SUSY Benchmark Studies for the CLIC CDR

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Outline

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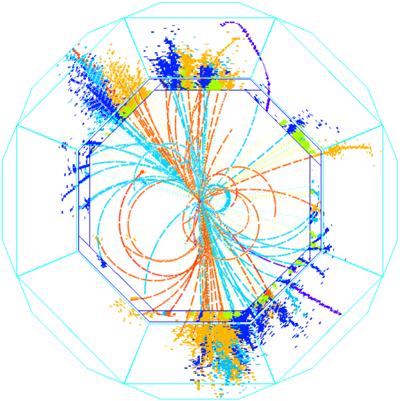
  - Background Suppression
- Benchmark Studies
  - Heavy Higgs
  - Squarks
  - Sleptons
  - Chargino/Neutralino



CLIC physics and detector CDR

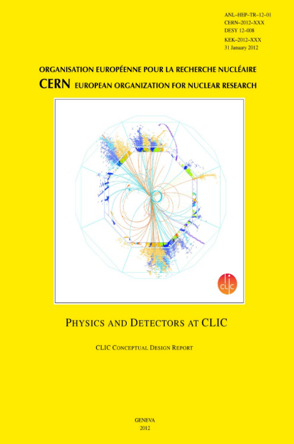
CLIC provides the potential for e+e- collisions up to $\sqrt{s} = 3$ TeV:

Challenging machine environment
→ detailed detector studies are needed

CLIC physics and detector CDR:

- Physics potential
- Demonstrate that the physics can be measured at CLIC

Release of the CDR text (20.12.2011):
https://edms.cern.ch/document/1177771



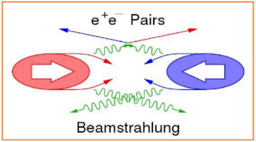
Review in October 2011:
https://indico.cern.ch/conferenceTimeTable.py?confId=146521

Conditions at CLIC

	CLIC at 3 TeV
L ($cm^{-2}s^{-1}$)	5.9×10^{34}
BX separation	0.5 ns
#BX / train	312
Train duration (ns)	156
Rep. rate	50 Hz
σ_x / σ_y (nm)	≈ 45 / 1
σ_z (μm)	44

Drives timing requirements for CLIC detector

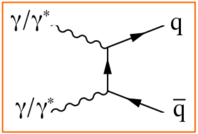
very small beam size



Beam related background:

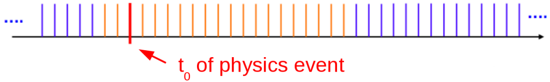
- Small beam profile at IP leads very high E-field

- **Beamsstrahlung**
  - Pair-background
  - γγ to hadrons



Background Suppression I

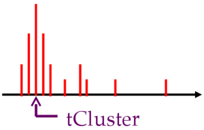
Triggerless readout of full bunch train:



Subdetector	Reco. window
ECAL	10 ns
HCAL Endcaps	10 ns
HCAL Barrel	100 ns
Silicon Detectors	10 ns
TPC	full train

1) Identify t_0 of physics event in bunch train

- Define reconstruction window
- All hits and tracks in this window are passed to the reconstruction
  → Physics objects (PFOs) with precise p_T and cluster time information

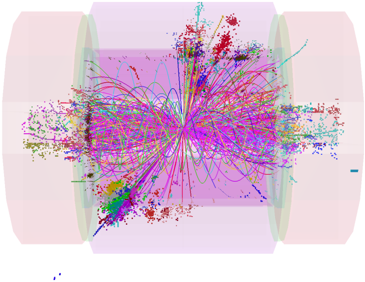


2) Apply cluster-based timing cuts

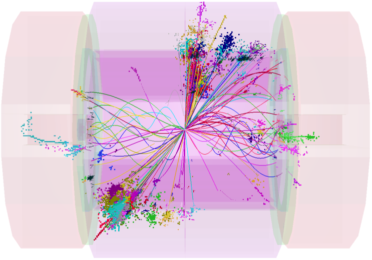
- Cuts depend on particle-type (charged, neutral and photons), p_T and detector region

→ Protects physics objects at high p_T

$e^+e^- \to H^+H^- \to t\bar{b}b\bar{t}$ (8 jet final state)



1.2 TeV
background in the
reconstruction window



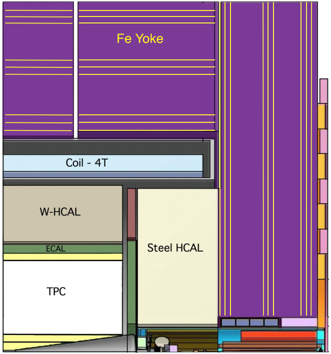
100 GeV
background after
(tight) timing cuts

for 60 BX of $\gamma\gamma \to$ hadron background

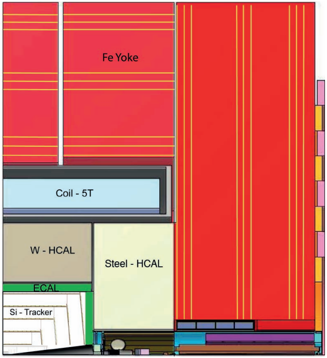
Detector Models

Based on validated ILC designs, adapted and optimized to the CLIC conditions:

- Denser HCAL in the barrel (Tungsten, 7.5 λ)
- Redesign of the vertex and forward detectors (backgrounds)



CLIC_ILD



CLIC_SiD

SUSY models

Two SUSY scenarios:

- Referred to as model I and model II
- Chosen to illustrate detector performance
- Emphasis on high-mass states for the 3 TeV case

Simulation

All benchmark channels based on

- Full Geant4 simulation including 60 BX $\gamma\gamma \rightarrow$hadron background
- Integrated luminosity of 2 ab^{-1}
- Reconstruction based on Particle Flow (PFA)

Heavy Higgs: Production (CLIC_ILD)

Study done in both SUSY models

- Model I: m(A) = 902 GeV and
- Model II: m(A) = 742 GeV

with neutral and charged Higgs nearly mass degenerate.

Production and predominant decay:

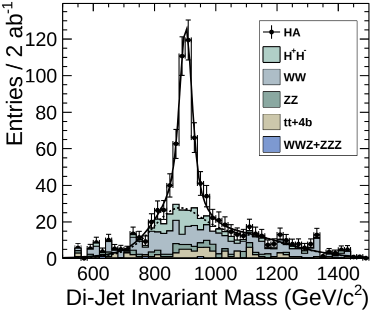
$$e^+e^- \rightarrow H^0A^0 \rightarrow b\bar{b}b\bar{b}$$
$$e^+e^- \rightarrow H^+H^- \rightarrow t\bar{b}b\bar{t}$$

Key detector performance aspects

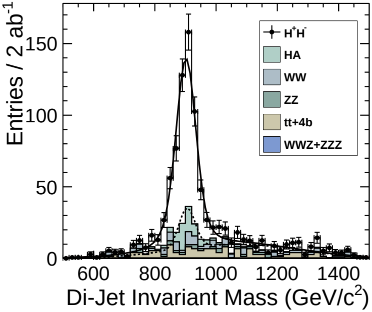
- Flavour tagging for high-energetic jets
- Invariant mass reconstruction of high mass states in a high multiplicity environment
- Identification of boosted top quarks from jet structure

Heavy Higgs: Results

$e^+e^- \rightarrow b\bar{b}b\bar{b}$



$e^+e^- \rightarrow t\bar{b}b\bar{t}$

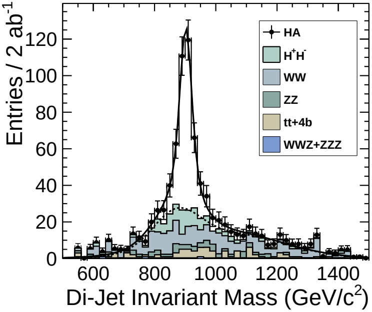


	SUSY model I		*SUSY model II*	
State	Mass [GeV]	Width [GeV]	Mass [GeV]	Width [GeV]
A/H	904.5 ± 2.8	20.6 ± 6.3	743.7 ± 1.7	22.2 ± 3.8
$H^\pm$	902.6 ± 2.4	20.2 ± 5.4	746.9 ± 2.1	21.4 ± 4.9

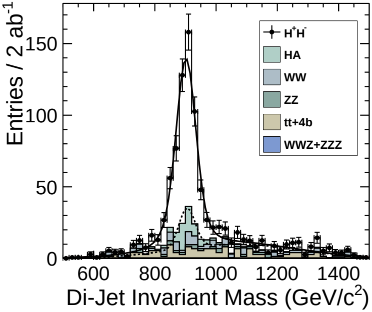
Masses and widths determined from fit with the sum of two BW, folded with a Gaussian resolution function

Heavy Higgs: Results

$e^+e^- \rightarrow b\bar{b}b\bar{b}$



$e^+e^- \rightarrow t\bar{b}b\bar{t}$



	SUSY model I		*SUSY model II*	
State	Mass [%]	Width [%]	Mass [%]	Width [%]
A/H	0.3	31	0.2	17
$H^\pm$	0.3	27	0.3	23

Masses and widths determined from fit with the sum of two BW, folded with a Gaussian resolution function

Squarks: Production (CLIC_ILD)

SUSY model I:

$m_{\tilde{u}_R} = m_{\tilde{c}_R} = 1125.7$ GeV, $m_{\tilde{d}_R} = m_{\tilde{s}_R} = 1116.1$ GeV

	Process	Cross Section
Signal	$e^+e^- \to \tilde{q}_R\tilde{q}_R \to q\bar{q}\tilde{\chi}_1^0\tilde{\chi}_1^0$	1.47 fb
SM background	$e^+e^- \to q\bar{q}\nu\bar{\nu}$	$\sim$ 1500 fb
	$e^+e^- \to q\bar{q}e^\pm\nu$	$\sim$ 5300 fb
	$e^+e^- \to \tau^+\tau^-\nu\bar{\nu}$	$\sim$ 130 fb

Key detector performance aspects

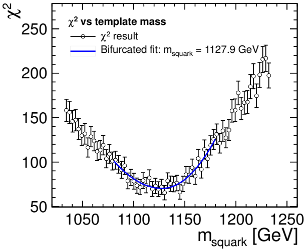
- Jet energy and missing energy reconstruction for high energy jets in a simple topology

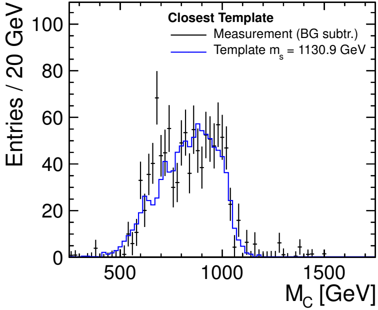
Squarks: Results

Mass determination with template fit and stat. errors from toy MC

Modified invariant mass:

$$M_C = \sqrt{2\left(E_1 E_2 + \vec{p}_1 \cdot \vec{p}_2\right)}$$



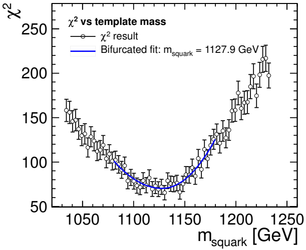


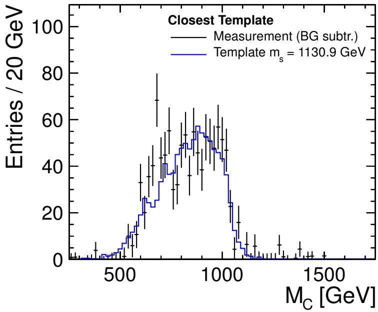
Observable	Result	Generator value
Averaged right-squark mass	1127.9 GeV $\pm$ 5.9 GeV	1123.7 GeV
Combined cross section	1.51 fb $\pm$ 0.07 fb	1.47 fb

Mass determination with template fit and stat. errors from toy MC

Modified invariant mass:

$$M_C = \sqrt{2\,(E_1 E_2 + \vec{p}_1 \cdot \vec{p}_2)}$$





Observable	Precision
Averaged right-squark mass	0.52 %
Combined cross section	4.6 %

SUSY model II:

$m(\tilde{e}_R) = m(\tilde{\mu}_R)$ = 1010.8 GeV

$m(\tilde{e}_L) = m(\tilde{\mu}_L)$ = 1100.4 GeV

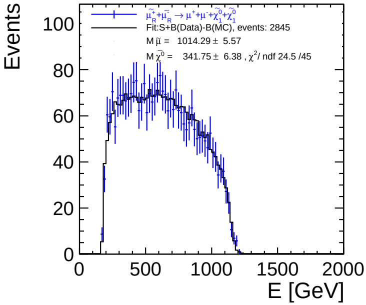
Process	σ (fb)	Decay Mode	$\sigma \times BR$ (fb)	$\sigma \times BR$ (ee4Q) (fb)
$e^+e^- \rightarrow \tilde{\mu}_R^+\tilde{\mu}_R^-$	0.72	$\mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	0.72	
$e^+e^- \rightarrow \tilde{e}_R^+\tilde{e}_R^-$	6.05	$e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	6.05	
$e^+e^- \rightarrow \tilde{e}_L^+\tilde{e}_L^-$	3.07	$\tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-(h/Z^0 h/Z^0)$	0.25	0.16
$e^+e^- \rightarrow \tilde{\nu}_e\tilde{\nu}_e$	13.74	$\tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^- W^+W^-$	4.30	1.82

Key detector performance aspects

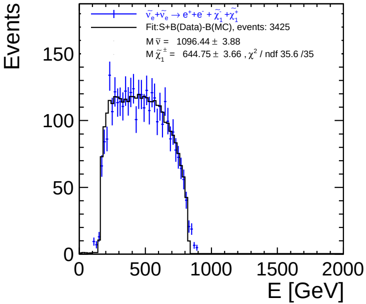
- Reconstruction and identification of high energy leptons
- Energy resolution for high energy electrons and muons in two lepton plus jets final states
- Boson mass resolution

Sleptons: Results

Mass extraction from kinematic edge of lepton energy, background subtracted, fit includes beam energy spectrum



$$e^+e^- \rightarrow \tilde{\mu}_R^+\tilde{\mu}_R^-$$

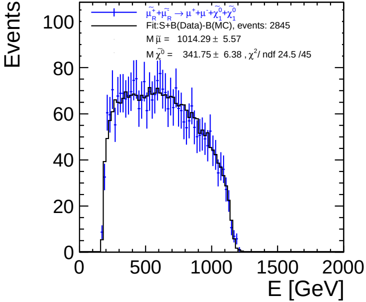


$$e^+e^- \rightarrow \tilde{\nu}_e\tilde{\nu}_e$$

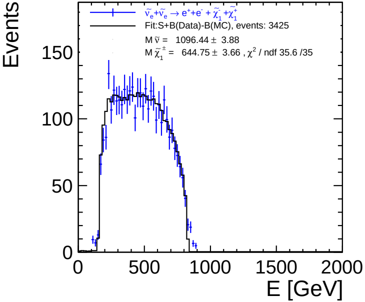
Process	Decay Mode	σ [fb]	$m_{\tilde{\ell}}$ [GeV]	$m_{\tilde{\chi}_1^0}$ or $m_{\tilde{\chi}_1^\pm}$ [GeV]
$e^+e^- \rightarrow \tilde{\mu}_R^+\tilde{\mu}_R^-$	$\mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	0.71 ± 0.02	1014.3 ± 5.6	341.8 ± 6.4
$e^+e^- \rightarrow \tilde{e}_R^+\tilde{e}_R^-$	$e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	6.20 ± 0.05	1001.6 ± 2.8	340.6 ± 3.4
$e^+e^- \rightarrow \tilde{e}_L^+\tilde{e}_L^-$	$\tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^- (h/Z^0 h/Z^0)$	2.77 ± 0.20		
$e^+e^- \rightarrow \tilde{\nu}_e\tilde{\nu}_e$	$\tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^- W^+W^-$	13.24 ± 0.32	1096.4 ± 3.9	644.8 ± 3.7

Sleptons: Results

Mass extraction from kinematic edge of lepton energy, background subtracted, fit includes beam energy spectrum



$e^+e^- \rightarrow \tilde{\mu}^+_R\tilde{\mu}^-_R$



$e^+e^- \rightarrow \tilde{\nu}_e\tilde{\nu}_e$

Process	Decay Mode	σ [%]	$m_{\tilde{\ell}}$ [%]	$m_{\tilde{\chi}^0_1}$ or $m_{\tilde{\chi}^{\pm}_1}$ [%]
$e^+e^- \rightarrow \tilde{\mu}^+_R\tilde{\mu}^-_R$	$\mu^+\mu^-\tilde{\chi}^0_1\tilde{\chi}^0_1$	2.8	0.6	1.9
$e^+e^- \rightarrow \tilde{e}^+_R\tilde{e}^-_R$	$e^+e^-\tilde{\chi}^0_1\tilde{\chi}^0_1$	0.8	0.3	1.0
$e^+e^- \rightarrow \tilde{e}^+_L\tilde{e}^-_L$	$\tilde{\chi}^0_1\tilde{\chi}^0_1 e^+e^-(h/Z^0 h/Z^0)$	7.2		
$e^+e^- \rightarrow \tilde{\nu}_e\tilde{\nu}_e$	$\tilde{\chi}^0_1\tilde{\chi}^0_1 e^+e^- W^+W^-$	2.4	0.4	0.6

SUSY model II:

m($\chi_1^{\pm}$)=643 GeV, m(χ_1^0)=340 GeV, m(χ_2^0)=643 GeV

$$e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow W^+\tilde{\chi}_1^0 W^-\tilde{\chi}_1^0$$
$$e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow h^0(Z^0)\tilde{\chi}_1^0 h^0(Z^0)\tilde{\chi}_1^0$$

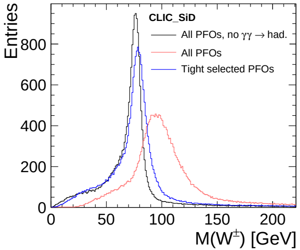
Type	Process	Cross section [fb]	Referenced with
Signal	$\tilde{\chi}_1^+\tilde{\chi}_1^-$	10.6	Chargino
	$\tilde{\chi}_2^0\tilde{\chi}_2^0$	3.3	Neutralino
Background	$\tilde{\chi}_2^+\tilde{\chi}_2^-$	10.5	SUSY
	$\tilde{\chi}_1^+\tilde{\chi}_2^-$	0.8	
	$\tilde{\chi}_1^+\tilde{\chi}_1^-\nu\overline{\nu}$	1.4	
	$\tilde{\chi}_2^0\tilde{\chi}_2^0\nu\overline{\nu}$	1.2	
	$q\overline{q}q\overline{q}\nu\overline{\nu}$	95.4	SM
	$q\overline{q}h^0\nu\overline{\nu}$	3.1	
	$h^0h^0\nu\overline{\nu}$	0.6	

Key detector performance aspects

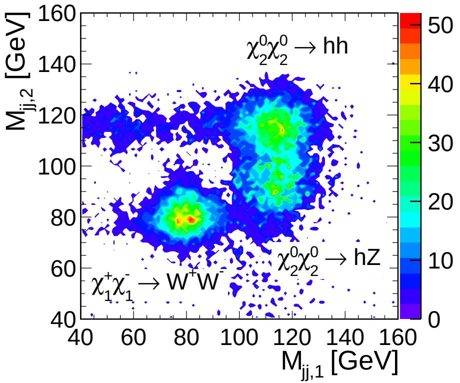
- Jet energy and missing energy reco in high energy decays
- Di-Jet mass reco and separation of hadronic Z, W and h decays

Chargino/Neutralino: Analysis

Background rejection with a Boosted Decision Tree



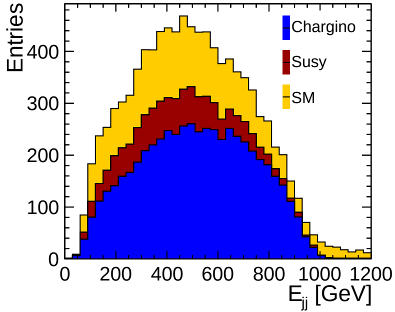
- Efficiency Charginos: 33%
- Efficiency Neutralinos: 25%
- Purity both: 56%

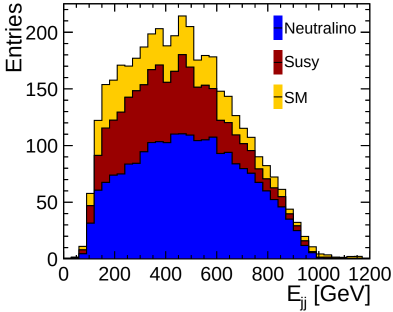


Application of timing cuts important in addition to jet reco to recover correct mass spectrum.

Chargino/Neutralino: Results

Mass and cross section from template (fully simulated) and least squares fits

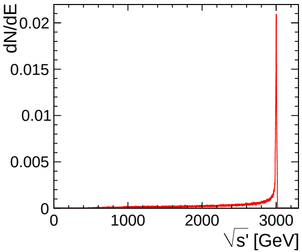




Parameter 1	Uncertainty	Parameter 2	Uncertainty
$M(\tilde{\chi}_1^\pm)$	6.3 GeV	$\sigma(\tilde{\chi}_1^+\tilde{\chi}_1^-)$	2.2%
$M(\tilde{\chi}_1^0)$	3.0 GeV	$\sigma(\tilde{\chi}_1^+\tilde{\chi}_1^-)$	1.8%
$M(\tilde{\chi}_2^0)$	7.3 GeV	$\sigma(\tilde{\chi}_2^0\tilde{\chi}_2^0)$	2.9%

consistent results with least squares fit

- So far only statistical uncertainties
- Work ongoing on systematic effects



One example: Luminosity spectrum
$\rightarrow$ Introduce uncertainties of 1% change of average $\sqrt{s}$ in luminosity spectrum:

- Squarks: negligible
- Sleptons: mass changes negligible, statistical errors dominant except for $\tilde{e}^+_R\tilde{e}^-_R \rightarrow e^+e^-\tilde{\chi}^0_1\tilde{\chi}^0_1$ with the largest cross section
- Charginos:
  - cross sections: similar size as statistical uncertainty
  - mass shift of typically half of the statistical uncertainty

Summary

- $\gamma\gamma \rightarrow$ hadron background can be sufficiently reduced by timing cuts at PFO level
- Masses and cross sections have been measured with good statistical accuracy
- Systematic uncertainties are on the way, first tests very promising
- Luminosity spectrum shape does not harm physics results

More Details

- Heavy Higgs
  LCD-Note-2010-006
- Squarks
  LCD-2011-027
- Sleptons
  LCD-Note-2011-018
- Chargino/Neutralino
  LCD-Note-2011-037

Signatories to support the physics case and R&D towards a future linear collider based on CLIC technology are currently collected here:

https://indico.cern.ch/conferenceDisplay.py?confId=136364

NO work or commitment involved!

BACKUP

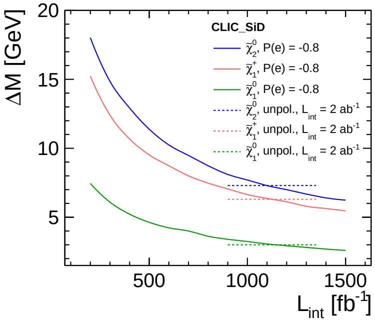
Summary I

Process	Decay mode	SUSY model	Observable	Stat. error
Heavy Higgs production	$HA \to b\bar{b}b\bar{b}$	I	Mass Width	0.3% 31%
		II	Mass Width	0.2% 17%
	$H^+H^- \to t\bar{b}b\bar{t}$	I	Mass Width	0.3% 27%
		II	Mass Width	0.3% 23%
Production of squarks	$\tilde{q}_R\tilde{q}_R \to q\bar{q}\tilde{\chi}_1^0\tilde{\chi}_1^0$	I	Mass σ	0.52% 4.6%

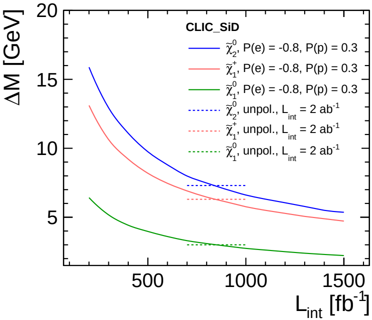
Summary II

Process	Decay mode	SUSY model	Observable	Stat. error
Sleptons production	$\tilde{\mu}_R^+\tilde{\mu}_R^- \rightarrow \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	II	σ $\tilde{\ell}$ mass $\tilde{\chi}_1^0$ mass	2.8% 0.6% 1.9%
	$\tilde{e}_R^+\tilde{e}_R^- \rightarrow e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		σ $\tilde{\ell}$ mass $\tilde{\chi}_1^0$ mass	0.8% 0.3% 1.0%
	$\tilde{e}_L^+\tilde{e}_L^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^- hh$ $\tilde{e}_L^+\tilde{e}_L^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^- Z^0Z^0$		σ	7.2%
	$\tilde{\nu}_e\tilde{\nu}_e \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^- W^+W^-$		σ $\tilde{\ell}$ mass $\tilde{\chi}_1^\pm$ mass	2.4% 0.4% 0.6%
Chargino and neutralino production	$\tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$	II	$\tilde{\chi}_1^\pm$ mass σ	1.1% 2.4%
	$\tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow h^0/Z^0h^0/Z^0\tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\chi}_2^0$ mass σ	1.5% 3.2%

Gaugino mass precision as a function of luminosity



for -80% electron polarisation only



for -80% electron polarisation combined with +30% positron polarisation

The horizontal lines represent the achieved mass precision with no polarization assuming 2 ab^{-1} of integrated luminosity.

Susy Model Parameters

SUSY model I:

GUT scale parameters:
M_1 = 780 GeV,
M_2 = 940 GeV,
M_3 = 540 GeV,
A_0 = -750 GeV,
m_0 = 303 GeV,
$\tan\beta$ = 24
and $\mu > 0$

SUSY model II:

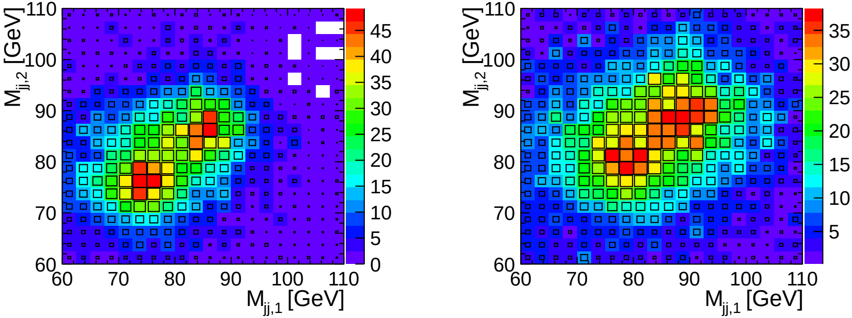
mSUGRA parameters:
$m_{1/2}$ = 800 GeV.
A_0 = 0,
m_0 = 966 GeV,
$\tan\beta$ = 51
and $\mu > 0$

W and Z Separation

From chargino decays to W and Z (different SUSY model)

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

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



00 BX

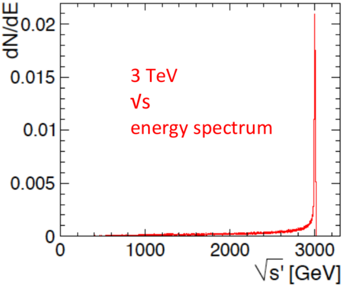
60 BX

Conditions at CLIC II

Beamstrahlung → important energy losses right at the interaction point.

Full luminosity:
$5.9 \times 10^{34}\ cm^{-2}s^{-1}$
Of which in the 1% most energetic part:
$2.0 \times 10^{34}\ cm^{-2}s^{-1}$

Most physics processes are studied well above production threshold => profit from full luminosity



Coherent e^+e^- pairs
- 7 x 10^8 per BX, very forward

Incoherent e^+e^- pairs
- 3 x 10^5 per BX, rather forward

γγ→ hadrons
- only 3.2 per bunch crossing
- main background in calorimeters

→

Simplified view:

Pair background
- Design issue

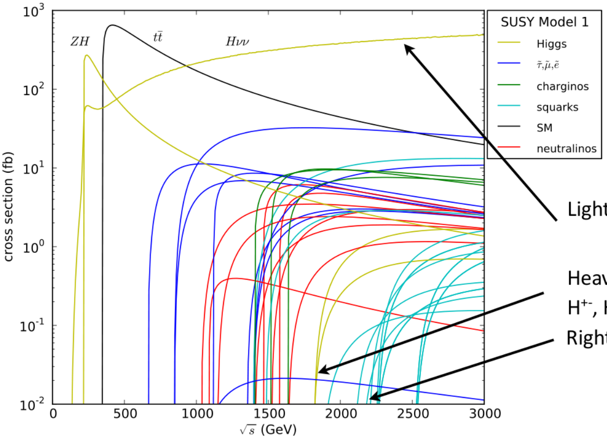
γγ → hadrons
- Impacts on the physics
- Needs suppression in data

Timing cuts

Region	p_T range	Time cut
Photons		
Central	$1.0\,\text{GeV} \leq p_T < 4.0\,\text{GeV}$	$t < 2.0\,\text{ns}$
$\lvert\cos(\theta)\rvert \leq 0.95$	$0.2\,\text{GeV} \leq p_T < 1.0\,\text{GeV}$	$t < 1.0\,\text{ns}$
Forward	$1.0\,\text{GeV} \leq p_T < 4.0\,\text{GeV}$	$t < 2.0\,\text{ns}$
$\lvert\cos(\theta)\rvert > 0.95$	$0.2\,\text{GeV} \leq p_T < 1.0\,\text{GeV}$	$t < 1.0\,\text{ns}$
Neutral hadrons		
Central	$1.0\,\text{GeV} \leq E_T < 8.0\,\text{GeV}$	$t < 2.5\,\text{ns}$
$\lvert\cos(\theta)\rvert \leq 0.95$	$0.5\,\text{GeV} \leq E_T < 1.0\,\text{GeV}$	$t < 1.5\,\text{ns}$
Forward	$1.0\,\text{GeV} \leq E_T < 8.0\,\text{GeV}$	$t < 1.5\,\text{ns}$
$\lvert\cos(\theta)\rvert > 0.95$	$0.5\,\text{GeV} \leq E_T < 1.0\,\text{GeV}$	$t < 1.0\,\text{ns}$
Charged particles		
All	$1.0\,\text{GeV} \leq p_T < 4.0\,\text{GeV}$	$t < 2.0\,\text{ns}$
	$0\,\text{GeV} \leq p_T < 1.0\,\text{GeV}$	$t < 1.0\,\text{ns}$

Two SUSY scenarios with non-unified gaugino masses:

- Chosen to illustrate detector performance
- Emphasis on high-mass states for the 3 TeV case



Model 1:
Squarks within CLIC 3 TeV reach, heavy neutral and charged Higgs

Light Higgs in W Fusion

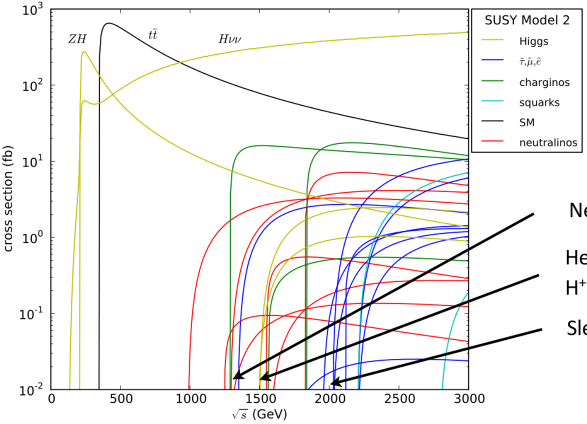
Heavy Higgs:
H^{+-}, H^0A^0

Right Squarks

SUSY models II

Two SUSY scenarios with non-unified gaugino masses:

- Chosen to illustrate detector performance
- Emphasis on high-mass states for the 3 TeV case



Model 2:
High mass sleptons,
Light charginos and
neutralinos dominated
by single decay mode

Neutralinos, Charginos

Heavy Higgs:
H^{+-}, H^0A^0

Sleptons