GGR, RESW and DGS

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Oxford 09-30-2011

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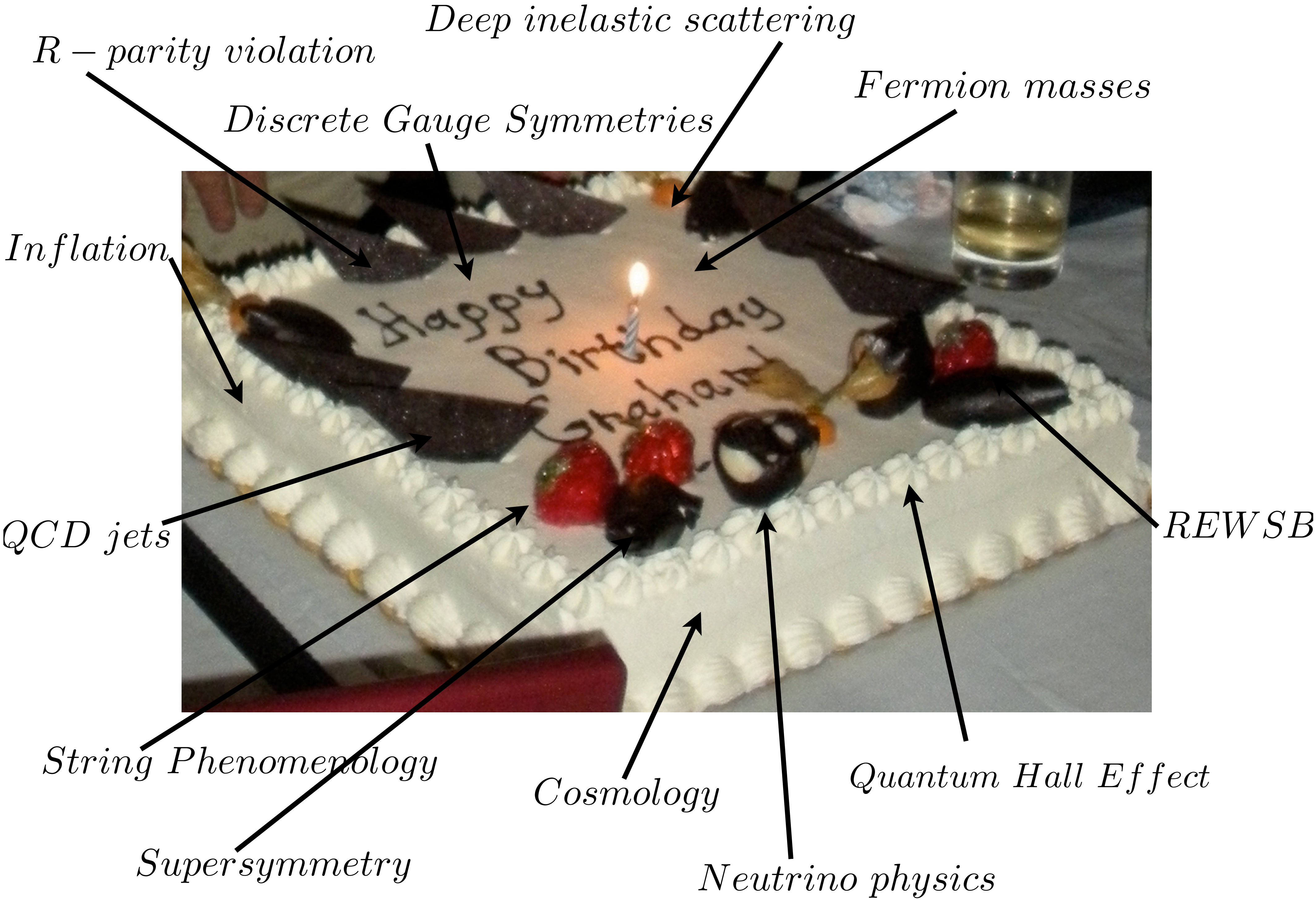

Deep inelastic scattering
R – parity violation
Fermion masses
Discrete Gauge Symmetries
Inflation
Happy Birthday Graham
QCD jets
REWSB
String Phenomenology
Cosmology
Quantum Hall Effect
Supersymmetry
Neutrino physics

Oxford 1981

Supersymmetry in 1981....

- In those days there was nobody working on Supersymmetry in Oxford (and almost anywhere)

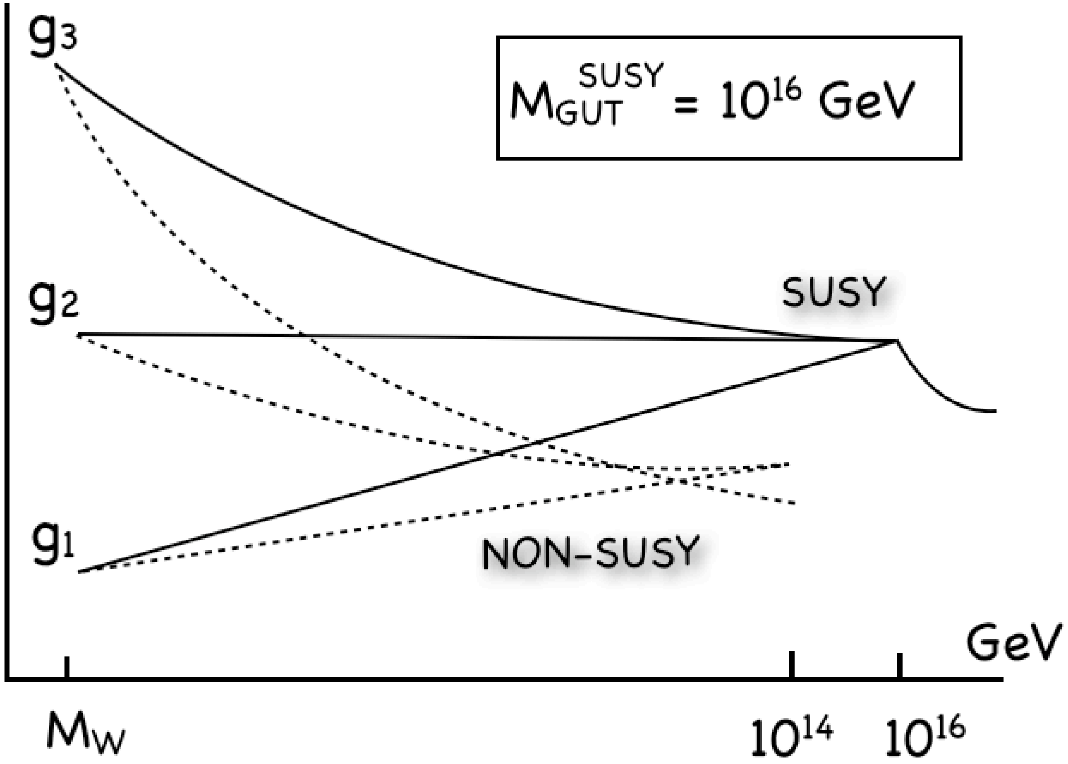
- Graham and I started to work in SUSY in spring 1981. The literature available was scarce and obscure (Fayet-Ferrara Physics Report...).

) Low-Energy Predictions in Supersymmetric Grand Unified Theories.
By Luis E. Ibanez, Graham G. Ross.
Phys.Lett. B105 (1981) 439.

2) SU(2)-L x U(1) Symmetry Breaking as a Radiative Effect of Supersymmetry Breaking in Guts.
By Luis E. Ibanez, Graham G. Ross.
Phys.Lett. B110 (1982) 215-220.


Lovely
GUIN

- Our first work in the subject was the computation of gauge coupling unification in the (now called) MSSM



Volume 105B, number 6 PHYSICS LETTERS 22 October 1981

LOW-ENERGY PREDICTIONS IN SUPERSYMMETRIC GRAND UNIFIED THEORIES

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Received 27 July 1981

Globally supersymmetric theories provide a solution to the gauge hierarchy problem without the need for a strongly interacting sector. We consider various such theories which generalise the standard SU(3) × SU(2) × U(1) model and compute their predictions for the unification scale M_X, $\sin^2\theta_W$ and fermion mass ratios.

Grand Unified Theories (GUTs) have many attractive features which suggest they may be relevant to the real world [1]. They unify the strong, weak and electromagnetic interactions relating quarks and leptons and predicting their couplings in terms of a single coupling constant g_G and the unification scale M_x [2]. This leads in SU(5) to the remarkably successful prediction of $\sin\theta_W(80) = 0.206 \pm 0.01$ and $M_x = (6.6 \pm 6) \times 10^{14}$ GeV [3]. For this value of M_x the proton lifetime is estimated to be $t_p = 8 \times 10^{30}$ yr [4].

However, there is a serious problem in the scalar sector of GUTs. Since scalar mass terms are not forbidden by a symmetry there is no reason why the Higgs H, which break the SU(3) × SU(2) × U(1), at a scale M_W, to SU(3) × U(1)$_{EM}$, should not have masses and vacuum expectation values of the same order as the Higgs ϕ, which generate the breaking, at a scale M_x, of SU(5) to SU(3) × SU(2) × U(1). It might be that a higher symmetry, exact at a scale above M_x, might keep the H Higgs light. However, radiative corrections will spoil this relation and lead again to a heavy H sector. This is the hierarchy problem [5,6]. Three solutions to this problem have been suggested. One is to have a strongly interacting scalar sector (the hierarchy problem rests on a perturbative analysis); a second solution is to have no elementary H scalars at all, their role being taken by a composite scalar as in technicolour theories. The third possibility is that the higher symmetry which keeps the H sector light is exact down to a scale $\sim O(M_W \alpha_G^{-1/2})$ thus ensuring that radiative corrections do not introduce large masses in the H sector ($\alpha_G = g_G^2/4\pi$).

In this paper we consider the latter possibility. Since the radiative corrections mixing the H and ϕ sector and giving the hierarchy problem involve scalar, fermion and vector loops we need a symmetry relating these contributions i.e. supersymmetry. The simplest possibility is to use a global supersymmetry and to assign the H scalars to chiral supermultiplets. Chiral symmetries which forbid fermion masses will also forbid the corresponding boson mass term. If this chiral symmetry remains to a scale $O(M_W \alpha_G^{-1/2})$ radiative corrections will not induce scalar masses $\gtrsim O(M_W)$ [6,7].

What is the minimal set of supersymmetric multiplets needed to solve the hierarchy problem? Each of the light fermion helicity states must be associated with two real scalar partners whose mass is $\leqslant O(M_W \alpha_G^{-1/2})$ so we need for each light fermion generation two copies of real scalar multiplets transforming as the fermion generation i.e. (3,2), (1,2), 2 × (3,1) and (1,1) under SU(3) × SU(2). The light vector bosons must also be in vector supermultiplets with Majorana fermions transforming as the adjoint under SU(3) × SU(2) × U(1) and with masses $\leqslant O(M_W \alpha_G^{-1/2})$.

This gives the minimal set of light ($\ll M_x$) particles consistent with a global supersymmetry [7]. We denote it by I. The scalars transforming as (1,2) can generate the spontaneous breaking of SU(3) × SU(2) × U(1). However, if the fermions and leptons are embedded in a GUT such as SU(5) it is necessary to stop the light (3,1) of Higgs from coupling to fermions, otherwise they will violate B at an unacceptable rate. If the (1,2) is in the same representation as the (3,1) [e.g. the $\bar{5}$ of

Table 1
Results for M_X and $\sin^2\theta_W$ in the various models considered in the text. Supersymmetry is assumed to be broken spontaneously at a scale $O(M_W)$.

Model	M_X(GeV)	$\sin^2\theta_W$
I	1.5×10^{18}	$0.199^{+0.016}_{-0.003}$
II	3.6×10^{16}	$0.227^{+0.014}_{-0.003}$
III	1.7×10^{15}	$0.212^{+0.015}_{-0.003}$
IV	1.7×10^{15}	$0.251^{+0.011}_{-0.004}$

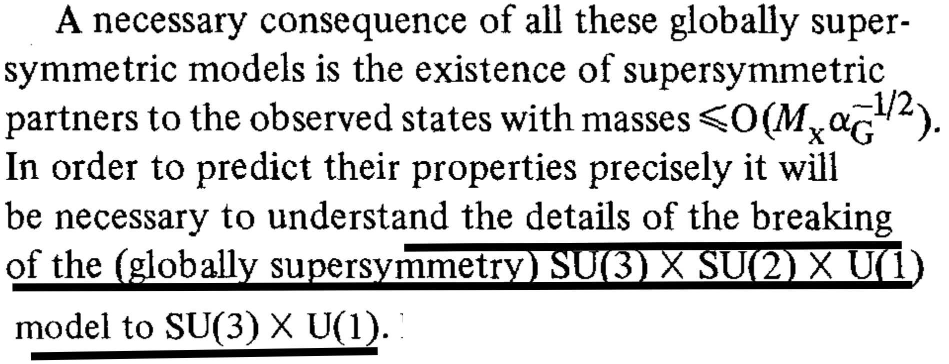
MSSM

- A previous computation by Dimopoulos, Raby and Wilczek had found

$$M_{GUT} \simeq 10^{18} GeV \ , \ sin^2\theta_W = 0.20$$

suggesting no $M_{GUT} - M_{Planck}$ gap (there was a later independent computation by Dimopoulos and Georgi)

- In those days data were not sufficiently precise to distinguish SUSY from non-SUSY predictions (had to wait for LEP)



A necessary consequence of all these globally supersymmetric models is the existence of supersymmetric partners to the observed states with masses $\leqslant O(M_X \alpha_G^{-1/2})$. In order to predict their properties precisely it will be necessary to understand the details of the breaking of the (globally supersymmetry) SU(3) × SU(2) × U(1) model to SU(3) × U(1).

SU(2)$_L$ × U(1) SYMMETRY BREAKING AS A RADIATIVE EFFECT OF SUPERSYMMETRY BREAKING IN GUTs

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Received 7 January 1982

It is shown how in a globally supersymmetric SU(3) × SU(2) × U(1) model supersymmetry breaking can, via radiative corrections, induce an effective Higgs potential which spontaneously breaks SU(2) × U(1) to U(1)$_Q$. We discuss the spectrum of the resulting theory particularly the many new fermions and scalar particles which should be produced by the next generation of accelerator. The inclusion of the model in supersymmetric GUTs is considered and a model is constructed in which no unnatural adjustment of parameters is required.

The gauge hierarchy problem [1] comes in several forms. The most pressing is that, in a theory with a large scale $M_X \sim M_{\text{planck}}$, it is natural for all scalars in the theory to develop large masses $\simeq M_X$ and, consequently, all spontaneous symmetry breaking in the theory will be at a scale $\gtrsim \sqrt{\alpha}\, M_X$ where α is a typical gauge coupling.

A possible solution is to use a new symmetry to forbid the appearance of some scalar masses. Such masses would arise only at the scale of breakdown of the new symmetry. The only known symmetry which can do this is supersymmetry and several groups have already tried to construct models using supersymmetry which contain a gauge hierarchy [2,3]. In the simplest of these models, it is supposed that the lagrangian is symmetric under the direct product of a global $N = 1$ supersymmetry and the SU(3) × SU(2) × U(1) gauge symmetry. To avoid the hierarchy problem, supersymmetry can be broken only at a scale $\lesssim M_W/\sqrt{\alpha}$. The structure may be embedded in a grand unified theory at a scale $\simeq M_X$.

In a previous letter [3], we considered simple models for the supersymmetric version of the standard SU(3) × SU(2) × U(1) model which could be simply included in a grand unified theory, and we computed the low-energy predictions for τ_p, $\sin^2\theta_W$ and M_b/M_τ in such models [‡1]. However, we did not discuss the low-energy breakdown of supersymmetry and of SU(2) × U(1). In this letter, we consider this problem in more detail. We show how SU(2) × U(1) breaking may appear as a radiative effect once supersymmetry is broken. We also propose a solution for the "second gauge hierarchy problem" which is how to avoid the appearance of light coloured scalars, grand unified partners of the scalars which break SU(2) × U(1). These scalars violate baryon number at an unacceptable rate unless they have a mass $\sim M_X$.

$N = 1$ supersymmetric theories may be built from fundamental vector and chiral multiplets. The vector (gauge) multiplet contains a massless vector field together with a Weyl spinor (left-handed or right-handed). The chiral multiplet contains a Weyl spinor of definite helicity together with a complex scalar field. To construct a supersymmetric lagrangian it is first necessary to assign all the particles of the standard SU(3) × SU(2) × U(1) model to supermultiplets. This is shown in table 1. The main uncertainty is in

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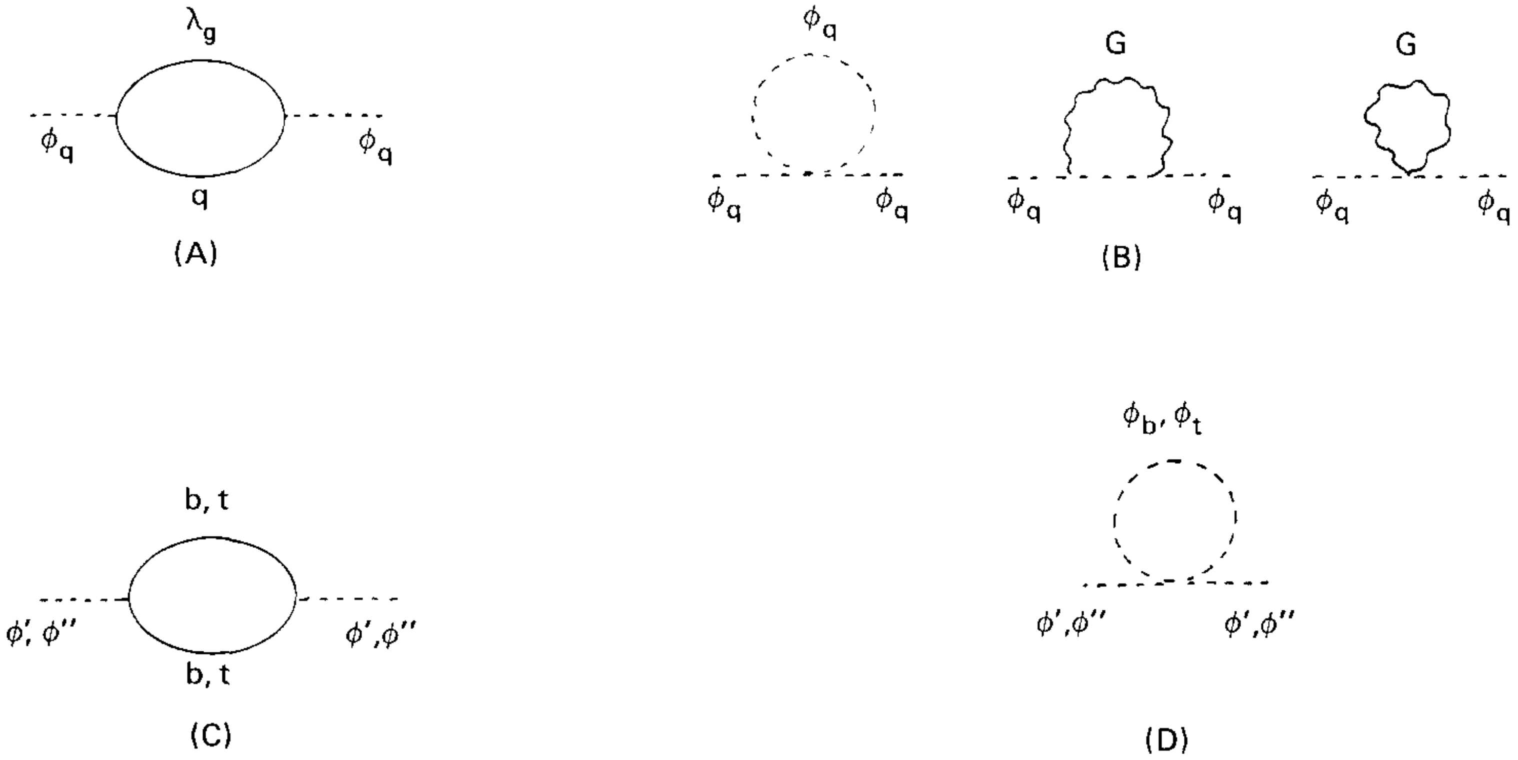
[2] And at Rutherford Laboratory, Chilton, Didcot, Berkshire, England.

[‡1] In ref. [3] there is an error in the quoted results for M_b/M_τ. This should be $\simeq 1.1$ times the usual SU(5) predictions for the two models considered. See also ref. [4].

- Assuming an explicit gluino mass one gets...



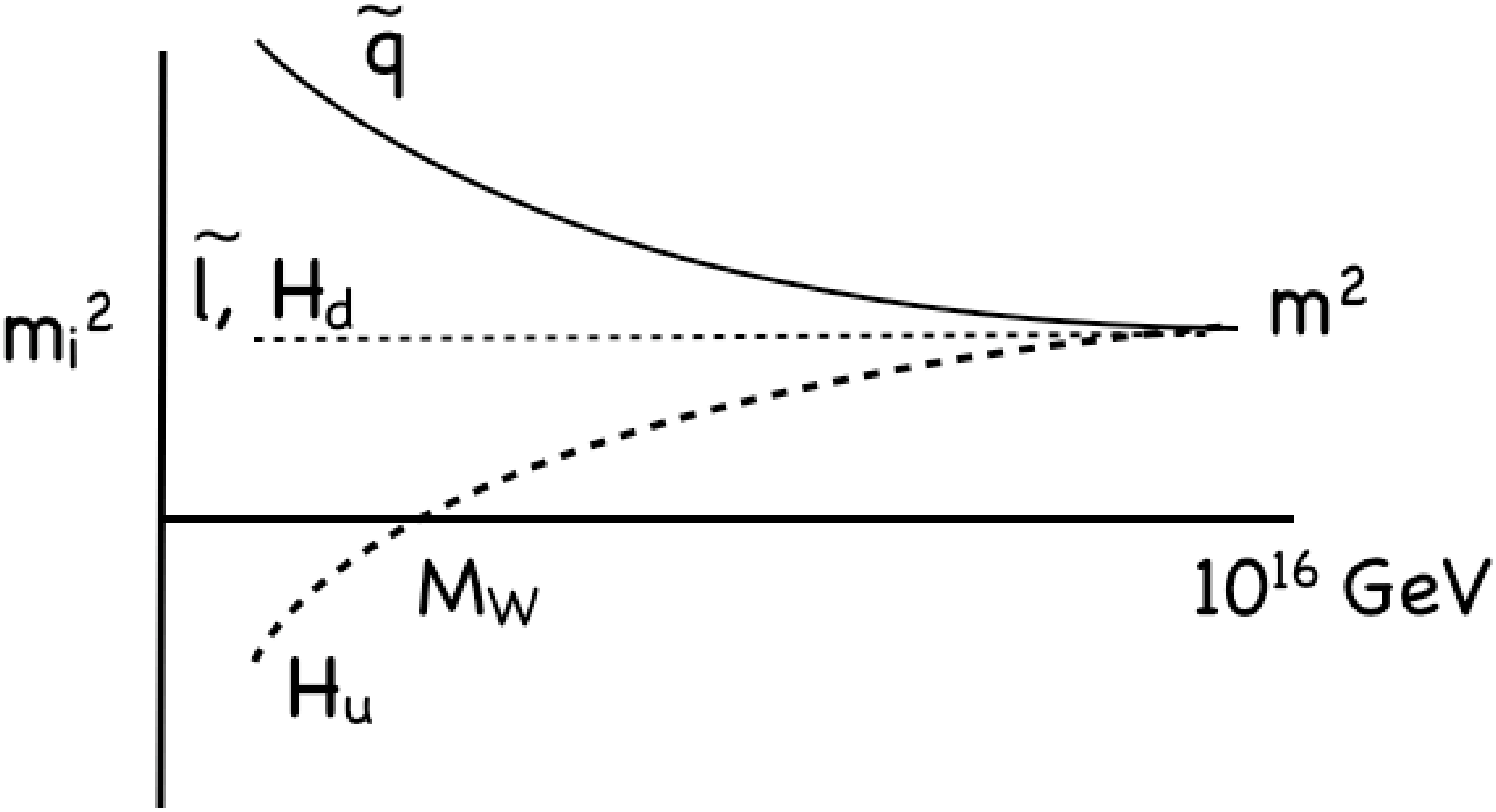
$(-)$ Fig. 1. Graphs contributing to scalar masses. $(+)$

$$M^2_{\phi_q} = (8/3\pi)\,\alpha_{\mathrm{QCD}} M^2_{\mathrm{ss}} \ln(\Lambda^2/M^2_{\mathrm{ss}}).$$

$$\mu^2_{\phi',\phi''} \simeq -(3/4\pi^2)\,h^2_{t,b} M^2_{\phi_q} \ln(\Lambda/M_{\phi_q}),$$

positive $m^2_{\tilde{q}}$

Spontaneous EW breaking


$\tilde{q}$
$\tilde{l}$, H_d
m_i^2
m^2
M_W
10^{16} GeV
H_u

6) Grand Unification with Large Supersymmetry Breaking.
By John R. Ellis, Luis E. Ibanez, Graham G. Ross.
Phys.Lett. B113 (1982) 283.

3) Towards A Realistic Sugra Gut.
By Luis E. Ibanez, Graham G. Ross.
Phys.Lett. B131 (1983) 335.

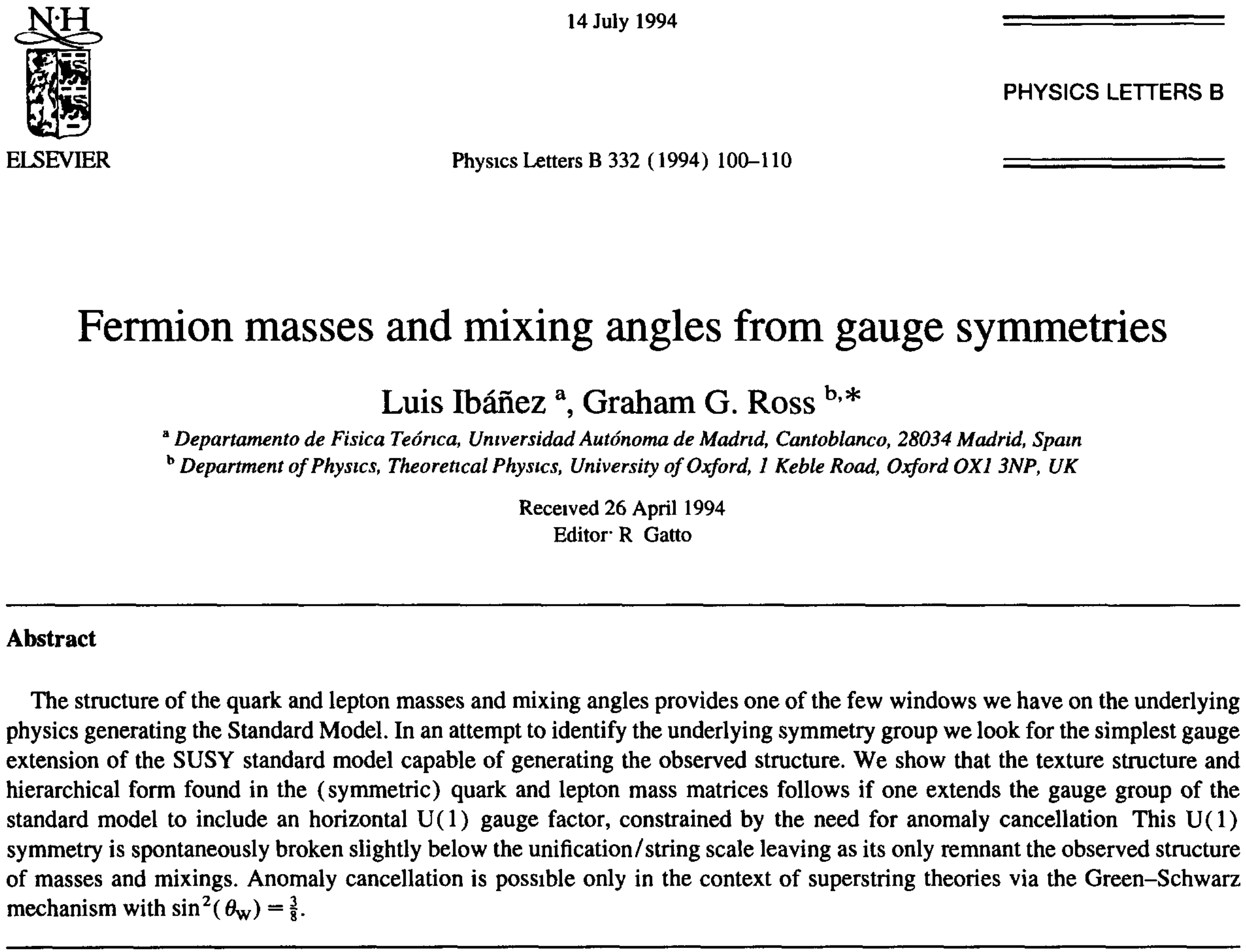
7) Supersymmetric Grand Unification.
By John R. Ellis, Luis E. Ibanez, Graham G. Ross.
Nucl.Phys. B221 (1983) 29-67.

Strings :

4) (0,2) Heterotic String Compactifications From N=2 Superconformal Theories.
By A. Font, Luis E. Ibanez, M. Mondragon, F. Quevedo, Graham G. Ross.
Phys.Lett. B227 (1989) 34.

10) Gauge coupling running in minimal SU(3) x SU(2) x U(1) superstring unification.
By Luis E. Ibanez, Dieter Lust, Graham G. Ross.
[hep-th/9109053].
Phys.Lett. B272 (1991) 251-260.

Fermion masses and anomalous $U(1)'s$



ELSEVIER

14 July 1994

Physics Letters B 332 (1994) 100–110

PHYSICS LETTERS B

Fermion masses and mixing angles from gauge symmetries

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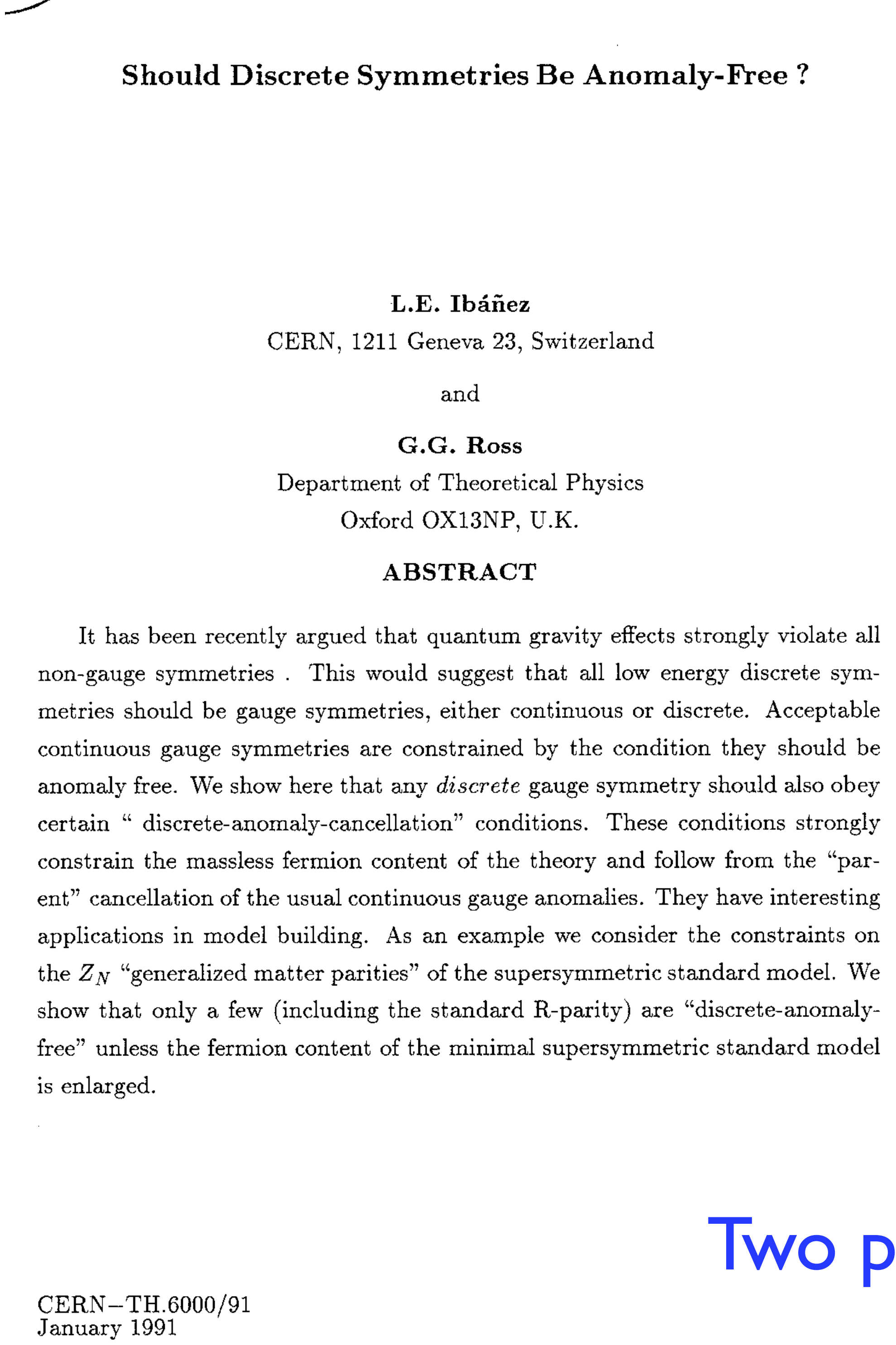
Editor: R Gatto

Abstract

The structure of the quark and lepton masses and mixing angles provides one of the few windows we have on the underlying physics generating the Standard Model. In an attempt to identify the underlying symmetry group we look for the simplest gauge extension of the SUSY standard model capable of generating the observed structure. We show that the texture structure and hierarchical form found in the (symmetric) quark and lepton mass matrices follows if one extends the gauge group of the standard model to include an horizontal U(1) gauge factor, constrained by the need for anomaly cancellation This U(1) symmetry is spontaneously broken slightly below the unification/string scale leaving as its only remnant the observed structure of masses and mixings. Anomaly cancellation is possible only in the context of superstring theories via the Green–Schwarz mechanism with $\sin^2(\theta_W) = \frac{3}{8}$.



Should Discrete Symmetries Be Anomaly-Free ?

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and

G.G. Ross
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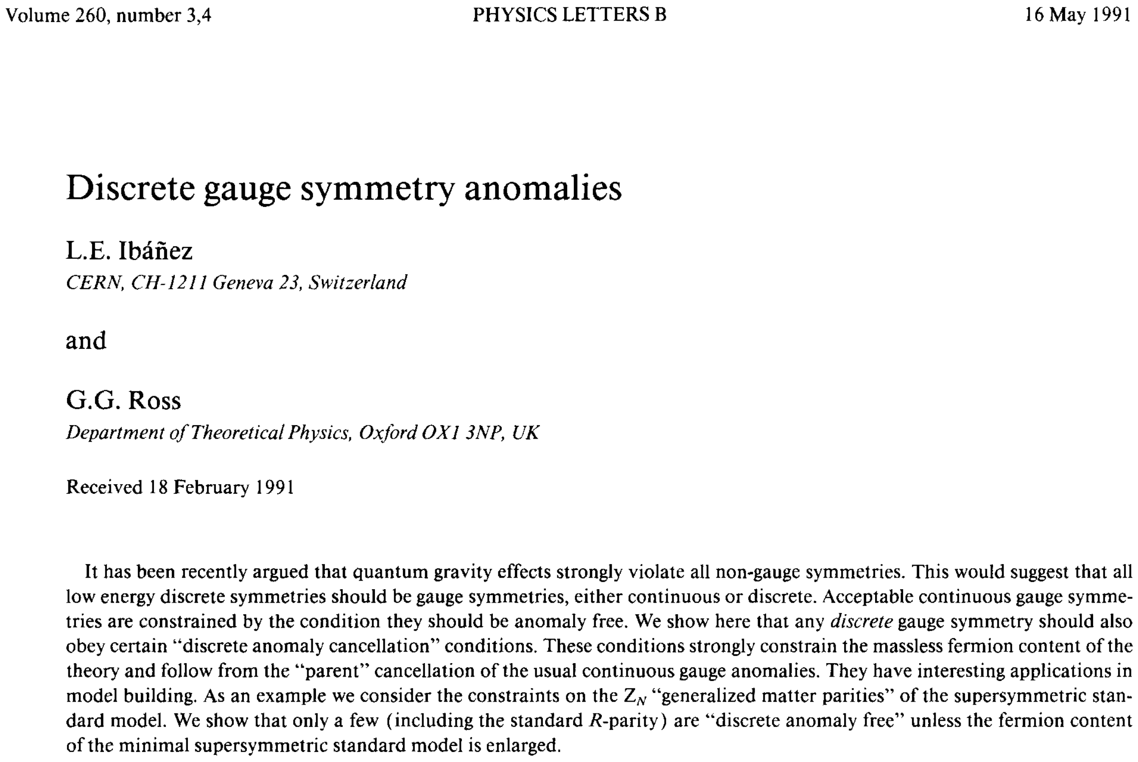
Oxford OX13NP, U.K.

ABSTRACT

It has been recently argued that quantum gravity effects strongly violate all non-gauge symmetries . This would suggest that all low energy discrete symmetries should be gauge symmetries, either continuous or discrete. Acceptable continuous gauge symmetries are constrained by the condition they should be anomaly free. We show here that any *discrete* gauge symmetry should also obey certain " discrete-anomaly-cancellation" conditions. These conditions strongly constrain the massless fermion content of the theory and follow from the "parent" cancellation of the usual continuous gauge anomalies. They have interesting applications in model building. As an example we consider the constraints on the Z_N "generalized matter parities" of the supersymmetric standard model. We show that only a few (including the standard R-parity) are "discrete-anomaly-free" unless the fermion content of the minimal supersymmetric standard model is enlarged.

CERN–TH.6000/91
January 1991



Volume 260, number 3,4 PHYSICS LETTERS B 16 May 1991

Discrete gauge symmetry anomalies

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Received 18 February 1991

It has been recently argued that quantum gravity effects strongly violate all non-gauge symmetries. This would suggest that all low energy discrete symmetries should be gauge symmetries, either continuous or discrete. Acceptable continuous gauge symmetries are constrained by the condition they should be anomaly free. We show here that any *discrete* gauge symmetry should also obey certain "discrete anomaly cancellation" conditions. These conditions strongly constrain the massless fermion content of the theory and follow from the "parent" cancellation of the usual continuous gauge anomalies. They have interesting applications in model building. As an example we consider the constraints on the Z_N "generalized matter parities" of the supersymmetric standard model. We show that only a few (including the standard *R*-parity) are "discrete anomaly free" unless the fermion content of the minimal supersymmetric standard model is enlarged.

Two papers?

(i) Cubic $\mathbb{Z}_N^3$ anomaly cancelation condition

$$\sum_i (q_i)^3 = rN + \tfrac{1}{8}\eta s N^3, \quad r, s \in \mathbb{Z},$$

where $\eta = 1, 0$ for $N =$ even, odd.

(ii) Mixed $\mathbb{Z}_N$–gravitational anomalies

$$\sum_i (q_i) = r'N + \tfrac{1}{2}\eta s' N, \quad r', s' \in \mathbb{Z}.$$

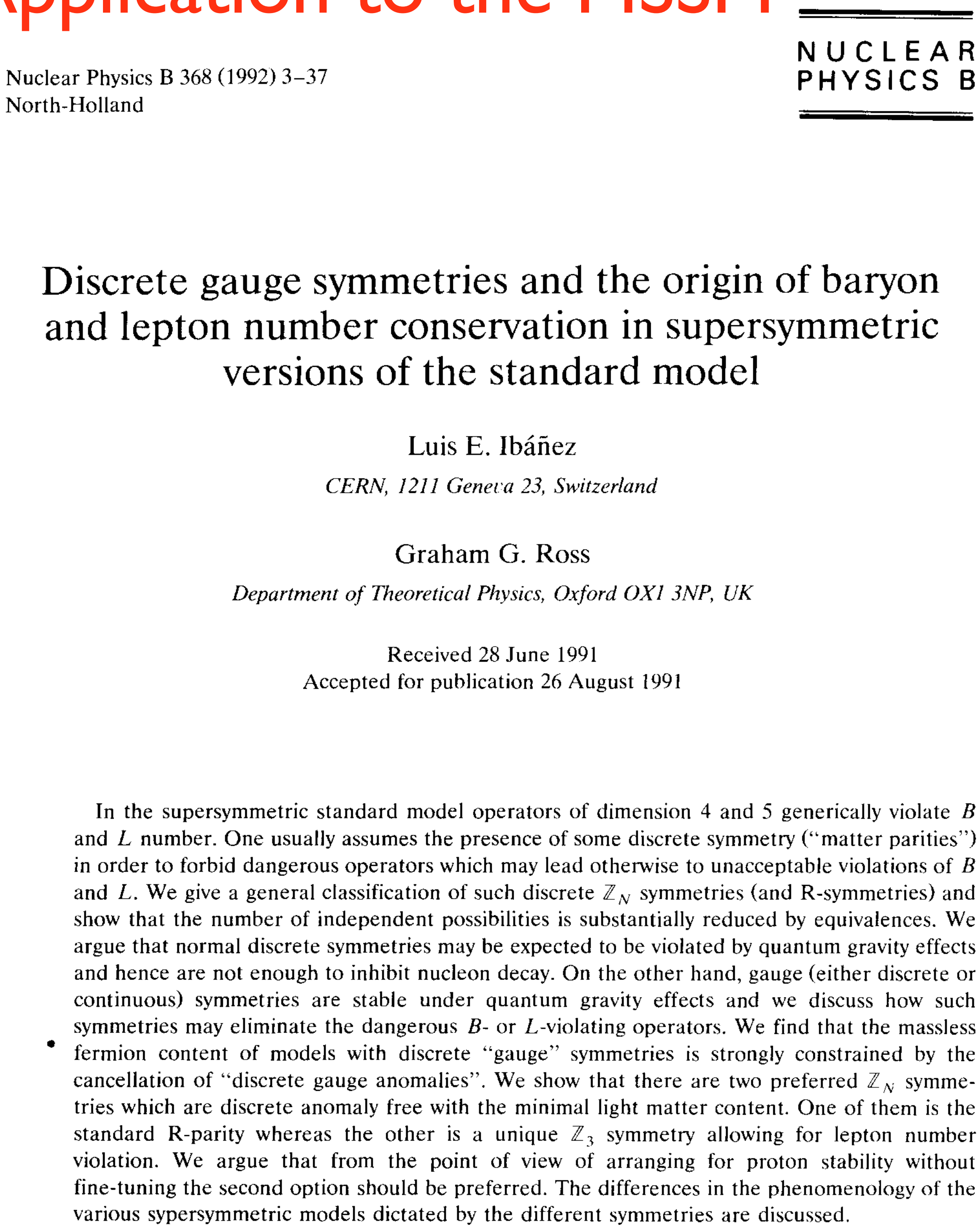
(iii) Mixed $\mathbb{Z}_N$–SU(M)–SU(M) anomalies:

$$\sum_i T_i(q_i) = \tfrac{1}{2} r'' N, \quad r'' \in \mathbb{Z}.$$

Discrete gauge symmetries must be anomaly free

Very restrictive conditions!!

Application to the MSSM



Nuclear Physics B 368 (1992) 3–37
North-Holland

NUCLEAR
PHYSICS B

Discrete gauge symmetries and the origin of baryon and lepton number conservation in supersymmetric versions of the standard model

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In the supersymmetric standard model operators of dimension 4 and 5 generically violate B and L number. One usually assumes the presence of some discrete symmetry ("matter parities") in order to forbid dangerous operators which may lead otherwise to unacceptable violations of B and L. We give a general classification of such discrete $\mathbb{Z}_N$ symmetries (and R-symmetries) and show that the number of independent possibilities is substantially reduced by equivalences. We argue that normal discrete symmetries may be expected to be violated by quantum gravity effects and hence are not enough to inhibit nucleon decay. On the other hand, gauge (either discrete or continuous) symmetries are stable under quantum gravity effects and we discuss how such symmetries may eliminate the dangerous B- or L-violating operators. We find that the massless fermion content of models with discrete "gauge" symmetries is strongly constrained by the cancellation of "discrete gauge anomalies". We show that there are two preferred $\mathbb{Z}_N$ symmetries which are discrete anomaly free with the minimal light matter content. One of them is the standard R-parity whereas the other is a unique $\mathbb{Z}_3$ symmetry allowing for lepton number violation. We argue that from the point of view of arranging for proton stability without fine-tuning the second option should be preferred. The differences in the phenomenology of the various sypersymmetric models dictated by the different symmetries are discussed.

DGS in the MSSM

- Family independent discrete symmetries may be classified in terms of 3 generators:

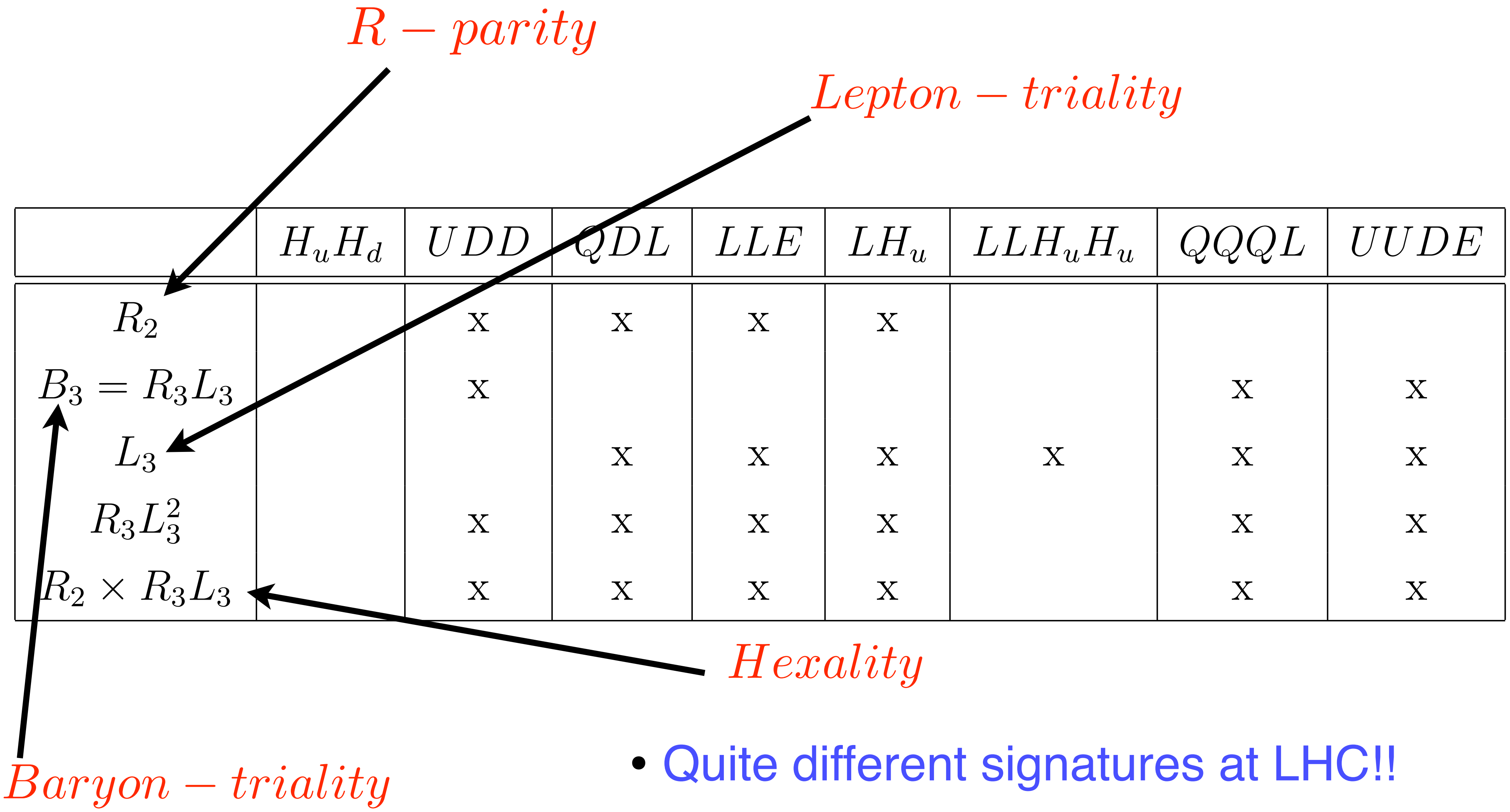
$$g_N = R_N^m \times A_N^n \times L_N^p \quad , \quad m, n, p = 0, 1, .., N-1 \ .$$

$$R_N = e^{i\,2\pi R/N} \ , \ L_N = e^{i\,2\pi L/N} \ , \ A_N = e^{i\,2\pi A/N}$$

	Q	U	D	L	E	N_R	H_u	H_d
R	0	-1	1	0	1	-1	1	-1
L	0	0	0	-1	1	1	0	0
A	0	0	-1	-1	0	1	0	1

Anomaly free DGS in the MSSM:

- Only a few anomaly free options!!



R – parity

Lepton – triality

	H_uH_d	UDD	QDL	LLE	LH_u	LLH_uH_u	$QQQL$	$UUDE$
R_2		x	x	x	x			
$B_3 = R_3L_3$		x					x	x
L_3			x	x	x	x	x	x
$R_3L_3^2$		x	x	x	x		x	x
$R_2 \times R_3L_3$		x	x	x	x		x	x

Hexality

Baryon – triality

- Quite different signatures at LHC!!

- Discrete symmetries do their job to get a stable proton but they have no apparent motivation at a more fundamental level

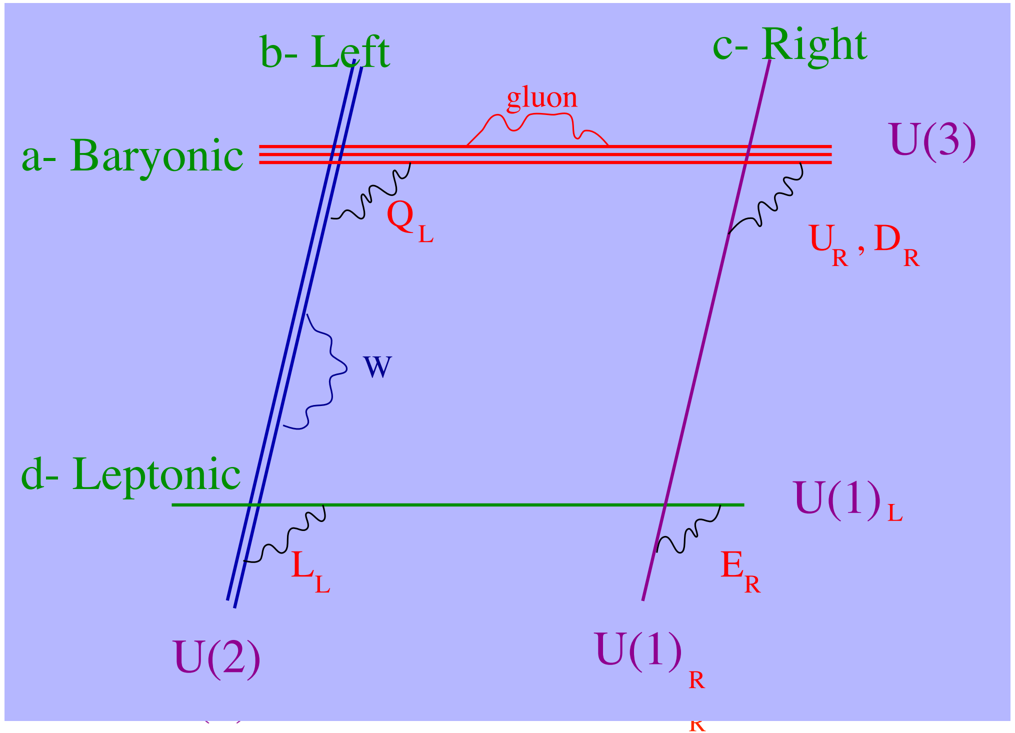
- It has been recently realized that:
  - Discrete gauge symmetries are generic in string models
  - In MSSM-like brane models the discrete gauge symmetries appearing are those clasified 20 years ago

M.Berasaluce, L.I., P.Soler, A.Uranga

arXiv:1106.4169 [hep-th]

The SM at intersecting branes

stack a	$N_a = 3$	$SU(3) \times U(1)_a$	Baryonic brane
stack b	$N_b = 2$	$SU(2) \times U(1)_b$	Left brane
stack c	$N_c = 1$	$U(1)_c$	Right brane
stack d	$N_d = 1$	$U(1)_d$	Leptonic brane



$$Note\ U(1)_a \times U(1)_b \times U(1)_c \times U(1)_d \xrightarrow{GS\ mechanism} U(1)_Y$$

- In theories with $B_{\mu\nu}$ fields with $n\ B \wedge F_{U(1)}$ couplings there are residual Z_n symmetries

$$\mathcal{L}_{4d} \sim n(B \wedge F) \quad \xleftrightarrow{dB = *da} \quad (da - nA) \wedge *(da - nA)$$

- Gauge invariant:

$$A \to A + d\lambda \ ; \qquad a \to a + n\lambda$$

- Pseudoscalar is charged $\qquad e^{ia} \to e^{in\lambda}\, e^{ia}$

$$\boxed{U(1) \to \mathbb{Z}_n}$$

- Interestingly:

★ $R_n \subset U(1)_c$ e.g. R-parity (n=2)

★ $L_3 \subset U(1)_d$

★ $R_3 L_3 \sim B_3 \subset U(1)_a$ Baryon triality

- The anomaly free DGS of the MSSM appear naturally in large classes of brane models !!!

- This gives a fundamental explanation for proton stability in the MSSM (due to the presence of DGS).

Album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PENN RELAYS
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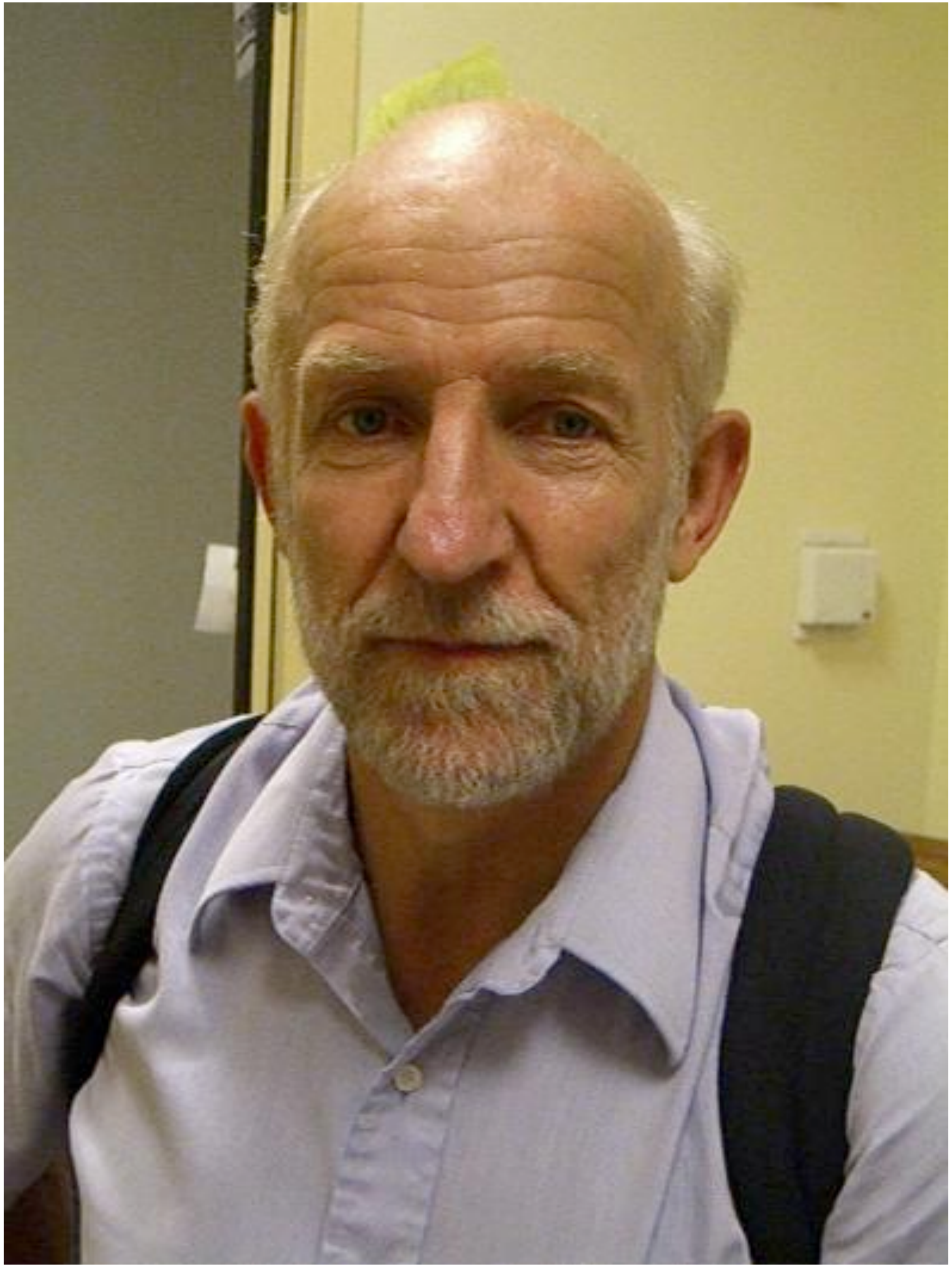
Lovely day fo
GUIN

Planck 2004

Bad Honnef



Santa Barbara 2006

Planck 2010, Geneva

Corfu 2011

Thanks
very much
for your
friendship
and for
your
great
physics
!!!!!!!