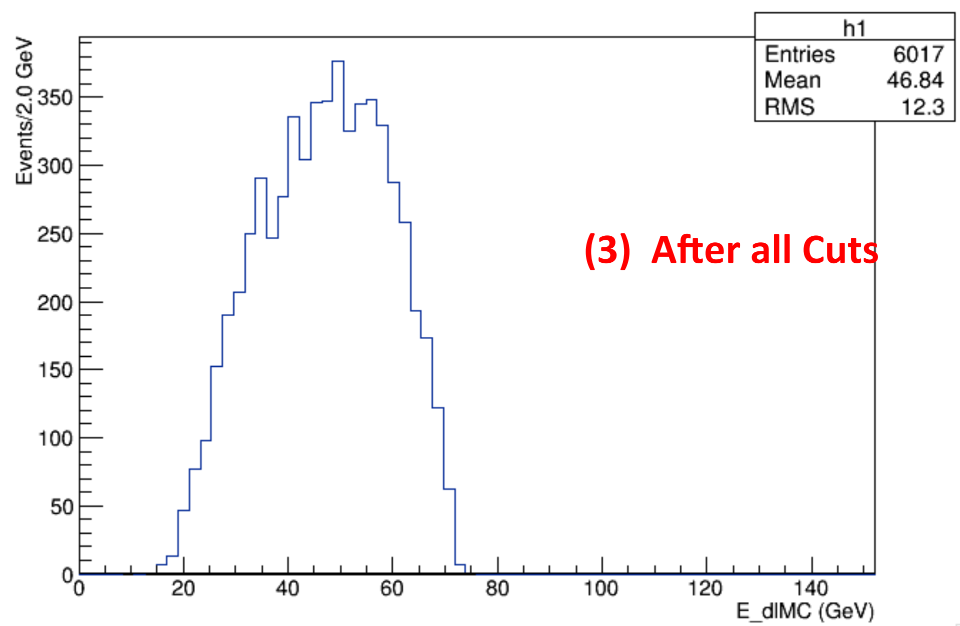
Bin width : 2 GeV





Cuts applied on Reconstructed variables



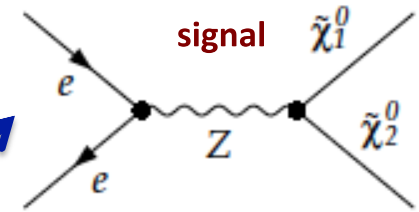


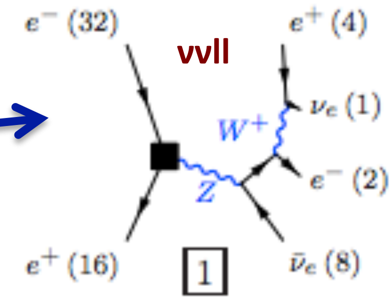
Event Selection

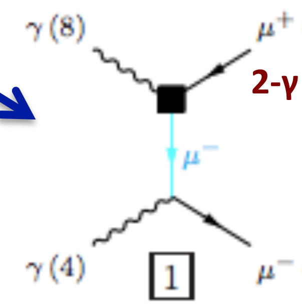
Neutralino mixed production with leptonic decay

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

- 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





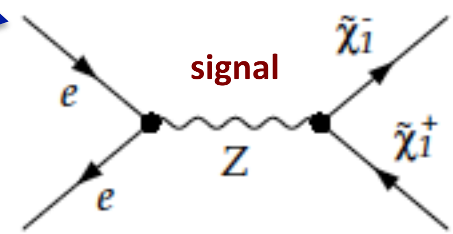


Chargino pair production with semileptonic decay

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

- 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.

  (signal significance > 100)



Cuts for 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 > 6 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<50 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

Cuts for C1C1

- lepton type (μ or e tag) and # of lepton =1
- Pt_mis > 10 GeV
- Jet Coplanarity < 1.0 rad
- |cosθjet1,2| < 0.95:
- nTrack(in jet) >1 :
- no hit in BeamCal :
- cosθjet1-lep < 0.2, cosθjet2-lep < 0 angle between jets and leptons
- Evis – Eγmax < 60 GeV :
- Emis > 400 GeV :
- |cosθmissing| < 0.98 :
- |cosθZ| < 0.98 :
- Pt_jj < 50 GeV :
- Minv<30 GeV :

last of all observe distributions of Minv and dijet energy (Ejj)

Kinematic edge is a function of Higgsino mass and ΔM

Cuts for 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 > 6 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<50 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

Cuts for C1C1

- lepton type (μ or e tag) and # of lepton =1
- Pt_mis > 10 GeV
- Jet Coplanarity < 1.0 rad
- |cosθjet1,2| < 0.95:
- nTrack(in jet) >1 :
- no hit in BeamCal :
- cosθjet1-lep < 0.2, cosθjet2-lep < 0 angle between jets and leptons
- Evis – Eγmax < 60 GeV :
- Emis > 400 GeV :
- |cosθmissing| < 0.98 :
- |cosθZ| < 0.98 :
- Pt_jj < 50 GeV :
- Minv<30 GeV :

last of all observe distributions of Minv and dijet energy (Ejj)

Kinematic edge is a function of Higgsino mass and ΔM

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