P-954:
Bringing the SciBar Detector to the Booster Neutrino Beam

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Outline

1. Low energy ν cross sections (Wascko)
2. FNAL Booster Neutrino beam
3. SciBar Detector (Nakaya)
4. SciBar Physics results from K2K
5. Current Status of K2K cross section analysis (with a mystery)
6. MiniBooNE cross sections (Wascko)
7. SciBar at BNB detector configuration
8. Physics of SciBar at BNB (Nakaya)
9. SciBar at BNB for MiniBooNE (Wascko)
10. Schedule (Nakaya/Wascko)
11. Construction Plans, Costs (Wascko/Lackowski)

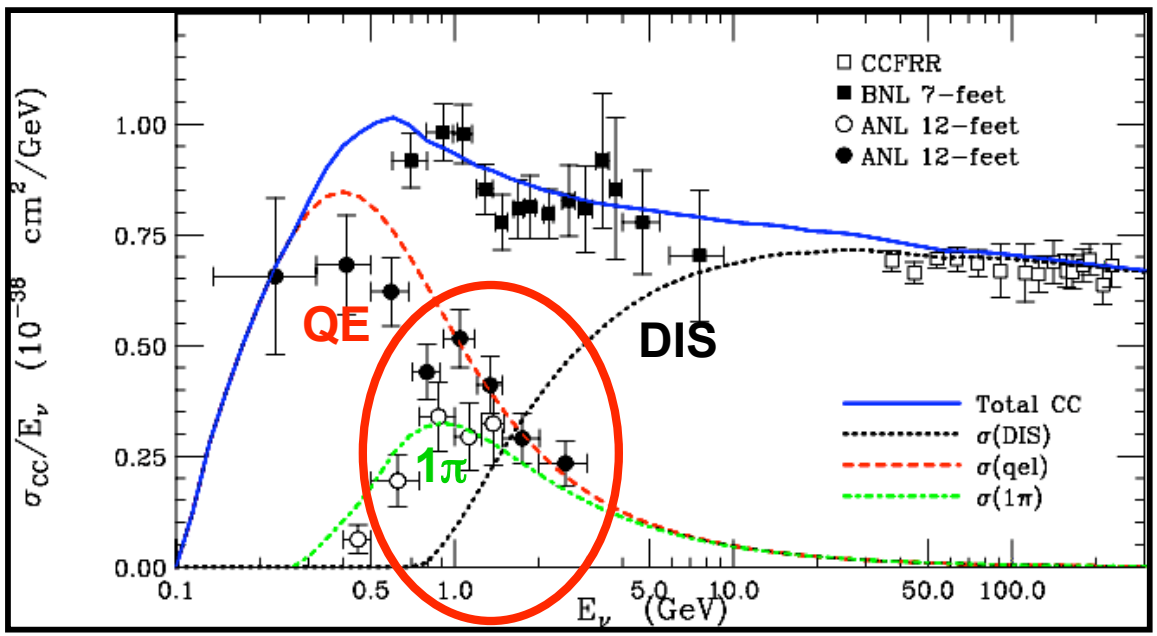
Collaboration Members

• **Barcelona**	F. Sanchez, J. Alcaraz, S. Andringa, X. Espinal, G. Jover, T. Lux, F. Nova, A. Y. Rodriguez
• **Colorado**	M. Wilking
• **Columbia**	K. B. M. Mahn, J. Monroe, G. P. Zeller
• **FNAL**	S. J. Brice, R. Stefanski
• **KEK**	Y. Hayato
• **Kyoto**	T. Nakaya, M. Yokoyama, H. Tanaka, K. Hiraide, Y. Kurimoto, Y. Kurosawa
• **LANL**	R. Van de Water
• **LSU**	M. O. Wascko
• **Rome**	L. Ludovici, U. Dore, P. F. Loverre, C. Mariani
• **Valencia**	J. J. Gomez-Cadenas, A. Cervera, M. Sorel, A. Tornero, J. Catala, P. Novella, E. Couce, J. Martin-Albo

10 institutes, ~40 people

1. Neutrino Physics at ~1 GeV

σ_ν in this E range interesting:



MINOS, NuMI

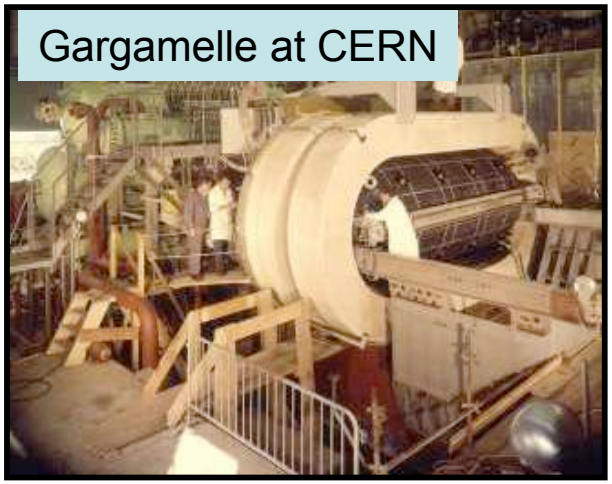
K2K, NOvA

MiniBooNE, T2K

Super-K atmospheric ν

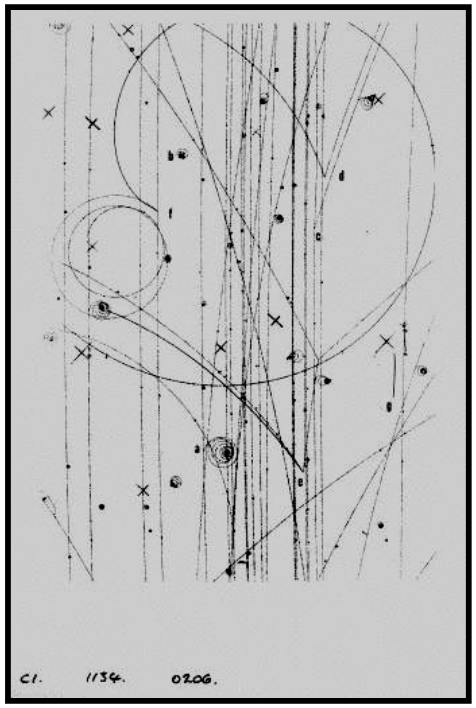
- imperative for future osc exps to precisely predict signal & bkgd rates
  - will be more sensitive to sources of systematic error
- increased interest in more precise σ_ν meas
- interesting nuclear effects expected in this E region (shadowing in the nucleus, low Q^2)
- new data from MiniBooNE & K2K shedding light on this
- More data at 1GeV with fine grained resolution will complete the picture

Previous Measurements



- most of present low energy (~ 1 GeV) ν cross section knowledge comes from bubble chamber experiments

- early experiments at ANL, BNL, FNAL, CERN, Serpukhov, etc.



- considerable errors due to:
  - low statistics
  - uncertainties in ν flux

- in addition to large errors, results often conflicting (some care in interpreting)

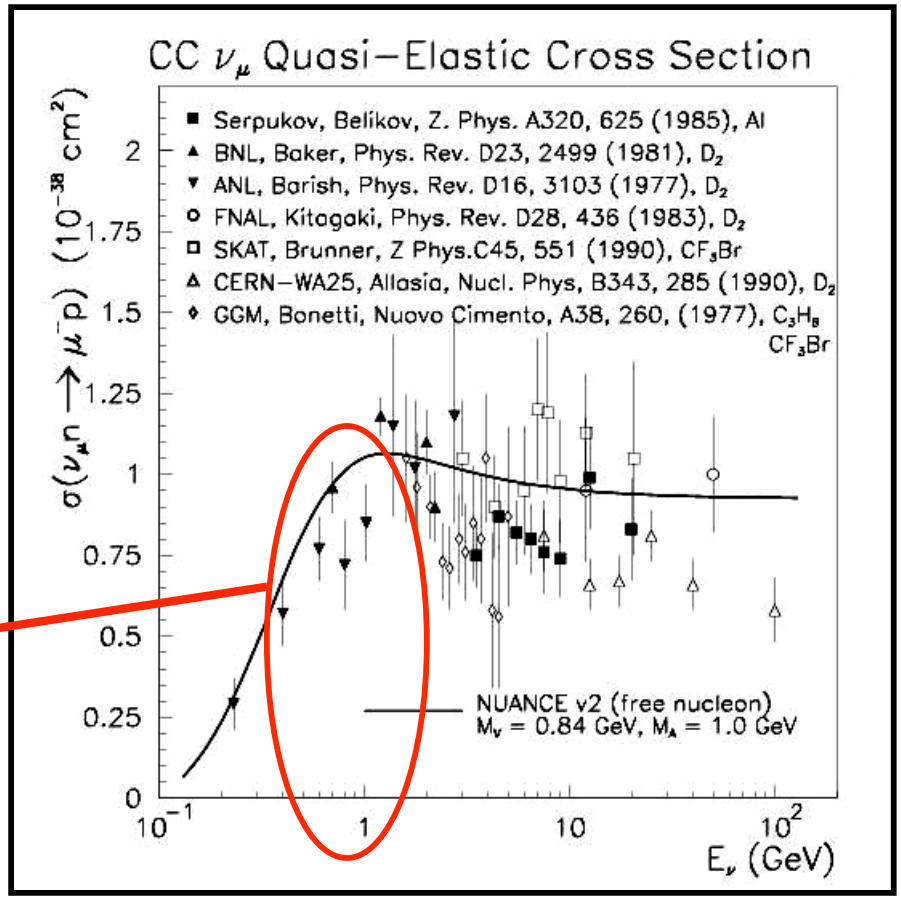
- large uncertainties noted by PDG $\rightarrow \sigma_\nu$ removed after 1996

- these data are used to constrain our MCs; there is certainly room for improvement

Low Energy ν Cross Sections: Quasi-Elastic (QE) Scattering

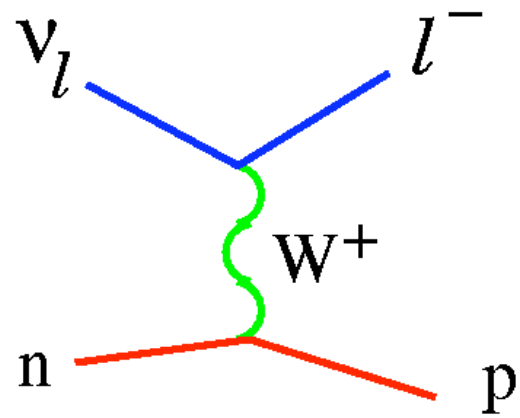
$\nu_\mu n \rightarrow \mu^- p$

- QE cross section measurements from past experiments (15-20%)
- highest statistics **~2500 events**
- data below 1 GeV all on light nuclear targets (D_2)
- **BNB advantage:**
  - * $\langle E_\nu \rangle$ ~ 700 MeV
  - * > order magnitude more stats already!



ν_μ CC Quasi-Elastic Scattering

Why are these events important?

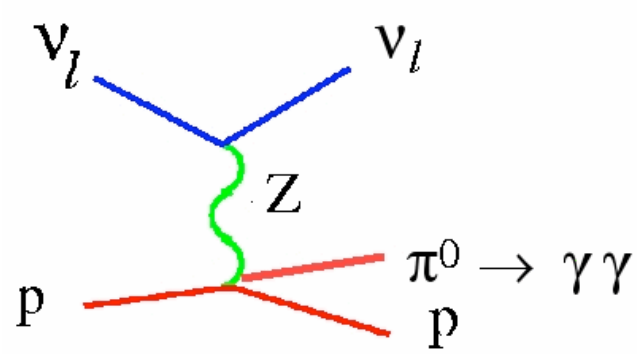


ν_μ n → μ^- p

- ν_μ QE events form signal for ν_μ disappearance
  - search for ν_μ → ν_s oscillations
- ν_μ QE σ necessary to accurately predict signal rates in ν_e appearance oscillation experiments
  - * ν_e QE events with similar kinematics, σ are main signal for ν_μ → ν_e appearance searches

NC π^0 Production

Why are these events important?



ν_μ p $\rightarrow$ ν_μ p π^0
n n

- understanding rate & kinematics of π^0 production important because dominant background to $\nu_\mu \rightarrow \nu_e$ oscillation searches

  * if γ's highly asymmetric in E or small opening angle (overlapping rings) can appear much like primary e^- emerging from a ν_e QE int in Cherenkov calorimeter detectors

  * primary method for estimating NC π^0 background has been thru MC

- can tell us about resonant vs. coherent π^0 production

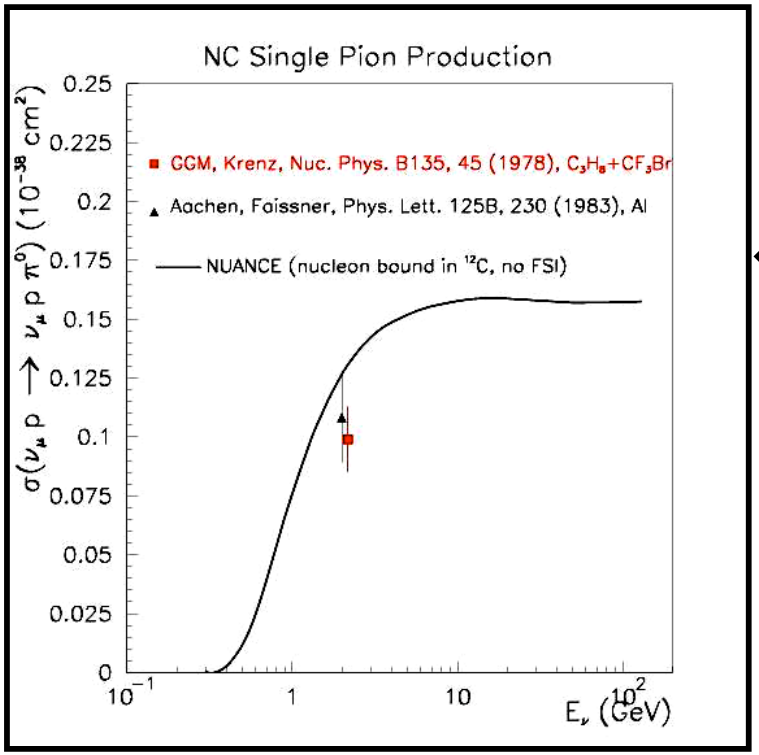
NC π^0 Production

- two mechanisms for NC π^0 production

resonant π^0 production

($\Delta \rightarrow N\ \pi$)

coherent π^0 production



← not many absolute NC π^0 σ_{RES} meas (two data points at $E_\nu \sim 2$ GeV)

- GGM σ from MiniBooNE reanalysis (E.A. Hawker, NuInt02)
- Aachen-Padova σ appearing as footnote in their paper (!)

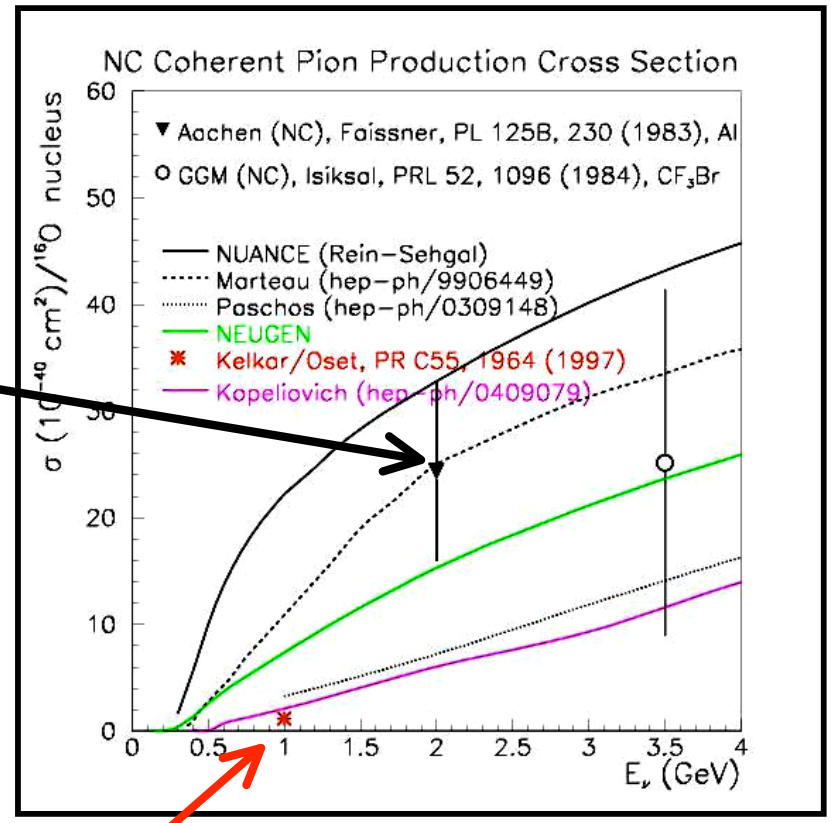
NC π^0 Production

- two mechanisms for NC π^0 production

resonant π^0 production

($\Delta \rightarrow N\ \pi$)

coherent π^0 production



- no coherent π^0 data below 2 GeV

- competing models differ by large factors in their predictions
  - most recent calcs predict 6-10x lower coherent π σ!

BNB

Coherent Pion Production

- coherently scatter off entire nucleus rather than its constituents (nucleus does not break up, quantum numbers are unchanged)

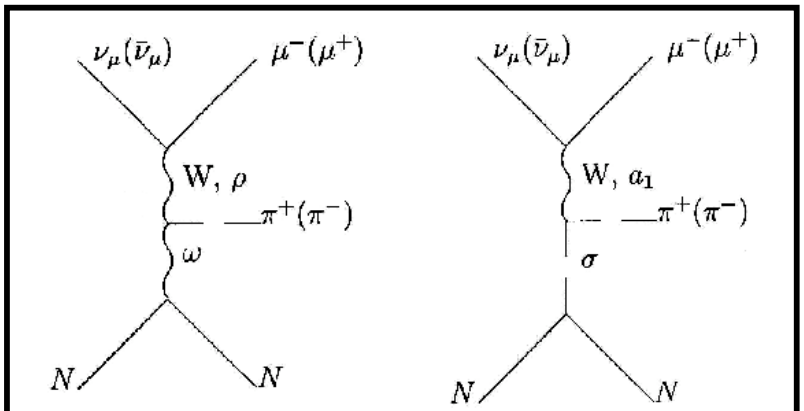
* both NC and CC processes

$$\begin{cases} \nu_\mu A \rightarrow \nu_\mu A \pi^0 & \textbf{(NC)} \\ \nu_\mu A \rightarrow \mu^- A \pi^+ & \textbf{(CC)} \end{cases}$$

* distinct kinematics:

  - negligible E transfer to target (low Q^2)
  - forward scattered π (compared to resonantly prod π's)

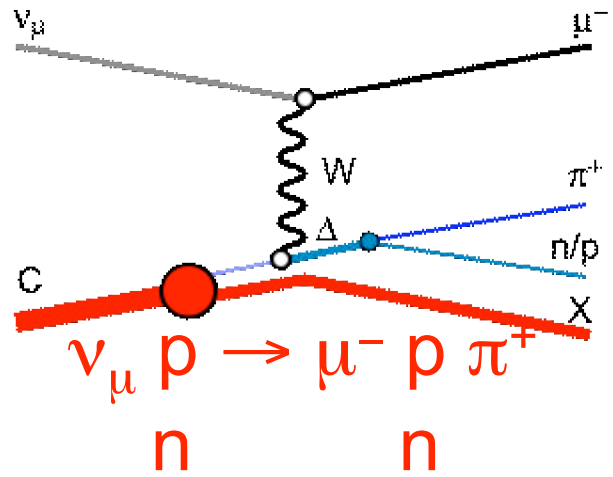
* rate of production not well known at low energy ($E_\nu \sim 1$ GeV)



Paschos & Kartavtsev, hep-ex/0309148

CC1π^+ Production

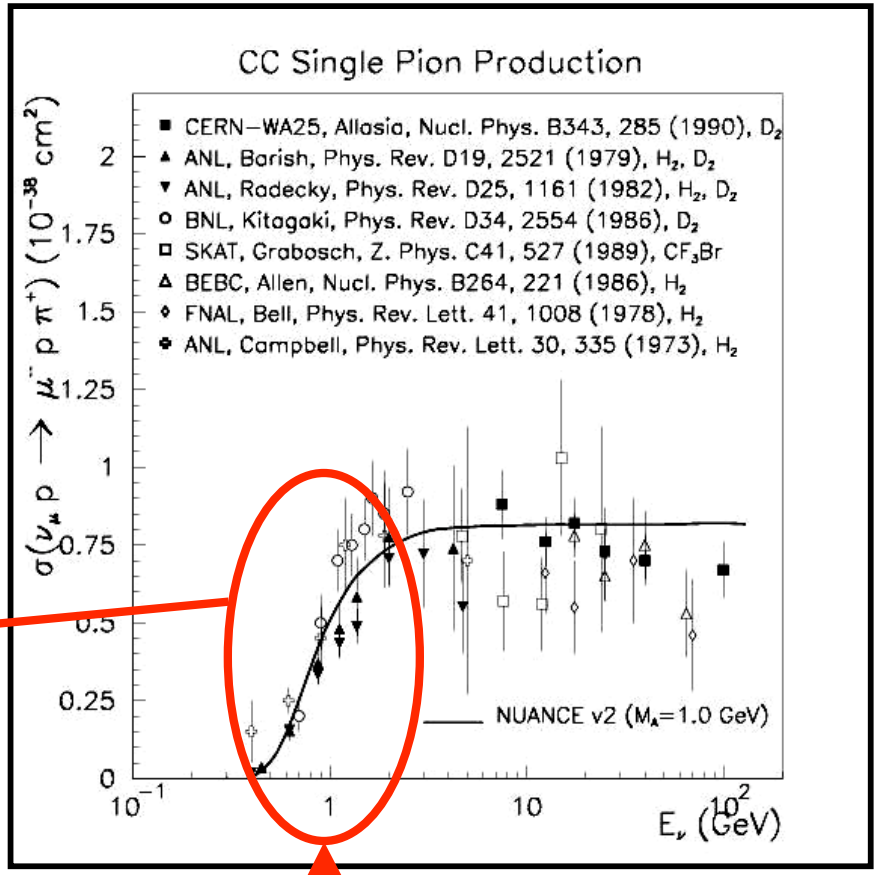
Why are these events important?



- largest background to QE samples (large σ, π^+ can be absorbed in nucleus, degrades energy resolution)
- useful for understanding Δ production in CH_2 ($\Delta \rightarrow N\,\gamma$ poses a background to $\nu_\mu \rightarrow \nu_e$ search)
- useful in understanding event reconstruction
- high statistics CC1π^+ oscillation search?

CC $1\pi^+$ Production

- CC$1\pi^+$ measurements at bubble chamber exps
  - all low E_ν data on light targets (H_2,D_2)
  - combined data of all exps **~7,000 CC$1\pi^+$ events**
    - large differences



- Exclusive final states in bubble chambers:

$\nu_\mu\, p \rightarrow \mu^-\, p\, \pi^+$

$\nu_\mu\, n \rightarrow \mu^-\, n\, \pi^+$

BNB (MB=CH_2, SB=CH)
$\langle E_\nu \rangle$ ~ 700 MeV

Where We've Been & Where We're Headed

Past Measurements
(bubble chamber exps)

Low E_ν

- low statistics
- 1st σ_ν measurements
- 70's, 80's

DIS
(larger, denser targets)

High E_ν

- high statistics
-probe nucleon structure
- 80's, 90's

Present Day
ν Oscillation Exps

Low E_ν

- more intense ν beams
- new ν data
(higher stats, quality than existing data)
- revisit σ_ν measurements
MiniBooNE, K2K

Future Dedicated
σ_ν Experiments

Low E_ν

- fine-grained detectors
- MINERvA
- **SciBooNE**

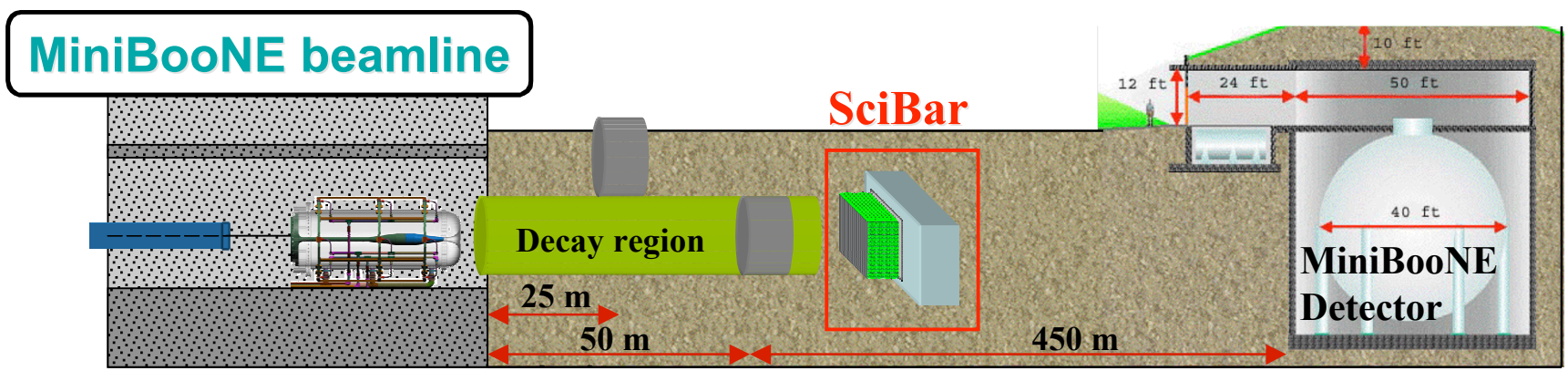
~2010:
Off-Axis Oscillations

Low E_ν

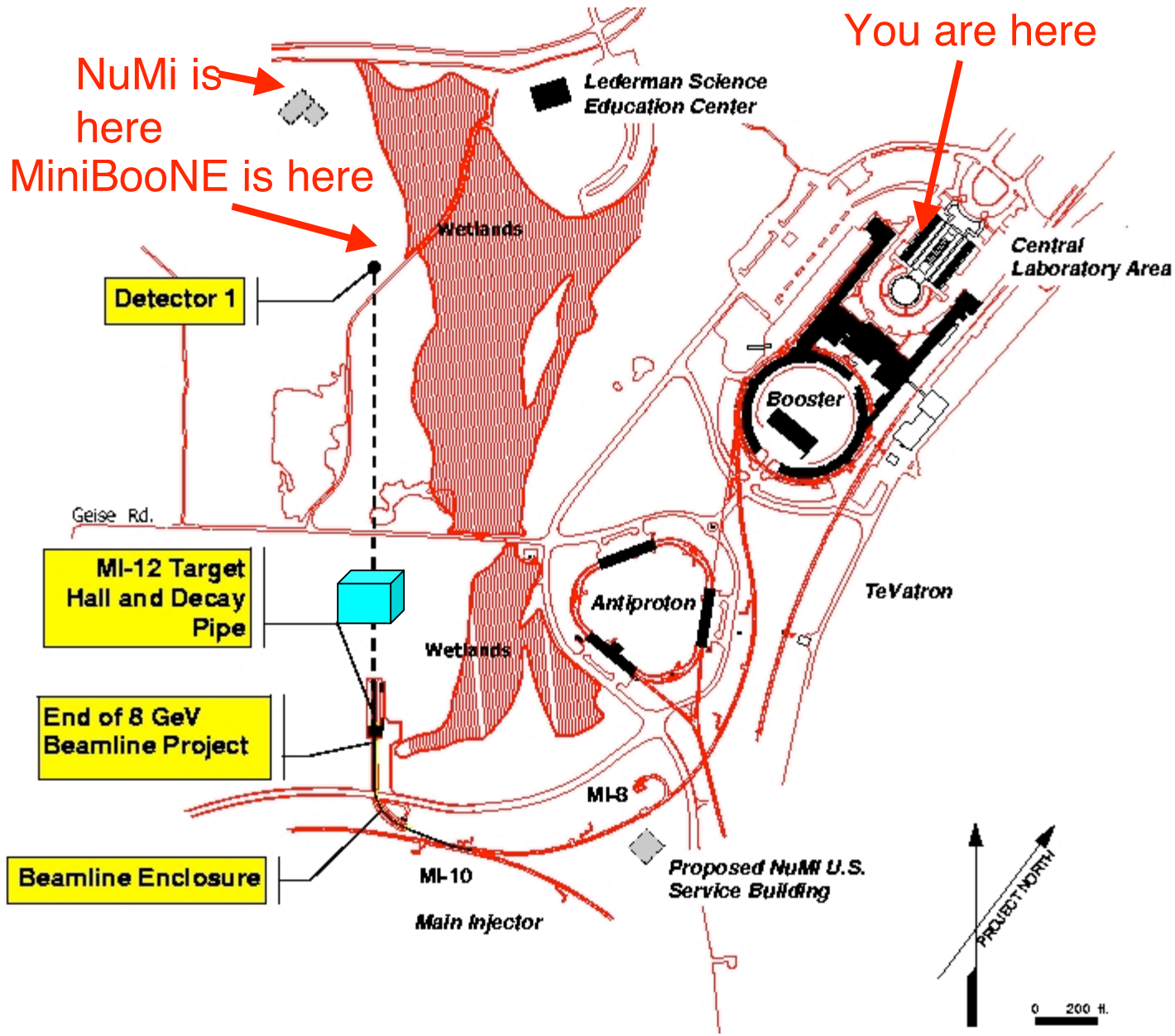
High precision osc. parameters
-CP violation
-Matter effects

2. The Booster Neutrino Beam

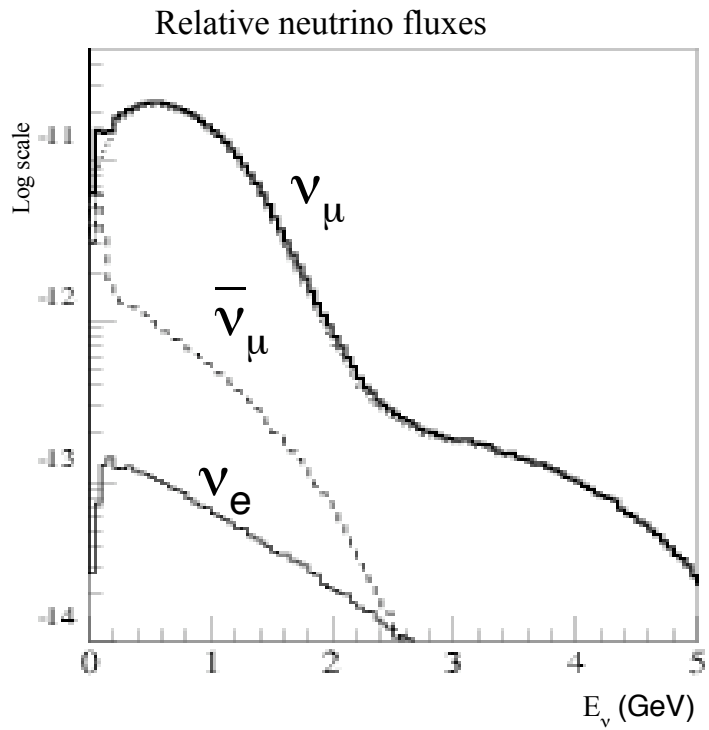
- 8GeV proton beam hits a fixed target to create mesons
- π^+,K^+ focused by a high-current focusing horn
- Focused mesons allowed to decay in open decay region
- Neutrinos travel to a distant detector
  - Now: MiniBooNE
  - In the future: SciBar

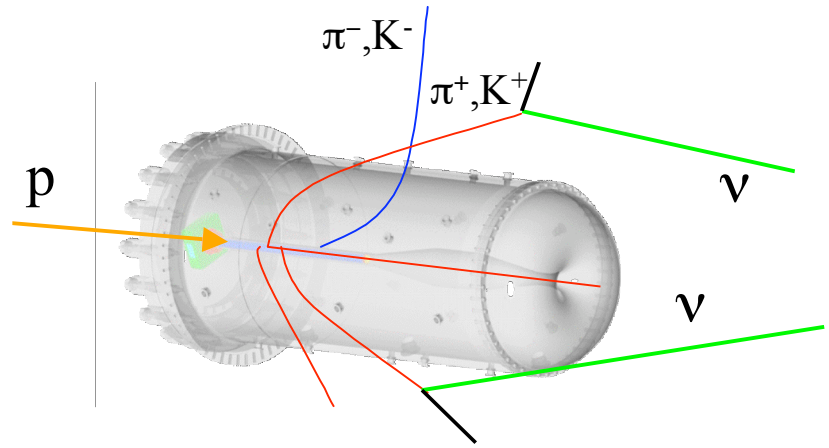


Fermilab Accelerator Complex



Creating Neutrinos at 8 GeV





$\pi^+ \rightarrow \mu^+ + \nu_\mu$ ← ~90% of all ν flux

$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$

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

$K^0 \rightarrow \pi^- + e^- + \bar{\nu}_e$

} ν_e ~0.6% of all ν's

$K^+ \rightarrow \mu^+ + \nu_\mu$

$K^+ \rightarrow \pi^0 + \mu^+ + \nu_\mu$

} ~3% of all ν's

Dominant flux channel – critical to overall normalization

Important intrinsic ν_e: backgrounds to oscillation signal

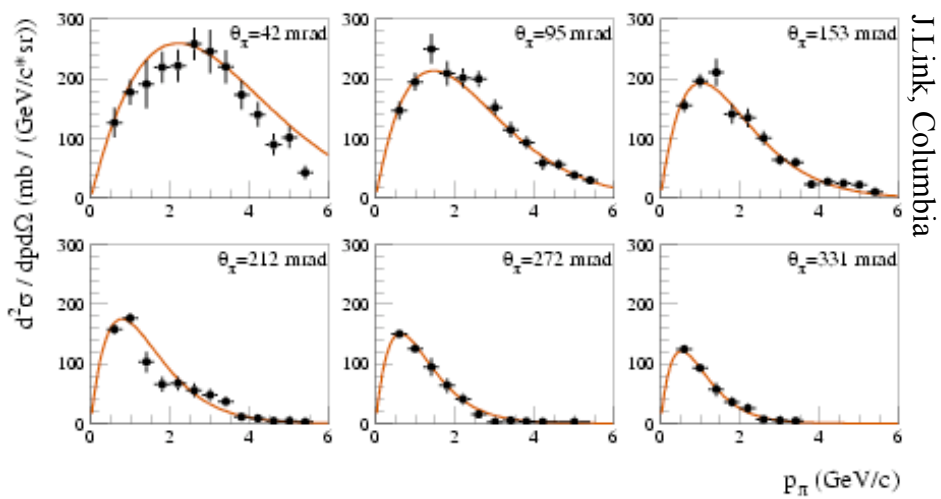
Non-negligible muon neutrino flux comes from kaon decays

Calculating the BNB Φ_ν

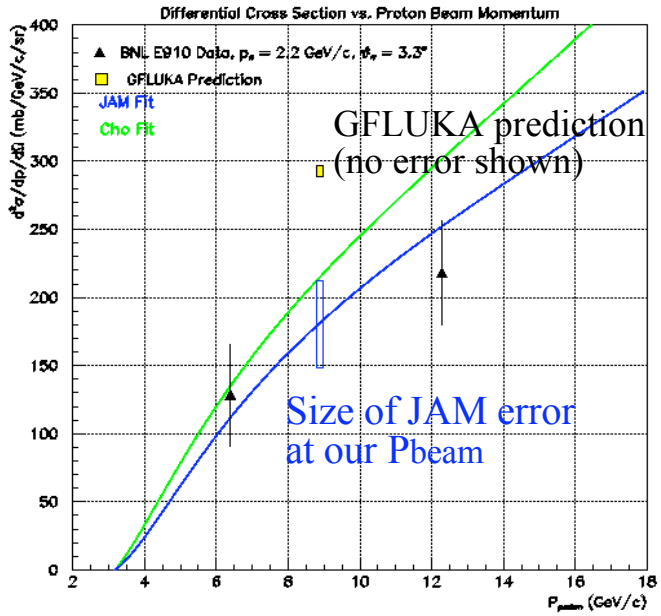
primary p Be → π^+ X interactions:

- Sanford-Wang parameterization fit to E910 hadron production data, 6 and 12 GeV

12.3 GeV/c E910 beryllium Data



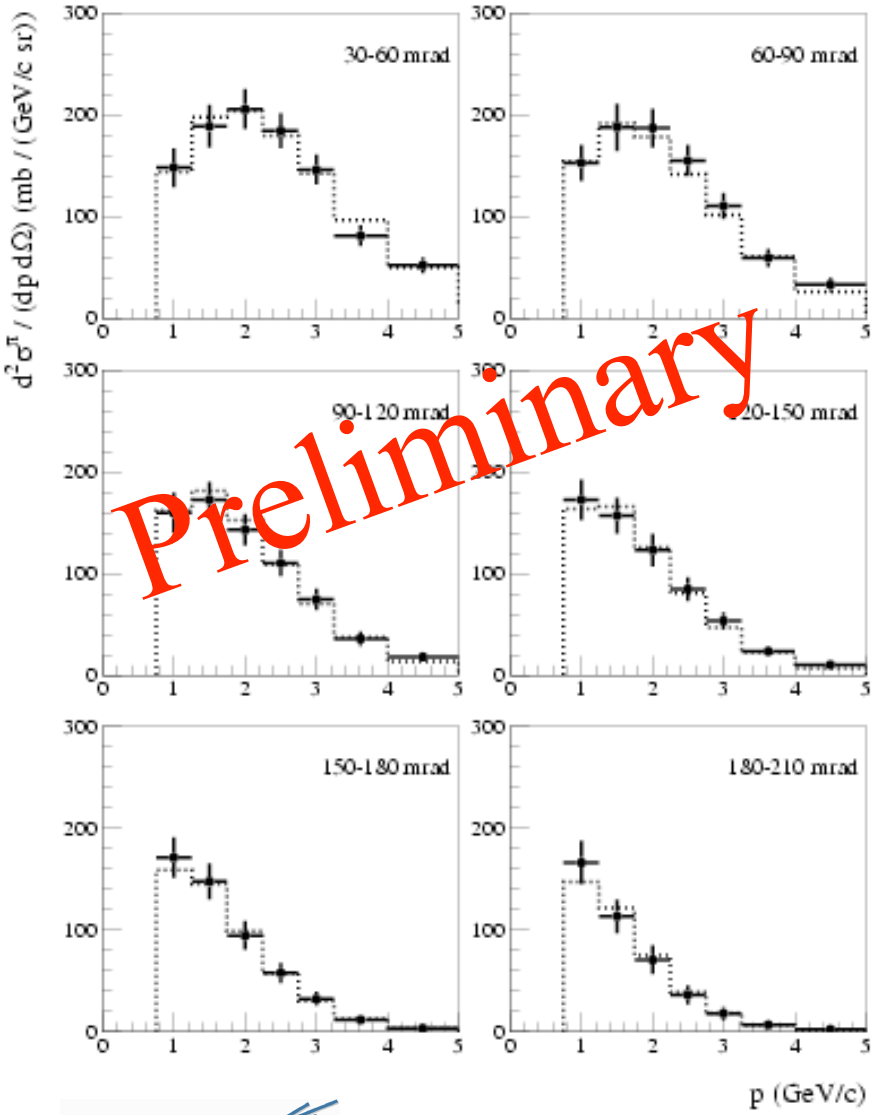
J.Link, Columbia



Y. Cho et al., Phys. Rev. **D4**, 1967 (1971)

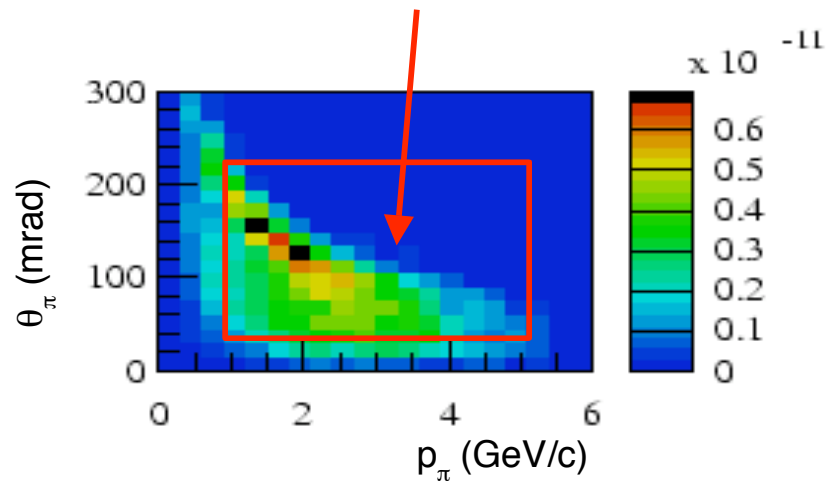
- Parametrization
  - allows extrapolation from various data sets (different p_{beam})
  - allows interpolation of cross section tables between existing experimental data
  - E910 publication in preparation
  - HARP will nail down production at 8 GeV with small errors (use E910 fit as cross check)

HARP Beryllium Thin Target Results



Preliminary double differential π^+ production cross sections from the Be 5% target are available

$0.75 < p_\pi < 5$ GeV/c
$30 < \theta_\pi < 210$ mrad



Momentum and Angular distribution of pions decaying to a neutrinos that pass through the MB detector.

Error Evaluation

For HARP p Al → π^+ X

- Thorough systematics error evaluation performed, to quantify errors on both:
  - $d^2\sigma^\pi/(dpd\Omega)\ (p,\theta)$

    Typical error: **8.7%**
  - $\sigma^\pi(0.75<p<6.5\,GeV/c, 30<\theta<210\,mrad)$

    Error on total cross-section: **4.7%**

Error Source	δ_{diff} (%)	δ_{int} (%)
Overall normalization	4.0	4.0
Momentum scale	3.6	0.3
Al target statistics	3.2	0.6
Acceptance correction	2.6	0.7
(π, p) PID	2.5	0.5
Empty target statistics	2.2	0.4
Electron PID	2.1	0.5
Momentum resolution (smearing)	1.3	1.6
Empty target normalization	1.2	1.1
Momentum resolution (model dep.)	1.0	1.1
Reconstruction efficiency	0.8	0.2
Kaon PID	0.3	0.1
Secondary interactions	0.2	0.1
PID probability cut	0.2	0.1
Total	8.7	4.7

Total: 8.7% 4.7%

Dominant error contributions:

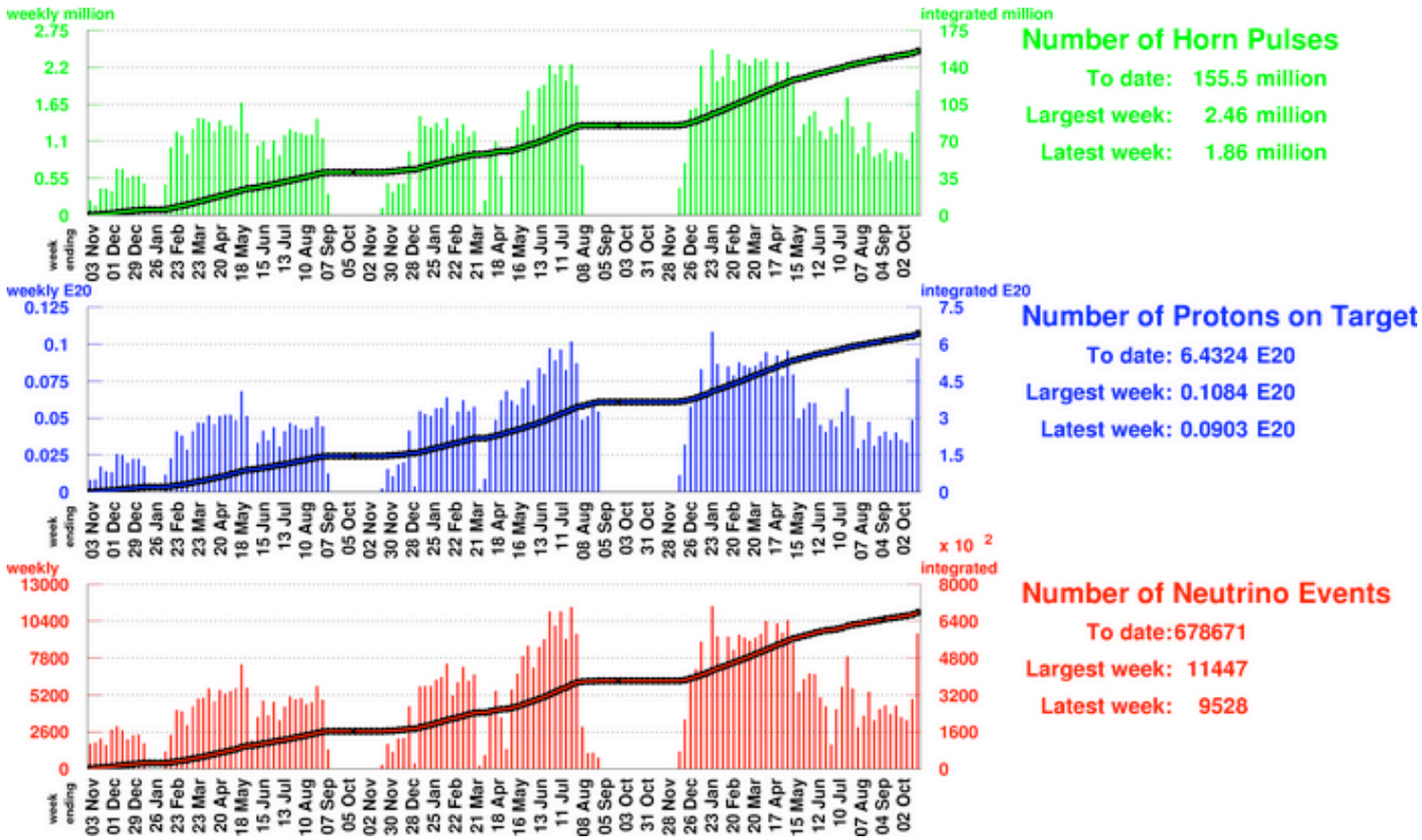
- Overall normalization
- Momentum scale
- Statistics

Similar systematics expected for Be

NBI 2005

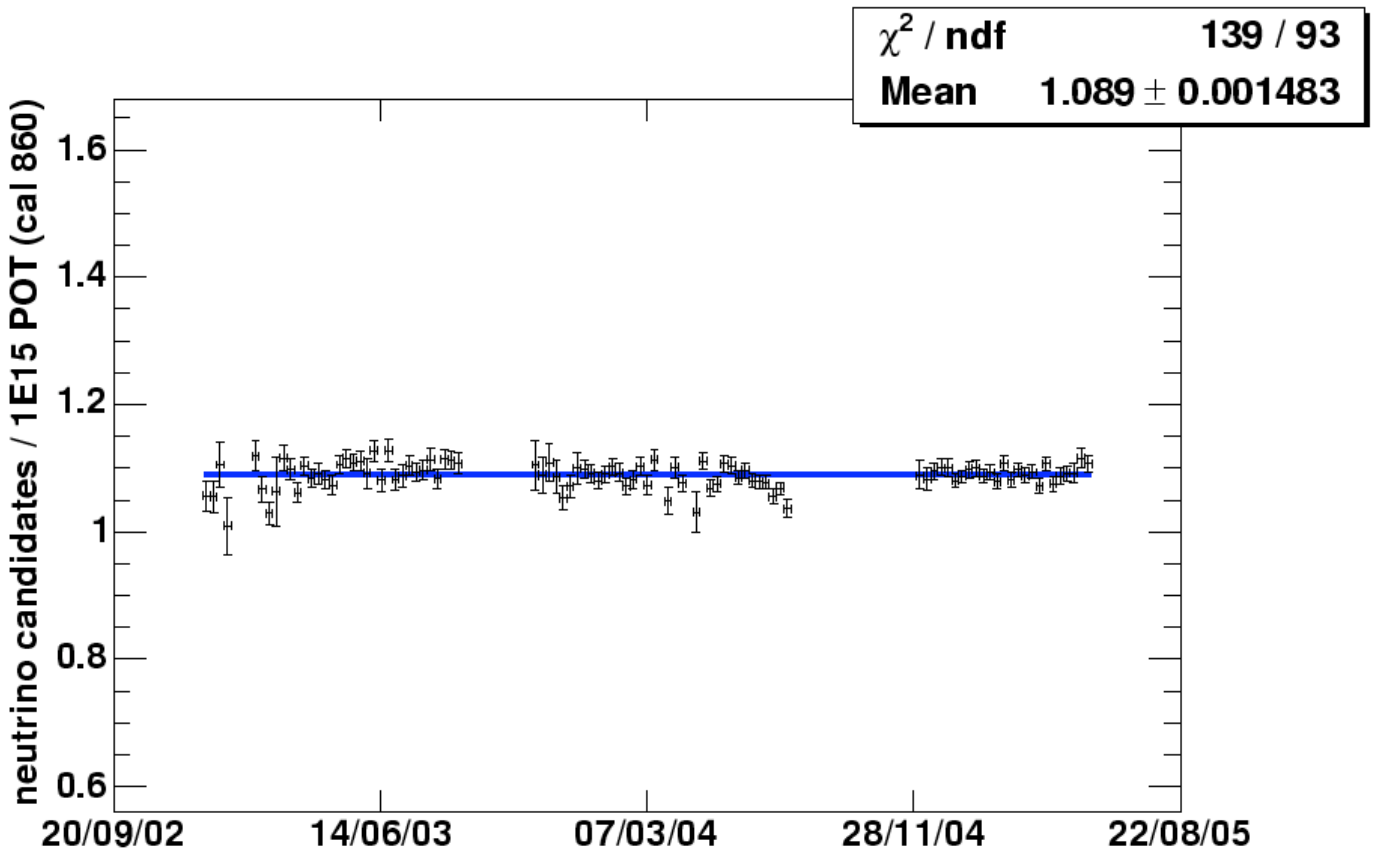
HARP data taken with thick targets will measure K fluxes

BNB Proton Delivery



- Directorate recommends planning on 1-2E20 POT
- We assume 2E20 POT in a one year run
  - 0.5E20 POT in ν mode, 1.5E20 in $\bar{\nu}$ mode
- This is consistent with FNAL Proton Plan

MiniBooNE Event Rates vs. Time

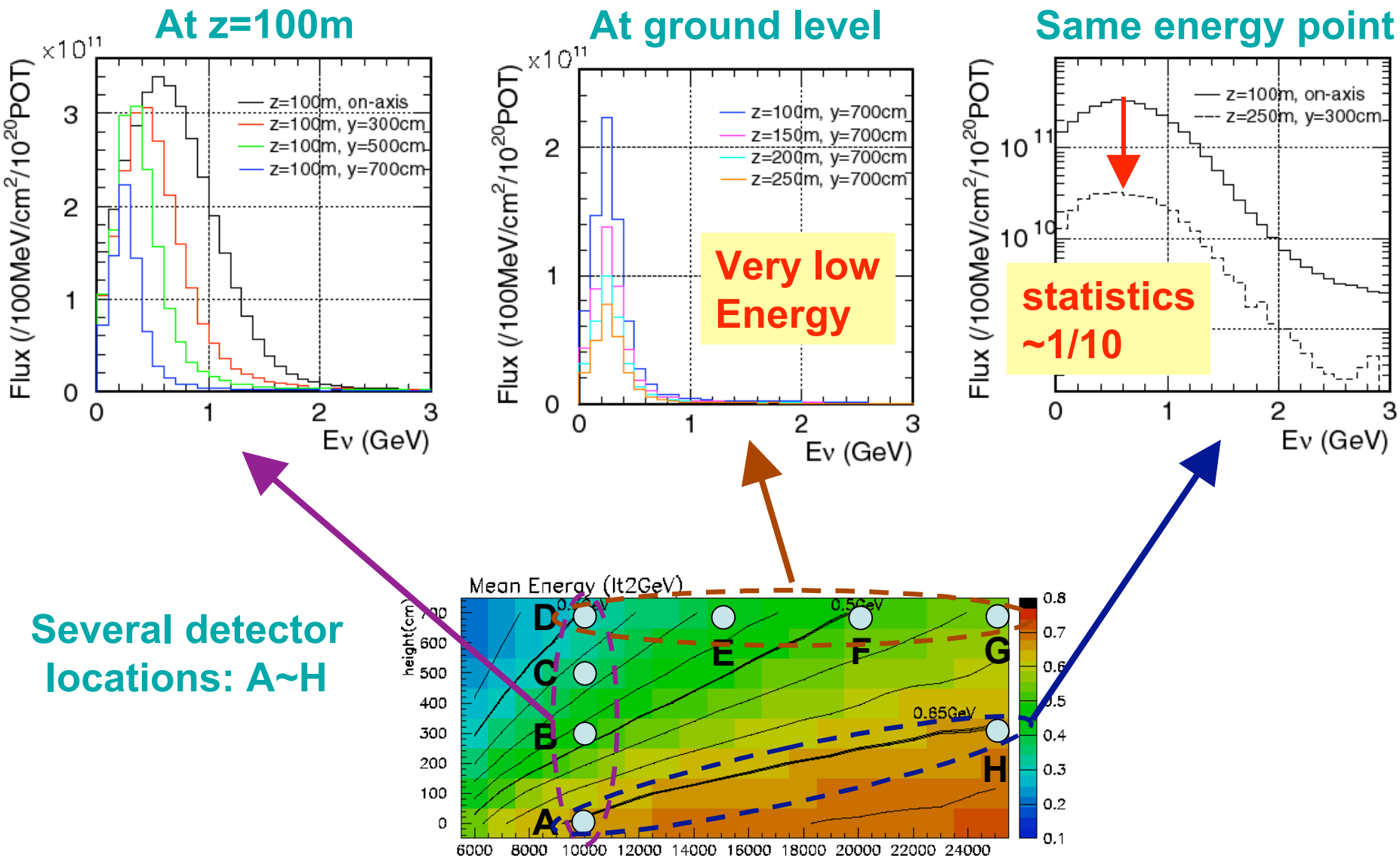


- ν/POT vs. time (Using simple ν cuts)
  - rate is constant!
  - spans two shutdowns,
  - two horns

Neutrino fluxes at different locations

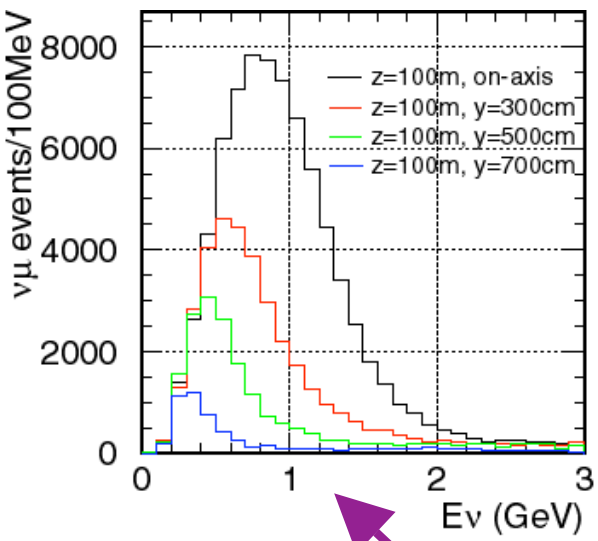
- Study neutrino flux, event rates at various locations
- Consider physics potential at each location
  - Total flux, energy spectrum, π/K fractions, WS BGs, cost
- Overwhelming conclusion:
  - On-Axis Location at 100 m is the best choice

Expected neutrino flux

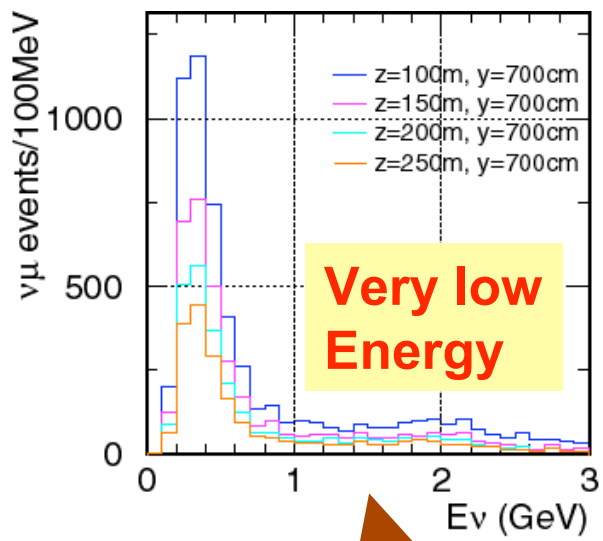


Expected ν_μ flux × σ spectra

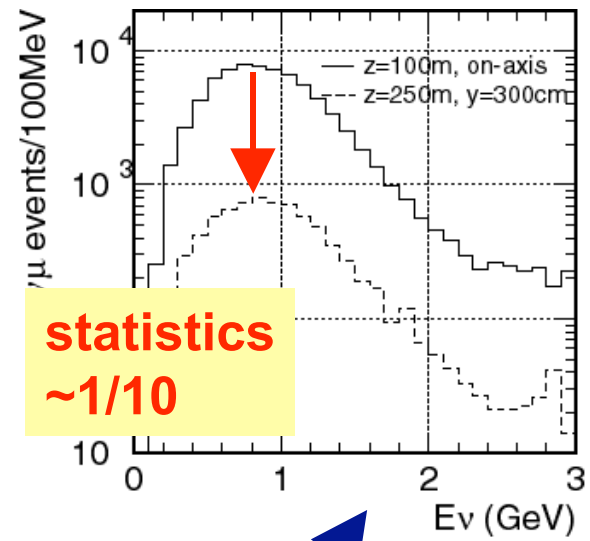
At z=100m



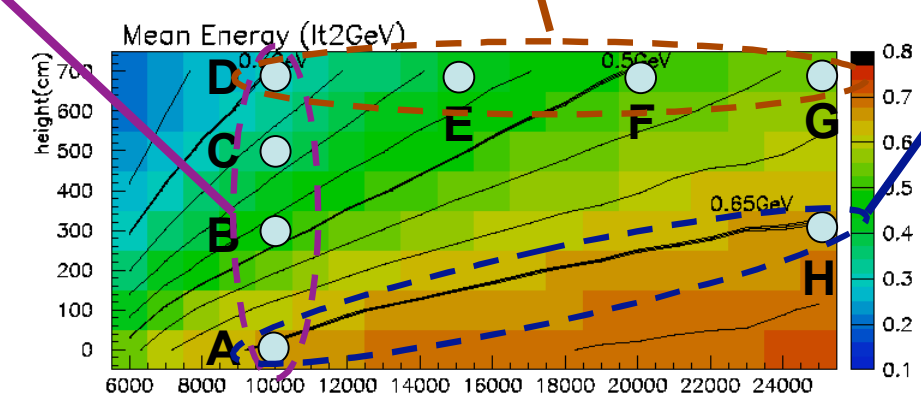
At ground level



Same energy point



Several detector locations: A~H



Comparison of all locations, ν mode

location	A	B	C	D	E	F	G	H
<Eν>	0.92	0.76	0.64	0.60	0.60	0.61	0.61	0.94
$\#\nu_\mu$	78,397	37,230	19,357	6,001	3,791	2,807	2,200	8,112
$\#\bar{\nu}_\mu$	1,138	636	467	176	113	88	67	109
$\#\nu_e$	669	415	268	128	68	46	39	61
$\#\nu_\mu$ CC	55,983	26,244	13,530	4,103	2,588	1,932	1,513	5,807
MRD Event	18,500	7,000	2,970	850	520	390	310	1,970
Statistics		X	X	X	X	X	X	X

Events in fiducial volume (9.38 tons), 0.5E20 POT

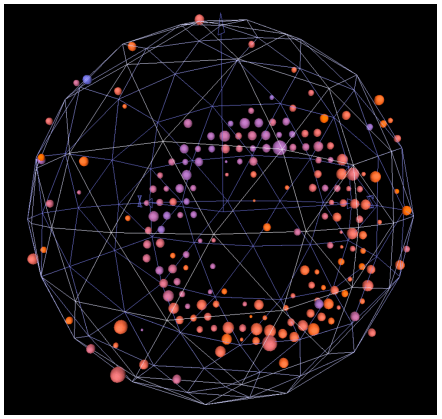
Conclusions from detector location study

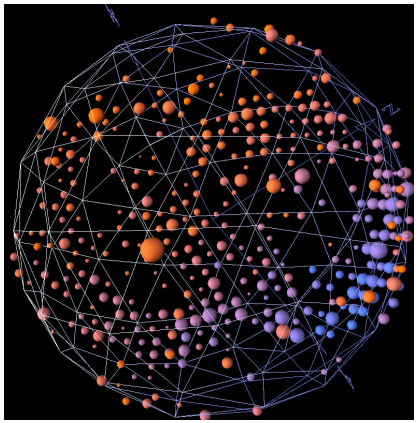
- On-axis is the best position.
- At location B (z=100m, y=300cm), neutrino energy is slightly lower and the total event rate is ~half the on-axis position.

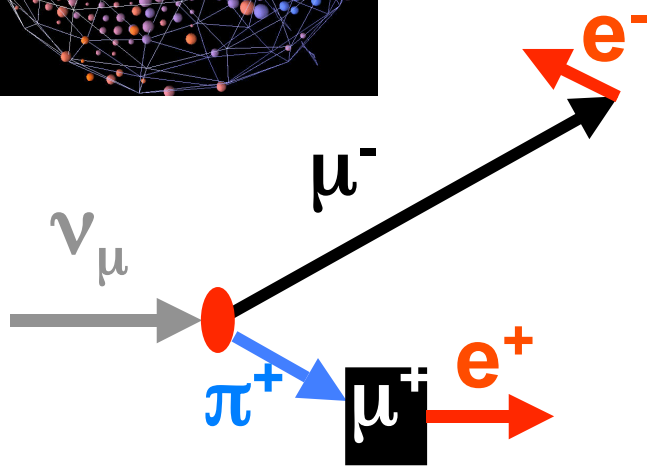
- At locations C~G
  - neutrino energy is too low to be of interest to next generation oscillation searches
  - Intriguing wrong sign and π/K mixes negated by low statistics
- At location H, neutrino energy is same as that of on-axis position, but statistics ~10× smaller.

6. MiniBooNE Cross Sections

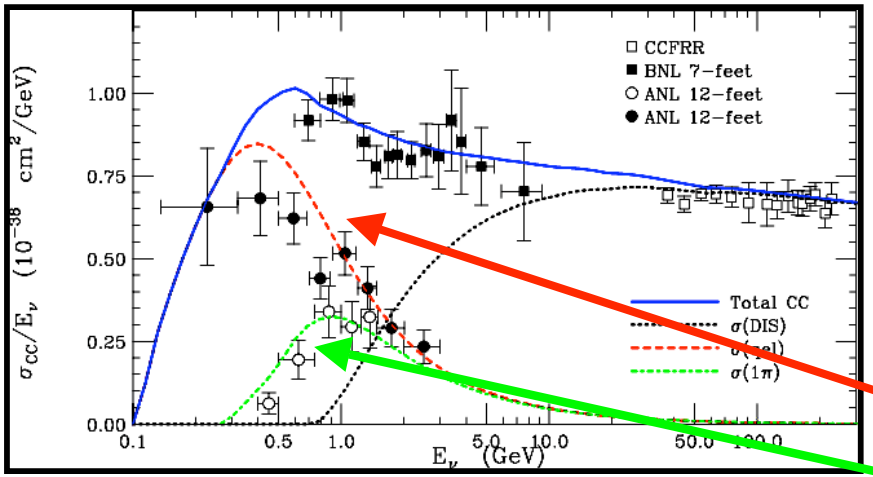
- Status of MiniBooNE cross section measurements
  - CC QE
  - CC1π+
  - NCπ0
- Excellent statistics
- Great new measurements of processes crucial to oscillation searches
- Seeing interesting clues to new physics in low Q^2 regions
- Cannot distinguish exclusive final states
  - Invariant mass reconstruction

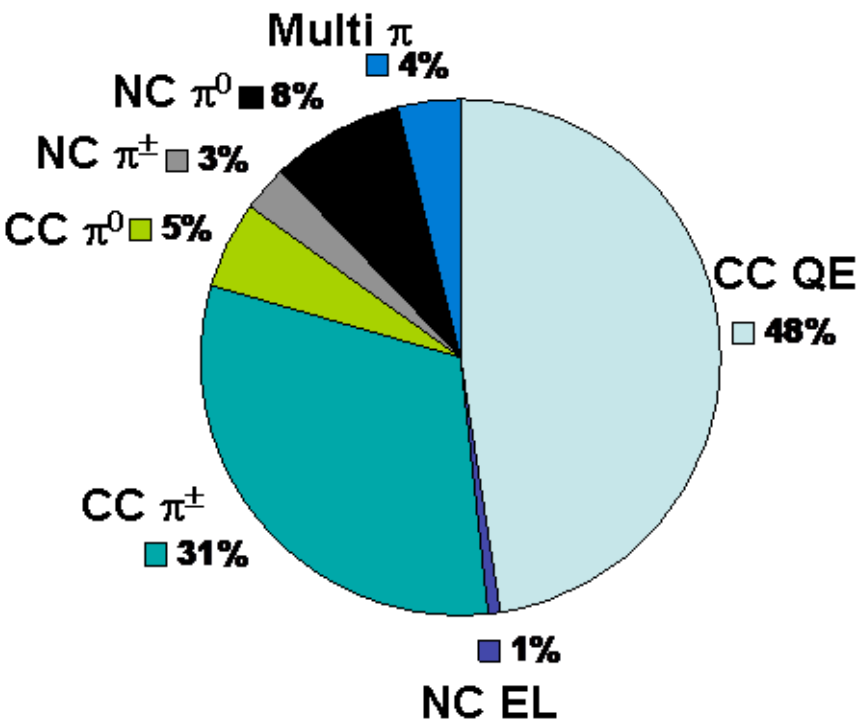






Event Fractions at MiniBooNE





MiniBooNE flux-averaged event composition after simple cuts:

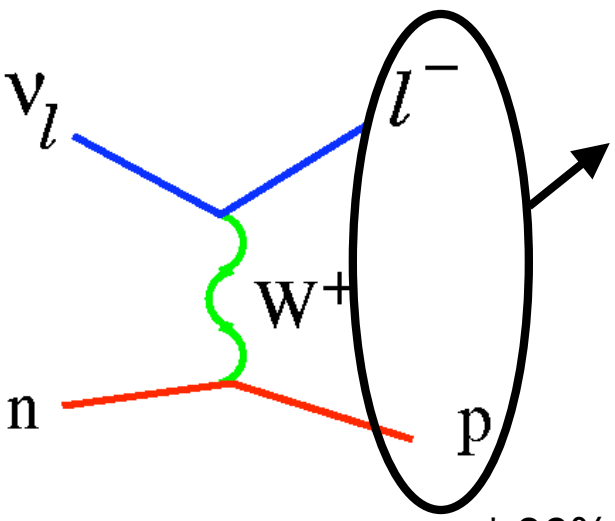
- 48% QE
- 31% CC π^+
- 8% NC π^0

- 5% CC π^0
- 4% multi-π
- 3% NC $\pi^{+/-}$
-1% NC EL
-1% DIS

ν_μ CC Quasi-Elastic Events

$\nu_\mu\, n \rightarrow \mu^-\, p$

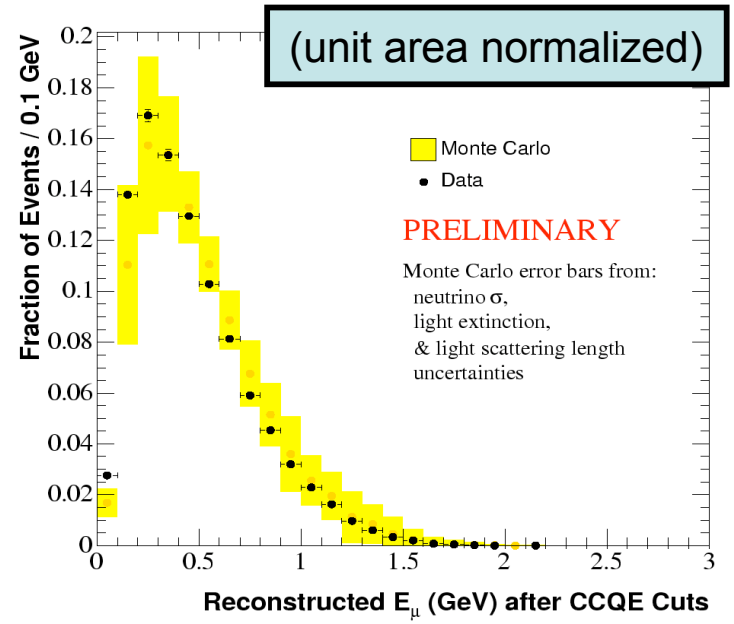
- QE most copious ints at these E's
- also simplest: two body kinematics

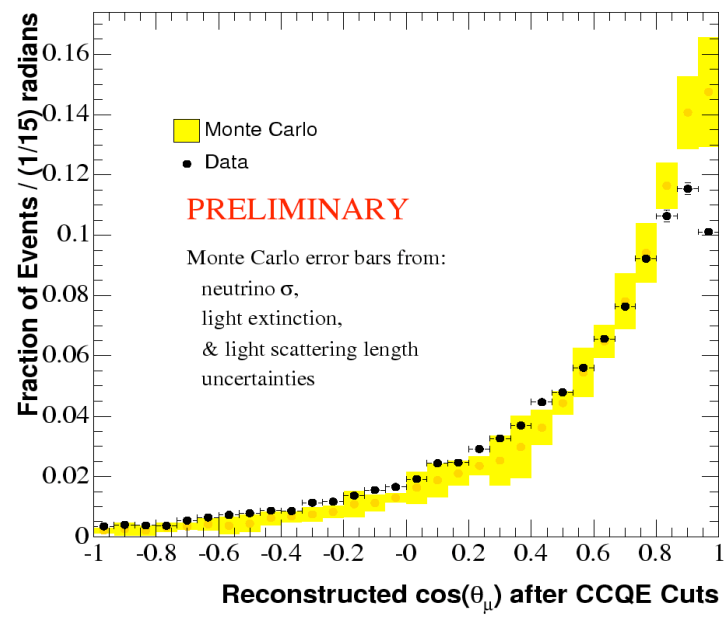


measure visible E and θ_μ from mostly Cherenkov (μ) + some scintillation light (*p*)

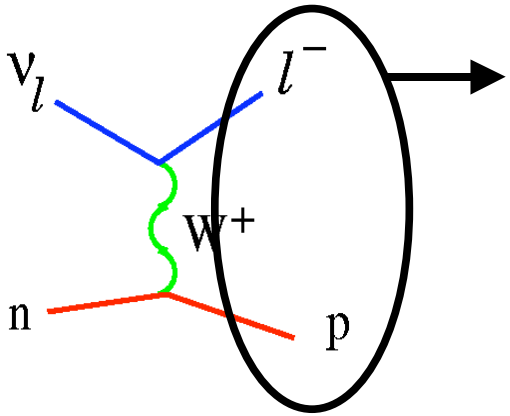
* 86% QE purity
* 30% efficiency
* dominant background: CC π^+ events (π^+ absorbed)

this set: ~60,000 QE events





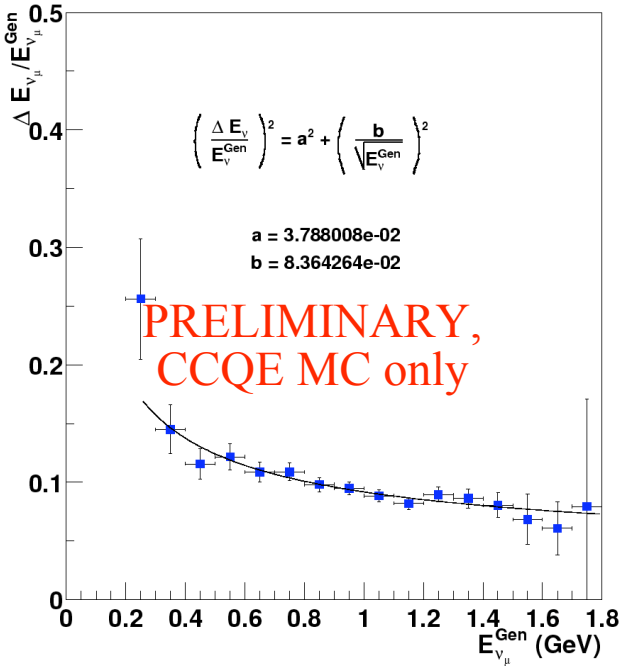
MiniBooNE CCQE Data

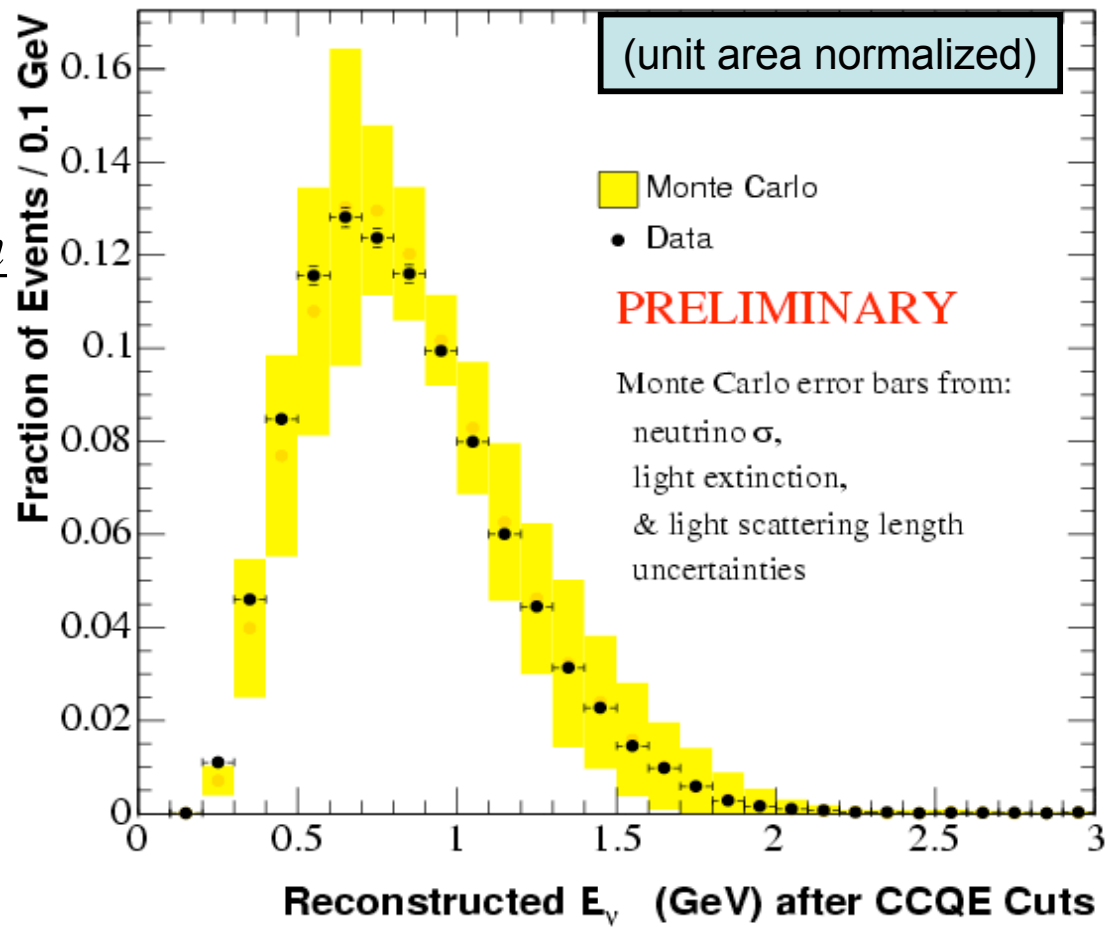


use measured μ^- visible energy and angle to reconstruct E_ν^{QE}

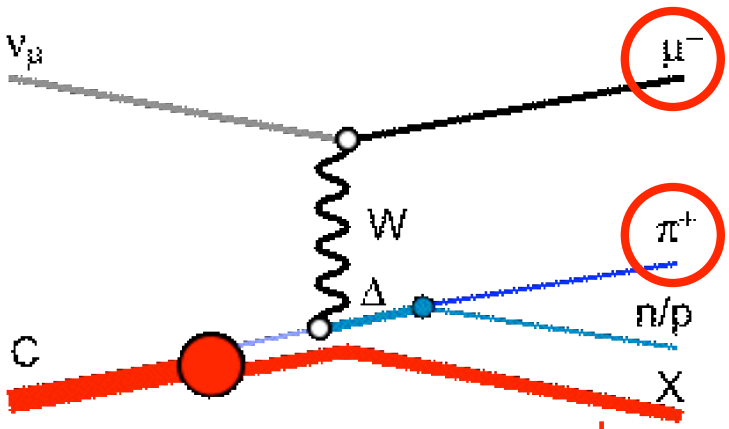
$$E_\nu^{QE} = \frac{1}{2}\frac{2M_p E_\mu - m_\mu^2}{M_p - E_\mu + \sqrt{(E_\mu^2 - m_\mu^2)}\cos\theta_\mu}$$

Neutrino Energy Reconstruction





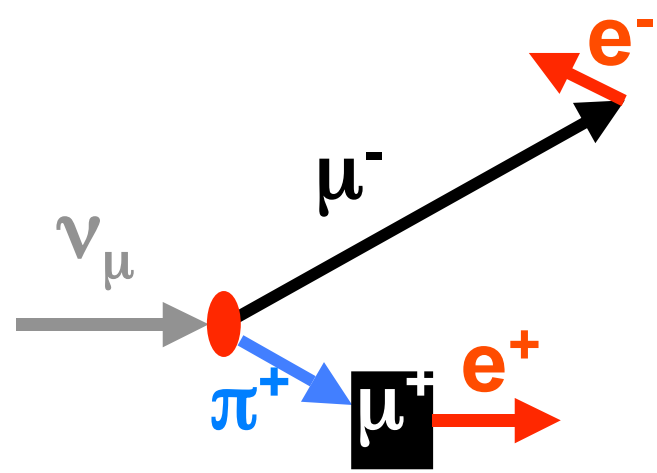
CC1π^+ Events at MiniBooNE



$$\nu_\mu \; p \rightarrow \mu^- \; p \; \pi^+$$
$$n \qquad\qquad n$$

- 2nd most numerous interaction at MiniBooNE
- large σ; ~1/2 rate of QE

- identify with 2 Michel electrons
- 84% pure selection of CC π+

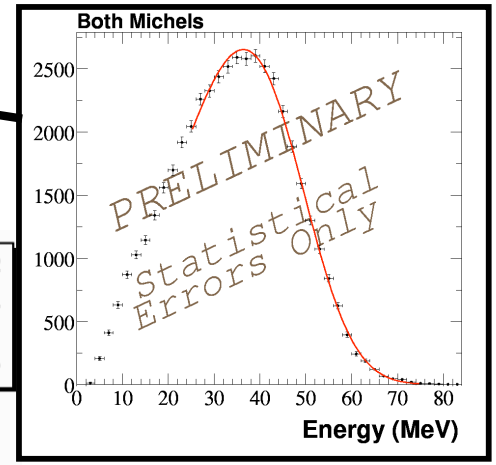


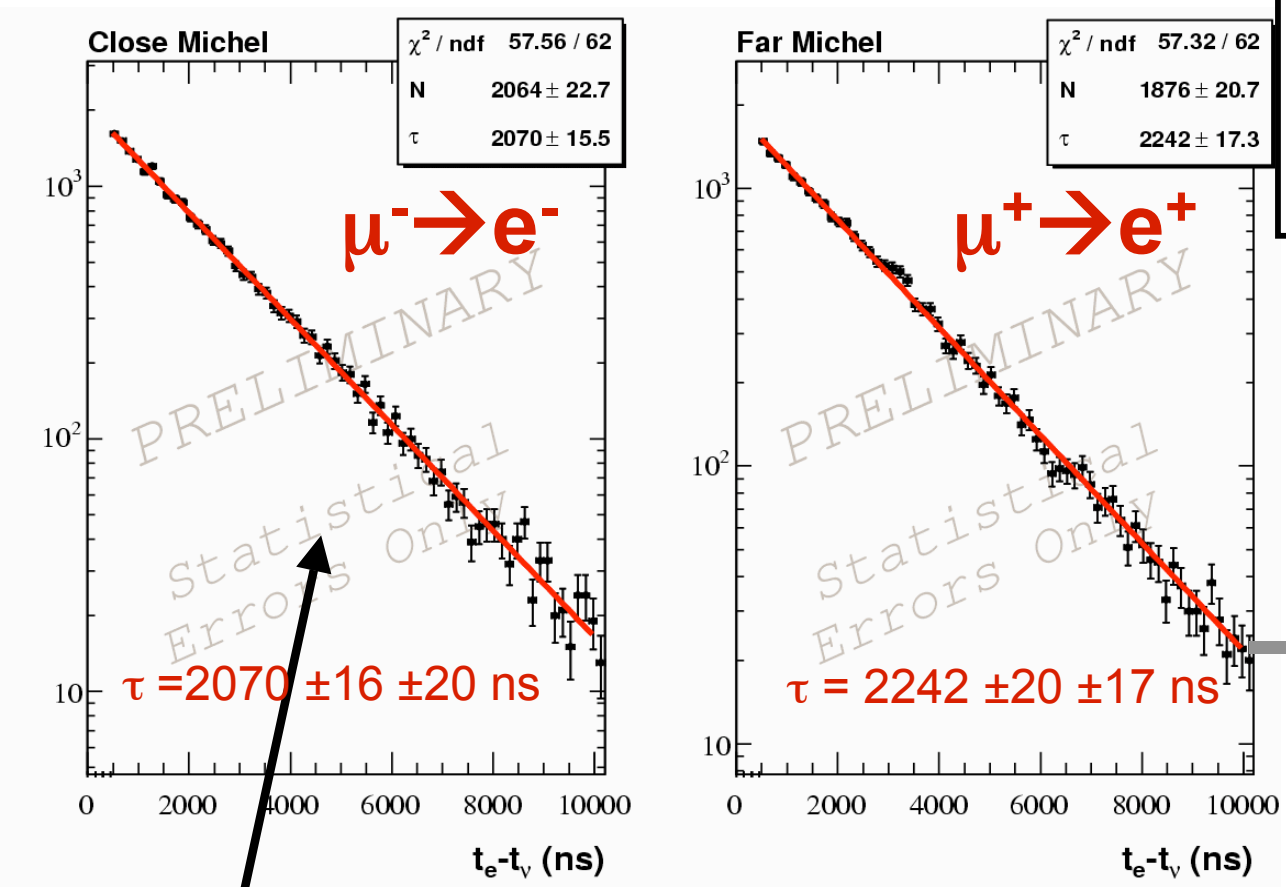
- **~44,000 events**
- 5x more than all previous bubble chamber data!

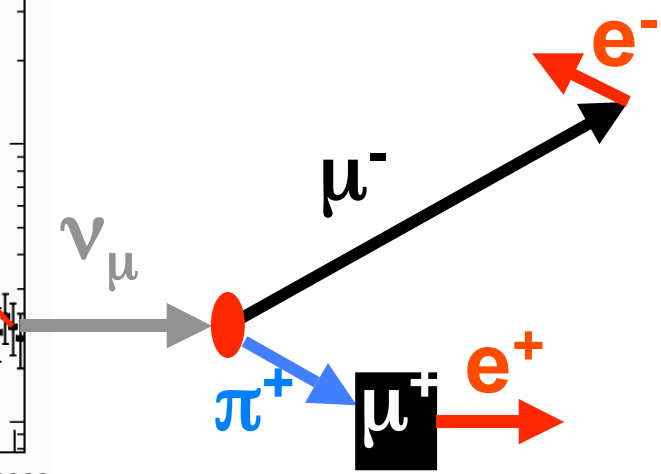
- Inclusive final states only

CC1π^+ Events at MiniBooNE

reconstructed energy spectrum
for Michel e^- candidates in CC π^+ sample

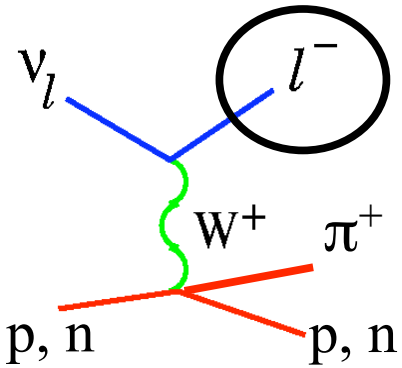




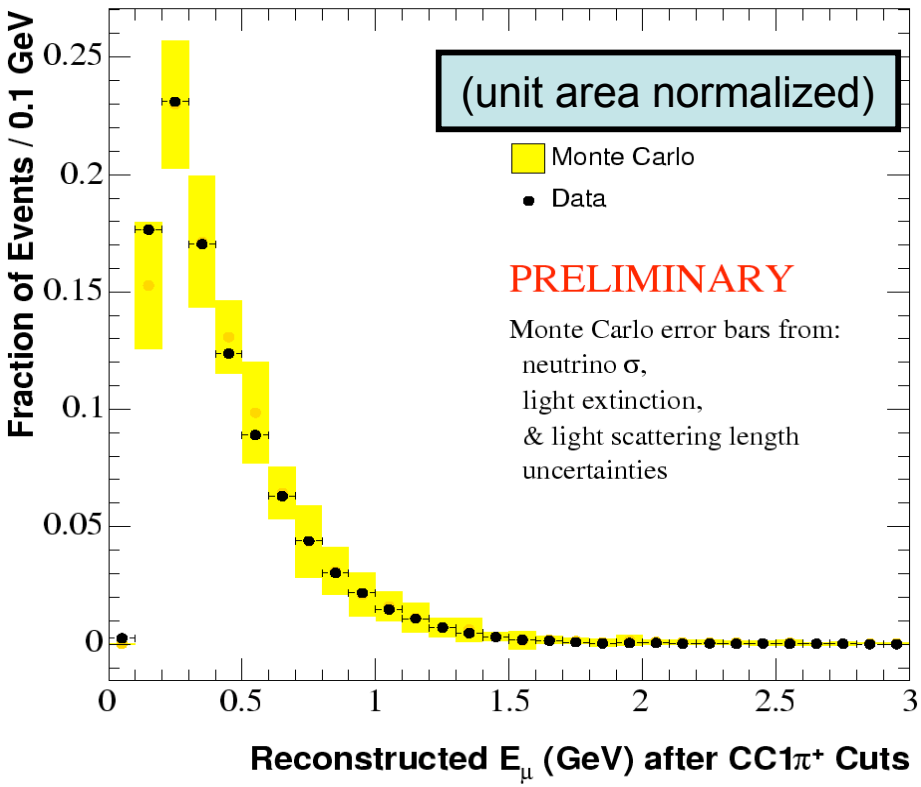


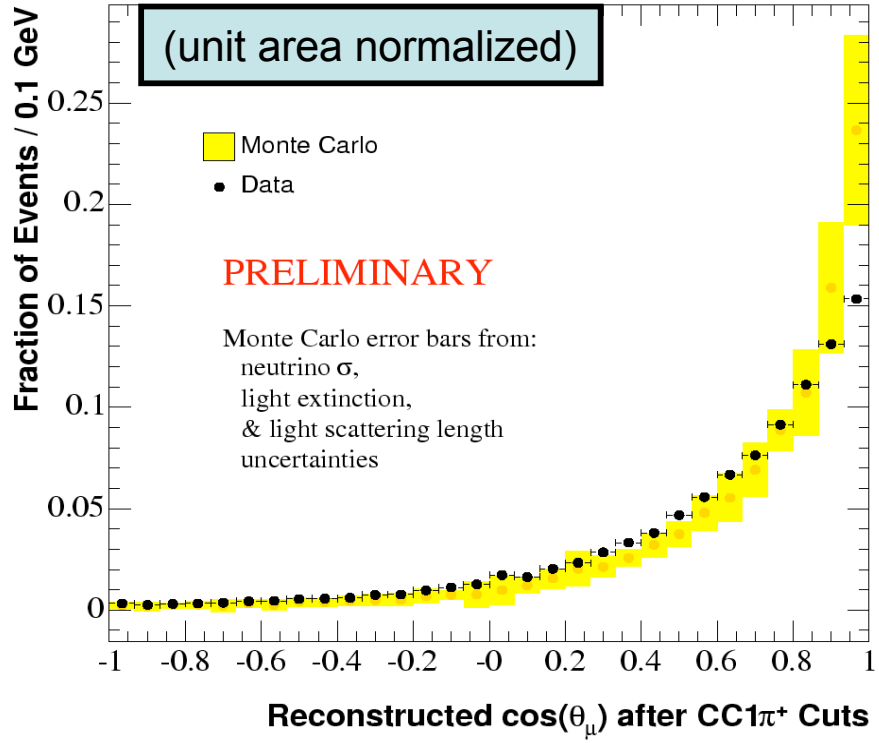
expect to have a shorter lifetime from μ^- capture (8%) in carbon

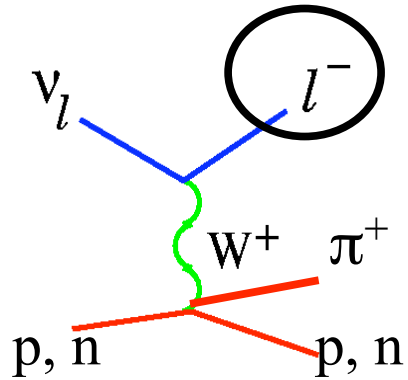
MiniBooNE CC1π^+ Data



measure visible energy from Cherenkov light only (to avoid light from π^+)

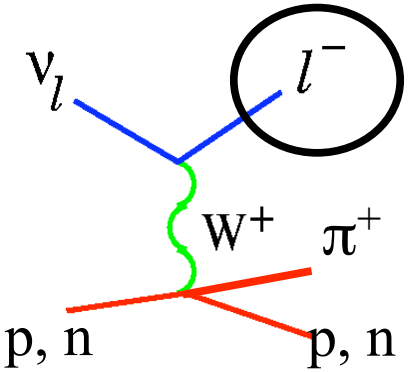






reconstruct μ^- direction from Cherenkov light, $\cos(\theta) = 1 \sim$ low Q^2

MiniBooNE CC1π^+ Data



use measured μ^- visible energy and angle to recon

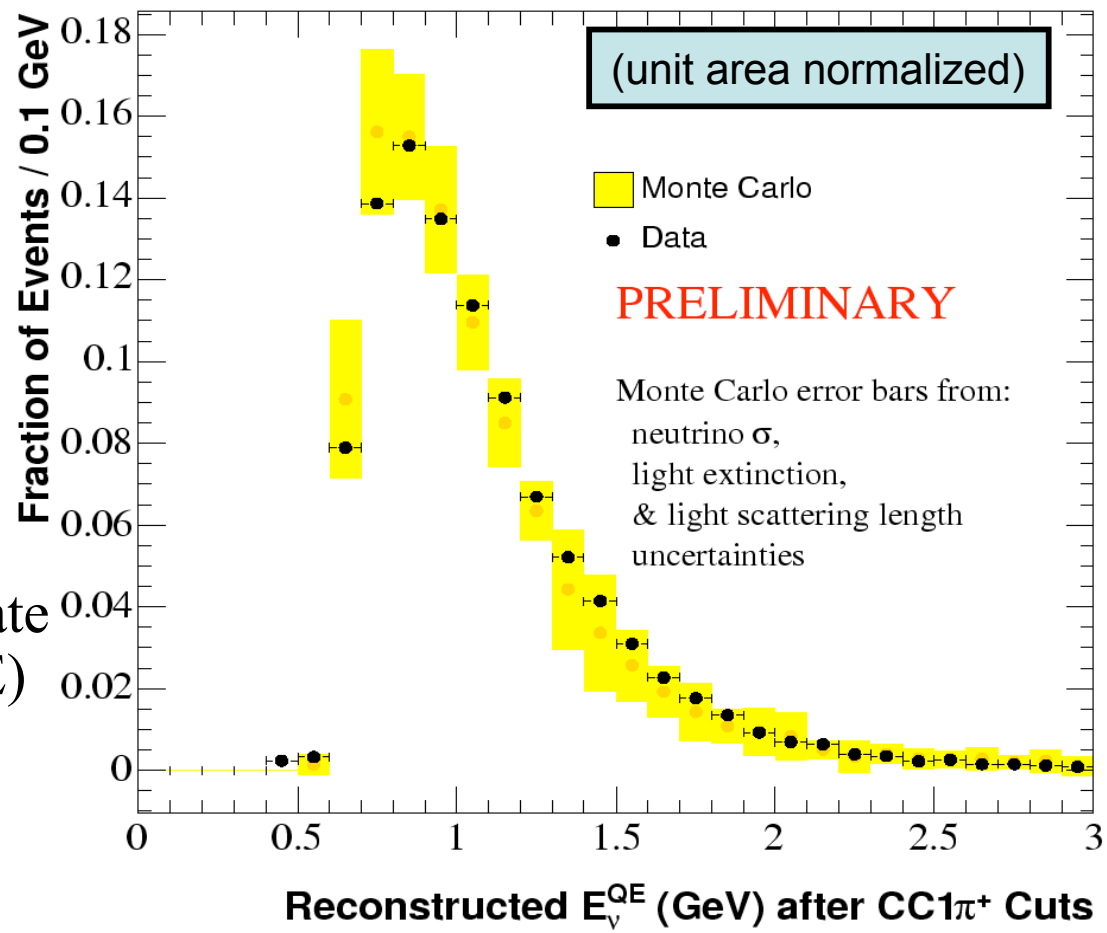
$$E_\nu^{QE} = \frac{1}{2}\frac{2M_pE_\mu - m_\mu^2 + (m_\Delta^2 - m_P^2)}{M_p - E_\mu + \sqrt{(E_\mu^2 - m_\mu^2)}\cos\theta_\mu}$$

Neutrino Energy Reconstruction

- Assume 2 body kinematics
- (as in CCQE)

- Assume $\Delta(1232)$ in final state
- (instead of a p as in CCQE)

- ~20% resolution



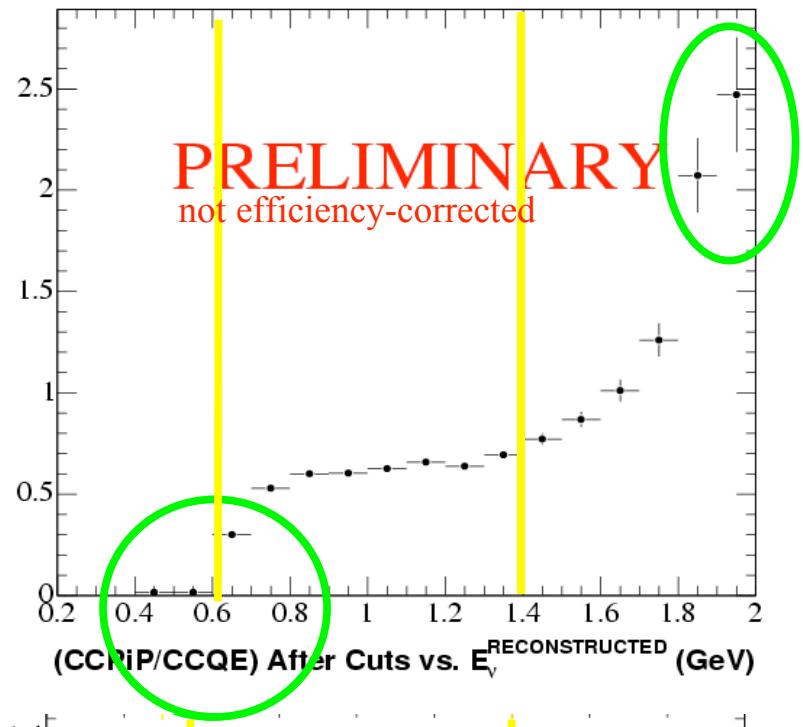
$CC1\pi^+/CCQE$ Ratio

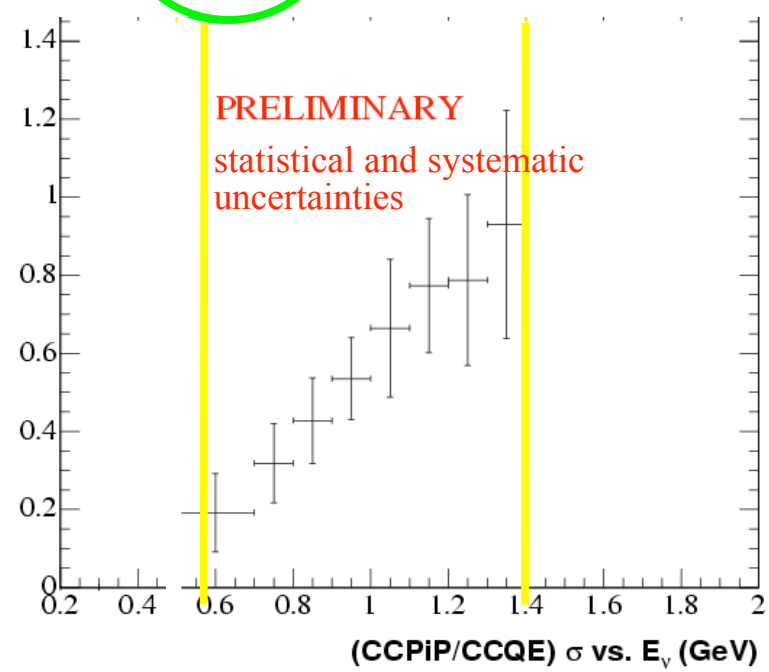
- Without cut efficiency corrections:
  - measured $N(CC1\pi^+)/N(CCQE)$ vs. E_ν^{QE}
    - CCQE cut eff. degrades at high E
      - due to exiting μ^-
    - $CC1\pi^+$ threshold > CCQE

- Motivation for measuring $(CC1\pi^+/CCQE)$ ratio:
  - possibility of ν_μ disappearance
  - like branching ratio measurements,
    - normalize to ``golden mode''
  - CCQE: ``golden mode'' of low E ν σs

- Efficiency corrected ratio measurement:
  - estimate efficiency correction in MC
  - 15% systematics due to ν σ
  - 20% photon atten. and scatt. λ in oil
  - 10% energy scale

- Cannot distinguish separate final states





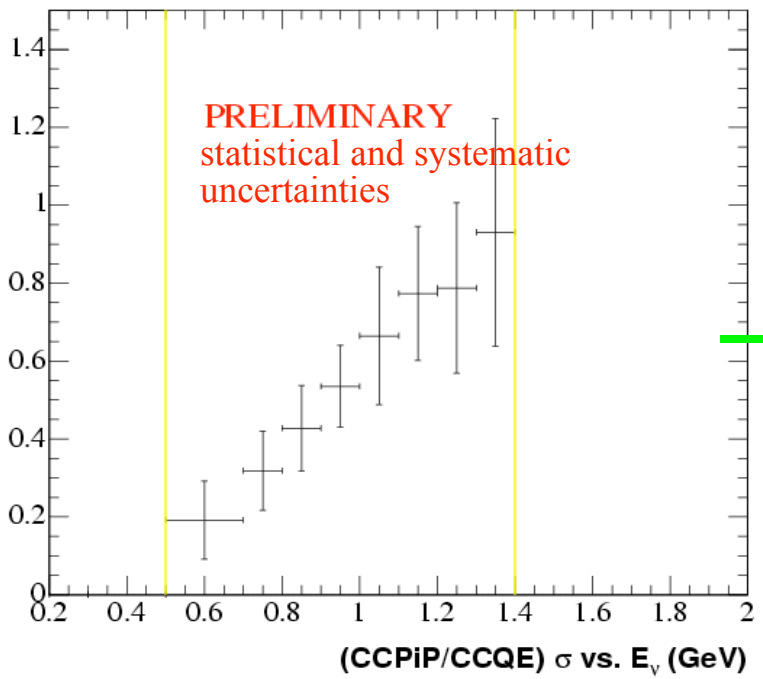
$CC1\pi^+$ σ on CH_2

- efficiency corrected ratio measurement as a function of ν energy:

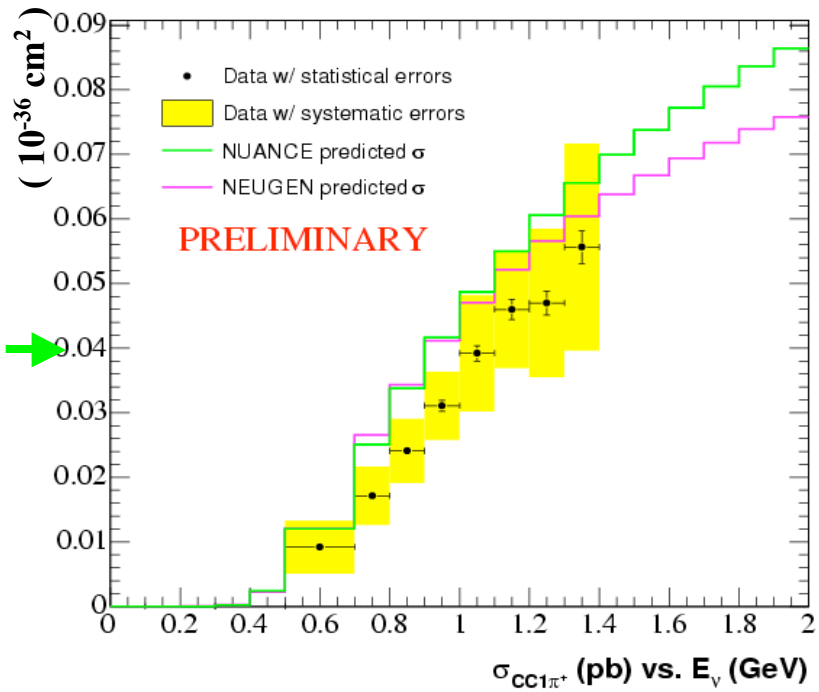
$$R_{MEASURED} = \frac{N(CC1\pi)}{N(CCQE)} = \frac{\sigma(CC1\pi)}{\sigma(CCQE)}$$

- use ``golden mode'' to convert to $\sigma(CC1\pi^+)$:

$$\sigma(CC1\pi) = R_{MEASURED} \times \sigma_{NUANCE}(CCQE)$$



Multiply by NUANCE MC σ CCQE m_A=1.03



- Shown for the first time at Fermilab at last week's Wine and Cheese Seminar

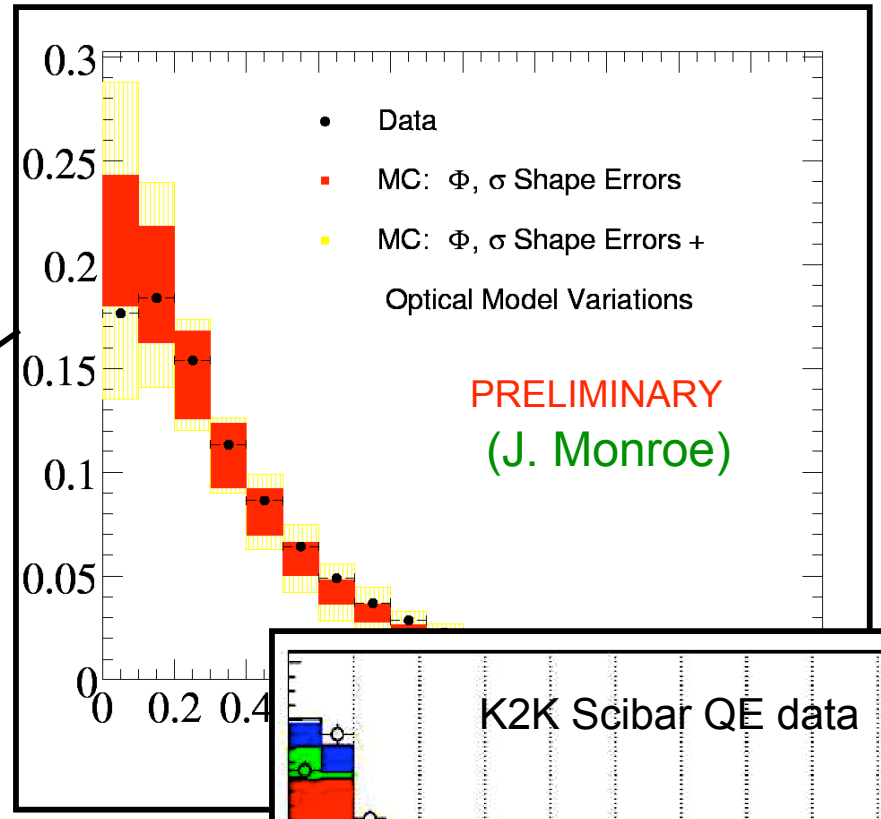
Q^2 Comparison: CCQE

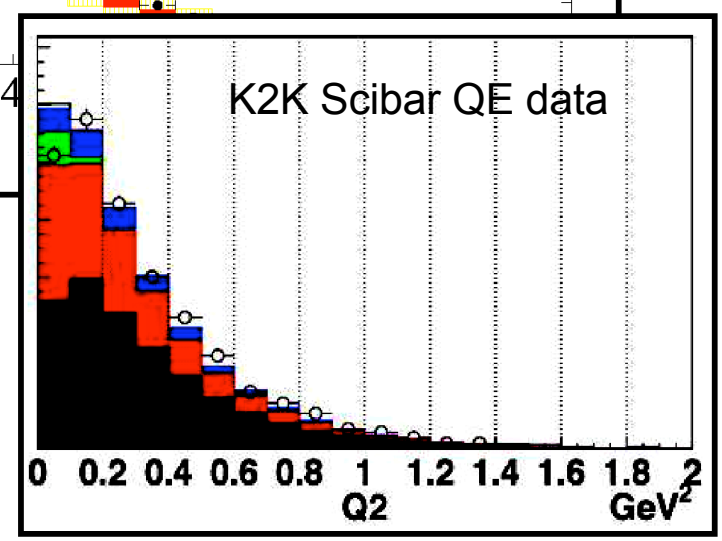
$\nu_\mu n \rightarrow \mu^- p$

$$Q^2 = m_\mu^2 - 2E_\nu(E_\mu - p_\mu \cos\theta_\mu)$$

- nuclear effects depend strongly on Q^2, so low Q^2 region provides information on modeling of ν scattering in carbon

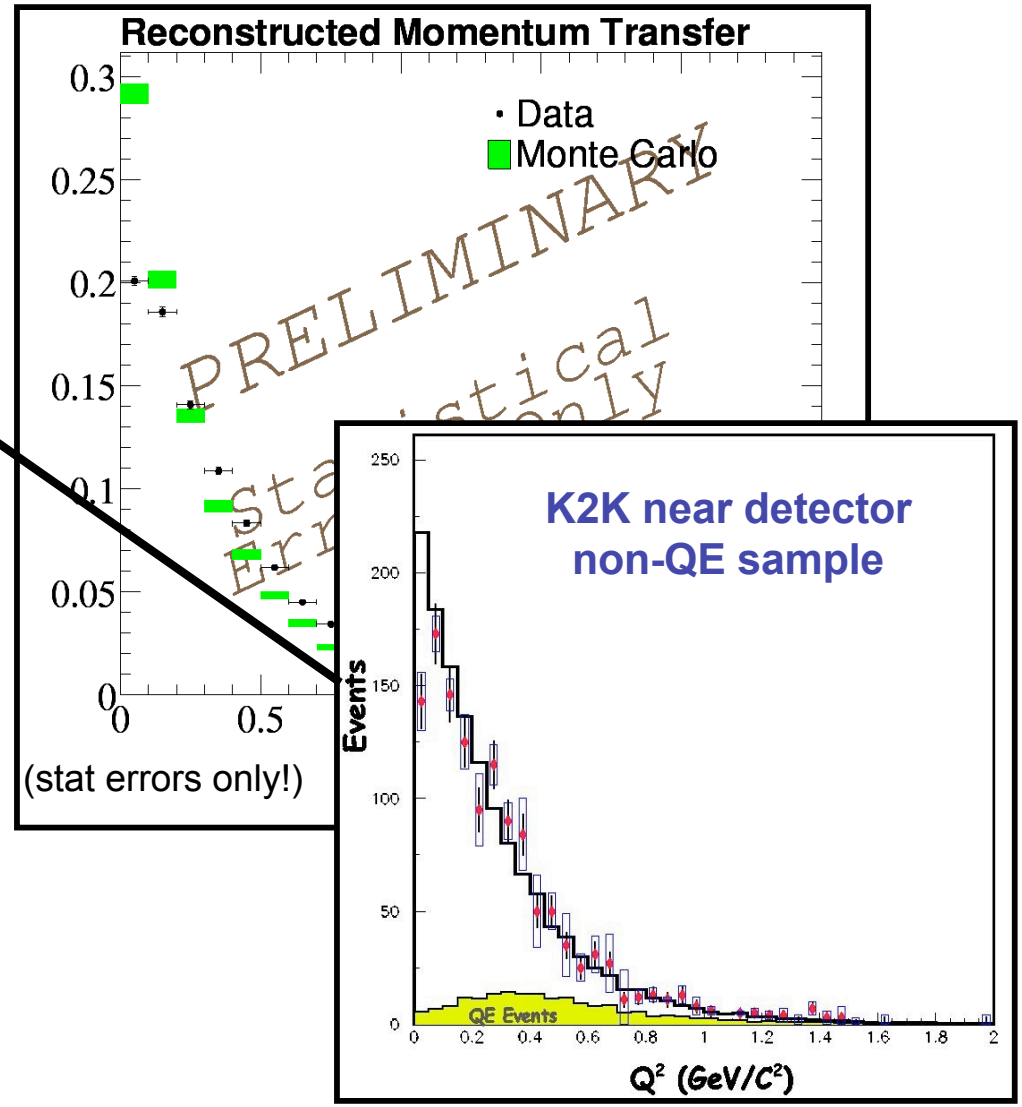
- interesting roll-over in data not tracked by Monte Carlo; also seen in K2K near detector data
  - has received a lot of attention recently
    - coherent production
  - points to a common model deficiency?
  - interesting new physics?





Q^2 Comparison:CC1π^+

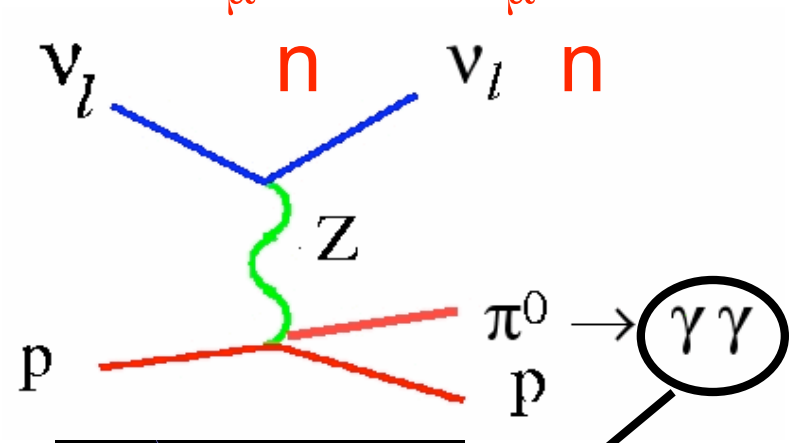
- interestingly, see larger low Q^2 deficit in CC π^+ than in our QE data
  - also seen at K2K

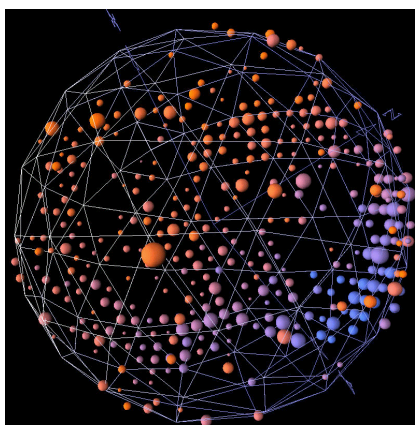


- pointing to lower CC coherent π^+ σ (populate low Q^2 region)
- another clue to what we're seeing at low Q^2 in CCQE samples

NC π^0 Sample

$\nu_\mu\ p \rightarrow \nu_\mu\ p\ \pi^0$



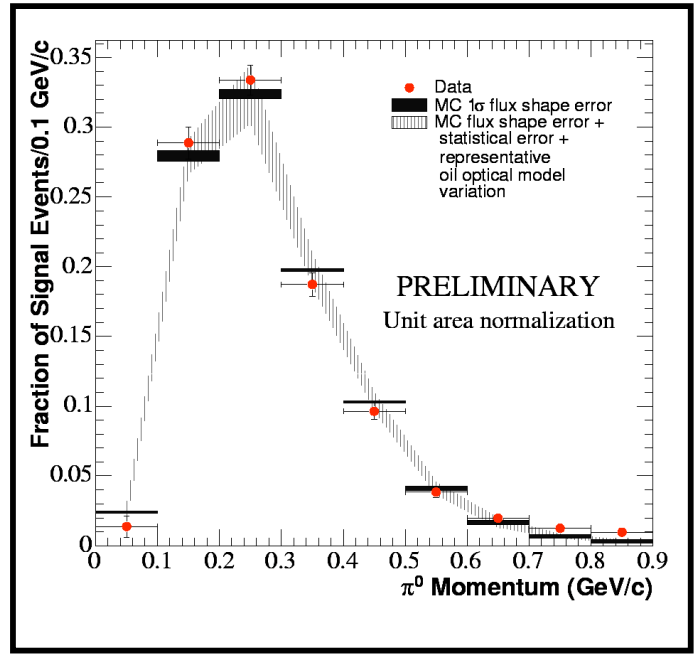


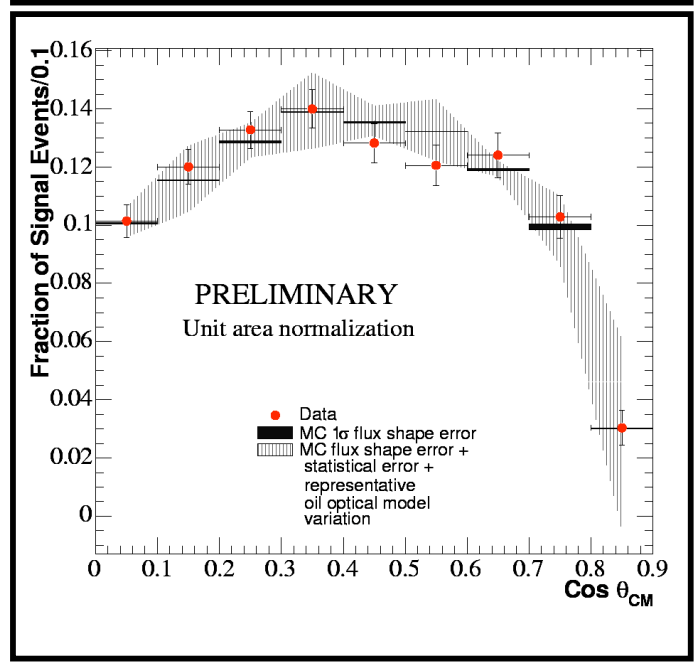
generic 2 ring fit
determine E, direction
of each Cherenkov ring
π decay kinematics

~7,000 NC π^0 events now

important to verify that kinem consistent w/ simulation
MC fits details of π^0 decays nicely →

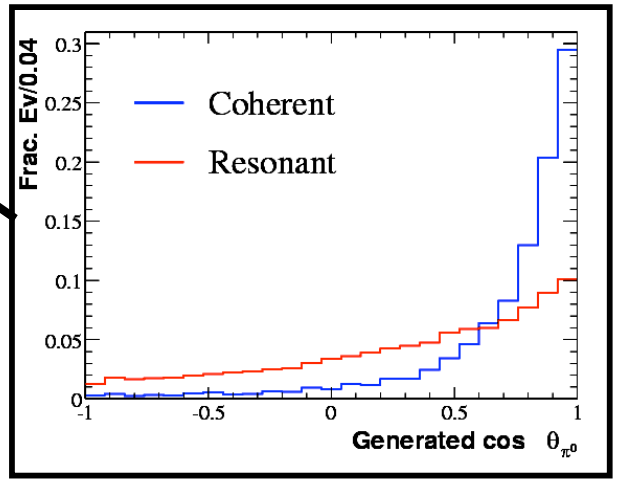
extracted signal π^0's in data & MC:





NC Coherent π^0 Production

π^0 angular distribution in lab sensitive to mode of production

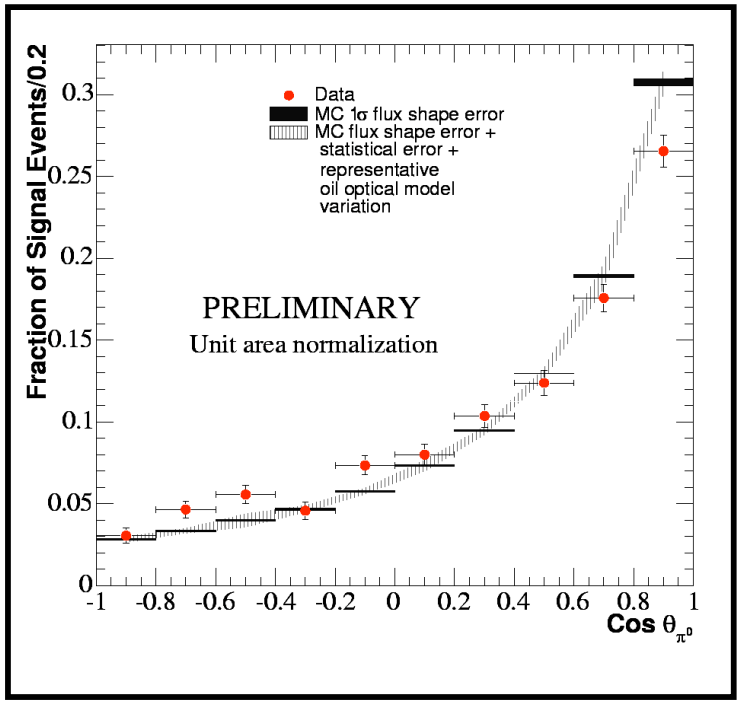


~ 80% **resonant** π^0 contribution (Δ)

- more isotropic

~ 20% **coherent** π^0 contribution

- sharp forward peaked distribution



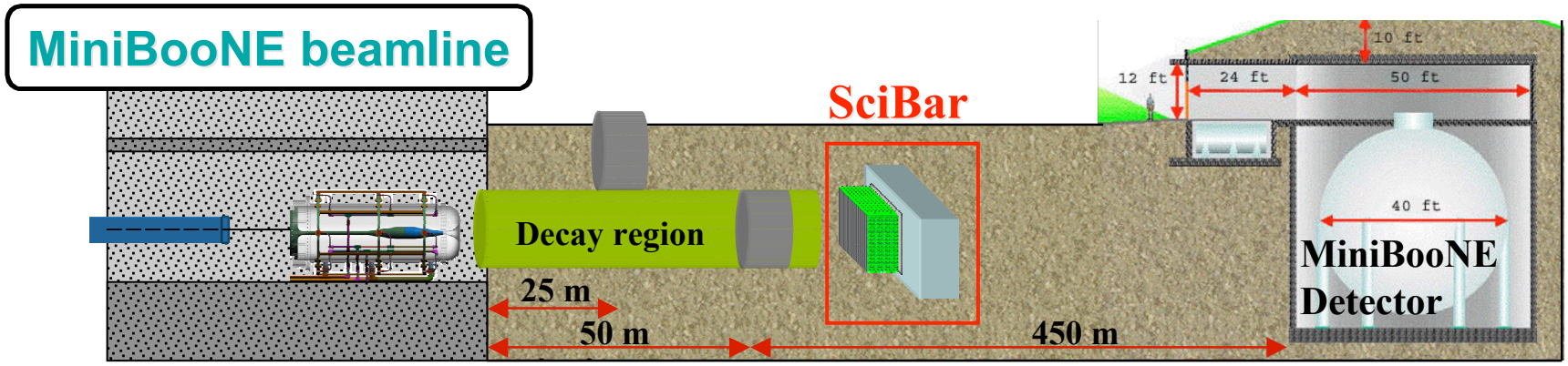
- data suggests lower level of coh. π^0 production predicted by Rein-Sehgal
  - also seen at K2K
    - lower $E_\nu \Rightarrow$ different bkgds
  - has implications on $\nu_\mu \rightarrow \nu_e$ bkgds

- Cannot measure neutrino energy
- Flux-averaged measurements only!

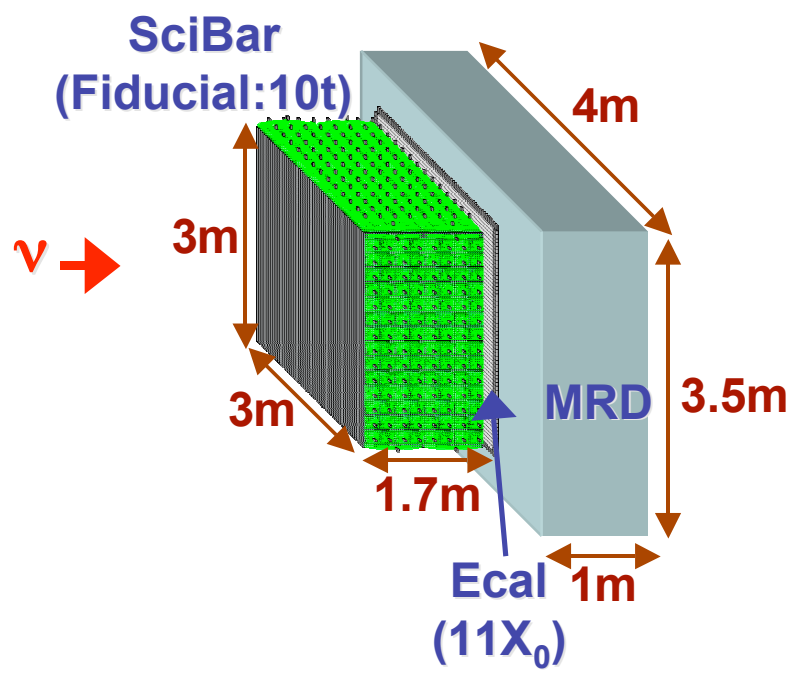
MiniBooNE σ_ν Wrap Up

- MiniBooNE data set is allowing σ_ν measurements around 1 GeV with unprecedented statistics
  - MB was designed to search for $\nu_\mu \rightarrow \nu_e$
    - Distinguish μ from e from π^0
- Final state resolution does not allow exclusive channel measurements
- Fine grained detector can greatly improve systematics on exclusive final state $\nu_\mu, \bar{\nu}_\mu$ σ measurements
  - Necessary for precision oscillation searches

7. SciBooNE Detector Configuration



- 100m from the target
- On-axis position
- (1~2)x10^{19} POT/month

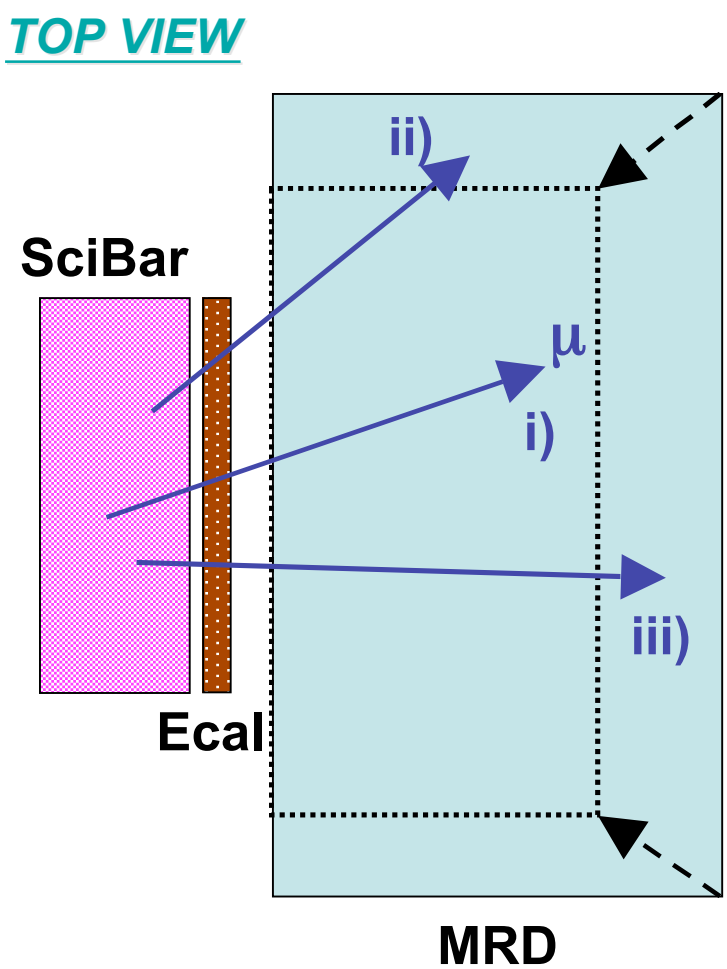


- Bring SciBar detector to FNAL (including readout electronics)
- Also bring EC
- Arrange MRD at FNAL

MRD Change

- MRD at K2K: 12 iron planes with drift chambers
  - Each: 7.6m×7.6m
- SciBooNE: iron planes 3.5m×4m with plastic scintillators
  - 12 planes, 5 cm
- Smaller angular coverage
- Finer muon range resolution

MRD size study



Strategy

1. Starting from K2K MRD size
   - Select MRD matching sample
2. Define new, smaller MRD
3. Calculate muon stopping point
   i) Stop in the new MRD
   ii) Exit from the side
   iii) Penetrate all layers
4. Case i) and iii) are accepted as new MRD matching samples.

→ **Estimate MRD matching efficiency**

MRD matching efficiency

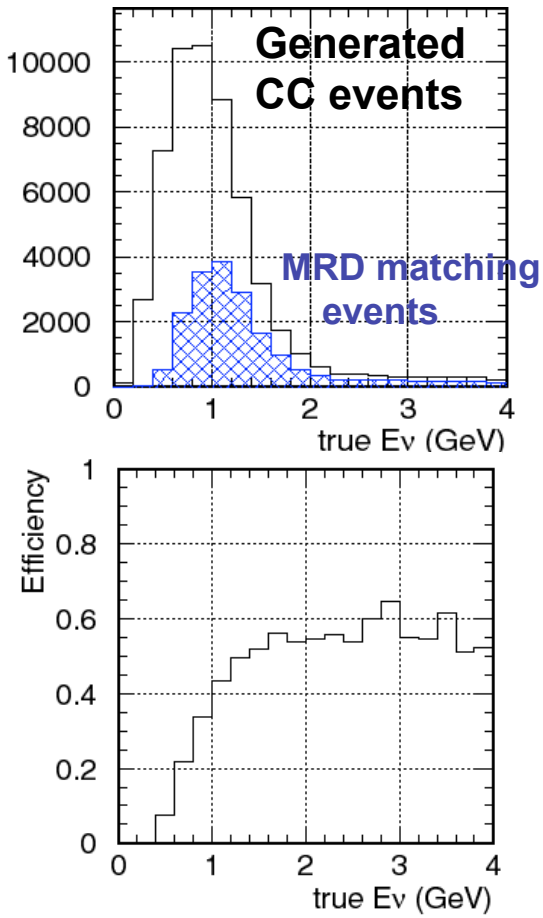
FNAL MRD size (4.0m x 3.5m)

$$\varepsilon_{MRD} = \frac{(\text{MRD match})}{(\text{generated CC})}$$

Compared to CC only

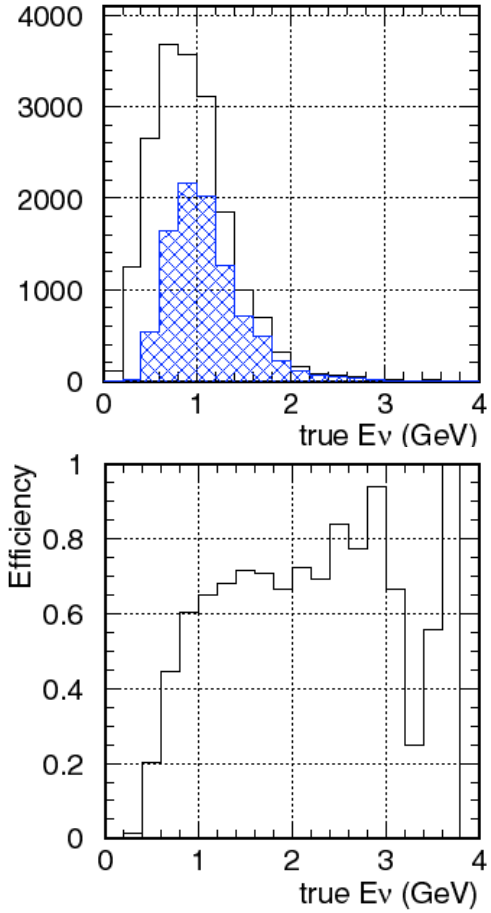
Compared to all events

Neutrino run



ε_{MRD} = 0.33

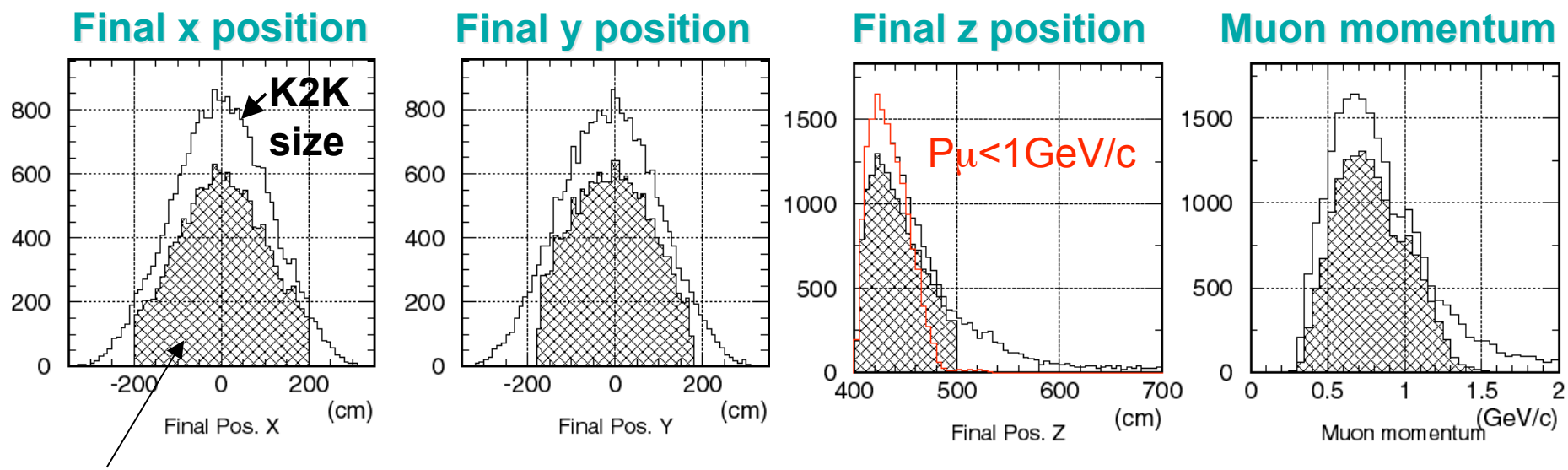
Anti-neutrino run



ε_{MRD} = 0.50

Muon stopping points

K2K MRD: 7.6m x 7.6m
FNAL MRD: 4.0m x 3.5m, 5cm-thick iron ~12 plates (w/ scinti.)



Stopped events in FNAL MRD

12 layers of 5cm-thick iron are sufficient
To measure muon momentum up to ~1GeV/c.

The number of MRD matching events

K2K MRD: 7.6m x 7.6m
FNAL MRD: 4.0m x 3.5m, 5cm-thick iron ~12 plates (w/ scinti.)

Neutrino run (5×10^{19} POT)

	K2K	FNAL	FNAL/K2K
All MRD sample	23,458 events	18,760 events	0.80
CC-QE	14,347	11,244	0.78
CC-$1\pi^+$	4,953	4,027	0.81
CC-coh. π	850	831	0.98
CC-multi π	2,324	1,851	0.80

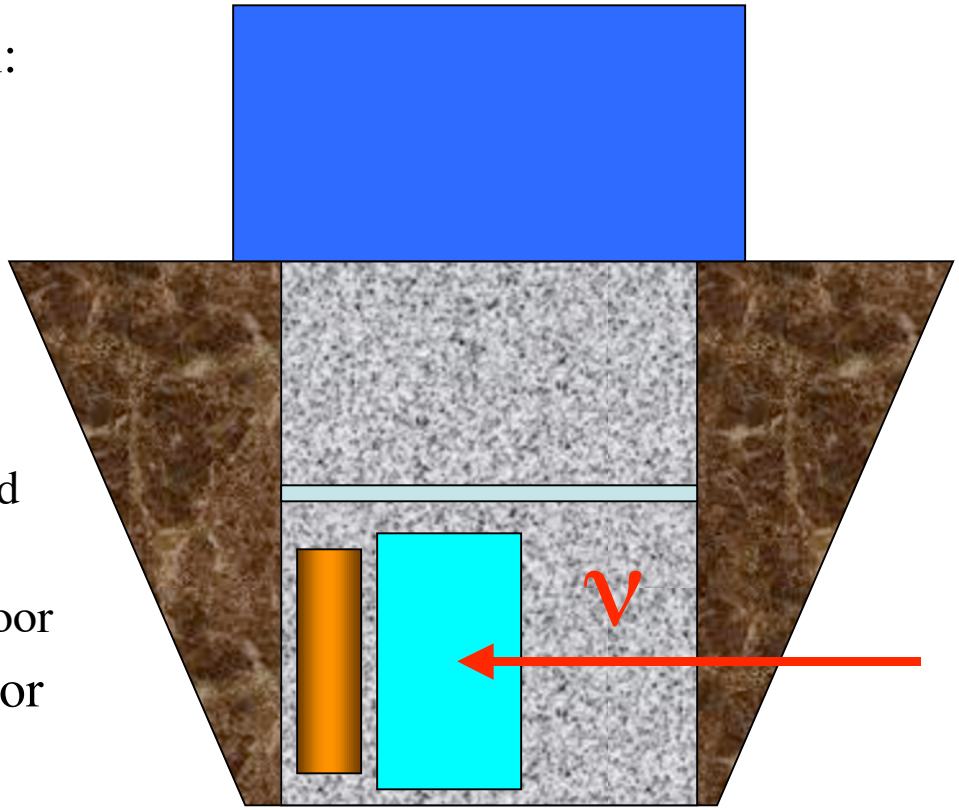
Anti-neutrino run (10^{20} POT)

	K2K	FNAL	FNAL/K2K
All MRD sample	11,016 events	9,659 events	0.88
CC-QE	7,987	6,870	0.86
CC-$1\pi^-$	1,440	1,307	0.91
CC-coh. π	770	755	0.98
CC-multi π	482	422	0.88

- FNAL MRD loses 10~20% compared to K2K. ← Acceptable
- (Note: the acceptance does not change for CC-coherent π.)

Detector Hall & Installation

- Construct a small hall for the on-axis position
- Assemble detector planes and install fibers/PMTs/front-end in NuMI surface hall
- After civil construction of detector hall:
  - See Tomski's talk for details
- Install iron planes for MRD
  - Lower with a mobile crane
  - Also scintillators/PMTs
- Lower detector into hall
  - Side PMTs read out by racks on ground floor
  - Top PMTs read out by racks on 2nd floor
- Steel grating ceiling/floor above detector



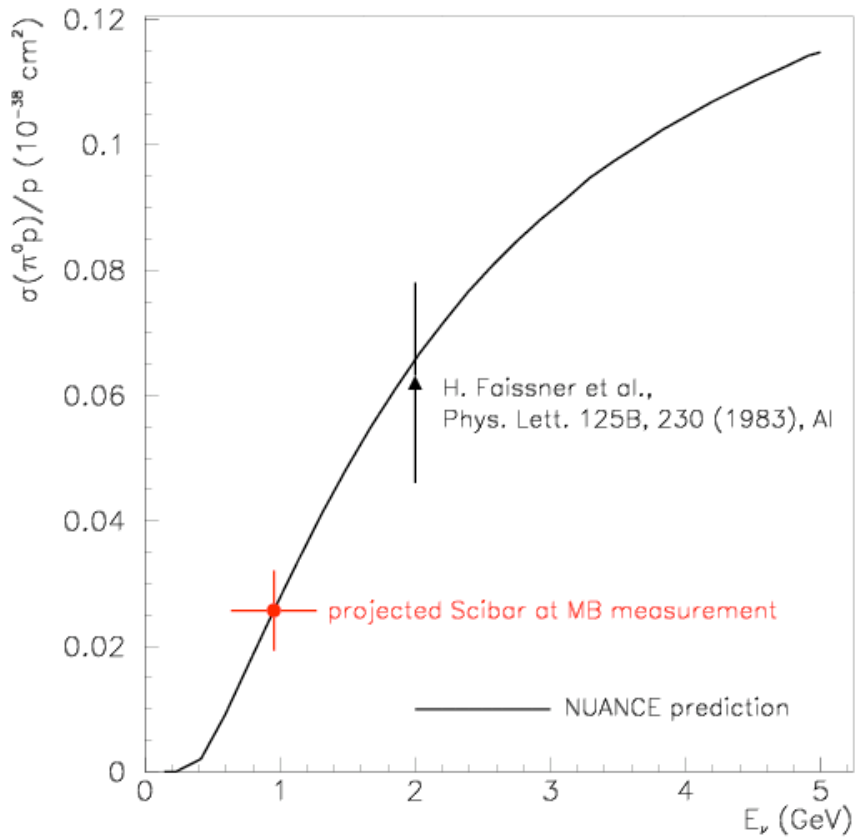
Drawing not to scale

8a. SciBooNE Physics Measurements

- Energy dependence of NCπ0 σ
  - Covered already
- Exclusive π-p final state measurements
- Radiative Δ decay
- Event rate expectations indicate many more σ_νs available for measurement

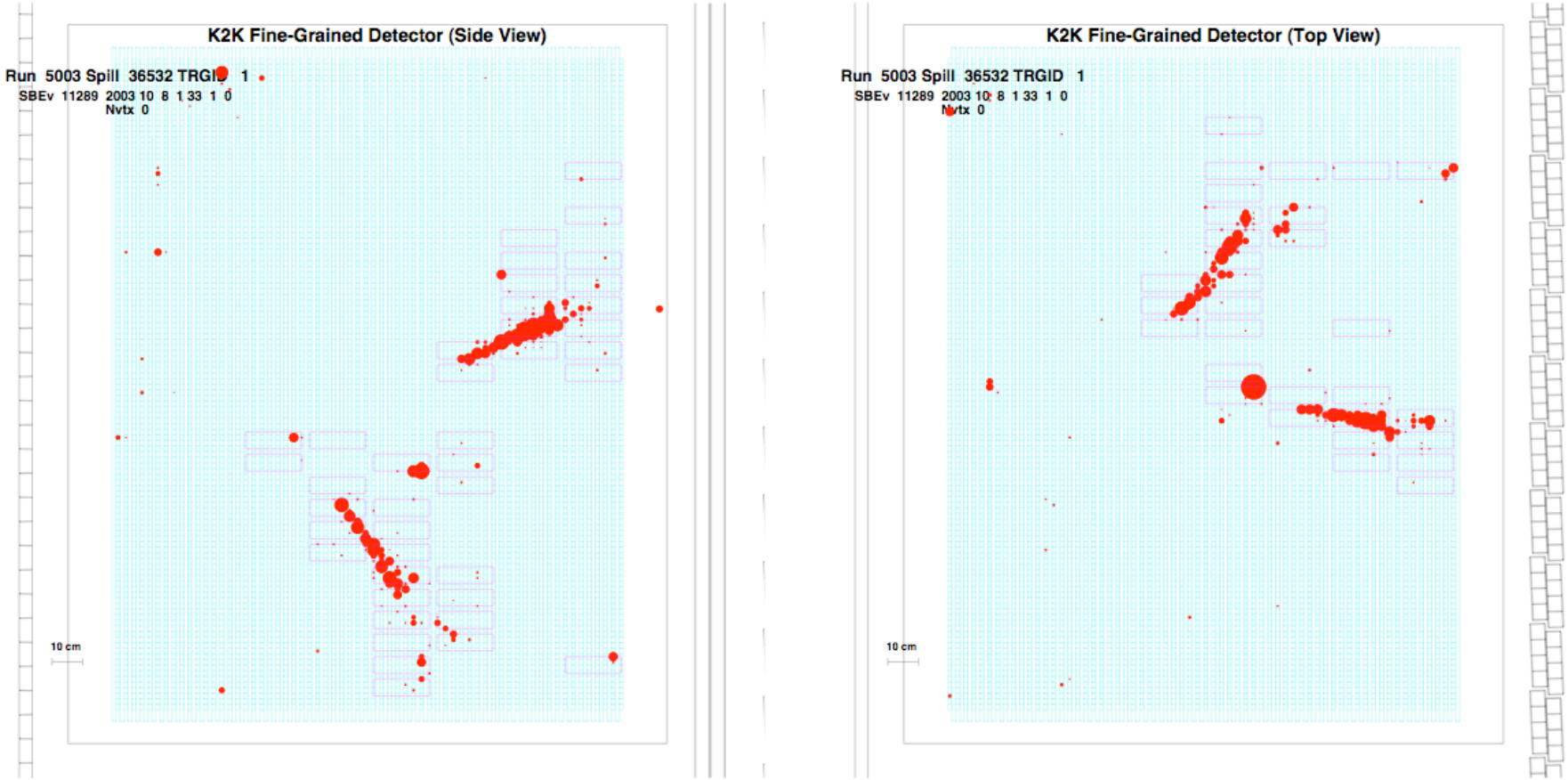
Exclusive π-p Final States

- Fine grained resolution allows observation of exclusive $\bar{\nu}_\mu p \rightarrow \bar{\nu}_\mu p \pi^0$
- Only one other published measurement
- Expect ~1100 events in antineutrino mode



- ν mode: Separation of contributions from Δ^0 and Δ^+ states

NCπ^0 Event in SciBar



- $\pi^0 \rightarrow \gamma\gamma$
- Photons pair produce, $e^+ + e^-$ pairs travel closely together
  - tracks visible
- Photon ($e^+ + e^-$) tracks distinguishable from single e^- tracks
  - dE/dx consistent with 1 or 2 MIPs

Radiative Δ Decay

- $\Delta \rightarrow N\gamma$ is a large and uncertain background for ν_e appearance (NOνA too!)
  - BR = 0.52(60)%
- Event signature
  - NC: recoil proton and detached photon track
  - CC: muon and recoil proton with shared vertex and photon with detached vertex
  - Each case: photon and proton tracks should be consistent with decay of Δ mass particle
  - π^0s provide calibration sample for photon tracks
- Expect ~45 events in total run (ν and $\bar{\nu}$ mode)
- Would be first observation and confirmation of (anti)neutrino induced Δ radiative decay

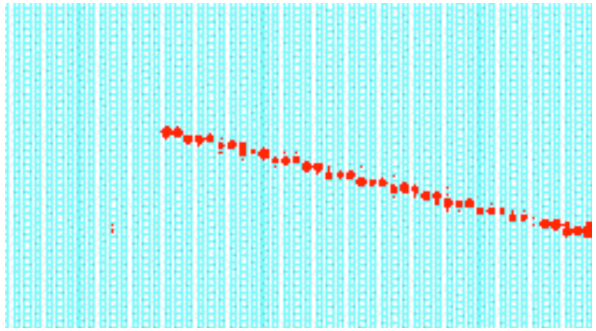
9. Measurements useful for MiniBooNE

- Wrong sign background spectrum in $\bar{\nu}$ mode
  - MiniBooNE cannot distinguish μ^- from μ^+
    - No magnetic field!
- External flux constraints for $\nu,\bar{\nu}$ disappearance
  - SciBar is not needed for MiniBooNE to check the LSND oscillation hypothesis
  - Particularly helpful for $\bar{\nu}_\mu$ disappearance!
- External constraint of intrinsic ν_e background
  - Direct measurement of intrinsic ν_e flux from BNB

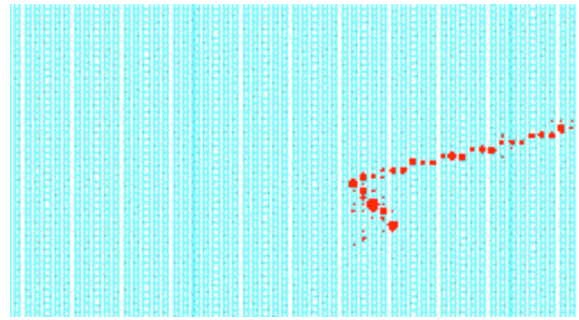
Reconstructed $E_{\bar{\nu}}, E_{\nu}$

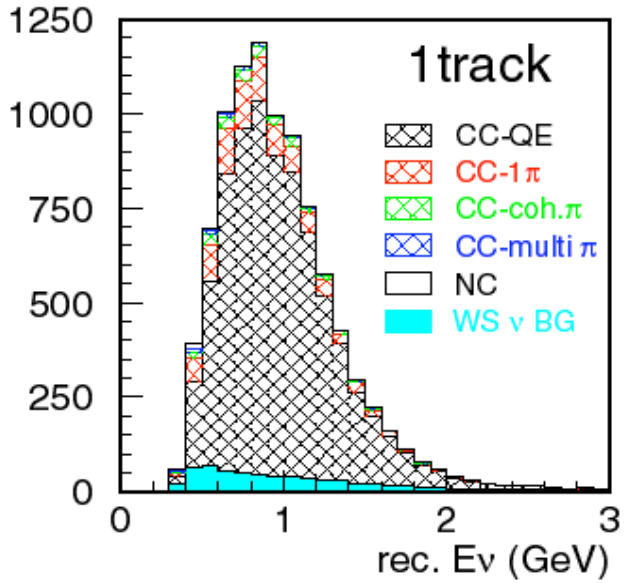
1.5x10^{20} POT

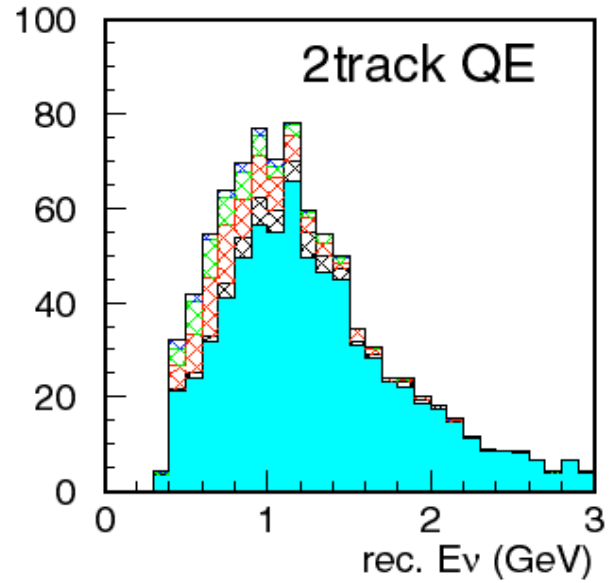
$\bar{\nu}+p \rightarrow \mu^{+}+n$



$\nu+n \rightarrow \mu^{-}+p$





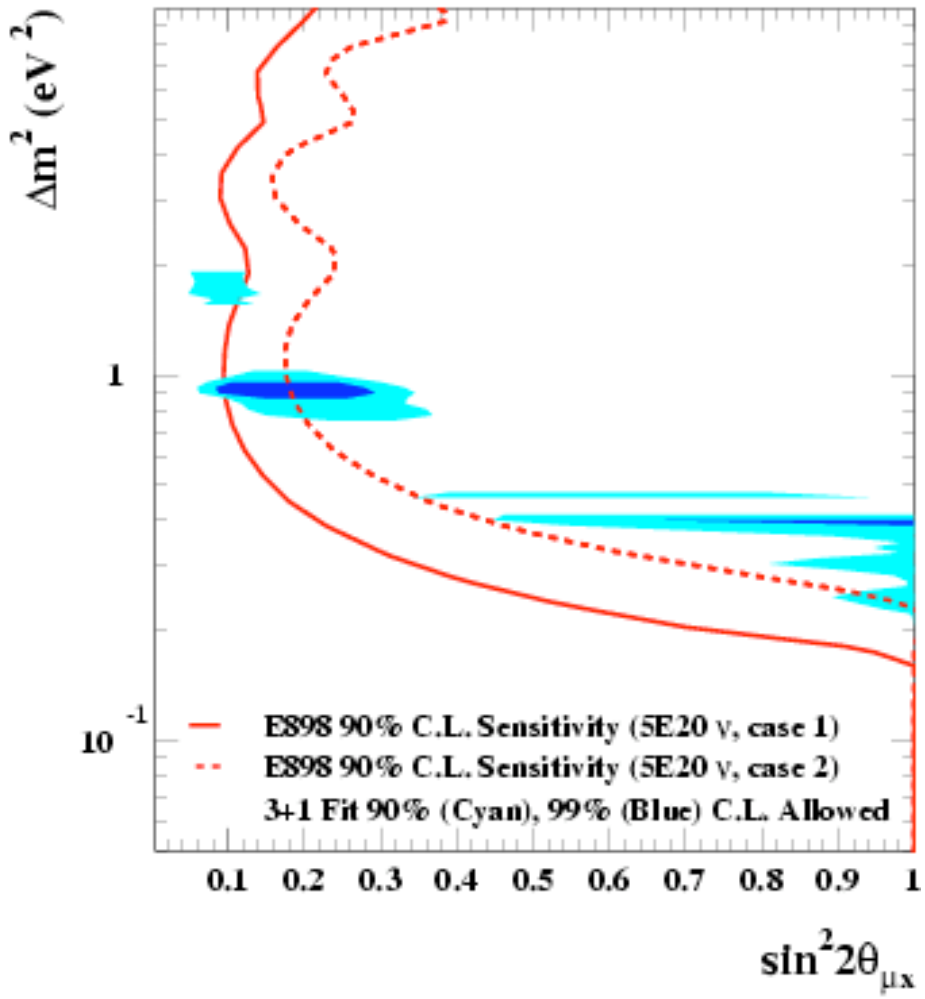


Anti-ν QE: ~80%
WS ν BG: ~7%
(compare to 30% in MiniBooNE!)

WS ν BG: ~80%

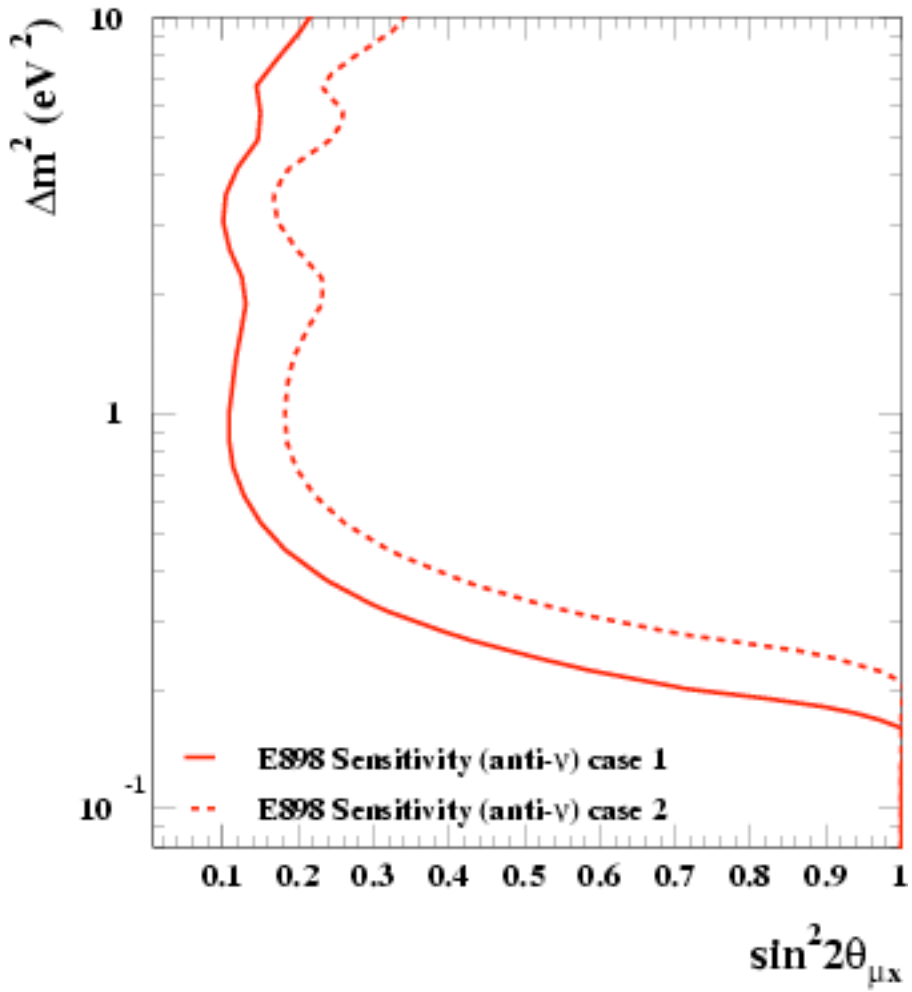
ν_μ Disappearance

- SciBar offers an external constraint on the flux
  - Actually $\Phi \times \sigma$
- Flux uncertainties are the dominant uncertainty for ν_μ disappearance
  - Flux *shape* is especially important, because spectral distortion is characteristic of ν oscillations
- Shown at right are sensitivity curves:
  - 5% shape and 10% normalization uncertainties
  - 10% shape and 25% normalization

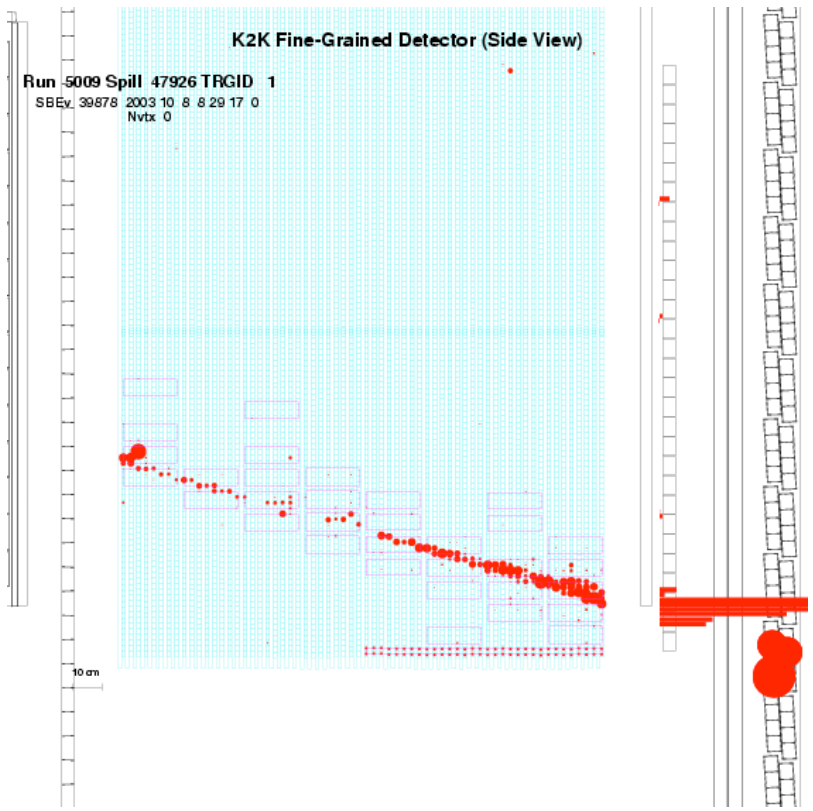


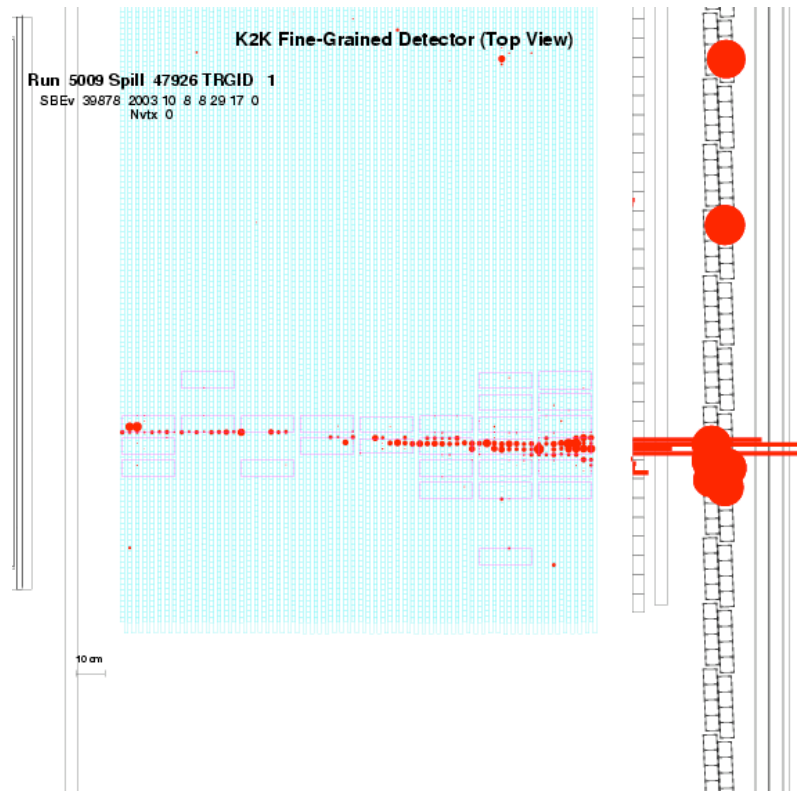
$\bar{\nu}_\mu$ Disappearance

- Flux shape is compared to event distribution shape for disappearance analysis
  - Requires good energy resolution
- Need to know spectrum of WS BGs for $\bar{\nu}_\mu$ disappearance
  - Must extract energy spectrum of $\bar{\nu}_\mu$ events
- Shown at right is the $\bar{\nu}_\mu$ disappearance sensitivity:
  - 5% shape and 10% normalization uncertainties
  - 10% shape and 25% normalization



Direct Intrinsic ν_e Measurement





- Electron catcher provides good electromagnetic ID and energy resolution
  - Can use dE/dx in SciBar as well
- Expect to directly measure ν_e flux to 10-20% in ν mode
- MiniBooNE's constraints are all *indirect*

10 & 11. Schedule and Costs

- Please see presentation by Tom Lackowski

Backup Slides

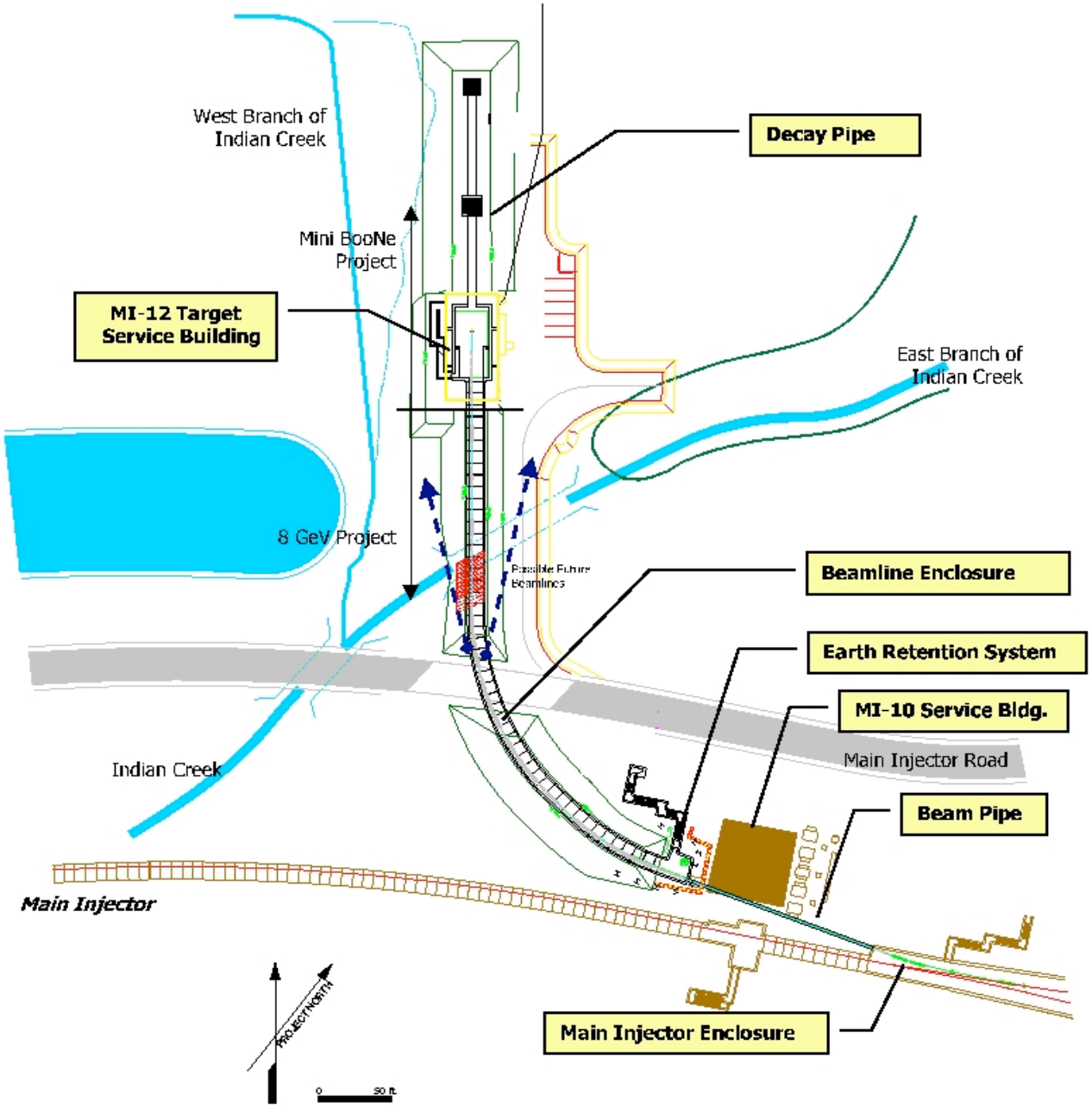
CC1π^0 Production

ν_μ n $\rightarrow$ μ^- p π^0

Why important?

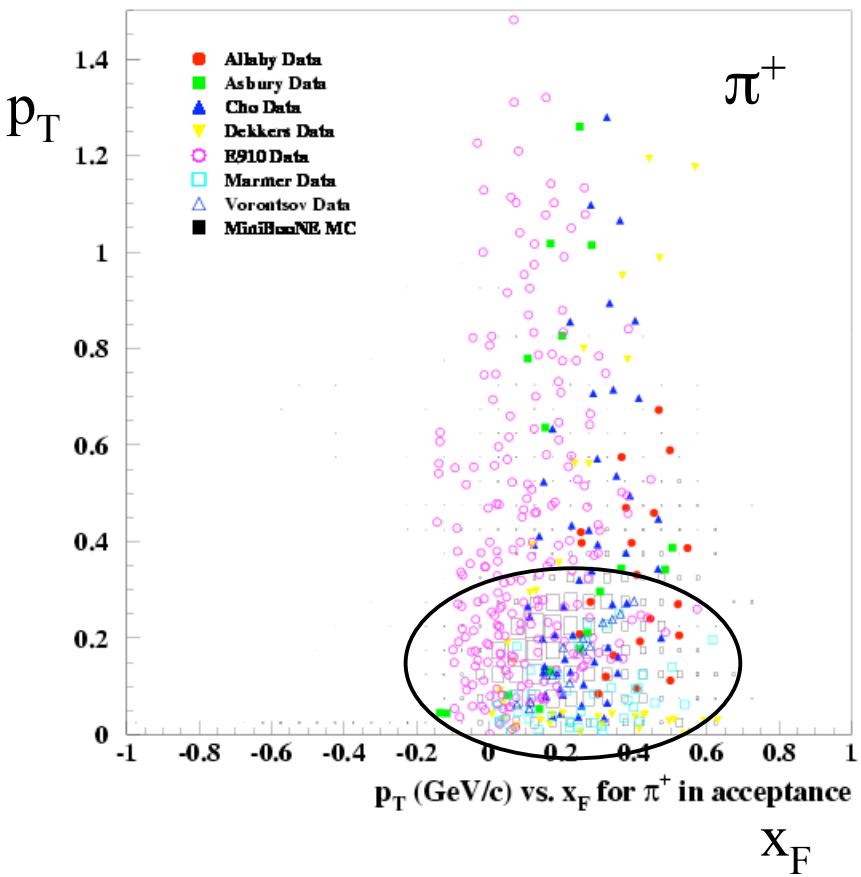
- Resonant production: related to CC1π^+
- No coherent production possible
  - Doesn't conserve charge
- Useful for constraining coherent/resonant fractions in CC1π^+ production

8 GeV Beamline



Simulating The BNB

primary p+Be interactions



- Most of the available data were taken in the 1970-80's.
- Low statistics
- Normalization errors often ~20%
- In some cases papers are missing important information
- Relevant data dominated by
  Brookhaven E910 experiment (5%)
  6 GeV/c & 12.3 GeV/c beam
- No available data at exactly MB beam energy

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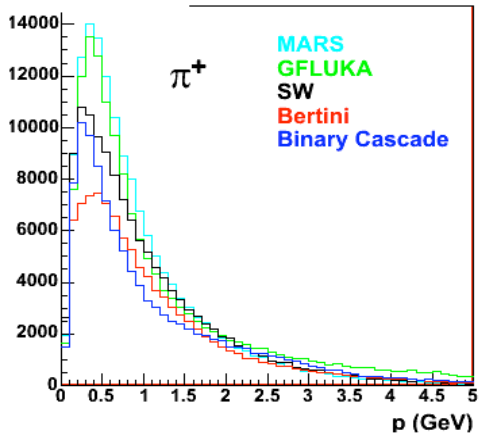
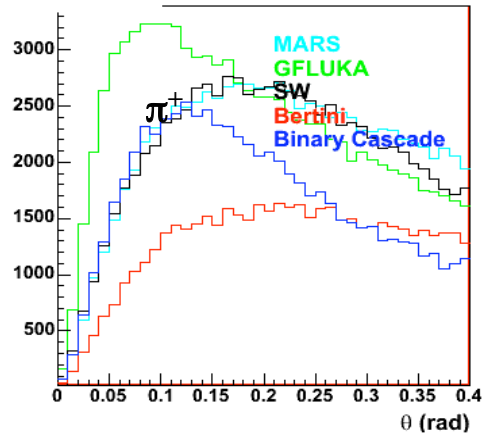
Simulating The BNB

primary p+Be interactions



pion momentum (GeV/c)



pion angle (rad)

- Simulate neutrino flux with many pion production (primary interaction) models

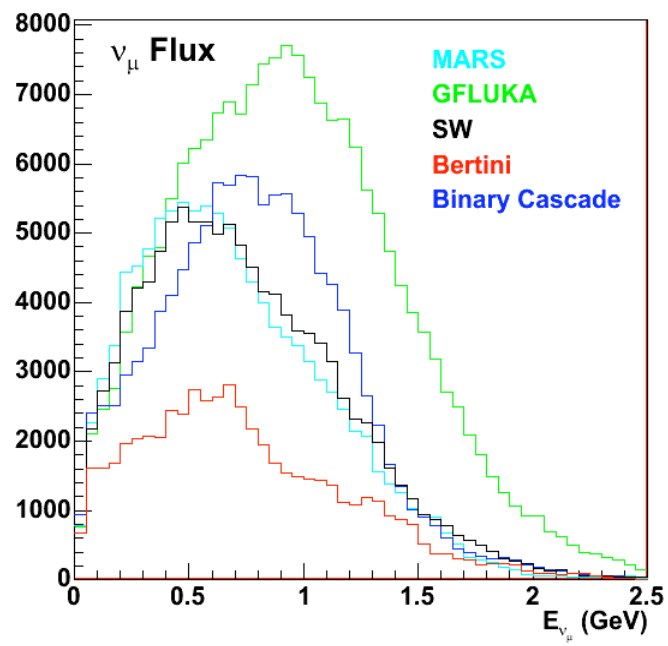
- Varying results most likely due to differences in:
  - data used to tune the models
  - phenomenological differences in implementation.

- Simulate 8.9 GeV/c protons on the MiniBooNE beryllium target and look at pion production for 5 different hadronic interaction models

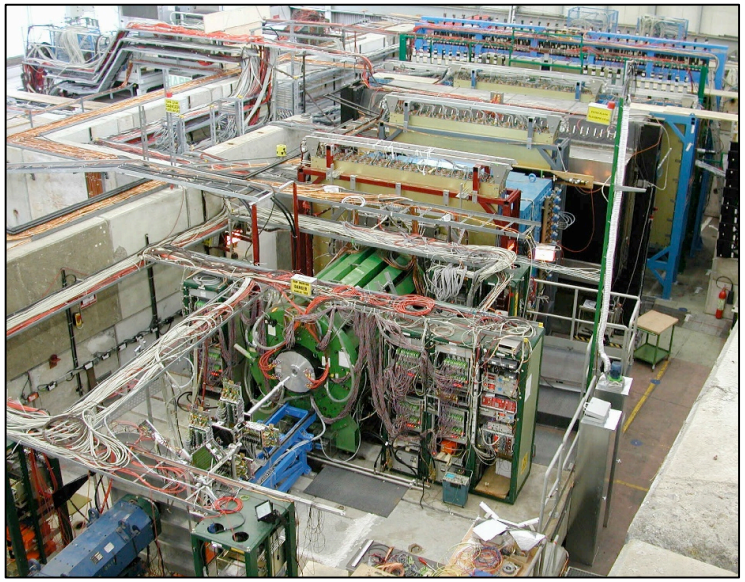
- MARS, GFLUKA, SW, Bertini, Binary

- Propagate through geometry and generate neutrino fluxes (from π^+) at MiniBooNE detector

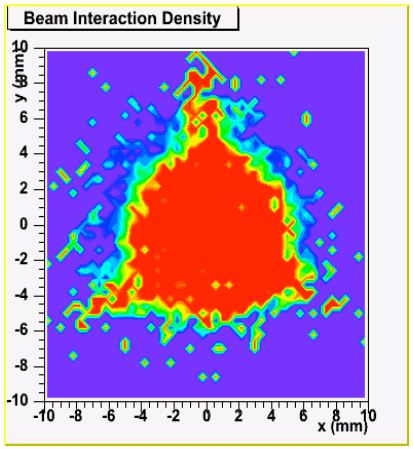
- HARP Be π^+ production uncertainties will be ~5% total



Hadron Production at HARP



- First HARP results on Al at 12 GeV for K2K
- Next goal is to measure π^+ production cross sections for Be at p_{proton} = 8.9 GeV/c.
- Additional measurements include:
  - π^- production (important for anti-n 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	

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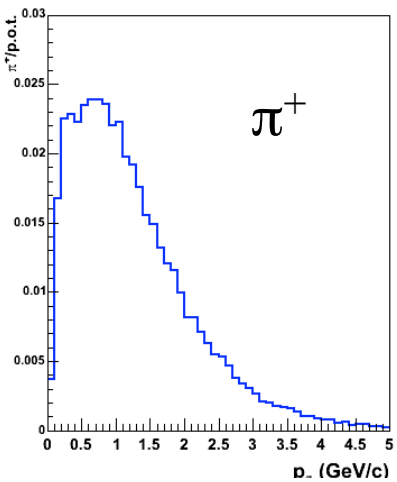
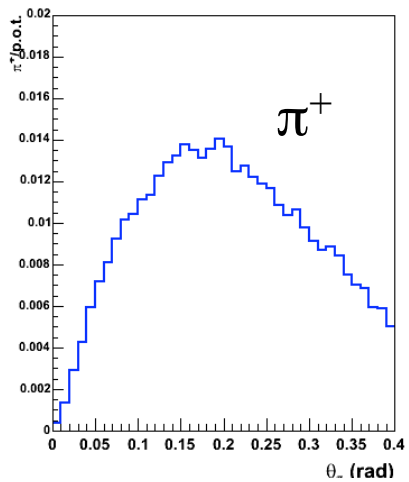
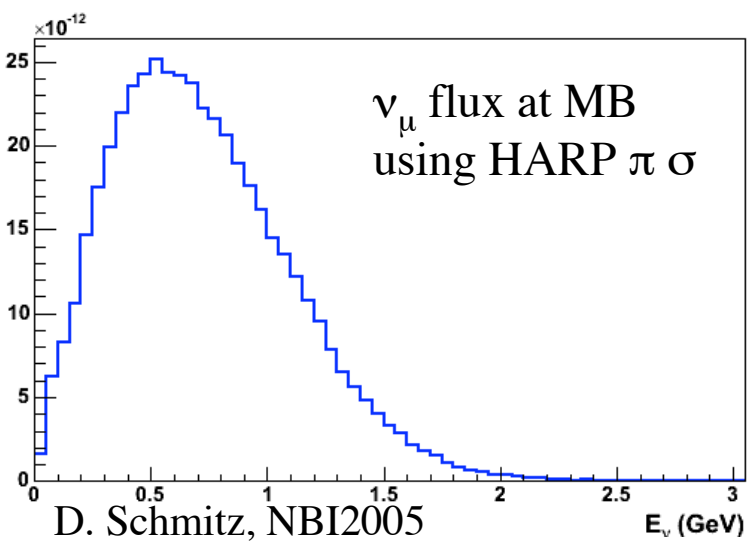
HARP Be Thin Target Results

- Use a SW parametrization fit to HARP data alone to generate pions in the MB Monte Carlo.







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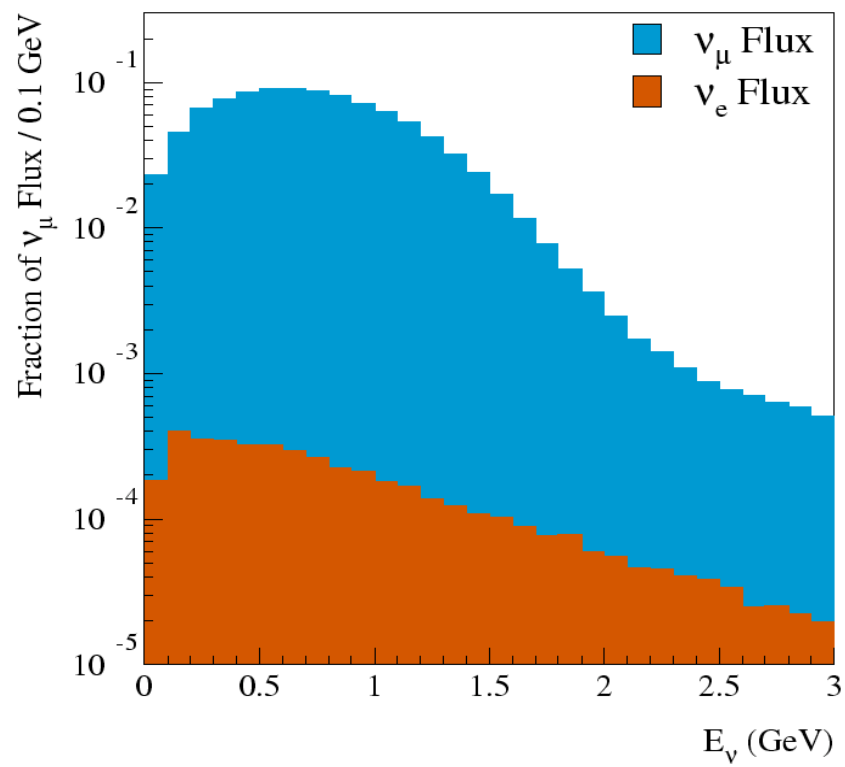
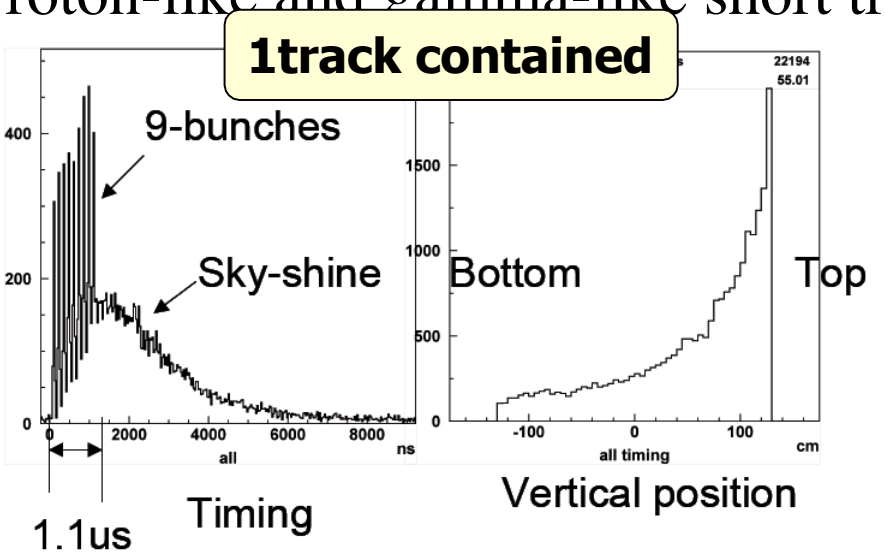
•HARP cross sections are similar (within ~10%) to the SW fits used to date (more quantitative study needed)

- HARP results will significantly reduce the MB flux uncertainty (full error studies to come as well)

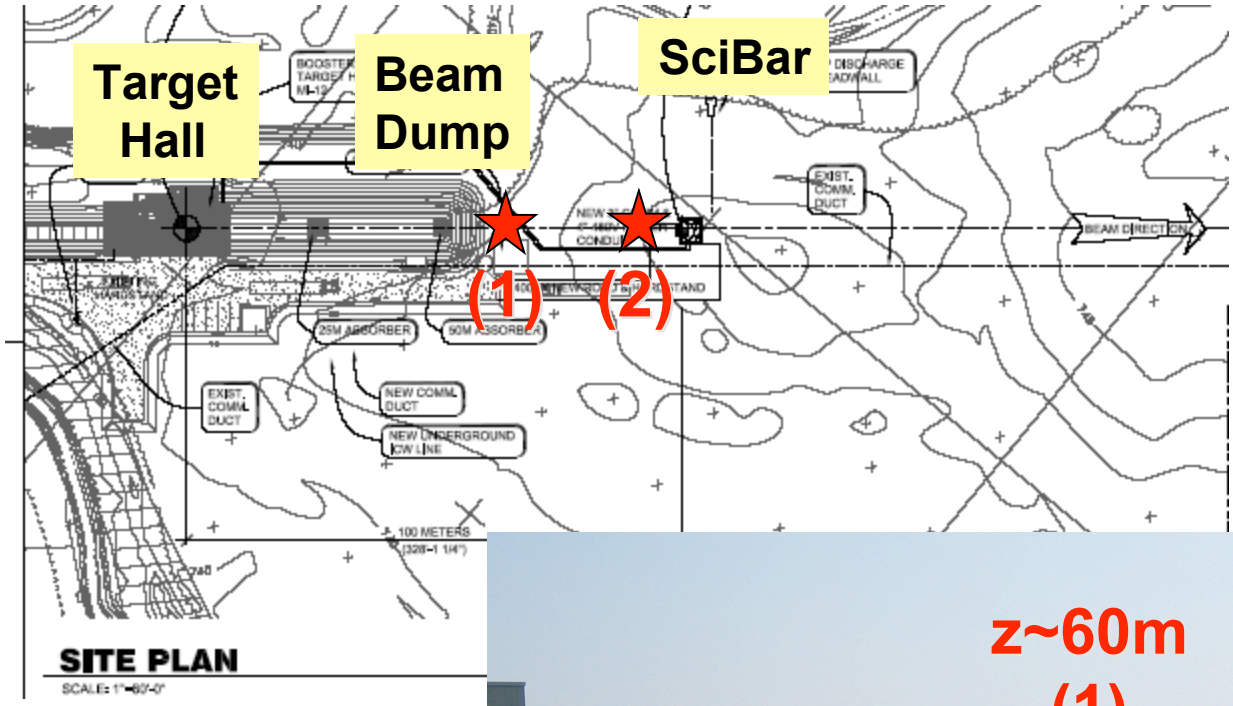


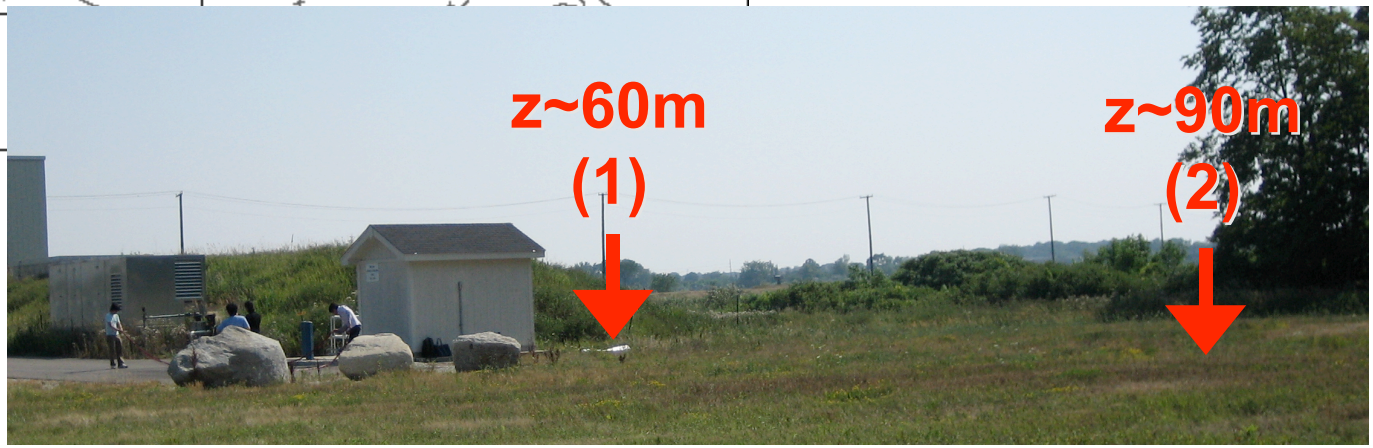
Beam related Background (1) ~Introduction~

- There exists beam related backgrounds at K2K near detector
  - From upward, upstream
  - Proton-like and gamma-like short tracks



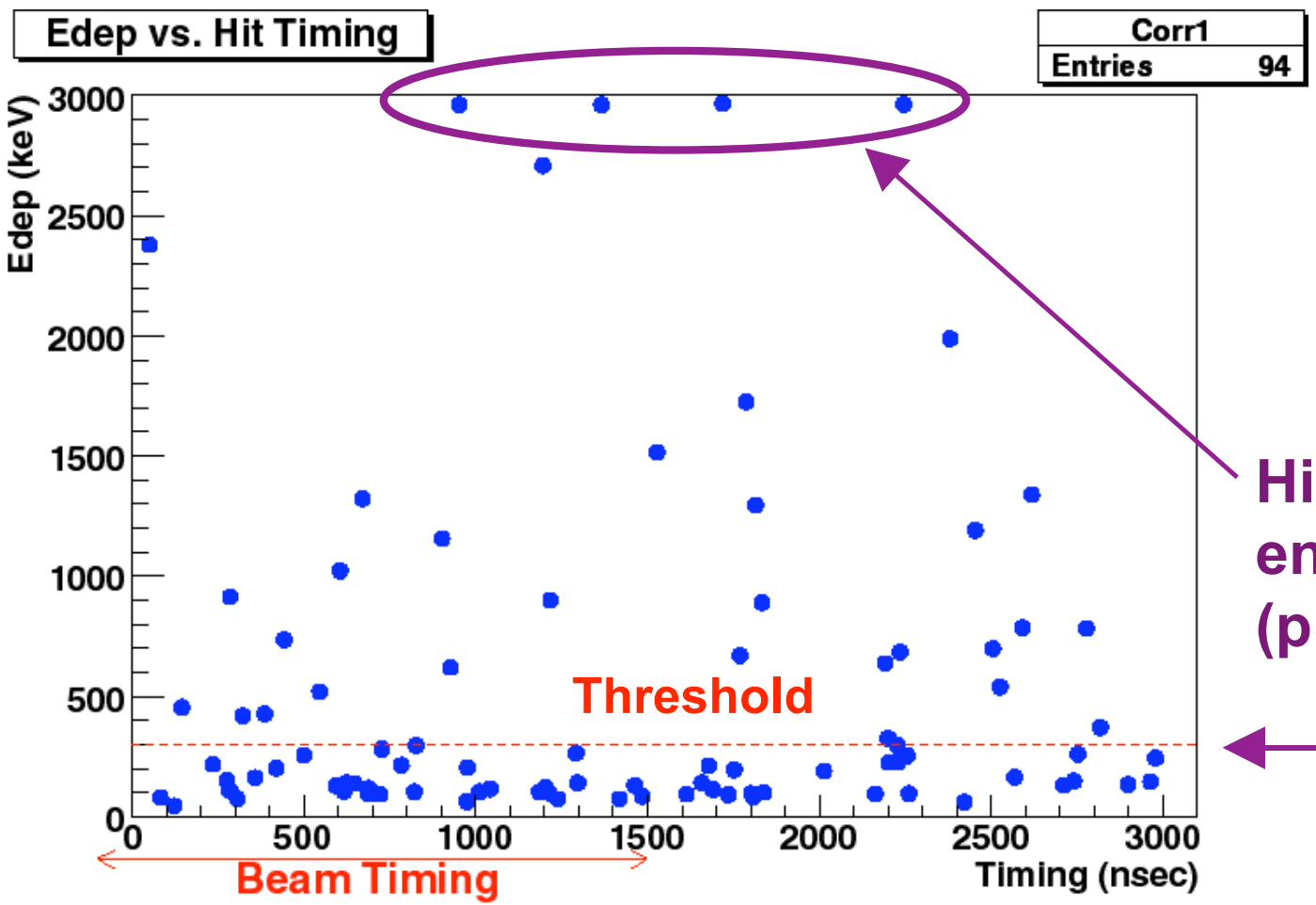
Beam related background (2)
~Measurement setup~





Scintillators were put on the ground

Beam related background (3)
~Energy deposit vs. Hit timing~



- z~60m
- On-timing (3μsec gate)
- 25,889 spills

Hits with large energy deposit (proton-like?)

Many low energy hits (gamma-like?)

Beam related background (4)
~Observed number of events at BNB~

	(1) z~60m		(2) z~90m	
	On-time	Off-time	On-time	Off-time
# of spills	25,889	10,072	33,441	10,233
Single hit Scinti. 1	16	0	14	0
Single hit Scinti. 2	37	0	20	1
coincidence	5	0	4	0

On-time: 1.5μsec gate at beam-timing
Off-time: 1.5μsec gate (~8msec after beam-timing)

The excess of hits at beam-timing was observed!

Beam related background (5)
~Comparison between BNB and K2K~

	Booster Neutrino Beam line		K2K Near Detector Hall	
POT/spill	$(4.0\sim4.5)\times10^{12}$		$\sim5\times10^{12}$	
Location	Z~60m Ground level	Z~90m Ground level	Top of SciBar	K2K-ND Hall Ground level
Single hit (Scinti. 1/2)	1) 38±10(stat) 2) 59±10(stat)	1) 26±7(stat) 2) 25±6(stat)	2.3	18
coincidence	8.0±3.6(stat)	4.9±2.5(stat)		

[# of events/spill/15tons]