SUSY parameters from higgsino measurements in high-energy electron-positron collisions

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PIER Helmholtz Graduate School
A Graduate Education Program of Universität Hamburg in Cooperation with DESY

Collaborative Research Centre 676
Particles, Strings, and the Early Universe
The Structure of Matter and Space-Time

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

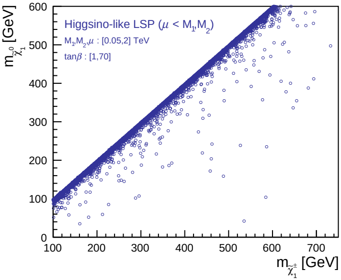
Outline

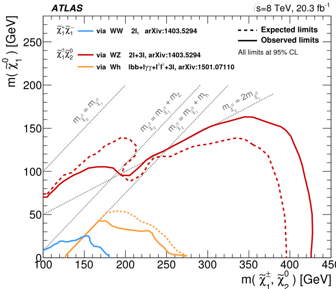
Why study light higgsinos

- Naturalness and small fine tuning require μ parameter at the EW scale:

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

- μ small $\implies$ light higgsinos
- Typical mass difference 10 - 20 GeV
  $\implies$ challenging for LHC if other sparticles are heavy





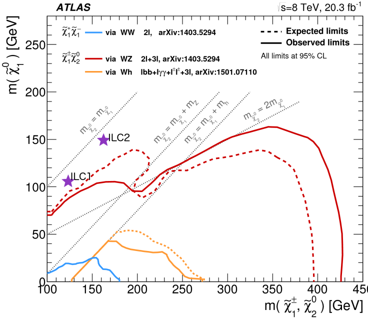
Benchmarks studied

- $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm$ observable, $\tilde{\chi}_3^0$ accessible with a small cross section
- Other sparticles heavy
- Mass gaps $\sim 10 - 20$ GeV $\Longrightarrow$ higgsinos decay via a virtual Z/W

Two specific benchmarks

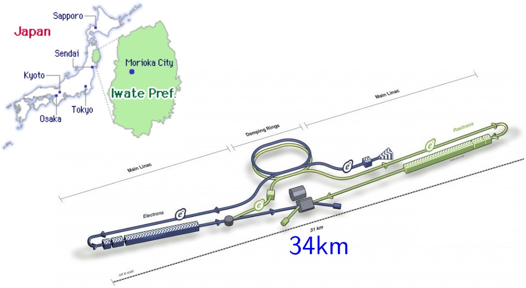
mass	ILC1	ILC2
$\tilde{\chi}_1^0$	103 GeV	148 GeV
$\tilde{\chi}_1^\pm$	117 GeV	157.8 GeV
$\tilde{\chi}_2^0$	124 GeV	158.3 GeV
$\tilde{\chi}_3^0$	267 GeV	539 GeV
$\tilde{g}$	1560 GeV	2830 GeV

Cross sections for production in e^+e^- at $\sqrt{s} = 500$ GeV several hundred fb

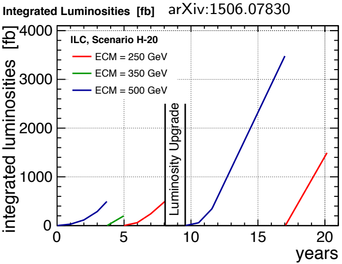


What is the International Linear Collider (ILC)

- Electron-positron collider at $\sqrt{s} = 250 - 500\text{GeV}$ (1TeV)
- Polarisation of electrons 80%, positrons 30%
- Well-defined initial state: 4-momentum and spin config.
- Clean and completely reconstructable final state
- Construction under political consideration in Japan

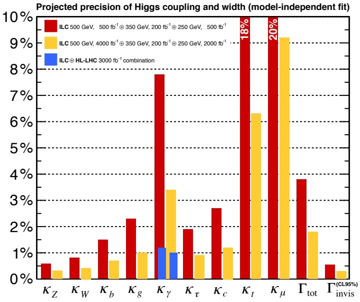


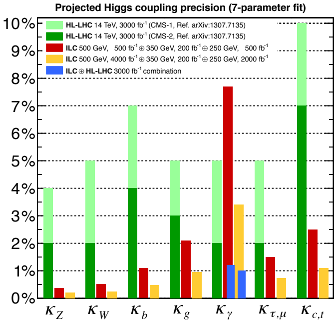
Typical 20yr running scenario



Higgs mass and BR measurements are important

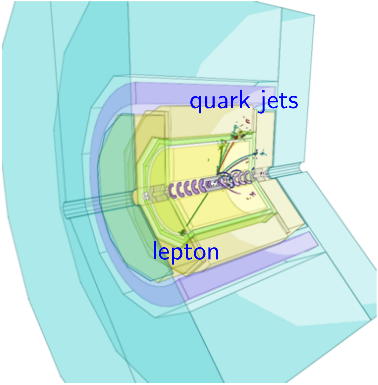
- ILC will measure m_h to 25 MeV (15 MeV) precision in initial (full) run
- Precision higgs measurements important for SUSY parameter determination





Detailed simulation study: 500 GeV, 500 fb^{-1}

$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0 q\bar{q}'\tilde{\chi}_1^0 e\nu_e$
in the International Large Detector

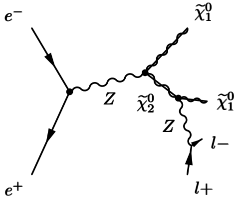


Soft tracks - no problem for ILC

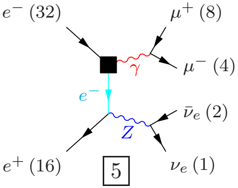
- Event generation `Whizard 1.95`, hadronisation `Pythia 6.422`
- Detailed ILD-specific software for simulation and reconstruction (`Mokka` & `Marlin`)
- Beam spectrum and ISR included

Neutralino measurement

- Neutralino signal: $e^+e^- \to \widetilde{\chi}_1^0\widetilde{\chi}_2^0 \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0 e^+e^-(\mu^+\mu^-)$
- Characterised by large missing energy and two fermions in the final state
- Main background 4-fermion processes $\nu\nu ll$



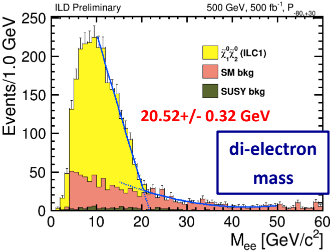
Neutralino signal

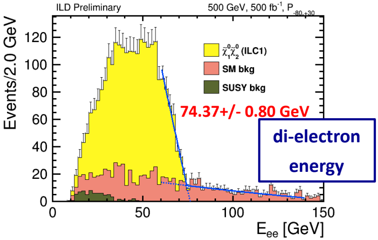


Background example

Mass extraction

- Kinematics: Maximum invariant mass gives the mass splitting. Then maximum of di-electron energy gives the absolute the masses since initial state known

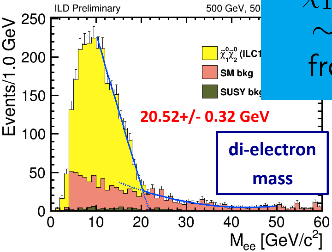


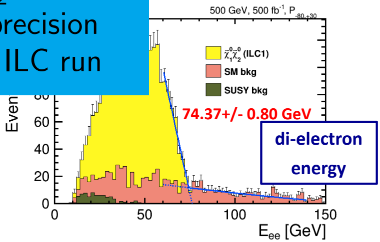


Mass extraction

- Kinematics: Maximum invariant mass gives the mass splitting. Then maximum of di-electron energy gives the absolute the masses since initia

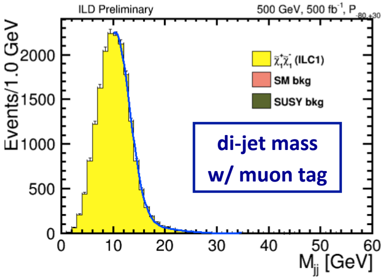
Preliminary result:
$\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ masses
$\sim$0.2% precision
from full ILC run

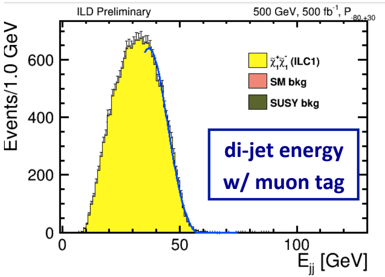




Chargino measurement

- Chargino signal: $e^+e^- \to \tilde{\chi}_1^- \tilde{\chi}_1^+ \to \tilde{\chi}_1^0 q\bar{q}' \tilde{\chi}_1^0 e\nu_e(\mu\nu_\mu)$
- Characterised by large missing energy, two jets from one W* and a lepton from the other W*





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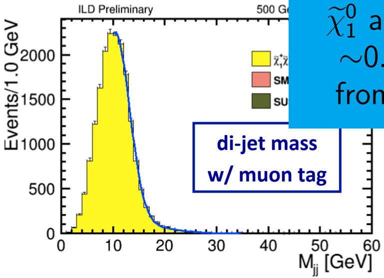
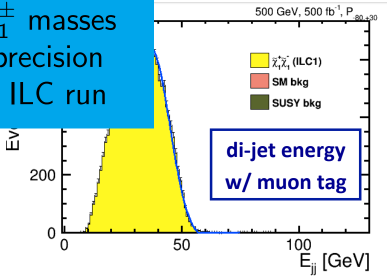
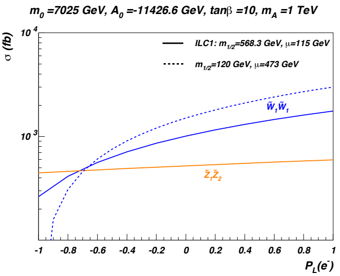




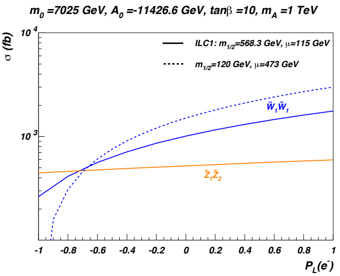
Cross section measurement

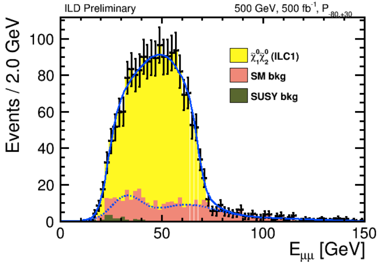
- Measure with different polarisation combinations
- Polarisation dependence reveals higgsino nature



Cross section measurement

- Measure with different polarisation combinations
- Polarisation dependence reveals higgsino nature
- Strategy: Fit overall shape to count events





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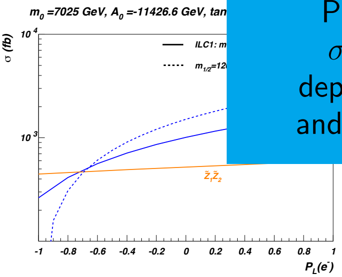
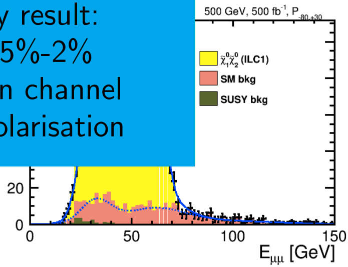


Preliminary result:
$\sigma\times$ BR 0.5%-2%
depending on channel
and beam polarisation



Parameter fitting

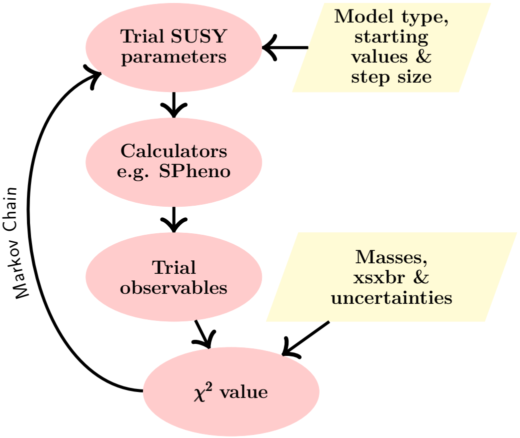
- What can we say about SUSY parameters based on these observables?
- Which parameters are determined and how accurately?
- Can we test the SUSY model type?
- Can we make predictions about the unobserved part of the spectrum?

Fitting parameters to observables with Fittino

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,
Higgs mass and BRs
FeynHiggs2.10.2

Parameters of ILC1

- Definition: NUHM2 model
  6 free parameters
  M_0, $M_{1/2}$, μ, m_A, $\tan\beta$, A_0

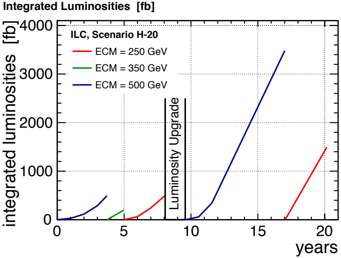
parameter	scale	ILC1
μ	weak	115
$M_{1/2}$	GUT	568.3
$\tan\beta$	weak	10
M_0	GUT	7025
A_0	GUT	-10426.6
m_A	weak	1000

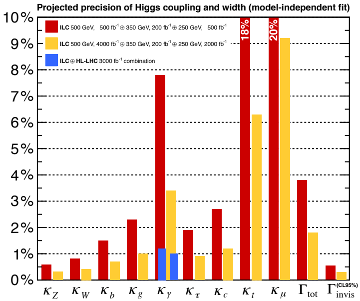
- Fit pMSSM-10 (at 1 TeV)

parameter	ILC1-pMSSM
μ	115
M_1	250
M_2	463
M_3	1270
$\tan\beta$	10
$M_{\tilde{t}_L}$	4820
$M_{\tilde{t}_R}$	1670
$M_{\text{other sfermions}}$	7150
$A_{t=b=\tau}$	-4400
m_A	1000

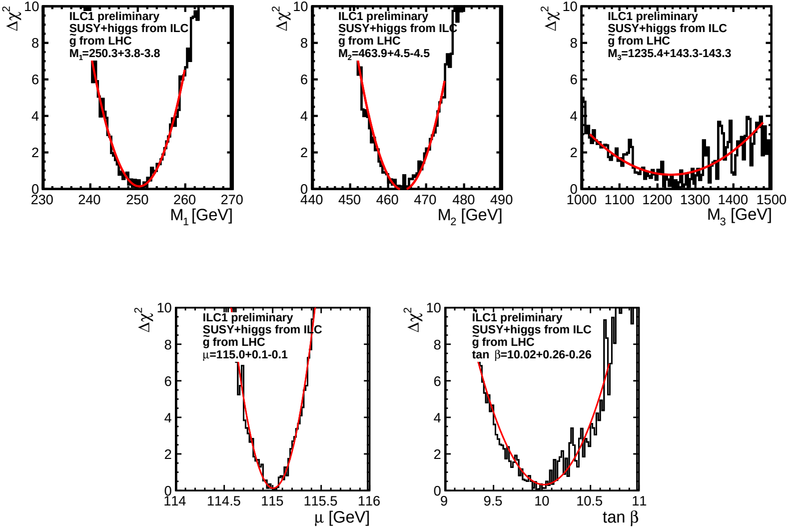
5 parameter fit with SUSY and Higgs

- Input: higgsino masses with 0.2% uncertainty, cross sections with 0.5%-2% uncertainty, 250, 350 and 500 GeV measurements
- Input: Higgs precisions from ILC 20yr running
- Input: gluino mass from HL-LHC with 10% uncertainty





Fit of 5 parameters relevant for gauginos



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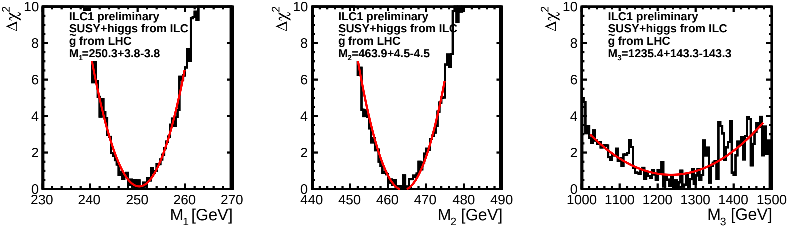
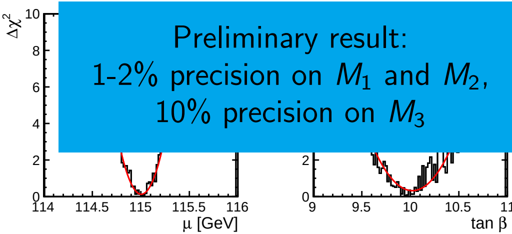
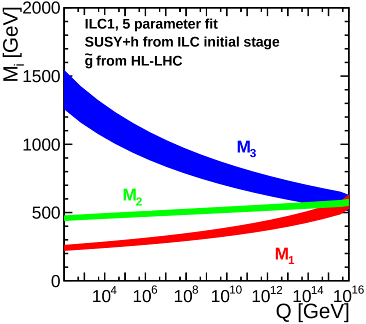




Preliminary result:
1-2% precision on M_1 and M_2,
10% precision on M_3

Test of gaugino mass unification

NUHM2 type scenario (ILC1)
initial stage ILC result



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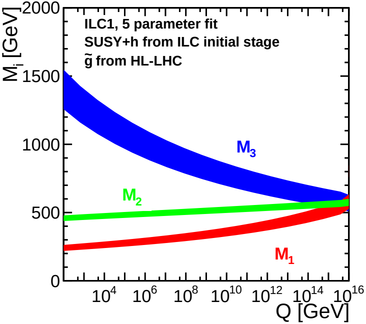
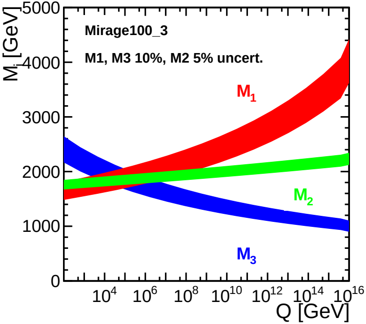


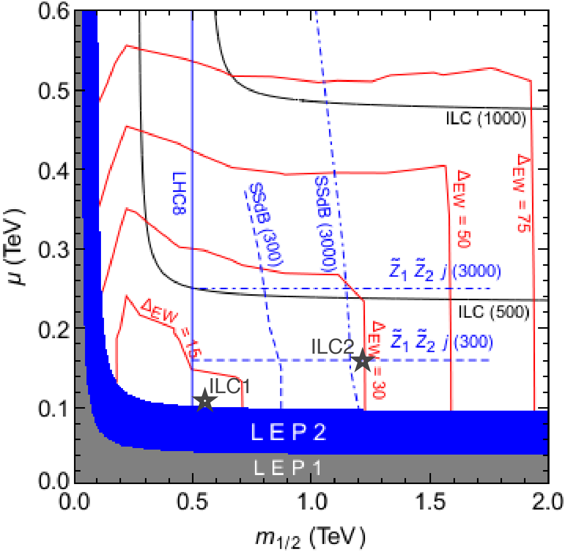
Mirage mediation scenario
similar precision expected



Summary

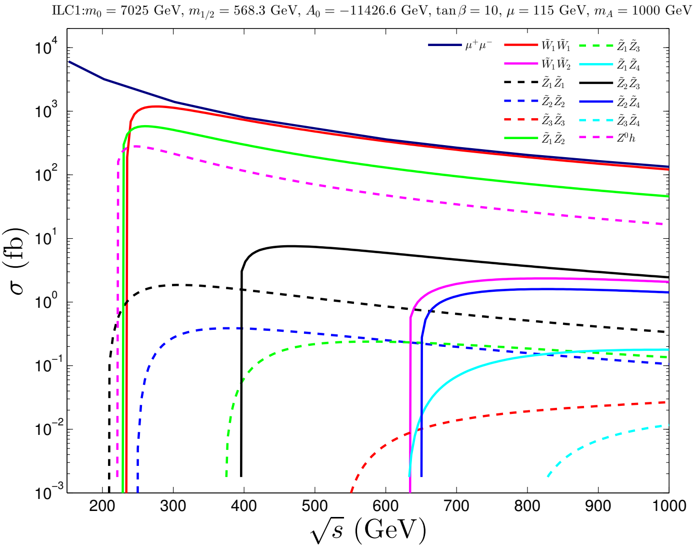
- Light higgsinos motivated by naturalness
- ILC would probe higgsinos complementary to LHC reach
  - either exclude masses up to $\sqrt{s}/2 = 500$ GeV for 1 TeV upgrade $\rightarrow$ wide coverage of natural SUSY scenarios
  - or discover regardless of mass scale of heavier states
- ILC would measure properties of higgsinos to percent-level precision, with full ILC run / threshold scans to sub-% precision
- Precise measurements allow for extracting some weak scale parameters and predicting mass scales of unobserved sparticles
- Can have sensitivity to GUT unification hypotheses

BACKUP



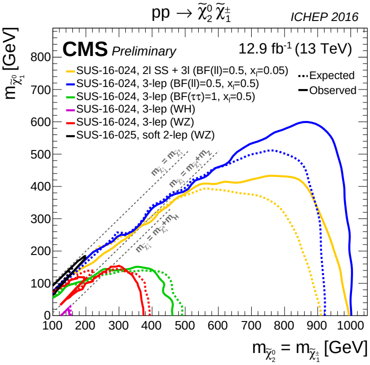
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0
0.5
1.0
1.5
2.0
μ (TeV)
$m_{1/2}$ (TeV)
ILC (1000)
ILC (500)
LHC8
SSdB (300)
SSdB (3000)
$\tilde{Z}_1 \tilde{Z}_2 j$ (3000)
$\tilde{Z}_1 \tilde{Z}_2 j$ (300)
$\Delta_{EW} = 15$
$\Delta_{EW} = 30$
$\Delta_{EW} = 50$
$\Delta_{EW} = 75$
ILC1
ILC2
LEP2
LEP1

ILC1 unpolarised cross sections

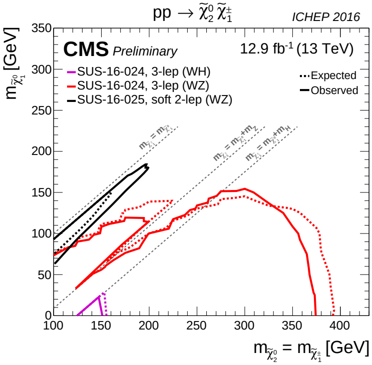


Fit observables

- mass $\widetilde{\chi}_1^0$, $\widetilde{\chi}_2^0$, $\widetilde{\chi}_1^\pm$
- xsxbr of $\widetilde{\chi}_1^+ \widetilde{\chi}_1^- \rightarrow q\bar{q}' l \nu_l$ (l=e, mu) for $\mathcal{P}(e^- = \mp 80\%, e^+ = \pm 30\%)$
- xsxbr of $\widetilde{\chi}_1^0 \widetilde{\chi}_2^0 \rightarrow \widetilde{\chi}_1^0 \widetilde{\chi}_1^0 ll$ (l=e, mu) for $\mathcal{P}(e^- = \mp 80\%, e^+ = \pm 30\%)$
- Higgs mass
- Higgs BRs $h \rightarrow bb, h \rightarrow cc$, $h \rightarrow \tau\tau, h \rightarrow gg$, $h \rightarrow \gamma\gamma$, $h \rightarrow ZZ^*, h \rightarrow WW^*$



pp → $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$
ICHEP 2016
CMS Preliminary
12.9 fb-1 (13 TeV)
SUS-16-024, 2l SS + 3l (BF(ll)=0.5, xl=0.05)
SUS-16-024, 3-lep (BF(ll)=0.5, xl=0.5)
SUS-16-024, 3-lep (BF(ττ)=1, xl=0.5)
SUS-16-024, 3-lep (WH)
SUS-16-024, 3-lep (WZ)
SUS-16-025, soft 2-lep (WZ)
Expected
Observed
m [GeV]
m = m [GeV]



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SUS-16-024, 3-lep (WH)
SUS-16-024, 3-lep (WZ)
SUS-16-025, soft 2-lep (WZ)
Expected
Observed
m [GeV]
m = m [GeV]

ILC1

Cross sections (pure beam polarizations)
√s=500 GeV with TDR beam parameters

(Pe-, Pe+)	(-1.0,+1.0)	(+1.0,-1.0)
$\sigma(\chi_1^+\chi_1^-)$ [fb]	1800	335
$\sigma(\chi_1^0\chi_2^0)$ [fb]	491	379
$\sigma(\chi_2^0\chi_3^0)$ [fb]	11.0	8.42
$\sigma(\chi_1^0\chi_1^0)$ [fb]	2.03	1.56
$\sigma(\chi_2^0\chi_2^0)$ [fb]	0.53	0.41
$\sigma(\chi_1^0\chi_3^0)$ [fb]	0.28	0.20

Branching ratios

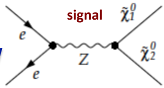
$BR(\chi_1^+ \to \chi_1^0 qq')$	67%
$BR(\chi_1^+ \to \chi_1^0 l\nu)$ (l=e,μ)	22%
$BR(\chi_2^0 \to \chi_1^0 qq')$	58%
$BR(\chi_2^0 \to \chi_1^0 ll)$ (l=e,μ)	7.4%

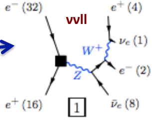
Event Selection

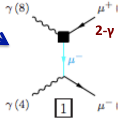
Neutralino mixed production with leptonic decay

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

- Reconstruct two leptons (ee or μμ) which originate from Z^* emission in decay of χ_2^0 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





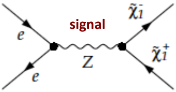


Chargino pair production with semileptonic decay

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

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

  (with signal significance > 100)



Major Residual bkg

in region of higher kinematic edge of Minv and Edl

4f_leptonic processes involving missing energy

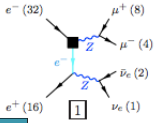
<u>μμ :</u> 4f_ZZWWMix_l, 4f_singleZnunu_l

<u>ee :</u> 4f_singleZeorsingleW_l

4f_leptonic BG drop to 1/10 for right pol

Grove 1

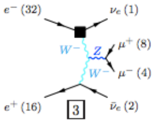
Multiplicity: 2
Resonances: 2
Log-enhanced: 1
t-channel: 1



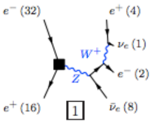
4f_sznu_leptonic

Grove 2

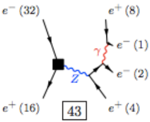
Multiplicity: 3
Resonances: 1
Log-enhanced: 2
t-channel: 2

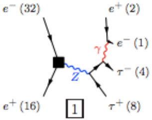


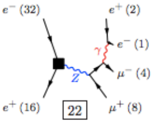
4f_szeorsw_leptonic



4f_sze_leptonic







These are not all the diagrams

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

Top-Level Parameters for TDR Baseline

Centre-of-mass energy	E_{CM}	GeV	200	230	250	350	500
Luminosity pulse repetition rate		Hz	5	5	5	5	5
Positron production mode			10 Hz	10 Hz	10 Hz	nom.	nom.
Estimated AC power	P_{AC}	MW	114	119	122	121	163
Bunch population	N	$\times 10^{10}$	2	2	2	2	2
Number of bunches	n_b		1312	1312	1312	1312	1312
Linac bunch interval	Δt_b	ns	554	554	554	554	554
RMS bunch length	σ_z	µm	300	300	300	300	300
Normalized horizontal emittance at IP	$\gamma\epsilon_x$	µm	10	10	10	10	10
Normalized vertical emittance at IP	$\gamma\epsilon_y$	nm	35	35	35	35	35
Horizontal beta function at IP	β_x^*	mm	16	14	13	16	11
Vertical beta function at IP	β_y^*	mm	0.34	0.38	0.41	0.34	0.48
RMS horizontal beam size at IP	σ_x^*	nm	904	789	729	684	474
RMS vertical beam size at IP	σ_y^*	nm	7.8	7.7	7.7	5.9	5.9
Vertical disruption parameter	D_y		24.3	24.5	24.5	24.3	24.6
Fractional RMS energy loss to beamstrahlung	δ_{BS}	%	0.65	0.83	0.97	1.9	4.5
Luminosity	L	$\times 10^{34}$ cm^{-2} s^{-1}	0.56	0.67	0.75	1.0	1.8
Fraction of L in top 1% E_{CM}	$L_{0.01}$	%	91	89	87	77	58
Electron polarisation	P_-	%	80	80	80	80	80
Positron polarisation	P_+	%	30	30	30	30	30
Electron relative energy spread at IP	$\Delta p/p$	%	0.20	0.19	0.19	0.16	0.13
Positron relative energy spread at IP	$\Delta p/p$	%	0.19	0.17	0.15	0.10	0.07

ILC Timeline - where are we now?