A. FNAL Experiment 866

1 Introduction

FNAL Experiment 866 (E866) is a high statistics measurement of the relative yield of Drell-Yan dimuon pairs from p+p and p+d collisions. The collaboration consists of Abilene Christian University, Argon National Laboratory, Fermi National Accelerator Laboratory, Georgia State University, Illinois Institute of Technology, Los Alamos National Laboratory, Louisiana State University, New Mexico State University, Oak Ridge National Laboratory, Texas A&M University and Valparaiso University. It should be noted that the full analysis of the main data set is the responsibility of ACU graduate student, Rusty Towell.

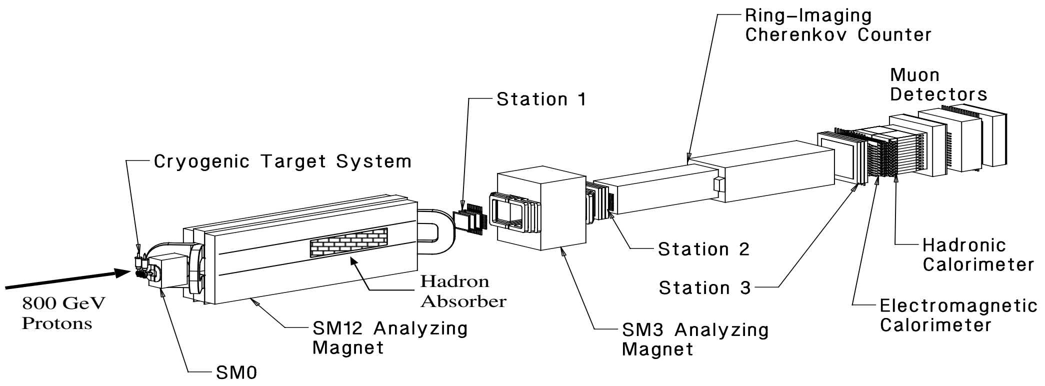

Figure 1: The E605/E772/E789/E866 Spectrometer.

E866 used the E605/E772/E789 spectrometer (figure 1) located in the Meson East area at FNAL. The main modifications from the E789 configuration involved the removal of the silicon strip vertex detector, the installation of a magnet (SM0) in front of the big dipole magnet (SM12), upgrading the trigger to a programmable VME based trigger [1], and the enlargement of the station one detectors. ACU helped with all of these modification and was responsible for rebuilding the station one hodoscopes.

Data was taken on 50 cm long liquid hydrogen (LH2) and liquid deuterium (LD2) targets. The target mechanism was capable of switching between the two targets, plus an empty target vessel, between each beam spill (at FNAL the protons are delivered over a 20 second period once per minute). At an intensity of $2x10^{12}$ protons/spill, the rates that the detectors handled were quite high. This is one of the reasons the experiment used the E605/E772/E789 spectrometer, since it had demonstrated excellent rate capabilities. The ability to cycle rapidly between the targets helped limit the systematic errors to 1%.

2 ACU's contribution to E866

For E866, ACU was responsible for maintaining the hodoscopes, which we rebuilt for E789 then again for E866. During the past four summers ACU had several students involved with rebuilding and recommissioning the hodoscopes. Station 1Y was expanded to 16 counters tall and Station 1X was completely rebuilt to cover the extended Y counters. This increased the solid angle for the D-Y events of interest by roughly a factor of 2. The careful work of these students in preparing the hodoscopes was demonstrated by the hodoscopes outstanding performance. Not a single channel of the hodoscopes failed once during the year long experiment.

Since so many students had worked for so many summers getting the spectrometer ready for beam, it was very rewarding for them to actually help take data. During the past summer (1997) five ACU undergraduate students worked on E866 (two of these were supported by LANL and three were supported by this grant). These students contributed significantly to the experimental effort by quickly learning how to run the experiment. This allowed them to take shifts where they were solely responsible for operating the spectrometer. In addition to taking shifts, each student performed other tasks including preliminary analysis, monitoring the gas system, copying data tapes, and filtering the study triggers from all of the data tapes. ACU has been able to make a very positive impact on experiments by providing manpower for labor intensive tasks and will continue to be an important partner in the Fermilab program.

While the undergraduate students were enjoying seeing the completion of several summers of work, Isenhower was the acting spokesman. Pat McGaughey who is the E866 spokesman and had spent a year living at Fermilab, returned to Los Alamos in mid-May. So Isenhower was the acting spokesman for much of the summer. He supervised the daily activities of data taking, interfaced with the lab in administrative matters, and managed 5 undergraduate students and one graduate student.

The funding for graduate student support has been to support Rusty Towell to work full-time on E866. Towell is a student at the University of Texas at Austin, where he took his course work and will receive his Ph.D. Isenhower serves as co-chair of Towell's graduate committee along with Dr. Peter Riley of U.T., and Sadler serves as one of the members of Towell's graduate committee. Towell was at FNAL throughout the experiment. He was one of the students involved in the previous three summer's work, and he has played a major role in supervising our undergraduate students during the past two summers. Towell was very valuable to the collaboration in maintaining and repairing various TDC, hodoscope, prompt tube, and Nevis Transport modules. Having someone on site at FNAL full time during the academic year has been extremely helpful in keeping ACU actively involved in this important experiment. When data taking was completed and the spectrometer was decommissioned, he moved to LANL to analyze the data. He has been assigned the full analysis of the $\bar{d}/\bar{u}$ data, which he will use as his dissertation topic.

During the past year Towell has presented E866 preliminary results in three talks. He was invited to talk at DIS 97 [2] and two informal talks to members of other experiments at FNAL. In February of this year Towell will give a high energy nuclear physics seminar at the University of Texas at Austin. Then in March Towell will give an invited talk at Moriond. These trips will be funded out of the ACU nuclear physics grant.

3 Measurement of $\bar{d}/\bar{u}$ in the Proton

Recent experiments have indicated that the light quark content of the nucleon sea is not flavor symmetric. Therefore, E866 set out to measure the ratio of $\bar{d}/\bar{u}$ in the proton over the interval $.02 < x_F < .35$. The data-taking for this measurement was completed in March 1997. The remainder of the fixed target run at Fermilab was used to study the nuclear dependence of $J/\psi, \psi'$, and Υ production in a wide kinematic range. Since data taking ended in August 1997 we have made significant progress in the analysis. Our first results showing the ratio $\bar{d}/\bar{u}$ have been submitted for publication to Phys. Rev. Lett. [3]

The abstract from this article states: "A precise measurement of the ratio of Drell-Yan yields from an 800 GeV/c proton beam incident on hydrogen and deuterium targets is reported. Over 140,000 Drell-Yan muon pairs with dimuon mass $M_{\mu^+\mu^-} \geq 4.5$ GeV/c^2 were recorded. From these data, the ratio of anti-down ($\bar{d}$) to anti-up ($\bar{u}$) quark distributions in the proton sea is determined over a wide range in Bjorken-x. A strong x dependence is observed in the ratio $\bar{d}/\bar{u}$, showing substantial enhancement of $\bar{d}$ with respect to $\bar{u}$ for $x < 0.2$. This result is in fair agreement with recent parton distribution parameterizations of the sea. For $x > 0.2$, the observed $\bar{d}/\bar{u}$ ratio is much nearer unity than given by the parameterizations."

Three different spectrometer settings were employed to optimize data collection at low, intermediate, and high masses of the muon pair. The data collected in the high mass setting are relatively free of the rate dependence efficiencies and the random coincidences that affect the other data sets. Therefore, the initial Phys. Rev. Lett. only reports the results from the high mass data set.

Figure 2 shows the mass spectrum for the data taken with the high mass setting (dashed curve) and all settings (solid curve). Also shown are the mass cuts used to remove the resonance families from the Drell-Yan continuum. Figure 3 shows the spectra of the kinematic quantities x_1, x_2, x_F, and p_t for dimuons recorded from all mass settings (solid) and from the high mass setting (dashed).

Figure 4 shows the ratio $\sigma^{pd}/2\sigma^{pp}$ of Drell-Yan cross sections verses x_2. Also shown are next-to-leading order calculations, weighted by acceptance, of the Drell-Yan cross section ratio using the CTEQ4M (solid)[5] and MRS(R2)[6] (dashed) parton distributions. Also shown is a leading order calculation of the cross section ratio using CTEQ4M (dotted). The lower curve shows the predicted ratio for a modified CTEQ4M parton distribution which

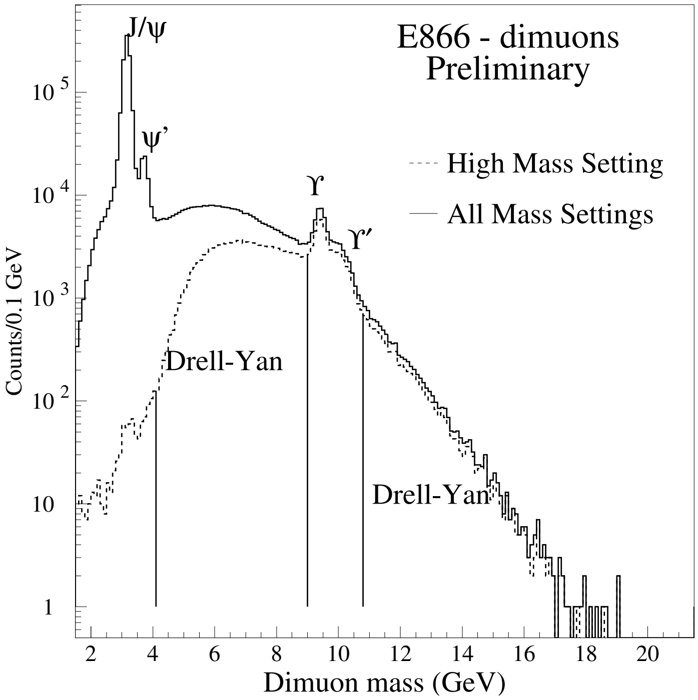

Figure 2: E866 Mass Spectrum.

maintains the parameterization for $\bar{d}_p + \bar{u}_p$ but sets $\bar{d}_p - \bar{u}_p = 0$. The errors are statistical only. An additional 1% systematic uncertainty is common to all points. The data are in reasonable agreement with the unmodified CTEQ4M and the MRS(R2) predictions for $x_2 < 0.15$. It is clear that $\bar{d}_p \neq \bar{u}_p$ in this range. Above $x_2 = 0.15$ the data lie well below both parameterizations.

The extracted $\bar{d}/\bar{u}$ ratio is shown in Fig. 5 along with the prediction made by CTEQ4M. A qualitative feature of the data, not seen in either parameterization, is the rapid decrease towards unity of the $\bar{d}/\bar{u}$ ratio beyond $x = 0.2$. At $x = 0.18$, the extracted $\bar{d}/\bar{u}$ ratio is somewhat smaller than the value obtained by NA51 [4]. Although the average value of Q^2 ($M^2_{\mu^+\mu^-}$) is different for the two data sets, the change in $\bar{d}/\bar{u}$ predicted by the parton distributions due to Q^2 evolution is small.

The analysis of the other data sets is progressing in a timely manner. The first and second pass analysis have been completed and currently the systematic effects are being studied. The analysis of the remaining data sets will extend the $\bar{d}/\bar{u}$ measurement down to smaller x values. This will provide an independent check of the NMC result of $\int_0^1 \left[\bar{d}_p(x) - \bar{u}_p(x)\right] dx = 0.147 \pm 0.039$.

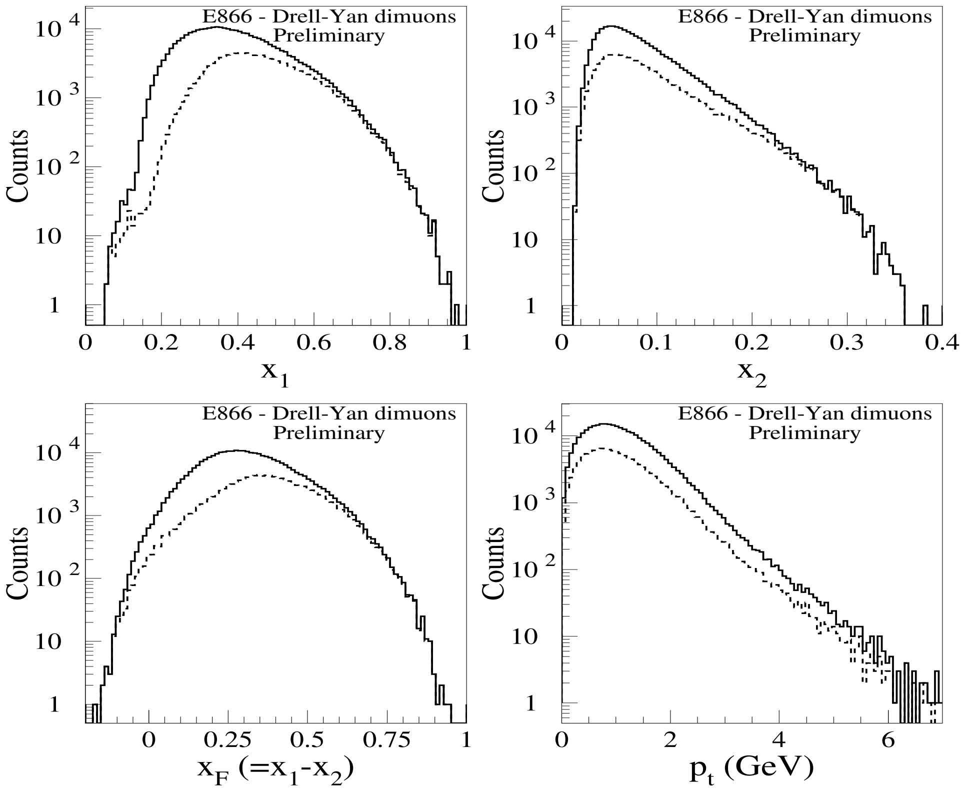

Figure 3: Spectra of the kinematic quantities $x_1,\ x_2,\ x_F$, and p_t for dimuons recorded from all mass settings (solid) and from the high mass setting (dashed).

4 Polarization of Drell-Yan Pairs and Quarkonia

High statistics pion-induced Drell-Yan[?, ?] and J/ψ[?] production data have been analyzed to study the decay angular distributions in θ_{CS} and ϕ_{CS} (Collins-Soper frame). Drell-Yan pairs were observed to be transversely polarized, as expected, except at very large x_F (> 0.8) where they became longitudinally polarized[?, ?]. This large x_F behavior was explained as a higher-twist effect[?]. The J/ψ was measured to be unpolarized except at large x_F where it also became longitudinally polarized[?, ?]. A detailed measurement of the decay angular distribution will also help investigate the role of the color-octet states in the production of charmonium[?], recently proposed to account for the unexpectedly large CDF ψ production cross sections[?]. Some models using color-octet intermediate states predict that the J/ψ

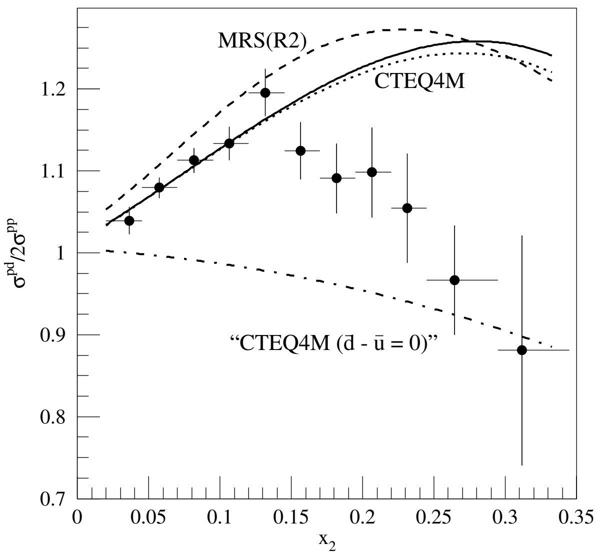

Figure 4: The ratio $\sigma^{pd}/2\sigma^{pp}$ of Drell-Yan cross sections *vs.* x_2. Shown are next-to-leading order calculations, weighted by acceptance, of the Drell-Yan cross section ratio using the CTEQ4M (solid) and MRS(R2) (dashed) parton distributions. Also shown is a *leading order* calculation of the cross section ratio using CTEQ4M (dotted). In the lower CTEQ4M curve $\bar{d}-\bar{u}$ has been set to 0 as described in the text. The errors are statistical only. An additional 1% systematic uncertainty is common to all points.

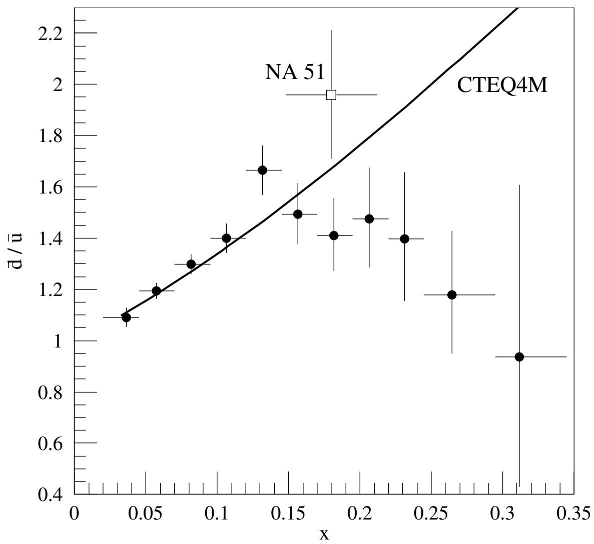

Figure 5: The ratio of $\bar{d}/\bar{u}$ in the proton as a function of x extracted from the Fermilab E866 cross section ratio. The curve is from the CTEQ4M parton distributions. The error bars indicate statistical errors only. An additional systematic uncertainty of ± 0.032 is not shown. The result from NA51 is also plotted as an open box.

and ψ' are strongly polarized at large p_T[?].

The literature contains no high statistics measurement of the polarization of proton-induced DY virtual photons. Analysis of beam-dump dimuons from E772[?] clearly demonstrated the feasibility of recording high statistics DY data even at large mass, large x_F, or large p_T where cross sections are small. So This measurement was made in April of 1997. During this rather short period of time about 10 million J/ψ and 200,000 Drell-Yan events were recorded. These beam-dump dimuons extend to large values of p_T and x_F and may reveal interesting aspects of the DY process. Angular distribution measurements in E866 are possible from the beam dump, because it provided for the necessary combination of large angular acceptance and high luminosity. These data are being used for the Ph.D. thesis of T.H. Chang of the New Mexico State University at Las Cruces and are progressing very well.

5 Nuclear-Dependence of J/ψ

The large nuclear dependencies found in hadronic production of quarkonium have inspired several explanations within the past few years. Parton energy loss, intrinsic heavy flavor, co-mover interactions, gluon shadowing, and color octet production are among the mechanisms proposed to explain the data. The yield of quarkonium in hadronic collisions is interesting not only in its own right, but is also advanced as one of the most important diagnostic tools for high-density nuclear matter created in heavy-ion collisions.

This measurement was completed in July of 1997. About 2 million J/ψ and 140,000 ψ' events were recorded from beryllium, iron, and tungsten targets. These events extended over a very wide kinematic range. These events had x_F values as low as -0.15 and as high as 0.95. Bill Lee of Georgia State University is currently analyzing these data which will be used for his Ph.D. thesis. It is expected that this analysis will be completed this year.

6 Low-Mass Drell-Yan Yields

The NMC[?] and FNAL-E665[?] experiments have observed 'shadowing' in deep inelastic scattering (DIS) on nuclear targets. This suppression of sea-quarks in heavy nuclei occurs at $x \leq 0.05$ and appears to saturate at $x \sim 0.001$. Although there is evidence of shadowing in the E772 data, it is important to extend the measurements to smaller values of x. To reach lower x, DY masses less than 4 GeV/c^2 must be explored. It is of interest to compare shadowing in DIS and DY because the virtual photons involved are different, being spacelike and timelike, respectively. Secondly, the DY events are selected to arise from sea quarks in the nuclear target, while the DIS data measure a composite of valence and sea quarks.

This measurement was completed in August 1997. About 1.1 million ρ, 500,000 ϕ, and 800,000 J/ψ events were recorded. These events were from a beryllium target, and two thicknesses of tungsten. These data are currently being analyzed by Paul Reimer, a post-doc from LANL.

7 Other E866 Run Extension Measurements

In addition to the plans listed in the E866 Run Extension Request submitted as an Appendix to the previous Progress Report for this grant, there was an additional measurement made in July 1997. This was to study single muon yields from the various processes that are of some concern for RHIC experiments. For this measurement, the University of New Mexico joined the E866 collaboration. Data were recorded for different targets at different positions to specifically aid PHOENIX in making plans for single muon rates they will see at RHIC. The data are expected to be analyzed during the next year or so and are progressing well based on reports given at the February 1998 E866 collaboration meeting.

E866 is also attempting to make an absolute cross-section measurement using a collection of the data recorded during the experiment. This requires understanding of a number of acceptance and efficiency issues and will take careful analysis. This will form the Ph.D. thesis of Jason Webb of New Mexico State University and will likely take 1-2 years to complete.

References

[1] C.A. Gagliardi *et al.*, Nucl. Instrum. Methods (submitted).

[2] R.S. Towell, *Measuring $\bar{d}/\bar{u}$ in the Proton: Fermilab E866,* **AIP Conference Proceedings 407: Deep Inelastic Scattering and QCD, 5^{th} International Conference,** J. Repond and D. Krakauer, eds., Chicago, April, 1997 (Woodbury, NY: AIP Press, 1997) 423.

[3] E.A. Hawker *et al.*, Phys. Rev. Lett. (submitted)

[4] A. Baldit *et al.*, Phys. Lett. B **332**, 244 (1994).

[5] H.L. Lai *et al.*, Phys. Rev. D **55**, 1280 (1997).

[6] A.D. Martin, R.G.Roberts and W.J. Stirling, Phys. Lett. B **387**, 419 (1996).