LET'S BEGIN BY RECALLING HOW THE STANDARD MODEL LOOKED BEFORE GRAND UNIFICATION WAS PROPOSED

....

ESPECIALLY, WHAT WERE THE FERMIONS?

THE LEFT-HANDED FERMIONS OF ONE GENERATION ARE

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

MANY BITS AND PIECES

- STRANGE FRACTIONS

SO IT WAS AN ILLUMINATION IN 1973 WHEN GEORGI-GLASH[OW] UNVEILED THE UNIFIED SU(5) MODEL, REDUCING A STANDARD MODEL GENERATION TO TWO PIECES

$$\begin{pmatrix} \bar{d} \\ \bar{d} \\ \bar{d} \\ \nu \\ e^- \end{pmatrix}_{\bar{5}} \oplus \begin{pmatrix} 0 & \bar{u} & \bar{u} & u & d \\ & 0 & \bar{u} & u & d \\ \cdots & & 0 & u & d \\ \cdots & & & 0 & e^+ \\ \cdots & & & & 0 \end{pmatrix}$$

AND EXPLAINING THE FRACTIONS.

TO ACHIEVE THIS, IT WAS NECESSARY TO PUT QUARKS AND LEPTONS (AND THEIR ANTIPARTICLES) IN THE SAME MULTIPLET ... AND (AS HAD BEEN ANTICIPATED BY PATI AND SALAM) THIS LED TO A PREDICTION OF PROTON DECAY

IN FACT THE SU(5) GAUGE BOSONS MAKE A MATRIX

$$\begin{pmatrix} \text{QCD GLUONS} & X, Y \\ \bar{X}, \bar{Y} & W, Z \end{pmatrix}$$

AND THE X, Y BOSONS MEDIATE PROCESSES SUCH AS

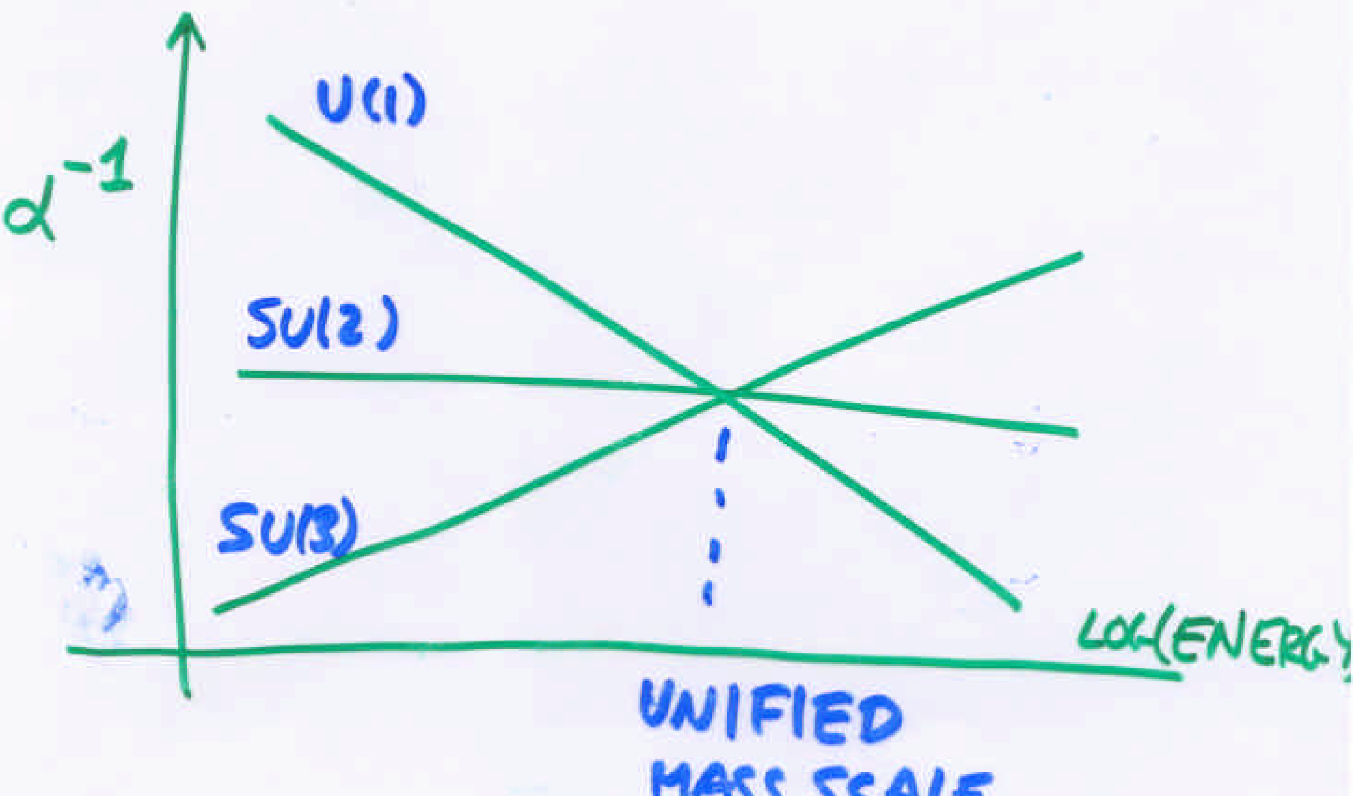
$$p \to e^+ \pi^0$$

THERE ARE A COUPLE OF IMMEDIATE PROBLEMS

* IF THE STRONG INTERACTIO[NS] ARE UNIFIED WITH THE WEAK AND ELECTROMAGNETIC INTERACTIONS, WHY ARE THEY SO MUCH STRONGER?

* * WILL THE PROTON BE SUFFICIENTLY LONG-LIVED?

THESE ISSUES WERE ADDRESSED IN 1974 BY GEORGI, QUINN, AND WEINBERG, WHO CALCULATED THE "RENORMALIZATION GROUP RUNNING OF THE STRONG, WEAK, AND ELECTROMAGNETIC COUPLINGS



THEY FOUND THAT UNIFICATION WAS POSSIBLE, PROVIDED THE WEAK MIXING ANGLE HAD THE RIGHT VALUE $\sin^2\theta_W \sim .2$ AND THE UNIFICATION SCALE WAS $\sim 10^{15}$ GeV

THESE WERE VERY NICE RESULTS, SINCE THE VALUE OF THE WEAK ANGLE WAS ABOUT RIGHT, AND THE VALUE OF THE UNIFICATION SCALE WAS FORTUITOUS

IN FACT, 10^{15} GeV WAS CLOSE ENOUGH TO THE PLANCK SCALE AS TO SUGGEST A UNIFICATION WITH GRAVITY ... AND BIG ENOUGH TO MAKE THE PROTON LONG-LIVED ... A PROTON LIFETIME OF ABOUT 10^{30} YEARS WAS PREDICTED

THE MODEL WOULD HAVE FAILED IF THE COMPUTED UNIFICATION SCALE WERE $< 10^{15}$ GeV AND WOULD HAVE BEEN STRANGE IF IT WERE $\gg 10^{19}$ GeV

IT WAS NICE IN SU(5)
TO REDUCE THE MESS OF A
STANDARD MODEL GENERATION TO
JUST TWO PIECES ... BUT
CAN ONE DO BETTER? IT
WAS SOON SEEN (GEORGI)
THAT BY GOING TO THE
LARGER GROUP SO(10),
ALL QUARKS AND LEPTONS OF
ONE GENERATION FIT NEATLY
IN A SINGLE IRREDUCIBLE
REPRESENTATION

THERE IS A PRICE, THOUGH
— YOU HAVE TO ADD A RIGHT HANDED
NEUTRINO. SINCE IT IS A
STANDARD MODEL SINGLET, IT IS
NATURAL FOR IT TO GET A
GUT SCALE MASS, AND THIS
LED TO THE IDEA OF THE
"SEESAW" MECHANISM FOR
NEUTRINOS (GRS, Yanagida)

THE SIMPLEST MODELS OF THIS TYPE GIVE A MASS MATRIX

$$\begin{pmatrix} \nu_L \\ \bar{\nu}_R \end{pmatrix} \qquad \begin{pmatrix} 0 & m \\ m & M \end{pmatrix}$$

WHERE m COMES FROM THE ELECTROWEAK HIGGS EFFECT, AND M CAN BE OF ORDER M_{GUT}

IF WE TAKE $m \sim M_W, M_Z$, WE GET A LIGHT NEUTRINO MASS OF ORDER

$$m_\nu \sim \frac{(100\,\mathrm{GeV})^2}{10^{15}\,\mathrm{GeV}}$$

$$\sim .01\ \mathrm{eV}$$

THIS ESTIMATE, WHICH WAS MADE IN THE LATE '70's, GAVE A BIG IMPETUS TO THE SEARCH FOR NEUTRINO MASSES AND OSCILLATIONS

HAVING COME THIS FAR,
CAN WE GO FARTHER AND

* UNIFY THREE GENERATIONS OF QUARKS AND LEPTONS IN ONE IRREDUCIBLE REPRESENTA OF A LARGER GAUGE GROUP?

* UNIFY HIGGS BOSONS WITH GAUGE FIELDS, OR WITH QUARKS AND LEPTONS?

THE ANSWER TO THESE QUESTIONS WAS "NO" IN THE FRAMEWORK OF FOUR-DIMENSIONAL GRAND UNIFICATION.

FOR EXAMPLE, THERE IS NO CANDIDATE GUT GROUP THAT PUTS SEVERAL CHIRAL FERMION FAMILIES IN ONE IRREDUCIBLE REPRESENTATION — WITHOUT "ANTIFAMILIES" OF OPPOSITE CHIRALITY

LIKEWISE, IN FOUR-DIMENSIONAL
GUTS, ONE CAN'T REALLY
UNIFY HIGGS PARTICLES
WITH QUARKS AND LEPTONS
OR GAUGE BOSONS
(OR FOR THAT MATTER, UNIFY
QUARKS AND LEPTONS WITH
GAUGE BOSONS)

THE CLOSEST TRY USES
SUPERSYMMETRY PLUS THE
E_6 MODEL I'LL GET TO SHORTLY

THE OTHER RECOGNIZED PROBLEM OF GUT's IN THIS PERIOD WAS THE "GAUGE HIERARCHY PROBLEM"

WHY IS

$$\frac{M_W}{M_X} \sim \frac{10^2 GeV}{10^{14} GeV} \sim 10^{-12}$$

SO SMALL ?

I'VE STRESSED THE SU(5) AND SO(10) MODELS WHICH MADE SENSE OF THE FERMION QUANTUM NUMBERS AND LED TO PREDICTIONS OF

* PROTON DECAY
* NEUTRINO MASSES

ARE THERE ANY BIGGER GROUPS THAT TEACH US MORE?

THERE ISN'T ANY FOUR-DIMENSIONAL MODEL THAT DOES BETTER – BUT THERE IS ONE MOREMODEL WORTHY OF NOTE – THE E_6 MODEL (GURSEY, RAMOND, et c

WHAT IS E_6?

FOR GAUGE THEORY, WE NEED TO PICK A GAUGE GROUP.

THERE ARE INFINITE FAMILIES

$$\left.\begin{matrix} SO(N) \\ SU(N) \\ Sp(N) \end{matrix}\right\} \text{ Any } N$$

OF POSSIBLE GROUPS, TWO OF WHICH – SU(5) AND SO(10) – ARE USED IN MODELS I MENTIONED SO FAR

AND THERE ARE FIVE EXCEPTIONS

G_2, F_4, E_6, E_7, E_8

NATURE IS EXCEPTIONAL, SO WHY NOT DESCRIBE IT USING AN EXCEPTIONAL LIE GROUP?

THERE IS ONE THAT BEAUTIFULLY WORKS – THE E_6 MODEL.

IT CAPTURES THE SUCCESSES OF THE SO(10) MODEL "EXCEPTIONALLY

BUT WHY E_6?

WHY WOULD NATURE GO HALFWAY DOWN THE CHAIN OF EXCEPTIONAL GROUPS?

$$G_2 \subset F_4 \subset E_6 \subset E_7 \subset E_8$$

IF NATURE LIKES EXCEPTIONAL GROUPS, WHY STOP HALF-WAY?

BUT E_6 IS THE ONLY EXCEPTIONAL GROUP THAT WORKS FOR FOUR-DIMENSIONAL GUT's ....

THE FOUR-DIMENSIONAL GUT

GROUPS THAT WORK FIT IN A CHAIN

$$SU(5) \subset SO(10) \subset E_6 \subset E_7 \subset E_8$$

AND, IN FOUR-DIMENSIONAL

GUTS, WE CAN ONLY GO

HALFWAY DOWN THIS CHAIN

BECAUSE OF THE V-A

STRUCTURE OF WEAK INTERACTIONS

THE NEXT DEVELOPMENTS I'LL MENTION WERE EXPERIMENTAL

* MORE ACCURATE MEASUREMENTS SHOWED THAT $\sin^2\theta_W$ IS CLOSE TO THE GUT VALUE, BUT NOT CLOSE ENOUGH
* THE PROTON LIFETIME TURNED OUT TO BE LONGER THAN THE GUT VALUE

BOTH OF THESE PROBLEMS WERE NEATLY ADDRESSED BY INCLUDING

(Dimopoulos -Raby -Wilczek 1981)

SUPERSYMMETRY

SUPERSYMMETRY RAISES THE GUT PREDICTION FOR $\sin^2\theta_W$ - WHICH BECOMES VERY CLOSE TO THE MODERN MEASUREMENT

IT ALSO RAISES THE GUT SCALE, MAKING THE PROTON LIFETIME LONG ENOUGH, AND LOWERING THE GAP BETWEEN M_{GUT} AND M_{PLANCK}.

FINALLY – SUSY STABILIZES THE HIERARCHY $\frac{M_W}{M_X} < 10^{-12}$ CANCELING LARGE RADIATIVE CORRECTIONS TO THE HIGGS BOSON MASS

SO, SINCE THE EARLY

1980's, SUSY-GUT's HAVE

BEEN THE ATTRACTIVE FORM

OF GUT's

GOING BACK TO THEORY, IT WAS SOON REALIZED (EW, 1983) THAT ALTHOUGH ONE CANNOT UNIFY THREE GENERATIONS IN FOUR DIMENSIONS, ONE CAN READILY DO SO IF ONE STARTS ABOVE FOUR DIMENSIONS

FOR EXAMPLE

AN SO(12) MODEL IN SIX DIMENSIONS

OR AN SO(16) MODEL IN TEN DIMENSIONS

A BIGGER CHANGE CAME IN 1984 WITH GREEN-SCHWARZ ANOMALY CANCELLATION AND CONSTRUCTION OF THE HETEROTIC STRING; (Gross, Harvey, Martinec, Roh

IT BECAME FEASIBLE TO COMBINE GUT's WITH STRING THEORY AND THUS UNIFY ALL THE FORCES, INCLUDING GRAVITY.

IN THIS FRAMEWORK, ONE HAS TO UNIFY ALL THE FORCES PLUS THREE GENERATIONS OF QUARKS AND LEPTONS PLUS HIGGS BOSONS IN ONE SUSY-MULTIPLET

... BECAUSE THAT IS ALL THERE IS

ONE ALSO HAS TO START IN TEN DIMENSIONS WITH

$$E_8 \times E_8 \qquad (\text{OR } SO(32))$$

BECAUSE THOSE ARE THE ONLY ALLOWED TEN-DIMENSIONAL GAUGE GROUPS

SO ONE IS FORCED TO CONTINUE THE GUT CHAIN TO THE END

$SU(5) \to SO(10) \to E_6 \to E_7 \to E_8$

AND TO UNIFY THE THREE FERMION GENERATIONS ...

TWO THINGS THAT DIDN'T WORK IN FOUR-DIMENSIONAL GUTs.

THE MODEL IS CONSTRUCTED

BY STARTING WITH

$$\mathbb{R}^4 \times K$$

$\mathbb{R}^4$: MINKOWSKI SPACE

K: COMPACT SIX-MANIFOLD CHOSEN TO PRESERVE FOUR-DIMENSIONAL SUSY

AND THEN TO OBEY THE

EQUATIONS OF MOTION, ONE IS

FORCED TO INTRODUCE VEV'S

FOR GAUGE FIELDS ON K,

BREAKING E_8 TO A

SUBGROUP

THE SIMPLEST CHOICES FOR THIS BREAK E_8 TO ONE OF THE USUAL GUT GROUPS

$$E_8$$

$$\swarrow \quad \searrow \quad \searrow$$

$$SU(5) \dashrightarrow SO(10) \dashrightarrow E_6$$

– WE DON'T KNOW WHICH CHOICE TO MAKE! – AND THE LIGHT FERMIONS OCCUR IN JUST THE RIGHT REPRESENTATI

WITH

NUMBER OF GENERATIONS = TOPOLOGICAL INVARIANT OF

THESE MODELS ARE NOT REALLY FOUR-DIMENSIONAL GUTS, SINCE UNIFICATION REALLY ONLY OCCURS IN TEN DIMENSIONS.

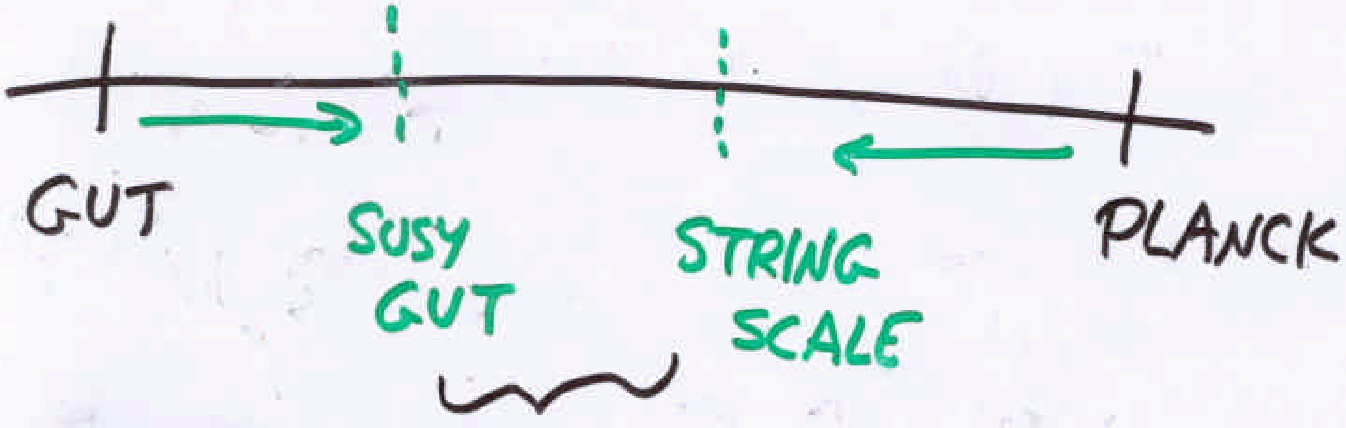
THEY ARE SIMILAR TO FOUR-DIMENSIONAL GUTS, WITH SOME DIFFERENCES THAT I WON'T STRESS TODAY.

I'LL JUST DRAW ATTENTION TO ONE DIFFERENCE – THE USUAL QUANTIZATION OF ELECTRIC CHARGE IS GENERALLY NOT OBEYED – THERE ARE SUPERHEAVY UNCONFINED PARTICLES WITH FRACTIONAL ELECTRIC CHARGE....

BUT THE PREDICTIONS FOR $\sin^2\theta_W$, THE PROTON LIFETIME, AND THE QUANTUM NUMBERS OF THE LIGHT FERMIONS ARE SIMILAR TO THOSE OF FOUR-DIMENSIONAL SUSY-GUTs.

ANOTHER THING THAT HAPPENED IS THAT THE GAP BETWEEN M_{GUT} AND M_{PLANCK} DROPPED AGAIN; IN THE ORIGINAL GEORGI-QUINN-WEINBERG CALCULATIO THE GAP WAS A FACTOR OF $10^4 - 10^5$

BUT IT HAS SINCE BEEN REDUCED TWICE:



THE PERTURBATIVE HETEROTIC STRING, GIVEN MEASURED VALUES OF G_{NEWTON} AND $\alpha = \frac{e^2}{\hbar c}$, PREDICTS A SUSY-GUT SCALE THAT DIFFERS BY A FACTOR OF 20 FROM THE VALUE INFERRED FROM LOW ENERGY MEASUREMENTS OF α_S AND $\sin^2\theta_W$

THE DISCREPANCY IS REAL, BUT STILL A CLOSE TRY. IT WAS ALREADY A MAJOR ADVANCE WHEN GEORGI, QUINN, WEINBERG IN 1974 CAME WITHIN A FACTOR OF 10^4!

THE TWO IMPROVEMENTS WERE BYPRODUCTS OF OTHER ADVANCES.

LATER IT WAS FOUND THAT GOING TO THE STRONGLY COUPLED HETEROTIC STRING (HORAVA AND EW) IS ONE WAY ONE MIGHT REDUCE OR ELIMINATE THE DISCREPANCY

WHAT HAS HAPPENED SINCE?

ONE IMPORTANT DEVELOPMENT IS CERTAINLY THAT OSCILLATIONS IN SOLAR AND ATMOSPHERIC NEUTRINOS HAVE POINTED TO NEUTRINO MASSES (OR AT LEAST MASS DIFFERENCES) IN ROUGHLY THE RANGE THAT HAD BEEN PREDICTED FROM GUT'S 20 YEARS EARLIER

ASTRONOMY HAS GIVEN OTHER CLUES -

THE ACCELERATION OF COSMIC EXPANSION SHOULD EVENTUALLY BE AN IMPORTANT CLUE ABOUT SUSY-GUT'S ...

AND THE OBSERVATIONS OF SMALL ANISOTROPIES IN THE COSMIC MICROWAVE RADIATION (COBE SATELLITE PLUS BALLOONS)

HAVE FOR THEIR SIMPLEST INTERPRETATION AN EARLY INFLATIONARY PERIOD OF THE UNIVERSE AT A SCALE NEAR THE SUSY - GUT SCALE....

SO THIS PLUS NEUTRINOS MAY BE TWO OBSERVATIONS OF THE GUT-SCALE

ANOTHER DEVELOPMENT IS

THAT THE TOP QUARK

MASS TURNED OUT TO BE

LARGE – AS ASSUMED IN

SUPERSYMMETRIC MODELS OF

ELECTROWEAK SYMMETRY BREAKIN

THAT WERE FORMULATED IN THE

EARLY 1980's

ALV. GAUMÉ
POLCHINSKI
WISE

AND OF COURSE, INCREASINGLY PRECISE TESTS OF THE STANDARD MODEL HAVE BEEN QUITE CONSISTENT WITH THE SUSY-BASED APPROACH TO THE HIERARCHY PROBLEM - WHILE ADDING TO THE CHALLENGES FACED BY OTHER APPROACHES TO THAT PROBLEM.

SO IN SHORT THE GUT-BASED APPROACH TO PHYSICS HAS BEEN ATTRACTIVE SINCE THE 1973 PAPER OF GEORGI AND GLASHOW; IT HAS BEEN ENRICHED BY NEW IDEAS, NOTABLY SUSY AND STRINGS AND THERE ARE REAL HINTS THAT IT IS ON THE RIGHT TRACK, NOTABLY FROM $\sin^2\theta_W$ AND NEUTRINO MASSES.

IF THIS APPROACH IS RIGHT, WHAT MAY WE FIND AT ACCELERATORS?

THE HIGGS BOSON REALLY SHOULD BE IN REACH - PERHAPS AT 115 GeV AS HINTED AT LEP - SINCE GUT-THEORIES DON'T WORK WITHOUT IT.

IT SHOULD APPEAR AT FERMILAB IF THE LUMINOSITY IS REACHED....

SUPERSYMMETRIC PARTICLES SHOULD
BE IN REACH OF THE LHC
- AND MAYBE OF FERMILAB -
SINCE THE SUPERSYMMETRIC APPROACH
TO THE HIERARCHY PROBLEM
DOESN'T MAKE SENSE IF THEY
ARE TOO HEAVY.

BUT WOULD THE SUPERWORLD REALLY LOOK LIKE? I DON'T THINK WE HAVE A CONVINCING PICTURE OF THIS, PARTLY BECAUSE OF PROBLEMS IN NONCONSERVATION OF

FLAVOR
BARYON NUMBER
CP

DUE TO SUSY PARTICLES

WE HAVE A HUNCH THAT SUPERSYMMETRY WILL BE FOUND.

BUT IF IT IS FOUND, THE DETAILS WILL BE SURPRISING, AT LEAST TO ME, SINCE NO MODEL OF THE TeV SCALE SUPERWORLD IS REALLY CONVINCING ... THAT IS PART OF WHAT MAKES THE SEARCH SO EXCITING

MOREOVER, EXPLORATION OF THE SUPERWORLD WILL BE A LONG PROJECT, BECAUSE OF THE NUMEROUS NEW PARTICLES AND NEW INTERACTIONS.

IT WILL REQUIRE HIGH PRECISION (ELECTRON COLLIDERS, SUCH AS TESLA) AS WELL AS HIGH ENERGY (PROTON COLLIDERS LIKE FERMILAB AND THE LHC)