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W Production Off Nuclear Targets

Thomas J. LeCompte
Argonne National Laboratory

1 Introduction

The A dependence of W production off nuclear targets has never been studied, primarily because it would take a beam of millions of TeV before threshold is reached. RHIC, however, allows us to use a nuclear beam of several hundred GeV as a "target" and thereby to investigate W production on nuclei.

With unpolarized beam (or polarized beam where the polarization is ignored), this allows STAR to investigate the antiquark distribution in nuclei, and how it differs from that of free nucleons. This can also be done with lepton probes in DIS, but these are typically at Q^2's of a few GeV^2. At collider energies, the evolution of the antiquark distributions can be studied, up to Q^2's of several thousand GeV^2.

There is a parity violating asymmetry using proton beam. However, unless the gold nucleus is polarized, there is no way to study the spin structure of the sea quarks in nuclei, because all effects proportional to the spin asymmetry in gold vanish for unpolarized gold beam. (This is an argument for a polarized ion beam, although since gold has spin 3/2, it may be better to use a spin-1/2 species. ^{169}Tm is a candidate, and the next lightest good candidate is ^{103}Rh.)

2 Accelerator Parameters

To study W production, we need to make W's. Table 1 shows PYTHIA's calculations for the W and Z cross sections at three center of mass energies.

Note that the standard $\sqrt{s} = 200$ GeV pA running (here $\sqrt{s}$ will always refer to the per nucleon center of mass energy) has a W cross section 65 times smaller than

$\sqrt{s}$ (GeV))	$\sigma(W)$ (pb)	$\sigma(Z)$ (pb)
200	98.7	23.0
316	1451	196.5
500	6435	1483

Table 1: PYTHIA calculations of W and Z cross sections in pp collisions.

the 500 GeV pp running, where we expect approximately 80,000 $W \to e\nu$ events per 100 day dedicated run at the highest luminosity. [1]

In this note, we assume that this running will occur late in RHIC operations, so that all of the enhancements to luminosity will be in effect. An "enhanced" pp luminosity of 2×10^{32} cm^{-2}/s is twenty times larger than the design luminosity of 1×10^{31} cm^{-2}/s, so we assume that the pA luminosity will also be twenty times larger than design: for gold, 1×10^{30} cm^{-2}/s instead of 5×10^{28} cm^{-2}/s. Assuming that W production scales as $A^{1.0}$, the rate is the same for pp and pA: the luminosity is 197 times lower, but the cross section is 197 times higher. However, accerator effects (described later) reduce the luminoisty at 200 GeV to only 40% of what it is at 500 GeV.

With the factor of 2/5 from accelerator luminoisty, and the factor of 1/65 from cross sections, we expect only about 500 $W \to e\nu$ events per run (And only 24 $Z \to e^+e-$ events). While this is enough to observe W production, it is insufficient to do high precision physics across several bins. Worse, the W mass is artificially low and the width is artificially broad at these energies, which increases the backgrounds dramatically. The reason is that the parton distributions are falling so steeply at these x_{Bj}'s that it is more probable to produce a low mass W several Γ off-shell than it is to produce on on-shell W.

Simply put, 200 GeV is too low in energy to do W physics seriously.

500 GeV proton-nucleus collisions would obviously be better. Unfortunately, the RHIC magnets are incapable of supporting a beam of heavy ions with energy 250A GeV. (625 GeV per *charged* nucleon). That leads us to consider *asymmetric* collisions: a proton beam at 250 GeV against a gold beam at 100 GeV per nucleon.

Such a collision will have $\sqrt{s} = 316.2$ GeV. Expected yields, including accelerator effects, would be 11,000 W's and 320 Z's. (Assuming an acceptance of $|\eta| \leq 1.0$. As will be discussed later, this is a slight underestimate of the yields)

3 Accelerator Issues

3.1 Luminosity

The luminosity of a hadron-hadron collider is given by the following expression:

$$\mathcal{L} = f\frac{N_A N_B}{4\pi\sigma_A\sigma_B}$$

where f is the collision frequency, N_A and N_B are the number of particles in each bunch of each beam, and σ_A and σ_B are the transverse sizes of the beams.

The beam size σ is proportional to the square root of the emittance ε: $\sigma_{A,B} \propto \sqrt{\varepsilon_{A,B}}$ It is often convenient to express the emittance in terms of the normalized emittance ε_N, which is a constant for any particular accelerator:

$$\varepsilon = \frac{\varepsilon_N}{6\pi\gamma}$$

For the same accelerator, therefore, the luminosity $\mathcal{L}$ is proportioanl to $\sqrt{\gamma_A\gamma_B}$. This is why the luminosity at 200 GeV is only 40% of what it is at 500 GeV, and why the luminosity at 316 GeV is 58% larger than it is at 200 GeV.

3.2 Orbit Length

Asymmetric collisions have one technical problem: the beams are travelling with different velocities. A 250 GeV proton is traveling with $\beta = .999993$, while a 100 GeV/nucleon gold nucleus is traveling only with $\beta = .999956$. The difference is 11.1 km/s. With a RHIC tunnel length of 3.834 km, the interaction points cycle around the ring every 345 ms. Unless these can somehow be phased with the RHIC RF and bunch structure (and that a satisfactory phase lock can be maintained) this situation will make experimentation extremely difficult.

The simplest way to get the two beams back in phase is to increase the proton beam's path length by

$$2\pi\left(1 - \frac{\gamma_p}{\gamma_A}\right)R,$$

or 14 cm.

To do this, one possibility is to put the proton beam in a circular orbit at a larger radius. Unfortunately, that new radius is 2.2 cm from the nominal radius. Operating this far from the magnet centerlines may prove difficult, especially through sextupoles and other correction elements. A second possibility would be to increase the amplitude of betatron oscillations. For typical tunes, this would require betatron oscillations of one to a few millimeters, probably uncomfortably large. [2] The third option is to slide one sector of one ring of RHIC out 7 cm (so-called "tromboning") and increase the path that way (Or move two sectors each out 3.5 cm, etc.). Apart from the labor in moving the string of magnets, this does not appear to be too difficult a job [2]. Nonetheless, because the changeover is rather labor intensive, it is unlikely that there will be willingness to do this more than once.

4 Detector Acceptance

A concern with asymmetric collisions is that all of the W's will go so far forward that nothing of interest will remain in STAR. Fortunately, this effect is calculable. The center of mass energy is 316.2 GeV, and the center of mass has $p_z = 150$ GeV. Thus,

$$\beta\gamma\sqrt{s} = 150 \text{ GeV}$$

$$\beta\gamma = \frac{150 \text{ GeV}}{316.2 \text{ GeV}}$$

$$\frac{\beta}{\sqrt{1-\beta^2}} = 0.4744$$

$$\beta = .4286$$

A particle with 4-velocity (1,1,0,0) in the center of mass frame will have 4-velocity (1.0,0.0,0.4744,1.1068) in the lab frame. This corresponds to $y = 0.458$. That is, the effect of the asymmetric collisions is to boost the system by about half a unit of rapidity.

An EMCal with a detector and one endcap covers from $\eta = -1.0$ to $\eta = 2.0$ in the lab frame. A boost of half a unit of rapidity causes this to become a quite central device, covering from $\eta = -1.5$ to $\eta = 1.5$ in the center of mass frame. So this covers all the central acceptance (from which the yields were calculated). As shown by Rykov and Shestermanov [3], but $\eta = 1.0$ most of the W^+'s that are going to be accepted already are, but the acceptance is still flat in W^-'s.[1] The net increase in yield is approximately 1000 additional W's, predominantly W^-'s.

5 Conclusions

W production in asymmetric p-nucleus collsions provides a unique way to study the antiquark sea in nuclei, and to determine how sea quarks in nuclei differ from sea quarks in the nucleus. This is at Q^2 values far above what can be measured in DIS. The STAR detector is well positioned to take advantage of this opportunity. Rather substantial modifications in RHIC are necessary for this, so it is likely that this sort of run will occur relatively late in RHIC operations.

References

[1] STAR-RSC (RHIC Spin Collaboration) UPDATE, 31 Augiat 1993.

[2] Todd Satogata, private communication.

[3] V. Rykov and K. Shestermanov, "$W^{\pm}$ and Z^0 Event Rates and Background Estimates for the STAR Detector at RHIC in pp Collisions", ANL-HEP-TR-93-89 (1993).

[1] This is because the W decay is parity violating. Because W's are produced by a collision between a valence quark and a sea antiquark (which tends to have less momentum than the valance quarks) the W is produced with substantial velocity in the z-direction. The W^+ decays in such a way as to throw the positron opposite the direction of motion - more centrally - and the W^- decays in such a way as to throw the electron along the direction of motion - more forward.