The MiniBooNE Experience with Hadronic Simulations

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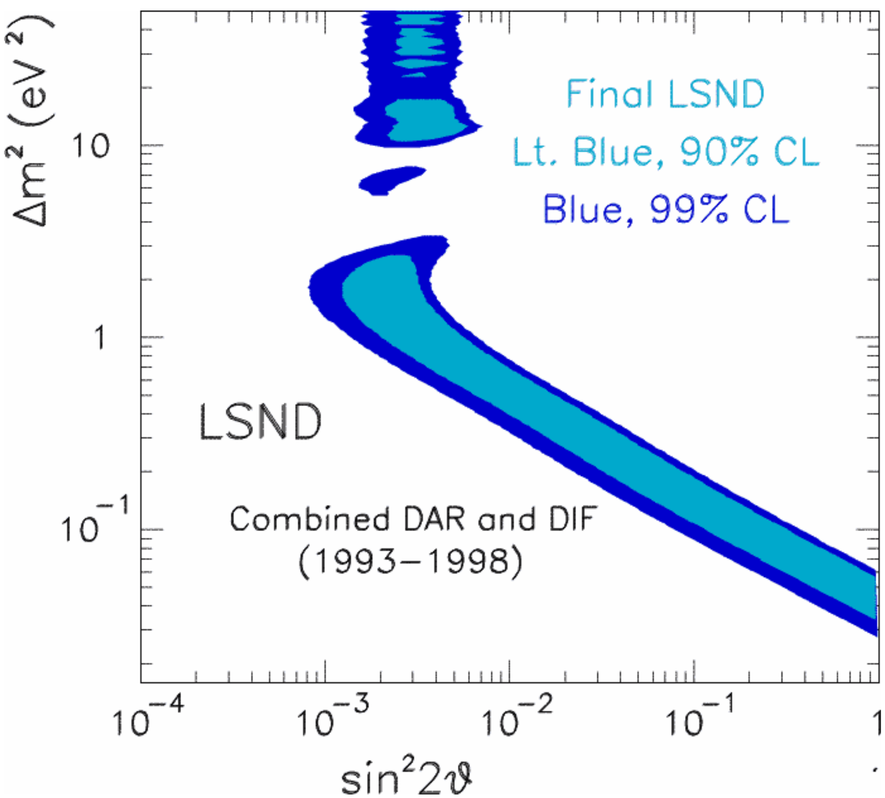
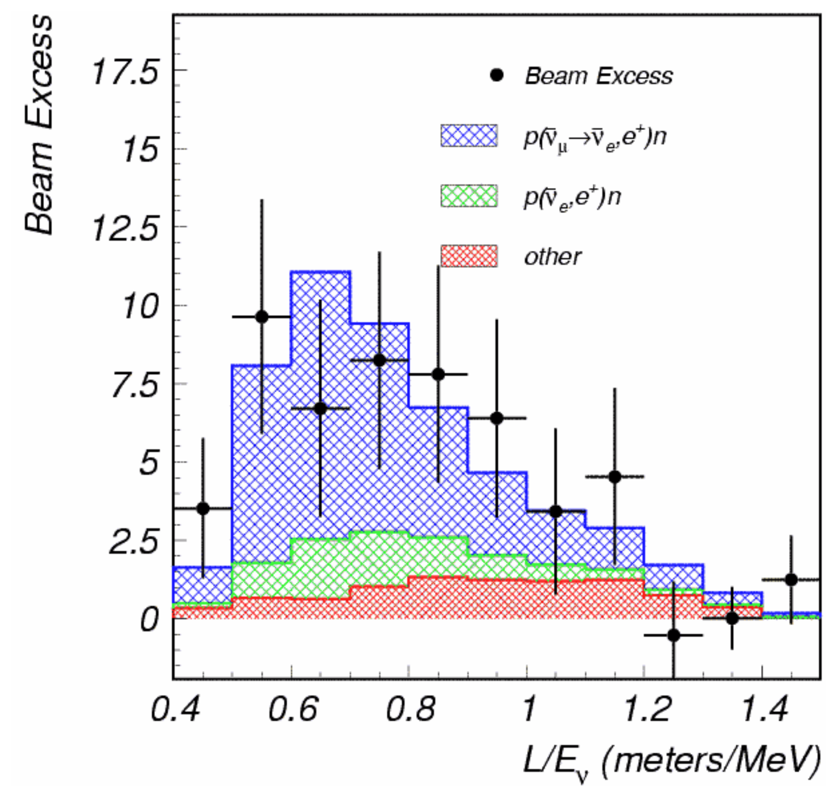
About MiniBooNE

MiniBooNE was designed to test the high Δm^2 neutrino oscillation signal observed by the LSND experiment.

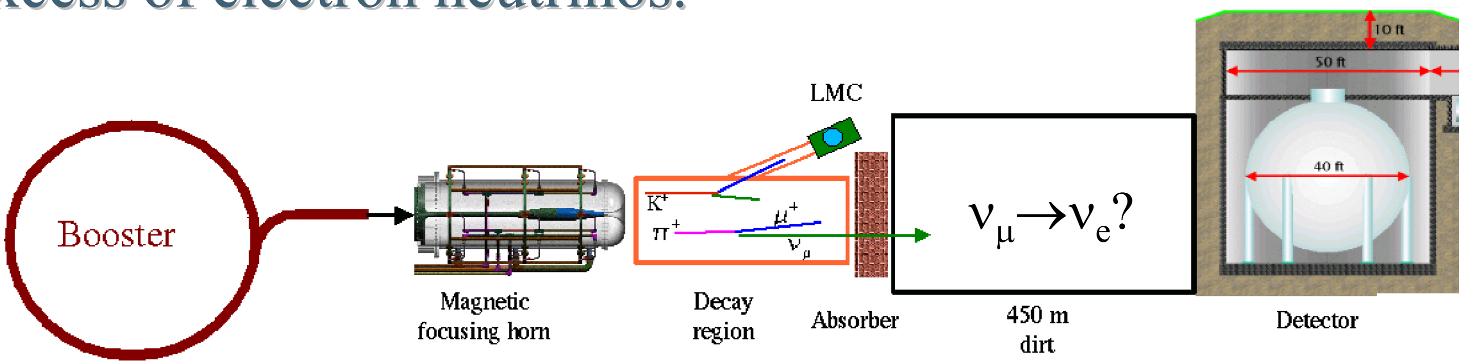




LSND saw an excess of electron antineutrinos in a stopped π^+ beam, which was initially devoid of electron antineutrinos.

About MiniBooNE (Continued)

MiniBooNE uses a π^+ decay in flight beam to produce a beam of muon neutrinos. Oscillations would be observed as an excess of electron neutrinos.



Unlike some other terrestrial beam neutrino experiments, MiniBooNE does not have a near detector to observe the unoscillated flux.

Therefore, modeling of particle production and propagation is crucially important to MiniBooNE.

The Issues

There are several things that we need to predict the neutrino flux:

1. Primary production of $\pi^{\pm}$, $K^{\pm}$, K_L, p and n in the interaction of 8.9 GeV protons on a beryllium target.

2. Secondary interactions of all particles in Be target and in the aluminum of the focusing horn.

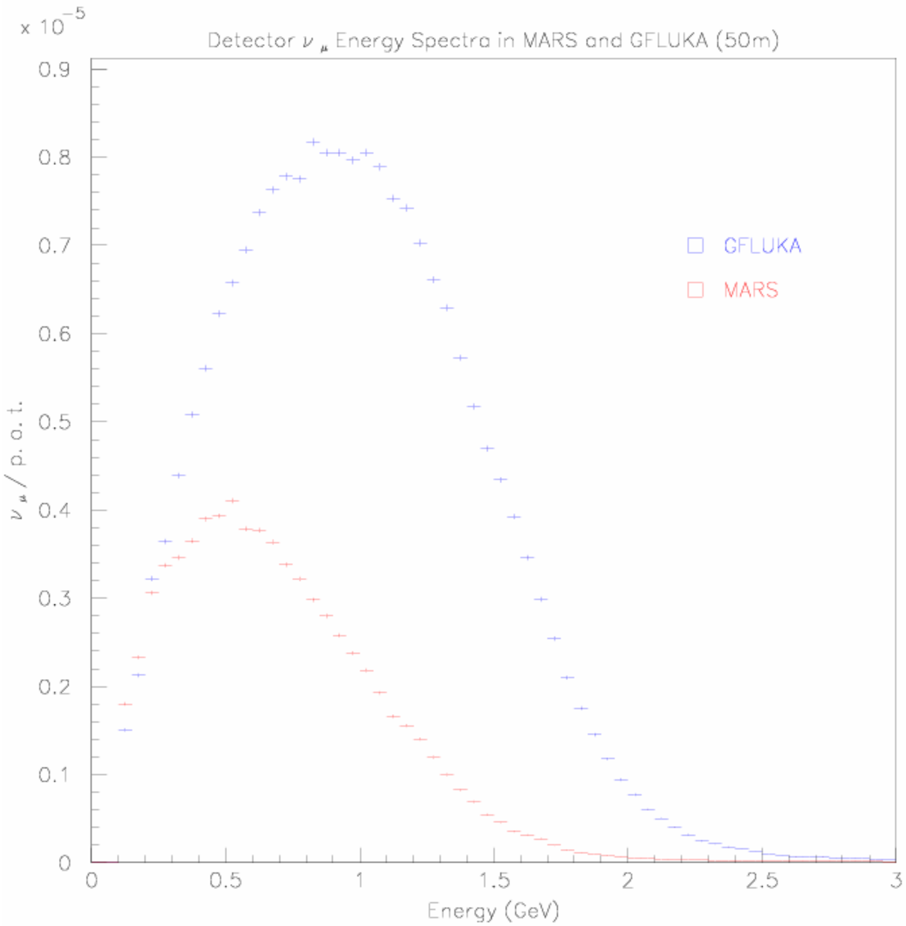
3. Propogation of particles in the horn magnetic field.

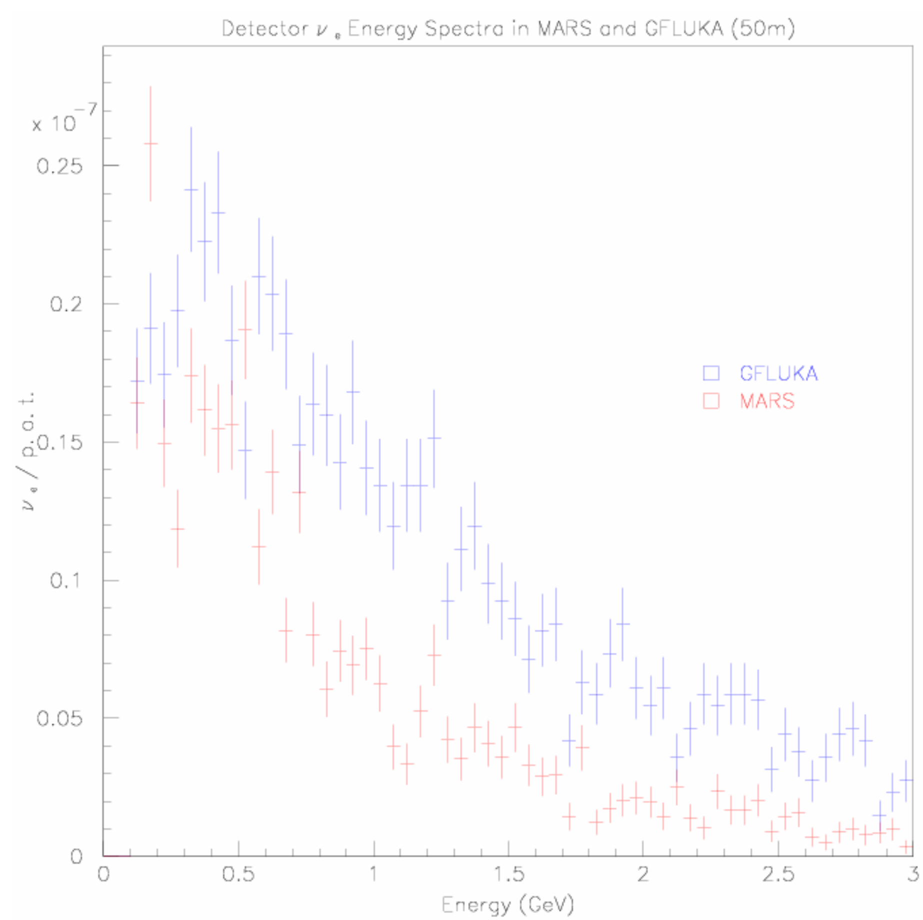
4. Decay of all particles in the decay volume.

We had to do the muon polarization ourselves!

Out of the Box Flux Predictions (2002)

We used MARS and GFLUKA (Geant3) to predict our neutrino flux…





…and they were in wild disagreement!

Why Do We Care?

Clearly we need to know the relative rate of intrinsic ν_e (from $K^{\pm}\to\pi^0 e^{\pm}\nu_e$, $K_L\to\pi^{\pm}e^{\mp}\nu_e$ and $\mu^{\pm}\to e^{\pm}\nu_e$) to ν_μ.

Other backgrounds come from misidentified ν_μ events (like neutral current π^0 production), so we need to get the muon neutrino spectrum right to predict these backgrounds.

Source of electron neutrino-like events

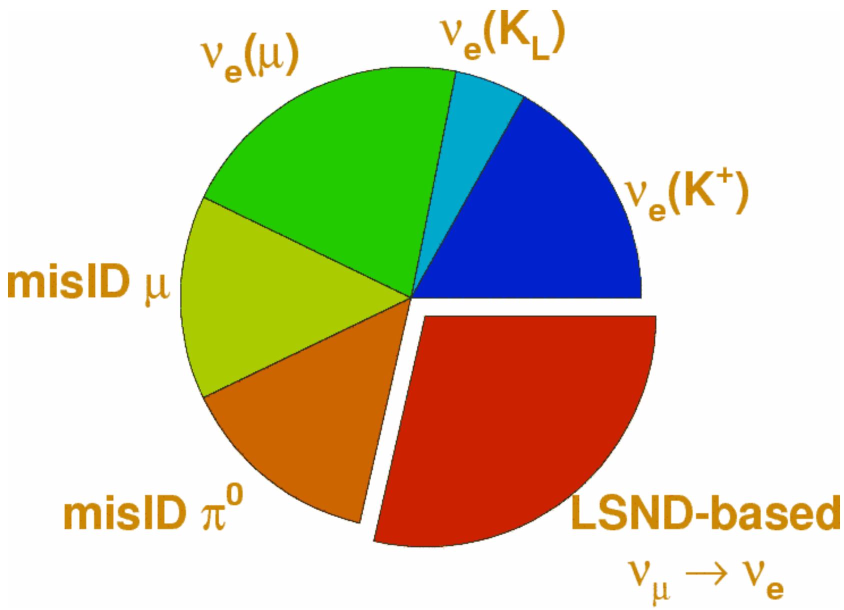
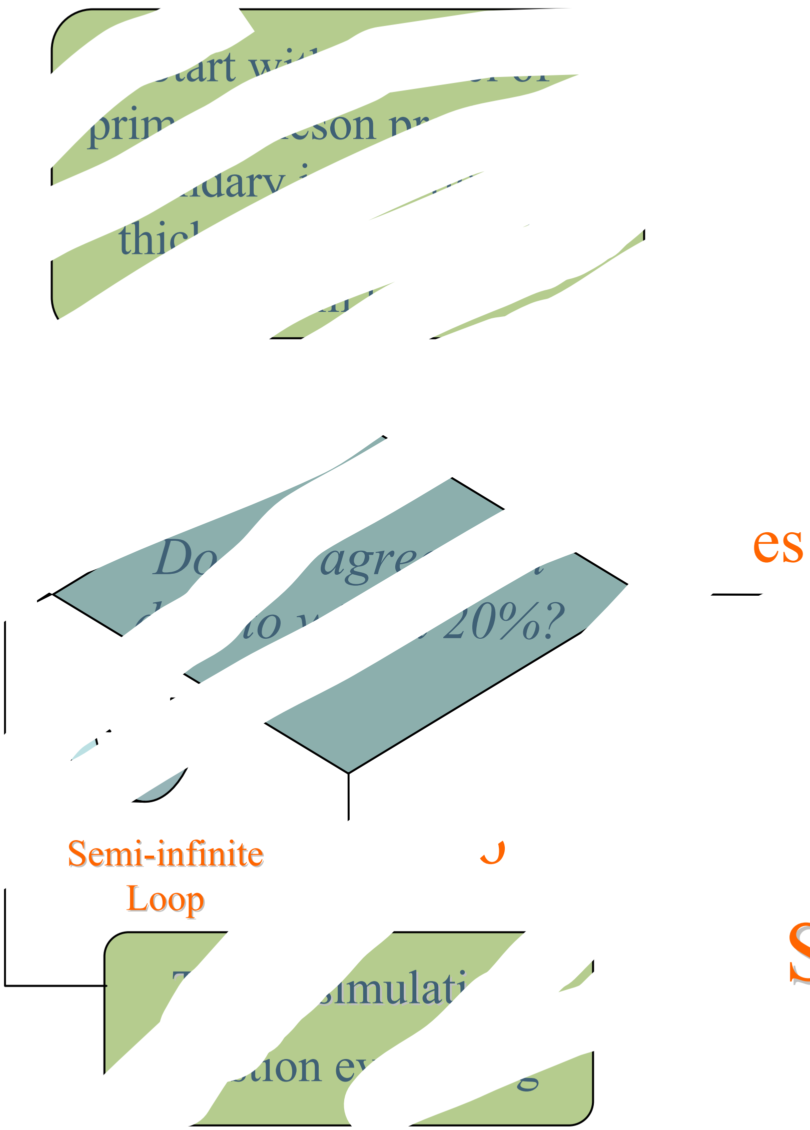


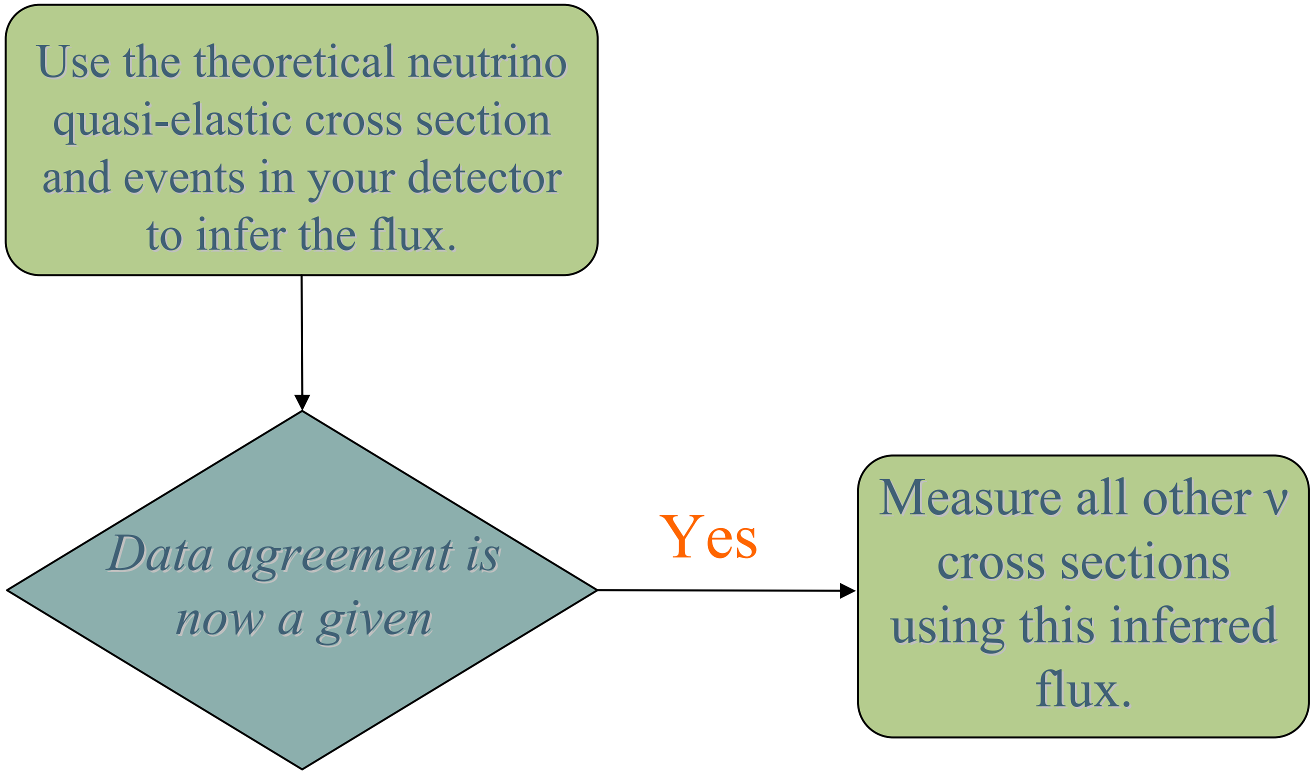
Diagram of a Neutrino Flux Prediction



A comical look (My apologies to anyone in the room who may have done this in the past)

Start Over…

Historical Diagram of Neutrino Flux Predictions



Bottom line: It may be that the neutrino quasi-elastic cross section has never *really* been measured (at least in the few GeV region).

The MiniBooNE Simulation Tools

Our beam Monte Carlo is based on Geant4, but we use our own cross section models for much of the relevant space.

The motivation for this is twofold:

1. We need to incorporate data from the HARP and E910 experiments which was not available when the pre-existing models where made.
2. We want to have levers at our disposal so that we can adjust the secondary interaction models to enforce agreement with the HARP thick target meson flux.

The Sanford-Wang Function

The parameterization of Sanford and Wang describes meson production as a function of beam momentum (p_B), secondary momentum (p), angle (θ), and 8 fit parameters ($C_1 \ldots C_8$)

$$S(p_B, p, \theta) = C_1 p^{C_2} \left(1 - \frac{p}{p_B - 1}\right) \exp\left(-\frac{C_3 p^{C_4}}{p_B^{C_5}} - C_6 \theta \left(p - C_7 p_B \cos^{C_8} \theta\right)\right)$$

This function is fit to all the data by minimizing the following χ^2

$$\chi^2 = \sum_{p_B} \sum_{p} \sum_{\theta} \frac{\left(\frac{d\sigma^2}{dp d\theta}(p_B, p, \theta) - \frac{1}{\Delta p \Delta \Omega} \int_{p_{lo}}^{p_{hi}} \int_{\theta_{lo}}^{\theta_{hi}} S(p'_B, p', \theta') dp' d\theta'\right)^2}{\sigma_{meas}^2}$$

Pre-existing Production Data

π Production

Experiment	P_{beam} (GeV/c)	Year
Allaby	19.1	1970
Cho	12.4	1971
Marmer	12.3	1969
Vorontsov	10.1	1983

E910 and HARP

K^0 Production

Experiment	P_{beam} (GeV/c)	Year
Abe	12	1987

E910

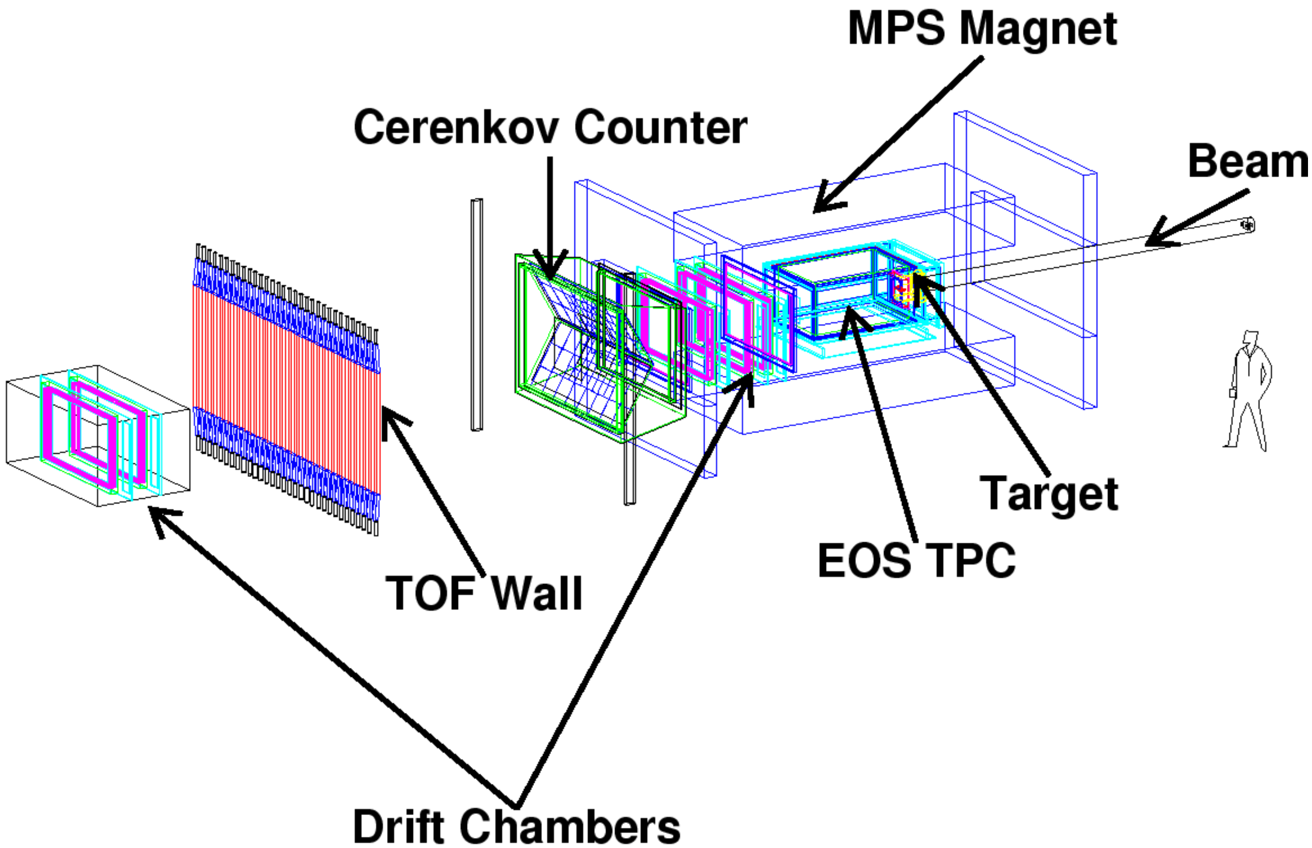
K^+ Production

Experiment	P_{beam} (GeV/c)	Year
Abbott	14.6	1992
Aleshin	9.5	1977
Allaby	19.1	1970
Dekkers	18.8, 23.1	1964
Eichten	24.0	1972
Lundy	13.4	1965
Marmer	12.3	1968
Piroue	2.74	1966
Vorontsov	10.1	1983

HARP (soon)

Brookhaven Experiment 910

E910 used a spectrometer with good acceptance and particle ID over the momentum and angular range of interest to MiniBooNE.



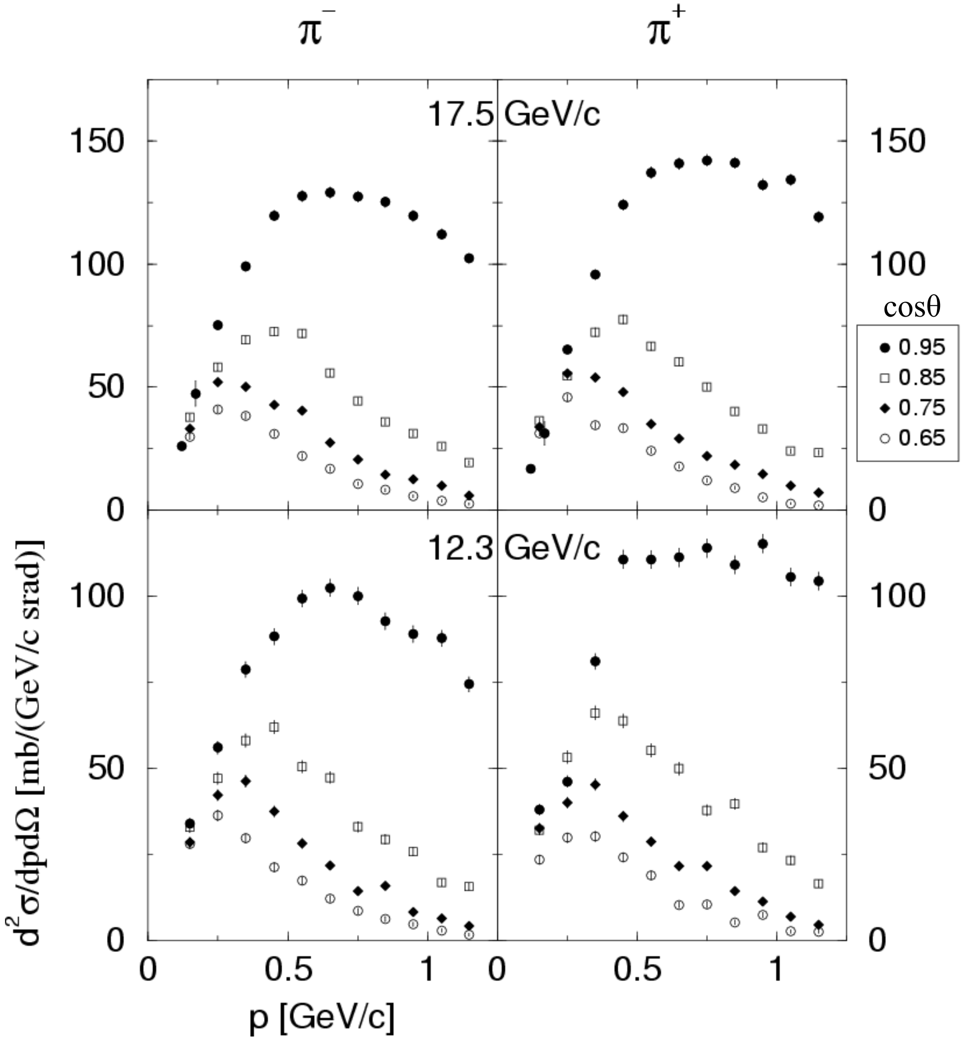
Particle ID from dE/dx in the TPC, threshold Čerenkov, and Time of Flight.

Pre-existing E910 Pion Production Results

Paper: "Inclusive soft pion production from 12.3 and 17.5 GeV/*c* protons on Be, Cu, and Au" (Phys.Rev.C65:024904)

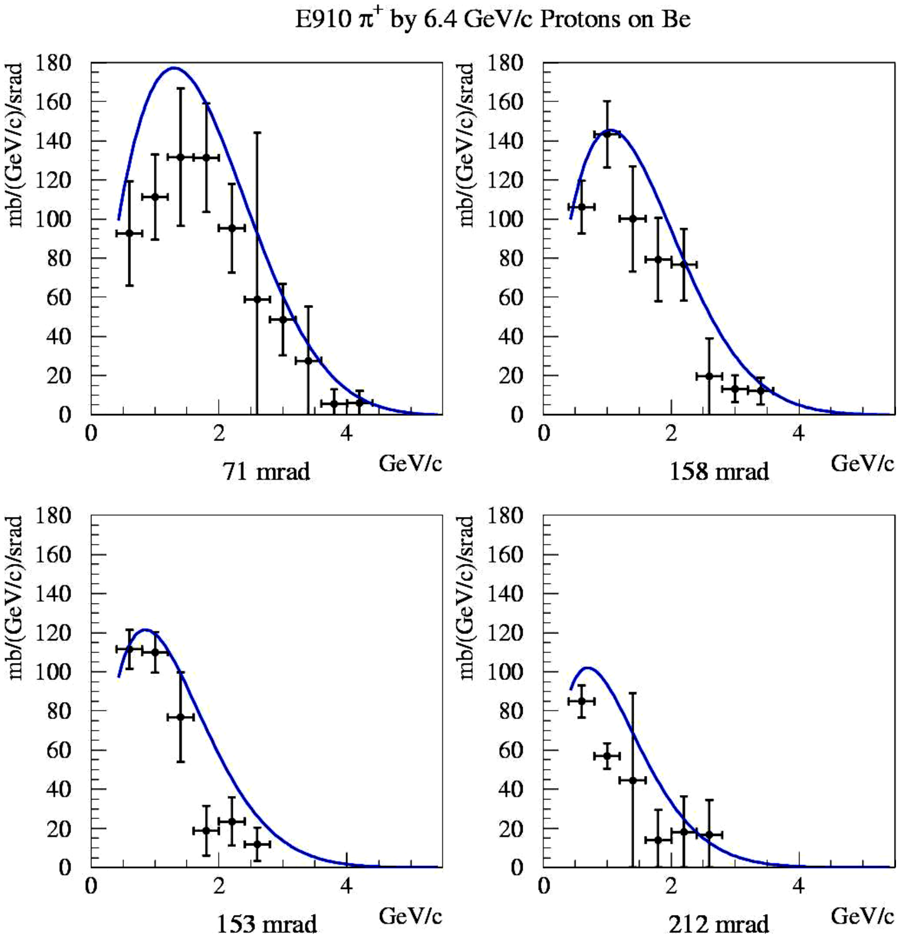
This paper focused on pions with momentum less that 1.2 GeV/c.

The MiniBooNE analysis extends the pion momentum range beyond 1.2 GeV/c and includes a small data set with beam momentum at 6.4 GeV/c.

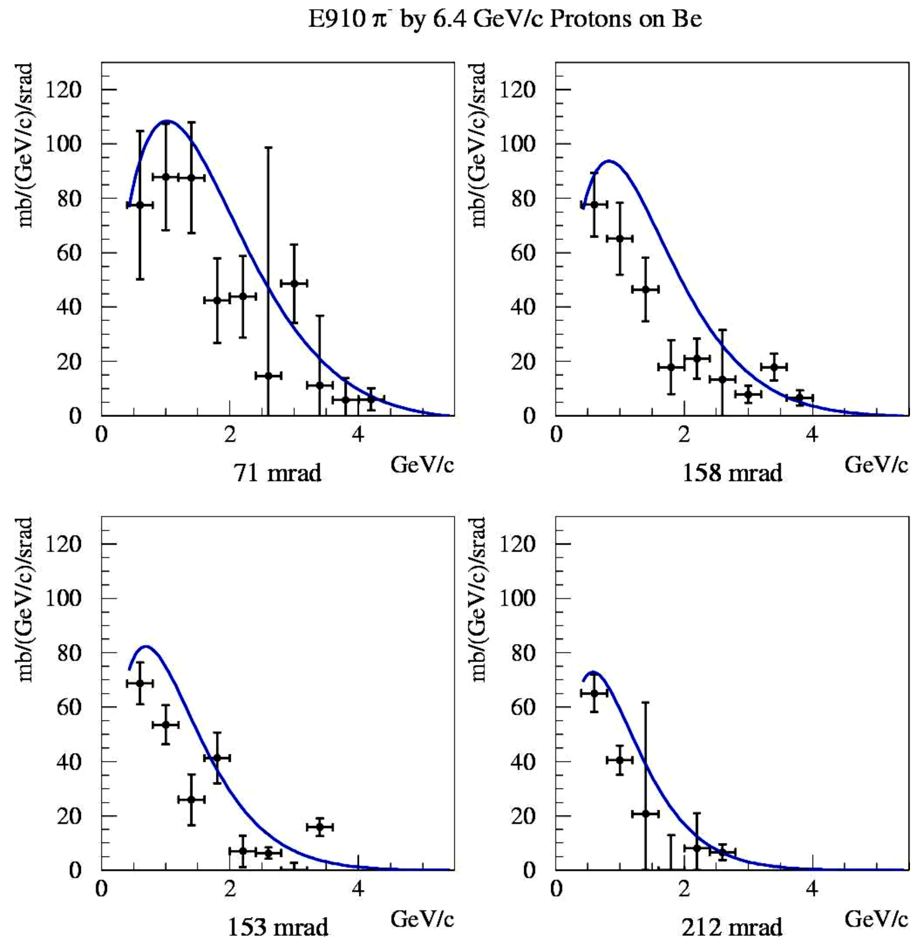


MiniBooNE E910 Pion Production Results

6.4 GeV/c Beam Momentum



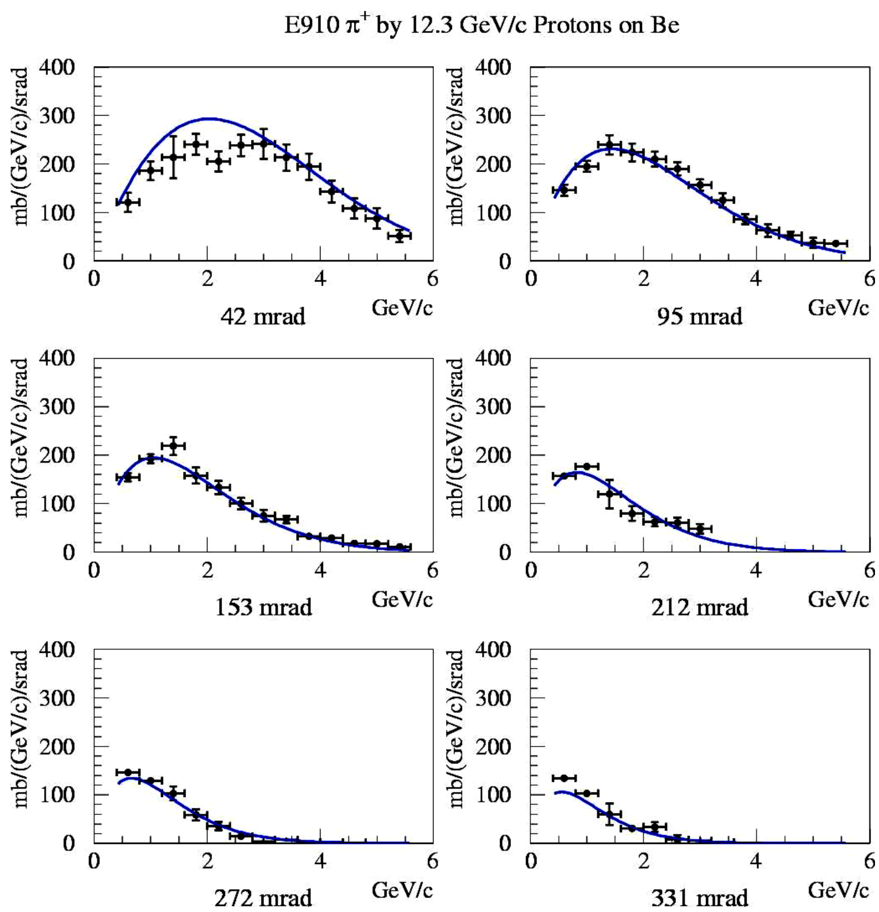
π^+



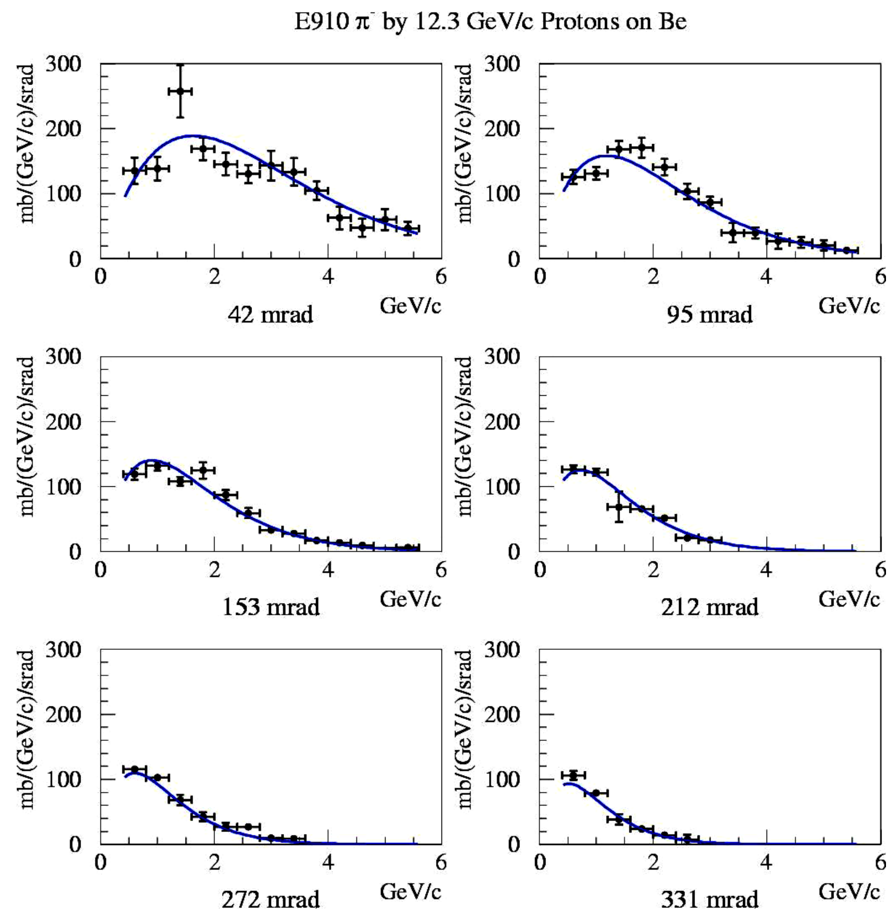
π^-

MiniBooNE E910 Pion Production Results

12.3 GeV/c Beam Momentum



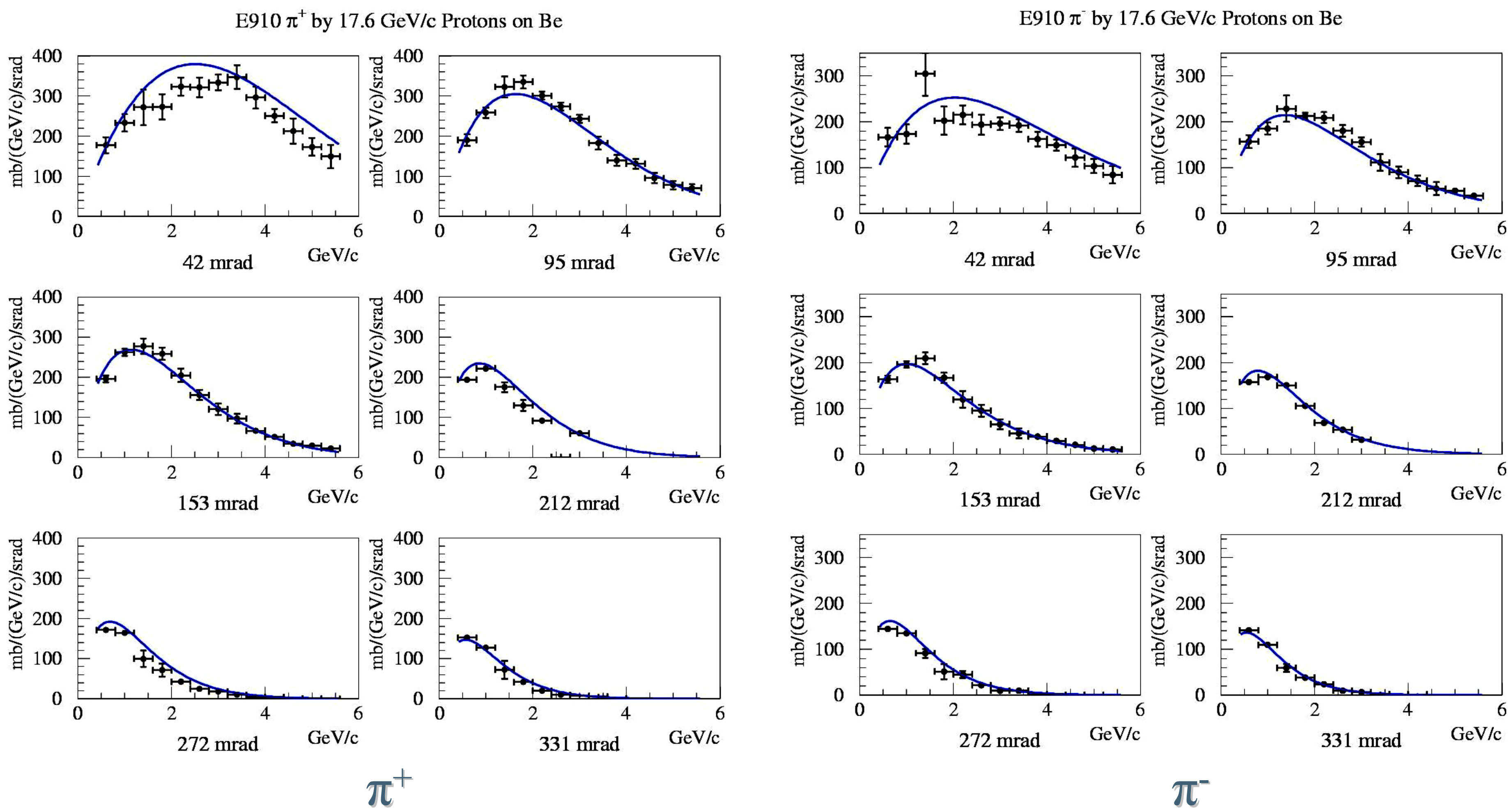
π^+



π^-

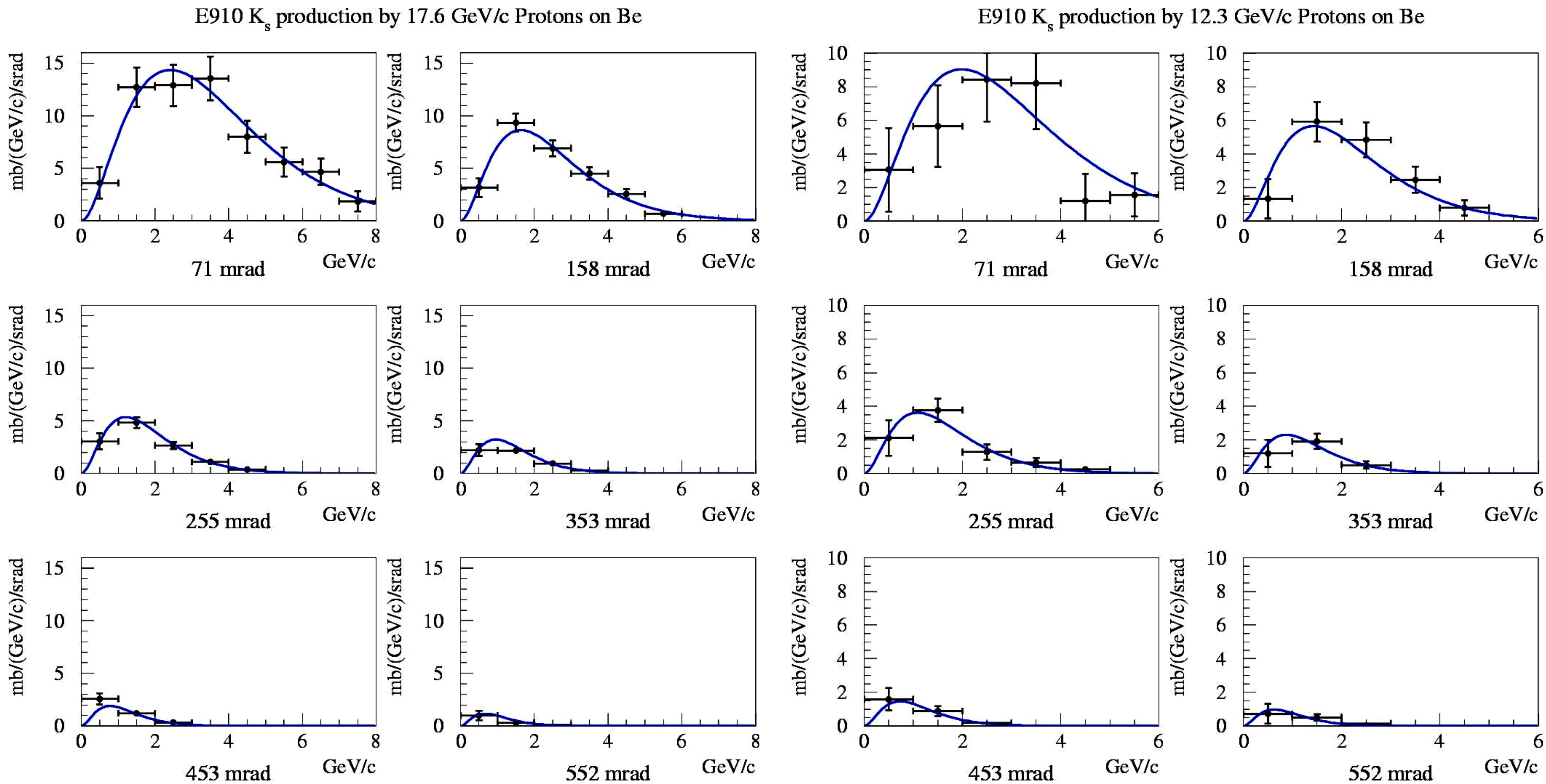
MiniBooNE E910 Pion Production Results

17.6 GeV/c Beam Momentum



MiniBooNE E910 K^0 Production Results

Preliminary



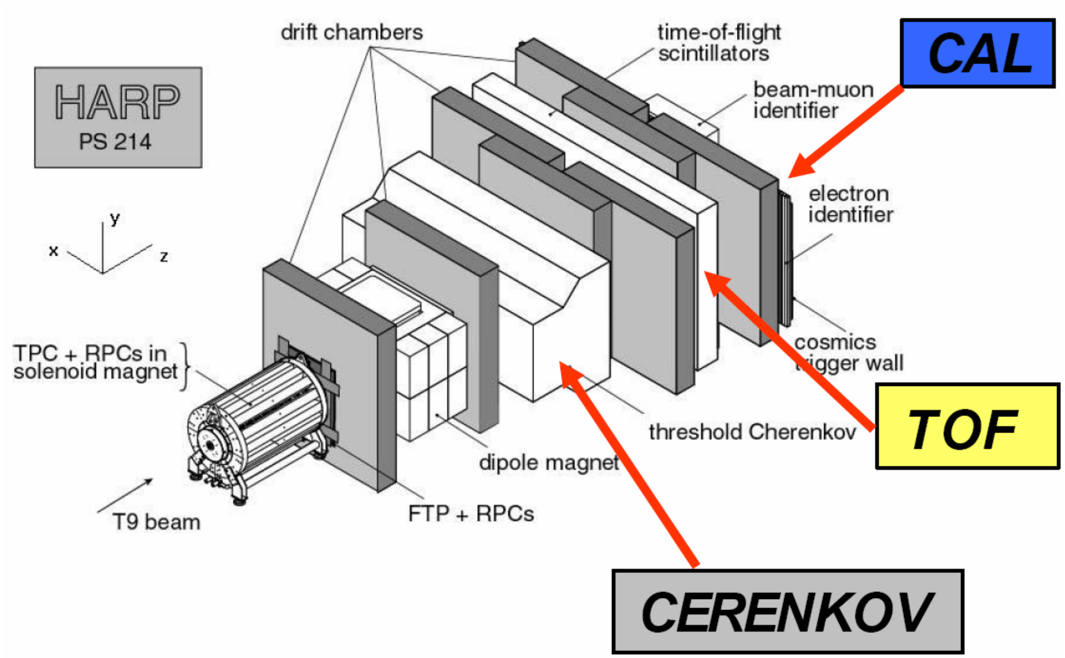
Here again the data are fit with the Sanford-Wang function.

The HARP Experiment

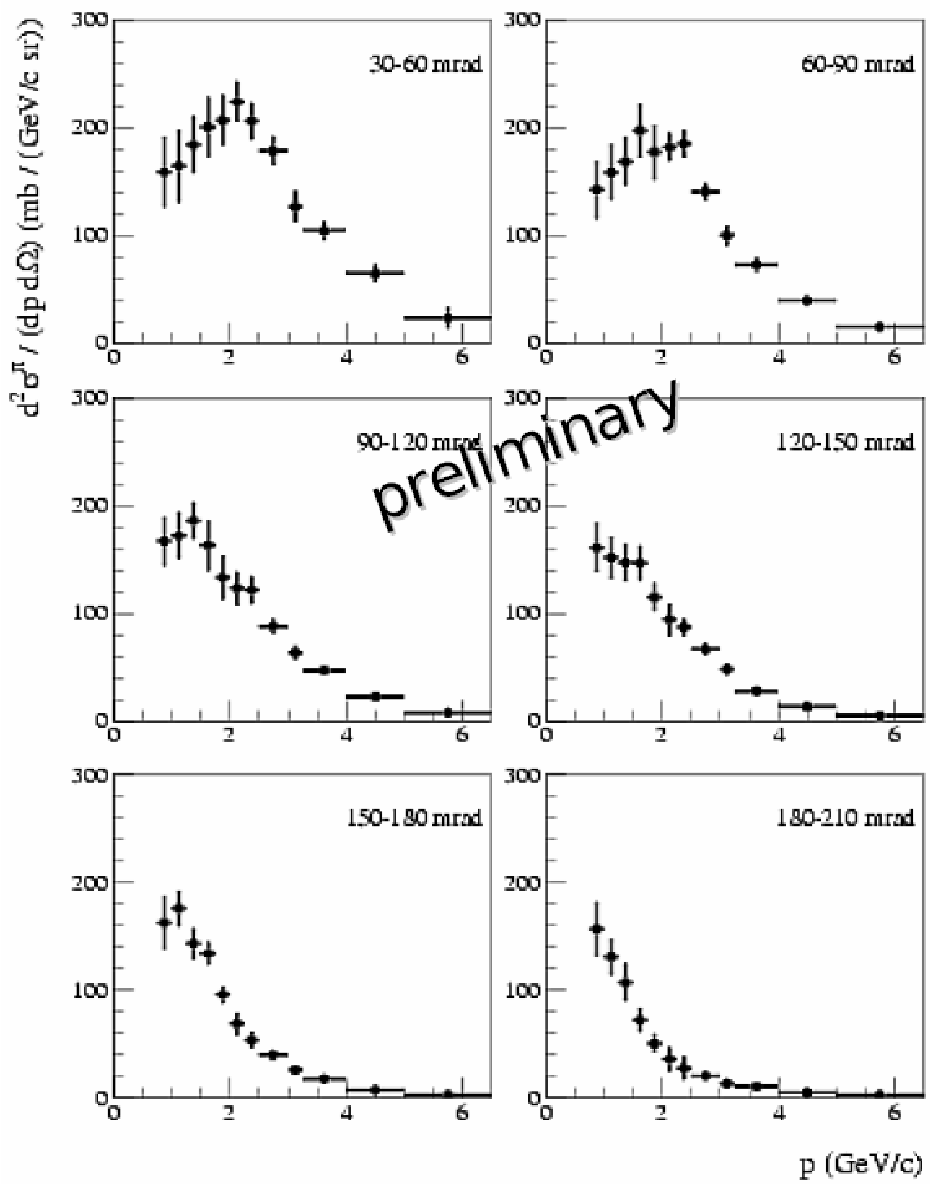
The HARP experiment is intended to measure hadron production (p, π and K), on a variety of targets (A=1-200), over a wide range of beam momenta (p_{beam}=1-15 GeV/c) with thick and thin targets.

For our purposes the Be & Al data with $E_{beam} \leq 8.9$ GeV are of most interest.

The thin target $\pi^{\pm}$ analysis is complete and the $K^{\pm}$ and thick target analyses are well underway.



The HARP p + Be → X + π^+ Analysis



The beam momentum is an exact match to MiniBooNE.

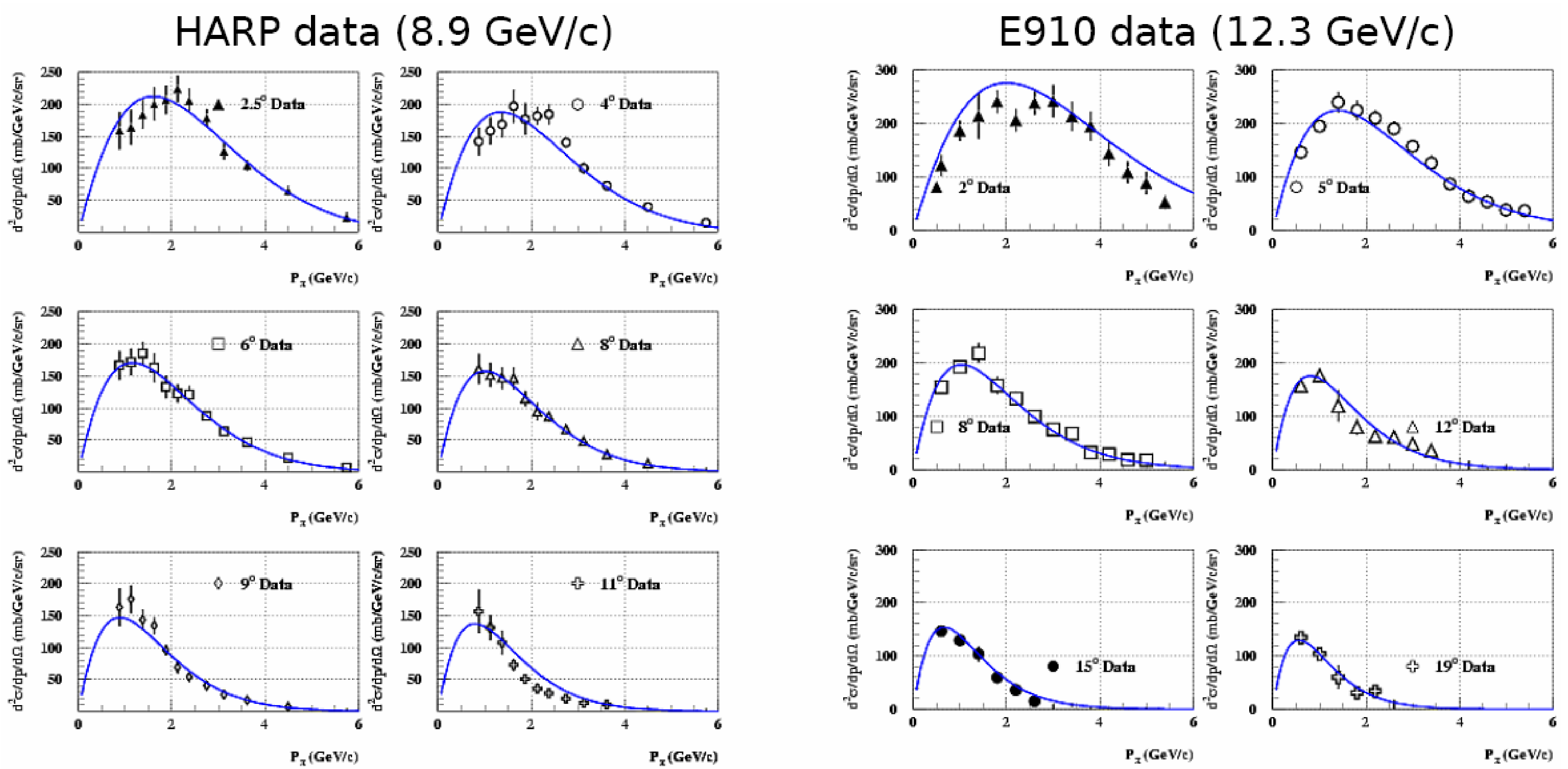
The current analysis is on thin target only, but data was also taken with replica MiniBooNE target slugs.

These data are in reasonably good agreement with the E910 SW fit.

This analysis was done by D. Schmitz.

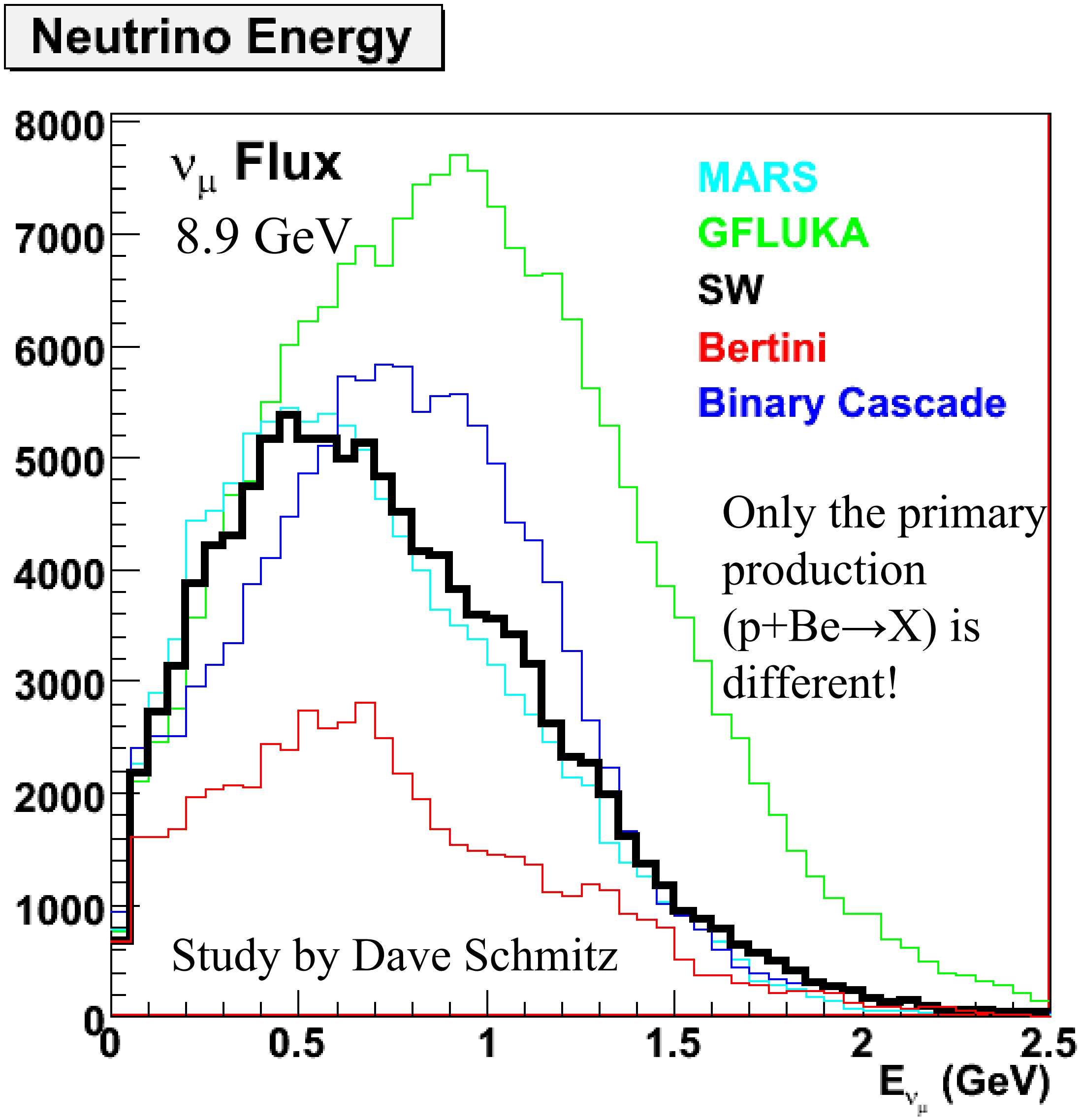
Global Sanford-Wang Fit

This Sanford-Wang fit is used for primary pion production in the MiniBooNE beam line simulation.



The MiniBooNE Sanford-Wang fits were performed by J. Monroe and M. Tzanov.

Comparison of Simulations with MB SW fit



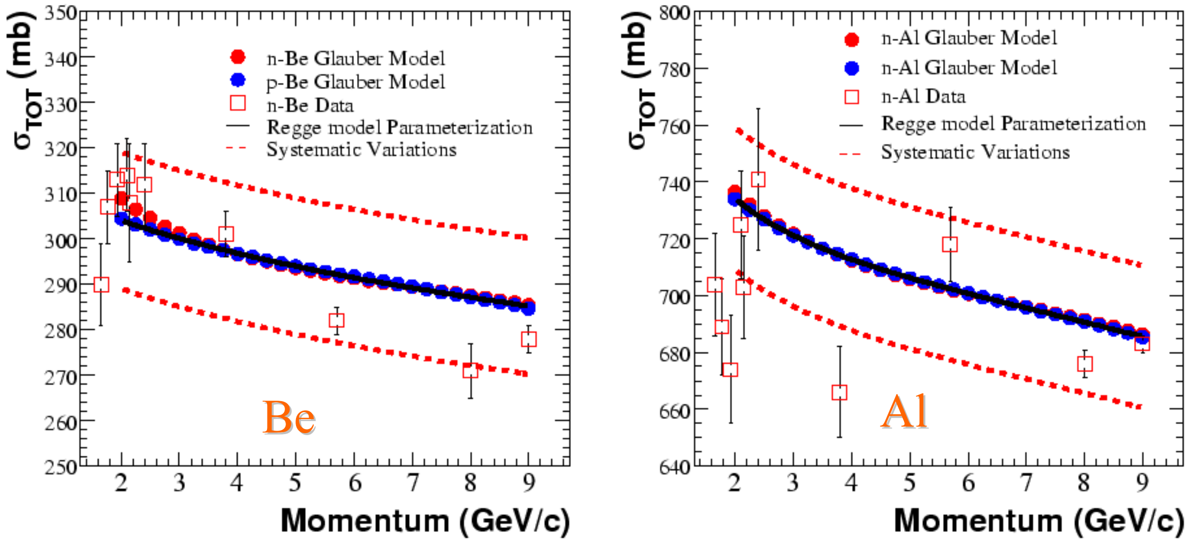
A comparing several common Monte Carlo tools results in a wide range of neutrino fluxes.

Both normalization and energy distribution vary.

MARS has the best match to our Sanford-Wang fit.

Other Cross Sections

We use the Glauber model to get the scattering cross sections for the $\pi^{\pm}$, proton and neutron across a wide range of momenta.



Work done by H. Tanaka

As an artifact of the way we were using our own primary pion production cross sections we found that we were double counting the quasi-elastic proton scattering in both the elastic and inelastic cross sections. So we are using our own, Glauber model based, calculation of each of these components.

Conclusions

MiniBooNE needs a robust and believable prediction of the meson production in its 8.9 GeV proton beam.

This task turns out to be very difficult, for reasons that may not only be due to deficiencies in hadronic simulations.

Nevertheless, the wide range of primary meson production simulation predictions casts doubts on that part of the flux prediction chain.

Pion production cross sections were measured in the E910 and HARP experiments and fit to a Sanford-Wang function.

The Sanford-Wang fit is a good match to the MARS simulation.