APPENDIX A

Producing Massive Neutral Intermediate Vector Bosons with Existing Accelerators(*)

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Abstract

We outline a scheme of searching for the massive weak boson ($M = 50 - 200$ GeV/c^2). An antiproton source is added either to the Fermilab or the CERN SPS machines to transform a conventional 400 GeV accelerator into a $p\bar{p}$ colliding beam facility with 800 GeV in the center of mass ($E_{eq} = 320{,}000$ GeV). Reliable estimates of production cross sections along with a high luminosity make the scheme feasible.

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The past ten years have seen remarkable progress in the understanding of weak interactions. First there is the experimental discovery of $\Delta S = 0$ weak neutral currents,[1] which when contrasted with the previous limits on $\Delta S = 1$ neutral current decay processes[2] leads to the suggestion of additional hadronic quantum numbers in nature.[3] Strong evidence now exists for new hadronic quantum numbers that are manifested either directly[4,5] or indirectly.[6] The experimental discoveries are complemented by the theoretical progress of unified gauge theories.[7,8] These developments lead to the expectation that very massive intermediate vector bosons (50 - 100 GeV/c^2) may exist in nature.[7,8] The search for these massive bosons require three separate elements to be successful: a reliable physical mechanism for production, very high center of mass energies, and an unambiguous experimental signature to observe them. In this note we outline a scheme which satisfies these requirements and that could be carried out with a relatively modest program at existing proton accelerators.

We first turn to the production process. We concentrate on neutral bosons because of the extremely simple experimental signature and because production is largely dominated by a single production resonant pole in the particle-antiparticle cross section. The best production reaction would of course be:

$$\begin{aligned} e^+ + e^- \to W^o &\to e^+ + e^- \\ &\to \mu^+ + \mu^- \\ &\to \text{hadrons} \end{aligned} \tag{1}$$

where a sharp resonance peak is expected for $2E_{e^+} = 2E_{e^-} = M$. In the

Breit-Wigner approximation near its maximum we get:

$$\sigma(e^+e^- \to W^o) \approx \frac{3}{4} \quad \pi\lambda\!\!\!^-{}^2 \frac{\Gamma_i \Gamma}{(2E - M)^2 + \frac{\Gamma^2}{4}} \tag{2}$$

where Γ_i, Γ are the partial width to the initial e^+e^- state and the total width, respectively. The decay widths into e^+e^- (and $\mu^+\mu^-$) pairs can be calculated in the first order of the semi-weak coupling constant: $\Gamma_{e^+e^\pm} \cong \Gamma_{\mu^+\mu^-} = 1.5 \times 10^{-7}\ M_W^3$ (GeV). For M = 100 GeV, $\Gamma_{e^+e^-} \approx 150$ MeV, which is surprisingly large. The total width is related to the above quantity by the branching ratio $B_{e^+e^-} = \Gamma_{e^+e^-}/\Gamma$ which is unknown. Crude guesses based on quark models suggest $B_{e^+e^-} \approx 1/10$, giving $\Gamma = 1.5$ GeV or $\Gamma/2E = 1.5\%$ for $M = 100$ GeV/c^2. At the peak of the resonance, $\sigma(e^+e^- \to W^o,\ 2E = M) = 3\pi\lambda\!\!\!^-{}^2\ B_i \approx 2.10^{-31}$ cm^2. Neutrino experiments[9] have found that $M_{W^+} > 20$ GeV/c^2. Therefore, if $M_{W^o} \sim M_{W^+}$, the neutral intermediate boson is out of reach of existing e^+e^- storage rings.

A more realistic production process is the one initiated by proton-antiproton collisions:

$$p + \bar{p} \to W^o + \text{(hadrons)}$$

which, according to the quark (parton) picture, proceeds by a reaction analog to (1), except that now incoming e^+ and e^- are replaced with q and $\bar{q}$. Strong support to the idea that W's are directly coupled to spin 1/2 point-like constituents comes from neutrino experiments[10] and from semi-leptonic hadron decays.[11] Furthermore neutrino experiments provide the necessary structure functions and have set limits[9] ($>$ 20 GeV) on any nonlocality in the parton form factor. The main difference with respect to e^+e^- is that now the kinematics is largely smeared out by the internal motion of q's and $\bar{q}$'s. The average center of mass energy squared of the q-$\bar{q}$ collision is roughly[12]:

$$< S_{q\bar{q}} > \sim S < x_q >_p < x_{\bar{q}} >_{\bar{p}p}$$

where S is the center of mass energy squared of the $\bar{p}p$ system and $< x_q >_p$ ($< x_{\bar{q}} >_{\bar{p}}$) is the mean fractional momentum of q's($\bar{q}$'s) in the proton (antiproton). From the neutrino measurements[9] and $< x_q >_p = < x_{\bar{q}} >_{\bar{p}}$ we find $< S_{q\bar{q}} > \sim 0.04$ S. For $M = 100$ GeV/c^2 this suggests $S \geq 2 \times 10^5$ GeV^2 or $\sqrt{S} \geq 450$ GeV. The production cross section can be evaluated by folding the (narrow) resonance (2) over the q and $\bar{q}$ momentum distributions:

$$\sigma(q\bar{q} \to W^o \to \mu^+\mu^-) = 3\pi\lambda\!\!\!^{-2} \frac{\Gamma_{q\bar{q}}}{\Gamma} \cdot \frac{\Gamma_{\mu\mu}}{\Gamma} \cdot \frac{dN}{dE} (E = M) \cdot 2\Gamma \qquad (3)$$

where $\frac{dN}{dE}$ is the probability (per unit of energy) of finding a $q\bar{q}$ collision with center of mass energy E, and the other symbols have the same meaning as in (2). Note that $\frac{\Gamma_{q\bar{q}}}{\Gamma} \simeq O(1)$ is a model-dependent parameter. The resultant cross section is $\sigma(p\bar{p} \to W^o + \text{hadrons} \to \mu^+ + \mu^- + \text{hadrons}) \simeq 6\pi\lambda\!\!\!^{-2} \frac{\Gamma_{q\bar{q}}}{\Gamma} \frac{dN}{dE} (E = M) \cdot \Gamma_{\mu\mu} \cong 10^{-32}$ cm^2. The numerical value is given for $M = 100$ GeV/c^2, $\sqrt{S} = 500$ GeV and $\frac{\Gamma_{q\bar{q}}}{\Gamma} = 1/2$. This derivation of the cross section exposes the basic simplicity of the assumptions and gives the order of magnitude of the expected cross section. More sophisticated calculations give similar results.[12] We note that calculations of $W^\pm$ production in proton-proton collisions are very uncertain in contrast to the present one due to the apparent small antiparton content in the nucleon and the unknown distributions of this component.[13]

We turn now to the question of the experimental observation.

The cleanest experimental signature for the program outlined here is:

$$\bar{p} + p \rightarrow W^{o} + \text{hadrons}$$
$$\hookrightarrow \mu^{+} + \mu^{-}$$

with the observation of a peak in the $\mu^{+}\mu^{-}$ invariant mass spectrum with the cross section of equation (3). A modest magnetized iron detector system is adequate to detect the high energy decay muons ($P_{\mu} \sim 50$ GeV) in the center of mass system. Electromagnetic production of $\mu^{+}\mu^{-}$ pairs is expected to be suppressed by a factor of $\tilde{\sim}\ (\alpha^{2}/G^{2}M_{W}^{4})$. Note that a similar suppression is expected to hold for any hadronic vector meson. Note also that the production and decay of charged vector bosons is more problematic since the decay sequence

$$\bar{p} + p \rightarrow W^{+} + X$$
$$\hookrightarrow \mu^{+} + \nu_{\mu}$$

leads to one muon and a missing neutrino which is difficult if not impossible to detect. In many previous discussions it has been assumed that the W^{+} would be produced with very little transverse momentum with respect to the incident beam direction and therefore the transverse momentum of the decaying μ would exhibit a sharp peak at $p_{\mu\perp} \sim M_{W}/2.$[14] Present evidence in case of the production of massive strongly interacting vector bosons (i.e., J/ψ) indicate that the parent is produced at relatively large $p_{\perp}$ and therefore the Jacobian peak is largely smeared out.[15] There is no obvious reason why the production of massive intermediate vector bosons should not follow the same behavior.[16] Without a sharp structure in the $p_{\mu\perp}$ distribution, a crucial experimental signature for the W^{+} is absent.

We now briefly outline the scheme of transforming an existing proton accelerator into high luminosity $p\bar{p}$ colliding beams[17] using standard vacuum ($p \simeq 10^{-7}$ Torr) and the separate function magnet system. The main elements are (1) an extracted proton beam to produce an intense source of antiprotons at 3.5 GeV/c, and (2) a small ring of magnets and quadrupoles that guides and accumulates the $\bar{p}$ beam, (3) a suitable mechanism for damping the transverse and longitudinal phase spaces of the $\bar{p}$ beam (either electron cooling[18] or stochastic cooling[19]), (4) an R.F. system that bunches the protons in the main ring and in the cooling ring, (5) transport of the "cooled" R.F. bunched $\bar{p}$ beam back to the main ring for injection and acceleration. A long straight section of the main ring is used as $p\bar{p}$ interaction region. A schematic drawing of these elements for the FNAL accelerator is presented in Fig. 1. The main parameters of the scheme are summarized in Table I.

The luminosity for two bunches colliding head-on is estimated using the relation

$$L = N_p N_{\bar{p}} \, \phi/a$$

where N_p and $N_{\bar{p}}$ are the number of protons and antiprotons circulating in the machine, respectively, ϕ is the revolution frequency and a is the effective area of interaction of the two beams. N_p is taken as 10^{12} protons in one R.F. bunch. The value of N_p is limited by the maximum allowed beam-beam tune shift ($N_p = 10^{12}$ for $\Delta\nu = 0.01$). We have verified the longitudinal stability of the bunch, the phase area growth due to R.F. noise, the transverse wall instability, the head-tail effect and non-linear resonances, including those arising from beam-beam interactions. None of these effects appears to be important.[20] We note that $N_p = 10^{12}$ corresponds to $i_{av} = 10$ mA and

$i_{peak} \approx 25A$ for $\ell_{bunch} = 2.5m$ and that the Brookhaven AGS currently accelerates twelve bunches of similar characteristics.

The production of antiprotons at 3.5 GeV is done with protons from the same accelerator and with an overall efficiency $\bar{p}/p \simeq 4 \times 10^{-6}$. In order to reach $N_{\bar{p}} = 3 \times 10^{10}$ we need 750 pulses with 10^{13}ppp. About 10 seconds must elapse between pulses in order to clear away the freshly injected antiprotons.[21] Therefore the formation of $\bar{p}$'s would take of the order of few hours.

In order to make the beam as small as possible one can reduce the value of the betatron function in the collision point ($\beta_v \simeq \beta_h = 3.5m$) and make the momentum compaction factor close to zero.[22] Then for standard beam emittances[23] and $E_p = E_{\bar{p}} = 250$ GeV we calculate $L = 5 \times 10^{29}$ cm^{-2}sec^{-1} for $N_{\bar{p}} = 3 \times 10^{10}$. In order to observe one event/hour at our estimated cross section we require a luminosity of 3×10^{28} cm^{-2}sec^{-1}. If the more pessimistic cross section of 10^{-33} cm^2 is used, a luminosity of 3×10^{29} cm^{-2}sec^{-1} is needed which is still appreciably less than the calculated value. Finally, the half-life of the luminosity due to beam-gas scattering is about 24 hours for an average residual pressure of 0.5×10^{-7} Torr.

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TABLE I. - List of Parameters

1. MAIN RING (Fermilab)

- Beam momentum	250 (400) GeV/c
- Equivalent laboratory energy for ($p\bar{p}$)	133 (341) TeV
- Accelerating and bunching frequency	53.14 Mc/s
- Harmonic number	1113
- R.F. peak voltage/turn	3.3×10^{6} Volt
- Residual gas pressure	$< 0.5 \times 10^{-7}$ Torr
- Beta functions at interaction point	3.5 m
- Momentum compaction at int. point	~ 0 m
- Invariant emittances ($N_p = 10^{12}$)	
- longitudinal	3 eV s
- transverse	$50\ \pi\ 10^{-6}$ rad m
- Bunch length	2.3 m
- Design luminosity	$5 \times 10^{29} (8 \times 10^{29}) cm^{-2} . s^{-1}$

2. ANTIPROTON SOURCE (Stochastic Cooling[21])

- Nominal stored $\bar{p}$ momentum	3.5 GeV/c
- Circumference of ring	100 m
- Momentum acceptance	0.02
- Betatron acceptances	$100\ \pi\ 10^{-6}$ rad m
- Bandwidth of momentum stochastic cooling	400 Mc/s
- Maximum stochastic accelerating R.F. voltage	3000 V
- Bandwidth of betatron stochastic cooling	200 Mc/s
- Final invariant emittances ($N_{\bar{p}} = 3.10^{10}$)	
- longitudinal	0.5 eV s
- transverse	$10\ \pi\ 10^{-6}$ rad m

Figure Caption

Fig. 1. General layout of the $p\bar{p}$ colliding scheme. Protons (100 GeV/c) are periodically extracted in short bursts and produce 3.5 GeV/c antiprotons which are accumulated and cooled in the small stacking ring. Then $\bar{p}$'s are reinjected in an R.F. bucket of the main ring and accelerated to top energy. They collide head-on against a bunch filled with protons of equal energy and rotating in the opposite direction.

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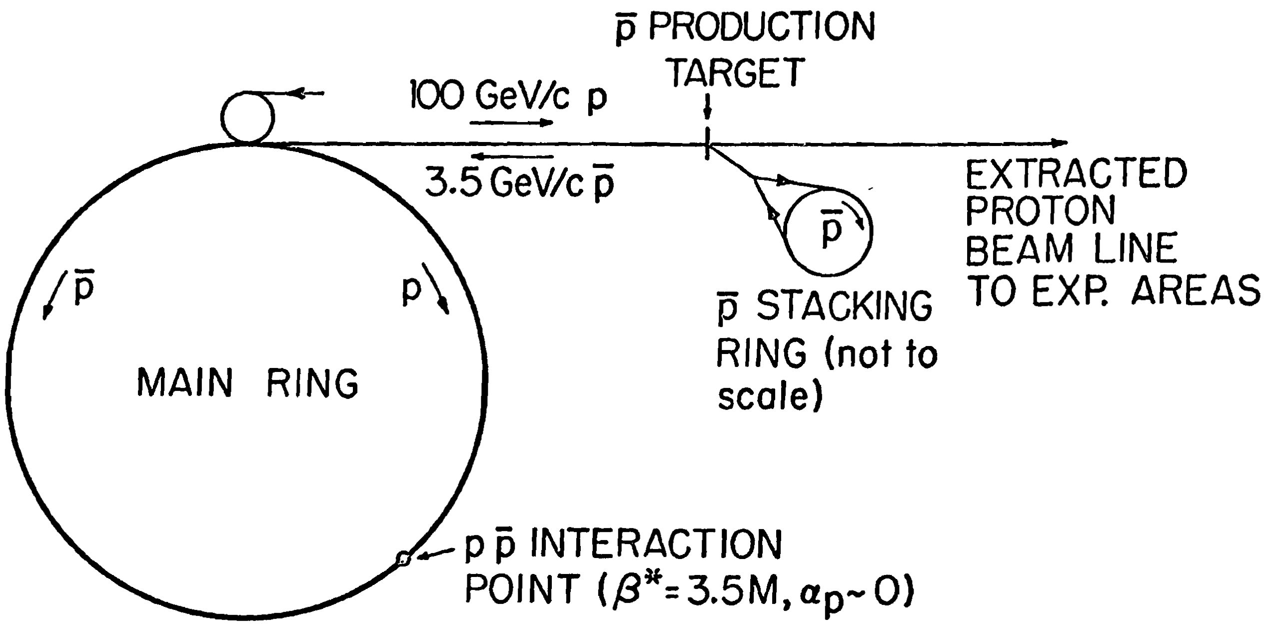
$\bar{p}$ PRODUCTION TARGET
100 GeV/c p
3.5 GeV/c $\bar{p}$
EXTRACTED PROTON BEAM LINE TO EXP. AREAS
$\bar{p}$
$\bar{p}$ STACKING RING (not to scale)
$\bar{p}$
p
MAIN RING
p $\bar{p}$ INTERACTION POINT (β^*=3.5M, α_p~0)

Fig. 1