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THEORETICAL IMPLICATIONS OF RECENT COLLIDER RESULTS

by

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Theoretical Implications of Recent Collider Results

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Abstract: After discussing the comparison of the properties of the W and Z bosons found at the CERN collider with what is expected in the standard model, I critically overview various theoretical speculations concerning some recently reported exotic events, like radiative Z decays, monojets, hot photons, and jet activity. No overwhelmingly favored theoretical explanation appears to spring forth for all the existing exotica.

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1. Standard Model Comparisons

The discovery of the $W^{\pm}$ bosons (Arnison et al., 1983a; Banner et al., 1983) and of the Z^{o} boson (Arnison et al., 1983b; Bagnaia et al., 1983) at the CERN $Sp\bar{p}S$ collider with masses in the ranges predicted by the Glashow-Salam-Weinberg model (Glashow 1961; Salam 1968: Weinberg 1967) is one of the outstanding successes of this theory. Because radiative corrections alter significantly the lowest order mass formulas, the precise prediction of the weak boson masses, in terms of parameters measured in low energy weak processes, requires the careful evaluation of these corrections. Although it is possible to define a variety of renormalized $\sin\theta_W$ - differing from each other by terms of $O(\alpha)$ - it has proven particularly convenient to adopt a renormalization framework where the renormalized $\sin\theta_W$ is defined directly in terms of the weak boson masses (Sirlin 1980):

$$\sin^2\theta_W = 1 - \left(\frac{M_W}{M_Z}\right)^2 \qquad (1)$$

After radiative corrections are computed (Marciano and Sirlin 1980, 1981; Llewellyn Smith and Wheater 1981) the lowest order best fit value extracted from deep inelastic ν_μ scattering and polarized eD scattering by Kim et al. (Kim et al., 1980):

$$\sin^2\theta_W\Big|_{\substack{\text{lowest}\\\text{order}}} = 0.229 \pm 0.009 \qquad (2)$$

gets substantially altered. For the definition of $\sin\theta_W$ adopted in Eq(1), Marciano and Sirlin and Llewellyn Smith and Wheater find

$$\sin^2\theta_W = \begin{matrix} 0.217 \pm 0.014 \\ 0.218 \pm 0.020 \end{matrix} \qquad \begin{matrix}(3a)\\(3b)\end{matrix}$$

where the upper (lower) value above applies for ν_μ scattering (eD scattering).

With the definition of $\sin\theta_W$ of Eq (1) the masses of M_W and M_Z follow from a formula which, to logarithmical approximation, is identical to the lowest order formula, except that α is replaced by $\alpha(M_W)$ - the fine structure constant evaluated at the W mass scale - and the Fermi constant is that extracted from, radiatively corrected, μ-decay. To be more precise, the W and Z masses are given by the formula (Marciano 1984a):

$$M_W = \left[\frac{\pi\alpha}{\sqrt{2}\,G_\mu \sin^2\theta_W (1-\Delta r)}\right]^{1/2} ; \; M_Z = \frac{M_W}{\cos\theta_W} \qquad (4)$$

Here α is the fine structure constant, $\alpha^{-1} = 137.035963$. and G_μ is the Fermi constant extracted from the, radiatively corrected, muon lifetime (Sirlin 1984)

$$\frac{1}{\tau_\mu} = \frac{G_\mu^2 m_\mu^5}{192\pi^3}\left(1 - \frac{8m_e^2}{m_\mu^2}\right)\left(1 + \frac{3m_\mu^2}{5M_W^2}\right)\left[1 + \frac{\alpha}{2\pi}\left(\frac{25}{4} - \pi^2\right)\left(1 + \frac{2\alpha}{3\pi}\ln\frac{m_\mu}{m_e}\right)\right] \qquad (5)$$

The quantity Δr is the complete $O(\alpha)$ radiative correction, whose value (Marciano 1984a), for m_t = 40 GeV and $m_H = m_Z$, is rather substantial:

$$\Delta r = 0.0696 \pm 0.0020 \qquad (6)$$

However, as indicated above, the main effect in Δr can be accounted for by a shift of α to $\alpha(M_W)$, this corresponding to a Δr of approximately 0.073.

Numerically, Eq (4) leads to the predictions

$$M_W = \frac{(38.65 \pm 0.04)}{\sin\theta_W}\ \text{GeV} \quad ; \quad M_Z = \frac{(77.30 \pm 0.08)}{\sin 2\theta_W}\ \text{GeV} \qquad (7)$$

Using Eq (3a) this leads to the theoretical values

$$M_W = 83.0 \begin{smallmatrix} +\ 2.9 \\ -\ 2.7 \end{smallmatrix}\ \text{GeV} \quad ; \quad M_Z = 93.8 \begin{smallmatrix} +\ 2.4 \\ -\ 2.2 \end{smallmatrix}\ \text{GeV} \qquad (8)$$

which are in excellent agreement with the weighted average of the UA1 and UA2 data

$$\bar{M}_W = 82.1 \pm 1.7\ \text{GeV} \quad ; \quad \bar{M}_Z = 93.0 \pm 1.7\ \text{GeV} \qquad (9)$$

Three remarks are in order:

(1) The radiative effects are indeed large, something that has been emphasized already for a number of years (Antonelli, Consoli and Corbo 1980; Veltman 1980; K. Aoki et al. 1981; Bardin, Christova and Fedorenko 1982). Using Eq (4), with $\Delta r = 0$ and the lowest order best value for $\sin\theta_W$ of Eq (2), gives $M_W \simeq 78.2$ GeV, $M_Z \simeq 89$ GeV. The data clearly seems to favor somewhat larger values than these. The approximate 5 GeV shift in M_W and M_Z is due to a 6% downward shift in $\sin^2\theta_W$ and a 7% decrease due to the $(1-\Delta r)$ factor.

(2) The statistics at the collider are still rough, and there are UA1/UA2 disparities. For example, the W mass determined by UA1 for the $e\nu$ mode is $M_W = 80.9 \pm 1.5 \pm 2.4$ GeV, while UA2 gives the value $M_W = 83.1 \pm 1.9 \pm 1.3$ GeV. After the forthcoming collider run, it is likely, however, that what will prevent an accurate test of higher order corrections will be the error on $\sin\theta_W$, from low energy experiments. Of course, one can eliminate θ_W from Eq (7) and obtain an interesting constraint between the W and Z masses (Consoli, Lo Presti, Maiani 1983; Hioki 1982; Sirlin 1984)

$$M_Z = M_W \left[1 - \left(\frac{(38.65 \pm 0.04)}{M_W(\text{GeV})} \right)^2 \right]^{-1/2} \qquad (10)$$

which directly tests the radiative corrections. The lowest order numerical factor in Eq (10) would be 37.3 GeV instead of 38.65 GeV .

(3) One can use Eq (7) and the average UA1 and UA2 W and Z masses to extract a value for $\sin\theta_W$. Using the weighted average of both determinations gives

$$\sin^2\theta_W = 0.222 \pm 0.007 \qquad (11)$$

The collider value for the Weinberg angle is seen to be in excellent agreement from that extracted from low energy experiments, Eq (3).

Although the mass of the Z^o at the collider appears standard, three out of the 12-16 Z^o decays into lepton pairs seen are accompanied by a rather hard photon. These "anomalous" radiative decays have generated an enormous amount of interest and, in the next section, I will discuss some of the theoretical speculations on their origin. Here, however, I first examine whether these events are really that extraordinary. The total decay rate, to $O(\alpha)$, for $Z^o \rightarrow \ell\bar{\ell}\gamma$ (Albert et al., 1980).

$$\Gamma\,(Z^o \rightarrow \ell\bar{\ell}\gamma) = \Gamma(Z^o \rightarrow \ell\bar{\ell})\left[1 + \frac{3\alpha}{4\pi}\right] , \qquad (12)$$

is clearly small. However, this rate is not a useful judge of the bremsstrahlung expectation. What is observed physically is the ratio

$$R(Z \rightarrow \ell\bar{\ell}\gamma\ ;\ w,\delta) = \frac{\Gamma(Z \rightarrow \ell\bar{\ell}\gamma\ ;\ E_\gamma > w;\ \text{coll. angle} > \delta)}{\Gamma(Z \rightarrow \ell\bar{\ell}(\gamma);\ E_\gamma < w;\ \text{coll. angle} < \delta)} \qquad (13)$$

in which one imposes certain cuts on the minimum photon energy, w, and collinearity angle, δ , between the photon and the lepton, which one can measure. The ratio R goes up by making the cuts on w and δ more and more stringent.

A careful reanalysis of R has been performed recently by a number of people (Berends and Kleiss 1983; Passarino 1983; Marciano 1984a; Caffo, Gatto and Remiddi 1984; Fleischer and Jegerlehner 1984). Fleischer and Jegerlehner, in particular, present results in which no small angle or soft photon approximations are made. These approximations can alter the results non negligibly. For instance, for $\delta = 5^o$, $\epsilon = w/M_Z = 0.1$, which are reasonable experimental values, the exact R is R = 0.034, while R = 0.023 is the small angle, $\omega \ll 1$, approximation. As can be seen from Figs 1 and 2 below, taken from Fleischer and Jegerlehner, R is very sensitive to cuts in δ and w. However, for sensible cuts, as those indicated above, R $\simeq$ 2-3% is a reasonable expectation. I should note incidentally, that similar calculations for W radiative decay give ratios R $(W \rightarrow \ell\nu\gamma)$ two to three times smaller than R $(Z \rightarrow \ell\bar{\ell}\gamma)$, for similar cuts.

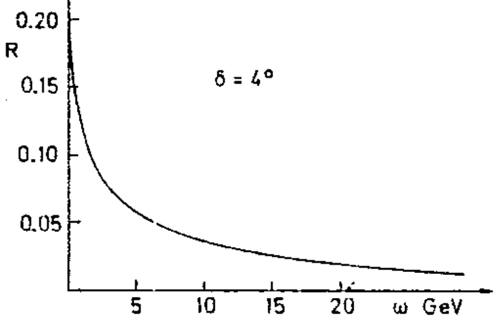

Fig 1: Dependence of R on w for fixed δ , from Fleischer and Jegerlehner 1984

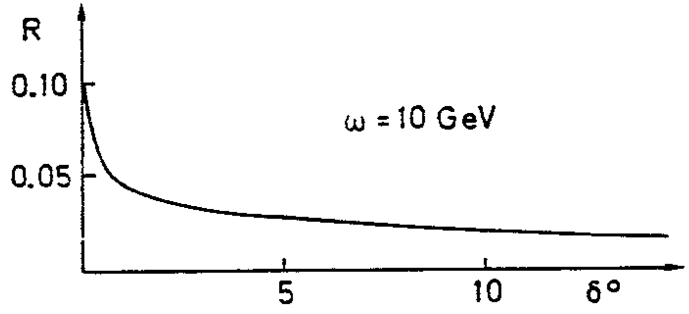

Fig 2: Dependence of R on δ for fixed w, from Fleischer and Jegerlehner 1984

2. Speculations Concerning Radiative Z° Decays

Given the above analysis the crucial question is whether the 3 radiative Z° decays observed by the UA1 and UA2 collaborations (Arnison et al., 1983b, 1983a; Bagnaia et al., 1983) are new physics or just a statistical fluctuation. Clearly one really needs more statistics to tell what is going on. Nevertheless, a number of brave (foolish?) theorists have taken the nominal UA1 - UA2 radiative rate

$$R_{UA1-UA2} \simeq 0.20 - 0.25 \qquad (14)$$

seriously, and have ventured a myriad suggestions for the origin of this very high radiative rate. These speculations can be broadly classified into four classes:

(i) Models which involve new scalar excitations (Baur, Fritzsch and Faissner 1984, Peccei 1984a, Renard 1984)
(ii) Models involving new excited leptons (Cabibbo, Maiani and Srivastava 1984, Enquist and Maalampi 1984, Renard 1984)
(iii) Models introducing new states degenerate with the Z° (Marciano 1984b; Matsuda and Matsuoka 1984; Holdom 1984)
(iv) Models with enhanced $Z\ell\bar{\ell}\gamma$ effective couplings (Gounaris, Kögeler and Schildknecht 1984, Tomozawa 1984, Duncan and Veltman 1984, Renard 1984, Barroso et al., 1984).

All the suggestions above to "explain" an $R \simeq 20\%$ suffer themselves from some problems. Except for models of type (iii), the kinematics of the observed $\ell\bar{\ell}\gamma$ events appear to be different than those of the suggested solutions (Renard 1984; Barger, Baer and Hagiwara 1984). Models involving new degenerate states and models which invoke some enhanced $Z\ell\bar{\ell}\gamma$ coupling have difficulties in producing enough of the new states or in justifying the desired enhancement. Finally, some models, particularly those of type (i), run into conflict with g-2 bounds (del Aguila, Mendez and Pascual 1984; Suzuki 1984; Drell and Parke 1984).

The kinematical configuration - but not the rate - of the three radiative decays is much like one would expect from bremsstrahlung. This is shown graphically in Fig 3. Because all three events have one of the e-γ invariant masses which is small, they necessarily sit at one edge of the Dalitz plot. Sequential decays of the type $Z^\circ \to \bar{\ell}\ell^*$; $\ell^* \to \ell\gamma$ or $Z^\circ \to S\gamma$; $S \to \ell\bar{\ell}$ would give lines of constant x_H or x, respectively. An enhanced $Z\ell\bar{\ell}\gamma$ coupling also would have no particular reason for populating the small x_L region.

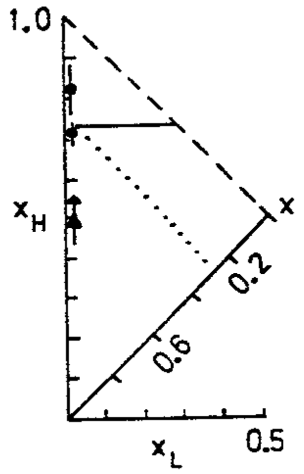

Fig 3: Distribution of $\ell\bar{\ell}\gamma$ events in the Dalitz plot. Here $x_H = m^2_{\ell\gamma}/M^2_Z$; $x_L = m'^2_{\ell\gamma}/M^2_Z$; $x = m^2_{\ell\bar{\ell}}/M^2_Z$ with $m_{\ell\gamma} > m'_{\ell\gamma}$. The solid line corresponds to the expected distribution for an excited lepton interpretation, the dotted line is the distribution expected in the case of a sequential decay to a scalar.

This kinematical pattern, however, can be reproduced if the radiative decays are due to the presence of a scalar or pseudoscalar state, roughly degenerate with the Z°, which decays dominantly via the graph of Fig 4.

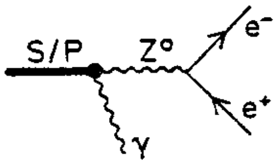

Fig 4: Graph which is supposed to dominate the S/P radiative decays

As emphasized by Matsuda and Matsuoka, helicity conservation tends to allign one of the emitted leptons along the direction of the photon. Further, the Z° propagator in Fig 4, if $M_{Z^\circ} \simeq M_{S/P}$, will force the $\ell\bar{\ell}$ pair to have a mass peak around 50 to 60 GeV. These are the characteristics of the events seen at the collider.

It is worthwhile to examine, therefore, the scenario (iii) with a bit more care, since, after all, it is the only scenario which can reproduce the

the kinematical characteristics of the collider events. In doing so one uncovers a variety of problems, which also tend to make this proposition rather suspect. I see four principal problems and a query:

(1) The S/P $Z^0\gamma$ vertex in Fig 4 is much bigger than what one could expect, if the S/P state was some onia. The coupling that Marciano (Marciano 1984b) needs, to obtain a sufficient number of $\ell\bar{\ell}\gamma$ decays, is about a factor of 10 bigger than that estimated by Guberina et al. (Guberina et al., 1980) for an onia - given the already very big production cross section for S/P (see below) assumed! Such a large coupling can only arise if the S/P <u>and</u> the Z^0 are composed of the same constituents.

(2) The vertex $S/P\,\gamma\gamma$ must be very small. If not, it is more likely that the S/P decay via 2γ, than radiatively. Further, the peaking in the $\ell\bar{\ell}$ mass would tend to be erased in the radiative decay itself. It seems difficult to ignore this problem entirely, by postulating that this coupling is indeed small. This is because, in a composite Z^0 scenario, required by point (1) above, vector dominance relates the $S/P\,\gamma\gamma$ and $S/P\,Z^0\gamma$ vertices. To wit, if g are the effective coupling constants, one has:

$$g_{S/P\gamma\gamma} = g_{S/P\,Z\gamma}\sin\theta_W \simeq \frac{1}{2}\,g_{S/P\,Z\gamma} \tag{15}$$

(3) If Fig (4) dominates, then one predicts that

$$\frac{\Gamma(S/P\to\nu\bar{\nu}\gamma)}{\Gamma(S/P\to\ell\bar{\ell}\gamma)} \simeq 6 \tag{16}$$

Two events of the type energetic photon plus missing energy ("hot photon" events) have been reported by the UA1 Collaboration (Arnison et al., 1984b), which perhaps could be associated with the decay $S/P\to\nu\bar{\nu}\gamma$. However, the transverse masses reported for these events seem too large $[m_T = 93 \pm 5$ GeV, 84 ± 6 GeV$]$ and this interpretation can be questioned. At any rate, it is clear that more events leading to missing energy plus hard photons are needed, if there exists really an S/P state. The statistics are marginal, but against this interpretation.

(4) The production of S/P is probably the most challenging problem. In the scenario of Marciano and of Matsuda and Matsuoka this must occur via gluon gluon fusion (Fig 5a, below), while for the model of Holdom it occurs, in associated production with a quark, by quark-gluon fusion (Fig 5b, below)

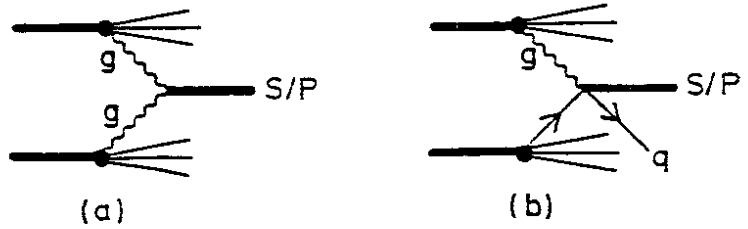

Fig 5: (a)Production of S/P state in the models of Marciano 1984b and Matsuda and Matsuoka 1984
(b)Production of this state in the model of Holdom 1984

To obtain a production rate which suffices, the decay $\Gamma(S/P\to 2g)$ must be of order of at least a GeV. This is 10^3 - 10^4 times what one would expect for a Higgs meson or a Technipion and it implies that the production rate comes close to saturating the unitarity-bound (see section 3 for more details on this point). Holdom's scenario runs into similar problems. The dimension 7 gqqS/P vertex is scaled by a parameter Λ_c, typifying the scale of compositeness. Only by taking $\Lambda_c \simeq 100$ GeV - a dubious choice - does one get enough S/P production.

(5) The most nagging query, however, remains: why is this state here at all? Sec. 3, in a different vein, provides a partial, but probably unsatisfactory, answer.

I shall not discuss at all the possibility that the radiative Z^0 decays are due to the deexcitation of the Z^0 to a scalar state, or states, of mass around 50 GeV, as this is covered in some detail already in my Bern report (Peccei 1984b). I will, however, make some comments on the excited lepton scenario. This scenario is actually the most straight forward one, were it not for the kinematical problem mentioned above. The scenario does have a theoretical puzzle in that, if the compositeness scale Λ_c is really greater than a TeV (Eichten, Lane and Peskin 1983), the rather "low" mass of the excited leptons needed is unexplained.

Excited electrons and muons give contributions to (g-2). However, as long as the effective lepton - excited lepton - gauge boson vertex is chiral (proportional to $1-\gamma_5$) then the (g-2) contribution is quadratically dependent on the lepton masses:

$$\delta(g-2) \simeq \alpha\left(\frac{m_\ell}{M_{\ell^*}}\right)^2 \tag{17}$$

Hence, rather low masses for excited leptons are allowed (Renard 1982) and M^*_μ, $M^*_e \sim 70$-80 GeV do not run into any (g-2) problems. If such states exist, then a ratio $R \simeq 0.2$ is rather easily achieved by postulating a magnetic transition between the ordinary leptons, the excited leptons and the weak gauge bosons, whose scale is set by $1/M^*_\ell$ and not by $1/\Lambda_c$ (Cabibbo, Maiani and Srivastava 1984). This transition can naturally be chiral by having the excited leptons couple, for example, only to the SU(2) doublet lepton fields.

Cabibbo, Maiani and Srivastava constructed specific SU(2) x U(1) models for the excited leptons in which these states had, alternatively, $I_W = 0$, 1/2, 1 and 3/2. For each of these models, specific predictions follow for other weak radiative decays like $Z\to\nu\bar{\nu}\gamma$ or $W\to\ell\nu\gamma$. With more data, these predictions can eventually be tested and (if correct!) a successful model identified. Perhaps the most interesting inference, however, that can be drawn from the possible existence of excited leptons with mass of O(100 GeV) is that also very probably excited quarks of similar masses should exist. These objects, called starks by De Rujula, Maiani and Petronzio (De Rujula, Maiani and Petronzio 1984), have interesting phenomelogical consequences - some of which I will discuss in the next section.

3. Spring Exotica

At the $p\bar{p}$ meeting in March of this year at Bern the UA1 and UA2 Collaborations unveiled a variety of spectacular events (Rubbia 1984, Schacher 1984; Roussaire 1984. More details are contained in Arnison et al., 1984b; Bagnaia et al., 1984). These events contain large transverse momenta and/or large transverse masses and include:

Monojets (Jet or Jets plus missing energy)
Hot Photons (Hard photon plus missing energy)
"W" + Jets (Jet(s) plus lepton plus missing energy)
Di-Jet shoulder at $M \gtrsim 150$ GeV

One of the peculiarites of the observations in that different phenomena were detected by UA1 and UA2, with UA1 being responsible for the monojets and the hot photons and UA2 for the rest.

I begin my discussion of these exotic phenomena with three general observations and then I'll enter into some selected discussion of the avalanche of theoretical papers which they have generated. (There are certainly more theoretical explanations than exotic events!):

(1) It is unlikely that all the collider exotica is some not well understood background or that they are all instrumental glitches. However, backgrounds do exist. For instance, as shown in Fig 6, ordinary QCD processes can give rise to W's plus a jet. However, the events reported by UA2 have enormous E_T (40-70 GeV), and are thus unlikely to be of pure QCD origin. It is clearly important in the Fall run of the collider to get more experimental information on the tails of ordinary processes, to see whether the "new" phenomena really stand out or not.

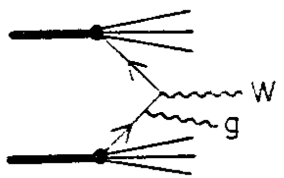

Fig 6: Background to W + Jet exotica

(2) The energy scale associated with the UA1 and UA2 events appear to be connected with phenomena at a scale higher than the Z^o. For instance, the transverse mass (which in general underestimates the real mass) of the jet + missing energy system in the UA1 Monojets ranges from 85 $\pm$ 12 GeV to 130 $\pm$ 16 GeV. Thus the connection of these new phenomena with the anomalous Z^o radiative decays is not so clear. The "hot photon" events could be $Z^o \to \nu\bar{\nu}\gamma$ or $S/P \to \nu\bar{\nu}\gamma$ decays and thus be related to the radiative decays. But, at any rate, they would be new physics!

(3) Although, as mentioned above, the theoretical speculations to "explain" the exotic events abound, independent of the underlying physics, the "mechanics" of the models to generate the exotica is essentially the same. Basically, one needs a sizable production for some "heavy object" ($\sigma_{H.O.} \simeq$ 1-10 nb). This "heavy object" then decays with a 5-10% probability into a Jet plus some electroweak boson. More sophisticated models have also a tiny ($\sim$ 1%) electroweak boson plus electroweak boson decay rate.

Broadly speaking the speculations for the Spring Exotica can be divided into four different classes. These are:

(i) Speculations based on Supersymmetry (Ellis and Kowalski, 1984a and 1984b; Haber and Kane 1984a; Reya and Roy 1984; Barger, Hagiwara, Woodside and Keung 1984; Allan, Glover and Martin 1984)
(ii) Speculations involving Stark production (De Rujula, Maiani and Petronzio 1984; Pancheri and Srivastava 1984; Kühn and Zerwas 1984)
(iii) Speculations involving a low mass scale technicolor scenario - the, so called, Fat Higgs scenario (Georgi and Glashow 1984; Düsedau, Lüst and Zeppenfeld 1984; Peccei, 1984c)
(iv) Speculations involving composite colored Vector Bosons (Fritzsch 1984; Baur and Streng 1984; Gounaris and Nicolaidis 1984)

I will discuss (i) in some detail, make some remarks on (ii) and discuss briefly the physics (and improbable assumptions) of (iii), which has some overlap with (iv). I will postpone the discussion of the even wilder speculations of Odoronia (Glashow 1984) to section 4.

In the last few years there has been intense theoretical speculation on the possibility that all particles may have supersymmetric partners. (This subject is reviewed in Ellis 1984; Haber and Kane 1984b) These, so called, spartners have the same quantum number properties as their partners but differ by 1/2 a unit in spin. If Supersymmetry (Susy) were exact, the spartners would be mass degenerate with the ordinary partners. Thus, clearly, one must assume that susy is broken, so that the absence of positive evidence for spartners is no fatal hindrance. Although the breaking of susy is largely arbitrary, there is some theoretical support for supposing that the lightest susy partner is the spin 1/2 photino. Further, it is quite natural to assume that, for all flavors, the squarks and sleptons have common mass $\tilde{m}$, with $\tilde{m} \gtrsim 20$ GeV to avoid conflict with e^+e^- experiments (Yamada 1983). The mass of the susy partners of the gluons - the gluinos - is largely uncertain, and one can entretain the possibilities that $\tilde{m} < m_{\tilde{g}}$ or vice versa.

If squarks ($\tilde{q}$) or gluinos ($\tilde{g}$) were sufficiently light, they would be abundantly produced at the Sp$\bar{p}$S collider by ordinary QCD processes, like $q\bar{q} \to \tilde{g}\tilde{g}$, etc. (Kane and Leveille 1982; Harrison and Llewellyn Smith 1983). Events with Jets plus missing energy would be a natural by-product of squark or gluinos production, with subsequent decays into photinos ($\tilde{q} \to q\tilde{\gamma}$; $\tilde{g} \to q\bar{q}\tilde{\gamma}$). The photino, being neutral, would give rise to the missing energy. In fact, if the $\tilde{q}$ or $\tilde{g}$ are too light, one risks to produce too much exotica.

The result of various recent independent calculations can be summarized as follows:

(1) Depending on whether $\tilde{m} < m_{\tilde{g}}$ or $m_{\tilde{g}} < \tilde{m}$, the monojet UA1 data admits an interpretation as being due to the production of squarks with masses in the range $\tilde{m} \simeq$ 30-40 GeV (Ellis and Kowalski 1984b; Barger, Hagiwara and Keung 1984; Allan, Glover and Martin 1984) or, alternatively, as being due to gluino production with $m_{\tilde{g}} \simeq$ 35-40 GeV (Ellis and Kowalski 1984a and 1984b; Reya and Roy 1984)
(2) Although ideally $\tilde{g}\tilde{g}$ production, followed by $\tilde{g} \to q\bar{q}\tilde{\gamma}$ decay (or $\tilde{q}\tilde{q}$ production, followed by $\tilde{q} \to q\tilde{\gamma}$ decay) should give rise to 4 Jets plus missing energy (2 Jets plus missing energy), these Jets are largely coalesced by the experimental algorithm used by the UA1 Collaboration to extract Jets. Fig 7 and Fig 8 show this phenomena, as calculated explicitly by Ellis and Kowalski 1984b.

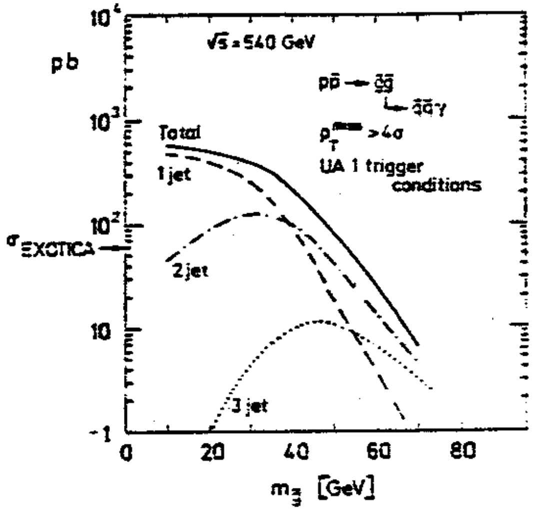

Fig 7: Jet decomposition for gluino production, with UA1 trigger conditions

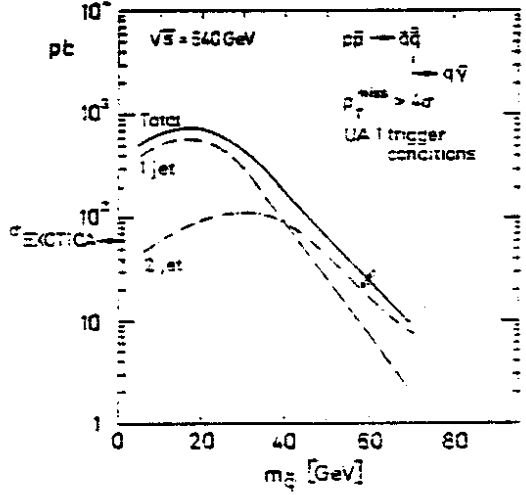

Fig 8: Jet decomposition for squark production, with UA1 trigger conditions

It is obvious from these figures that if $m_{\tilde{g}}$ or $\tilde{m}$ is too light, then too much exotica would ensue.

(3) Although both squark and gluino production, with $\tilde{m}$ and $m_{\tilde{g}}$ in the ranges given in (1), produce the experimentally observed monojet cross section, the squark interpretation is slightly favored. The Jets in the UA1 data are extremely "thin", containing just a few particles, which make them unlikely to be by-products of multijet coalescence, as is the case for gluinos. Further, there appears to be a long $(p_\perp)_{missing}$ tail which fits better the harder $p_\perp$ produced from the two-body $\tilde{q} \to q\tilde{\gamma}$ decay. Clearly more data, unbiased if at all possible by Jet-algorithms, is needed to decide the issue. However, the "thinness" of the observed jets is already a worry - also for squarks.

(4) Not all exotica is explained by susy. For instance, the "hot photons" are a problem. Haber and Kane 1984a, suggest that the "W" plus Jet events seen by the UA2 Collaboration might be due to $\tilde{w}\tilde{g}$ (or $\tilde{w}\tilde{q}$) production, for sufficently light Wino. In these cases the missing energy would be due to both photino and sneutrino production.

Excited quarks (starks), if they exist, may provide an alternative explanation of the Spring Exotica. Starks can be produced by quark gluon fusion, as shown schematically in Fig 9.

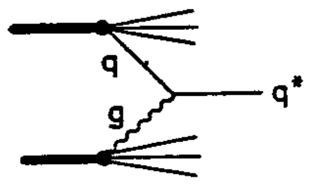

Fig 9: Stark production by quark gluon fusion

Using the same kind of magnetic coupling (scaled by $1/M^*$), as employed for the excited leptons, to parametrize the qq^*g vertex, De Rujula, Maiani and Petronzio 1984 find abundant q^* production at the collider, up to massses of order of 150 GeV. The decay of the starks back into the quark gluon channel dominates, giving rise to two jet events. However, these two jet events may not stand out against the normal QCD background. Of course, the UA2 shoulder in the 2 jet invariant mass around 150 GeV can temptily be interpreted as stark production, but this is probably too rash.

Starks of $M^* > 120$ Gev can have a sizable ($\sim 10\%$) decay rate into quarks plus W, Z or γ. These decays could account for the UA1 monojets, through the sequential process $q^* \to qZ$; $Z \to \nu\bar{\nu}$. They are, of course, natural candidates for the UA2 "W" plus Jet events. Although the absolute rate of expected exotica is a little dependent on parameters, the relative rate of various processes is bounded (Kühn and Zerwas 1984). These authors find that, in the simplest $SU(2) \times U(1)$ doublet model for the starks, one expects for $M^* = 150$ GeV

$$\frac{N(\gamma + \mathrm{Jet})}{N(W \to e\nu + \mathrm{Jet})} \gtrsim 1.6 \qquad (18a)$$

$$\frac{N(\gamma + \mathrm{Jet})}{N(Z \to \nu\bar{\nu} + \mathrm{Jet})} \gtrsim 2.8 \qquad (18b)$$

Interpreting the 3 UA2 events of "W" plus Jet and the UA1 monojet events (event A does not fit this pattern, because of the presence of a muon in the jet) as being due to stark decay, clearly begins to be dangerous, because of the apparent non existence of correspondingly many γ plus Jet events. Of course, the above bounds can be vitiated if the starks have more complicated weak isospin assignments (Pancheri and Srivastava 1984). At any rate, for the stark interpretation to hold, events with large transverse mass of a photon-jet system must eventually begin to appear in the Fall collider run.

The last scenario for the Spring exotica which I want to discuss here is the one in which the spectacular collider events are attributed to the presence of some low mass remnant of a technicolor theory. this "Fat Higgs" scenario is already discussed in some detail in Peccei 1984c, and so I shall be brief here. In a usual technicolor scenario (Susskind 1979; Weinberg 1979) one supposes that the interactions among the technipions - which give mass to the W bosons, and eventually produce a strong interaction among them - are just like those among pions, but scaled up by a factor $(\sqrt{2}G_F)^{-1/2}/f_\pi \simeq 2500$. The existence of an attractive, $I = 0$, s-wave partial wave and a broad σ enhancement in π-π scattering has its counterpart in a broad 0^+ resonance at $M \simeq 1.5$ TeV, with perhaps a 1 TeV width, in the technicolor theory (The Fat Higgs). The ρ meson of π-π scattering, similarly implies the presence of a Technirho state at $M \simeq 1.7$ TeV, etc. Clearly, these states, even if they existed, would have no implication for the present collider experiments.

To make technicolor relevant for the Spring exotica requires that one assume that the technipion interactions, although having the same threshold behaviour as those of pions, become stronger much sooner. This is shown schematically in Fig 10, where the behaviour of the π-π A_0^0 partial wave amplitude, naively extrapolated from threshold, is contrasted with what one would want to happen in the technicolor theory.

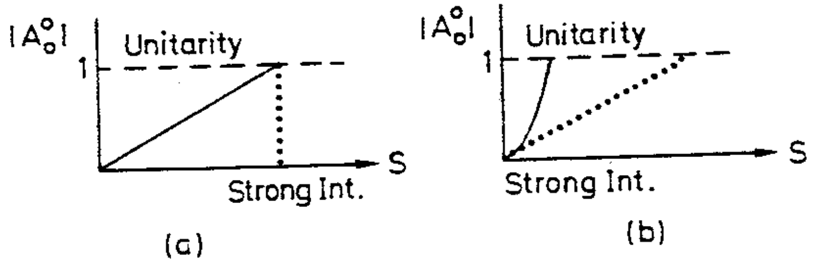

Fig 10: (a)Threshold s-wave π-π scattering rises linearly with s until it saturates unitarity
(b)Desired behaviour of the technipion scattering amplitude

The bold assumption that this might indeed happen, and be the root cause for the collider peculiar events, has been put forth recently by Georgi and Glashow 1984. However, before one can really ascribe the exotica to the production of a low mass Fat Higgs, one needs a mechanism for producing this object. Gluon fusion, as shown in Fig 11, seems to be the only possibility. Unfortunately, as already observed when discussing the production of the ζ/ρ state - which is really very akin to the Fat Higgs - one needs unnaturally large gluon couplings to generate enough exotica.

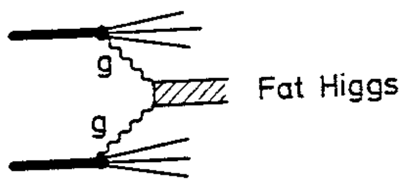

Fig 11: Production of Fat Higgs by gluon fusion

Georgi and Glashow, to produce enough exotica, assumed that the production cross section of an 150 GeV Fat Higgs at the collider could amount to 10 nb. In fact, (Düsedau, Lüst and Zeppenfeld 1984) unitarity restricts this production cross section to perhaps only a tenth of a nanobarn. So it is very unlikely that this could be the mechanism for generating all the exotica, unless the decay of the Fat Higgs into channels containing a jet plus an electroweak boson is comparable to the two gluon channels. This latter type of possibility has many features in common to the colored vector boson scenario (Fritzsch 1984; Baur and Streng 1984).

4. Jet Activity

The latest bit of apparent non standard behaviour, which was discussed in this meeting by Tuominiemi (Tuominiemi, 1984), is a tendency of the Z° events, of the UA1 Collaboration, to have an unusual amount of jets associated with them. Such jet activity does not seem to be so prevalent in the UA2 Z° events. Qualitatively, if this observation is not just some statistical fluctuation, this could point to the Z° being composite of constituents which have color. The jets could then be associated with gluon radiation off these constituents. A schematic sketch of this idea is presented in Fig 12

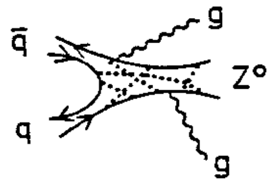

Fig 12: Origin of jet activity in a picture in which both quarks and the Z° are composite of colored constituents

Quantitatively, however, it is difficult to implement such a picture without, at the same time, spoiling other desirable properties.

Glashow (Glashow 1984) has proposed recently a clever, if a bit outlandish, idea to explain the jet activity, by inventing yet another new strong interaction force "odor". Not only does odor provide a way for the Z^o's to be produced with additional jets, but it also gives one another mechanism for generating the monojet events of UA1 (Odor does not lead to "W" plus Jet events). The basic idea of Glashow is that there are two sources for Z^o's, one directly from $q\bar{q}$ production and the second arising from the decay of Odoronia to a Z^o plus a light Higgs. Z^o's coming from this second source would often be accompanied by Jets from the Higgs decay into Jet-Jet or $\tau\bar{\tau}$. These accompanying jets would be characteristically "thin jets". If the Odoronia produced Z^o's decayed into neutrinos, as they would do a good fraction of the time, then the Higgs initiated jets would be a natural source for the "thin" monojets seen by UA1.

Glashow's mechanism works only because Odoronia - which is the quarkonia of new quarks carrying the new quantum number odor - is much more likely to be produced that a similar (heavy) $q\bar{q}$ bound state. Basically, higher Odoronia bound states cannot dissociate into states containing an odor quark and an ordinary quark, and so must all cascade down to the lowest Odoronia state. This is why the production cross section is big. The J=1 Odoronia ground state has itself almost an equal probability of decaying into three gluons or into HZ^o and/or $H\gamma$, since the Higgs coupling to the heavy odor quarks ($m_{q_o} \simeq$ 60-70 GeV?) is large (see Fig 13). So this unusual suggestion can really produce enough exotic events. However, as Kane and Maiani (Kane and Maiani 1984) point out, the Glashow scheme may be too much of a good thing. Beside the decay channels shown in Fig 13, Odoronia can have also sizable decays into other channels.

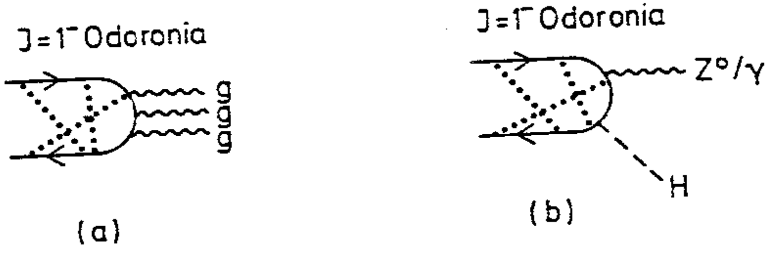

Fig 13: Odoronia decays in the Glashow scheme

In particular, Kane and Maiani estimate that for every Odoronia induced monojet there should exist both an e^+e^- and a $\mu^+\mu^-$ direct Odoronia decay. These, as yet unseen high mass dilepton events, are a powerful constraint on the whole scheme.

5. Concluding Remarks

The $Sp\bar{p}S$ collider has confirmed important predictions of the standard model, concerning the existence of W and Z bosons with specifically predicted masses. At the same time, in the last year, experiments at the collider have produced a set of tantalyzing events, which appear to be difficult to explain conventionally. The prudent attitude would be to wait until the Fall run of the collider is completed, to see better which of the various phenomena are confirmed and which are rendered moot. Maybe then it will become clear if there is indeed some new physics. My own feeling is that it is unlikely that all the phenomena observed will quietly fade away. There is some new physics here, although it is difficult to clearly identify its sources. Indeed, the impression that emerges from looking at all the various theoretical explanations is that nothing really fits all phenomena terribly well. So before a really coherent picture emerges it will be necessary that some of the exotica should fade away and some become even more prevalent. The results of the Fall run at the $Sp\bar{p}S$ collider are awaited with baited breath.

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