Observation of neutral current charm production in $\nu_\mu Fe$
scattering at the Tevatron

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We report on the first observation of open charm production in neutral current deep inelastic neutrino scattering as seen in the NuTeV detector at Fermilab. The production rate is shown to be consistent with a pure gluon-$Z^0$ boson production model, and the observed level of charm production is used to determine the effective charm mass. As part of our analysis, we also obtain a new measurement for the proton-nucleon charm production cross section at $\sqrt{s} = 38.8$ GeV.

I. INTRODUCTION

Measurements of charged current (CC) charm production in deep inelastic (DIS) neutrino and anti-neutrino scattering have proven to be an excellent source of information on the structure of the nucleon, the dynamics of heavy quark production, and the values of several fundamental parameters of the Standard Model (SM) of particle physics [1]. The only evidence to date of neutral current (NC) charm production in $\nu_N$ or $\bar{\nu}_N$ scattering is an unconfirmed observation of $J/\psi$ production [2,3]. Using a new Sign Selected Quadrupole
Train (SSQT) beam with the high energies of the Fermilab Tevatron, NuTeV is able to perform a sensitive search for NC charm production through detection of events with wrong sign muon (WSM) final states. This occurs whenever an interaction produces a single muon and the muon has the opposite lepton number as the neutrino beam. The SSQT produced event ratios of $\bar{\nu}_\mu/\nu_\mu$ in neutrino and a $\nu_\mu/\bar{\nu}_\mu$ anti-neutrino mode of $0.8 \times 10^{-3}$ and $4.8 \times 10^{-3}$, respectively, making possible the WSM identification.

In SM NC interactions, charm quarks must be produced in pairs. As is the case for CC charm production, considerable suppression of the $\nu_\mu N \rightarrow \nu_\mu c\bar{c}X$ rate occurs due to the non-zero charm quark mass $m_c$. This measured suppression can be used to experimentally determine $m_c$. If $m_c$ is a fundamental parameter of the SM, then it should have the same value, up to possible quantum chromodynamics (QCD) corrections, in NC and CC $\nu_\mu N$ charm production, and in other physical processes such as the photo-production of charm and the spectrum of charmonium.

In the fixed-flavor (FF) implementation of QCD [4], NC charm pair production can be attributed completely to hard scatters between the the exchanged virtual $Z^0$ boson and a gluon in the nucleon sea; this process, known as boson-gluon fusion, is illustrated in Fig. 1. Other implementations of QCD [5,6] envision an intrinsic charm quark parton distribution function (PDF) $c(x, Q^2)$, that depends on the Bjorken scaling variable $x$ and the absolute value of the squared momentum transfer $Q^2$. In addition, some have suggested [7–9] that non-perturbative QCD effects may produce an unusually large $c(x, Q^2)$, particularly at high $x$. In FF QCD, $c(x, Q^2) \simeq 0$ over the $Q^2$ range probed by NuTeV. The validity of this assumption can be tested with the data.

II. EXPERIMENTAL APPARATUS AND BEAM

The NuTeV (Fermilab-E815) neutrino experiment collected data during 1996-97 with the refurbished Lab E neutrino detector and a newly installed Sign-Selected Quadrupole Train (SSQT) neutrino beamline. Figure 2 illustrates the sign-selection optics employed by
the SSQT to pick the charge of secondary pions and kaons which determine whether $\nu_\mu$ or $\bar{\nu}_\mu$ are predominantly produced. During NuTeV’s run the primary production target received $1.13 \times 10^{18}$ and $1.41 \times 10^{18}$ protons-on-target in neutrino and anti-neutrino modes, respectively.

The Lab E detector, described in detail elsewhere [10], consists of two major parts, a target calorimeter and an iron toroid spectrometer. The target calorimeter contains 690 tons of steel sampled at 10 cm intervals by 84 m × 3 m scintillator counters and at 20 cm intervals by 42 m × 3 m drift chambers. The toroid spectrometer consists of four stations of drift chambers separated by iron toroid magnets. Precision hadron and muon calibration beams monitored the calorimeter and spectrometer performance throughout the course of data taking. The calorimeter achieves a sampling-dominated hadronic energy resolution of $\sigma_{E_{\text{HAD}}}/E_{\text{HAD}} = 2.4\% \oplus 87\% / \sqrt{E_{\text{HAD}}}$ and an absolute scale uncertainty of $\delta E_{\text{HAD}}/E_{\text{HAD}} = 0.5\%$. The spectrometer’s muon energy resolution (dominated by multiple Coulomb scattering) is $\sigma_{E_\mu}/E_\mu = 11\%$ and the muon momentum scale is known to $\delta E_\mu/E_\mu = 1.0\%$. With the selection criteria used in this analysis, the muon charge mis-identification probability in the spectrometer is $2 \times 10^{-5}$.

III. ANALYSIS PROCEDURE

Much of the analysis procedure follows that used for a search for flavor changing neutral currents using the same data set [11], and further details may be obtained from the article describing that analysis and in Ref. [12].

A. Introduction and Data Selection

The analysis technique consists of comparing the visible inelasticity, $y_{\text{vis}} = E_{\text{HAD}} / (E_{\text{HAD}} + E_\mu)$, measured in the $\nu_\mu$ and $\bar{\nu}_\mu$ wrong sign muon (WSM) data samples to a Monte Carlo (MC) simulation containing all known conventional WSM sources and a possible NC charm signal. The NC charm signal peaks at large values of $y_{\text{vis}}$ because the
decay muon from the heavy flavor hadron is usually much less energetic than the hadron shower produced in the NC interaction. The largest background, beam impurities, is concentrated at low $y_{vis}$ in $\nu_\mu$ mode due to the characteristic $(1 - y)^2$ behavior of interactions of the $\bar{\nu}_\mu$ wrong-flavored beam background.

Events in the WSM sample must satisfy a number of selection criteria (“cuts”). The fiducial volume cut requires that event vertices be reconstructed at least 25 cm-Fe (cm of iron) from the outer edges of the detector in the transverse directions, at least 35 cm-Fe downstream of the upstream face of the detector, and at least 200 cm-Fe upstream of the toroid. Events must contain a hadronic energy of at least 10 GeV (increased to 50 GeV for the final NC charm fit), and exactly one track (the muon) must be found. The muon is required to be well-reconstructed and to pass within the understood regions of the toroid’s magnetic field. The muon’s energy must be between 10 and 150 GeV, and its charge must be consistent with having the opposite lepton number as the primary beam component. Requiring that the muon energy reconstructed in different longitudinal sections of the toroid agree within 25% of the value measured using the full toroid reduces charge mis-identification backgrounds to the $2 \times 10^{-5}$ level. This latter number has been verified using the muon calibration beam.

**B. Source and Background Simulations**

Conventional WSM sources arise from beam impurities, right-flavor CC events where the charge of the muon is mis-reconstructed, CC and NC events where a $\pi$ or $K$ meson decays in the hadron shower, and CC charm production where the primary muon is not reconstructed or the charm quark is produced via a $\nu_\epsilon$ interaction. Table I lists the fractional contribution of each background component. The relatively large beam impurity background consists of contributions from hadrons (including charm) that decay before the sign-selecting dipoles in the SSQT, neutral kaon decays, muon decays, decay of hadrons produced by secondary interactions in the SSQT (“scraping”), and from decay of wrong-sign pions produced in kaon
decays. Table II summarizes the relative contributions of each beam source. For this analysis the beam sources can be further tuned using WSM data in $\bar{\nu}_\mu$ mode. This procedure, which yields in passing a new measurement of $\sigma (pN \rightarrow c\bar{c}X)$ at $\sqrt{s} = 38.8$ GeV, is detailed in the Appendix.

After impurities, the next largest WSM source comes from CC production of charm in which the charm quark decays semi-muonically, and its decay muon is detected in the spectrometer. The primary lepton is either an electron, which is lost in the hadrons shower, or a muon which exits from or ranges out in the calorimeter. The $\nu_e$ beam fraction is $1.9(1.3)\%$ in $\nu (\bar{\nu})$ mode, and 22% of the CC charm events which pass WSM cuts originate from a $\nu_e$.

Charged current charm production produces a broad peak at high $y_{vis}$ that must be handled with care. The CC charm background is simulated using a leading-order QCD charm production model with production, fragmentation, and charm decay parameters tuned on neutrino dimuon data collected by NuTeV [19] and a previous experiment using the same detector [24]. Overall normalization of the source is obtained from the measured charm-to-total CC cross section ratio and the single muon right-sign data sample. Simulated dimuon events are passed through the full GEANT simulation of the detector. Figure 3 provides a check of the modelling of this source through a comparison of the distribution of $y_{vis}' = E_{\text{HAD}} / (E_{\text{HAD}} + E_{\mu^2})$, where $E_{\mu^2}$ is the energy of the WSM in the event, between data and MC for dimuon events in which both muons are reconstructed by the spectrometer. This distribution should closely mimic the expected background to the $y_{vis}$ distribution in the WSM sample. A $\chi^2$ comparison test between data and model yields a value of 19 for 17 degrees of freedom.

Finally, a NC $c\bar{c}$ event produces a WSM when the $c (\bar{c})$-quark decays semi-muonically in $\nu_\mu (\bar{\nu}_\mu)$ mode. To compute effects of fragmentation, heavy quark decay, acceptance, and resolution, production is simulated with a $Z^0$-gluon fusion model [4] with charm mass pa-
rameter $m_c = 0.5 \text{ GeV}/c^2$ and the GRV94-HO [23] PDF set. No corrections for the nuclear environment are applied, but possible effects are considered in the systematic error. The NC charm quarks are fragmented and decayed using procedures adapted from the CC charm modelling, and the resulting WSM events are then simulated with the full detector MC and processed with the data reconstruction code.

**IV. RESULTS AND INTERPRETATION**

**A. Fits to Data**

Binned maximum likelihood fits are performed to the measured neutrino mode $y_{vis}$ distribution using a model consisting of all conventional WSM sources described and a possible $c\bar{c}$ signal. The fitter varies the NC charm contribution in shape and level by allowing the charm mass parameter, $m_c$, to float; it also varies the normalization of the beam impurities. Figure 4 shows the $y_{vis}$ distribution for the data with the background plus fitted NC charm signal superposed. The shape indicates a preference towards including the NC charm signal, and the fit yields $m_c = 1.42^{+0.77}_{-0.34} \text{ GeV}/c^2$ with a beam normalization of $1.00 \pm 0.06$, where the errors are purely statistical. The fitted value of the beam normalization validates the beam impurities model and the $\bar{\nu}_\mu$ WSM tuning procedure described in the Appendix.

In Fig. 5 the $y_{vis}$ distribution of WSM’s is shown with the additional requirement that $E_{\text{had}}$ be larger than 50 GeV. This cut removes 85% of the beam impurities while keeping 75% of the NC charm events. Performing the fit again on this reduced sample with the background normalization fixed at 1.0 yields a consistent value for the charm mass of $m_c = 1.40^{+0.83}_{-0.36} \text{ GeV}/c^2$, with the error again purely statistical.

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1The choice of a low input MC mass allows for consistent re-weighting of the cross section over a wide range in the final fit procedure.
B. Systematic Errors

Estimates of the systematic uncertainty are obtained by varying parameters associated with background and signal simulations and event selection criteria within known bounds. Systematic errors are assumed to be independent and thus can be added in quadrature. More details on systematic error studies may be found in Refs. 11 and 12. The most important contributions are from modelling the level of CC charm events which reconstruct as WSM, from energy and momentum calibration uncertainties, from charmed quark fragmentation, from the choice of the gluon PDF used in the $c\bar{c}$ production model, from possible nuclear effects, and from the beam impurity model.

The number of dimuon events which reconstruct as a WSM can be normalized either from the total right sign muon sample and the measured charm production fraction or from the observed number of events reconstructed with two events in the toroid. These two normalizations disagree by 3%, and switching to the latter normalization shifts $m_c$ by +0.10 GeV/$c^2$. Replacing the drift-chamber-tracking-based method to reject events with two muons by a calorimeter-pulse-height-based algorithm leads to a further shift $\delta m_c = +0.04$ GeV/$c^2$.

Shifting $E_\mu$ by ±1% calibration uncertainty changes $m_c$ by $+0.05_{-0.02}$ GeV/$c^2$. Shifting $E_{\text{had}}$ by ±0.5% changes $m_c$ by ±0.01 GeV/$c^2$. A total systematic error of 0.05 GeV/$c^2$ is thus attributed to calibration.

The fragmentation model, based on CC charm analysis of the same experiment [19], is tested by using events with the same production kinematics and the Lund string fragmentation model [20]. This change increases $m_c$ by 0.14 GeV/$c^2$.

The only possible relatively-unknown input to the boson-gluon fusion cross section model besides the charm quark mass is the gluon PDF. Changing from the GRV94HO set to CTEQ4M raises $m_c$ by 0.04 GeV/$c^2$. Varying the CTEQ gluon PDF according to the prescription given by its authors [21] produced a maximum variation in $m_c$ of $-0.04$ GeV/$c^2$, and this is used as the systematic error on the gluon PDF.
It is unclear whether the EMC correction \cite{22} for nuclear effects should be applied to boson-gluon fusion processes, so the NC charm fit is performed with and without it. Applying the EMC correction increases the measured \(m_c\) by 0.12 GeV/c\(^2\), and this shift is included as a possible systematic error.

The final systematic error is due to the size of the beam impurities. The beam fit described in the Appendix returns a normalization value and error for each of five separate beam sub-sources. To examine the sensitivity to each individual source, each source normalization is fixed one sigma high and low of its best fit value, and the other sources’ normalizations are extracted. These alternative settings are then applied to \(\nu\)-mode beam impurities, and \(m_c\) is re-extracted. The largest change occurs for scraping and the second largest for beam-produced charm. The sum, in quadrature, of all changes is a shift in \(m_c\) of 0.13 GeV/c\(^2\).

The sum of all systematic errors in quadrature is 0.26 GeV/c\(^2\).

V. SUMMARY AND CONCLUSIONS

Wrong sign muon data in \(\nu_\mu\)Fe scattering data show clear evidence for NC open charm production. The result of a boson-gluon fusion fit with the GRV94HO gluon PDF set to the data yields \(m_c = 1.40^{+0.83}_{-0.36} \pm 0.26\) GeV/c\(^2\). This value of charm mass corresponds to a production cross section \(\sigma(\nu_\mu N \to \nu_\mu c\bar{c}X) = (0.21^{+0.18}_{-0.15})\) fb at an average neutrino energy \(\langle E \rangle = 154\) GeV. The \(m_c\) governing NC neutrino charm production is consistent with the value obtained from CC neutrino charm production \cite{24}, from photo-production, and from charmonium spectroscopy \cite{27}.

Differential cross sections computed with this charm mass, the GRV94HO gluon PDF, and the gluon fusion model are compared to electro-production data in Fig. 6. Our data is sensitive in a region that overlaps the EMC experiment \cite{28}, and it extends to slightly higher \(Q^2\) and slightly lower \(x\). It is consistent with this electro-production data within rather large errors, providing evidence that the boson-gluon fusion process is probe-independent,
as expected from QCD.

Finally, since the NC charm signal can be adequately described by the boson-gluon fusion diagram, there is no evidence for the existence of either a perturbative or non-perturbative intrinsic charm sea from NuTeV data.

ACKNOWLEDGMENTS

We would like to thank the staffs of the Fermilab Particle Physics and Beams Divisions for their contributions to the construction and operation of the NuTeV beamlines. We would also like to thank the staffs of our home institutions for their help throughout the running and analysis of NuTeV. This work has been supported by the U.S. Department of Energy and the National Science Foundation.
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APPENDIX A: DETERMINATION OF CHARM PRODUCTION IN $pN$ SCATTERING AT 800 GEV FROM $\bar{\nu}_\mu$ MODE WSM DATA

Beam impurities are responsible for over 80% of the WSM’s in $\bar{\nu}$-mode. The beam impurities are due to scraping, hadrons (including charm) that decay before the sign-selecting dipoles in the SSQT, neutral kaon decays, muon decays and $K \rightarrow \pi \rightarrow \mu$. Several of these sources are not well-constrained by previous measurements; and $\bar{\nu}$-mode WSM’s can be used to improve knowledge of their normalization. For the case of WSM’s from charm decay, this effectively amounts to performing a new measurement of $\sigma (pN \rightarrow c \bar{c}X)$.

Secondary $\pi$’s and $K$’s are modelled by Malensek’s parameterization [14] of Atherton’s data [15]. The interaction of secondaries with beam elements (scraping) is modeled by GHEISHA [30]. The $K^0$ production is handled by extending Malensek’s charged kaon parameterizations using the quark counting relation $K^0_L = (3K^- + K^+) / 4$. The $K \rightarrow \pi \rightarrow \mu$ process is correctly modeled. Muon decay is a well understood process; however, there is some uncertainty in the polarization $P$ of the beam which should lie within the range $P = 0.1^{+0.2}_{-0.0}$.

Two experiments measure the inclusive cross section for production of $D^\pm$ and $D^0/\bar{D}^0$ mesons with an 800 GeV proton beam (Ammar et al. [17] and Kodama et al. [18]). The weighted average of their production parameters are used as the starting value in this analysis.

A model of the WSM’s is constructed from the beam sources added, with adjustable weights, to non-beam sources (CC and NC charm, $\pi/K$ decay in the shower, and charged mis-measurement), and a binned likelihood fit is performed jointly to the neutrino energy distribution and the vertical position of WSM neutrino interactions in $\bar{\nu}_\mu$ mode. The fit constrains the weight of beam sources, other than charm production, to be consistent with 1.0 within their estimated a priori errors. Table [III] lists these errors and gives the fit results. The only significant deviations from unity of any source normalizations are in the scraping
and charm contributions. The charm result indicates that \( \sum_i \sigma(D_i) \times BF(D_i \rightarrow \nu_\mu) = (9.8 \pm 2.2) \mu b \) be increased of almost 50\% over the a priori estimate. Recalling that there are two mesons for each \( c\bar{c} \) pair, using \( BF(c \rightarrow \mu) = 9.9 \pm 1.2\% \) \[24\], and assuming linear A dependence, one obtains \( \sigma(p + N \rightarrow c\bar{c}) = (49 \pm 11)\mu b \). Figure 7 shows the agreement between neutrino energy \( E_\nu \) of data and MC before and after the fit.

The dominant systematic error, on \( \sigma(p + N \rightarrow c\bar{c}) \), is 5.0 \( \mu b \) due to the uncertainty in \( BF(c \rightarrow \mu) \). The only other large systematic error is 2.3 \( \mu b \) due to the different methods of rejecting events with two muons described in the systematic errors above. Systematic errors due to the normalization of non-beam sources, energy calibrations, parameterization of \( p_t \) and \( x_f \), and the use of the \( y_{vis} < 0.5 \) cut are small. The total of all of these sources is 5.6 \( \mu b \) yielding the final result of \( \sigma(p + N \rightarrow c\bar{c}) = (49 \pm 11 \pm 6) \mu b \).

Using PYTHIA’s \[20\] fragmentation of \( c \) quarks into mesons one can transform Kodama’s and Ammar’s measurements into the measurements of \( \sigma(p + N \rightarrow c\bar{c}) \) found in Table IV. NuTeV’s measurement is consistent with these previous measurements, and has smaller errors.
FIG. 1. Feynman diagram for boson-gluon fusion
FIG. 2. Schematic of the SSQT beamline

FIG. 3. Comparison of data to MC of $E_{\text{had}}/(E_{\text{had}} + E_{\mu2})$ for dimuon events where both muons are toroid-analyzed.
FIG. 4. Distribution of $y_{vis}$ in $\nu_{\mu}$-mode WSM’s for data(solid), background (dashed), and background plus fitted NC signal(dotted).
Fig. 5. Distribution of $y_{vis}$ for WSM's for data (solid), backgrounds (dashed), and background plus NC signal (dotted) with an additional requirement $E_{had} \geq 50$ GeV.

$\chi^2 = 15.1097/14$ dof
FIG. 6. $F_{2}^{charm}$ as a function of $x$, for various $Q^2$. The bands are the gluon-boson fusion cross section using $m_c = 1.40^{+0.83}_{-0.36}$ and the GRV94HO gluon PDF. Data points are from charged lepton scattering from refs. 28 and 29. Our data are sensitive in a region that overlaps EMC but extends to slightly higher $Q^2$ and slightly lower $x$. 
FIG. 7. The $E_\nu$ distribution of WSM events in $\bar{\nu}$-mode before and after the fit.
# TABLES

| Source                        | $\nu$-mode(%) | $\bar{\nu}$-mode(%) |
|-------------------------------|---------------|-----------------------|
| Beam Impurity                 | 67            | 83                    |
| Charged Current Charm         | 19            | 8                     |
| Charge Misidentification      | 5             | 5                     |
| Neutral Current Charm         | 5             | 2                     |
| Neutral Current $\pi/K$ decay | 2             | 1                     |
| Charged Current $\pi/K$ decay | 1             | 1                     |

**TABLE I.** Percentage of WSM’s for each source in a given mode.

| Source                  | $\nu$-mode | $\bar{\nu}$-mode |
|-------------------------|------------|-------------------|
| $\nu > 20$ GeV scraping | 53%        | 24%               |
| charm                   | 10%        | 25%               |
| $K^0$                   | 12%        | 16%               |
| other prompt            | 9%         | 22%               |
| muon decay              | 11%        | 11%               |
| $K \rightarrow \pi \rightarrow \mu$ | 5%        | 2%               |

**TABLE II.** The percentage of beam impurities due to a given source in each mode.
TABLE III. Results of $\bar{\nu}$-mode beam fits. * The $a$ priori charm error is not used to constrain this fit.

| Source | Value | Error | $A$ priori Error Estimate |
|--------|-------|-------|---------------------------|
| charm  | 1.47  | 0.33  | 0.30*                     |
| $K^0$  | 1.01  | 0.29  | 0.20                      |
| scrape | 1.22  | 0.34  | 0.40                      |
| other  | 1.00  | fixed | 0.03                      |
| muon   | 0.95  | 0.11  | 0.07                      |
| prompt | 1.02  | 0.21  | 0.10                      |

TABLE IV. Previous charm meson production cross-sections transformed into charm quark production cross-sections.

| Exp           | $\sigma(p + p \rightarrow c\bar{c})$ from $D^\pm$ measurement | $\sigma(p + p \rightarrow c\bar{c})$ from $D^0$ measurement |
|---------------|---------------------------------------------------------------|----------------------------------------------------------|
| Kodama(1991)  | 75$\pm$18$\pm$28                                            | 47$\pm$4$\pm$16                                          |
| Ammar(1988)   | 51$\pm$8$\pm$13                                             | 27$^{+11}_{-9}$ $\pm$7                                   |