A Review of Secondary Production Measurements for ν Flux Determination: *E910, HARP, and MIPP*

Motivations
Experiments
Results & Implications
Outlook

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Motivation

- A simple truth in neutrino physics:

Contains everything interesting: oscillation physics, exotic event rates, cross sections, etc.

$$\left(\text{observed event rate}\right) = \left(\text{cross section}\right)\left(\text{flux of neutrinos}\right)\left(\text{detection efficiency}\right)$$

The subject of this talk

Neutrino Beam Fluxes

- **Neutrino beams are produced in the laboratory by the weak decays of nuclei, nucleons, and μ, π, and K mesons.**
- **The spectrum of neutrinos from these decays is known extremely well**
- **The only *significant* flux uncertainty comes from the production cross section of the parent particle and its subsequent scattering in target materials (ignoring neutrino oscillation parameters that is!)**
- **In *decay-at-rest beams*, this is simply an overall normalization factor. A single well-understood *neutrino cross section* is enough to completely determine the neutrino flux (e.g. νe elastic process, or an inverse β-decay transition)**

However, in <u>decay-in-flight beams</u>, the complete differential production cross sections of the parent particles are needed, along with their interactions in material along their flight paths

Decay-in-Flight ν Beams

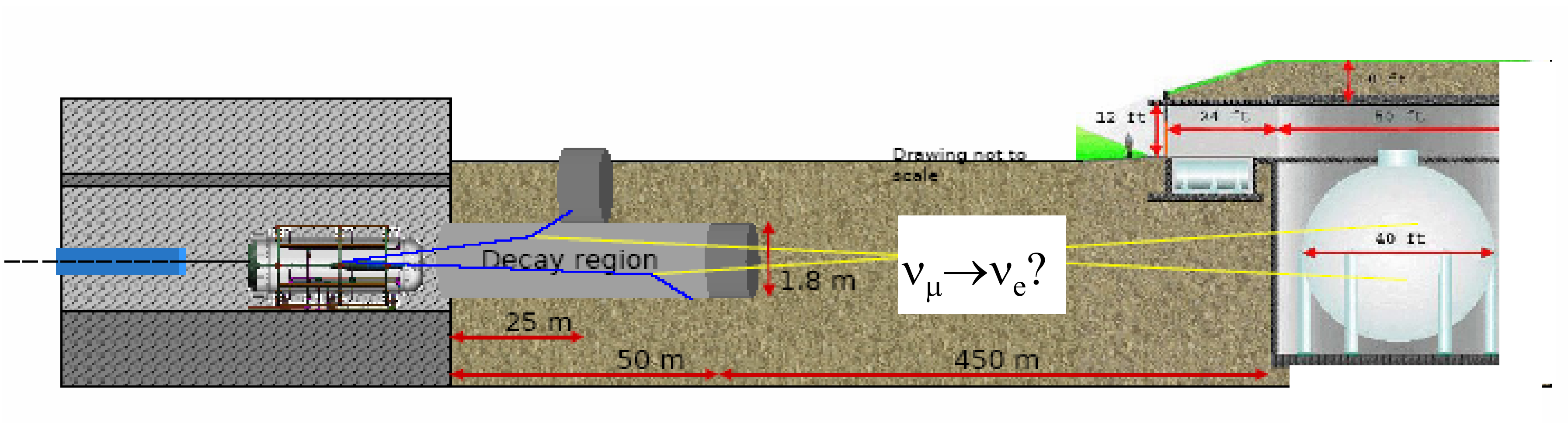
- **The calculation of secondary-production cross sections of π and K mesons in proton-nucleus collisions is not reliable, although new data is challenging modelers to make improvements**

- **Phenomenological parameterizations can be valid over limited energy and angle ranges, more useful at higher energies (> ~15 GeV) (e.g. Sanford-Wang or others)**

- **There are large discrepancies in the various hadron production models used in MC generators (MARS, FLUKA, MCNP, GHEISHA, etc.), although the situation is has been improving**

In order to predict fluxes with uncertainties less than ~10%, direct measurements in the appropriate energy and angular ranges are necessary

A "Typical" Example: The MiniBooNE Neutrino Beam

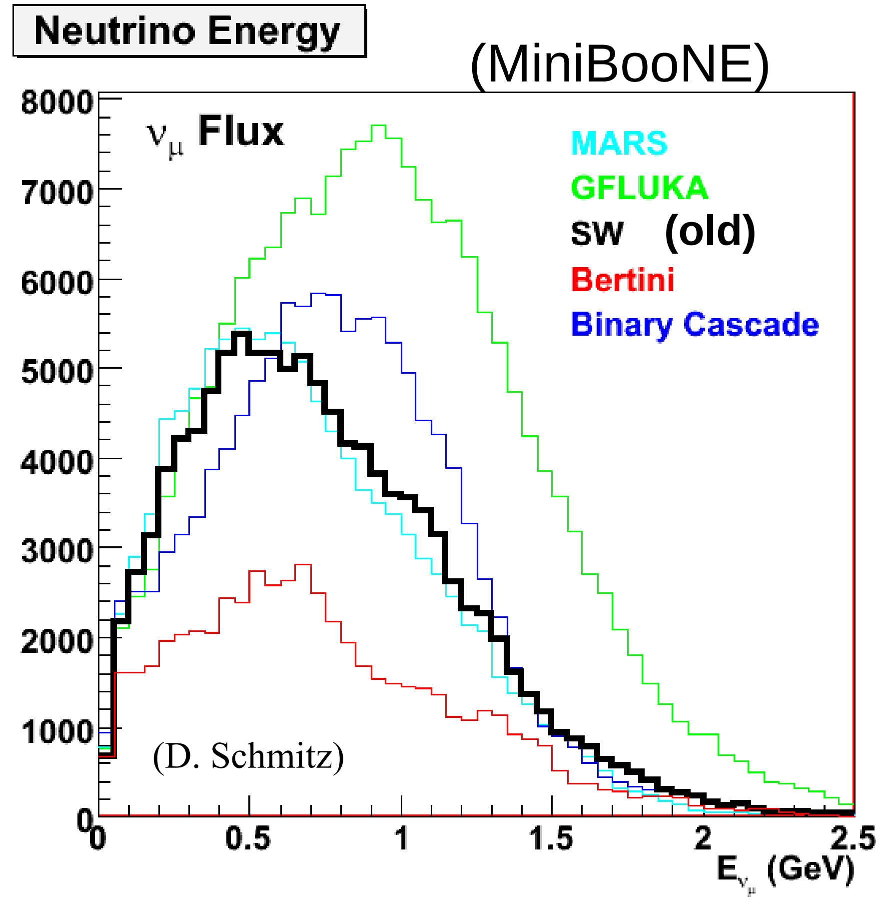


- Many studies have shown that the largest uncertainty in the ν flux prediction is the knowledge of the π/K production cross sections

- Various models are known to have large differences in neutrino rate predictions

∴ *It is vital to calibrate neutrino production target s in a proton beam*

Variation in MC Predictions of ν Flux



Conclusion: the neutrino beam is sensitive to poorly understood, forward (small angle), pion production rates

Mitigation of the Problem

- ***Experimental design*** **helps in neutrino oscillation measurements (although not in cross section measurements)**

- **near/far ratio (two detectors): (K2K/MINOS)**
  - **This is the simplest solution, although somewhat more costly. Useful in both appearance and disappearance measurements, a large signal helps!**

- ν_e / ν_μ **"ratio": (MiniBooNE)**
  - **In appearance experiments, the *source neutrino channel* (usually ν_μ) can be used to measure the expected *oscillated flux* under a particular oscillation hypothesis. This assumes only "lepton-universality" in the reaction cross sections, but accurate background measurements are important.**

Nevertheless, flux uncertainties can result in much poorer experimental sensitivities and better flux predictions are warranted

Experimental Meson Production Data

- **Significant amount of data exists but a match between energy, angular range, and nuclear target is required to avoid systematic errors due to interpolation or extrapolation in (E_{beam},θ,A)**

- **At energies above ~15 GeV and in certain angular ranges, "x-scaling" seems to be reliable for extrapolating to nearby energies**

- **Most "historical" data is in the form of single-arm spectrometer measurements of meson inclusive production cross sections. These typically have high statistics, good spectral shape determination, but they can suffer from knowledge of the absolute efficiency. Hence they have a somewhat limited value in neutrino flux predictions**

Recently, modern 4π detector technology efforts have been mounted to measure absolute meson-production in proton-nucleus over a variety of nuclei ranging from hydrogen to uranium

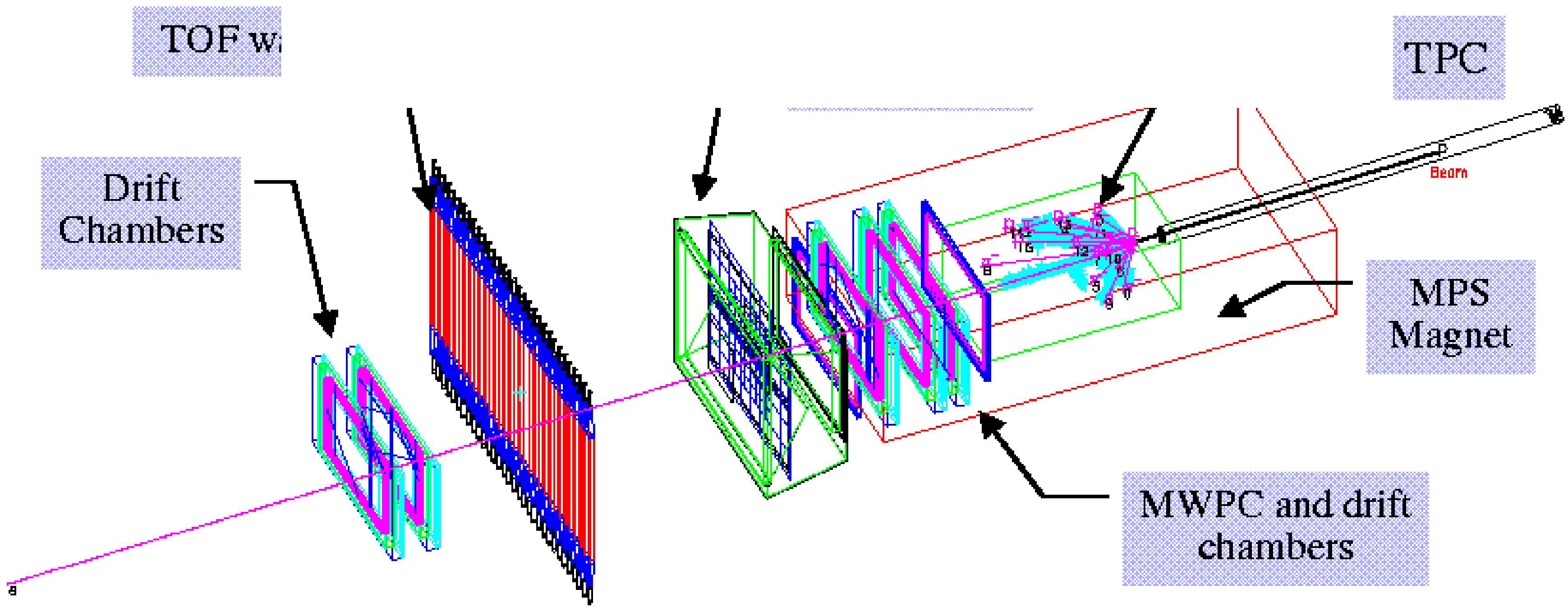
Modern 4π Experiments

- ***The E910 experiment at Brookhaven NL***
  - designed to measure intra-nuclear cascade effects in strange particle and resonance production by comparing production from light and heavy nuclei
  - Proton momenta in the range of 6-18 GeV/c
- ***The PS214 experiment (HARP) at CERN***
  - designed to measure secondary meson production on a wide range of nuclei hydrogen - lead
  - Proton momenta in the range1.5-15 GeV/c
  - included liquid cryogenic targets (H_2, D_2) and (N_2, O_2), relevant for atmospheric neutrino production
  - Data with beam energies and target configurations specific to MiniBooNE (8.9 GeV/c, Be target) and K2K (12.9 GeV/c, Al target)
- ***The E907 experiment (MIPP) at Fermilab***
  - measures scaling laws in secondary particle production at incident beam energies in the range 20-120 GeV/c on a wide range of nuclei, hydrogen-uranium
  - secondary production on the NuMI target

BNL/E910 Apparatus

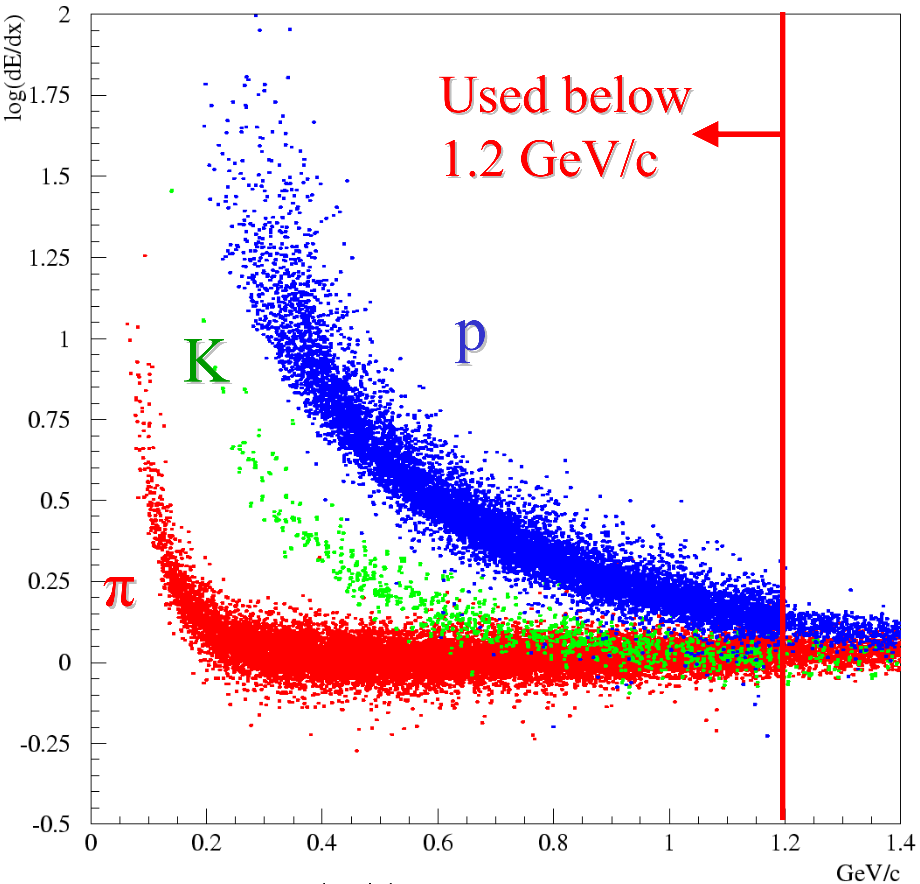
20M Triggers	6/12/18 GeV/c Beam	Be/Cu/Au/U Targets

E910 - Experimental Layout



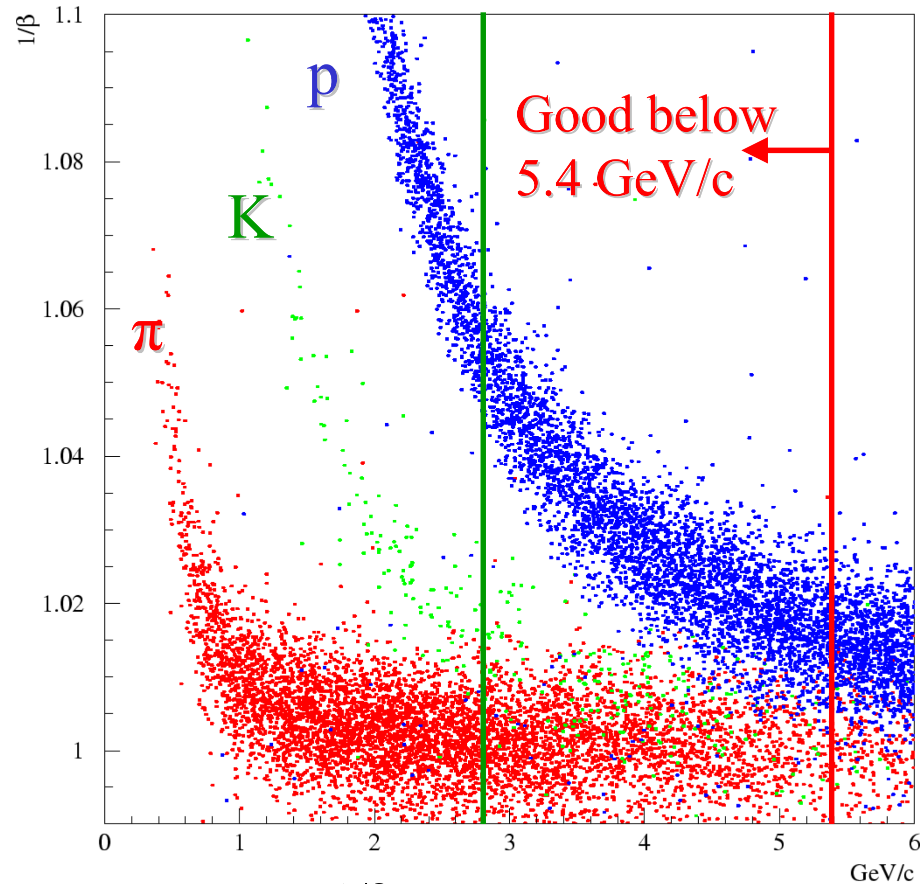
Particle Identification

TPC dE/dx



Log dE/dx vs. Momentum

Time of Flight

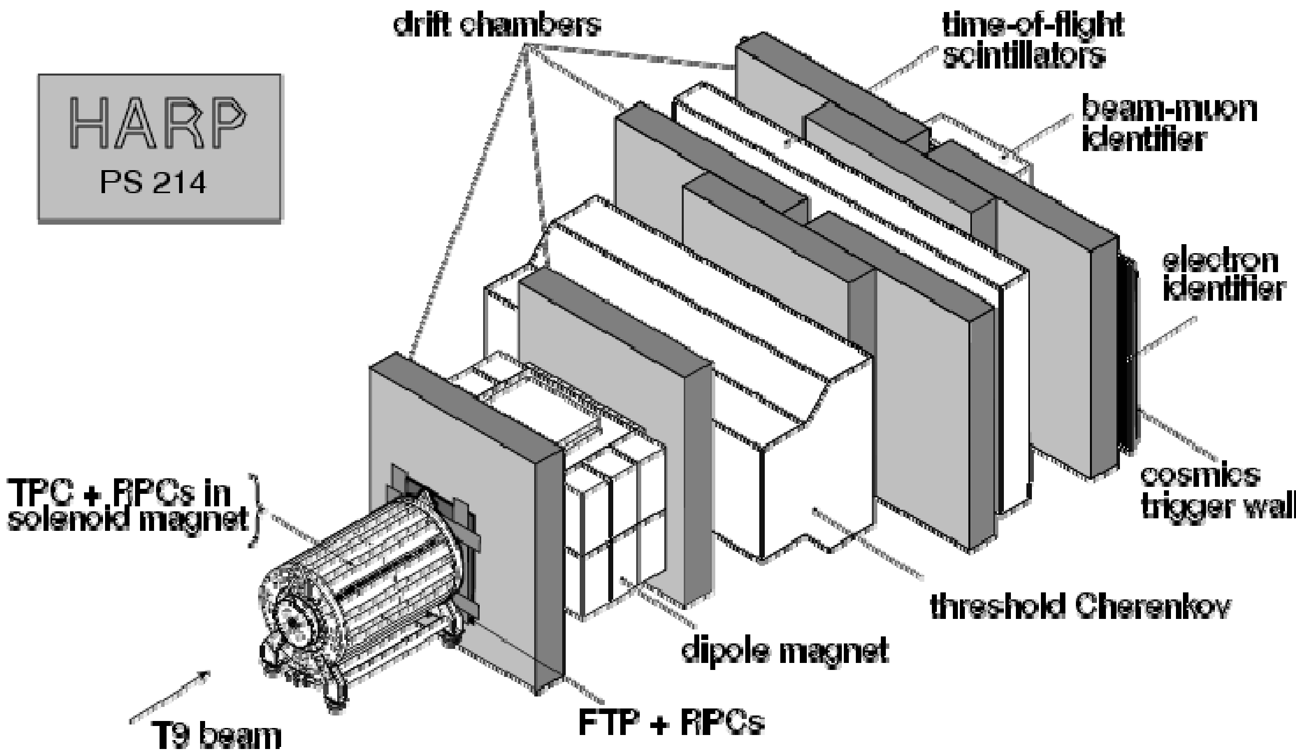


1/β vs. Momentum

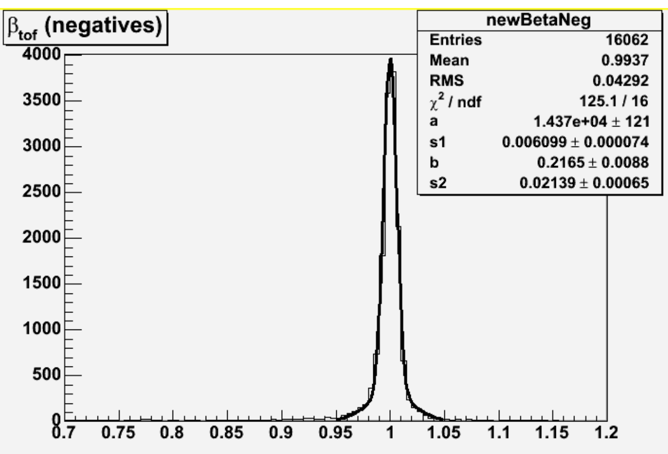
(J. Link)

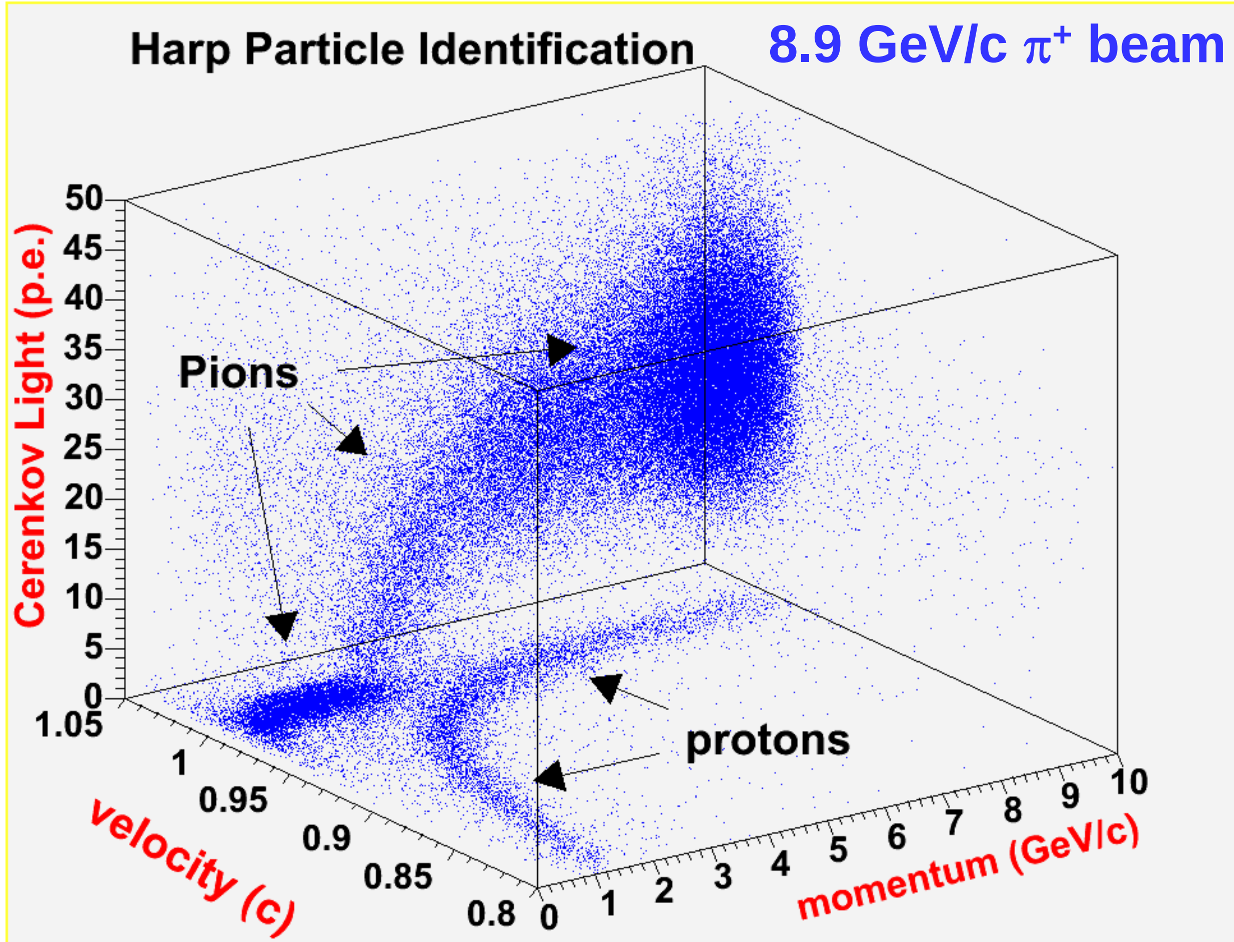
CERN/HARP Apparatus

400 M Triggers 1.5/**3**/**5**/**8**/8.9/**12**/12.9/**15 GeV/c Beam**
H/D/Be/C/N/O/Al/Cu/Sn/Ta/Pb Targets (5%,100%)
plus MiniBooNE and K2K runs



HARP Forward Spectrometer



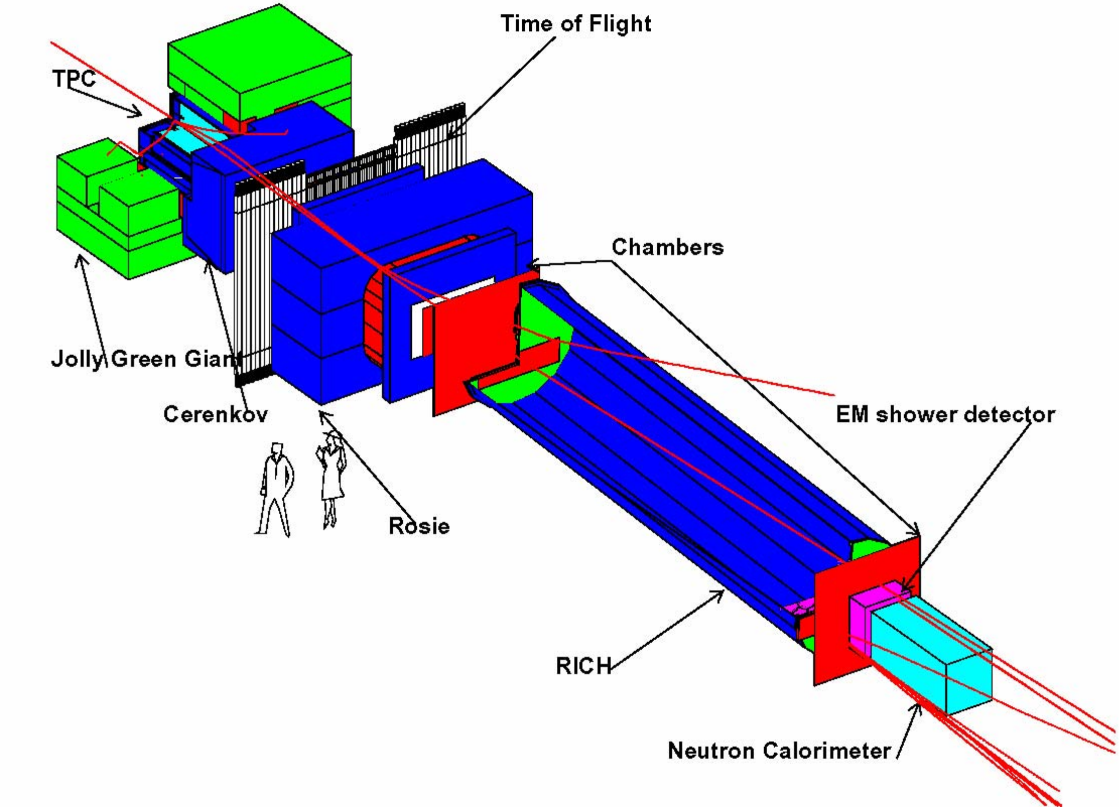


FNAL/MIPP Apparatus

5 M Triggers 20/35/60/120 **GeV Beams**

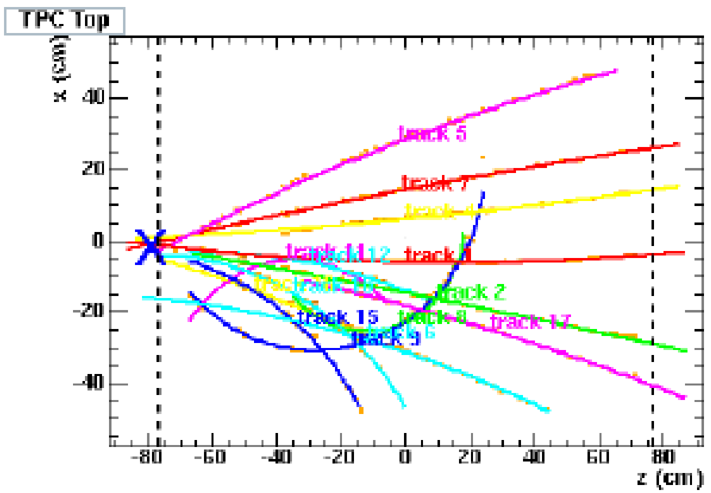
Thin Be/C Targets plus NUMI target

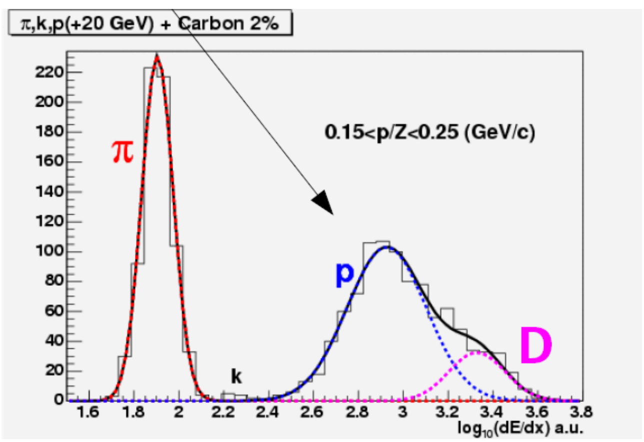
Horizontal cut plane



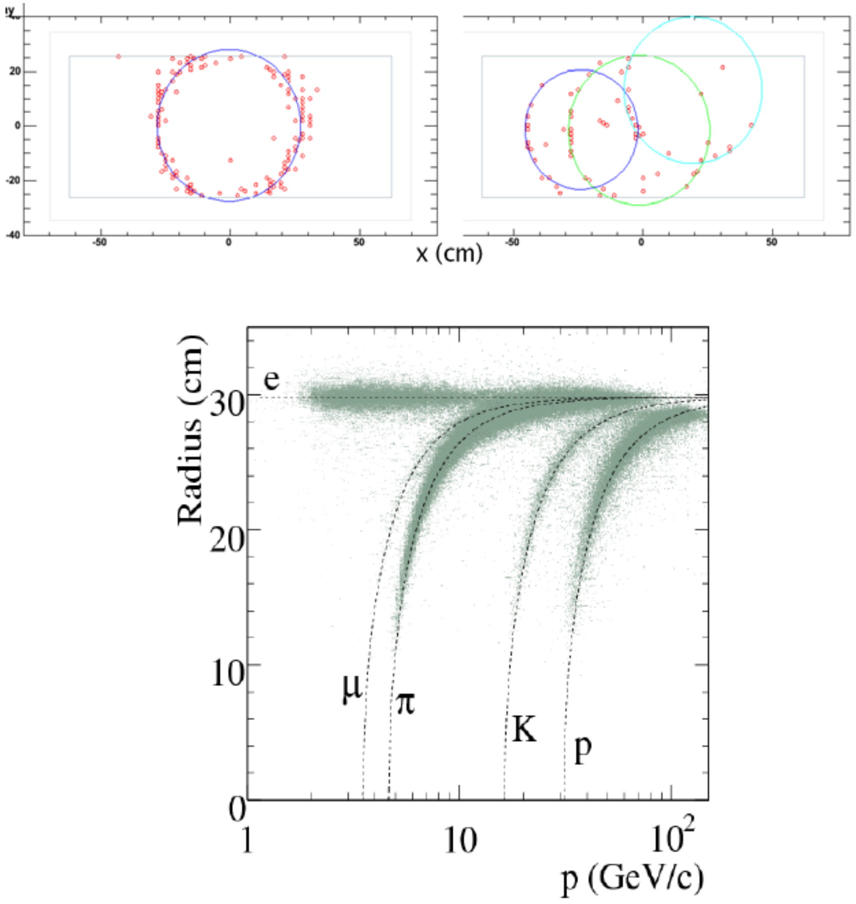
MIPP Performance

TPC detector





RICH detector



(see J. Paley Nu2006 poster)

Relevance to ν Physics

- **The E910 experiment at Brookhaven NL**
  - **Primarily relevant to MiniBooNE**
  - **6.4, 12.3 GeV/c on Be target with ~ 4π angular acceptance**
  - **6.4 GeV/c data has poor statistics**
  - **Must extrapolate to 8.9 GeV/c**
  - **Results for Be pion/kaon production at 6/12 GeV/c**
- **The PS214 experiment (HARP) at CERN**
  - **Primarily relevant to MiniBooNE and K2K**
  - **8.9 GeV/c on Be target and 12 GeV/c on Al target**
  - **4π angular acceptance however only forward spectrometer used in present analyses**
  - **No extrapolation needed in E_{beam} or A, only needed for angles > 210 mrad**
  - **Results on thin Al and Be, 5% targets at 12.9 and 8.9 GeV/c resp.**
- **The E907 experiment (MIPP) at Fermilab**
  - **Meson production for NuMI/Minos at 120 GeV**
  - **Systematic check of secondary scaling in 20-120 GeV beams on many nuclei**

HARP Results: 12.9 GeV/c Al Thin Target Data

- **Directly applicable to K2K's results (See Richard Gran's talk)**
- **K2K's oscillation result is mostly insensitive to this because they measure a *near/far ratio***

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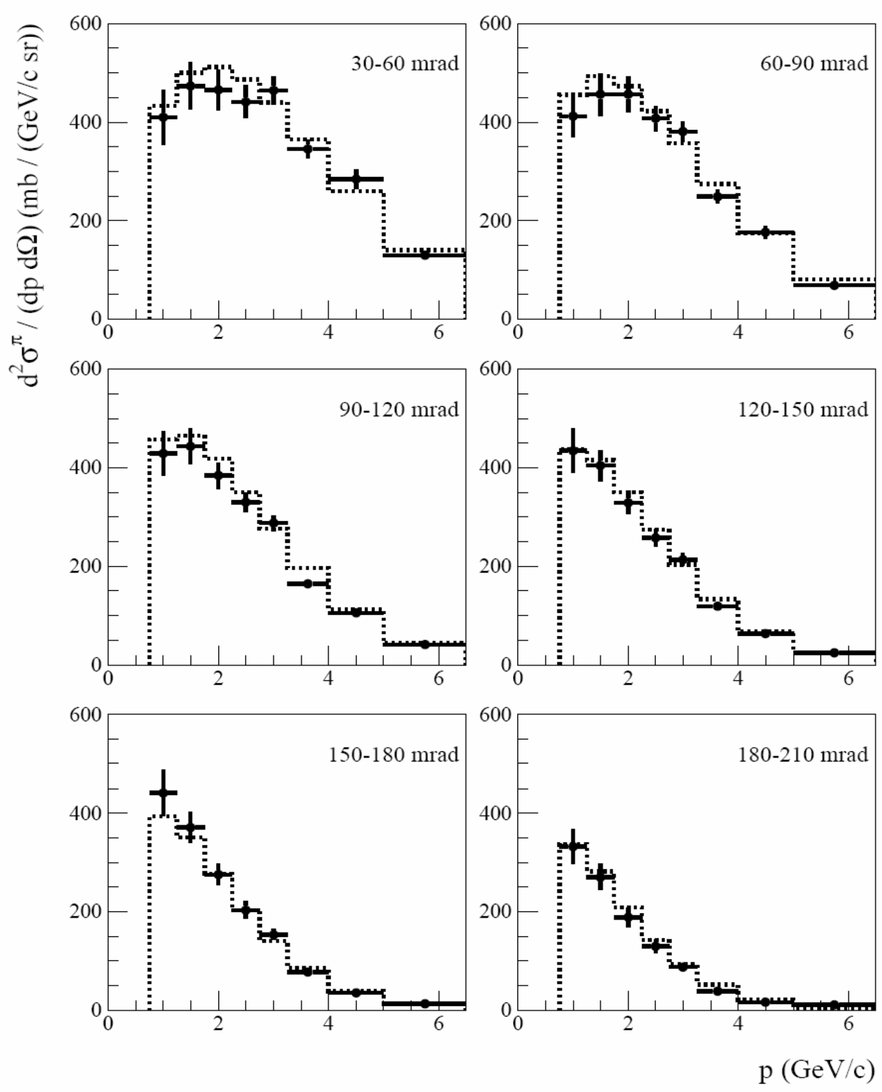
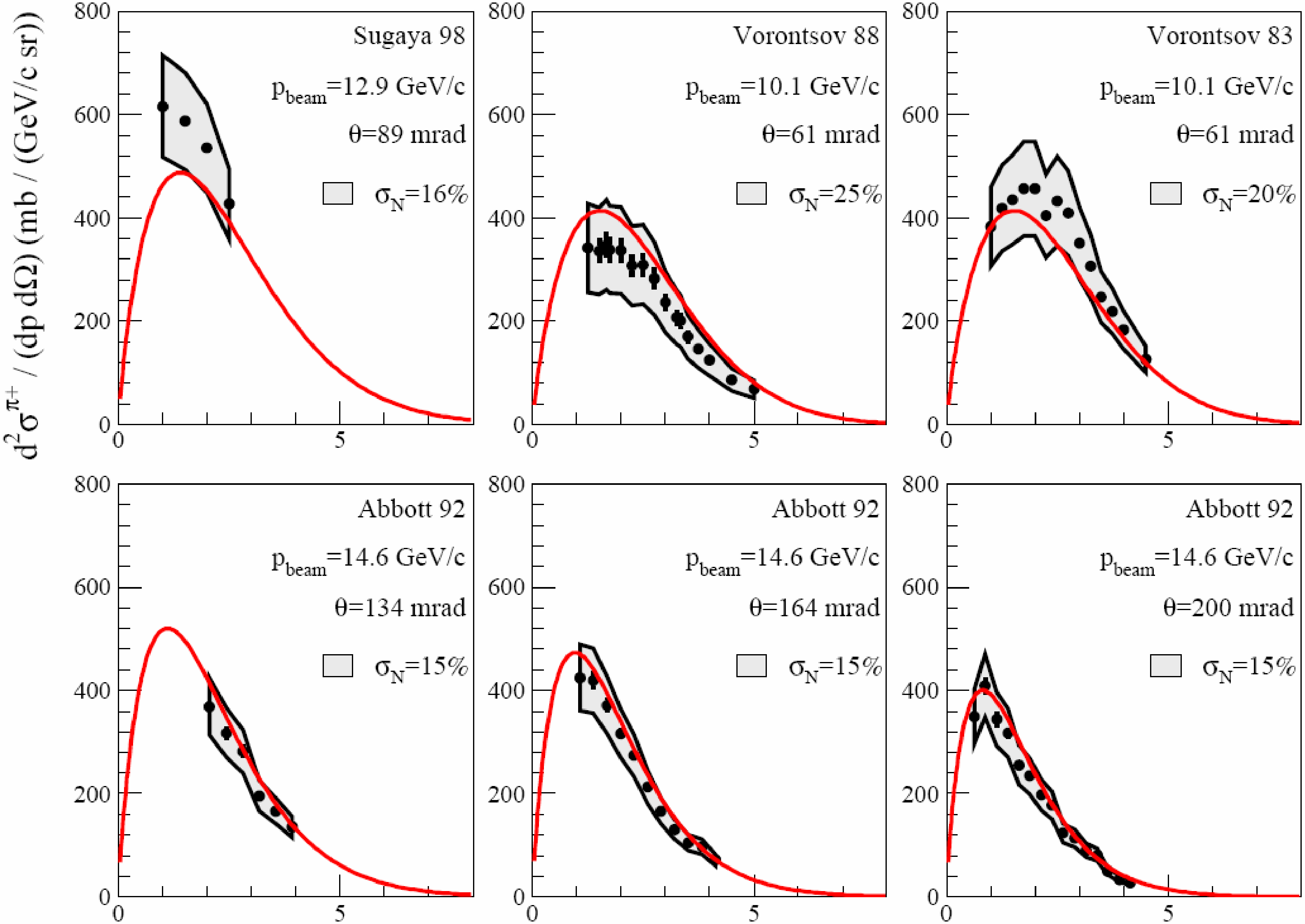


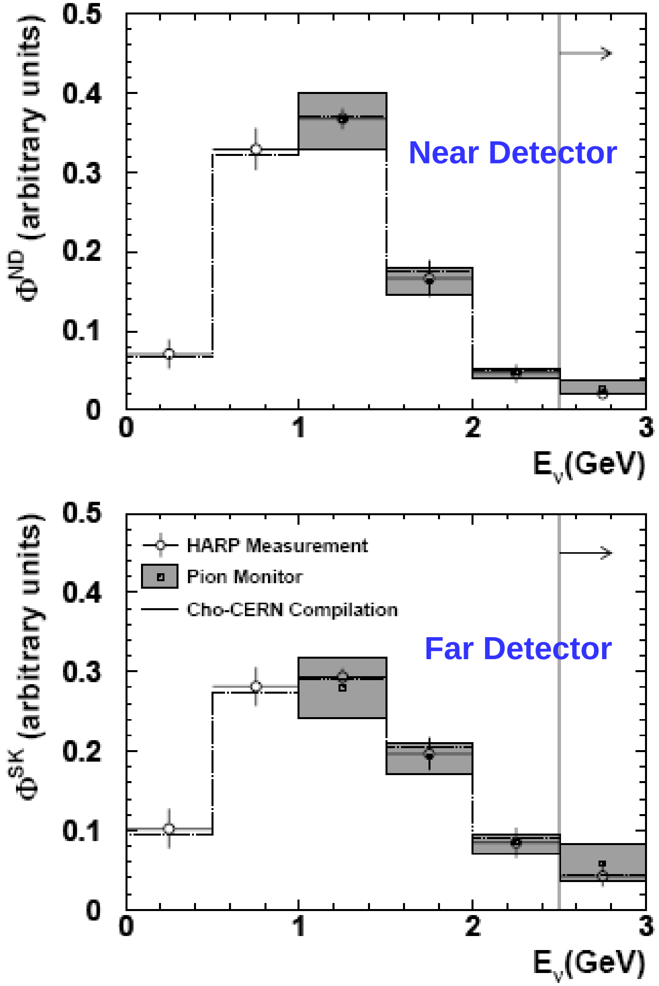
Comparison to Previous Aluminum Data Near K2K's 12.9 GeV/c beam momentum:

(M. Sorel)

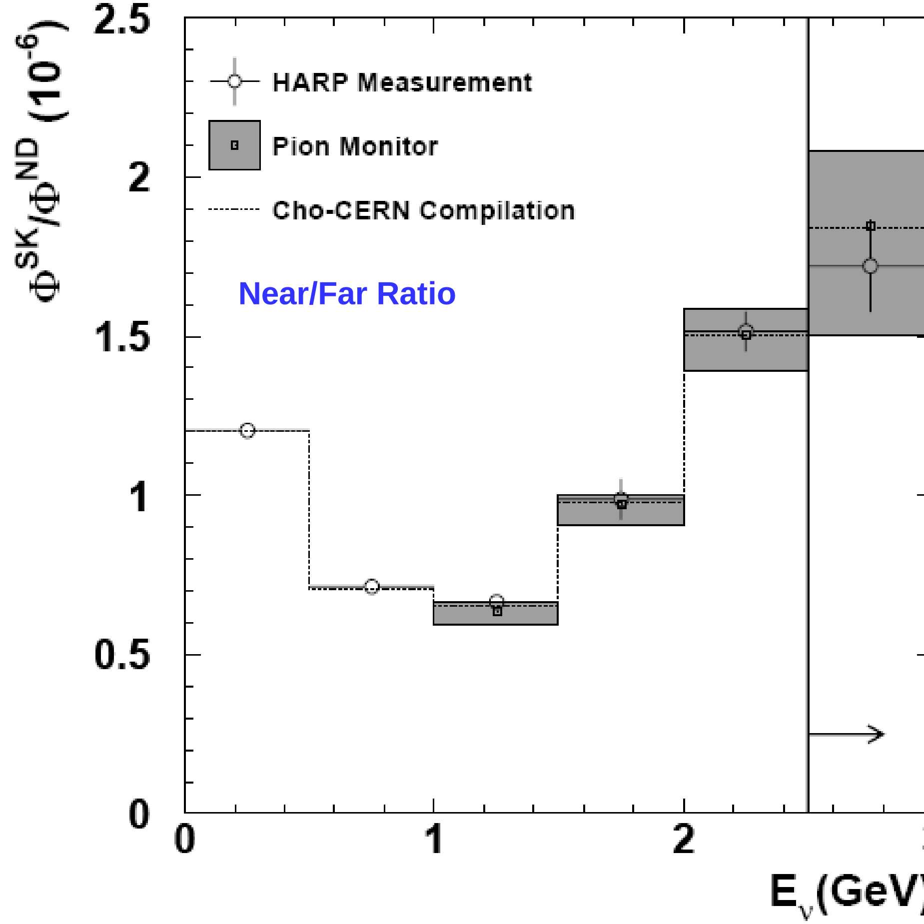


K2K Near/Far Ratio

Predicted Flux Shape



Predicted Far/Near Ratio



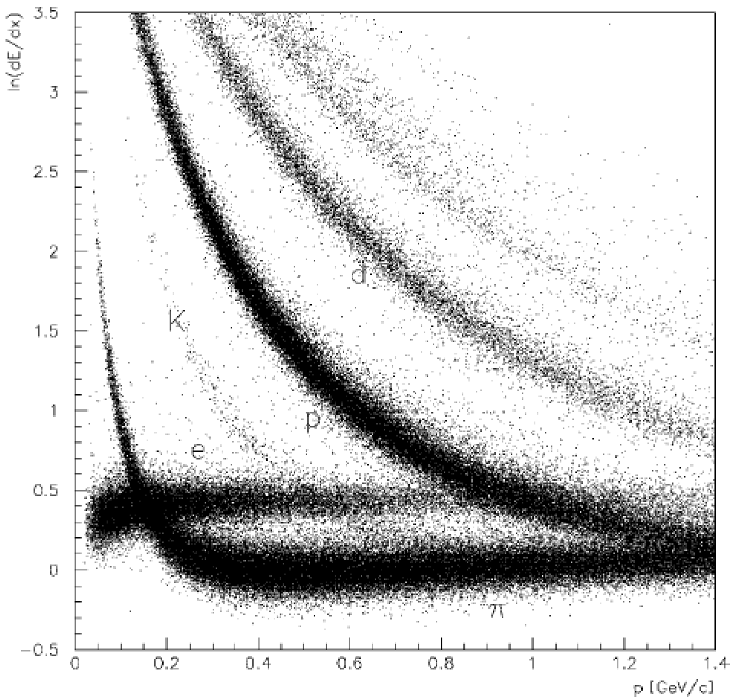
Near/far ratio errors are greatly reduced with the inclusion of Harp Data

Conclusions for Al Data

- **p-Al π^+ cross sections at 12.9 GeV/c are now well determined**
- **The cross section is different by as much as 20% from extrapolations that neutrino experiments have used in this energy region, however it is still consistent with the systematic errors of previous measurements**
- **We are now in a better position to understand neutrino cross sections in this energy range**

E910 TPC results (<1.2 GeV/c)

TPC performance



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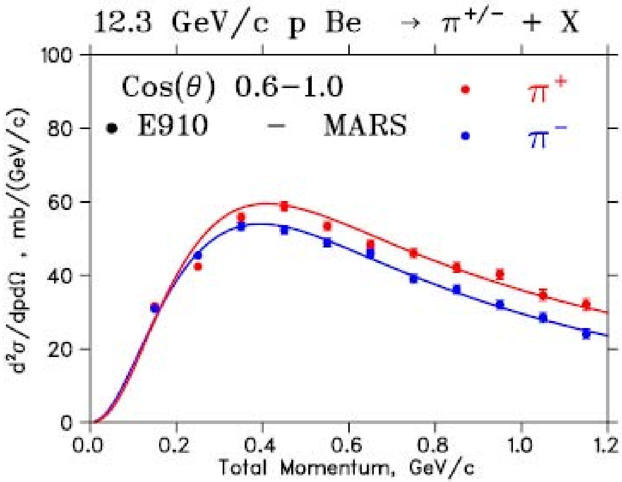
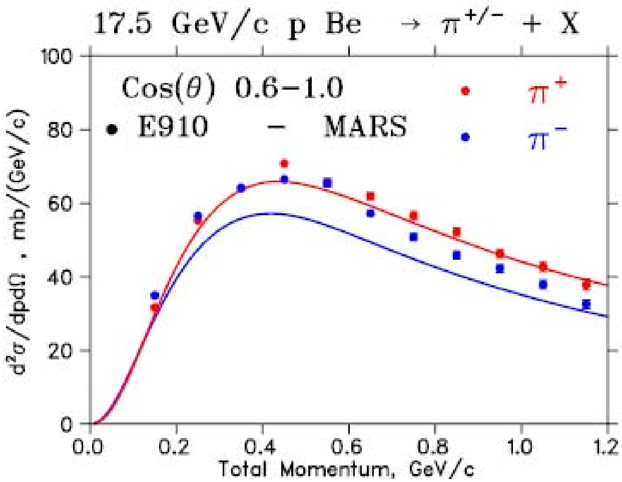
(H. Kirk)

proton Be Interactions

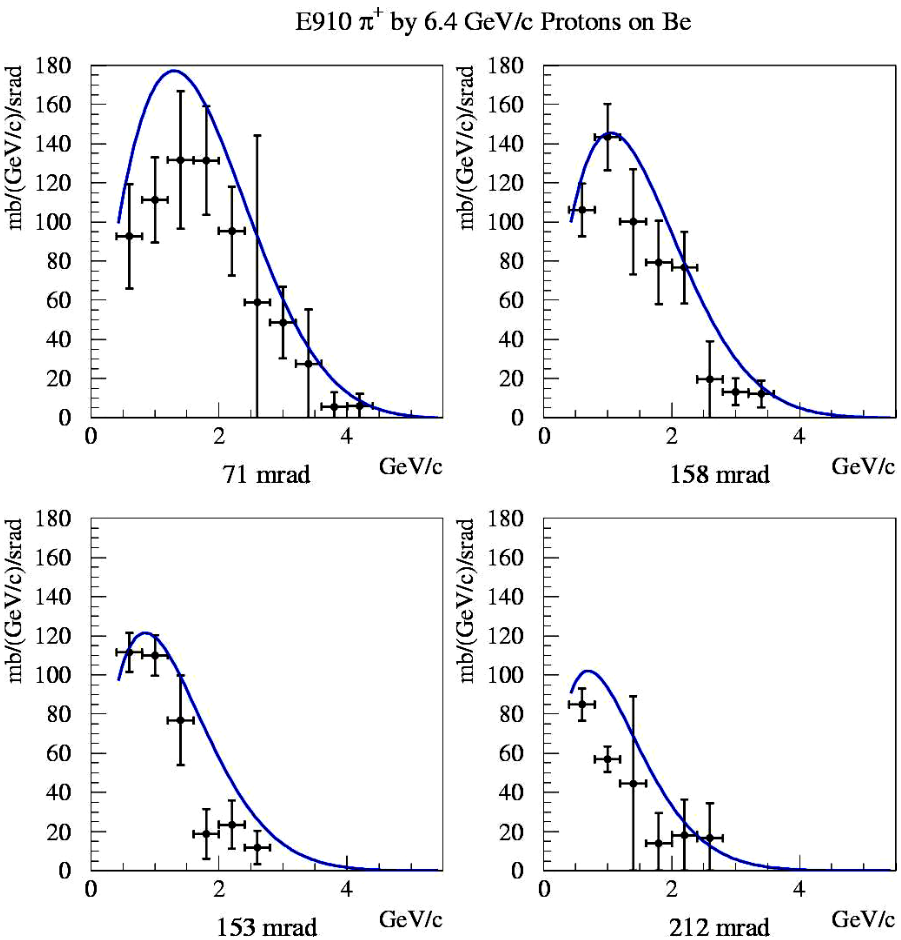




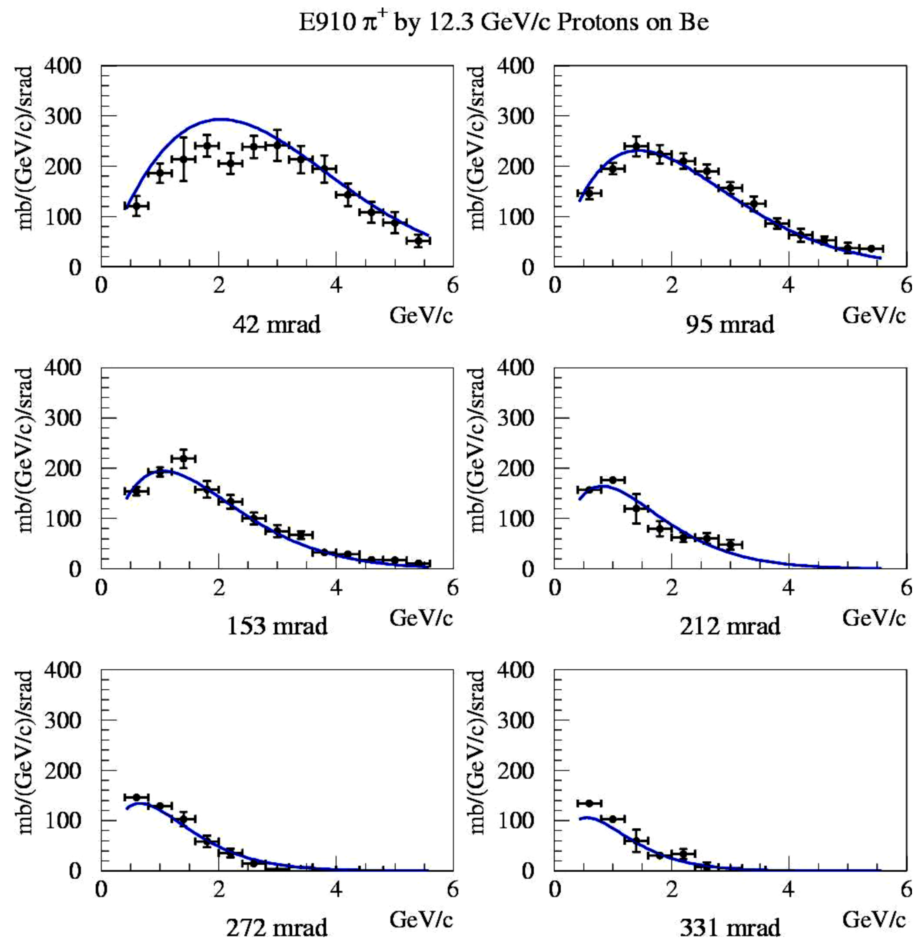
E910: Preliminary π^+ Production on Be

Curve is a Sanford-Wang Fit

6.4 GeV/c

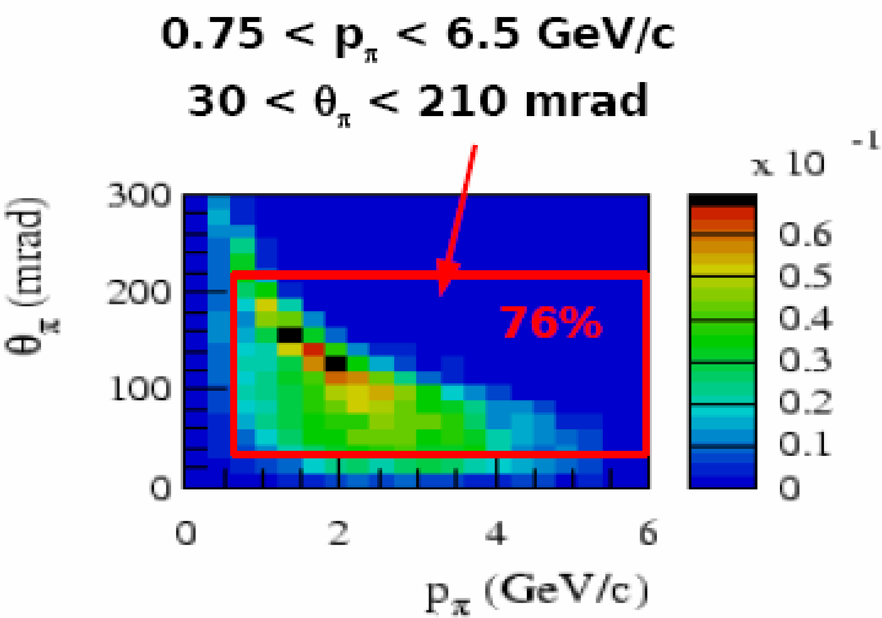


12.3 GeV/c



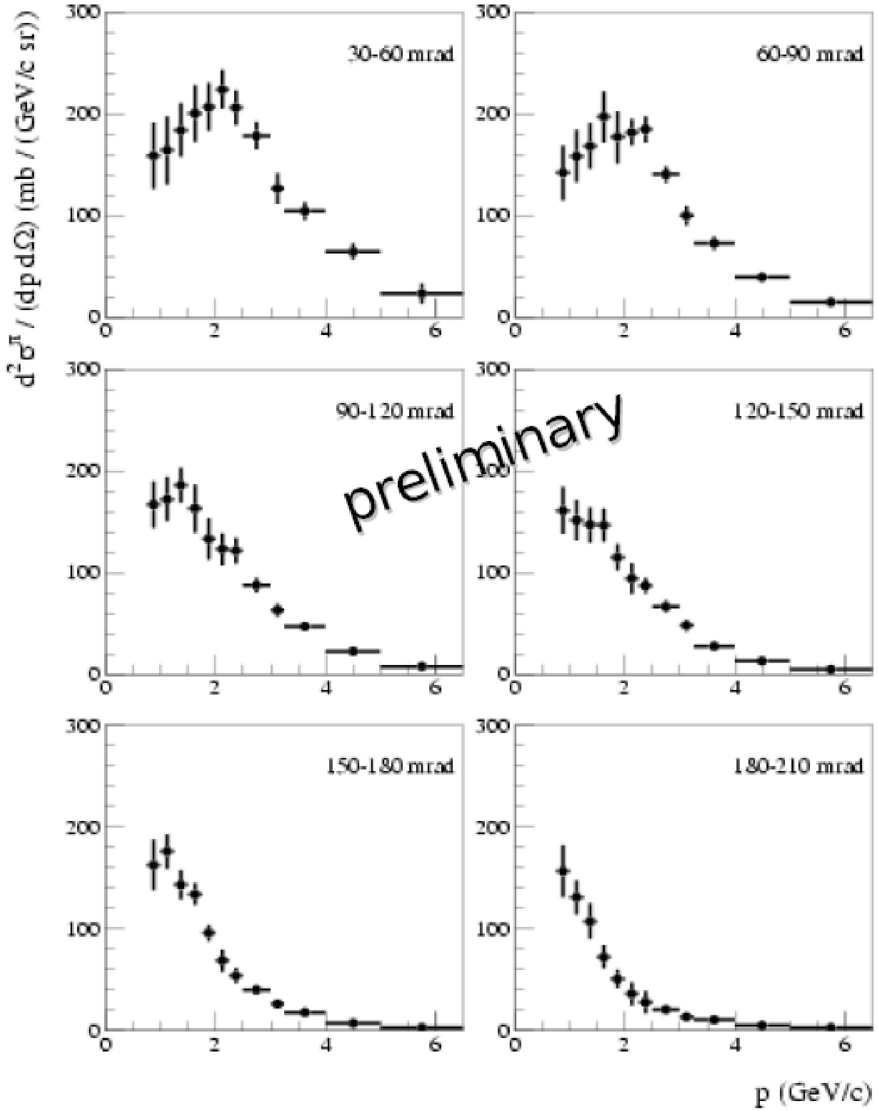
(J.M. Link)

Preliminary HARP Be Thin Target Results



Momentum and Angular distribution of pions decaying to a neutrino that passes through the MB detector.

(D. Schmitz)



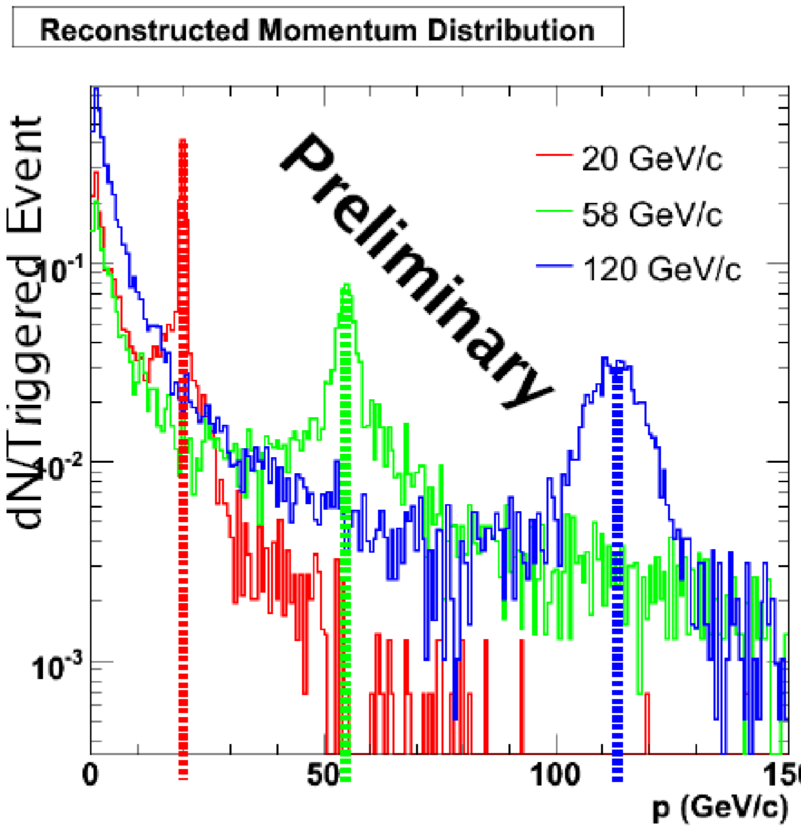
Conclusions for Be Data

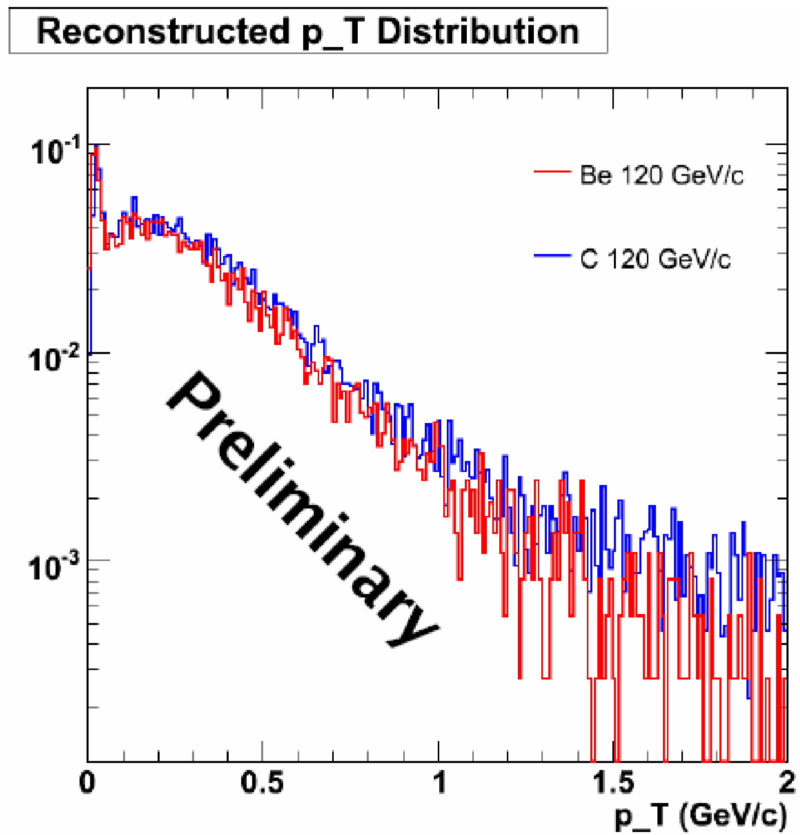
- **p-Be π^+ production cross sections at 8.9 GeV/c are now well determined**

- **We are now in a better position to understand neutrino cross sections from beams in this energy range**

- **HARP thick target analysis is proceeding and will be ready later this summer**

Preliminary MIPP Results





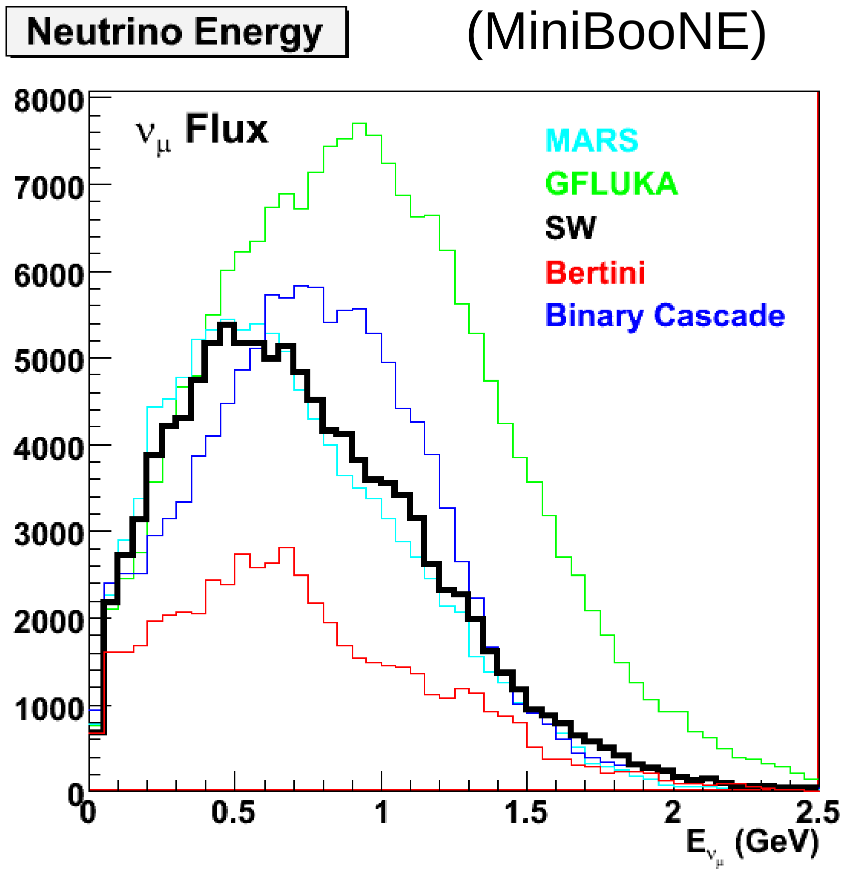
(see J. Paley poster)

Outlook

- **HARP:**
  - **Analysis of thick target data will shed light on secondary interactions in K2K and MiniBooNE and measure yields below 30 mrad**
  - **K^+ production data analysis for MiniBooNE is in progress**

- **MIPP:**
  - **Analysis proceeding**
  - **Results possible by end of this year!**
  - **Upgrade to improve event rates has been proposed**

Variation in MC Predictions of ν Flux



Post-HARP flux predictions should have an uncertainty better than 10%

End