Neutrino Flux Predictions for Cross Section Measurements

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Flux Predictions are Important!

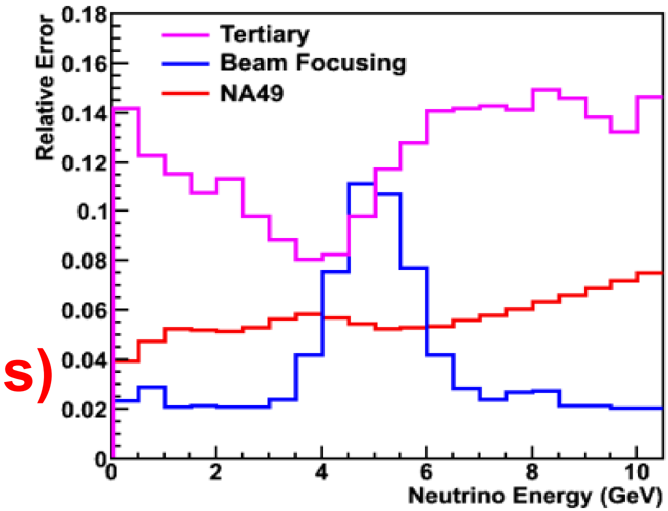
T2K CC Inclusive (A. Weber)

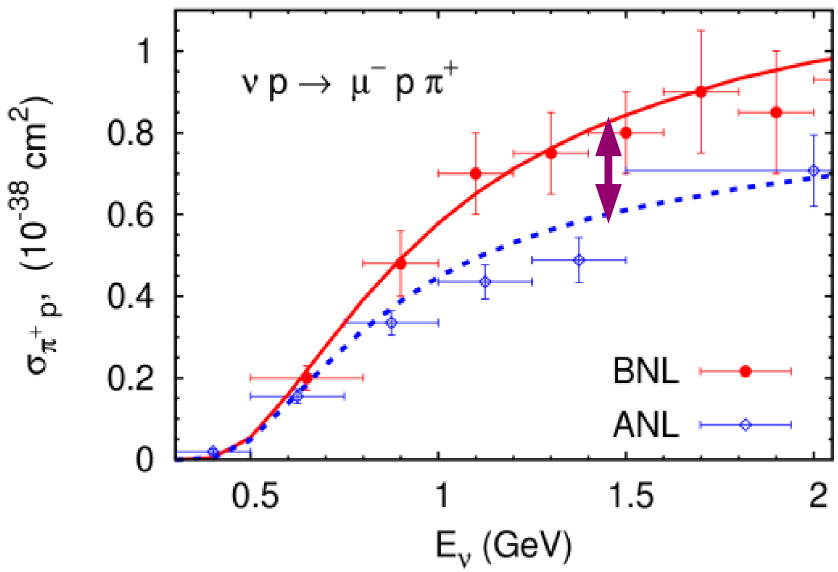
$$\langle\sigma_{CC}\rangle_\phi = (6.93 \pm 0.13(stat) \pm \boxed{0.85(syst)}) \times 10^{-39} \frac{\mathrm{cm}^2}{\mathrm{nucleons}}$$

Error source	Normalization uncertainty (%)
anti-ν flux	9
Backgrounds	9
Detector	5
Unfolding	2
Total (includes correlations)	**14**

MiniBooNE $\bar{\nu}_\mu$ CCQE (J. Grange)

MINERvA CCQE Results (L. Fields)

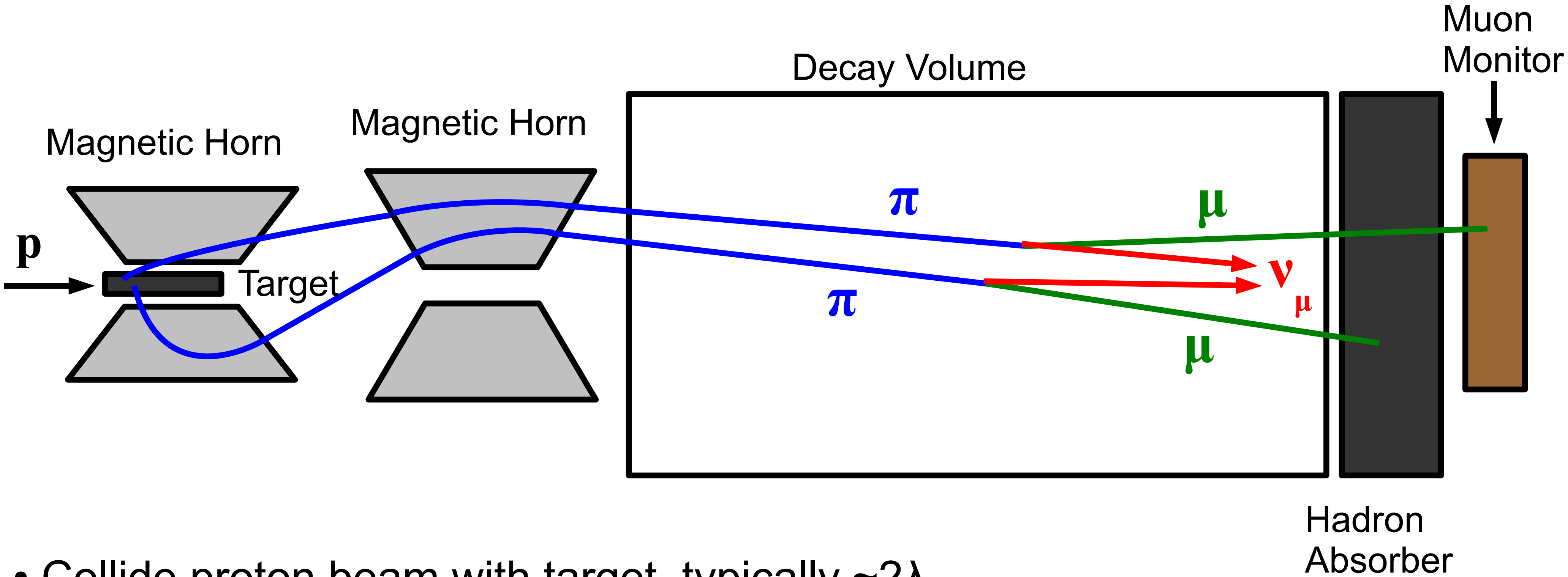




Pion Production Calculations (O. Lalakulich)

"ANL and BNL are compatible within errors and flux uncertainties"

Producing Neutrinos with Proton Beams



- Collide proton beam with target, typically ~2λ
- Focus charged particles with magnetic horns
  - Select charge based on horn polarity
- $\pi^{\pm}$ (also $K^{\pm}$, K^0_L, $\mu^{\pm}$) decay, producing neutrinos
- Optimized decay region for fraction of muon decays in flight
- Detect muons from hadronic decays producing neutrinos

Beam Lines at ν Experiments

Some important features of the beam lines and experiments I will discuss in this talk:

	NuMI (MINERvA, MINOS, ArgoNeuT)	Booster (MiniBooNE)	T2K
Proton Energy	120 GeV	8 GeV	30 GeV
Peak Neutrino Energy	3-8 GeV	800 MeV	600 MeV
On/off-axis Detectors?	on-axis	on-axis	off-axis (~2.5°)
Target	Carbon (graphite)	Beryllium	Carbon (graphite)
Hadron production data	NA49, NA61	HARP	NA61
Simulation Models	GEANT4 (FTFP)	GEANT4 (QGSP)	FLUKA+ GEANT3

Predicting the Neutrino Flux

Bottom-up approach

Other in situ methods discussed later in this talk

Used by all experiments

Simulate the physical processes involved in the neutrino production

Interaction of proton beam in target → Focussing of particles by horns → Propagation of particles through decay region → Particle decays to neutrinos

Sources of uncertainty

1) Modeling of hadronic interactions in the target and other materials

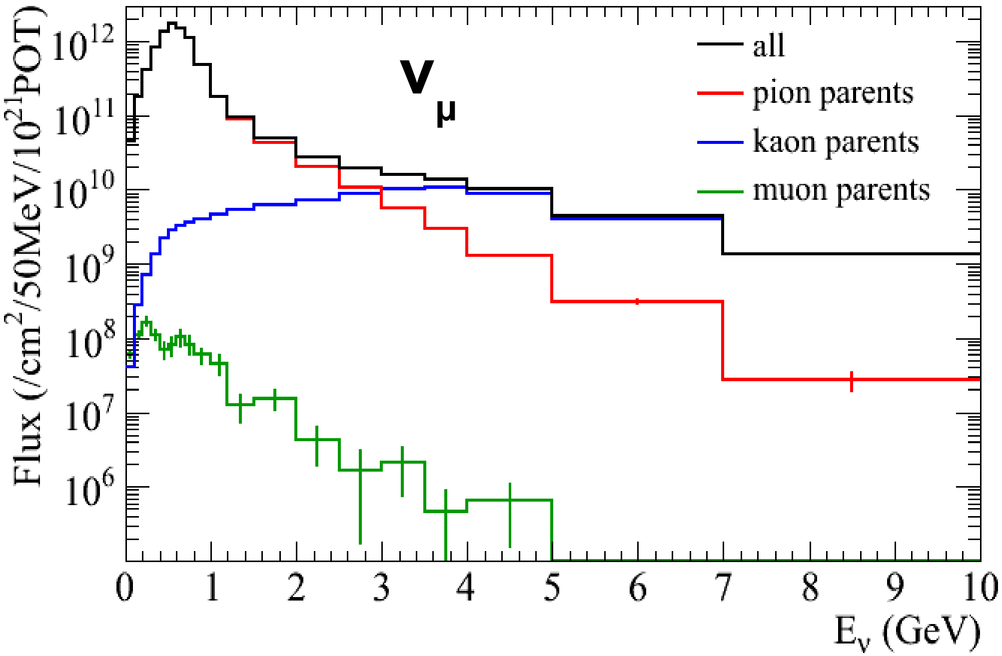
2) Properties of the proton beam when it hits the target

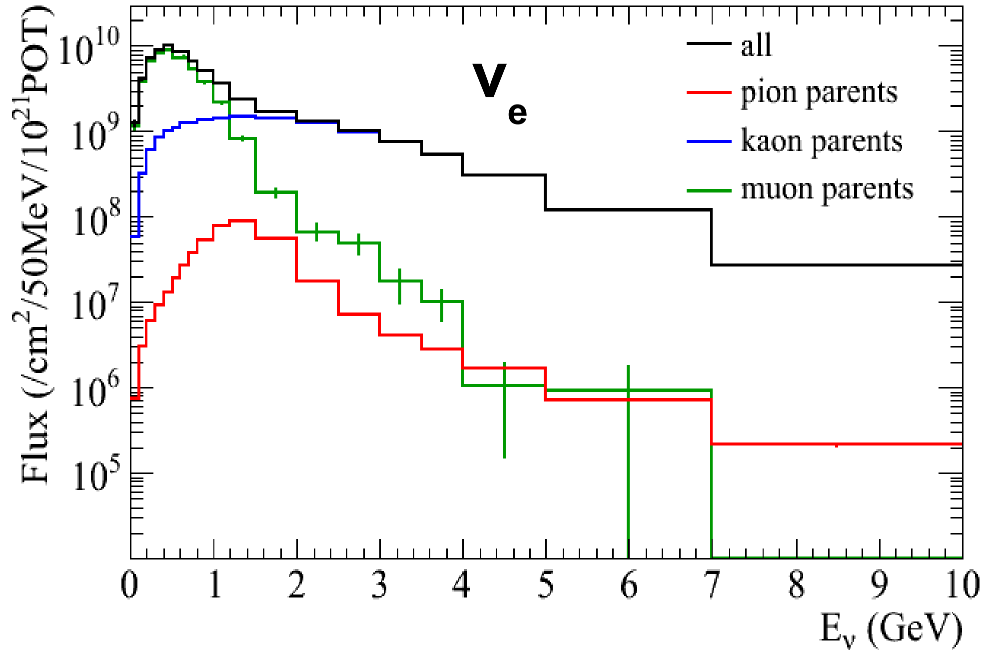
3) Alignment of the target and horn

4) Modeling of the horns' magnetic field

Data driven simulation to reduce systematic uncertainties

T2K Flux (At ND280)



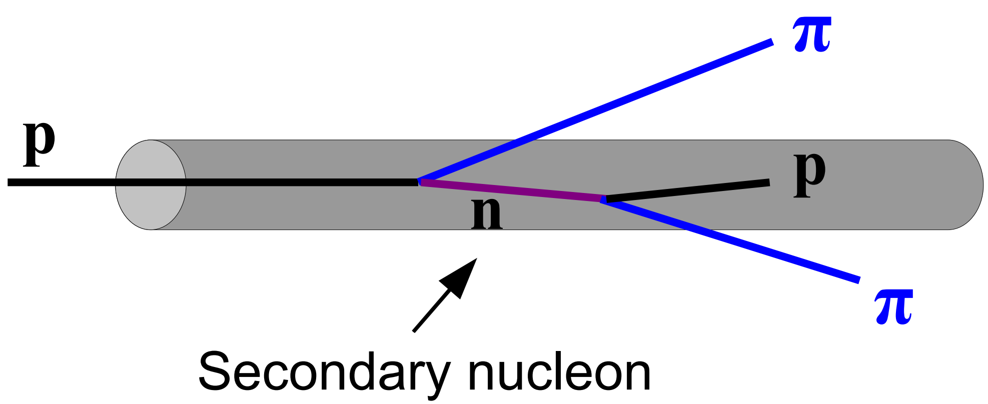


Near peak:

- ν_μ from pion decays
- ~1% ν_e background from muon decays

Neutrinos from kaon decays dominate at high energy

Hadron Interactions



Secondary Production:

Primary proton interacts and produces particle that decays to neutrino (**~50-90%** of neutrinos depending on beam)

Tertiary Production:

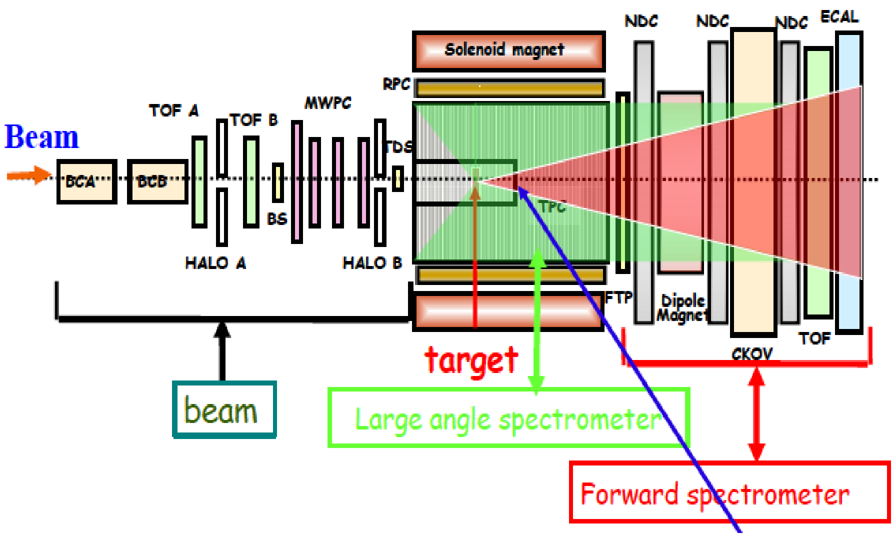
More than one hadronic inelastic interaction to produce the neutrino parent (~10% outside of target for focussed flux)

Important measurements:

- Differential pion and kaon production for proton/nuclei interactions at beam energy on target material
- Inelastic cross sections for protons, pions and kaons
- Differential production at lower incident particle energies, also on other materials in decay volume

Hadron Production Experiments

HARP



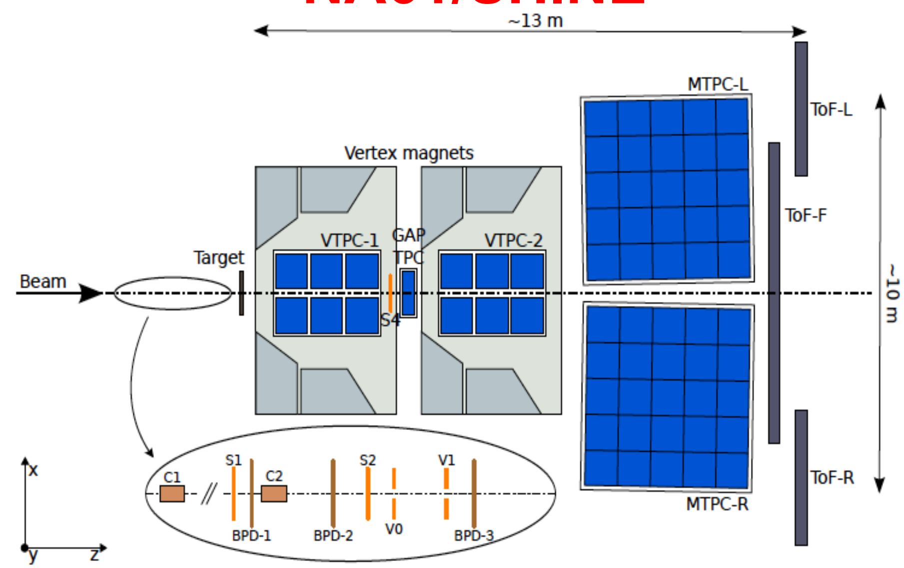
0.025 < θ < 0.25 rad

12 GeV protons on Al for K2K

8 GeV protons on Be for MiniBooNE

Thin target and thick target data

NA61/SHINE



31 GeV protons on C for T2K

120 GeV protons on C for NuMI planned

Dedicated T2K runs:

0.04λ thin target

T2K replica target

Common features:

Beam instrumentation: particle identification and position/direction at target

Spectrometer: momentum/angle of produced hadrons

dE/dx and TOF capabilities for particle identification

NA61 Data for T2K

Measure 30 GeV proton cross section on carbon: $\sigma_{prod} = 229.3 \pm 9.2 \ mb$

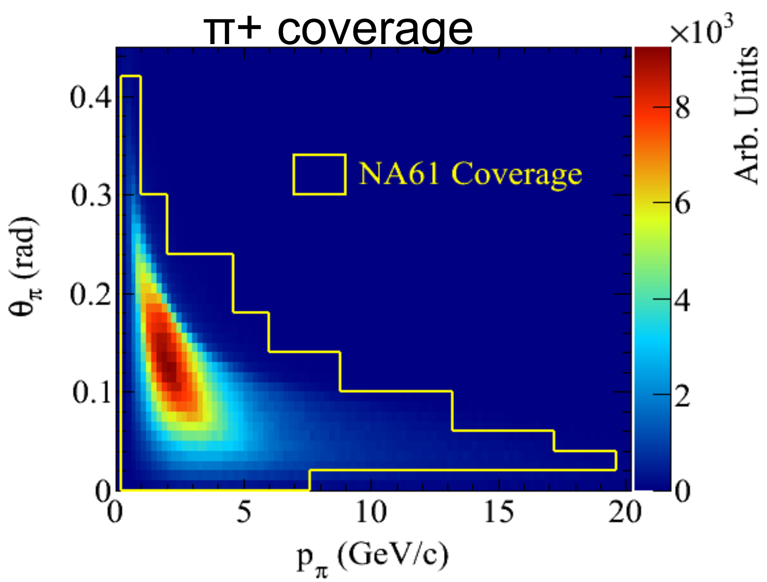
Measure differential $\pi^{\pm}$ (K^{+}) production multiplicity

Systematic uncertainties of 5-10% for each point in p-θ space

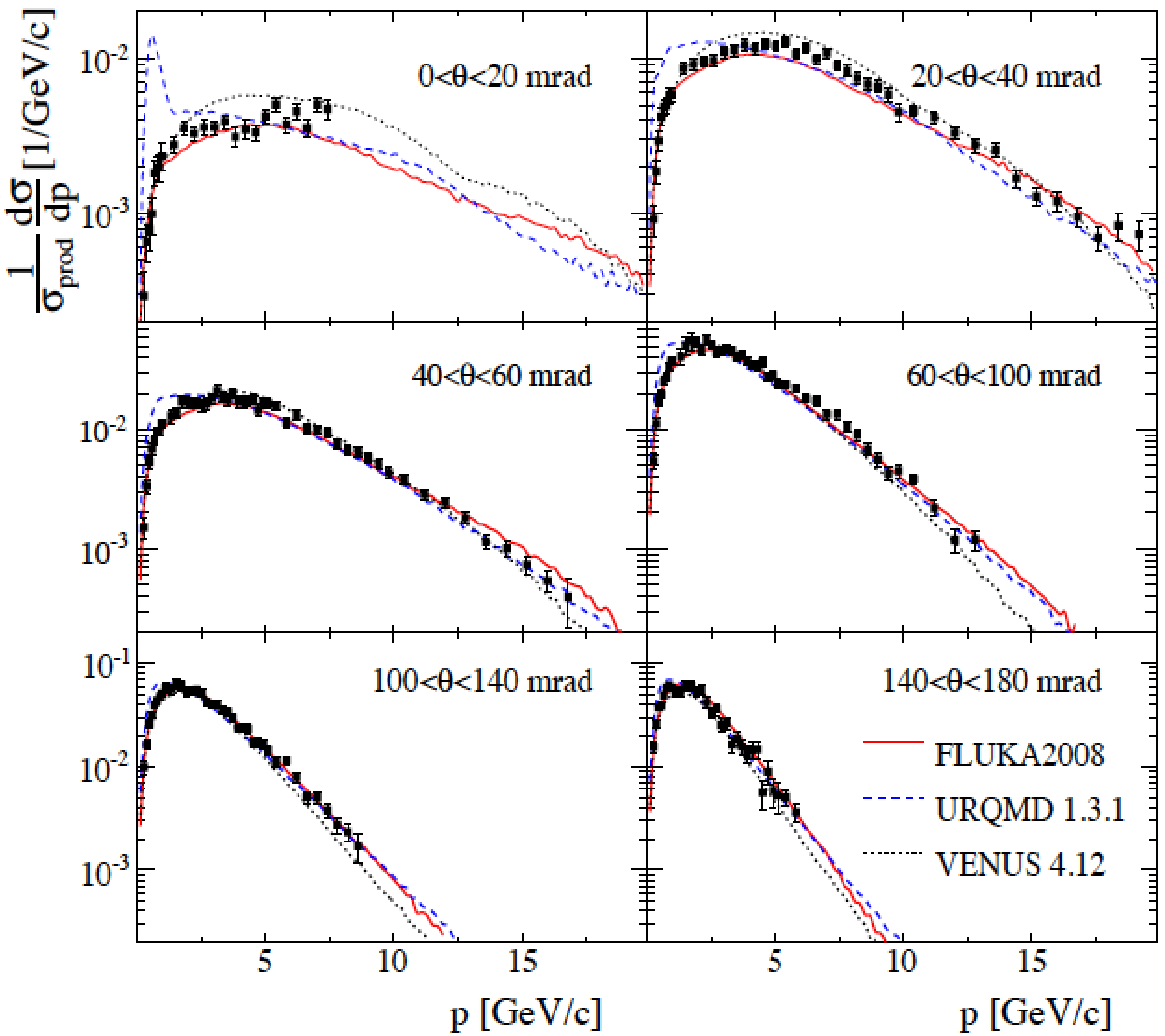
2.3% normalization uncertainty

Uncertainties propagated into T2K flux prediction

π+ coverage



Phys. Rev. C84 (2011) 034604



Extrapolating Data

Often need to tune the modeling of hadron production at incident particle energies where there are no data

Tuning tertiary production

Lack of data at primary energy (NA49 data for NuMI)

Need a method to extrapolate data from one center of mass energy to another

Feynman scaling: the production is independent of center of mass energy when represented in the space of p_T and a scaling variable:

$$x_F = \frac{p_L^{cm}}{p_{max}^{cm}}$$

$$x_R = \frac{E^{cm}}{E_{max}^{cm}}$$

Fraction of maximum longitudinal momentum or energy of the produced particle in the center of mass frame

Scaling Uncertainties

Scaling becomes less exact at lower energies, particularly $\sqrt{s} < 10\ GeV$

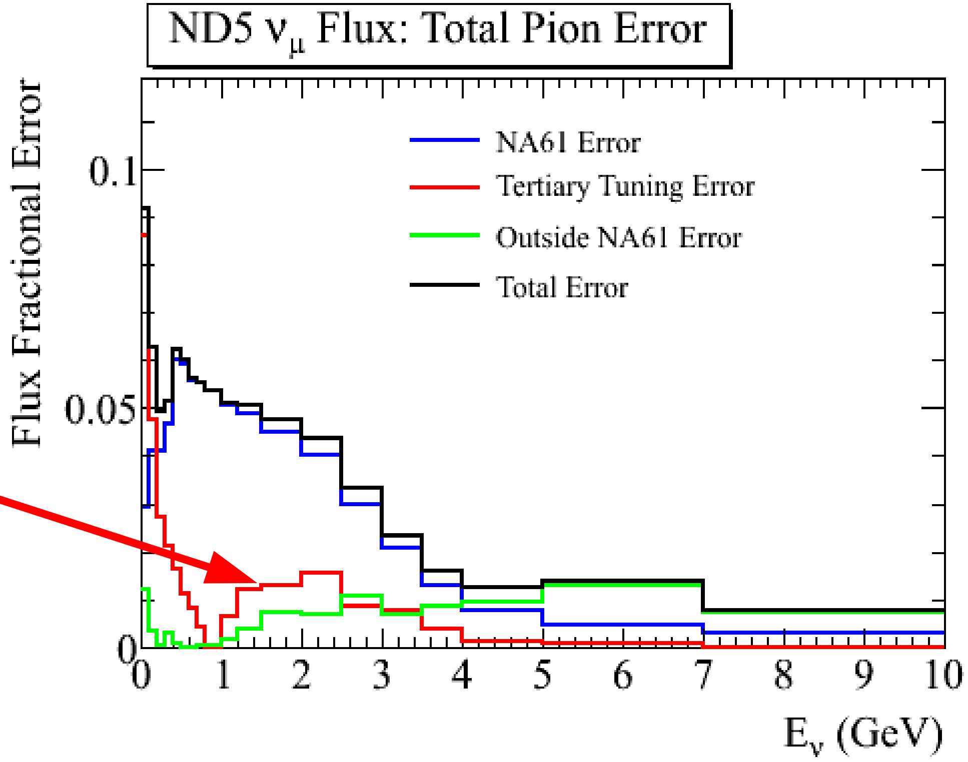
T2K considers two methods for tuning of tertiary production:

1) Convert NA61 data/MC ratios to different proton energies using x_F-p_T scaling

2) Use E910 (BNL) pBe data at proton momenta of 12.5 and 17.2 GeV/c

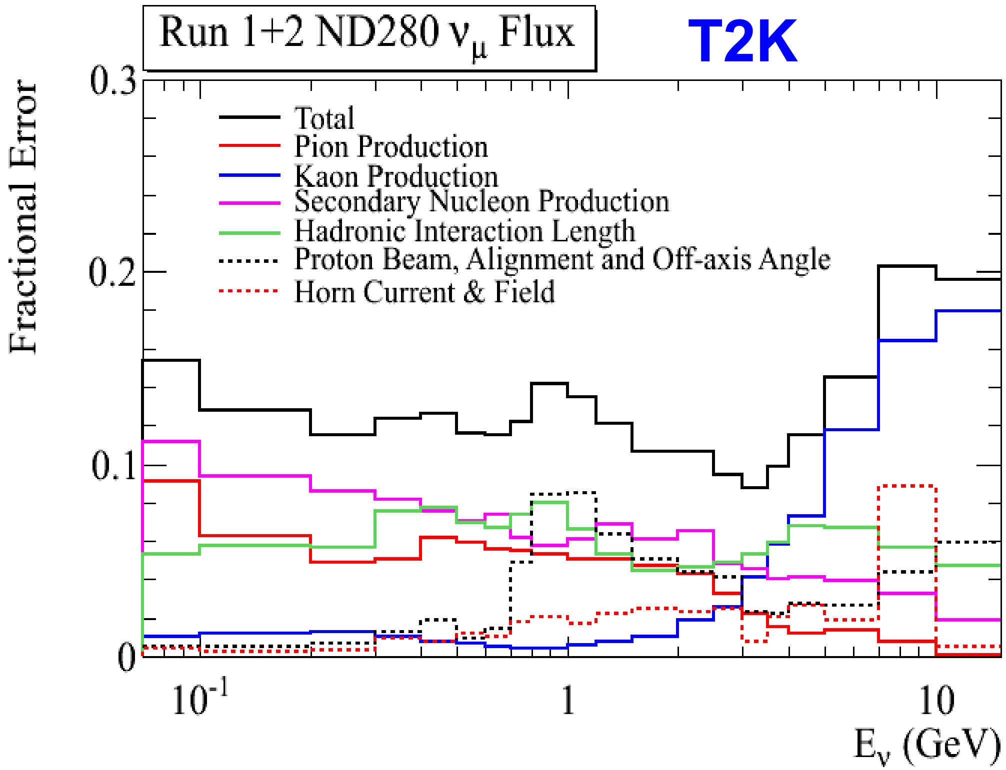
PRC 77, 015209 (2008)

Even at the T2K beam energy, the uncertainty associated with scaling is relatively small

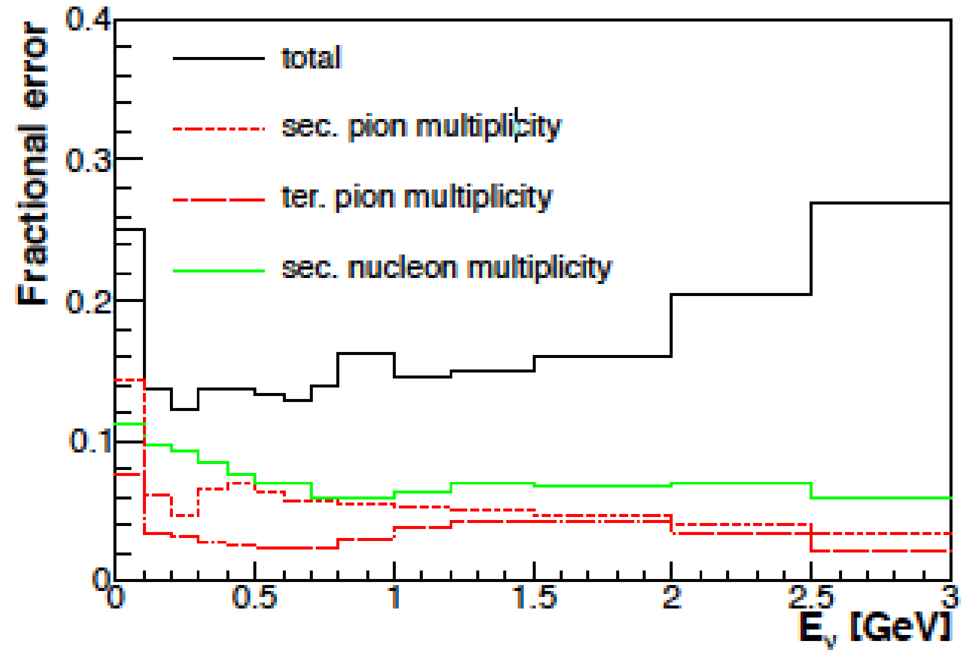


Hadronic Interaction Uncertainties

T2K



T2K (older flux)



Hadron interaction uncertainties are dominant

Secondary production is important

But also tertiary production, and inelastic cross sections

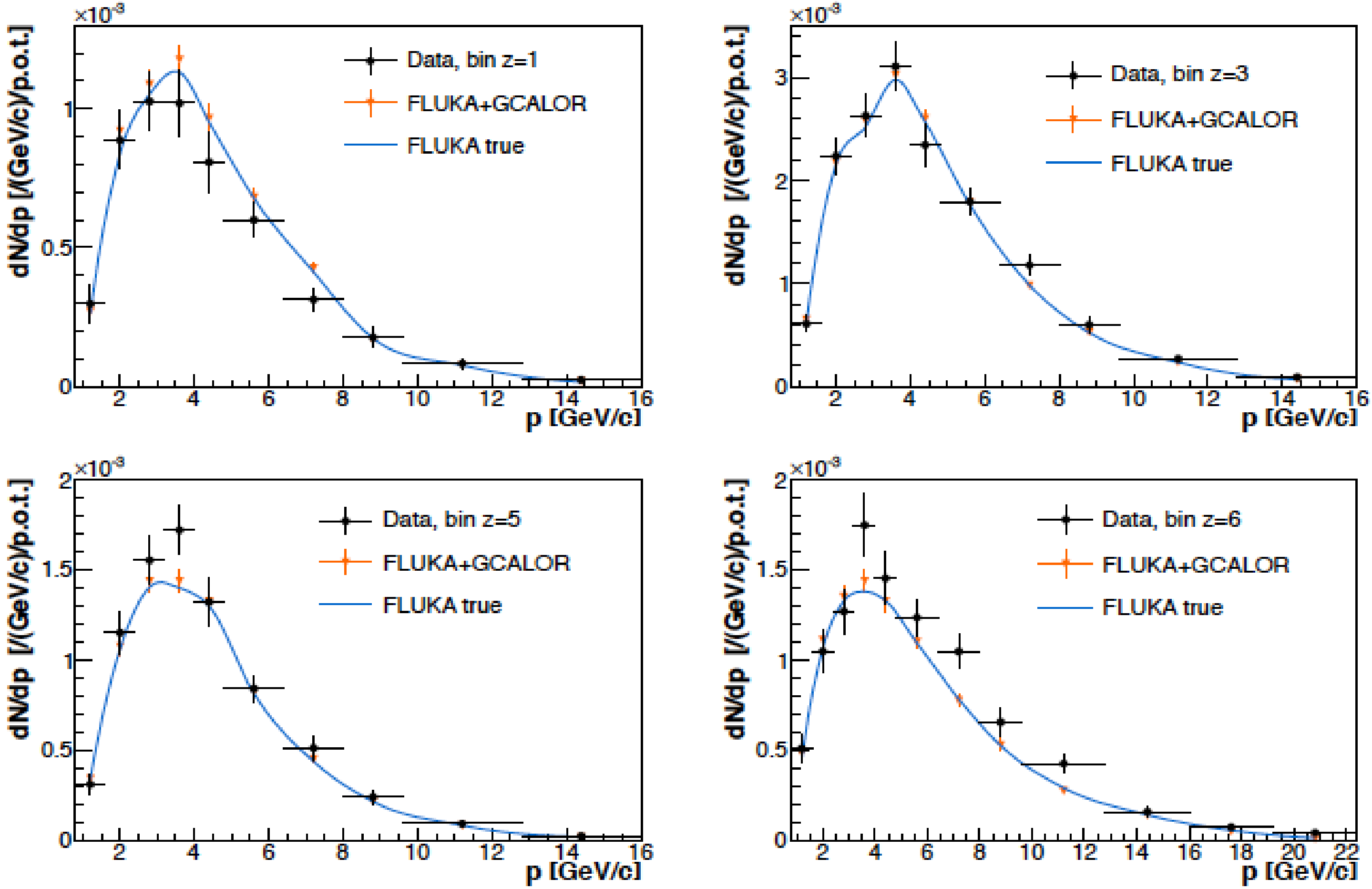
Data from a replica target would reduce these uncertainties

NA61 Replica Target Data for T2K

NA61 took 3 sets of data on a T2K replica target

Preliminary analysis with first set 0.2e6 protons (eventually 14e6 protons)

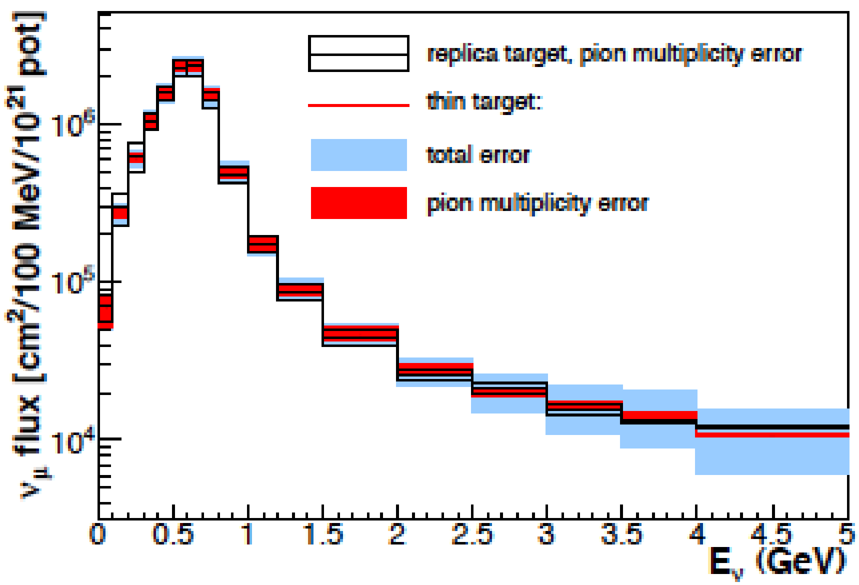
Measured π+ production with z bins along target and at downstream face

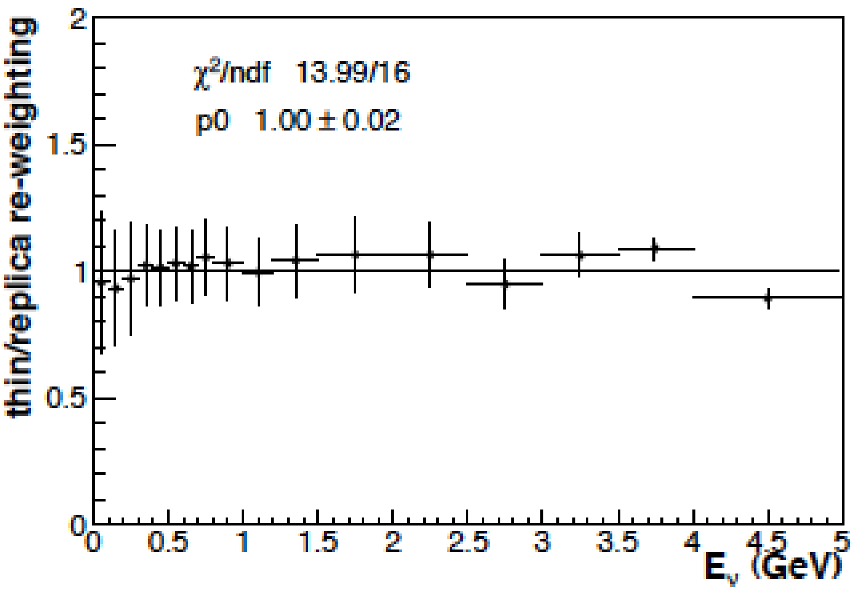


Neutrino Flux with Replica Target

The T2K flux prediction is tuned using the replica target data instead of thin target data

Accepted by NIM, arXiv:1207.2114





Predicted flux is consistent with the thin target tuned flux

Uncertainties are still large with low statistics data set, preliminary analysis

Expect to reduce T2K in-target hadron production uncertainties to ~5% when full data set is used

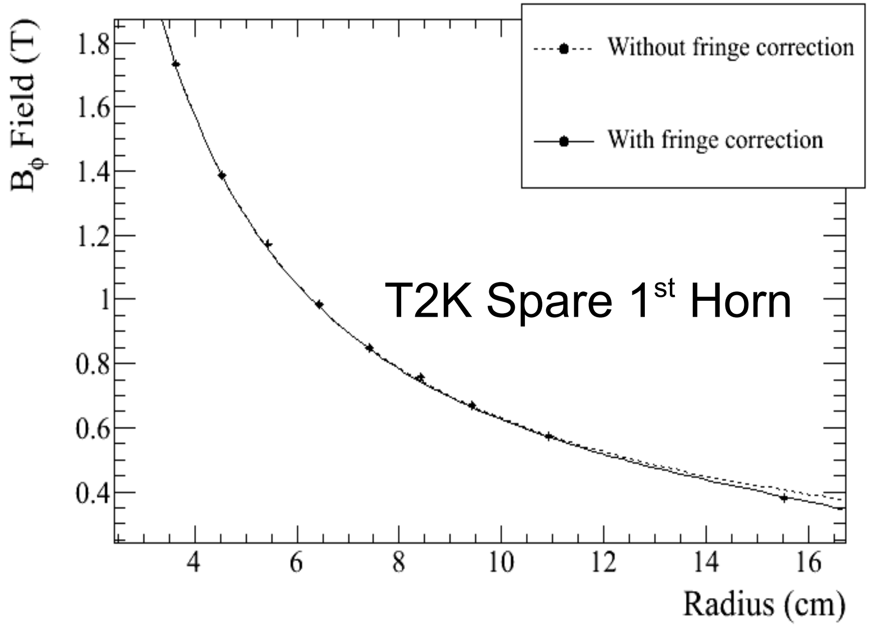
Other Sources of Uncertainty

Proton Beam:

- Typically ~2% normalization uncertainty from beam intensity measurement
- Uncertainty of beam position at target shifts spectrum peak
  - For T2K 0.4 mrad uncertainty = ~10 MeV shift
  - Measuring the beam profile is important → How to make minimally destructive measurements in ~1 MW power beams

Horn Magnetic Fields

- Horn fields can be measured prior to installation
- Deviations from radial field are simulated and typically ~5% or less
- Absolute horn current uncertainty is also typically ~5% or less



Alignment Uncertainties

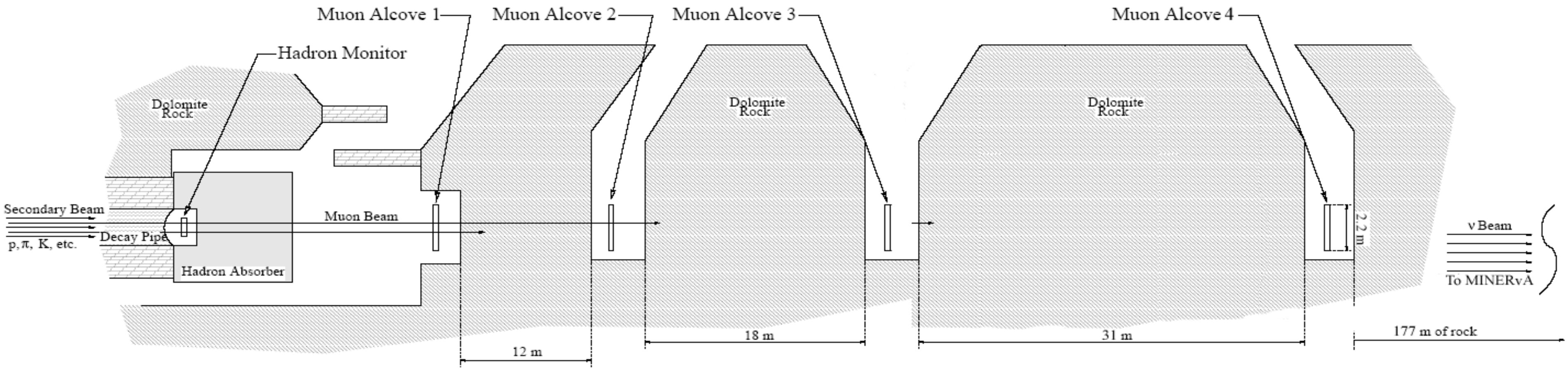
- Move horn/target in simulation within uncertainties → few percent uncertainty on the flux

In situ flux measurements

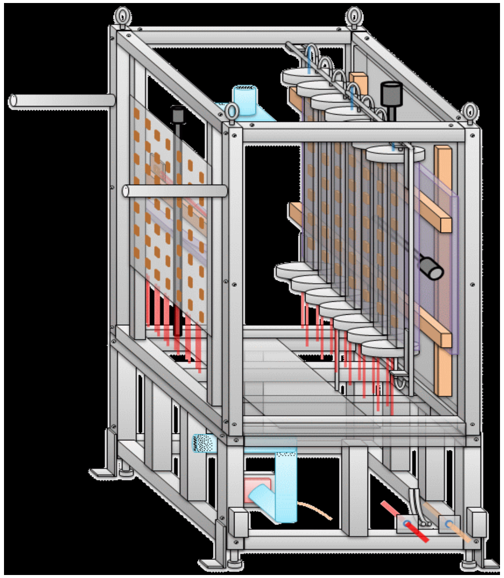
Muon Monitor Constrains on ν Flux

Measure rate of muon interactions downstream of hadron absorber

Three arrays of ionization chambers in the **NuMI** beam



Single pair of silicon and ionization chamber arrays for **T2K**



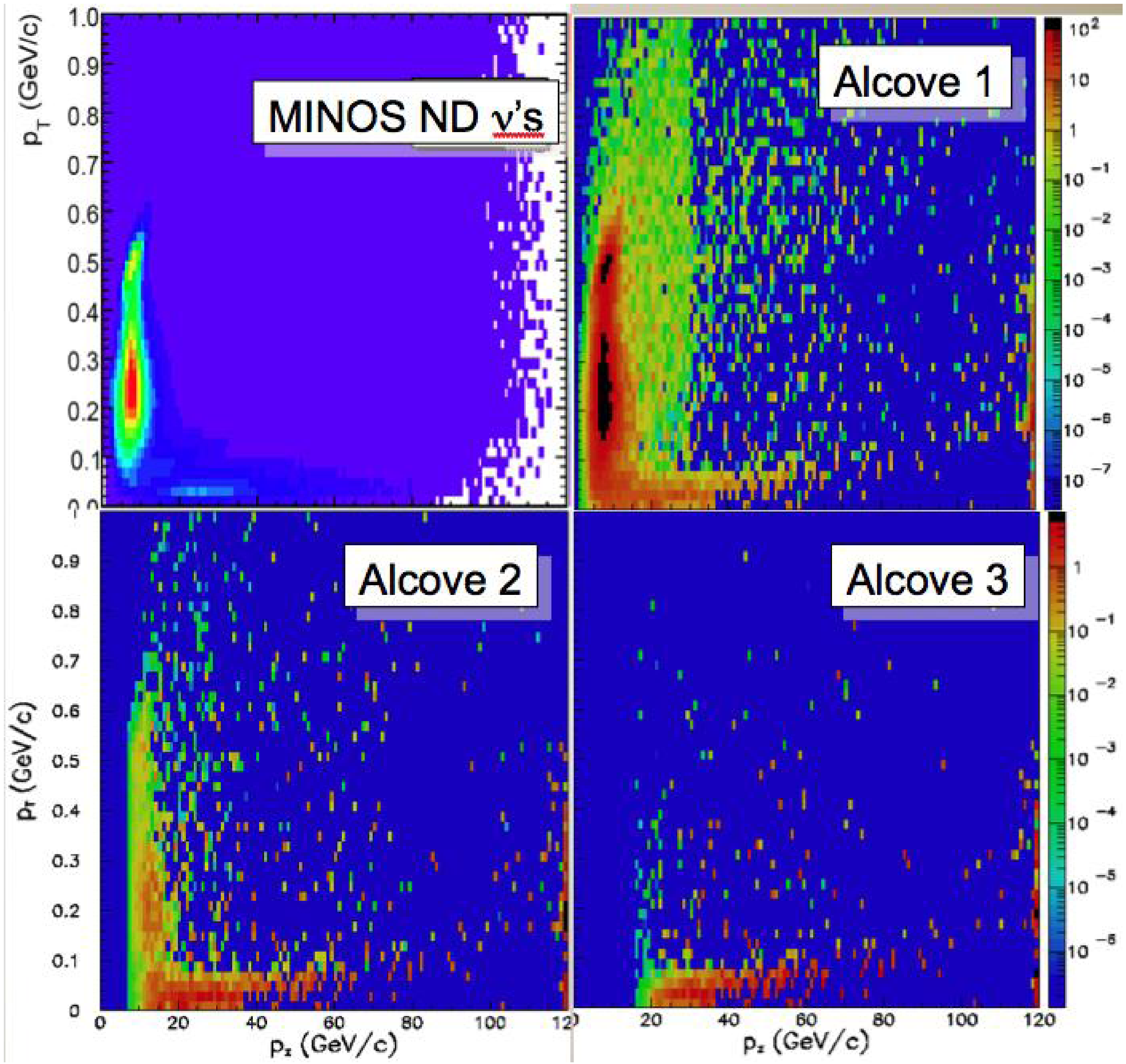
Since muons are mostly from two body pion and kaon decays, can measurements directly constrain the neutrino flux?

NuMI Muon Monitor Constraint

Muon monitors cover the phase space for neutrino production

Muons traverse different length of rock to each muon monitor

Maps out different regions of the parent pion phase space



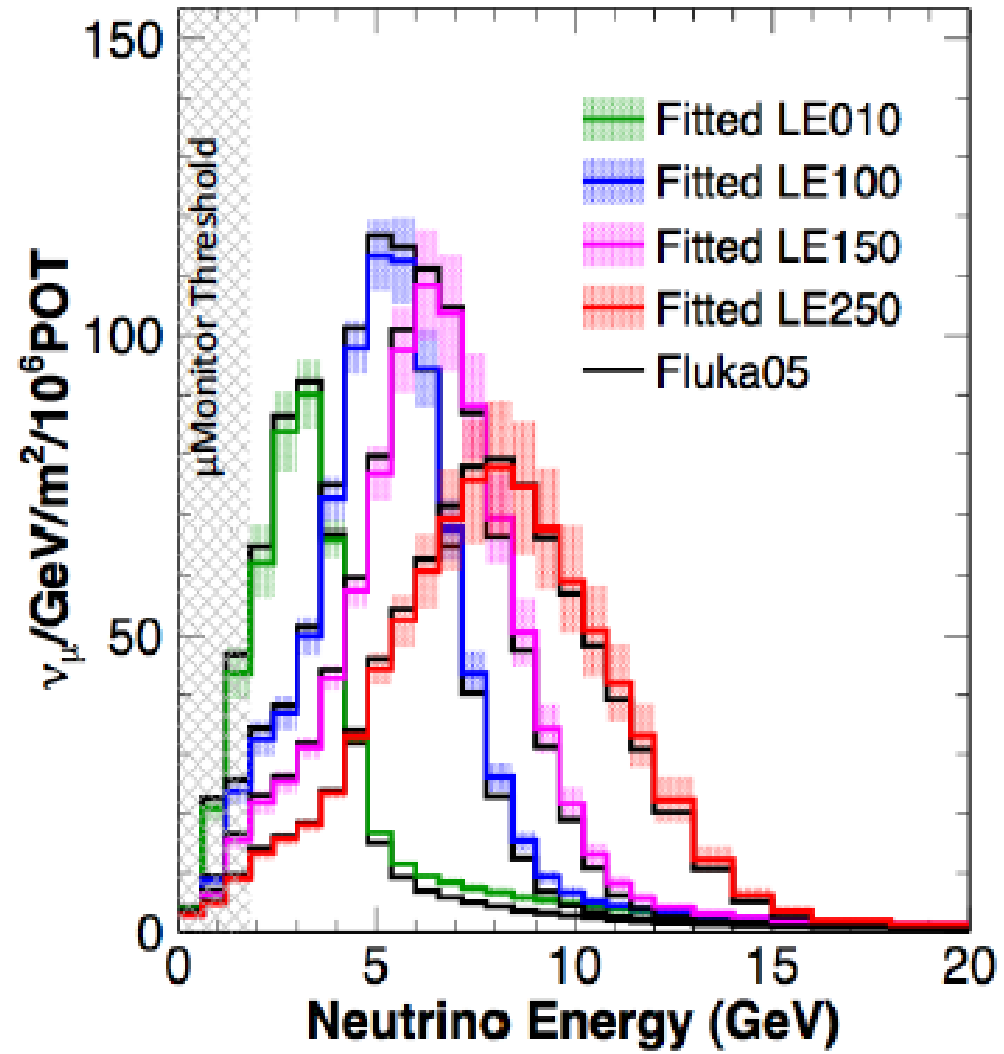
NuMI Muon Monitor Constraint

Flux prediction is tuned by moving empirical parametrization of the hadron production to fit the muon monitor data

Good agreement with muon monitors is achieved

Largest uncertainties from absolute normalization and δ ray production in the rock: as much as 30% of the monitor signal

→ T2K took data on emulsion plates. Similar measurement may be useful for NuMI.

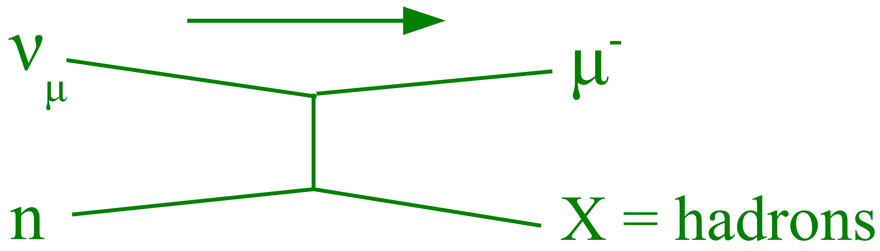


L. Loiacono, "Measurement of the Muon Neutrino Inclusive Charged Current Cross Section on Iron Using the MINOS Detector," PhD Thesis, UT Austin 2010

The Low ν Technique

- Consider CC interactions on nucleons

Initially developed by CCFR/NUTEV



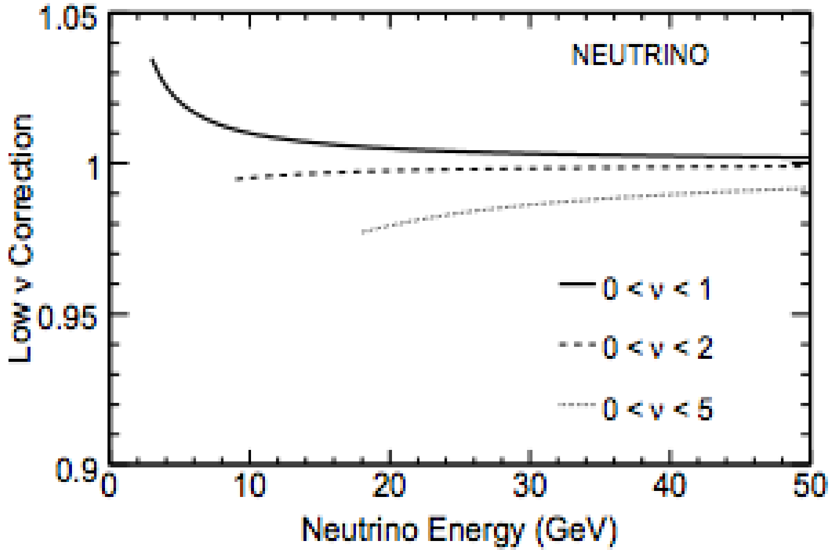
- ν is the energy of hadronic system in final state
- For hadronic energy → 0, cross section only depends on the structure function F_2 – no energy dependence

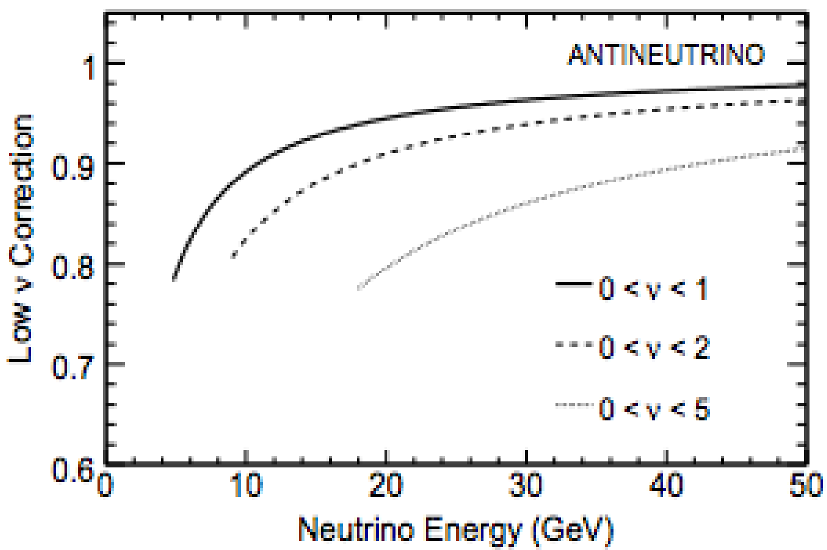
$$\frac{d\sigma}{d\nu} \propto F_2 \quad as\,\nu \rightarrow 0$$

- Reconstruct events with small hadronic energy relative to neutrino energy
- Fully reconstruct energy of the event → measure the energy dependence of the flux
- Normalization must be set separately

Low ν Method at MINOS

MINOS uses the low ν correction to extract the flux shape above 3.5 GeV (normalized to world average cross section above 30 GeV)

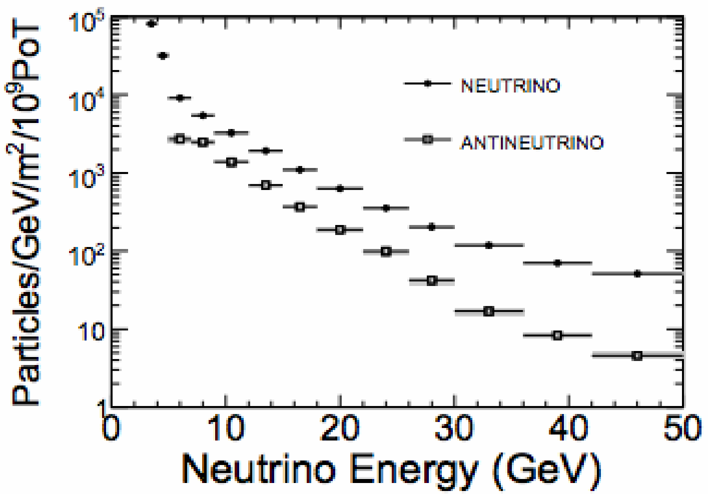




Neutrino and anti-neutrino fluxes extracted with ~10% uncertainty or less

Up to 30% difference from nominal flux simulation

Phys. Rev. D 81, 072002 (2010)



Extending Low ν to Lower Energies?

Investigated by A. Bodek et. al.

At energies of 1 GeV and below, account for energy dependent corrections to low ν cross section

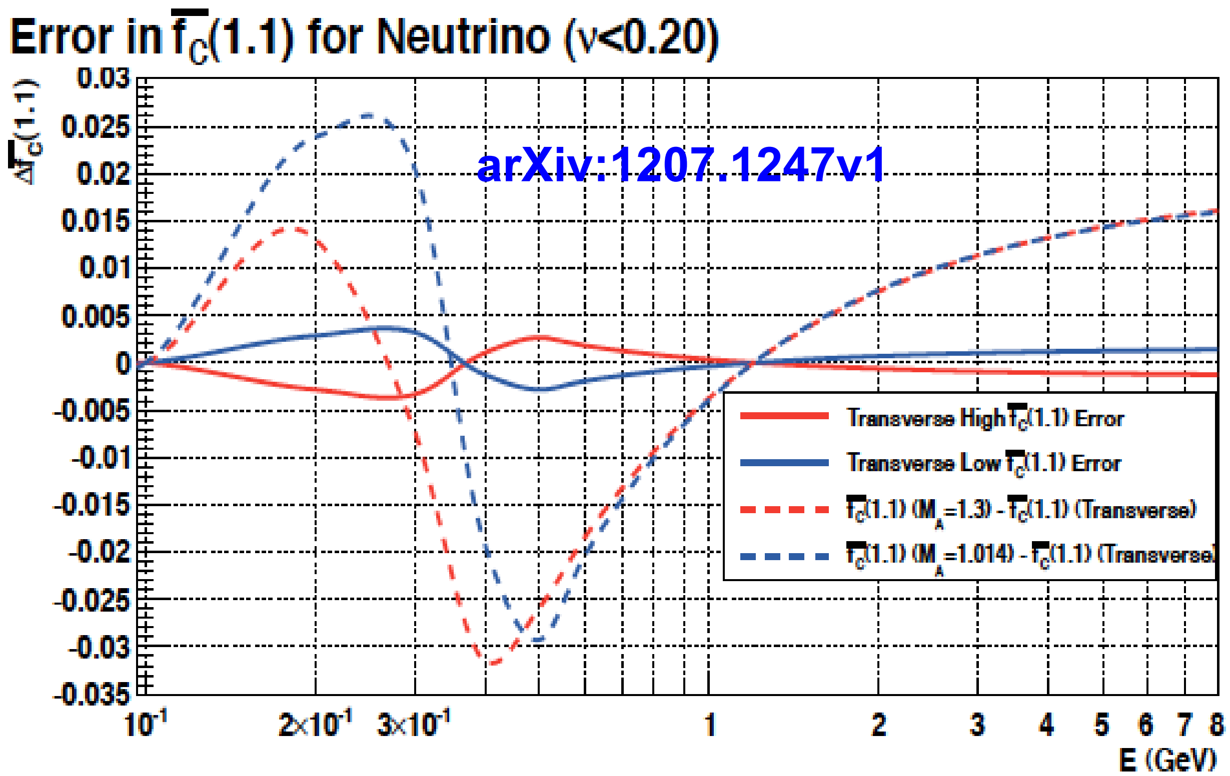
$$\propto \nu / E \quad \text{or} \quad m_\mu^2 / E^2$$

For ν<0.2 GeV

Energy dependence has little dependence on M_A

Changes ~5% for E_ν>500 MeV when transverse enhancement is applied

Can experiments achieve the hadronic energy resolution to apply this method?



Dashed lines = difference in low ν cross section correction for RFG and with transverse enhancement

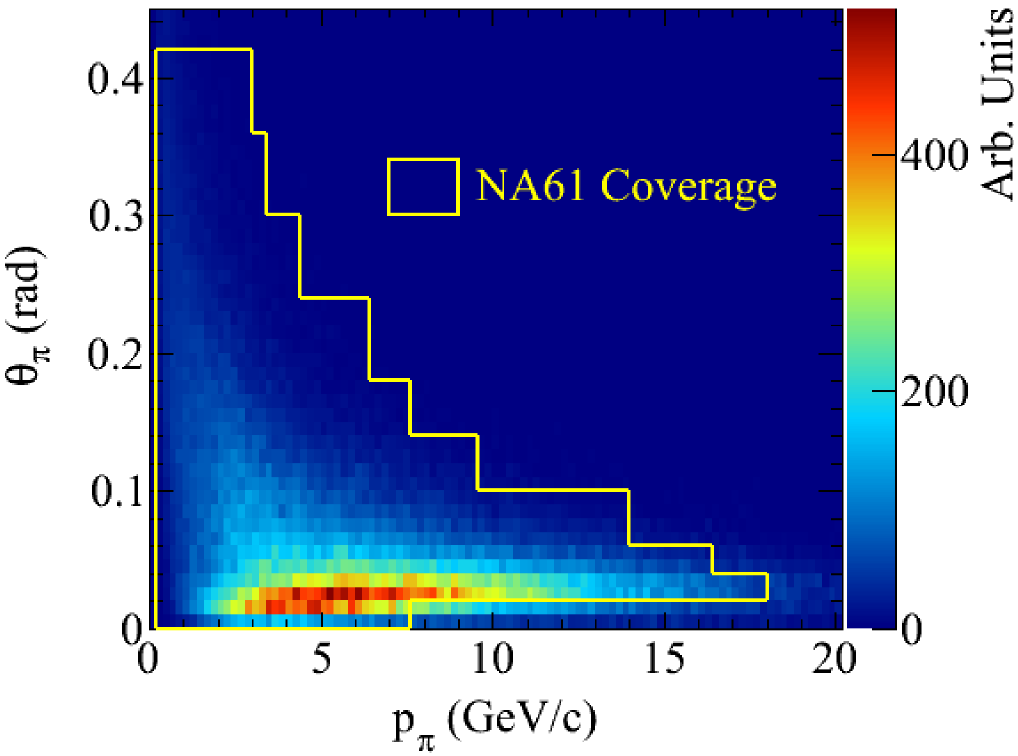
Conclusions

- Neutrino fluxes for cross section measurements are predicted by data driven simulations of the production
  - Dominant uncertainties are from hadronic interactions
  - Experiments such as HARP and NA61 provide hadron interaction data
  - Replica target data from NA61 can allow T2K hadron interaction uncertainties to be reduced to ~5%
- In situ measurements are important cross checks, but have limitations
  - δ ray backgrounds for muon monitors
  - Larger model dependent uncertainties for low ν method at low neutrino energy, better hadronic energy resolution is needed

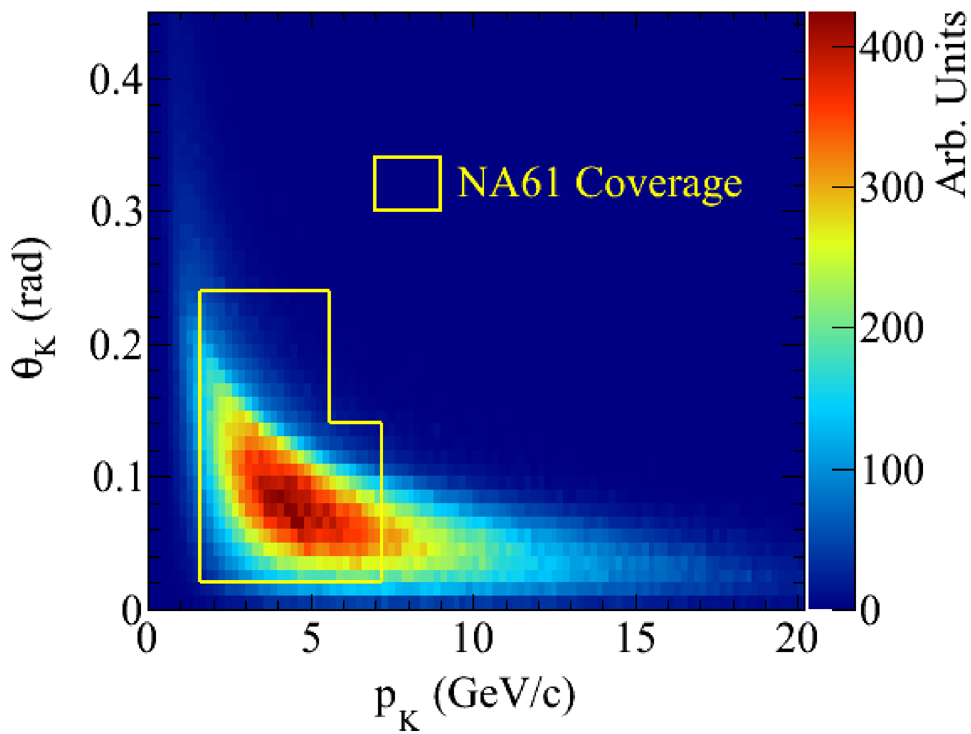
Extra Slides

NA61 Coverage

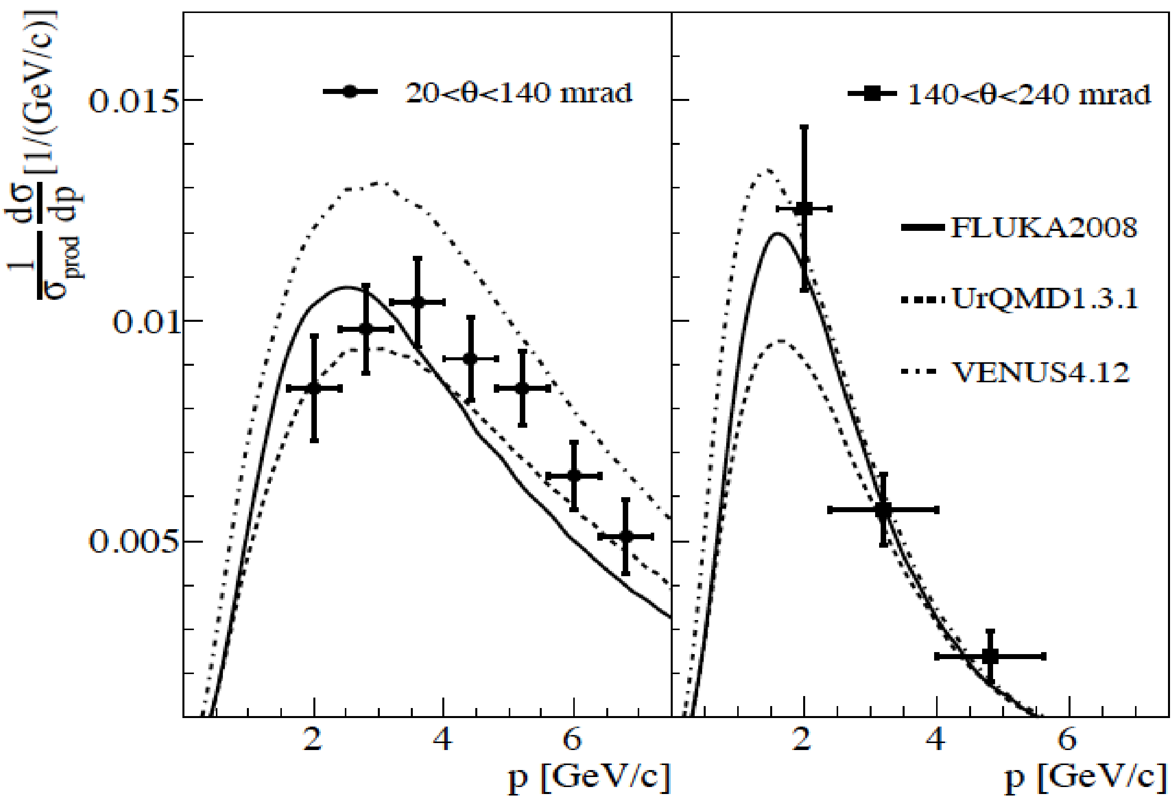
π- (defocussed) coverage



K+ coverage



NA61 K+ Data



PRC 85, 035210 (2012)

Analysis with 7e5 protons

Only K+ due to limited statistics

Updated analysis with x10 statistics will give K- and larger phase space

Inelastic Cross Sections

- Tune the reaction rate for protons, pions kaons
- Experiments typically measure:

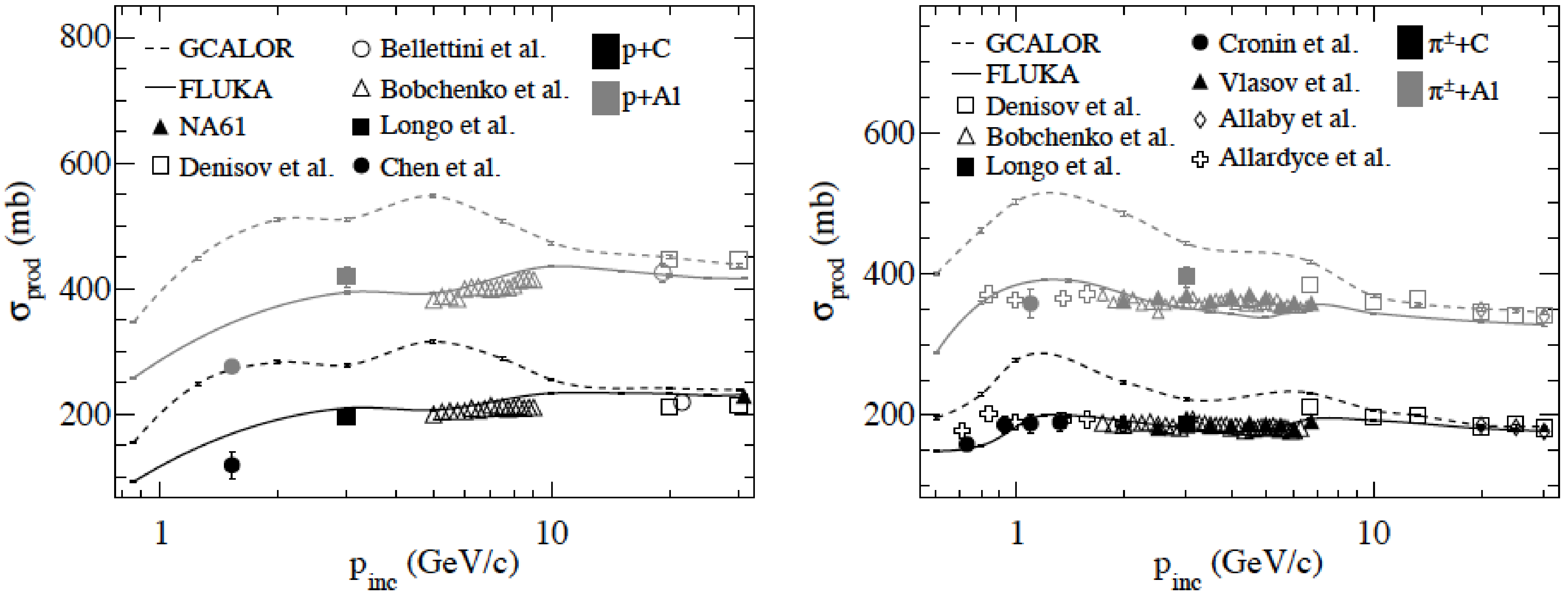
$$\sigma_{\text{inel}} = \sigma_{\text{prod}} + \sigma_{\text{qel}}$$

Cross section for particle production

Quasi-elastic: cross section for elastic like scattering off of nucleons

- Interested in the production cross section for neutrino fluxes
- Subtract quasi-elastic component from measurements
  - Glauber model calculations
  - Simple models based on hadron+N elastic scattering

Production Cross Sections



FLUKA fit production cross section data well

Largest uncertainty is the quasi-elastic component that is subtracted from the data

Hadron Interaction Reweighting

- Hadron interactions reweighted to data by T2K in two steps:
  - Pion and kaon differential multiplicity weights:

$$\frac{dn}{dp}(\theta, p_{in}, A) = \frac{1}{\sigma_{prod}(p_{in}, A)} \frac{d\sigma}{dp}(\theta, p_{in}, A).$$

Multiplicity definition

$$W(p_{in}, A) = \frac{[\frac{dn}{dp}(\theta, p_{in}, A)]_{data}}{[\frac{dn}{dp}(\theta, p_{in}, A)]_{MC}}.$$

Multiplicity weights

  - Production cross section weights:

$$W = \frac{\sigma'_{prod}}{\sigma_{prod}} e^{-x(\sigma'_{prod} - \sigma_{prod})\rho}.$$

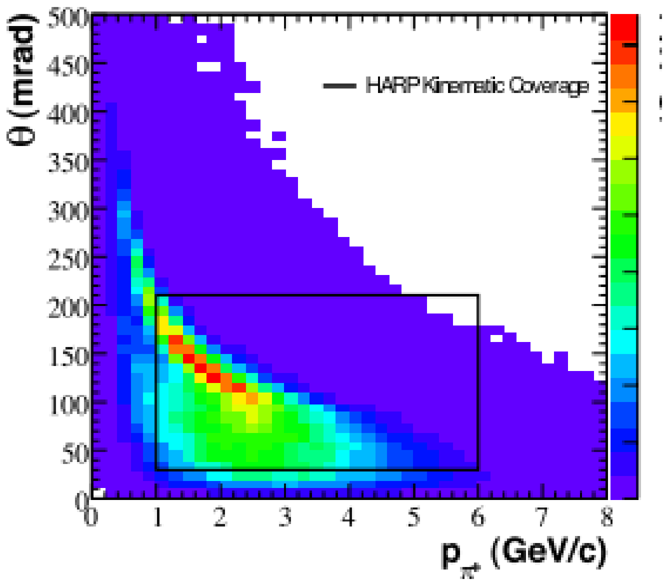
Weight includes attenuation factor

HARP Data for MiniBooNE

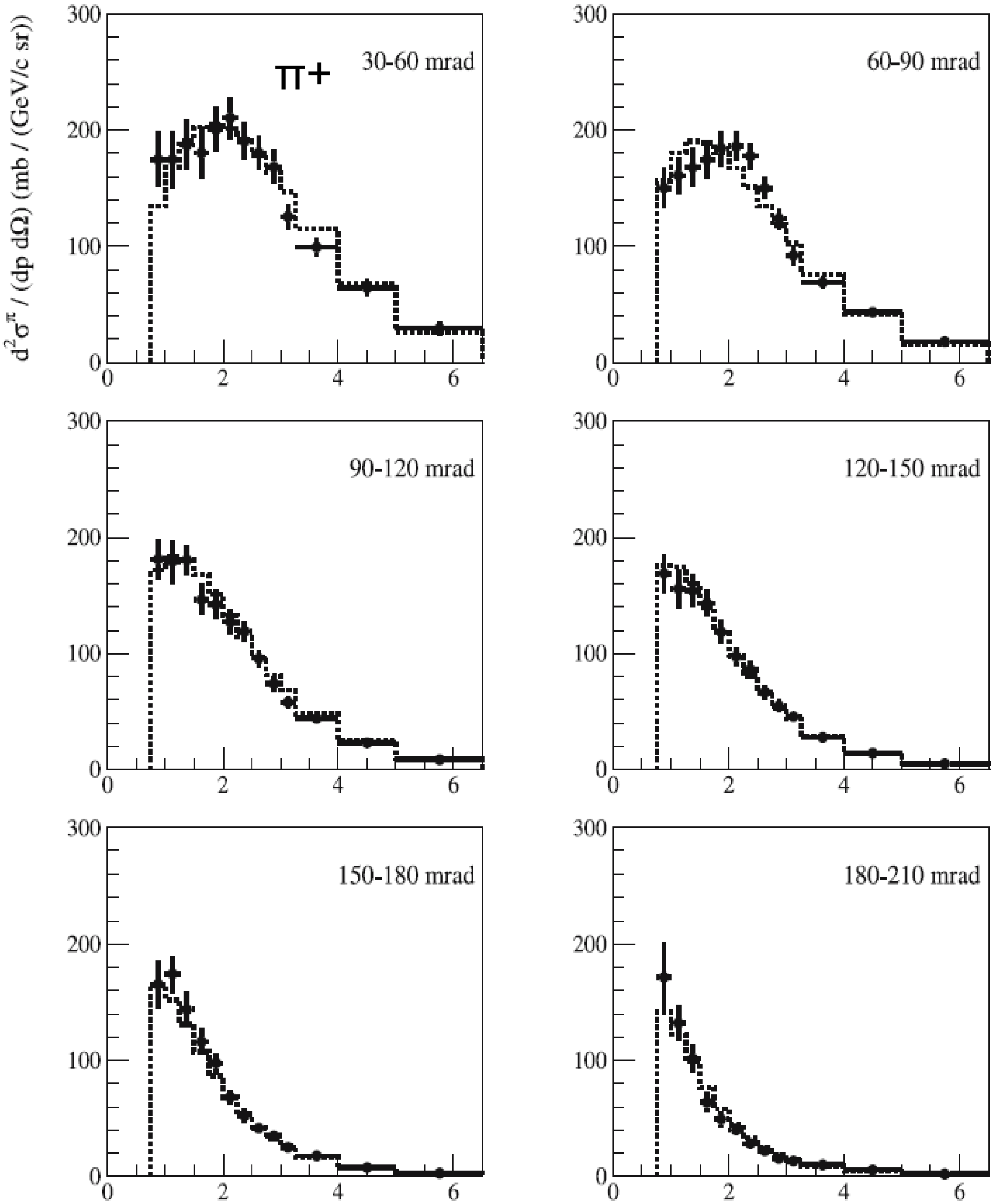
EPJ C 52 (2007) 29

Measured on a 0.05λ Be target

Data point errors ~10%

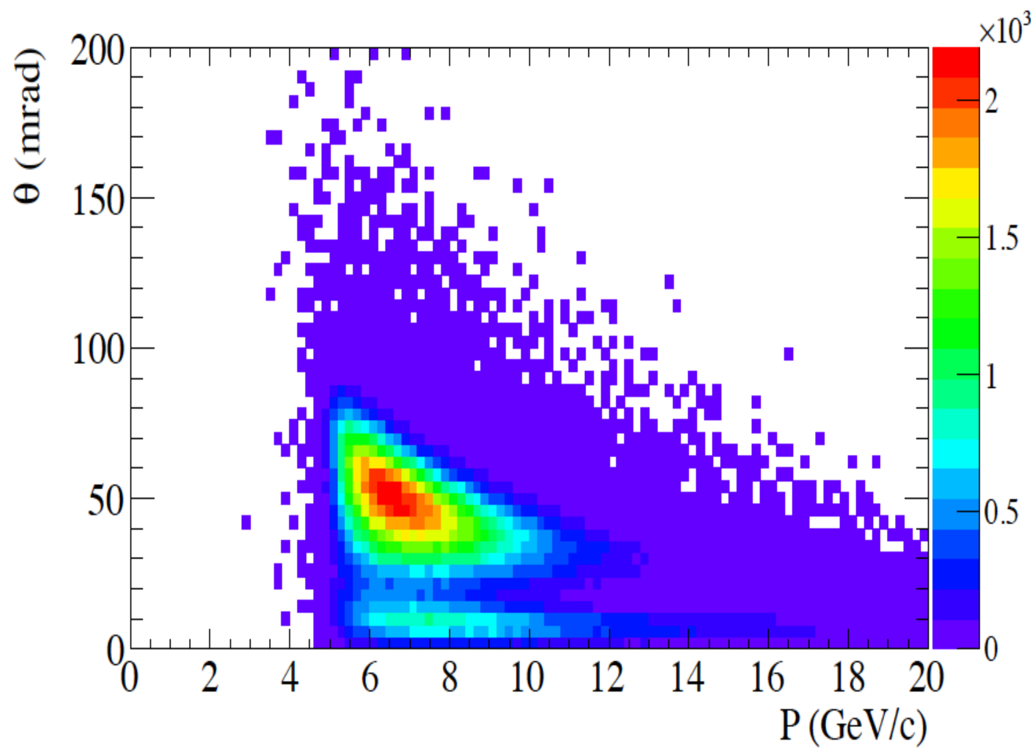


>80% coverage of MiniBooNE phase space

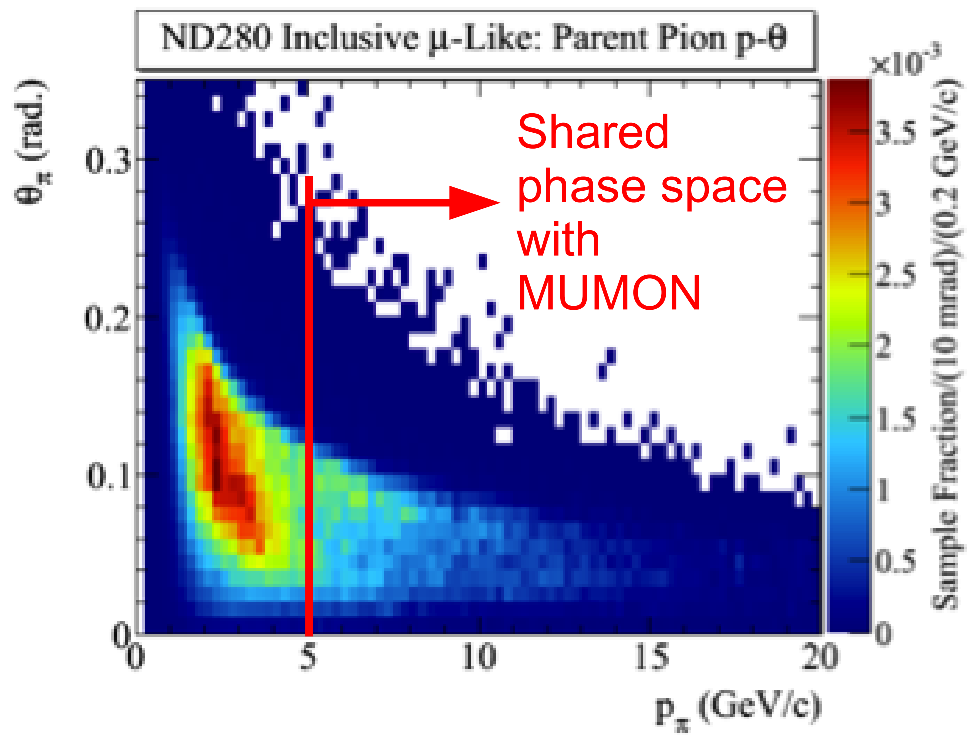


T2K Muon Monitor (MUMON)

Parent pion phase space at MUMON



Parent pion phase space at near detector



Little overlap between pion parent phase space of muons and neutrinos

Can't directly constrain T2K neutrino flux with muon monitor

Use MUMON to tune and monitor the beam direction, monitor the rate stability

Extrapolating Data

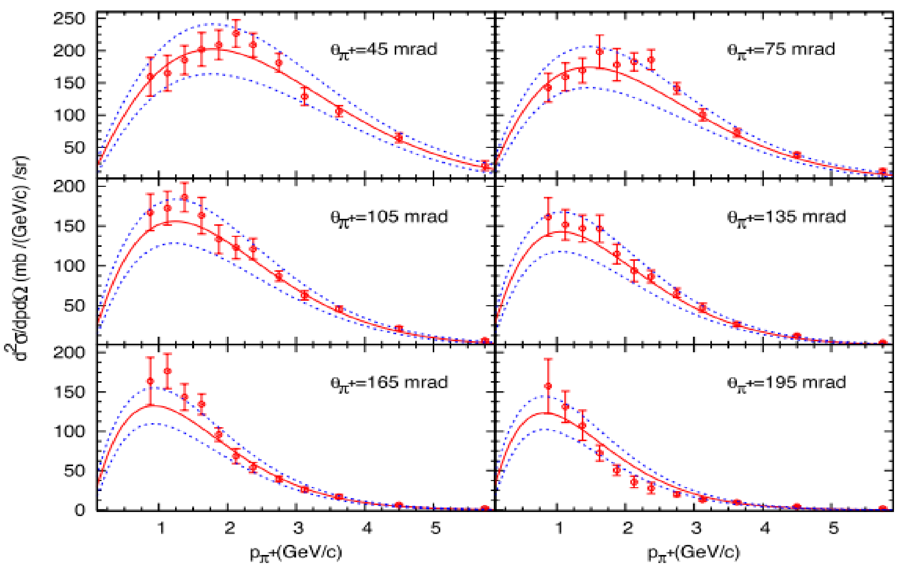
Available hadron production data may not cover all phase space of interest (out going or incident particles) → Need methods to extrapolate data

Parametrized production formulas → Sanford-Wang, BMPT

$$\frac{d^2\sigma}{dp\,d\Omega}(p,\theta) = c_1 p^{c_2}\left(1-\frac{p}{p_B-c_9}\right)\exp\left(-c_3\frac{p^{c_4}}{p_B^{c_5}} - c_6\theta\left(p-c_7 p_B\cos^{c_8}\theta\right)\right)$$

Used by MiniBooNE, K2K

Beam energy dependence

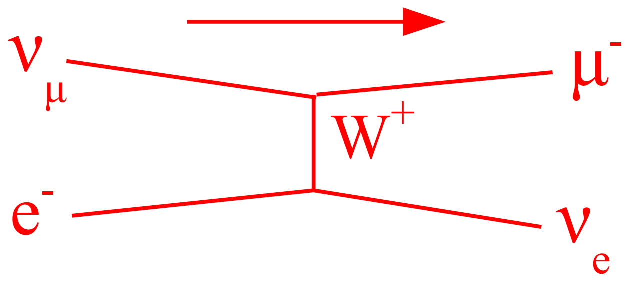


MiniBooNE SW fits to the HARP π+ data

Constraining the Flux with ν Interactions

- Can the flux be constrained by measuring neutrino interactions?
- Need neutrino interaction modes that are "independent" of interesting cross section measurements

Inverse Muon Decay



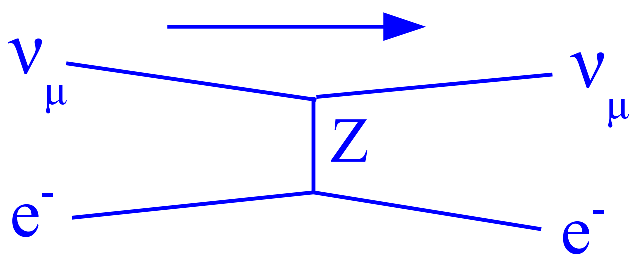
Used by NOMAD for high energy flux

Threshold at E_ν > 12 GeV

ν in final state → energy not fully reconstructed

Limited by statistics

NC Neutrino/Electron Scattering



ν in final state → energy not fully reconstructed

Limited by statistics