IC/77/88

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

DILEPTON PRODUCTION IN PP AND $\overline{P}P$ COLLISIONS AS A PROBE TO THE NATURE OF THE NEUTRAL CURRENT INTERACTION

H.S. Mani

Jogesh C. Pati

Subhash Rajpoot

and

Abdus Salam

INTERNATIONAL ATOMIC ENERGY AGENCY

UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

1977 MIRAMARE-TRIESTE

IC/77/88

International Atomic Energy Agency
and
United Nations Educational Scientific and Cultural Organization

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

DILEPTON PRODUCTION IN PP AND $\bar{\text{P}}$P COLLISIONS AS A PROBE TO THE NATURE OF THE NEUTRAL CURRENT INTERACTION *

H.S. Mani
International Centre for Theoretical Physics, Trieste, Italy,
and
Indian Institute of Technology, Kanpur 208016, India,

Jogesh C. Pati **
Department of Physics, University of Maryland, College Park, Md., USA.
and
International Centre for Theoretical Physics, Trieste, Italy,

Subhash Rajpoot and Abdus Salam
International Centre for Theoretical Physics, Trieste, Italy,
and
Imperial College, London, England.

ABSTRACT

The dilepton production and the asymmetry parameters in PP and $\bar{\text{P}}$P collisions including the effects of neutral currents are calculated in the $SU_L(2) \times SU_R(2) \times U_{L+R}(1)$ theory.

MIRAMARE – TRIESTE
August 1977

* To be submitted for publication.

** Supported in part by National Science Foundation Grant No.GP43362X.
Address from 1 September 1977: Department of Physics, University of Maryland,

I. The near null results of atomic parity violation experiments [1], taken at their face value, appear to suggest that the underlying low-energy limit of the unified theory of weak and electromagnetic interactions may be the left-right symmetric [2] $SU_L(2) \times SU_R(2) \times U_{L+R}(1)$ theory rather than its left-handed limit $SU_L(2) \times U(1)$. [3] The left-right symmetric theory displays the interesting feature that one of its two neutral gauge bosons may be reasonably light - of the order of 50-70 GeV in mass (corresponding to Q_W for Bismuth of order + 130 and zero, respectively) - to be compared to neutral mass for $SU_L(2) \times U(1)$ of order 80 GeV (corresponding to $Q_W \approx -130$ and $\sin^2\theta_W \approx 0.28$). In view of this lower mass possibility and in view of the proton-proton and proton-anti-proton accelerators being projected, it is of interest to examine the cross-sections and asymmetries in reactions like $P + P \to \mu^+ + \mu^- + X$, $P + \bar{P} \to \mu^+ + \mu^- + X$ with a view to distinguishing between the two theories [4]. In this note we calculate (1) $\frac{d\sigma}{dm_{\mu\mu}}$, where $m_{\mu\mu}$ is the invariant mass of $(\mu^+\mu^-)$ pair; (2) the energy asymmetry $\langle\Delta E\rangle = \langle E_+\rangle - \langle E_-\rangle$ and the related ratio

$$\Delta N/N = (n(E_+ > E_-) - n(E_- > E_+))/(n(E_+ > E_-) + n(E_- > E_+)) \quad ,$$

where E_+ and E_- refer to the energies of μ^+ and μ^- from the same event, in PP collisions and finally (3) forward-backward asymmetry $A_{\mu\mu} = (N_f - N_b)/(N_f + N_b)$ in $\bar{\text{P}}$P , where N_f and N_b refer to the numbers of μ^+'s travelling in the forward or the backward hemisphere relative to $\bar{P}$.

II. In the $SU_L(2) \times SU_R(2) \times U_{L+R}(1)$ theory, $\mathcal{L}_{effective}$ for weak neutral currents of muons, arising due to the exchange of neutral vector bosons N_1 and N_2 is

$$-\mathcal{L}_{eff} = (\bar{\mu}\gamma_\mu\mu)\,(G^p_{VV}\,\bar{p}\gamma_\mu p + G^p_{VA}\,\bar{p}\gamma_\mu\gamma_5 p) + (\bar{\mu}\gamma_\mu\gamma_5\mu)\,(G^p_{AV}\,\bar{p}\gamma_\mu p + G^p_{AA}\,\bar{p}\gamma_\mu\gamma_5 p)$$
$$+ \text{ similar terms for } n + (p \leftrightarrow c + n \leftrightarrow \lambda) \quad .$$

Here p,n,λ,c refer to quarks. The eight functions $G^p_{VV},\ldots$, etc. are given in terms of the masses m_{N_1} and m_{N_2} of the neutral gauge bosons and the square of the momentum transfer $q^2 \equiv m^2_{\mu\mu}$ by the expressions [5]:

$$\left[(3r+1)/(1-r)(3r-1)\right] G^p_{VV}(q^2) = -\left[(3r+1)/(1+r)(3r-1)\right] G^n_{VV} =$$

$$(G_F/\sqrt{2}) \left[D_1(q^2)\sin^2\beta + D_2(q^2)\cos^2\beta\right] \; ; \quad G^p_{VA} = -G^n_{VA} =$$

$$-(G_F/\sqrt{2}) \left\{(3r-1)/2(3r+1)^{\frac{1}{2}}\right\} \sin 2\beta \left[D_2(q)^2 - D_1(q^2)\right] \; ;$$

$$\left[2(3r+1)^{\frac{1}{2}}/(1-r)\right] G^p_{AV} = -\left[2(3r+1)^{\frac{1}{2}}/(1+r)\right] G^n_{AV}$$

$$= (G_F/\sqrt{2}) \sin 2\beta \, (D_2(q^2) - D_1(q^2)) \; ; \quad G^p_{AA} = -G^n_{AA} =$$

$$-(G_F/\sqrt{2}) \left[D_1(q^2)\cos^2\beta + D_2(q^2)\sin^2\beta\right] \; ;$$

$$D_{1,2}(q^2) = m^2_{W^+_L}/(q^2 - m^2_{N_{1,2}} + i m^2_{N,2}\Gamma_{1,2})$$

r and β are two parameters of the theory [5]; and we have assumed the widths $\Gamma_{1,2} \approx 1$ GeV. In terms of these functions, and assuming that the hadronic tensor entering the cross-sections is given by the Drell-Yan mechanism [6], the quantities computed in this note are given by the formula:

1) $$\frac{d\sigma}{dm_{\mu\mu}} = \frac{4\pi\alpha^2}{3m^2_{\mu\mu}} \tau \int_0^1 dx_1 \int_0^1 dx_2 \, \delta(x_1x_2 - \tau/s) \sum_{i = n,p,\lambda} f^i_A(x_1) \, f^i_B(x_2)$$

$$\left\{\left[q^i + (m^2_{\mu\mu}/e^2)\, G^i_{VV}(m^2_{\mu\mu})\right]^2 + (m^2_{\mu\mu}/e^2)\left[G^{i^2}_{VA} + G^{i^2}_{AV} + G^{i^2}_{AA}\right]\right\} .$$

Here q^i are quark charges, $f^i_A(x)$ is the quark structure function for the i^{th} quark in the particle A (A = P or $\bar{P}$) $\tau = (m^2_{\mu\mu}/s)$ and $\sqrt{s}$ is the centre-of-mass energy. The sum i extends over both quarks and anti-quarks.

2) Energy asymmetry for PP:

$$\left\{(d\sigma/dm_{\mu\mu}) \times (\langle E_+\rangle - \langle E_-\rangle)\right\} = -(\alpha\sqrt{\tau}/3) \sum_i \int_0^1 dx_1 \int_0^1 dx_2$$

$$\delta(x_1x_2 - \tau)\,(x_1 - x_2) \left[f^i_A(x_1)\, f^{\bar{i}}_B(x_2) + f^{\bar{i}}_A(x_2)\, f^i_B(x_1)\right] A_i(m^2_{\mu\mu}) \quad ,$$

where

$$A_i(m^2_{\mu\mu}) = \mathrm{Re}\left[G^i_{AA}(m^2_{\mu\mu})\,(q^i + G^i_{VV}(m^2_{\mu\mu}/e^2)) + (m^2_{\mu\mu}/e^2)\, G^{*i}_{AV}\, G^i_{VA}\right] ,$$

while (in turns out that)

$$\left[n(E_+ > E_-) - n(E_- > E_+)\right] \Big/ \left[n(E_+ > E_-) + n(E_- > E_+)\right] = 3/2 \left\{(\langle E_+\rangle - \langle E_-\rangle)/m_{\mu\mu}\right\} .$$

3) And finally for $\bar{P}P$ the forward-background asymmetry $A_{\mu\mu} = (N_f - N_b)/(N_f + N_b)$ is given by

$$2\alpha\tau/s \int_\tau^1 \frac{dx}{x} \frac{(x + \tau/x)}{[4\tau + (x - \tau/x)^2]^{3/2}} \times \sum_i \left[f^i_A(x)\, f^{\bar{i}}_B(\tfrac{\tau}{x}) - f^{\bar{i}}_A(\tfrac{\tau}{x})\, f^i_B(x)\right] \times A^i(m^2_{\mu\mu}) \quad .$$

Remarks

(A) For the quark structure functions, summed over three colours, we have taken [4] $s(x) = 0.15\,(1-x)^7/x = \bar{s}(x) = \bar{u}(x) = \bar{d}(x)$, $u(x) = 1.79\,(1-x)^3 \times (1 + 2.3x)/\sqrt{x} + s(x)$, $d(x) = 1.07\,(1-x)^{3.1}/\sqrt{x} + s(x)$.

(B) The energy asymmetry $\langle E_+\rangle - \langle E_-\rangle$ for PP has its origin in the presence of VV as well as AA interactions, such that the $(\mu^+\mu^-)$ pair is produced both in $C = -1$ as well as $C = +1$ eigenstates. The interference between these gives rise to the effect of energy asymmetry [7]. For the proton-anti-proton system, $f^{\bar{i}}_{\bar{P}}(x) = f^i_P(x)$, so that we obtain vanishing energy asymmetry between μ^+ and μ^- consistent with CP conservation.

(C) The forward-background asymmetry vanishes for the proton-proton system, since we are dealing here with identical particles.

III. In the accompanying figures 1, 2 and 3, the results of our calculations at $\sqrt{s}$ = 200 GeV are plotted, for a range of $m_{\mu\mu}$ lying between 30 and 100 GeV. The results are presented for three values of Q_W for Bismuth (Q_W = +138, Q_W = 0 and Q_W = 132). The last value of Q_W corresponds to the $SU_L(2) \times U(1)$ limit. The corresponding expected masses (m_{N_1}, m_{N_2}) in the theory are (55,96), (70,107) and (83,∞) GeV, respectively, when $\sin^2\theta_W = 0.28$ (i.e. $r = \frac{4}{9}$). For the range of $m_{\mu\mu}$ considered, we find numerically that $|G_{AA}(m^2_{\mu\mu})|$ predominates over the other functions $|G_{VV}|, |G_{AV}|$ and $|G_{VA}|$ by one to two orders of magnitude, so that the function $A_i(m^2_{\mu\mu})$ occurring in the asymmetry expressions has the characteristic form:

$$\cos^2\beta\left(m^2_{\mu\mu} - m^2_{N_1}\right)\Big/\left([m^2_{\mu\mu} - m^2_{N_1}]^2 + m^2_{N_1}\Gamma^2_1\right) + \sin^2\beta\left(m^2_{\mu\mu} - m^2_{N_2}\right)\Big/\left[(m^2_{\mu\mu} - m^2_{N_2})^2 + m^2_{N_2}\Gamma^2_2\right].$$

For small β, $A_i(m^2_{\mu\mu}) \approx 0$ for $m_{\mu\mu} = m_{N_1}$. It changes sign around this point and with it the asymmetries. The noteworthy features of the results are:

i) There are the characteristic - rather high peaks (three orders of magnitude) which are rather broad at the base (≈25 GeV wide) - in $\frac{d\sigma}{dm_{\mu\mu}}$. As expected, these arecentered at m_{N_1}. Note the manner in which the purely electromagnetic values of the cross-section provide an asymptotic cushion on the lower side of the peaks. We have also computed $\frac{d\sigma}{dm_{\mu\mu}}$ for ISR energies, but find its magnitude rather small (≈4 × 10^{-40} cm^2/GeV for $m_{\mu\mu} \approx$ 30 GeV).

ii) The energy asymmetry in PP increases with energy from a few percent at $\sqrt{s} \approx$ 60 GeV to ≈ -15% for $\sqrt{s}$ = 400 GeV. It does not seem to rise above this value in the energy range considered.

iii) The angular asymmetry in $P\bar{P}$ is large, varying between 20% to -30% as $m_{\mu\mu}$ varies between 30 to 100 GeV at $\sqrt{s}$ = 200 GeV. This asymmetry is relatively large even at $\sqrt{s}$ = 60 GeV. For example, at $m_{\mu\mu} \approx$ 40 GeV, $A^{\mu\mu}$ = 0.45, 0.28 and 0.15 for Q_W = 138, 0 and -132, respectively. However,

the cross-section $\frac{d\sigma}{dm_{\mu\mu}}$ at $\sqrt{s}$ = 60 GeV is around 7 × 10^{-40} cm^2/GeV for $m_{\mu\mu}$ = 40 GeV. When $\sqrt{s}$ is increased to 400 GeV, $A_{\mu\mu}$ decreases and is down to levels between +10% and -10% for 30 < $m_{\mu\mu}$ < 100 GeV. It would thus appear that $\sqrt{s} \approx$ 200 GeV represents an optimum energy for this effect.

iv) We are aware that several important corrections to the Drell-Yan mechanism have been left out in this calculation. However, we belive that the qualitative features discussed here should be reliable.

ACKNOWLEDGMENTS

We would like to thank Drs. K. Maschke, S. Prakash and G. Alberi for their generous help in computations. One of us (H.S.M.)would like to acknowledge a conversation with T. Das. Three of us (H.S.M., S.R., and J.C.P.) would like to acknowledge the hospitality of the International Centre for Theoretical Physics, Trieste.

REFERENCES AND FOOTNOTES

1) F. Baird, et al. Nature 264, 529 (1976). We thank Drs. Baird and Sandars for early communication of their new results.

2) J.C. Pati and Abdus Salam, Phys. Rev. Letters 31, 661 (1973); ibid. Phys. Rev. D10, 275 (1974); J.C. Pati, S. Rajpoot and Abdus Salam, Imperial College, London, preprint ICTP/76/11. We use the notation of this paper. All the present $\nu_L(\bar{\nu}_R)$ data has been fitted in the chiral limit of $SU_L(2) \times SU_R(2) \times U(1)$ with r = 4/9 corresponding to $\sin^2\theta_W = 3r/(6r+2) = 0.28$, while $\tan 2\beta = (2\sqrt{3r+1}/r)\,[Q_W/(Q_W - 2Q_{W0})]$ (Q_{W0} is the limiting SU(2) × U(1) value for Q_W); H. Fritzsch and P. Minkowski, Nucl. Phys. B103, 61 (1976); R.N. Mohapatra and D.P.Sidhu, Phys. Rev. Letters 38, 667 (1971) and BNL preprint (22561). A. De Rujula, H. Georgi and S.L. Glashow, Harvard preprint 1977.

3) S. Weinberg, Phys. Rev. Letters 19, 1264 (1967); Abdus Salam in Elementary Particle Physics, Ed. N. Svartholm (Almquist and Wicksell, Stockholm 1968), p.367; S.L. Glashow, J. Iliopoulos and L. Maiani, Phys. Rev. D2, 1285 (1970). For earlier work see S.L. Glashow, Nucl. Phys. 22, 579 (1961) and Abdus Salam and J.C. Ward, Il Nuovo Cimento 11, 568 (1959); and Phys. Letters 13, 168 (1964).

4) Calculations based on SU(2) × U(1) has been done recently by Ronald F. Peierls, T.L. Trueman and Ling Lie Wang (see Ling Lie Wang, BNL-22661 preprint (1977)); L.B. Okun and M.B. Voloshin, Nucl. Phys. B120, 459 (1977).

5) J.C. Pati, S. Rajpoot and Abdus Salam, Imperial College, London, preprint ICTP/76/15.

6) S.D. Drell and T.M. Yan, Phys. Rev. Letters 25, 316 (1970) and Ann. Phys. (NY) 66, 578 (1971).

7) These effects are produced even if P and C are conserved. They are, for example, produced also by 2γ exchanges producing the $\mu^+\mu^-$ pair. These effects have been studied by R. Gatto and G. Preparata, Lettere al Nuovo Cimento 7, 89 (1973). We expect their magnitude for our energies to be small though they have not yet been fully calculated.

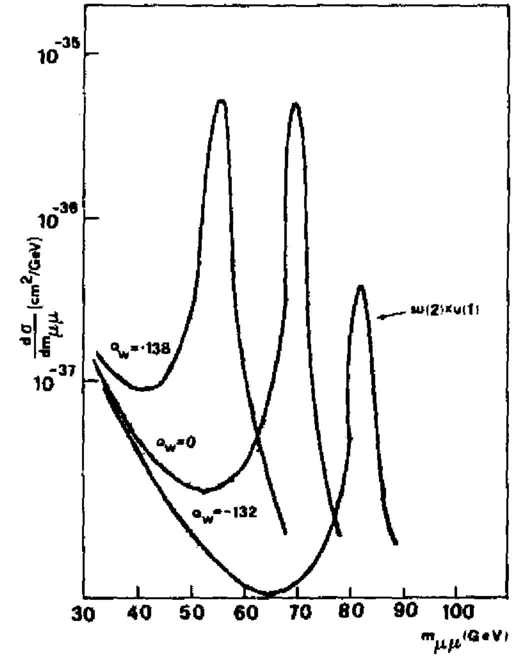

Fig.1

A plot of $\frac{d\sigma}{dm_{\mu\mu}}$ vs. $m_{\mu\mu}$ for $PP \to \mu^+\mu^- X$ ($\sqrt{s}$ = 200 GeV).

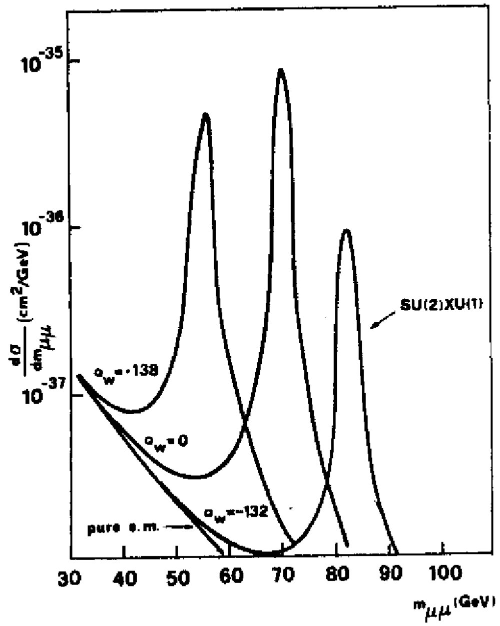

Fig.2

A plot of $\frac{d\sigma}{dm_{\mu\mu}}$ vs. $m_{\mu\mu}$ for $P\bar{P} \to \mu^+\mu^- X$ ($\sqrt{s}$ = 200 GeV).

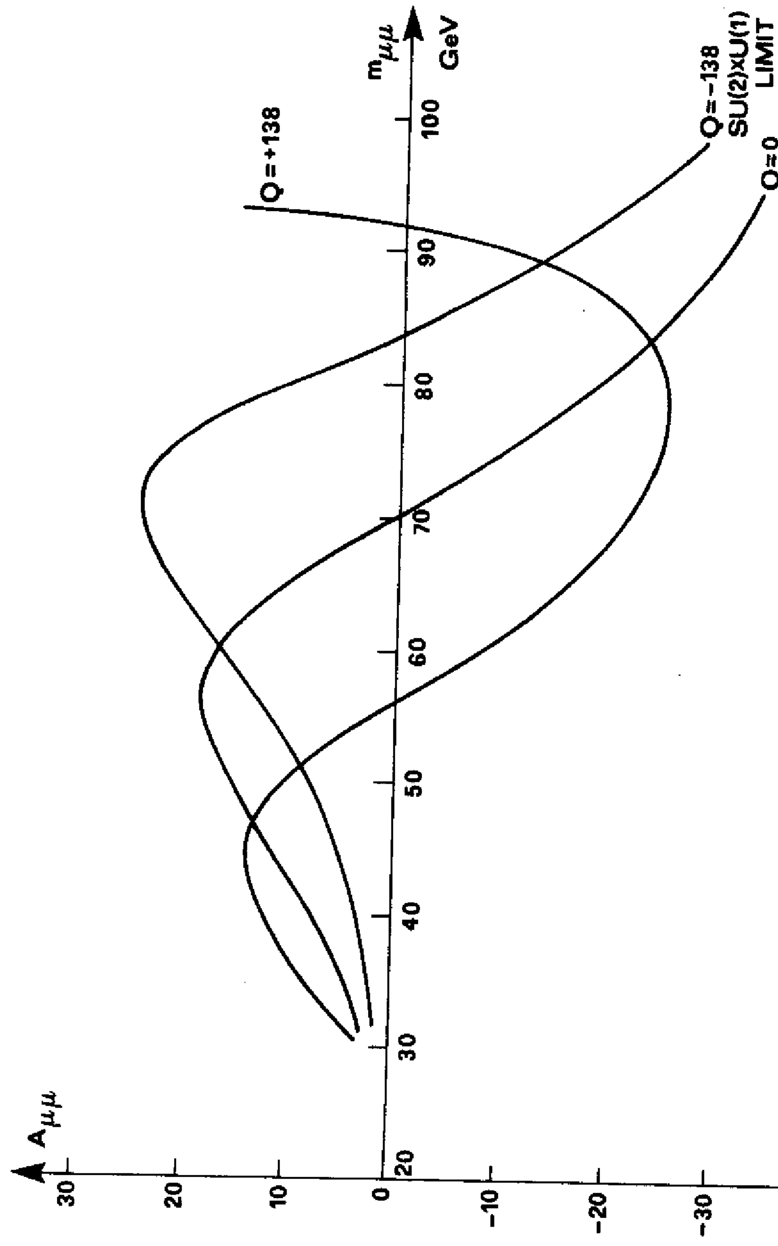

Fig.3

A plot of $A^{\mu\mu}$ vs. $m_{\mu\mu}$ for $P\bar{P} \to \mu^+\mu^- X$ ($\sqrt{s}$ = 200 GeV).