What String Theorists need to know about e^+e^- Linear Colliders

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In this lecture, I will discuss

Why does string theory need experiment ?

Why does string theory need the
e^+e^- Linear Collider ?

What should you be doing about it ?

String theory has strong claims to be the underlying fundamental theory of Nature:

naturally produces Yang-Mills interactions with unified couplings

only known quantum theory of gravity with a well-defined perturbation expansion

prima facie explanation of black hole entropy

particular solutions predicts the low-energy gauge group, number of fermion generations

But

Exactly which string degrees of freedom are the Standard Model gauge bosons, quarks, and leptons ?

Are there phenomena in Nature that are distinctly stringy?

In 1954, Yang and Mills wrote a beautiful set of field equations, but they applied them to the wrong physical context.

It took 20 years -- and considerable input from experiment -- to find the correct connection between Yang-Mills theory and the strong and weak interactions.

The full story is complex, but at least two experimental results were essential:

maximal parity violation in μ decay

$\rightarrow$ V - A

scaling in deep inelastic electron scattering

$\rightarrow$ asymptotic freedom

In 1954, no one could anticipate that there were the crucial experiments; we had to measure everything to find this out.

Similarly, to find the correct way to interpret string theory, we will probably need some crucial advice from experiment.

We do not know today which experiments will be the most important, but probably we will need to measure many new parameters.

Some important experiments will certainly be done

LHC,   cold dark matter searches

But others are in danger of being postposed indefinitely ...

This year, the US high energy physics community is asked by DOE and NSF to write a plan for the near term and for the next 20 years.

A major question is:

Should the community call for construction of a 500 GeV e^+e^- linear collider as its next major accelerator project ?

similar projects are being proposed in Germany and in Japan,

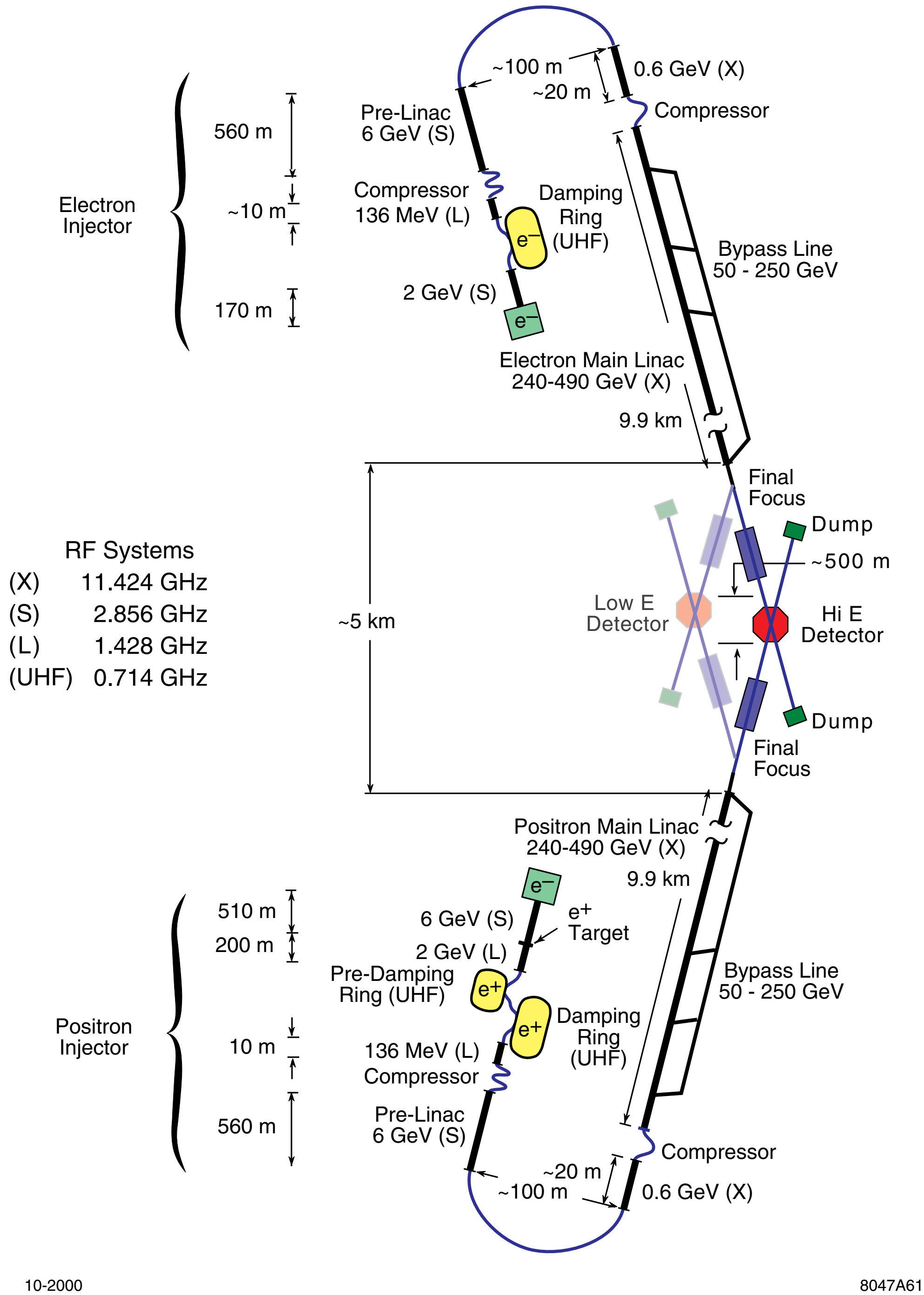
however,

this accelerator is sufficiently expensive (~ $ 5 B) that it will require cooperation among all three regions

In the US, a strong mandate is needed; OMB has tried to slash the R & D funds for the linear collider in each of the last two fiscal years.

Is this project relevant to string theory, and should you care about it ?

Next Linear Collider plan:



initial stage: 500 GeV in CM

upgradable to: 1000 GeV

with 2-beam RF: > 3000 GeV

location: most probably, Fermilab

Justification to agnostic experimenters:

precision study of the Higgs boson
in the reaction $e^+e^- \to Z^0 h^0$

precision electroweak measurements
predict $m_h < 165$ GeV

measure Higgs boson coupling to
Z, W, b, c, τ, gg, $\gamma\gamma$
to test whether this particle is the origin
of all SM masses

precision measurement of m_t ,
W and t gauge couplings,

significant window for discovery and
precision study of new particles

see hep-ex/0007022

Justification to string theorists:

I will discuss the examples of

orthodox paradigm : TeV - scale SUSY

new vectors bosons
and contact interactions

large extra dimensions

Orthodox paradigm:

String theory leads to a low-energy effective field theory with supersymmetry

$m_{String} \sim m_{GUT}$ to m_{Planck}

Gauge hierarchy problem is solved by supersymmetry

This scenario naturally incorporates
- grand unification of couplings,
- smallness of higher-dimension operators mediating baryon, lepton no. violation

Realized in string theory with
- weak-coupling Calabi-Yau compactification
- Horava-Witten construction
- flat 3-branes in AdS
- ...

In this scenario, we expect superpartners to appear below 1 TeV

e.g. "universal soft terms", $\tan\beta = 10$,

$$m_W^2 = -1.3\ \mu^2 + 0.3\ m_{\tilde{g}}^2 + \ldots$$

so it is possible for gauginos to be heavier than TeV, but this requires two decimal places of fine-tuning.

Most SUSY models have the lightest chargino below 250 GeV; see the ref. above for a review.

The next step is where the story becomes interesting ...

The Standard Model has 19 parameters
(+ neutrino mass)

g, g', g_s

6 quark masses, 4 CKM angles

3 lepton masses

Higgs mass and coupling, 1 observable θ

adding SUSY adds two more

μ, $\tan\beta = \langle H_2 \rangle / \langle H_1 \rangle$

but predicts the Higgs mass and coupling

g, g', g_s are accounted for by grand unification at 2×10^{16} GeV with TeV-scale SUSY

The hierarchial pattern of quark and lepton masses has many explanations, none definitive.

To obtain more information about fundamental physics, we must measure more terms of the low-energy effective Lagrangian

Supersymmetry breaking provides a large number of new parameters:

$$L = m_a \bar{\lambda}_a \lambda_a + M_i^2 |\phi_i|^2$$
$$+ A_u \bar{U} H_2 Q + \cdots$$
$$+ B \mu H_1 H_2 + \text{h.c.}$$

M_i^2, A_f may be matrices with off-diagonal elements (constrained by FCNC effects)

The pattern of soft mass terms may depend on flavor or only on SM quantum numbers

Dimopoulos-Georgi: supersymmetry breaking must arise in a "hidden sector" and be transmitted to SM superpartners by quantum corrections or gravity

The spectrum of soft SUSY-breaking masses can reflect the nature of the hidden sector and the geometry of supersymmetry breaking.

examples:

Horava mechanism, "Gaugino mediation"

Schmaltz, Skiba

SM and hidden sector lives on different branes separated by $1/m_{GUT}$. The branes are connected by moduli that turn on

$$\int d\,\theta^2 \;\; F_S \theta^2 \;\; W^{\alpha} W_{\alpha}$$

giving a RG boundary condition m_a nonzero, $M_i = 0$.

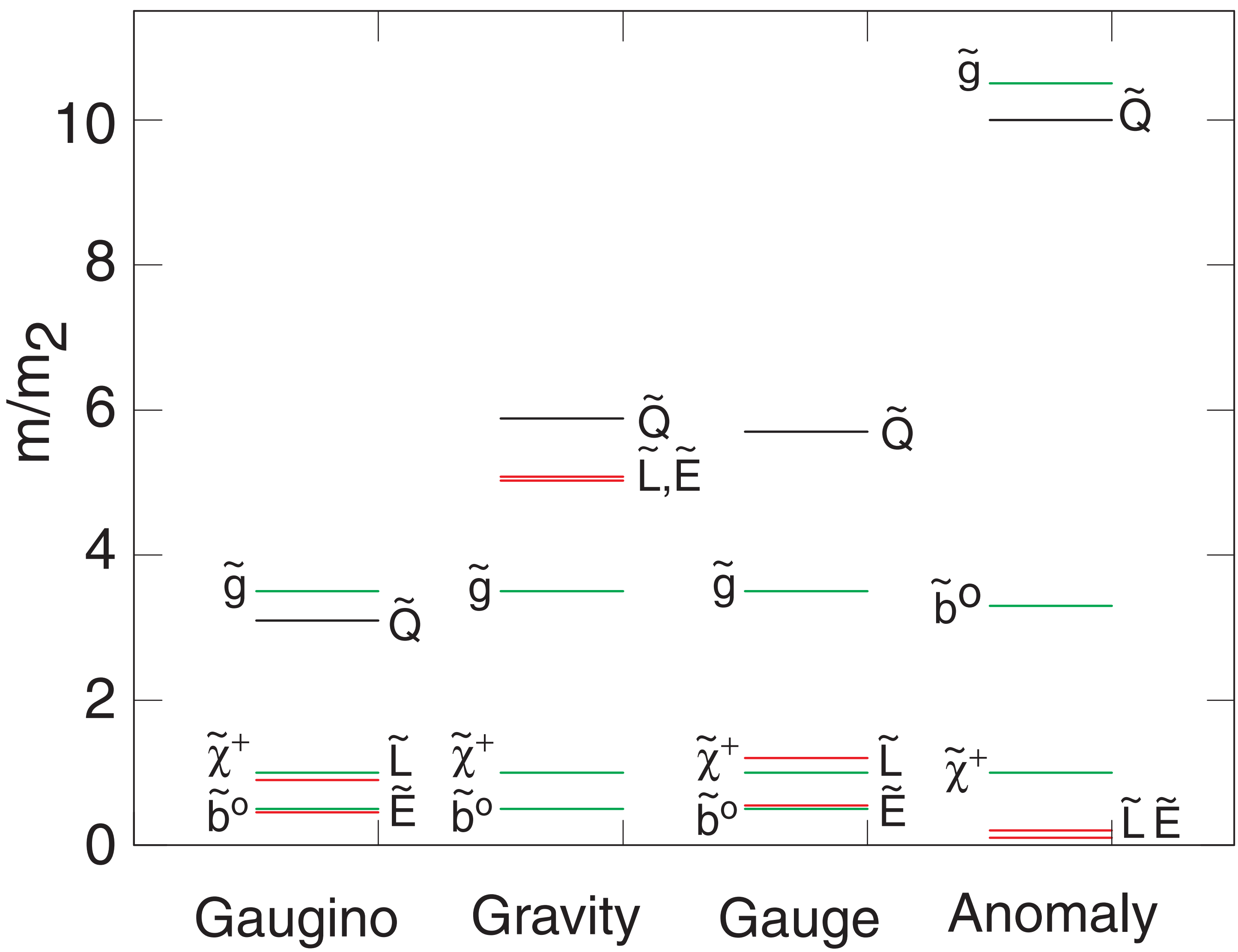
"Anomaly mediation"

Randall and Sundrum, Giudice et al.

SM and hidden sector lives on different branes separated by $1/m_{GUT}$. The branes are connected by moduli that do not couple to SM superfields.

Radiative corrections induce a pattern of soft masses proportional to RG coefficients γ_0 / β_0

Characteristic prediction: $\tilde{W}^0$, $\tilde{W}^+$ are light, near-degenerate



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Brian Greene's summary:

"The masses and charges of the superpartner particles would reveal the detailed way in which supersymmetry is incorporated into the laws of nature. String theorists would then face the challenge of seeing whether this implementation can be fully realized or explained by string theory."

It is therefore important that e^+e^- annihilation experiments are the best way to measure the Lagrangian parameters governing supersymmetric particles:

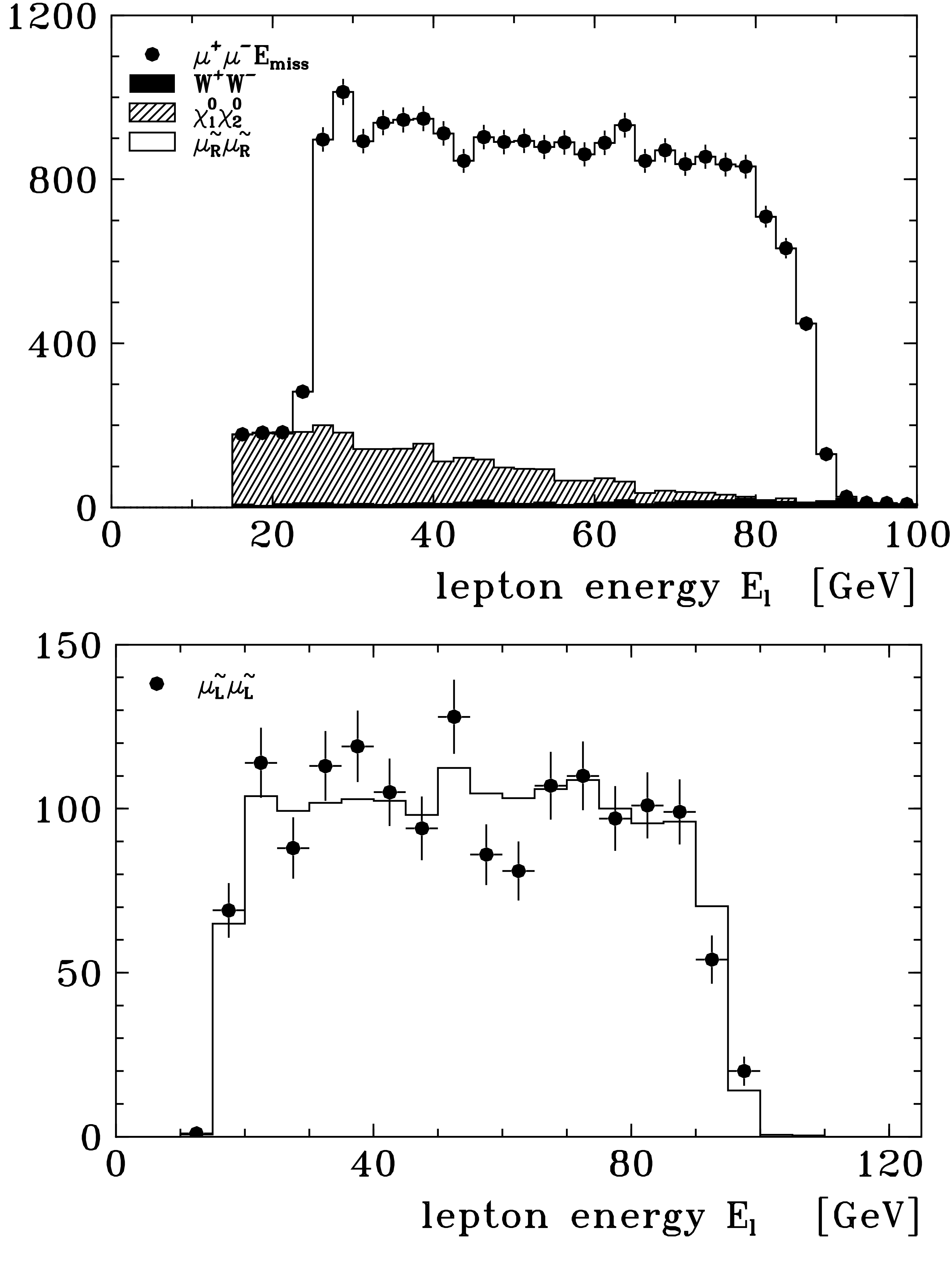
precision measurement of masses

(below 1% from kinematics;
parts per mil from threshold measurements)

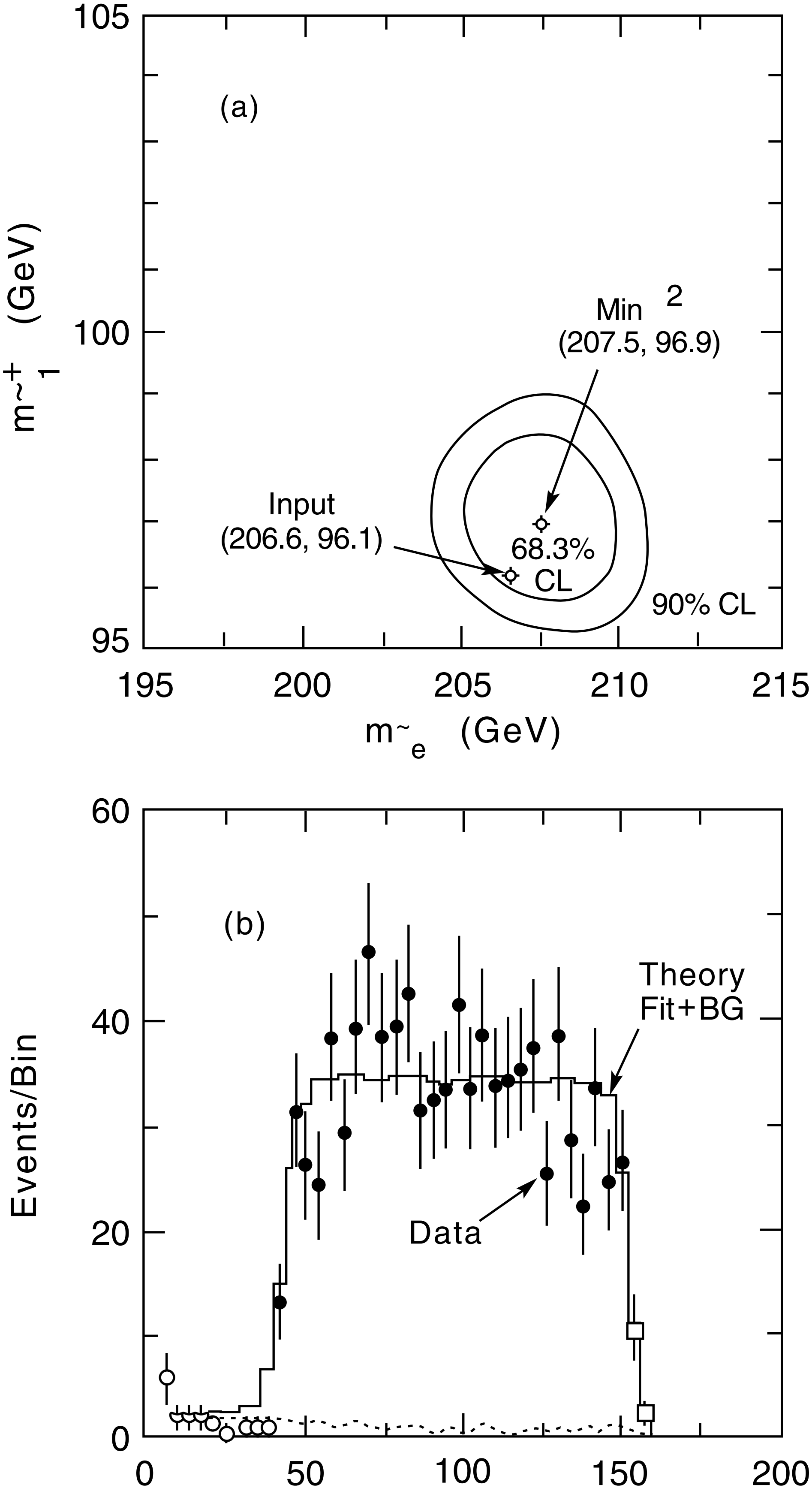
measurement of mixing angles

(electron beam polarization is essential;
the measurements access A_i and μ.)

sensitive searches for flavor-dependence, flavor-violation, CP violation in soft SUSY parameters



Blair and Martyn



(a)
Min 2
(207.5, 96.9)
Input
(206.6, 96.1)
68.3%
CL
90% CL
105
100
95
195
200
205
210
215
m~+1 (GeV)
m~e (GeV)
(b)
Theory
Fit+BG
Data
60
40
20
0
0
50
100
150
200
Events/Bin
Ee (GeV)
5–96
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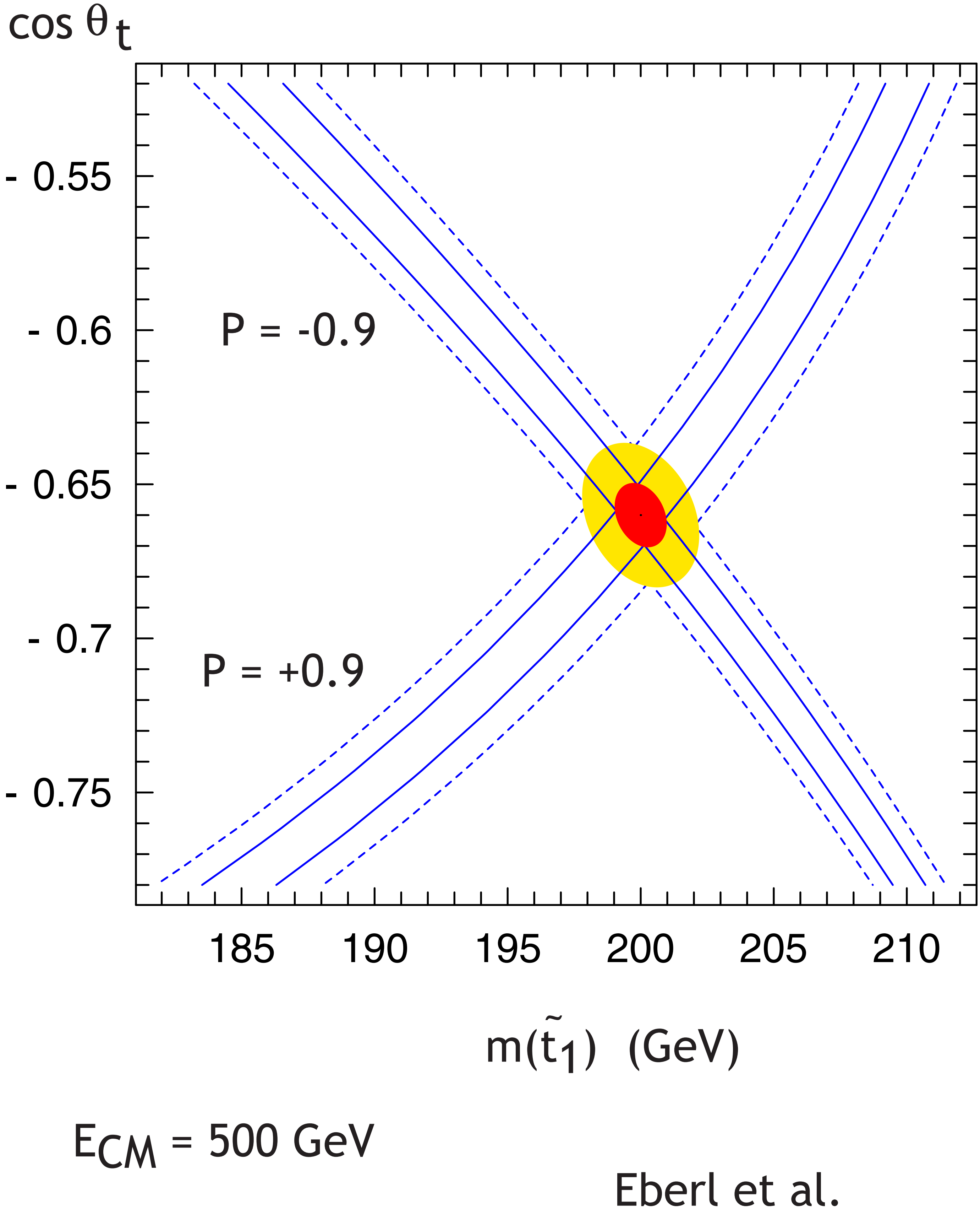
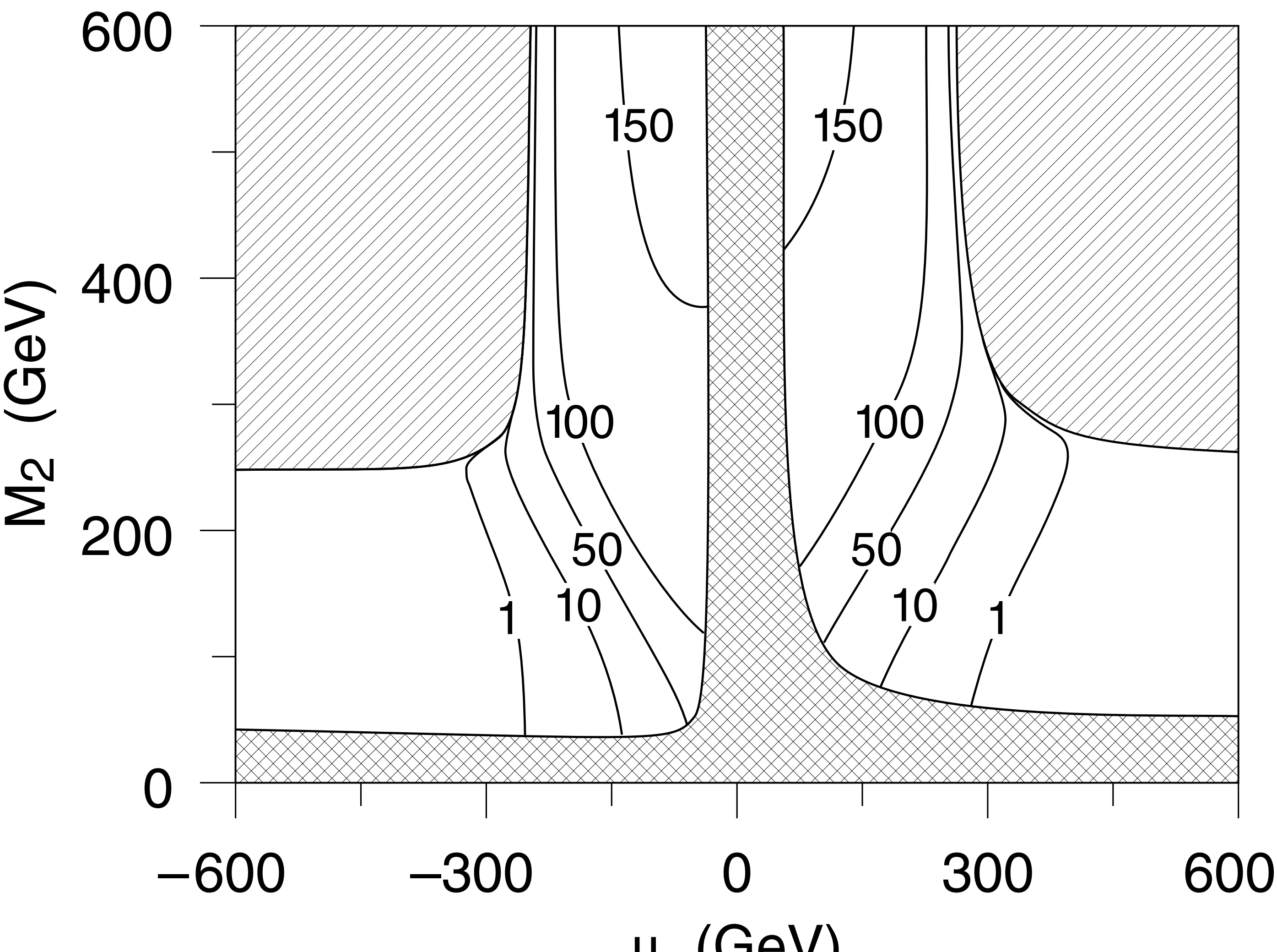
Baer et al.

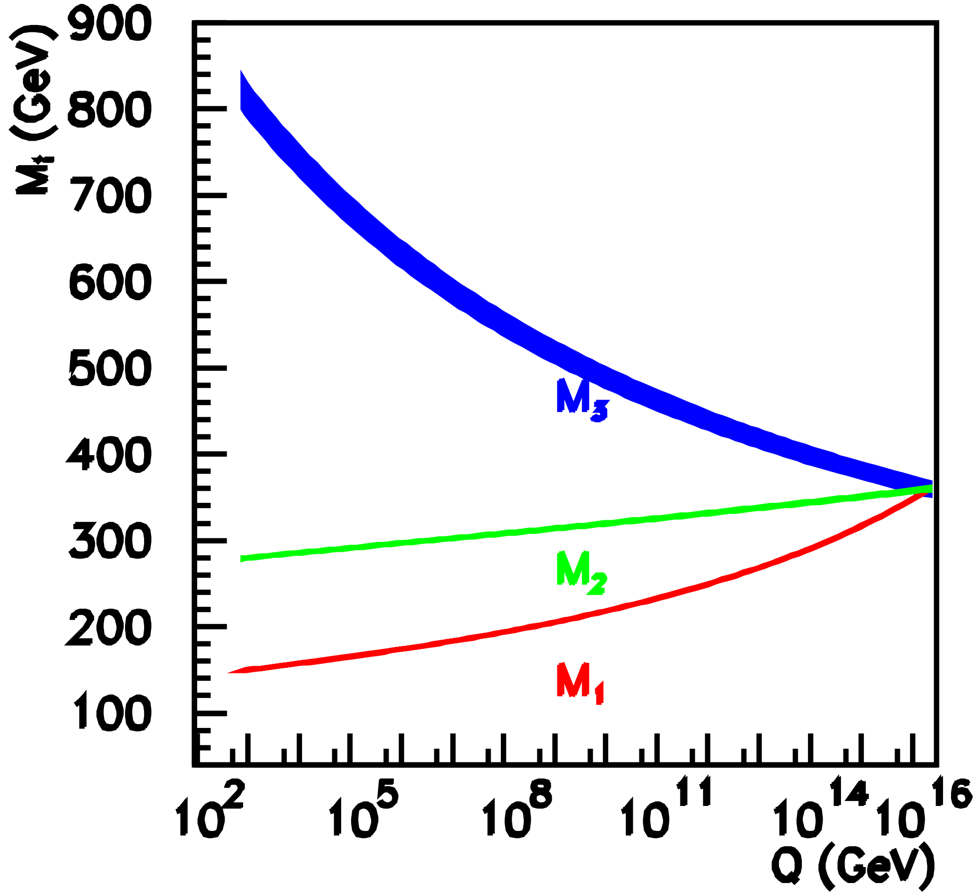


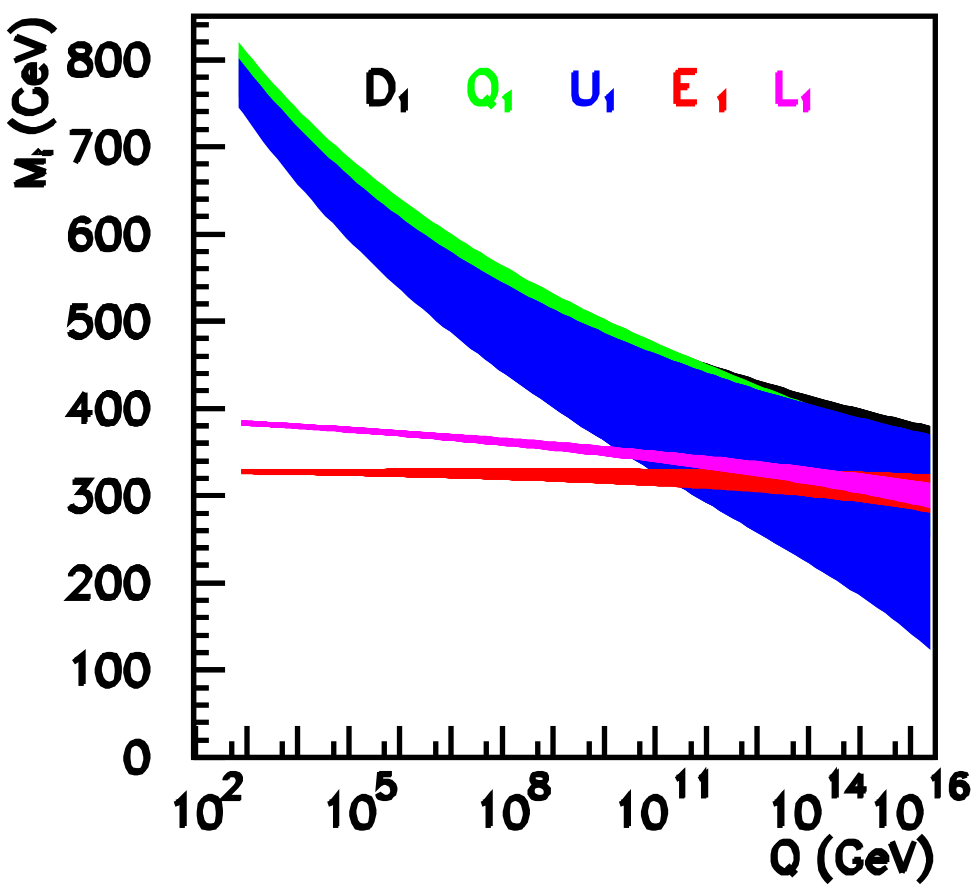
cos θ t
- 0.55
- 0.6
- 0.65
- 0.7
- 0.75
P = -0.9
P = +0.9
185
190
195
200
205
210
m(t̃1) (GeV)
E CM = 500 GeV
Eberl et al.

$\sigma\ (e^-_R\ e^+ \to \chi^+_1\ \chi^-_1)$ (fb)



Feng et al.





Blair, Porod, and Zerwas

Many string models predict additional gauge bosons beyond the Standard Model bosons,

New U(1) bosons are especially common in free-fermion and orbifold string constructions

Kakushadze-Tye brane world model has the SM gauge group inside O(6) X O(4).

The best way to look for new gauge bosons is to serarch for pp -> X + l^+l^- at the LHC.

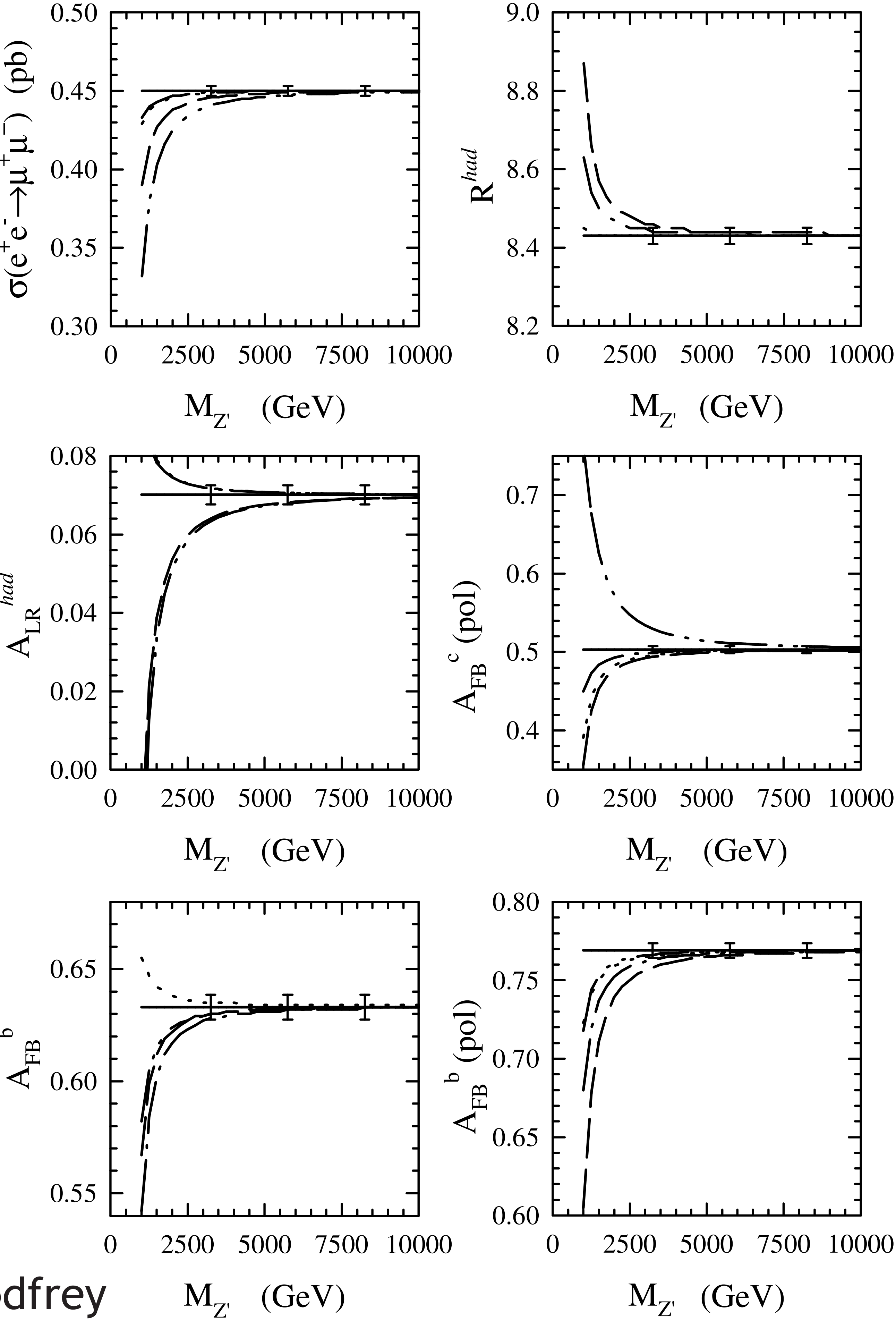
But then, how do we know what we have found ?

New gauge bosons are visible through indirect effects in the reactions

$$e^+ e^- \rightarrow \gamma + Z^0 + \cdots \rightarrow f \bar{f}$$

Effects of a new gauge boson can be looked for for each final state flavor, in angular distributions, electron beam polarization asymmetries.

These measurements will go far toward characterizing a new boson discovered at LHC.



σ(e+e-→μ+μ-) (pb)
0.50
0.45
0.40
0.35
0.30
0
2500
5000
7500
10000
M_Z' (GeV)
R^had
9.0
8.8
8.6
8.4
8.2
M_Z' (GeV)
A_LR^had
0.08
0.06
0.04
0.02
0.00
M_Z' (GeV)
A_FB^c (pol)
0.7
0.6
0.5
0.4
M_Z' (GeV)
A_FB^b
0.65
0.60
0.55
M_Z' (GeV)
A_FB^b (pol)
0.80
0.75
0.70
0.65
0.60
M_Z' (GeV)

Godfrey

The sensitivity of an e^+e^- collider to a new Z^0 is comparable to that of the LHC already at 500 GeV in the center of mass.

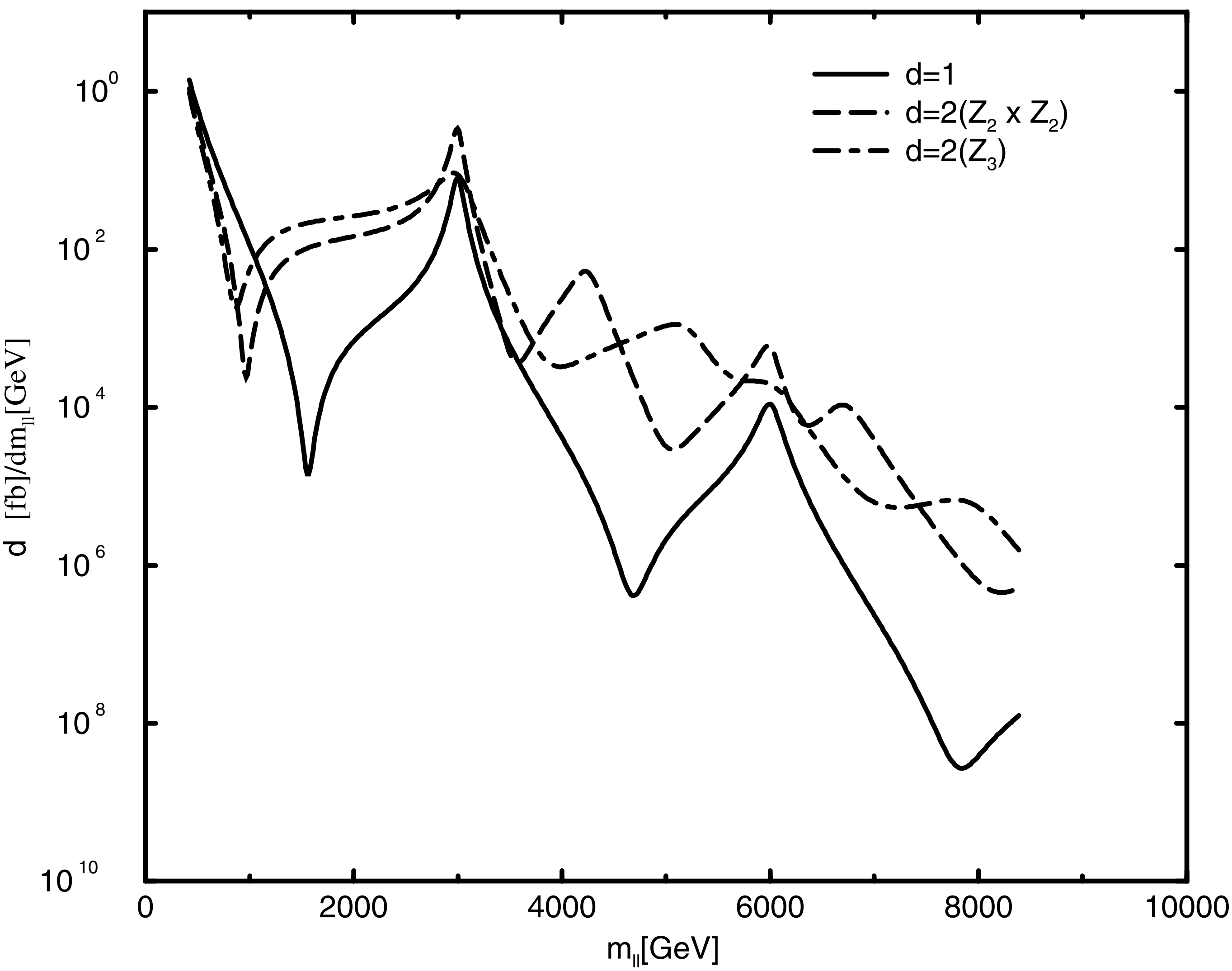
	200 fb^{-1}	LHC
χ	4.5	4.5
ϕ	2.6	4.1
η	3.3	4.2
SSM	5.6	4.9
LRM	5.2	4.5

mass reach in TeV

In the most optimistic scenario, the extra dimensions predicted by string theory might have sizes 1/TeV or even larger.

Then we can look for the effects of extra dimensions on particle reactions at next-generation colliders.

For example, the number and shape of extra dimensions can be reflected in the spectrum of Kaluza-Klein gauge bosons.

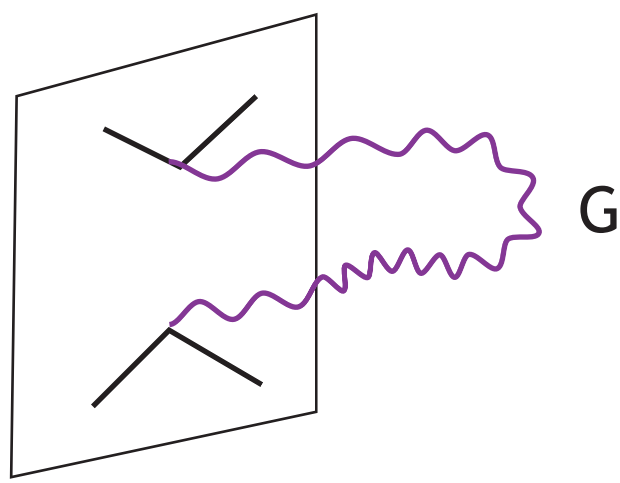


Nath, Yamada, Yamaguchi

Much attention has recently been given to the idea of Arkani-Hamed-Dimopoulos-Dvali of quantum gravity at the TeV scale.

test this model through:

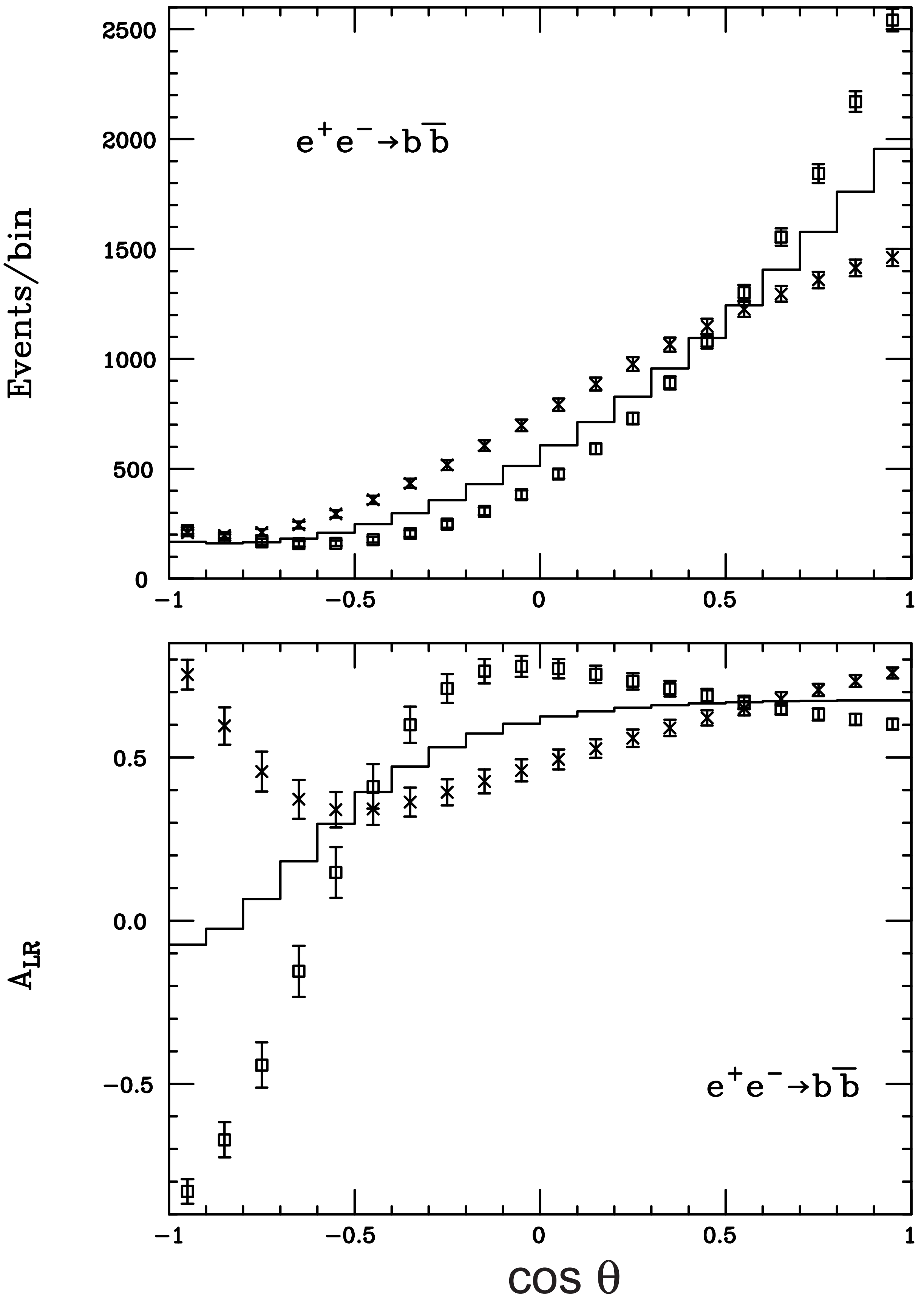
Corrections to high-energy reactions by virtual graviton exchange:



Hewett, Han et al. , Giudice et al.

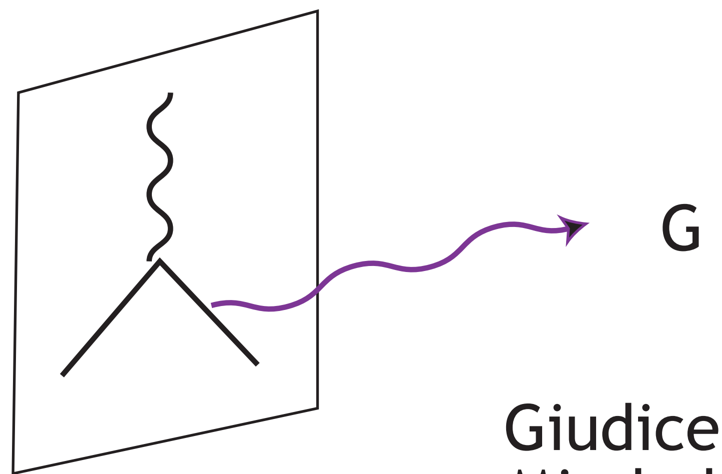
The same methods used to analyze new Z bosons are very useful here.

Hewett



Gravitational radiation into the extra dimensions:

In the same way, the process



Giudice et al.
Mirabelli et al.

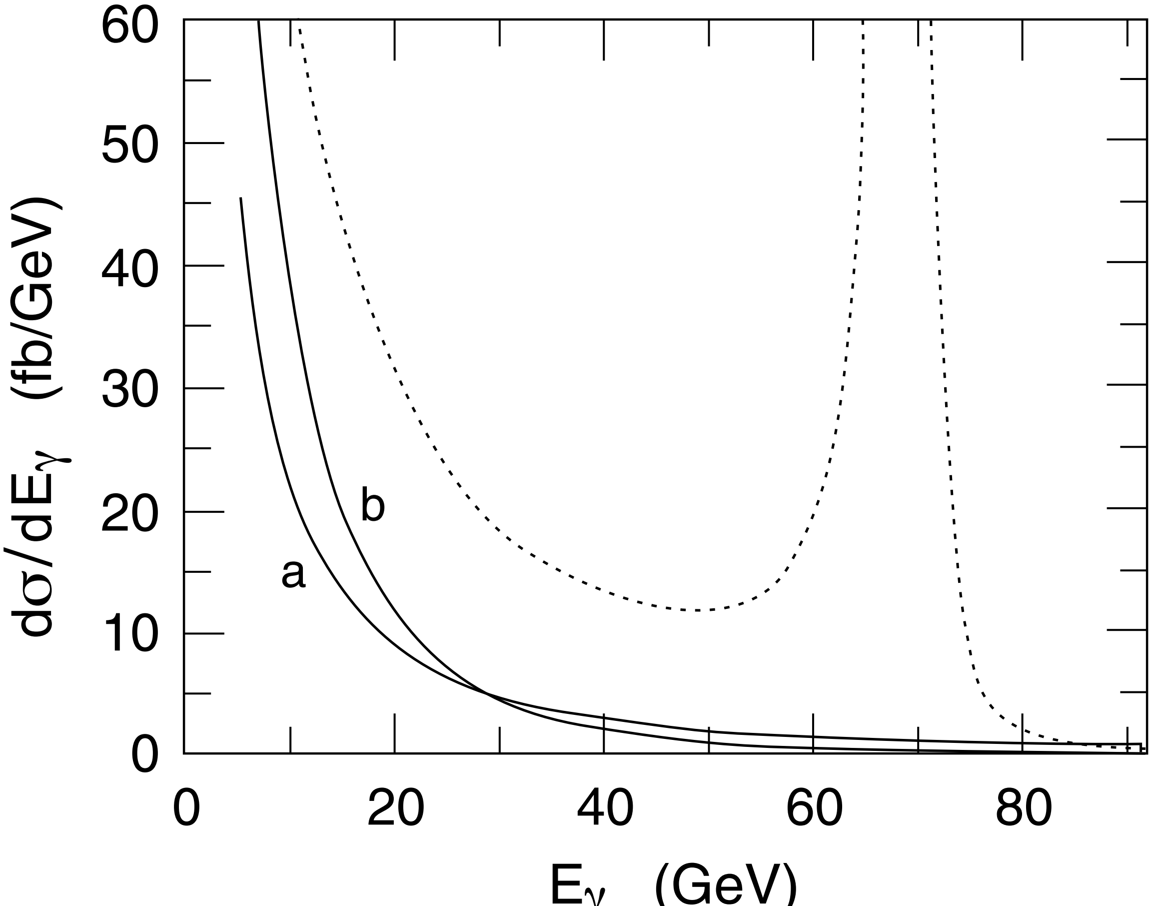
becomes important at high energy. Look for this in

$$e^+ e^- \to \gamma\ G \ , \qquad q\ \bar{q} \to g\ G$$

High energy is a premium: $\sim E^n$

The cross section is positive and model-independent, so this search puts definite bounds on R and $\mathcal{M}$.

(prediction for LEP 2 experiments)



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Present and future constraints on $\mathcal{M}$ (GeV) from gravitational radiation

	n=2	n=4	n=6
Present:			
SN1987A	50000*	1000	100
LEP 200	1200	730	530
Tevatron	1140	860	780
Future:			
LC:	7700	4500	3100
LHC:	12500	7500	6000*

* $R = 3\,\mu$ (red asterisk)

* $R = 3$ fm (green asterisk)

If the Planck scale is at TeV energies,
the string scale should also be there.

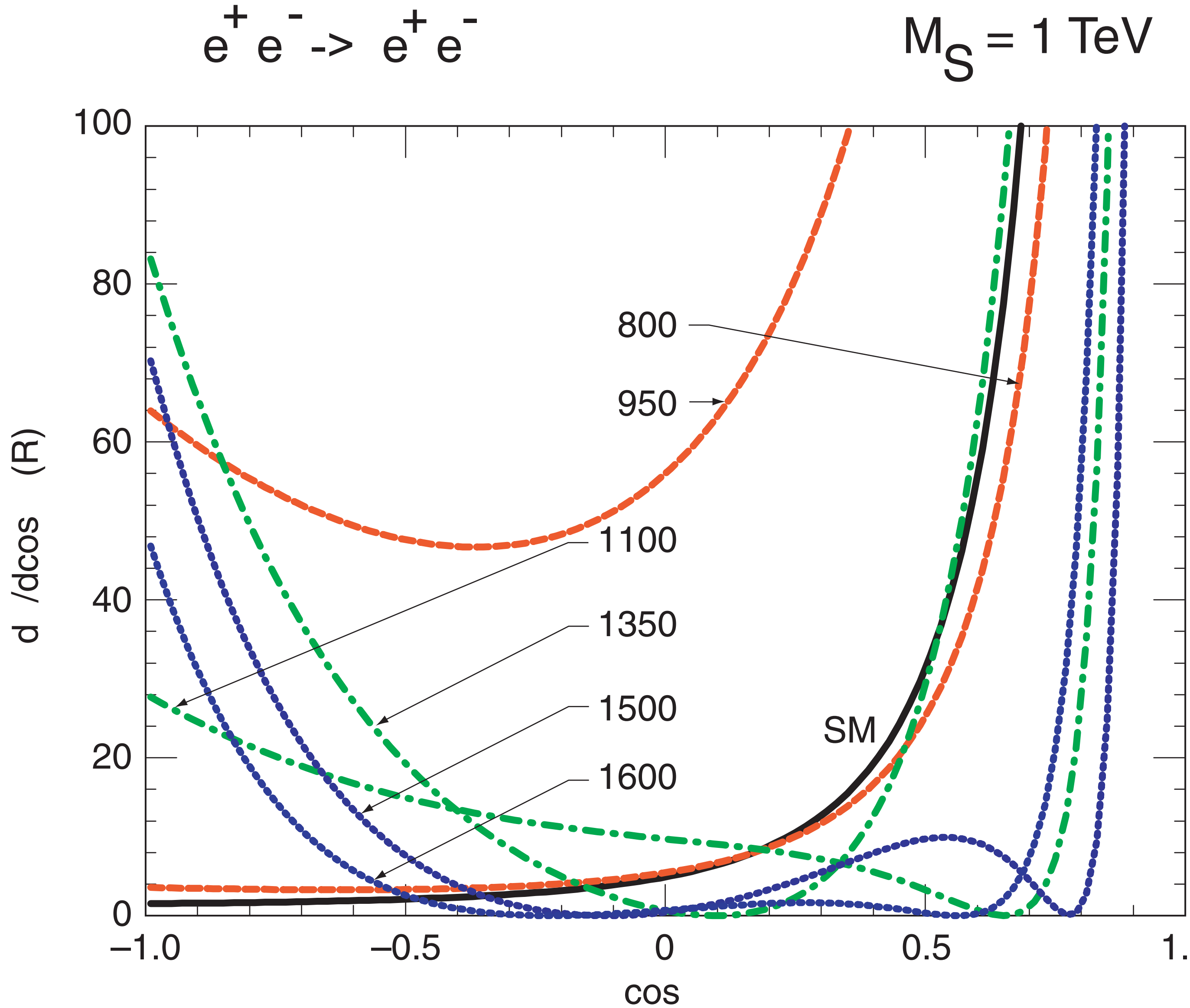
Then we expect:

string excited states as resonances in all scattering processes

decay of resonances ~10% of the time to missing energy (gravitons)

dramatic increases over standard model cross sections at high energy, especially for forward scattering, multiple particle production (going to the limit of black hole scattering ?)

current limit (Tevatron): $m_{string} > 1$ TeV



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So, what should you do now ?

The conclusions on the next few slides are independent of whether you agree or not with my case for a 500 GeV e^+e^- collider.

The US High-Energy Physics community is debating its future this year;

the DOE and NSF have convened a panel and requested a report;

the needs of string theory ought play a role in their conclusions.

0. Join the American Physical Society, and its Division of Particles and Fields

Otherwise you are completely out of the loop !

(This organization also controls other subjects that string theorists care about, e.g., print and electronic journal publishing.)

1. Think about how string theory could be tested experimentally in the next 20 years.

Many possibilities present themselves:

SUSY spectrum
new interactions at high energy
modifications of standard cosmology
modifications of gravity
exotic identity for dark matter

Which should experimenters be searching for ?

If it will take 10 years to succeed, they ought to start now.

Don't wimp out ! This is one of the hardest questions about string theory. But even a partial answer or an informed guess provides useful guidance.

2. Write a letter to the HEPAP subpanel.

In January 2001, DOE and NSF constituted a subpanel on "Long-Range Planning for US High Energy Physics"

The co-chairs are Barry Barish (Caltech) and Jonathan Bagger (Johns Hopkins U)

The panel is charged to report

"What are the central questions that define the intellectual frontier of HEP?"

a recommendation for the next HEP facility

a 20-year plan for HEP

the draft report is due October 1, 2001.

see:

http://hepserve.fnal.gov:8080/doe-hep/lrp-panel/index.html

Write a letter to Barish and Bagger, explaining why experiment that potentially test string theory should be given high priority in their conclusions.

If the string theory community has the vision for the field of high-energy physics, this is the time to demonstrate it.

The previous HEPAP subpanel met in 1996-98. String theorists ignored it. At Strings `96, Lenny Susskind gave a memorable lecture saying that all we needed was pure thought.

(And, the HEP community made no progress toward a consensus on a future facility beyond LHC.)

3. Attend the Snowmass 2001 workshop.

This summer, July 1-21, the APS Division of Particles and Fields and the Division of Particle Beams will hold a 3-week workshop on the future of high-energy physics in Snowmass, Colorado.

Attend! Talk to experimenters!
Spread new ideas!

It is not necessary to compute cross sections or run Monte Carlos. Professionals in these areas will be at Snowmass. String theorists should bring new and unexpected ideas about future directions.

Witten, Gross, Polchinski, and Dine will be there. Why not you?

see:

http://www.snowmass2001.org/

The experimental verification of string theory is far off, but we have to keep it in sight. Otherwise, we may be doing mathematics, but we are not doing physics.

The necessary experiments in high-energy physics and cosmology are themselves long-range programs that will be played out over a decade or more.

If we want to see these experiments done, we should be calling for them now. If we believe that string theory is a science, we should put our best ideas for experimental tests foward -- loudly -- and hope that they are taken seriously.