Paths of Discovery
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TOTALLY UNEXPECTED DISCOVERIES: A PERSONAL EXPERIENCE

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1. The Unexpected Discoveries of the 20th Century

Let me show a synthesis of achievements in Physics during the last Century (Figures 1, 2, 3).

First 50 Years

1 Lorentz Invariance (Lorentz).
2 The quantum nature of the World (Planck).
3 Two worlds: 'Time-like' and 'Space-like' (Einstein).
4 The photon (Einstein).
5 Gauge Invariance (Weyl).
6 The Space-Time curvature (Einstein).
7 Bose-Einstein statistics (Bose-Einstein).
8 The structure of the atom (Bohr).
9 Wave nature of particles (de Broglie).
10 Wave function (Schrödinger) and its probabilistic interpretation (Born).
11 Nuclear Forces (Rutherford) and their 'glue' (Yukawa).

Figure 1.

12 The proof that Quantum Mechanics is self consistent (no contradictions) (Von Neumann).

13 The Weak Forces (Fermi).

14 The Exclusion Principle (Pauli).

15 The Uncertainty Principle (Heisenberg).

16 Fermi statistics (Fermi).

17 The antiparticles (Dirac).

18 The neutron (Chadwick).

19 Time Reversal Invariance (Wigner).

20 Other Invariance Laws (Wigner-Parity; Dirac, Weyl-charge conjugation; Pauli CPT).

21 The neutrino (Pauli, Fermi).

22 The Stars are 'nuclear-fusion' candles (Bethe).

23 Electronic computing (Von Neumann).

24 The sequence of unexpected Fermi discoveries: *Fermi-coupling*, *Fermi-gas*, *Fermi-momentum*, *Fermi-temperature*, *Fermi-surface*, *Fermi-statistics*, *Fermi-transition*, *Fermi-length* (plus two others quoted above).

Figure 2.

For the first 50 years, I have listed 24 totally unexpected events, with 23 discoveries, and the invention of electronic computers by Von Neumann, which no one could have imagined at the beginning of the 20th Century.

Point no. 24 refers to the impressive list of Fermi discoveries: once again, all totally unexpected.

THE SECOND HALF OF THE 20th CENTURY

25 The Subnuclear World.

26 The Standard Model and Beyond.

27 The Superworld.

Figure 3.

The discoveries of the second 50 years are grouped into 3 classes:

- one is the 'Subnuclear World'
- the second is the 'Standard Model and Beyond'
- the third is the 'Superworld'.

This is the frontier of our knowledge which exists as a fascinating mathematical structure, but lacks the Galilean experimental proof.

The existence of the Subnuclear World and the Standard Model are strictly correlated.

The greatest synthesis of all times in the study of fundamental phenomena (it is called the Standard Model and Beyond [Figures 4, 5, 6, 7, 8]) has been reached through a series of totally unexpected discoveries.

2. The Standard Model and Beyond

The superb synthesis called the 'Standard Model' is a part of a more general structure, where many problems are open. We call this structure 'The Standard Model and Beyond', 'SM&B'.

This Structure brings to the unification of all Fundamental Forces of Nature, suggests the existence of the Superworld and produces the need for a non-point-like description of Physics processes (the so-called Relativistic Quantum String Theory: RQST), thus opening the way to quantize gravity. This is summarised in Figure 5.

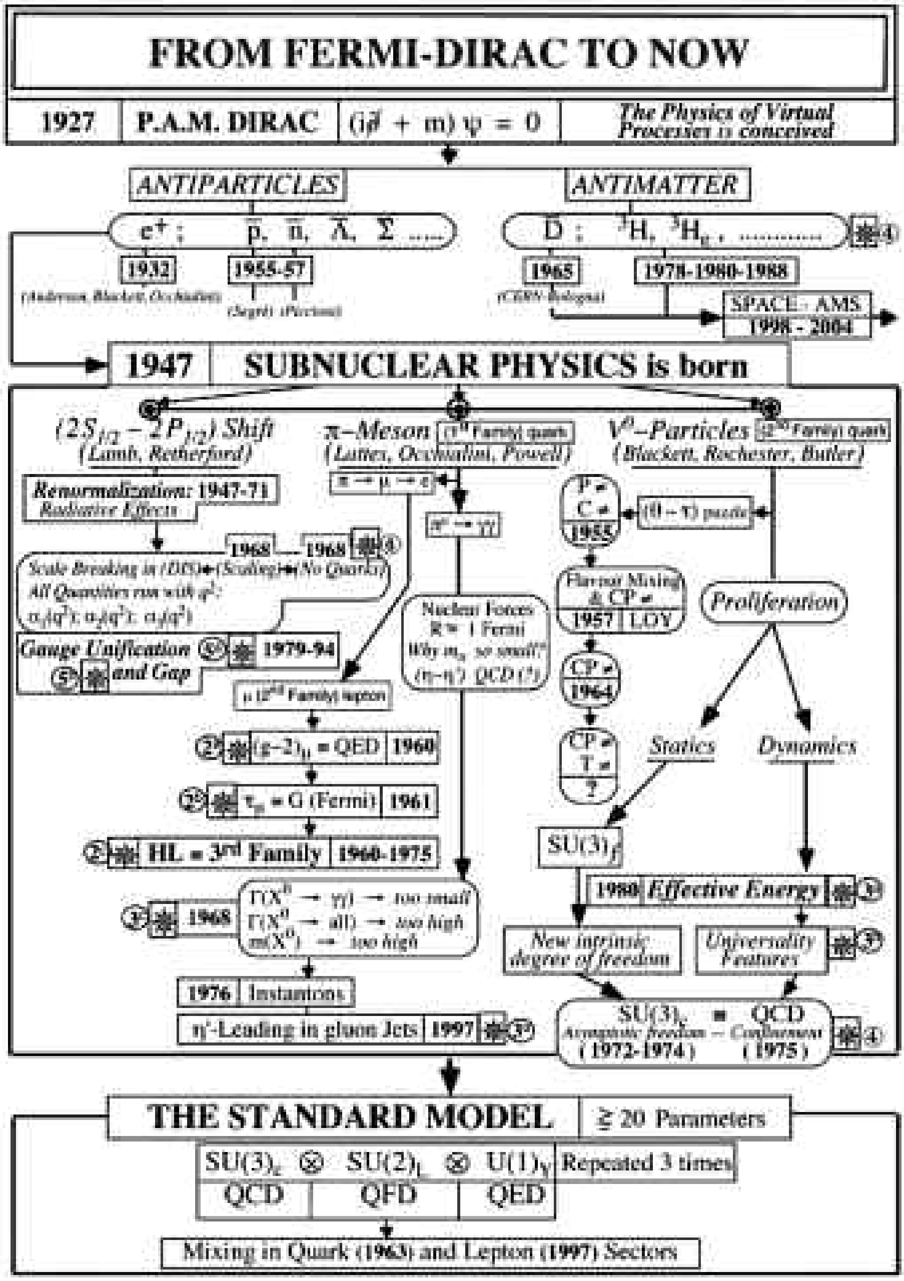
FROM FERMI-DIRAC TO NOW
1927
P.A.M. DIRAC
The Physics of Virtual Processes is conceived
ANTIPARTICLES
ANTIMATTER
1932
1955-57
1965
1978-1980-1988
SPACE - AMS
1998 - 2004
1947
SUBNUCLEAR PHYSICS is born
(Lamb, Retherford)
π–Meson
(Lattes, Occhialini, Powell)
(Blackett, Rochester, Butler)
Renormalization: 1947-71
Radiative Effects
1968
1968
Nuclear Forces
Proliferation
Flavour Mixing
1955
1957
1964
Gauge Unification
and Gap
1979-94
Statics
Dynamics
1960
1961
HL = 3rd Family
1960-1975
1968
1976
Instantons
1997
1980
Effective Energy
New intrinsic degree of freedom
Universality Features
(1972-1974)
(1975)
THE STANDARD MODEL
≧ 20 Parameters
Repeated 3 times
QCD
QFD
QED
Mixing in Quark (1963) and Lepton (1997) Sectors

Figure 4.

DETAILED INFORMATION ON THE STANDARD MODEL AND BEYOND

① RGEs (α_i ($i = 1, 2, 3$); m_j ($j = q, l, G, H$)) : $f(k^2)$.
- GUT ($\alpha_{GUT} \simeq 1/24$) & GAP ($10^{16} - 10^{18}$) GeV.
- SUSY (to stabilize $m_F/m_P \simeq 10^{-17}$).
- RQST (to quantize Gravity).

② Gauge Principle (hidden and expanded dimensions).
— How a Fundamental Force is generated: SU(3); SU(2); U(1) and Gravity.

③ The Physics of Imaginary Masses: SSB.
— The Imaginary Mass in SU(2) × U(1) produces masses ($m_{W^\pm}; m_{Z^0}; m_q; m_l$), including $m_\gamma = 0$.
— The Imaginary Mass in SU(5)⇒SU(3)×SU(2)×U(1) or in any higher Symmetry Group (not containing U(1)) ⇒ SU(3) × SU(2) × U(1) produces Monopoles.
— The Imaginary Mass in $SU(3)_c$ generates Confinement.

④ Flavour Mixings & CP ≠ , T ≠ .
— No need for it but it is there.

⑤ Anomalies & Instantons.
— Basic Features of all Non-Abelian Forces.

Note: q	≡	quark and squark;	m_F	≡	Fermi mass scale;
l	≡	lepton and slepton;	m_P	≡	Planck mass scale;
G	≡	Gauge boson and Gaugino;	k	≡	quadrimomentum;
H	≡	Higgs and Shiggs;	C	≡	Charge Conjugation;
RGEs	≡	Renormalization Group Equations;	P	≡	Parity;
GUT	≡	Grand Unified Theory;	T	≡	Time Reversal;
SUSY	≡	Supersymmetry;	≠	≡	Breakdown of Symmetry Operators.
RQST	≡	Relativistic Quantum String Theory;			
SSB	≡	Spontaneous Symmetry Breaking.			

The five basic steps in our understanding of nature. ① The renormalization group equations (RGEs) imply that the gauge couplings (α_i) and the masses (m_j) all run with k^2. It is this running which allows GUT, suggests SUSY and produces the need for a non point-like description (RQST) of physics processes, thus opening the way to quantize gravity. ② All forces originate in the same way: the gauge principle. ③ Imaginary masses play a central role in describing nature. ④ The mass-eigenstates are mixed when the Fermi forces come in. The Abelian force QED has lost its role of being the guide for all fundamental forces. The non-Abelian gauge forces dominate and have features which are not present in QED.

Figure 5.

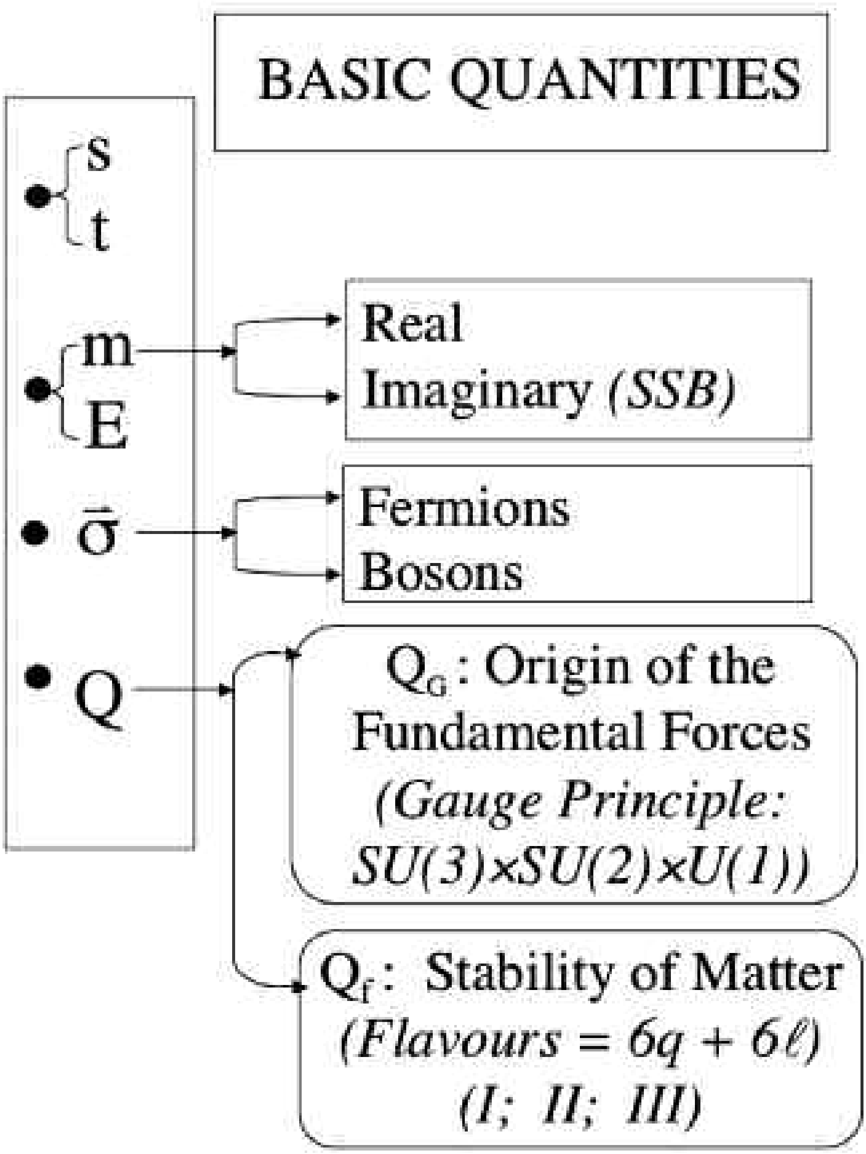
BASIC QUANTITIES
s
t
m
E
σ⃗
Q
Real
Imaginary (SSB)
Fermions
Bosons
Q_G : Origin of the Fundamental Forces (Gauge Principle: SU(3)×SU(2)×U(1))
Q_f : Stability of Matter (Flavours = 6q + 6ℓ) (I; II; III)

Figure 6.

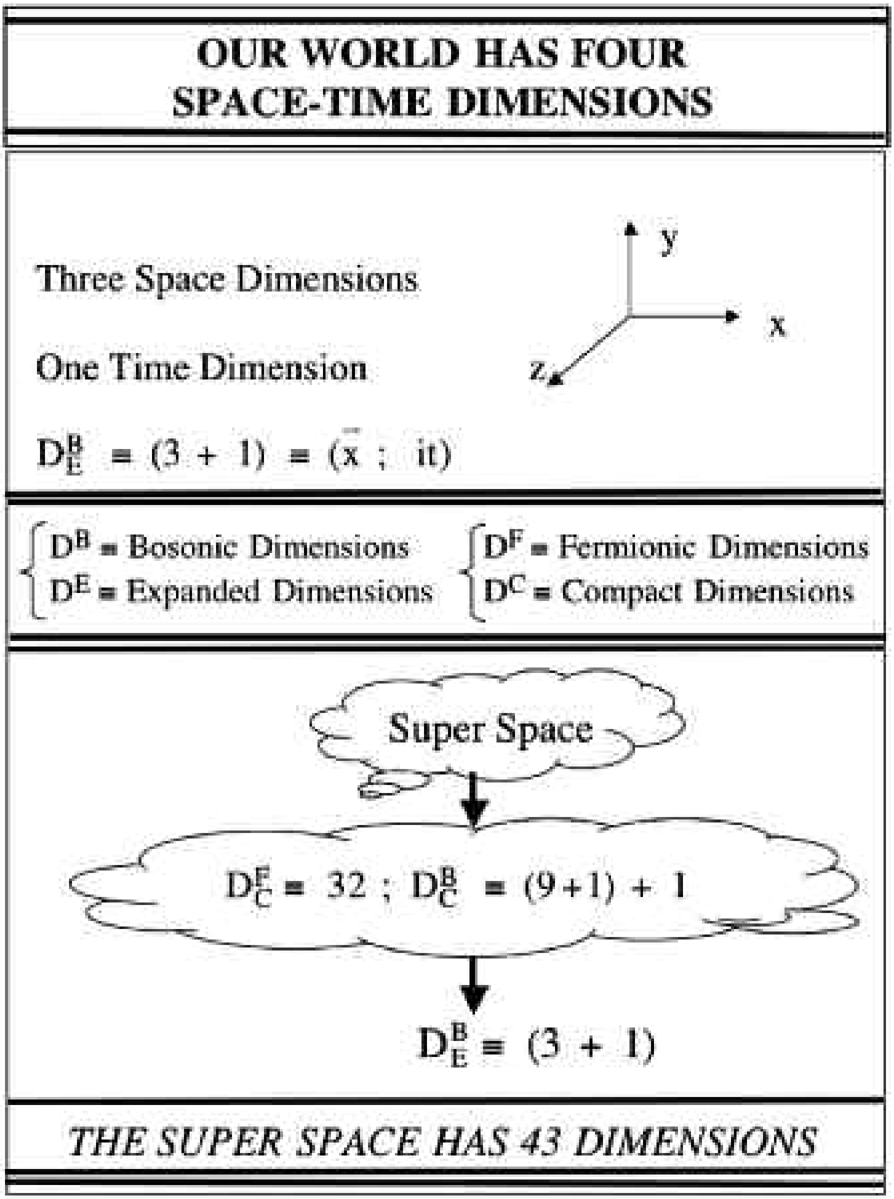
OUR WORLD HAS FOUR
SPACE-TIME DIMENSIONS
Three Space Dimensions
One Time Dimension
y
x
z
$D^B_E \equiv (3 + 1) \equiv (\vec{x}\ ;\ it)$
$D^B \equiv$ Bosonic Dimensions
$D^E \equiv$ Expanded Dimensions
$D^F \equiv$ Fermionic Dimensions
$D^C \equiv$ Compact Dimensions
Super Space
$D^F_C \equiv 32\ ;\ D^B_C \equiv (9+1) + 1$
$D^B_E \equiv (3 + 1)$
THE SUPER SPACE HAS 43 DIMENSIONS

Figure 7.

3. A Few Examples Where I Have Been Involved

I will now discuss a few cases, where I have been involved (Figure 8).

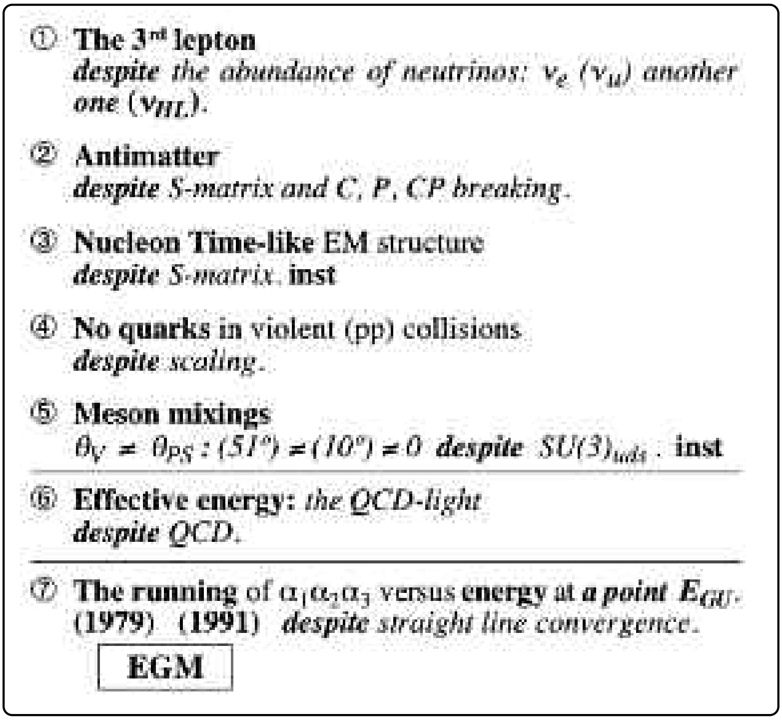

Figure 8.

POINT 1. The Third Lepton, and the other unexpected events in Electroweak Interactions are illustrated in Figure 9.

Note that for the Electroweak force, Nature has not chosen the simplest way out SU(2), but unexpectedly SU(2)×U(1).

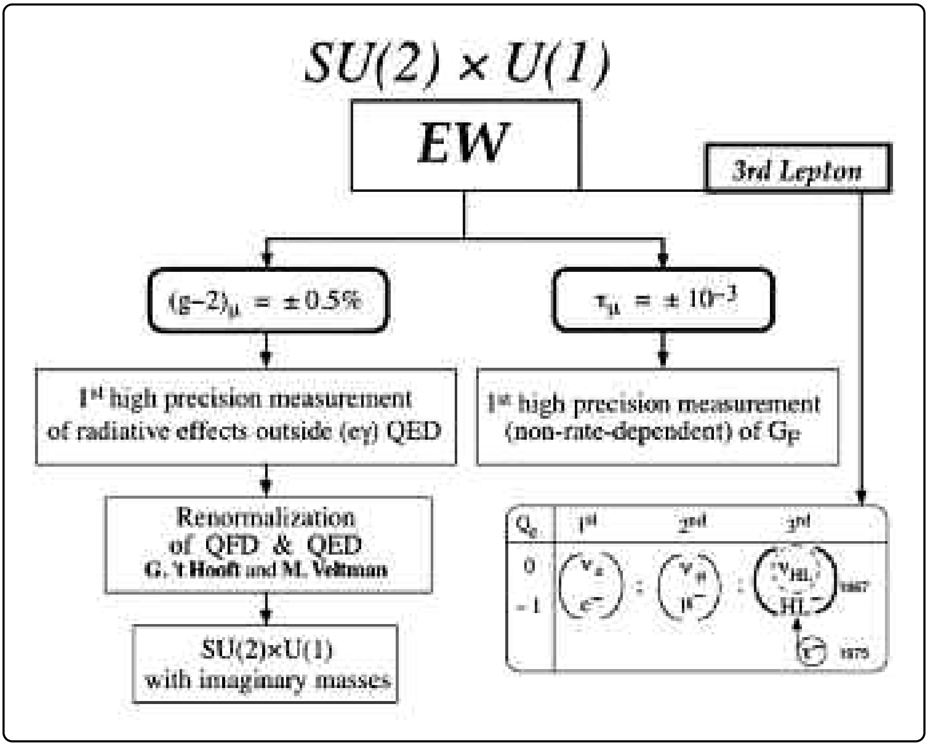

Figure 9.

POINT 2. The incredible series of events which originated with the problem of understanding the stability of matter is shown in Figures 10 and 11, together with the unexpected violation of the Symmetry Operators (C, P, T, CP) and the discovery of Matter-Antimatter Symmetry.

Mass ≠ Matter

$$|m_i\rangle \equiv \text{Mass} \equiv \text{Antimass} \equiv |\overline{m}_i\rangle$$

$i \equiv 1$ (Intrinsic); $i \equiv 2$ (Confinement); $i \equiv 3$ (Binding)

$$C|m_i\rangle = |m_i\rangle \qquad \boxed{***}$$

$$i \equiv 1, 2, 3$$

$$|m_i Q_i\rangle \equiv \text{Matter} \neq \text{Antimatter} \equiv |m_i \overline{Q}_i\rangle$$

$Q_i \equiv$ Flavour Charges

$j \equiv (u \;\; d \;\; c \;\; s \;\; t \;\; b) \equiv (1, 2, 3, 4, 5, 6)$

$(\nu_e \;\; e^- \;\; \nu_\mu \;\; \mu^- \;\; \nu_{HL} \;\; HL^-) \equiv (7, 8, 9, 10, 11, 12)$

$HL^- \downarrow \tau^-$

$$C|m_i Q_j\rangle = |m_i \overline{Q}_j\rangle \qquad \boxed{***}$$

$i = 1, 2, 3$; $J = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12.$

Figure 10.

There are in fact seven decades of developments which started from the antielectron and C-invariance and brought us to the discovery of nuclear antimatter and to the unification of all gauge forces with a series of unexpected discoveries, reported in Figure 11.

THE INCREDIBLE STORY
TO DISENTANGLE THE ORIGIN OF THE STABILITY OF MATTER
SEVEN DECADES FROM THE ANTIELECTRON TO ANTIMATTER
AND THE UNIFICATION OF ALL GAUGE FORCES

- **The validity of C invariance from 1927 to 1957.**

After the discovery by Thomson in 1897 of the first example of an elementary particle, the Electron, it took the genius of Dirac to theoretically discover the Antielectron thirty years after Thomson.

1927 → Dirac equation [1]; the existence of the antielectron is, soon after, theoretically predicted. Only a few years were needed, after Dirac's theoretical discovery, to experimentally confirm (Anderson, Blackett and Occhialini [2]) the existence of the Dirac antielectron.

1930-1957 → Discovery of the C operator (charge conjugation) H. Weyl and P.A.M. Dirac [3]; discovery of the P Symmetry Operator [E.P. Wigner, G.C. Wick and A.S. Wightman [4, 5]]; discovery of the T operator (time reversal) [E.P. Wigner, J. Schwinger and J.S. Bell [6, 7, 8, 9]]; discovery of the CPT Symmetry Operator from RQFT (1955-57) [10].

1927-1957 → Validity of C invariance: e^+ [2]; $\bar{p}$ [11]; $\bar{n}$ [12]; $K_2^0 \to 3\pi$ [13] but see LOY [14].

- **The new era starts: C ≠ ; P ≠ ; CP ≠ (*).**

1956 → Lee & Yang P ≠ ; C ≠ [15].

1957 → Before the experimental discovery of P ≠ & C ≠, Lee, Oehme, Yang (LOY) [14] point out that the existence of the second neutral K-meson, $K_2^0 \to 3\pi$, is proof neither of C invariance nor of CP invariance. Flavour antiflavour mixing does not imply CP invariance.

1957 → C.S. Wu et al. P ≠ ; C ≠ [16]; CP ok [17].

1964 → $K_2^0 \to 2\pi = K_L$: CP ≠ [18].

1947-1967 → QED divergences & Landau poles.

1950-1970 → The crisis of RQFT & the triumph of S-matrix theory (i.e. the negation of RQFT).

1965 → Nuclear antimatter is (experimentally) discovered [19]. See also [20].

1968 → The discovery [21] at SLAC of Scaling (free quarks inside a nucleon at very high q^2) but in violent (pp) collisions no free quarks at the ISR are experimentally found [22]. Theorists consider Scaling as being evidence for RQFT not to be able to describe the Physics of Strong Interactions. The only exception is G. 't Hooft who discovers in 1971 that the β-function has negative sign for non-Abelian theories [23].

1971-1973 → β = − ; 't Hooft, Gross & Wilczek. The discovery of **non-Abelian** gauge theories. Asymptotic freedom in the interaction between quarks and gluons [23].

1974 → All gauge couplings α_1 α_2 α_3 run with q^2 but they do not converge towards a unique point.

1979 → A.P. & A.Z. point out that the new degree of freedom due to SUSY allows the three couplings α_1 α_2 α_3, **to converge towards a unique point** [24].

1980 → QCD has a "hidden" side: the multitude of final states for each pair of interacting particles: (e^+e^- ; $p\bar{p}$; πp; Kp; νp; pp; etc.)
The introduction of the Effective Energy allows to discover the Universality properties [25] in the multihadronic final states.

1992 → All gauge couplings converge towards a unique point at the gauge unification energy: $E_{GU} \approx 10^{16}$ GeV with $\alpha_{GU} \approx 1/24$ [26, 27].

1994 → The Gap [28] between E_{GU} & the String Unification Energy: $E_{SU} \approx E_{Planck}$.

1995 → **CPT loses its foundations at the Planck scale (T.D. Lee)** [29].

1995-1999 → **No CPT theorem from M-theory (B. Greene)** [30].

1995-2000 → A.Z. points out the need for new experiments to establish if matter-antimatter symmetry or asymmetry are at work.

(*) The symbol ≠ stands for 'Symmetry Breakdown'.

Figure 11.

Let me say a few words to illustrate this group of unexpected events.

Since the dawn of civilization, it was believed that the stability of matter was due to its weight: the heavier an object, the better for its stability.

The Greeks were convinced that the stability of the columns for their splendid temples was due to the 'heaviness' of the columns.

The first unexpected event started with the discovery by Einstein that mass and energy could transform each other.

> When (1905) Einstein discovered that
>
> $$mc^2 = E$$
>
> he could not sleep at night.
>
> (*Peter G. Bergmann testimony*)

If matter can transform into energy, the world becomes unstable and we could not exist.

Fortunately (for Einstein) in 1897 J.J. Thomson had discovered the 'electron'. Since its charge is opposite to that of the proton, the electric charge is enough to guarantee the stability of matter.

In fact, charge conservation forbids the transition,

$$p \rightarrow e^- \gamma; \text{ thus } p \not\rightarrow e^- \gamma . \tag{1}$$

Einstein stopped being worried and could relax; the world is stable, despite

$$E = mc^2.$$

The only detail is that 'm' must be understood as being the 'mass' of an object, not its matter. Thus the basic distinction shown on top of Figure 10. Our Greek ancestors could not believe in this sequence of unexpected events.

And this is not all.

Another totally unexpected event had to occur a quarter of a century later, when (1930) Dirac realized that the evolution of the electron (the same particle which is in the atoms of our body) in Space-Time (with the property discovered by Lorentz in his investigation of the invariance of the Maxwell equations, i.e. they cannot both be 'real', one of them – either

Space or Time – must be 'imaginary') brought him to discover an incredibly unexpected fact: that the antielectron must exist; i.e. a very light particle with the same charge as that of the proton.

If this is the case, then the reaction

$$p \rightarrow e^{+} + \gamma \tag{2}$$

can take place and the stability of matter is again gone. The world becomes unstable.

Thus Stueckelberg invented another unexpected deviation from simplicity: the quantum number 'baryonic charge' which (according to Stueckelberg) must be conserved in nature.

The reaction (2) is forbidden by this new conservation law:

$$p \not\rightarrow e^{+} + \gamma \tag{3}$$

Life would have been far simpler if the Greeks were right in their way of explaining the stability of matter.

Despite the complications described above, the story of the stability of matter does not end with equation (3). Another unexpected discovery was needed. This came with the understanding that the word 'charge' corresponds to two totally different and fundamental physical properties.

There are in fact two types of 'charge'.

One is called 'gauge charge', and this is responsible for the existence of a Fundamental Force of Nature. There are in fact three *gauge charges*, the 'electromagnetic', the Subnuclear 'weak' and the Subnuclear 'strong'. (For simplicity we will ignore the gravitational force). The corresponding forces are described by the Gauge Symmetry Groups U(1) (for the electromagnetic forces), SU(2) (for the Subnuclear weak forces) and SU(3) (for the Subnuclear strong forces).

There is a further unexpected discovery: the two Gauge Symmetry Groups U(1) and SU(2) are mixed and it is their *mixing* which produces the effective forces which allow our TV and radio plus all electromagnetic instruments to work and the Stars to function, thanks to the effective weak force which controls very well their level of burning.

In fact, it is the strength (called Fermi coupling) of the weak forces (also called Fermi forces) which controls the amount of protons which transforms into neutrons (plus a neutrino and a positive electron) every second in a Star, thus allowing the 'nuclear fuel' (the neutrons) for the Stars to exist.

All we have said refers to the 'gauge charges', which are responsible for the existence of the fundamental forces. But the stability of matter has to be there and, contrary to what Einstein thought in 1905, it is not guaranteed by the existence of the electric charge: this is in fact a ‘gauge charge’.

In order to have the stability of matter, we need a totally unexpected type of charge, called *flavour charge*. The number of these charges is again unexpectedly 12, as illustrated in Figure 10. The incredible story is that these charges are four times more than the ‘gauge charges’; so far nobody knows why this is so.

The answer could come from the Superworld.

The conclusion of the long way to understand the origin of the stability of matter is that many unexpected discoveries were needed, as reported in Figure 11. From the Greeks who associated ‘stability’ of matter with ‘heaviness’ to our present understanding, the number of unexpected events is really impressive.

Let us skip the points 3 and 4 and move to 5, the Physics of Instantons in QCD.

POINT 5. The mixing in the pseudoscalar and in the vector mesons: the Physics of Instantons (Figure 12).

In the Physics of Mesons the totally unexpected result was the difference existing between the two mesonic mixing angles, pseudoscalar and vector:

$$\theta_{PS} \neq \theta_V .$$

They should both be zero if $SU(3)_{uds}$ was a good Symmetry. The existence of Instantons was not known. They came after the unexpected discovery that $\theta_{PS} \neq \theta_V$. (See Figure 12, page 287)

POINT 6. Newton discovered that Light is the sum of different Colours. The modern mathematical structure which describes light is Quantum ElectroDynamics: QED. In the Subnuclear world of *quarks and gluons* the mathematical structure which describes these forces is called Quantum ChromoDynamics. The interaction between *quarks and gluons* produce *Jets* made of many *pions*

$$pp \rightarrow \pi + X .$$

The energy spectrum of these *pions* is shown in Figure 13.

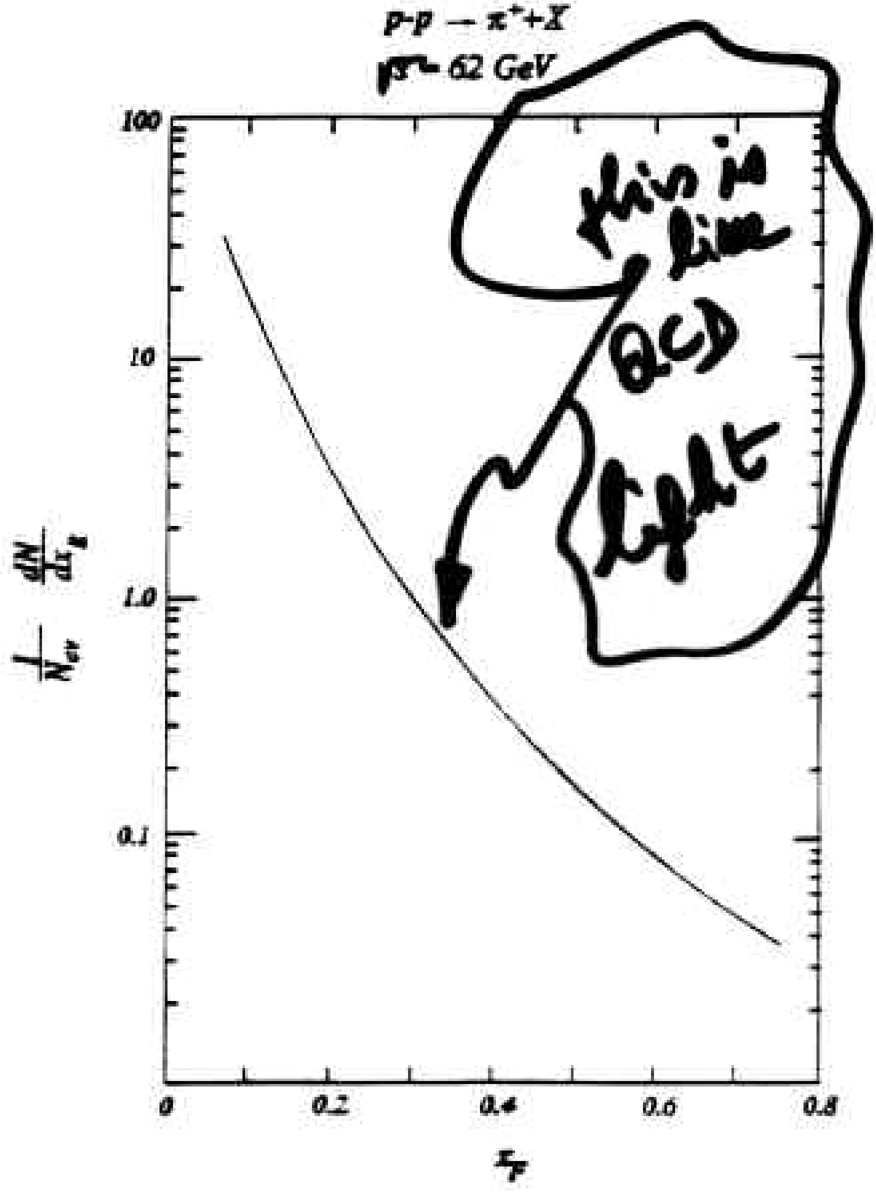

Figure 13.

This is what Gribov defined: *The QCD light*. In fact this unique 'line' is the sum of all 'lines' shown in Figure 14 (see page 288). This is the discovery of the Effective Energy, once again a totally unexpected quantity.

The non-Abelian nature of the Interaction describing quarks, gluons and the Effective Energy with the set of unexpected discoveries is illustrated in Figure 15.

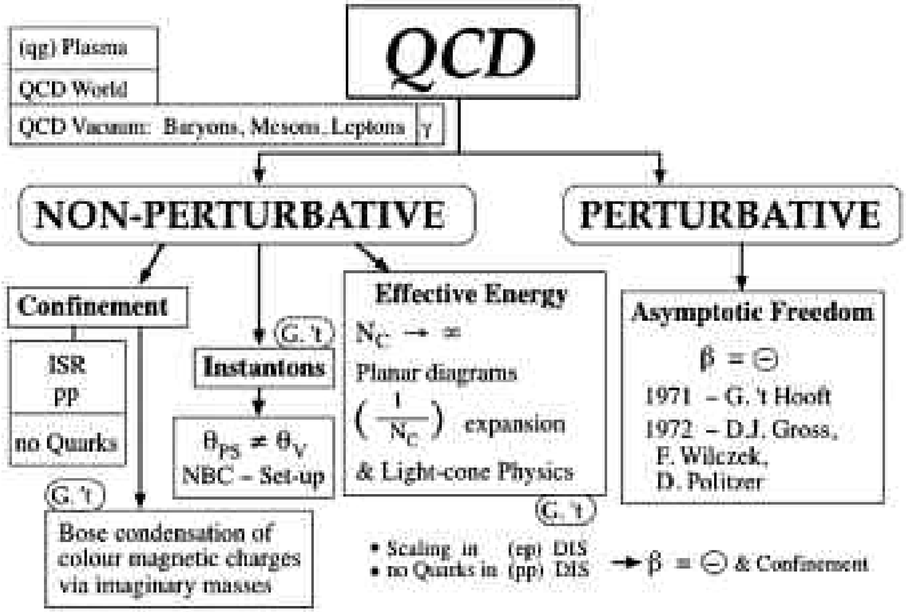

Figure 15.

POINT 7. The Unification of all Forces and the Supersymmetry threshold with its problems are reported in Figures 16 and 17 (see pages 289-90) respectively. This Figure illustrates the EGM effect in bringing down by a factor 700 the threshold for the production of the lightest superparticle.

The mathematical formalism which has been used to obtain the results shown in these Figures is a system of three differential non-linear equations coupled via the gauge couplings

α_i , α_j (with i = 1,2,3; and J = 1,2,3 but $i \neq j$),

as shown in Figure 18.

THE UNIFICATION OF ALL FUNDAMENTAL FORCES

$$\mu \frac{d\alpha_i}{d\mu} = \frac{b_i}{2\pi} \alpha_i^2 + \sum_j \frac{b_{ij}}{8\pi^2} \alpha_i \alpha_j$$

Figure 18.

For more than ten years (from 1979 to 1991), no one had realized that the energy threshold for the existence of the Superworld was strongly dependent on the ‘running’ of the masses.

This is now called: the EGM effect (from the initials of Evolution of Gaugino Masses).

To compute the energy threshold using only the ‘running’ of the gauge couplings (α_1, α_2, α_3) corresponds to neglecting nearly three orders of magnitude in the energy threshold for the discovery of the first particle (the lightest) of the Superworld [30], as illustrated in Figure 17.

Let me now illustrate in Figure 19 (see page 291) the Platonic Grand Unification in the Convergence of the three Gauge Couplings $\alpha_1, \alpha_2, \alpha_3$.

The ‘Platonic’ Simplicity would indicate the series of points making up the straight line as the ideally simple solution. The real solution is the sequence of points which totally deviate from the straight line.

This is just an example of comparison between the 'Platonic' Simplicity and the 'real world', with the unexpected events needed to deal with the Grand Unification (see Figure 16, page 289).

Talking about Supersymmetry, there is another important step: how we go from pure Theoretical Speculations to Phenomenology.

The proof is given in Figure 20 where it is shown how many important properties of the physics to be described have been neglected by some authors (AdBF) whose claim was to 'predict' the energy scale at which Supersymmetry is broken.

In order to attempt to give such a prediction, there are at least five 'details' to be taken into account, as reported in the last five columns of Figure 20.

	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩
Authors	Input data	Errors	EC	M_{SUSY}	CC	UC	ΔT_L	M_X	ΔT_H	EGM
ACPZ [47, 49–54]	WA	$\pm 2\sigma$	all possible solutions (26)	Yes	physical	Yes	Yes	Yes	Yes	Yes

Authors	Input data	Errors	EC	M_{SUSY}	CC	UC	ΔT_L	M_X	ΔT_H	EGM
AdBF [55]	only one experiment	$\pm 1\sigma$	only one solution	Yes	Geometrical	No	No	No	No	No

① WA = World Average
② Errors = Uncertainty taken from all data (World Average) or from a single experiment
③ EC = Evolution of Couplings
④ M_{SUSY} = Mass Scale assumed to represent the Supersymmetry Scale breaking
⑤ CC = Convergence of Couplings
⑥ UC = Unification of Couplings above E_{GUT}
⑦ ΔT_L = Low Energy threshold
⑧ M_X = Mass Scale at the breaking of the Grand Unified Theory to the $SU(3) \times SU(2) \times U(1)$
⑨ ΔT_H = High Energy threshold
⑩ EGM = Evolution of Gaugino Masses

Figure 18.

4. Conclusions

In the field of Subnuclear Physics, the totally unexpected discoveries date back to the beginning of Galilean Science. We have listed those of the 20th Century ending up with present-day frontiers in Subnuclear Physics.

Question. *What about other fields?* One which is very intensive in a number of discoveries is the field of condensed matter.

Let me quote Tony Leggett (University of Illinois, Urbana – Champaign, USA), Nobel 2003 for 'Superfluidity': 'It is relatively rare in Condensed-Matter Physics to predict discoveries, it is a field where you fall over them by accident'.

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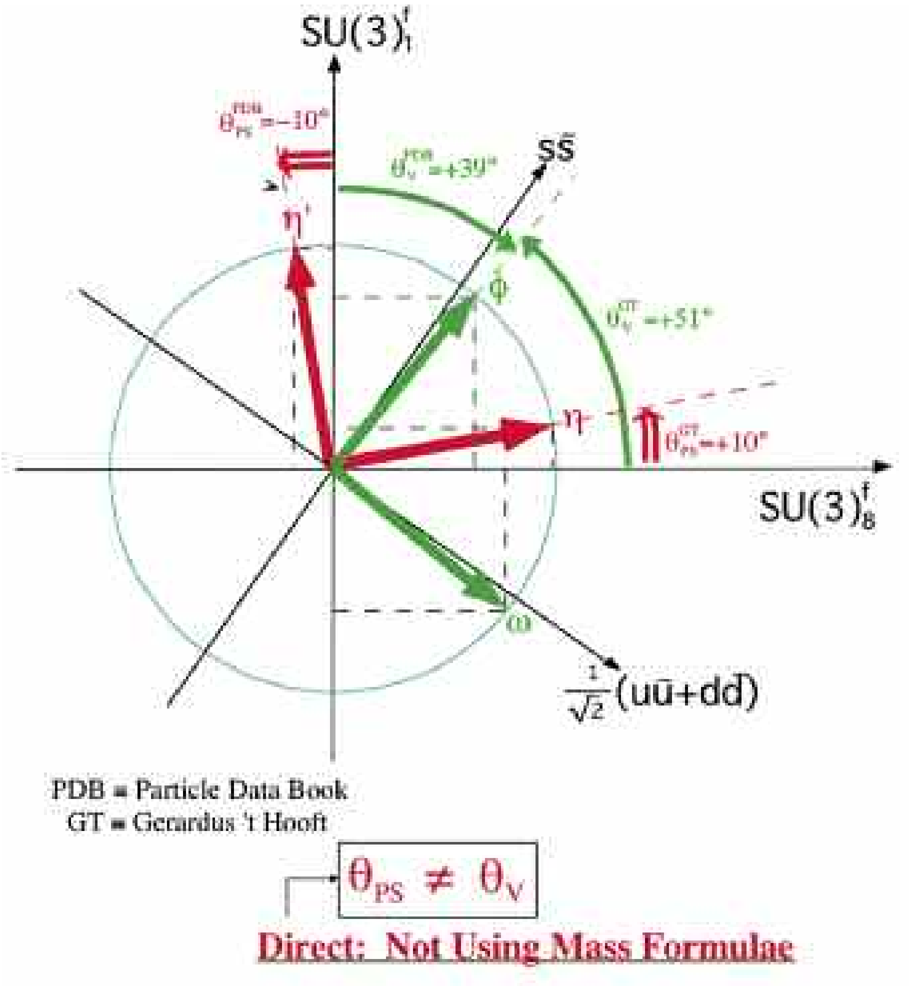

SU(3)$^f_1$
SU(3)$^f_8$
$s\bar{s}$
$\frac{1}{\sqrt{2}}(u\bar{u}+d\bar{d})$
η'
η
ϕ
ω
$\theta^{GT}_V = +51°$
$\theta^{GT}_{PS} = +10°$
PDB = Particle Data Book
GT = Gerardus 't Hooft
$\theta_{PS} \neq \theta_V$
Direct: Not Using Mass Formulae

Figure 12.

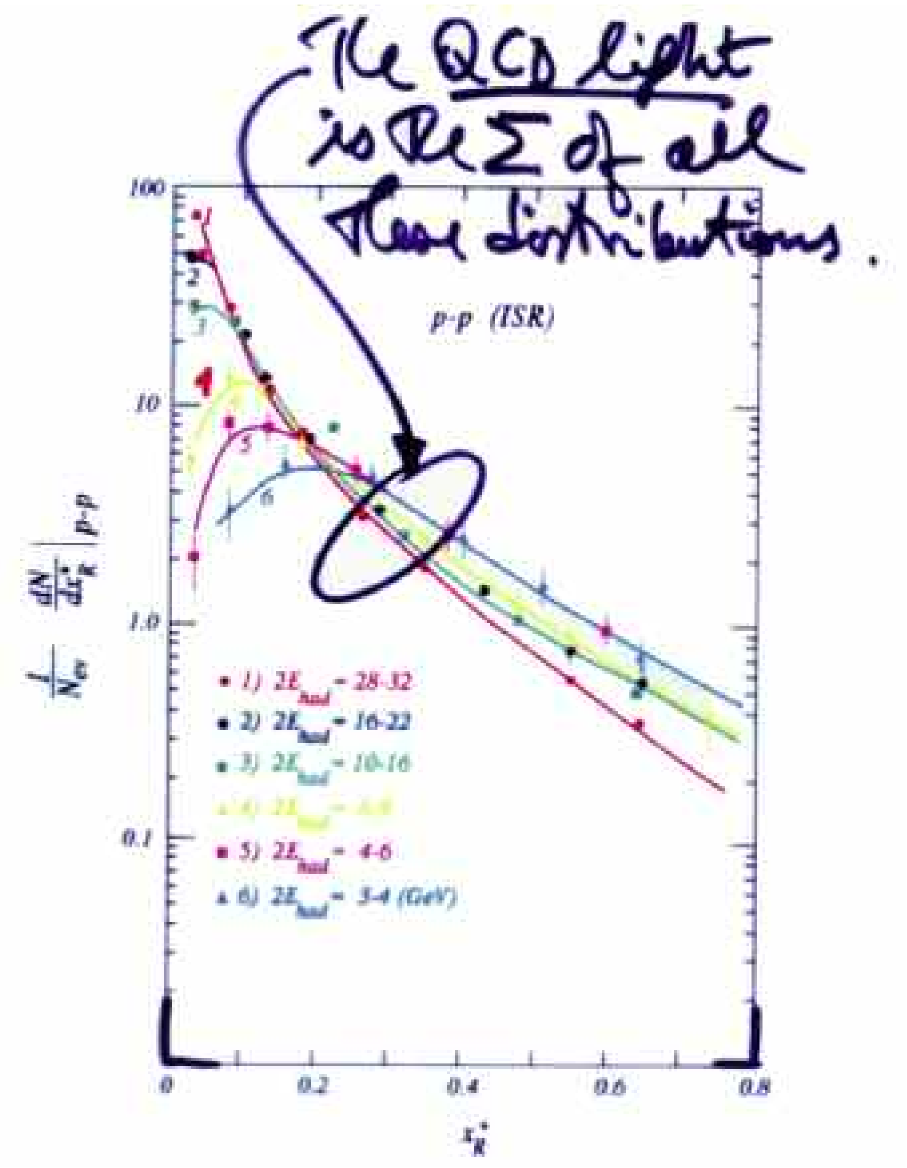

The QCD light is the Σ of all these distributions.
p-p (ISR)
100
10
1.0
0.1
0
0.2
0.4
0.6
0.8
1) 2E_had = 28-32
2) 2E_had = 16-22
3) 2E_had = 10-16
5) 2E_had = 4-6
6) 2E_had = 3-4 (GeV)

Figure 14.

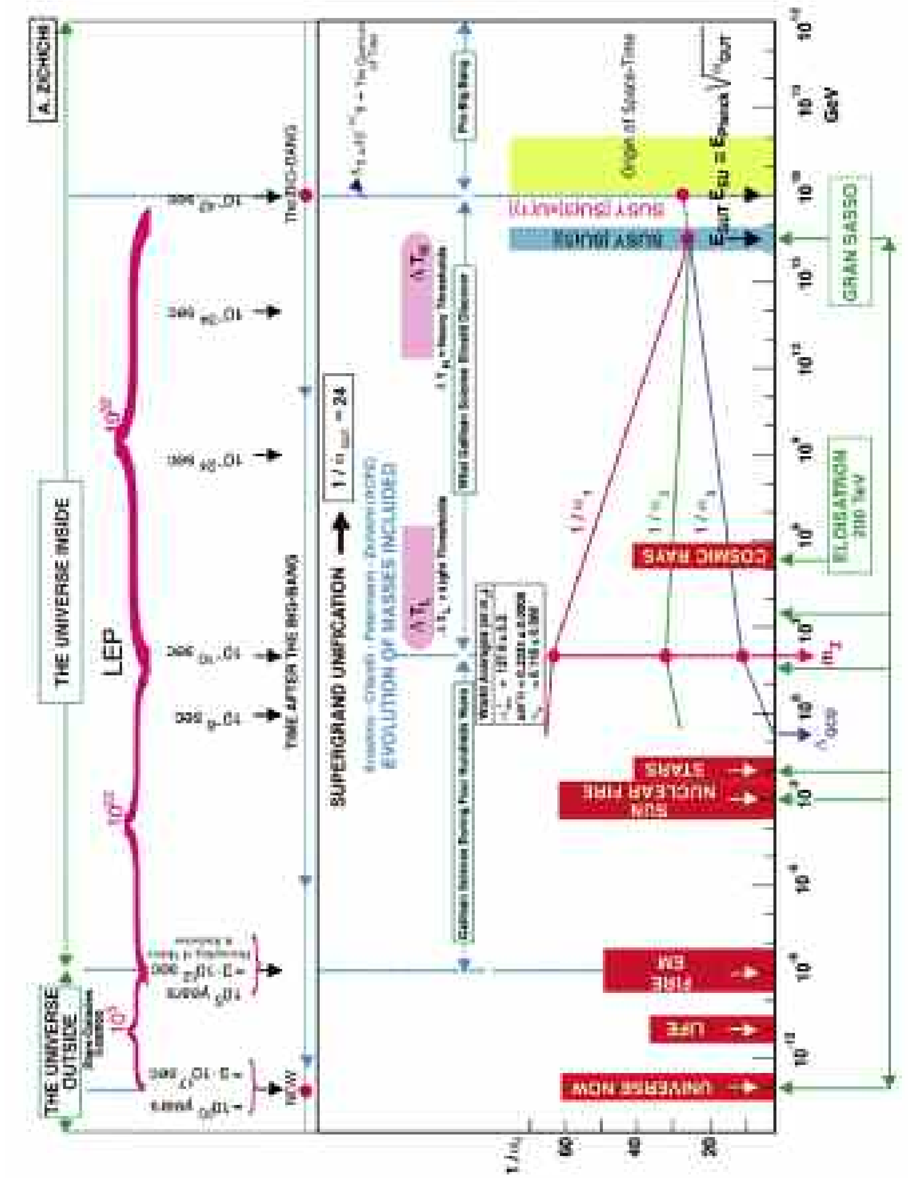

A. ZICHICHI
THE UNIVERSE INSIDE
THE UNIVERSE OUTSIDE
LEP
TIME AFTER THE BIG-BANG
SUPERGRAND UNIFICATION
EVOLUTION OF MASSES INCLUDED
UNIVERSE NOW
LIFE
FIRE EM
SUN NUCLEAR FIRE
STARS
COSMIC RAYS
ELOISATRON
GRAN SASSO
GeV

Figure 16.

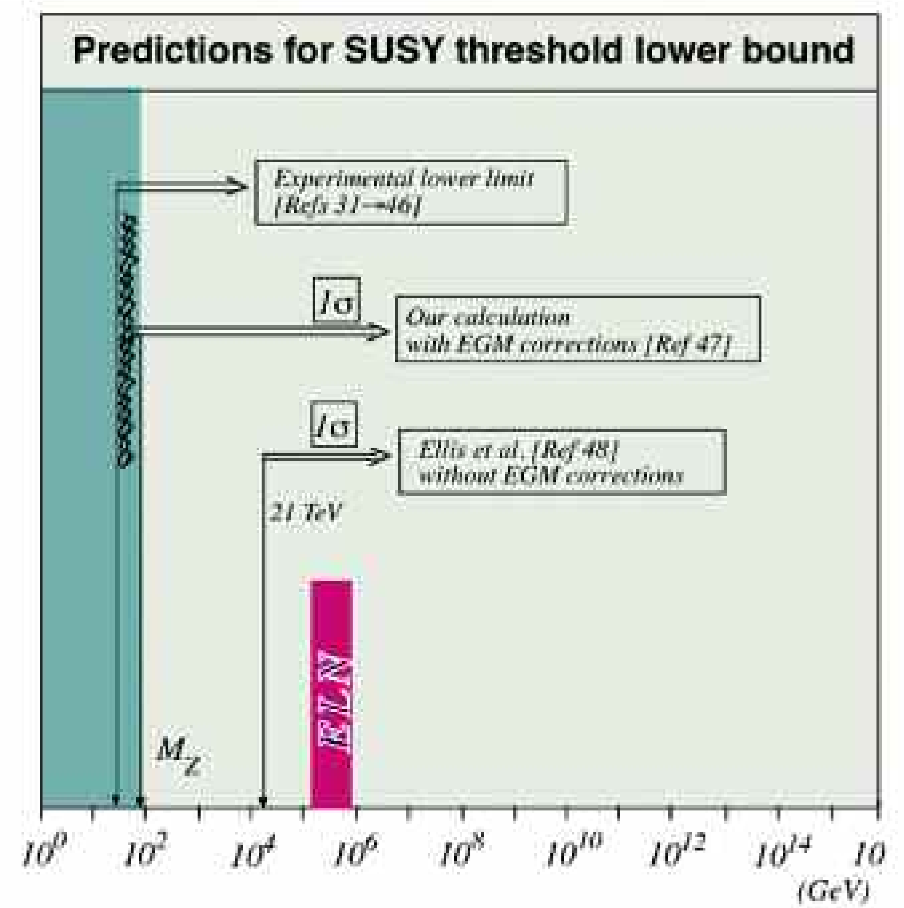
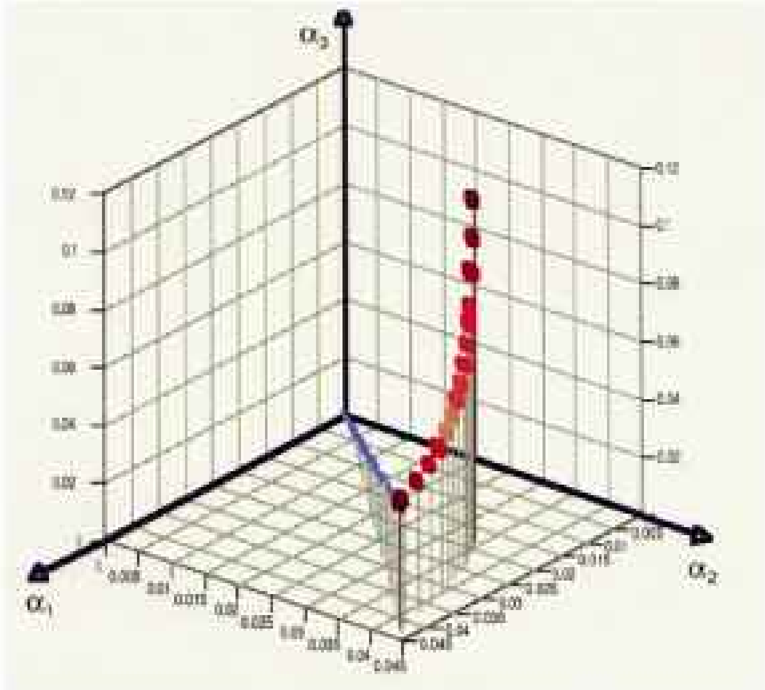

Predictions for SUSY threshold lower bound
Experimental lower limit
[Refs 31→46]
1σ
Our calculation
with EGM corrections [Ref 47]
1σ
Ellis et al. [Ref 48]
without EGM corrections
21 TeV
ELN
M_Z
10^0
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
10
(GeV)

Figure 17.



The points have a sequence of 100 GeV in energy. The last point where the 'ideal' platonic straight line intercepts the theoretical prediction is at the energy of the Grand Unification. This corresponds to $E_{GU} = 10^{16.2}$ GeV. Other detailed information on the theoretical inputs: the number of fermionic families, N_F, is 3; the number of Higgs particles, N_H, is 2. The input values of the gauge couplings at the Z^0-mass is $\alpha_3 (M_Z) = 0.118 \pm 0.008$; the other input is the ratio of weak and electromagnetic couplings also measured at the Z^0-mass value: $\sin^2 \theta_W (M_Z) = 0.2334 \pm 0.0008$.

Figure 19.