SUPERSYMMETRY

PRO AND CON

SUPERSYMMETRY IS A VISION OF WHAT MAY BE STORE IN PARTICLE PHYSICS...

THERE ARE SERIOUS PROS AND CONS, i.e. REASONS TO BE OPTIMISTIC OR LESS OPTIMISTIC ABOUT SUPERSYMMETRY, AND I WAN TO SURVEY SOME OF THEM TODAY

ON THE PLUS SIDE ARE SOME FAMILIAR ARGUMENTS:

* THE HIERARCHY PROBLEM

  SMALLNESS OF M_W / M_{GUT}

* NOT JUST A TECHNICAL SOLUTION

  – A UNIQUE NEW SYMMETRY AND PART OF A LARGER VISION OF PHYSICS

* VALUE OF $\sin^2\theta_W$ AND SUSY GUTS

* NATURAL MECHANISM OF ELECTROWEAK SYMMETRY BREAKING

* COMPATIBLE WITH ELECTROWEAK TEST

TO UNDERSTAND SOME OF THESE POINTS, WE SHOULD RECALL THAT IN FACT GRAND UNIFICATION HAS SOME STRIKING MERITS:

* MAKE SENSE OF QUARK AND LEPTON QUANTUM NUMBERS

$$\begin{pmatrix} u \\ d \end{pmatrix}_{1/3} \oplus \bar{u}_{-4/3} \oplus \bar{d}_{2/3} \oplus \begin{pmatrix} \nu \\ e^- \end{pmatrix}_{-1} \oplus e^+_2$$

A SINGLE GENERATION IS NEATLY INTERPRETED AS $\bar{5} \oplus 10$ OF SU(5)

OR 16 OF SO(10)

* THE UNIFICATION SCALE M_{GUT} INFERRED FROM LOW ENERGY DATA IS RELATIVELY CLOSE TO THE PLANCK SCALE ...

AND HIGH ENOUGH TO AVOID DISASTER WITH THE PROTON LIFETIME ....

* THE NEUTRINO MASS SCALE SUGGESTED IN THE LATE 1970's BASED ON GUT's

$$m_\nu \sim \frac{M_W^2}{M_{GUT}} \sim 10^{-2}\ \text{eV}$$

HAS PROVED TO BE ABOUT RIGHT

– 20 YEARS LATER.

* FITS NEATLY WITH STRINGS, QUANTUM GRAVITY

* CMB FLUCTUATIONS AND GUT SCALE?

THESE SUCCESSES OF GUT's ARE ALSO HINTS OF SUPERSYMMETRY AS THE OTHER PREDICTION OF GUT's - THE VALUE OF THE WEAK ANGLE $\sin^2\theta_W \simeq .23$ - WORKS OUT BEAUTIFULLY WITH SUPERSYMMETRY, AND NOT WITHOUT IT.

MOREOVER, GUTs NEED SUPERSYMMETRY FOR OTHER REASONS:

THE PROTON LIFETIME AS ORIGINALLY ESTIMATED FROM GUT's TURNED OUT TO BE TOO SHORT, BUT SUPERSYMMETRY NATURALLY RAISES IT

AND SUPERSYMMETRY MOVES THE UNIFICATION SCALE EVEN CLOSER TO THE PLANCK SCALE, SHARPENING THE HINT OF A UNIFICATION WITH GRAVITY.

AS THIS ILLUSTRATES, SUPERSYMMETRY ISN'T JUST A TECHNICAL SOLUTION TO PROBLEMS LIKE THE HIERARCHY PROBLEM

IT IS

* A UNIQUE NEW SYMMETRY PRINCIPLE
* PART OF AN ATTRACTIVE, LARGER PICTURE IN GUT's
* AN ESSENTIAL PART OF AN EVEN MORE AMBITIOUS PICTURE IN STRING THEORY

MOREOVER, WHILE SOME ALTERNATIVE THEORIES OF THE SMALLNESS OF THE ELECTROWEAK SCALE - LIKE MODELS OF COMPOSITE HIGGS BOSONS - HAVE REPEATEDLY HAD TROUBLE, SUPERSYMMETRY IS COMFORTABLY CONSISTENT WITH THE PRECISION ELECTROWEAK TESTS.

FINALLY, I THINK I SHOULD

ADD THAT WITH SUPERSYMMETRY

THERE IS AN ELEGANT

AND NATURAL MECHANISM –

FOUND 20 YEARS AGO AND STILL

ATTRACTIVE TODAY-

FOR ELECTROWEAK SYMMETRY

BREAKING

... SAME MODELS AS 20 YEARS AGO

BUT FOR TODAY, WE ARE NOT GOING TO DWELL ON THESE HAPPY THOUGHTS... WE ARE GOING TO LOOK AT THE DRAWBACKS OF SUPERSYMMETRY.

ONE OBVIOUS DRAWBACK OF SUPERSYMMETRY IS SIMPLY THAT IT HAS NOT BEEN FOUND YET

THIS IS DISAPPOINTING, BUT FOR THE MOST PART PERHAPS NOT REALLY SURPRISING ....

IF CHARGED SUPERPARTNERS ARE JUST A LITTLE ABOVE M_Z, WE WOULDN'T HAVE SEEN THEM YET

BUT THERE IS PERHAPS ONE MISSING

PARTICLE THAT IS A LITTLE

EMBARRASSING - THE HIGGS BOSON....

WITH THE MINIMAL SUPERSYMMETRI

SPECTRUM, ONE HAS AT

TREE LEVEL

$$M_{HIGGS} \lesssim M_Z \sim 91 \text{ GeV}$$

COMPARED TO THE EXPERIMENTAL

BOUND

$$M_{HIGGS} \geq 114 \text{ GeV}$$

ACTUALLY THERE IS A LARGE RADIATIVE CORRECTION DUE TO THE HEAVY TOP QUARK, AND THE THEORETICAL BOUND ON THE HIGGS MASS IS USUALLY QUOTED AS

$$M_{HIGGS} \lesssim 130 \text{ GeV}$$

SO THERE ISN'T QUITE A CONTRADICTION ... BUT RATHER OPTIMISTIC ASSUMPTIONS GO INTO GETTING THE RADIATIVE CORRECTION SO LARGE ....

ONE NEEDS COUPLINGS NOT FAVORED BY MANY OF THE MODELS AND/OR SUPERPARTNER MASSES SO LARGE AS TO MAKE THE SMALLNESS OF M_Z LOOK A LITTLE UNNATURAL....

THOUGH THERE IS NO CONTRADICTION YET, IT WOULD CERTAINLY CLARIFY THINGS A LOT TO KNOW WHAT M_{HIGGS} IS...

AND IT WOULD BE REALLY NICE IF IT TURNED OUT TO BE

$$M_{HIGGS} \simeq 115\,GeV$$

THE VALUE HINTED AT BY LEP.

AT A DIFFERENT LEVEL, SUPERSYMMETRY WOULD HAVE BEEN MORE CONVINCING IF IT HAD ACHIEVED SOME SIMPLIFICATION IN THE STANDARD MODEL ... FOR EXAMPLE, COULD THE HIGGS BOSON BE A SUPERPARTNER OF THE ELECTRON? UNFORTUNATELY, NO: MODELS THAT TRIED THINGS LIKE THAT DIDN'T WORK.

THAT IS WHY THE "MINIMAL SUPERSYMMETRIC STANDARD MODEL" ESSENTIALLY DOUBLES THE STANDARD MODEL SPECTRUM.

EVEN SO, WHILE EXPLAINING THE SMALLNESS OF M_Z/M_{GUT} AND THE VALUE OF $\sin^2\theta_W$, SUPERSYMMETRY REOPENS SOME PROBLEMS THAT SEEMED SETTLED W THE STANDARD MODEL

FOR EXAMPLE, ONE TRIUMPH OF THE STANDARD MODEL IS TO NATURALLY CONSERVE BARYON AND LEPTON NUMBER, BECAUSE THERE ARE NO RENORMALIZABLE (PERTURBATIVE) INTERACTIONS OF STANDARD MODEL FIELDS THAT VIOLATE THESE SYMMETRIES.

THIS IS LOST WITH SUPERSYMMETRY, WHERE RENORMALIZABLE INTERACTIONS

CAUSING CATASTROPHIC PROTON DECAY ARE POSSIBLE

THE MOST COMMONLY ADOPTED SOLUTION OF THIS PROBLEM IS TO ASSUME A Z_2-SYMMETRY CALLED R-PARITY; THIS IS POSSIBLE BUT NOT OBVIOUSLY COMPELLING.

SUPERSYMMETRY ALSO INTRODUCES AT THE GUT SCALE A NEW SCENARIO OF PROTON DECAY VIA DIMENSION FIVE OPERATORS

... TROUBLESOME FOR MANY MODES GIVEN MODERN EXPERIMENTAL BOUNDS ON THE PROTON LIFETIME.

BROADLY SPEAKING, THERE ARE TWO CLASSES OF MODELS OF SUPERSYMMETRY BREAKING:

* GRAVITY MEDIATION

SUPERSYMMETRY BROKEN AT A VERY HIGH SCALE AND SUSY BREAKING MEDIATED TO STANDARD MODEL VIA SUPERGRAVITY INTERACTIONS

* GAUGE MEDIATION

SUPERSYMMETRY BREAKING AT $\lesssim$ 100 TeV; COMMUNICATED TO STANDARD MODEL VIA GAUGE FORCES

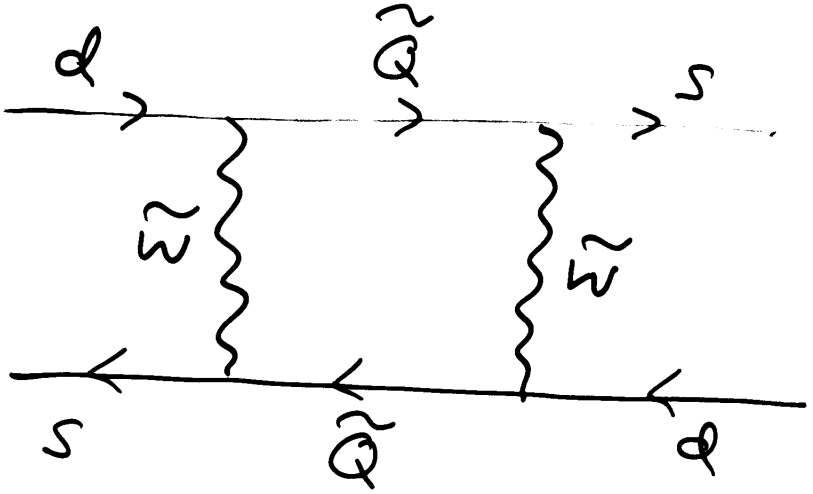
EACH TYPE OF MODEL HAS ITS VIRTUES, AND NONE HAS GIVEN A CLEAR PATH TO SOLVING ALL THE PROBLEMS.

FOR EXAMPLE, IF WE THINK ABOUT THE COSMOLOGICAL CONSTANT, WE MIGHT DECIDE WE FAVOR GRAVITY MEDIATION:

$$V = \left| \frac{DW}{D\Phi_i} \right|^2 - G_N |W|^2$$

↑ Newton's constant

IF INSTEAD WE THINK ABOUT FLAVOR-CHANGING NEUTRAL CURRENTS, WHERE SUSY AGAW INTRODUCES NEW TROUBLESOME POSSIBILITIES



WE MIGHT DECIDE WE FAVOR GAUGE MEDIATION.

ALONG WITH BARYON, LEPTON, AND FLAVOR SYMMETRIES, WE SHOULD ALSO WORRY ABOUT CP_3 AS WE WERE REMINDED EARLIER THIS AFTERNOON.

HERE IN FACT THE STANDARD MODEL ISN'T ENTIRELY SATISFACTORY BECAUSE OF THE STRONG CP PROBLEM — WHY IS THE NEUTRON ELECTRIC DIPOLE MOMENT SO SMALL?

THE "AXION" IS AN ELEGANT SOLUTION AND HERE ACTUALLY IS ONE OF THE TRIUMPHS OF STRING THEORY:

IN FIELD THEORY, THE IDEA OF THE AXION SEEMS TECHNICALLY NATURAL BUT PERHAPS CONTRIVED, WHILE STRING THEORY FORCES AXIONS UPON US, ALONG WITH QUANTUM GRAVITY, EXTRA DIMENSIONS, AND ALL THE REST.

HOWEVER ...

TeV SCALE SUSY + AXION "a"

IMPLY EXISTENCE OF A SCALAR

PARTNER "s" OF a

a COUPLES TO TWO GLUONS, SO

s DOES ALSO

$$a \, \mathrm{Tr} \, F_{\mu\nu} \tilde{F}^{\mu\nu} + s \, \mathrm{Tr} \, F_{\mu\nu} F^{\mu\nu}$$

UNIFICATION $\Rightarrow$ a AND s COUPLE

TO TWO PHOTONS OR TWO W, Z

BOSONS ALSO.

THE MEASURED GAUGE COUPLINGS WILL DEPEND UPON THE VACUUM EXPECTATION VALUE $\langle s \rangle$

AND THIS ADDS TO THE BURDEN THAT MUST BE BORNE BY A SUPERSYMMETRY BREAKING SCHEME:

GENERATE A POTENTIAL FOR s WITH A SENSIBLE MINIMUM,

NO RUNAWAY.

"IN FOR A PENNY, IN FOR A POUND"

TO OUR LIST OF DRAWBACKS OF SUSY, WE SHOULD ADD THAT SUSY ALSO INTRODUCES NEW AND POTENTIALLY TOO BIG SOURCES OF POSSIBLE CP VIOLATION, AS IT DOES WITH BARYON AND LEPTON NUMBER AND FLAVOR QUANTUM NUMBERS.

TO ME, THE CENTRAL DRAWBACK OF SUPERSYMMETRY IS THAT WE DON'T HAVE A CONVINCING, WORKABLE PICTURE OF WHAT THE TEV SUPERWORLD WOULD REALLY LOOK LIKE.

IF WE HAD SUCH A PICTURE, WE'D BE MORE CONFIDENT OF FINDING SUPERSYMMETRY, BUT WE'D HAVE LESS TO LEARN BY DOING SO.

MY PURPOSE IN DWELLING ON THE DRAWBACKS OF SUPERSYMMETRY IS NOT TO CONVINCE YOU THAT IT IS WRONG.

SUPERSYMMETRY ALSO HAS BIG PLUSES, AS SKETCHED IN THE FIRST PART OF THE TALK!

BUT THE DRAWBACKS ARE ENOUGH THAT IT WOULD BE QUITE DRAMATIC TO LEARN THAT NATURE DID SOLVE ALL THOSE PROBLEMS...

AND IF SO, EACH PROBLEM I'VE DESCRIBED WOULD TURN INTO AN OPPORTUNITY TO LEARN A FUNDAMENTAL NEW LESSON ABOUT NATURE