Detailed studies of neutrino-nucleus scattering with νSTORM

Ian TAYLOR[*] **(University of Warwick)**

E-mail: i.taylor@warwick.ac.uk

The Neutrinos from Stored Muons (νSTORM) facility, recently proposed to FNAL and CERN, has the potential to produce excellent neutrino cross-section measurements, as well as definitively answering the question of sterile neutrinos and serving as a technology test bed for future muon accelerator projects.

The main strength of its cross-section measurements is the ability to produce a beam of ν_e and $\bar{\nu}_\mu$ (or $\bar{\nu}_e$ and ν_μ) from muon decay, with absolute confidence in the flavour contributions and 1% precision on the neutrino energy and flux. Previous high-statistics neutrino cross-section measurements have been limited by beam precision, and the resulting uncertainties have often constituted the dominant systematic uncertainty in neutrino oscillation experiments. Improved measurements and models would lead to significant increases in the sensitivity of future long-baseline experiments.

---

[*]Speaker.

1. Introduction

The proposed Neutrinos from Stored Muons (νSTORM) Facility [1, 2] has been designed to deliver beams of $\overset{\scriptscriptstyle(-)}{\nu}_\mu$ and $\overset{\scriptscriptstyle(-)}{\nu}_e$ from the decay of a stored $\mu^\pm$ beam with a central momentum of 3.8 GeV/c and a momentum spread of 10%. The proposed facility is unique in that it will:

- Serve the future long- and short-baseline neutrino-oscillation programmes by providing definitive measurements of neutrino and anti-neutrino scattering cross-sections with percent-level precision, for both electron and muon flavours;

- Allow searches of exquisite sensitivity for sterile neutrinos to be carried out; and

- Constitute the essential first step in the incremental development of muon accelerators as a powerful new technique for particle physics.

Neutrino physics has seen some very exciting results recently, with first measurements of the last unknown neutrino mixing angle, θ_{13}, from the T2K[3], Daya Bay[4], RENO[5], and Double Chooz[6] experiments. A relatively large value of θ_{13} has ensured that measurements of the CP violating phase, δ, will be possible for the next generation of long-baseline ν oscillation experiments; LBNE, LBNO & T2HK.

However, the measurements of this next phase will require a large increase in sensitivity, as the detection of a non-zero δ will rely on observing differences between either a) the rates of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation or b) the ν_e flux in the 1st and 2nd maxima of $\nu_\mu \to \nu_e$ oscillation. The sensitivity to CP-invariance violation depends critically on cross-section dependent systematic effects in general and $\overset{\scriptscriptstyle(-)}{\nu}_e N$ cross-sections in particular. At νSTORM, the flavour composition and neutrino-energy spectrum of the beam can be determined to a precision of 1% or better. This makes νSTORM unique in being able to measure $\overset{\scriptscriptstyle(-)}{\nu}_e N$ and $\overset{\scriptscriptstyle(-)}{\nu}_\mu N$ cross-sections with a precision $\simeq 1\%$ over the required neutrino-energy range, $0.5 < E_\nu < 3$ GeV, including detailed studies of different nuclear targets and hadronic final states.

2. Neutrino Nucleon Scattering

2.1 Current Generation Measurements

The current generation of neutrino-oscillation experiments employ neutrino-interaction models developed in the 1970's and 1980's [7–9]. In the energy region of interest to long-baseline oscillation experiments, 0.1 GeV - 3 GeV, the dominant reaction types are quasi-elastic scattering, resonant and coherent pion-production, and deep inelastic scattering. High statistics neutrino-nucleon scattering measurements made by K2K [10–13], MiniBooNE [14–20] and SciBooNE [21–24] indicate that the quasi-elastic scattering and pion-production models do not describe nature. The basic neutrino-nucleon cross-sections are only known to the 20%-30% level. The two main contributing factors are the poor knowledge of neutrino fluxes and the use of nuclear targets for all recent cross-section measurements. The measurements made are all a convolution of an energy-dependent neutrino flux, energy-dependent neutrino-nucleon cross-sections, energy-dependent nuclear effects, and energy-dependent event selection criteria in particle detectors.

2

Neutrino-nucleon charged-current quasi-elastic (CCQE) scattering, $\nu_l + n \rightarrow l^- + p$, is the dominant cross-section in the 1 GeV energy region, and normally the selected oscillation signal. It also has the advantage of allowing for an estimate of neutrino energy, reconstructed from the energy and angle of the exiting lepton, with respect to the neutrino beam direction. Despite this importance to the field and its relative simplicity, the CCQE cross-section is known with limited accuracy. This is due to the large neutrino-flux uncertainties of pion decay produced neutrino beams and the complicated nuclear effects of interacting with bound nucleons in a nuclear target. For example, the SciBooNE ν_μ-CCQE measurement [21] was of an effective neutrino-carbon cross-section with a CCQE purity of 65%. The systematic uncertainty of the measurement was energy-dependent and in the region of 25%.

The standard theoretical models of CCQE scattering have assumed that the channel was governed by a single free parameter, the axial mass (M_A). However, recent measurements have shown a wide range of M_A results (1.07 – 1.35), all significantly larger than the previous world average of 1.02. This was particularly marked in the $\nu_\mu C$ double-differential result from MiniBooNE [15]. As MiniBooNE was insensitive to final-state nucleons, and was using a carbon target as opposed to D_2, the measurement is strictly of CCQE-like events. Several theoretical groups [25, 26] have demonstrated that models containing significant contributions from $np - nh$ mechanisms, which allow n particles and n holes, with $n \geq 2$, in the final state, can provide better agreement, but complicate the modelling process.

The CCQE channel has been discussed as an example of the state of current models, but is in no way unique in terms of the model complexity, disagreement with nature or general uncertainties. Differences are expected between ν_μ and ν_e cross-sections, due to the difference in outgoing lepton mass and radiative corrections, but no ν_e beam has ever been available to directly measure and confirm those differences. Models and approximations are relied upon for all ν_e predictions in long-baseline experiments, limiting the possible precision of any ν_e appearance measurement.

2.2 Limitations of Pion Produced Beams

Despite the complications of multiple nuclear targets and correctly identifying the final states of neutrino interactions, the main uncertainty in neutrino-nucleus cross-sections is due to the uncertainty in the flux and energy spectrum of the measured neutrino beam. The production method for most ν_μ beams is fairly standard: protons are accelerated to high energies (8 GeV for Mini-BooNE/SciBooNE, 30 GeV for T2K, 120 GeV for MINOS) and sent into a solid target (Beryllium for MiniBooNE/SciBooNE, graphite for T2K/MINOS). The subsequent interaction produces large quantities of pions and kaons. A series of magnetic horns is used to focus the positive particles, while simultaneously defocussing the negative particles. The ν_μ are produced from the decay of these particles:
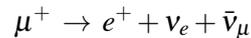
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$K+ \rightarrow \mu^+ + \nu_\mu, \pi^+ + \pi^0$$

The decay volume generally ends in a beam dump, to slow the secondary muons and prevent their
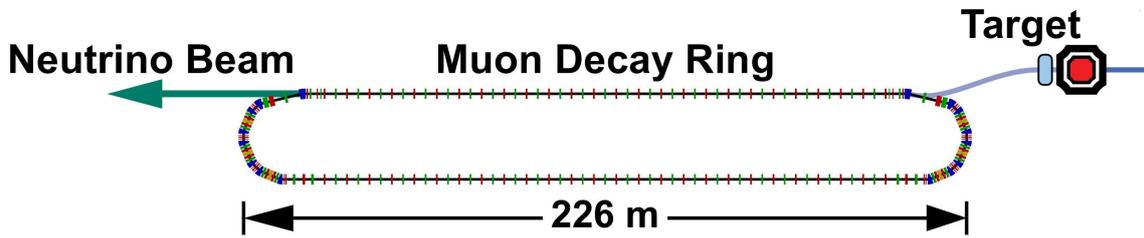
Figure 1: Schematic of the νSTORM facility.

decays at high energy. Still, some proportion of the muons will decay in flight:

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

producing a contamination of ν_e and $\bar{\nu}_\mu$ in the neutrino beam.

Characterisation of a pion-produced beam relies on a complicated Monte Carlo, covering the full chain of particle production and decay. Indirect measurements can be made, for example by monitoring high energy muons in the beam dump, but the method still leads to large uncertainties in both the absolute number of neutrinos and their energy distribution. These represent an irreducible limit on cross-section measurements, at approximately the 10% level.

3. The νSTORM Proposal

The νSTORM proposal represents the simplest form of the neutrino factory idea. Neutrinos are produced from the decay of muons in flight, which can be well characterised from beam monitoring tools. The full Neutrino Factory design [27, 28] uses accelerated muons with a central beam momentum of 25 GeV/c, a process which relies on the initial cooling of the muon beam [29]. In the νSTORM design, neutrinos come from an un-cooled, un-accelerated, muon beam, produced using the same mechanism of pion decay as described in the previous section. This results in a lower energy, lower luminosity beam, but still provides the benefits of a precise neutrino flux.

Two of the world's proton-accelerator laboratories, CERN and FNAL, have the infrastructure required to mount νSTORM. No siting decision has been made, and investigations are progressing for implementations of νSTORM at both locations, with an international collaboration hoping for support from both sites. A Proposal has been submitted to FNAL PAC and an Expression of Intent to CERN, requesting funding to prepare a full design report.

3.1 Neutrino Beam Production

Figure 1 shows a schematic of the proposed νSTORM beamline. The target facility operates under the same principles as described previously, with 60 (100) GeV protons from the Fermilab Main Injector (CERN SPS). Details for the target are still being investigated, including the target material and position of potential focussing magnets.
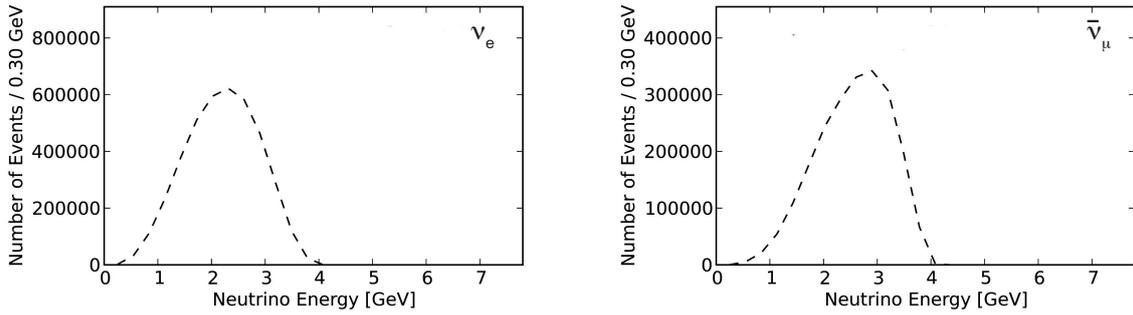
Figure 2: ν_e (left) and $\bar{\nu}_\mu$ (right) event rates per 100 T in a detector placed ~ 50 m from the end of one of the straight sections (for a stored μ^+ beam) at νSTORM.

Pions from the target are channelled through a magnetic chicane, effectively removing all particles other than the correctly charged pions (pion charge can be selected by reversing magnetic fields). The pions are then injected into a racetrack style decay ring, with two straight sections of 185 m each and a total circumference of 480 m (for the current FNAL design). A proportion of the pions will decay along the first straight, leaving muons travelling along the beamline. The turns of the decay ring have been tuned to turn muons with momentum of 3.8 GeV $\pm$ 10%. After the first lap, only muons survive, leaving a clean sample to produce neutrinos through the decay:

$$\mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e$$

νSTORM could equally produce a ν_μ, $\bar{\nu}_e$ beam, by reversing magnet polarities.

This guarantees that the number of neutrinos and anti-neutrinos produced by νSTORM will be exactly equal. The number of muons can be measured by beam monitoring tools at the beginning and end of the decay straight, which gives a precise prediction of the neutrino flux. Our measurement goals for the suite of beam instrumentation diagnostics in the decay ring include:

- Measuring the circulating muon intensity (on a turn by turn basis) to 0.1% absolute.

- Measuring the mean momentum to 0.1% absolute.

- Measuring the momentum spread to 1% (FWHM).

The energy of the produced neutrinos is dependent only on the physics of muon decay, which is precisely known, and the momentum of the decaying muon, allowing for an accurate prediction of the energy spectrum, as shown in Figure 2.

3.2 Cross-section Measurement Facility

The precisely defined beam will allow νSTORM to make excellent measurements of neutrino cross-sections, but this will also require a suitable selection of particle detectors. The range of measurements to be made is very wide, and the νSTORM proposal doesn't claim to know the best selection of detectors required to make the best measurements. Instead, the goal is to provide a communal facility for cross-section measurements. The Near Detector (ND) Hall will be located 20 m from the end of the decay ring (in the FNAL proposal), a short distance that will maximize

the neutrino flux and ensure that even sterile neutrino oscillation parameters wouldn't effect the neutrino beam composition. The ND Hall will have slots for three neutrino detectors.

The first detector will be the near detector for the short baseline sterile neutrino oscillation search. The Super B Iron Neutrino Detector (SuperBIND), an iron and scintillator calorimeter similar in concept to the MINOS detector, will be a 100 ton magnetized detector, optimized for measuring CCQE ν_μ interactions, the golden channel of the sterile neutrino search, and paired with a 1.6 kton far detector at 1.5 km. It is expected to have limited possibilities for cross-section measurements.

The detectors for the two remaining slots are undefined, but initial investigations are under way. The second detector is proposed to be a test bed for the near detector of one of the next generation long-baseline experiments, either LBNE or LBNO. This will provide an excellent opportunity to understand the ND before it is used to characterise a long-baseline beam. By calibrating the detector with the νSTORM 'ν light source' beam, the relevant cross-sections, detector uncertainties and energy thresholds can be determined prior to LBNE/LBNO running. This would allow the ND to make a direct measurement of the LBNE/LBNO beam, rather than the convolution of beam, cross-section and detector effects described earlier.

The final detector slot would be for dedicated cross-section measurements. Detectors wouldn't necessarily be installed for the full 5 years of νSTORM's initial proposed run. Instead, detectors could be designed and tuned to specific cross-section measurements. This would allow for a range of detector technologies to be used and tested; a targeted detector design has been observed to be more effective at cross-section measurements than a generic detector. The detector required to correctly reconstruct a 200 MeV π^0 from a $\nu_l + X \rightarrow \nu_l + X' + \pi^0$ interaction is very different in design to a detector optimised for momentum measurements of 2 GeV muons while simultaneously detecting low energy nucleons for a concerted effort at measuring ν_μ CCQE. Early calculations for a ND Hall at 50 m show that in a 1 year period, with νSTORM running in μ^+ configuration, a ND could expect to see almost 8,000 ν_e CC and over 4,000 $\bar{\nu}_\mu$ CC events per ton of fiducial volume [1].

Multiple detectors would also allow for the inclusion of multiple nuclear target materials. The LBNE, T2HK and LBNO experiments are expected to have far detector targets of Ar, H_2O and C respectively. Cross-section measurements for all of these materials would allow for better comparisons and combined fits between the three experiments. At the same time, the best way to disentangle the effects of neutrino-nucleon interactions and nuclear effects is to take data with H_2 and D_2 targets. H_2 allows for directly measuring the neutrino-nucleon interaction, while a D_2 target provides the simplest state containing a neutron, required for a ν_l CCQE measurement. Data of this type has not been taken since the bubble chamber measurements at CERN in the 1980's (e.g. [30]). Theorists have expressed great interest in modern, higher statistics measurements of these channels.

In fact, one option of particular interest to this researcher is reviving the bubble chamber detector. A rapid cycling H_2 bubble chamber, using fast CMOS detectors, would be a good match in cycling rate to the νSTORM beam, providing a fully instrumented detector with excellent vertex activity detection and particle identification abilities. There are obvious difficulties and safety concerns in working with H_2, which would require detailed examination, but the physics potential of the measurement makes for a compelling prospect.

4. Summary

The νSTORM facility represents an opportunity to provide a 'neutrino light source', an unparalleled beam with a precise flux, known to the 1% level. This would remove the main systematic uncertainty from previous measurements of neutrino cross-sections, and with the correct set of neutrino detectors could move the field past its current limits of 20–30% errors in even the best channels. Simultaneously, the facility would serve as an important technology test bed for muon accelerator technology, leading to future Muon Colliders or Neutrino Factories, and would definitely answer the question of sterile neutrinos, with 10σ coverage of the region of interest within 5 years.

Proposals have been presented to both FNAL and CERN, requesting funding for detailed design studies over the next 2 years, sited at either of the facilities. The proposals would include two slots for community-defined neutrino detectors, with a clear goal of world-leading cross-section measurements and detector technology development. The νSTORM collaboration is new, having grown organically through the preparation of the initial proposals, and welcomes input from parties interested in contributing ideas or effort; please contact Alan Bross, bross@fnal.gov.

References

[1] **nuSTORM Collaboration** Collaboration, P. Kyberd *et al.*, "nuSTORM - Neutrinos from STORed Muons: Letter of Intent to the Fermilab Physics Advisory Committee," arXiv:1206.0294 [hep-ex].

[2] **nuSTORM Collaboration** Collaboration, D. Adey *et al.*, "Neutrinos from stored muons (storm): Expression of interest," Tech. Rep. CERN-SPSC-2013-015. SPSC-EOI-009, CERN, Geneva, Apr, 2013.

[3] **T2K Collaboration** Collaboration, K. Abe *et al.*, "Indication of Electron Neutrino Appearance from an Accelerator-produced Off-axis Muon Neutrino Beam," *Phys.Rev.Lett.* **107** (2011) 041801, arXiv:1106.2822 [hep-ex].

[4] **DAYA-BAY Collaboration** Collaboration, F. An *et al.*, "Observation of electron-antineutrino disappearance at Daya Bay," *Phys.Rev.Lett.* **108** (2012) 171803, arXiv:1203.1669 [hep-ex].

[5] **RENO collaboration** Collaboration, J. Ahn *et al.*, "Observation of Reactor Electron Antineutrino Disappearance in the RENO Experiment," *Phys.Rev.Lett.* **108** (2012) 191802, arXiv:1204.0626 [hep-ex].

[6] **DOUBLE-CHOOZ Collaboration** Collaboration, Y. Abe *et al.*, "Indication for the reactor anti-neutrino disappearance in the Double Chooz experiment," *Phys.Rev.Lett.* **108** (2012) 131801, arXiv:1112.6353 [hep-ex].

[7] C. Llewellyn Smith, "Neutrino Reactions at Accelerator Energies," *Phys.Rept.* **3** (1972) 261–379.

[8] R. Smith and E. Moniz, "NEUTRINO REACTIONS ON NUCLEAR TARGETS," *Nucl.Phys.* **B43** (1972) 605.

[9] D. Rein and L. M. Sehgal, "Neutrino Excitation of Baryon Resonances and Single Pion Production," *Annals Phys.* **133** (1981) 79–153.

[10] **K2K Collaboration** Collaboration, R. Gran *et al.*, "Measurement of the quasi-elastic axial vector mass in neutrino-oxygen interactions," *Phys.Rev.* **D74** (2006) 052002, arXiv:hep-ex/0603034 [hep-ex].

[11] **K2K Collaboration** Collaboration, A. Rodriguez *et al.*, "Measurement of single charged pion production in the charged-current interactions of neutrinos in a 1.3-GeV wide band beam," *Phys.Rev.* **D78** (2008) 032003, arXiv:0805.0186 [hep-ex].

[12] **K2K Collaboration** Collaboration, C. Mariani, "Charged current neutral pion cross section measurement at K2K," *AIP Conf.Proc.* **1189** (2009) 339–342.

[13] **K2K Collaboration** Collaboration, S. Nakayama *et al.*, "Measurement of single pi0 production in neutral current neutrino interactions with water by a 1.3-GeV wide band muon neutrino beam," *Phys.Lett.* **B619** (2005) 255–262, arXiv:hep-ex/0408134 [hep-ex].

[14] **MiniBooNE Collaboration** Collaboration, A. Aguilar-Arevalo *et al.*, "Measurement of muon neutrino quasi-elastic scattering on carbon," *Phys.Rev.Lett.* **100** (2008) 032301, arXiv:0706.0926 [hep-ex].

[15] **MiniBooNE Collaboration** Collaboration, A. Aguilar-Arevalo *et al.*, "First Measurement of the Muon Neutrino Charged Current Quasielastic Double Differential Cross Section," *Phys.Rev.* **D81** (2010) 092005, arXiv:1002.2680 [hep-ex].

[16] **MiniBooNE Collaboration** Collaboration, A. Aguilar-Arevalo *et al.*, "Measurement of the ν_μ charged current π^+ to quasi-elastic cross section ratio on mineral oil in a 0.8-GeV neutrino beam," *Phys.Rev.Lett.* **103** (2009) 081801, arXiv:0904.3159 [hep-ex].

[17] **MiniBooNE Collaboration** Collaboration, A. Aguilar-Arevalo *et al.*, "Measurement of Neutrino-Induced Charged-Current Charged Pion Production Cross Sections on Mineral Oil at $E_\nu \sim 1$ GeV," *Phys.Rev.* **D83** (2011) 052007, arXiv:1011.3572 [hep-ex].

[18] **MiniBooNE Collaboration** Collaboration, A. Aguilar-Arevalo *et al.*, "Measurement of ν_μ-induced charged-current neutral pion production cross sections on mineral oil at $E_\nu \in 0.5 - 2.0$ GeV," *Phys.Rev.* **D83** (2011) 052009, arXiv:1010.3264 [hep-ex].

[19] **MiniBooNE Collaboration** Collaboration, A. A. Aguilar-Arevalo *et al.*, "Measurement of nu(mu) and anti-nu(mu) induced neutral current single pi0 production cross sections on mineral oil at E(nu) O(1- GeV)," *Phys.Rev.* **D81** (2010) 013005, arXiv:0911.2063 [hep-ex].

[20] **MiniBooNE Collaboration** Collaboration, A. Aguilar-Arevalo *et al.*, "Measurement of the Neutrino Neutral-Current Elastic Differential Cross Section on Mineral Oil at $E_\nu \sim 1$ GeV," *Phys.Rev.* **D82** (2010) 092005, `arXiv:1007.4730 [hep-ex]`.

[21] **SciBooNE Collaboration** Collaboration, J. L. Alcaraz-Aunion and J. Walding, "Measurement of the nu(mu)-CCQE cross-section in the SciBooNE experiment," *AIP Conf.Proc.* **1189** (2009) 145–150, `arXiv:0909.5647 [hep-ex]`.

[22] **SciBooNE Collaboration** Collaboration, Y. Nakajima *et al.*, "Measurement of inclusive charged current interactions on carbon in a few-GeV neutrino beam," *Phys.Rev.* **D83** (2011) 012005, `arXiv:1011.2131 [hep-ex]`.

[23] **SciBooNE Collaboration** Collaboration, Y. Kurimoto *et al.*, "Measurement of Inclusive Neutral Current Neutral pi0 Production on Carbon in a Few-GeV Neutrino Beam," *Phys.Rev.* **D81** (2010) 033004, `arXiv:0910.5768 [hep-ex]`.

[24] **SciBooNE Collaboration** Collaboration, Y. Kurimoto *et al.*, "Improved measurement of neutral current coherent π^0 production on carbon in a few-GeV neutrino beam," *Phys.Rev.* **D81** (2010) 111102, `arXiv:1005.0059 [hep-ex]`.

[25] J. Nieves, I. Ruiz Simo, and M. Vicente Vacas, "The nucleon axial mass and the MiniBooNE Quasielastic Neutrino-Nucleus Scattering problem," *Phys.Lett.* **B707** (2012) 72–75, `arXiv:1106.5374 [hep-ph]`.

[26] M. Martini, M. Ericson, and G. Chanfray, "Neutrino quasielastic interaction and nuclear dynamics," *Phys.Rev.* **C84** (2011) 055502, `arXiv:1110.0221 [nucl-th]`.

[27] **ISS Physics Working Group** Collaboration, A. Bandyopadhyay *et al.*, "Physics at a future Neutrino Factory and super-beam facility," *Rept. Prog. Phys.* **72** (2009) 106201, `arXiv:0710.4947 [hep-ph]`.

[28] **IDS-NF Collaboration** Collaboration, S. Choubey *et al.*, "International Design Study for the Neutrino Factory, Interim Design Report," `arXiv:1112.2853 [hep-ex]`.

[29] The MICE collaboration, "MICE: An International Muon Ionization Cooling Experiment,Technical Reference Document." MICE-TRD-2005, 2005.

[30] P. Allen *et al.* [Aachen-Birmingham-Bonn-CERN-London-Munich-Oxford Collaboration], "A Study Of Single Meson Production In Neutrino And Anti-neutrinos Charged Current Interactions On Protons," Nucl. Phys. B **264** (1986) 221.

PoS(DIS 2013)265