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Autor: Schacher, J.
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STATUS AND FUTURE OF PARTICLE PHYSICS AT HADRON COLLIDERS*

J. Schacher, Laboratorium für Hochenergiephysik, Universität, CH-3012 Bern, Switzerland

Abstract: This report summarizes the most important results obtained at the CERN proton-antiproton collider during the first operating periods. Clear evidence for the production of both jets and intermediate vector bosons was found. Although the standard model is in good shape, extensions are necessary in order to explain many open parameters. Experimental input from future hadron colliders should give some guidance in which direction the standard model needs to be enlarged.

1. Introduction

The physics at hadron colliders is in most of the cases determined by the interaction between the hadron constituents, the coloured quarks and gluons. The underlying theories are quantum chromodynamics (jet physics) and to a smaller extent also the electroweak Glashow-Salam-Weinberg (GSW) model (W and Z physics).

The first run at the CERN proton-antiproton collider at the total centre-of-mass energy $\sqrt{s}$ = 546 GeV took place in the second half of 1981 and provided the first net evidence for high transverse momentum hadronic jets.

At the end of 1982, the second run culminated in the discovery of the intermediate vector bosons (IVB) W^+ and W^-, and half a year later, the neutral IVB Z^o was also evidenced in a further run.

In the second last run during fall 1984, the CERN collider energy was increased to $\sqrt{s}$ = 630 GeV, and at the end of this year, the total amount of data, accumulated separately in the two large experiments UA1 and UA2, corresponded to a total integrated luminosity L ≈ 0.4pb^{-1} (UA1: L = 399nb^{-1}; UA2: L = 452 nb^{-1}). The data of 1984 confirmed the results of the previous runs and

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led to some detailed information about jet (e.g. estimate for α_s) and IVB production (e.g. distribution of the W transverse momentum).

The last data taking during a longer period took place at CERN last fall ($L \approx 0.4 pb^{-1}$). Up to now, the analysis is still in progress, and we await a further consolidation in the jet and IVB physics.

Let me add few words about the short term future of hadron colliders. After the upgrade of the CERN collider (new Antiproton COLlector = ACOL) as well as of the UA experiments, the physics runs will start again in fall 1987, and by the end of 1988, we expect to have collected data corresponding to an integrated luminosity of about $10 pb^{-1}$ in each experiment. In the same period the Tevatron $p\bar{p}$ collider at Fermilab (USA) will start operation and provide two large experiments (CDF and later DΦ) with data corresponding to around $1 pb^{-1}$ integrated luminosity.

In the following I shall discuss briefly the Standard Model (SM) and the experimental evidence for its correctness, then the "why" and "how" to go beyond the SM and in this context the expectations from present, future and far future hadron colliders.

2. Test of the Standard Model

A. The Standard Model

In the last decade we have learned that the so-called standard model of the electroweak and strong interaction describes the observed phenomena in particle physics successfully. This model, based on the gauge group structure $SU(3)_{colour} \times SU(2)_{weak} \times U(1)$ with eight couloured gluons, with the three weak intermediate vector bosons W^+, W^-, Z^o and the photon γ (Tab. 1), is the quantum field theory of the basic building blocks of nature, the quarks (in three colours r, b,g) and the leptons (Fig. 1), and the fundamental interactions between them [1]. One of the most important clues for the correctness of the electroweak sector of the SM was the discovery of the very heavy field quanta of the weak interaction. In 1983, the two large experiments UA1 and UA2 at the CERN proton-antiproton collider announced the detection of few events which showed clearly the signature of the W and Z electronic decays [2-5].

Table 1

Standard model of the electroweak and strong interaction and contribution from CERN $p\bar{p}$ experiments UA1 and UA2.

GAUGE GROUP	$SU(3)_{colour}$	$SU(2)_{weak}$	$U(1)$
gauge bosons (≙ number of group generators)	$g_1, g_2, \dots g_8$ 8 massless coloured vector gluons	W^+, W^-, "Z°" 3 massive intermediate vector bosons	"γ" 1 massless photon
coupling	g_s	$g_\tau \equiv g$	g_y
interaction	strong	weak-electro	
contributions from CERN (UA1 and UA2)	parton physics: evidence for particle jets (interaction of quarks and gluons)	discovery of W^+, W^- and Z° with masses around 100 GeV/c^2	

In the following I would like to describe some relations of the electroweak part of the SM (Glashow-Salam-Weinberg model) and derive crucial predictive quantities, such as the masses of the IVBs which can be tested in experiments very precisely.

Let me start by pointing out that the unification of the electromagnetic and weak interaction leads to similar coupling strengths for these interactions (Fig. 2) as can be seen from

$$e = g \cdot \sin \Theta_W, \tag{1}$$

where e is the electromagnetic and g the fundamental weak coupling constant. The Weinberg angle Θ_W is a free parameter and can be deduced from experimental neutral current data [6]. The old well known Fermi coupling constant G, which dictates the β and also the μ decay rate, must also be related to g:

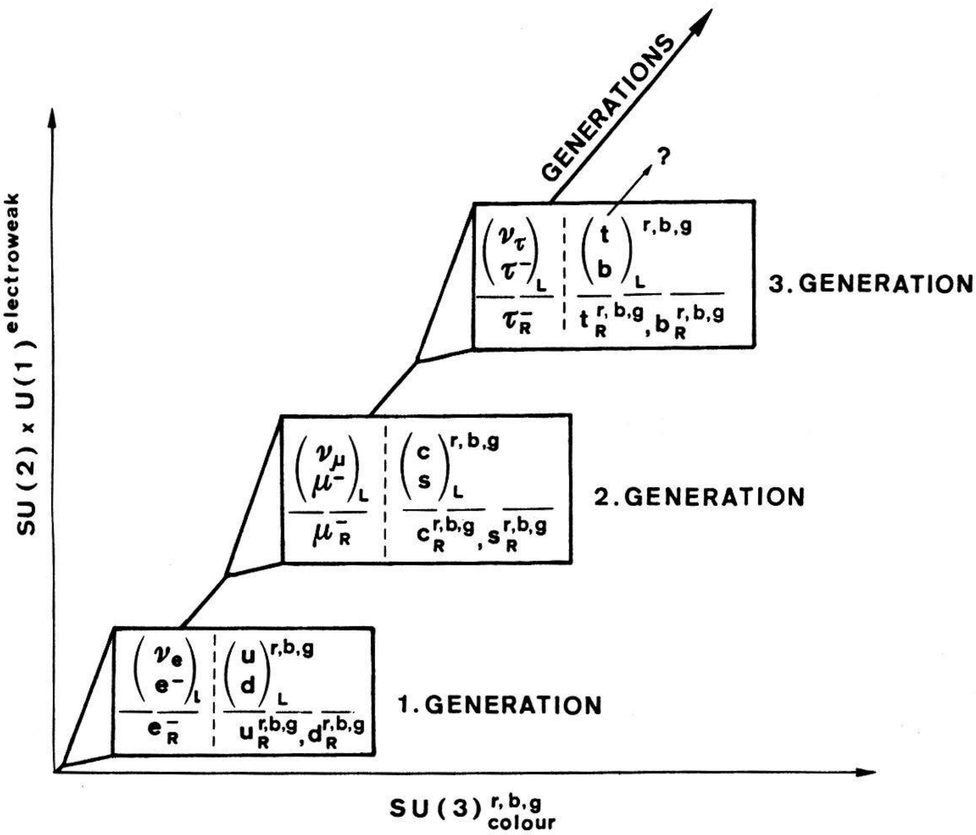

Fig. 1 Scheme of the generation structure of the quarks and leptons.

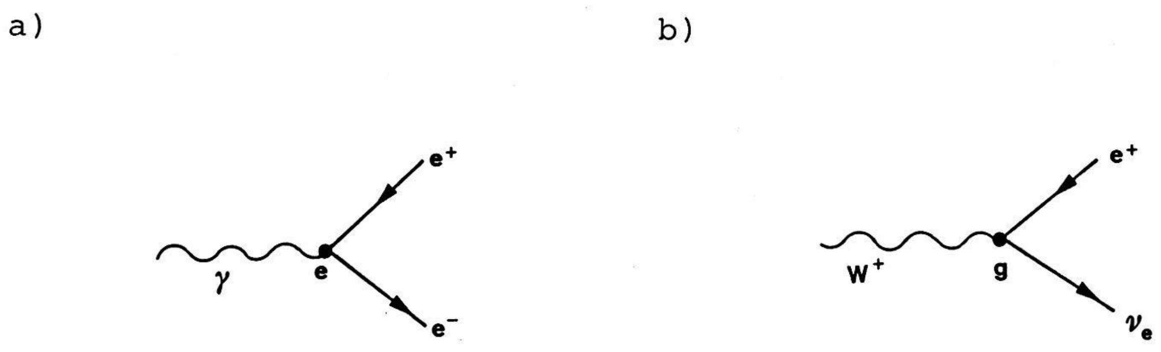

Fig. 2 Fundamental Feynmann graphs for the a) electromagnetic and b) weak interaction.

$$\frac{G}{\sqrt{2}} = \frac{g^2}{8M_w^2}. \qquad (2)$$

The quantity M_w is the mass of the charged IVB. Combining the equations (1) and (2), one finds the following prediction:

$$M_w^{(o)} = [\frac{\sqrt{2}}{2G}]^{1/2} \frac{e}{2\sin\Theta_w} = \frac{a}{\sin\Theta_w}. \qquad (3)$$

In the framework of the minimal SM ($\rho = \frac{M_w^2}{M_z^2\cos^2\Theta_w} = 1$, i.e. minimal SM with only one isodoublet of complex Higgs fields) the mass of the neutral IVB is given by

$$M_z^{(o)} = \frac{M_w}{\cos\Theta_w} = \frac{a}{\sin\Theta_w\cos\Theta_w}. \qquad (4)$$

The expressions (3) and (4) are evidently not the full truth because of omission of radiative corrections. Taking into account higher order diagrams the "best" values [7,8] for the W and Z masses are given by

$$M_w = M_w^{(o)} (1-\Delta r)^{-1/2} = (82.4 \pm 1.1)\ \mathrm{GeV}/_c, \qquad (5)$$
$$M_z = M_z^{(o)} (1-\Delta r)^{-1/2} = (93.3 \pm 0.9)\ \mathrm{GeV}/_c. \qquad (6)$$

These mass values, to be compared later with hadron collider data, are obtained by inserting in the above equations $\sin^2\Theta_w = 0.220 \pm 0.008$ [6] (world average) and for the effect of radiative corrections $\Delta r = 0.0696 \pm 0.0020$.

The second pillar of the SM, beside the unified electroweak sector, is formed by quantum chromodynamics (QCD), the field theory of interacting quarks and gluons. The new degree of freedom, which governs strong interaction processes, is a charge-like quantity, called colour, and the quarks, constituents of the hadrons, as well as the gluons, the mediator of the strong force, are colourful. In the context of hadron colliders it is essential to test the predictions of QCD at short distances. The generally accepted picture for hadron-hadron interactions at high energies, e.g. $p\bar{p}$ collisions at $\sqrt{s}$ = 630 GeV, is the hard scattering of coloured gluons and quarks, so-called partons (hadron constituents). Since the scattered objects carry colour and naked colour never has been observed, we expect two hadronic jets in the final state through a kind of materialization, the fragmentation, of the scattered partons.

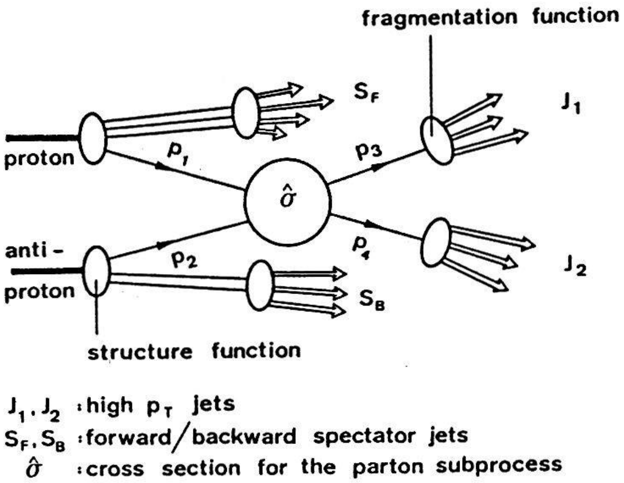

Fig. 3 Schematic $p\bar{p} \to$ jet+jet+X production mechanism in the parton picture.

To briefly summarize the experimental situation about strong interaction or jet physics at the CERN collider, we can state that all the observations, e.g. jet transverse momentum and two-jet mass spectra as well as the angular distribution of parton-parton scattering, are well reproduced by QCD. The bulk of the data in events having large transverse energy confirms the anticipated dominance of the two-jet configuration (Fig. 4), but we have also learned that for a quantitative description gluon bremsstrahlung effects are not negligible - a not unexpected issue. Furthermore, it is important to take into account the non-abelian character of QCD, i.e. diagrams due to gluon self-coupling. Having these facts in mind, the UA1 and UA2 collaborations have been able to extract from their data a first estimate for the strong coupling constant ($\alpha_s \simeq 0.2$ for the momentum transfer $Q \approx 90$ GeV) at CERN collider energies [15].

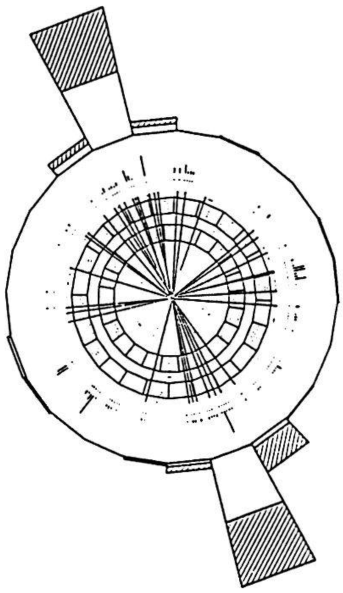

Fig. 4 Configuration of a hadronic event with large ΣE_T. Transverse view of the vertex detector and calorimeter.

B. Experimental Evidence for the Glashow-Salam-Weinberg Model

Let us first come to the W and Z production mechanism at the CERN $p\bar{p}$ collider and then to their experimental detection. In principle the IVBs are generated through the same channels, in which they can decay with a certain probability after around 10^{-24}s (see quark and lepton doublets in Fig. 1). Therefore, a "quark-antiquark" colliding beam facility could be used as an efficient W and Z production source. On the other hand, it is known that collisions between free quarks and antiquarks could not be observed. The best way out is to let collide protons with antiprotons and, hence, to make use of bound quarks and antiquarks. Since quarks, confined in a hadron, carry only a fraction of the hadron momentum, a beam energy adequate for W and Z production should amount to ~300 GeV [16]. The once generated IVBs live only for a very short time and, therefore, we were directed to detect the debris of their decays (Fig. 5). Because of higher energy resolution and lower background contamination, the UA groups concentrated on the detection of leptonic and in particular of the electronic decay modes (UA1: $W \to \left\{ {e\nu \atop \mu\nu} \right\}$, $Z \to \left\{ {ee \atop \mu\mu} \right\}$; UA2: $W \to e\nu$, $Z \to ee$).

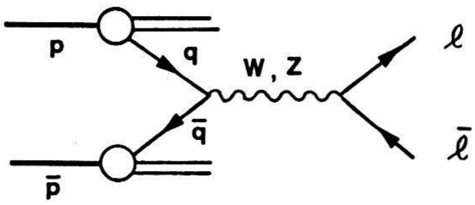

Fig. 5 Scheme of IVB production in $p\bar{p}$ collisions and decay into lepton pairs.

In the following I discuss the main features of the electron identification in the UA2 experiment [17]. This detector, illustrated in Fig. 6, consists of a vertex detector which measures charged particles in a region with no magnetic field by means of a set of coaxial cylindrical drift and multiwire proportional chambers. The position of the vertex can be determined with a precision of ± 1 mm in all directions. The vertex detector is surrounded in the central region ($40^\circ<\theta<140^\circ$) by 240 cells of a highly segmented electromagnetic (lead-scintillator) and hadronic (iron-scintillator) calorimeter which allows a good measurement of electron energies. The longitudinal segmentation of each cell provides electron-hadron separation. In order to give precise spatial information on the position of the electromagnetic shower from electrons and photons a cylindrical tungsten converter of 1.5 radiation length followed by a proportional chamber is located just outside the vertex chamber. The forward regions ($20^\circ<\theta<37.5^\circ$ and $142.5^\circ<\theta<160^\circ$) are each equipped with twelve toroidal magnet sectors with a mean field integral of 0.38 Tm followed successively by drift chambers, 1.4 radiation length thick lead-iron converter plus multitube proportional chambers and electromagnetic calorimeters subdivided into 240 independent cells. In many cases it is possible to determine the sign of the charge of the particles analysed in these forward regions - this is crucial if we want to check the V-A structure (parity violation) of weak interaction by means of the anticipated electron-positron asymmetry.

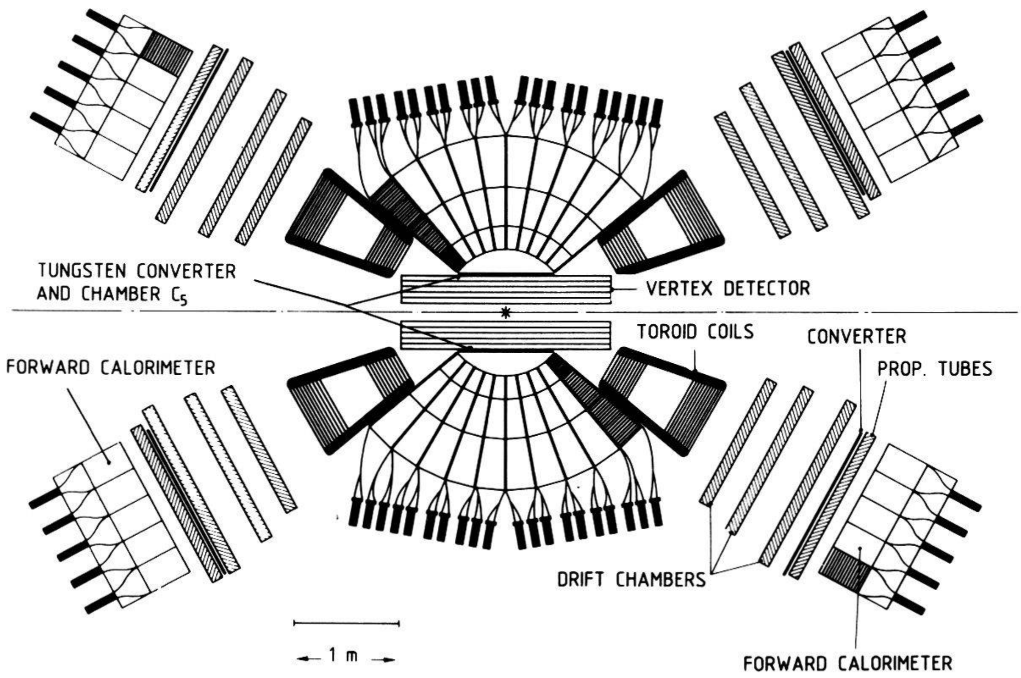

Fig. 6 Schematic cross section of the UA2 detector in the vertical plane containing the beam.

In the analysis chain of UA2 an electron candidate is defined by the presence of

1. a track in the tracking device,
2. an early electromagnetic shower in the so-called preshower counter (synonym for converter plus proportional chamber),
3. a large energy deposition in the electromagnetic calorimeter and
4. only a small signal in the hadronic calorimeter (small leakage).

After applying a topological cut which reduces significantly the hadronic background accompanied by a jet at opposite azimuth, the final UA2 $W\to e\nu$ sample (all data up to 1984 [11]) is found whose transverse electron momentum distribution, characteristic for the W decay, is shown in Fig. 7.

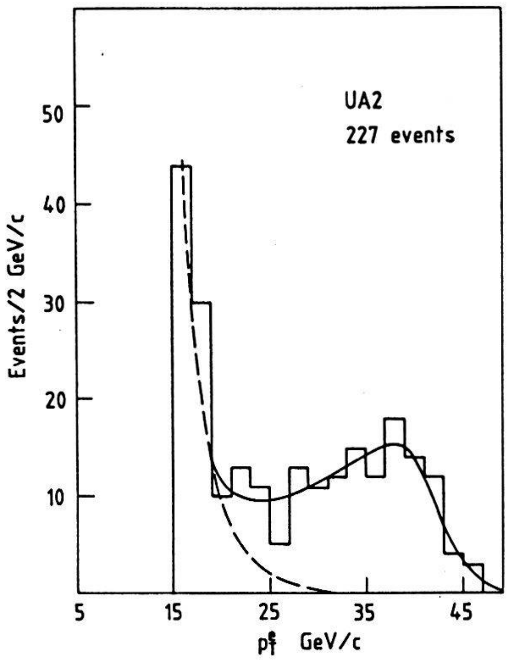

Fig. 7 The p_T^e distribution for electron candidates in the UA2 experiment. Broken curve: estimated hadronic background. Full curve: expected distribution for the value of M_W (UA2) in Tab. 2.

The $Z^o \to e^+e^-$ samples of both experiments UA1 and UA2 (all data up to 1984 [11])are characterized by the presence of two high transverse momentum electron candidates per event with an invariant mass around 100 GeV/c^2. The distributions of the invariant mass, M_{ee}, of the electron-pair candidates above a threshold of 20 GeV/c^2 show a rapidly falling continuum for masses lower than 50 GeV/c^2 and a well-separated peak near $M_{ee} \approx 90$ GeV/c^2 (Fig. 8). Therefore, the events in this peak are interpreted as $Z^o \to e^+e^-$ decays.

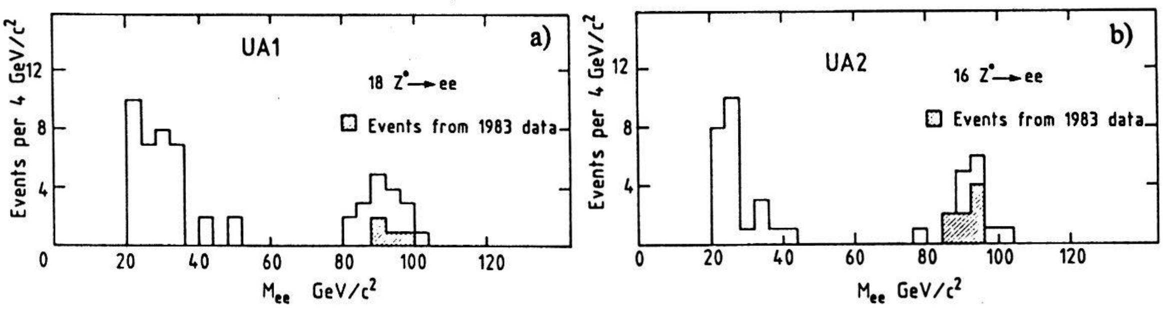

Fig. 8 Invariant mass distribution of electron pairs measured in the UA1 a) and UA2 b) experiments. The shaded events are $Z^o \to e^+e^-$ decays observed in the 1982-83 data samples.

In the next section we compile and compare the UA results with the predictions of the GSW model. Up to now, excluding the still not fully analysed 1985 data, the UA1 collaboration collected around 150 $W \to e\nu$ and 18 $Z^o \to e^+e^-$ candidates, whereas UA2 extracted around 110 $W \to e\nu$ and 16 $Z^o \to e^+e^-$ from his data sample. By estimating the expected number of IVB events, basing on the integrated luminosity ($\sim 0.4 pb^{-1}$), the combined acceptance and efficiency and the predicted cross-sections for $W \to e\nu$ ($\sim$500pb) or $Z \to ee$($\sim$50pb) production, one finds an agreement with observations. The quite rich data samples allow to perform detailed studies about electroweak parameters and the production mechanism by QCD. The results [7-11] of the UA1 and UA2 collaboration together with theoretical predictions are summarized in Tab. 2.

As shown in Tab. 2, the measured values of M_W and M_Z can be taken to check the predictions of the SM. To do so, we use the scheme [7,12] where $\sin^2\Theta_W$ is defined by

$$\sin^2\Theta_W = 1 - \left(\frac{M_W}{M_Z}\right)^2 \quad (\hat{=} \sin^2\Theta_W{}^{I}) \text{ and} \tag{7}$$

which leads to the predictions

$$M_W{}^2 = \frac{A^2}{(1-\Delta r)} \; \frac{1}{\sin^2\Theta_W} \quad \text{and} \tag{8}$$

$$M_Z{}^2 = \frac{(2A)^2}{(1-\Delta r)} \; \frac{1}{\sin^2 2\Theta_W} \tag{9}$$

with $A = \left(\frac{\pi\alpha}{\sqrt{2}G}\right)^{1/2} = (37.2804 \pm 0.0003)$ GeV/c^2 inserting the measured values of α and of the muon decay constant G [8]. In the above equations the quantity Δr reflects the one-loop radiative corrections and has been calculated to be $\Delta r = 0.0696 \pm 0.0020$ (see Sect. 2) for a mass of the top quark $m_t = 36$ GeV/c^2 and assuming a mass of the Higgs boson $M_H = M_Z$. Using (8) and (9), we can deduce two values for $\sin^2\Theta_W$ ($\hat{=} \sin^2\Theta_W{}^{II}$) from the measured values of M_W and M_Z. We then combine them to get the best estimate, where the systematic error is due to the uncertainty on the experimental mass scale from the uncertainty of the calorimeter calibration.

In the previous discussion the ρ parameter, defined as [13]

$$\rho = \left(\frac{M_W}{M_Z}\right)^2 \frac{1}{\cos^2\Theta_W}, \qquad (10)$$

is assumed to be $\rho = 1$, what follows directly from the definition $\sin^2\Theta_W\ I$ (see eq. (7)). On the other hand, we can test this assumption by combining eqs. (8) and (10) yielding

$$\rho = \left(\frac{M_W}{M_Z}\right)^2 \frac{1}{1-\left(\frac{B}{M_W}\right)^2}$$

where $B = \frac{A}{\sqrt{1-\Delta r}}$ (see Tab. 2). The results of UA1 and UA2 agree with each other and also with the low energy result [7,14], $\rho = 1.02 \pm 0.02$.

Finally, we check the sensitivity of the measured M_W and M_Z to the radiative corrections as shown in the diagram $(M_Z - M_W)$ versus M_Z (Fig. 9), in which the 68 % confidence level contours from the two experiments are plotted [11]. Also shown in Fig. 9 are the regions of $\sin^2\Theta_W$ and ρ allowed by low energy measurements. Within the present statistical and systematic errors we cannot demonstrate the need for radiative corrections in the SM.

Table 2
Electroweak parameters and $W\to e\nu$ & $Z\to ee$ cross sections.

	UA1		UA2		theory	
	$W\to e\nu$	$Z\to ee$	$W\to e\nu$	$Z\to ee$	$W\to e\nu$	$Z\to ee$
mass (GeV/c^2)	$83.5^{+1.1}_{-1.0}\pm2.8$	$93.0\pm1.4\pm3.2$	$81.2\pm1.1\pm1.3$	$92.5\pm1.3\pm1.5$	82.4 ± 1.1	93.3 ± 0.9
width (GeV/c^2)	<6.5 (90%CL)	$4.3^{+2.5}_{-1.6}$	<7 (90%CL)	$2.19^{+0.70}_{-0.50}$	2.65	2.72
σ(pb) at $\sqrt{s}$ = 546 GeV	$550\pm80\pm90$	$41\pm20\pm6$	$500\pm90\pm50$	$110\pm39\pm9$	360^{+110}_{-50}	42^{+13}_{-6}
σ(pb) at $\sqrt{s}$ = 630 GeV	$630\pm50\pm90$	$85\pm23\pm13$	$530\pm60\pm50$	$52\pm19\pm4$	450^{+140}_{-80}	51^{+16}_{-10}
$r = \frac{\sigma(630\ \text{GeV})}{\sigma(546\ \text{GeV})}$	1.15 ± 0.19		1.06 ± 0.23		1.26 ± 0.02	
$\sin^2\Theta_W\ I$	0.194 ± 0.031		0.229 ± 0.030		average of low-energy data	
$\sin^2\Theta_W\ II$	$0.216^{+0.004}_{-0.005}\pm0.014$		$0.226\pm0.005\pm0.008$		0.220 ± 0.008 [6]	
ρ	$1.028\pm0.037\pm0.019$		$0.996\pm0.033\pm0.009$		minimum SM: $\rho = 1$	

(The second error is the systematic uncertainty.)

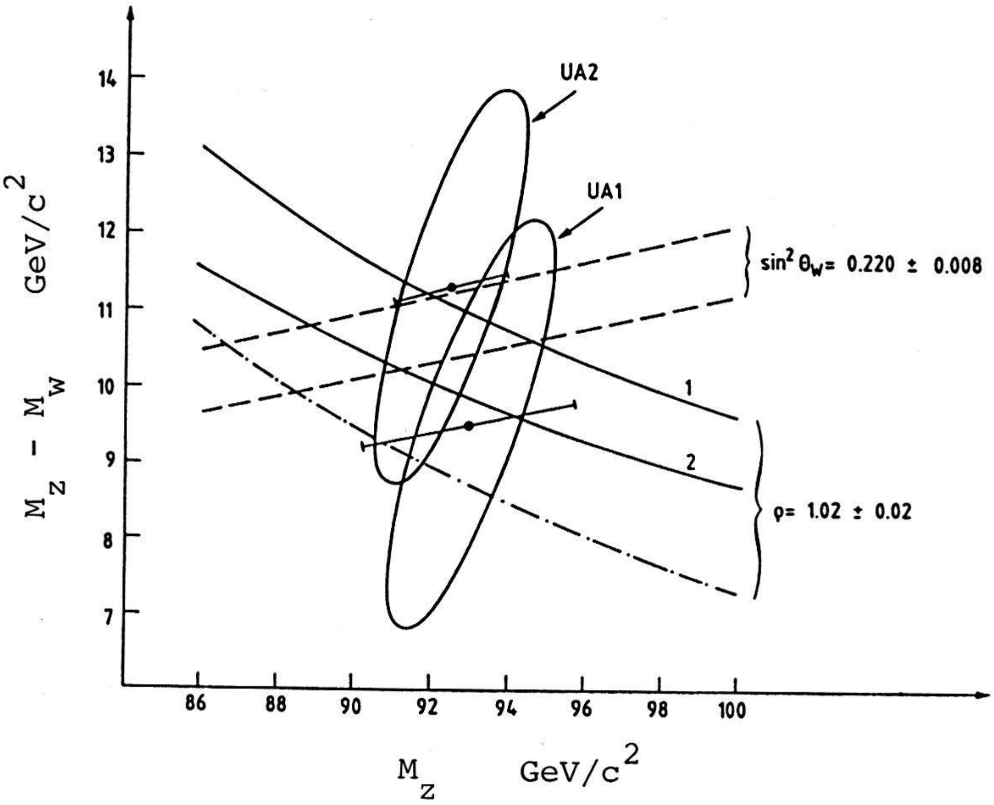

Fig. 9 Contours for the 68 % confidence level in the plot of M_Z-M_W versus M_Z taking into account the statistical errors only. The error bars applied to the centre of the ellipses respresent the translations allowed by the magnitude of the systematic errors. Curve 1 (2) is the prediction of the Standard Model with (without) radiative corrections. The region between the two dashed lines is the region allowed by the low-energy measurement of $\sin^2\Theta_W$; that between curve 1 and the dash-dotted line is allowed by the low-energy measurement of ρ.

3. Beyond the Standard Model

We learned that the SM passed successfully the test of many experiments, in particular at the CERN $p\bar{p}$ collider, where

a) clear evidence for hadronic jets (QCD) and
b) clean signal of the intermediate vector bosons (GSW model)

were found. On the other hand, UA1 observed a hand full events which could be due to the production and subsequent semileptonic decay of top quarks ($W \to t\bar{b}$; $t\bar{t}$), but more data are eagerly needed in order to get a conclusive answer about the existence of the flavour top [11,18]. Another still very open question in the SM is the existence of the Higgs scalar (mass not predicted by SM!), a spin zero particle, which is predicted to be the only surviving particle from the mass generating mechanism. Through the interaction with the omnipresent Higgs field the quarks, charged leptons, W and Z are thought to get their masses.

Generally speaking, the SM works pretty well in the energy domain up to 100 GeV, but one of the most important problems is the fact that there is still a lot of freedom or, in other words, unexplained mysteries in this theory. First of all, a large number (about 20) of gauge couplings and masses are left unspecified. Furthermore, the existence of three similar generations of quark and lepton flavours is astonishing and explained not at all. Also it is the declared goal of particle physics to unify all fundamental interactions observed in nature. In this context we should also mention the totally unexplained "hierarchy" problem, i.e. the presence of two very different mass or energy scales in nature:

1. the Fermi scale (Fermi coupling constant):
   $G_F^{-1/2} = O(M_W) \approx 3 \cdot 10^2 \text{GeV}$
2. the Planck scale (Newton coupling constant):
   $G^{-1/2} \equiv M_{PL} \approx 10^{19} \text{GeV}$

Therefore, in order to make progress, we need to go beyond the limited SM which seems to be the debris of a more fundamental theory.

The question which arises now is the following one: In which direction should one extend the SM? There exist many possibilities, but without going into details I present some "popular" ideas, being currently explored, in Fig. 10. Then, the next crucial point, I would like to bring up, are the anticipated implications accessible to future experimental studies. One obvious consequence of these extensions (enlarged multiplets, fourth generation, supersymmetry) is a proliferation of particles and field quanta, some or all of which may be too heavy for direct detection at future accelerators, but still indirect indications (e.g. of a heavy fourth generation) could come from

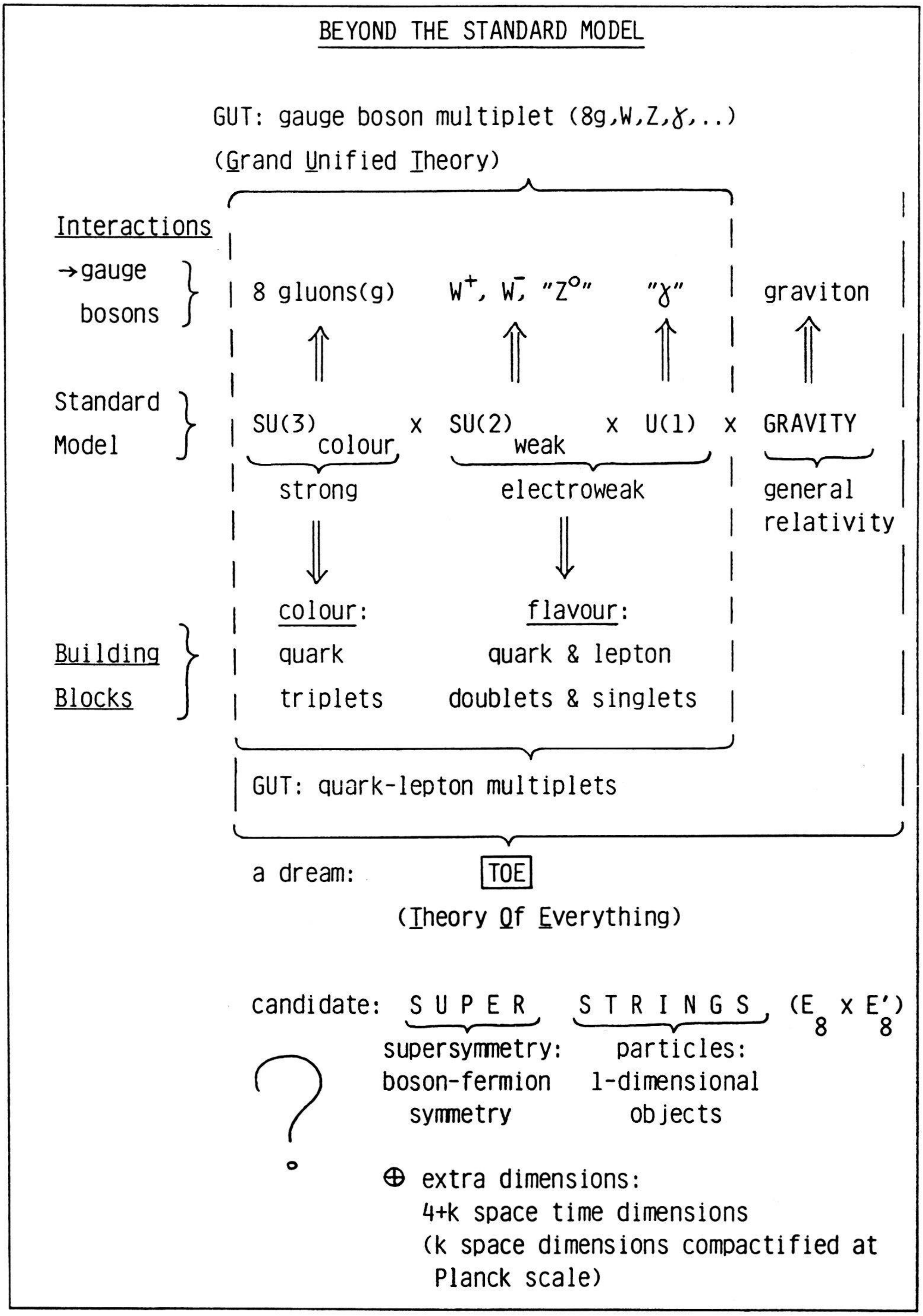

Fig. 10 Possibilities to go beyond the standard model.

precisely measured W and Z properties [19]. Another extension, not mentioned in Fig. 10, is the idea of compositeness, the idea that quarks, leptons, W, Z ... may be bound states of more fundamental entities. So far as we know today, the quarks and leptons are fundamental particles in the sense that present experiments could not reveal any sub-structure. By studying the angular distribution of the two jet data and the inclusive jet cross section for high transverse momentum jet production at the CERN $p\bar{p}$ collider, the UA collaborations were able to estimate an upper limit for the quark radius: $R_{quark} \lesssim O(10^{-18} m)$ [20]. Of course, one cannot exclude that future experiments at higher energies (see Sect. 4: HERA or SSC/LHC) will find a new layer beneath the quarks and leptons - the so-called preons.

4. Expectations from Hadron Colliders

In order to learn what can be expected from hadron colliders let me list the existing and planned hadron-hadron and for comparison also electron-positron and electron-hadron colliders in Tab. 3. For the short and long term future a main line of experimental particle physics should be to continue the research started at the CERN collider in 1981, we mean, first the more profound study of the electroweak parameters including the top quark and Higgs search and second the exploration of the physics in the few TeV range at the particle constituent (quarks and gluons) level where in the literature already mentioned SM extensions or new phenomena could show up. The proposed upgraded as well as new hadron and electron beam machines listed in Tab. 3 meet the above guideline very well. To be more specific, several items either concerning the SM or going beyond (the SM) are collected in Tab. 4, and these are related there by stars(*) to those colliders from which a significant contribution, confirming or non-confirming, can be anticipated. By inspecting this Tab. 4, the general trend is obvious: There is still a good chance to get additional and more precise information about SM physics (eg. more evidence for the existence of the top quark and measurement of the ratio M_W/M_Z with a precision of about 1.5×10^{-3} [11]) from experiments performed at the improved CERN $p\bar{p}$ collider as well as at the soon operational FNAL Tevatron, but the main

HADRON-HADRON COLLIDERS

Name	Energy (GeV)	Particle Types	Luminosity ($cm^{-2}s^{-1}$)	Status
Sp$\bar{p}$S (CERN, Geneva)	315+315	$p\bar{p}$	$>10^{29}$ $5x10^{30}$	completed 1981 upgrade 1987 ($\bar{p}$ collector)
Tevatron (FNAL, USA)	800+800	$p\bar{p}$	$\gtrsim 10^{30}$ (design)	first test 1985 operational in late 1986
UNK (Serpukhov, USSR)	400+3000	pp	10^{32} (design)	completion projected for 1990's
LHC* (CERN, Geneva)	6000+6000?	pp	10^{33} (design)	1990's?
SSC	20000+20000	pp	10^{33}	proposed for completion in 1994?

*Currently under discussion (pp in LEP tunnel).

FUTURE ELECTRON-POSITRON AND ELECTRON-HADRON COLLIDERS

Name	Energy (GeV)	Particle types	Luminosity ($cm^{-2}s^{-1}$)	Status
TRISTAN (KEK, Japan)	30+30	e^+e	$\sim 10^{31}$ (design)	scheduled for completion in 1986
SLC (SLAC, USA)	50+50	e^+e^-	$>10^{30}$ (design)	scheduled for completion in early 1987
LEP (CERN, Geneva)	50+50	e^+e^-	$\sim 10^{31}$ (design)	scheduled for completion late 1988
	100+100			energy upgrade of the facility planned for early 1990's
HERA (DESY, Hamburg)	30+820	e^-p	$\sim 5x10^{31}$ (design)	scheduled for completion in 1990

Table 3

Table 4

Expected outcome from hadron and electron colliders.

		hadron-hadron			electron-positron
		$Sp\bar{p}S$, CERN (upgrade → ACOL)	Tevatron, FNAL	SSC, USA LHC, CERN	SLC, SLAC LEP, CERN
	energy at constituent level	~100 GeV	$\gtrsim$100 GeV	$\gtrsim$1 TeV	~100 GeV
STANDARD MODEL	electroweak parameters	* *	* *		* * *
	Z°-width	*	*		* * *
	t-quark	* *	* *		* * *
	Higgs-particle			* * *	* *
BEYOND STANDARD MODEL	New Particles:				
	heavy {quarks Q, leptons L}	*	* *	* * *	* *
	superstring-Z'	*	* *	* * *	
	new IVBs: W',Z'			* * *	
	supersymmetric particles		*	* * *	*
	q-&ℓ-constituents		*	* * *	
	unexpected phenomena	(?)	?	new energy range } SURPRISE ?	?

* low chance
* * good chance
* * * high chance

step forward in this domain will certainly be achieved at the Stanford Linear Collider, SLC, and at LEP (Large Electron Positron). So much about the SM, the successful, but incomplete theory! How should we proceed? In order to get out of this unpleasant situation we need experimental input to show the good track for extensions beyond the SM. It is not excluded that some hints could come from non-accelerator experiments (e.g. proton decay, ν masses), but many questions (see Tab. 4) must be attacked by searching for new heavy fermions or bosons. In this respect, it is natural to look for a next generation accelerator at the TeV-level (see Tab. 4: SSC/LHC). Another important point when going to higher energies is the possible emergence of unexpected phenomena inspiring new ideas [21].

One machine, now in the construction phase, lies between the described categories of hadron and electron colliders, the electron-proton collider at DESY, called HERA. The main contribution of this project to the physics "beyond" will be to probe matter more deeply than ever before and to reveal possibly a sub-structure inside the quarks and leptons.

5. Conclusion

Let me first summarize where we stand in particle physics today. A lot of experimental tests have shown that the SM of the electroweak and strong interaction is in good shape. However, the best confirmation comes from the W and Z discovery along with the measurements of their masses and decay properties. In fact, we have reached the point where the electroweak part of the SM will be soon tested at the level of loop corrections.

We conclude: The SM describes many physical phenomena down t distances of $O(10^{-18}m)$, but on the other hand, about 20 parameters have to be introduced! From this, it seems to be clear that the SM is not the final theory, and that we should go beyond the SM - we need extensions.

The goal of particle physics is to construct the "Theory of Everything" (TOE), an "economic" description of nature and the universe with few parameters by unifying all the present interactions including gravity. There exists a variety of propositions how to extend the SM, and I would like to restrict myself by listing only some of the possibilities:

- Grand Unified Theory (GUT),
  the unification of the weak, electromagnetic and strong interactions
- Supersymmetry,
  the boson-fermion symmetry
- Compositeness,
  quark and lepton constituents
- generalized Kaluza-Klein models,
  an enlargement of space-time to 4 + k dimensions (k extra dimensions).

Because of many nice features (e.g. anomaly cancellation) the superstrings, the theory of supersymmetric particle strings (e.g. in 10 dimensions with an $E_8 x E'_8$ gauge symmetry), are considered by some people as a candidate TOE [22].

In view of all these speculations we need to be guided to the right ideas by a variety of experimental information, including the exploration of the next higher energy level accessible (SSC/LHC) and maybe data from the very unique high energy "laboratory", the primordial explosion of the Big Bang.

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