US-NA61:

SHINE Measurements for the Fermilab Neutrino Program

(Addendum to NA61 SPSC-P-330)

Plans and Requests for 2015

The US-NA61 Collaboration

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Outline

- Motivation
- Fermilab Neutrino Program
- Beam Request
  - Reactions and Schedule
- US Group Contributions
  - FTEs
  - Hardware Upgrades
- Summary

Motivation

- U.S. intensity frontier program in neutrino physics is currently based on a number of active and planned neutrino experiments
- These experiments all plan to use high-intensity proton beams from the Fermilab in the energy range 80-120 GeV that impinge upon thick (a few λ_I) graphite and/or beryllium targets.
- A precise understanding of the neutrino flux from those beams is of paramount importance to the program.

Motivation, cont.

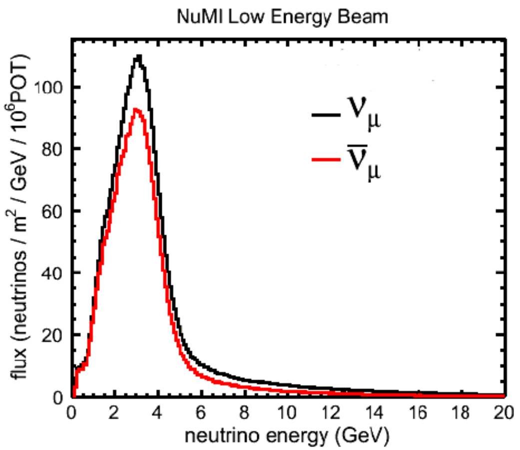
- The modeling of strong-interaction cascades and hadronic yields from thick targets relies on detailed knowledge of underlying physics and cross-sections, which must be provided as a starting point to simulations.
- The resulting prediction of the flux of neutrinos, produced from decays of pions, kaons, and muons emerging from a hadronic shower and beamline re-interactions, an essential part of simulations of most neutrino experiments.
- Precise calculations of neutrino fluxes in such high-energy accelerator beams are limited at present by our knowledge of hadron production cross-sections in hadron-nucleus collisions – The proposed NA61/SHINE measurements will make critical contributions.

Fermilab Neutrino Program: Experiments

→ NuMI: MINERνA (a dedicated neutrino-nucleus scattering experiment), MINOS+ (continuation of MINOS running with the medium energy setting), NOνA (long baseline ν_e appearance experiment complementary to T2K)

(For comparison T2K used 30 GeV protons and the peak neutrino energy was ~600 MeV)

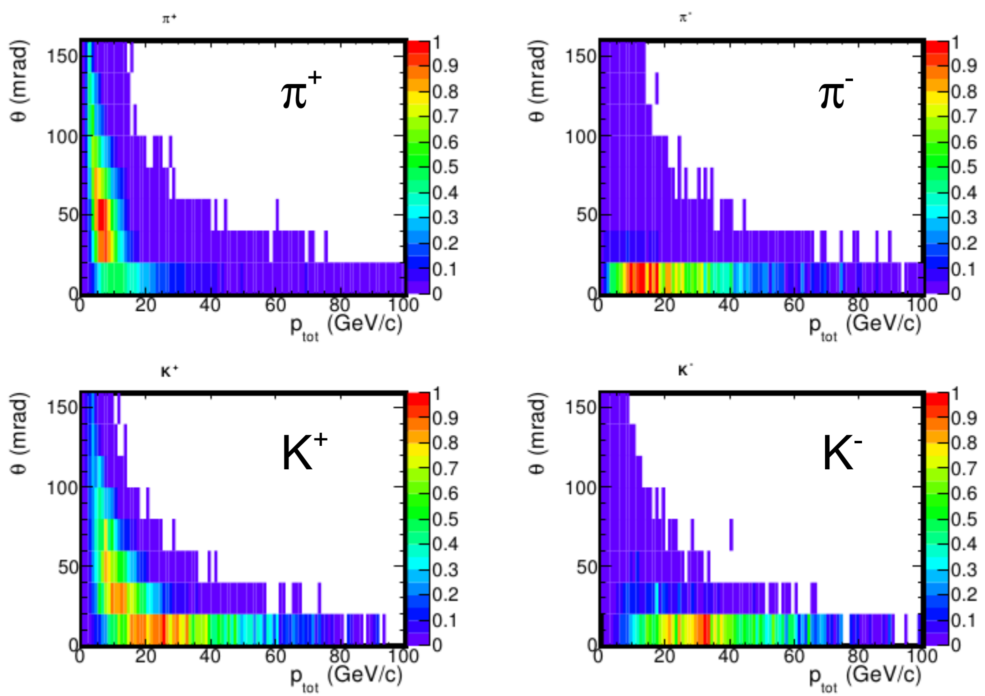
Neutrino Beam generated from Main Injector (120 GeV p) →



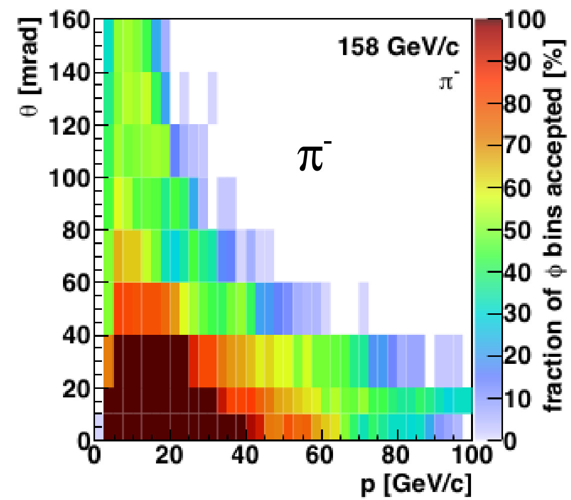
→ LBNE/F: next step in long baseline neutrino oscillation physics. Goals are to measure the mass hierarchy and CP violation in the lepton sector.

→ Without an identical near detector (similar to T2K), the systematic errors due to the detector response will not cancel in a Far/Near event yield ratio and therefore a precise flux prediction is critical.

Hadron Phase Space Appropriate for LBNE/F



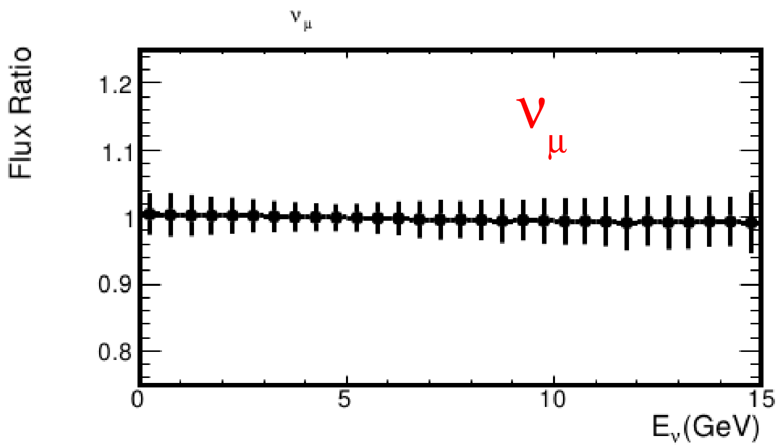
- Distributions of Pion and Kaon kinematics (normalized to each hadron type) that contribute to the total neutrino flux at the LBNE far site

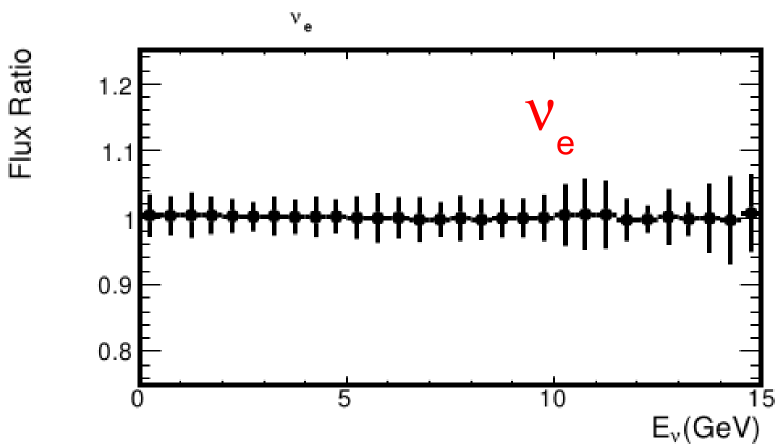


- Reconstruction acceptance of the NA61 spectrometer for charged pions at the full magnetic field.

- Good Overlap

Expected Improvements to LBNE Flux Prediction





(The expected LBNE Flux peaks around ~3 GeV, with very little flux above 10 GeV)

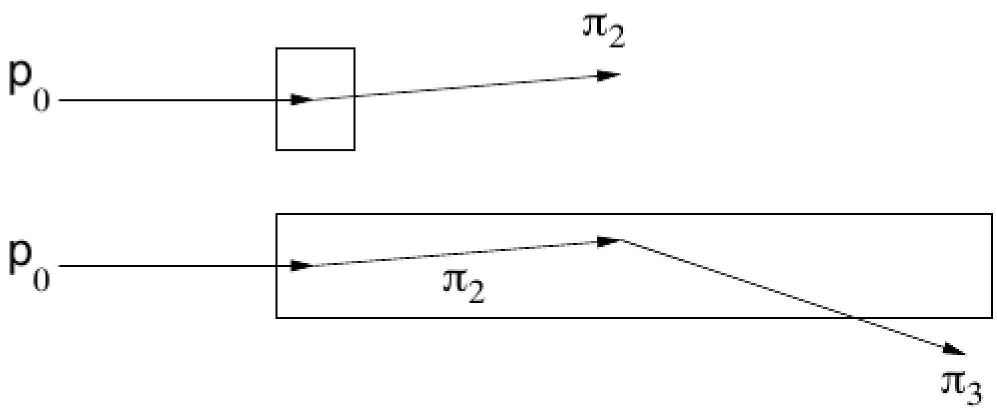
- Predicted fractional errors on the neutrino flux at the LBNE far site using our assumed NA61 constraints
- Currently, the estimates of the overall flux uncertainties are 11-15% based on our NuMI experience.
  - Dominated by the uncertainties of the hadron production data.
  - NA61 measurements* are expected (based on a preliminary study) to bring the total flux uncertainty down to <5% (a factor of 2-3 reduction)
  - Exploit T2K experience using NA61 measurements

(*Based on the systematic errors given in the NA61 measurements made for T2K, NA61 could potentially make measurements at 120 GeV with 3-5% errors on the π + production and 10% errors on the K + production in the regions of interest)

Improved NuMI Flux Predictions for all FNAL Users: NuMI-X Collaboration

- Determining the neutrino flux in any neutrino beamline is both essential for physics objectives and and the same time challenging
- The NuMI beam has, or soon will service, six experiments (MINOS, MINERνA, NOνA, MINOS+, MicroBooNE, ArgoNeut)
  - All with diverse detectors and physics programs
- NuMI-X: A pan-experimental NuMI flux working group to develop common tools to simulate the NuMI beamline and produce a reference beam line flux simulation.
- The NA61 measurements would be an important ingredient.

NuMI Target Predictions using Thin Target Data



- Pions created in primary proton interactions escape out of thin targets without re-interaction.
- For the NuMI target there is a high probability that a pion will re-interact

- Approximately 20−40% of the pions which yield neutrinos in the peak of the NuMI low energy beam ($p_\pi \approx 5 - 10$ GeV/c) were created from tertiary hadrons produced by secondary interactions in the NuMI target. (Similar fraction expected for LBNF)
- A good understanding of re-interactions, both in the NuMI target and in other beam-line elements such as the focusing horns, decay pipe gas and walls, and target hall air, is important for precision flux and oscillation experiments: Need to use different targets(A)
  - A comprehensive program will combine NuMI replica target data at the primary beam momentum with thin target data.
  - Use thin target data to predict what is expected for NuMI target data – make measurement with NuMI target as “checksum”

Proposed Beam Request

Proton+pion event totals for target and beam settings relevant to US oscillation neutrino experiments:

proton+pion event totals	Incident proton/pion beam momentum		
Target	120 GeV/c	60 GeV/c	30 GeV/c
NuMI (spare) replica	(*future*)		
LBNE replica	(*future*)		
thin graphite ($< 0.05\lambda_I$)	(*future*)	3M	(T2K data)
thin aluminum ($< 0.05\lambda_I$)		3M	3M
thin iron ($< 0.05\lambda_I$)	(*future*)	(*future*)	(*future*)
thin beryllium ($< 0.05\lambda_I$)	(*future*)	3M	3M

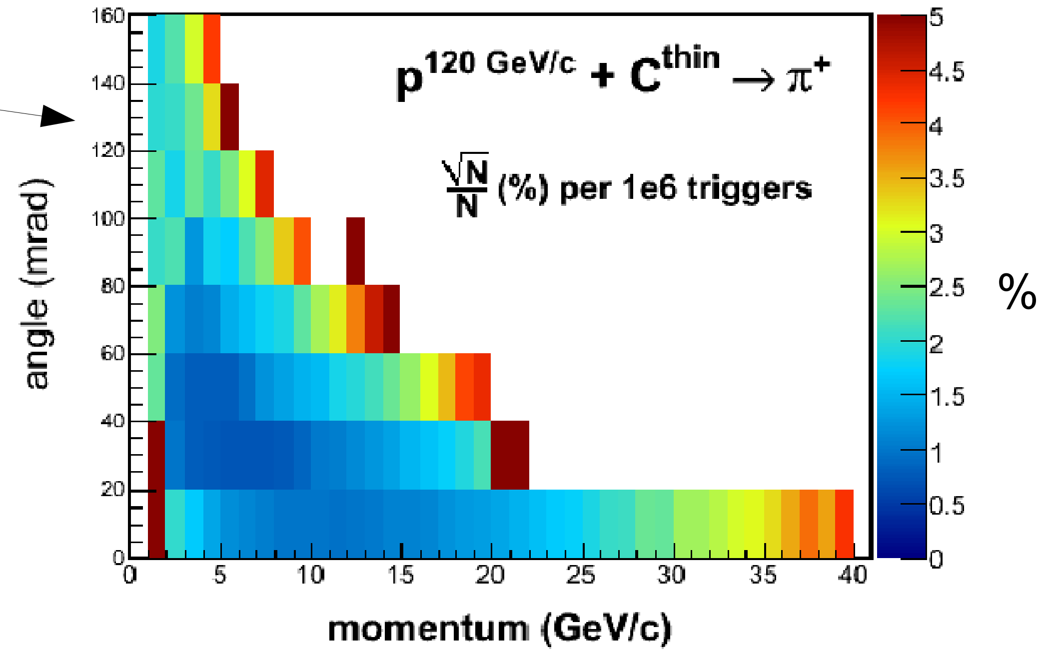
- The first set of runs requested in 2015
  - Labeled with 3M (the number of incident pion and proton triggers)
- We wish to start with the lower energy ones: Wait for the detector upgrades for remaining runs.
- Other relevant runs would take place in the future, possibly during 2016.

Proposed Beam Request: Statistics and Beam Time

Includes production statistics and detector acceptance, but NOT data quality selection cuts.

(The NA61/SHINE data acquisition was able to record ~10^6 events per day. Includes 10% target-out data, with a beam setting of 120 GeV/c during our pilot run in 2012)

Expected Statistical Errors: θ *vs* p



- With 3-5% total error (including systematics)
  - 3M triggers (both protons+pions) per week
  - For the five configurations in 2015:
    - ~ 5 weeks total

US Group Contributions

	Senior Personnel (Fraction FTE/yr)	Post Docs (Fraction FTE/yr)	Graduate Students (Fraction FTE/yr)
FY2014	1.6	0.7	1.0
FY2015-18	2	2.5	3.7

→ Total > 8 FTEs

Summary of estimated US-NA61 staffing commitments.

Contributing institutions for FY2015-2018:

- University of Colorado, Boulder, Colorado 80302, USA
- Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
- Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
- University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA
- University of Texas at Austin, Austin, Texas 78712, USA
- College of William & Mary, Williamsburg, Virginia 23187, USA

US Group Contributions: Analysis

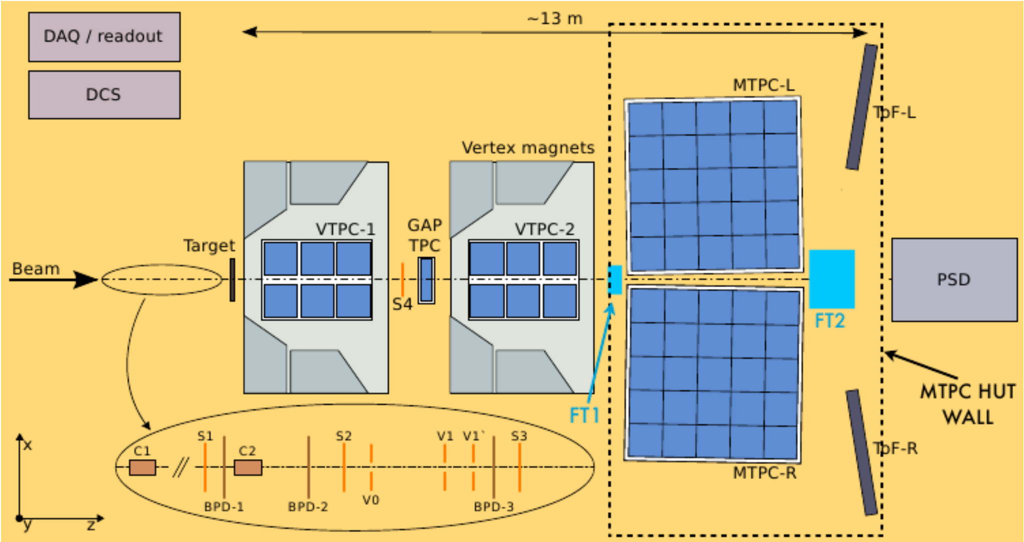
- Presently or near future contributions:
  - Analysis of test run data (2012) – total cross section measurement
  - Beam Line and Gap TPC Calibration
  - TPC gas system expert
  - dE/dx calibration
  - Personnel listed in previous slide to analyze data runs
- Presently the cycle time between data taking and publication is 4-5 years:
  - The US groups will contribute in ways that will speed up this process to 2-3 years: Calibration and Monte Carlo

US Group Contributions: Hardware

- Contribute to electronics readout upgrade
- Present ToF system based on FASTBUS/CAMAC
  - Difficult to find spare parts, wish to replace with more modern system (~3600 channels).
  - Use DRS ASIC developed at PSI
    - Waveform digitizer (5 GSPS) employing switched capacitor arrays.
    - System design - University of Geneva
    - The Pittsburgh group will be responsible for the procurement, assembly, testing and delivery of the 6U motherboards. (~$115k from DOE)

US Group Contributions: Hardware

- FTPC (in cyan):



- Most useful for high energy runs (*i.e.* 120 GeV)
  - Improved separation of protons from π^+ for high momentum and forward direction → into the MTPC gap
  - University of Colorado, Boulder is collaborating (with DOE support) with the Wigner Institute, Budapest
  - Present schedule: Completed in early 2016
    - High energy runs will be requested at that time

Summary

- FNAL Neutrino program has an interest in improved neutrino flux predictions
- A precise understanding of neutrino flux is fundamental to the success of oscillation experiments
- Hadron production measurements are a critical ingredient: *Successfully implemented by T2K using NA61 data*
- Wish to make appropriate measurements for the FNAL neutrino program within **NA61/SHINE**:

  → DOE just approved funds for our upgrade plans and has allowed lab and university operating budgets to be used.
- If our proposed **NA61/SHINE** program is approved (specific beam-time request presented on slide 11) it would make a significant contribution to the effort.

Backup

Responses to Reviewers Comments

Q. It might be nice to see something like Fig.5 both with and without the new forward TPCs, to better appreciate their impact (section 6.2 mentions that the protons they would detect represent 25% of the final neutrino flux; but that's not trivial to connect to Fig.5 and the corresponding discussion in section 3.6). At the very least I think the figure caption should state whether it assumes the new TPCs are there or not. Similarly for Fig.3.

A. A full simulation is being developed to study that question and other optimization questions. At the moment we know that there is an 80 GeV/c tracking cutoff on tracks originating in the target. Those particles are important because they have a high probability to re-interact in the target. ...

Q. The timeline for the new TPCs is very tight, starting already this month; does that mean you've effectively already started on the upgrade?

A. Yes it is very tight. We just received DOE approval for the upgrade so it hasn't started yet. However the higher energy runs, where the FTPC would be most useful, will not be requested till the 2016 runs.

Q. Did I miss something, or is Fig.7 not referenced anywhere in the text? That should probably be rectified.

A. Removed

Q. Section 4.1 mentions tertiary interactions in the target, but I think you might mean secondary interactions, which produce tertiary hadrons.

A. Wording changed

Q. Another spell-check is probably good to do before final submission, as I spotted a couple of typos ("personnal" on p.21, "protptype" on p.34).

A. Done

Responses to Reviewers Comments

Q.. End of section 3.4: it would be good to concretise if the expected "less than 6%" spread is good enough for the neutrino measurements.

A. The "less than 6%" will correspond to a factor of two improvement over present uncertainties. This will be a substantial gain for current neutrino experiments. The improvement for future experiments will depend upon the specifics of the neutrino beam design, but we believe that achieving a 5-6% overall error will be sufficient..

Q. Section 3.6: is the mentioned 5-6% uncertainty statistical or systematic in nature, or the combination of the two? In other words, how taking more or less data for a given setting would influence the final physics outcome? (that also applies to data in Table 3, and text in section 5.4, why exactly 3M events?) What is the main source of the uncertainty? (btw, later I see 3-5%, end of section 5.1)

A. The 5-6% number is a conservative estimate of the systematic errors we expect to have, plus a small contribution from statistical errors (1-2%). One of the important aspects of our run plan is to take both pion and proton data. The 3M figure comes from desiring 1M good interactions for each sample (30% loss from beam selection). Current pion data is of poor quality and sparse over the energy range of interest. Our data will fill in those gaps and lead to a well constrained scaling model for pion production.

Q. I think I understand that you view the directly incoming beam as secondary since it is not the primary beam from SPS. Still, the input beam for NA61 could be simply called primary (instead of secondary) and the secondaries as secondaries (and not tertiaries).

A. Wording changed

Q. Beginning of section 4.1: I assume that the GeV values for secondaries are averages, it cannot be a fix momentum

A. Yes. They are typical values. Wording added

Q. The statement "as beam momentum increases ... the fraction .. from reinteraction grows" is is contradiction with Fig 8-left, where reinteraction seems to decrease with increasing p

A. The series of curves refer to the minimum momentum allowed. *i.e.* all secondary momenta > “cut”

Responses to Reviewers Comments

Q. Fig 5: what is the uncertainty of the beam-momentum scaling with a model? what would be the systematic from that source?

A. The scaling uncertainty is expected to be small compared to errors shown because we hope to take several runs with different energies spanning the appropriate energy regime.

Q. Section 5: the time between data taking and publication is indeed long (you mention 4-5 years), and your proposal promises to reduce that by factor 2; it would be fantastic!

A. We hope!

Q. section 5.1: you need ^2 for the double differential formulae

A. Fixed

Q. Section 5:3: triggers T3 and T4 are not described or defined

A. They are. T3 and T4 are the same as T1 and T2 without the CEDER PID

Q. Section 5.3: you should describe why and where there is He near the beam line

A. We're assuming the second best thing to a vacuum is He but we didn't design the beamline so maybe this is a better question for the full NA61 collaboration

Q. Section 5.7.2: I miss some numbers on the measured/detected fraction of the total inelastic/elastic cross section. It is important since also events missed by the trigger can result in hadrons producing neutrinos later on

A. Did not address

Q. section 5.7.2: can you identify reinteraction vertices? is the resolution of z-vertex good enough?

A. Not in the thin target.

Responses to Reviewers Comments

Q. Figs 11 and 12 need units on both axes

A. Units added to caption – couldn't regenerate the original plots.

Q, section 6: both readout and forward tracking upgrades are very ambitious and the timeline is very tight

A, No argument from us. However for some of the runs the upgrades are not critical and we request those to be taken first.

Q End of section 6.1: I think having the two systems operating and debugged side-by-side, is very optimistic. You could devote more time for standalone testing and debugging.

A. Agreed. We expect the changeover would only be done during a relatively long beam down time.

Q. Section 6.2: how do you plan to identify/unfold the very high momentum pion component? what is meant by "high momentum" here? is dE/dx good enough there (logarithmic rise stops somewhere)?

A. Above 80 GeV/c, the magnets are not strong enough to bend the particles into the MTPCs. In that region, it may be possible to still separate positive pions from protons on a statistical basis by using the dE/dx information of the FTPCs plus the GTPC.

Q. Section 6.2: there is no mention about the costs of the two forward TPCs

A. The cost estimate is being worked on presently. We have a preliminary cost estimate for the TPCs field cages, power supplies, and pad circuit boards. The electronics will be recycled VTPC readout boards and channels.

Responses to Reviewers Comments

Q, Do you have an estimate of the relative weight of the systematic error due to the uncertainty in the knowledge of the neutrino flux with respect to the overall systematic error on the CP violation phase measured at LBNE ?

A. This requires a full simulation which we don't have at this time.

Q. Can the measurements performed at NA61 be used also to calibrate the neutrino flux for off-, off-off and off-off-off axis detectors at the NuMI facility? In other words, how does the phase space (theta vs p) covered by NA61 overlap with that covered by these off-axis detectors?

A. Yes! We hope to use these measurements to help other experiments.

Q. Fig.5: which is the neutrino spectrum expected at LBNE? Which fraction of it will be below 10 GeV?which would be the impact of the new TPCs on this plot?

A. The expected LBNE Flux peaks around ~3 GeV, with very little flux above 10 GeV. We expect the forward TPC's to improve the prediction in the peak region.

Q. Data samples: 3-5 days per setting, where the required settings are as follows:- incident proton/pion momentum = 120 GeV/c, thin graphite (<0.05 lambdaI) and thin Berillium (<0.05 lambdaI).- incident proton/pion momentum = 60 GeV/c, thin graphite, thin Aluminum and thin Berillium. Pions and protons are collected simultaneously for each setting. Hence: overall 5 settings, of 3-5 days each. When do you plan to take these data? Fall 2015? 2016?

A. We wish to take the 60 GeV and some of the 30 GeV runs in 2015 where the FTPC are not as important. The higher energy ones in 2016.

Responses to Reviewers Comments

Q. Fig.13 shows the expected statistical error in bins of momentum and angle for 1 M proton events in NA61.

You claim that the statistical error on the final cross section will be below 3% over the range of interest of LBNE

but the range of interest for LBNE extends up to 80-100 GeV while in this plot only the range 0-40 GeV/c is shown.

Which is the statistical accuracy you can reach in the upper part of the momentum range?

A. In the region above 80 GeV/c we are mostly interested in the forward proton production, which have a high probability to re-interact in the target. That data will have small statistical error due to the high forward scattering cross section.

Q. Fig.11 & 12: how the (good) separation degrades when particles with p>4 GeV are considered?

A. A new plot has been added to the updated addendum (new figure 12). In general the particle ID is performed by using a fit the the dE/dx only. Figures 11 and 12 show how the TOF-L/R systems can be used to cross check the dE/dx over a limited angular range. The PID from dE/dx remains roughly uniform up to 80 GeV/c where the dE/dx begins to saturate.

Q. Why the schedule for the installation of the two TPCs is so tight? What is the US experiment that is driving such a tight schedule ?

A. If the TPC installation is delayed until 2016, we will take data with it in 2016, there is no difficulty with that. We will be able to develop our analysis tools and software with the data we collect in 2015. As mentioned above, the forward data has very high statistics.

Fig. 2: title of the canvas: (mrad-1 GeV-1) --> (rad-1 GeV-1) Fixed

Fig.7 is not referenced anywhere. At which energy were taken the points from NA49 and NA61 in this plot? Removed

p.20: understanding --> Understanding Fixed

p. 20: below in Table 3 --> above in Table 3. Done

Fig.11 & 12: dEdX vs m^2 --> m^2 vs dE/dX; Done

p.34 protptype --> prototype Done

US Group Contributions

	Senior Personnel (Fraction FTE/yr)	Post Docs (Fraction FTE/yr)	Graduate Students (Fraction FTE/yr)
FY2014	1.6	0.7	1.0
FY2015-18	2	2.5	3.7

Summary of estimated US-NA61 staffing commitments.

Institution	Senior Personnel (Fraction FTE/yr)	Post Docs (Fraction FTE/yr)	Students (Fraction FTE/yr)
Los Alamos	0.25	0.5	0.2
University of Colorado	0.75	1	2
University of Pittsburgh	0.75	1	1
William and Mary	0.25	0	0.5

Proposed US-NA61 staffing commitments by institution for FY2015-2018