Review of the Standard Model

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LHC DAYS IN SPLIT

Split, October 3 - 7, 2006

The contents:

1. Basic features of the SM

- in prize of the SM

2. Three sectors of the SM

- gauge (force)
- matter
- symmetry breaking

3. Reasons for going BSM

- in the past
- today

1. The basic facts on

THE STANDARD MODEL

- the most complete math. THEORY ever developed
- encompasses "all of chemistry and most of physics" (DIRAC on Q.M.)

- two distinct but related components

SU(2) ⊗ U(1) electroweak gauge theory

SU(3) colour gauge theory

◊ core concepts { SSB, AF

◊ assignments of { LEPTONS & QUARKS

as relevant d.o.f.

Nobel prizes in physics since 1957 related to the Standard Model.

Year	Recipient(s)	Subject
1957	T. D. Lee and C. N. Yang	Parity violation
1960	D. A. Glaser	Bubble chamber
1965	R. P. Feynman, J. S. Schwinger, and S. I. Tomonaga	Quantum electrodynamics
1968	L. W. Alvarez	Discovery of resonances
1969	M. Gell-Mann	Particle classification
1976	B. Richter and S. C. C. Ting	J/ψ discovery
1979	S. L. Glashow, A. Salam, and S. Weinberg	Electroweak unification
1980	J. W. Cronin and V. L. Fitch	CP violation
1982	K. G. Wilson	Critical phenomena
1984	C. Rubbia and S. Van Der Meer	W and Z discovery via S$\bar{p}p$S collider
1988	L. M. Lederman, M. Schwartz, and J. Steinberger	Discovery that $\nu_\mu \neq \nu_e$
1990	J. I. Friedman, H. W. Kendall, and R. E. Taylor	Deep inelastic electron scattering
1992	G. Charpak	Particle detectors
1995	M. L. Perl	τ lepton
	F. Reines	Neutrino detection
1999	G. 't Hooft and M. J. G. Veltman	Electroweak interactions

2002 R. Davis, M. Koshiba — Cosmic neutrino detection

2004 D. Gross, D. Politzer, F. Wilczek — Discovery of asymptotic freedom of the strong force

Physics beyond the SM

The list at ICHEP'06 (Kazakov)

- Low Energy Supersymmetry
- Extra gauge bosons
- Axions
- Extra dimensions
- Deviation from Unitarity triangle
- Modification of Newton law
- Free quarks
- New forces / particles
- Violation of Baryon number
- Violation of Lepton number
- Monopoles
- Violation of Lorentz invariance
- Compositeness

Not found so far …


CERN site

2. The ingredients of the SM

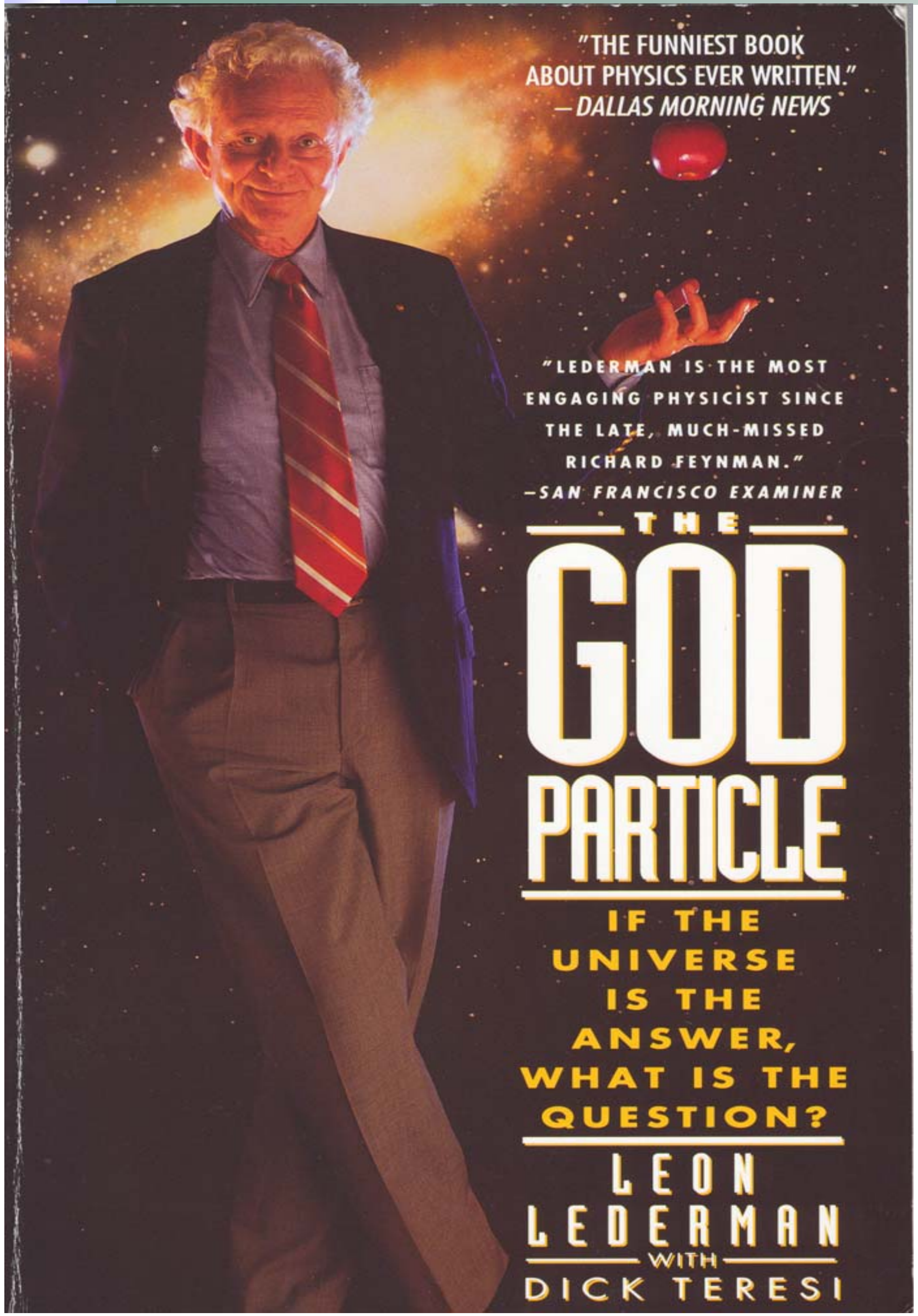
2.1 The force sector

2.2 The matter sector

2.3 The SB sector

2.1 The force (gauge) aspect

- Gauge-theory prehistory (the point sources of the forces)
- QED ideal
- EW unification



THE DALMATIAN PROPHET

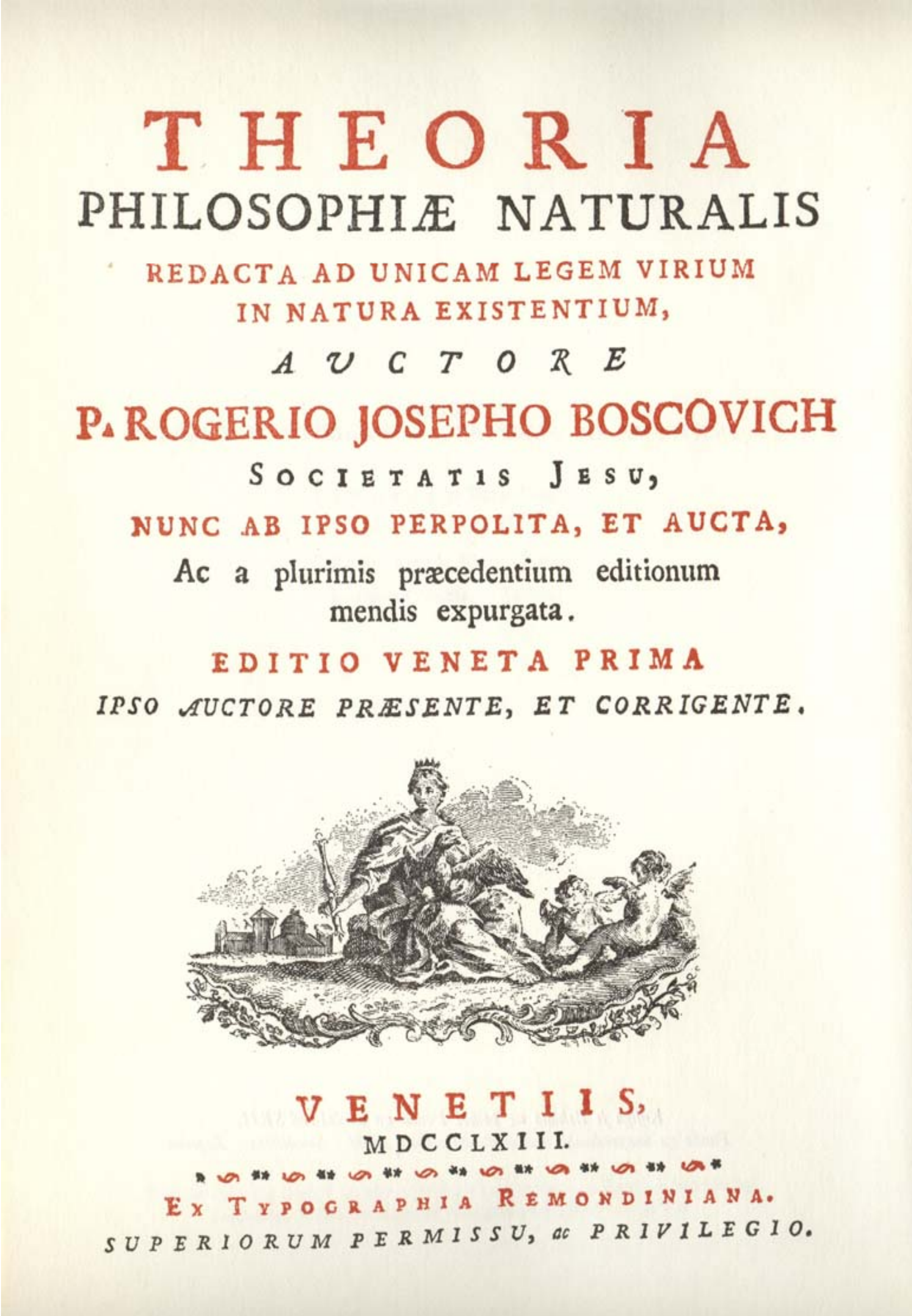
A final note on this first stage, the age of mechanics, the great era of classical physics. The phrase "ahead of his time" is overused. I'm going to use it anyway. I'm not referring to Galileo or Newton. Both were definitely right on time, neither late nor early. Gravity, experimentation, measurement, mathematical proofs . . . all these things were in the air. Galileo, Kepler, Brahe, and Newton were accepted — heralded! — in their own time, because they came up with ideas that the scientific community was ready to accept. Not everyone is so fortunate.

Roger Joseph Boscovich, a native of Dubrovnik who spent much of his career in Rome, was born in 1711, sixteen years before Newton's death. Boscovich was a great supporter of Newton's theories, but he had some problems with the law of gravitation. He called it a "classical limit," an adequate approximation where distances are large. He said that it was "very nearly correct but that differences from the law of inverse squares do exist even though they are very slight." He speculated that this classical law must break down altogether at the atomic scale, where the forces of attraction are replaced by an oscillation between attractive and repulsive forces. An amazing thought for a scientist in the eighteenth century.

Boscovich also struggled with the old action-at-a-distance problem. Being a geometer more than anything else, he came up with the idea of *fields of force* to explain how forces exert control over objects at a distance. But wait, there's more!

Boscovich had this other idea, one that was real crazy for the eighteenth century (or perhaps any century). Matter is composed of invisible, indivisible a-toms, he said. Nothing particularly new there. Leucippus, Democritus, Galileo, Newton, and others would have agreed with him. Here's the good part: Boscovich said these particles had no size; that is, they were geometrical points. Clearly, as with so many ideas in science, there were precursors to this — probably in ancient Greece, not to mention hints in Galileo's works. As you may recall from high school geometry, a point is just a place; it has no dimensions. And here's Boscovich putting forth the proposition that matter is composed of particles that have no dimensions! We found a particle just a couple of decades ago that fits such a description. It's called a quark.

We'll get back to Mr. Boscovich later.

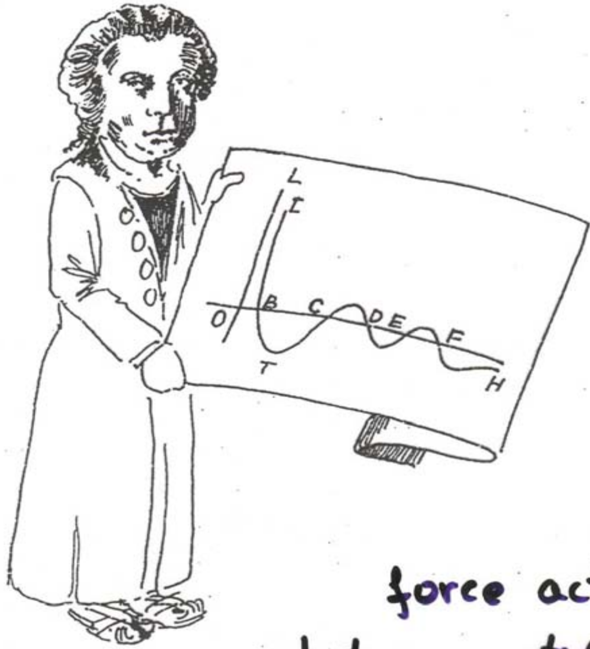


THEORIA
PHILOSOPHIÆ NATURALIS
REDACTA AD UNICAM LEGEM VIRIUM
IN NATURA EXISTENTIUM,
AUCTORE
P. ROGERIO JOSEPHO BOSCOVICH
SOCIETATIS JESU,
NUNC AB IPSO PERPOLITA, ET AUCTA,
Ac a plurimis præcedentium editionum
mendis expurgata.
EDITIO VENETA PRIMA
IPSO AUCTORE PRÆSENTE, ET CORRIGENTE.

VENETIIS,
MDCCLXIII.
EX TYPOGRAPHIA REMONDINIANA.
SUPERIORUM PERMISSU, ac PRIVILEGIO.

GAUGE-THEORY PREHISTORY

◊ **Rudjer Bošković** (1711 - 1787) "Theoria Philosophiae Naturalis" (1763)

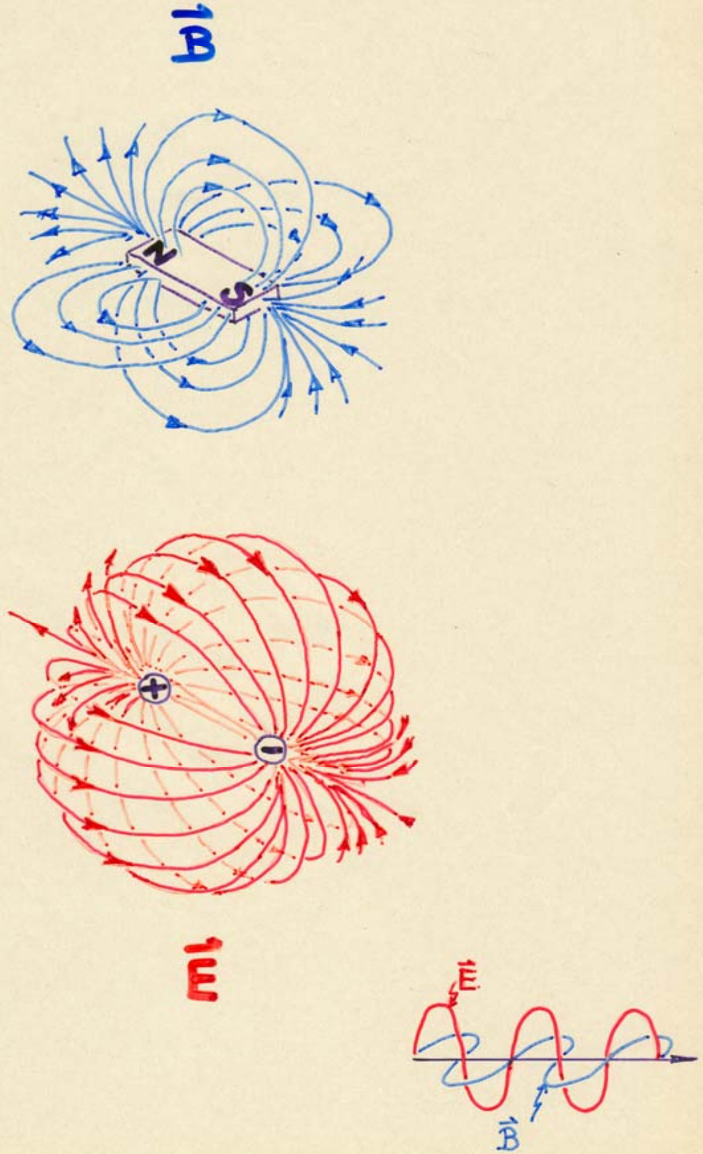


force acting
- between particles of matter

◊ **John Lesslie** (Edinburgh) besides lecturing from 1785 on Bošković's theory

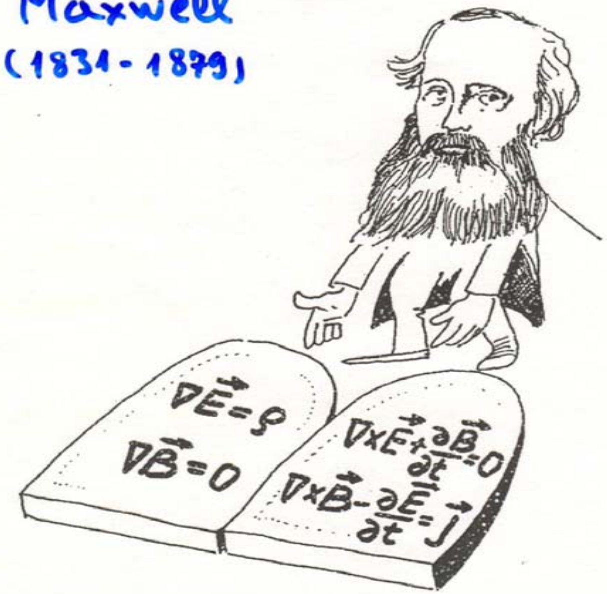
introduced separate forces acting
- between two particles of light
- between particle of matter and particle of light

basic ingredients in the SM of forces !



1^{st} GRAND UNIFICATION IN PHYSICS

- Maxwell
(1831 - 1879)



Maxwell equations
supplemented by Lorentz's force law

$$\vec{F} = e_E \vec{E} + e_M \frac{\vec{v}}{c} \times \vec{B}$$

$$\boxed{e_E = e_M = e}$$

at ordinary velocities ($v \ll c$)
magnetism is weak

Involved "old" principles

QED involved principles	recovered through dilemmas / new scales	
◇ QUANTUM MECHANICS	particle or wave ?	Bohr radius $r_B \simeq 5\cdot10^{-11}$ m
◇ RELATIVITY	particle or field ?	Compton w-length $r_C \simeq 4\cdot10^{-13}$ m

+ the local (gauge) symmetry

◊ GAUGE / LOCAL SYMMETRY principle

requires the existence of the photon field

$U(1)_{QED}$:

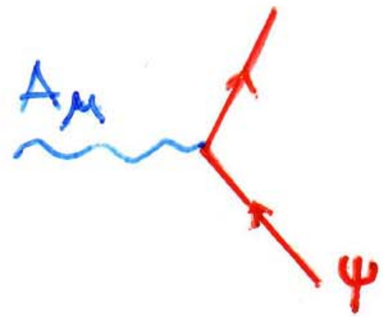
$$\psi(x) \to \psi'(x) = e^{i\varepsilon(x)Q}\psi(x)$$

$$A_\mu(x) \to A'_\mu(x) = A_\mu(x) + \frac{1}{e}\partial_\mu \varepsilon(x)$$

$$\partial_\mu \psi \to D_\mu \psi = [\partial_\mu + ieQA_\mu]\psi$$

- in interaction

$$eQA_\mu(x)\underbrace{\bar{\psi}(x)\gamma^\mu\psi(x)}_{j^\mu_{em}}$$



"non-Abelian QED"

- **QCD - strong interaction**

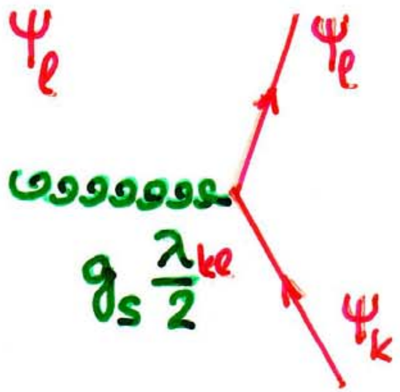
  has a separate / QED-like appearance

  SU(3) :

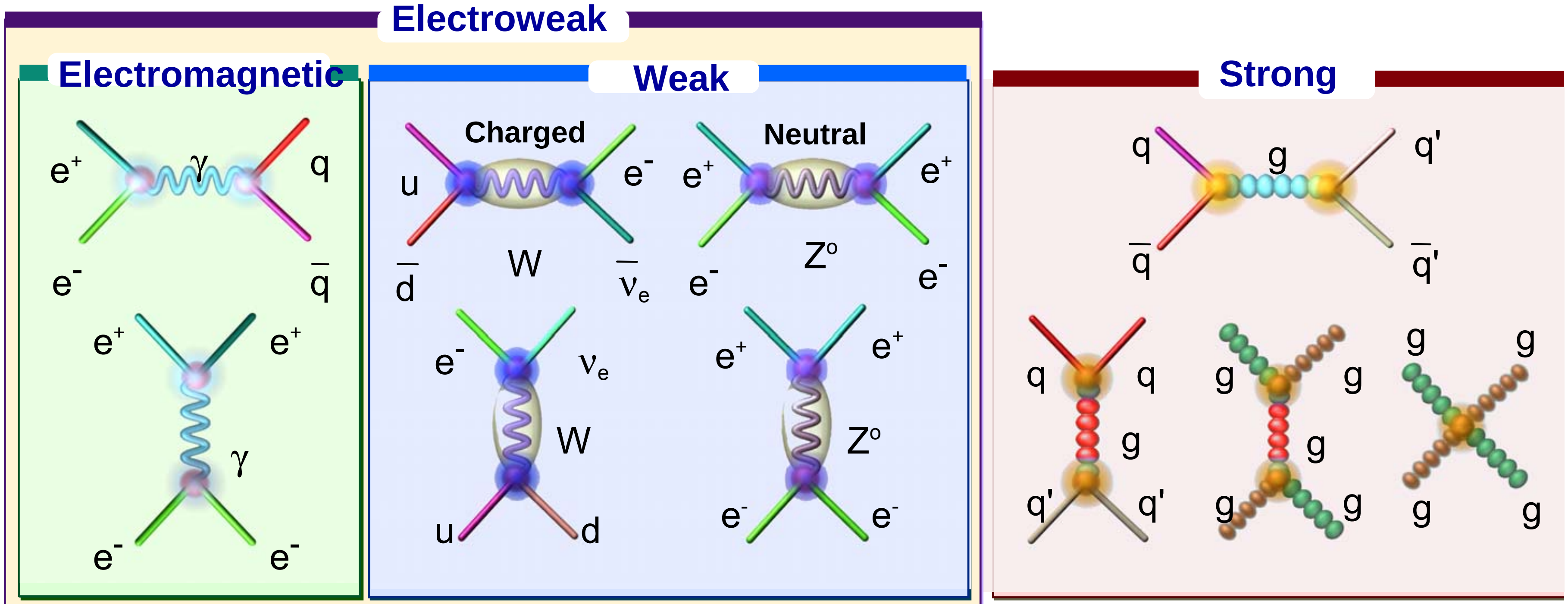
$$\psi \rightarrow \psi' = e^{i\,\theta^a(x)\,\frac{\lambda^a}{2}}\,\psi \quad ; \; a = 1, 2, \ldots 8$$

$$\partial_\mu \psi_k \rightarrow D_\mu \psi_k = \partial_\mu \psi_k - i g_s \frac{\lambda^a_{kl}}{2} A^a_\mu \psi_l$$

8 gluons



Two distinct & related components



Range ∞, relative strength ≤ 10^{-2}

Range ~10^{-18} m, relative strength 10^{-14}

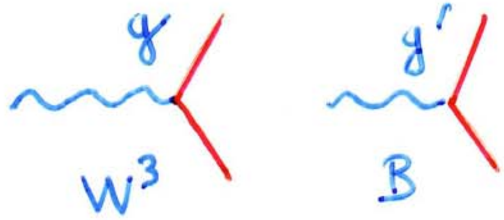
Range ~ 10^{-15} m, relative strength = 1

The electroweak unification

◊ ELECTROWEAK $SU(2)_W \times U(1)_Y$

symmetric/mathematical theory at the fundamental scale

$$-i g \vec{J}_\mu \vec{W}^\mu - i g' \frac{1}{2} j^Y_\mu B^\mu$$



charged weak current + ordinary light

$W^\pm$, W^3 & B

electroweak mixing

neutral physical currents

ordinary light $A_\mu = B_\mu \cos\Theta_W + W^3_\mu \sin\Theta_W$

"heavy light" $Z_\mu = -B_\mu \sin\Theta_W + W^3_\mu \cos\Theta_W$

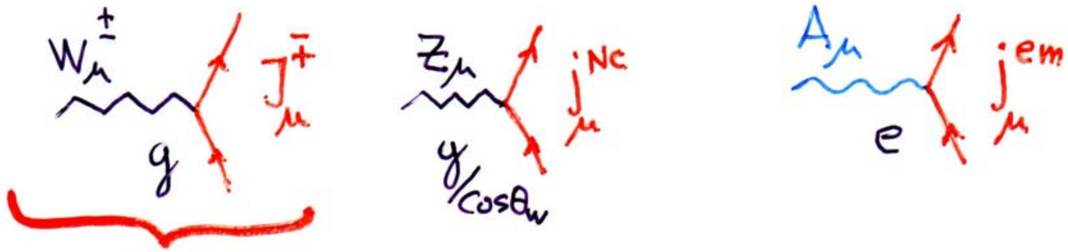
$$j^{em}_\mu = j^3_\mu + \frac{1}{2} j^Y_\mu$$

$$j^{NC}_\mu = j^3_\mu - \sin^2\Theta_W \, j^{em}_\mu$$

Generalises the Maxwell's unification

$$SU(2)_W \otimes U(1)_Y \xrightarrow{\text{BROKEN}} U(1)_{em}$$

in order to have a massless photon only!



Unification of the electromagnetic and weak interaction

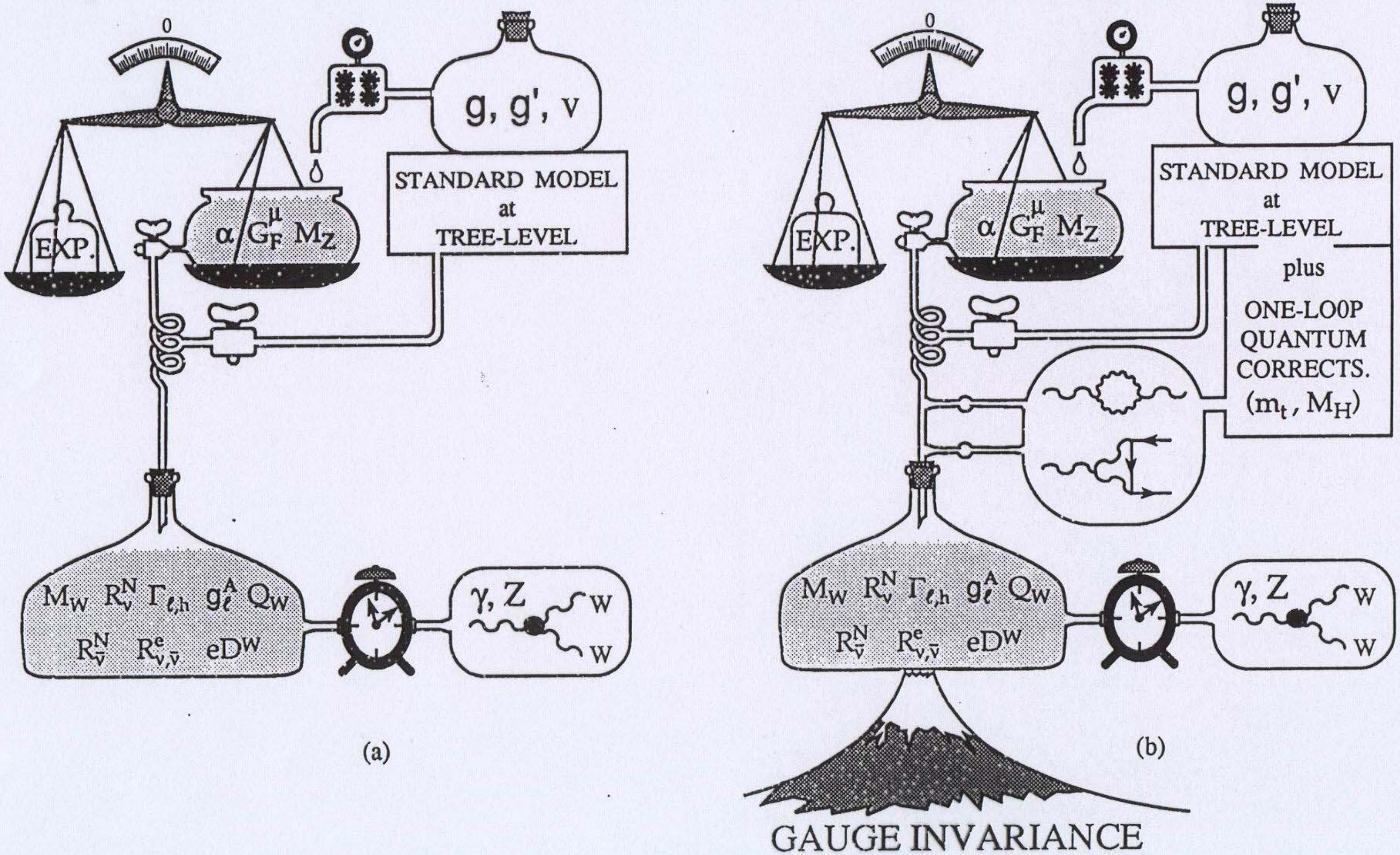
$$e = g \sin\Theta_W$$

expressed in terms of the parameter Θ_W!

Renormalizability of the SM proven by ‘t Hooft & Veltman

SU(2)⊗U(1) ELECTROWEAK MODEL

SU (2) ⊗ U (1) ELECTROWEAK THEORY



(a) (b)

OBLIQUE CORRECTIONS

- only affect the propagation/mixing of the GAUGE BOSONS
- suitable for considering the "new physics" contributions

$$\Pi^{\mu\nu}_{AB}(q^2) \sim g^{\mu\nu}\Pi_{AB}(q^2) + C_{AB}(q^2) q^\mu q^\nu$$

expanded in powers q^2/M^2_{new}

$$\Pi_{\gamma\gamma}(q^2) = q^2 \Pi'_{\gamma\gamma}(0) + \dots$$

$$\Pi_{\gamma Z}(q^2) = q^2 \Pi'_{Z\gamma}(0) + \dots$$

$$\Pi_{ZZ}(q^2) = \Pi_{ZZ}(0) + q^2 \Pi'_{ZZ}(0) + \dots$$

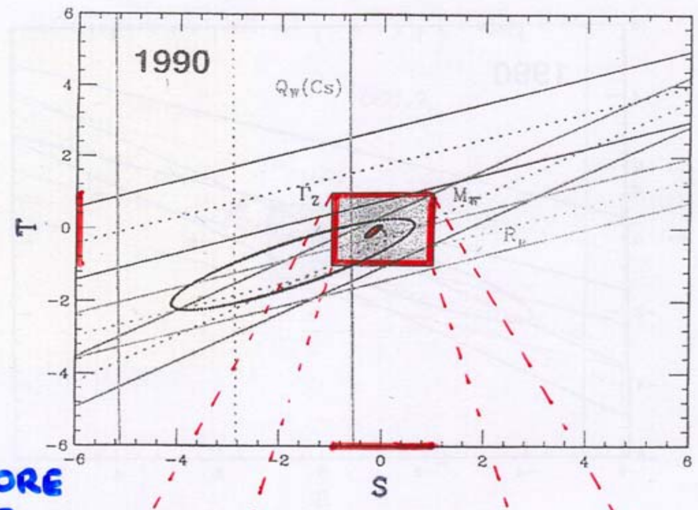
$$\Pi_{WW}(q^2) = \Pi_{WW}(0) + q^2 \Pi'_{WW}(0) + \dots$$

6-parameters (3 absorbed into α, G_μ, M_Z)

$\Rightarrow$ 3 left (**S**, **T**, **U**)

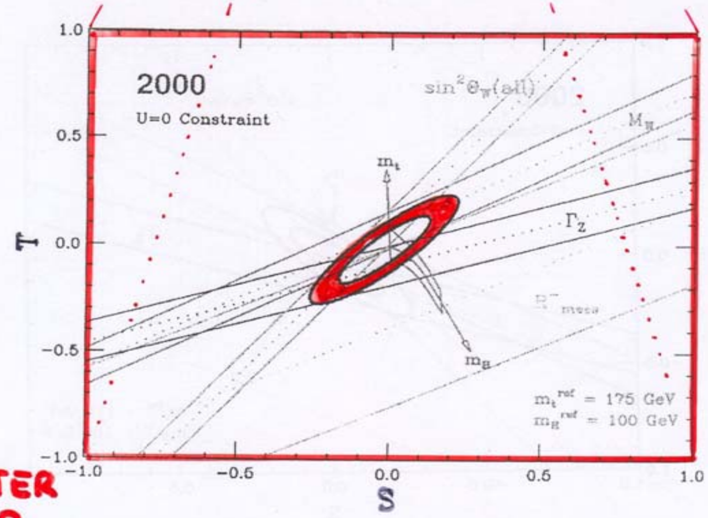
e.g. $$\alpha \mathbf{T} = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2}$$

enters the ρ-parameter $$\rho = 1 + \delta_\rho^{SM} + \alpha T$$



BEFORE LEP

Data on fundamental electroweak parameters in 1990. There was broad consistency with minimal $SU(2) \times U(1)$, but little sensitivity to radiative corrections.



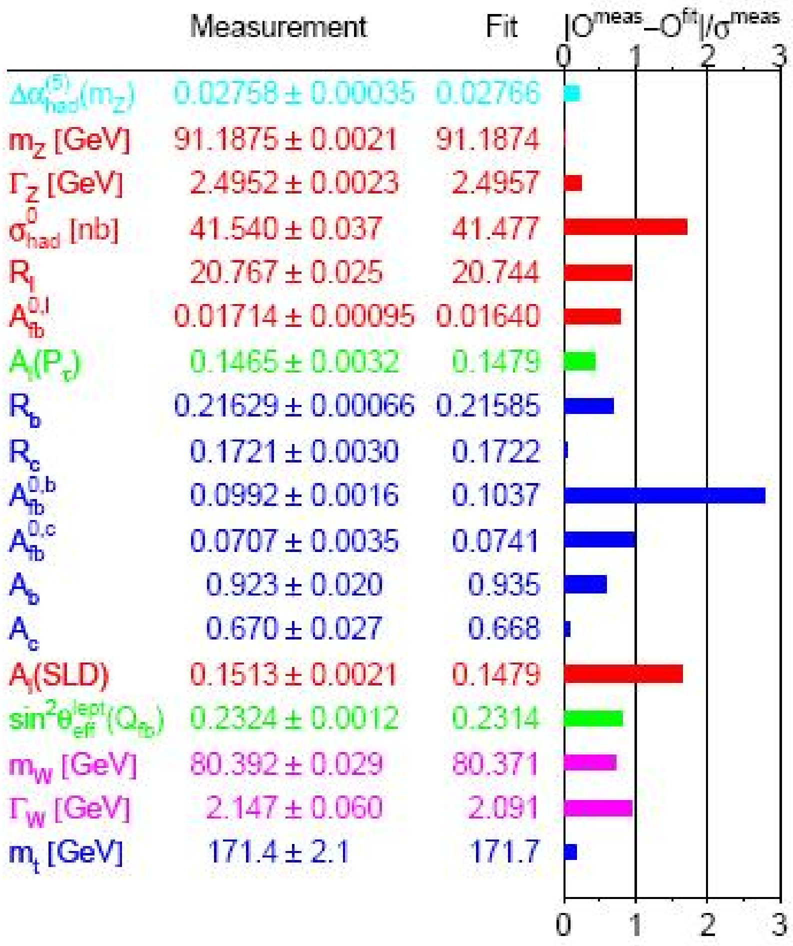
AFTER LEP

Data on fundamental electroweak parameters in 2000. Careful inclusion of the radiative corrections, including loops containing both W and Z bosons and the color gluons of QCD, is necessary to do justice to the data. One can discriminate the effects of the top quark mass and the Higgs boson mass.

Global fit to ew precision data

$\chi^2/\text{dof}=17.8/13$ (16.6%)

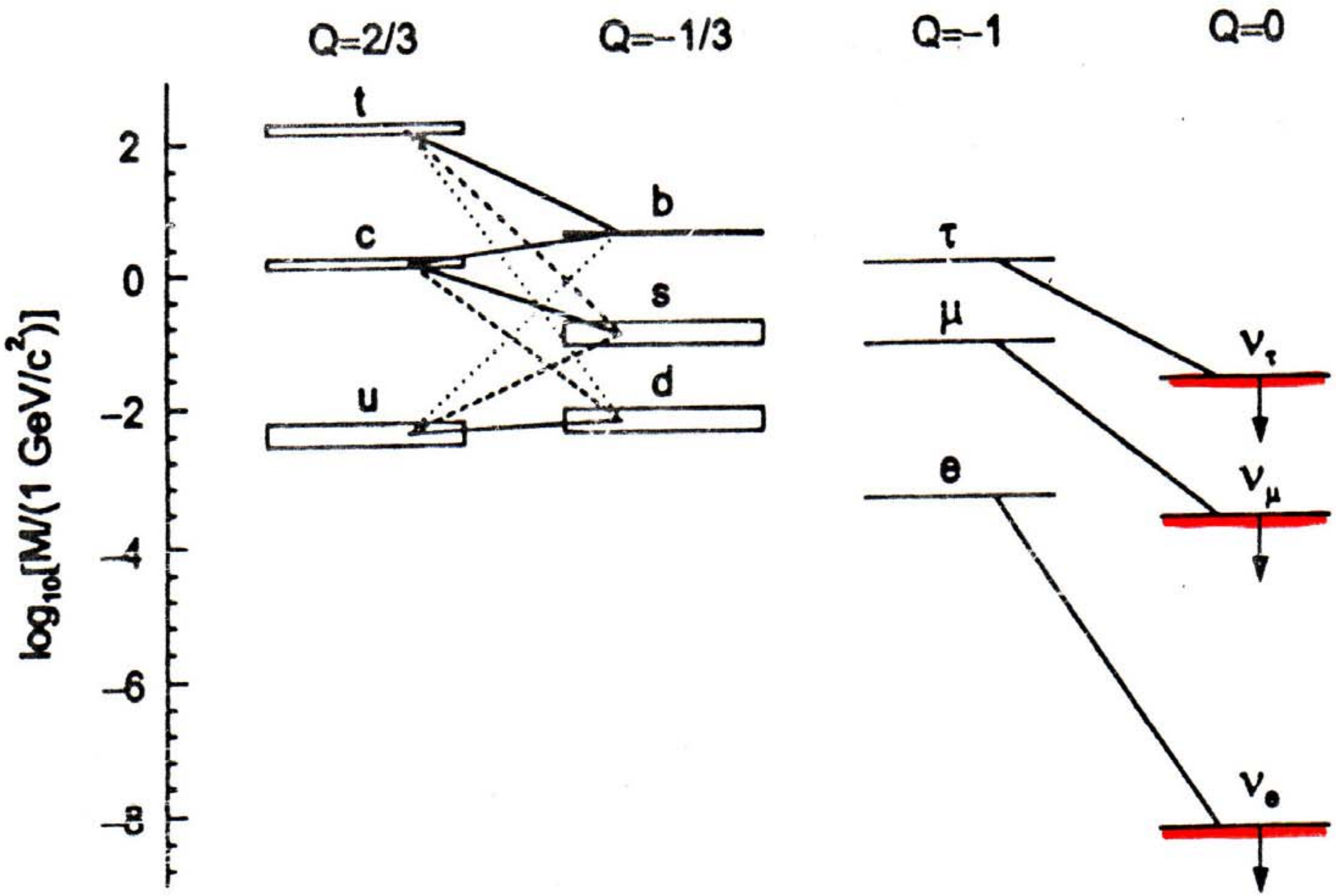
Largest pull is from LEP b-quark forward/backward asymmetry.



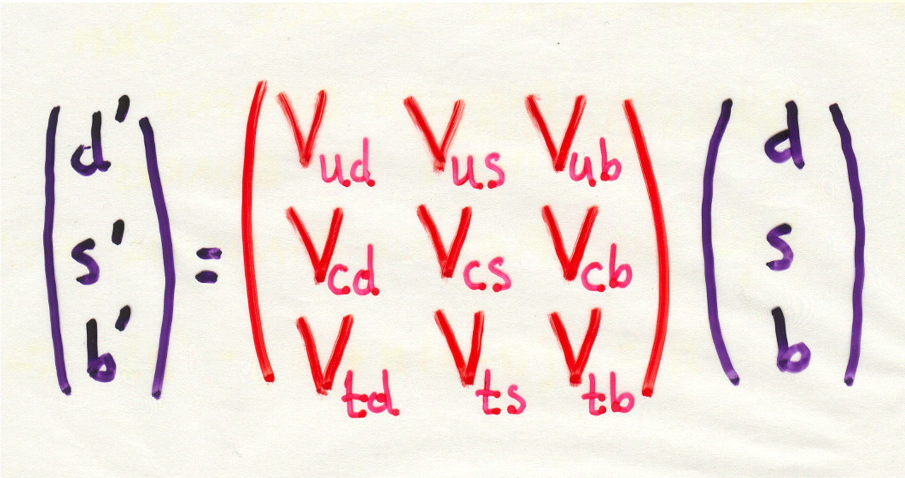
2.2 The matter sector

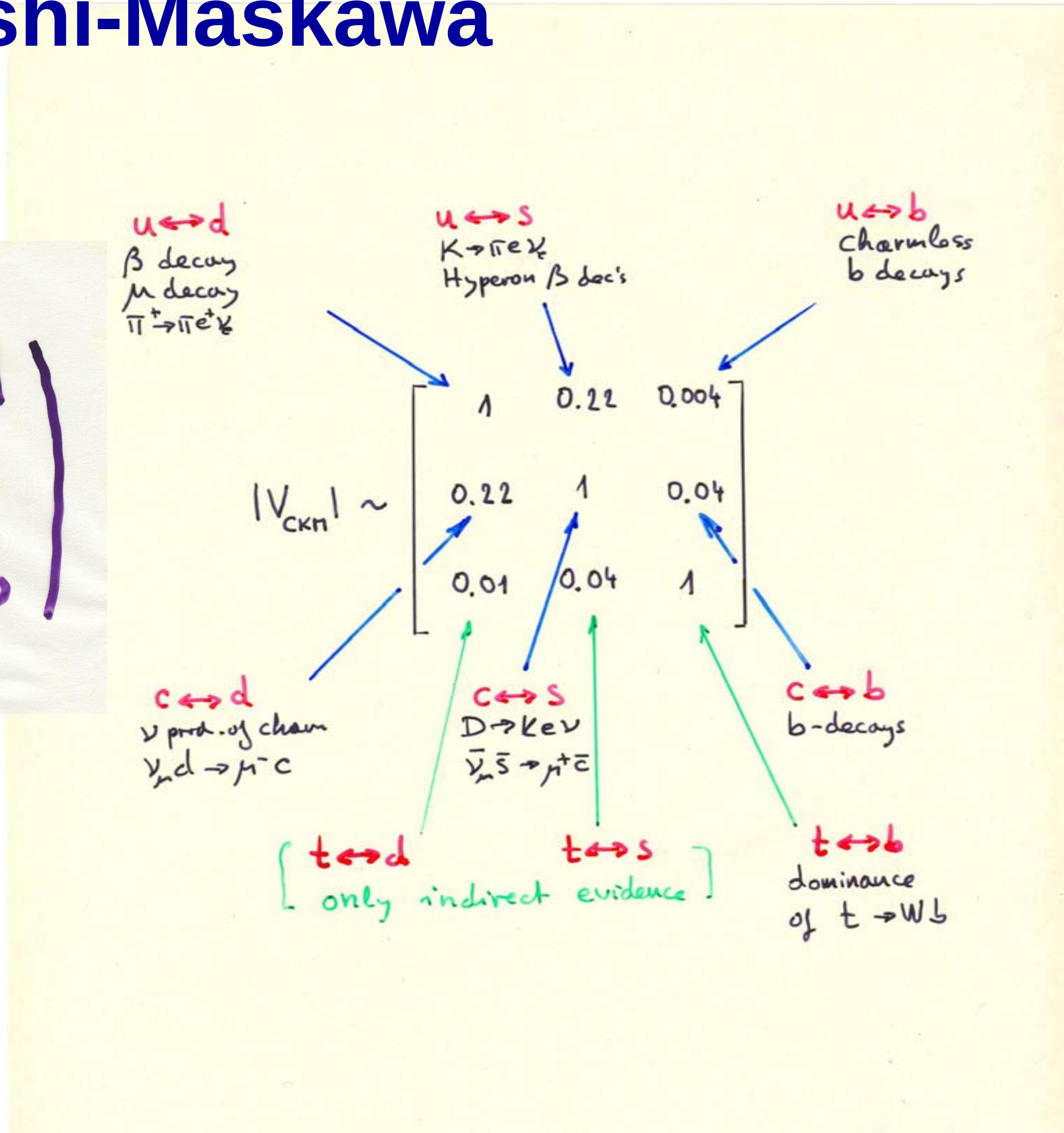
- **New d.o.f.**
- **Anomaly cancelation**
- **Origin of texture**

The quark-lepton spectrum



Quark mixing
Cabibbo-Kobayashi-Maskawa





COUNTING the SM's FREE PARAMETERS

3 Gauge couplings

3 g_s, g, g' or $\alpha = \frac{e^2}{4\pi}, \theta_W, \Lambda_{QCD}$

2 Higgs parameters

2 μ, λ or M_H, λ

9 fermion masses

m_e, m_u, m_d ; m_μ, m_c, m_s ; m_τ, m_t, m_b

4 CKM parameters for 3 generations

$\vartheta_1, \vartheta_2, \vartheta_3$ (mixing angles) & δ (CP-phase)

1 parameter of $\not{CP}$ in QCD

θ_{QCD}

---

19 parameters in the minimal case (massless neutrinos)

"OLD SM"

MATTER

3 FAMILIES/GENERATIONS of fundamental fermions

	LEPTONS	QUARKS
1^{st}	ν_e	u
	e^-	d
2^{nd}	ν_μ	c
	μ^-	s
3^{rd}	ν_τ	t
	τ^-	b

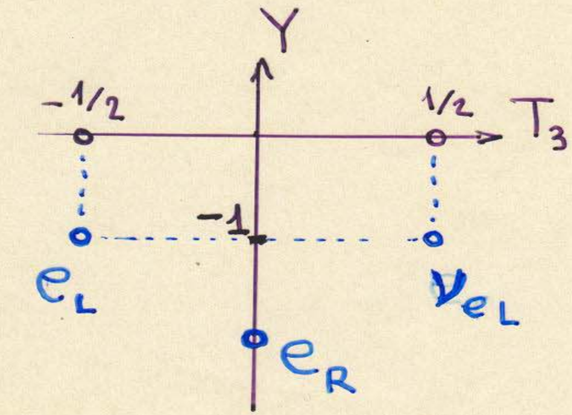
all we need ?

needed for CP̸ and for our very existence !

with 15 helicity states in each

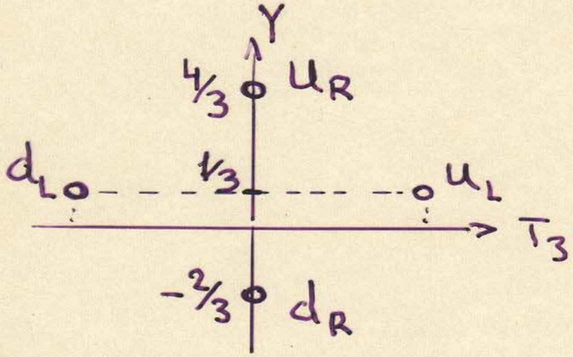
SM charge content enabling anomaly cancellation

INGREDIENTS/ REPRESENTATIONS
accounting for one (e.g. 1st) generation



$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$ $(1, 2)_{-1}$

e_R $(1, 1)_{-2}$



u_R $(3, 1)_{4/3}$

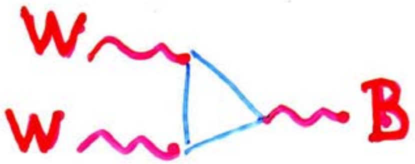
$\begin{pmatrix} u \\ d \end{pmatrix}_L$ $(3, 2)_{1/3}$

d_R $(3, 1)_{-2/3}$

$SU(3) \times SU(2) \times U(1)_Y$

fortuitous anomaly cancellation

$[SU(2)]^2 Y$

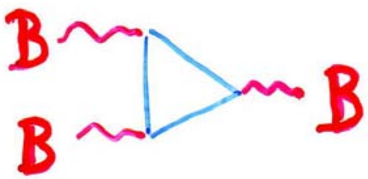


$$\mathrm{Tr}(\{\tau^i, \tau^j\} Y) = 2\delta^{ij}\, \mathrm{Tr}\, Y$$

$$\sum_{\text{leptons}} Y + \sum_{\text{quarks}} Y = 0$$

$(-1)\cdot 2 + 2 \qquad 3\left(\frac{1}{3}\cdot 2 - \frac{4}{3} + \frac{2}{3}\right)$

Y^3



$$\propto \mathrm{Tr}\, Y^3 =$$

$$(-1)^3 + (-1)^3 + (2^3) + 3\cdot\left[\left(\tfrac{1}{3}\right)^3 + \left(\tfrac{1}{3}\right)^3 + \left(-\tfrac{4}{3}\right)^3 + \left(\tfrac{2}{3}\right)^3\right]$$

$\uparrow \nu_L \quad \uparrow e_L \quad \uparrow e^c_L \quad \uparrow u_L \quad \uparrow d_L \quad \uparrow u^c_L \quad \uparrow d^c_L$

2.3 The symmetry breaking sector

- The least constrained sector of SM
- Vacuum stability vs. triviality
- Hierarchy problem of scales

Higgs mass bounds (GeV)

- lower >114

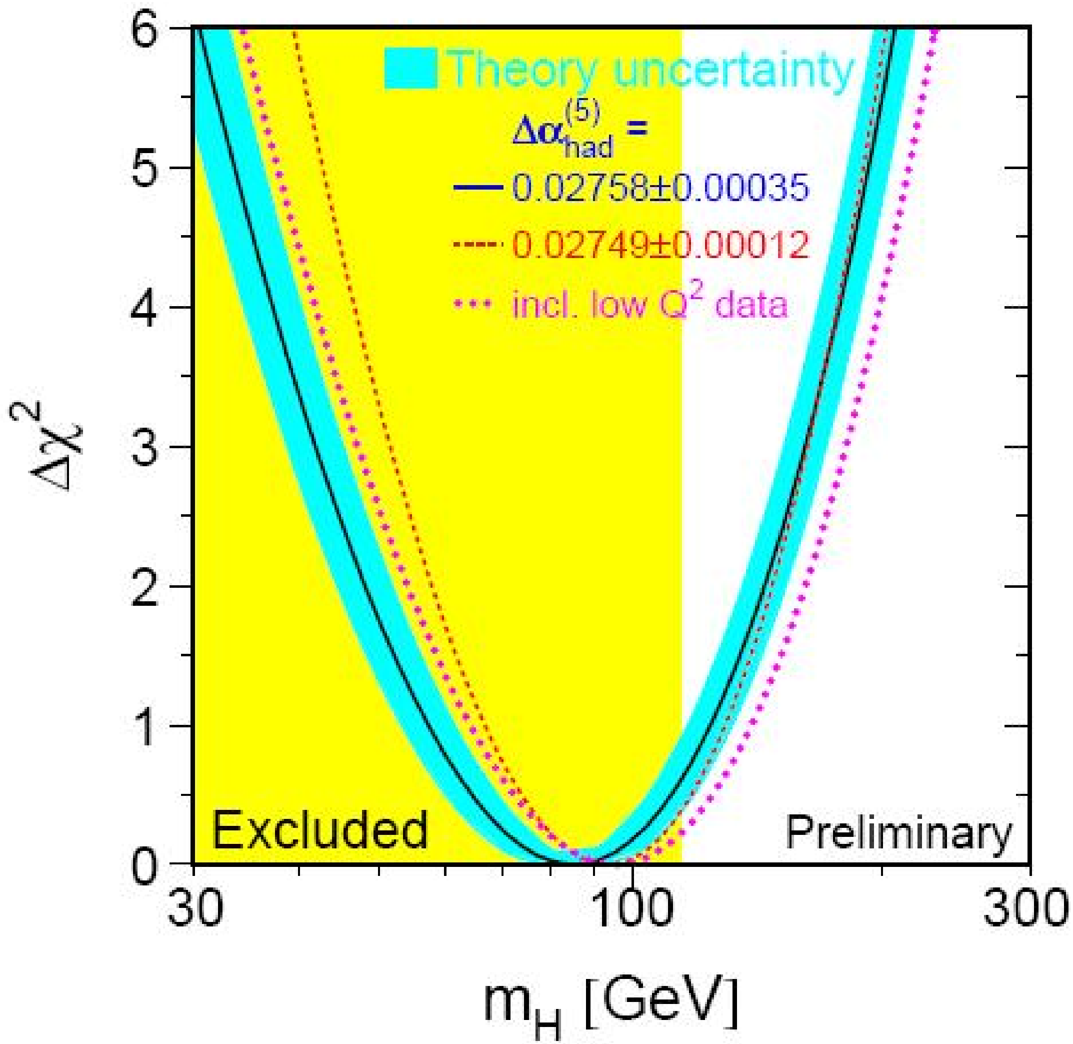
Non-
  observation

at LEP

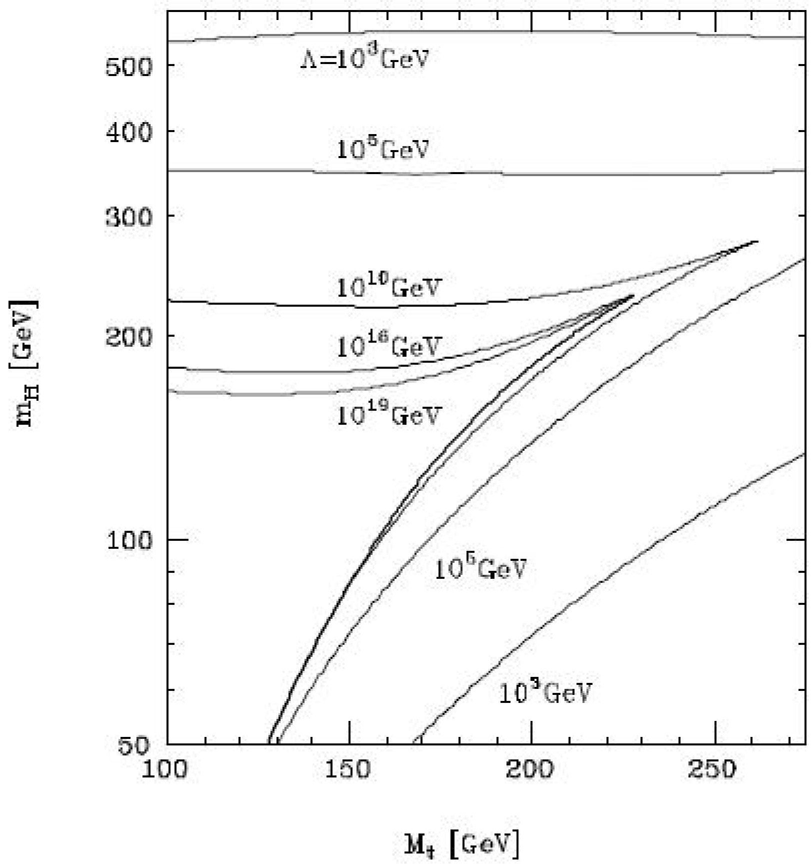
- Upper <185

Global fit plot

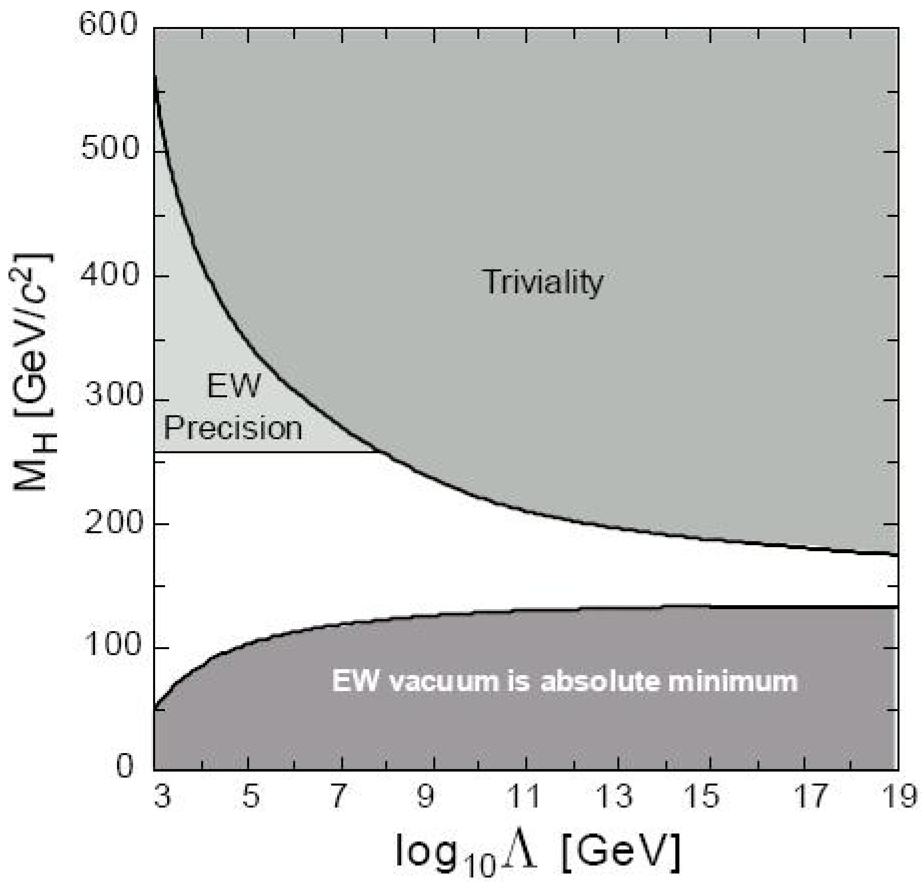
("blue-band")



Theoretical bounds

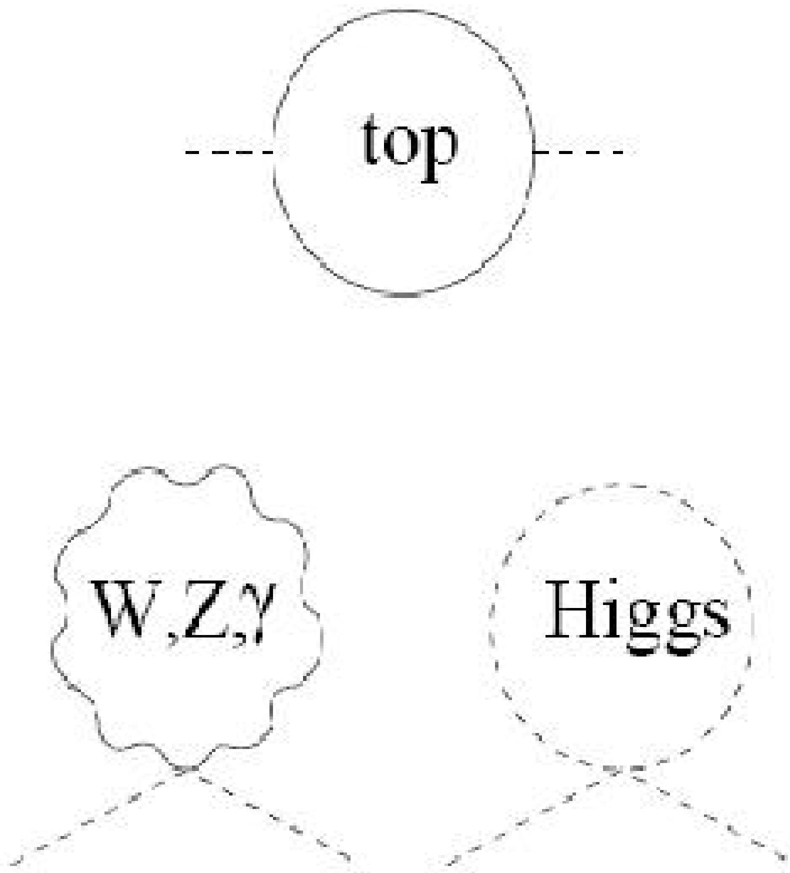


(a)



(b)

Quant. Fluct. destabilise Higgs



$$-\frac{3}{8\pi^2}\lambda_t^2\Lambda^2 \sim -(2\,TeV)^2$$

from the top loop,

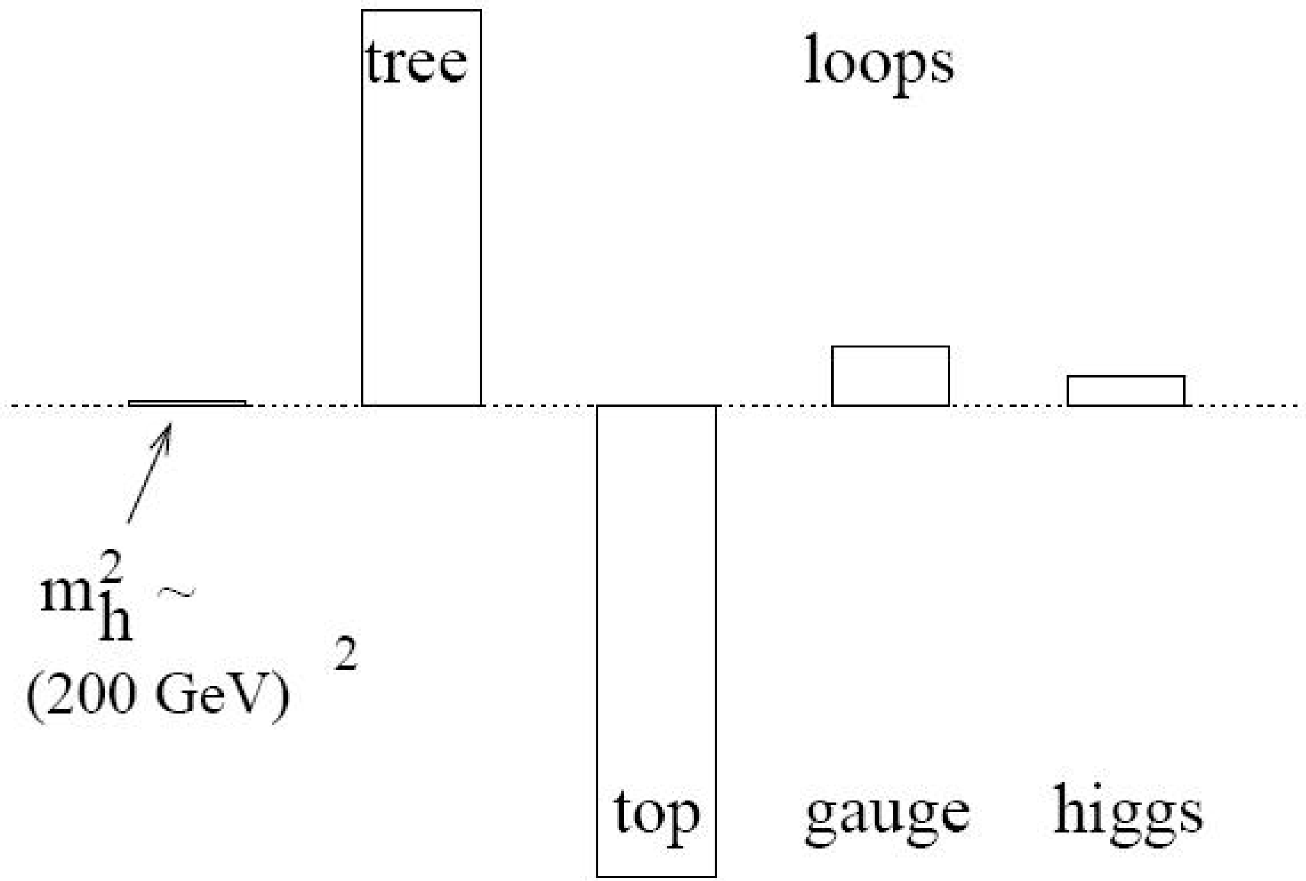
$$\frac{1}{16\pi^2}g^2\Lambda^2 \sim (700\,GeV)^2$$

from the gauge loop, and

$$\frac{1}{16\pi^2}\lambda^2\Lambda^2 \sim (500\,GeV)^2$$

from the Higgs loop.

fine-tuning keeps the Higgs light



Naturalness problem of the Higgs sector

◊ OBSERVED MASSES

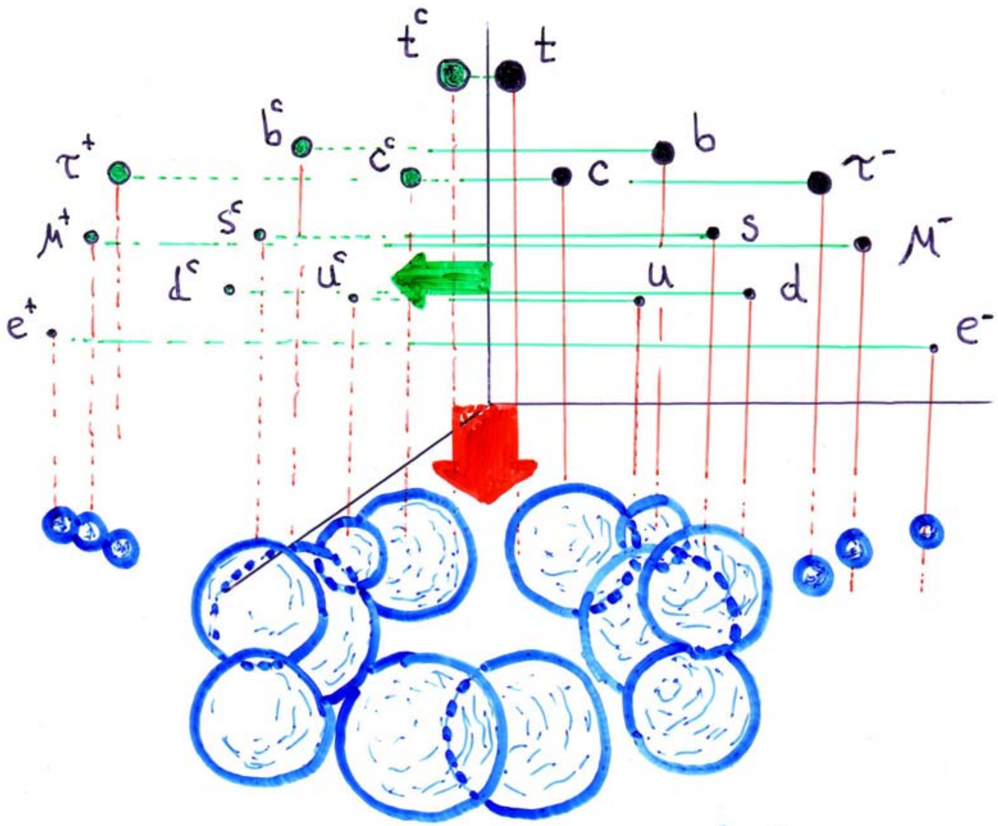
m_q , m_ℓ , m_W , m_Z v.s. $M_{P\ell}$

SM sector	Protective symm
forces	gauge
matter	chiral
symm. break.	? ← SuSy !!

◇ **CPT** invariance of the Dirac eq. $(i\gamma^\mu\partial_\mu - m)\psi = 0$
– the reason for the ANTIPARTICLES

◇ **B ↔ F** symmetry ⇒ 2^{nd} doubling

antiparticles & particles



SuSy "shadow" particles
DARK MATTER

3. Reasons for going BSM

- **3.1 Observational**
- **3.2 Theoretical**

3.1 Observational reasons to go BSM

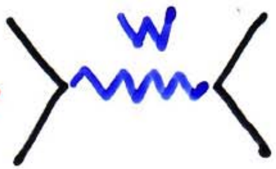
- **New d.o.f. because of non-observations & Unitarity violations**
- **Neutrino masses and the "New SM"**
- **A tension when comparing to SM of cosmology**

Unitarity violation & "the then BSM"

Fermi theory → **IVB theory**

CC ampl.

$\sim G_F s$ →



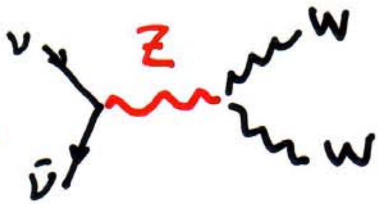
$\sim g^2 \frac{s}{s - M_W^2}$

$$\sigma(\bar{\nu}_\mu \mu^- \to \bar{\nu}_e e^-) = \frac{G_F^2 s}{3\pi} \quad (s \ll M_W^2) \to \frac{g^4}{s^2} \quad (s \gg M_W^2)$$

IVB theory

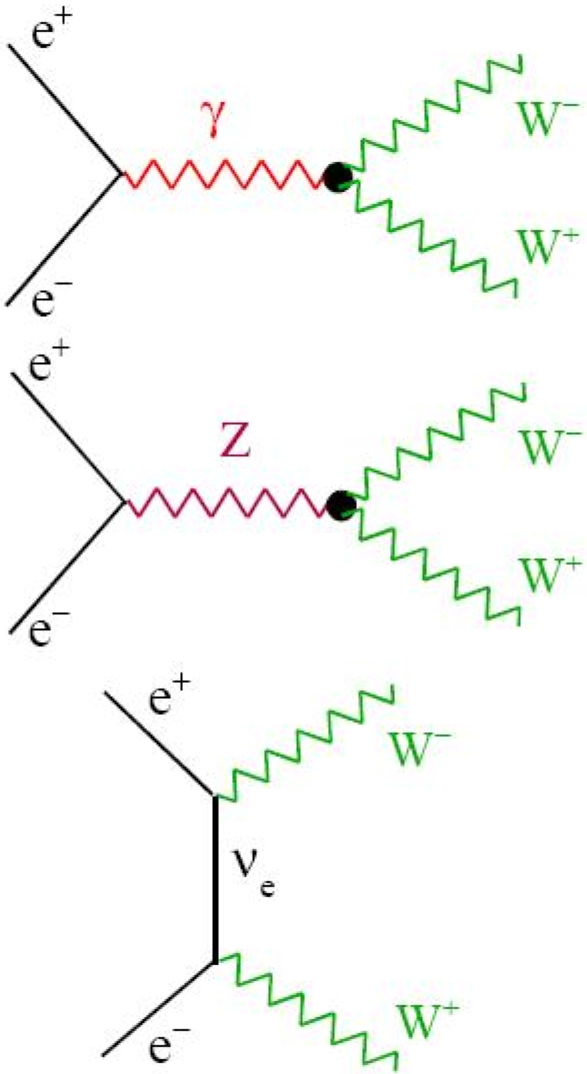
NC ampl.

cured by

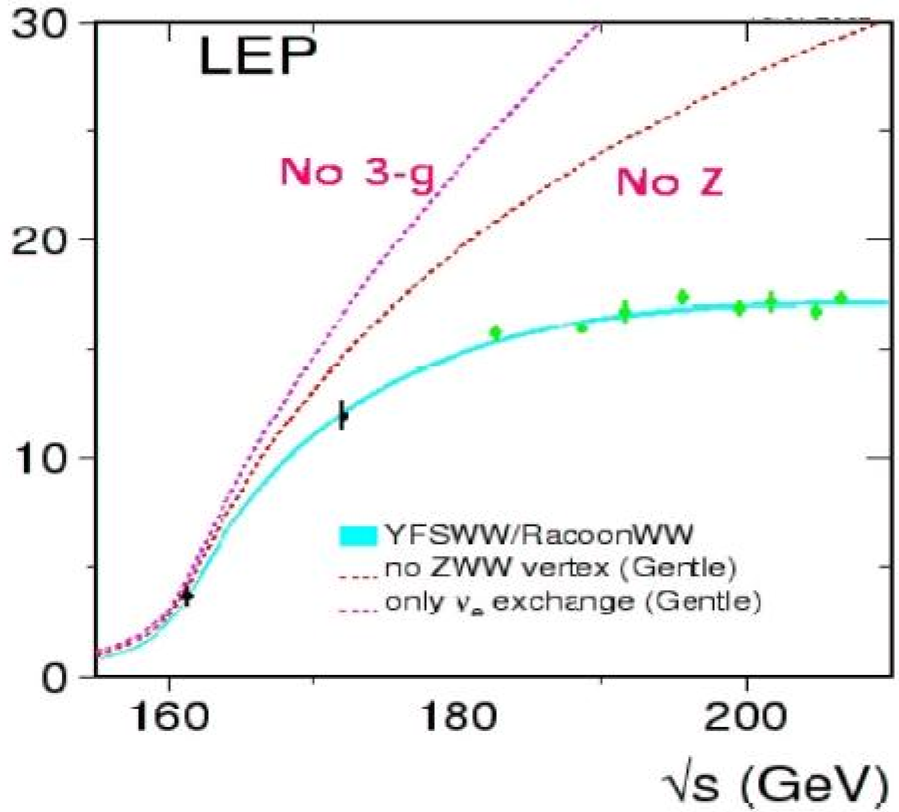


$$\sigma(\bar{\nu}\nu \to W^+_{long.} W^-_{long.}) \sim \frac{g^4}{M_W^2} \frac{s}{M_W^2}, \quad s = E^2$$

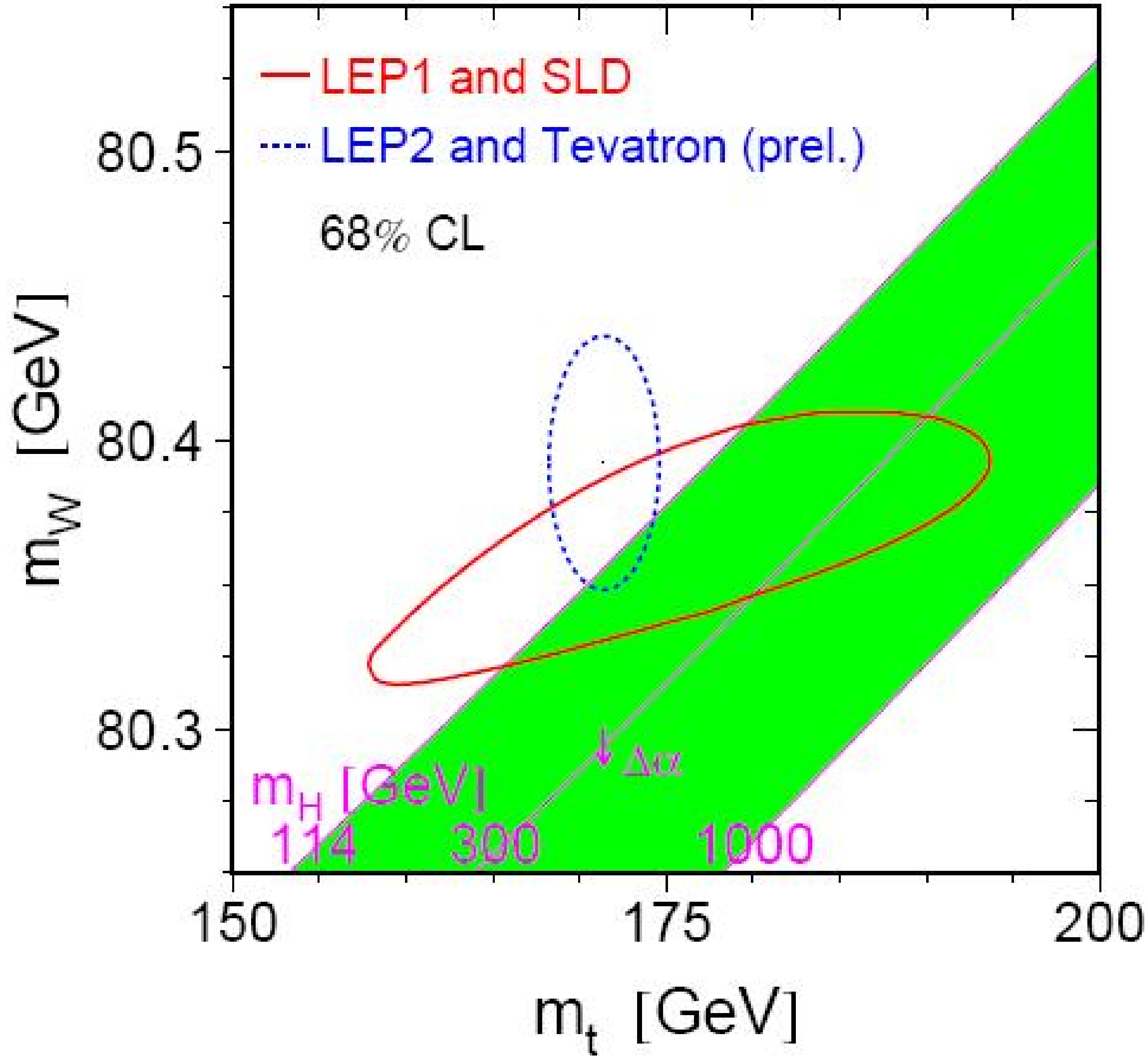
$$E_{crit} = \left(\frac{\sqrt{2}\pi}{G_F}\right)^{1/2} \simeq 600 \text{ GeV}$$



$\sigma(e^+e^- \rightarrow W^+W^-)$[pb]

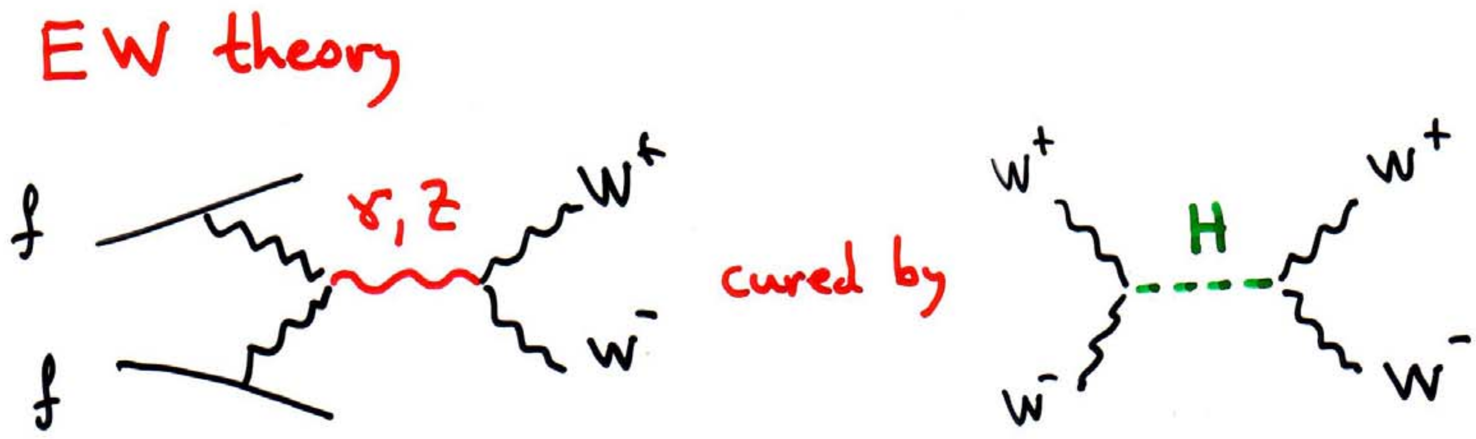


Altarelli '03



LEP1 and SLD
LEP2 and Tevatron (prel.)
68% CL
80.5
80.4
80.3
m_W [GeV]
$\Delta\alpha$
m_H [GeV]
114
300
1000
150
175
200
m_t [GeV]

EW theory regulated by the weakly coupled Higgs

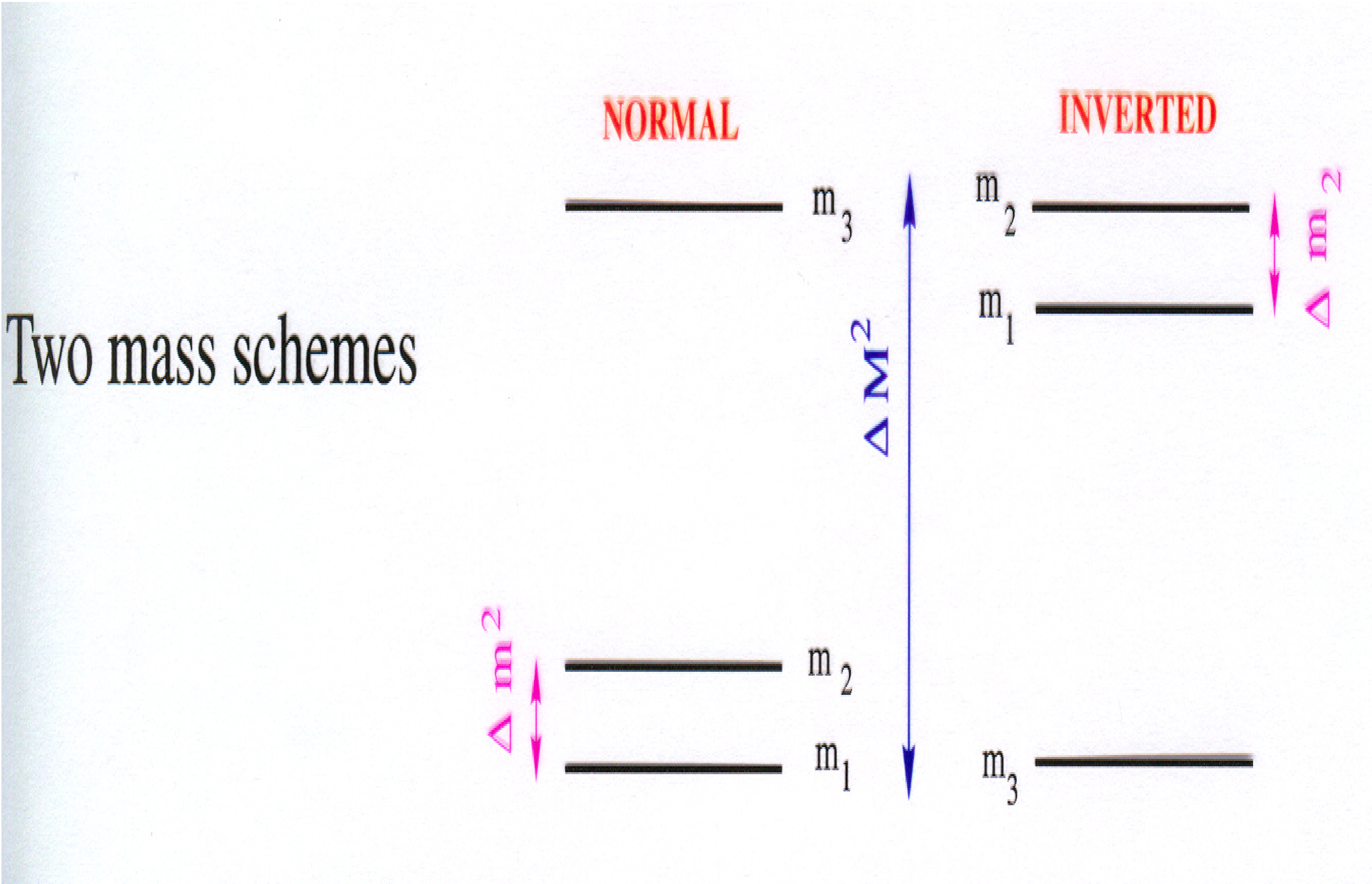


$$E_{crit} \approx \left(\frac{4\sqrt{2}\,\pi}{G_F} \right)^{1/2} \simeq 1.2 \text{ TeV}$$

[Chanowitz & Gaillard '85]

The pattern of neutrino masses and mixings call for an explanation

- **Various see-saw scenarios**



Neutrino Oscillations & Mixing

(Pontecorvo-Maki-Nakagawa-Sakata)

LFV as first tangible BSM

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

EXTRA PARAMETERS IN THE "NEW SM"

after SNO results

3 neutrino masses

4 MNSP parameters

3 mixing angles & 1 CP-phase

⇒ **7**

---

eventually (in the see-saw scenario)

3 Majorana N's masses

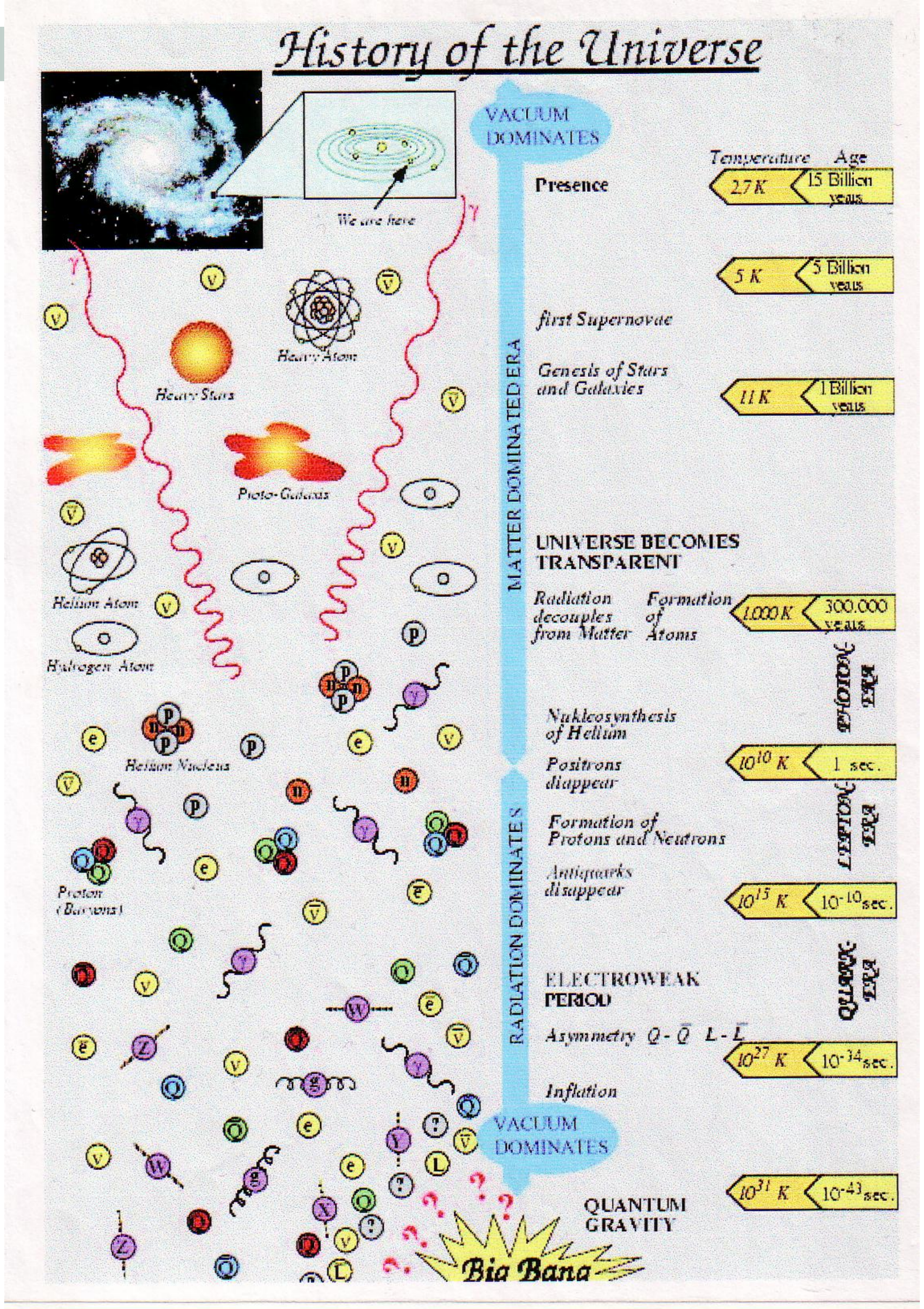
2 other angles

⇒ 12 new parameters

& nothing is the same!

Cosmological tension

- Non-baryonic matter
- BAU
- SM Higgs can not provide the needed inflation



3.2 Theoretical reasons to go BSM

- Unification
- Flavour problem
- Hierarchy problem

The BSM Routes

- GUT chains
- SuSy GUTs
- AGUT (family replicated gauge group model - Bennett, Nielsen &IP PLB'88)
- Lorentz noninvariance

  H.B. Nielsen & collaborators, early 80's

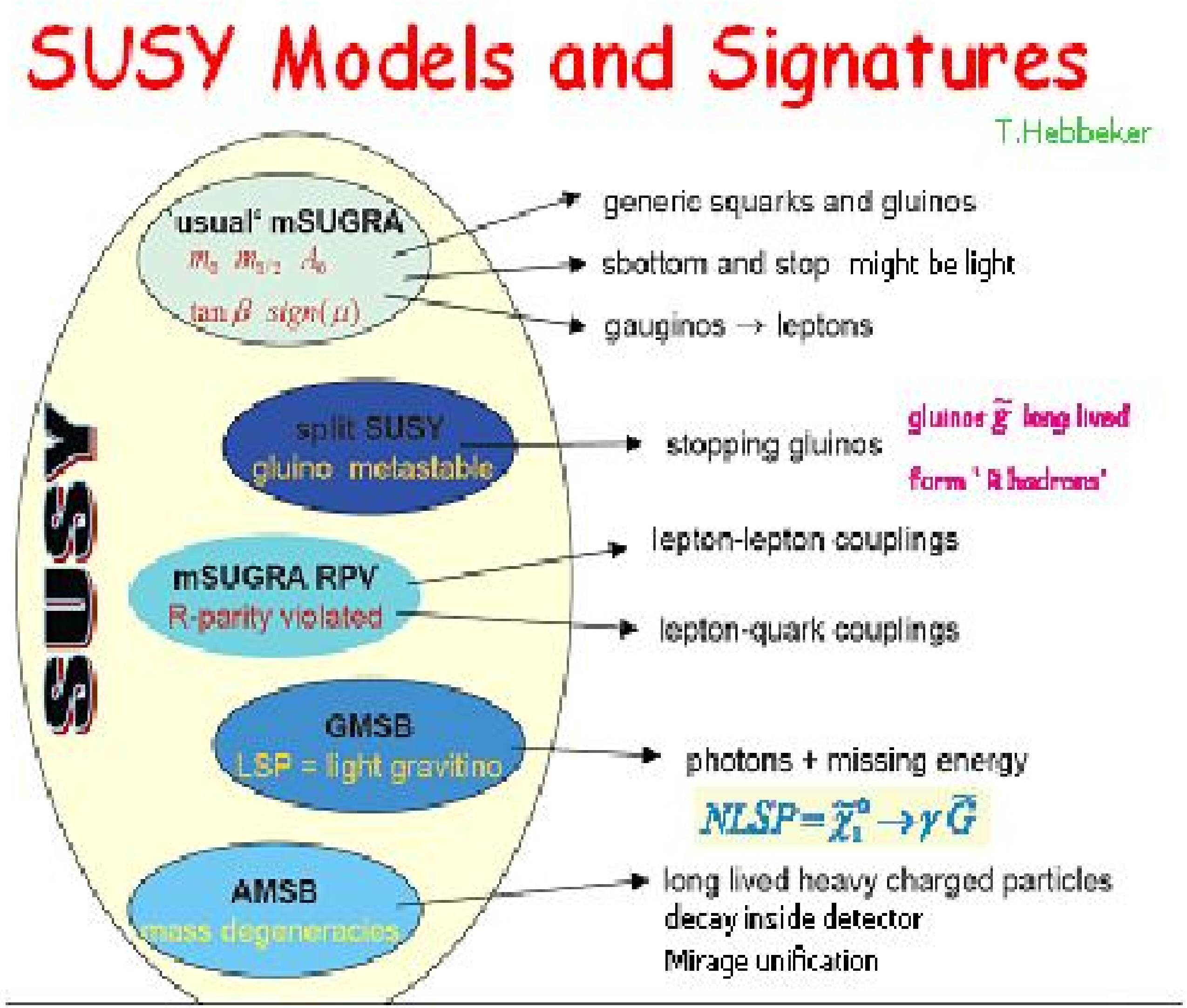
  A. Kostelecky & collab.'s SME

Hierarchy & SuSy

- **Split-SuSy**

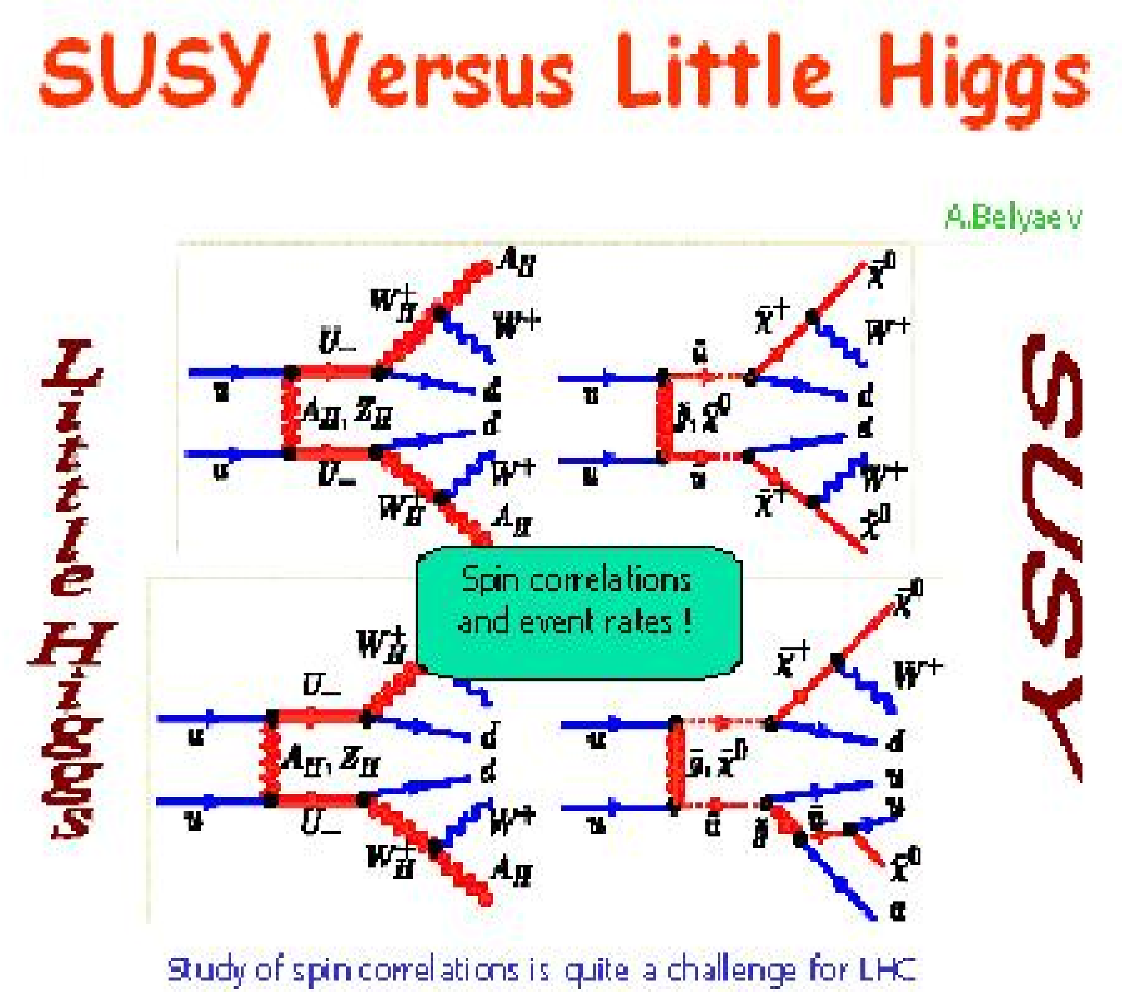
Neutral Higgs

120-165 GeV



Little hierarchy & Little Higgs

- **Vector-like T quark (signal at LHC)**



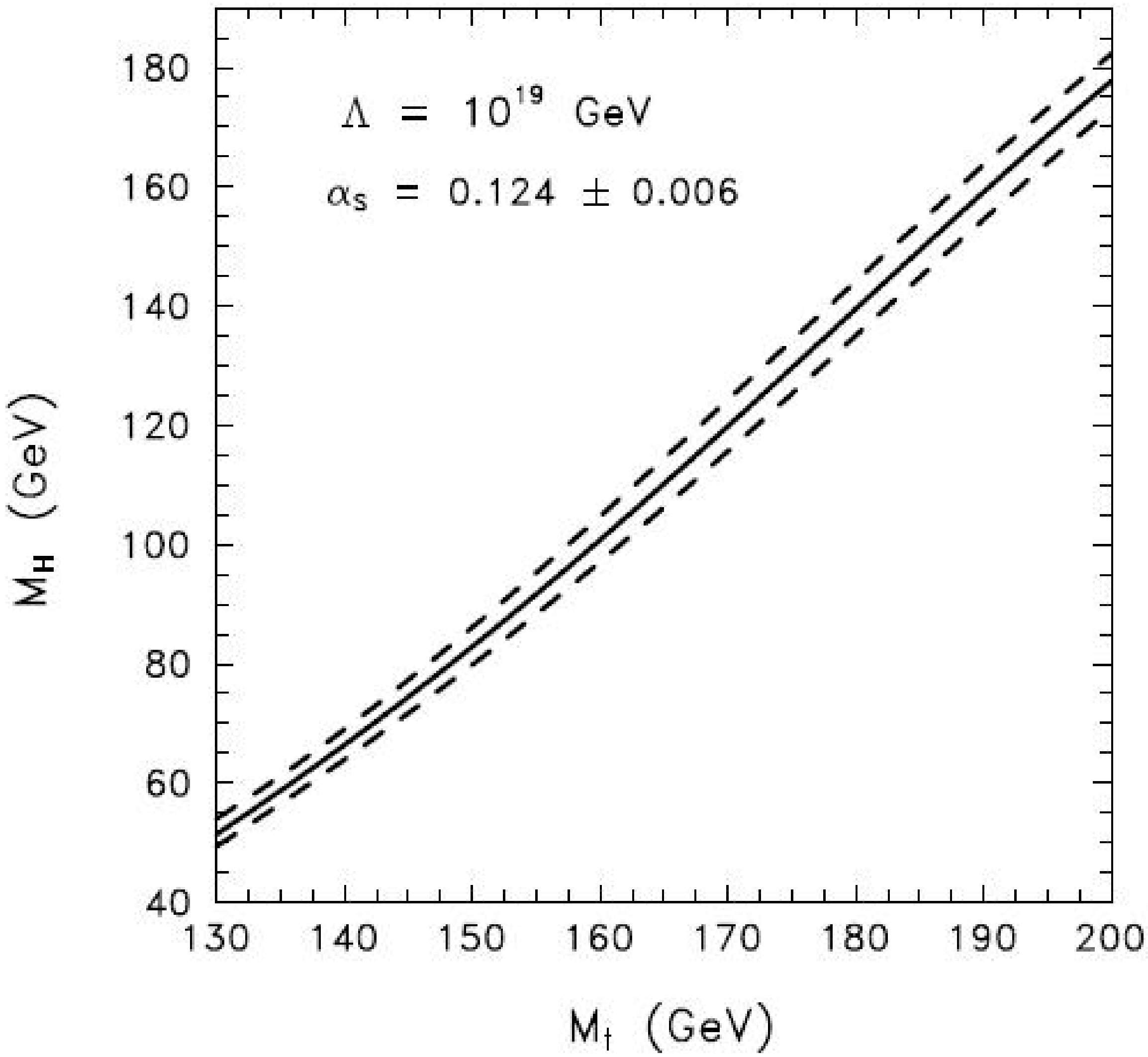
Multiple Point Principle

- **Froggatt & Nielsen,**

PLB'96

135±9 GeV/

173±5 GeV



From a tension to the synergy of the PP & Cosmological SMs