Hadron Production Measurements for Fermilab Neutrino Beams

US participation in the NA61/SHINE experiment at CERN

Letter of Intent

May 2, 2012

Abstract

This is a Letter of Intent to develop a limited-scope collaboration with the NA61/SHINE experiment at CERN to exploit its unique capabilities for particle production measurements. This effort would allow the US group to collect dedicated and optimized high-precision hadron production data needed for improved neutrino beams modeling necessary for ongoing and future experiments at Fermilab. The ultimate goal of this effort is to expose thin targets and replicas of targets used at Fermilab to the NA61 hadron beam to accumulate a suitably large sample of events to provide a data set which would be essential for future neutrino beams.

An initial phase of this program, to be supported by existing funds, will be a two-day pilot run during the start-up of the 2012 run of NA61/SHINE. The pilot run will use a 120 GeV/c proton beam on a thin graphite target. It could provide valuable data for the MINERvA experiment, and would allow the US group to gain better practical understanding of the capabilities of the NA61/SHINE experiment so that a broader collaborative program can be fully developed for later years. We envision this program to serve many future accelerator-based neutrino experiments at Fermilab and elsewhere.

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1 Introduction

Precision calculations of neutrino fluxes in high energy accelerator beams are presently limited by insufficiently detailed knowledge of hadron production cross-sections in proton-nucleus collisions. Modeling of strong interaction cascades and hadronic yields from targets which are a couple of interaction-lengths long relies on detailed knowledge of underlying physics and cross-sections which must be provided as a starting point to simulations. The resulting prediction of the flux of neutrinos, produced from decays of pions, kaons, and muons emerging from a hadronic shower and beamline re-interactions, is usually an essential part of simulations of most neutrino experiments. Even two-detector neutrino oscillations experiments, which predict the neutrino flux at the far detector by using neutrino fluxes “calibrated” (or appropriately scaled) by event energy spectra measured in the near detector, must rely on the beam simulations since the decay pipe (i.e., the neutrino source) extends different angular acceptance for the two detectors. An opportunity to help remedy this situation for the NuMI and possibly other Fermilab beams, similar to the T2K effort on NA61, is briefly presented in this letter of intent.

2 The US-NA61 Collaboration

We propose to exploit an attractive, cost-effective opportunity to measure the secondary hadron production spectra in the kinematical region of interest to ongoing and future neutrino experiments at Fermilab, by launching a limited in scope and duration collaboration (henceforth referred to as US-NA61) with an existing CERN experiment NA61/SHINE [1]. By collecting large statistical data samples in dedicated runs, this work would significantly improve modeling of neutrino beam fluxes – an essential component of precision experiments at the Intensity Frontier.

2.1 Project time line

We expect this effort to span a period of about 4-5 years. The proposed work will include simulations of the NA61/SHINE detector (to optimize the detector for Fermilab beams), then data taking, calibration, reconstruction, and analysis. The main deliverables of this work will be particle production yields that could be directly applied in beam simulations. The time scale is suitable to involve graduate students and postdocs so that they could participate in all phases of this plan and could build a high-level expertise in hadron production and neutrino (or other) beam simulations. Such experts are greatly needed for the Intensity Frontier program at Fermilab.

Presently we are establishing closer contacts with NA61/SHINE to better understand both the physics potential of the experiment and future operational relationship to execute the proposed US program. Our goal is to develop a detailed proposal that will include expanded (compared to the LOI) descriptions of impacted experiments, motivations for data, data requirements, schedule, and funding issues. We are recruiting students/postdocs to do Monte Carlo studies of NA61 acceptance and triggering with technical input from the NA61/SHINE collaboration. Additional studies of systematics for impacted neutrino experiments with and without these data will be also conducted. As a result, a detailed run plan using different targets, target orientations, beam energies, and needed statistics will be developed. It will need to be proposed in collaboration with NA61/SHINE and will be blended with their existing program which, as we are informed, will very likely be able to accommodate the US part. In May 2012, representatives of the US group will attend the NA61/SHINE collaboration meeting and discuss the proposal and plans in person with the leaders of the NA61/SHINE collaboration. After agreement between the two parties has been reached, we will submit a formal request to the DOE.

As an initial phase of this collaboration with NA61/SHINE, the US university groups on T2K that are also involved in this proposal will start to help in the analysis of existing NA61/T2K thick-target data to gain experience with the NA61/SHINE analysis packages and procedures. This work will continue for at least a year. In June 2012, the US group will visit CERN to participate in the pilot run of a 120 GeV/c beam on a thin target. This will be the existing T2K thin carbon target and holder. The run will allow the US group to become familiar with the capabilities of the NA61 detector, and will help in better understanding what exactly will be needed for future US-NA61 runs. No beam is expected in 2013, so all targets, target supports, and any required hardware needs for specialized triggering that will be determined by the detailed Monte Carlo studies may be fabricated during that period.

In this Letter, we sketch out the physics motivation for the proposed measurements and outline a tentative work-plan for this effort. As context for this work, we also provide some details on the NA61/SHINE experiment and briefly summarize the existing relevant data .

2.2 Necessary resources

2.2.1 Manpower

From recent discussions with our NA61/SHINE colleagues, the US effort required to put a NuMI target replica into NA61 and produce useful results will ultimately require about 15 man-years of collaboration and analysis effort. A survey of US institutions resulted in an estimate of committed manpower and is summarized in Table 1 and shows that this requirement can be met with the present level of interest. The large majority of these FTE's would be paid for by redirecting existing operating budgets from the contributing institutions. For FY2012 no new DOE personnel funds will be required. In FY2013-15 funds for approximately a quarter of a postdoc for each year is requested. In FY2013 support for a quarter of graduate student and in FY2014-15 support for a full graduate student per year is anticipated.

	Senior Personnel (Fraction FTE)	Post Docs (Fraction FTE)	Graduate Students (Fraction FTE)
FY2012	1.6	1.3	1.6
FY2013	1.7	2.1	3.3
FY2014-15	2	2.8	3.8

Table 1: Summary of Estimated US-NA61 Manpower Commitments

2.2.2 Travel

As described in section 2.1 there will be periods of time that members of US institutions will be involved with the data taking at CERN and attending NA61/SHINE collaboration meetings. An estimate of the projected travel costs for the anticipated project period is summarized in Table 2. Both funds from redirection of existing operating budgets and anticipated additional requests to US funding agencies are shown.

	Travel Costs (Redirection of existing Funds)	Travel Costs (New Requests)
FY2012	\$23K	\$15K
FY2013	\$29K	\$40K
FY2014-15	\$26K	\$40K

Table 2: Summary of Estimated US-NA61 Travel Requests

2.3 Future requests for detector operations

Other than the redirected manpower efforts and travel, the required resources are target and supplies, possibly the upgraded Time-of-Flight (ToF) electronics, and collaboration common funds.

During the June 2012 run with 120 GeV/c protons on a thin target, we expect to use the T2K carbon thin target and holder and therefore will not be required to produce these items. For the bulk of the future running (2014) we plan on using the spare NuMI (96 cm-long) target. Preliminary discussions with FNAL indicate that we will be allowed access and use of this target at that time.

A possible US hardware contribution to NA61/SHINE is an upgrade to the ToF readout electronics. The present system is based on FASTBUS so NA61/SHINE is having a difficult time finding spare parts and therefore wishes to replace it with more a modern system. The estimate to replace the approximately 2000 channels is about \$300K. The request is for the ToF electronics to be operational for the 2014 run period. In addition, members of the NA61/SHINE collaboration are expected to supply 9K CHF per year per institution in the form of common funds.

3 The two-day pilot run in June 2012

A two-day pilot run is agreed upon with the NA61/SHINE collaboration to take place on June 23 and 24, 2012. The data with 120 GeV/c proton beam on a thin carbon target will allow to determine primary pion and kaon production cross-sections over a range of momenta and angles relevant for the NuMI and LBNE beams. The data will be useful for MINERvA to measure neutrino cross-sections, and for MINOS+ in high-statistics neutrino oscillation studies. The pilot

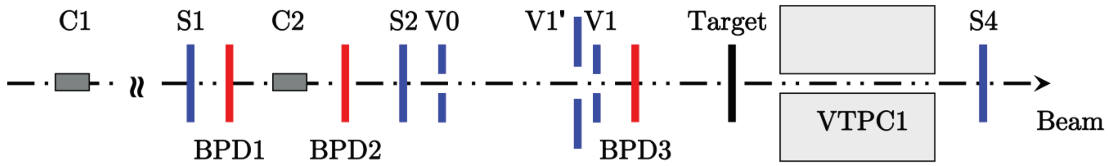


Figure 1: The layout of the trigger counters used to form the various beam triggers. The S counters are scintillators, the V counters are veto scintillators with a 1 cm hole for the beam, the C counters are Cherenkov detectors for determining particle type, and the BPD are proportional wire chambers with cathode strip readout. C1 is a CEDAR (Cherenkov Differential counter with Achromatic Ring Focus) device and C2 is a threshold Cherenkov counter.

Target	Trigger	prescale	Logic	B field	Events
Thin Graphite	prot. interaction	1	$S1 \cdot S2 \cdot \overline{V} \cdot C1 \cdot \overline{C2} \cdot \overline{S4}$	6.8 T-m	900k
Thin Graphite	beam particle	200	$S1 \cdot S2 \cdot \overline{V}$	6.8 T-m	250k
Thin Graphite	interaction	10	$S1 \cdot S2 \cdot \overline{V} \cdot \overline{S4}$	6.8 T-m	250k
NoTarget	interaction	1	$S1 \cdot S2 \cdot \overline{V} \cdot \overline{S4}$	6.8 T-m	10k

Table 3: Trigger configurations for June run. There will be three trigger types: a proton interaction trigger, and two beam pre-scaled triggers, with and without interaction requirement. In addition, a target-out run will be necessary to measure non-target related backgrounds. In this table $\overline{V} \equiv \overline{V_0} \cdot \overline{V_1} \cdot \overline{V_1'}$.

run will also help evaluate the capabilities of NA61/SHINE, and will acquaint US-NA61 collaborators with the NA61/SHINE hardware, electronics, triggering system, reconstruction software, and analysis software. This operational experience will be helpful in planning for the full US-NA61 program after the CERN shutdown in 2013.

Figure 1 is a schematic of the NA61/SHINE beamline trigger instrumentation. The instrumentation includes three scintillator counters (S1, S2, and S4), a differential Cherenkov counter (C1), a threshold Cherenkov counter (C2), and three veto counters (V0, V1, and V1') . The configuration of the trigger will include a proton interaction trigger, a prescaled beam particle trigger, and a prescaled "all interaction" trigger which includes pions and kaons along with the protons, as shown in Table 3.

The pilot run data will be analyzed over the next year with the goal of publishing a result in the summer of 2013. We will be dependent upon the NA61/SHINE collaboration for software and calibration support, and it is hoped that the TPC calibration can be done in a timely fashion after the NA61/SHINE run ends in late 2012. A successful completion of this analysis will improve the likelihood of success of the overall US-NA61 proposal.

4 Physics motivation

The lack of precision measurements of hadron yields has been a long-standing problem pursued from both the theoretical and experimental side. A number of dedicated experiments [1, 2, 3, 4, 5, 6] were conducted in the past thus significantly complementing earlier results [7, 8, 9, 10, 11, 12]. Results of these experiments constituted phenomenological inputs into various beamline modelings. The most common and useful models developed over the years [13, 14] are much improved but fall short in correctly predicting energy spectra measured by recent Fermilab experiments [15, 16] which use the Neutrinos at the Main Injector beamline (NuMI) and the Booster Neutrino Beam (BNB). This mis-modeling will constitute a serious if not the dominant limiting factor in the upcoming precision measurements by MINERvA, MINOS+, MiniBooNE, MicroBooNE, NOvA, and future Long Baseline Neutrino Experiment (LBNE).

An opportunity to make hadro-production measurements in a cost effective manner has presented itself recently at the NA61/SHINE experiment. NA61 [1] is an upgraded NA49 spectrometer [18], presently operating at the North Area's SPS beamline at CERN whose main physics goals are proton-nucleus and nucleus-nucleus collisions. A schematic of the experiment is shown in Figure 2. This beam and detector provide currently the best experimental setup to measure the necessary cross-sections for present and future Fermilab neutrino beams and targets. The experiment has been already used to provide similar measurements for the T2K experiment [20, 21].

Members of Fermilab neutrino experiments that use both the NuMI and BNB beams have been invited to join the NA61/SHINE effort to conduct measurements of hadronic yields from Fermilab targets. These measurements could potentially span energies ranging from 9 GeV to 120 GeV on a number of target materials. A possible set of measurements is shown in Table 4. Those measurements are designed to cover the needs of MINERvA, MINOS, MINOS+, NOvA, MicroBooNE,

	Incident proton/pion beam momentum			
Target	120 GeV/c	90 GeV/c	60 GeV/c	8.9 GeV/c
NuMI (spare) replica	201X			
BNB replica				201X
LBNE replica	201X			
thin graphite ($< 0.05\lambda_I$)	**2012**	201X	201X	
thick graphite ($\sim 1\lambda_I$)	201X	201X	201X	

Table 4: Target and beam settings which could be relevant to US neutrino experiments. The **2012** entries are settings that might be run in 2012, while the 201X entries correspond to settings that could be run after the CERN 2013-14 shutdown.

MiniBooNE, and LBNE. This program cannot be executed before the CERN shutdown, presently planned for 2013, and thus may become a part of NA61/SHINE program in 2014 and beyond. However, as a first step in this program, we propose to take a pilot run during the NA61/SHINE startup period at 120 GeV that would provide some critical measurements for the NuMI beam and for LBNE. That data would be used in the NuMI modeling to directly help MINERvA determine the neutrino flux more precisely, which would result in reduced uncertainties of MINERvA absolute cross-section measurements. These improvements would also help in the optimization of the LBNE target and beamline design and provide more reliable event rate estimates needed in detector design.

5 The NA61/SHINE detector

The NA61/SHINE detector is an upgrade of the NA49 spectrometer. It is a large magnetic spectrometer comprised of large gas TPC's for particle tracking and particle ID. The Particle ID is accomplished with a combination of ToF counters and dE/dx measurements [32]. It has now been used successfully to measure hadro-production in proton-carbon collisions at 31 GeV/c for the T2K neutrino experiment [20, 21]. Figure 2 shows a schematic of the NA61 detector. The detector is built around two large dipole magnets with a combined bending power of up to 9 T-m. The

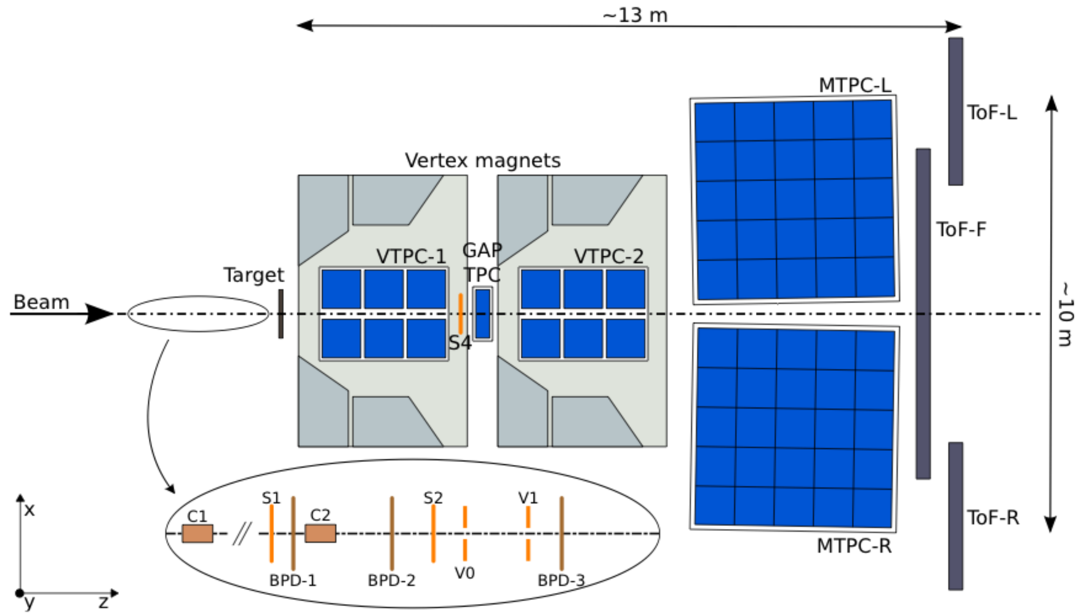


Figure 2: The NA61 experimental apparatus. The experiment is centered around two large dipole magnets, which can generate a combined 9 T-m of bending power. The magnet gaps and downstream area are filled with a large TPC system, which is in turn followed by a wall of ToF counters. The beam trigger is comprised of two Cherenkov counters C1/C2, two scintillator counters S1/S2, two veto counters (V0/V1, and three tracking chambers BPD1-3.

air gaps in the dipoles, and the space following the dipoles are filled with TPC particle tracking systems. The TPC's are designed to measure both charged particle momenta, and to provide dE/dx measurements for particle identification (PID). The TPC's are followed by three separate sections of time-of-flight (ToF) counters, ToFR, ToFL, and ToFF, which aid in PID below momenta of about 5 GeV/c. The ToFR/L sections are tiled sections of scitillator with a timing resolution of about 60 ps, while the forward ToFF are long bars with a resolution of about 110 ps.

Typical acceptances of the NA61 spectrometer for charged particles are shown in Figure 3 for four different magnet settings.The efficiencies scale roughly as momentum divided by magnetic field (p/B), so that one can rescale the plots in Figure 3 to any field setting. A setting of 6.96 T-m might be suitable for a 120 GeV proton energy, although the optimal settings are still being studied. That setting should provide good coverage for pions and kaons relevant for the NuMI and LBNE neutrino beams.

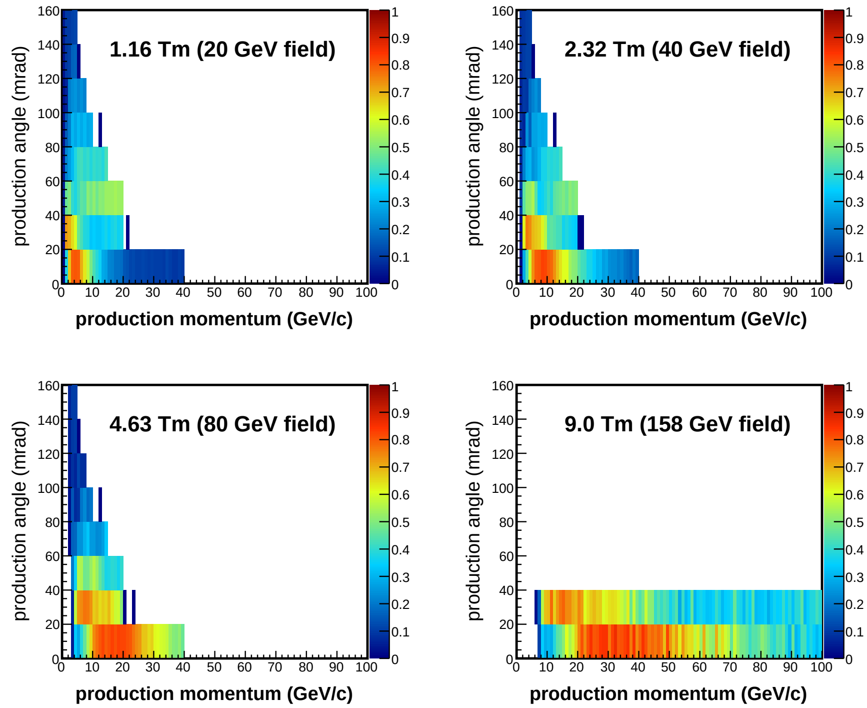


Figure 3: Reconstruction acceptance [20, 21] of the NA61 spectrometer for charged pions at the indicated magnetic field setting.

6 Improving neutrino experiments at Fermilab

The new data will improve neutrino experiments at Fermilab and beyond. Results will enhance the modeling of all neutrino beams, primarily NuMI, BNB, and possibly LBNE. We also note that the neutrino experiments themselves, particularly those collecting large event samples, provide additional constraints on the flux simulations. However, they do not supply direct information on primary interactions. As an example, the NuMI beam will be used by three experiments (MINERvA, MINOS+, and NOvA) all with different detector technologies and kinematical beam ranges thus giving different systematics for event spectra. Although the work to coordinate beam work among these experiments has been initiated, it is expected that the main improvement in neutrino beam simulation will have to come from precision measurements of hadronic yields.

Below we present brief comments on how improved beam simulation will impact the ongoing and upcoming Fermilab experiments.

6.1 MINERvA

MINERvA [27] is a dedicated neutrino-nucleus scattering experiment positioned just upstream of the MINOS near detector in the NuMI neutrino beam at Fermilab. The goal of the experiment is high-statistics, absolute measurements of inclusive and exclusive interaction rates for neutrinos and antineutrinos in the 1–20 GeV energy range. MINERvA makes use of a fine-grained, fully active detector design and a range of nuclear target materials (H_2O, He, C, Fe, Pb). By measuring rates on different atomic nuclei in the same detector and neutrino beam, MINERvA will study the effects of the dense nuclear medium on neutrino interactions.

As a neutrino cross section experiment, much of MINERvA's physics program is directly impacted by the accuracy of the neutrino flux determination, so dedicated hadro-production data represents an important opportunity for the experiment. Also, the physics program of MINERvA is closely tied to the goals of future long-baseline neutrino oscillation experiments. Precision measurements of neutrino oscillation parameters, including the discovery of CP violation, will require detailed knowledge of inclusive and exclusive cross sections for both neutrinos and antineutrinos.

6.2 MINOS+

MINOS+ [28] will be the continuation of MINOS running with the medium energy setting of the NuMI beam required by the the NOvA experiment. This will involve a reconfiguration of the current NuMI beam to achieve a higher energy broad neutrino spectrum peaking at about 9 GeV. The target and horn configuration will be different than was used in any of the MINOS settings. The new setting will be close to the MINOS medium energy setting (for which the target was moved upstream rather than the horn moved downstream), and gave the worst agreement when the target hadro-production model was tuned to reproduce the near detector event energy spectra. MINOS+ will have much higher statistics than MINOS, thus the results will be more sensitive to systematic errors in the knowledge of the simulated flux. This is a strong motivation for improved hadro-production data, that would yield a more precise neutrino flux prediction.

6.3 NOvA

The NOvA experiment [29] will be the flagship neutrino experiment at Fermilab. It will operate with two detectors thus, to first order, will be less sensitive to uncertainties of simulations of the neutrino flux and related backgrounds since the near detector will be used to characterize the beam and its composition. However, as large statistics are accumulated in NOvA, its precision in measurements of neutrino oscillations and the scope of the near detector physics will increasingly depend on detailed understanding of the *new* medium energy beam. Thus, improved beam simulations will be necessary to fully exploit NOvA physics reach. As already noted, NOvA's competing and complementary experiment T2K has been following a similar path forward, including exposure of the T2K target using the NA61 beam and detector [19].

6.4 The Long Baseline Neutrino Experiment (LBNE)

The LBNE experiment [30] may be the next step in long baseline neutrino oscillation physics whose goals are to measure the mass hierarchy and CP violation in the lepton sector. The experiment would likely design a new high intensity beam and target which would use the 120 GeV beam from the Main Injector. With the measured large value of $\theta_{13} \approx 9$ degrees by Daya Bay [31], the rate of electron neutrino interactions will be high, and the corresponding effects due to CP violation and mass hierarchy become a smaller relative effect. That means the precision of the CP violation measurement will be limited by systematic errors, which provides a strong motivation for better determination of hadro-production by an experiment like NA61/SHINE.

7 Existing hadro-production data

Neutrino flux predictions require not only good knowledge of the total pion and kaon production cross-sections but additionally, and more importantly, differential cross-section information in terms of the momentum and angle (p, θ) of the produced particle or equivalently the transverse momentum and Feynman-x (p_T,x_F). These data are required for incident protons at the primary beam energy on the neutrino target's nucleus (carbon for NuMI). Data for incident protons, neutrons and pions at lower energies are also needed to constrain tertiary production.

Most of the currently available data do not cover all the phase space at NuMI or BNB. An illustration of this mismatch is shown in Figure 4.

7.1 Proton incident data

The following datasets are particularly useful and are already employed by MINERvA and MINOS to constrain the NuMI flux.

NA49 pC data [22]: The experiment reports the invariant cross-section ($E\frac{d^3\sigma}{dp^3}$) for π and K production by protons on a thin carbon target at 158 GeV/c. The π production data span most of the (x_F,p_T) range interesting to MINERvA ($x_F < 0.5, p_T < 0.8\, GeV/c$) and have combined systematic and statistical errors which are generally less than 10%. The measured cross-section points are overlaid with the spectrum of pions yielding neutrinos in MINERvA in Fig. 5. The K production measurements are reported in a Ph.D. thesis and cover the range ($x_F < 0.2$) [25].

NA49 pp data [23]: The experiment reports the invariant cross-section ($E\frac{d^3\sigma}{dp^3}$) for π, K and p production by protons on a thin hydrogen target at 158 GeV/c. The data cover most of the range interesting to MINERvA, including at higher x_F than the carbon data. Uncertainties are generally smaller than the pC data.

MIPP [24]: MIPP ran at Fermilab in 2005-6 with 120 GeV/c protons on a replica NuMI target as well as a series of thin targets. The most useful existing output is the kaon/pion ratio for 120 GeV/c protons on a thin carbon target [24]. The ratio was measured at several points in the range $0.0 < x_F < 0.5$ with uncertainties of 10-50%. These data can be combined with the NA49 measurements to provide a modest constraint on kaon production.

NA61 [26]: Data were collected for protons on a thin carbon target at 31 GeV/c. The experiment reports $\frac{d\sigma}{dp_\pi}$ integrated over different angular bins. These data can be converted into a bin-averaged invariant cross-section in terms of x_F,p_T and compare well with the NA49 pC data, as shown in Fig. 7. This allows one to scale the NA49 pC data to predict the pion production cross-section on carbon for proton momenta between 31 GeV/c and 158 GeV/c.

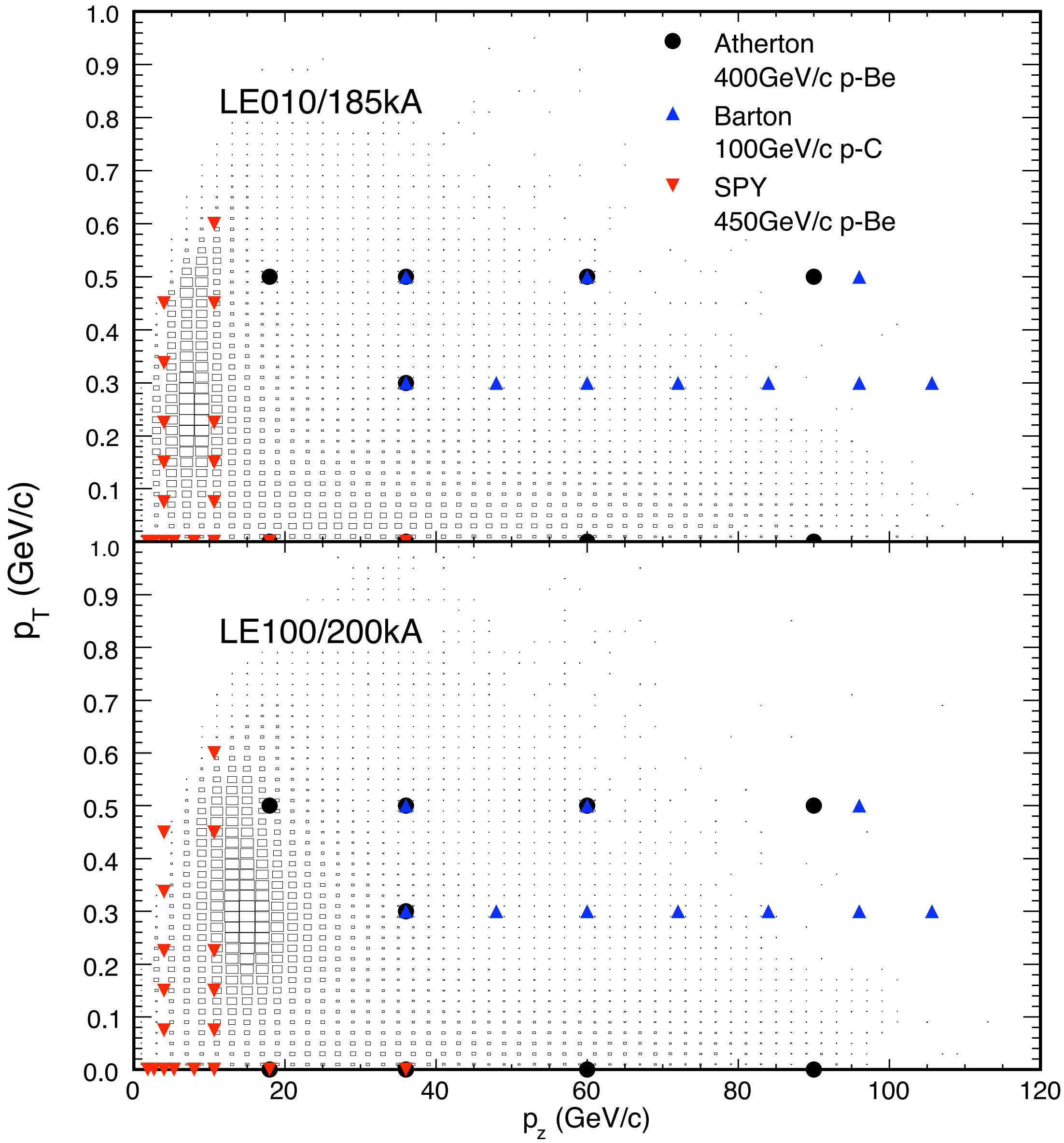


Figure 4: The distribution of transverse and longitudinal momentum of π^+ that contribute to neutrinos at the MINOS Near Detector for two different beam configurations, low energy (LE010/185kA) and medium energy (LE100/200kA). The size of the box is proportional to the number of charged current neutrino events in the MINOS Near Detector that come from π^+ momentum $p = (p_z, p_T)$. Overlaid are the points that indicate the part of the phase-space measured by the three relevant hadron production experiments (taken at higher primary energies) [3, 11, 12]. It should be emphasized that the measurements shown are not taken with a 120 GeV proton beam, they are scaled from other energies, and have an error associated with the particular scaling model employed.

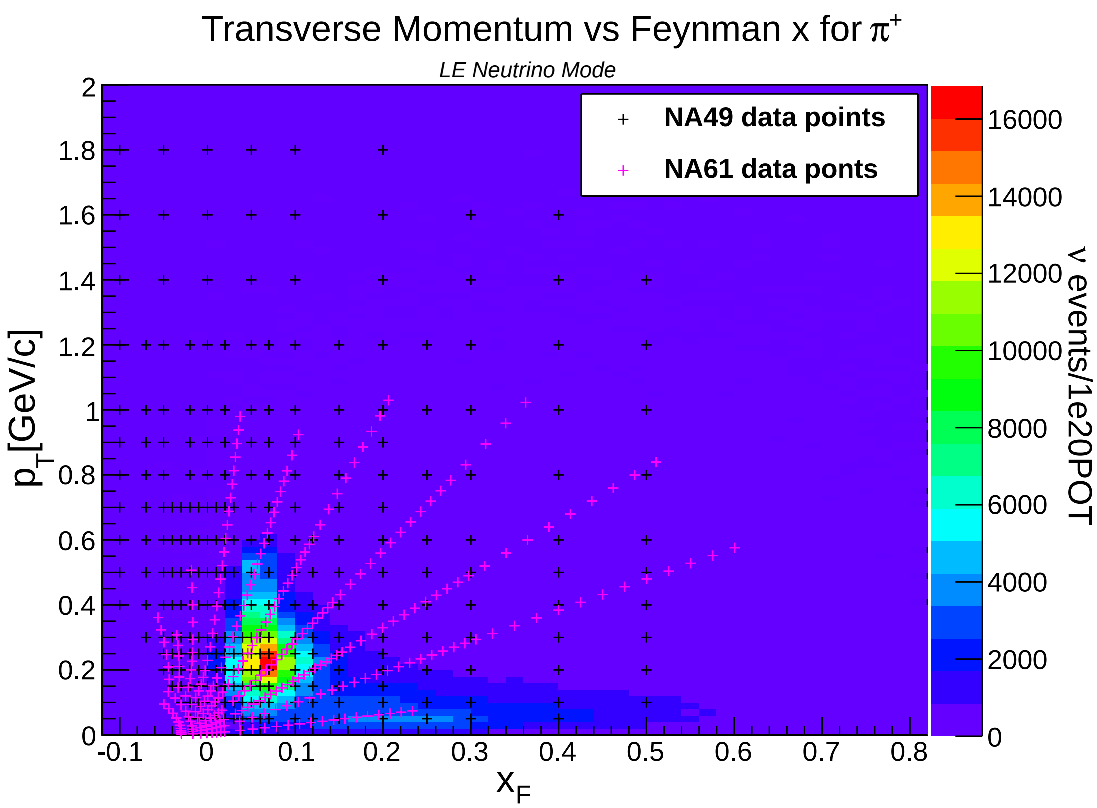
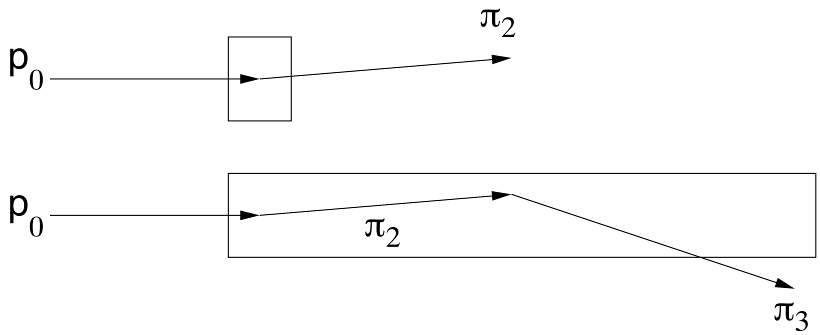


Figure 5: The distribution, in momentum space, of pions which decay to product a neutrino which interacts in MINERvA. The points at which NA49pC [22] and NA61 [26] measured the cross-section for $pC \to \pi X$ are overlaid. It should be emphasized that the measurements shown are not taken with a 120 GeV/c proton beam, they are scaled from other energies, and have an error associated with the particular scaling model employed.



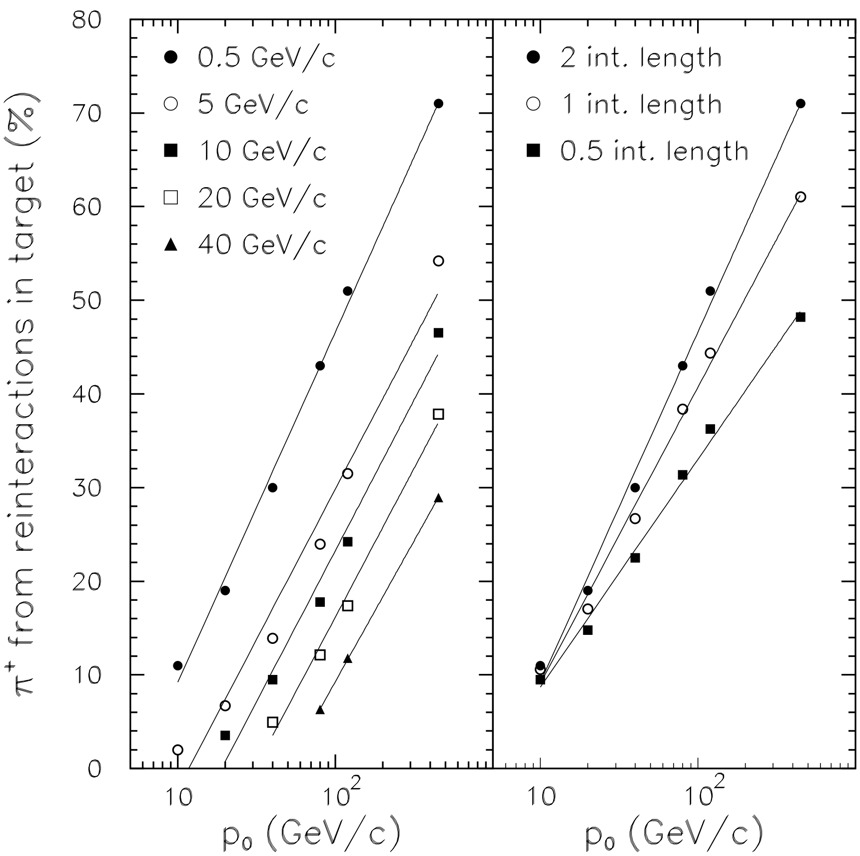


Figure 6: Pions created in primary proton interactions can escape out of the thin target without re-interaction. For a long target there is a high probability that a pion will re-interact (top). The calculation of the fraction of tertiary π^+ production from re-interactions in a graphite target as a function or primary beam momentum p_0 is shown. The calculation was done using FLUKA [13]. The left plot shows the re-interaction fraction for a two interaction lengths long target with several pion momentum thresholds (p_z). The right plot shows the re-interaction fraction for three different lengths of the target.

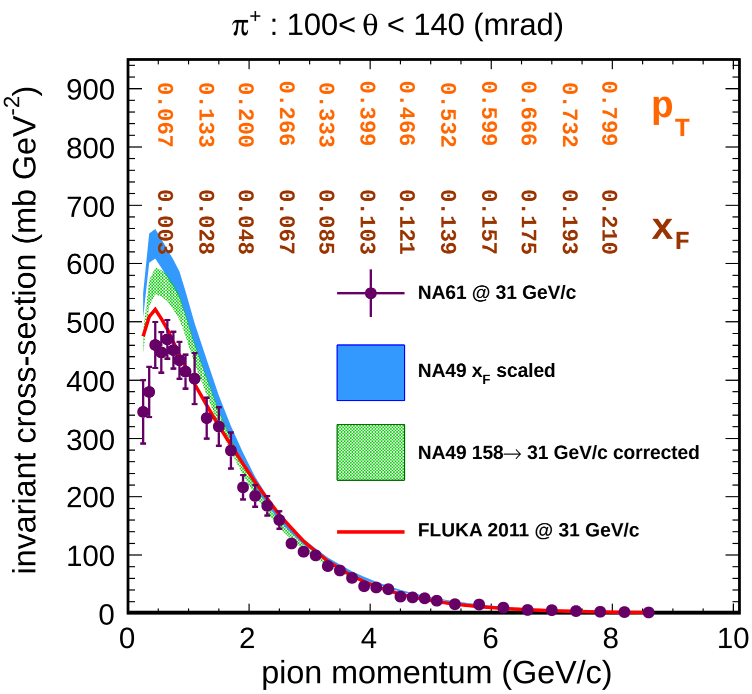


Figure 7: A comparison of hadron production data collected on a thin carbon target with primary proton momenta of 158 GeV/c [22] and 31 GeV/c [26]. The 158 GeV/c data points were interpolated to yield $E\frac{d^3\sigma}{dp^3}$ at the same (x_F,p_T) position as measured at 31 GeV/c. The 31 GeV/c measurements are integrated yields and were corrected to yield a bin averaged $E\frac{d^3\sigma}{dp^3}$. In the scaling limit, one expects the invariant cross-sections at the two energies to be equal. A correction for non-scaling was done on the 158 GeV/c data with FLUKA 2011 [13]. There is good agreement between the two datasets and the FLUKA MC for $p_\pi > 1.5\ GeV/c$, the region most interesting for NuMI.

Barton *et al.* **data [12]:** Data were collected with incident π, K and p at 100 GeV/c on a range of nuclear targets including carbon. The experiment reports $E\frac{d^3\sigma}{dp^3}$ for π, K, p and $\bar{p}$ production as a function of x_F at $p_T = 0.3, 0.5\,GeV/c$. Some additional points were also measured at $0.18\,GeV/c$. The data are interesting because they cover $x_F > 0.5$, have incident π and K as well as p, and and offer a handle on A dependence. However, the $pC \to pX$ cross-sections differ from NA49 by $\sim 20\%$ in the region where the two datasets overlap and this difference must be taken as a systematic error when computing neutrino fluxes.

7.2 Interaction cross-sections

A few experiments have reported interaction cross-sections as a function of incident particle species and energy and target nucleus. These data are useful for validating the MC simulation and assigning an uncertainty to the cross-section scale.

Denisov *et al.* **data [7]:** Absorption cross-section for incident protons, pions and kaons as a function of energies from $6-60\,\mathrm{GeV/c}$. Different nuclear targets and analysis of A dependence. Although not explicitly mentioned in the paper, the measurement includes quasi-elastic scattering which must be removed for comparison with experiments measuring inelastic/pion-production cross-sections. No differential information.

Carroll *et al.* **data [8]:** Inelastic cross-section for incident protons, pions and kaons at 60, 200 and 280 GeV/c. Different nuclear targets and analysis of A dependence. No differential information.

Roberts *et al.* **data [9]:** Inelastic cross-section for incident neutrons with several points between 160-375 GeV/c. Different nuclear targets and analysis of A dependence. No differential information. They report a modestly higher cross-section than the incident proton data.

These measurements are summarized in Fig. 8.

7.3 What more is needed?

Approximately 40% of the ν_μ that interact in MINERvA and MINOS are due to pions and kaons which were not created directly by a pC collision at 120 GeV/c. Instead, these neutrinos are produced in secondary and higher order reinteraction processes like these:

$$
\begin{aligned}
&p(120\,GeV/c)C \rightarrow p(60\,GeV/c)X \\
&\qquad\qquad\qquad\qquad \hookrightarrow pA \rightarrow \pi^+(20\,GeV/c)X \\
&\qquad\qquad\qquad\qquad\qquad\qquad\qquad \hookrightarrow \pi^+ \rightarrow \mu^+\nu_\mu(8\,GeV/c)
\end{aligned}
$$

$$
\begin{aligned}
&p(120\,GeV/c)C \rightarrow \pi(30\,GeV/c)X \\
&\qquad\qquad\qquad\qquad \hookrightarrow \pi A \rightarrow \pi^+(15\,GeV/c)X \\
&\qquad\qquad\qquad\qquad\qquad\qquad\qquad \hookrightarrow \pi^+ \rightarrow \mu^+\nu_\mu(7\,GeV/c)
\end{aligned}
$$

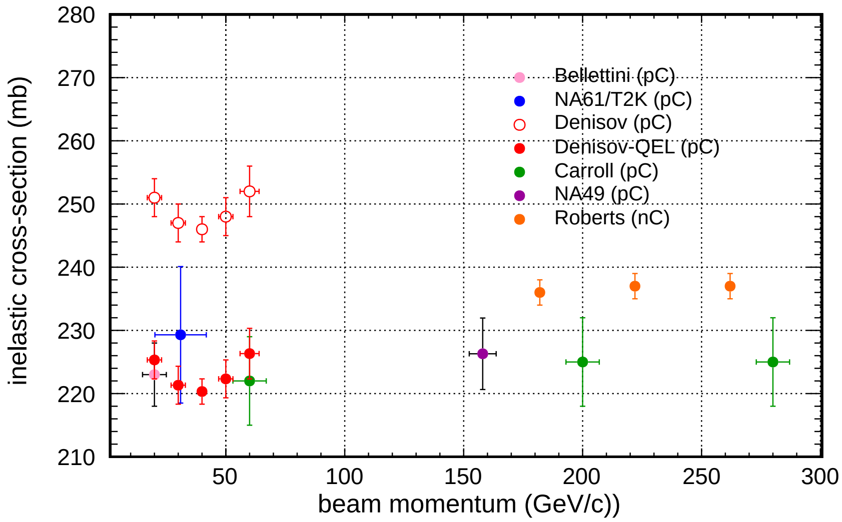


Figure 8: The inelastic cross-section for proton-carbon collisions as a function of energy. The original Denisov *et al.* measurements included quasi-elastic interactions. A correction has been performed to allow for comparison with the other datasets. The cross-section for the QGSP hadronic interaction model in GEANT4 9.4.02 is also shown for comparison.

Reinteractions occur copiously in the few interaction length targets used in neutrino beams. Figure 6 shows the fraction of pions from target reinteractions as a function of the primary beam momentum. One can see that, as the beam momentum increases, the fraction of pions from reinteractions grows. The fraction also grows as the pion momentum decreases. Approximately $20-40\%$ of the pions which yield neutrinos in the peak of the NuMI low energy beam ($p_\pi \approx 5-10\,\mathrm{GeV/c}$) were created in tertiary interactions in the target. A good understanding of reinteractions, both in the target and in other beamline elements such as the focusing horns, decay pipe gas and walls, and target hall air, is important for precision flux and oscillation experiments.

8 Summary

In summary, we propose a program to remedy a long-standing problem in neutrino physics at Fermilab for experiments that use the 120 GeV/c beam, by measuring hadron production at the CERN NA61/SHINE experiment. The data would be relevant for MINERvA, MINOS, MINOS+, and LBNE. The program would take about four years to complete. This includes a pilot run in

June 23-24, 2012, with a primary goal to evaluate the capabilities of NA61/SHINE in a 120 GeV/c proton beam, and to acquaint US-NA61 collaborators with NA61/SHINE. By exploiting NA61's well developed detector technology that program would be the most cost-effective and timely means of obtaining well understood neutrino beams at Fermilab.

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