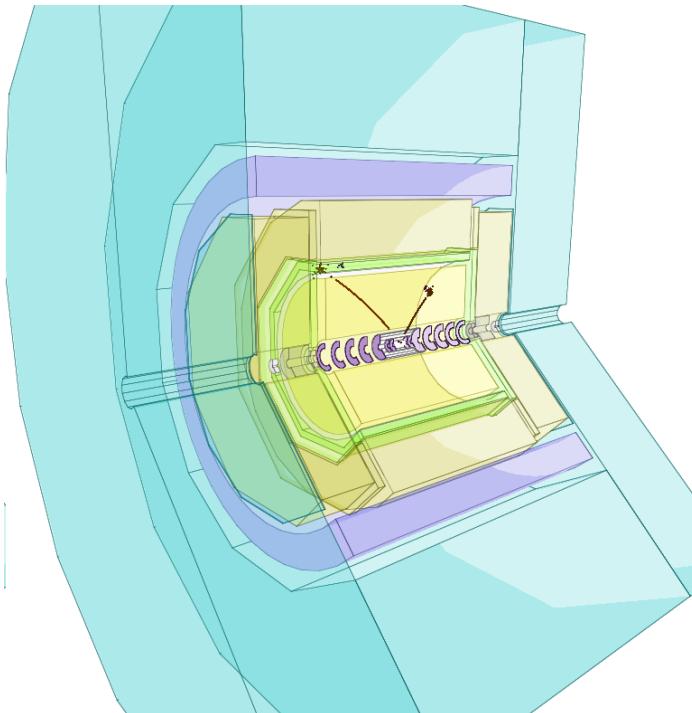


Characterizing Light Higgsinos from Natural SUSY at the ILC

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Keisuke Fujii, Jacqueline Yan (KEK)



December 20, 2017
ILD Analysis/Software Meeting

Contents

- **Introduction**
 - Motivation, benchmarks
- **Neutralino channel (N1N2)**
 - Event selection, kinematic edges
- **Chargino channel (C1C1)**
 - Event selection, kinematic edges
- **Results**
 - Mass global fits, Cross section estimation
- **Parameter extraction**
 - Prediction of heavy states, extrapolation to GUT-scale physics

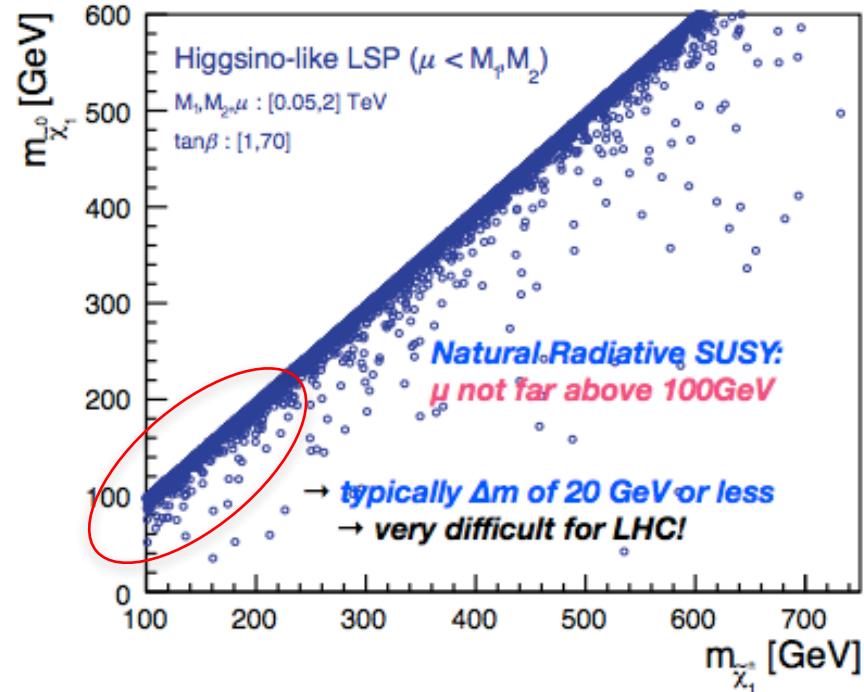
Why study light Higgsinos?

[arXiv:1212.2655, arXiv:1404.7510]

- Naturalness. The Higgsino mass (μ) should be close to the electroweak scale for small fine-tuning.

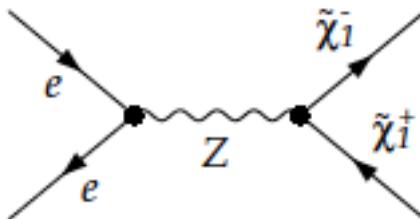
$$\frac{M_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u) \tan^2 \beta}{\tan^2 \beta - 1} - \mu^2$$

- Small Higgsino mass & large gaugino masses imply light Higgsinos with compressed mass spectra
- In the most natural cases, the mass difference is $\Delta M \sim O(10)$ GeV. [Our benchmark models are based around these points.]
- These are also the most challenging for the LHC.
- ILC, including its energy upgrade ~ 500 GeV, is expected to discover natural SUSY (or finally rule it out).

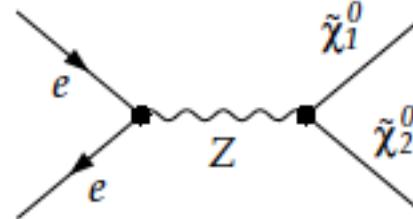


Benchmark Points

Chargino Pair
Production
 $e+e^- \rightarrow C_1 + C_1^-$



Neutralino Mixed
Production
 $e+e^- \rightarrow N_1 N_2$



3 benchmark points with natural higgsinos:

Mass (GeV)	ILC1	ILC2	nGMM1
M(N1)	102.7	148.1	151.4
M(N2)	124.0	157.8	155.8
$\Delta M(N_2, N_1)$	21.3	9.7	4.4
M(C1)	117.3	158.3	158.7
$\Delta M(C_1, N_1)$	14.6	10.2	7.3

Cross Section	ILC1	ILC2	nGMM1
C1C1 (e-L, e+R)	1799.9	1530.5	1520.6
C1C1 (e-R, e+L)	334.5	307.2	309.5
N1N2 (e-L, e+R)	490.9	458.9	463.5
N1N2 (e-R, e+L)	378.5	353.8	357.3

*Other SUSY particles are heavy

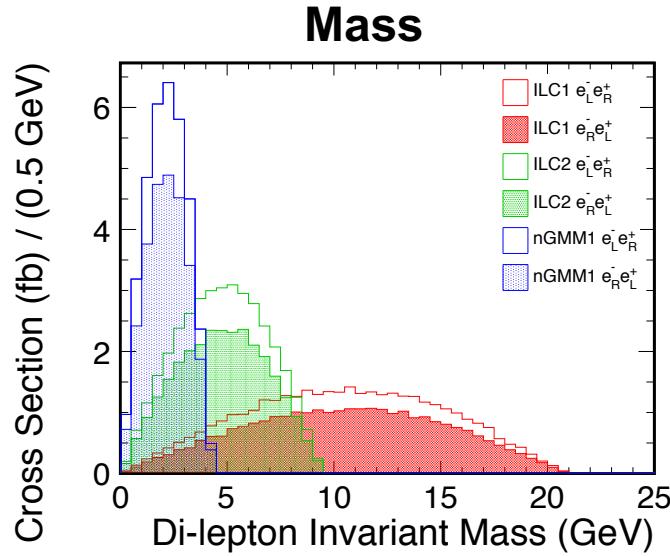
(Assuming discovery and)

How well can we reconstruct the masses and cross section?

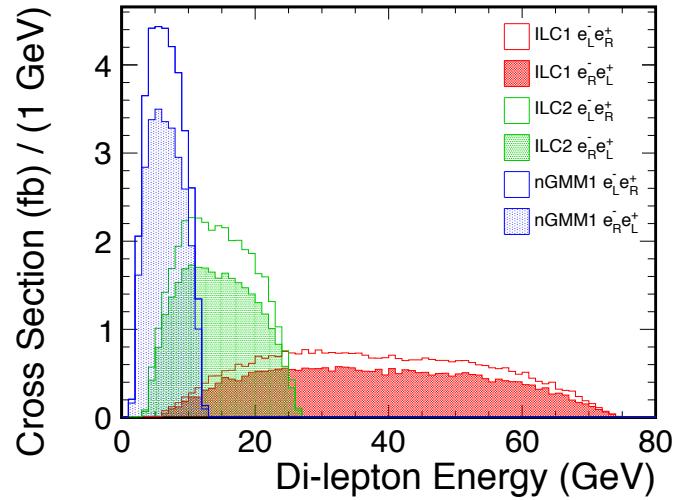
Generator-level Distributions

- Key observables in this study: di-lepton / di-jet mass and energy.
- Their maximum values (edges) can be used to extract the masses.

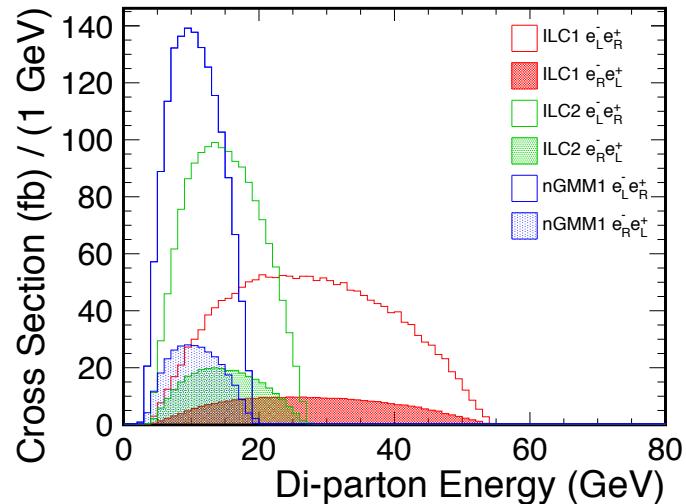
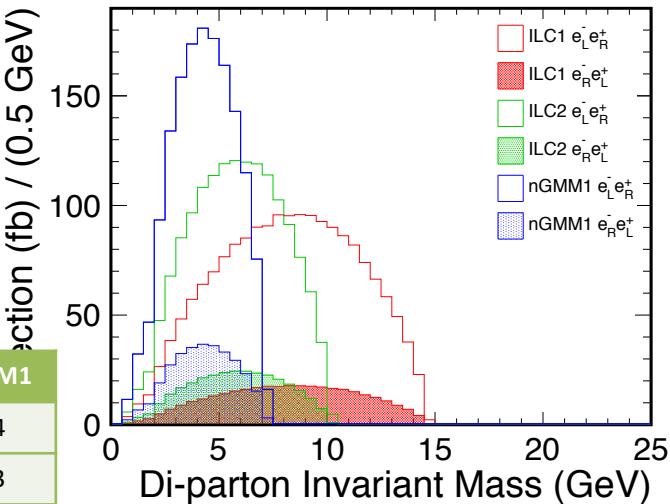
N1N2



Energy



C1C1



	ILC1	ILC2	nGMM1
$\Delta M(N2, N1)$	21.3	9.7	4.4
$\Delta M(C1, N1)$	14.6	10.2	7.3

Equations

Maximum energy of the di-lepton / di-jet system is given by

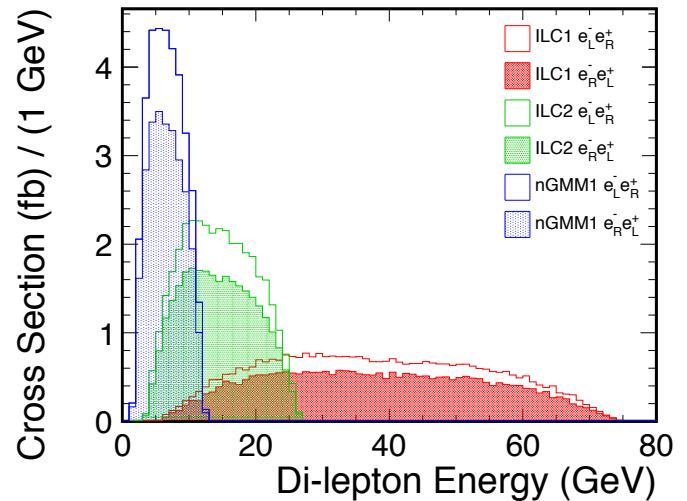
$$E^* = \frac{\gamma(1 + \beta)}{2} \left(1 + \frac{M_1}{M_2} \right) \Delta M$$

where

$$\frac{1}{\gamma} = \sqrt{1 - \beta^2} \quad \frac{1}{\beta} = \sqrt{1 + \left(\frac{M_2}{p^*} \right)^2}$$

$$\Delta M = M_2 - M_1$$

$$p^* = \frac{\sqrt{s}}{2} \sqrt{1 - 2 \left[\left(\frac{M_1}{\sqrt{s}} \right)^2 + \left(\frac{M_2}{\sqrt{s}} \right)^2 \right] + \left[\left(\frac{M_2}{\sqrt{s}} \right)^2 - \left(\frac{M_1}{\sqrt{s}} \right)^2 \right]^2}$$



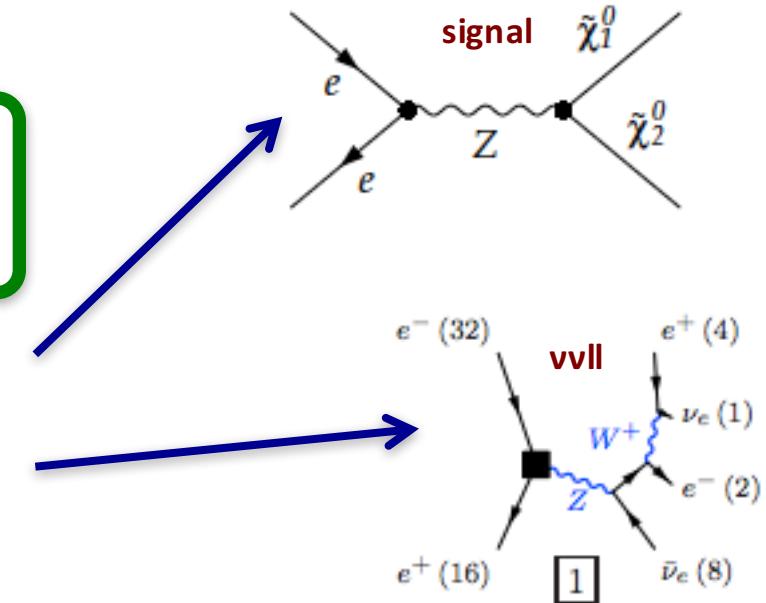
Event Selection

DBD software and samples used

Neutralino mixed production with leptonic decay

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

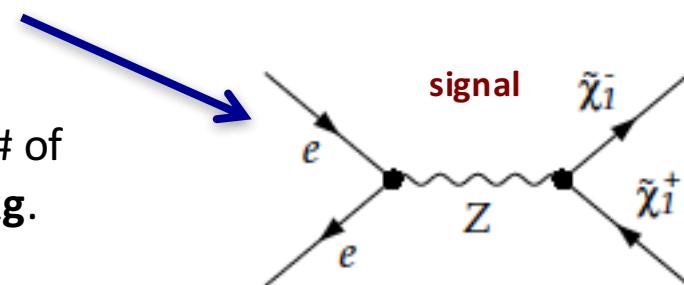
- Identify **two leptons (ee or $\mu\mu$)**
- Major residual bkg. are 4f processes accompanied by large missing energy ($vvll$)
- 2- γ processes removed by BeamCal veto, cuts on lepton track p_T , and coplanarity



Chargino pair production with semileptonic decay

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

- Find an **isolated lepton (e or μ)**
- Reconstruct **two jets** from the rest
- BeamCal veto, cuts on missing p_T , # of tracks, # of leptons, and coplanarity **remove almost all bkg.**



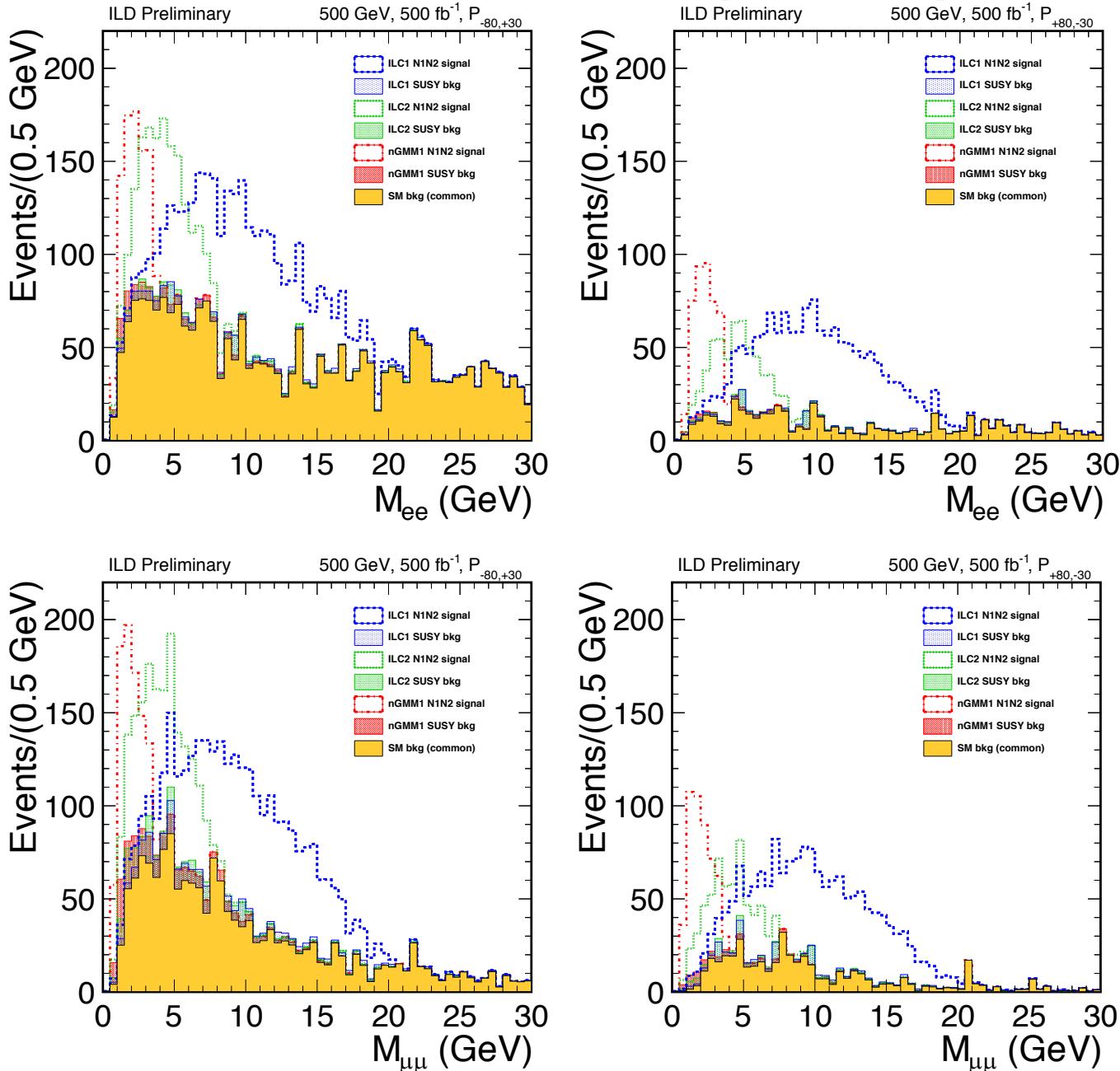
N1N2

Event Selection (N1N2)

1. Pair of isolated leptons (e or μ) **[preselection]**
 2. Visible Energy in the event $< 25 \text{ GeV}$
 3. Missing Energy in the event $> 300 \text{ GeV}$
 4. Missing $|\cos\theta| < 0.98$
 5. No BeamCal hits
 6. # of tracks with $pT > 2 \text{ GeV} = 2$
 7. Lepton $pT > 2.3 \text{ GeV}$, $|\cos\theta| < 0.95$
 8. di-lepton coplanarity < 0.8
 9. di-lepton $|\cos\theta| < 0.98$
- 10. di-lepton mass cuts for di-lepton energy measurement
(process-dependent)**

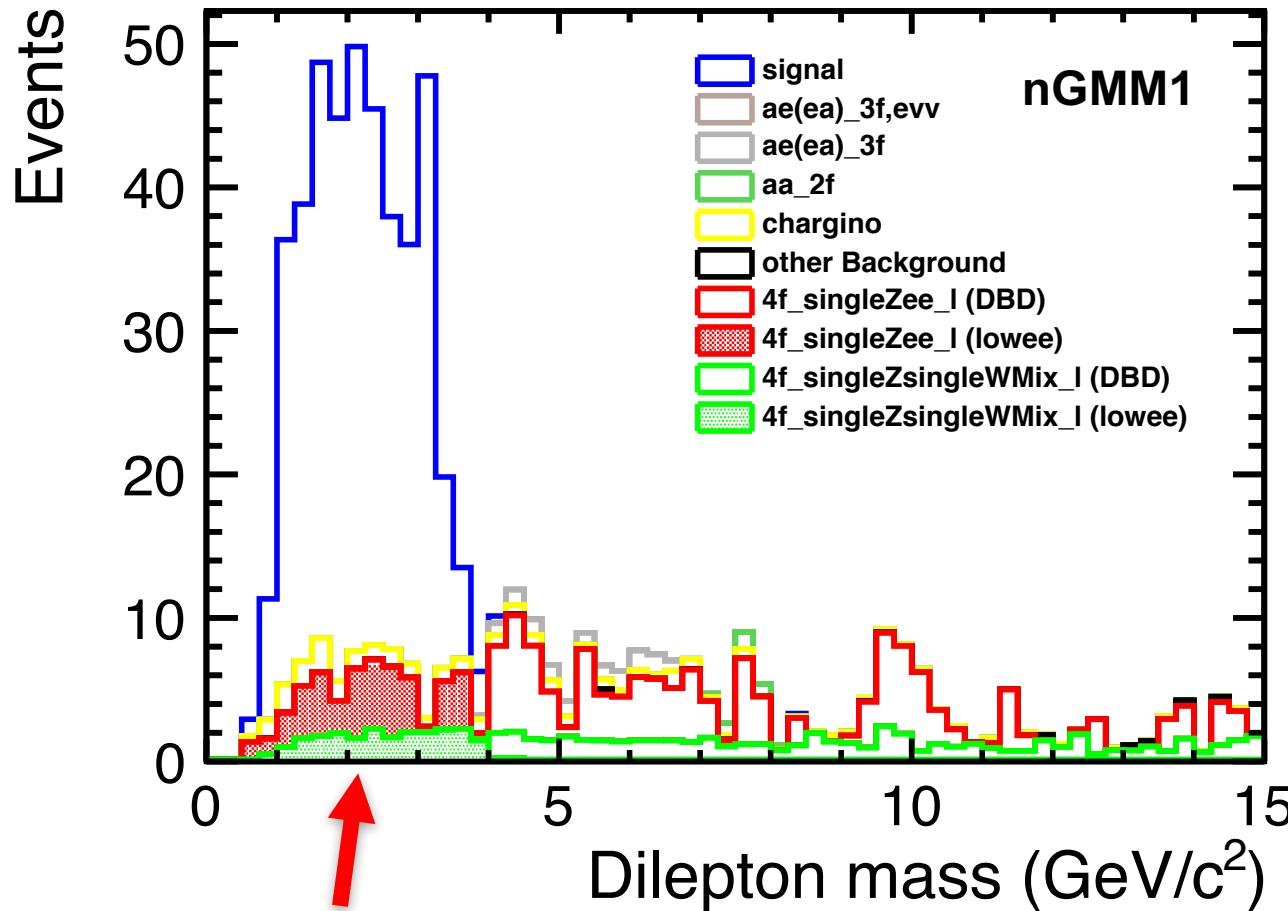
Consistent across all benchmarks (ILC1/ILC2/nGMM1) **[except #10]**, final states (e/mu), and beam polarizations.

Di-lepton Mass (N1N2)



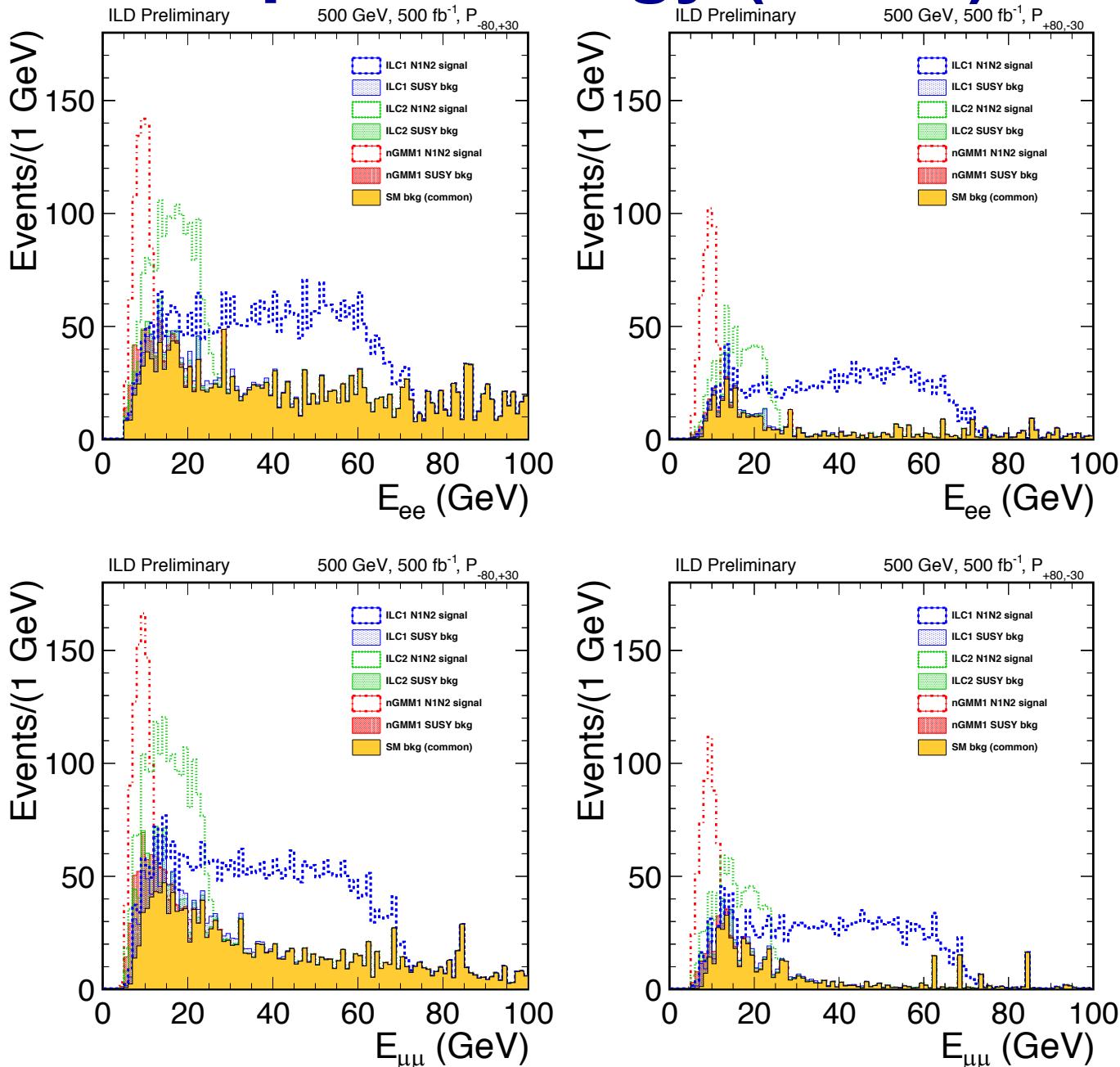
Missing Phase Space

Previously missing phase space in 4-fermion backgrounds (due to generator-level cut)
is now supplemented by including additional samples (full/fast)
[Thanks to H. Ono, A. Miyamoto, M. Berggren]



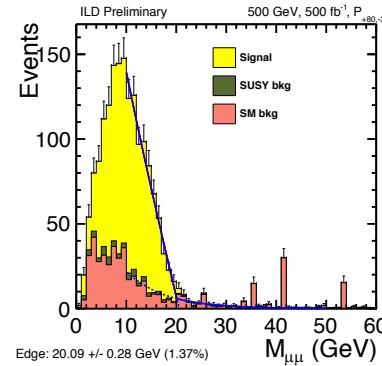
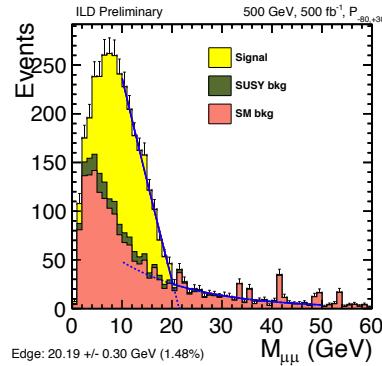
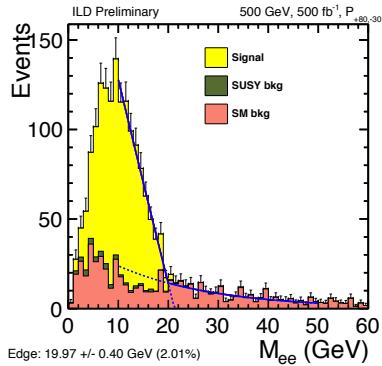
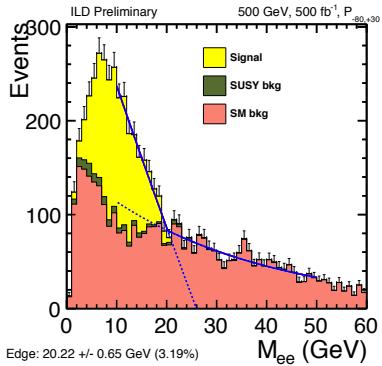
Di-lepton Energy (N1N2)

without cut #10

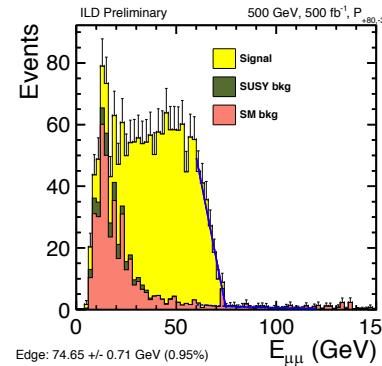
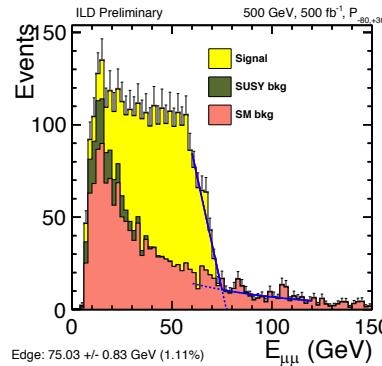
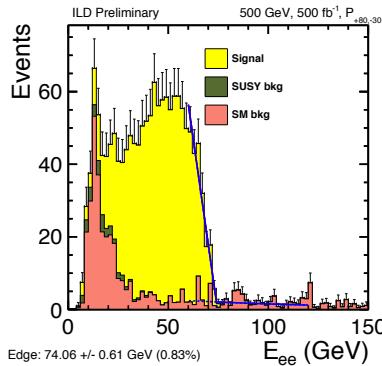
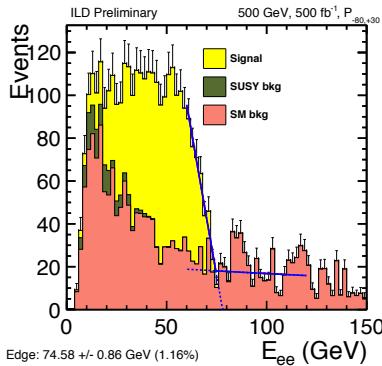


Kinematic Edges: ILC1 (N1N2)

M



E

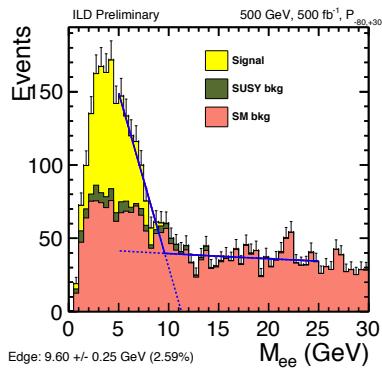


The kinematic edge is modeled as: straight line (signal) + exponential (background). The precision is estimated using toy MC experiments.

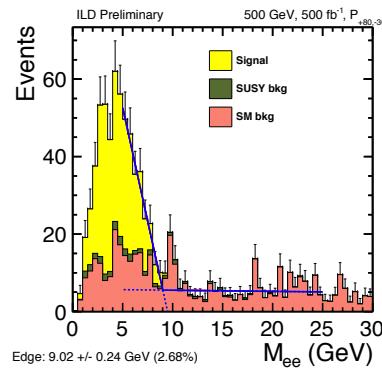
Kinematic Edges: ILC2 (N1N2)

M

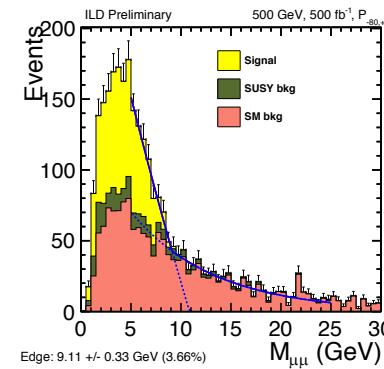
$ee, (-80, +30)$



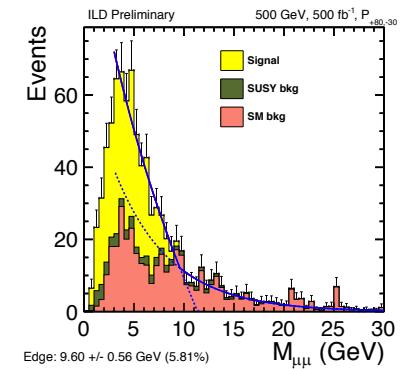
$ee, (+80, -30)$



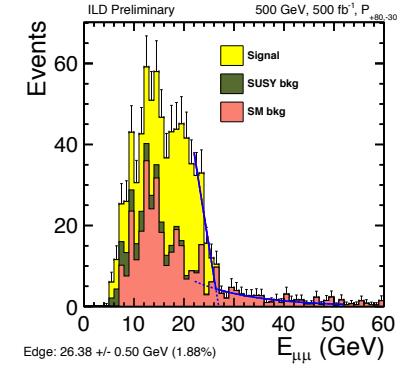
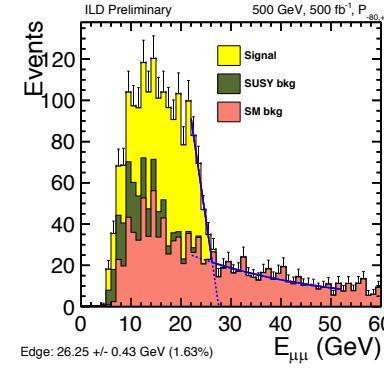
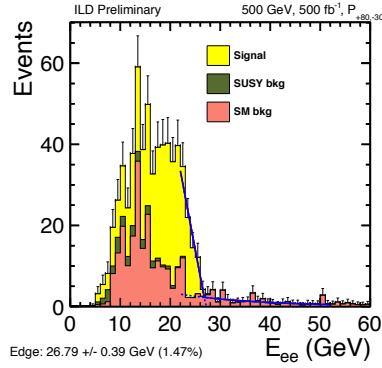
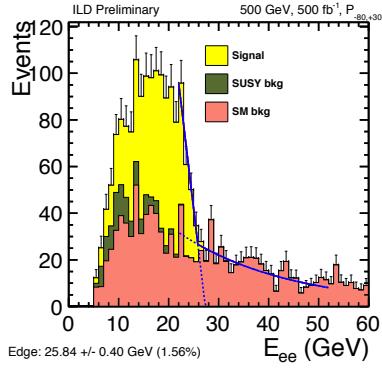
$\mu\mu, (-80, +30)$



$\mu\mu, (+80, -30)$



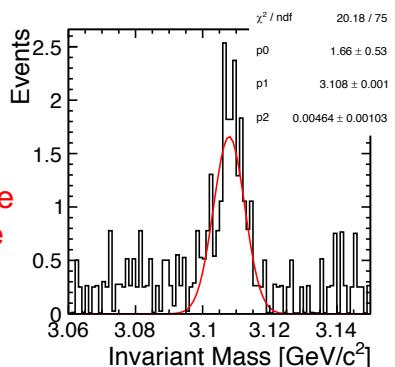
E



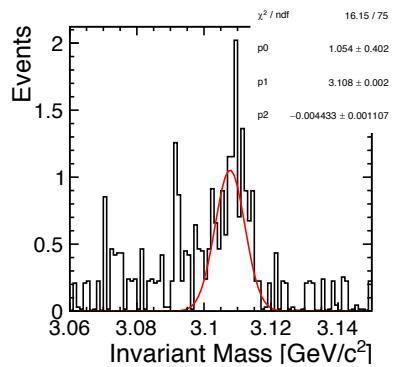
The kinematic edge is modeled as: straight line (signal) + exponential (background). The precision is estimated using toy MC experiments.

Kinematic Edges: nGMM1 (N1N2)

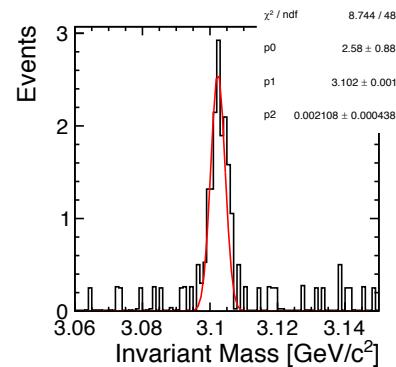
$ee, (-80, +30)$



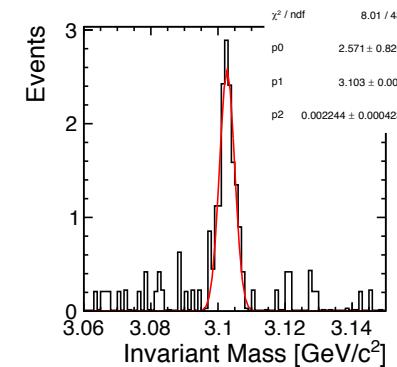
$ee, (+80, -30)$



$\mu\mu, (-80, +30)$



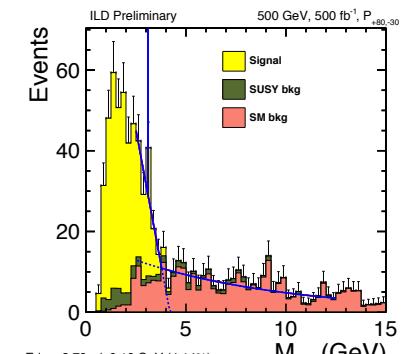
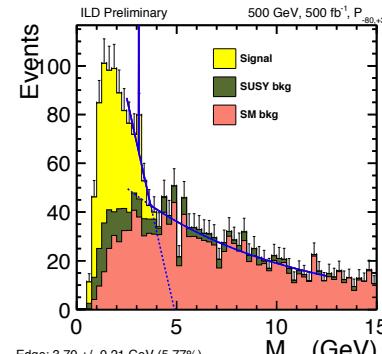
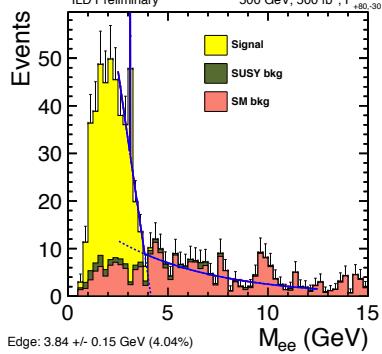
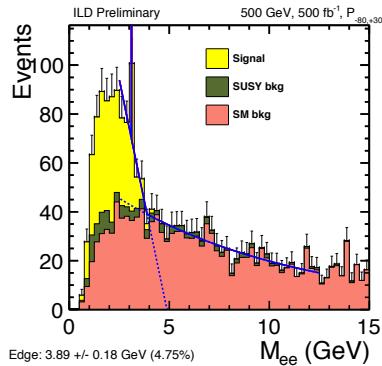
$\mu\mu, (+80, -30)$



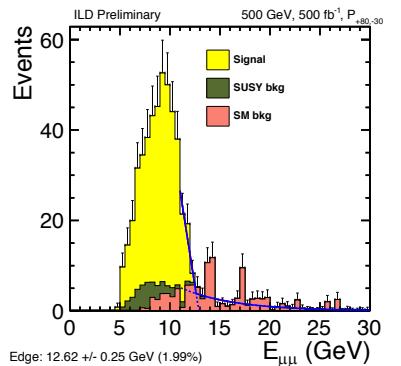
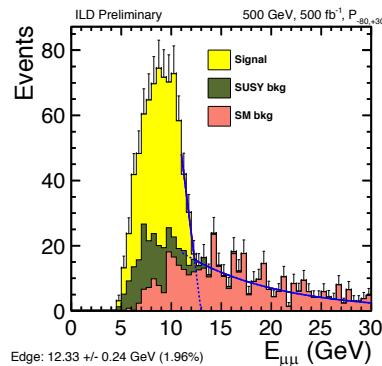
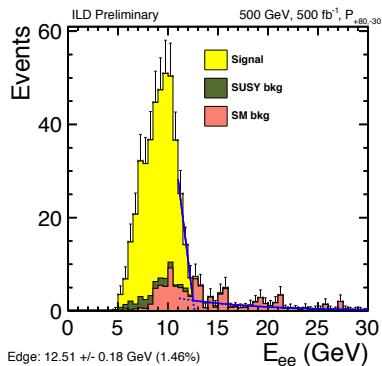
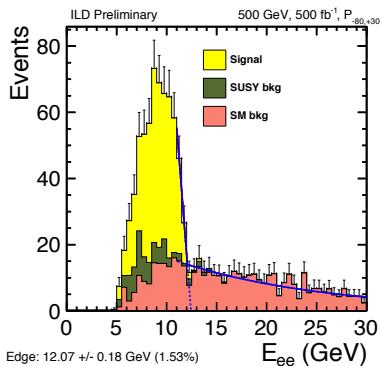
$M(J/\psi)$

J/ ψ masses are a bit off: will be investigated

M



E



C1C1

Event Selection (C1C1)

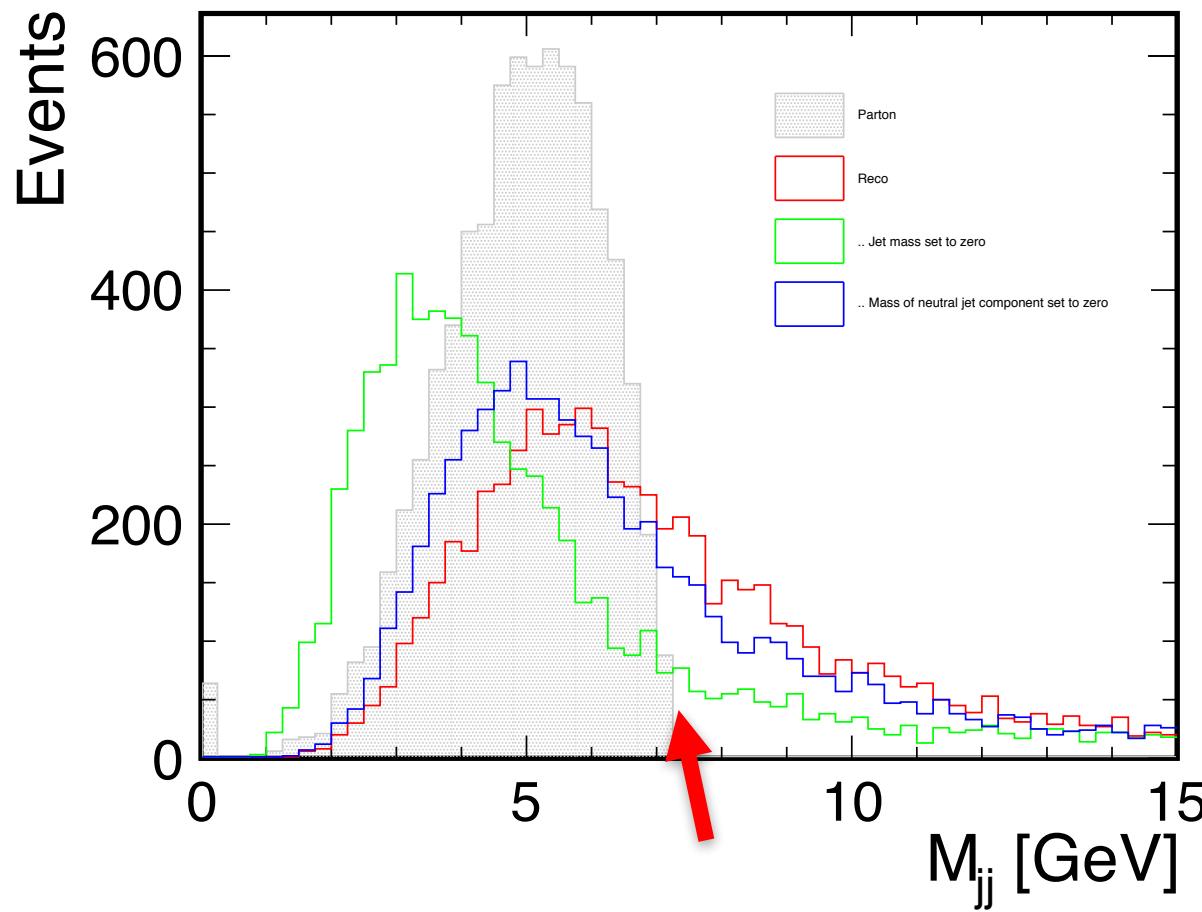
1. One isolated lepton (e or μ) **[preselection]**
2. No BeamCal hits
3. Lepton $pT > 5 \text{ GeV}$ (suppress two-photon background)
4. # of tracks in event ≥ 4 (suppress ae_3f background)
5. Missing Energy $> 400 \text{ GeV}$
6. Missing $|\cos\theta| < 0.99$
7. Visible Energy $< 80 \text{ GeV}$
8. Each jet $|\cos\theta| < 0.98$
9. di-jet coplanarity < 1.0
10. Angle between lepton and dijet system $|\cos\theta| < 0.2$

Consistent across all benchmarks (ILC1/ILC2/nGMM1), final states (e/μ), and beam polarizations.

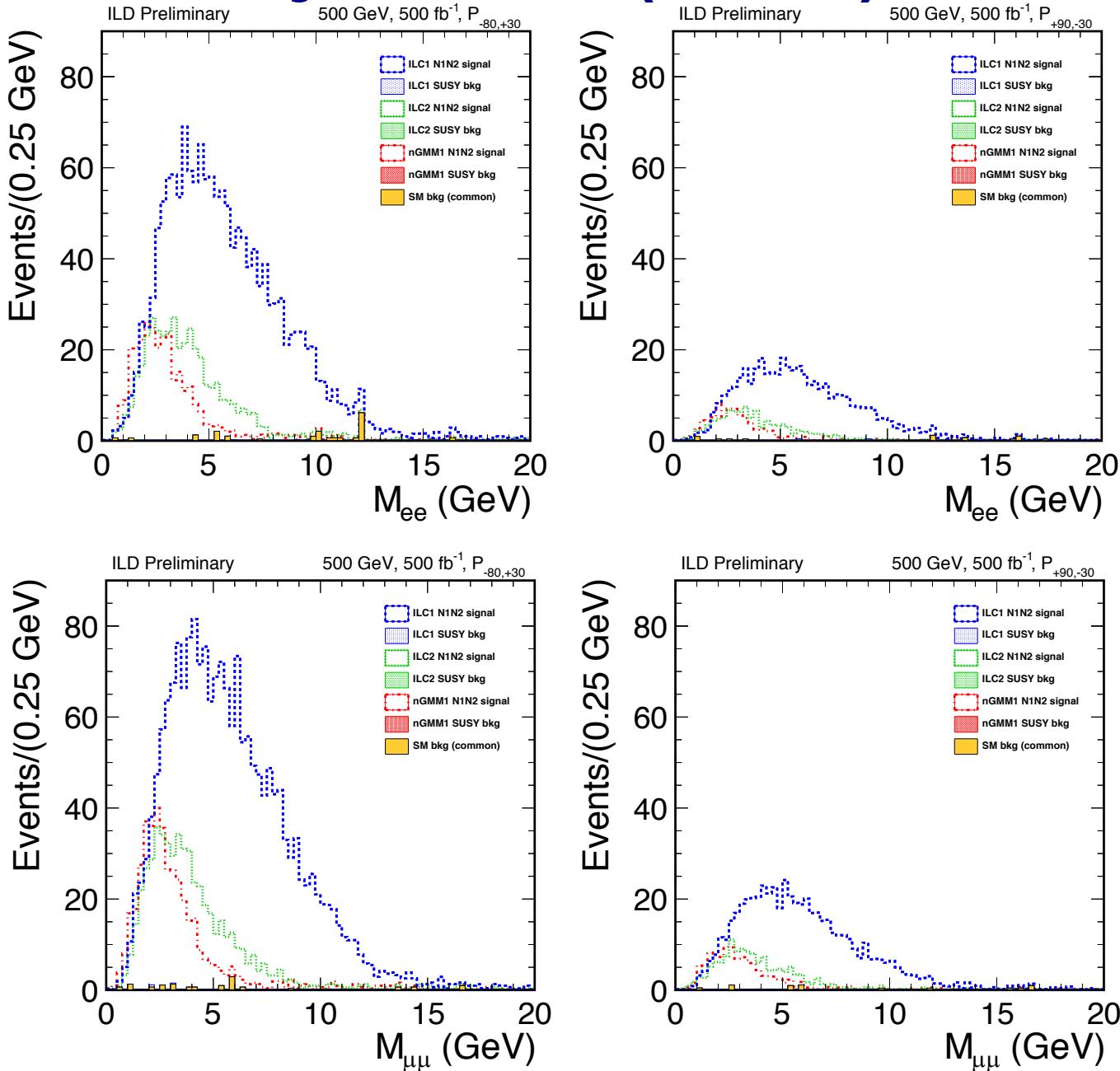
The event selection is much tighter compared to previous results. This is to ensure the removal of the 2-photon and ae_3f backgrounds.

Di-jet Reconstruction

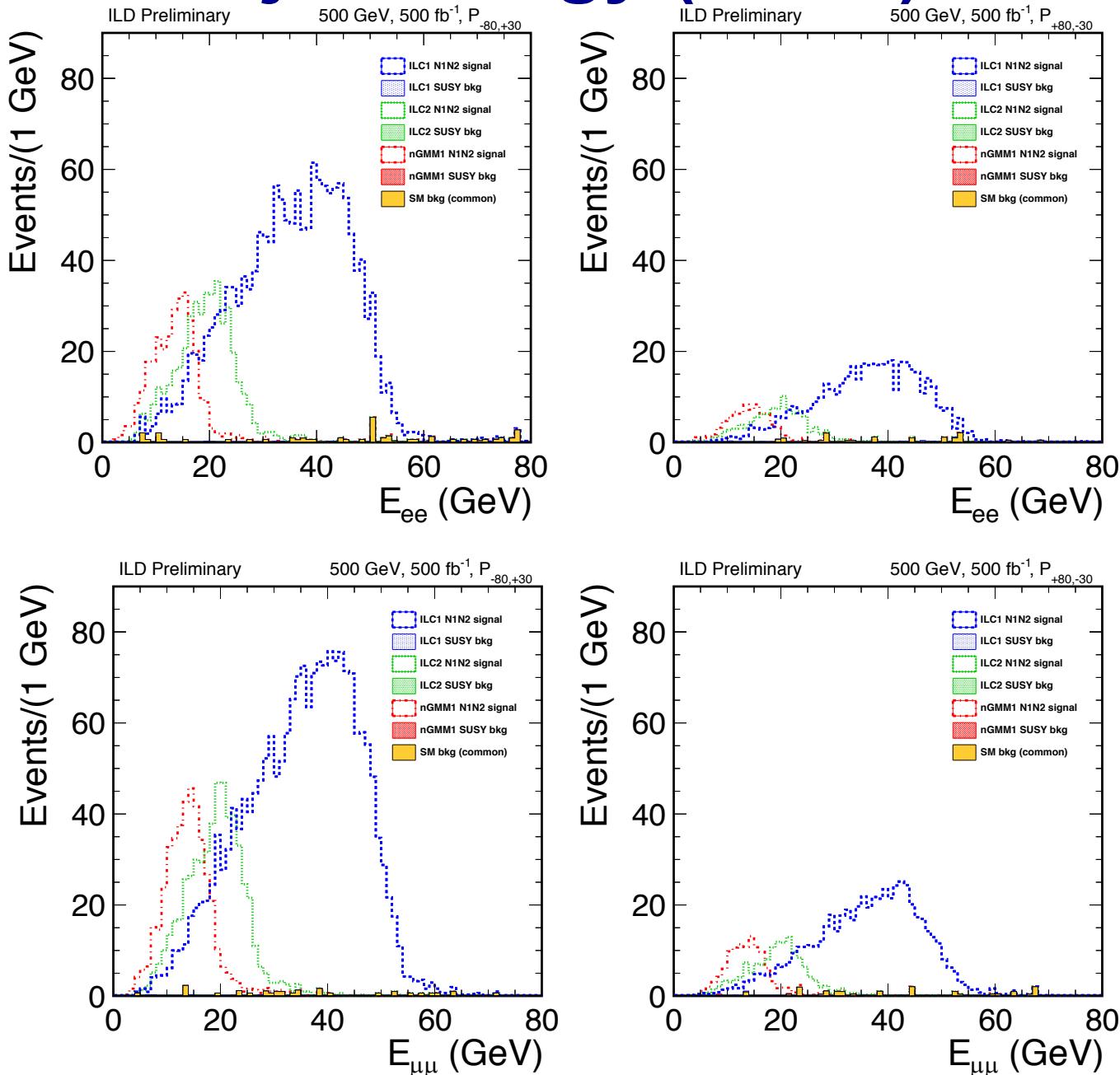
- Naïve reconstruction of di-jet mass suffers from heavy tail
- Dominant effect: neutral reconstruction (**NOT detector resolution**)
- Set only the neutral component of the jet to have zero mass → improves core reconstruction but the tail remains
- Set jet mass to zero → overcompensation in the core but reproduces the edge → used in this study.



Di-jet Mass (C1C1)



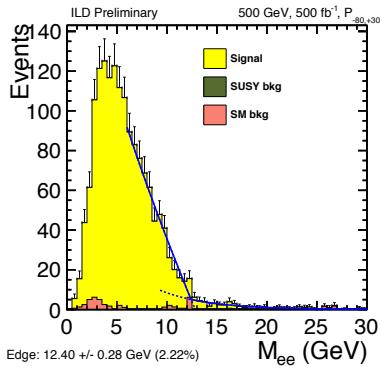
Di-jet Energy (C1C1)



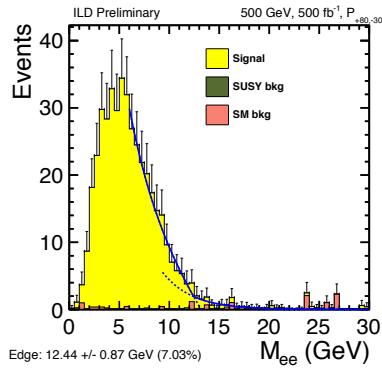
Kinematic Edges: ILC1 (C1C1)

M

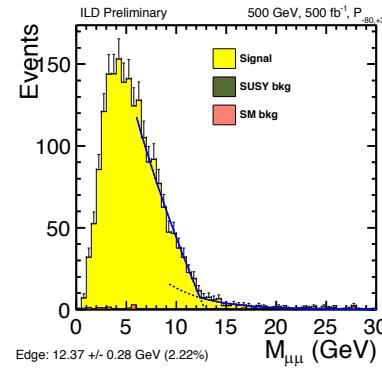
$|l|=e, (-80, +30)$



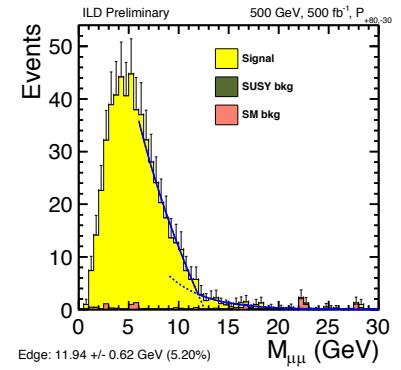
$|l|=e, (+80, -30)$



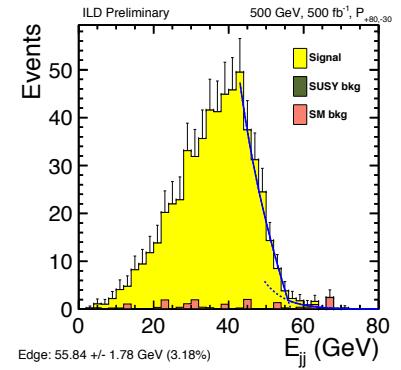
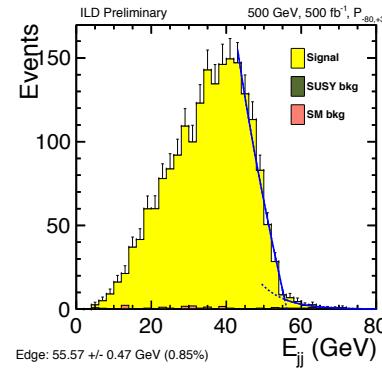
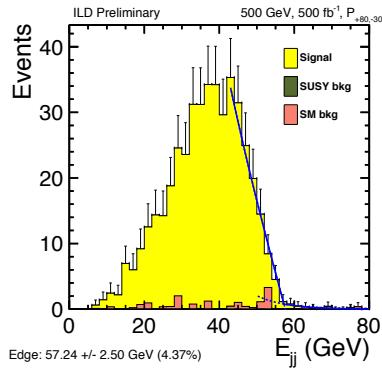
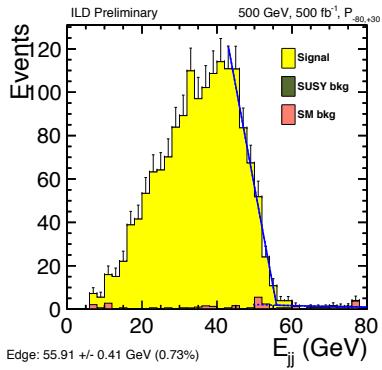
$|l|=\mu, (-80, +30)$



$|l|=\mu, (+80, -30)$



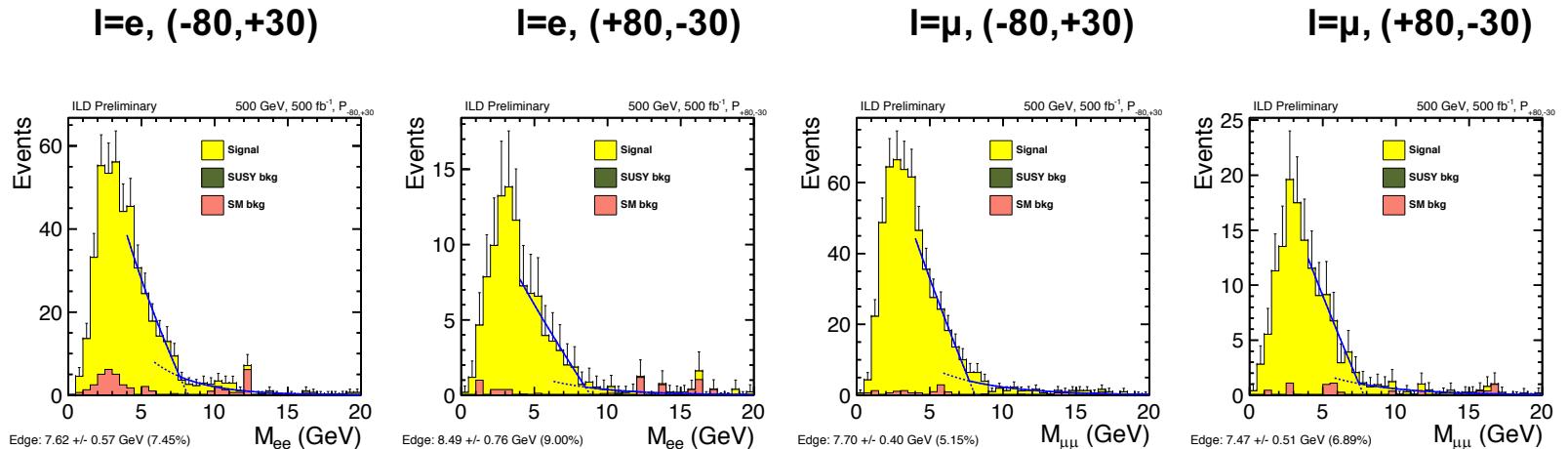
E



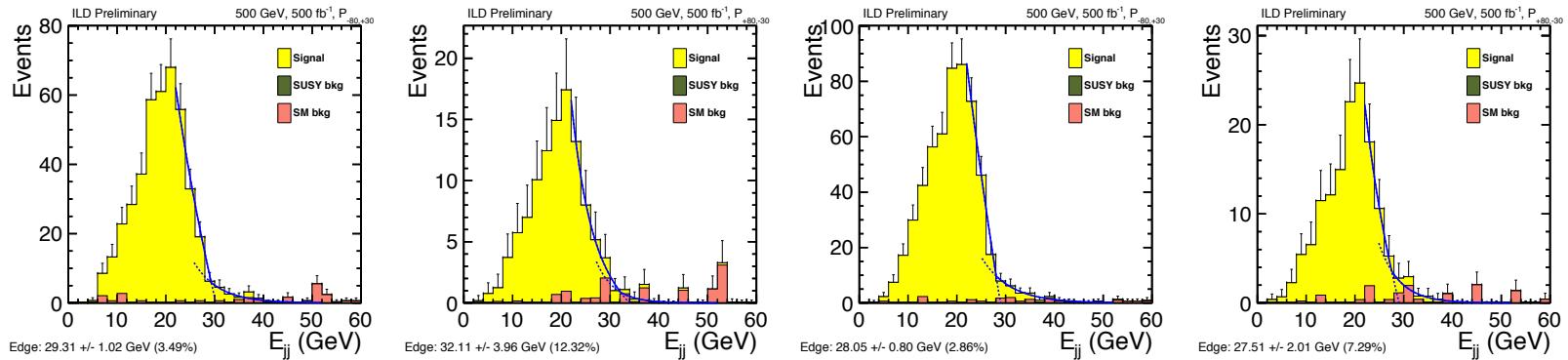
- The core is model with a straight line, while the tail is model with an exponential. The intersection is extract as the edge. The precision is estimated using toy MC experiments.
- A shift in the extract value (bias) is seen. This is correct by a scaling factor.

Kinematic Edges: ILC2 (C1C1)

M



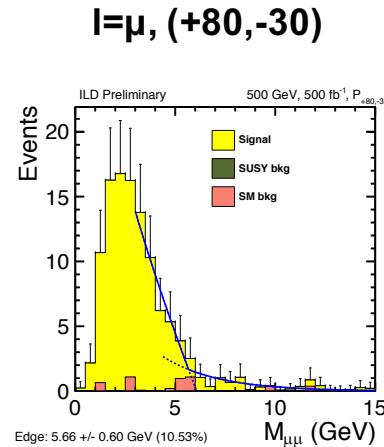
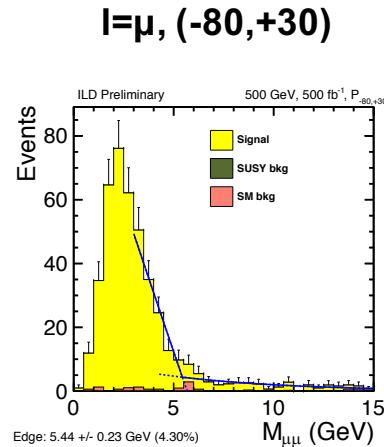
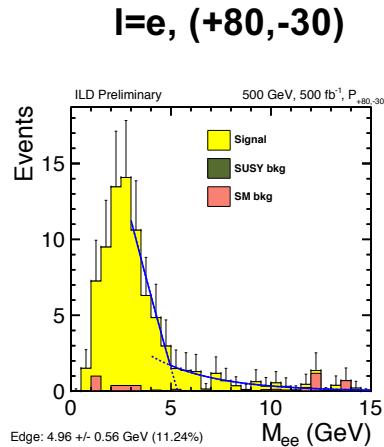
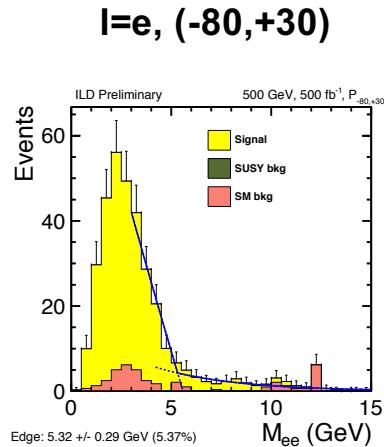
E



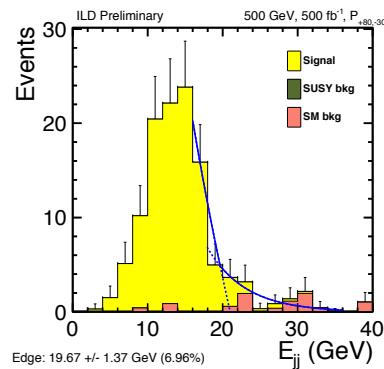
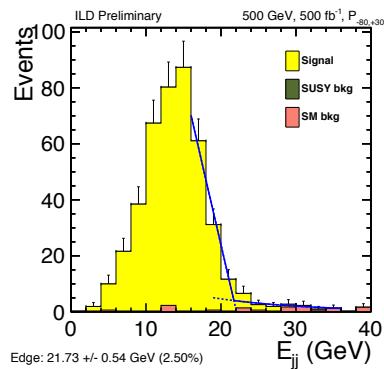
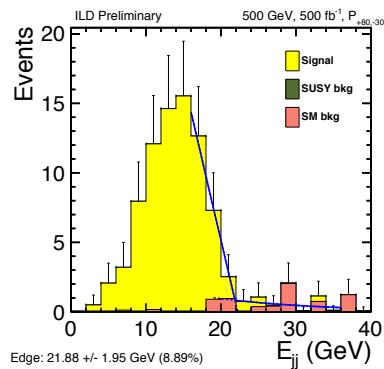
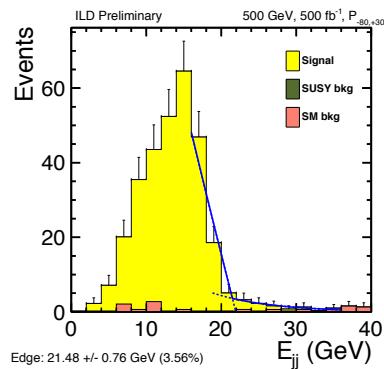
- The core is model with a straight line, while the tail is model with an exponential. The intersection is extract as the edge. The precision is estimated using toy MC experiments.
- A shift in the extract value (bias) is seen. This is correct by a scaling factor.

Kinematic Edges: nGMM1 (C1C1)

M



E



- The core is model with a straight line, while the tail is model with an exponential. The intersection is extract as the edge. The precision is estimated using toy MC experiments.
- A shift in the extract value (bias) is seen. This is correct by a scaling factor.

Results

Mass Extraction

- 3 masses as fitted values which are used to compute the two observables: di-lepton/di-jet invariant mass and maximum energy
- 16 measurements: {N1N2,C1C1} x {e,mu} x {E,M} x {2 polarizations}
- Least-squares fit assuming Gaussian errors and independent measurements
- Calibration applied to M_{jj} edge: assume uncertainty scales linearly and without additional error

$\sqrt{s}=500 \text{ GeV}$ $L=500 \text{ fb}^{-1}$	$M(N1)$	$M(N2)$	$M(C1)$
ILC1	$102.6 \pm 0.85 \text{ GeV}$ (0.84%)	$123.7 \pm 0.99 \text{ GeV}$ (0.80%)	$117.2 \pm 0.95 \text{ GeV}$ (0.81%)
ILC2	148.2 ± 1.9 (1.31%)	157.9 ± 2.1 (1.31%)	158.5 ± 2.1 (1.30%)
nGMM1	151.0 ± 2.6 (1.72%)	155.3 ± 2.7 (1.72%)	158.4 ± 2.7 (1.68%)

Percent-level precision for neutralino and chargino masses.
(Sub-percent expected for H-20 luminosities.)

Event selection dedicated to each benchmark will improve the precision.

Cross Section

- Event counting within optimized mass window
 - N1N2:
 - ILC1: [0, 20] GeV
 - ILC2: [0, 9] GeV
 - nGMM1: [0, 3.5] GeV
 - C1C1: use all selected events
- Cross section significance computed via $S/\sqrt{S+B}$ for each channel, combined via squared-sums → converted to statistical uncertainty

$\sqrt{s}=500 \text{ GeV}$ $L=500 \text{ fb}^{-1}$	$\Delta\sigma/\sigma \text{ (N1N2)}$	$\Delta\sigma/\sigma \text{ (C1C1)}$
ILC1	1.73%	1.51%
ILC2	2.90%	2.99%
nGMM1	3.03%	3.46%

A few percent precision for neutralino and chargino masses.
(Percent-level expected for H-20 luminosities.)

Event selection dedicated to each benchmark will improve the precision.

Parameter Extraction

SUSY Parameter Fit

S.-L. Lehtinen

Input

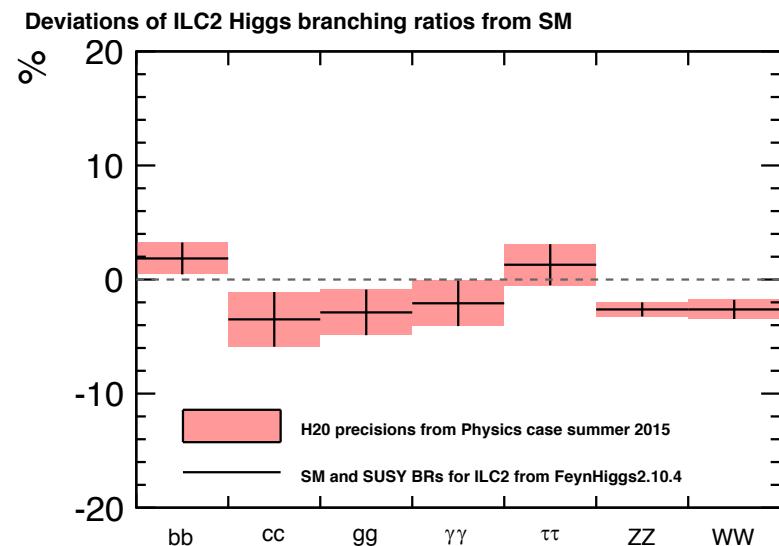
Mass N1, N2, C1
Cross Sections

Higgs Mass
Higgs Couplings

Fit

Output

$\mu, M_1, M_2, M_3, \tan\beta$



SUSY Parameter Fit: Details

S.-L. Lehtinen

Chi-square (χ^2) from experimental observables and theory predictions
→ Uncertainty taken from experimental observables

Find SUSY parameters that minimize χ^2

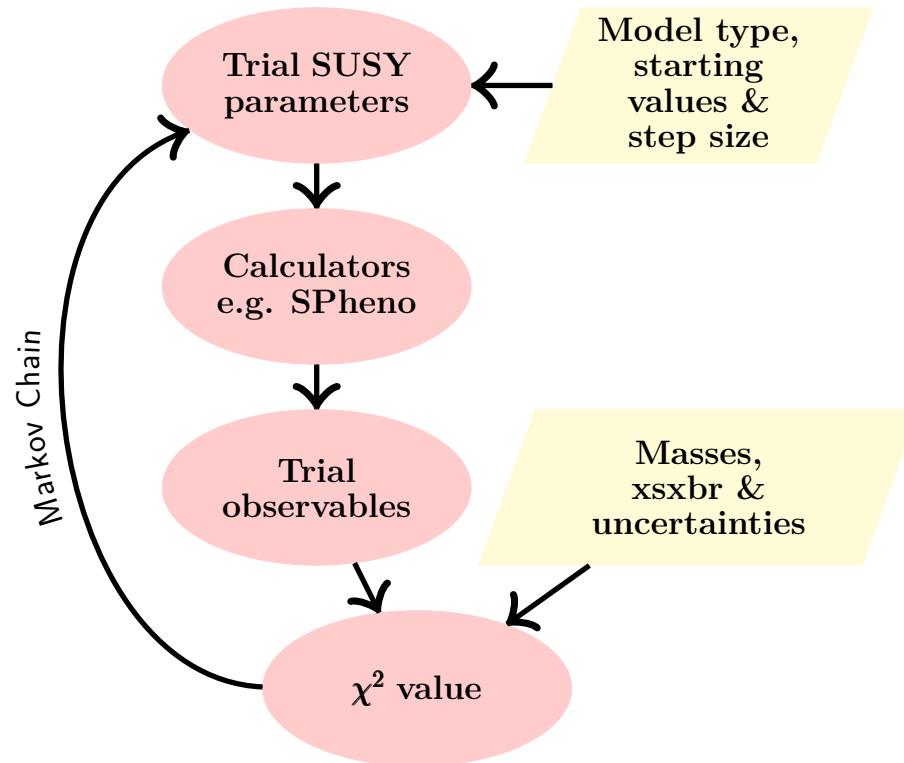
The range of values $\Delta\chi^2 = [0,1]$ gives the uncertainty

Fittino minimises

$$\chi^2 = \left(\frac{\mathcal{O}(ILC) - \mathcal{O}(theory)}{\Delta\mathcal{O}(ILC)} \right)^2$$

(arXiv:hep-ph/0412012)

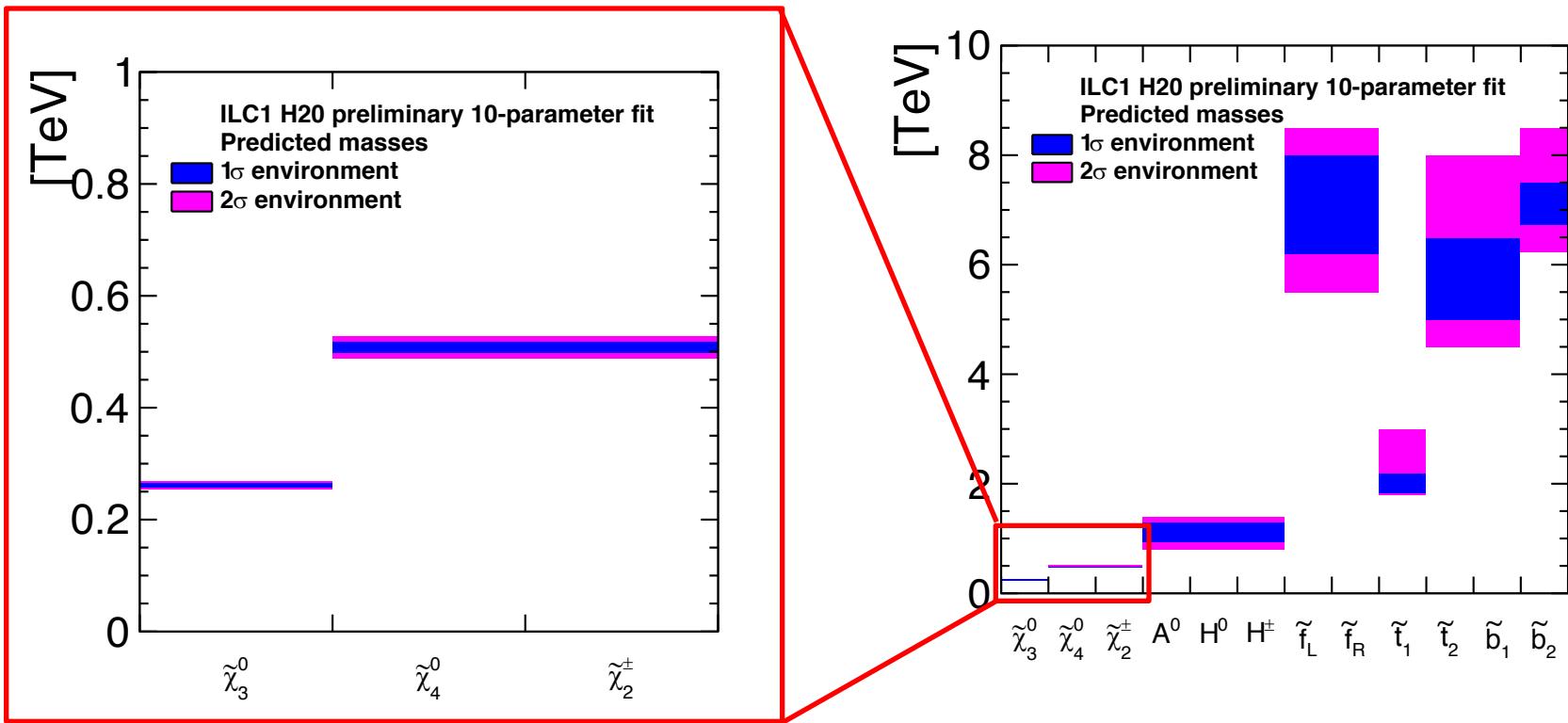
SPheno 3.3.9beta,
FeynHiggs2.10.2 for Higgs,
MicrOMEGAs and
AstroFit for DM



Prediction of heavy states

Example: ILC1

- Heavier neutralino/chargino masses predicted to $\sim 2\%$
 \rightarrow Sets the energy scale of ILC Upgrade, e.g. $\sqrt{s} = 1 \text{ TeV}$
- Rough predictions for heavy Higgs, stop, heavy sfermions



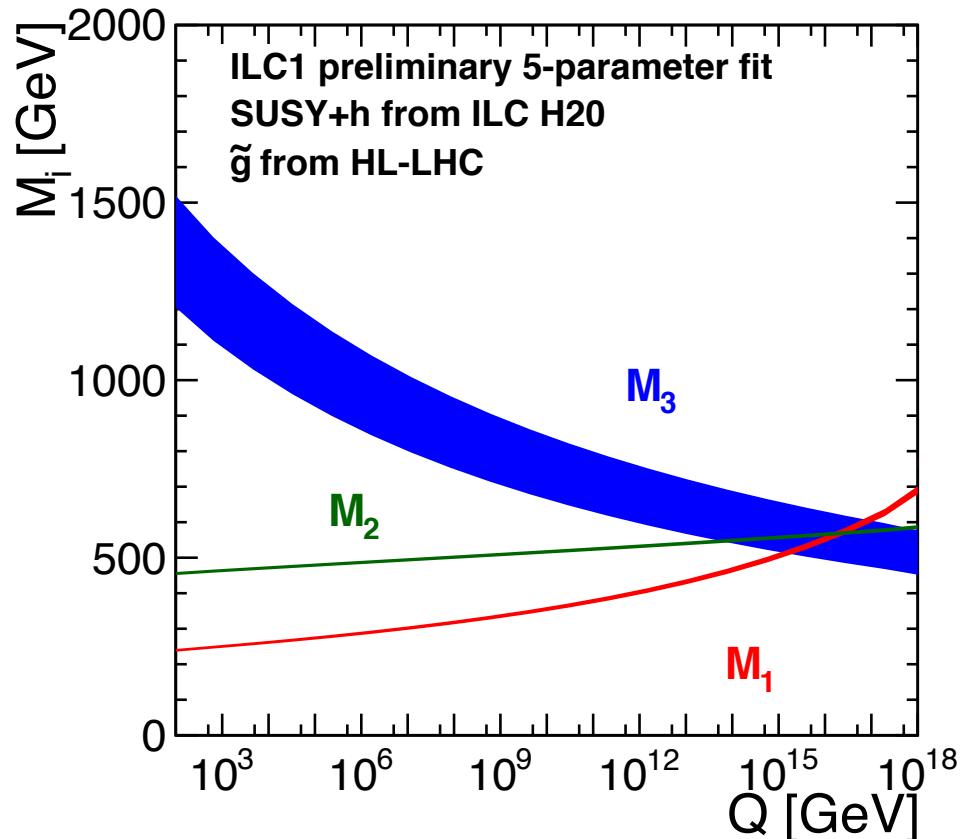
Test of GUT-scale Physics (1)

To be updated (S.-L. Lehtinen)

Example: ILC1 [20 year run]

In this scenario, the LHC sees the gluino ($M=1.4$ TeV), assume mass precision of 10% at LHC

- Take determined parameters at 1 TeV
- Run up to GUT scale with two-loop RGEs
- Other parameters fixed to model values

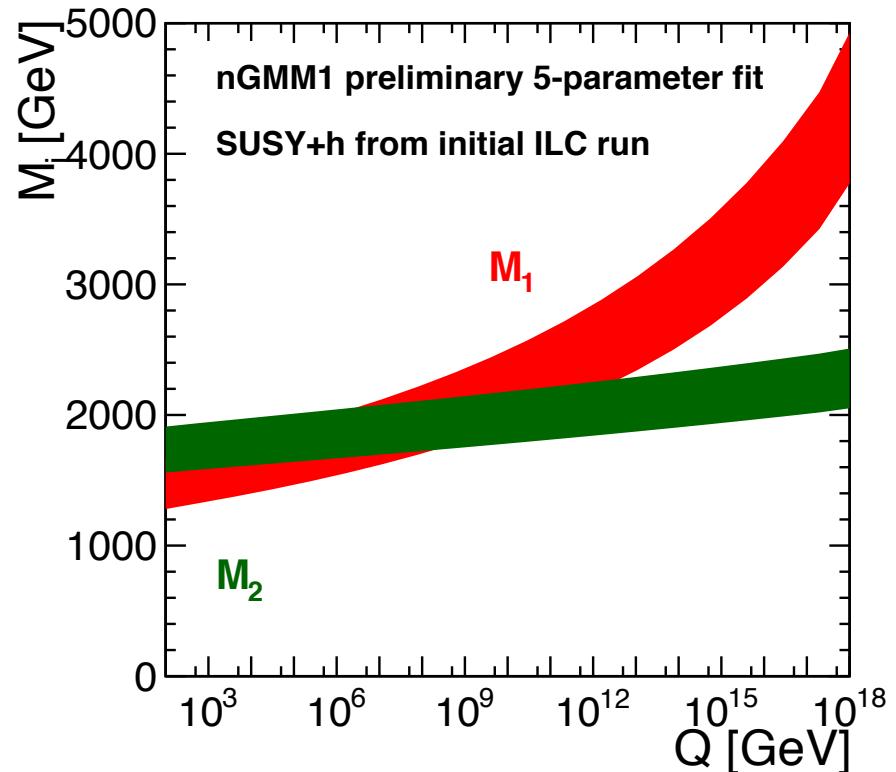
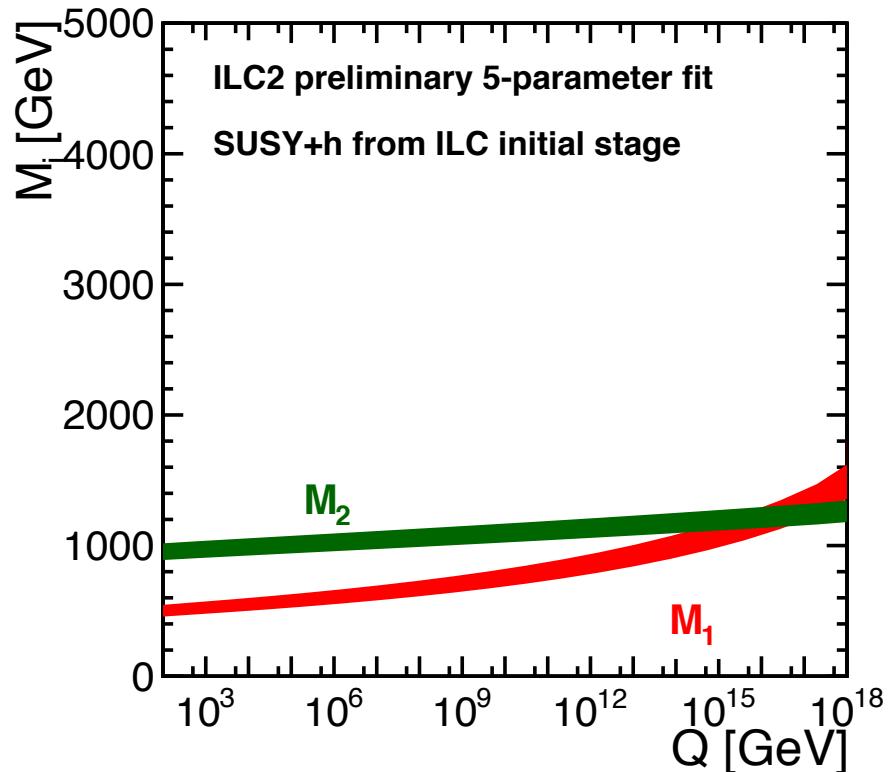


**Test of Gaugino Mass Unification
LHC + ILC Synergy**

Test of GUT-scale Physics (2)

To be updated (S.-L. Lehtinen)

Example: ILC2 vs. nGMM1



Two scenarios with similar higgsino masses are
distinguishable with ILC precision

Summary

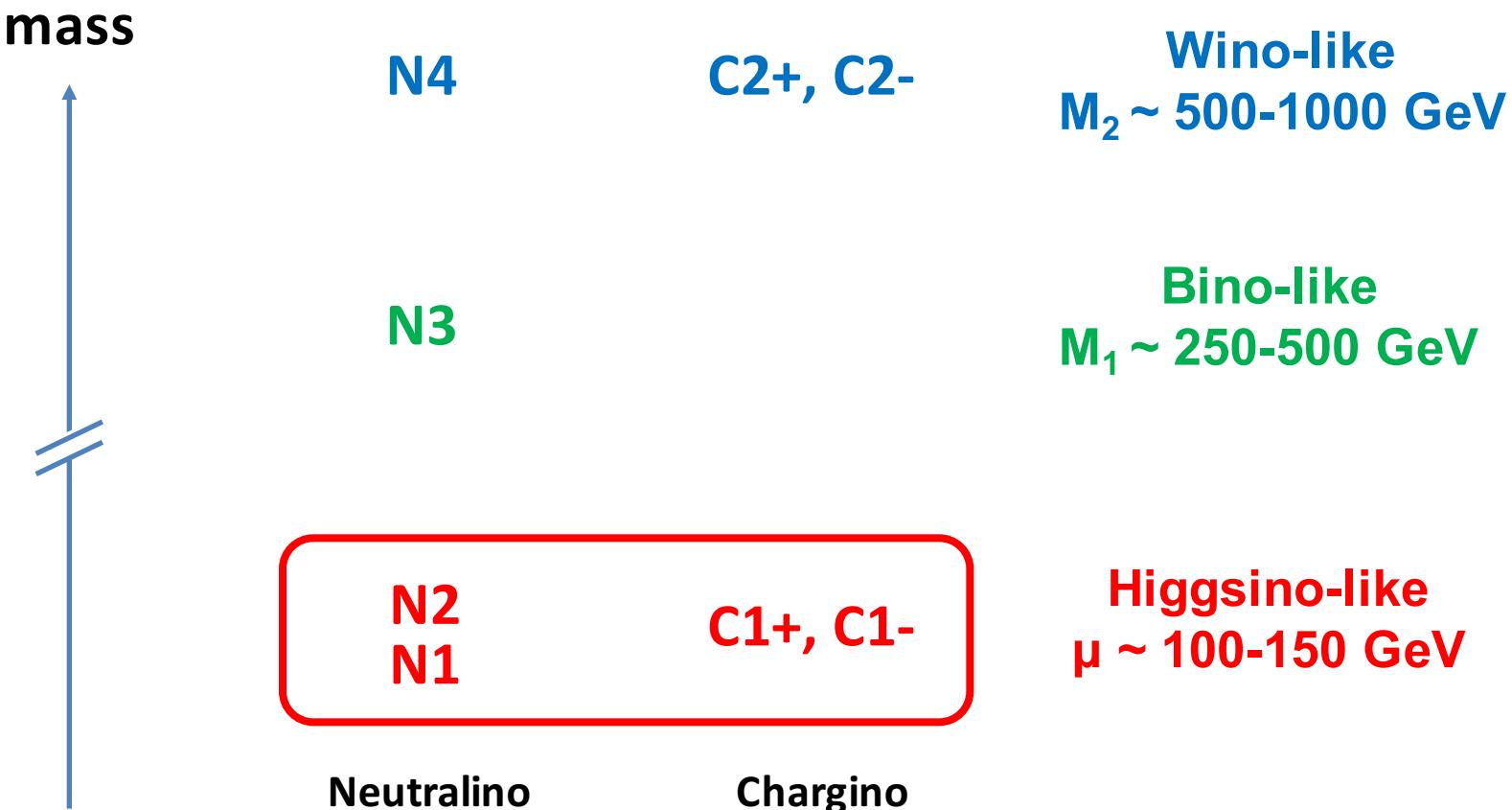
Physics:

- Natural SUSY predicts light Higgsinos which are compressed if other particles are heavy. The ILC, including its update, can probe these Higgsinos, and, if discovered, measure their mass & cross sections at percent level with the “full” dataset.
- These precise measurements allow us to predict the heavy states and to extract the underlying SUSY parameters. Test of GUT-scale physics is possible, including the distinction of various scenarios such as unified gaugino mass vs. mirage/string-like unification.

ILD:

- Please send us comments on the simulation part. The update of the parameter extraction part will begin soon using the final results of the simulation part.
- Publication is under preparation, draft for ILD review expected to be ready toward END of January.

Backup



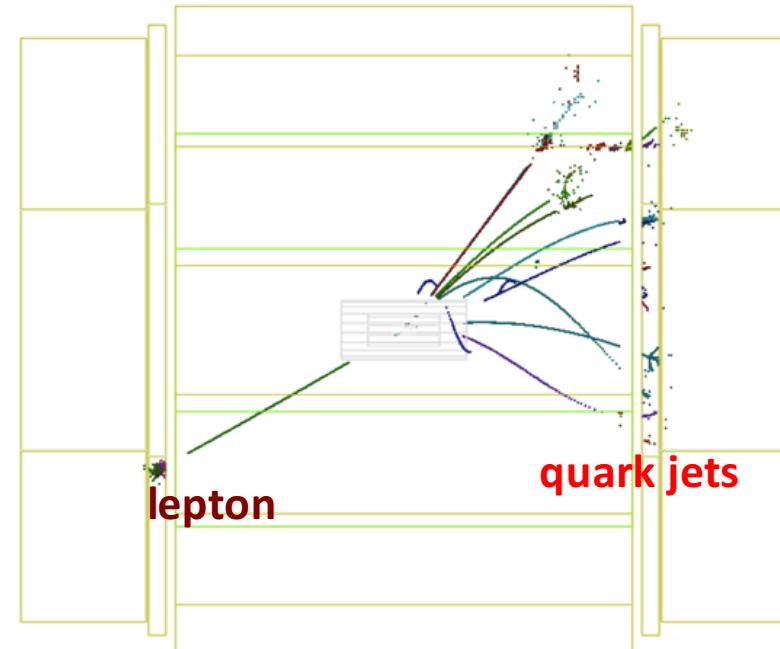
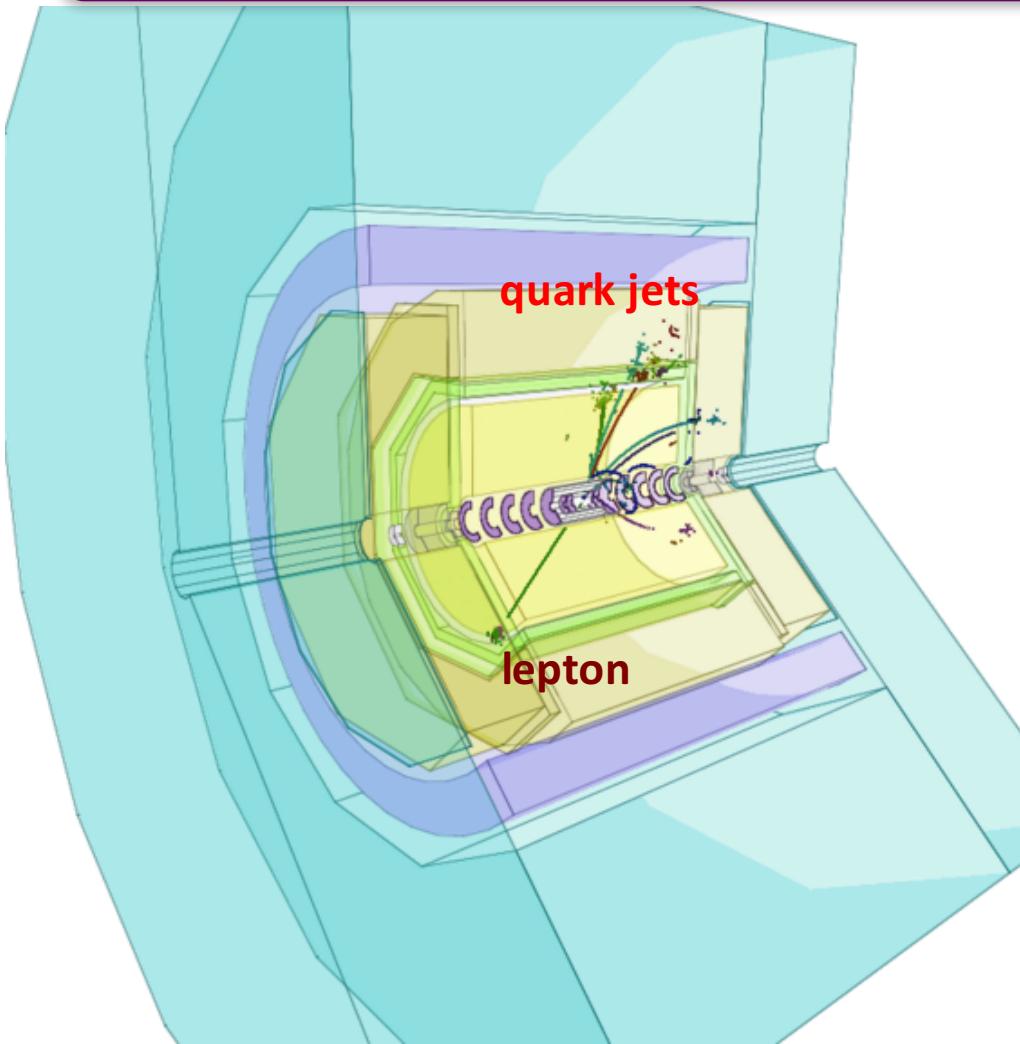
Thanks to the small mixings of Higgsino / Bino / Wino,
the Bino & Wino are resolvable from the precision
measurements of the **polarized cross sections** & **mass** of
the lightest Higgsino-like states.

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

$\sqrt{s} = 500 \text{ GeV}$

Chargino pair production with semileptonic decay

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

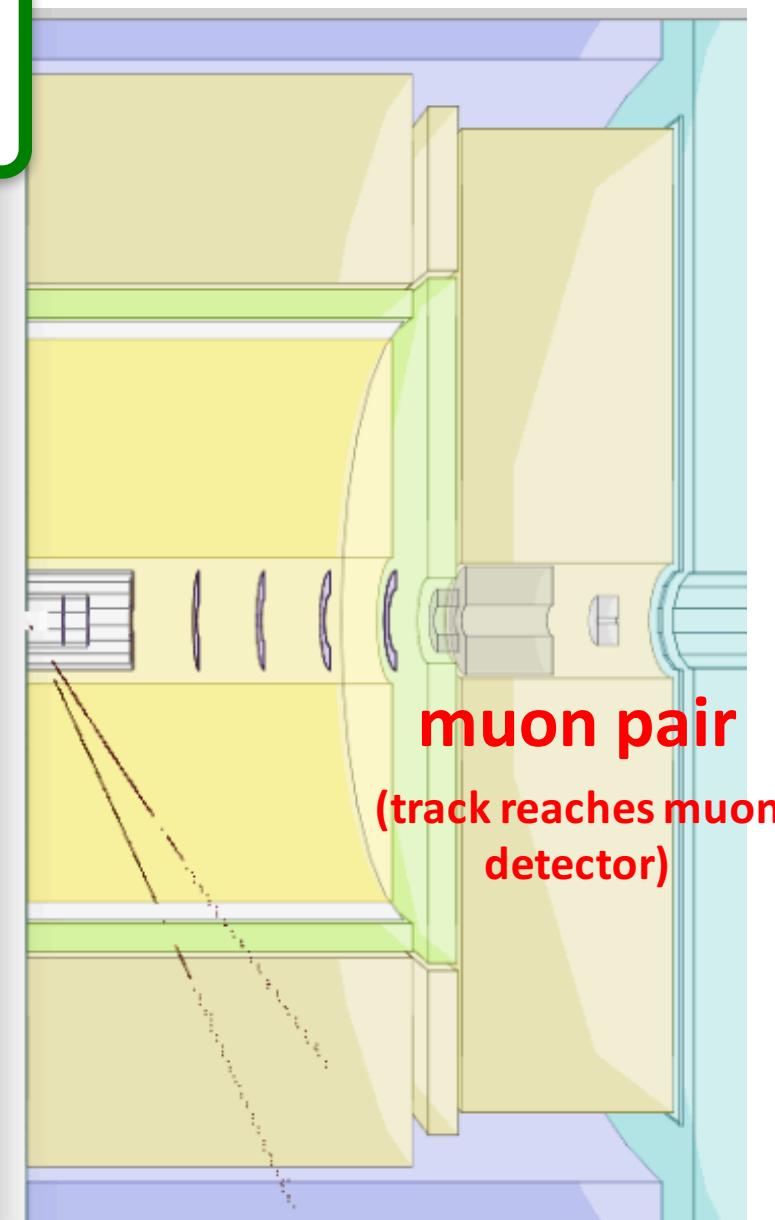
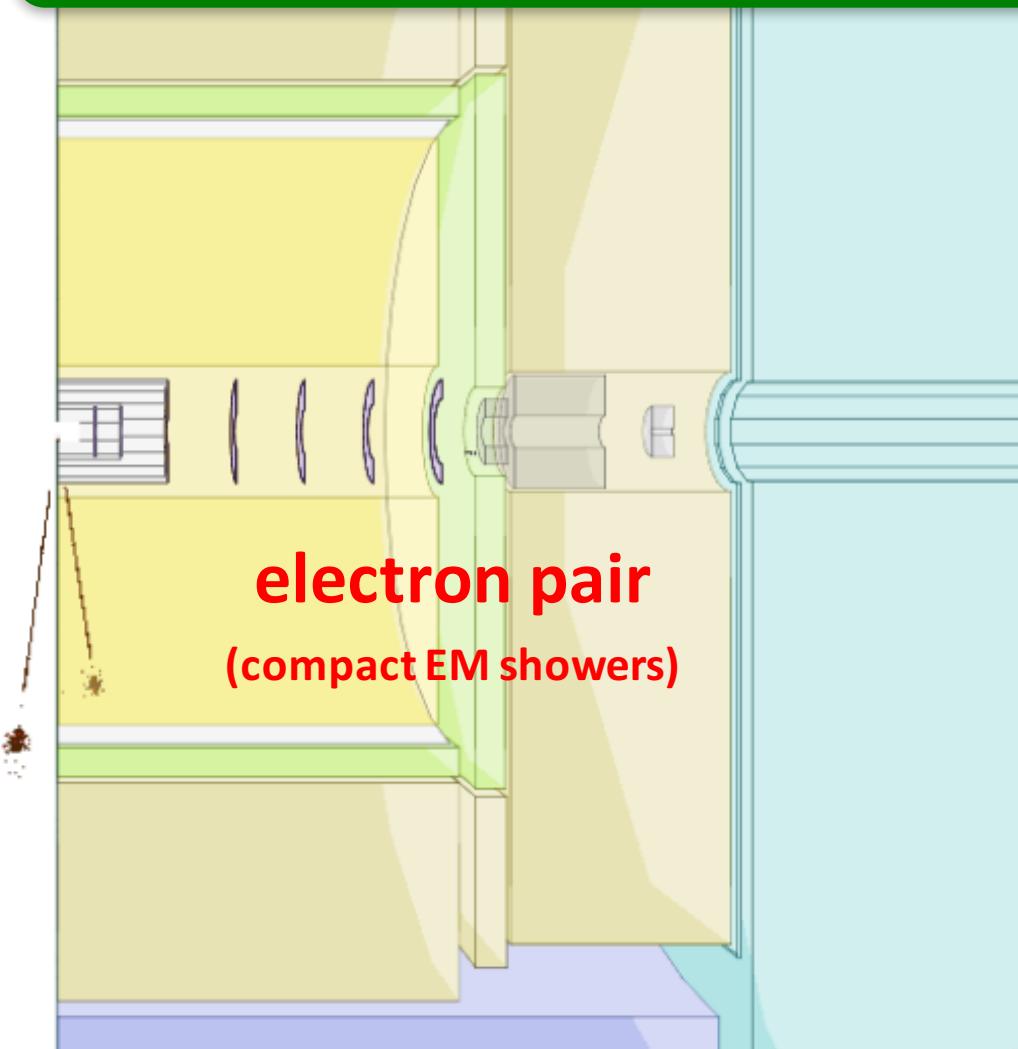


How do these signals look in the detector? (2)

$\sqrt{s} = 500 \text{ GeV}$

Neutralino mixed production with leptonic decay

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



Comparison with LCWS2016 results

- Background consideration more complete
 - 4f (previously missing phase space in low ee-pair invariant mass)
 - two-photon, $a\bar{e} \rightarrow 3f$
- Event selection “reoptimized” to be consistent across all channels
 - Ensuring measurement at nGMM1 means that tighter cuts were applied for ILC1
 - Tighter selection for C1C1 to ensure (almost) background-free signal selection
 - The numbers are worse for ILC1 (all channels) and for C1C1 (all benchmarks)
- Fitting strategy revised
 - Impact on precision is minimal compared to the impact due to changes in selection efficiencies

Higgsino Mass Precisions (combined) ILC1

apply χ^2 fit to “observables” (kinematic edges)

($E_{\ell\ell}^{\text{max}}$, E_{jj}^{max} , $M_{\ell\ell}^{\text{max}}$, M_{jj}^{max} are functions of Higgsino masses)

Scale results to H20

For each polarization:

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

	channel	M	$\Delta M/M$	$\Delta M/M$
Neutralino μμ and ee combined	$\chi^0_1 \chi^0_2$	500 fb $^{-1}$		H20 (1600 fb $^{-1}$)
	MN1	102.54	0.8%	0.4%
	MN2	123.36	0.7%	0.4%
Chargino μ-tag and e-tag combined	channel	M	$\Delta M/M$	$\Delta M/M$
	$\chi^{\pm}_1 \chi^{\mp}_1$	500 fb $^{-1}$		H20(1600fb $^{-1}$)
	MN1	116.60	0.4%	0.2%
	MC1	132.80	0.4%	0.2%

Theoretic values: MN1 = 102.7 GeV MN2 = 124.0 GeV, MC1 = 117.3 GeV

MN1: χ^0_1 mass

MN2: χ^0_2 mass

MC1: χ^{\pm}_1 mass

Cross section results

ILC1

channel	$\Delta \sigma / \sigma$	$\Delta \sigma / \sigma$
$\chi 01 \chi 02$	500 fb $^{-1}$	H20 (1600 fb $^{-1}$)
$\mu \mu$, left	3.5%	2.0%
ee, left	3.2%	1.8%
combined	2.3%	1.3%
$\mu \mu$, right	2.8%	1.6%
ee, right	2.4%	1.3%
combined	1.8%	1.0%
channel	$\Delta \sigma / \sigma$	$\Delta \sigma / \sigma$
$\chi 1+ \chi 1-$	500 fb $^{-1}$	H20 (1600 fb $^{-1}$)
μ -tag, left	0.9%	0.5%
e-tag, left	0.8%	0.5%
combined	0.6%	0.3%
μ -tag, right	1.8%	1.0%
e-tag, right	1.7%	1.0%
combined	1.2%	0.7%

ILC2

channel	$\Delta \sigma / \sigma$	$\Delta \sigma / \sigma$
$\chi 01 \chi 02$	500 fb $^{-1}$	H20 (1600 fb $^{-1}$)
$\mu \mu$, left	2.8%	1.6%
$\mu \mu$, right	3.6%	2.0%

channel	$\Delta \sigma / \sigma$	$\Delta \sigma / \sigma$
$\chi 1+ \chi 1-$	500 fb $^{-1}$	H20 (1600 fb $^{-1}$)
μ -tag, left	3.9%	2.2%
μ -tag, right	5.2%	2.9%