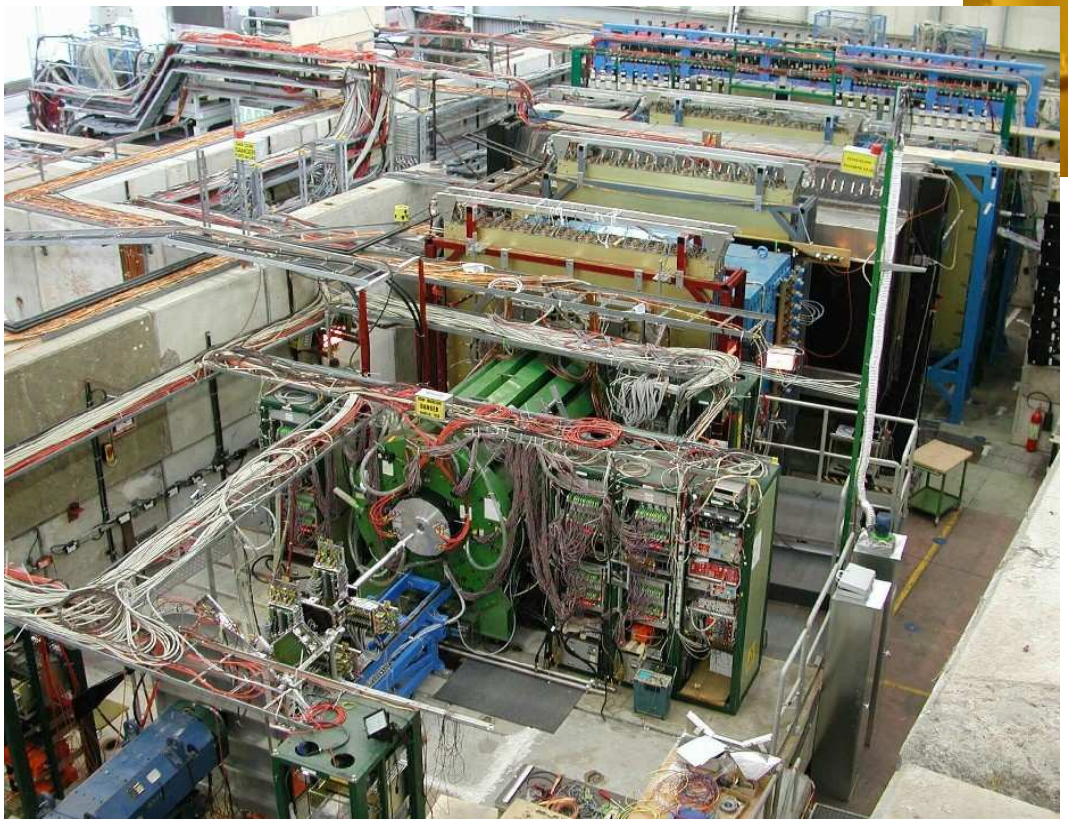
Secondary Production Measurements for MiniBooNE

MiniBooNE Detector E898 at Fermilab



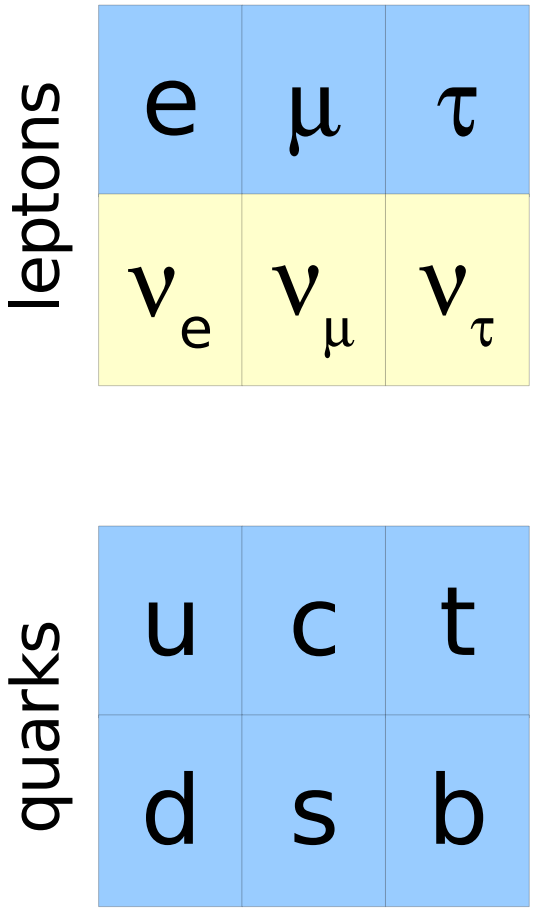
HARP Detector PS214 at CERN

Fermilab Users' Meeting

May 31 & June 1, 2006

Dave Schmitz - Columbia University

An introductory note on neutrinos



Standard Model Particles

despite spectacular progress in neutrino physics in recent decades there are still relatively basic properties of neutrinos that we do not understand

- neutrino masses (the PDG lists the electron mass = 0.51099892 +- 0.00000004 MeV, and the electron neutrino mass as something less than 3 eV)
- neutrino mixing parameters (is θ_{13} zero or just very small? what about a CP violating phase?)
- are there additional, sterile neutrinos?
- neutrino interaction cross-sections

this talk is about step one from the list of challenges that must be addressed in order to begin answering some of these questions

To do list :

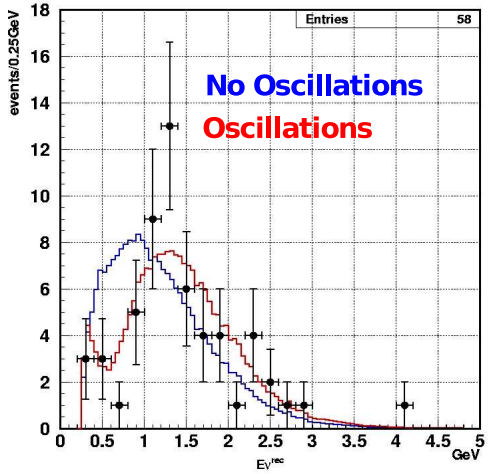
1.) create a well understood neutrino beam with which to make ***precision measurements***

2.) ...

Precision neutrino measurements: Two examples

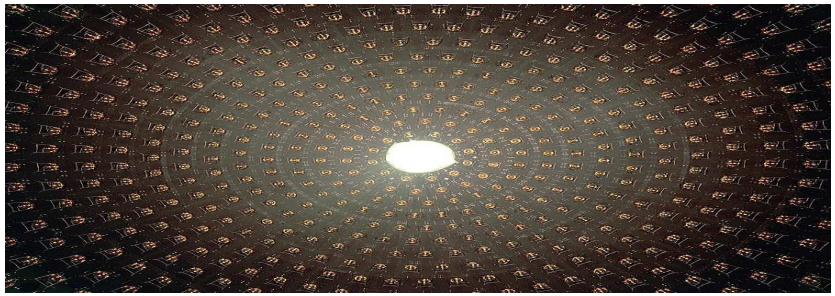
K2K

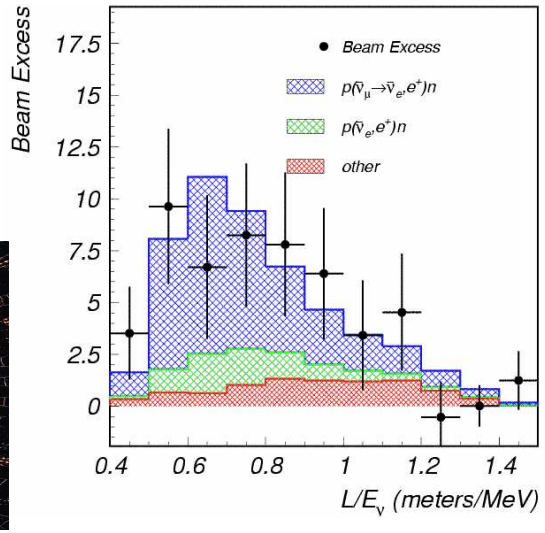
confirmation of atmospheric oscillations by a measurement of ν_μ disappearance in a long-baseline accelerator-based experiment



MiniBooNE

confirm or refute the LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation signal in a definitive and independent way.





Fermilab is home to two accelerator neutrino beams

neutrinos from the main injector

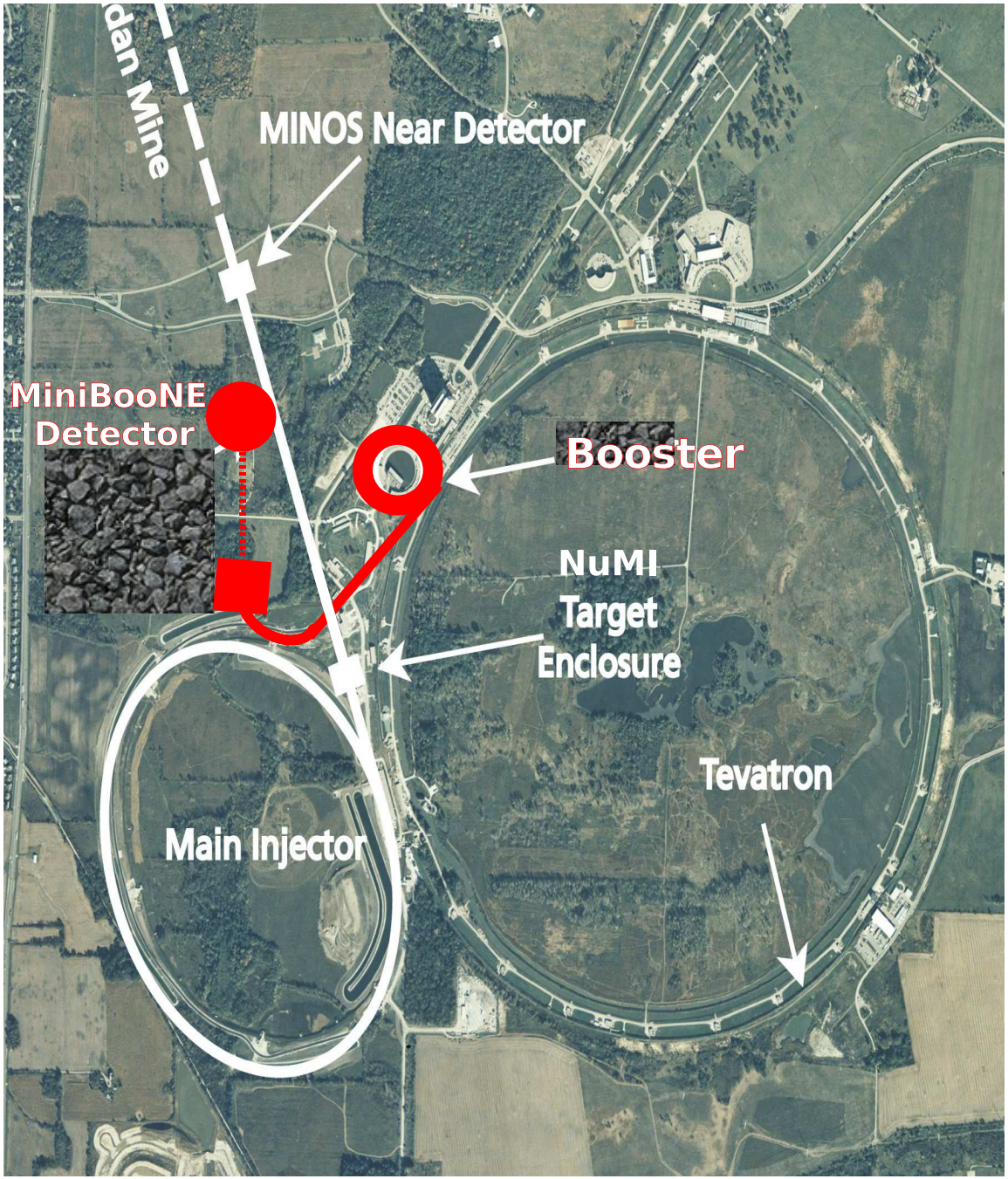
neutrinos from the booster

and multiple detectors

MINOS

MiniBooNE

SciBooNE



The Nobel Prize in Physics 1988

"for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino"

Leon M. Lederman

Melvin Schwartz

Jack Steinberger

Outline

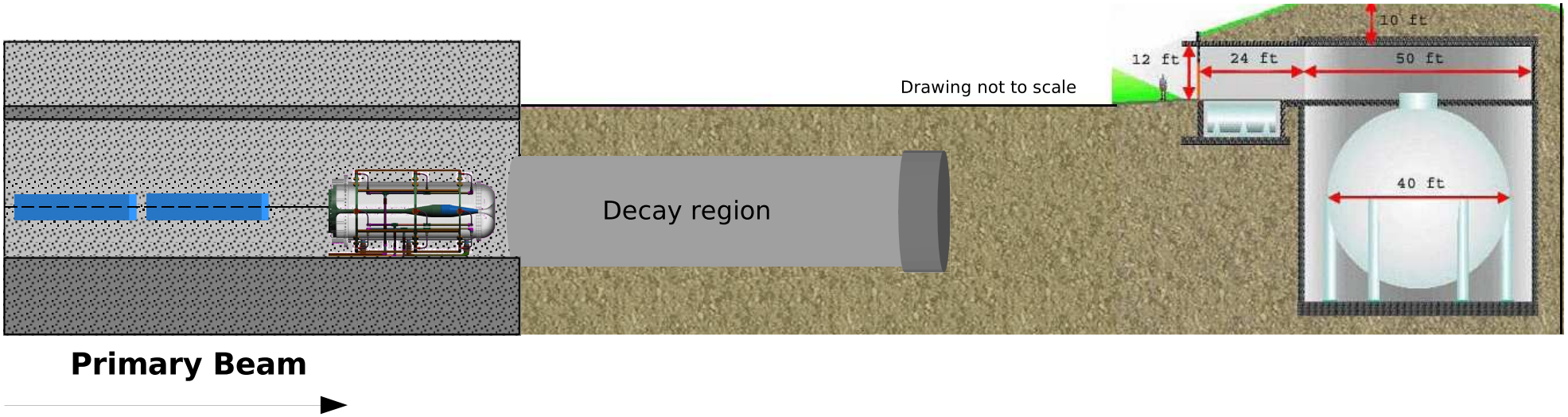
- **Accelerator neutrino beams**
  - experimental setup of a conventional accelerator neutrino beam
  - Ex: the Fermilab Booster neutrino beam
- **HARP – hadron production measurements at CERN**
  - physics motivation for the HARP experiment
  - the data sets of interest to the Booster neutrino beamline
  - a cross-section measurement at HARP
- **Relevance of HARP results for MiniBooNE**
  - neutrino cross-section measurements
  - oscillation measurements via ν_μ disappearance require a well understood ν_μ flux
  - oscillation measurements via ν_e appearance require knowledge of ν_e backgrounds

A conventional neutrino beam

the **Boo**ster **N**eutrino beam at Fermilab

"**E**" is for Experiment

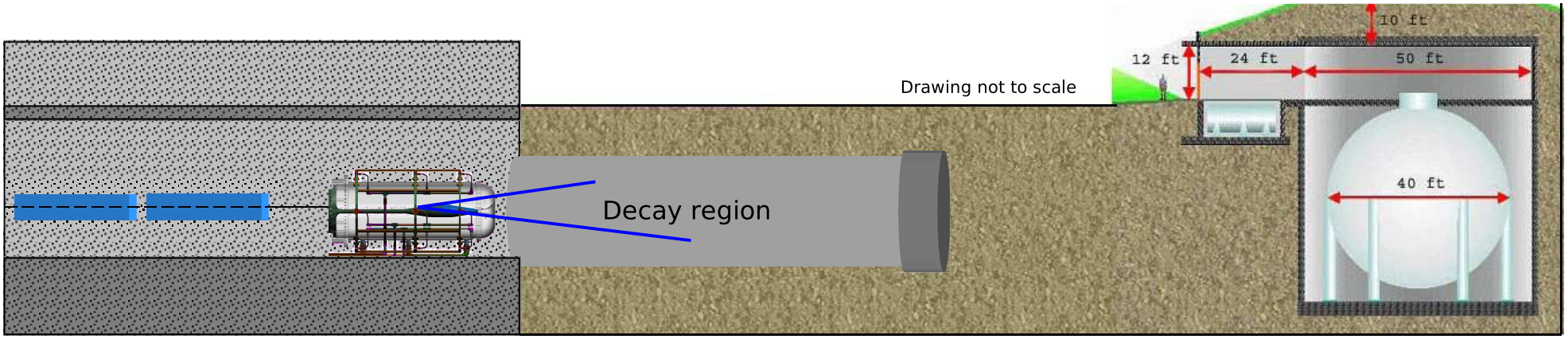
A conventional neutrino beam



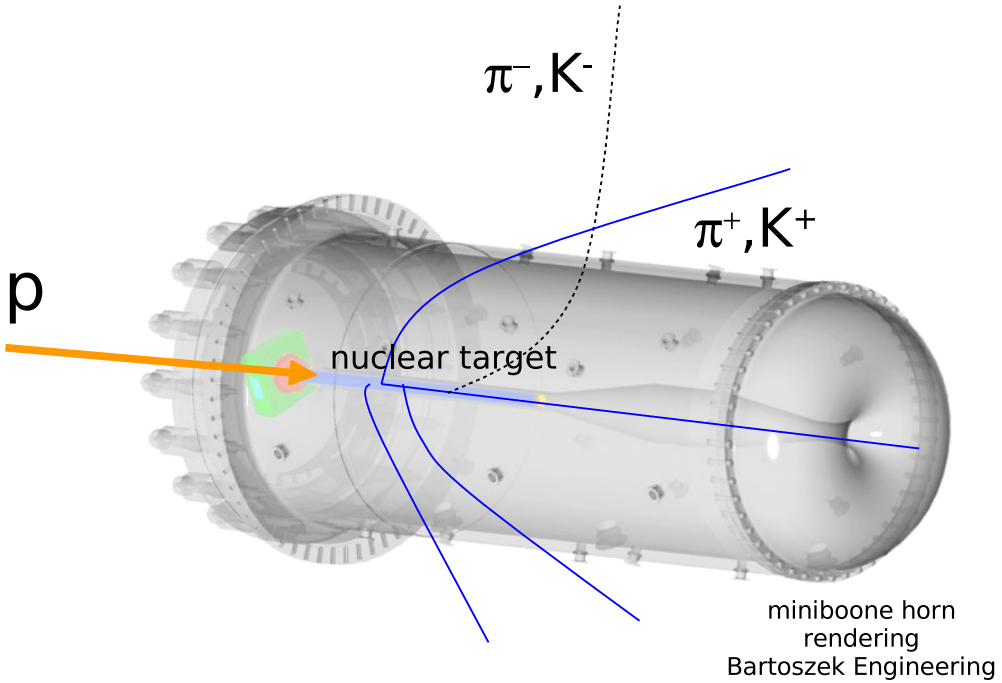
8 GeV extraction line to MI-

- primary proton beams order 1-100's GeV
  - Fermilab Booster – 8 GeV
  - KEK PS – 12 GeV
  - J-PARC – 50 GeV
  - Fermilab M.I. – 120 GeV
  - CERN SPS – 400 GeV

A conventional neutrino beam



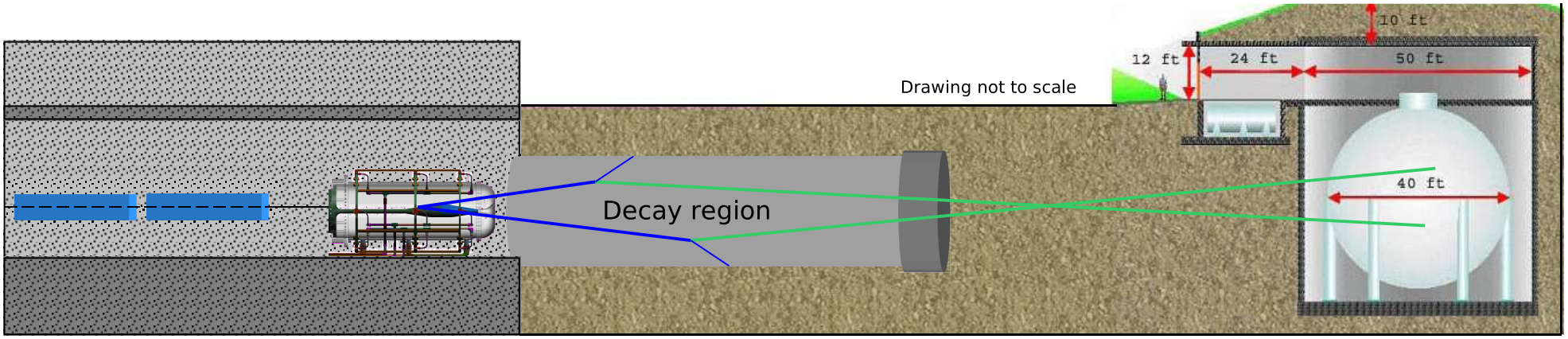
Primary Beam ★**Secondary Beam**



miniboone horn rendering
Bartoszek Engineering

- primary protons impinge upon fixed nuclear targets (Be, Al, C,...) creating secondary mesons (p, π^+, π^-, K^+, K^-)
- targets are thick: 1-2 λ. effects of reinteractions are important (1.7 λ)
- mesons are focused into an open decay region by special high-current “horns” (170,000 amps)
- relevant production is forward, but can extend out to 20 degrees due to effect of horn
- ★production cross-sections for the secondary beam is a main focus of this presentation

A conventional neutrino beam



Primary Beam → **Secondary Beam** → **Neutrino Beam**

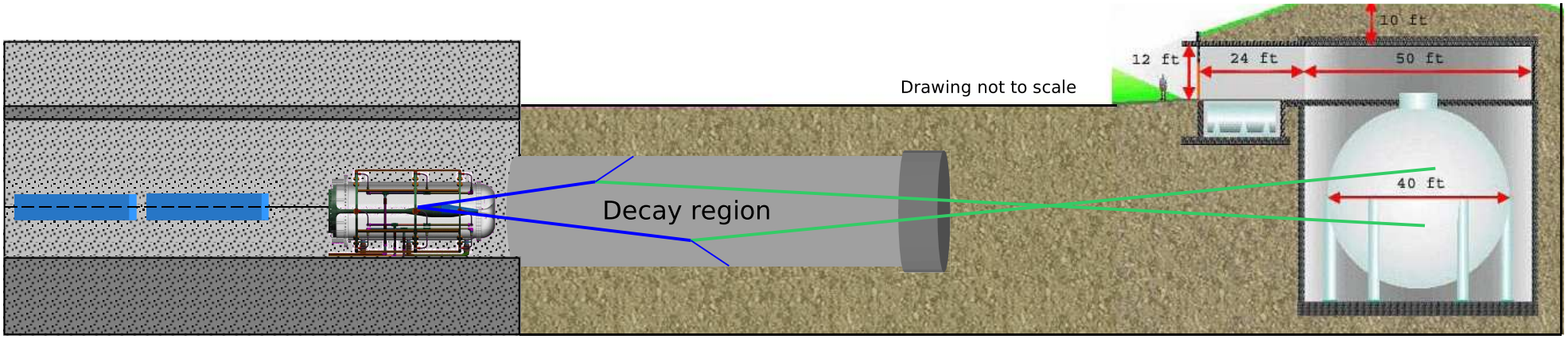
- short-lived pions and kaons decay to create a forward beam of neutrinos of mixed flavor

- determined by relatively straight forward decay kinematics and branching ratios

$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \overline{\nu_\mu}$$

$$K^+ \to \mu^+ + \nu_\mu$$
$$K^+ \to \pi^0 + \mu^+ + \nu_\mu$$
$$K^+ \to \pi^0 + e^+ + \nu_e$$
$$K^0 \to \pi^\pm + e^\mp + \overline{\nu_e}$$
$$K^0 \to \pi^\pm + \mu^\mp + \overline{\nu_\mu}$$

A conventional neutrino beam



Primary Beam → **Secondary Beam** → **Neutrino Beam**

★ the key here is to understand the **flux of neutrinos** of various flavors through any **detectors** near the beam where one expects to make *cross-section* or *oscillation* measurements

and the main component is an understanding of **hadron production** and interactions

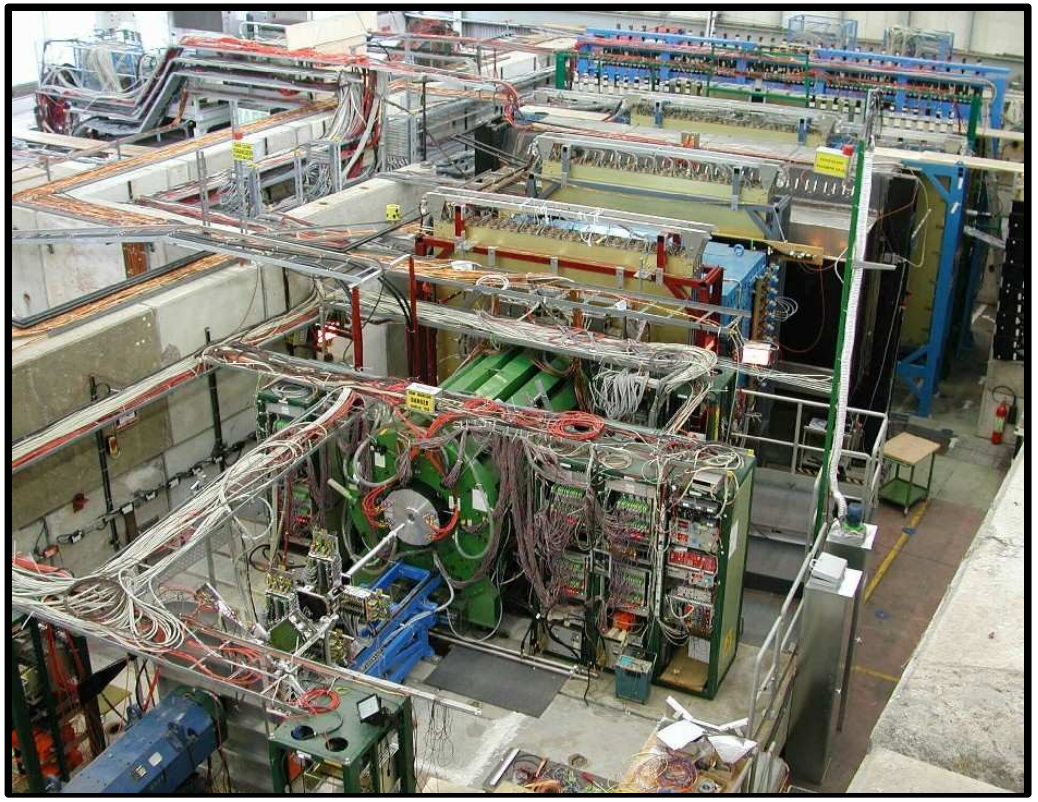
$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \overline{\nu_\mu}$$
$$K^+ \to \mu^+ + \nu_\mu$$
$$K^+ \to \pi^0 + \mu^+ + \nu_\mu$$
$$K^+ \to \pi^0 + e^+ + \nu_e$$
$$K^0 \to \pi^\pm + e^\mp + \overline{\nu_e}$$
$$K^0 \to \pi^\pm + \mu^\mp + \overline{\nu_\mu}$$

HARP – PS214 at CERN

Hadron **Pr**oduction measurements at CERN

HARP – PS214 at CERN

HARP is a large angle spectrometer to measure hadron production from various nuclear targets and a range of incident beam momenta

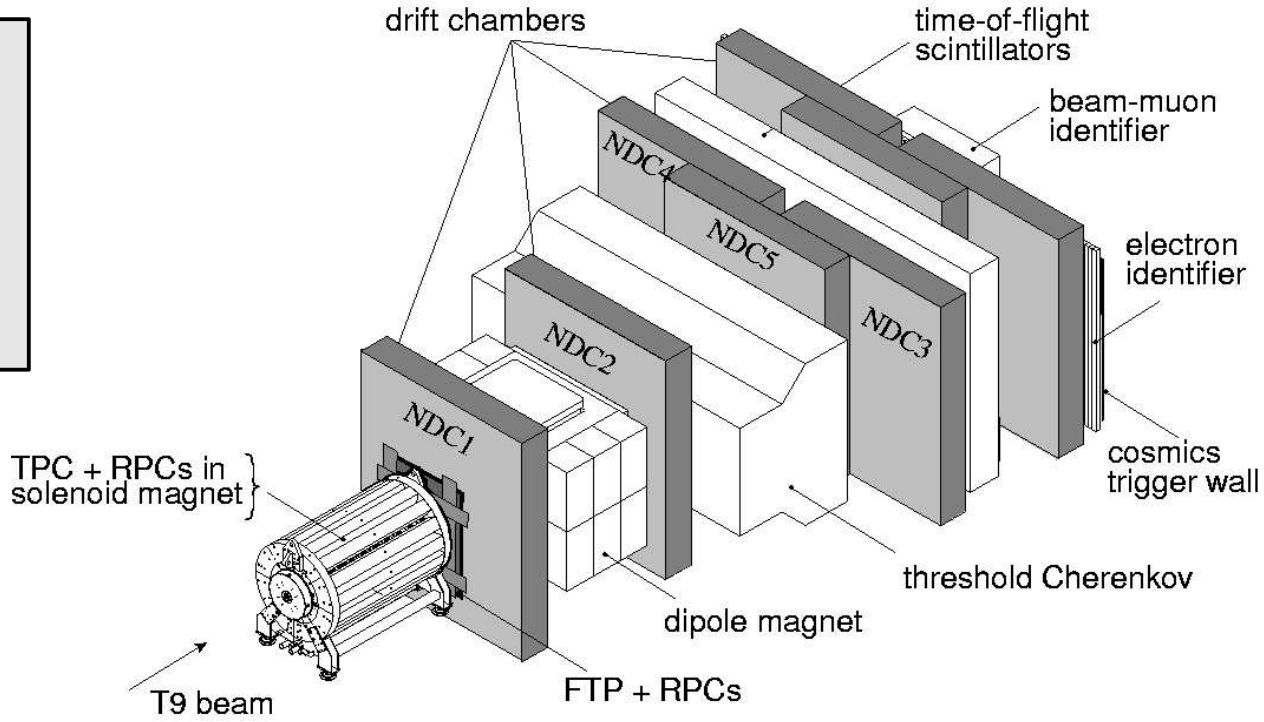


- Nuclear target materials : A = 1 – 200
- Nuclear target thickness : λ = 2 – 100%
- Beam particles : h = p, π^{+-},e^{+-}
- Beam momenta : p_{beam} = 1 – 15 GeV/c
- Secondaries measured : h = p, π^{+-},K^{+-}
- Kinematic acceptance of forward spectrometer
  - p = 0.5 – 8.0 GeV/c
  - θ = 20 – 250 mrad

hadron production measurements in *"seven dimensions"*

HARP – PS214 at CERN

HARP is a large angle spectrometer to measure hadron production from various nuclear targets and a range of incident beam momenta



HARP Physics Goals

- Neutrino factory design
- Atmospheric neutrino flux predictions
- GEANT4 hadronic libraries
- Neutrino flux predictions for accelerator-based experiments : MiniBooNE and K2K

Recipe for a cross-section

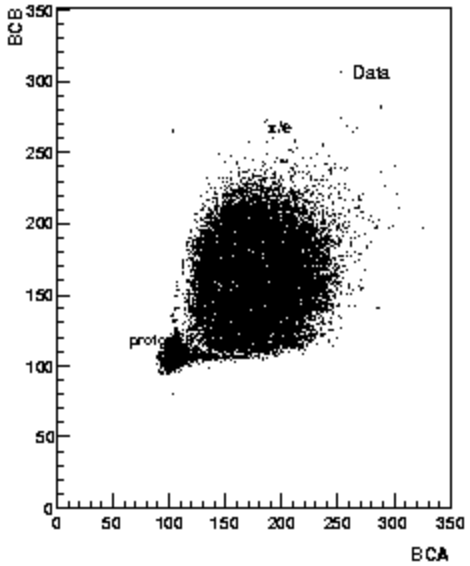
$$\frac{d^2\sigma^{\pi}}{dp\,d\Omega} = \frac{A}{N_A \rho\, t\, N_{\text{pot}}} \frac{1}{\left[\text{correction factors}(p,\theta)\right]} \frac{\Delta^2 N^{\pi}}{\Delta p \Delta \Omega}$$

- Select events identified as primary protons interacting in the target
- For each event reconstruct tracks and their 3-momentum
- Identify pions among secondary tracks

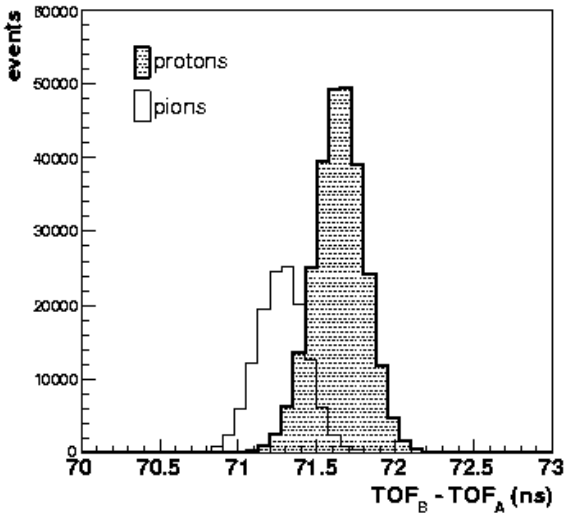
- Apply corrections for reconstructed-to-true pion yield conversion:
  - Momentum resolution
  - Spectrometer angular acceptance
  - Track reconstruction efficiency
  - Efficiency and purity of pion identification
  - Other

- Count protons on target corresponding to selected events
- Multiply by physics constants and accurately measured target properties

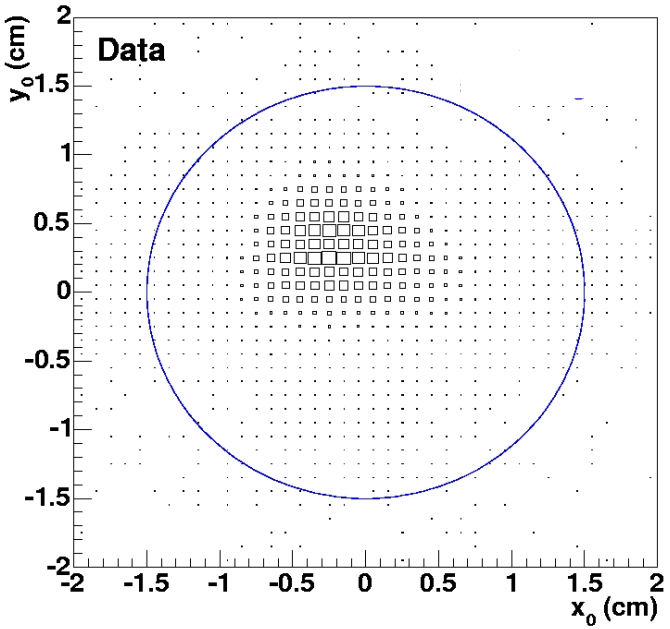
Event Selection



2 Beam Cerenkov Detectors



2 Beam ToF Detectors

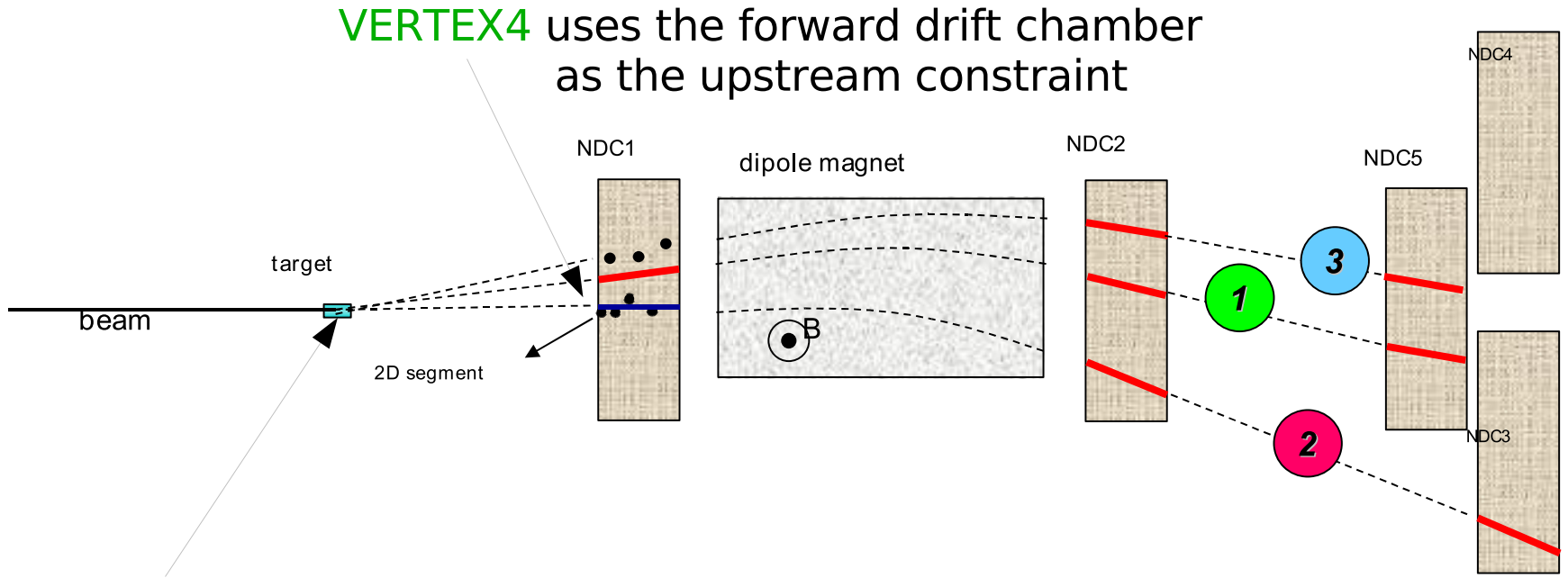


4 Multi-wire Proportional Counters

- **Event selection for protons on target** (“*normalization trigger*”)**:**
  - Well-behaved transverse impact point and direction of primaries via 4 MWPCs and scintillators (BS, TDS, HALO A, HALO B)
  - Primaries identified as protons via beam ToF and Cerenkov systems (TOFA, TOFB, BCA, BCB). Beam ToFs also used for interaction time.
- **Event selection for proton inelastic interactions** (“*physics trigger*”)**:**
  - Same as normalization trigger, plus signal in forward trigger scintillator plane (FTP)

Track Reconstruction

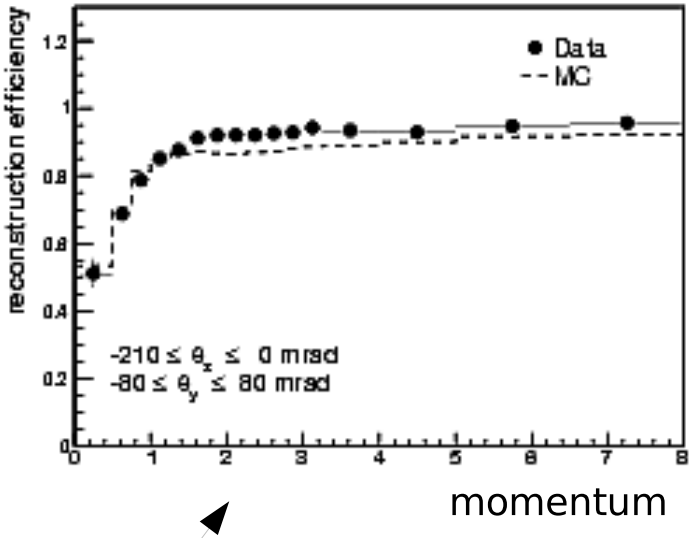
- two independent methods of momentum reconstruction given a downstream segment



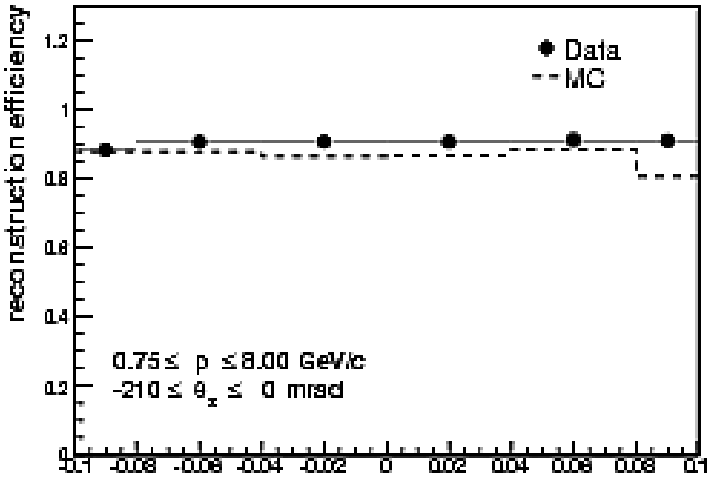
- we use VERTEX4 tracks as a control sample to measure the efficiency for VERTEX2 reconstruction. VERTEX2 eff is > 99%.

Track Efficiency and Resolution

~90%



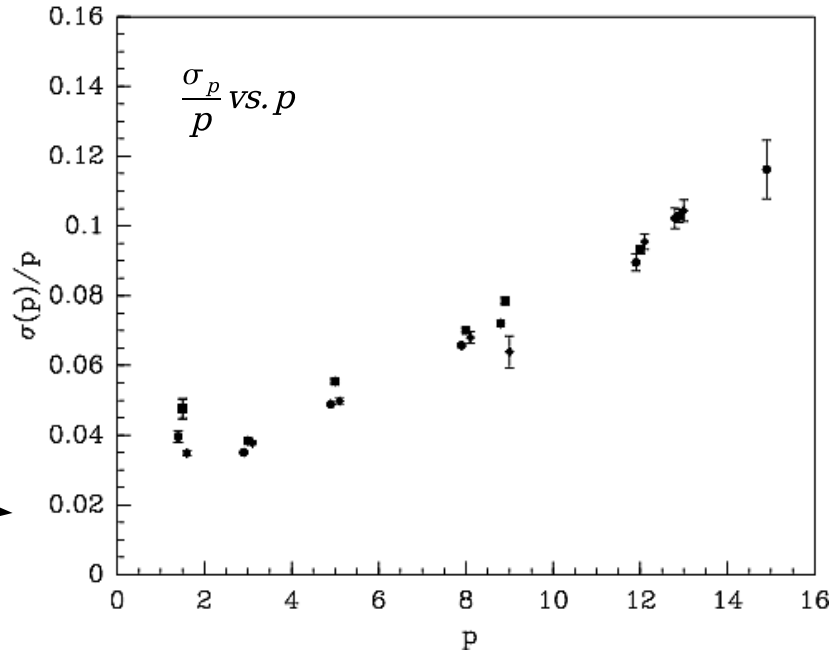
momentum



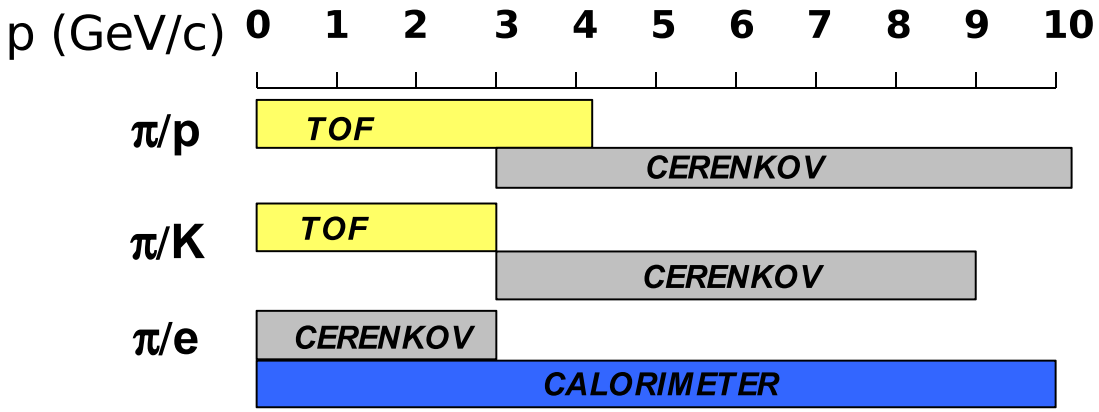
vertical position

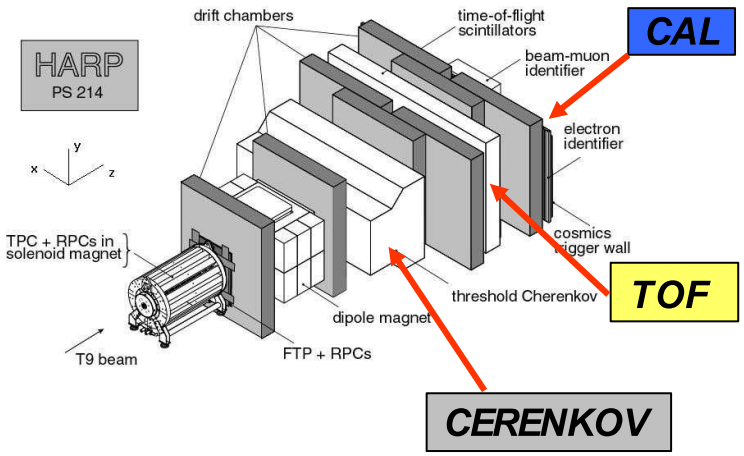
- a useful analysis track requires a match to a time-of-flight hit as well as a reconstructed momentum and so is included in the total reconstruction efficiency

- momentum resolution in empty target data and monte carlo

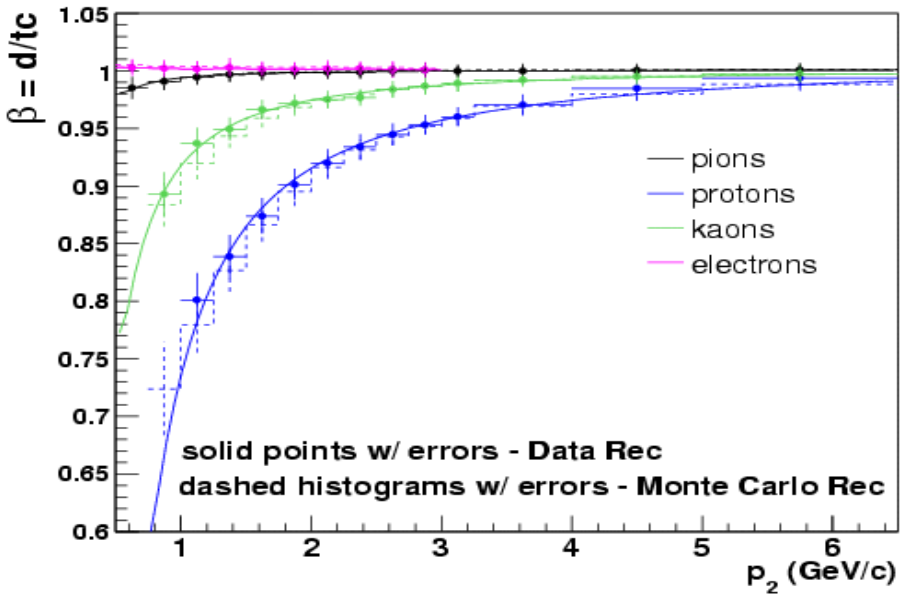


Particle Identification

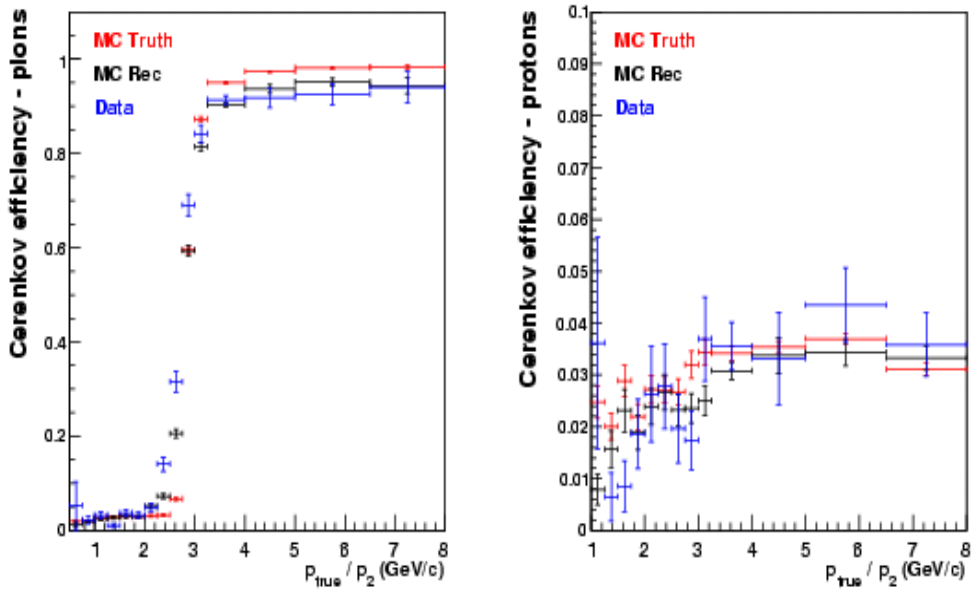




ToF π/p/K response



CERENKOV π/p response



Available online at www.sciencedirect.com
SCIENCE DIRECT
ELSEVIER
Nuclear Physics B 752 (2006) 1–45
NUCLEAR PHYSICS B

First HARP Physics Publication!

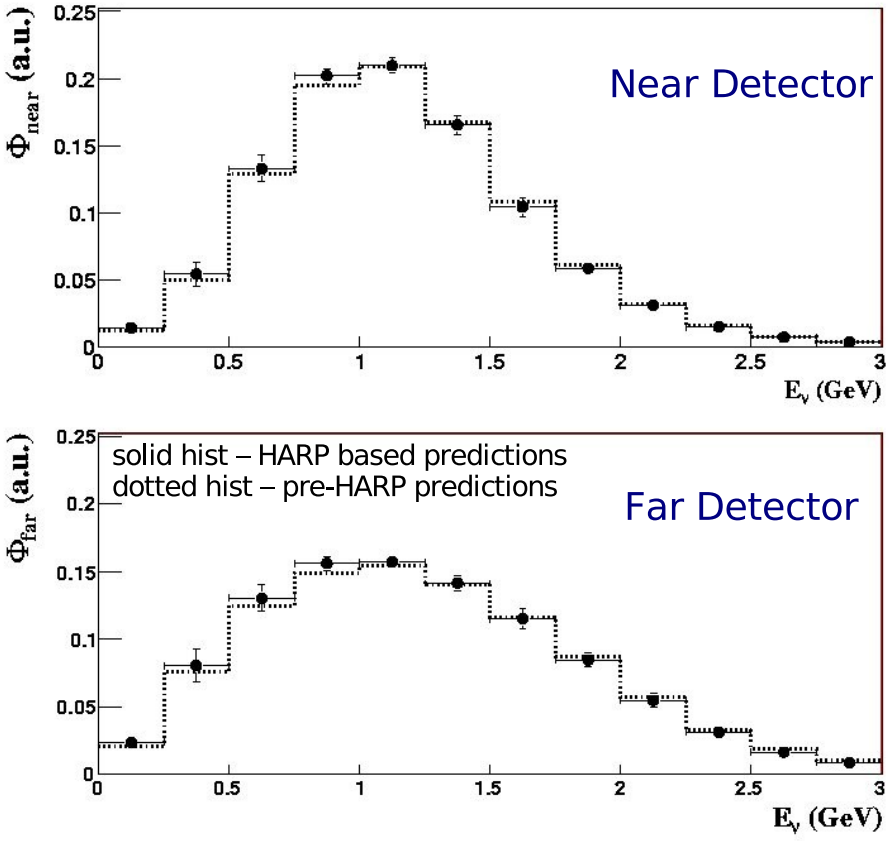
Measurement of the production cross-section of positive pions in p–Al collisions at 12.9 GeV/c

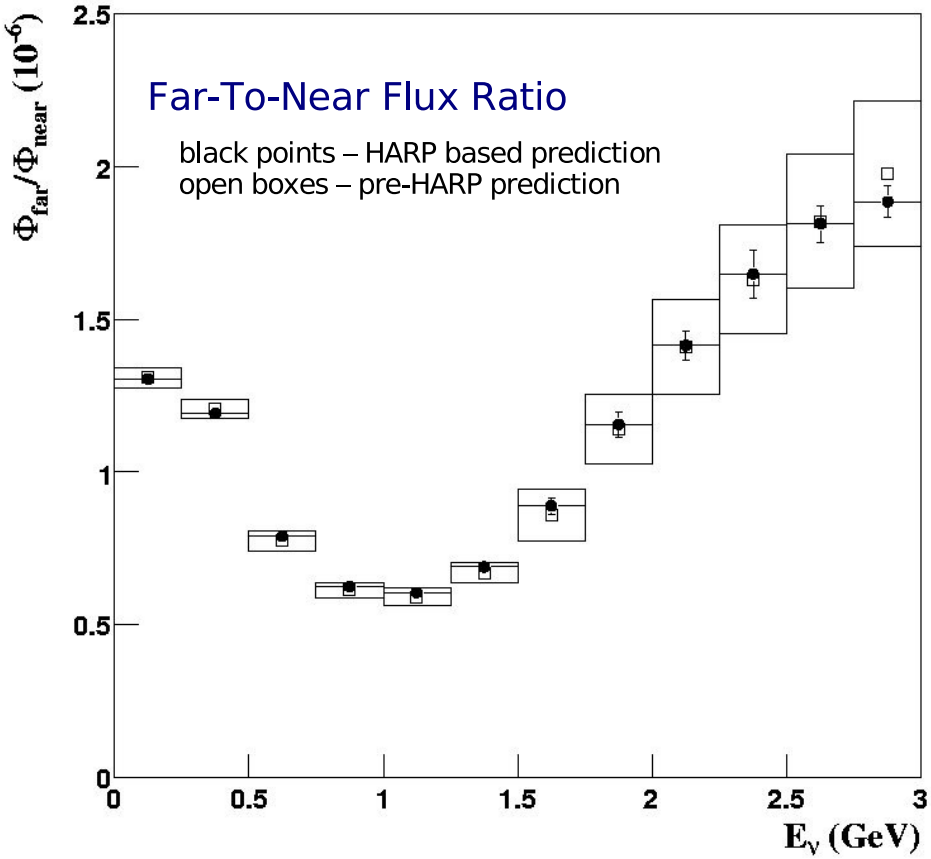
HARP Collaboration

Abstract

A precision measurement of the double-differential production cross-section, $d^2\sigma^{\pi^+}/dp\,d\Omega$, for pions of positive charge, performed in the HARP experiment is presented. The incident particles are protons of 12.9 GeV/c momentum impinging on an aluminium target of 5% nuclear interaction length. The measurement of this cross-section has a direct application to the calculation of the neutrino flux of the K2K experiment. After cuts, 210 000 secondary tracks reconstructed in the forward spectrometer were used in this analysis. The results are given for secondaries within a momentum range from 0.75 to 6.5 GeV/c, and within an angular range from 30 mrad to 210 mrad. The absolute normalization was performed using prescaled beam triggers counting protons on target. The overall scale of the cross-section is known to better than 6%, while the average point-to-point error is 8.2%.
© 2005 Elsevier B.V. All rights reserved.

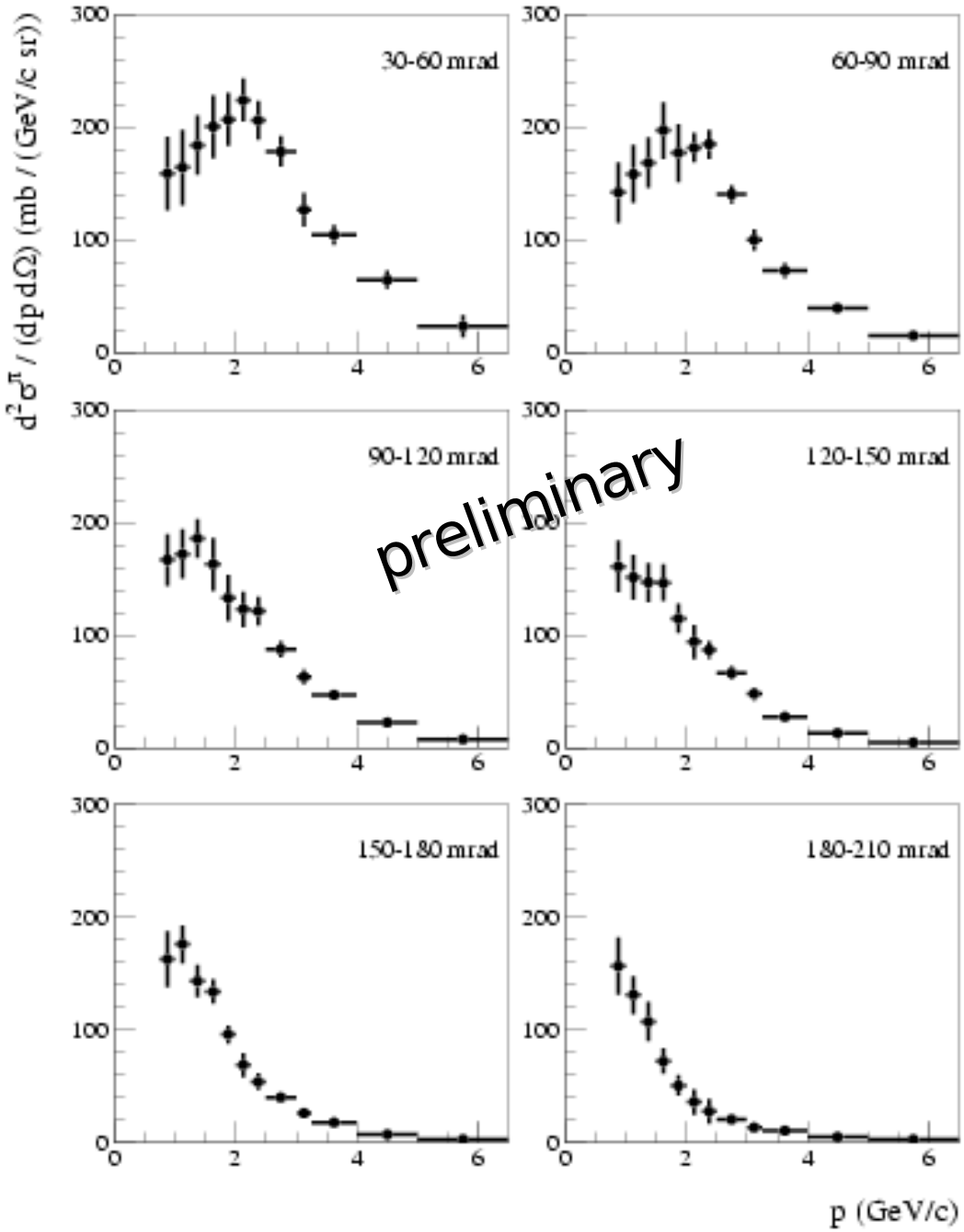
HARP-Based Neutrino Flux Predictions For K2K





- HARP result will be incorporated into the K2K final oscillation analysis. The current 7% systematic uncertainty on the F/N ratio prediction is expected to decrease significantly (HARP contribution: ~1%), and the sensitivity to oscillations to increase. paper in preparation.

Plots by P. Novella



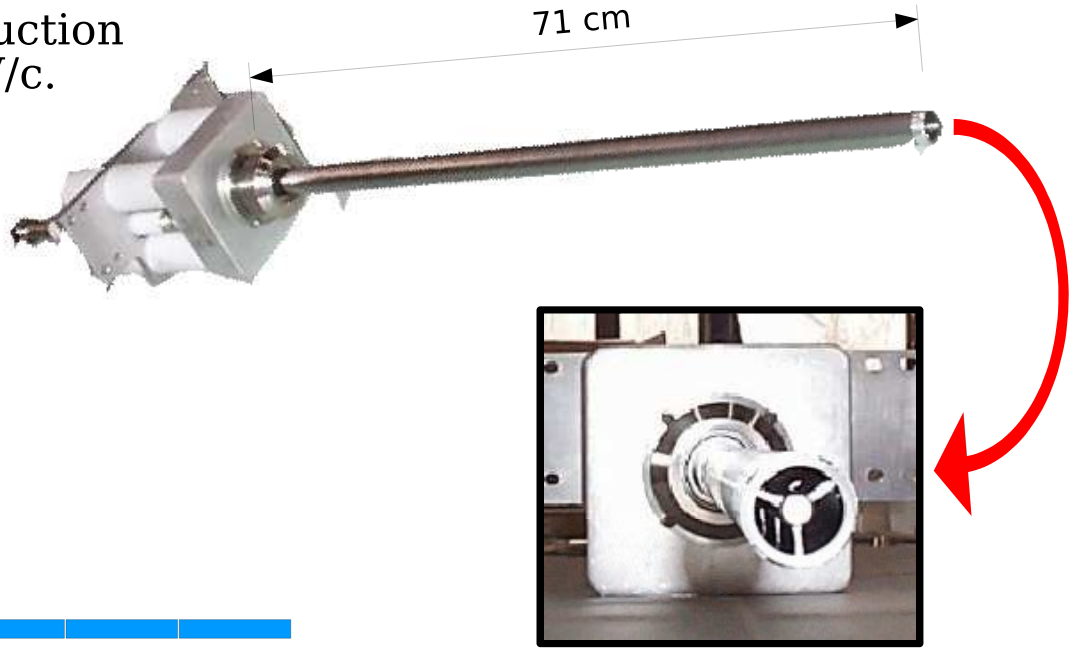
Next publication this summer

$$p(8.9\,GeV/c)+Be\rightarrow\pi^{+}+X$$

- paper exists in internal draft form and is being edited
- full systematic errors have been evaluated
- measurement currently being used for preliminary studies by MiniBooNE

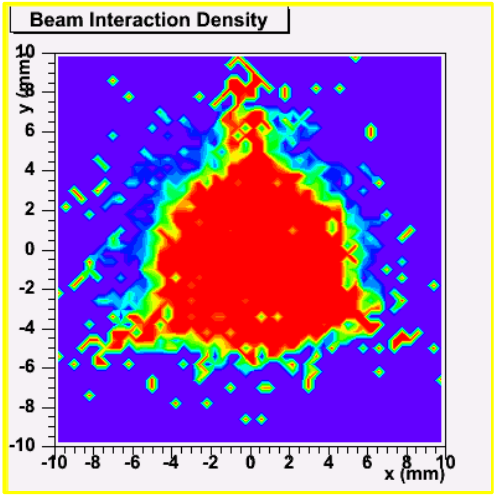
HARP data sets relevant to MiniBooNE

- The first goal was to measure π^+ production cross sections for Be at p_{proton} = 8.9 GeV/c.



- Additional measurements include:
  - π^- production (important for anti-ν running)
  - K^+ production (important for intrinsic ν_e backgrounds)
  - Thick target secondary yields

No target	5.7 M events	Subtraction
5% Be Disc	7.3 M events	p+Be x-section
50% λ MB replica	5.2 M events	Effects specific to MB target reinteraction absorption scattering
100% λ MB replica	6.4 M events	



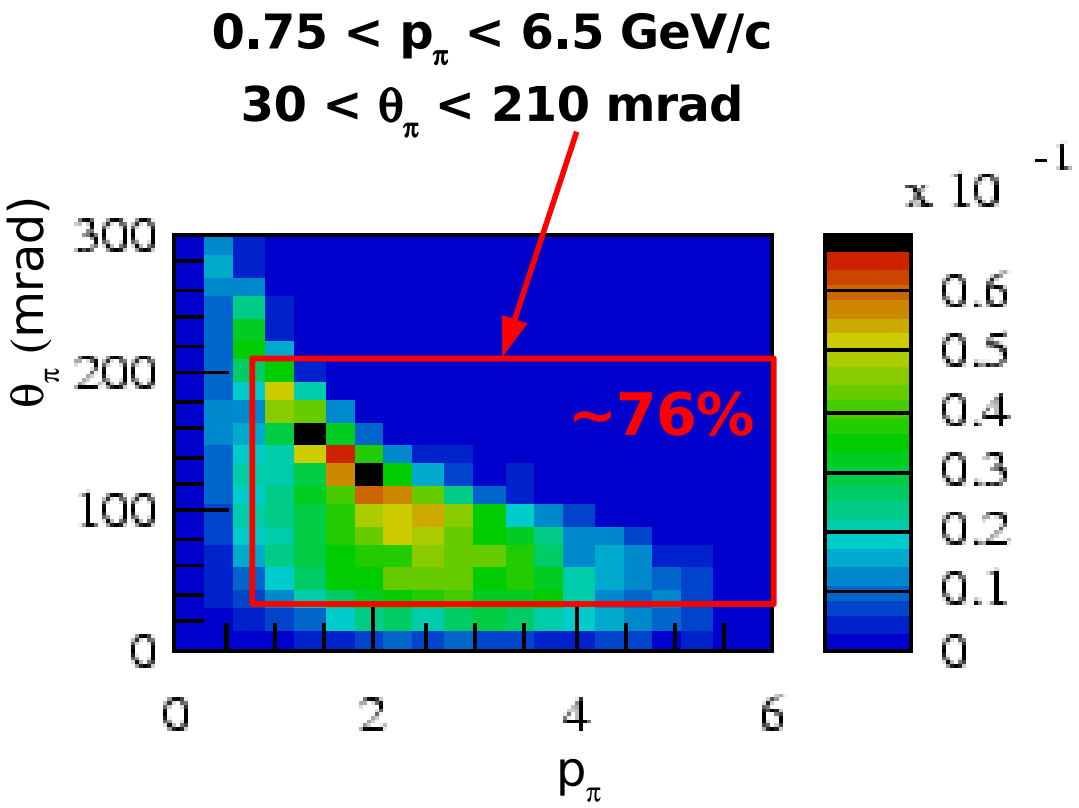
Relevant pion phase space

- thin target p+Be measurement at HARP provides excellent coverage of relevant pion phase space

- combined with thick target yields to be analyzed this summer should provide a definitive flux prediction for MiniBooNE

- Efforts to expand acceptance of HARP measurement to 0 degrees and 500 MeV/c. >90% coverage

- many other HARP data sets that could aid in tuning the MiniBooNE beam monte carlo
  - p, π + Al
  - range of momenta



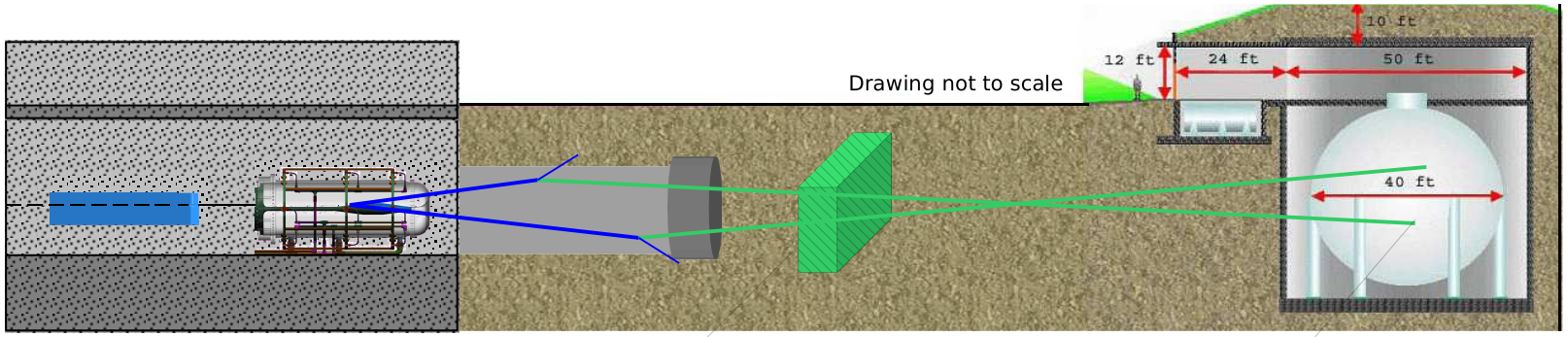
Momentum and Angular distribution of pions decaying to a neutrino that passes through the MiniBooNE detector.

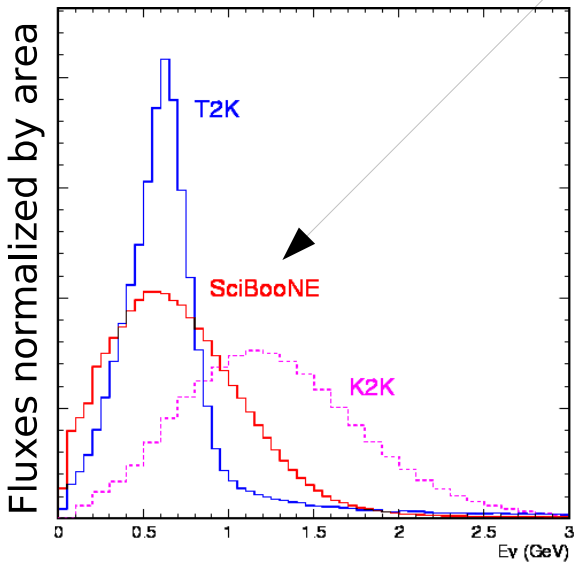
“E” is for Experiment

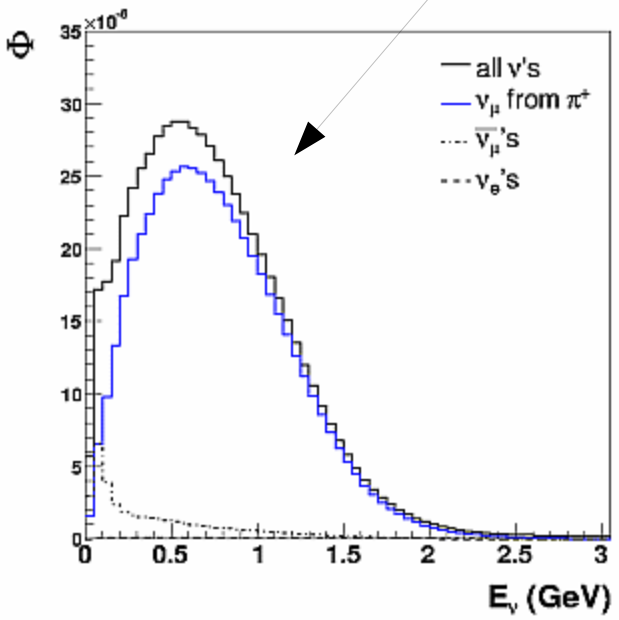
Relevance of HARP results to
MiniBooN**E**, SciBooN**E**
and future BooN**E**s of all kinds

Predicting neutrino fluxes

- recall the goal here is the accurate prediction of neutrino fluxes at any detectors in the neutrino beam
- use monte carlo simulations seeded with hadron production results

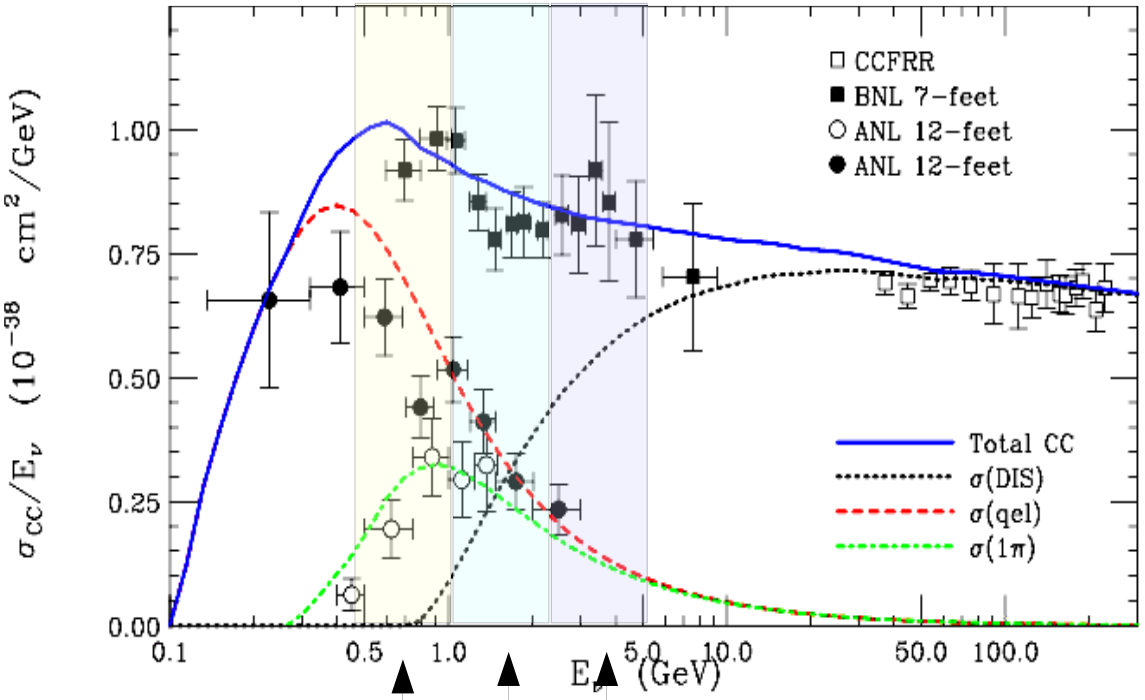






Neutrino cross-section measurements

$$\sigma(\mathrm{E}) \propto \frac{N(\mathrm{E})}{\Phi(\mathrm{E})}$$



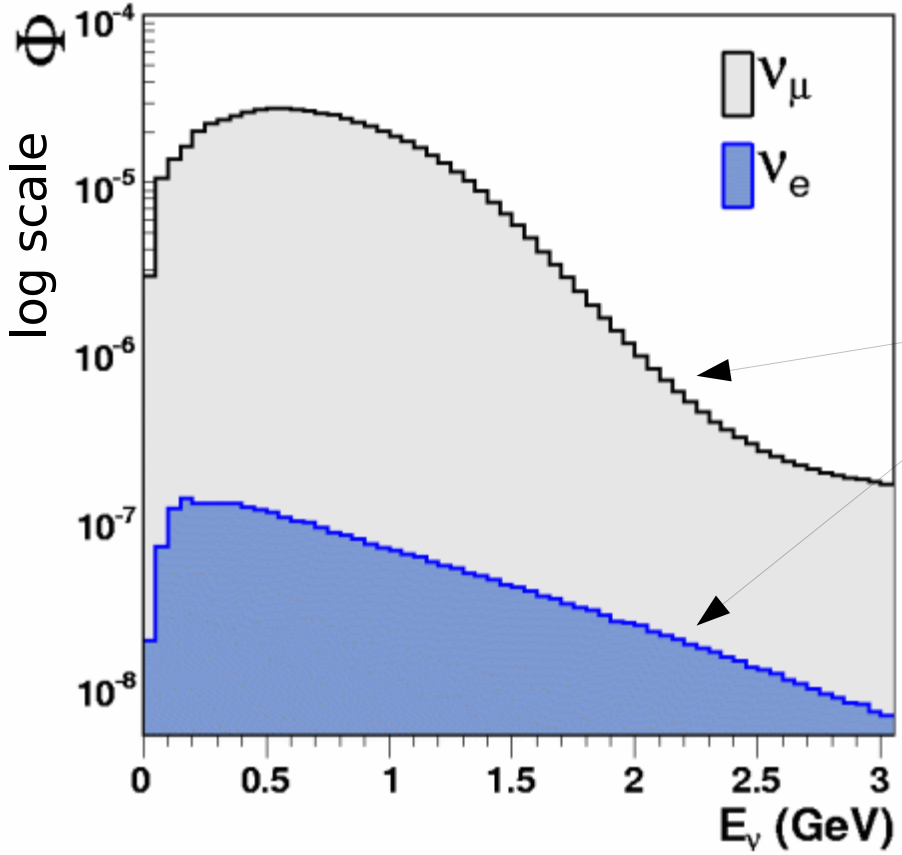
MINOS

K2K

MiniBooNE, SciBooNE, T2K

- A well understood flux prediction allows one to do **absolute cross-section measurements**
- MiniBooNE and SciBooNE will record more statistics with more controlled systematics than any previous experiment in this energy range
- cross-sections in this range are important to next-generation mixing parameter experiments
- anti-neutrino cross-sections are in particularly poor shape. The Booster neutrino beam is currently running in anti-neutrino mode

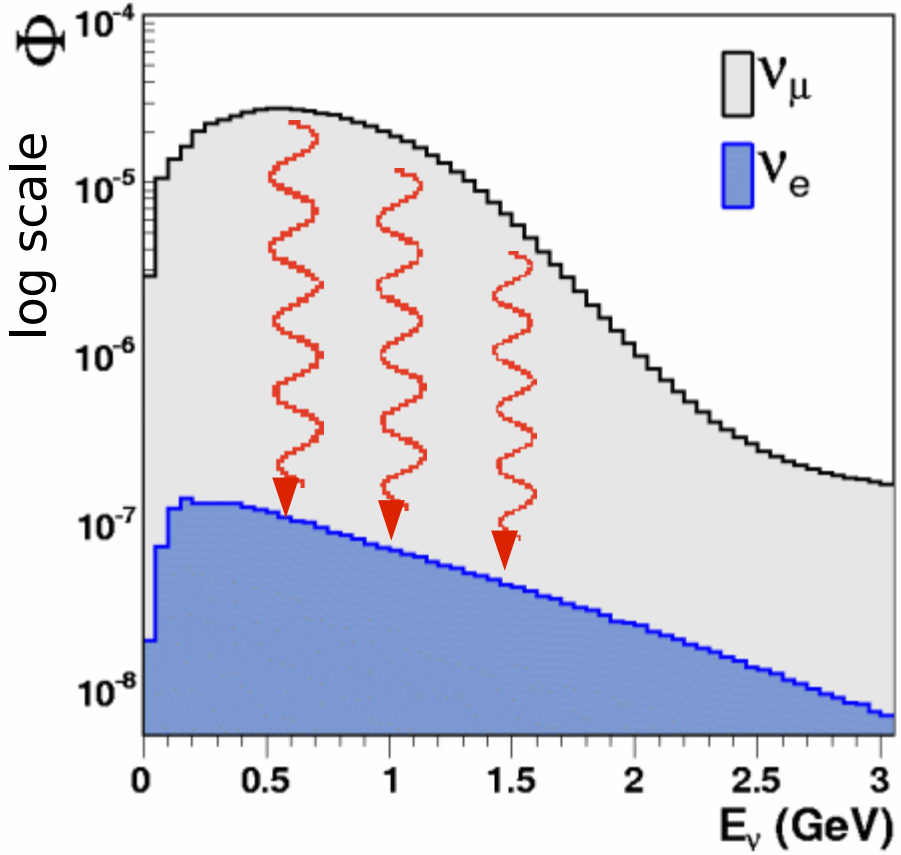
Neutrino oscillations via ν_e appearance at MiniBooNE



- At MiniBooNE we are looking for an excess of electron neutrinos above expected backgrounds

- Therefore, we want to know the **expected** fluxes of muon and electron neutrinos at the detector without oscillations

Neutrino oscillations via ν_e appearance at MiniBooNE



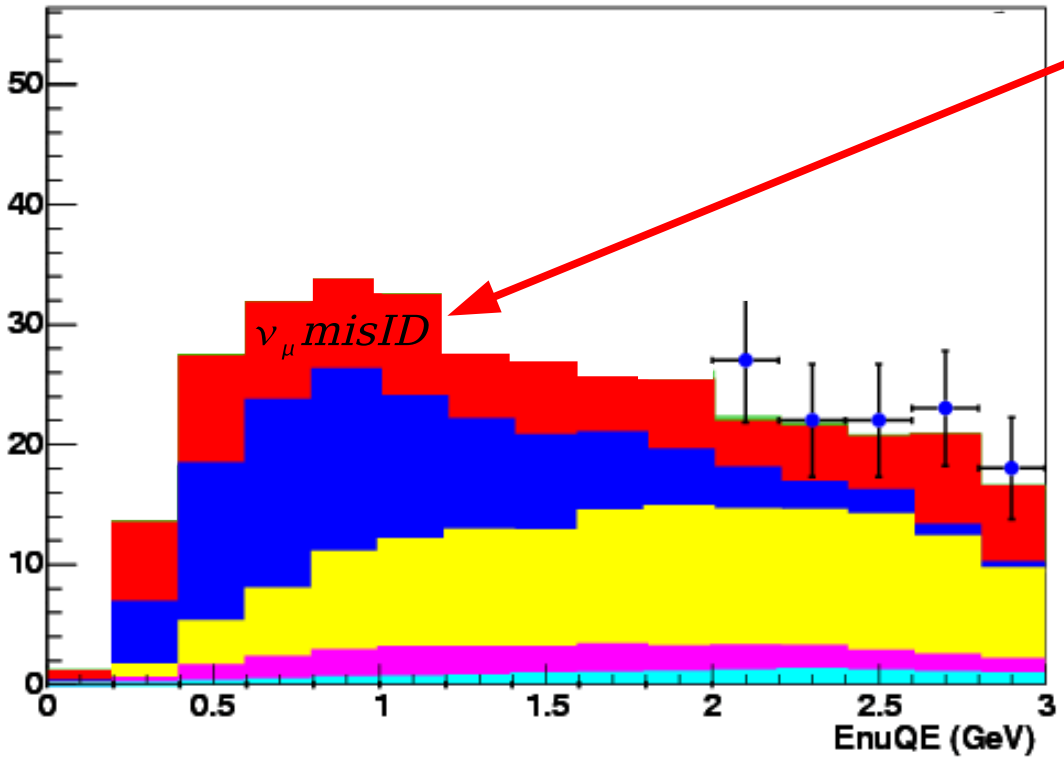
- At MiniBooNE we are looking for an excess of electron neutrinos above expected backgrounds

- Therefore, we want to know the expected fluxes of muon and electron neutrinos at the detector without oscillations

- Any excess would imply that a tiny fraction of the muon neutrinos had **oscillated** into an electron type before reaching the detector

Neutrino oscillations via ν_e appearance at MiniBooNE

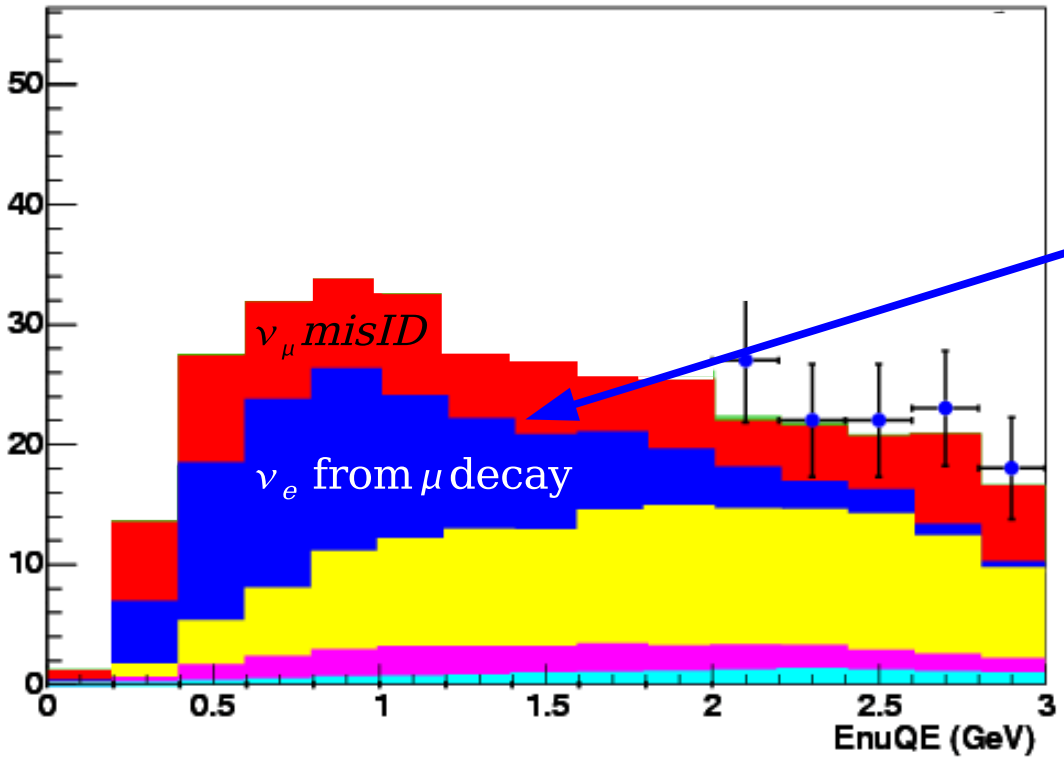
- So we make a prediction of the ν_e event rate at the detector including intrinsics and ν_μ mis-IDs



ν_μ events mis-ID'd as electron neutrinos mostly π^0 events

Neutrino oscillations via ν_e appearance at MiniBooNE

- So we make a prediction of the ν_e event rate at the detector including intrinsics and ν_μ mis-IDs



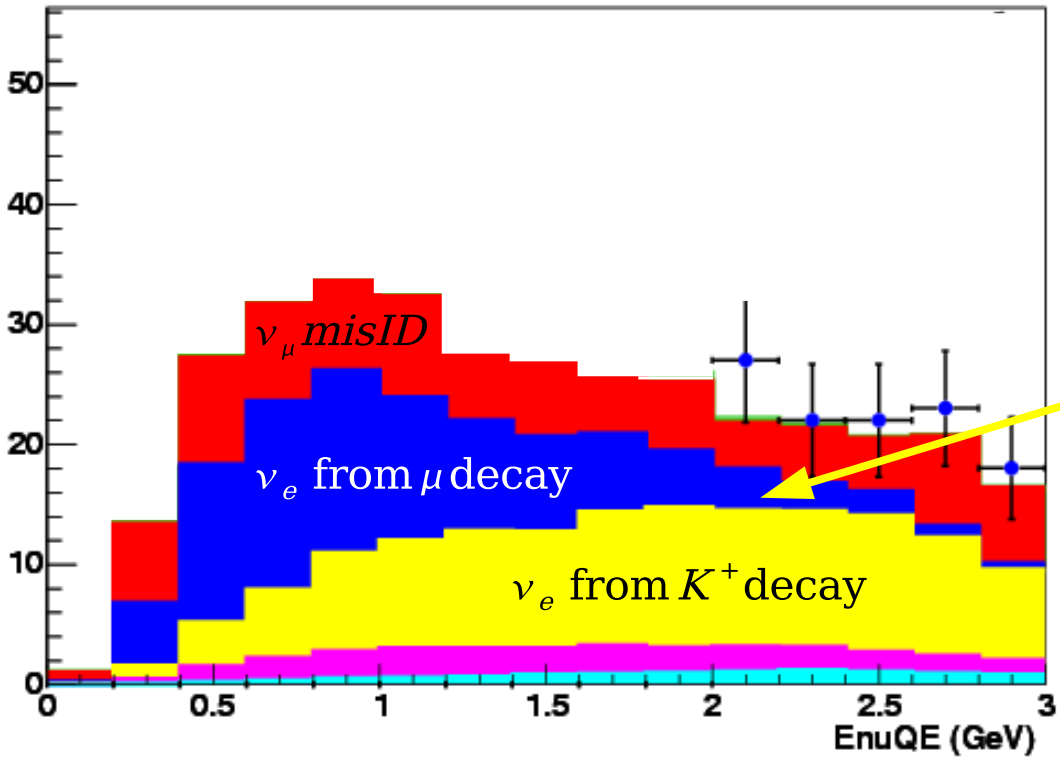
ν_μ events mis-ID'd as electron neutrinos mostly π^0 events

ν_e from μ decays

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \overline{\nu_\mu}$$

Neutrino oscillations via ν_e appearance at MiniBooNE

- So we make a prediction of the ν_e event rate at the detector including intrinsics and ν_μ mis-IDs



ν_μ events mis-ID'd as electron neutrinos mostly π^0 events

ν_e from μ decays

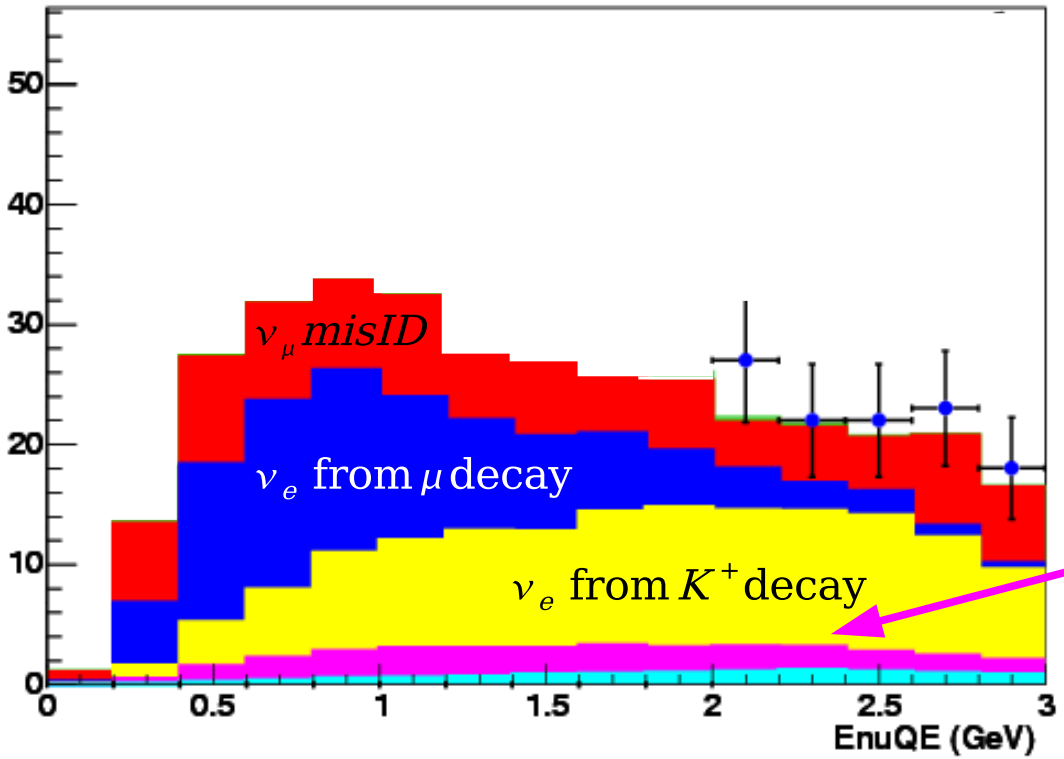
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \overline{\nu_\mu}$$

ν_e from K^+ decays

$$K^+ \rightarrow \pi^0 + e^+ + \nu_e$$

Neutrino oscillations via ν_e appearance at MiniBooNE

- So we make a prediction of the ν_e event rate at the detector including intrinsics and ν_μ mis-IDs



ν_μ events mis-ID'd as electron neutrinos mostly π^0 events

ν_e from μ decays

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \overline{\nu_\mu}$$

ν_e from K^+ decays

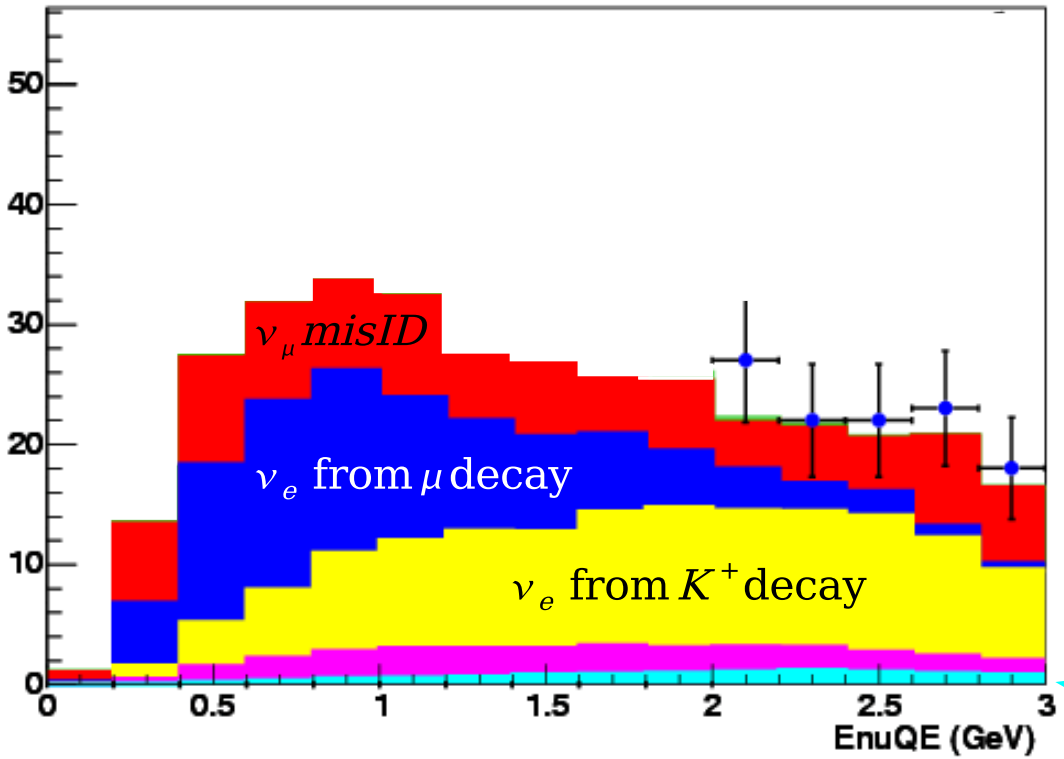
$$K^+ \rightarrow \pi^0 + e^+ + \nu_e$$

ν_e from K^0 decays

$$K^0 \rightarrow \pi^\pm + e^\mp + \overline{\nu_e}$$

Neutrino oscillations via ν_e appearance at MiniBooNE

- So we make a prediction of the ν_e event rate at the detector including intrinsics and ν_μ mis-IDs



ν_μ events mis-ID'd as electron neutrinos mostly π^0 events

ν_e from μ decays

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \overline{\nu_\mu}$$

ν_e from K^+ decays

$$K^+ \rightarrow \pi^0 + e^+ + \nu_e$$

ν_e from K^0 decays

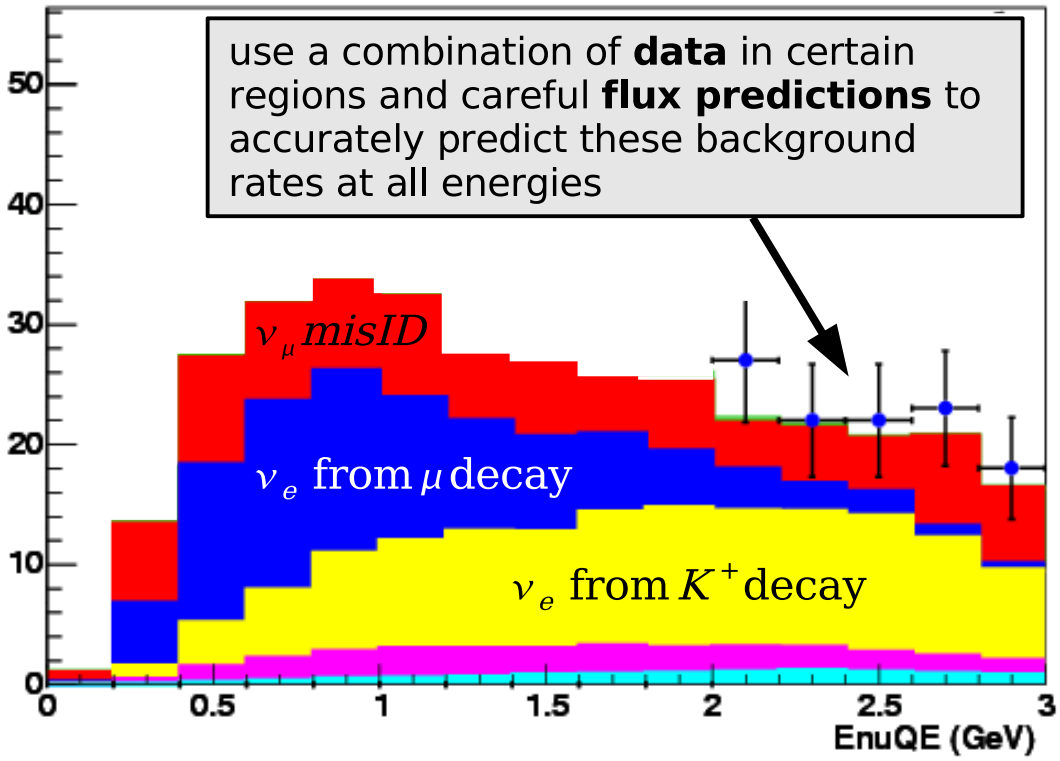
$$K^0 \rightarrow \pi^\pm + e^\mp + \overline{\nu_e}$$

ν_e from π^+ decays

$$\pi^+ \rightarrow e^+ + \nu_e$$

Neutrino oscillations via ν_e appearance at MiniBooNE

- So we make a prediction of the ν_e event rate at the detector including intrinsics and ν_μ mis-IDs



ν_μ events mis-ID'd as electron neutrinos mostly π^0 events

ν_e from μ decays

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \overline{\nu_\mu}$$

ν_e from K^+ decays

$$K^+ \rightarrow \pi^0 + e^+ + \nu_e$$

ν_e from K^0 decays

$$K^0 \rightarrow \pi^\pm + e^\mp + \overline{\nu_e}$$

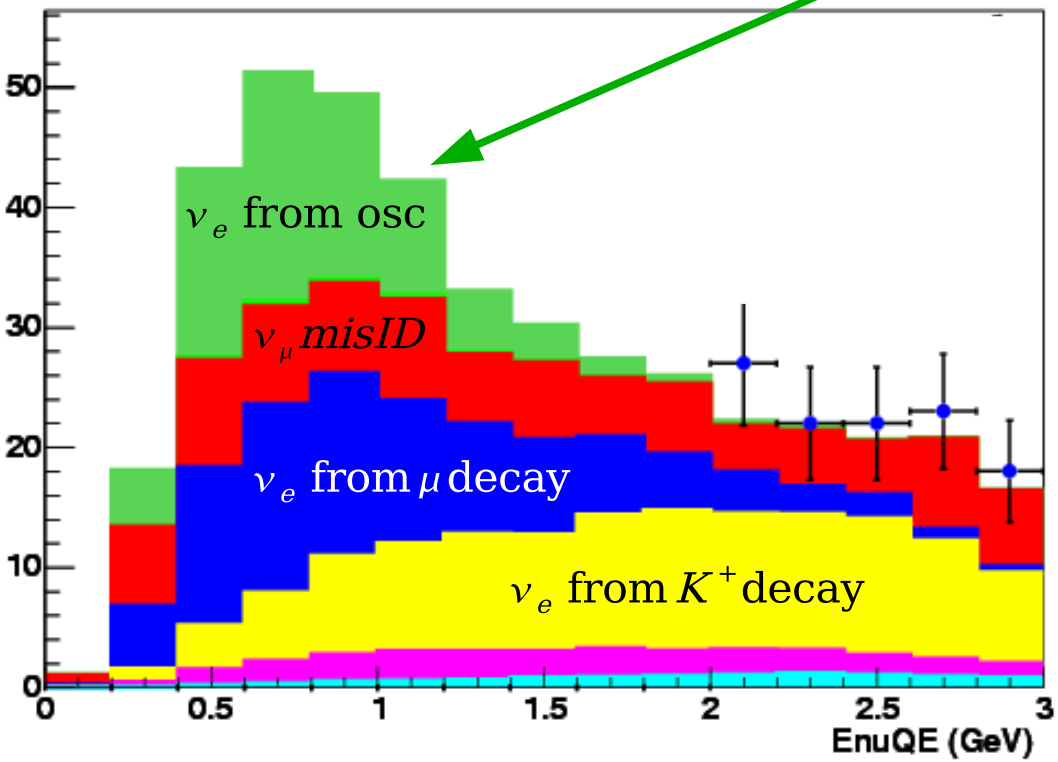
ν_e from π^+ decays

$$\pi^+ \rightarrow e^+ + \nu_e$$

INTRINSIC ν_e

Neutrino oscillations via ν_e appearance at MiniBooNE

- So we make a prediction of the ν_e event rate at the detector including intrinsics and ν_μ mis-IDs... AND...



look for an excess of events implying oscillations!!

ν_μ events mis-ID'd as electron neutrinos mostly π^0 events

ν_e from μ decays

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \overline{\nu_\mu}$$

ν_e from K^+ decays

$$K^+ \rightarrow \pi^0 + e^+ + \nu_e$$

ν_e from K^0 decays

$$K^0 \rightarrow \pi^\pm + e^\mp + \overline{\nu_e}$$

ν_e from π^+ decays

$$\pi^+ \rightarrow e^+ + \nu_e$$

summary

- **NEUTRINO PHYSICS**
  - despite tremendous progress, there remain fascinating and difficult questions within neutrino physics
  - while I haven't had the time today to motivate these interesting questions, I have instead given some idea of how we seek to answer them experimentally

- **HARP**
  - π^+ cross-section paper is in draft form and should be ready for publication this summer
  - thick target data is available and ready for analysis – monte carlo is in production
  - K^+ analysis tools and techniques are being developed – hopeful for preliminary results this summer

- **MINIBOONE**
  - have incorporated first HARP results into MiniBooNE beam simulations (currently processing)
  - full HARP-based booster neutrino beam fluxes coming soon
  - on the road to exciting cross-section and oscillation measurements**. . .**

BACKUPS

ν_μ event rate normalization

- The MiniBooNE Run Plan reported we were seeing ~1.5 times as many events as the Monte Carlo predicted
  - For an inclusive ν event sample
- This normalization difference is now ~1.2
- Major changes in rate prediction since Run Plan (not complete list)

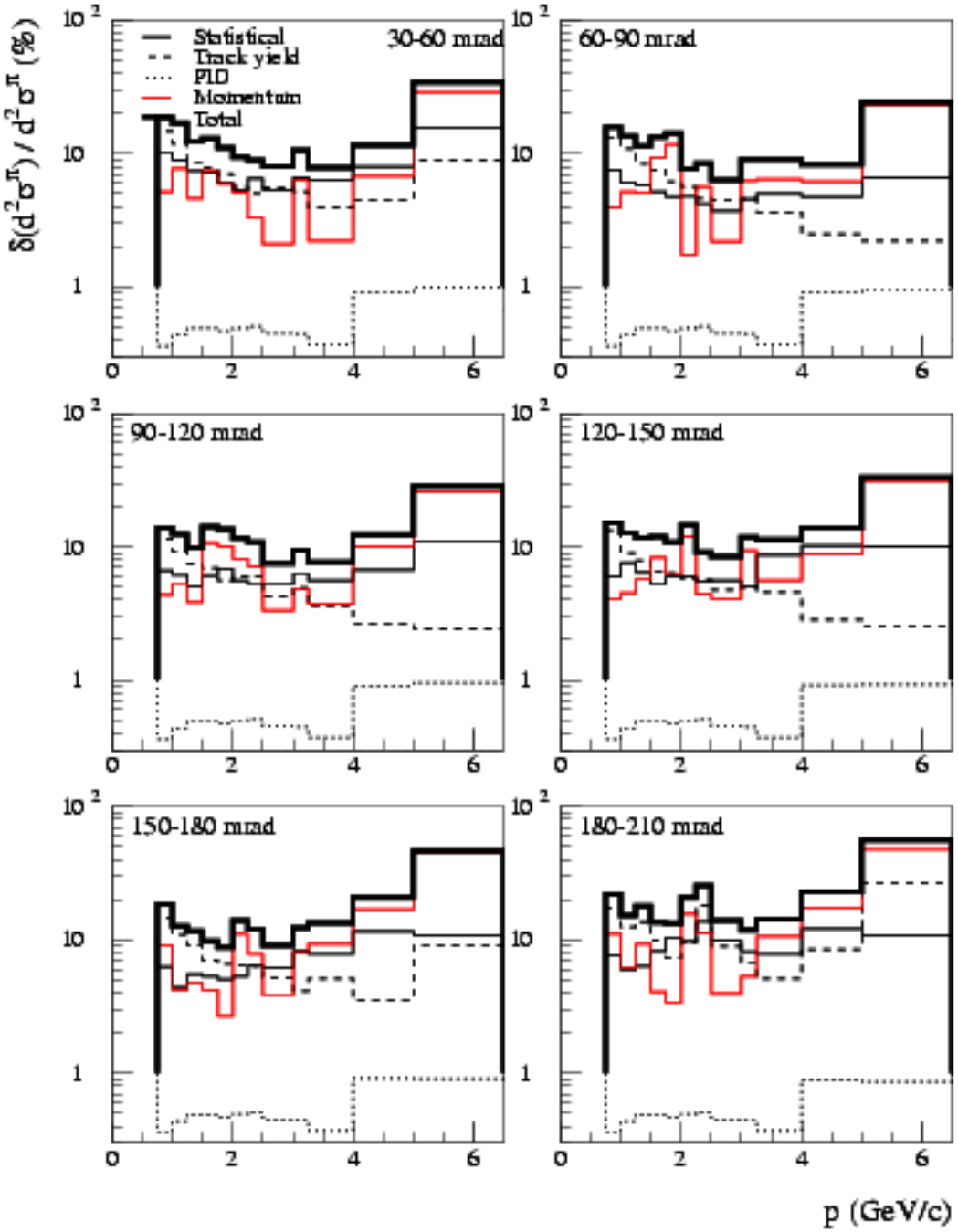
-3.5%	from better ν cross-section modeling
+17.5%	from better modeling of incoming proton beam
+5.2%	from CCQE cross-section tuning (M_A extraction)
-6.0%	from better modeling of secondary beam interactions
+16.2%	from HARP π^+ measurement + horn current + better modeling of primary proton interactions

- After a huge amount of cross-checking the agreement between data and MC ν rates is now far less of an issue

systematic error contributions

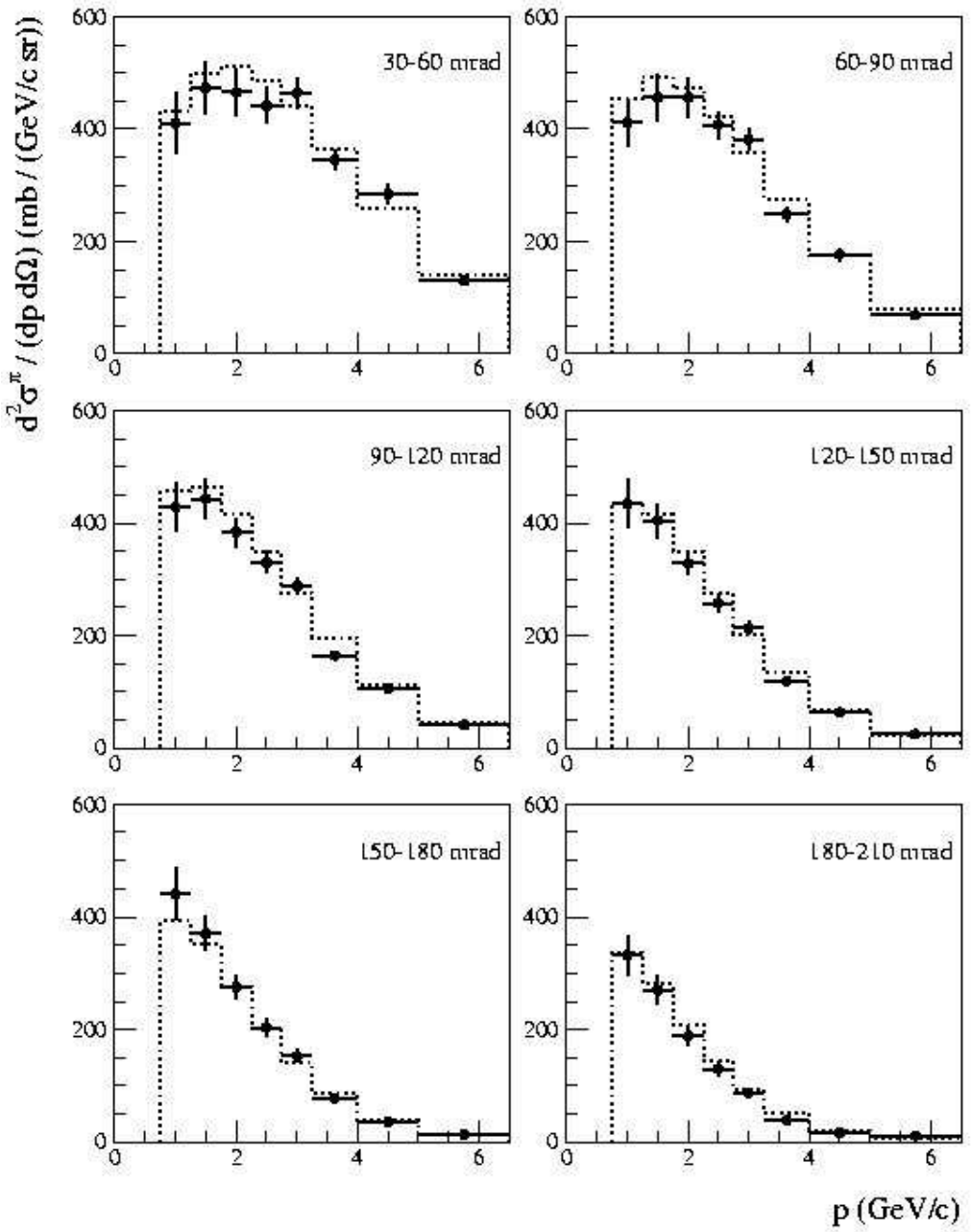
Error Category	Error Source	$\delta^{\pi^-}_{diff}$ (%)	$\delta^{\pi^+}_{int}$ (%)
Statistical	Be target statistics	4.1	0.6
	Empty target subtraction (stat.)	4.6	0.6
	Sub-total	**6.2**	**0.8**
Track yield corrections	Reconstruction efficiency	1.8	1.0
	Pion, proton absorption (syst.)	2.4	2.6
	Pion, proton absorption (MC stat.)	0.9	0.2
	Tertiary subtraction (syst.)	6.9	6.5
	Tertiary subtraction (MC stat.)	0.5	0.1
	Empty target subtraction (syst.)	1.3	1.2
	Sub-total	**8.0**	**7.2**
Particle Identification	Electron veto	0.2	<0.1
	Pion, proton ID correction	0.4	0.1
	Sub-total	**0.5**	**0.1**
Momentum reconstruction	Momentum scale	3.8	0.1
	Momentum resolution (syst.)	3.9	2.0
	Momentum resolution (MC stat.)	1.5	0.1
	Sub-total	**6.2**	**2.0**
Overall normalization	**Sub-total**	**4.0**	**4.0**
All	**Total**	**13.0**	**8.5**

systematic error contributions



HARP Results

Inclusive, double-differential π^+ production cross-section in the interactions of 12.9 GeV/c protons in a 5% λ Al target



Data points: HARP results

Dotted histogram: best-fit parametrization

Experimental Uncertainties

Thorough systematics error evaluation performed, to quantify errors on both:

- Double-differential cross-section: $d^2\sigma^\pi/(dpd\Omega)\ (p,\theta)$. Typical error: 8.2%
- Total cross-section: $\sigma^\pi(0.75<p<6.5\ \text{GeV/c}, 30<\theta<210\ \text{mrad})$. Error: 5.8%

Error Category	Error Source	δ_{diff} (%)	δ_{int} (%)
Statistical	Al target statistics	1.6	0.3
	Empty target subtraction (stat.)	1.3	0.2
	Sub-total	**2.1**	**0.4**
Track yield corrections	Reconstruction efficiency	0.8	0.4
	Pion, proton absorption	2.4	2.6
	Tertiary subtraction	3.2	2.9
	Empty target subtraction (syst.)	1.2	1.1
	Sub-total	**4.5**	**4.1**
Particle identification	PID Probability cut	0.2	0.2
	Kaon subtraction	0.3	0.1
	Electron veto	2.1	0.5
	Pion, proton ID correction	2.5	0.4
	Sub-total	**3.5**	**0.7**
Momentum reconstruction	Momentum scale	3.0	0.3
	Momentum resolution	0.6	0.6
	Sub-total	**3.2**	**0.7**
Overall normalization	**Sub-total**	**4.0**	**4.0**
All	**Total**	**8.2**	**5.8**

Dominant errors: overall normalization, momentum scale, secondary interactions

Parametrization of HARP Data

- HARP data on inclusive pion production fitted to Sanford-Wang parametrization:

$$\frac{d^2\sigma(p+A\rightarrow\pi^+ +X)}{dpd\Omega}(p,\theta)=c_1 p^{c_2}(1-\frac{p}{p_{beam}})\exp[-c_3\frac{p^{c_4}}{p_{beam}^{c_5}}-c_6\theta(p-c_7 p_{beam}\cos^{c_8}\theta)]$$

where:

X: any other final state particle

p_{beam}= proton beam momentum (GeV/c)

p, θ: π^+ momentum(GeV/c), angle(rad)

$d^2\sigma/(dpd\Omega)$ units: $mb/(GeV/csr)$, where $d\Omega\equiv 2\pi\, d(\cos\theta)$

$c_1,\ldots,c_8$: emprical fit parameters

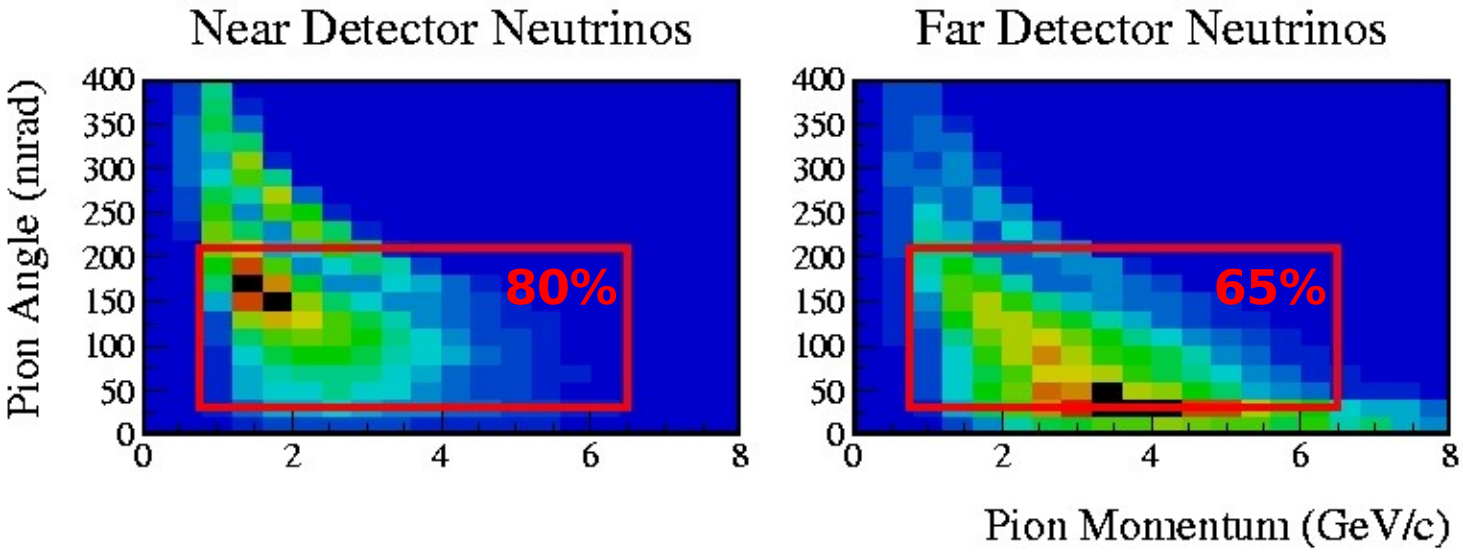
Sanford-Wang parametrization used to:

- Use HARP data in beam MC
- Translate HARP pion production uncertainties into flux uncertainties
- Compare HARP results with previous results in similar beam momentum, pion phase space range

Relevance of HARP for K2K

- Neutrino flux at far detector is obtained from near detector measurement, times far/near neutrino flux ratio obtained from the beam MC simulation
  - »F/N ratio is dominant systematic error in spectrum distortion analysis
- $\pi^+ \to \mu^+ \nu_\mu$ decays are responsible for ~97% of all the K2K neutrino flux
- HARP pion production result covers: $0.75 < p_\pi < 6.5 \ \ GeV/c, \ \ 30 < \theta_\pi < 210 \ \ mrad$

Good coverage of phase space of relevance to K2K



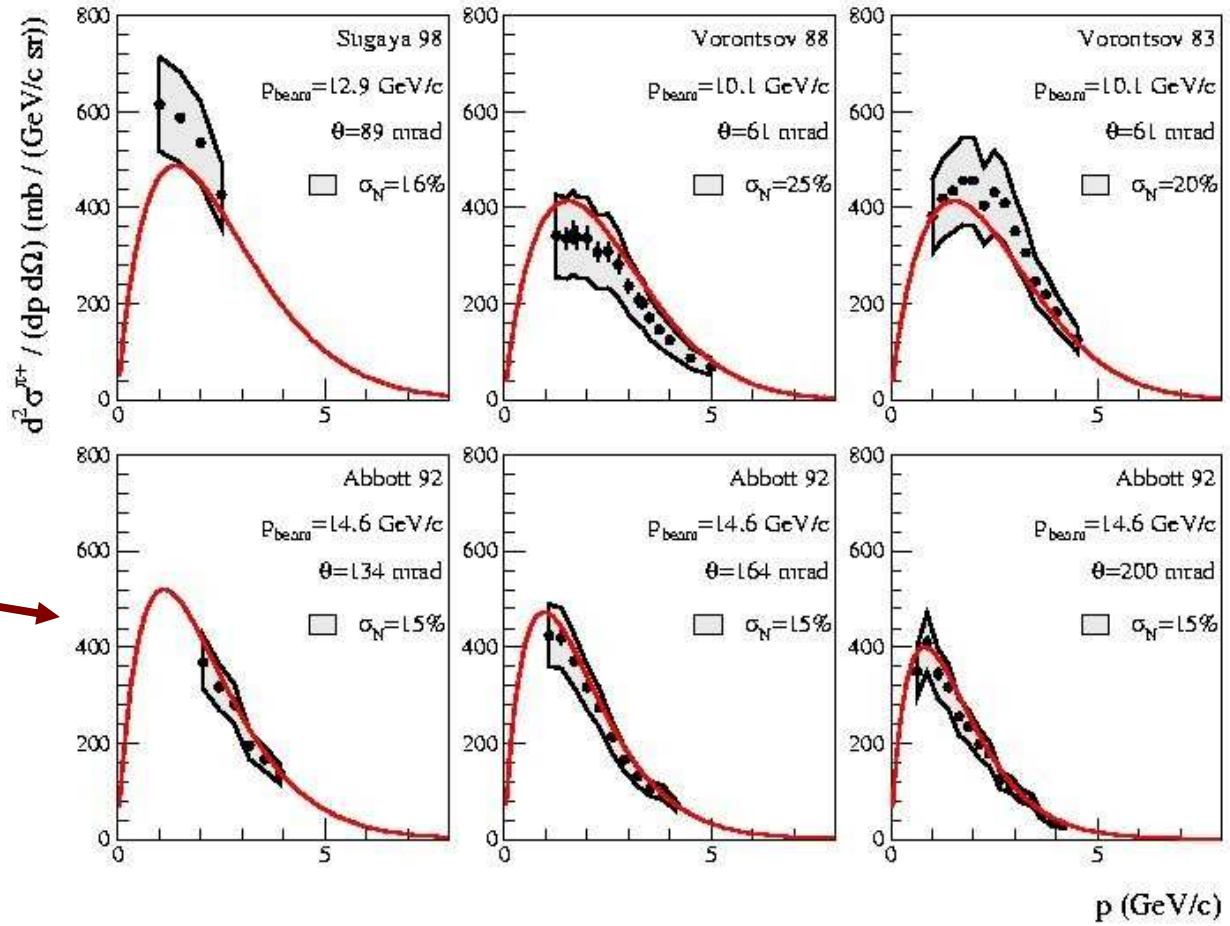
Compare HARP with previous data

- Reasonable agreement between HARP and previous results on $p + Al \rightarrow \pi^+ + X$

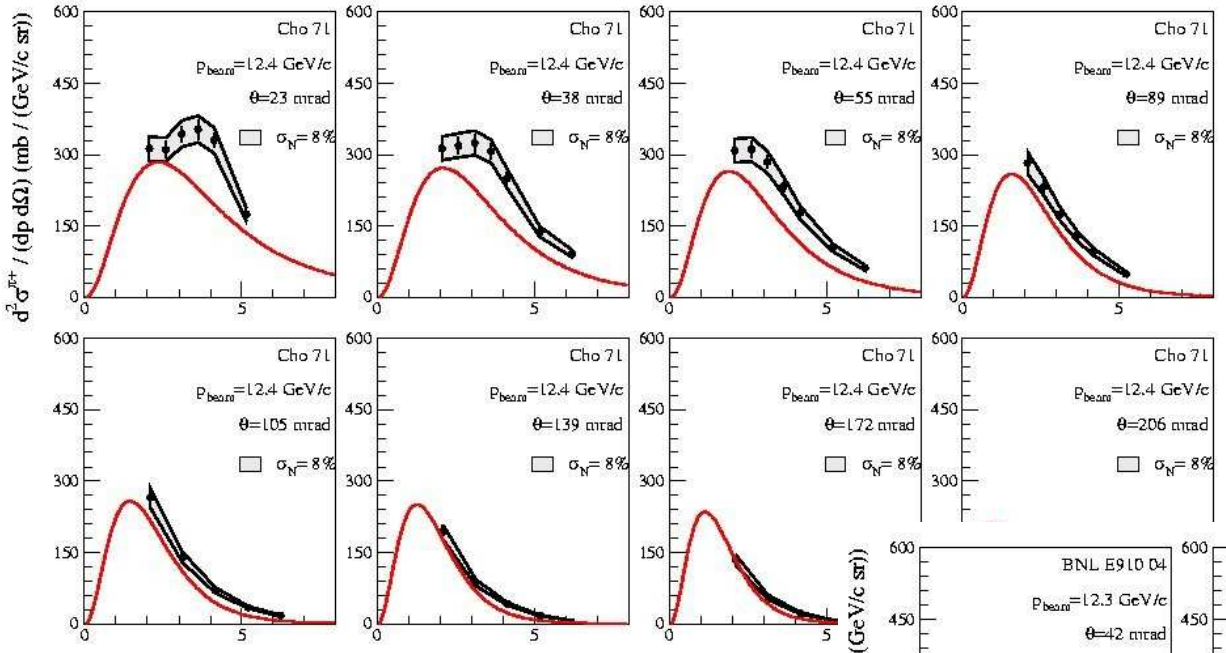
Restrict comparison to:

- Proton beam momentum between 10 and 15 GeV/c,
- Forward pion production (<200 mrad).

Red curve: HARP S-W parametrization

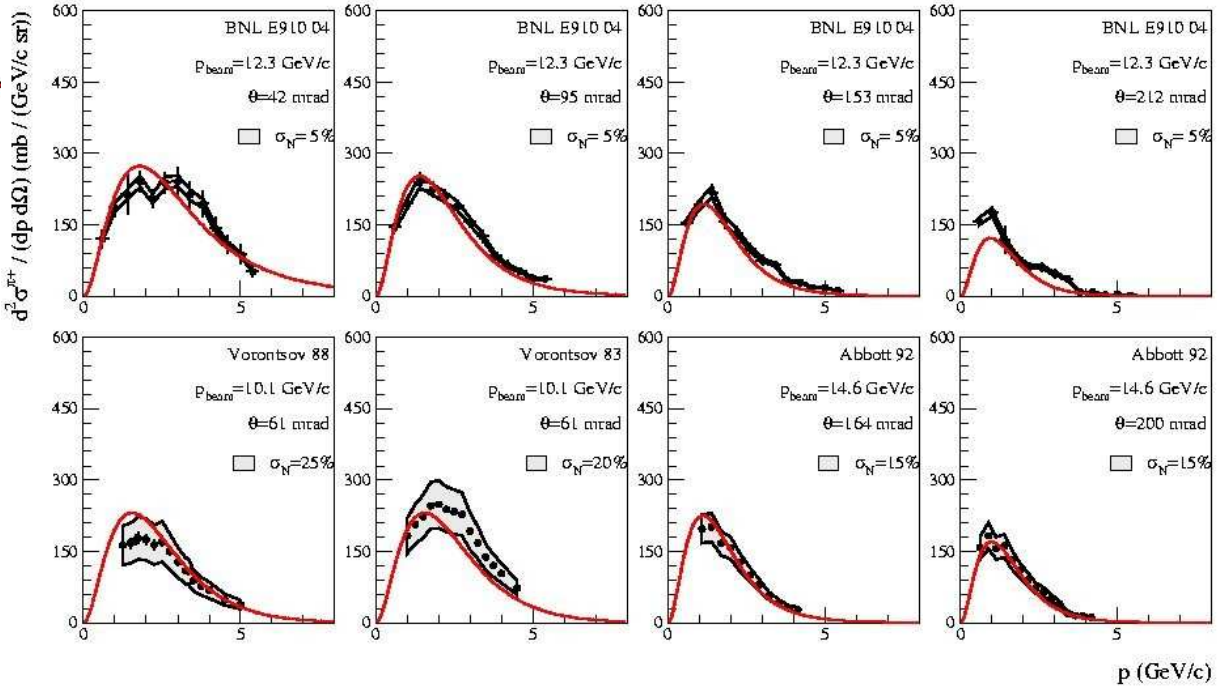


Compare HARP with previous data



$$p + Be \rightarrow \pi^{+} + X$$

Red curve: HARP S-W parametrization



Restrict comparison to:

- Proton beam momentum of ~10 GeV/c
- Forward pion production (<200 mrad).

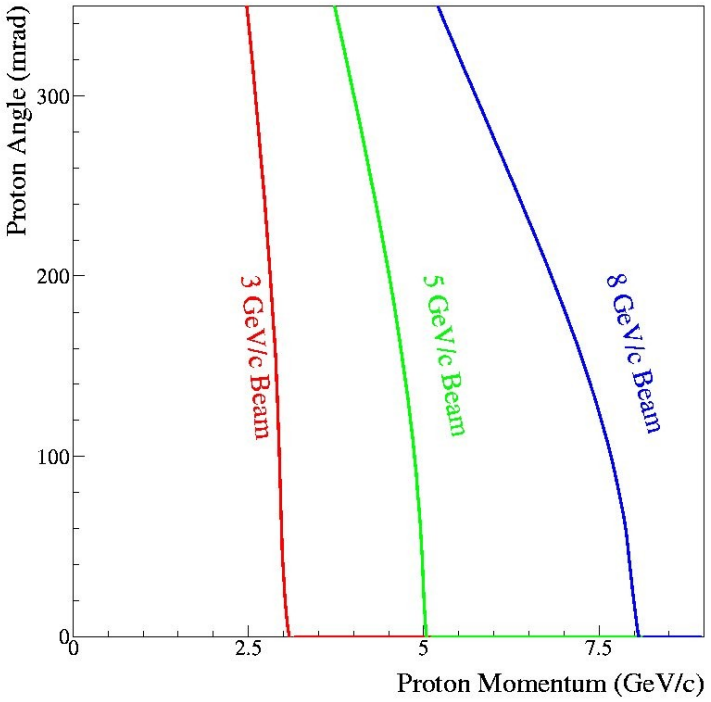
Correction Factors

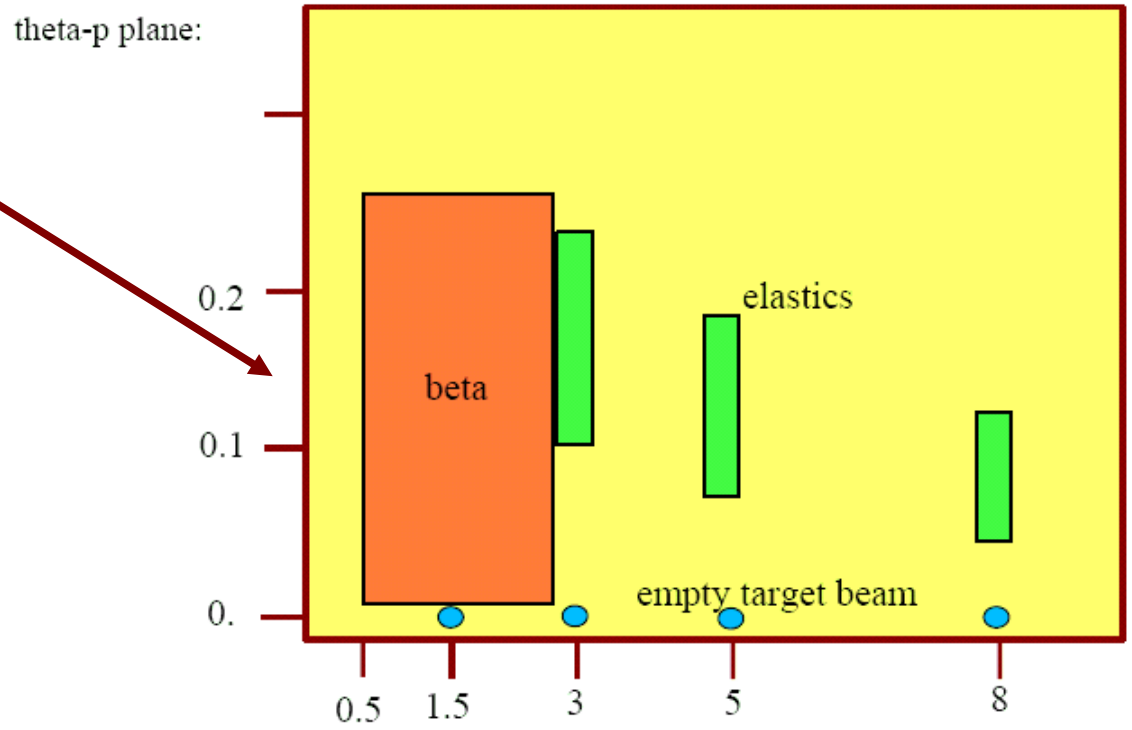
- A number of corrections are needed to convert the reconstructed pion yields

Correction Type	Effect on Cross-Section	Obtained With
Momentum resolution	Affects shape	MC
Track Reconstruction Efficiency	~10% up	Data
Geometrical Acceptance Correction	~100-160% up	Analytical
Pion ID : Efficiency	<5% up	Data
Pion-to-proton migration	<5% down	Data
Absorption/decay of secondaries	10-30% up	MC
Tertiary production	<5% down	MC
Electron-veto efficiency	<2% up	Data
Kaon subtraction	1-3% down	Data/MC
Empty target subtraction	~20% down	Data

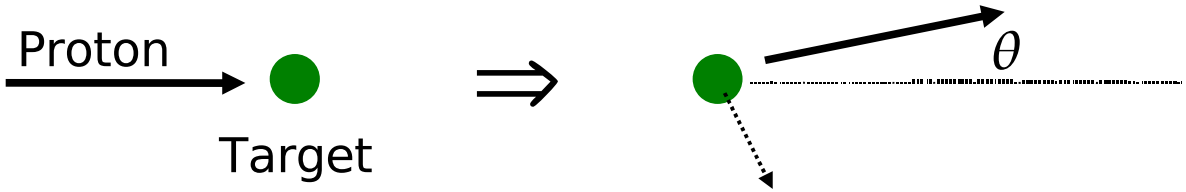
Measuring Momentum Resolution

- Three methods used





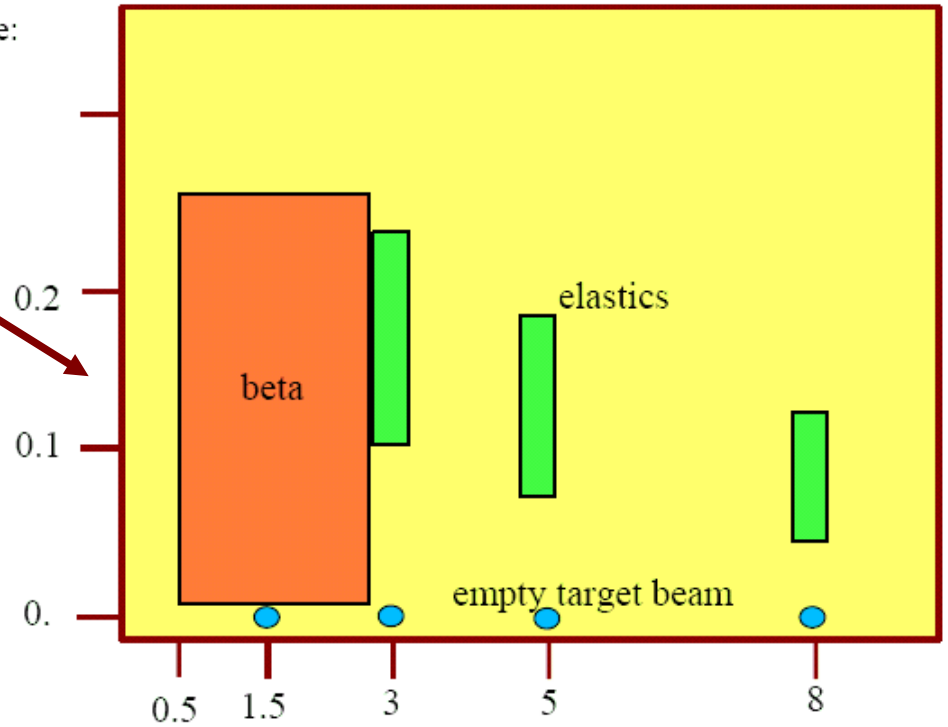
- Elastics method: infer momentum from measured proton scattering angle

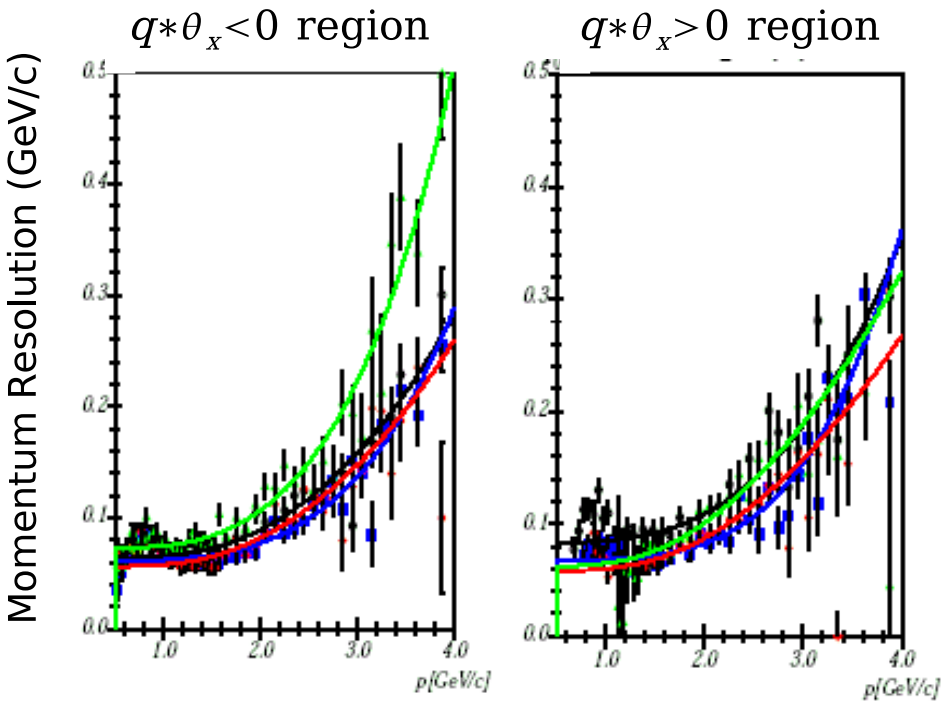


- Probe different (momentum,angle) regions with different beam momentum settings

Measuring Momentum Resolution

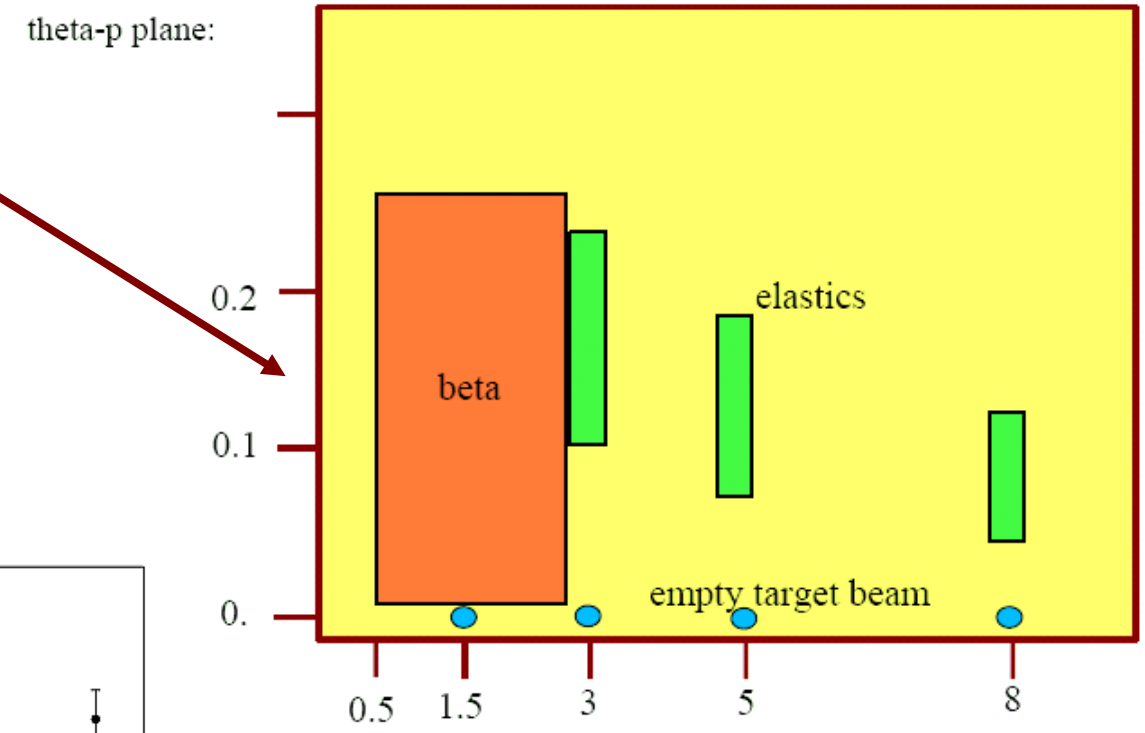
- Three methods used

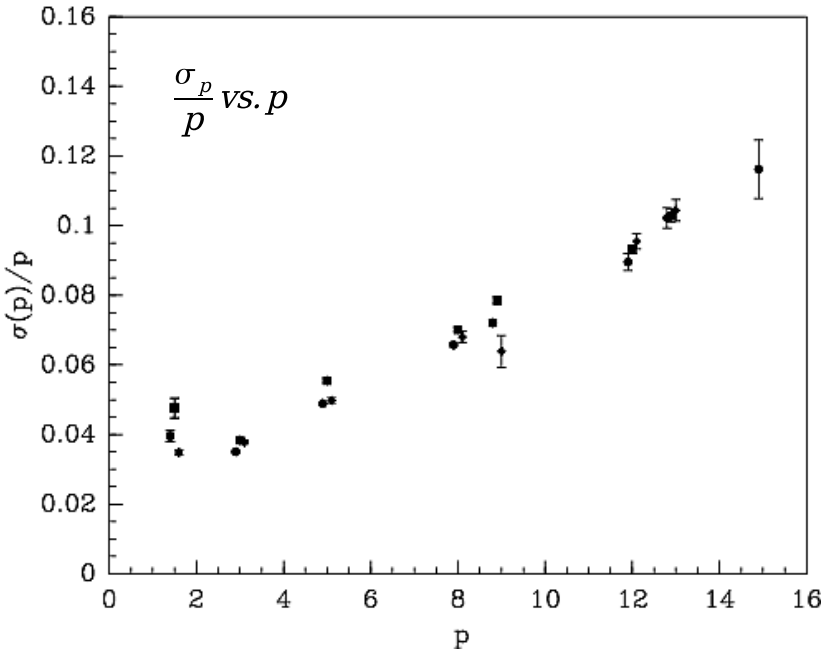




Measuring Momentum Resolution

- Three methods used

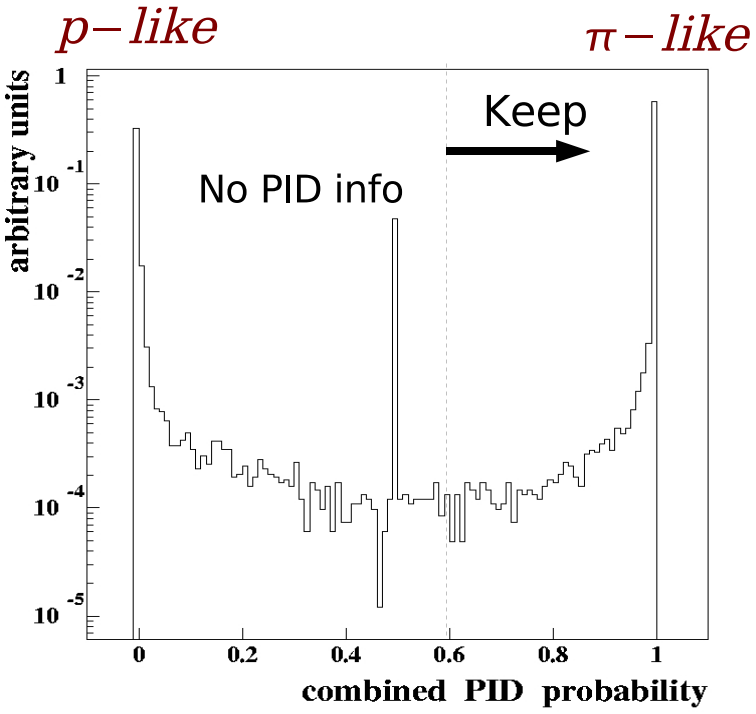




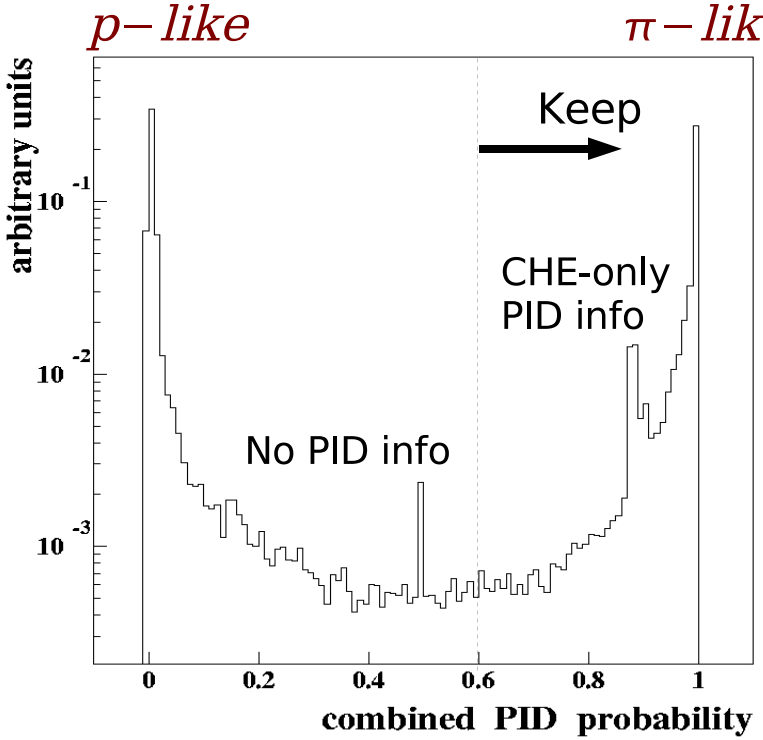
Pion Identification

- Apply electron-veto cut and subtract kaon contribution
- Reconstruct both pion and proton yields, combining measured TOFW and CHE response information, via Bayes theorem
- Optimal PID probability cut: $P_{PID} > 0.6\ for\ pions,\ \ P_{PID} < 0.4\ for\ protons$

Below Cerenkov Threshold

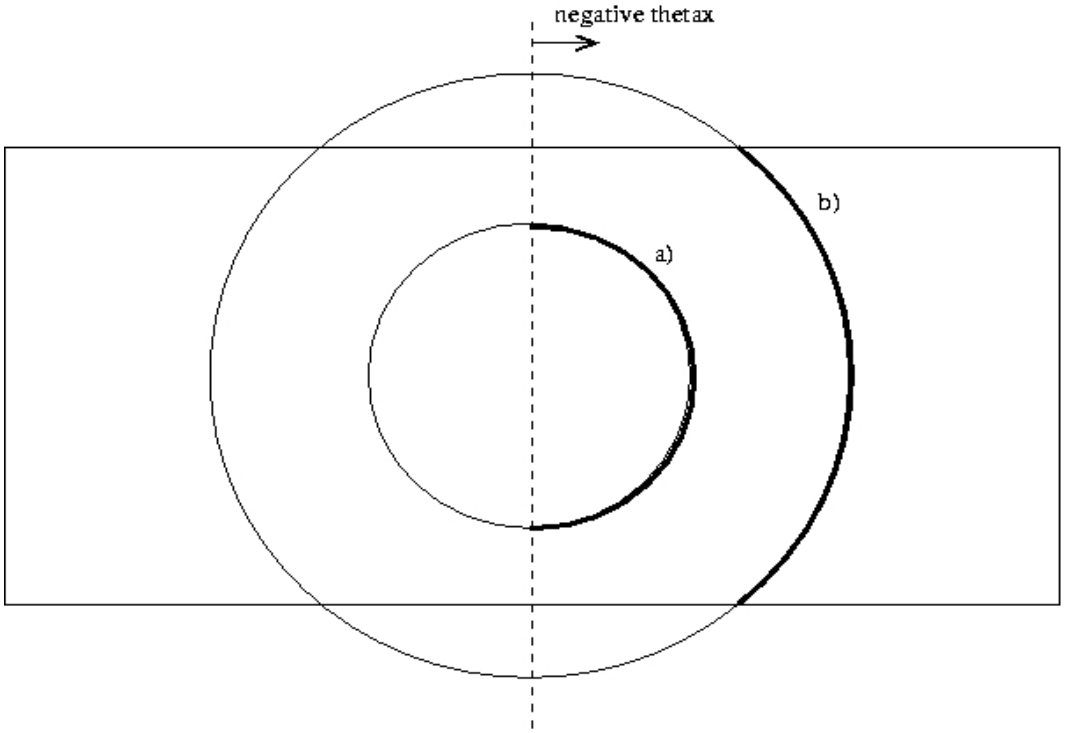


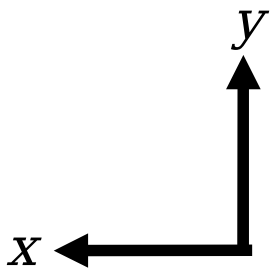
Above Cerenkov Threshold



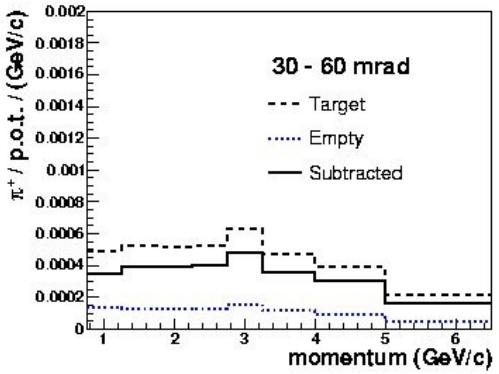
Geometrical Acceptance

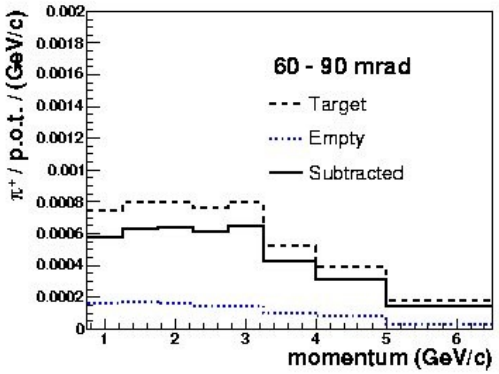
- Geometrical acceptance $\alpha(\theta)$ is corrected for analytically
- Depending on the value of θ_y, two cases are possible:
  - Case a): $|\theta_y| < \theta_y^{cut} = 80\,mrad \;\rightarrow\; \alpha(\theta) = 1/2$
  - Case b): $|\theta_y| > \theta_y^{cut} = 80\,mrad \;\rightarrow\; \alpha(\theta) = \frac{1}{\pi}\arcsin\left(\frac{\tan(\theta_y^{cut})}{\tan(\theta)}\right)$

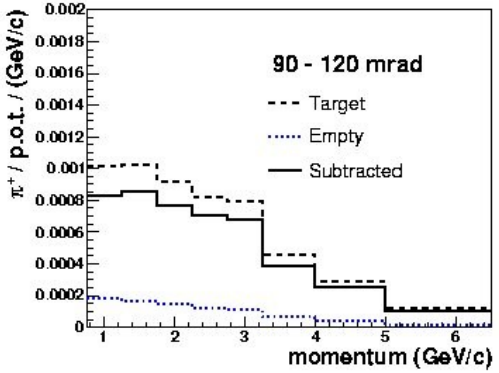


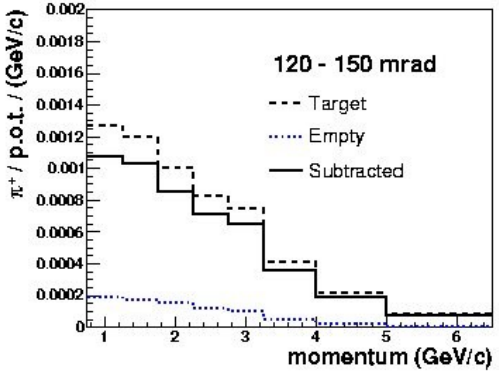


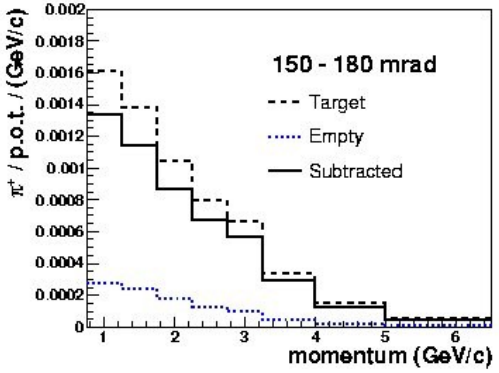
Empty Target Subtraction

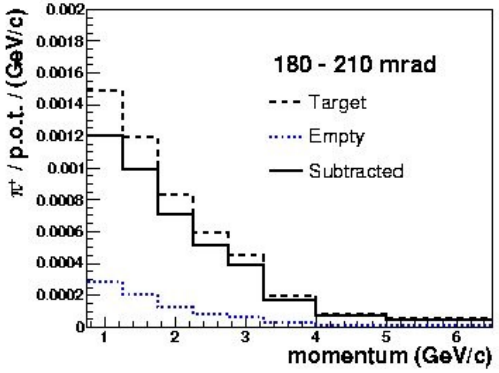












Fermilab is home to two accelerator neutrino beams

neutrinos from the main injector

neutrinos from the booster

and multiple detectors

MINOS

MiniBooNE

SciBooNE