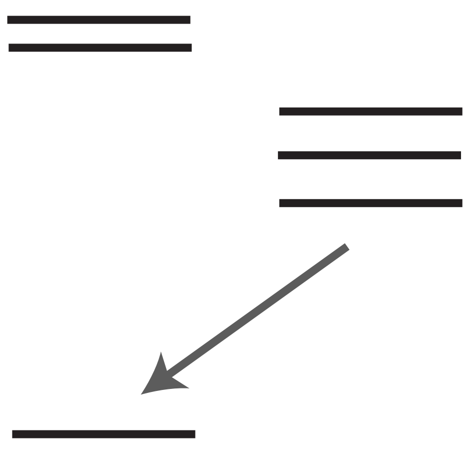
# Supersymmetry: the Next Spectroscopy



M. E. Peskin
December, 2001

This talk is a part of the celebration of Werner Heisenberg's centenary.

We celebrate particularly the achievements of Heisenberg and the Copenhagen-Göttingen-Munich school in building a new mathematical picture of physical reality.

Today, we have a "Standard Model" of microphysics which explains the detailed properties of the strong, weak, and electromagnetic interactions.

The difficulties with this model are mainly conceptual.

This contrasts with the great periods of revolution in physics,

when specific, concrete measurements contradicted the established theory and its simple variants.

Nothing illustrates this better than the work of Werner Heisenberg.

Heisenberg's breakthrough arose from his quest to understand specific physical phenomena: the anomalous Zeeman effect and the absorption and emission of light in gases.

In 1925, with his breakthrough paper already in press, Heisenberg lectured in Cambridge on

"Termzoologie und Zeemanbotanik"

In 1926, Heisenberg confirmed the new picture of quantum dynamics with his explanation of ortho- and para-Helium.

At this moment in physics, it is impossible to see our way to an ultimate theory, which lies beyond the next era of crisis and resolution.

Instead, we should be asking, How can we reach this era?

Can we imagine a future in which new data challenges us to change physics in a revolutionary way? Where will this data come from?

In the 21st century, when probes into new distances scales require enormous expense -- for accelerators, satellites, caverns full of equipment -- we must justify these explorations with some concrete expectation of where they can lead.

In this lecture, I would like to describe my hope for a pathway to this next era.

Its crucial element is the appearance of supersymmetry in high-energy physics.

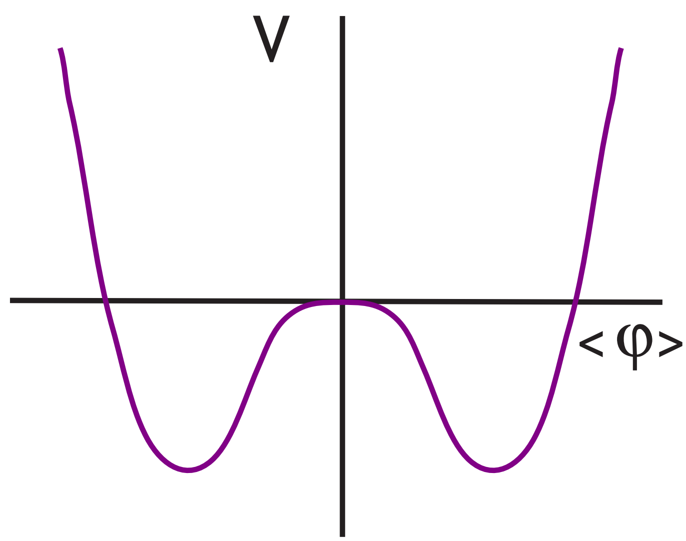
The major result of high-energy physics in the 1990's was the detailed confirmation of the SU(3) X SU(2) X U(1) gauge theory of strong, weak, and electromagnetic interactions, the Standard Model (SM).

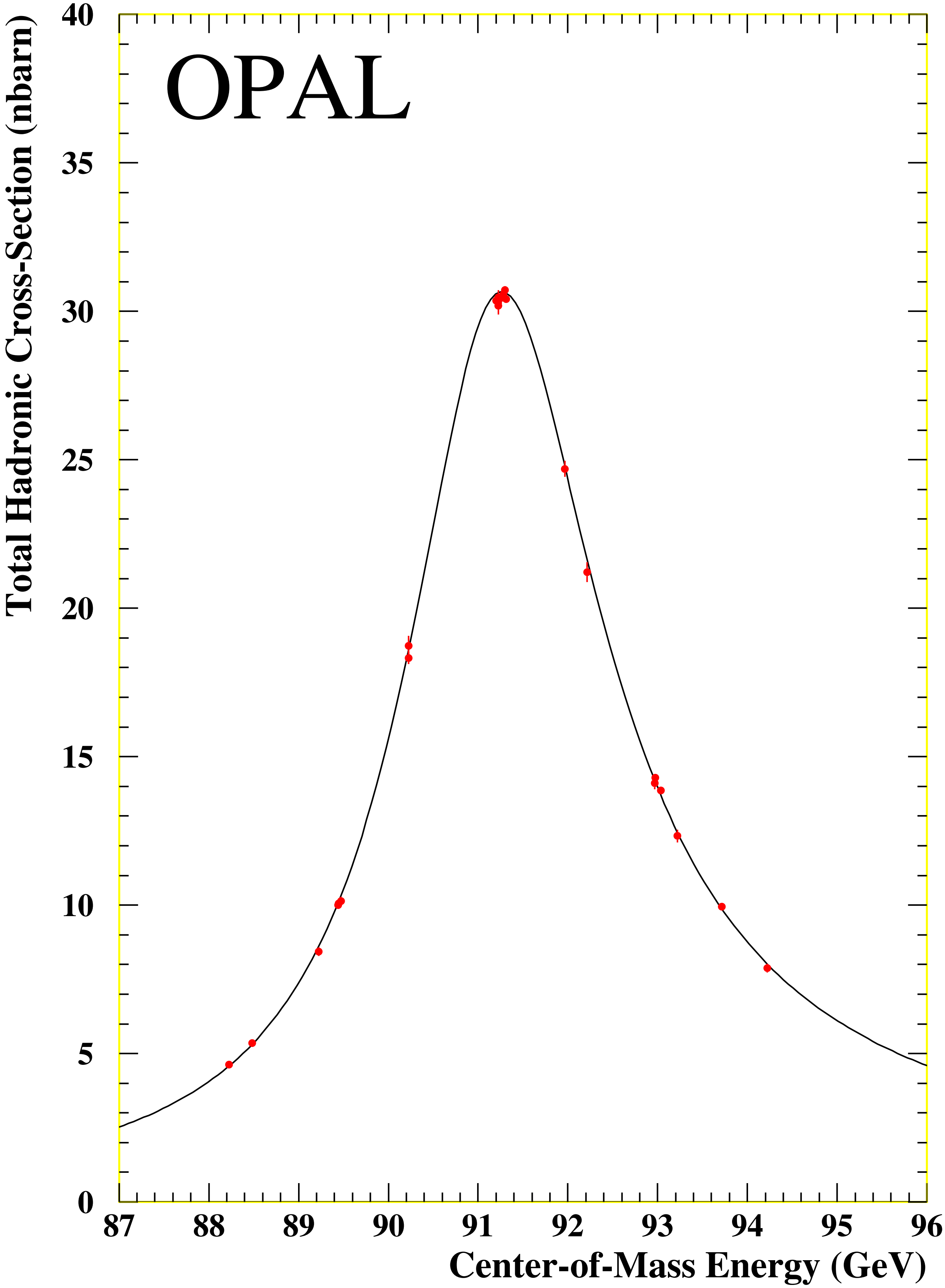
As an example, the theory of the Z boson resonance line-shape agrees with the SM to parts-per-mil accuracy.

This success requires the presence of the gauge symmetries as exact symmetries of Nature, and their spontaneous breaking by a Higgs field $\varphi$ .

This highlights the question:

What is the origin of $\varphi$ ?
Why does its energetics favor symmetry-breaking?




OPAL
Total Hadronic Cross-Section (nbarn)
0
5
10
15
20
25
30
35
40
87
88
89
90
91
92
93
94
95
96
Center-of-Mass Energy (GeV)

The explanation should encompass a number of other phenomena:

heavy top quark:

$m_t \,/\, m_W = 2.1$

light Higgs boson:

precision electroweak: $m_h < 196$ GeV

observed at LEP?

values of microscopic couplings:

$\alpha_1' = 1/\ 98.5 \quad \alpha_2 = 1/\ 29.6 \quad \alpha_3 = 1/\ 8.5$

cosmological dark matter:

$\Omega_m = 0.3$

cosmological dark energy:

$\Omega_\Lambda = 0.7$

anomaly in the muon (g-2) ?

# What is supersymmetry (SUSY) ?

Golfand-Likhtman, Volkov-Akulov, Wess-Zumino

a symmetry $Q_a$ , $[Q_a, H] = 0$ , such that

$Q_a$ |boson> = |fermion> , $Q_a$ |fermon> = |boson>

$Q_a$ obviously has spin-1/2, but this leads to more profound constraints.

Consider $\{ Q_a, Q_b^\dagger \}$ This is:

- nonzero:

$$\langle\psi| \{Q_a, Q_a^\dagger\} |\psi\rangle = \| Q_a |\psi\rangle \|^2 + \| Q_a^\dagger |\psi\rangle \|^2$$

- a 4-vector
- a conserved charge

Coleman-Mandula:

There is only one possibility. This object is proportional to energy-momentum:

$$\{ Q_a , Q_b \} = 2 \gamma^m_{ab} P_m$$

We might modestly suggest that SUSY is only a partial symmetry of part of Nature.

However, if SUSY is fundamental,
the square of $Q_a$ is the energy-momentum of everything.

This implies that every particle must have a partner with the opposite statistics:

$$\gamma \rightarrow \tilde{\gamma} \qquad W^+ \rightarrow \tilde{W}^+$$

$$e^-_L \rightarrow \tilde{e}^-_L \qquad e^-_R \rightarrow \tilde{e}^-_R$$

$$u_L \rightarrow \tilde{u}_L \qquad u_R \rightarrow \tilde{u}_R$$

indeed,

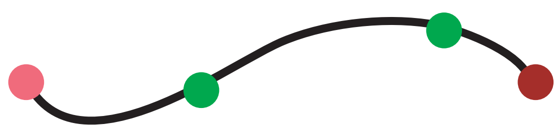
$$G_{mn} \rightarrow \Psi_{ma}$$

which signals a change in the basic equations of space-time.

SUSY originated in string theory, from the generalization of a relativistic string in space-time

$X^m(\sigma)$

by the extension Neveu-Schwarz-Ramond



$X^m(\sigma)\,, \quad \psi^m(\sigma)$

so that the string moves in a superspace with fermionic coordinates.

We will take more inspiration from string theory later in the lecture.

Perhaps surprisingly,  SUSY provides a coherent picture of what could lie beyond the SM, one which resolves many of the issues I have listed.

It is not the only such picture, but it is the most complete and compelling.

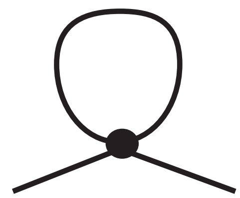
(for a review,
see my SLAC Summer Institute lectures)

Let's now discuss the elements of that picture.  These come from taking the universality of SUSY very seriously.

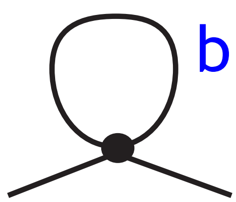
In only a few years
- at the latest, when the LHC runs -
we will know if this picture is correct.

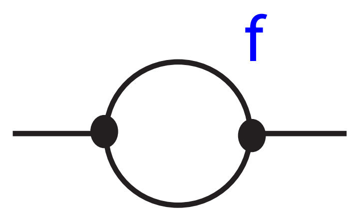
## 1. Higgs field

In ordinary quantum field theory

$m_h^2 = m_h^2(\text{bare})$ +  + . . .

the correction is $O(\alpha\Lambda^2)$, with $\Lambda > 10^{18}$ GeV, while $m_h \sim 100$ GeV . It is difficult even to understand the sign of $m_h^2$.

In SUSY, 

\+ 

= 0

up to terms of order $m^2 \log \Lambda^2 / m^2$ .
We can compute the Higgs field's potential.

If $m_t > m_W$ , the largest contribution comes from loops with $\tilde{t}_L$ , $\tilde{t}_R$

and these give $m_h^2 < 0$ : instability !

## 2. Coupling constants

from precision experiments at LEP, SLC:

$$\alpha_1' = 1/\ 98.5 \quad \alpha_2 = 1/\ 29.6 \quad \alpha_3 = 1/\ 8.5$$

In quantum field theory, the size of coupling constants depends on the distance scale. At very small distances:

vacuum polarization: $\alpha$ becomes larger
asymptotic freedom: $\alpha$ becomes smaller

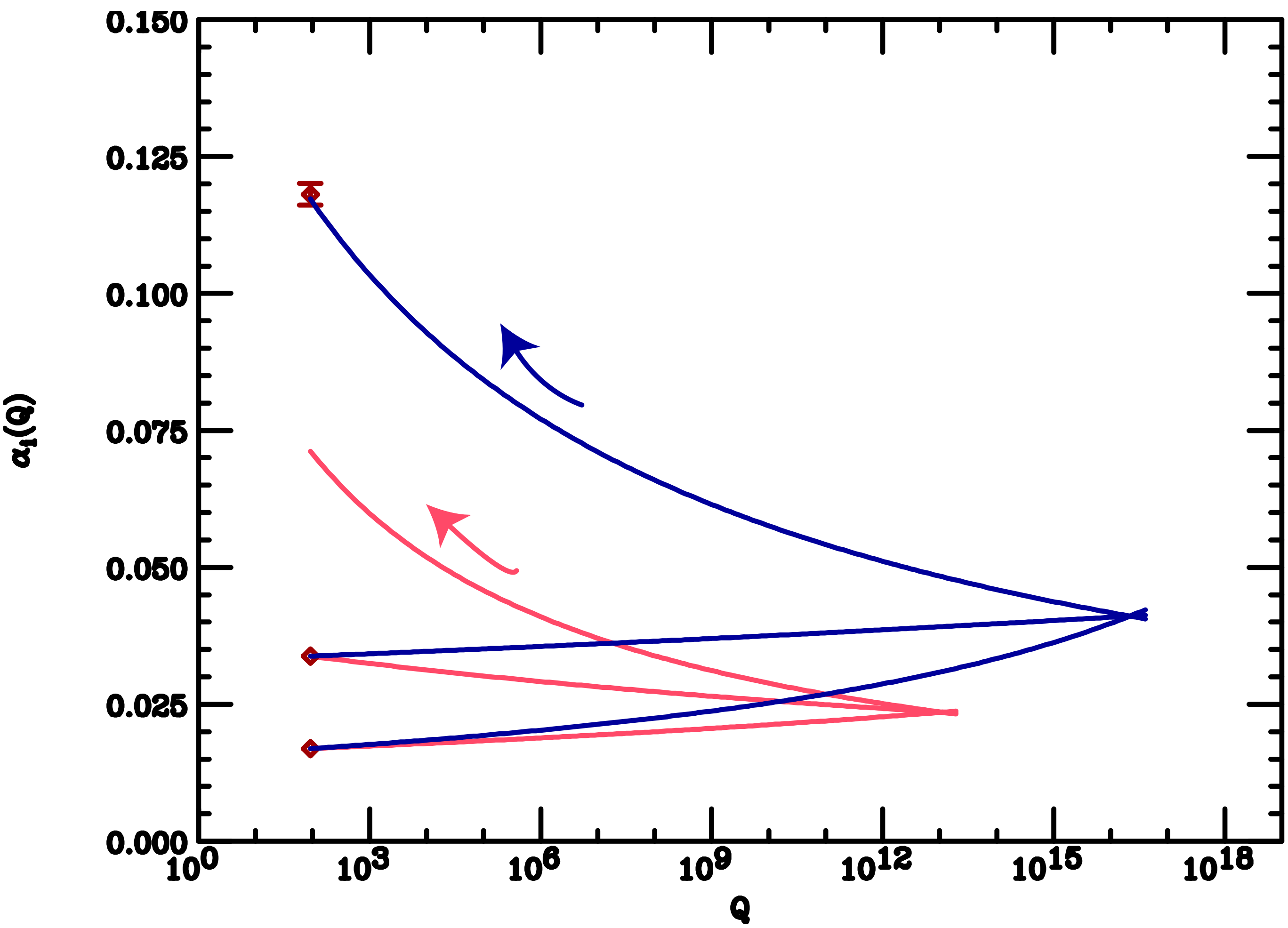
Extrapolate into the unknown region of small distances. Can we find a single, unified coupling?

QFT evolution:

$$\alpha_i^{-1} = \alpha_U^{-1} - \frac{b_i}{2\pi} \log \frac{m_U}{m_Z}$$

for unification within SU(5), SO(10), ... , normalize

$$\alpha_1 = \frac{5}{3} \alpha_1'$$



0.150
0.125
0.100
0.075
0.050
0.025
0.000
$\alpha_i(Q)$
$10^0$
$10^3$
$10^6$
$10^9$
$10^{12}$
$10^{15}$
$10^{18}$
Q

Directly from the measured values, we can define

$$B = \frac{b_3 - b_2}{b_2 - b_1} = \frac{\alpha_3^{-1} - \alpha_2^{-1}}{\alpha_2^{-1} - \alpha_1^{-1}}$$

$$= 0.715 \pm 0.008 \pm 0.03$$

expt. theory

which can be compared to the predictions:

SM: 0.528 SUSY: $\frac{5}{7} = 0.714$

Grand unification with an elementary Higgs field implies an upper limit on the Higgs coupling, and, in consequence,

$$m_h < 210 \text{ GeV}$$

Quiros, Espinosa

## 3. Dark matter

Many probes of the cosmological mass distribution (galactic rotation curves, dynamics of clusters of galaxies, cosmic microwave background) indicate that the matter of the universe is dominated by massive particles with small cross section.

$$\rho_m \sim 0.3\, \rho_c \sim 1\ \mathrm{GeV/\ m^3}$$

SUSY gives a natural mechanism for the survival of such particles from the Big Bang. Let

$$R = (-1)^{B - L + 2J}$$

If R is conserved, the lightest particle with R = -1 is stable.

This could be $\tilde{\gamma}$ $(\tilde{B})$, with $m \sim m_h \sim 100$ GeV.

## 4. Dark energy

From the acceleration of the universe, observed in supernova red shifts, the universe has vacuum energy

$$\rho_\Lambda \sim 0.7\ \rho_c \sim (2 \times 10^{-14}\ m_h)^4$$

This observation is probably the greatest mystery in contemporary physics.

Without SUSY, it is difficult even to begin on a solution. With SUSY, at least there is a natural zero of energy

$$H = \frac{1}{4}\,\mathrm{tr}\,\{ Q_a, Q_a^\dagger \} > 0$$

Proposed solutions involve superstring dualities, higher dimensions, and other exotic notions.

## 5. Hints, anomalies

observation of the Higgs boson at LEP ?

$$m_h = 115 \text{ GeV}$$

the minimal SUSY extension of the SM predicts

$$m_h \sim 80 - 125 \text{ GeV}$$

anomaly in the muon (g-2) ?

$$\Delta(g-2)/2 \sim 4 \text{ ppb}$$

This is the expectation for (e.g.)

$$m(\tilde{l}) \sim m(\tilde{W}) \sim 200 \text{ GeV} \quad \text{and} \quad \tan\beta \sim 10$$

(but, mind the hadronic QED corrections)

Melnikov

So far, I have only been arguing that SUSY provides a coherent resolution of our present difficulties in high-energy physics.

If this is true, SUSY partners will soon be discovered.

But I am mainly interested in what lies further down this path.

To describe Nature, SUSY must be a spontaneously broken symmetry.

Many aspects of the unified picture depend on parameters of SUSY breaking ($m_h$, $\rho_m$).

Within the SUSY extension of the SM, there is no apparent mechanism for SUSY breaking.

In fact, SUSY breaking cannot come from the SM dynamics:

str $m^2$ sum rule $\rightarrow$ $m(\tilde{d}) < m_b$

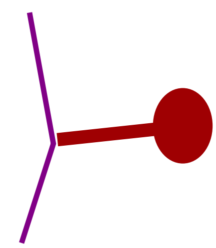
no large SUSY contrib. to $\Delta m_K^2$, $\Delta m_B^2$ $\rightarrow$ SUSY-breaking must be approx. indep. of flavor

Most likely, SUSY-breaking arises in a
`hidden sector'
with very weak coupling to the SM particles.

## A hidden sector ?  What requires this ?

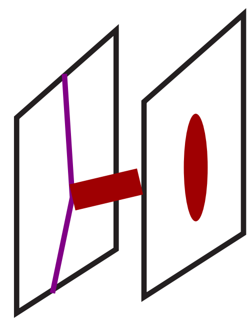
String theory gives some examples:
Its formalism requires a large superstructure, including 7 extra space dimensions.  The SM fills out only a part of this.

Extended gauge group:



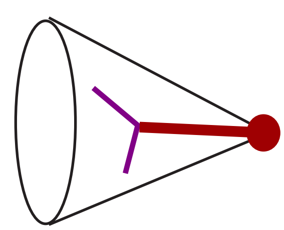
weak coupling heterotic string:  $E_8 \times E_8$
more generally, $G_1 \times G_2$ , often with $U(1)^N$

Branes:



hypersurfaces in the large space, with embedded gauge theories

Geometric singularities:



a brane wrapping a singular point in extra dimension leads to an extended gauge group

In all cases, SM can live in one sector, SUSY-breaking in another.

These are interesting speculations,
but how can we know if they are right?

SUSY-breaking terms are created at a very high mass scale:

$\langle F \rangle$ SUSY-breaking expectation value

$M$ `messenger scale'

but the magnitude of these terms must be $m_h$

$$m \sim 100 - 1000 \text{ GeV} \sim \langle F \rangle / M$$

The SUSY partners must be accessible at the next generation of accelerators;

Find these particles, measure their spectrum, try to recognize the pattern it contains.

I should note that a pattern in the SUSY breaking parameters, generated at M, may look very different when measured at m due to quantum field theory (RGE) corrections.

This is analogous to the situation of the SM gauge couplings.

for gauginos: $$m_i(m) = \frac{\alpha_i(m)}{\alpha_i(M)} \; m_i(M)$$

grand unification implies:

$$m_1 : m_2 : m_3 = 1 : 2 : 3 = 0.5 : 1 : 3.5$$

for scalars:

$$m_f^2(m) = m_f^2(M) + \sum \frac{2}{b_i} C_i(R) \frac{\alpha_i^2(m) - \alpha_i^2(M)}{\alpha_2^2(m)} m_2^2$$

m = 0 at the unification scale implies:

$$m_{eR} : m_{eL} : m_{dR} : m_{uR} : m_{QL} : m_2$$

$$= 0.5 : 0.9 : 3.09 : 3.10 : 3.24 : 1$$

In addition, several sets of superpartners can mix:

$(\tilde{\tau}_R, \tilde{\tau}_L) \qquad (\tilde{b}_R, \tilde{b}_L) \qquad (\tilde{t}_R, \tilde{t}_L)$

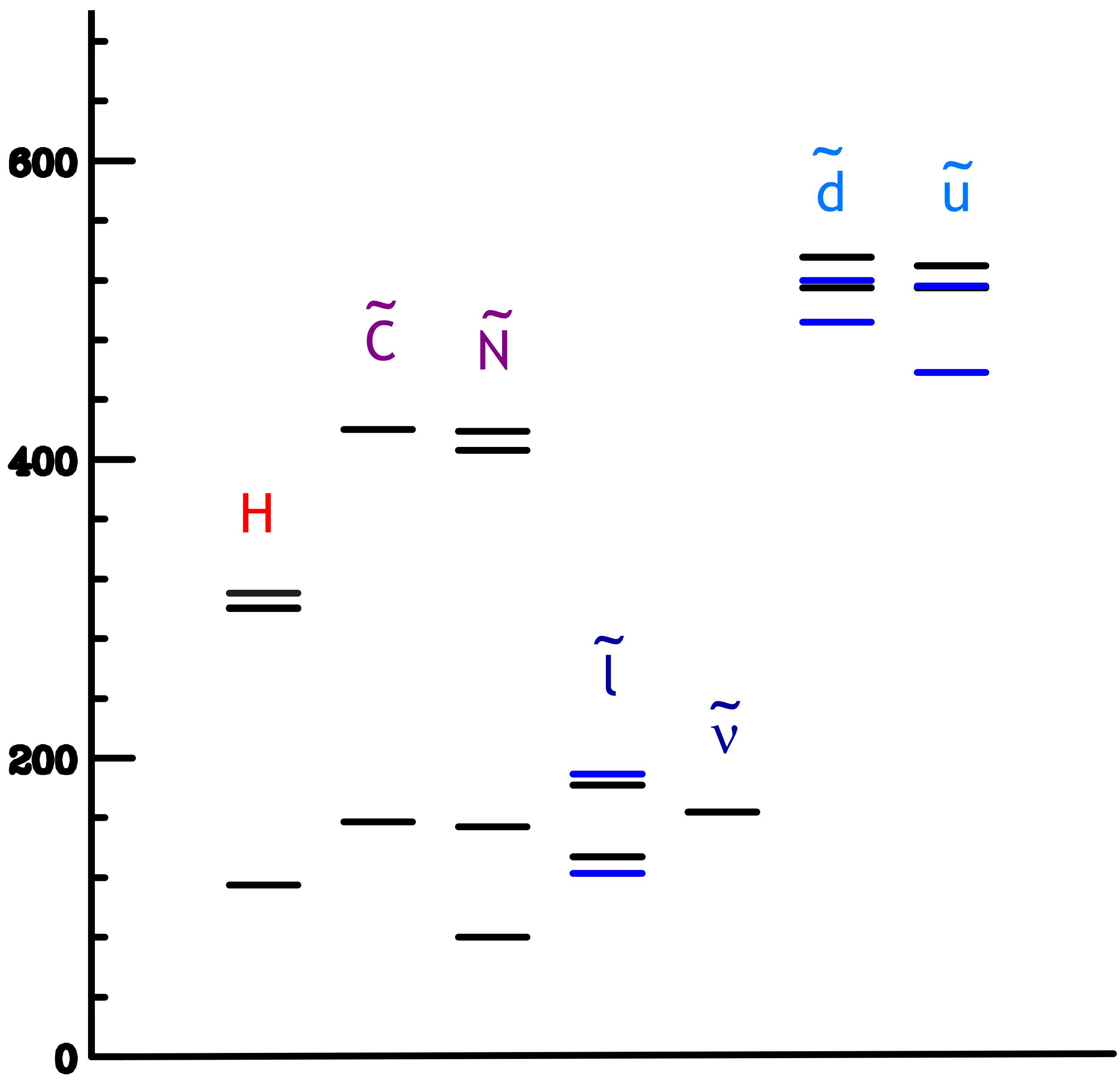
(mixing of $(\tilde{t}_R, \tilde{t}_L)$ is connected to the generation of the Higgs potential)

$$(\tilde{W}^+, \tilde{\varphi}^+) \quad \rightarrow \quad \tilde{C}_i^+$$

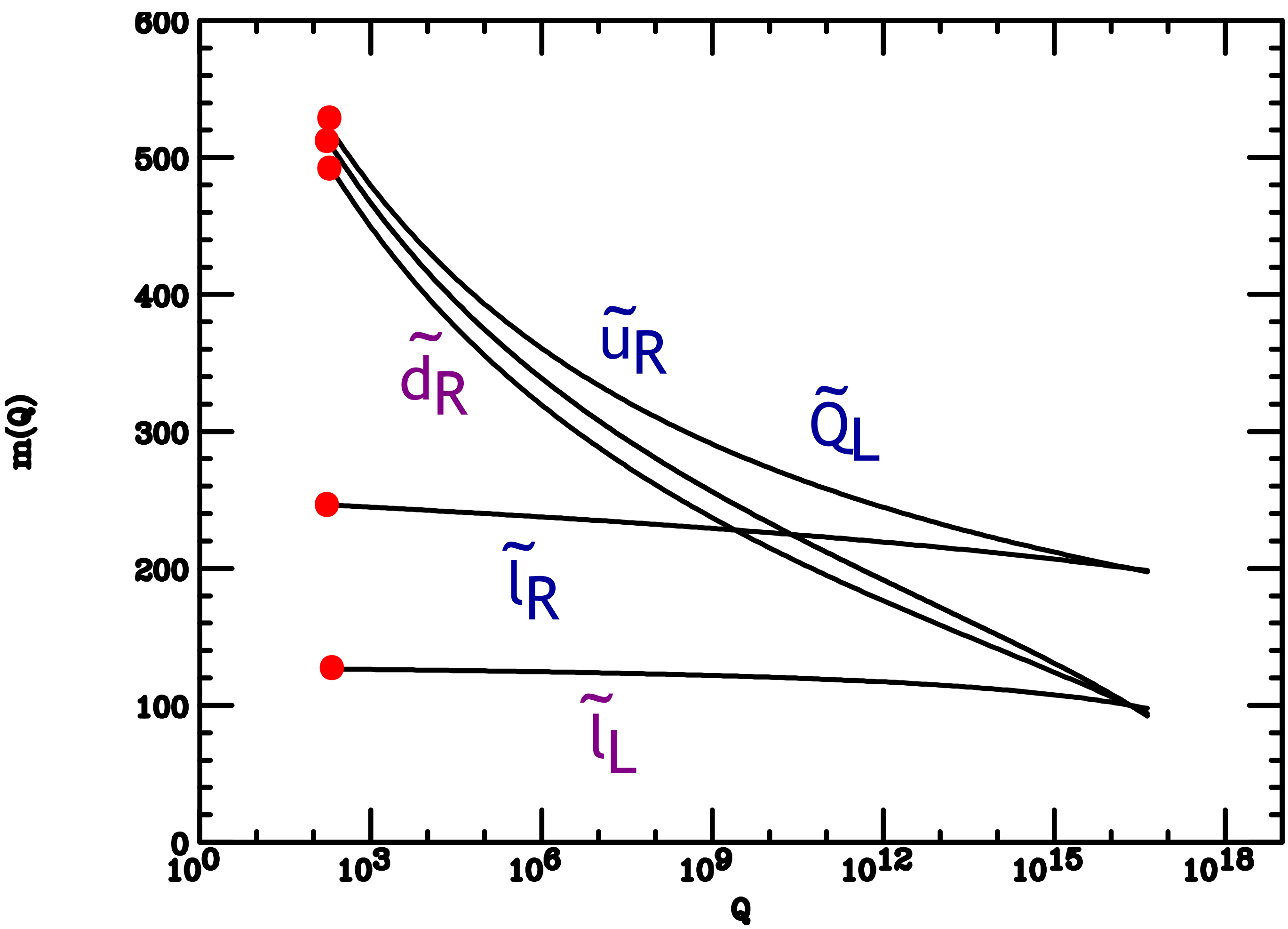
$$(\tilde{B}^0, \tilde{W}^0, \tilde{\varphi}_1^0, \tilde{\varphi}_2^0) \quad \rightarrow \quad \tilde{N}_i^0$$

We need detailed measurements of the SUSY spectrum to see through these effects to the underlying pattern.

A spectrum generated with universal (structureless) SUSY breaking terms:



# A different pattern with less universality:



## Where will the data come from?

The accelerator experiments of the next decade should give specific information about the parameters of the SUSY spectrum.

The most important contributions will come from the LHC and the $e^+e^-$ linear collider.

Low-energy probes -- including the precise cosmic density of dark matter -- will provide integrals that check the completeness of the picture.

At the LHC, supersymmetry partners are produced through the reactions:

$$gg \to \tilde{g}\,\tilde{g}\,, \quad \tilde{q}\,\tilde{\bar{q}} \qquad\qquad gq \to \tilde{g}\,\tilde{q}$$

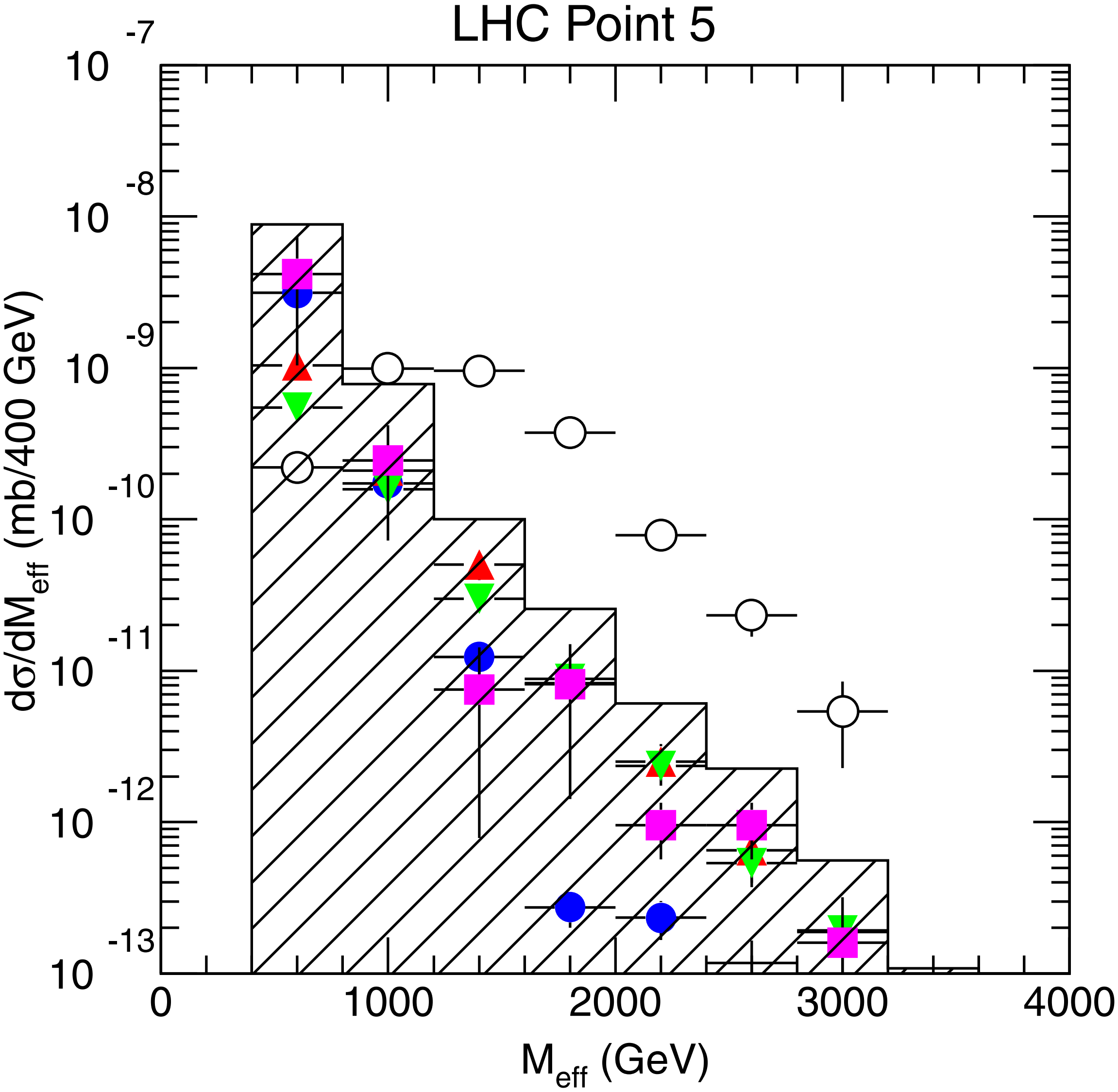
with $\tilde{g}$, $\tilde{q}$ decaying in cascades to lighter states.

These are striking events, with large jet activity as well as missing energy.

ATLAS:

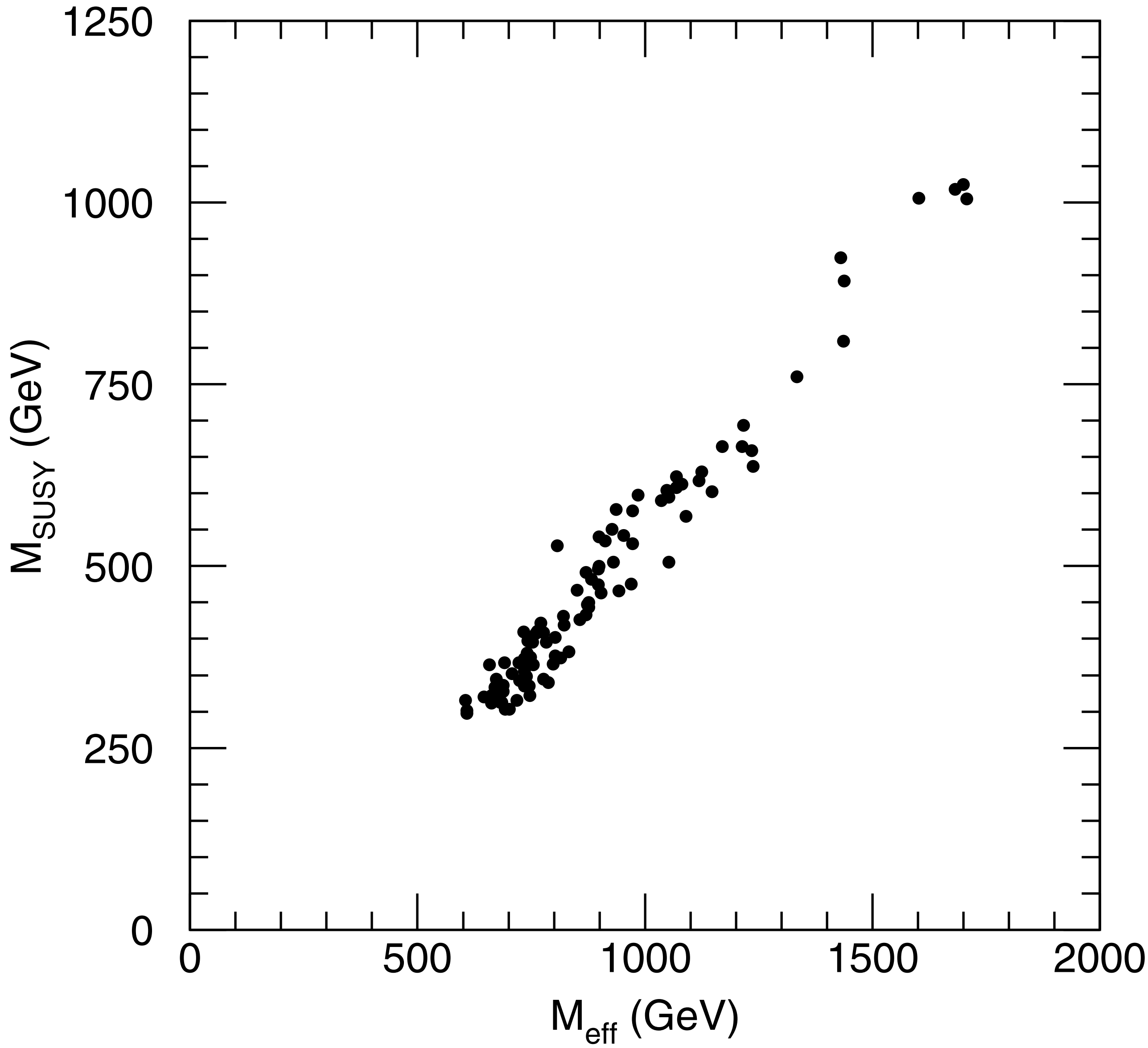
$$M_{eff} = \not{E}_T + \sum_1^4 E_{Ti}$$

comparison of SUSY signal to SM backgrounds with missing $E_T$:




ATLAS

$M_{eff}$ is a effective predictor of the $\tilde{g}$ or $\tilde{q}$ mass scale:



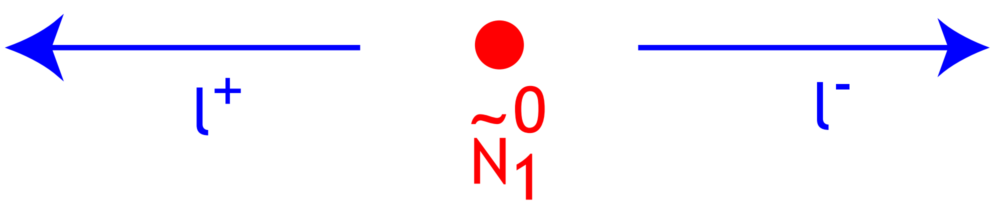

ATLAS

The LHC data can yield high-precision measurements of SUSY parameters by making use of more detailed features of the spectroscopy.

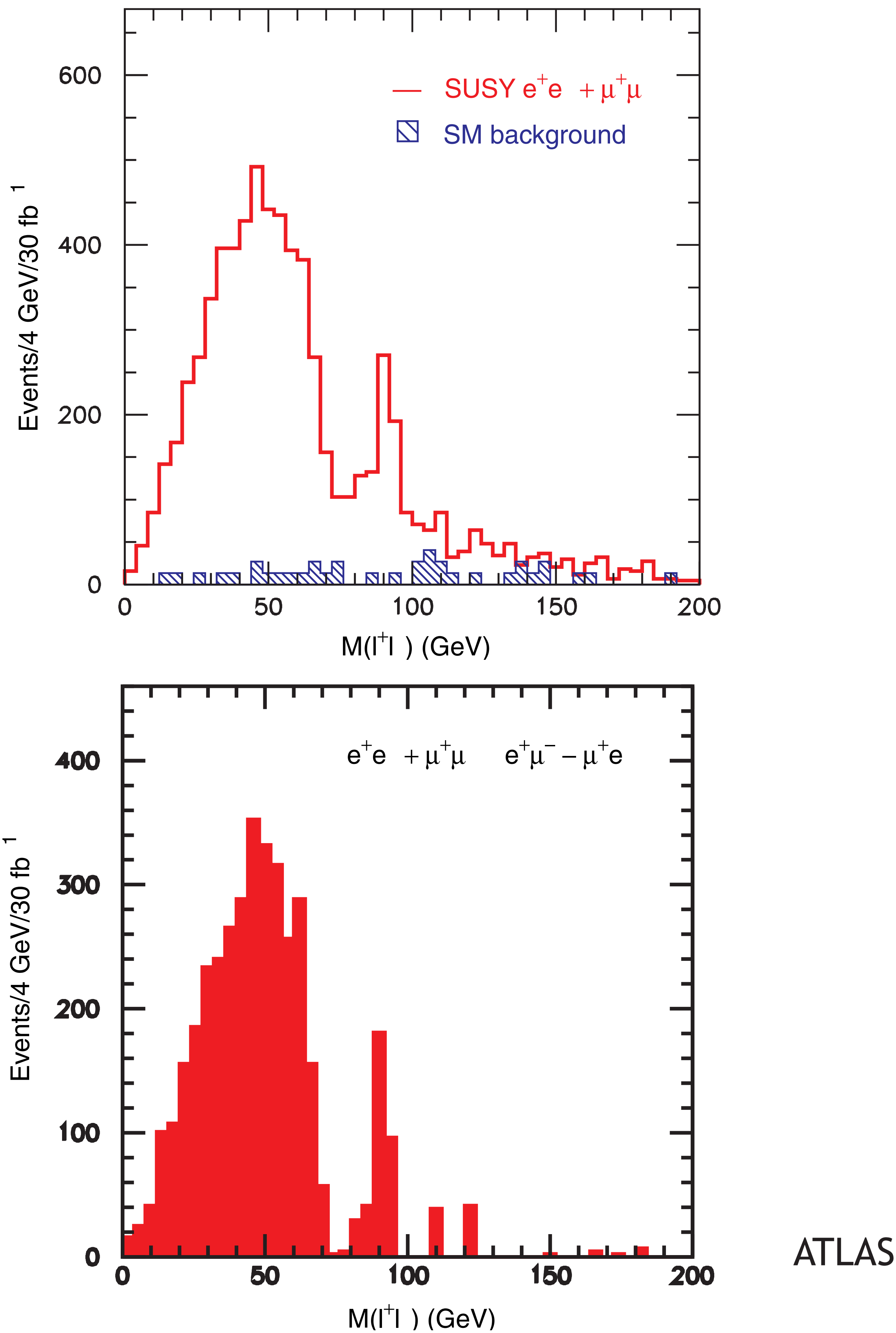
as an example, if $m(\tilde{N}_2^0) - m(\tilde{N}_1^0) < m_Z$ ,

the decay $\tilde{N}_2^0 \to \tilde{N}_1^0 + l^+l^-$ has a sharp endpoint, which gives the mass difference.

for events near the endpoint, $\tilde{N}_1$ is at rest in the $l^+l^-$ frame:

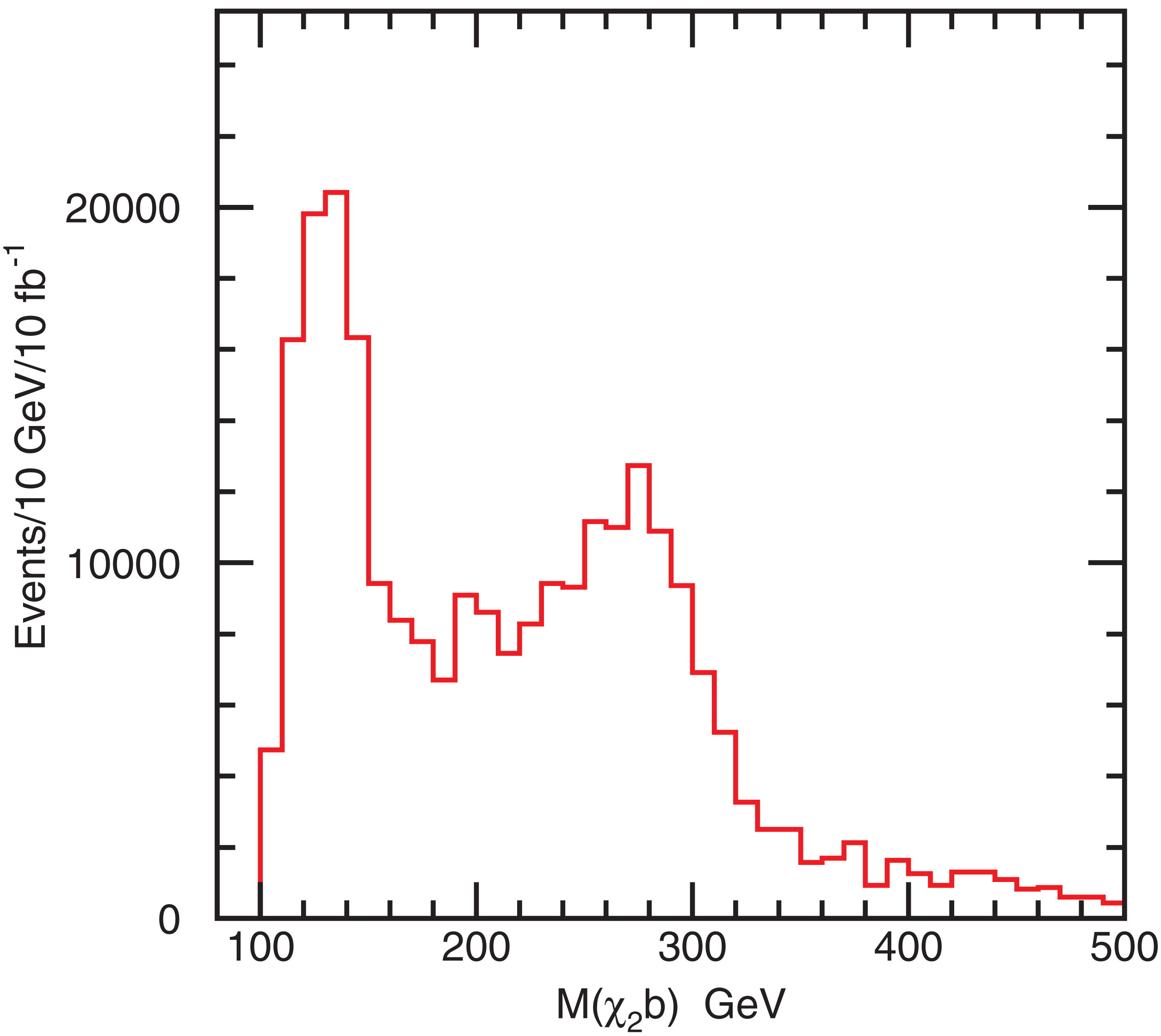



add jets ($q$ or $\bar{q}$) and reconstruct $\tilde{q}$ , $\tilde{g}$ as resonances.



SUSY $e^+e^- + \mu^+\mu^-$
SM background
Events/4 GeV/30 fb$^{-1}$
$M(l^+l^-)$ (GeV)
0
200
400
600
50
100
150
$e^+e^- + \mu^+\mu^- - e^+\mu^- - \mu^+e^-$
300
ATLAS

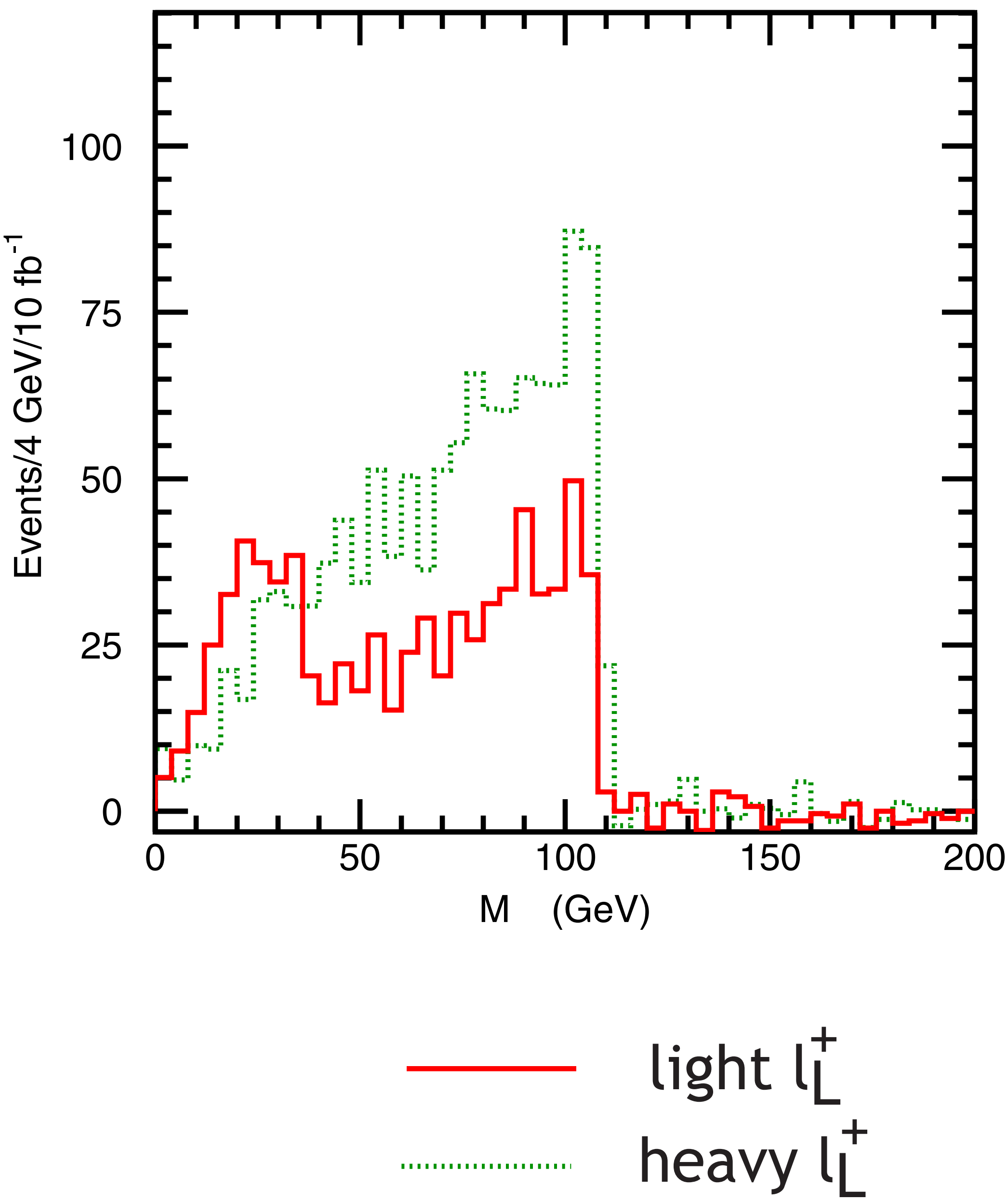
Add a b jet to the reconstructed $\tilde{N}_2^0$ :




ATLAS

Here is a more involved examples, with two kinematic edges from

$$\tilde{N}_2^0 \rightarrow \tilde{l}_R^+ + l^- \quad , \quad \tilde{N}_2^0 \rightarrow \tilde{l}_L^+ + l^-$$




ATLAS

Another view of the SUSY spectrum will come from experiments at the

$e^+e^-$ Linear Collider (TESLA, NLC, JLC)

This accelerator allows the production of supersymmetry partners one by one, through the very simple reaction

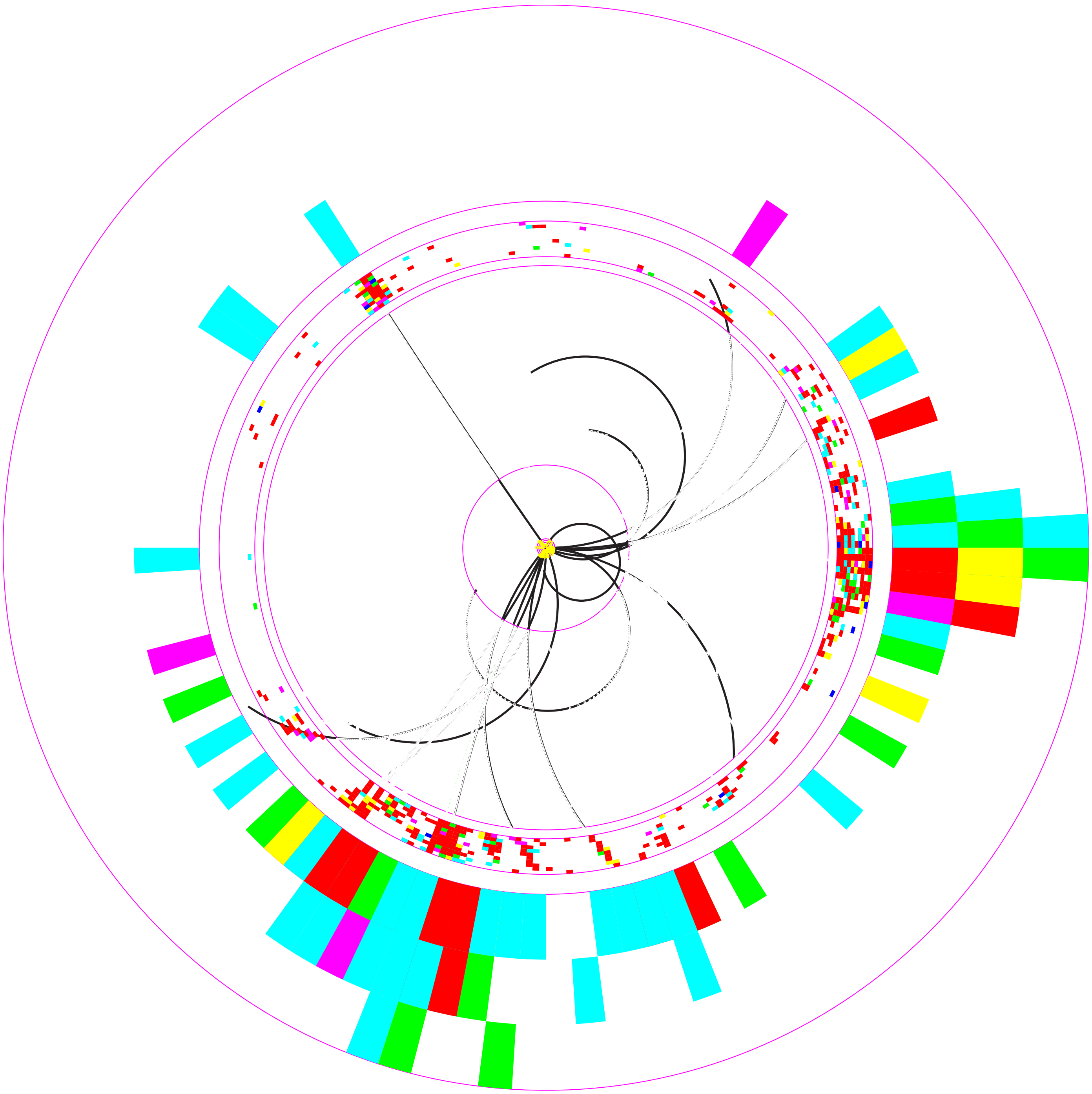
$$e^+e^- \rightarrow \tilde{X} \, \bar{\tilde{X}}$$

The cross section of this reaction gives directly the spin and electroweak charges of X.

We can explore the SUSY spectrum from the lightest states, in a way that does not depend on the specific scenario.

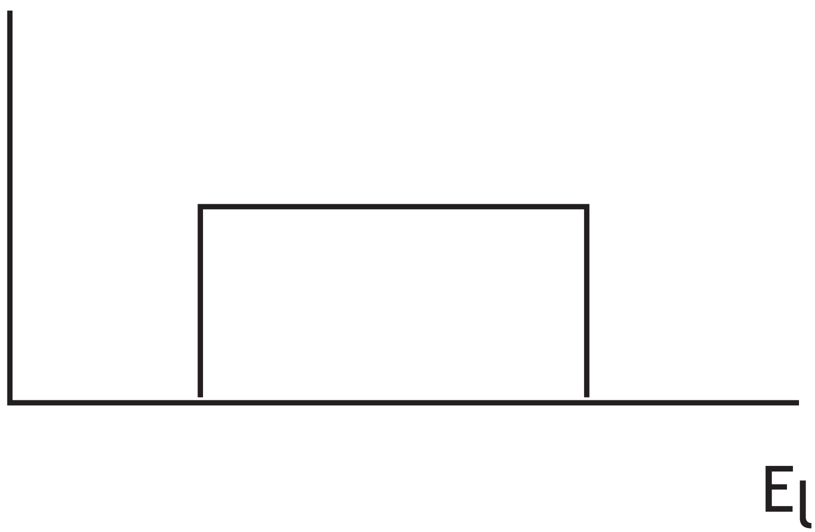
$$e^+e^- \to \tilde{C}_1^+ \tilde{C}_1^-$$

$$\to \quad e^+ \nu \tilde{N}_1^0 \quad q \bar{q} \tilde{N}_1^0$$



Scalar pair production is especially simple:

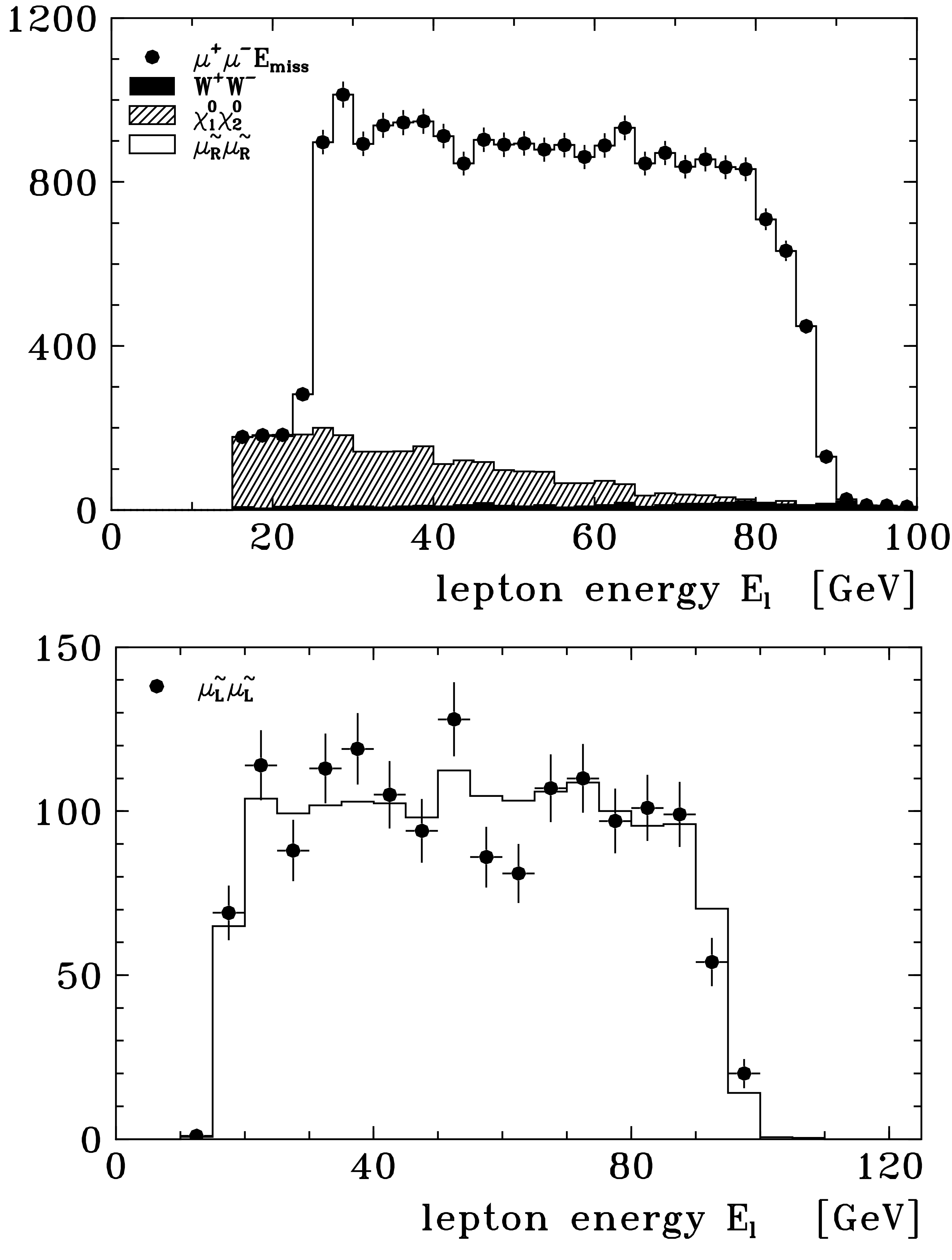
for sleptons, e.g., production of $\tilde{l}^{+}\tilde{l}^{-}$
at a fixed energy $E_b$,
and isotropic decay $\tilde{l} \to l\,\tilde{N}^0$
leads to the flat distribution




in which the endpoints determine the
parent and daughter masses.

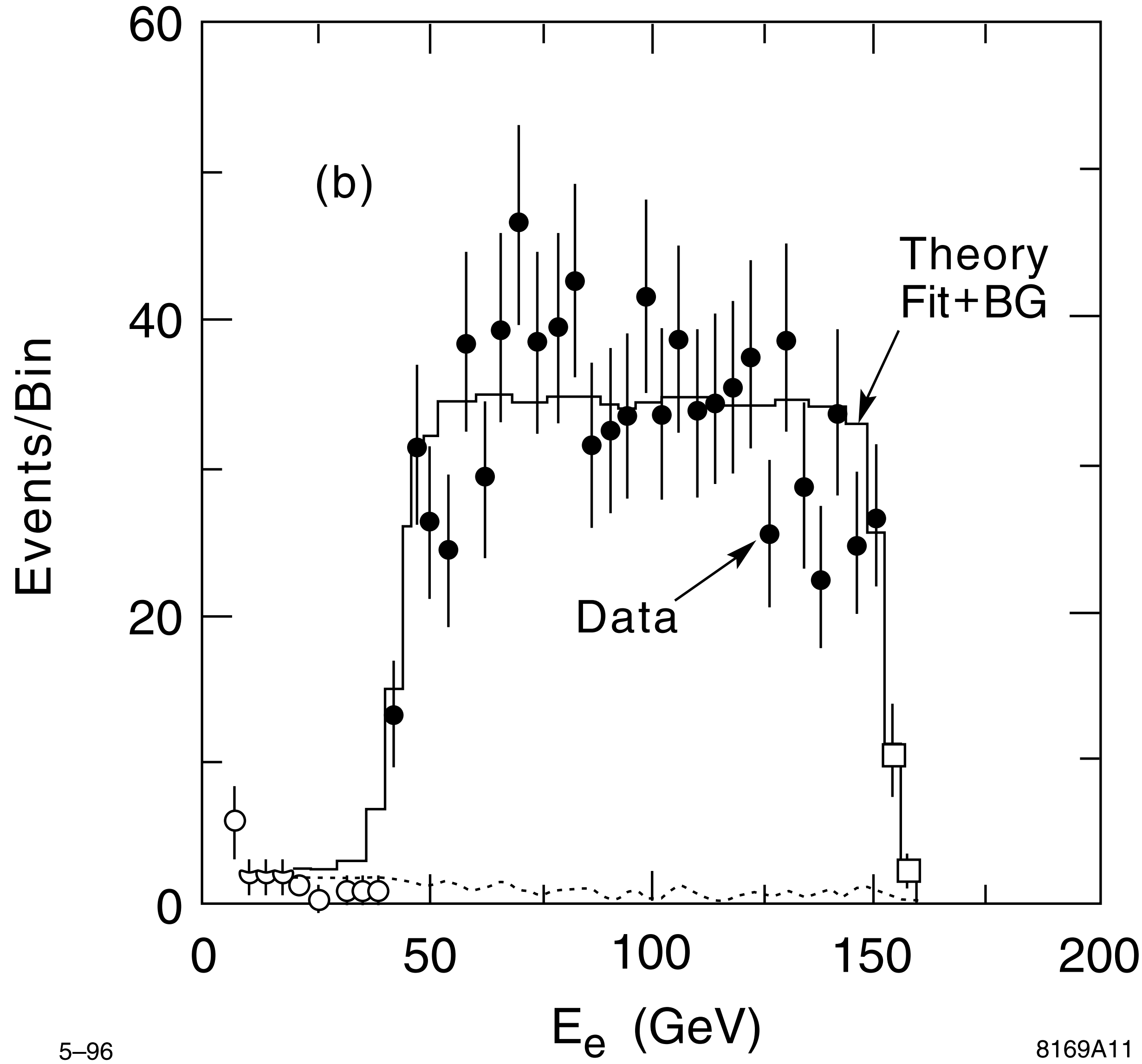
By extension, kinematic endpoints give
the precise masses for gauginos also.

Tsukamoto et al.



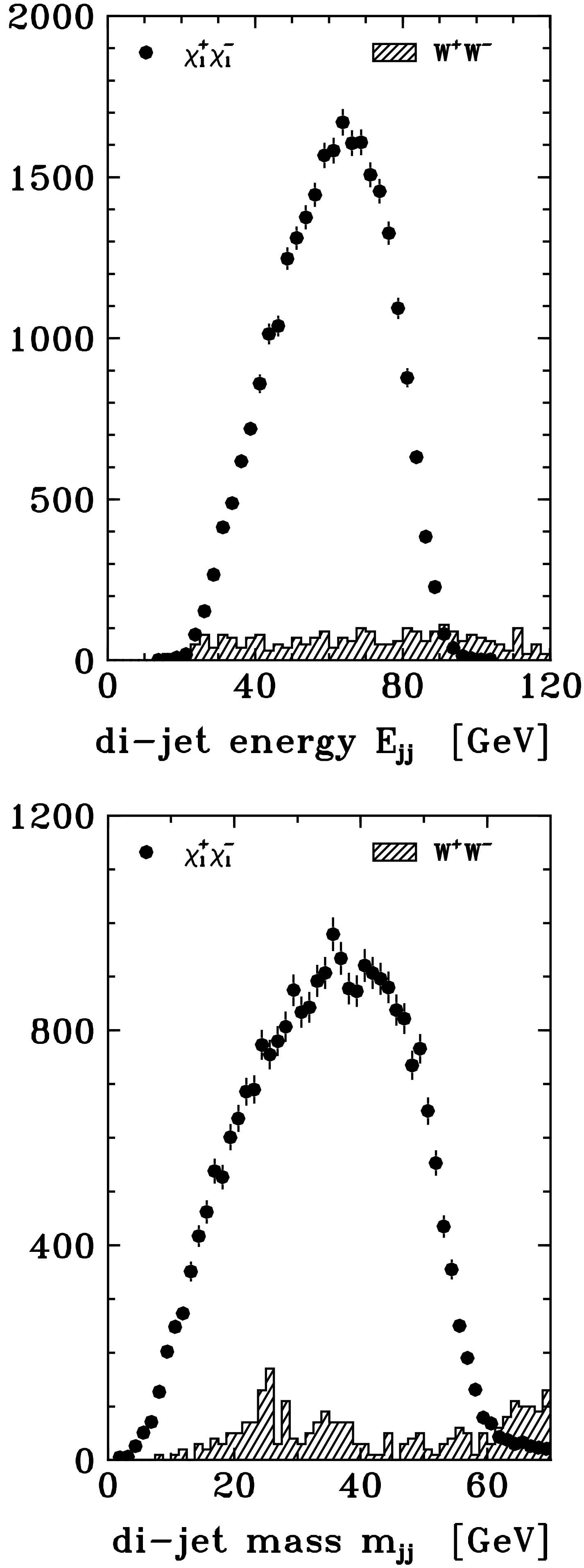

Blair and Martyn

$\tilde{\nu}_e \tilde{\nu}_e$




Baer et al.

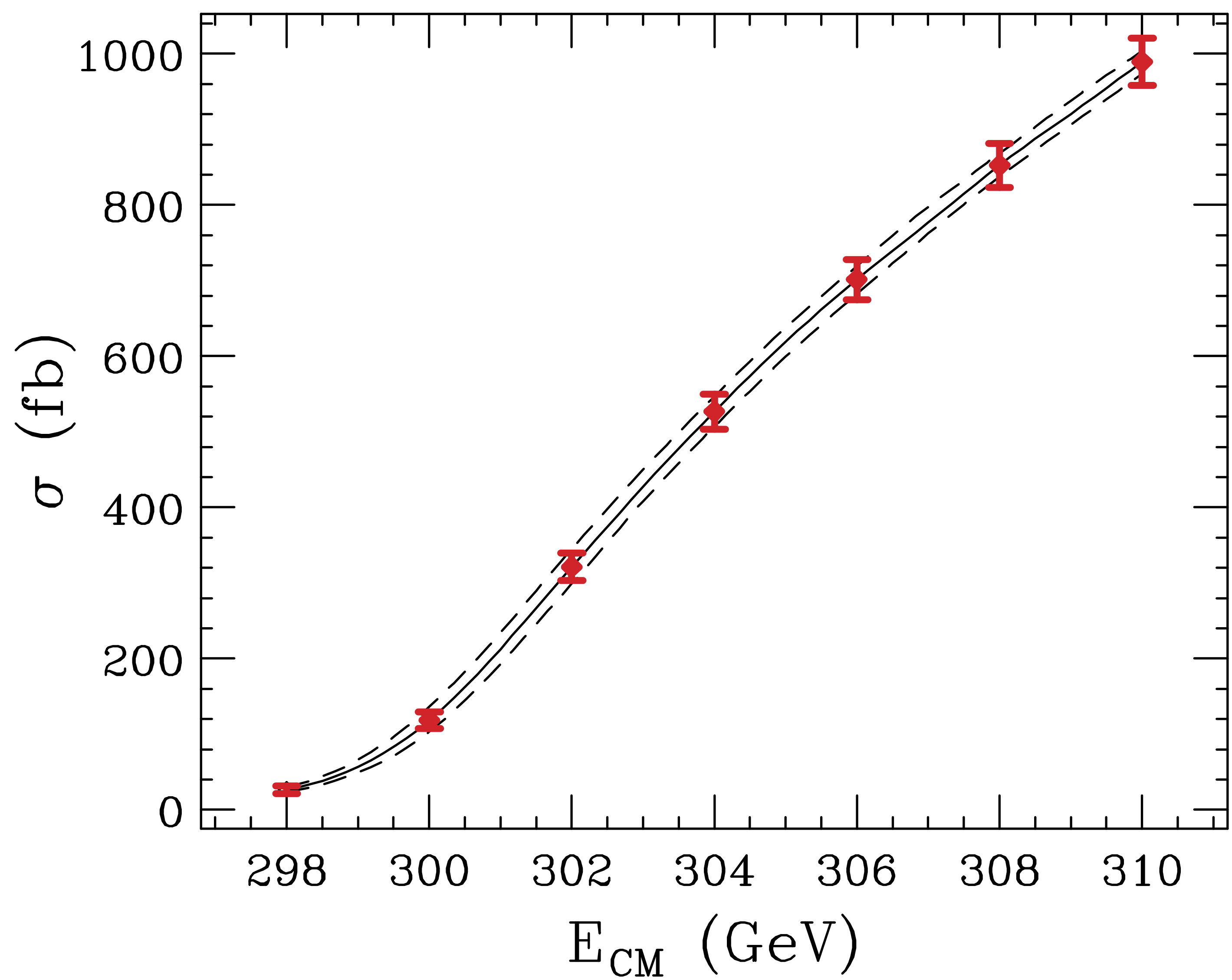
$\tilde{C}_1^+ \tilde{C}_1^-$




Blair and Martyn

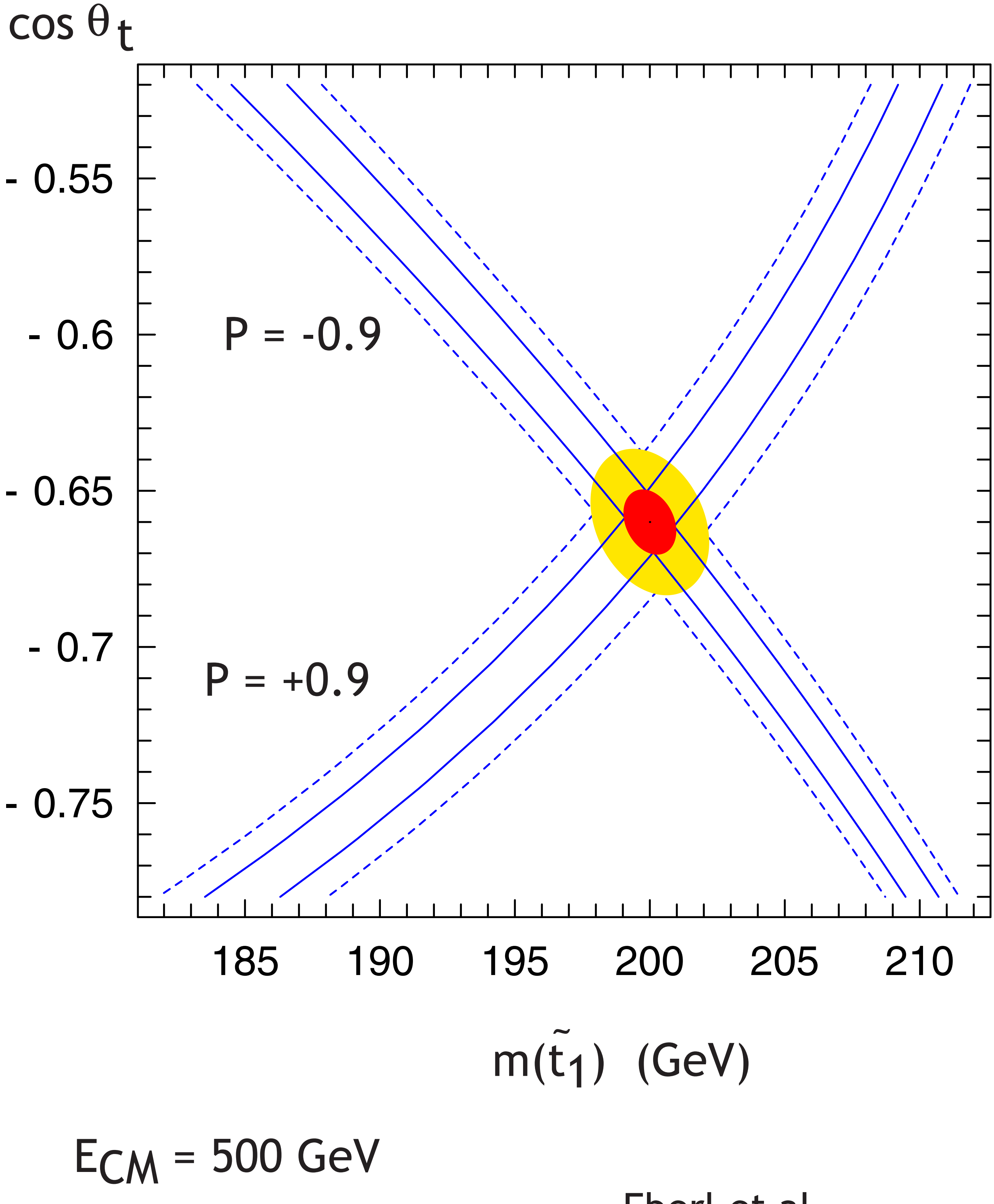
These features prepare the ground for a high-precision determination of SUSY masses, mixing angles, and transitions.

$e^- e^- \rightarrow \tilde{e}^-_R \, \tilde{e}^-_R$



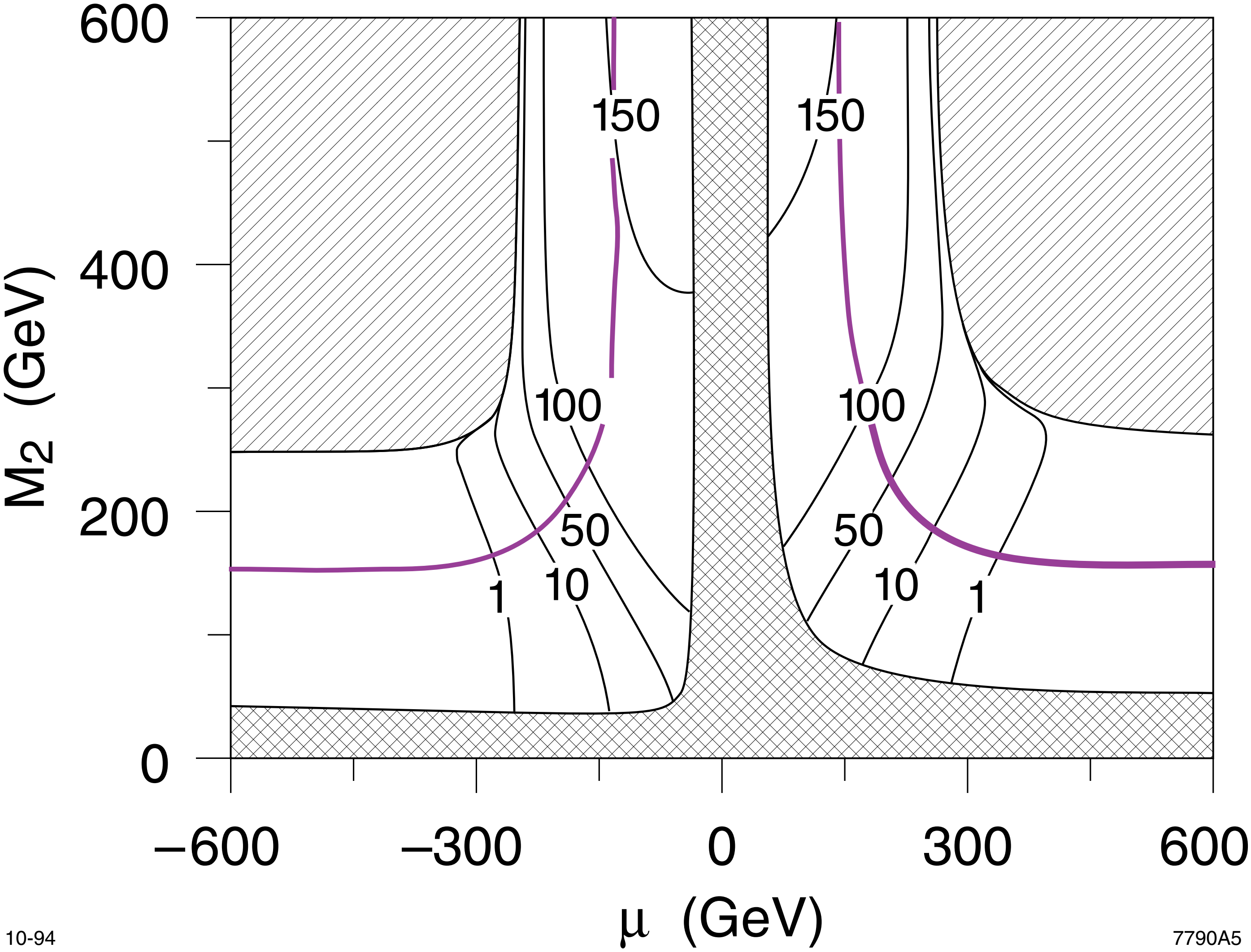

variation of $m(\tilde{e}_R)$ by 100 MeV,
for $m(\tilde{e}_R)$ = 150 GeV

Feng et al.



cos θ t
- 0.55
- 0.6
- 0.65
- 0.7
- 0.75
P = -0.9
P = +0.9
185
190
195
200
205
210
m(t̃1) (GeV)
E CM = 500 GeV
Eberl et al.

$\sigma\,(e_R^- e^+ \rightarrow \tilde{C}_1^+ \tilde{C}_1^-)$ (fb)




Feng et al.

line of fixed $\tilde{C}_1$ mass

We can know the details of the SUSY spectrum, and, with data from the LHC and the LC, we will.

What picture will these data suggest ?

It is possible that we will find a structureless `minimal' or `universal' paradigm.

But, alternatively, we might find a pattern that reflects a grander physical picture, for example, with couplings reflecting the geometry with which fermions, gauge bosons, and hidden particles are arranged in higher dimensions.

Best of all, we might find a pattern that has no ready explanation,

... a challenge for the
next Werner Heisenberg
to grapple with and solve!