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W + 1 jet to W + 0 jet Ratio at the Tevatron: A Hint of New Physics?

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ABSTRACT

We interpret the reported disagreement between the measured ratio, R_{10} , of the W + 1 jet crosssection to the W + 0 jet cross-section at the Tevatron and the Standard Model (SM) prediction, as the effect of interactions mediated by a colour-octet analogue of the W boson, the W_8 . The presence of a W_8 with mass $\mathcal{O}(300)$ GeV, and with couplings to quarks and gluons of the order of electroweak strength, allows the observations of the D0 collaboration to be reproduced quite accurately. Such an interaction is not in contradiction with the present CDF data on $W^+W^$ or dijet production, though higher luminosities may reveal measurable effects.

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Among the various physics programmes at hadron colliders, studies of the production of W+jet(s) have attracted considerable interest since this is an important testing ground for next-toleading order (NLO) QCD corrections to the Drell-Yan process [1]. One particular observable in this context is the ratio, R_{10} , of the W + 1 jet cross-section to the W + 0 jet cross-section. As several systematic effects tend to cancel in the ratio, R_{10} seems likely to yield a clean measurement of the strong coupling constant α_s . It was with this motivation that the ratio was originally measured by the UA1 and UA2 collaborations [2] at the CERN $Sp\bar{p}S$ collider at a centre-ofmass energy of 630 GeV. At the Tevatron, operating at the much higher centre-of-mass energy of 1.8 TeV, the D0 collaboration has carried out a more precise determination [3] of this ratio and finds that, in fact, the measured quantity has very little dependence on α_s . With hindsight, this paradox can be attributed to the fact that the variation with α_s of the parton-level cross-section for W + jet(s) is compensated by an opposite variation in the gluon distribution within the proton. Although this weak dependence on α_s defeats the original motivation for studying R_{10} , it turns out, rather surprisingly, that there is a large mismatch between the experimental result at the Tevatron and theoretical predictions of W + jet(s) production from NLO QCD calculations incorporated in the DYRAD Monte Carlo program [1]. The discrepancy is well above three or even four standard deviations for most of the kinematic range studied (except in the region of very large transverse momentum of the jet where the errors are large). A difference of this magnitude between the theoretical prediction and the experimental data cannot be accounted for by variation of α_s and may thus be said to constitute an ' R_{10} -anomaly'. It is only fair to mention, however, that similar studies reported recently by the CDF Collaboration [4] are consistent with QCD predictions and show no signs of anomalous behaviour.

While so large a discrepancy has been reported only recently, a modest excess in the experimentally measured R_{10} over the theoretical prediction has been consistently reported by the D0 Collaboration for some time [5]. Earlier errors being large, however, this excess (which was at the level of two standard deviations or less) was of marginal significance and an explanation could perhaps be given in terms of the uncertainty in the theoretical predictions resulting from the lack of precise knowledge of the gluon flux. An additional complication arises because gluon distributions are not the only source of theoretical uncertainty in the QCD predictions — both the experimental determination and the theoretical prediction of R_{10} depend on the proper definition of a jet via some 'standard' algorithm. This immediately makes the result susceptible to effects associated with the soft physics of jets. Resummation of the soft radiation could possibly lead to significant effects — an issue addressed recently by Balazs and Yuan [6], who present an estimate based on a Collins-Soper-Sterman-type [7] resummation calculation. Unfortunately, the magnitude of this effect is small even when compared to the earlier 2σ disagreement [4, 5] and cannot be held to explain the current large excess [3]. Another feature of their calculation is that the effects of soft gluon radiation, not surprisingly, are dependent on the jet transverse energy E_T , and tend to be more pronounced at the smaller end of the E_T spectrum. The observed discrepancy, however, is equally significant over the entire range of E_T^{\min} , the minimum required transverse energy of the jet, (see Fig. 1). The highest E_T^{\min} bins have larger errors, of course, but even in this region the discrepancy is substantial and it is rather improbable that the effect at such high values of E_T should owe its existence to soft gluon radiation.

In view of the above remarks it is difficult to see how the ' R_{10} -anomaly' can be explained in the SM and one is thus tempted to consider it an indication for new physics beyond the SM. This is strengthened by the obvious fact that the Tevatron probes a hitherto-unexplored kinematic region, one not accessible to the CERN $Sp\bar{p}S$ collider. One candidate that immediately suggests itself [8, 9, 10] is the colour-octet analogue of the W^{\pm} boson, which we denote W_8^{\pm} . Such objects are predicted in a whole class of composite models, wherein the known fermions and bosons are assumed to be composed of more elementary constituents [11] called preons. Consider, for example, the *haplon* model of Fritzsch and Mandelbaum [12], which has both spin- $\frac{1}{2}$ and scalar preons transforming under the gauge group $SU(3)_c \times U(1)_{em} \times G_H$, where $G_H (\equiv U(1), SU(N))$ is a local 'hypercolour' symmetry. Isospin is no longer a local gauge symmetry and the weak interaction is interpreted as a residual van der Waals-type force. The matter content is given by two spinors $\alpha(3, -\frac{1}{2}, N)$ and $\beta(3, \frac{1}{2}, N)$ and two scalars $x(3, -\frac{1}{6}, \bar{N})$ and $y(\bar{3}, \frac{1}{2}, \bar{N})$. The SM particles are composed of two preons each and are held together by the hypergluons. Specifically, the W^+ is now nothing but the colour singlet¹ $\bar{\alpha}\beta$. Clearly, a colour-octet partner of the W^+ naturally exists in this model.

The haplon model is, of course, only one example of a preonic model. Even in the simplest version of the Pati-Salam model [11], a W_8 exists as a bound state of two scalar 'chromons'. Similarly the *rishon* models [13] also predict a W_8 . A complete survey of these models may be found in Ref. [14]. In this letter, we do not attempt to study the specific properties of preonic models in detail. We simply invoke these to point out that there *exist* well-known composite models with (possibly light) colour-octet analogues of the W boson. Our chief concern is to study the implications of such a particle for measurements leading to the ratio R_{10} . With this rather modest aim in view, it is sufficient to parametrize the effective couplings of a W_8 following Gounaris and Nicolaidis [8]:

$$\mathcal{L}_{1} = -\frac{g_{8}}{\sqrt{2}} \mathcal{W}_{\mu a}^{+} \bar{u}_{L} \gamma^{\mu} \frac{\lambda_{a}}{2} d_{L} + \text{h.c.}$$

$$\mathcal{L}_{2} = -g_{B} \mathcal{W}_{\mu}^{+} \mathcal{W}_{\nu a}^{-} G_{a}^{\mu \nu} - g_{B}^{\prime} \epsilon^{\mu \nu \lambda \sigma} \mathcal{W}_{\mu}^{+} \mathcal{W}_{\nu a}^{-} G_{\lambda \sigma a} + \text{h.c.}$$

$$(1)$$

where $a = 1, \ldots, 8$ and $G^{\lambda \sigma a}$ represents the gluon field-strength tensor. The term \mathcal{L}_2 represents the interaction of the W_8 with a W and a gluon via a parity-conserving term with coupling g_B and a parity-violating term with coupling g'_B respectively. Since these couplings arise in effective interactions, it is also of interest to consider how they scale with increase in the centreof-mass energy of the process under consideration, especially as one approaches the scale of the underlying new physics. To account for such effects without calculating them in a specific model, we assume that the coupling constants scale as

$$g_8(Q^2) = g_8(0) \left[1 + \frac{Q^2}{\Lambda^2}\right]^{-n}$$
 (2)

and similarly for g_B, g'_B , where the scaling index n = 0, 1, 2, ... and Λ is the compositeness scale $(\mathcal{O}(1) \text{ TeV})$.

We can now calculate various processes involving the W_8 . Within the SM, a W+ jet final state can occur due to either $q\bar{q}' \rightarrow Wg$ or $qg \rightarrow q'W$. The presence of W_8 simply introduces an *s*-channel diagram in the first case and a *t*-channel one in the second. The parton-level

¹It is argued that the corresponding lightest scalar states are heavier [12].

cross-section for the process $u\bar{d} \to W^+g$ can be expressed as

$$\frac{d\hat{\sigma}}{d\hat{t}}(u\bar{d} \to W^{+}g) = \frac{1}{16\pi\hat{s}^{2}} \left[T_{SM} + T_{W8} + T_{int}\right]
T_{SM} = \frac{2g^{2}g_{s}^{2}}{9} \left[\frac{\hat{t}^{2} + \hat{u}^{2} + 2M_{W}^{2}\hat{s}}{\hat{t}\hat{u}}\right]
T_{W8} = \frac{g_{8}^{2}(g_{B}^{2} + 4g_{B}')}{9M_{W}^{2}} \left[\frac{(\hat{s} + 2M_{W}^{2})(\hat{t}^{2} + \hat{u}^{2})}{(\hat{s} - M_{8}^{2})^{2} + (M_{8}\Gamma_{8})^{2}}\right]
T_{int} = -\frac{4gg_{s}g_{8}}{9} \left[\frac{g_{B}M_{8}\Gamma_{8}(\hat{s} - M_{W}^{2}) - 2g'_{B}(\hat{s} + M_{W}^{2})(\hat{s} - M_{8}^{2})}{(\hat{s} - M_{8}^{2})^{2} + (M_{8}\Gamma_{8})^{2}}\right],$$
(3)

with the decay width Γ_8 given by

$$\Gamma_{8} = \sum_{i} \Gamma(W_{8} \to u_{i}\bar{d}_{i}) + \Gamma(W_{8} \to Wg)$$

$$\Gamma(W_{8} \to u\bar{d}) = \frac{g_{8}^{2}M_{8}}{192\pi} \left[2 - (x_{u} + x_{d}) - (x_{u} - x_{d})^{2}\right] \lambda(1, x_{u}, x_{d}) \qquad (4)$$

$$\Gamma(W_{8} \to Wg) = \frac{g_{B}^{2} + 4g_{B}^{\prime 2}}{96\pi} M_{8} (1 - x_{W})^{3} \left(1 + \frac{1}{x_{W}}\right) ,$$

where $\lambda(a, b, c) \equiv \sqrt{(a - b - c)^2 - 4bc}$ and $x_i \equiv m_i^2/M_8^2$. The LO cross-section(s) for the process(es) $qg \to q'W^+$ can be obtained from eq.(3) simply by exploiting the crossing symmetry.

In order to obtain the hadron-level cross-sections, these formulae need to be convoluted with the corresponding parton densities in the incoming proton-antiproton pair. We do this by using the CTEQ3M [15] distributions, which were calculated using the package PDFLIB [16].

To identify the W, the D0 experiment has used the $e\nu$ decay channel [3, 5]. The final state thus consists of a hard electron accompanied by large missing energy and one or more jets. The angular coverage and the energy threshold of the hadronic calorimeter requires that

$$E_{\rm jet} \ge 20 \,\mathrm{GeV}, \qquad |\eta_{\rm jet}| < 4$$
, (5)

for a jet to be identified as one. Here η refers to the pseudorapidity. For the purpose of this measurement, the experiment concentrated on relatively central but hard electrons with

$$p_T(e) \ge 25 \text{ GeV}, \qquad |\eta_e| < 1.1$$
 (6)

Further, the electron was required to be isolated from the jet(s) by imposing a fixed cone algorithm with angular separation between the electron and any jet

$$\Delta R \equiv \sqrt{(\delta\eta)^2 + (\delta\phi)^2} > 0.4 , \qquad (7)$$

where $\delta \phi$ is the difference in the azimuthal angles. Events with more than one electron track passing the above selection criteria were removed to eliminate background from Z decays. And finally, an event was required to have a minimum missing transverse momentum:

$$p_T > 25 \,\text{GeV} \ . \tag{8}$$

Using a set of cuts closely modelled on the above, we make a parton-level Monte Carlo estimate of the value of R_{10} in the presence of the W_8 . For this purpose, we use the NLO results

for the SM contribution, but only the LO results of Eq.(3) for the additional contribution due to the W_8 . The numerical results are presented in Fig.1 As a guide we refer once again to the haplon model [12] and note that it predicts $M_8 - M_W \sim \alpha_s \Lambda$ which immediately leads to $M_8 \sim 200-300$ GeV.



Figure 1: Ratio of W+1 jet to W+0 jet production cross-sections at the Tevatron in the presence of a W_8 with $g'_B = 0$. E_T^{min} (jet) represents the cut on minimum transverse energy of the jet. The SM plus W_8 (LO) results are shown for (a) three illustrative values of M_8 (marked, in GeV) and scale-independent couplings g_B and g_8 ; (b) $M_8 = 300 \text{ GeV}$ and form-factor exponents (Eq.2) n = 0, 2. The form-factor is assumed to be identical for both g_B and g_8 , and the compositeness scale is taken as $\Lambda = 1$ TeV.

Now, a change in E_T^{\min} , the minimum hadronic transverse energy required of an event, is expected to lead to a strong variation in R_{10} . This is especially true of the SM contribution as the radiated jets are predominantly soft. We note that the W + 0 jet cross-section receives a substantial contribution from W + 1 (or more) jet events where the jet fails to satisfy the selection criteria.

In Fig. 1, we illustrate the effect of a W_8 with typical values of the mass $M_8 = 250, 300$ and 350 GeV. These are shown by solid lines, to be compared with the SM prediction (dotted line) and the D0 data with 1σ error bars. For this figure, we assume the couplings to have no scale-dependence, *i.e.* n = 0, and that there is no parity violation in the gWW_8 coupling, *i.e.* $g'_B = 0$. It may be observed that we now have a fairly good agreement with the data within the errors for $M_8 = 300$ GeV, while the other values lead to cross-sections which are too large or too small, as the case may be. However, this is not very restrictive, since the cross-sections scale as the couplings g_8, g_B . Figure 1b illustrates the effect of considering a form-factor-like behaviour of the couplings with n = 2 while the n = 0 case is also shown for comparison. Clearly, for $n = 2, M_8 = 300$ GeV is no longer a suitable choice; $M_8 \sim 250$ GeV appears to be a better choice. With the present state of our knowledge of the masses, couplings and scale-dependence, however, it is hard to be more specific than to say that couplings of electroweak strength and $M_8 = 300 \pm 100$ GeV might explain the observed discrepancy.

A closer look at Fig. 1 will reveal that although the relevant solid curve fits the data within the errors, there is still room for improvement. This is because the curve is somewhat flatter than

the general trend of the data seems to indicate. One possible remedy might be to consider a nonvanishing g'_B , which means a parity-violating gWW_8 interaction. In Fig. 2 we have illustrated the effect of this for the combinations

(a)
$$g_8 = g$$
, $g_B = 0$, $g'_B = g/2$,
(b) $g_8 = g$, $g_B = 0$, $g'_B = -g/2$,
(c) $g_8 = g/2$, $g_B = g$, $g'_B = g/2$,
(d) $g_8 = g/2$, $g_B = g$, $g'_B = -g/2$

and for suitably chosen values of the mass M_8 in the range 200–400 GeV. A close look will reveal that the shape of the curve(s) changes and now resembles the trend of the data more accurately, although it is difficult to find a combination of masses and couplings that will fit every single



Figure 2: As in Fig.1 but for various combinations of g_B and g'_B . Couplings are assumed to be scale-invariant.

data point within 1σ without resorting to rather fine tuning. At the present level of accuracy, this may not even be desirable, so we can only conclude that the data may contain a hint of non-vanishing g'_B interactions. It is also noteworthy that higher-order corrections to the W_8 induced diagrams will tend to change the shape of the curves and, in particular, it is plausible that soft-gluon resummation effects in the W_8 -induced diagrams will tend to make the low- E_T part of the spectrum steeper than the behaviour shown by the LO results presented here. The question of g'_B interactions remains, therefore, an open one.

As the above comments show, a colour-octet W_8 boson with requisite masses and couplings may be the answer to the excess in W + 1 jet events seen by the D0 Collaboration at the Tevatron. We must now consider the possibility that a new interaction of this nature may have observable consequences in other experiments. Perhaps the most obvious ones to suggest are low-energy measurements of flavour-changing neutral current (FCNC) processes such as neutral meson mixing and rare K and B meson decays. These would be affected if the current in Eq.(1) contained two quark fields of different flavours with a mixing angle factor, as indeed seems quite natural since the colour-singlet current must have this feature. Even if we assume that the mixing elements in the octet sector are of the same size as those in the singlet sector, it is easy to see that the additional contributions to Δm_K or Δm_B are well below the SM values for the parameter ranges of interest. Furthermore, (a) the mixing angles appearing in the colour-octet W_8 interactions need not always be identical with the Cabbibo-Kobayashi-Maskawa matrix [10] and (b) there could be other contributions to FCNC amplitudes from exotics such as colour sextet quarks. Thus, FCNC processes are unlikely to yield definitive constraints on W_8 interactions and we do not consider them any further.

We also need to consider possible constraints from the electroweak precision variables as measured at LEP. The decay $Z \to b\bar{b}$ giving rise to the well-measured parameter R_b is the simplest process to be affected through vertex corrections involving a W_8 . These do not require flavour-changing vertices and hence cannot be wished away. If the only interactions given in the theory are those given by Eq.(1), then, indeed, one can obtain fairly stringent constraints on the coupling g_8 . However, great caution needs to be exercised in such an attempt since Eq.(1) is evidently not the whole story. By itself, it would give a divergent contribution to R_b and both the other relevant interactions (*e.g.*, ZW_8W_8) and particles (*e.g.*, Z_8) in the model have to be considered for a definitive statement to be made. Similar arguments also hold for the ρ parameter². With so many free parameters (although they are calculable in principle, assuming one can handle the dynamics of preonic interactions) and mutually cancelling contributions, it seems a phenomenologically sound procedure to ignore the R_b constraint altogether, and this is what has been done in the present study. It must be pointed out, though, that the naive bounds may be evaded by simply scaling down g_8 and compensating the effect by scaling up g_B (g'_B).

It might seem, from the above discussion, that models with colour-octet W_8 bosons are difficult to pin down because of a plethora of unknown particles and parameters which can be varied at will. Does this mean that the W_8 solution of the R_{10} anomaly loses the prime virtue of falsifiability? Fortunately, the answer is, No. At the Tevatron itself, one can check for processes involving the g_8 and $g_B(g'_B)$ couplings *separately* (and no others). In principle, non-observation of both would rule out the solution suggested in this letter since, as explained above, one can tolerate a reduction in one or the other, but not in both. We thus turn to a discussion of other observables at the Tevatron.

In $p\bar{p}$ collisions at 1.8 TeV, a 250–300 GeV W_8 would naturally contribute to processes of the form $q_1\bar{q}'_2 \rightarrow q_3\bar{q}'_4$ resulting in a possible enhancement of dijet rates at the Tevatron [18, 19]. As in the case of W + 1 jet production, the leading W_8 contribution arises from the resonance diagram, and hence, it is instructive to concentrate on it. Once produced, the W_8 can decay into either of dijet or the gW channel, with the relative branching fractions given by Eq.(4).

²Direct preonic contributions can also be relevant, although the numbers depend rather strongly on the preon dynamics [17].

To appreciate the CDF bounds on new particles decaying into dijets [19], let us compare the production rate for W_8 with that of a W' in an extended gauge model. It is easy to see that, for identical mass and coupling,

$$\sigma(p\bar{p} \xrightarrow{W_8} u\bar{d} + X) = \frac{2}{9} \sigma(p\bar{p} \xrightarrow{W'} u\bar{d} + X).$$

Thus, the enhancement in the dijet rate is well below the constraints of Fig.3 of Ref. [19] for $g_8 \approx g$. However, as the statistics improve with time, we can expect an improvement in this constraint.

Another immediate consequence of the Lagrangian of Eq.(1) is that the process $gg \to W^+W^$ is now allowed at the tree-level through *t*- and *u*-channel exchange of the W_8 . The corresponding differential cross section is given by

$$\begin{aligned} \frac{d\hat{\sigma}}{d\hat{t}}(gg \to W^+W^-) &= \frac{\pi}{\hat{s}^2} \left(\frac{g_B^2 + 4g_B^2}{16M_W^2 M_8^2}\right)^2 \left[\frac{f(\hat{t})}{(\hat{t} - M_8^2)^2} + \frac{f(\hat{t}, \hat{u})}{(\hat{t} - M_8^2)(\hat{u} - M_8^2)} + (\hat{t} \leftrightarrow \hat{u})\right] \\ f(\hat{t}) &\equiv M_8^4 \hat{t}^2 (2\hat{s}^2 + 2\hat{s}\hat{t} + \hat{t}^2) - 4M_W^2 M_8^4 \hat{t} (2\hat{s}^2 + 3\hat{s}\hat{t} + \hat{t}^2) \\ &+ 2M_W^4 \left[\hat{t}^2 (4M_8^2 \hat{s} + \hat{t}^2) + M_8^4 (4\hat{s}^2 + 9\hat{s}\hat{t} + 3\hat{t}^2)\right] \\ &- 4M_W^6 \left[M_8^4 (2\hat{s} + \hat{t}) + 4M_8^2 \hat{s}\hat{t} + 2\hat{t}^3\right] \\ &+ M_W^8 (M_8^4 + 8M_8^2 \hat{s} + 12\hat{t}^2) - 8M_W^{10}\hat{t} + 2M_W^{12} \end{aligned} \tag{9}$$

$$f(\hat{t}, \hat{u}) &\equiv M_8^4 \hat{t} \hat{u}(\hat{t}^2 + 3\hat{t}\hat{u} + \hat{u}^2) - 4M_W^2 M_8^4 \hat{t} \hat{u}(\hat{t} + \hat{u}) \\ &+ M_W^4 \left[\hat{t}^2 \hat{u}^2 + M_8^4 \left\{4(\hat{t}^2 + \hat{u}^2) + 10\hat{t}\hat{u}\right\}\right] \\ &+ 8M_W^6 M_8^2 (\hat{t} + \hat{u})(\hat{t} + \hat{u} - 2M_8^2) \\ &+ M_W^8 \left[17M_8^4 + \hat{t}^2 + \hat{u}^2 - 8M_8^2 (\hat{t} + \hat{u})\right] \\ &- 4M_W^{10} (\hat{t} + \hat{u}) + 5M_W^{12} . \end{aligned}$$

Consequently, one may expect to see deviations in the W-pair cross-section as measured at the Tevatron from the SM predictions. In Fig.3, we present the variation of the total cross section as a function of the W_8 mass for $g_B^2 + 4g_B'^2 = g^2$. For smaller values of M_8 , the deviation is quite significant and this effect could thus serve as a discriminant for our explanation of the W + 1 jet excess. However, in view of the large statistical errors in the measurement [20], we are still some way from a definitive statement.

It is interesting to note that the cross-section in Eq.(9) grows with the energy. This is a reflection of the lack of SU(2) gauge invariance in the theory and of the underlying compositeness. This energy behaviour can be cured either by postulating an energy-dependence of the couplings (see Eq.(2) and Fig. 3) or through the introduction of a Z_8 with the right couplings.

To summarise, then, the reported discrepancy between the experimental determination of the ratio R_{10} and the SM prediction seems to be of a magnitude not easily explicable in terms of conventional effects such as soft-gluon resummation. If the discrepancy persists even after more careful analyses have been done and more data are available, then it is very likely to be due to some new physics. The fact that this effect shows up at energies close to the electroweak scale suggests that the mechanism of electroweak symmetry-breaking may be intimately linked to the



Figure 3: W^+W^- production cross-section at the Tevatron as a function of M_8 . For the W_8 mediated process, only the LO contribution has been included while the NLO result for the SM has been taken from Ref.[21]. The three solid curves correspond to three different values of the form-factor exponent (Eq. 2) n = 0, 1, 2. The dotted line corresponds to the SM value, while dashes give the experimental central value and the 1σ upper bound from CDF [20].

physics of strong interactions. Such an interpretation is also viable in the context of the recently discovered large- Q^2 anomaly at HERA [22], and has been investigated in a number of recent theoretical papers [23]. It is interesting to note that the haplon model, among others, predicts a light leptoquark state $(\bar{x}y)$ with quantum numbers $(3, \frac{2}{3}, 1)$ which will decay into either of an e^+d or a νu final state — this is just the kind of new particle that seems to be indicated by the HERA high- Q^2 anomaly. While the HERA issue is still a debatable one, it is undoubtedly true that in some of the well-known composite models, colour-octet incarnations of the W boson are predicted; we find that the inclusion of these coloured bosons through the effective interactions given above helps resolve the discrepancy between the data and theory. The mass of the W_8 required for an agreement with the data is in excess of 250 GeV, which might explain why its effects have not yet been seen in other experiments. The results presented in this paper suggest that the time is ripe to carry out a detailed, global analysis of the data from the LEP and the Tevatron to study if there are other manifestations of this kind of new physics. It is just possible that we are standing at the threshold of a new era of sub-quark and sub-lepton physics which is just beginning to show up in deviations from the SM at the edge of the kinematic range studied till now. We can thus look forward to an exciting period as as more data are acquired and analysed at the running high-energy experiments.

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