Supersymmetry and String Theory
. . . for the rest of us

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Outline

- **Supersymmetry: Theory/Phenomenology**
- **Supersymmetry: Particle searches**
- **Connections to String Theory**
- **An Experiment to Search for Strings**

CLEO Lunch Seminar
November 11, 2003

Disclaimer

I must have been out of my mind to agree to this.

Think of this talk as a book report

J. H. Schwarz and N. Seiberg,
"String theory, supersymmetry, unification, and all that,"
Rev. Mod. Phys. 71, S112 (1999)

PDG Mini Reviews in Phys. Rev. D 66, 010001 (2002):
"Supersymmetry, Part I" (Theory, by H.E. Haber)
"Supersymmetry, Part II" (Experiment, by M. Schmitt)

Csaba Csáki's lunch talk:
http://agenda.cern.ch/fullAgenda.php?ida=a031365

N. Isgur, V. A. Kostelecky and A. P. Szczepaniak,
"Background enhancement of CPT reach at an asymmetric ϕ factory," Phys. Lett. B 515, 333 (2001)

(Plus other papers by V. A. Kostelecky.)

To make a long story short...

This subject ("SuperStrings") is a good example of Feynman's "scaffold".

The Standard Model has a problem ("naturalness") and supersymmetry is ONE possible solution to the problem.

String theory is an old subject, first invented to explain the strong interactions. Over 30 years ago, it was shown that string theory required supersymmetry, which was eventually seen to add structure to ordinary spacetime.

QCD replaced string theory. Then it was shown that string theory could be made to look like quantum gravity.

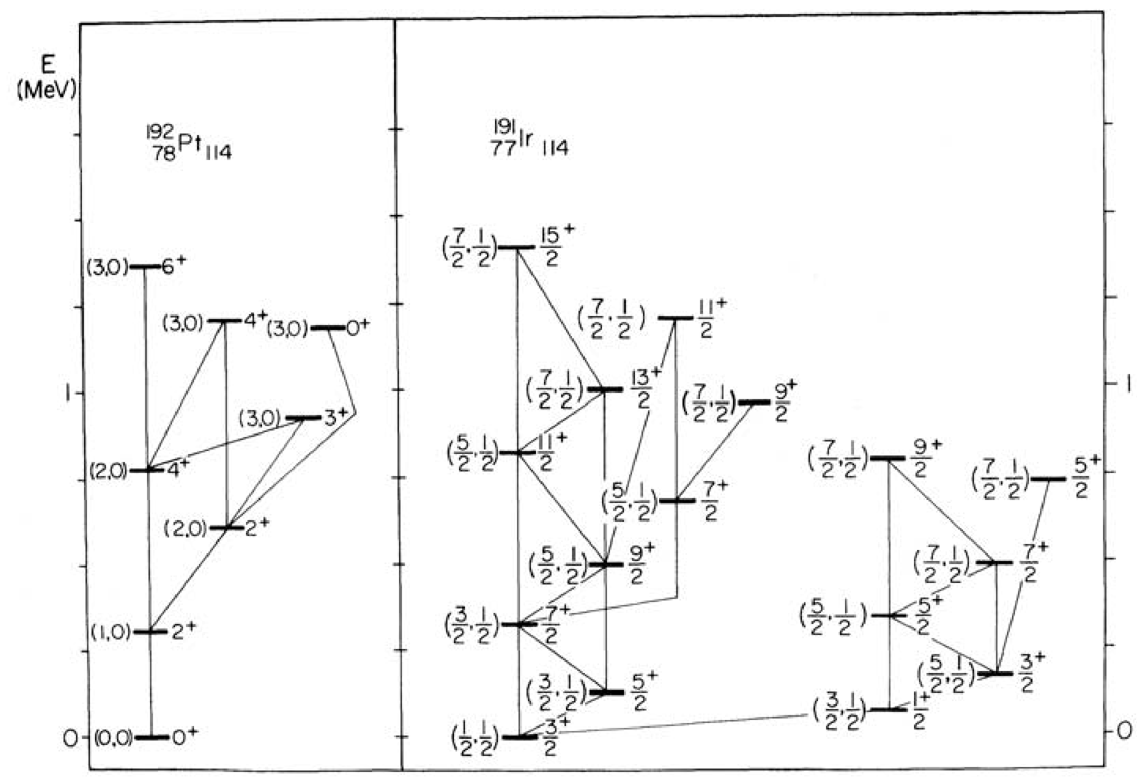
Do SuperStrings fix the Standard Model ...AND unify all the forces of nature?

Supersymmetry has a long history all its own

L. Corwin, Y. Ne'eman and S. Sternberg, "Graded Lie Algebras In Mathematics And Physics (Bose-Fermi Symmetry)," Rev. Mod. Phys. 47, 573 (1975)

"Graded Lie algebras have recently become a topic of interest in physics in the context of 'supersymmetries,' relating particles of differing statistics."

F. Iachello, "Dynamical Supersymmetries In Nuclei," Phys. Rev. Lett. 44, 772 (1980).



Supersymmetry: Theory/Phenomenology

(1) Adding structure to spacetime

Familiar spacetime coordinates $X^\mu = (t, x, y, z)$ commute:

$$X^\mu X^\nu = X^\nu X^\mu$$

(Operators or parameters? Not sure about this. . .)

Supersymmetry adds four new "fermionic" dimensions:

$$\theta^\mu \theta^\nu = -\theta^\nu \theta^\mu$$

A function $\Phi(X, \theta)$ is at most fourth order in θ, so it can be replaced by "expansion coefficients" $\phi(X)$ ("bosons") and $\psi(X)$ ("fermions").

Anything can be written down in this expanded space. Supersymmetric quantum field theory is a more generic form of field theory, not something entirely different.

(2) Bosons and Fermions

So, suppose we build a quantum field theory in this supersymmetric space. It naturally has this symmetry between bosons and fermions.

S. R. Coleman and J. Mandula, "All Possible Symmetries Of The S Matrix," Phys. Rev. 159, 1251 (1967):

This symmetry *(apparently)* can only be realized with spacetime observables (e.g. P^μ and $P^\mu P_\mu = M^2$) and not with internal symmetries.

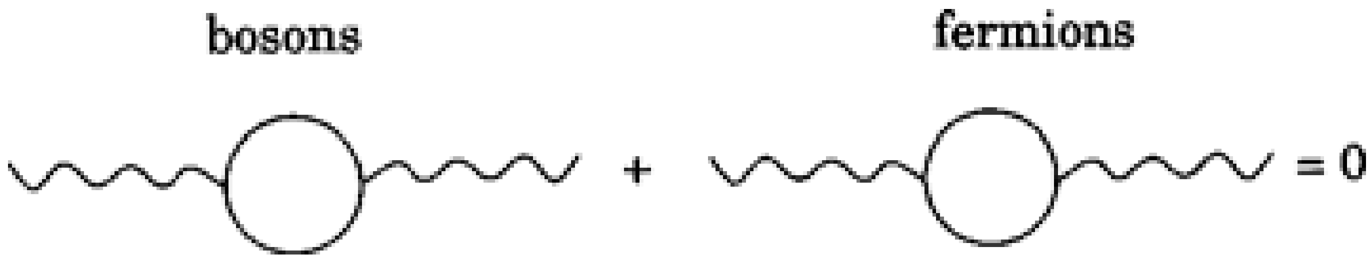
In terms of the group's generators Q_α,

$$[Q_\alpha, P^\mu] = 0 \qquad \left[Q_\alpha, M^2\right] = 0$$

⇒ Boson/Fermion partners (i.e. members of a SUSY multiplet) must have the same mass.

(3) Loops

Equal mass but different different commutation signs means that loops will cancel exactly:



This fixes lots of infinities in field theories and makes it possible to make many exact calculations.

It also means there is no such thing as the Lamb Shift.

Oops! Supersymmetry must be broken (at some level).

(4) The naturalness problem and its solution in SUSY

The Standard Model of particle physics works very well.

The Higgs Boson is a key to formulating the theory.

But why is the Higgs mass M_h (and the masses of the $W^{\pm}$ and Z^0) in the neighborhood of 1 TeV, when the "natural" scale is the Planck Mass $M_P \approx 10^{19}$ GeV?

This is not just aesthetics! Loops will cause M_h to get a mass closer to M_P.

SUSY cures this! Loops will (almost) cancel out!

(5) Minimal Supersymmetric Standard Model (MSSM)

Nobody knows (yet) what is the dynamical origin of supersymmetry. (SuperStrings? Later. . .)

MSSM: Add partners to all known particles, and put in the supersymmetry breaking terms by hand:

Scalar Mass	$\phi_i^\star \phi_i$
Gaugino Mass	$\lambda\lambda + \text{H.C.}$
Real Scalar Mass, Cubic	$\phi^2, \phi^3 + \text{H.C.}$

Discovering SUSY particles determines these parameters.

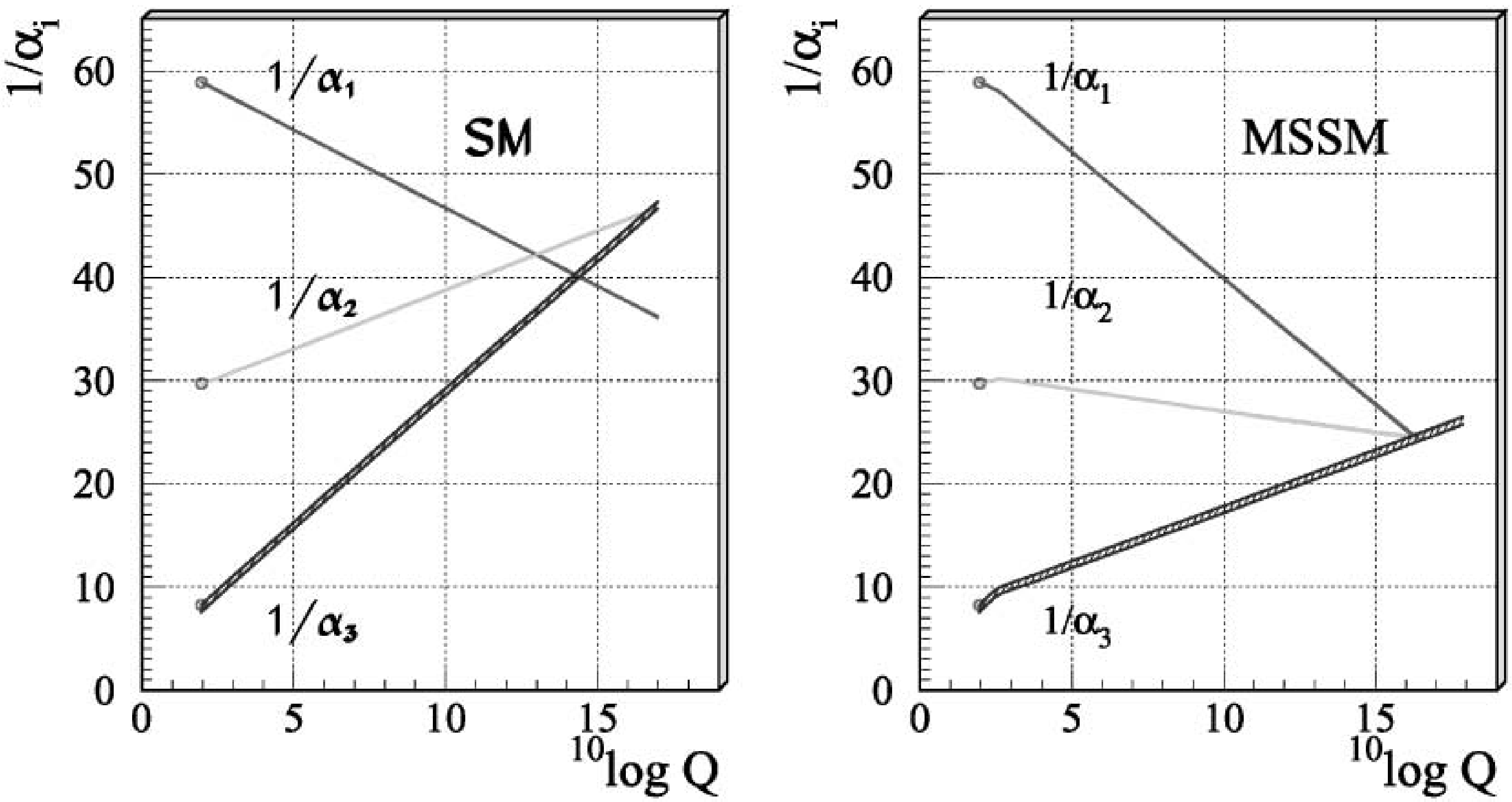
$B - L$ invariance included, leading to R-parity invariance. $R = +$ for SM particles, $R = -$ for SUSY particles.

$\Rightarrow$ The Lightest Supersymmetric Particle (LSP) is stable!

Could this be dark matter??

(6) Evolution of Coupling Constants in the MSSM

D. I. Kazakov, Phys. Rept. 344, 309 (2001)



⇒ Adding a new scale at ~ 1 TeV changes the slopes and lets the α's converge at a single point.

"Experimental evidence" for supersymmetry?

Supersymmetry: Particle Searches

First, a supersymmetric particle (*sparticle*) inventory.
(See discussion and mixing formulas in the PDG.)

Spin-1/2 partners of gauge and higgs particles are "ino's".
Some are neutral (e.g. $\tilde{\gamma}$, $\tilde{Z}^0$, $\tilde{g}$, some higgsino's)
and some are charged (e.g. $\tilde{W}^{\pm}$, some higgsino's).

These will mix! Mixing depends on MSSM parameters.
We talk of charginos $\tilde{\chi}^{\pm}_{1,2}$ and neutralinos $\tilde{\chi}^{0}_{1,2,3,4}$.

Spin-0 partners $\tilde{f}$ of quarks and leptons are "squarks", charged "sleptons", and uncharged "sneutrinos".

These also mix, both by generation and $\tilde{f}_L/\tilde{f}_R$ mixing.
Note: There is no $\tilde{\nu}_R$ in the MSSM...
...but what about massive neutrinos?

Two Big Challenges for SUSY Searches

1) What do you look for?

***Assuming R-parity is conserved*, look for the LSP.**

For most MSSM parameter scenarios, the LSP is a neutralino, which is neutral and colorless.
$\Rightarrow$ Look for "missing energy".

2) How do you interpret null results?

The answer depends on MSSM parameter assumptions.

Note: The MSSM has 124 truly independent free parameters, only 18 are from the Standard Model itself.

S. Dimopoulos and D. W. Sutter, "The Supersymmetric flavor problem," Nucl. Phys. B 452, 496 (1995)

Example: Neutralino Pair Production at LEP, $\sqrt{s} = 189$ GeV

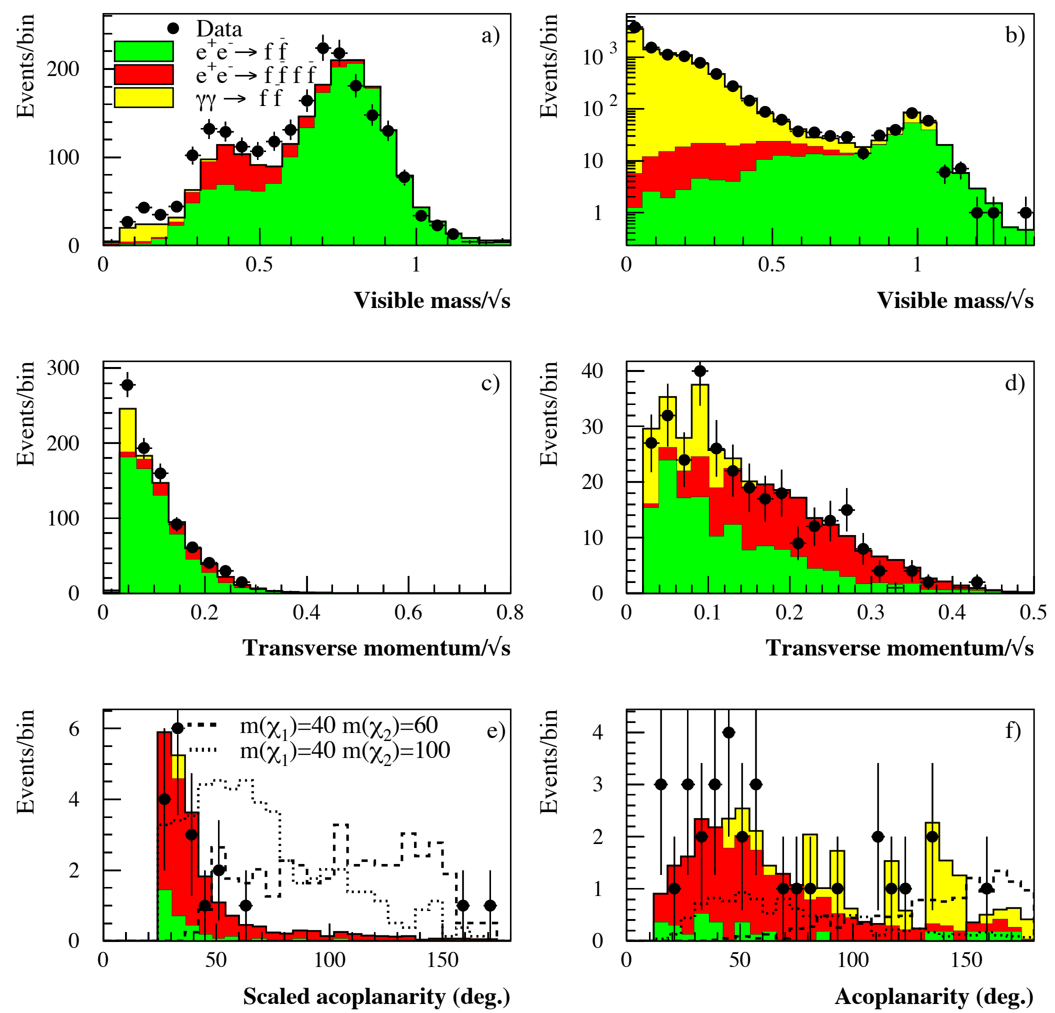
DELPHI Collaboration, Eur. Phys. J. C19, 201 (2001)

LSP $= \tilde{\chi}_1^0$

$$e^+e^- \rightarrow \tilde{\chi}_k^0 \; \tilde{\chi}_1^0$$
$$\hookrightarrow \tilde{\chi}_1^0 + f\bar{f}$$

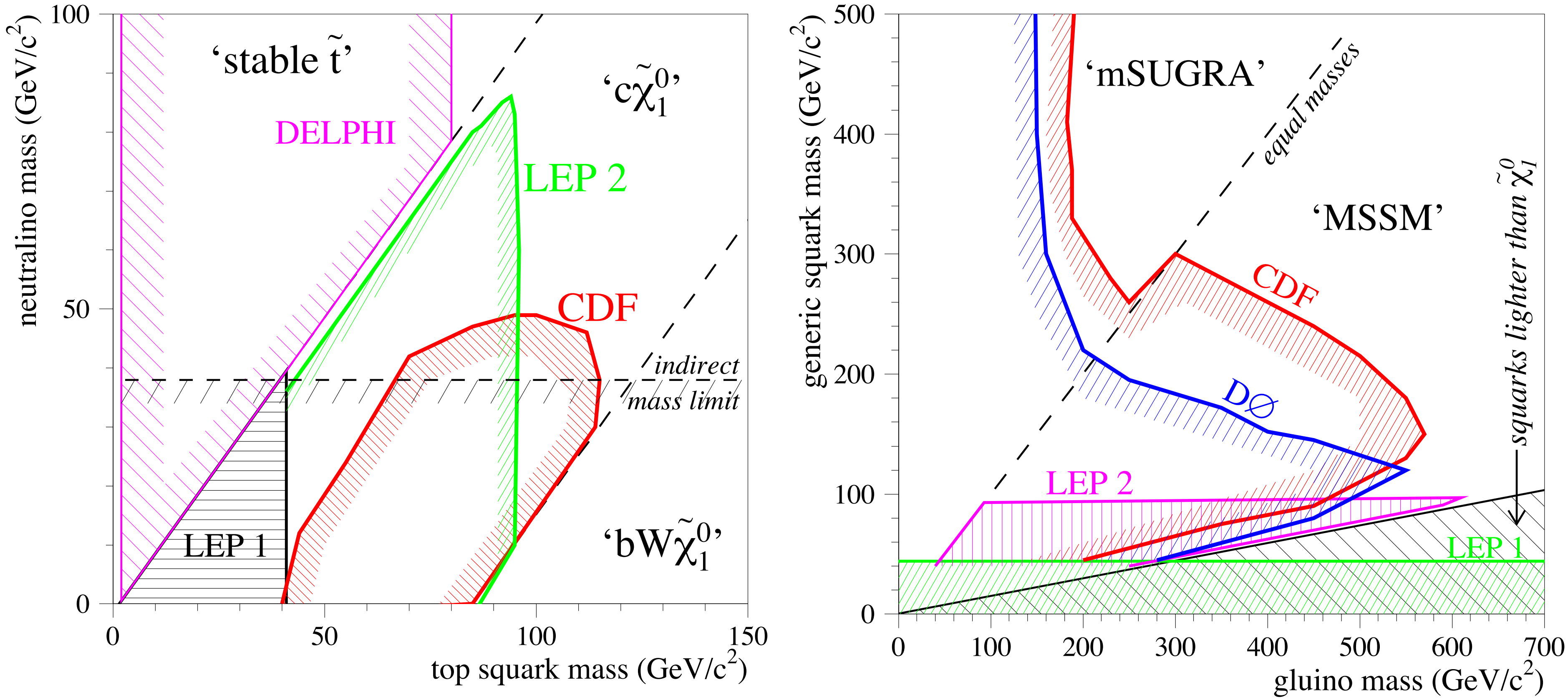
Both $\tilde{\chi}_1^0$'s escape

⇒ Look for a pair of jets *or* leptons with missing energy and acoplanarity.



Limits from LEP, CDF, and D0

PDG Compilation



Note: LEP analyses are still in progress

http://lepsusy.web.cern.ch/lepsusy/

Caveats and More Caveats

Special thanks to Jim Gates, University of Maryland

- **Can construct algebras with powers higher than θ^4**
  $\Rightarrow$ "Extended" Supersymmetry

- **Maybe *R*-parity is not conserved**
  $\Rightarrow$ The LSP will decay to SM particles

- **Perhaps squarks are lighter than gauginos**
  (See S. J. Gates, Jr. and O. Lebedev,
  "Searching for supersymmetry in hadrons,"
  Phys. Lett. B477(2000)216.)
  $\Rightarrow$ SUSY could be hiding in *shadrons*

- **. . .**

Connection to String Theory

Old Problem:
How to build a quantum field theory of gravity.

Scales: $M_P = \left(\frac{\hbar c}{G}\right) \sim 10^{19}\ \mathrm{GeV}/c^2$ $\qquad \frac{\hbar c}{M_p c^2} \sim 10^{-20}\ \mathrm{fm}$

Perturbative renormalizability breaks down.
The causal nature of relativistic spacetime breaks down.

String theory was around in the 1960's for strong interactions. ***(The Berkeley crowd??)***
1971: Adding fermions required supersymmetry

J. Scherk and J. H. Schwarz, "Dual Models And The Geometry Of Space-Time," Phys. Lett. B52, 347 (1974).
$\Rightarrow$ Maybe (super)string theory can describe gravity?

The First SuperString Revolution (1984-1985)

Five different SuperString theories are possible.
They all have *ten* dimensions, nine space and one time.

- **Type I**
- **Type IIA**
- **Type IIB**
- **$E8 \times E8$ heterotic (HE)**
- **$SO(32)$ heterotic (HO)**

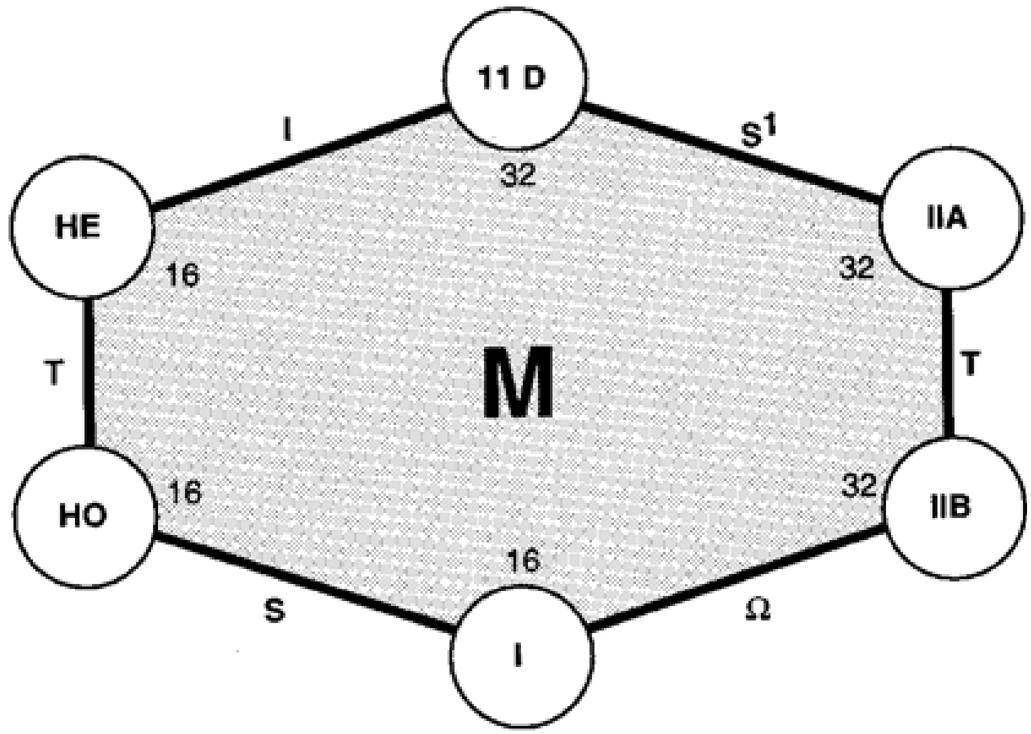
The six "extra dimensions" must somehow curl up and be invisible to us if these theories are to make sense.

The Second SuperString Revolution (1994-?)

The five SuperString theories are actually different perturbation expansions about different points in the "moduli space of consistent vacua."

Another vacuum appears. It has *eleven* dimensions.

***M*-Theory**



http://www.theory.caltech.edu/people/jhs/
http://superstringtheory.com/

An Experiment to Search for Strings

V. A. Kostelecky and S. Samuel, "Spontaneous Breaking Of Lorentz Symmetry In String Theory," Phys. Rev. D 39, 683 (1989)

V. A. Kostelecky and R. Potting, "CPT and strings," Nucl. Phys. B 359, 545 (1991)

V. A. Kostelecky and R. Potting, "CPT, strings, and meson factories," Phys. Rev. D 51, 3923 (1995)

So what's the point? Strings violate Lorentz Invariance, so CPT might be violated, too. By how much?

Rough guess for mesons:
$|M(m) - M(\bar{m})|/M(m) \sim \Lambda_{QCD}/M_P \sim 10^{-19}$

This is *not* out of reach!

L. K. Gibbons *et al.* [E731 Collaboration],
"CP and CPT symmetry tests from the two-pion decays of the neutral kaon with the Fermilab-E731 detector"
Phys. Rev. D 55, 6625 (1997)

$$\left| \frac{M_{K^0} - M_{\bar{K}^0}}{M_{K^0}} \right| < 2.0 \times 10^{-18}$$

How can you do a hundred times better?
More kaons and *perhaps* a fortuitous interference:

$$\gamma p \to \left(K^0 \bar{K}^0 \right)_{(\ell=0,1)} p$$

(See Isgur, Kostelecky and Szczepaniak.)

Conclusions

Supersymmetry was re-invented to fix a big problem - "naturalness" - in field theory. There is no experimental evidence that it is correct.

It connects nicely with "String Theory", another beautiful theory with absolutely no supporting experimental evidence.

These ideas might be right! The experimental physics community should continue to look for evidence.