Models with new particles produced at ILC

If new particles are within the kinematic reach, an electron positron collider is the ideal place to study their properties in great detail

There are good reasons to believe that a TeV collider (ILC) will have this great opportunity (see day 1)

The best motivated + best studied models for such a scenario are

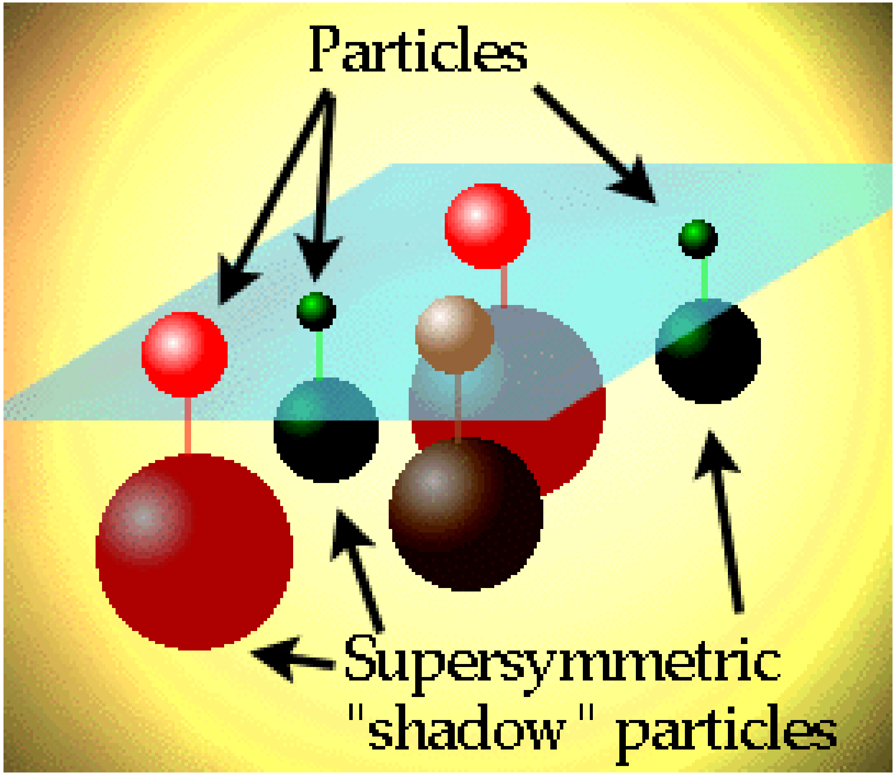
1. Supersymmetry
2. Models with TeV-scale extra space dimensions

Both address the hierarchy problem – but SUSY has many other strong points

SUSY due to its rich phenomenology is also an ideal place-holder for any direct new signals to be studied at ILC

3. Supersymmetry

SUSY is one of the most attractive extensions to the SM!



Simple Idea:

Symmetry between Bosons and Fermions

↳ each SM particle has a SUSY partner with same Quantum numbers and Spin differing by ½.

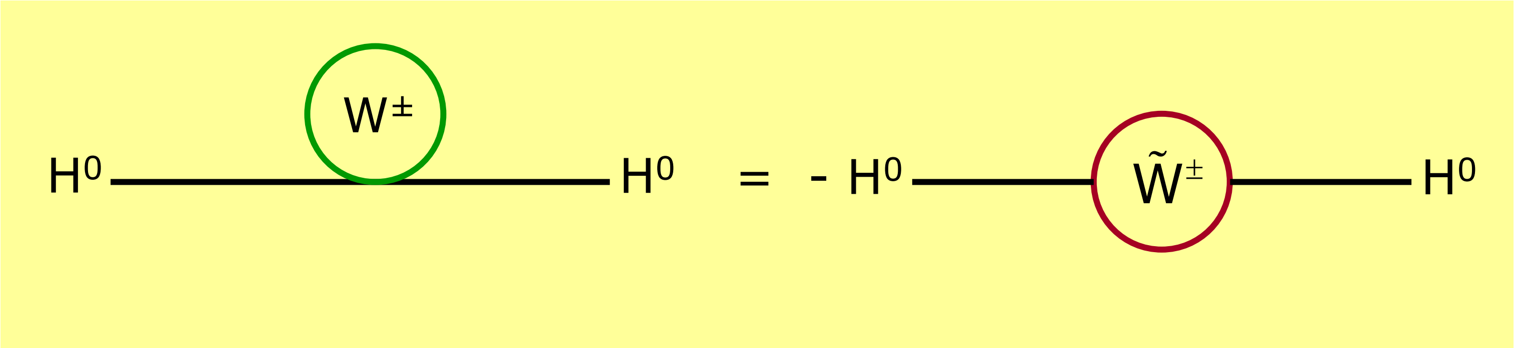
But where are the SUSY Partners? Must be heavy

SUSY must be broken!

Why is it so attractive, then?

3. Supersymmetry

1. It solves the Hierarchy problem:

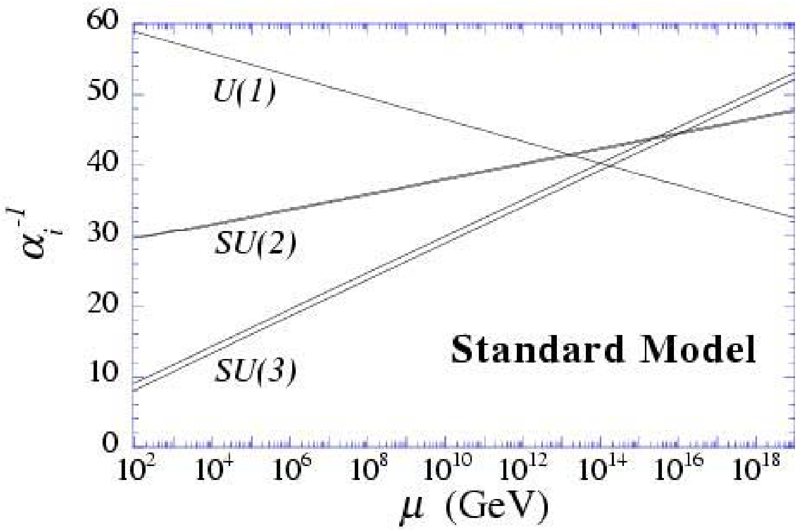


The divergency in the Higgs mass corrections is cancelled exactly for unbroken SUSY.

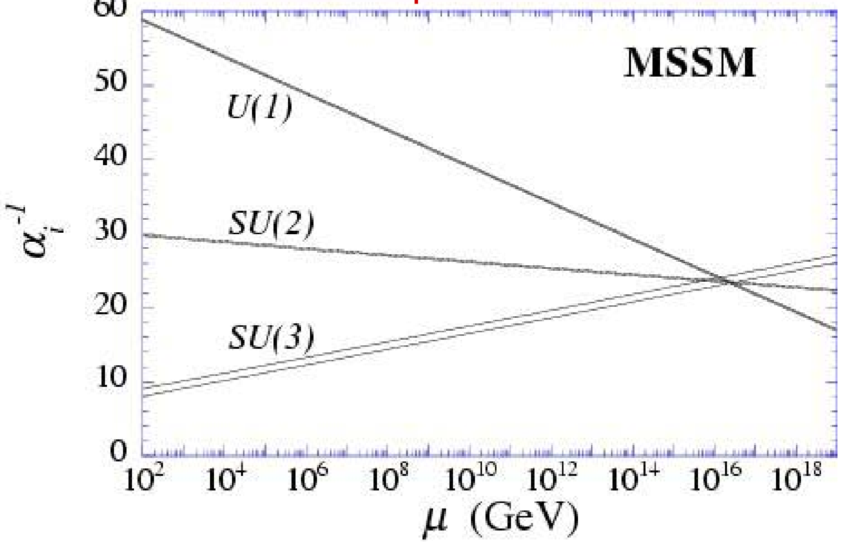
If it is not broken too heavily (i.e. if the SUSY partners are at <~ 1 TeV), there is no fine tuning necessary.

3. Supersymmetry

2. It shows a path to Grand unification:



Minimal SUSY prediction:



(requires light (< TeV) partners
of EW gauge bosons)

This is achieved for $\sin^2\theta_W^{\mathrm{SUSY}} = 0.2335(17)$

Experiment: $\sin^2\theta_W^{\mathrm{exp.}} = 0.2315(2)$

3. Cold Dark Matter:

The lightest SUSY partner particle might well be stable and is an excellent candidate for the observed cold dark matter

4. Link to Gravity:

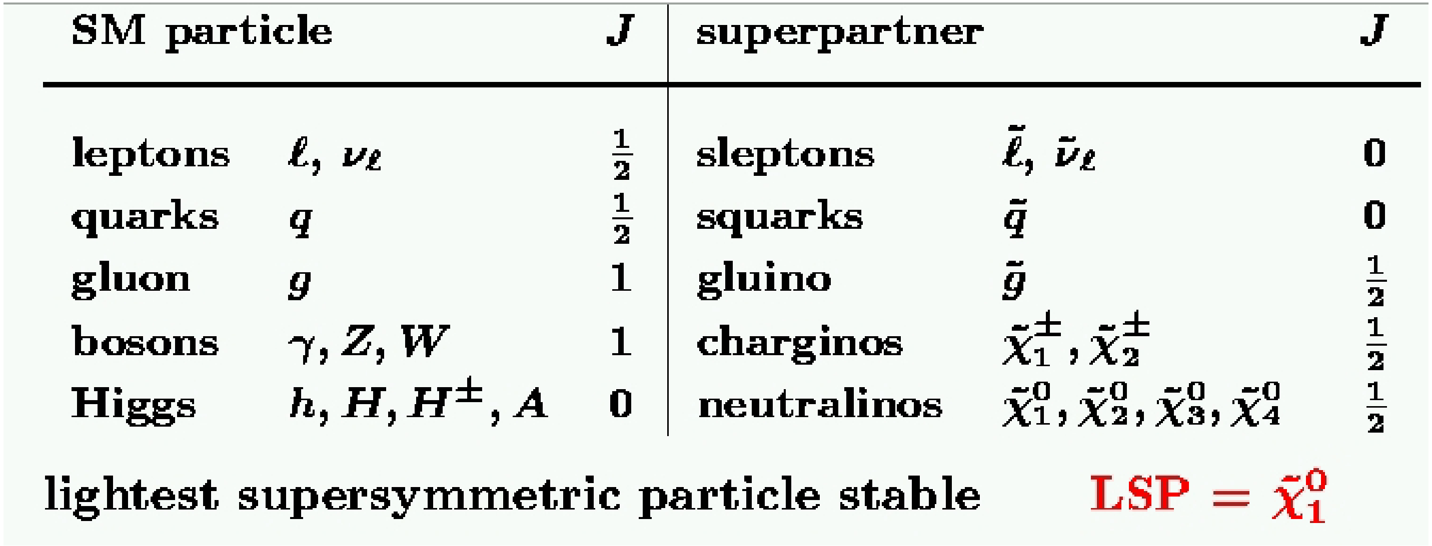
SUSY offers the theoretical link to incorporate gravity. Most string models are supersymmetric.

5. Light Higgs Boson:

SUSY predicts a light (< 135 GeV) Higgs boson as favoured by electro-weak precision data from LEP and Tevatron.

3. Supersymmetry

Sparticle spectrum



SM particle		J	**superpartner**		J
leptons	$\ell,\ \nu_\ell$	$\frac{1}{2}$	**sleptons**	$\tilde{\ell},\ \tilde{\nu}_\ell$	0
quarks	q	$\frac{1}{2}$	**squarks**	$\tilde{q}$	0
gluon	g	1	**gluino**	$\tilde{g}$	$\frac{1}{2}$
bosons	γ, Z, W	1	**charginos**	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$	$\frac{1}{2}$
Higgs	$h, H, H^\pm, A$	0	**neutralinos**	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$	$\frac{1}{2}$

lightest supersymmetric particle stable $\mathbf{LSP} = \tilde{\chi}_1^0$

The minimal supersymmetric model (MSSM) has 105 new parameters

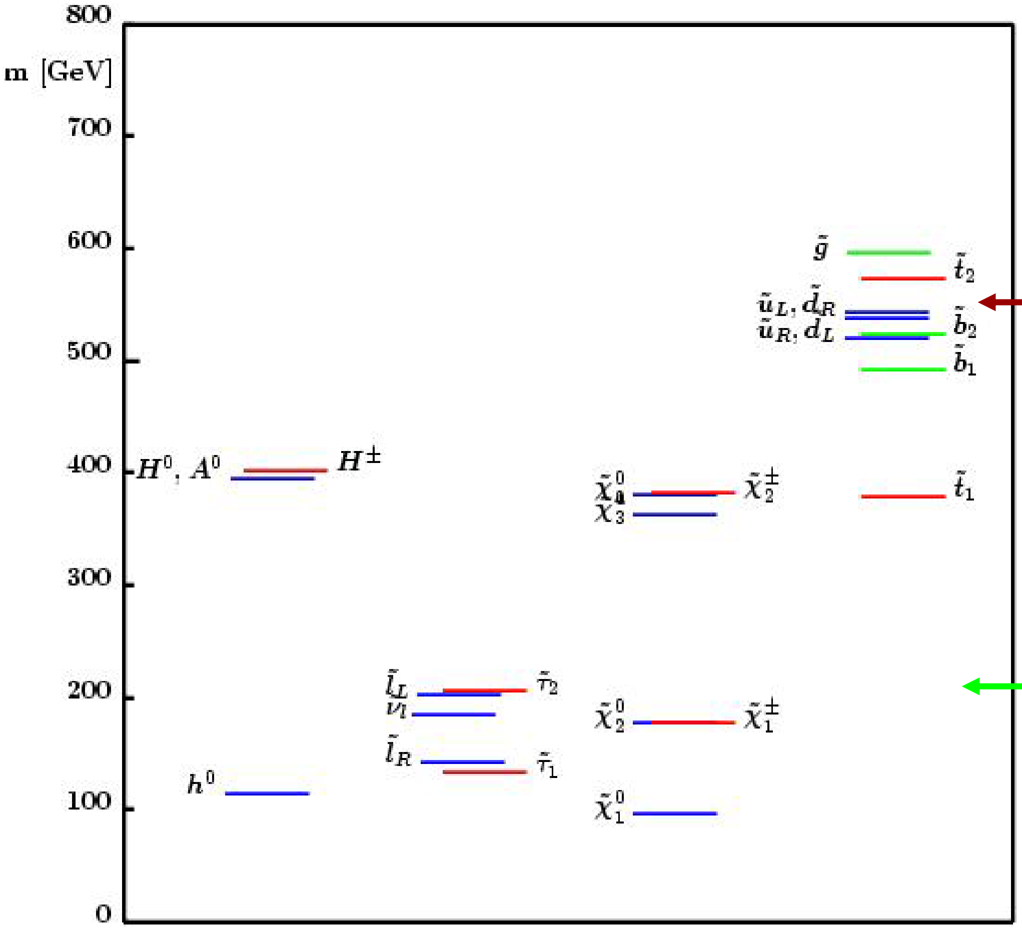
Most of them arise from our ignorance about the way SUSY is broken

Explicit models of SUSY breaking typically only have few parameters
e.g., mSUGRA: $\tan\beta$, $m_{1/2}$, m_0, A_0, $\mathrm{sgn}(\mu)$

3. Supersymmetry

Typical SUSY spectrum

typical mSUGRA-inspired SUSY spectrum (SPS 1a)

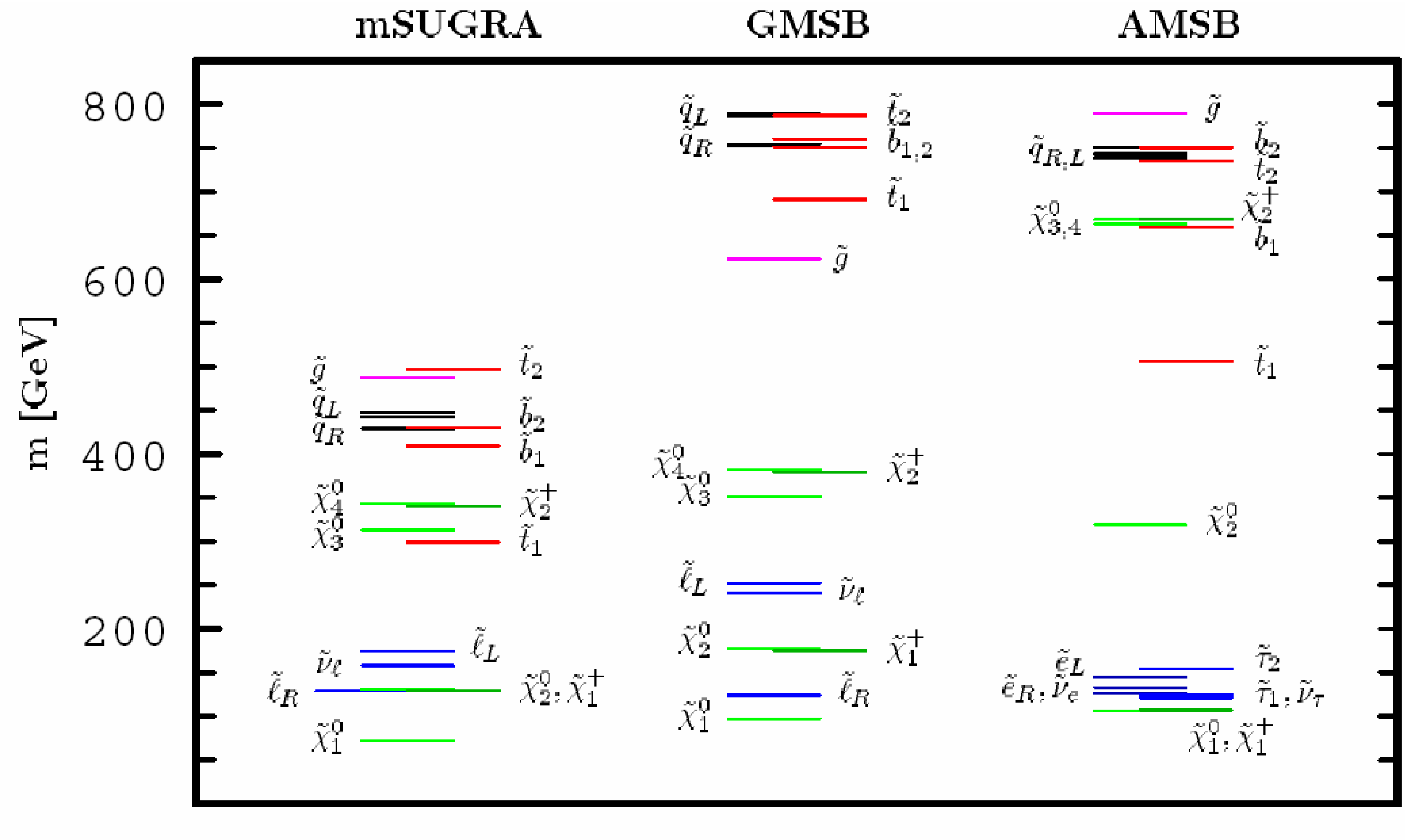


well measurable at LHC

precise spectroscopy at LC

3. Supersymmetry | Task of LC

different SUSY breaking mechanisms yield different spectra:



3. Supersymmetry

Task of the LC

After discovery, the task is to reveal the underlying theory of SUSY breaking. The LC can do this by precision measurements of the masses and properties of the accessible part of the spectrum

- is it really SUSY?

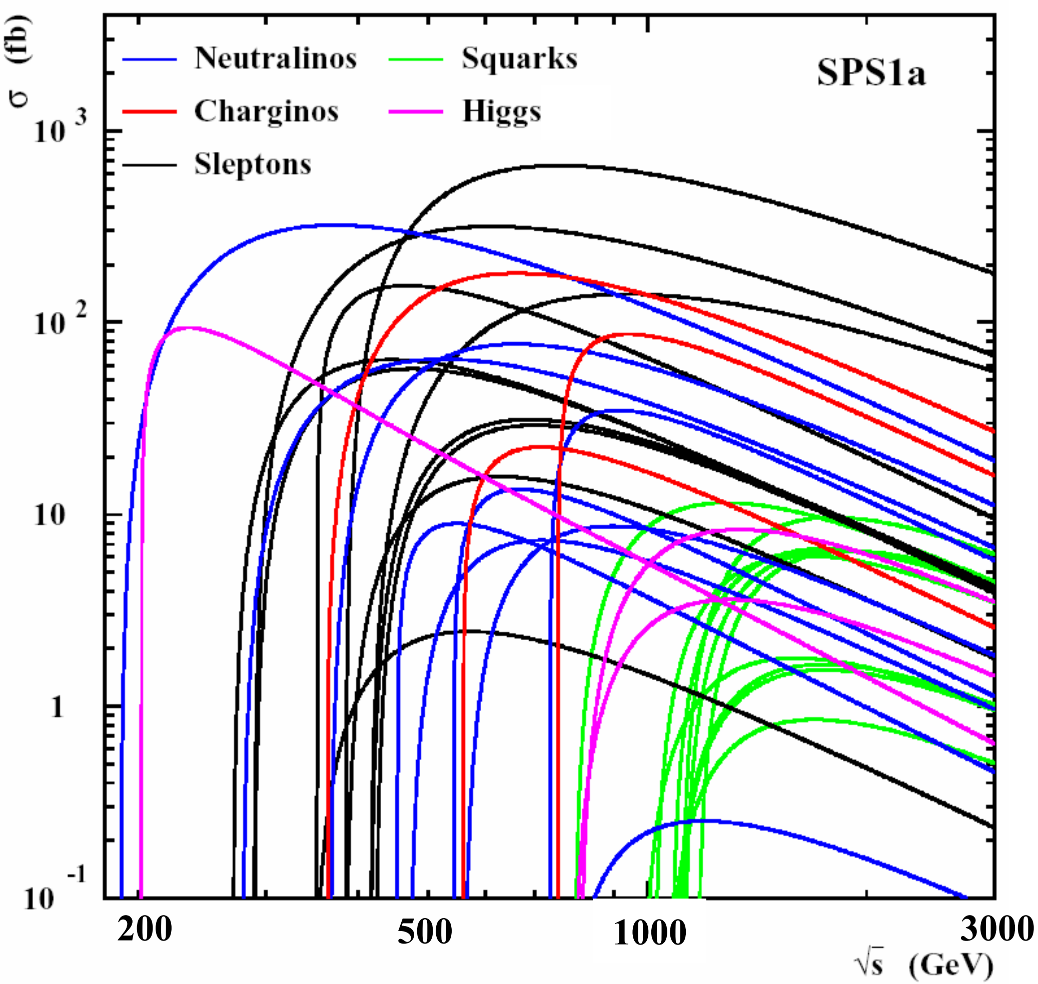
- how is it realized?
  (particle content) MSSM, NMSSM, …

- how is it broken?
  measure as many of the >100 LE parameters as possible
  measure them as precisely as possible -> extrapolation to high scale
  (bottom-up approach)

Note: successfully fitting the parameters of a constrained model to the observations is a necessary but not a sufficient test of the model.

3. Supersymmetry | Production at LC

This will be fun…



cross sections in the
10 – 1000 fb range

o(10^3 – 10^5) events

to disentangle this 'chaos'
the various LC options,
in particular

- tunable √s
- tunable beam polarisation

are vital!

SUSY at LC

Plan:

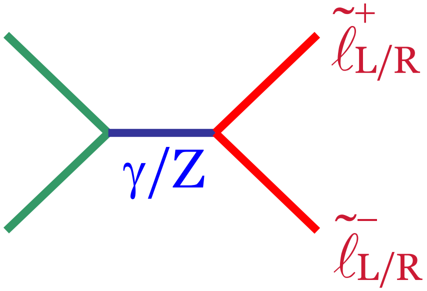
1. Sleptons
2. Charginos + Neutralinos
3. Stop
4. Dark Matter
5. Exotic Signatures
6. Split SUSY

3. Supersymmetry

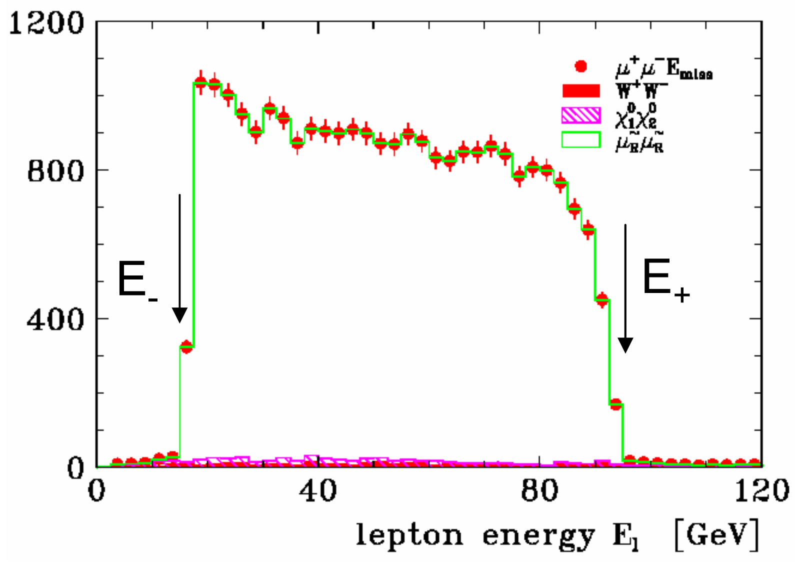
Sleptons

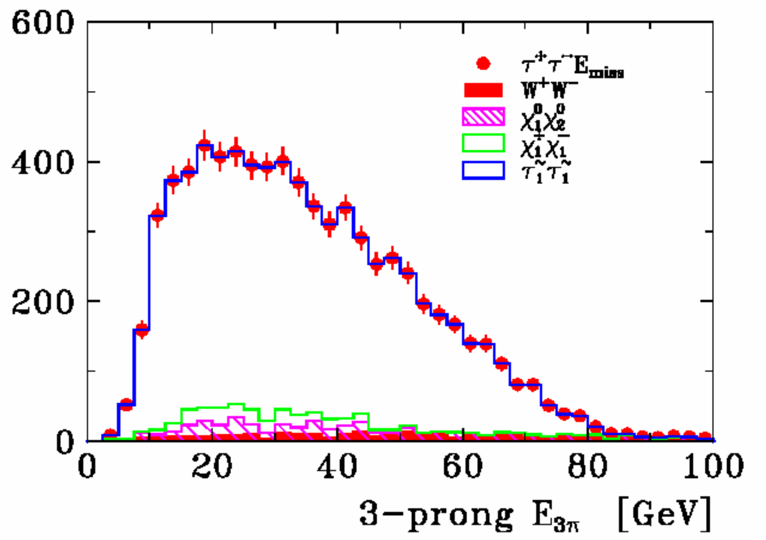
Pair-production

$$\begin{aligned} e^+e^- &\to \tilde{e}_R\tilde{e}_R,\ \tilde{e}_L\tilde{e}_L,\ \tilde{e}_R\tilde{e}_L,\ \tilde{\nu}_e\bar{\tilde{\nu}}_e \\ e^+e^- &\to \tilde{\mu}_R\tilde{\mu}_R,\ \tilde{\mu}_L\tilde{\mu}_L,\ \tilde{\nu}_\mu\bar{\tilde{\nu}}_\mu \\ e^+e^- &\to \tilde{\tau}_1\tilde{\tau}_1,\ \tilde{\tau}_2\tilde{\tau}_2,\ \tilde{\tau}_1\tilde{\tau}_2,\ \tilde{\nu}_\tau\bar{\tilde{\nu}}_\tau \end{aligned}$$



Examples:





Simple two-body kinematics and beam-constraint allow for mass measurement of both slepton and lightest neutralino

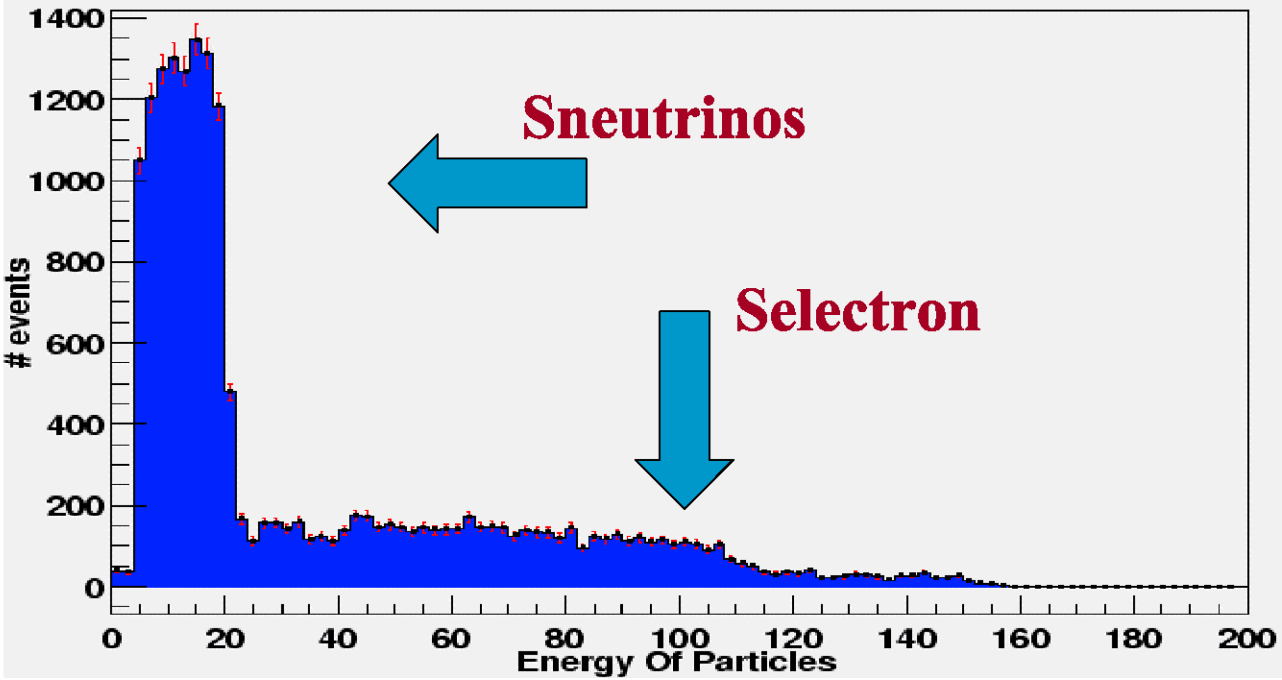
$$\boxed{\begin{aligned} m_{\tilde{l}} &= \frac{\sqrt{s}}{E_- + E_+}\sqrt{E_- E_+} \\ m_{\tilde{\chi}} &= m_{\tilde{l}}\sqrt{1 - \frac{E_- + E_+}{\sqrt{s}/2}} \end{aligned}}$$

Sleptons

Sneutrinos have huge cross section but are difficult to detect

If $m(\tilde{\nu}) > m(\chi^{\pm})$ the decay $\tilde{\nu} \rightarrow e^{+}\chi^{-} \rightarrow e^{+}\tau^{-}\nu_{\tau}\chi_{1}^{o}$ is possible

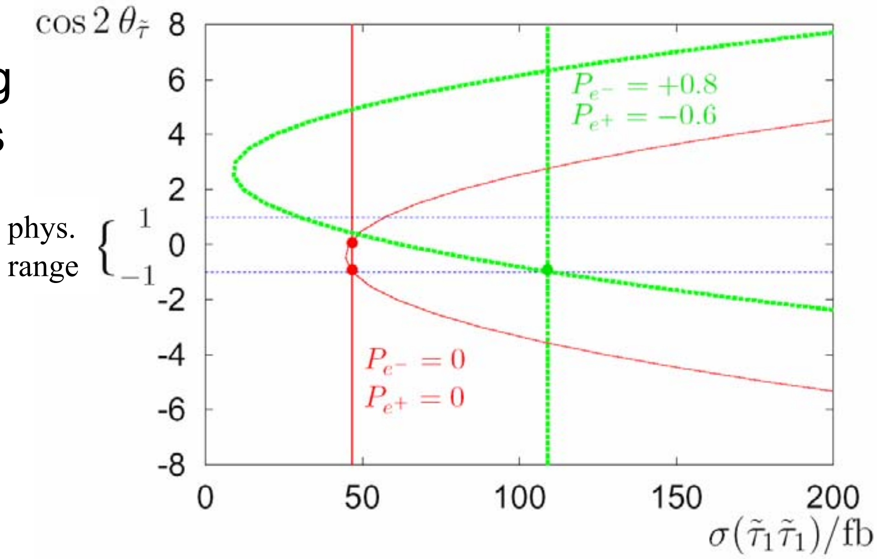
Electron-sprectrum in eμ+miss. energy final states:



3. Supersymmetry | Sleptons

3rd generation: expect large mixing between left and right chiral states

Determine mixing angle θ_τ from measurement of polarized cross section $\sigma(\tilde{\tau}_1\tilde{\tau}_1)$
Precision for SPS1a:
cos 2θ = -0.84±0.04



Ultimately, one wants to measure the tri-linear coupling A_τ

from chargino/neutralino sector

$$A_\tau = \frac{m^2_{\tilde{\tau}_2} - m^2_{\tilde{\tau}_1}}{m_\tau} \sin 2\theta_{\tilde{\tau}} + \mu \tan\beta$$

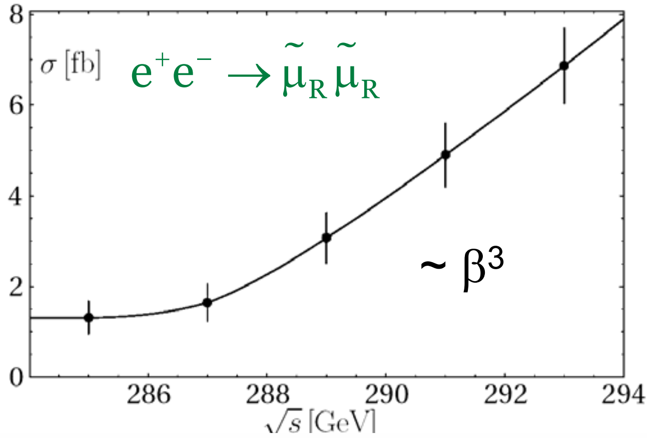
from chargino/neutralino
or from Higgs sector
or from τ polarisation measurement

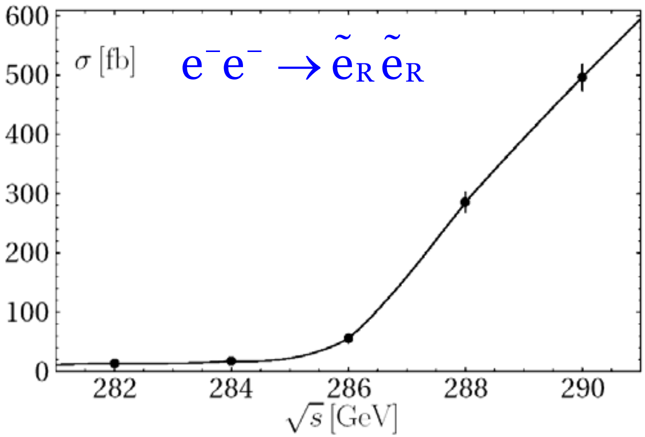
best from global fit to all observables! (later)

3. Supersymmetry

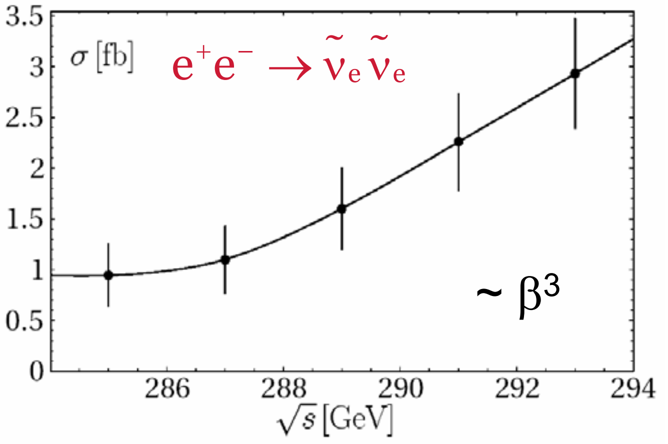
Sleptons: Threshold Scans

e^+e^- offers possibilty to vary the centre-of-mass energy
Production threshold of SUSY processes:
→ most precise mass determination (50-500 MeV)
→ sensitivity to sparticle width (50-200 MeV)



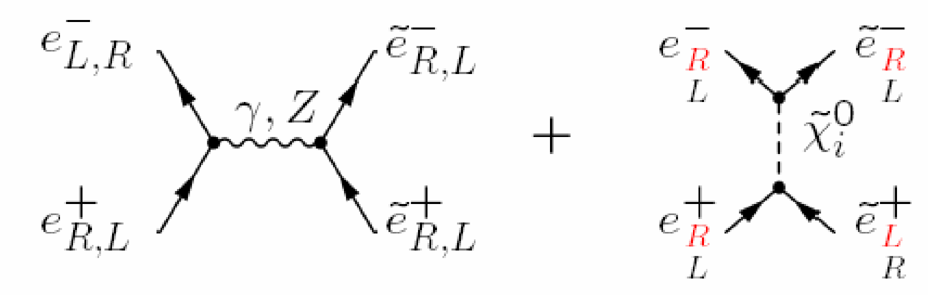


e^-e^- has highest sensitivity due to steep rise
$\sim \beta$

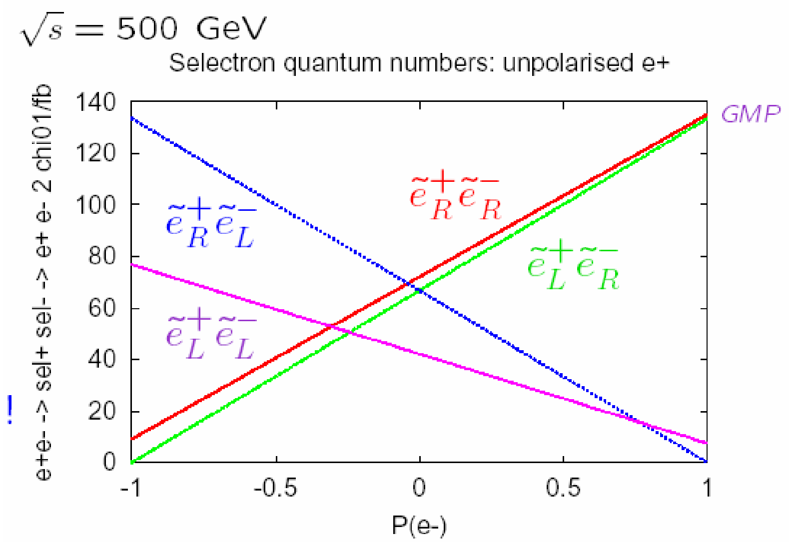


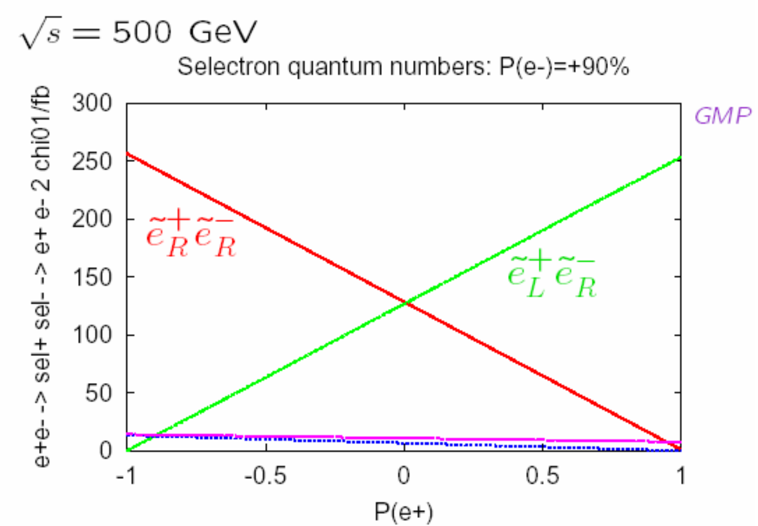
need to take into account
- higher-order corrections
- threshold corrections
- finite width effects
- beam spread

3. Supersymmetry | Selectron Couplings

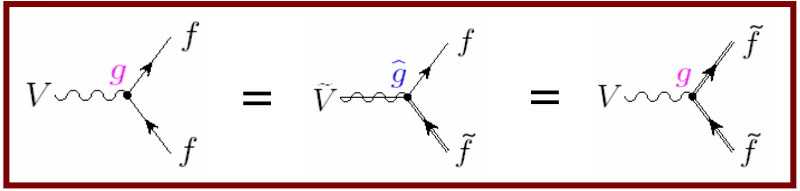


Find out which are the chiral partners of R and L electron
Exploit t-channel diagram. Need both beams polarized





Cross section measurements
check fundamental SUSY relation:

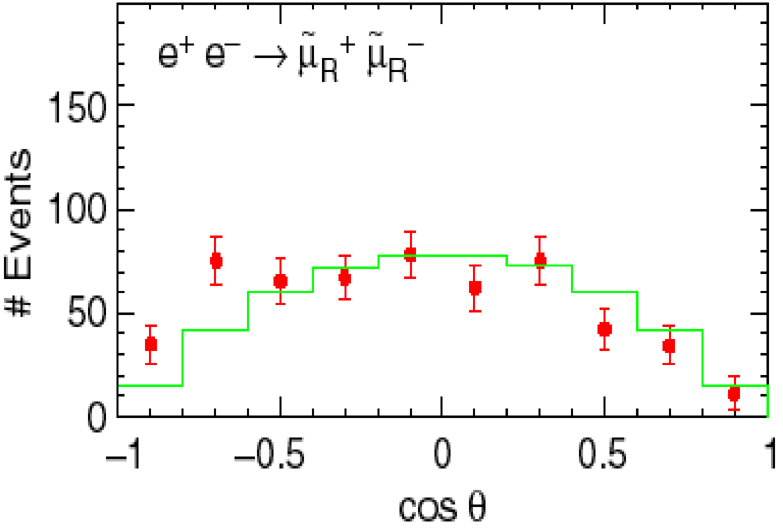


Sleptons: Spin

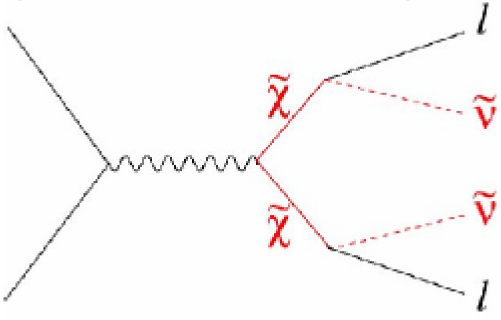
SUSY: sleptons + leptons differ in spin by ½

Spin cleanly determined from production angle distribution:

Spin 0: ~$\sin^2\theta$



or are they charginos after all?
(if sneutrino = LSP)



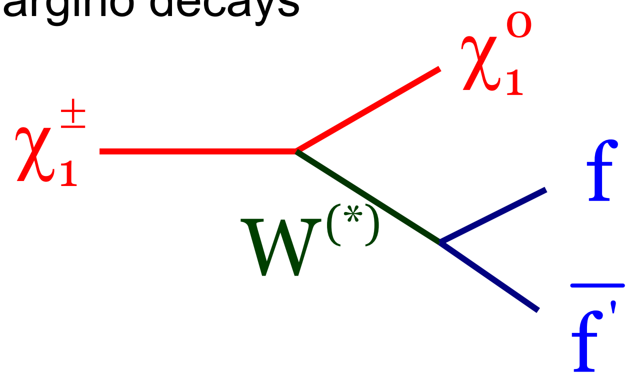
Charginos

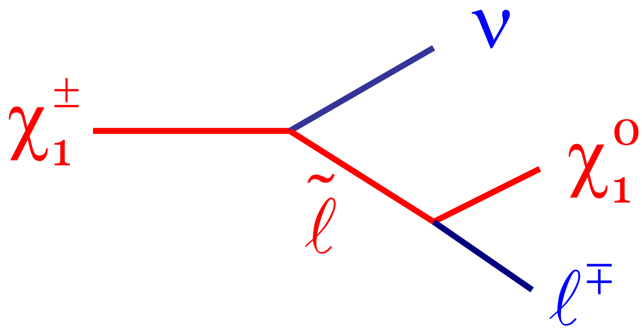
Chargino mass matrix $X = \begin{pmatrix} M_2 & \sqrt{2}\, m_W\, s_\beta \\ \sqrt{2}\, m_W\, c_\beta & \mu \end{pmatrix}$

Depends on tree level on 3 parameters M_2, μ, tanβ
Gets diagonalized by two unitary matrices (angle ϕ_R ϕ_L)

Measurement of mass and polarized cross section required to extract the tree-level parameters of the chargino sector

Chargino decays





for large tanβ often dominant for

$\tilde{\ell} = \tilde{\tau}_1$ → τ final states important

3. Supersymmetry | Charginos: mass measurement

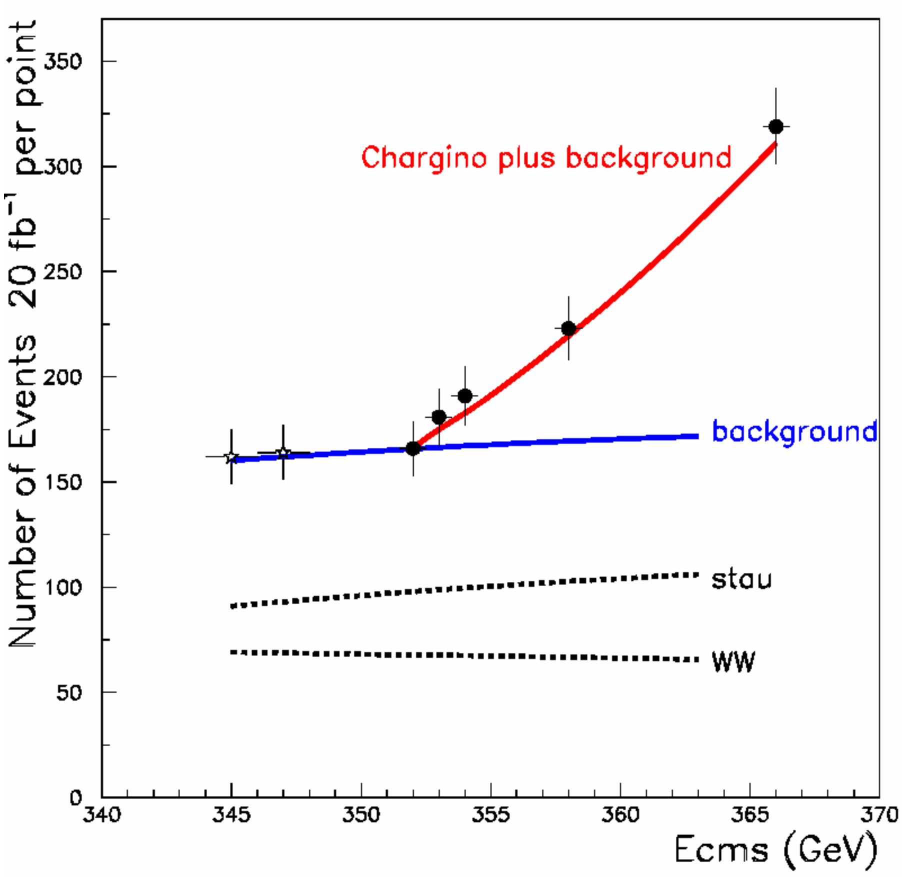
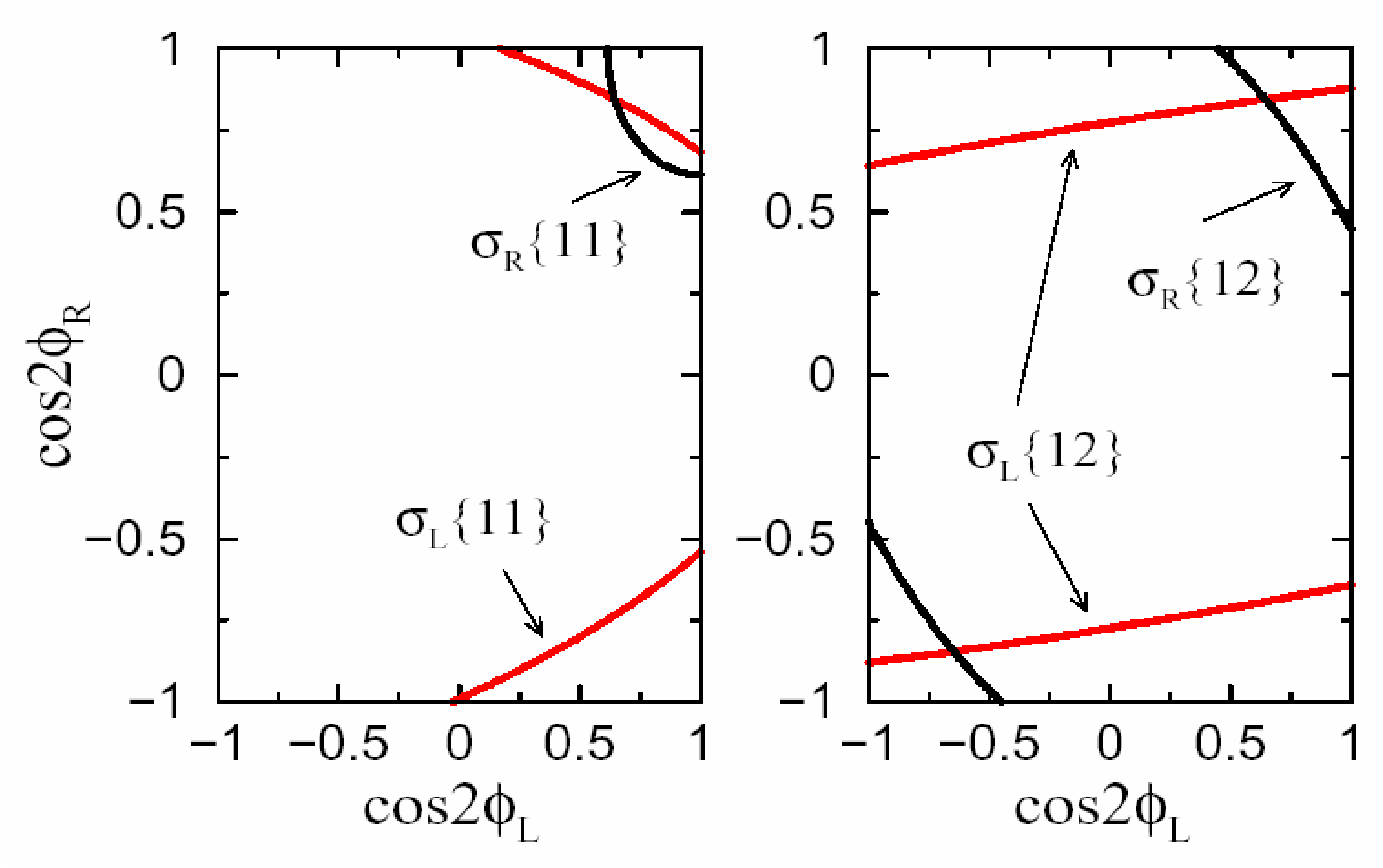


Figure 5.32: Threshold scan of $e_R^+ e_L^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^1 \to \tau^+ \nu_\tau \tilde{\chi}_1^0 \, \tau^- \nu_\tau \tilde{\chi}_1^0$ for SPS 1a assuming $\mathcal{L} = 100\,\mathrm{fb}^{-1}$

Precision:
550 MeV for 100 fb^{-1}
for SPS1a

Charginos: cross section measurement

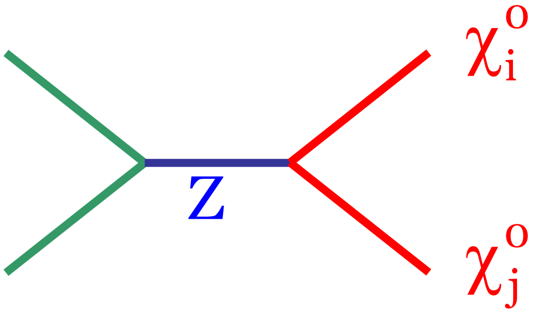


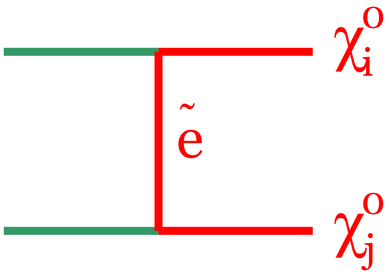
measurement of cross section with left- and right-handed electrons solves for angle ϕ_R,ϕ_L which diagonalize mass matrix: →parameter determ.

3. Supersymmetry | Neutralinos

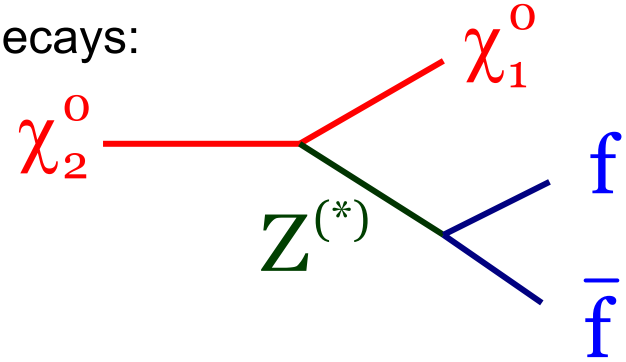
Neutralinos are pair-produced via the processes

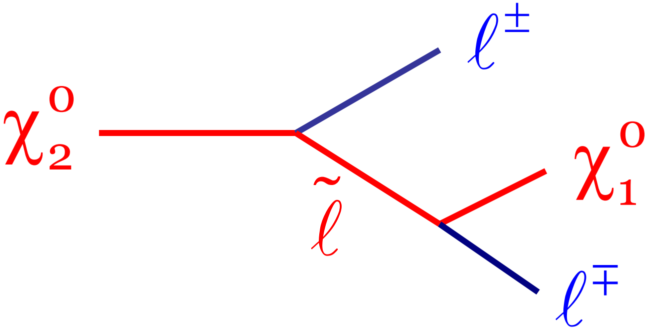
$$e^+e^- \to \chi^o_i \chi^o_j \quad i,j=1,4$$





Decays:





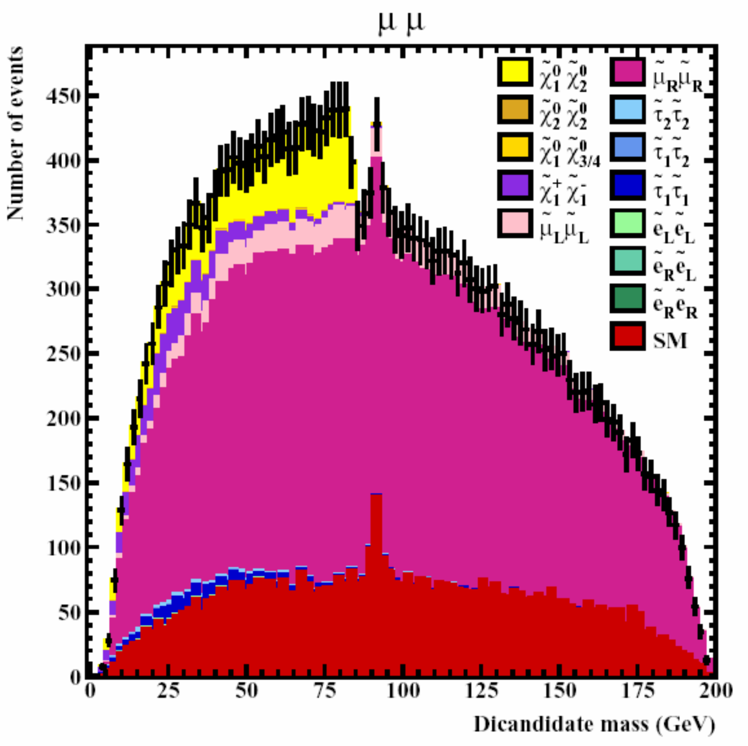
for large tanβ often dominant for

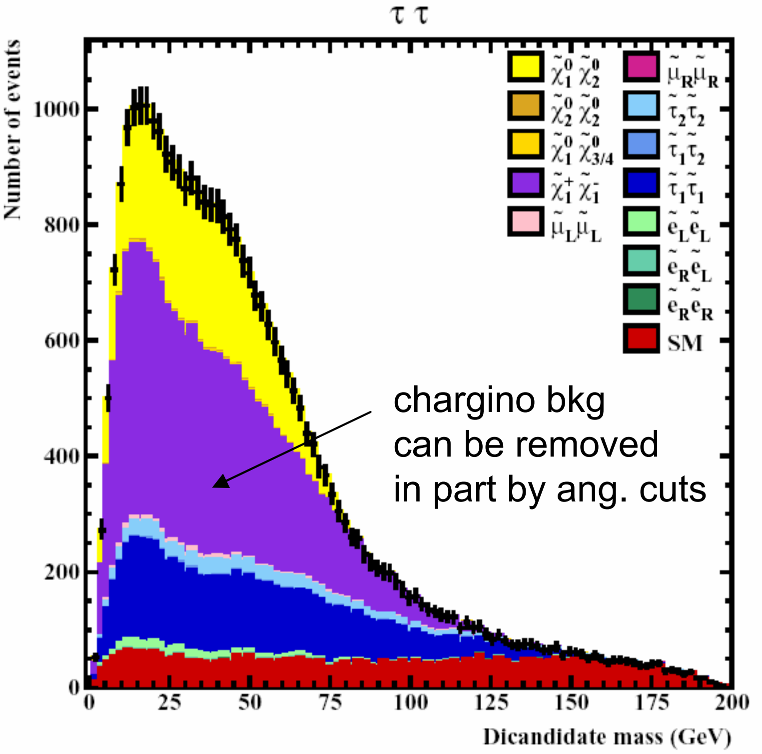
$\tilde{\ell} = \tilde{\tau}_1$ → τ final states important

Neutralinos

Detection of $\chi_1^{o}\chi_2^{o}$ is not straight-forward (SUSY background)

Inclusive SUSY di-lepton selection for unpolarized beams at 500 GeV:





chargino bkg
can be removed
in part by ang. cuts

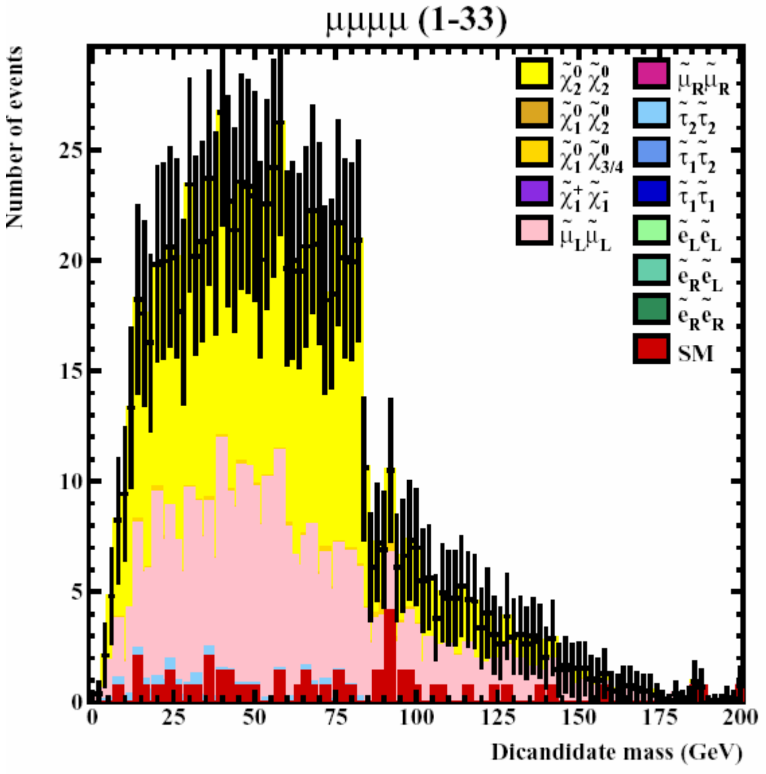
Polarisation and angular distributions will further help to separate signal
Mass measurement best if μ/e final states have high enough BR

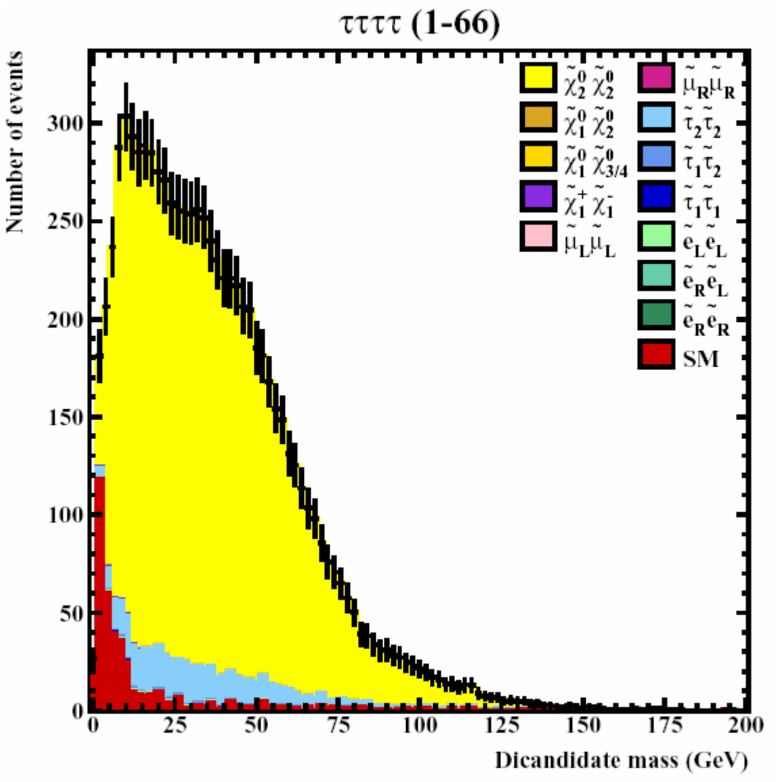
3. Supersymmetry

Neutralinos

Detection of $\chi_2^0\chi_2^0$ in 4-lepton final state is easier

Two subsets of the inclusive SUSY 4-lepton selection at 500 GeV:



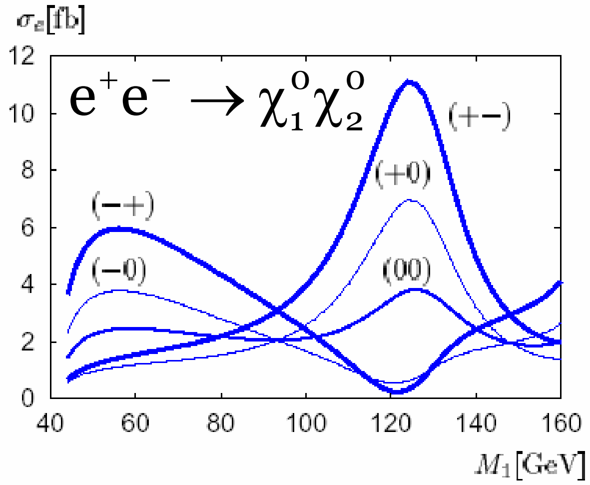


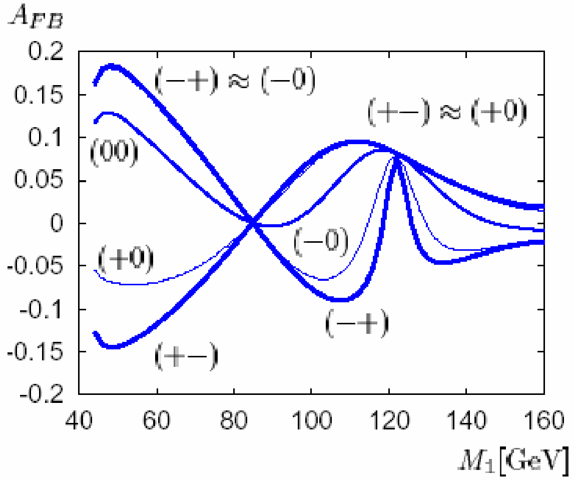
3. Supersymmetry | Neutralinos

Neutralino mass matrix contains M_1 in addition to chargino parameters M_2, μ, tanβ

$$Y = \begin{pmatrix} M_1 & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta \\ 0 & M_2 & m_Z c_W c_\beta & -m_Z c_W s_\beta \\ -m_Z s_W c_\beta & m_Z c_W c_\beta & 0 & -\mu \\ m_Z c_W c_\beta & -m_Z c_W s_\beta & -\mu & 0 \end{pmatrix}$$

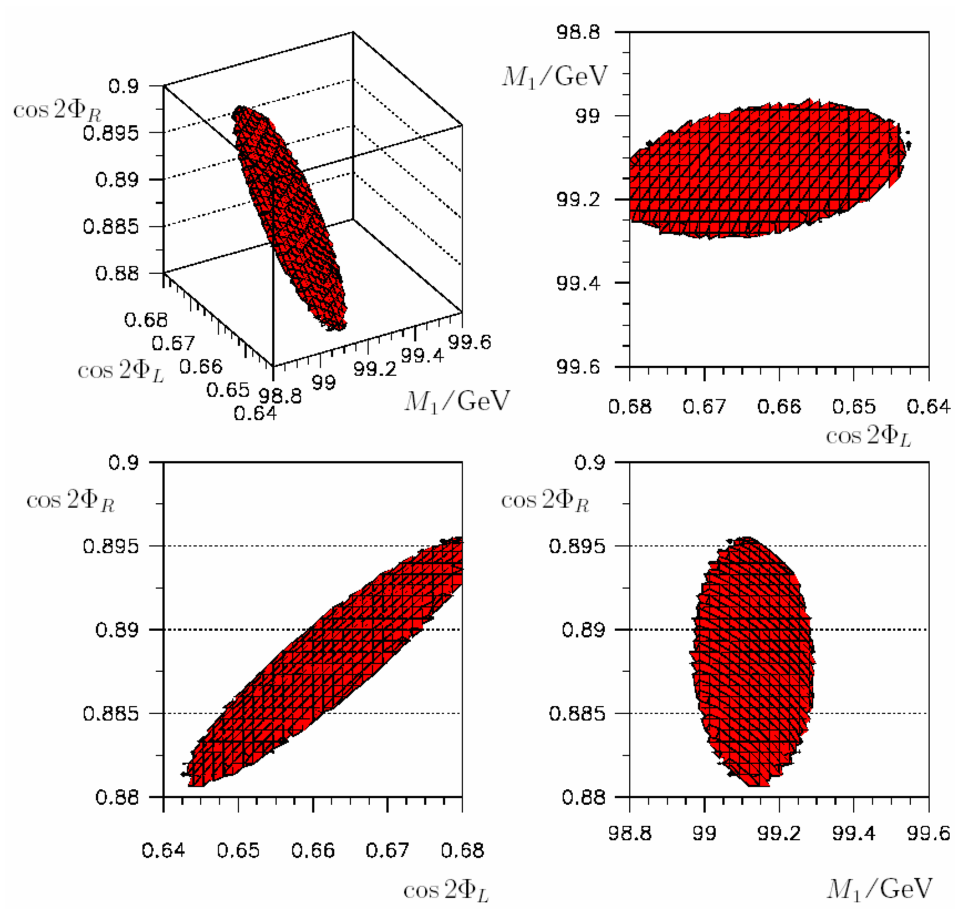
M_1 can be determined (at tree-level) from neutralino masses – but cross section and angular distributions (FB asymmetry) gives further constraints (discriminate against larger neutralino sectors, e.g. NMSSM with 5 neutralinos)





need polarization!

3. Supersymmetry | Neutralinos+Charginos: Parameter determination



An example:
mass measurements of
$\chi_1^o, \chi_2^o, \chi_1^\pm$
and polarized cross sections
for $\chi_1^o\chi_2^o$, $\chi_1^+\chi_1^-$
in SPS1a
put into tree-level fit for
chargino-nuetralino sector

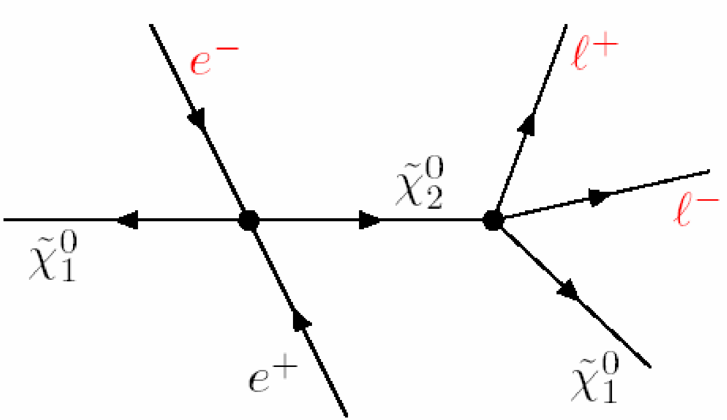
(more on loop-level fits
on Friday)

SUSY Parameters				Mass Predictions		
M_1	M_2	μ	$\tan\beta$	$m_{\tilde{\chi}_2^\pm}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_4^0}$
99.1 ± 0.2	192.7 ± 0.6	352.8 ± 8.9	10.3 ± 1.5	378.8 ± 7.8	359.2 ± 8.6	378.2 ± 8.1

3. Supersymmetry | Neutralinos: CP violation

Parameters M_1 and μ may have complex phases → CP violation
Sensitivity at ILC: explore spin correlations:

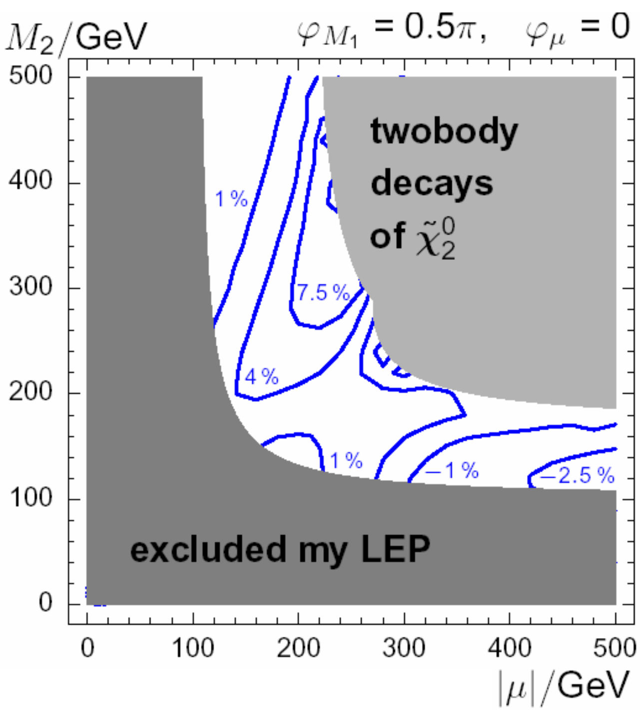
$$e^+e^- \longrightarrow \tilde{\chi}_1^0 + \tilde{\chi}_2^0 \longrightarrow \tilde{\chi}_1^0 + \tilde{\chi}_1^0 \ell^+ \ell^-$$



CP sensitive observable:

$$\mathrm{T} = \vec{p}_{e^-} \bullet (\vec{p}_{\ell^+} \times \vec{p}_{\ell^-})$$

$$A_T = \frac{\sigma(\mathcal{T} > 0) - \sigma(\mathcal{T} < 0)}{\sigma(\mathcal{T} > 0) + \sigma(\mathcal{T} < 0)}$$



expect 1-10% effects – needs more experimental study
similar method for 2-body decays

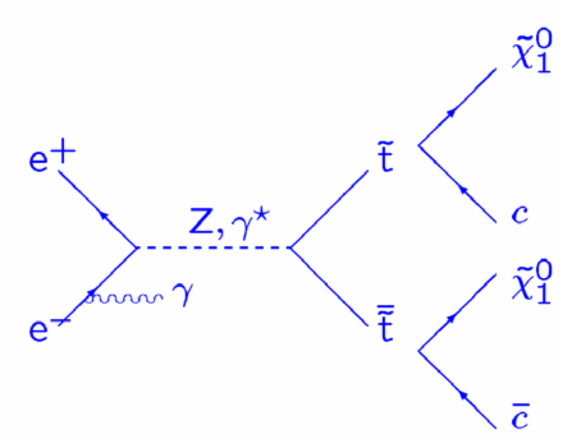
3. Supersymmetry | Light Stop

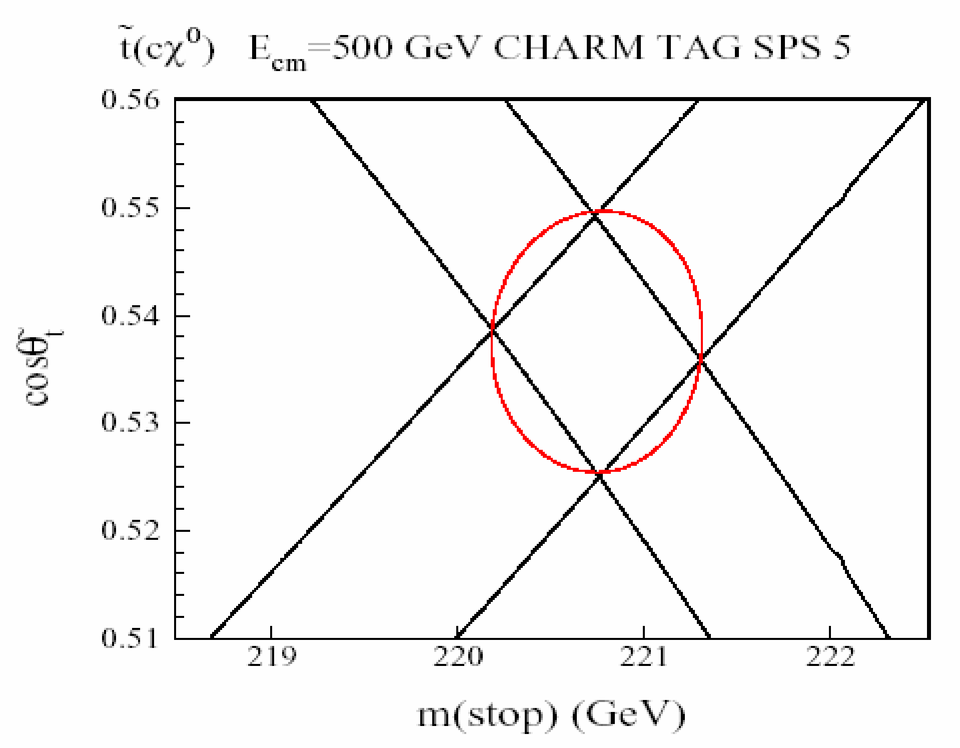
Often, stop squark lighter than other quarks due to large mixing.
Example (SPS5 benchmark):

$$m_{\tilde{t}_1} = 220\,\mathrm{GeV}$$

$$m_{\chi_1^0} = 120\,\mathrm{GeV}$$

$$\cos\theta_{\tilde{t}} = 0.54$$





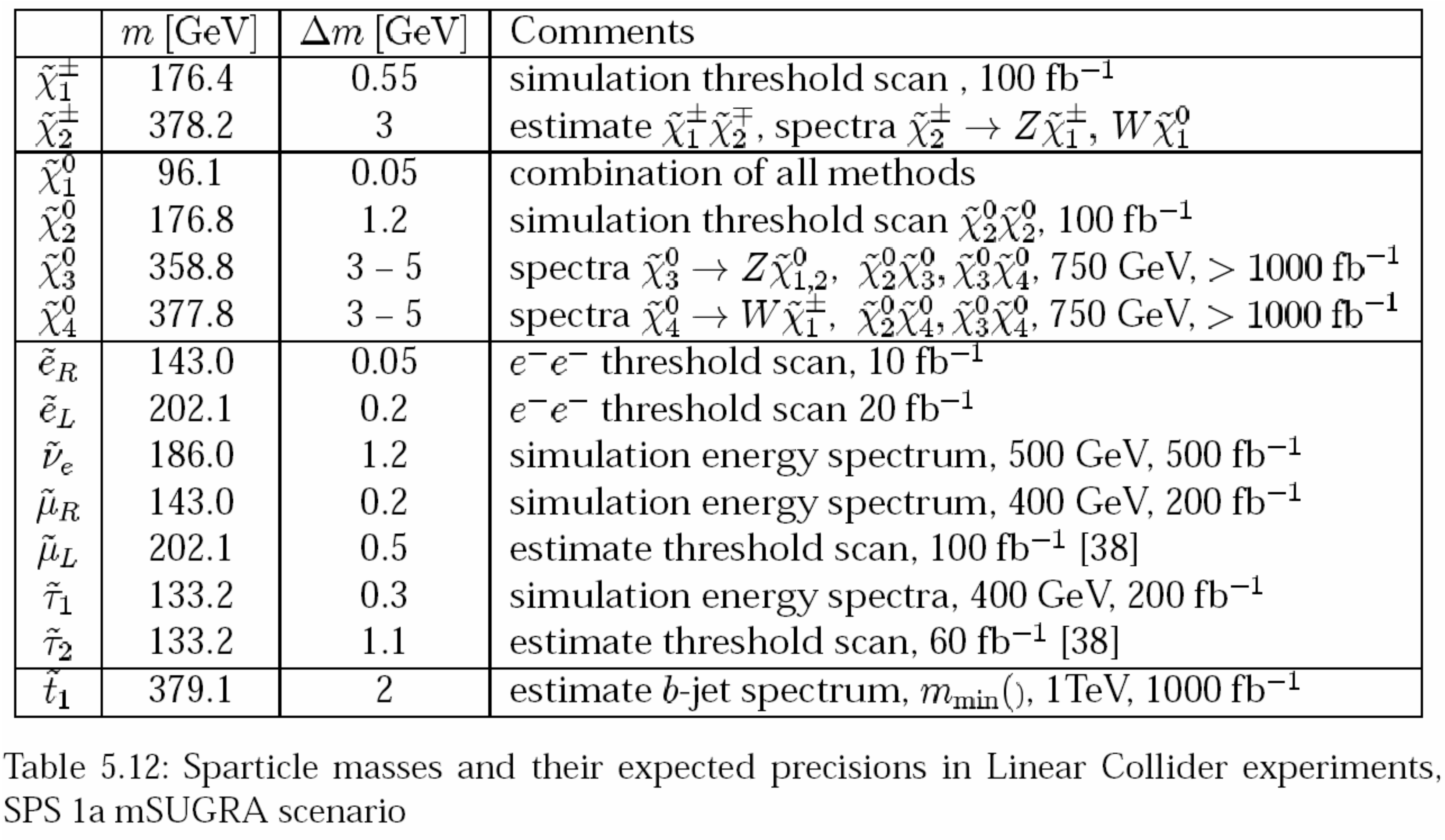
measurement of LR and RL cross sections to extract

$$m_{\tilde{t}_1} = 220 \pm 0.6\,\mathrm{GeV}$$

$$\cos\theta_{\tilde{t}} = 0.54 \pm 0.01$$

3. Supersymmetry

Summary of achievable mass precisions

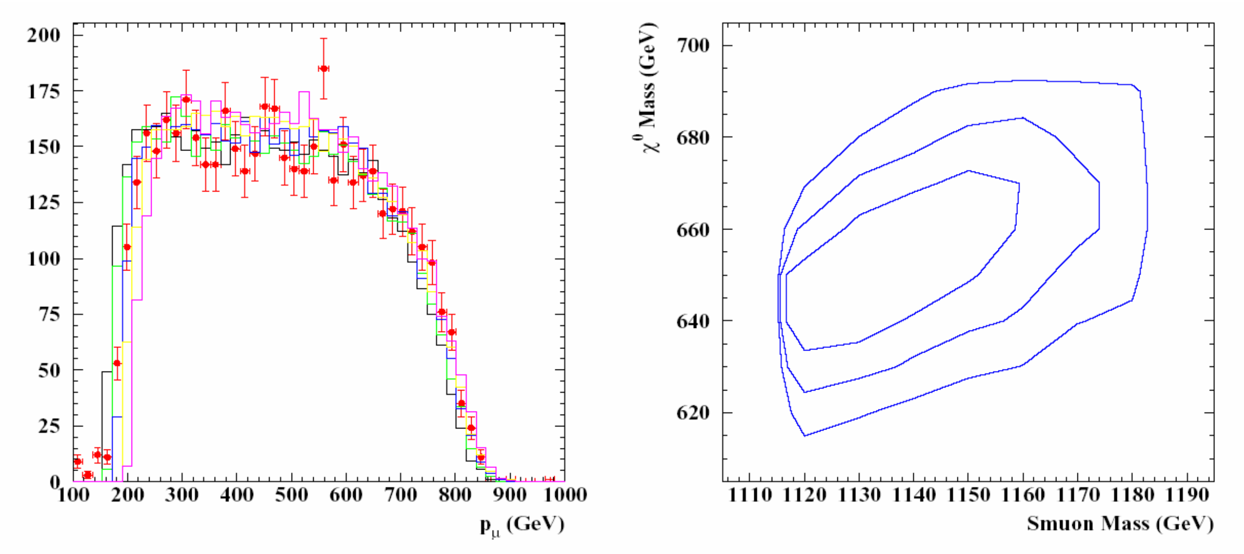


	m [GeV]	Δm [GeV]	Comments
$\tilde\chi_1^\pm$	176.4	0.55	simulation threshold scan , 100 fb^{-1}
$\tilde\chi_2^\pm$	378.2	3	estimate $\tilde\chi_1^\pm\tilde\chi_2^\mp$, spectra $\tilde\chi_2^\pm \to Z\tilde\chi_1^\pm$, $W\tilde\chi_1^0$
$\tilde\chi_1^0$	96.1	0.05	combination of all methods
$\tilde\chi_2^0$	176.8	1.2	simulation threshold scan $\tilde\chi_2^0\tilde\chi_2^0$, 100 fb^{-1}
$\tilde\chi_3^0$	358.8	3 – 5	spectra $\tilde\chi_3^0 \to Z\tilde\chi_{1,2}^0$, $\tilde\chi_2^0\tilde\chi_3^0$, $\tilde\chi_3^0\tilde\chi_4^0$, 750 GeV, > 1000 fb^{-1}
$\tilde\chi_4^0$	377.8	3 – 5	spectra $\tilde\chi_4^0 \to W\tilde\chi_1^\pm$, $\tilde\chi_2^0\tilde\chi_4^0$, $\tilde\chi_3^0\tilde\chi_4^0$, 750 GeV, > 1000 fb^{-1}
$\tilde e_R$	143.0	0.05	e^-e^- threshold scan, 10 fb^{-1}
$\tilde e_L$	202.1	0.2	e^-e^- threshold scan 20 fb^{-1}
$\tilde\nu_e$	186.0	1.2	simulation energy spectrum, 500 GeV, 500 fb^{-1}
$\tilde\mu_R$	143.0	0.2	simulation energy spectrum, 400 GeV, 200 fb^{-1}
$\tilde\mu_L$	202.1	0.5	estimate threshold scan, 100 fb^{-1} [38]
$\tilde\tau_1$	133.2	0.3	simulation energy spectra, 400 GeV, 200 fb^{-1}
$\tilde\tau_2$	133.2	1.1	estimate threshold scan, 60 fb^{-1} [38]
$\tilde t_1$	379.1	2	estimate b-jet spectrum, $m_{\text{min}}()$, 1TeV, 1000 fb^{-1}

Table 5.12: Sparticle masses and their expected precisions in Linear Collider experiments, SPS 1a mSUGRA scenario

3. Supersymmetry at CLIC

3 TeV signifcantly extends the mass reach for SUSY precision studies. In most scenarios, this particulary important for squarks – sometimes also for sleptons.



$$m_{\tilde{\mu}_L} = 1150\,\mathrm{GeV}$$

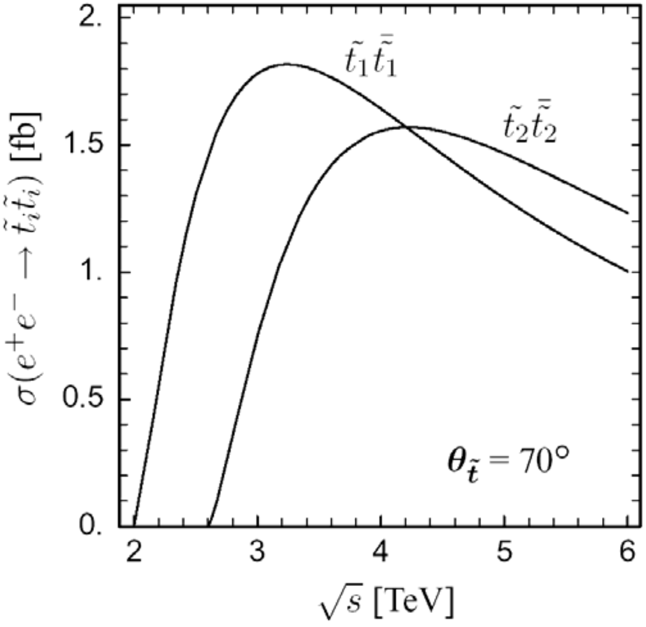
$$m_{\chi_1^0} = 660\,\mathrm{GeV}$$

Often tight constraints on the MSSM parameters space already come from the lighter states (generally accessible at ILC) but precise study of heavy sector may become important.

If only charginos/neutralinos are seen at ILC, slepton (selectron/sneutrino) masses up to 10 TeV can be probed via t-channel exchange!

3. Supersymmetry at CLIC

Heavy stop production:



$m_{\tilde{t}_1} = 1000\,\mathrm{GeV}$

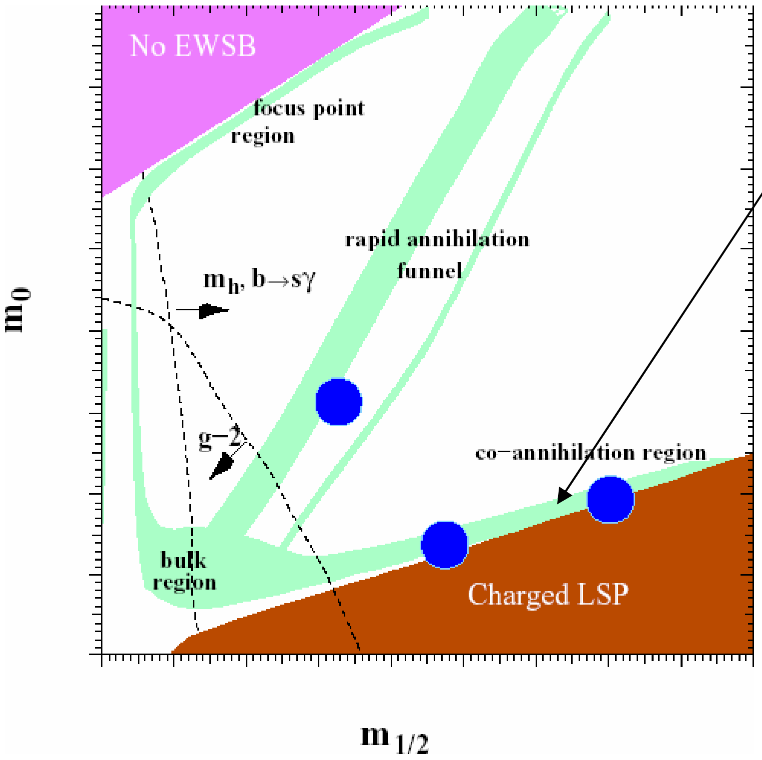
$m_{\tilde{t}_2} = 1300\,\mathrm{GeV}$

can use polarized cross section measurement to obtain information on trilinear coupling A_t

Dark Matter

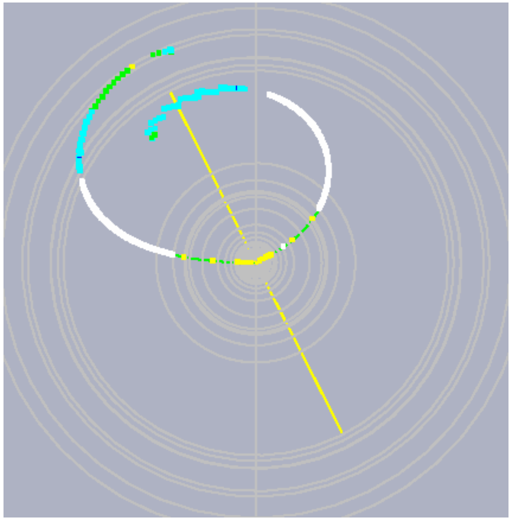
If SUSY LSP responsible for Cold Dark Matter, need accelerators to show that its properties are consistent with CMB data

- Future precision on $\Omega h^2 \sim 2\%$ (Planck) – match this precision!
- WMAP points to certain difficult regions in parameter space:



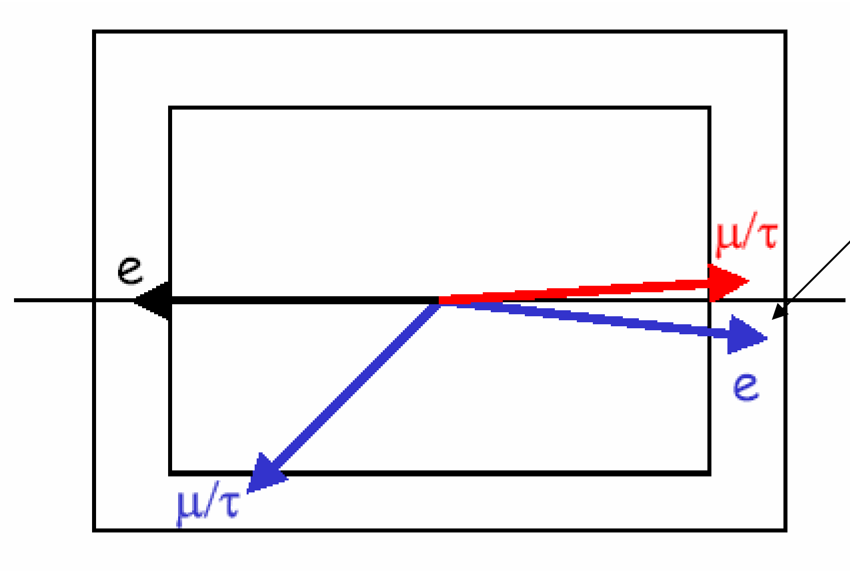
small $\Delta M = M_{\tilde{\ell}} - M_{\chi_1^o}$

e.g. smuon pair production at 1TeV
only two very soft muons!
need to fight backgrounds

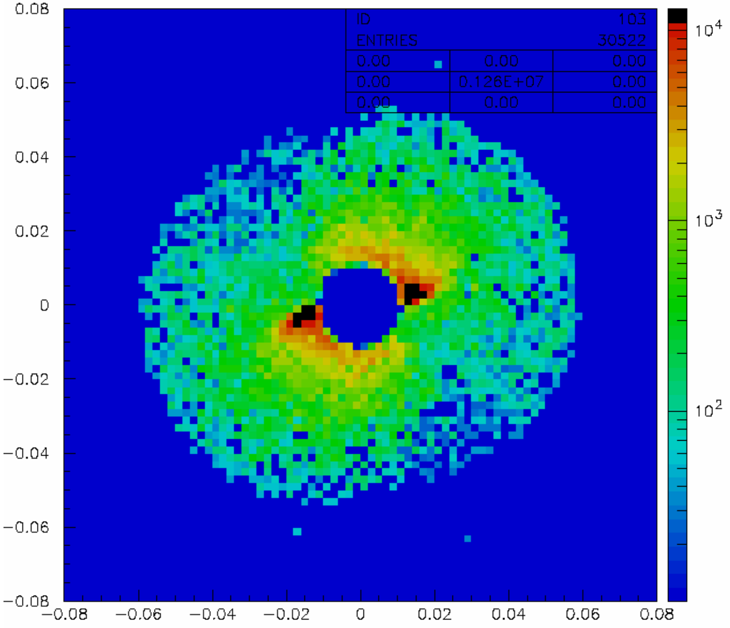


3. Supersymmetry | Dark Matter

Huge Background from two-photon processes: $e^+e^- \to \mu\mu ee$ etc



need to veto these scattered beam electrons at very low angles



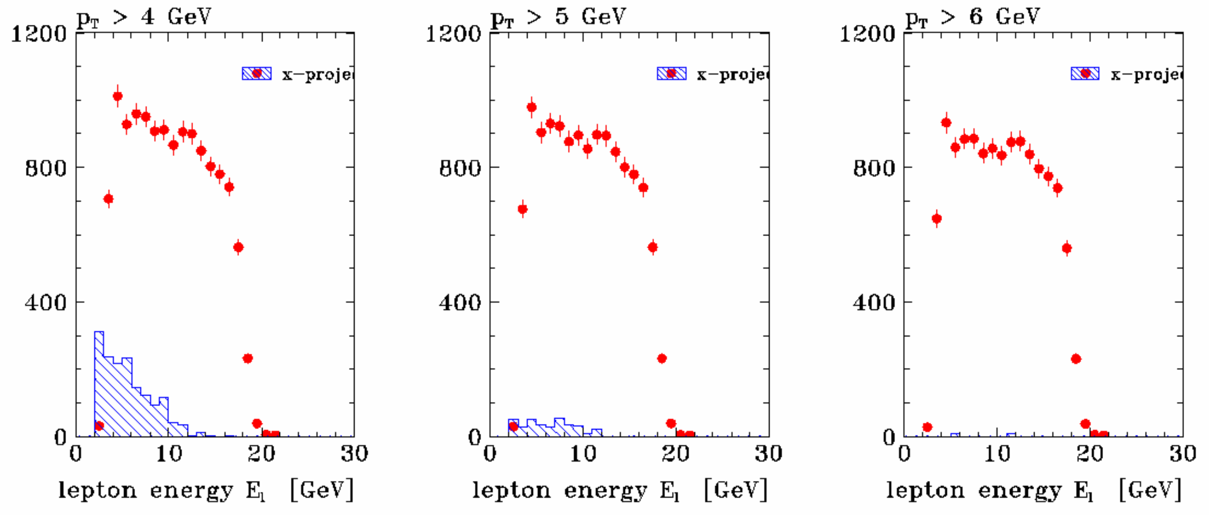
several TeV/BX energy from beamstrahlung close to beampipe

→ need highly granular rad-hard, fast forward instrumentation

3. Supersymmetry

Dark Matter

Works for smuons down to ΔM ~ 5 GeV
more difficult for staus, but ok for ΔM ~ 5 GeV, need more thinking below



smuons at
ΔM = 8 GeV

Results on Ωh^2:

ΔM (GeV)	5	7	9
δm(stau) (MeV)	420	400	150
$\Delta(\Omega h^2)$ (%)	5.0	3.1	1.6

Split SUSY

Split Supersymmetry

Motivation: give up solving fine-tuning problem but retain
other goodies of SUSY (DM candidate, GUT unification)
get rid of FCNC, p-decay problems

Realisation: all scalars except h are ultra-heavy
gauginos remain light

Collider consequences:

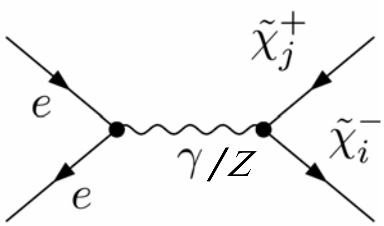
meta-stable gluinos (interesting for LHC)
charginos + neutralinos only through Drell-Yan at LHC (challenging)

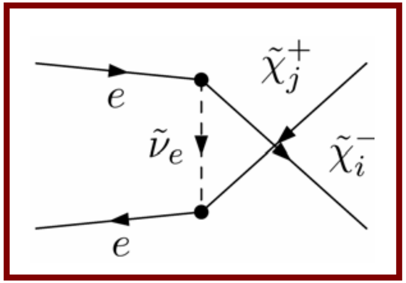
At ILC: precise measurement of chargino+neutralino+Higgs properties
allows us to test the model

3. Supersymmetry | Split SUSY

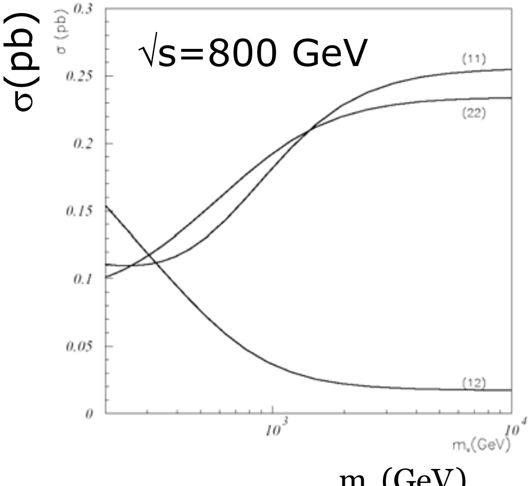
1. are the scalars really heavy?

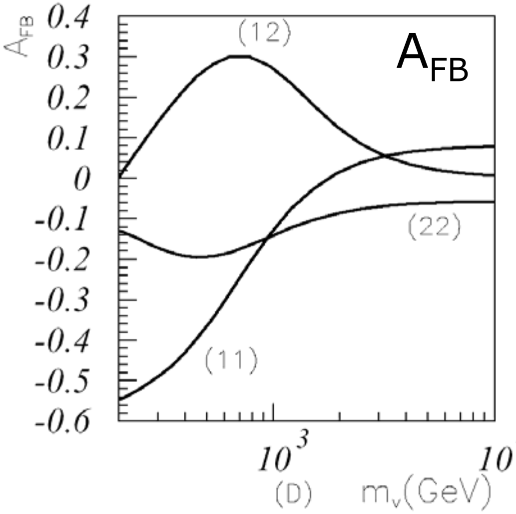
sensitivity to (heavy) sneutrino
in t- channel chargino production

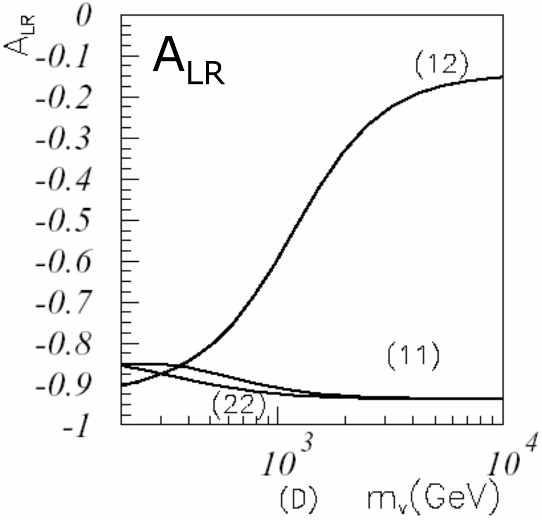




- through total cross section
- through forward-backward asymmetry
- through LR polarisation asymmetry





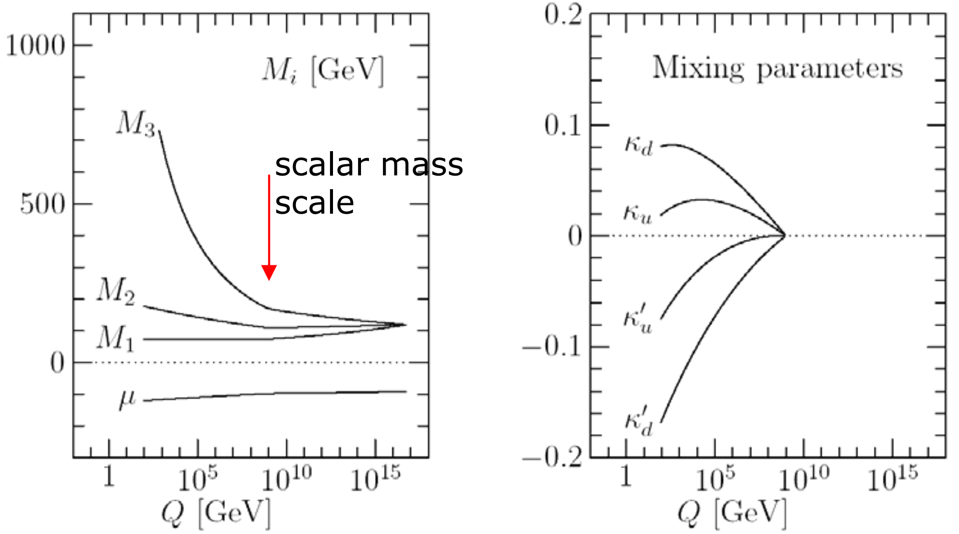


$m(\chi^+_1)$ = 148 GeV
$m(\chi^+_2)$ = 267 GeV

sensitive to $m_{\tilde{\nu}} \sim$ 10 TeV

3. Supersymmetry | Split SUSY

2. how heavy are the scalars?



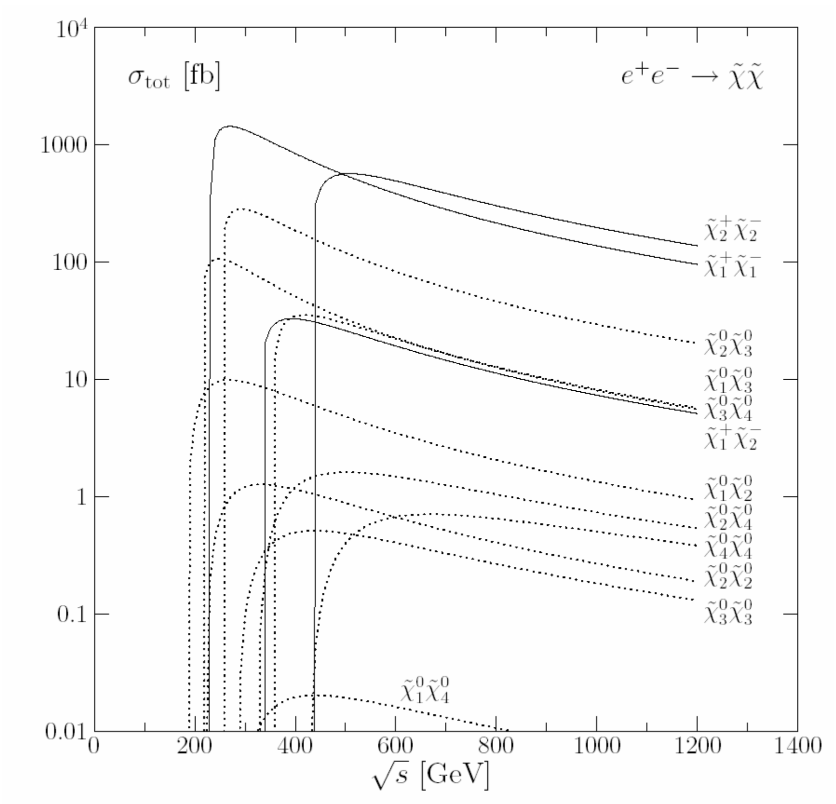
Chargino/Neutralino mixings receive non-SUSY RGE corrections different from low-scale SUSY

$$\frac{\tilde{g}_u}{g\sin\beta} \equiv 1+\kappa_u = 1+0.018 \qquad \frac{\tilde{g}_d}{g\cos\beta} \equiv 1+\kappa_d = 1+0.081$$

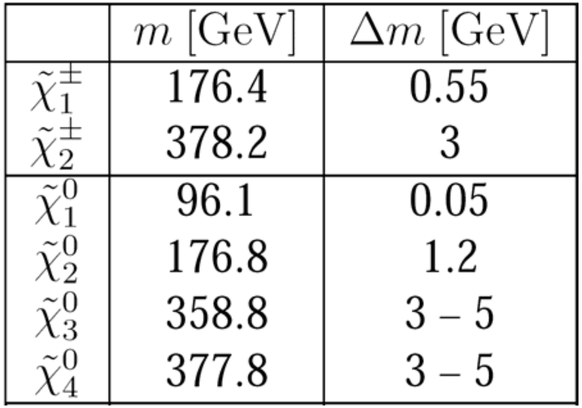
$$\frac{\tilde{g}'_u}{g'\sin\beta} \equiv 1+\kappa'_u = 1-0.075 \qquad \frac{\tilde{g}'_d}{g'\cos\beta} \equiv 1+\kappa'_d = 1-0.17$$

3. Supersymmetry | Split SUSY

Those can be measured from precise mass + cross section measurements of the complete chargino+neutralino sector



ILC precisions from detailed simulations (for SPS1a param.)



	m [GeV]	Δm [GeV]
$\tilde\chi_1^\pm$	176.4	0.55
$\tilde\chi_2^\pm$	378.2	3
$\tilde\chi_1^0$	96.1	0.05
$\tilde\chi_2^0$	176.8	1.2
$\tilde\chi_3^0$	358.8	3 – 5
$\tilde\chi_4^0$	377.8	3 – 5

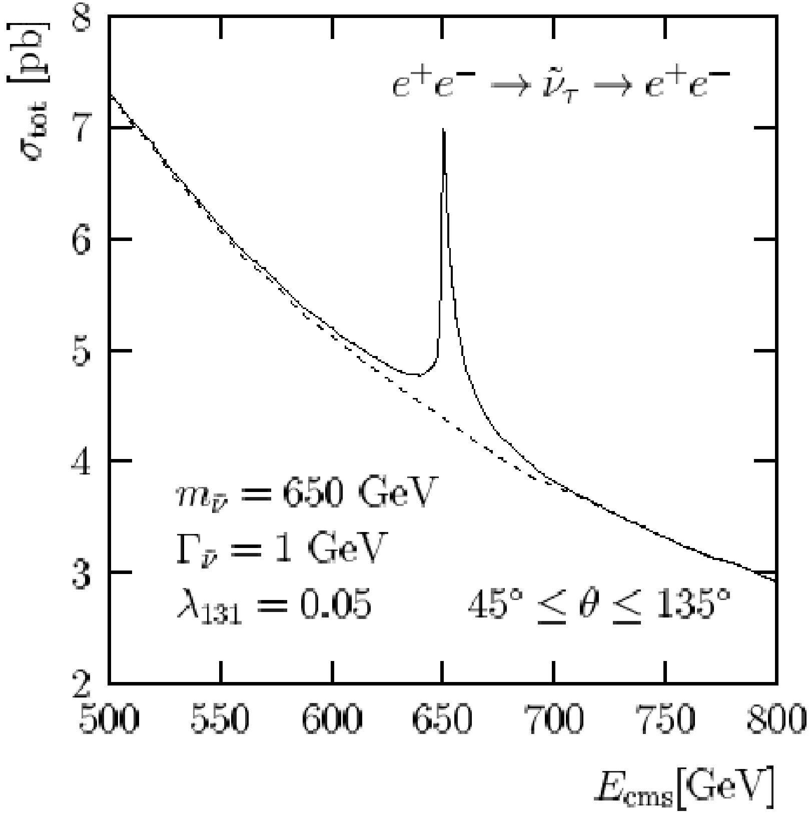
(still room for improvements…)

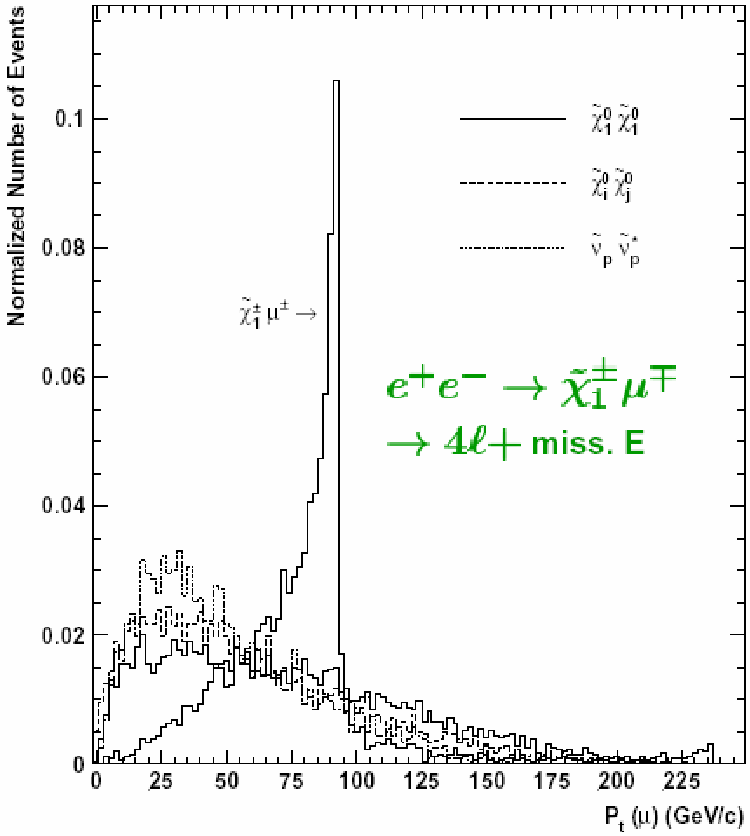
→ measure anomalous Yukawa couplings to precision of 0.01 to 0.1

add. possibility: directly measure $e^+e^- \to \chi^+\chi^- h$ (o(0.1fb) cross section)

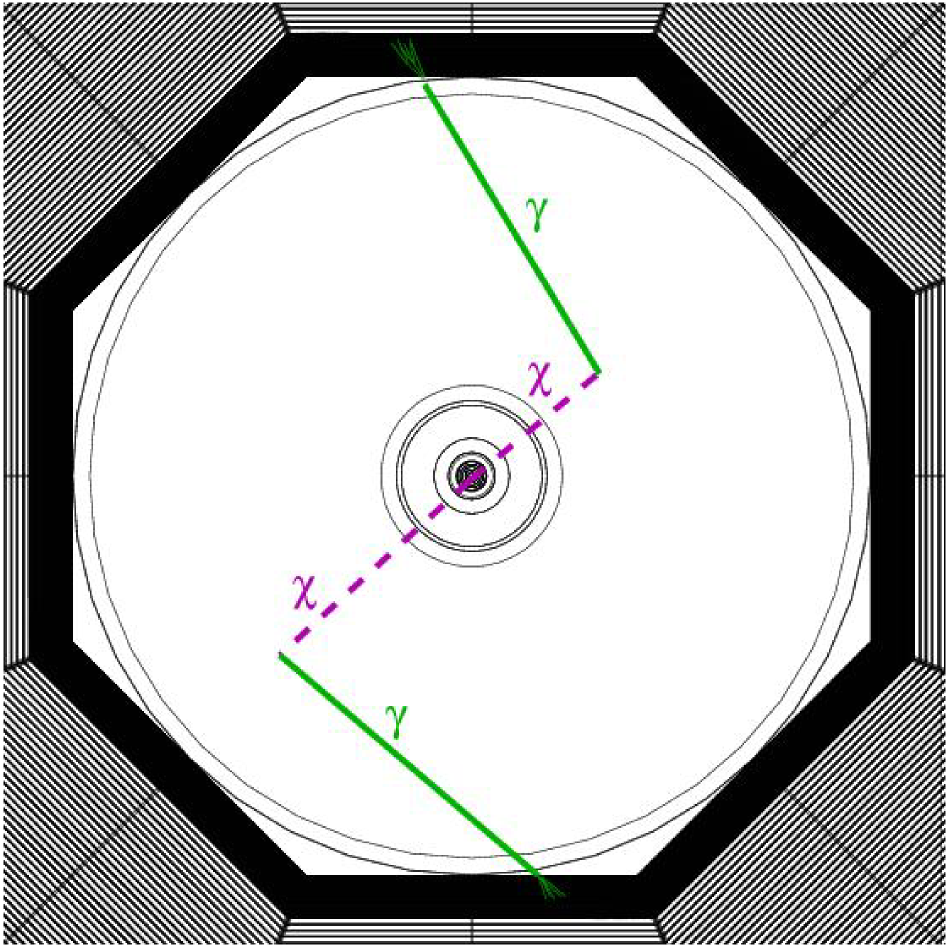
Exotic SUSY

R–Parity violation may provide spectacular signatures!





GMSB signatures



In some SUSY scenarios ('GMSB') the Neutralino is not stable:

$$\widetilde{\chi}_1^0 \rightarrow \gamma \widetilde{G}$$

'non-pointing' photon signature
demanding for calorimetry!

3. Supersymmetry

Summary

- Supersymmetry best-motivated extension of SM (solves many puzzles at once)
- Direct (pair-) production of SUSY partners at LC is the best tool to study their properties (mass, cross sections, distributions) in detail often at permil – percent level
- Enough information to extract (together with LHC) the complete MSSM parameters (no constraints on SSB mechnanism) → Friday
- Polarized beams particularly useful for SUSY (test of fundamental SUSY relations)
- CLIC can extend the mass reach (squarks) and cover corners of parameter space