
String Phenomenology

SOME REVIEWS

phenomenological

- "AN INTRODUCTION TO SUPERGRAVITY", D.G. CERDEÑO, C. MUÑOZ
  JHEP Proceedings, corfu98

- "LECTURES ON SUPERSTRING PHENOMENOLOGY", F. QUEVEDO
  hep-th/9603074

- "SOFT SUPERSYMMETRY BREAKING TERMS FROM SUPERGRAVITY AND SUPERSTRINGS"
  A. BRIGNOLE, L.E. IBAÑEZ, C.MUÑOZ, hep-ph/9707209

- "QUARK AND LEPTON MASSES AND MIXING ANGLES FROM SUPERSTRING CONSTRUCTIONS", S.A. ABEL, C.MUÑOZ
  hep-ph/0212258

- "A KIND OF PREDICTION FROM SUPERSTRING MODEL BUILDING", C. MUÑOZ, hep-ph/0110381

- "CHIRAL FOUR-DIMENSIONAL STRING COMPACTIFICATIONS WITH INTERSECTING D-BRANES", A. URANGA, hep-th/0301032

- "THE FLUXED MSSM", L.E. IBAÑEZ, hep-ph/0408064

- "DESPERATELY SEEKING THE STANDARD MODEL", C. MUÑOZ
  hep-ph/0312091

FIRST LECTURE

CARLOS MUÑOZ

WHAT DO WE OBSERVE EXPERIMENTALLY?

THE WORLD IS DESCRIBED BY THE **STANDARD MODEL**

AT ENERGIES $\lesssim 10^2$ GeV

IT IS BASED IN $\left[\begin{array}{l}\text{QUANTUM MECHANICS}\\ \text{SPECIAL RELATIVITY}\\ \text{POINT-LIKE PARTICLES}\end{array}\right]$ QFT

WITH GAUGE SYMMETRY $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

AND THREE FAMILIES OF QUARKS AND LEPTONS

$$\begin{pmatrix} u_i \\ d_i \end{pmatrix}_L \quad u_{iR} \quad d_{iR} \quad \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad e_R$$

THEY ARE CHIRAL
L AND R HAVE
DIFFERENT $SU(2)_L \otimes U(1)_Y$
QUANTUM NUMBERS

spin $\frac{1}{2}$ particles

u	c	t
~ 5	~ 1350	~ 184000
d	s	b
~ 10	~ 200	~ 5000
e	μ	τ
~ 0.51	105.6	~ 1784
ν_e	ν_μ	ν_τ
0	0	0

spin 1 particles

γ	$g_{1,\dots 8}$	$W^\pm, Z^0$
0	0	~ 80000

ORDINARY MATTER IS MADE FROM FIRST FAMILY u, d, e

SECOND AND THIRD FAMILIES ARE HIGHLY UNSTABLE c, s, μ
t, b, τ

THE STANDARD MODEL WORKS OUTSTANDINGLY WELL IN PRACTICE

BUT

IT EXHIBITS SEVERAL ASPECTS THAT ARE NOT SATISFACTORY

THEORETICAL QUESTIONS

- ELECTROMAGNETISM + WEAK THEORY ARE PARTIALLY UNIFIED IN $SU(2)_L \otimes U(1)_Y$

  CAN WE UNIFY $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ IN A SINGLE THEORY?

  A THEORY WITH ONLY ONE GAUGE COUPLING

- GRAVITY IS THE FOURTH INTERACTION IN NATURE

  CAN WE QUANTIZE AND UNIFY IT WITH THE STANDARD MODEL ?

The theory is in its nature descriptive and not explanatory

All the data (list of elementary particles, masses, spins, charges and interactions with one another) are put into the theory at the beginning

METAPHYSICAL QUESTIONS

THE STANDARD MODEL ANSWERS : WHAT ARE THE PHENOMENA
HOW DO THEY OCCUR

BUT IT DOES NOT ANSWER **WHY?**

- WHY DO WE LIVE IN $D=4$?
- WHY IS THE GAUGE GROUP $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$?
- WHY IS NATURE DOMINATED BY GAUGE INTERACTIONS ?
- WHY ARE THERE THREE FAMILIES OF PARTICLES ?
- WHY DOES FERMIONIC MATTER EXIST AT ALL ?

- WHY NATURE REPEATS THE e^- AT 211 TIMES (μ^-) AND 3568 TIMES (τ^-) ITS MASS ?
- WHY THE STRANGE PATTERN OF QUARK MASSES AND MIXING ANGLES ?

  e.g. $m_t = 36800\, m_u$
- WHY IS THE FINE STRUCTURE CONSTANT GIVEN BY $\alpha = 1/137$?
- - - - - - - - - - - - - - -
  - - - - - -

RELATED WITH THE 19 PARAMETERS THAT HAVE TO BE FIXED BY EXPERIMENT

g_1, g_2, g_3

$\lambda_e, \lambda_u, \lambda_d$

$\lambda_\mu, \lambda_c, \lambda_s$

$\lambda_\tau, \lambda_t, \lambda_b$

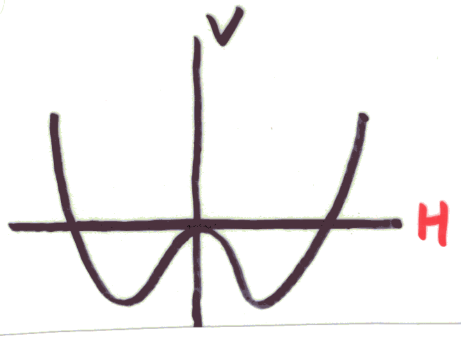
$\theta_c, \theta_{13}, \theta_{23}, \delta$

μ^2, λ

θ_{QCD}

MOST OF THEM ARE PARAMETERS RELATED TO THE

HIGGS-YUKAWA SECTOR OF THE THEORY



ELEMENTARY SCALAR

$$V = \mu^2 H^2 + \lambda H^4 \quad \mu^2 < 0$$

$$\langle H \rangle \neq 0$$

$$\mathcal{L}_{YUKAWA} = \lambda_u Q_u H^* u^c + \lambda_d Q_u H d^c + \lambda_e L_e H e^c + \text{OTHER FAMILIES}$$

$$\text{e.g.} \quad \left.\begin{array}{l} m_u = \lambda_u \langle H \rangle \\ m_t = \lambda_t \langle H \rangle \end{array}\right\} \lambda_t \gg \lambda_u \Rightarrow m_t \gg m_u$$

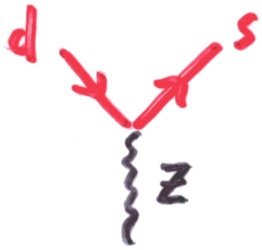
IN THE FRAMEWORK OF THE STANDARD MODEL $\mu^2, \lambda, \lambda_u, \ldots$ ARE JUST INITIAL PARAMETERS PUT BY HAND WITHOUT ANY POSSIBLE HINT ABOUT THEIR ORIGIN spin 0 particle H

AS THE HISTORY OF THE STANDARD MODEL SHOWS,
SOLVING THEORETICAL PROBLEMS → IMPORTANT DEVELOPMENTS

e.g.

*  → 

FERMI THEORY → STANDARD MODEL with prediction of W, Z

* 

→ $\begin{pmatrix}u\\d\end{pmatrix}\begin{pmatrix}c\\s\end{pmatrix}$

TO AVOID FCNC → GIM MECHANISM

* CP VIOLATION IN KAONS → 3 FAMILIES, i.e. $\begin{pmatrix}t\\b\end{pmatrix}$

GAUGE HIERARCHY PROBLEM

WE NEED THE HIGGS DOUBLET TO BREAK THE ELECTROWEAK SYMMETRY

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \xrightarrow[\langle H \rangle \neq 0]{} SU(3)_c \otimes U(1)_{e.m.}$$

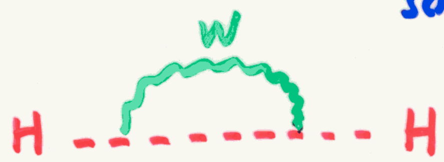
$$\rightarrow \; m_H \sim 10^2 \, \text{GeV}$$

BUT IN THE PRESENCE OF A GUT THE CUTOFF $\Lambda_{GUT} \sim 10^{15}$ GeV

$$\rightarrow \; m_H^2(M_W) \sim m_H^2(\Lambda_{GUT}) + \Lambda_{GUT}^2$$

DUE TO QUADRATIC DIVERGENCES IF THE HIGGS IS A ELEMENTARY SCALAR PARTICLE

e.g.



EXTREME **FINE-TUNING** $\dfrac{m_H^2}{\Lambda_{GUT}^2} \sim 10^{-26}$

EVEN IN THE ABSENCE OF A GUT WE KNOW THAT GRAVITY PROVIDES SUCH A CUTOFF, WITH $\Lambda_{cutoff} \sim M_P \simeq 10^{19}$ GeV

SUPERSYMMETRY

NEW SYMMETRY RELATING PARTICLES DIFFERING BY ONE HALF $\underbrace{\text{UNITS IN}}_{N=1}$ HELICITY

$$Q|\lambda\rangle = |\lambda - \tfrac{1}{2}\rangle$$

BOSON $\longleftrightarrow$ FERMION

e.g. $e \longrightarrow \tilde{e}$

$\gamma \longrightarrow \tilde{\gamma}$

SUSY $\Longrightarrow$ BUNCH OF NEW PARTICLES :

$\tilde{q}, \tilde{e}, \tilde{\gamma}, \tilde{g}, \ldots$

i.e. A RICH PHENOMENOLOGY

HIERARCHY STABLE :

$$(+) \quad + \quad (-) \quad = 0$$

QUADRATIC DIVERGENCES ARE CANCELLED

$$m^2(M_W) \sim m^2(M_{Planck}) + \cancel{M^2_{Planck}}$$

$\tilde{u}$ $\tilde{c}$ $\tilde{t}$

$\tilde{d}$ $\tilde{s}$ $\tilde{b}$

$\tilde{e}$ $\tilde{\mu}$ $\tilde{\tau}$

$\tilde{\nu}_e$ $\tilde{\nu}_\mu$ $\tilde{\nu}_\tau$

spin 0 particles $\longrightarrow$ ${}_{1,2}$ $\tilde{H}_{1,2}$

$\tilde{\gamma}$ $\tilde{g}$ $\tilde{W}^{\pm}, \tilde{Z}^0$

spin $\frac{1}{2}$ particles

EXTENDED SUSY

$$Q_N \quad ; \quad N > 1$$

$\downarrow$

ARE UNATTRACTIVE **NON-CHIRAL**

e.g. $N = 2 \longrightarrow Q_{1,2} |\lambda\rangle = |\lambda - \tfrac{1}{2}\rangle$

$$Q_1 Q_2 |\lambda\rangle = |\lambda - 1\rangle$$

$\tfrac{1}{2} \longrightarrow -\tfrac{1}{2}$ IN THE SAME MULTIPLET

$\cancel{e_R \in SU(2)}$ $\quad e_L \in SU(2)$

$E_R \in SU(2)$ "MIRROR" PARTNER

MUST HAVE A MASS BEYOND THE CURRENT EXPERIMENTAL BOUND

HOWEVER, CHIRAL ANOMALY CANCELS WITHIN EACH GENERATION

WHY SUCH MIRROR STATES SHOULD EXIST?

A THEORY INVOLVING THE GRAVITON WITH $|\lambda| = 2$, AND THAT DOES NOT CONTAIN STATES WITH $|\lambda| > 2$, MUST HAVE

$$\boxed{N \leq 8}$$

LEP has been built in order to explore the mass range of 100 GeV, corresponding to dimensions of 10^{-18} m, which is the ideal domain to test the Standard Model of particles and interactions. Its success however does raise new questions which cannot be answered by LEP alone. One more quark, the top quark has so far escaped detection and we believe that it would be very unlikely that it lies within the operating range of LEP. We would like to know if in addition to three families of quarks and leptons there are types of yet undetected particle families, called super-symmetric particles. These particles if discovered may have a fundamental importance in understanding the dark matter in the Universe.

We would like finally to know why the W and Z have such a huge mass, whereas the photon is massless. More generally, does the Higgs field permeate the vacuum or is there another mechanism that provides particles with mass?

These are among the most profound questions which now confront us in physics. To answer them, we need to achieve a further order of magnitude in resolution, down to 10^{-19} m, which implies collision energies at the constituents level in the 1000 GeV(1 TeV) range.

This is the Large Hadron Collider (LHC) project illustrated in this publication. It would achieve proton-proton collisions of 16,000 GeV (or 16 TeV) in the centre-of-mass, and also allow two other types of particle collision, namely electron-proton events up to an energy of 1700 GeV in the centre-of- mass with collisions against the LEP electron beam, and ion-ion collisions up to an energy of 1312 TeV per nucleus, using lead-ion beams from the lead-ion source to be added to the CERN accelerator complex in the next years.

If the LHC is approved by 1992, the construction could be completed by 1997 and the first experiments could commence in 1998. With both LEP200 and LHC, CERN will be able to maintain its prominent position in particle physics in the world and face the challenges of research all the way till the end of the present millennium and well beyond with great confidence.

Carlo Rubbia

Carlo Rubbia

The ATLAS Experiment

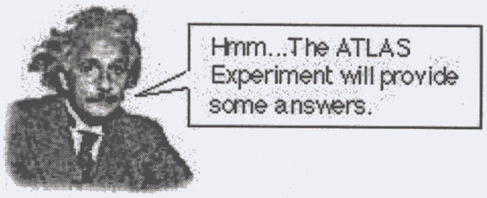
TAKE an eTOUR!

What Questions Remain?

The Standard Model answers many of the questions of the structure and stability of matter with its six types of quarks, six leptons, and the four forces.

But the Standard Model leaves many other questions unanswered:

- Why are there three types of quarks and leptons of each charge?
- Is there some pattern to their masses?
- Are there more types of particles and forces to be discovered at yet higher-energy accelerators?
- Are the quarks and leptons really fundamental, or do they, too, have substructure?
- What particles form the dark matter in the universe?
- How can the gravitational interactions be included in the standard model?



Questions such as these drive particle physicists to build and operate new accelerators, such as the **LHC** with the **ATLAS** detector, in the hope that higher-energy collisions can provide clues to their answers.

Understanding Matter, Energy, Space and Time:
The Case for the Linear Collider

A summary of the scientific case for the $e^+ e^-$ Linear Collider, representing a broad consensus of the particle physics community.

April 2003

(12)

- *Understanding the Higgs boson*

The prime goal for the next round of experimentation is finding the agent that gives mass to the gauge bosons, quarks and leptons. This quest offers an excellent illustration of how the LHC and the e^+e^- Linear Collider will magnify each other's power. If the answer is the standard model Higgs boson, the LHC will see it. However, the backgrounds to the Higgs production process at the LHC are large, making the measurements of the couplings to quarks, quantum numbers, or Higgs self-couplings difficult. The LC can make the Higgs boson with little background, producing it in association with only one or two additional particles, and can therefore measure the Higgs properties much more accurately. Even if it decays into invisible particles, the Higgs can be easily seen and studied at the LC through its recoil from a visible Z boson.

The precision measurements at the LC are crucial for revealing the character of the Higgs boson. If the symmetry of the electroweak interaction is broken in a more complicated way than foreseen in the standard model, these same precision measurements, together with new very precise studies of the W and Z bosons and the top quark only possible at the LC, will strongly constrain the alternate picture.

- *New discoveries beyond the standard model*

Although the standard model with the simplest Higgs boson is in excellent agreement with all we have observed so far, there are very strong reasons for believing that this is far from the complete story. We now know of at least two disparate energy scales that operate for elementary particle physics: the Planck scale at about 10^{19} GeV where the strengths of gravity and the other interactions become comparable, and the electroweak scale at a few hundred GeV. In addition, the strengths of the strong, electromagnetic and weak forces become similar at about 10^{16} GeV where many theories suggest the possibility of grand unification of the three forces. However, an extrapolation of present measurements to higher energies with the simple standard model fails to provide exact unification. To achieve it, some new physics is required at the 100 – 1000 GeV scale. Moreover, the extreme disparity of the electroweak and Planck scales cannot be understood in the standard model; the Higgs, W and Z boson masses are all unstable to quantum fluctuations and would naturally rise to the Planck scale without some new physics at the few hundred GeV scale. This behavior, known as the *hierarchy problem*, gives us confidence that the standard model with its Higgs boson will be supplemented with new phenomena at the TeV scale and that these can be discovered by the LC or LHC.

One such possibility is the existence of new *supersymmetric* space and time coordinates, which brings a set of sister supersymmetric '*sparticles*' nearly identical to all the particles we presently know, save that the partner of a *fermion*

12 v1

As discussed above, one of the main advances in particle physics in the past decade was the accelerator-based studies at the energy frontier leading to the prospect for Higgs boson discoveries and possible new phenomena such as supersymmetry. Another important front has been the rapid evolution of our knowledge about neutrinos. Experiments, particularly those at underground laboratories, have now demonstrated that neutrinos have non-zero mass and that they mix in a way analogous to the quarks, although the numerical values of masses and mixing angles are puzzling.

The small neutrino masses may suggest the presence of new physics at a scale near the grand unification energy. The connection between such a high energy scale glimpsed through the neutrino masses and that inferred from precision studies at the LC may prove to be deep and illuminating. Though not yet demonstrated experimentally, the possibility that charge conjugation and parity (CP) symmetry violation could occur for neutrinos, as well as for quarks, offers a potential opportunity to gain new understanding of the puzzling excess of matter over antimatter in the universe. The LC studies of CP violation effects in supersymmetric particles, taken together with the information from the quark and neutrino sectors, could lead to a more fundamental understanding of origin of the matter-antimatter asymmetry.

Increasingly, particle physics is intertwined with cosmology, and particle astrophysics, and the combination of ideas and methods brings qualitatively new insights.

Cosmologists have deduced from the measurements of the cosmic microwave background that there is almost exactly the right amount of matter and energy to close the universe, but the ordinary matter of stars and interstellar gas comprises only about 4% of the necessary material. Another 23% is inferred from galactic motions as 'dark matter'. The best dark matter candidate to date is the lightest of the supersymmetric particles, which can be precisely studied at the LC. The final 73% or so of the universe's matter is inferred from experiments that study supernova explosions using techniques of particle physics experiments, and is presently wholly mysterious. The standard model predicts that the Higgs boson would contribute far too much 'dark energy' to the universe, so some new physics beyond the standard model would be needed to counteract it. We may hope that the LC and LHC can give us a clue of what this new ingredient could be.

The ultra-high energy cosmic ray particles coming from outer space defy conventional explanation, and may well be harbingers of new particle physics at very high energies, comparable to what can be sensed through the precision measurements at the LHC and LC.

Future LHC and LC experiments will tell us how the unified electroweak force operates. Particle physics experiments have also brought understanding of the is a *boson*, and vice versa. (Fermions such as electrons and quarks have ½ unit of intrinsic spin; bosons have spins of 0 or 1 unit.) We have seen no such supersymmetric particles in experiments to date, but there is reason to expect some of them below a few hundred GeV.

If supersymmetry exists and bears upon the hierarchy problem, we are confident that the LHC will discover it and observe some of the superpartners – in particular the sisters of the quarks and gluons. The partners of the electron, muon, neutrinos, γ, W, and Z are difficult to study precisely at the LHC, but their properties can be measured in detail at the LC. While the LHC has a larger mass reach for superpartners, the precision with which the LC can determine the mass of the accessible sparticles is substantially better (by about an order of magnitude) than for LHC. This is important for sorting out the kind of supersymmetric theory at work, and in pointing the way to how the supersymmetry itself is broken at much higher energies. For the accessible sparticles, the LC will be capable of measuring the full range of their defining properties such as mass, spin, parity, and the mixing parameters among the states of similar character.

In supersymmetry, there is more than one Higgs boson, and the LHC and LC give quite complementary capabilities to discover them and measure their properties. The LC is also unique in its ability to measure the mass of the lightest sparticle precisely. To understand the cosmological origin of this particle, it is necessary to establish its character as a partner of Higgs or of gauge bosons – and the measurements of its couplings at the LC will be unique in establishing this. Knowledge of the lightest particle properties will in turn permit the LHC experiments to make their measurements much more incisive. In many cases, each accelerator must provide crucial information for the other to maximize the sensitivity of its studies, so the combination is much more powerful than the sum of the two independent endeavors.

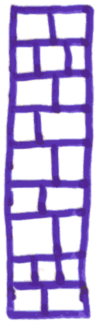
Other ideas to solve the hierarchy problem postulate extra spatial dimensions beyond the three that we know, or new particles at the several TeV scale. If such ideas are correct, we again expect observable consequences at the LHC and the LC and a synergy will exist between them. For example, the LC and LHC combined can deduce both the size and number of extra dimensions. The new states expected from extra dimensions could perhaps be sensed directly at the LHC, but the precision measurements at the LC can measure their effects even for particles well above the range of the direct measurements.

- *The benefit of precision measurements and the interplay of LHC and LC*

- **GAUGE HIERARCHY PROBLEM**
  (global supersymmetry gives a possible solution)

- **GRAVITY** is NOT INCLUDED in THE STANDARD MODEL
  the fourth interaction in nature !

$\underbrace{SU(3)_c \otimes SU(2)_L \otimes U(1)_Y}_{\text{quantum theory (1973)}}$



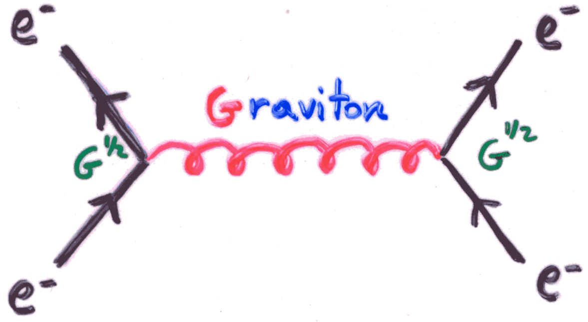
$\underbrace{\text{GENERAL RELATIVITY}}_{\text{classical theory (1915)}}$

* CAN WE QUANTIZE GENERAL RELATIVITY AND UNIFY IT WITH THE STANDARD MODEL ?

THE STARTING POINT IS THE GRAVITON

An elementary particle whose relationship to the classical gravitational field is analogous to that of the photon to the electromagnetic field

THE CHARGE ASSOCIATED WITH GRAVITY IS MASS ($\equiv$ ENERGY)



e⁻
e⁻
Graviton
$G^{1/2}$
$G^{1/2}$
e⁻
e⁻

SUPERGRAVITY

SUPERGRAVITY IS THE GAUGE THEORY OF GLOBAL SUPERSYMMETRY

* CONSIDER TWO CONSECUTIVE INFINITESIMAL GLOBAL SUPERSYMMETRIC TRANSFORMATIONS OF A BOSON FIELD B

first one $\delta_1 B \sim \bar{\varepsilon}_1 F$

second one $\delta_2 F \sim \varepsilon_2 \partial B$

ε is an anticommuting fermionic parameter with $[\varepsilon] = -\frac{1}{2}$

THUS TWO INTERNAL SUPERSYMMETRIC TRANSFORMATIONS HAVE LED TO A SPACETIME TRANSLATION

$$\{\delta_1, \delta_2\} B \sim a^\mu \partial_\mu B \quad ; \quad a^\mu = \bar{\varepsilon}_2 \gamma^\mu \varepsilon_1$$

$\Longrightarrow$ SUPERSYMMETRY IS AN EXTENSION OF THE POINCARE SPACETIME SYMMETRY

$$\{Q, \bar{Q}\} = 2\gamma^\mu P_\mu$$

THE GENERATOR Q IS NOT AN INTERNAL SYMMETRY GENERATOR LIKE, e.g., THE ONES OF THE STANDARD MODEL SYMMETRIES $SU(3)\times SU(2)\times U(1)$

IT IS RELATED TO THE GENERATOR OF SPACE TIME TRANSLATIONS P^μ

$$\text{GLOBAL SUPERSYMMETRY} = \sqrt{\text{translations}}$$

* SO WHEN GLOBAL SUPERSYMMETRY IS PROMOTED TO LOCAL $\varepsilon = \varepsilon(x)$ SPACE TIME DEPENDENT TRANSLATIONS $a^\mu(x)\partial_\mu$ THAT DIFFER FROM POINT TO POINT ARE GENERATED

i.e. A GENERAL COORDINATE TRANSFORMATION $\longrightarrow$ GRAVITY

$$\underbrace{\text{LOCAL SUPERSYMMETRY}}_{\text{SUPERGRAVITY}} = \sqrt{\text{general relativity}}$$

i.e. LOCAL SUPERSYMMETRY IMPLIES GRAVITY

SUPERGRAVITY

$g_{\mu\nu} \longrightarrow \psi^{\mu}_{3/2} \longrightarrow$ GAUGE PARTICLE OF SUPERGRAVITY

GRAVITON GRAVITINO

ONE MAY COUPLE SUPERGRAVITY TO THE STANDARD MODEL

* THE PROBLEM IS THAT THE GRAVITATIONAL INTERACTION IS SO WEAK

$$G = M_p^{-2} \approx 10^{-38} (\mathrm{GeV})^{-2}$$

THAT EXPERIMENTAL VERIFICATION OF QUANTUM GRAVITY AT LOW ENERGIES $\sim M_W$ WILL BE UNLIKELY

e.g. • THE CONTRIBUTION OF THE ABOVE DIAGRAM TO e^-e^- SCATTERING IS NEGLIGIBLE WITH RESPECT TO

$$\alpha_{e.m.} \approx \frac{1}{137} \gg \alpha_G = \frac{E^2}{M_p^2} \approx 10^{-34}$$

* HOWEVER EXPERIMENTAL VERIFICATION OF LOCAL SUPERSYMMETRY (SUPERGRAVITY) IS, IN PRINCIPLE, POSSIBLE

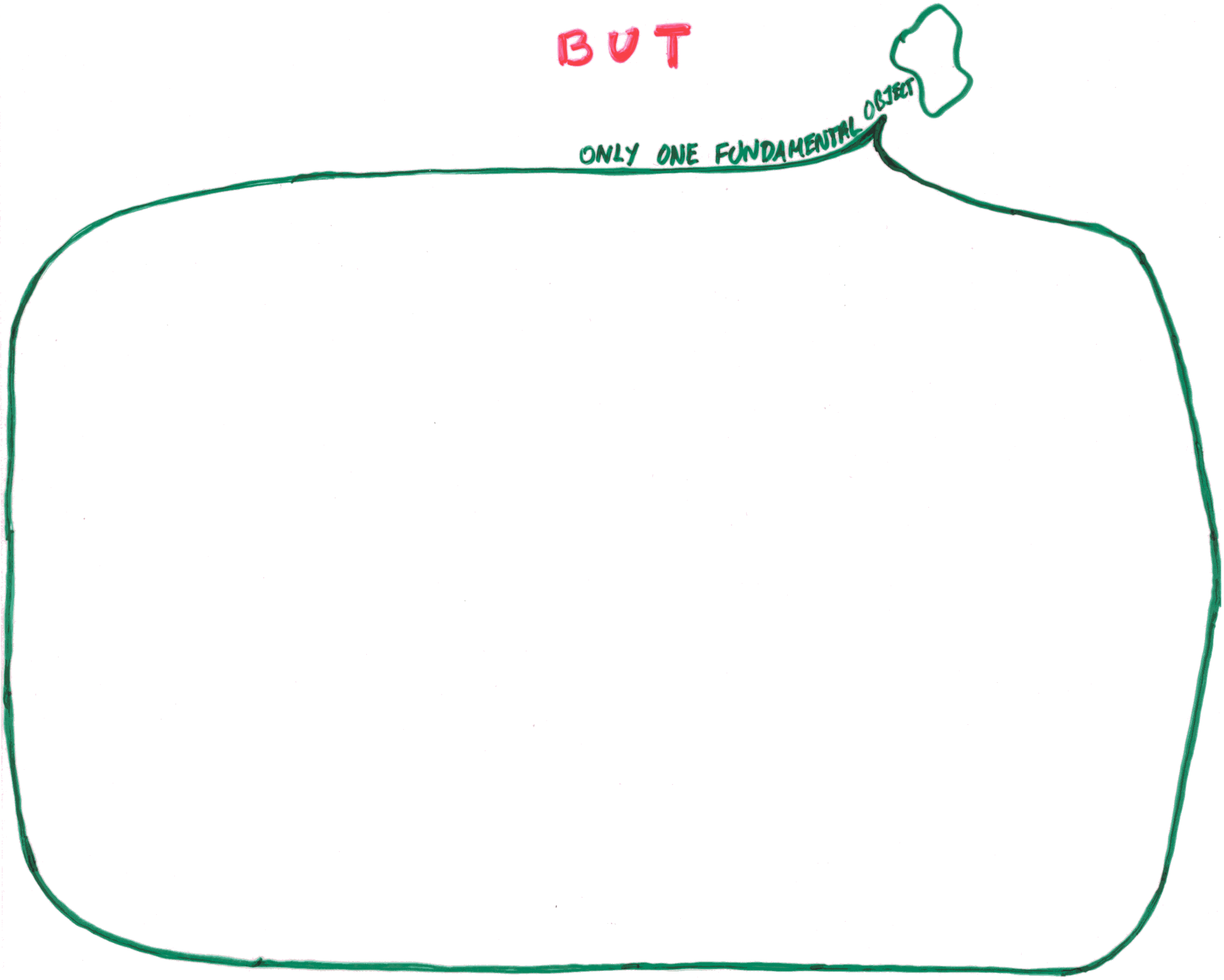
spin 2 particle

$G \quad \tilde{G}$

spin 3/2 particle

FROM THE UNIFICATION VIEWPOINT
THIS DOES NOT SEEM A GREAT SUCCESS

BUT



THE STRING HAS VIBRATIONAL MODES

EACH OF THESE MODES REPRESENT A SET OF PARTICLES IN THE SPECTRUM

SO A STRING DESCRIBES :

- A FINITE NUMBER OF MASSLESS PARTICLES

  GRAVITON, QUARKS, LEPTONS, ...

- AN INFINITE TOWER OF MASSIVE PARTICLES $(\sim M_P)$

IN ADDITION POINT-LIKE OBJECTS → STRINGS

MAY ALSO ALLOW US TO ANSWER THE METAPHYSICAL QUESTIONS

WHAT IS STRING PHENOMENOLOGY?

The Search of the Standard Model in String Theory

SUSY

MAY BE Str. Phen. is NOT ONLY THIS

BUT THIS is, AT LEAST, A NECESSARY CONDITION!

BUT SUSY MUST BE BROKEN, OTHERWISE $m_{\tilde{e}} = 0.5$ MeV

ONE MAY INTRODUCE TERMS WHICH EXPLICITLY BREAK SUSY (e.g. scalar and gaugino masses) WITHOUT INTRODUCING QUADRATIC DIVERGENCES :

$$m_\alpha^2 \phi_\alpha \phi_\alpha^* , \; M_a \bar{\lambda}^a \lambda^a , \; A_{\alpha\beta\gamma} \phi_\alpha \phi_\beta \phi_\gamma , \; B_{\alpha\beta} \phi_\alpha \phi_\beta$$

SOFT TERMS

IN THE MSSM ASSUMING UNIVERSALITY OF SOFT TERMS :

m, M, A, B

they determine the susy spectrum ($\tilde{q}, \tilde{\ell}, \tilde{\gamma}, \ldots$)

BUT $\quad m_H^2 \sim m^2 + M^2 + A^2 + \ldots$

NO FINE-TUNING $\longrightarrow$ $m_{SUSY} \lesssim 1$ TeV

$\boxed{\bullet \text{ WHY } m_{SUSY} << \Lambda_{GUT} \text{ ?}}$

$\boxed{\bullet \text{ WHAT IS THE ORIGIN OF THE SOFT TERMS ?}}$

SUGRA MAY BE THE ANSWER!

$100\ \text{GeV} \lesssim m_{susy} \lesssim 1000\ \text{GeV}$

$\downarrow$ EXPERIMENTAL BOUND

$\downarrow$ THEORETICAL BOUND (FINE TUNING)

also e.g. CCB constraints

$|A_u|^2 \leq 3(m^2_{Q_L} + m^2_{u^c_L} + m^2_{H_2})$

$\boxed{\text{WHY } m_{susy} \ll M_{Planck} \text{ ?}}$

$\boxed{\text{WHAT IS THE ORIGIN OF THE SOFT TERMS ?}}$

SUGRA MAY BE THE ANSWER

ORIGIN OF THE SOFT TERMS

$\boxed{\text{WHEN SUGRA IS SPONTANEOUSLY BROKEN THE SOFT TERMS ARE GENERATED}}$

$\mathcal{L}_{SUGRA}$ IS SPECIFIED IN TERMS OF G AND f

$$\left.\begin{array}{l} G(\phi_\alpha, \phi_\alpha^*) = K(\phi_\alpha, \phi_\alpha^*) + \log|W(\phi_\alpha)|^2 \\ f_a(\phi_\alpha) \longrightarrow G = \prod_a G_a \end{array}\right\} \phi_\alpha = \tilde{q}, \tilde{\ell}, H_{1,2}, h$$

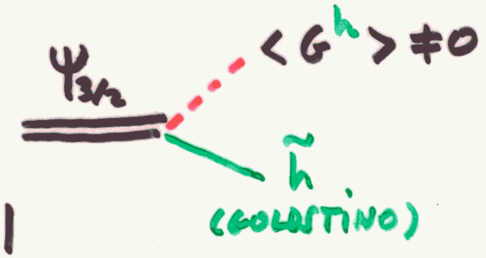
PARTICLES WITH NO $SU(3)\times SU(2)\times U(1)$ QUANTUM NUMBERS WHICH COUPLE TO THE "OBSERVABLE SECTOR" (quarks, leptons, ...) ONLY GRAVITATIONALLY

"HIDDEN SECTOR"

e.g. $$\boxed{\frac{1}{4}\frac{\partial f_a}{\partial \phi_\alpha} e^{G/2} (G^{-1})^\beta_\alpha}\, \bar{\lambda}^a \lambda^a \, , \quad V = \boxed{e^G\left(G_\alpha (G^{-1})^\alpha_\beta G^\beta - 3\right)}$$

SUGRA IS BROKEN WHEN AT THE MINIMUM OF V, $\langle h \rangle \neq 0$

AND $\langle G^h \rangle \equiv \langle \frac{\partial G}{\partial h} \rangle \neq 0$



$$m_{3/2} = e^{G/2} = e^{K/2}|W(h)|$$

SIGNALS FROM HIDDEN SECTOR : SOFT TERMS

$$\boxed{M_a}\, \bar{\lambda}^a \lambda^a \qquad \boxed{m_\alpha^2\, \phi_\alpha \phi_\alpha^* \quad A_{\alpha\beta\gamma}\, \phi_\alpha \phi_\beta \phi_\gamma \quad B_{\alpha\beta}\, \phi_\alpha \phi_\beta}$$

PLUGGING G AND EXPANDING

$$M_a, m_\alpha, A_{\alpha\beta\gamma}, B_{\alpha\beta} \sim m_{3/2}$$

A HIDDEN SECTOR MIGHT BE PRESENT IN STRINGS

e.g. in the heterotic string the gauge group is $E_8 \times E_8$

THE FINAL LAGRANGIAN with up to two derivatives TURNS OUT TO DEPEND ONLY ON A SINGLE ARBITRARY REAL AND GAUGE INVARIANT FUNCTION OF THE SCALAR FIELDS

$$\underbrace{G(\phi^*,\phi)}_{\text{KÄHLER FUNCTION}} = \underbrace{K(\phi^*,\phi)}_{\text{KÄHLER POTENTIAL}} + \ln|\underbrace{W(\phi)}_{\text{SUPERPOTENTIAL}}|^2$$

K and W entering through G (unlike the case of global susy) expresses the fact that the scalar field space in sugra is a Kähler manifold (i.e. a special type of analytic Riemann manifold)

G (AND THEREFORE $\mathcal{L}$) IS INVARIANT UNDER THE TRANSFORMATION

$$\left.\begin{aligned} K &\longrightarrow K + F(\phi) + F^*(\phi^*) \\ W &\longrightarrow e^{-F}W \end{aligned}\right\}$$

F IS AN ARBITRARY FUNCTION

LET US SPLIT THE SUGRA LAGRANGIAN INTO TERMS AS

$$\mathcal{L} = \mathcal{L}_B + \mathcal{L}_{FK} + \mathcal{L}_F$$

$\mathcal{L}_B$: only bosonic fields

$\mathcal{L}_{FK}$: fermionic fields and covariant derivatives

$\mathcal{L}_F$: no covariant derivat.

$$e^{-1}\mathcal{L}_B = -\frac{1}{2}R - \underbrace{G_{ij^*} D_\mu\phi^i D^\mu\phi^{*j}}_{\text{KINETIC TERMS}} - \underbrace{e^G\left(G_i (G^{-1})^{ij^*} G_{j^*} - 3\right)}_{\text{TREE LEVEL F-TERM SCALAR POTENTIAL}}$$

fundamental equation for model building (soft terms)

VIERBEIN

$$e \equiv \det e^m_\mu = \sqrt{-\det g_{\mu\nu}}$$

$$G_i \equiv \frac{\partial G}{\partial \phi_i} \quad , \quad G_{ij^*} = \frac{\partial^2 G}{\partial\phi_i \partial\phi^*_j} = K_{ij^*} \; ; \; \frac{1}{\kappa} = \frac{M_P}{\sqrt{8\pi}} = 2.4\times10^{18}\,\text{GeV} \equiv M_p = 1$$

K determines the kinetic terms of the chiral mult.

gravitino → covariantized with respect to gravity

$$e^{-1}\mathcal{L}_{FK} = -\frac{1}{2} e^{-1}\varepsilon^{\mu\nu\rho\sigma}\bar\Psi_\mu\gamma_5\gamma_\nu D_\rho\Psi_\sigma + \frac{1}{4} e^{-1}\varepsilon^{\mu\nu\rho\sigma}\bar\Psi_\mu\gamma_\nu\Psi_\rho\left(G_i D_\sigma\phi^i - G_{i^*} D_\sigma\phi^{*i}\right)$$

→ usual fermions

$$+\Big[\frac{i}{2}G_{ij^*}\bar\Psi^i_L \not{D}\Psi^j_L + \frac{i}{2}\bar\Psi^i_L\not{D}\phi^j\Psi^k_L\left(-G_{ijk^*}+\frac{1}{2}G_{ik^*}G_j\right)$$

$$+\frac{1}{\sqrt{2}}G_{ij^*}\bar\Psi^\mu_L\not{\partial}\phi^{i*}\gamma_\mu\Psi^j_R + h.c.\Big]$$

THIS CONTAINS THE KINETIC TERMS FOR THE FERMIONS AND SOME NON-RENORMALIZABLE INTERACTION TERMS e.g.

$$e^{-1}\mathcal{L}_F = e^{G/2}\bar\Psi^\mu\sigma_{\mu\nu}\Psi^\nu + \Big[\frac{1}{2}e^{G/2}\left(-G_{ij} - G_iG_j + G_{ijk^*}(G^{-1})^{k^*l}G_l\right)\bar\Psi^i_L\Psi^j_R$$

$$e^{G/2}G_i\bar\Psi^\mu_L\gamma_\mu\Psi^i_L + h.c.\Big] + \text{FOUR-FERMION TERMS}$$

THIS CONTAINS THE FERMION YUKAWA COUPLINGS $G_{ij} \to W_{ij} \sim \phi^K$

AND NUMEROUS NON-RENORMALIZABLE TERMS if $W \sim \phi^i\phi^j\phi^K$

BESIDES, IF SOME OF THE SCALAR FIELDS ϕ_i DEVELOP EXPECTATION VALUES, A GRAVITINO MASS MAY APPEAR (susy breaking)

* INCLUDING VECTOR SUPERMULTIPLETS

$$\mathcal{L}_{GLOBAL} = \int d^4\theta\, K(\Phi^\dagger e^V, \Phi) + \int d^2\theta \left(W(\Phi) + h.c.\right) + \int d^2\theta \left(f_{ab}(\Phi) W^\alpha_a W_{\alpha b} + h.c.\right)$$

V IS THE VECTOR SUPERFIELD

W^α_a IS THE GAUGE FIELD STRENGTH SUPERFIELD

$\alpha \to$ spinor index

$a \to$ gauge index

$f_{ab}(\Phi)$ IS AN ARBITRARY FUNCTION OF THE CHIRAL SUPERFIELDS WHICH WOULD BE JUST $\frac{\delta_{ab}}{g^2}$ IN THE RENORMALIZABLE CASE

$\to$ GAUGE KINETIC FUNCTION

GLOBAL $\longrightarrow$ LOCAL $\Rightarrow$ THE FINAL LAGRANGIAN WHICH COUPLES
N=1 PURE SUPERGRAVITY to
N=1 CHIRAL SUPERFIELD MATTER and
N=1 SUSY YANG-MILLS is :

$$\mathcal{L} = \mathcal{L}_B + \mathcal{L}_{FK} + \mathcal{L}_F + \mathcal{L}_B^V + \mathcal{L}_{FK}^V + \mathcal{L}_F^V$$

$\mathcal{L}_F \to D_\mu$ also covariantized with respect to the gauge group

e.g. $\bar{\psi}^i \not{D} \psi^j$

$$e^{-1}\mathcal{L}_B^V = -\frac{1}{4}\underbrace{(\mathrm{Re}\, f_{ab})}_{1/g^2}(F_a)_{\mu\nu}(F_b)^{\mu\nu} + \frac{i}{4}(\mathrm{Im}\, f_{ab})(F_a)_{\mu\nu}\tilde{F}_b^{\mu\nu}$$
$$\underbrace{-\frac{1}{2}(\mathrm{Re}\, f_{ab})^{-1} G_i (T_a)^{ij}\phi_j\, G_k (T_b)^{kl}\phi_l}_{\text{D-TERM}}$$

WHERE $f_{ab} = f_{ab}(\phi)$

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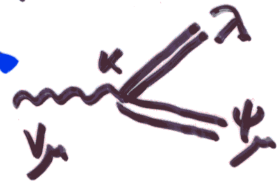
$$e^{-1}\mathcal{L}^V_{FK} = \frac{1}{2}\,\mathrm{Re}\, f_{ab}\Big(\frac{1}{2}\bar\lambda_a \not{D}\lambda_b + \frac{1}{2}\overset{\text{gaugino}}{\bar\lambda_a}\gamma^\mu\sigma^{\nu\rho}\psi_\mu (F_b)_{\nu\rho} + \frac{1}{2}G_i D^\mu\phi^i\bar\lambda_{aL}\gamma_\mu\lambda_{bL}\Big)$$

$$-\frac{i}{8}\,\mathrm{Im}\, f_{ab}\, D_\mu(e\bar\lambda_a\gamma_5\gamma^\mu\lambda_b) - \frac{1}{2}\frac{\partial f_{ab}}{\partial\phi^i}\bar\psi_{iR}\sigma^{\mu\nu}(F_a)_{\mu\nu}\lambda_{bL} + \mathrm{h.c.}$$

e.g. 

$$e^{-1}\mathcal{L}^V_F = \underbrace{\frac{1}{4}e^{G/2}\frac{\partial f^*_{ab}}{\partial\phi^{j*}}(G^{-1})^{jk^*}G_{k^*}}\lambda_a\lambda_b$$

$$-\frac{i}{2}G_i(T_a)^{ij}\phi_j\bar\psi_{\mu L}\gamma^\mu\lambda_{aL} + 2i\, G^i_j(T_a)_{ik}\phi^k\bar\lambda_{aR}\psi_{iL}$$

$$-\frac{i}{2}\,\mathrm{Re}\, f^{-1}_{ab}\frac{\partial f_{bc}}{\partial\phi_k}G^i(T_a)_{ij}\phi^j\bar\psi_{kR}\lambda_{cL} + \mathrm{h.c.}$$

+ four-fermion terms

IF SOME OF THE SCALAR FIELDS ϕ_i DEVELOP EXPECTATION VALUES, GAUGINO MASS TERMS MAY APPEAR

SUMMARIZING : THE SUGRA LAGRANGIAN DEPENDS ONLY ON THE TWO FUNCTIONS

$$G(\phi,\phi^*) = K(\phi,\phi^*) + \ln|W(\phi)|^2\ ,\quad f_{ab}(\phi)$$

THIS POSSIBILITY $\langle V \rangle = \langle e^G (G_i (G^{-1})^{ij^*} G_{j^*} - 3) \rangle = 0$

SEEMS TO BE PREFERRED PHENOMENOLOGICALLY

BY THE ABSENCE OF A COSMOLOGICAL CONSTANT :

EXPERIMENTAL BOUND IS $\Lambda \lesssim 10^{-45}\ \mathrm{GeV}^4$

IF $V \neq 0$ ITS VALUE WOULD BE

$$\langle V \rangle \approx m_{3/2}^2 M_p^2 \gtrsim (10^3\,\mathrm{GeV})^2 (10^{18}\,\mathrm{GeV})^2 = 10^{42}\,\mathrm{GeV}^4$$

$$\frac{\langle V \rangle}{\Lambda} \gtrsim 10^{87}$$

IN ANY CASE, IT IS NOT CLEAR WHY THE TERMS IN THE SCALAR POTENTIAL SHOULD CONSPIRE TO HAVE $\langle V \rangle = 0$ AT THE MINIMUM

This is the cosmological constant problem in Sugra

(also higher order terms)

AT LOW-ENERGIES ONE IS LEFT WITH

$$\mathcal{L}_{SUGRA} \sim \mathcal{L}_{GLOBAL\ SUSY} + \mathcal{L}_{SOFT}$$

$SU(2)_L \otimes U(1)_Y$ BREAKING

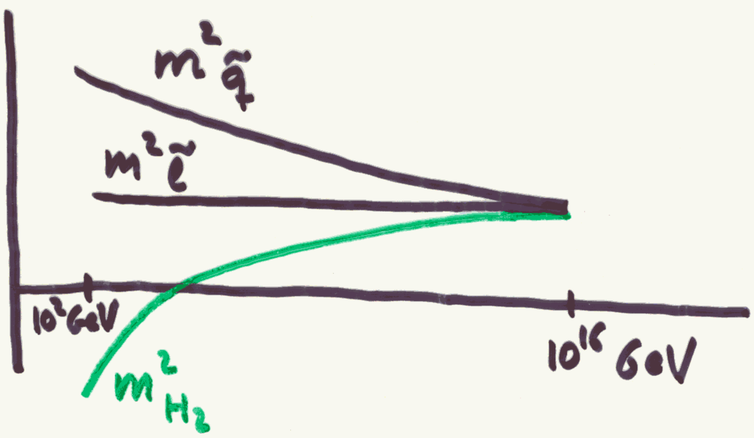
THE HIGGS POTENTIAL IS MORE NATURALLY GENERATED THAN IN THE NON-SUSY STANDARD MODEL $V = m^2 |H|^2 + \lambda |H|^4$

$$V(H_1, H_2) = \underbrace{\frac{1}{8}(g_2^2 + g'^2)\left[|H_1|^2 - |H_2|^2\right]^2}_{\text{D-terms}} + \underbrace{m_1^2 |H_1|^2 + m_2^2 |H_2|^2}_{\text{soft terms}} + (B\mu\, H_1 H_2 + h.c.)$$

$W = \mu H_1 H_2 + \dots$

EXTRA BONUS : RADIATIVE BREAKING OF $SU(2)_L \otimes U(1)_Y \to U(1)_{e.m.}$

$$\frac{dm_2^2}{dt} \simeq g_2^2 M_2^2 - \lambda_t^2 m_{\tilde t}^2$$



THE μ PROBLEM

THE PRESENCE OF THE μ TERM IS CRUCIAL

$$\mu = 0 \Rightarrow \begin{cases} \bullet \text{ THE MINIMUM OF } V_{H_{1,2}} \text{ OCCURS FOR } \langle H_1 \rangle = 0 \\ \bullet \text{ UNACCEPTABLE AXION} \end{cases}$$

BUT IN PRINCIPLE THE NATURAL SCALE OF μ IS M_P !

SINCE $W = \mu H_1 H_2 + \ldots$

MANY SOLUTIONS HAVE BEEN PROPOSED, e.g.:

- COUPLING IN THE SUPERPOTENTIAL $\lambda W(h) H_1 H_2 \Rightarrow \mu \sim \lambda \langle W(h) \rangle$; $m_{3/2}^2$

- IF $K = Z H_1 H_2 + h.c. + \ldots$

  AN EFFECTIVE LOW-ENERGY B TERM IS GENERATED

$$V = \underset{m_{3/2}}{B}\ \underset{m_{3/2}^2 Z}{\mu}\ H_1 H_2$$

FOR THESE MECHANISMS TO WORK, THE $\mu H_1 H_2$ MUST BE ABSENT IN W (OTHERWISE $\mu \sim M_P$)

THIS IS AUTOMATICALLY GUARANTEED IN STRINGS AND BESIDES BOTH SOLUTIONS ARE <u>NATURALLY</u> PRESENT

⊛ $$W = \lambda N H_1 H_2$$

$$\mu = \lambda \langle N \rangle$$

WHY $m_{3/2} \ll M_P$?

CORRECT SUSY BREAKING $\rightarrow$ $m_{3/2} \sim M_W$ BUT $m_{3/2} \sim W(h)$

WHY $\langle W(h) \rangle \sim M_W$?

A POSSIBLE EXPLANATION IS GAUGINO CONDENSATION IN SOME HIDDEN GAUGE GROUP

IT CAN BE DESCRIBED BY AN EFFECTIVE NON-PERTURBATIVE SUPERPOTENTIAL

$$W^{np} \sim \Lambda_c^3 \sim M_P^3\, e^{-\frac{24\pi^2}{b_0 g^2}}$$

$$m_{3/2} \sim M_P\, e^{-\frac{24\pi^2}{b_0 g^2}} \lesssim 1 \text{ TeV}$$

$\rightarrow$ SINCE THE EXPONENTIAL CAN BE VERY SMALL FOR REASONABLE b_0, g

$M_P \sim 10^{18}$ GeV

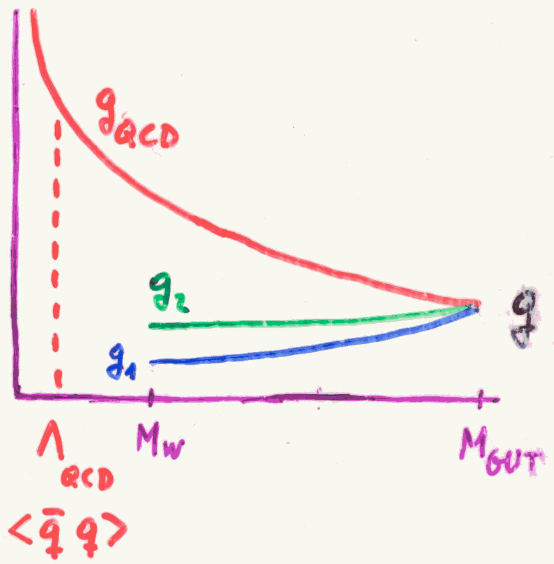
e.g. FOR $g = 0.74$, $G_H = SU(4)$ i.e. $b_0 = 12$ $\rightarrow$ $\frac{24\pi^2}{b_0 g^2} = 36$

i.e. $m_{3/2} \sim 0.5$ TeV ; $\Lambda_c \sim 10^{13}$ GeV

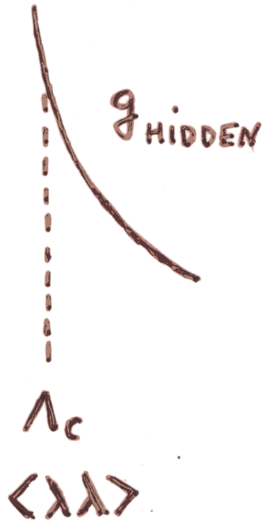
WHEN A GAUGE INTERACTION BECOMES STRONG AT SOME SCALE IT IS FAVOURED THE APPEARANCE OF FERMION CONDENSATES

e.g. QUARK CONDENSATES IN QCD

$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$



$\otimes\ G_H$



IN THE SAME WAY, IN A SUPERSYMMETRIC YANG-MILLS THEORY WHEN THE COUPLING BECOMES STRONG (IN A HIDDEN SECTOR) THERE APPEAR GAUGINO CONDENSATES

$$\langle\lambda\lambda\rangle = \Lambda_c^3$$

$$\frac{1}{g^2(\mu)} = \frac{1}{g^2(M)} - \frac{b_0}{16\pi^2}\log\left(\frac{M}{\mu}\right)^2 \quad ;$$

WHERE b_0 IS THE β-FUNCTION COEFFICIENT OF G_{HIDDEN}

$b_0 = 3\,C(G_H)$

$$g^2(\mu = \Lambda_c) \longrightarrow \infty \quad \Rightarrow \quad \Lambda_c \sim M\, e^{-\frac{8\pi^2}{b_0 g^2(M)}}$$

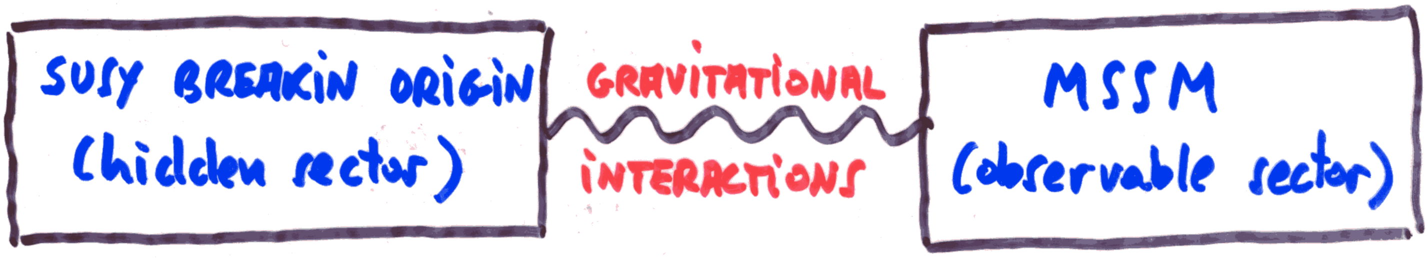
$$\langle\lambda\lambda\rangle \sim M^3\, e^{-\frac{24\pi^2}{b_0 g^2(M)}}$$

SUMMARIZING: SUSY BREAKING OCCURS IN A "HIDDEN SECTOR" OF PARTICLES WHICH HAVE NO $SU(3)\times SU(2)\times U(1)$ QUANTUM NUMBERS

BUT COUPLE TO THE OBSERVABLE SECTOR THROUGH (non-renormalizable) GRAVITATIONAL INTERACTIONS

$$\phi_i = \tilde{q},\ \tilde{\ell},\ H_{1,2},\ h$$

$$\lambda_a = \tilde{g},\ \tilde{\gamma},\ \dots$$



* THE CHARACTERISTICS OF THE SOFT TERMS ARE DETERMINED BY THE TYPE OF SUPERGRAVITY THEORY UNDER CONSIDERATION

e.g. $K = \sum_i \phi_i \phi_i^* = \tilde{q}\tilde{q}^* + \tilde{e}\tilde{e}^* + \dots + \underline{h h^*}$

canonical kinetic terms $\frac{\partial^2 K}{\partial \phi_i \partial \phi_j^*} D_\mu \phi_i D^\mu \phi_j^*$

$f_{ab} = \delta_{ab} \underline{h}$ → non-vanishing gaugino masses $M_a \propto \frac{\partial f}{\partial h}$

$$W = W^h(\underline{h}) + W^{obs}$$

$W^{obs} = Y_u Q_L H_2 u^c + Y_d Q_L H_1 d^c + Y_e L_L H_1 e^c + \mu H_1 H_2$

responsible for the susy breaking when $\langle h \rangle \neq 0$

$$V = e^G \left(G_i (G^{-1})^{ij^*} G_{j^*} - 3 \right) = e^K \left[\sum_i \left| \frac{\partial W}{\partial \phi_i} + \phi_i^* W \right|^2 - 3|W|^2 \right]$$

+ D-TERMS

$$= \sum_i \left| \frac{\partial W^{obs}}{\partial \phi_i^{obs}} \right|^2 + \sum_i \frac{\partial W^{obs}}{\partial \phi_i^{obs}} \phi_i^{obs} \underline{W^{*h}} + \sum_i \phi_i^{obs} \phi_i^{*obs} \underline{e^{K^h} |W^h|^2} + \dots$$

In taking the low-energy limit, we need to hold $m_{3/2}$ fixed as $M_p \to \infty$

$$= \sum_i \left| \frac{\partial W^{obs}}{\partial \phi_i^{obs}} \right|^2 + W_t^{obs} (\underline{W^{*h} + \dots}) + W_b^{obs} (\underline{W^{*h} + \dots}) + \sum_i \phi_i^{obs} \phi_i^{obs*} \underline{m_{3/2}^2}$$

+ D-TERMS

$m_i = m_{3/2}$ → UNIVERSALITY! desirable property to avoid FCNC effects $m_{\tilde{u}} \approx m_{\tilde{c}}$, $m_{\tilde{d}} \approx m_{\tilde{s}}$, $m_{\tilde{e}} \approx m_{\tilde{\mu}}$

$B = A - m_{3/2} = m_{3/2} h^* \frac{\partial G}{\partial h^*} - m_{3/2}$

$M_a = m_{3/2} \frac{\partial G}{\partial h} (h + h^*)^{-1}$

We have learnt things about soft terms even <u>without</u> knowing the details of susy breaking i.e. $W^h(h)$ (in $m_{3/2}, \frac{\partial G}{\partial h}$)

PREDICTIVITY FOR SOFT TERMS?

ONCE K, W, f AND h ARE KNOWN, THE SOFT TERMS (m, M, A, B) ARE CALCULABLE

e.g. $K = \sum_\alpha \phi_\alpha \phi_\alpha^* = h h^* + \tilde{q}\tilde{q}^* + \tilde{e}\tilde{e}^* + \dots$

$$\begin{cases} m_\alpha^2 = m_{3/2}^2 + \langle V \rangle \\ A_{\alpha\beta\gamma} = m_{3/2}\, h^* \dfrac{\partial G}{\partial h^*} \\ B = A_{\alpha\beta\gamma} - m_{3/2} \end{cases}$$

$W(h)$

PRESENT COSMOLOGY $\Rightarrow \langle V \rangle = 0$

SUSY BREAKING MECHANISM SHOULD IMPLY IT

SOFT SCALAR MASSES ARE UNIVERSAL!

THIS IS A DESIRABLE PROPERTY NOT ONLY TO REDUCE THE NUMBER OF INDEPENDENT PARAMETERS $21 \longrightarrow 1$

BUT

ALSO TO AVOID FCNC

$m_{\tilde{u}} \sim m_{\tilde{c}}$
$m_{\tilde{d}} \sim m_{\tilde{s}}$
$m_{\tilde{e}} \sim m_{\tilde{\mu}}$

HOWEVER THIS RESULT IS SUGRA MODEL DEPENDENT

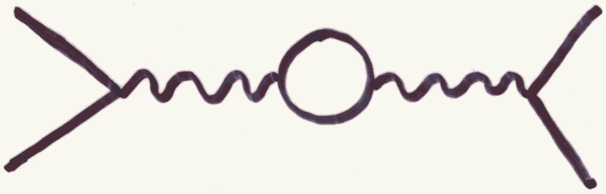
$K = ?$ $\quad f = ?$ $\quad h?$ → NO SLIGHTEST IDEA OF WHAT FIELDS COULD BE INVOLVED IN SUGRA BREAKING

IN THE SUGRA THEORY COMING FROM STRINGS

- THERE ARE NATURAL CANDIDATES FOR h
- K, f ARE CALCULABLE

SUGRA IS NON RENORMALIZABLE

THE STANDARD MODEL IS NOT FINITE (ULTRAVIOLET DIVERGENCES)

 $= \infty$

BUT THE TOOL OF RENORMALIZATION ALLOW US TO CANCEL THE DIVERGENCES

WHEN GRAVITY IS INCLUDED THE THEORY IS NONRENORMALIZABLE

$$G_N = M_P^{-2}$$

WE MUST CONSIDER THE SUGRA LAGRANGIAN AS AN EFFECTIVE PHENOMENOLOGICAL LAGRANGIAN WHICH COMES FROM A BIGGER ESTRUCTURE, RENORMALIZABLE OR EVEN FINITE (SUPERSTRINGS ?)

$$P << M_P$$

SIMILAR SITUATION TO THE ONE OF THE FERMI THEORY

DISCUSSION

* $\sqrt{}^{N=0}$ QUANTUM GRAVITY IS NONRENORMALIZABLE

* $\sqrt{}^{N\geq 1}$ SUPERGRAVITY INCLUDES GRAVITY IN A NATURAL WAY BUT IT IS ALSO NON RENORMALIZABLE

* THEN, IS TO WORK AT LOW ENERGIES WITH THE PHYSICALLY RELEVANT $\underbrace{\ }_{N=1}$ SUPERGRAVITY CONSISTENT ?

YES IF WE ARE CONSIDERING THE SUPERGRAVITY LAGRANGIAN AS AN EFFECTIVE PHENOMENOLOGICAL LAGRANGIAN WHICH COMES FROM A BIGGER STRUCTURE, RENORMALIZABLE OR EVEN FINITE

THIS SITUATION IS SIMILAR TO THE ONE OF THE OLD FERMI THEORY

nonrenormalizable interaction since $[G_F] = -2$

HOWEVER FOR $p \ll M_W$ IS O.K. TO WORK WITH THIS GRAPH

BUT FOR $p \approx M_W$ WE MUST USE

ALTHOUGH FOR $p \approx M_P$ WE MUST USE THE THEORY BEHIND SUPERGRAVITY

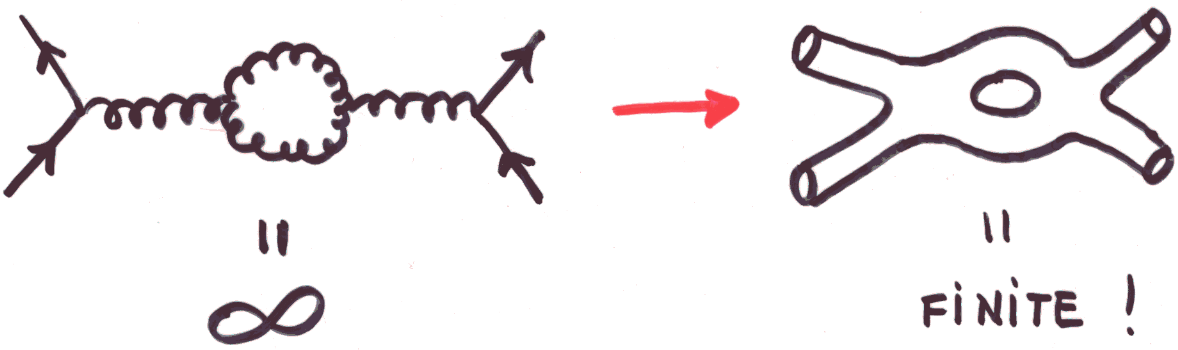
FOR $p \ll M_P$ IS O.K. TO WORK WITH SUPERGRAVITY ALTHOUGH IT IS NONREN.

* BELOW M_P (i.e. in the so-called flat limit where $M_P \to \infty$ but $m_{3/2}$ is kept fixed) ONE IS LEFT WITH A GLOBAL SUSY LAGRANGIAN PLUS SOFT SUSY-BREAKING TERMS

THIS EFFECTIVE LAGRANGIAN IS RENORMALIZABLE AND IN ORDER TO STUDY PHENOMENOLOGY WE ARE INTERESTED ONLY IN THIS REGION

* THERE IS, AT THE TIME OF GIVING THIS LECTURE, ONLY ONE KNOWN THEORY DESCRIBYING QUANTUM GRAVITY IN THE PRESENCE OF MATTER WHICH MAY BE FINITE :

SUPERSTRING THEORY



THE LOW-ENERGY LIMIT (massless modes) OF SUPERSTRING THEORY IS A SUPERGRAVITY THEORY !

FROM SUPERSYMMETRY

$\boxed{\text{SUPERSTRING THEORY}}$ $\qquad E \gtrsim M_p$

$\downarrow$

$\boxed{\text{SUPERGRAVITY}}$ $\qquad E \lesssim M_p$

$\downarrow$

$\boxed{\text{MSSM}}$ $\qquad E \ll M_p$

* IT IS THEREFORE CRUCIAL TO UNDERSTAND THE INTERMEDIATE STEP, SUPERGRAVITY, BETWEEN THE POSSIBLE FINAL THEORY OF ELEMENTARY PARTICLES AND THE POSSIBLE LOW-ENERGY EFFECTIVE THEORY (EXPERIMENTS!)

CONCLUSIONS

WORKING BEYOND THE STANDARD MODEL

WE HAVE PARTIALLY SOLVED SOME PROBLEMS

- SUSY "SOLVES" THE HIERARCHY PROBLEM
- SUGRA INCLUDES GRAVITY AND EXPLAINS THE ORIGIN OF THE SOFT TERMS (ALTHOUGH IS NON RENORMALIZABLE)

BUT

STILL WE HAVE NOT ANSWERED

THE QUANTIZATION OF GRAVITY

MOST OF THE METAPHYSICAL QUESTIONS

THESE EXTENSIONS ARE JUST QFTs