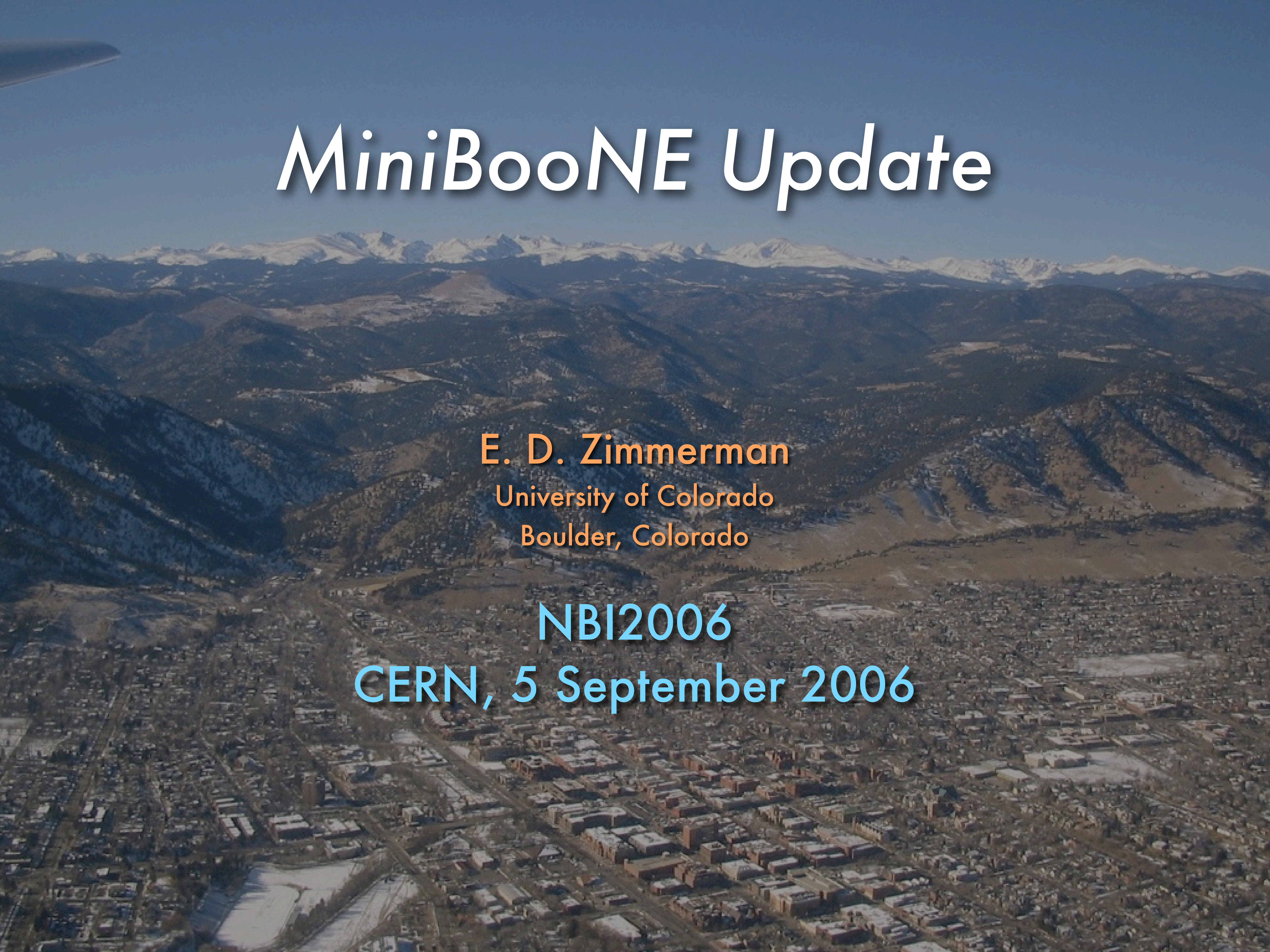

MiniBooNE Update

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NBI2006
CERN, 5 September 2006

MiniBooNE Update

- Intro to MiniBooNE
- The Booster Neutrino Beam
- The oscillation and cross-sections analyses
- Previews of BooNE talks at NBI

MiniBooNE: E898/E944 at Fermilab

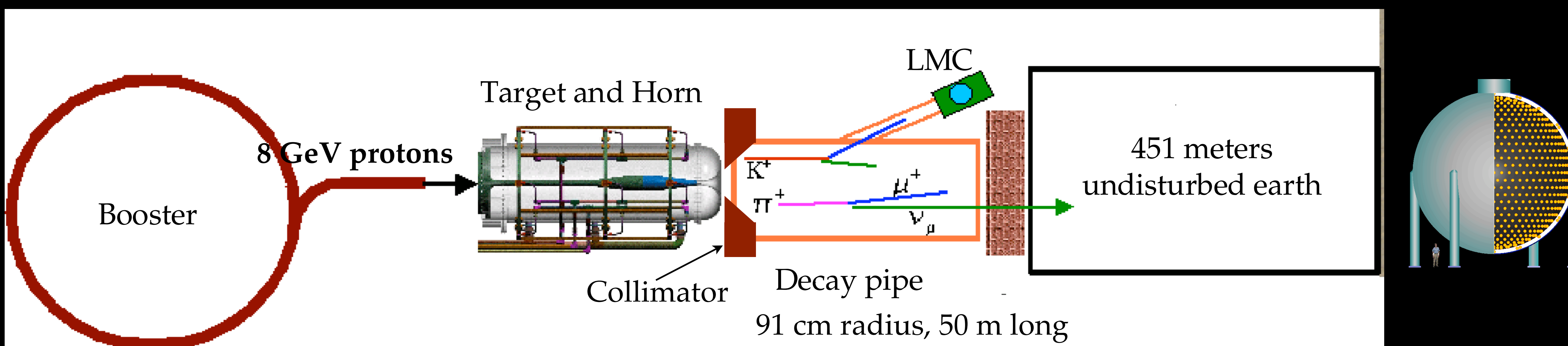
Purpose is to test LSND with:

- Higher energy
- Different beam
- x10 statistics
- Different oscillation signature
- Different systematics
- Antineutrino-capable beam

8 GeV primary proton beam from FNAL Booster

L=500 meters, E=0.5−1 GeV: same L/E as LSND.

MiniBooNE Beamline



- Booster provides about 5 pulses per second, 5×10^{12} protons per 1.6 μs pulse under optimum conditions – reached for the first time two weeks ago!

Data-taking status

- First oscillation result from 2002-2005 E898 data set (5.7E20 pot).
- Running since January 2006 in antineutrino mode as E944; 0.74E20 pot as of 8/25. (See M. Wascko's talk)

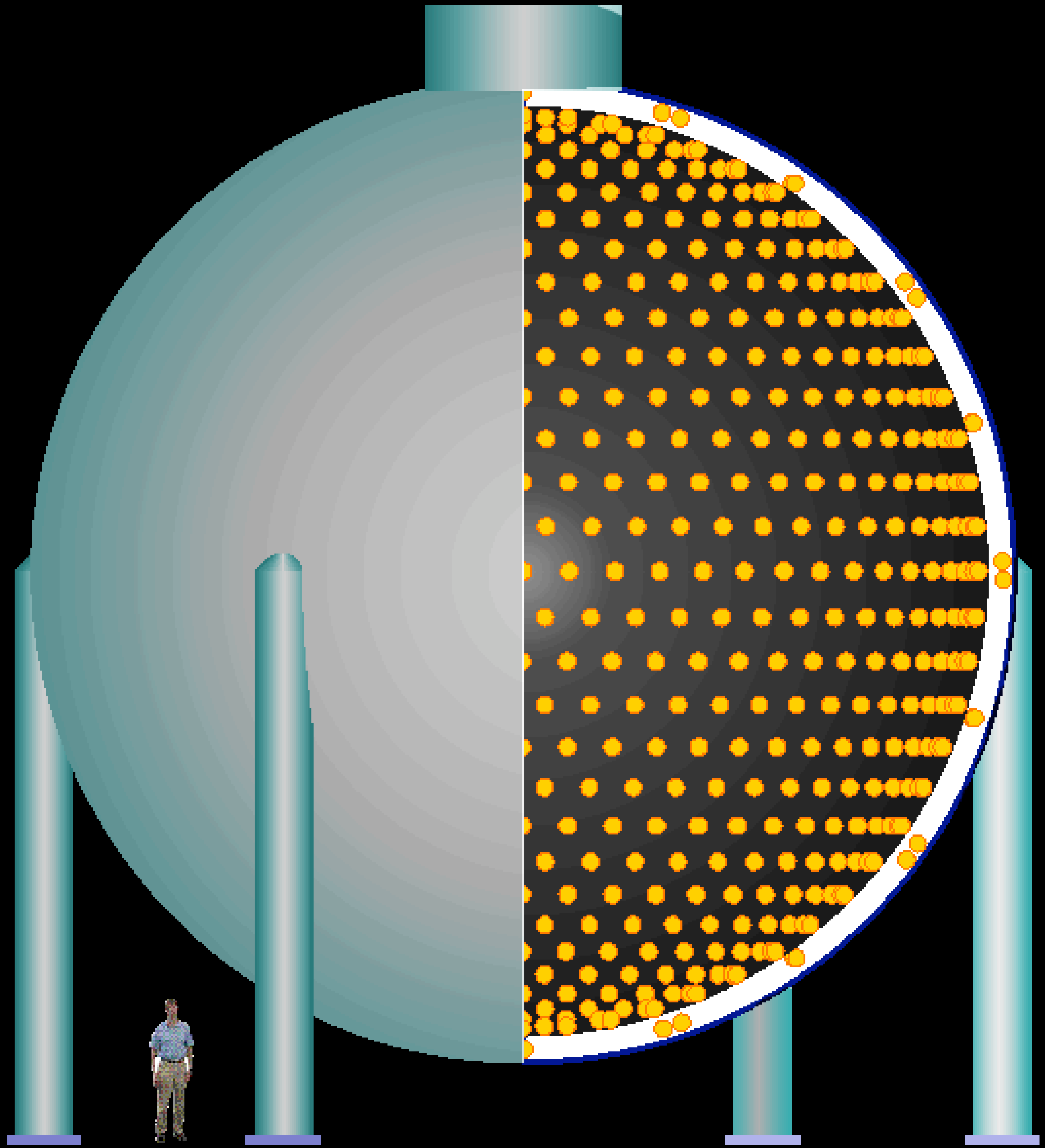
Oscillation Signature at MiniBooNE

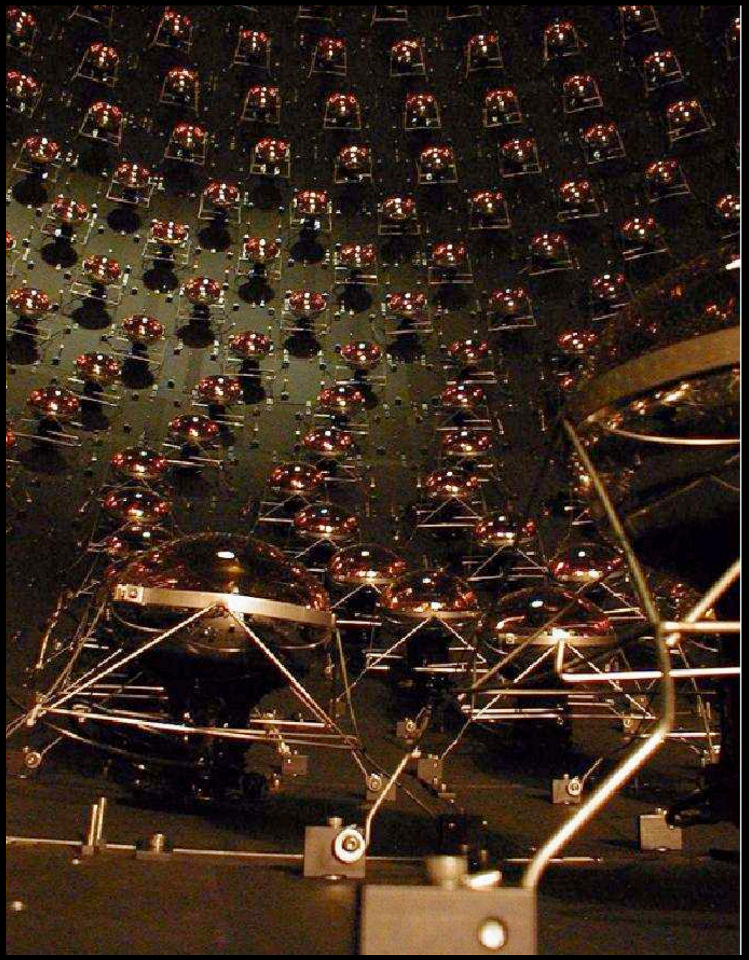
- Oscillation signature is charged-current quasielastic scattering:

$$\nu_e + n \to e^- + p$$

- Backgrounds to oscillation:
  - Intrinsic ν_e in the beam
    $\pi \to \mu \to \nu_e$ in beam
    $K^+ \to \pi^0 e^- \nu_e$, $K_L^0 \to \pi^0 e^\pm \nu_e$ in beam
  - Particle misidentification in detector
    μ mis-id as e, decay unseen
    π^0 produced in NC, decays to $\gamma\gamma$, mis-ID as e
    NC $\Delta^0 \to n\gamma$ branching ratio ~1%

The BooNE neutrino detector





- Pure mineral oil
- 800 tons; 40 ft diameter
- Inner volume: 1280 PMTs
- Outer veto volume: 240 PMTs

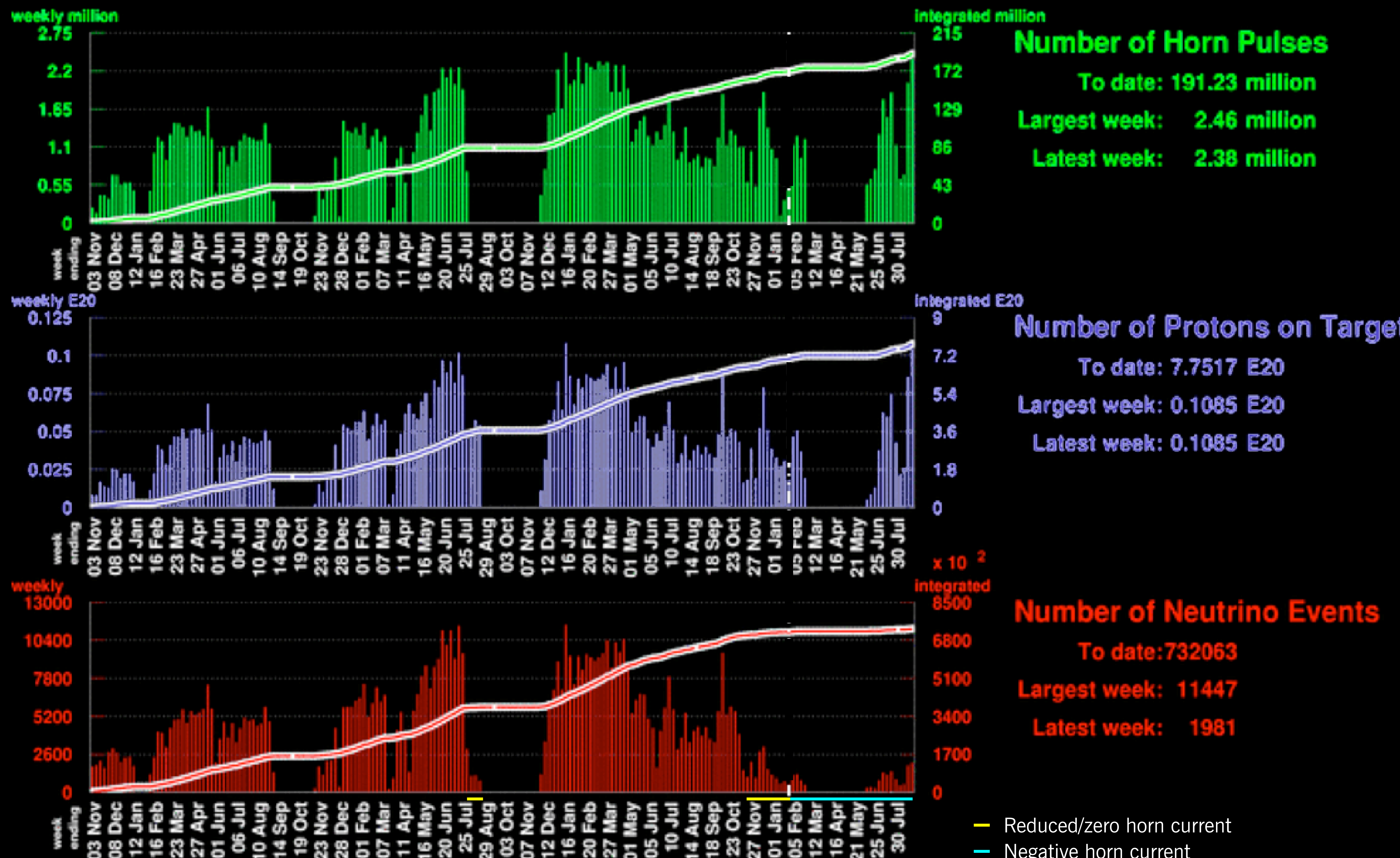
Booster Neutrino Beam

- Booster
- Primary beam
- Horn and target
- Decay region/absorber

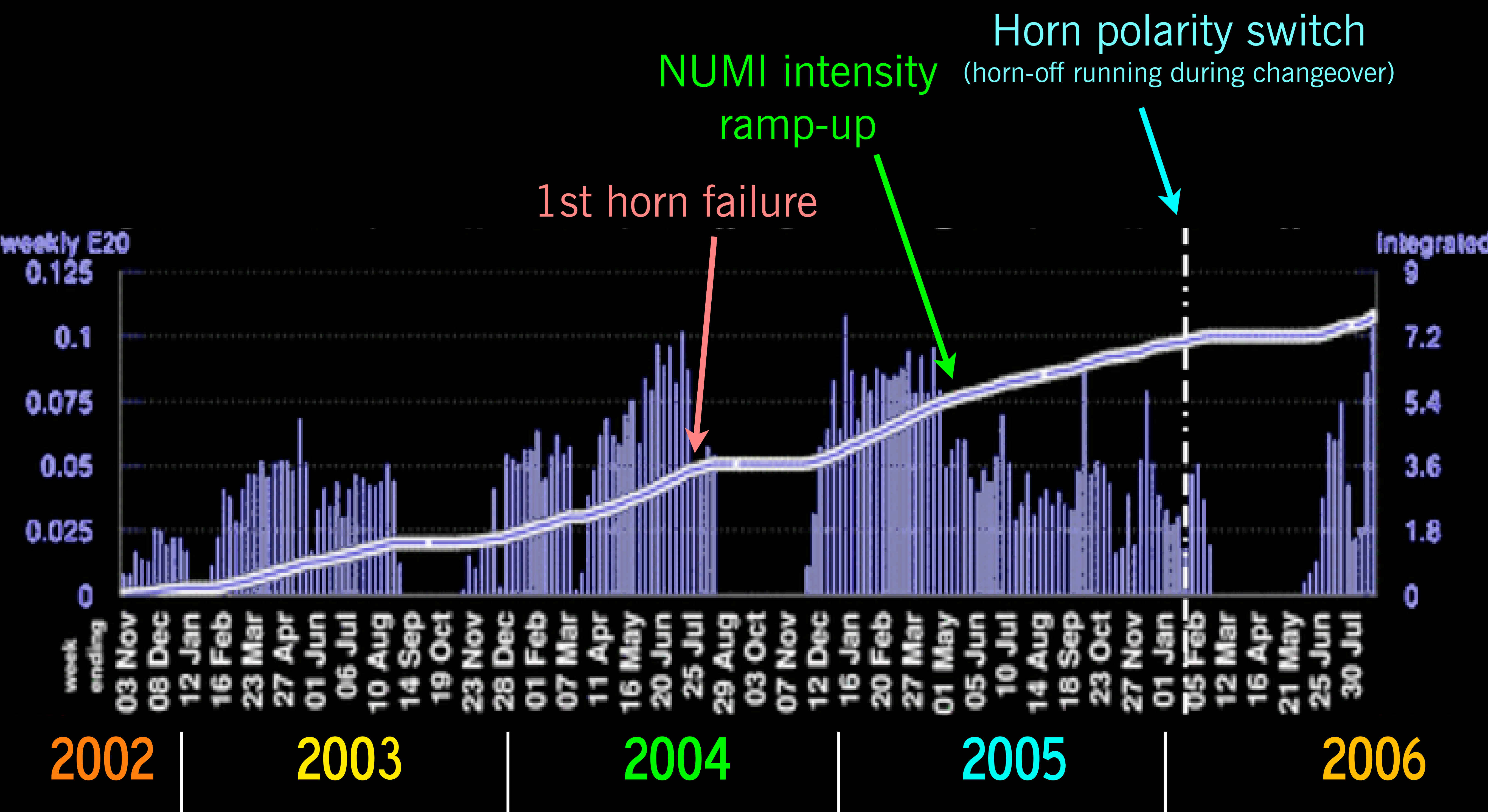
Booster

- 8 GeV proton synchrotron with resonant extraction
  - 1.6 μs spill
  - 15 Hz magnet cycling rate
- This accelerator is as old as the speaker!
- Record throughput being asked of this machine (x20 pre-2002 operation) with MiniBooNE, NuMI, and antiproton source demands.

Beam Delivery



Beam Delivery Milestones



Record intensities!

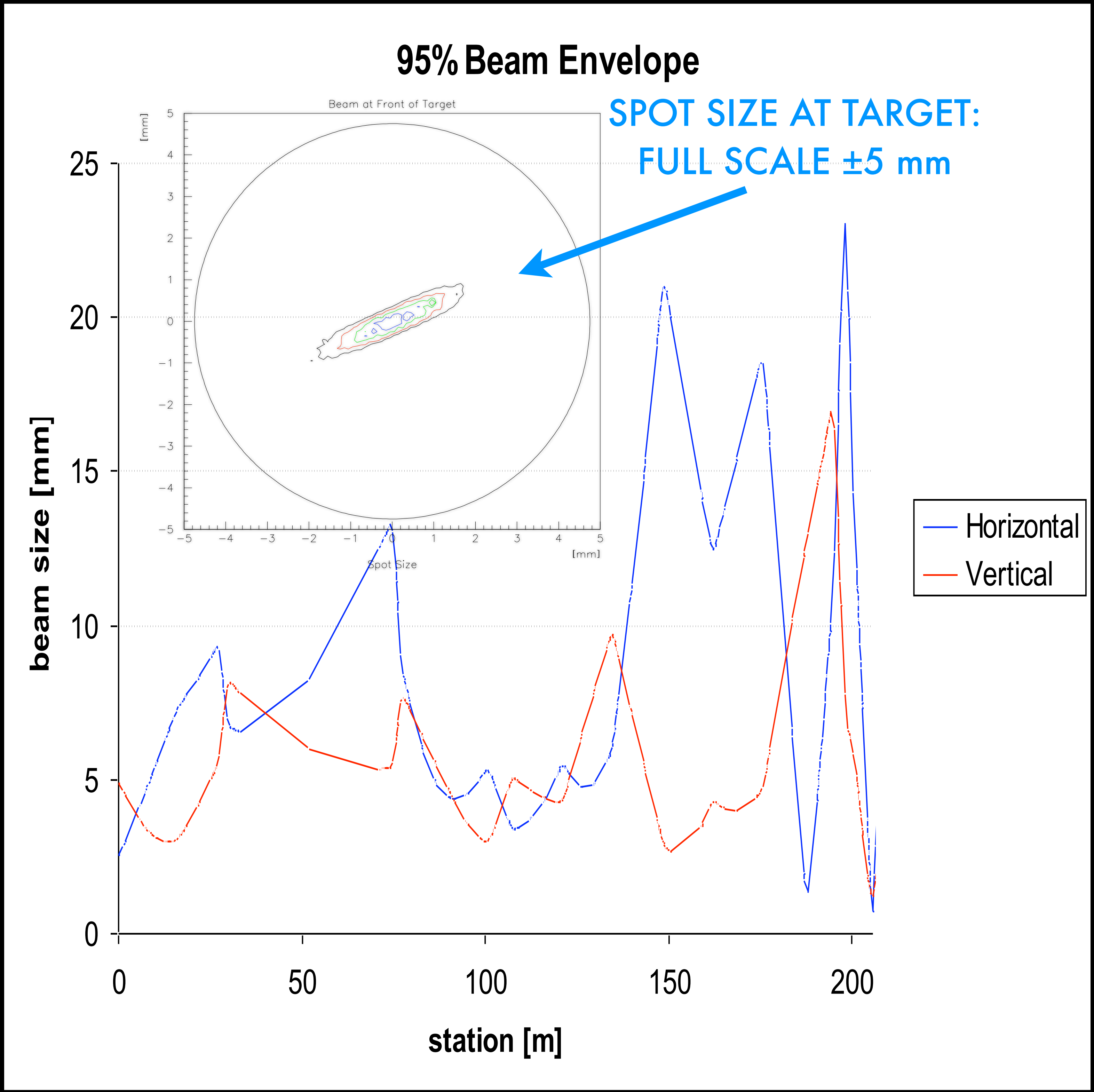
- The week of August 21 saw two records.
  - Highest hourly rate: >9E16 pph! This is the design goal for MiniBooNE.
  - Most protons in a week: 1.09E19, achieved August 21-28 (and again Aug. 29-Sept.4)

Recent Booster Improvements

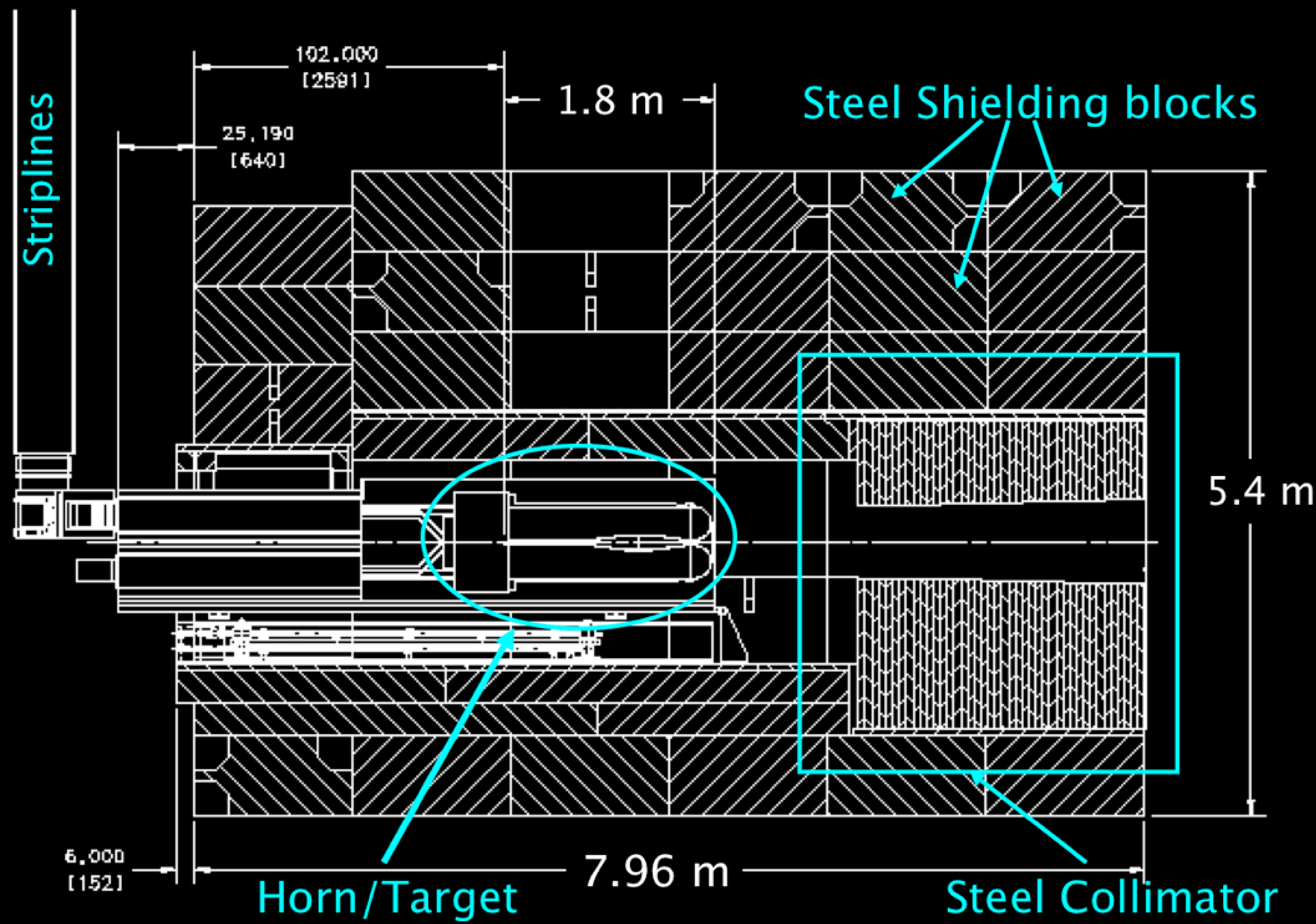
- New injection line/bump system: injected and circulating beam are better matched, reduced lattice distortions. (Repetition rate can be increased too – haven't taken advantage yet.)
- Booster abort dump relocated: dump was at the old Main Ring extraction location. Removed this extraction region, moved dump to the Main Injector extraction. This removed an aperture restriction and allowed easier beam steering.

Beam on target

- Beam on target has sigma <1mm.
- Short-timescale intensity measurement using resistive wall monitor



Target pile and collimator



Secondary beam: target

- Target is beryllium, 71 cm (1.7λ). Target is segmented in seven “slugs,” has fins for support in cooling tube.
- Target is cooled by forced air.
- Cooling tube and target are cantilevered into the neck of the horn

Secondary beam: horn

Welding the inner conductor

Beryllium target inside!

MiniBooNE horn runs at 174 kA, 140 μs pulse.

This horn survived 96 million pulses -- a world record! -- before failing in July 2004.

MiniBooNE horn experiences: first horn

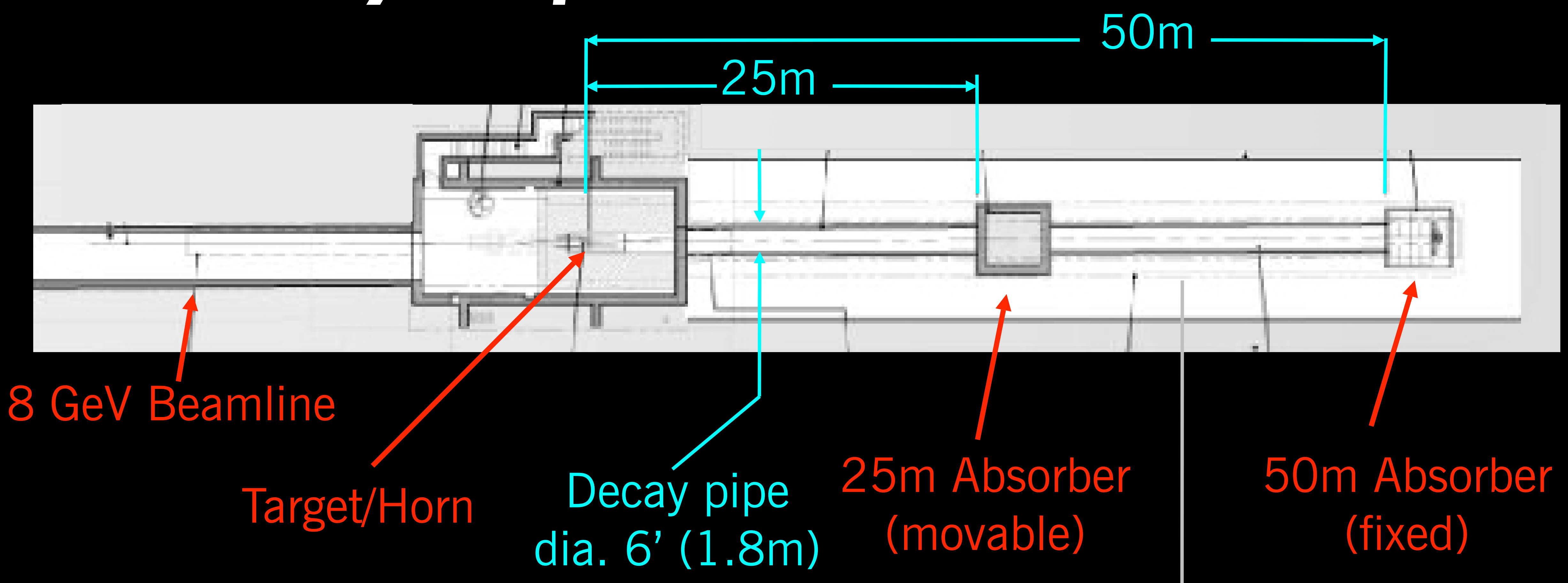
- Water leaks and a ground fault killed the first horn at 96 million pulses (see NBI'05 talk by Bartoszek)
- Stripline/horn connection was seen very corroded
- Suspect is galvanic corrosion at bellows seal

Changes for second horn

- We welded the flanges on the bottom six bellows eliminating one aluminum seal
- We added an auxiliary drain to prevent water from collecting in the bottom six bellows
- The leak collection tank became a permanent part of the RAW system
- We improved the ability of the spare horn platform to route water to the leak tank
- We added a new dehumidification system to the horn box

- Second horn has already outlived the first: >100 million pulses so far and no disturbing signals.

Decay Pipe and absorber



- Decay region is filled with stagnant air shared with target pile.
- The 25m Absorber is designed to be dropped in for cross-checks if MiniBooNE sees a signal.
- Both absorbers contain muon monitors.

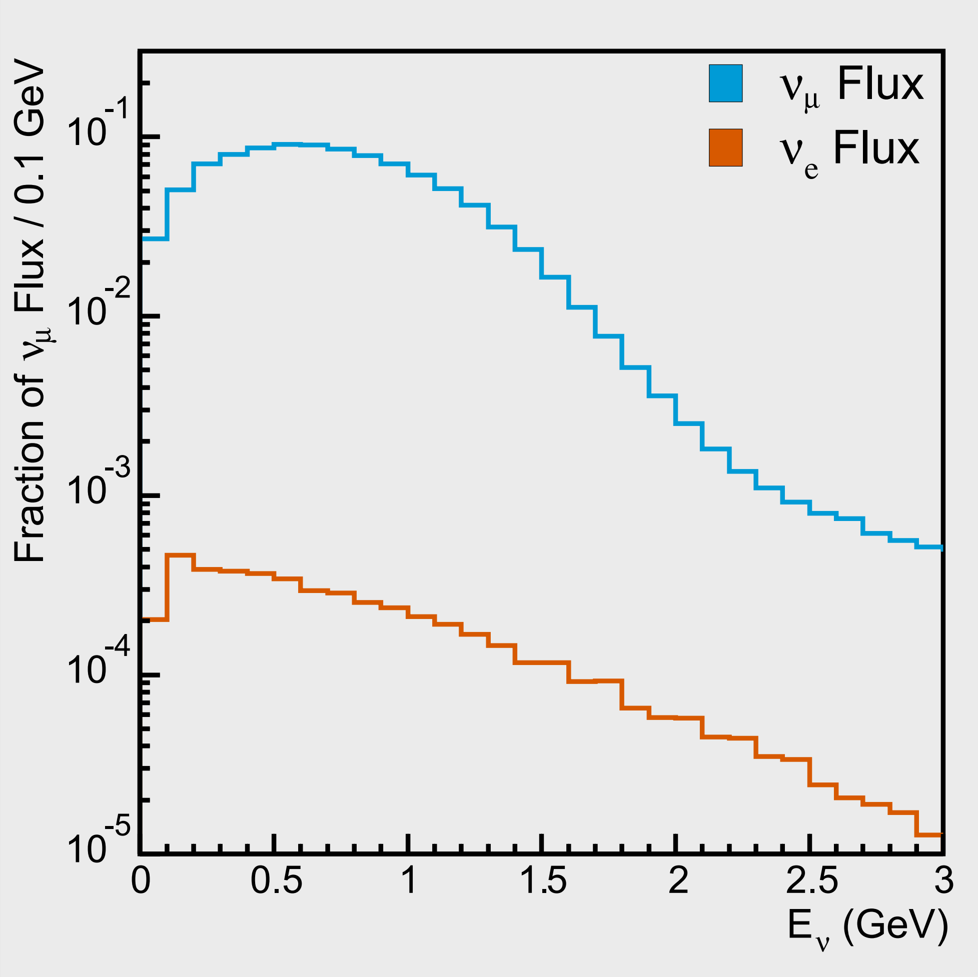
The berm can be cooled via air ducts and a heat exchanger embedded in the fill.

Oscillation Analysis

- Steps to an oscillation result:
  - Understand the flux
  - Understand the detector: "optical issues"
  - Particle Identification
- Expected statistics and sensitivity

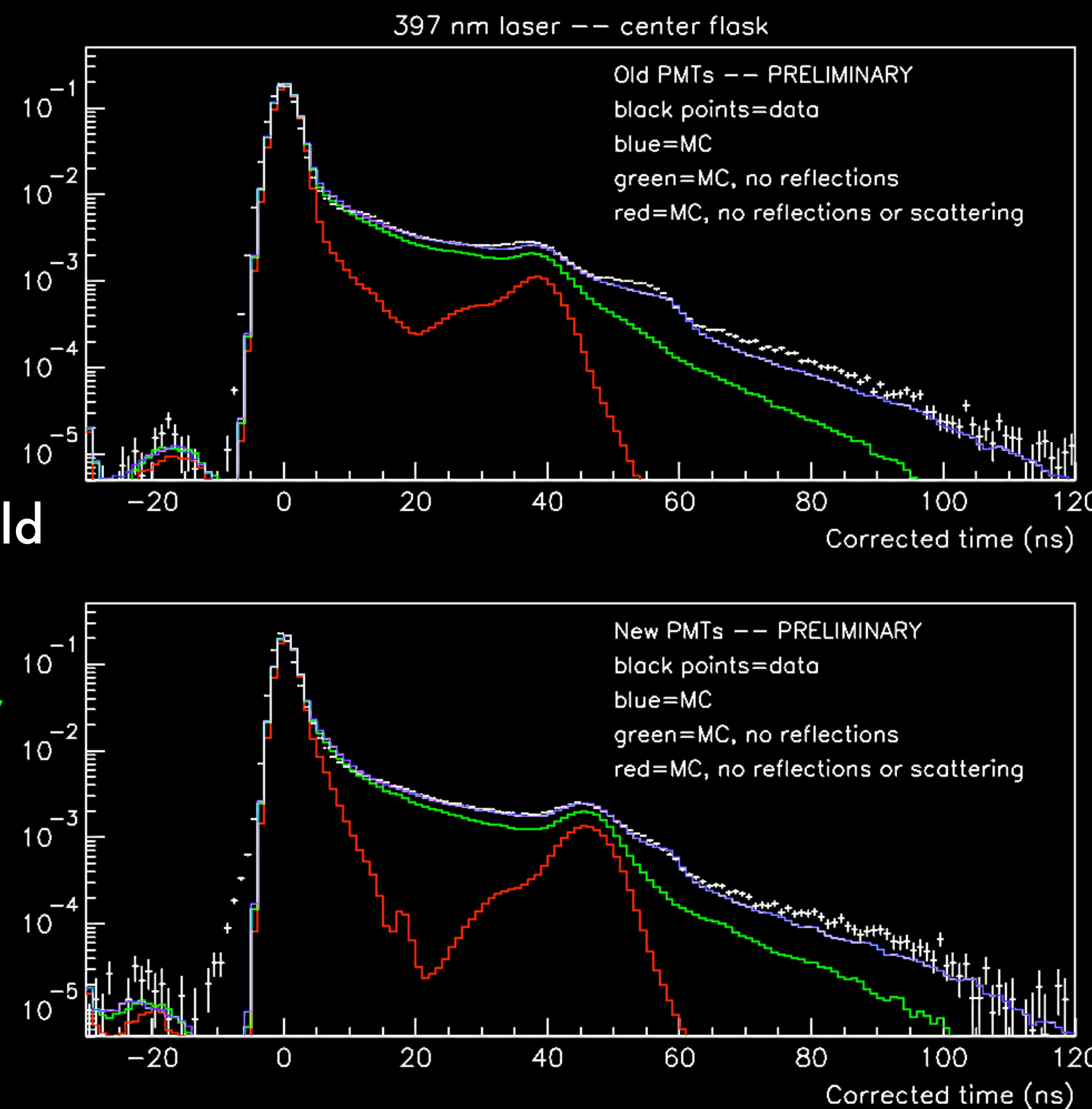
Understanding the neutrino flux

- Primary p-Be interactions:
  - π^+ are produced from a parametrized p-Be cross-section using external measurements including recent results from BNL E910 and HARP. (See talk by K. Mahn)
  - K^+ from external data fit too; agrees well with MARS. Will incorporate internal measurements from dedicated beam monitor (See talk by M. Tzanov), studies of highest-energy neutrinos in detector (see talk by K. Mahn). HARP data will be coming too.
- Neutrinos from muon decay:
  - This is a tertiary decay: constrain it from observed ν_μ in detector, since these events originate from the same pions as the muon decays.



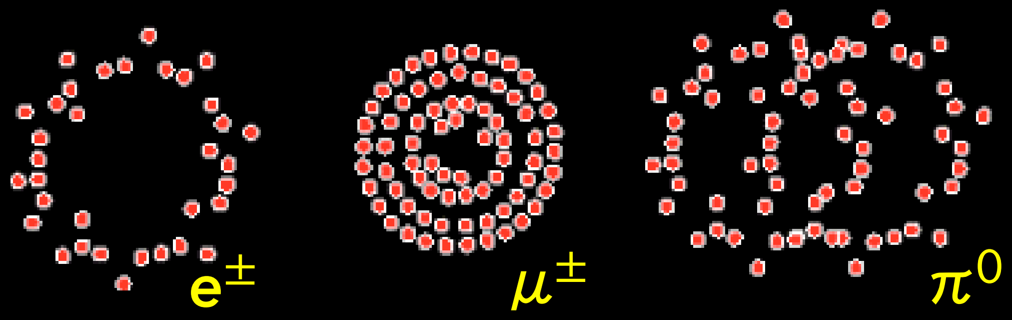
MiniBooNE "optical" issues

- **Cherenkov light production**
  - Emitted promptly, in cone
  - $1/\lambda^2$ wavelength distribution
- **Scintillation light**
  - Emitted isotropically
  - Several lifetimes, emission modes
  - λ = 270-340 nm
  - Particles below Cherenkov threshold still scintillate
- **Optical properties of oil, detectors:**
  - Absorption
  - Rayleigh and Raman scattering
  - Fluorescence
  - PMT response



MiniBooNE Particle ID

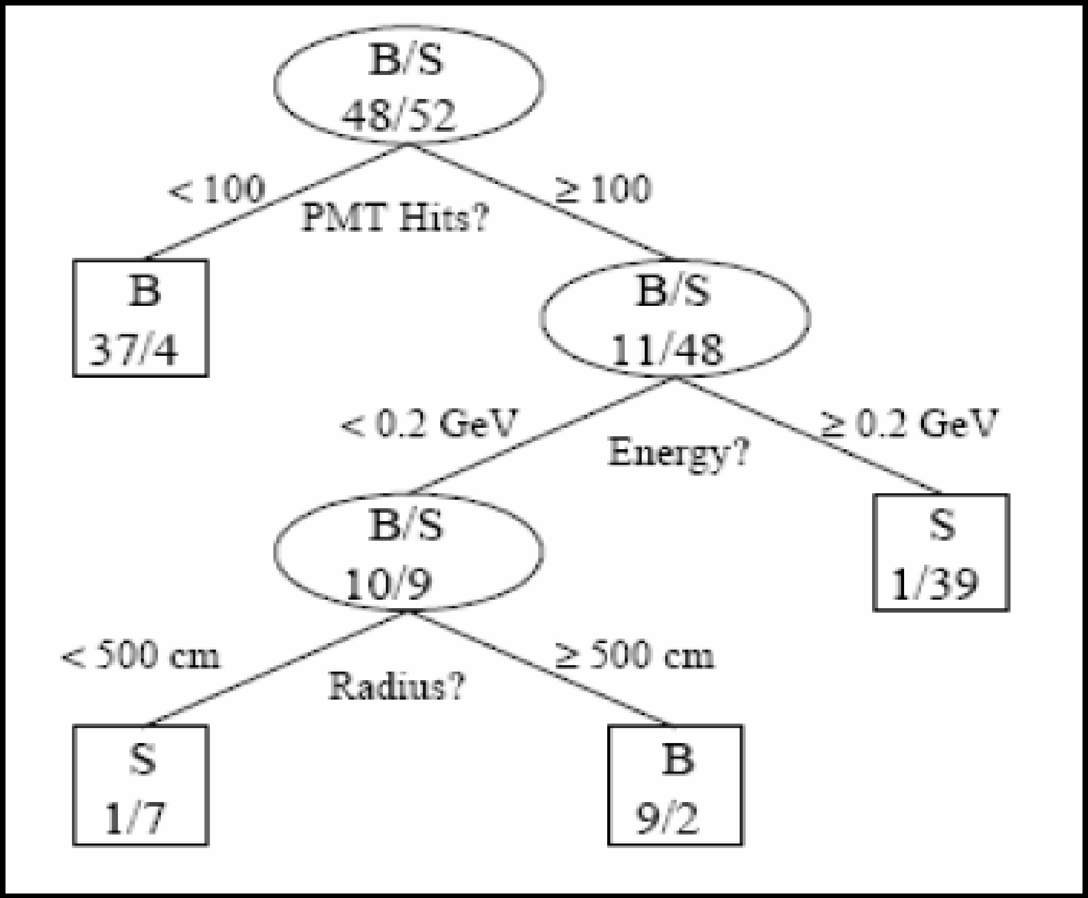
- Use ring shape, topology to identify particles:

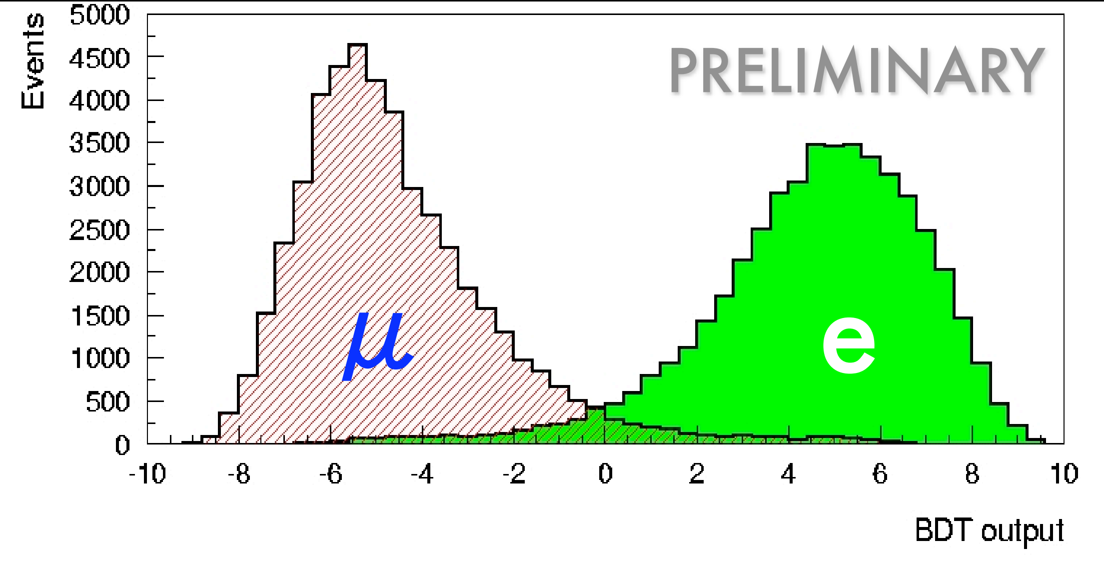


- Parallel approaches to PID analysis:
  - Likelihood analysis: simpler, but less sensitive
  - Boosted decision trees harder to understand(!) but appear to give better results: B. Roe *et al.*, *Nucl. Inst. Meth.* **A543** *577* (2005)

Boosted Decision Trees

- Go through all PID variables and find best variable and value to split a Monte Carlo data set.
    - For each of the two subsets repeat the process
    - Proceeding in this way, a "decision tree" is built, whose final nodes are called leaves
- After the tree is built, additional trees are built with the leaves re-weighted to emphsize the previously misidentified events (since those are hardest to classify).
- The process is repeated until best S/B separation is achieved.
- PID output is a sum of event scores from all trees.
- MiniBooNE uses about 200 input variables to train the trees

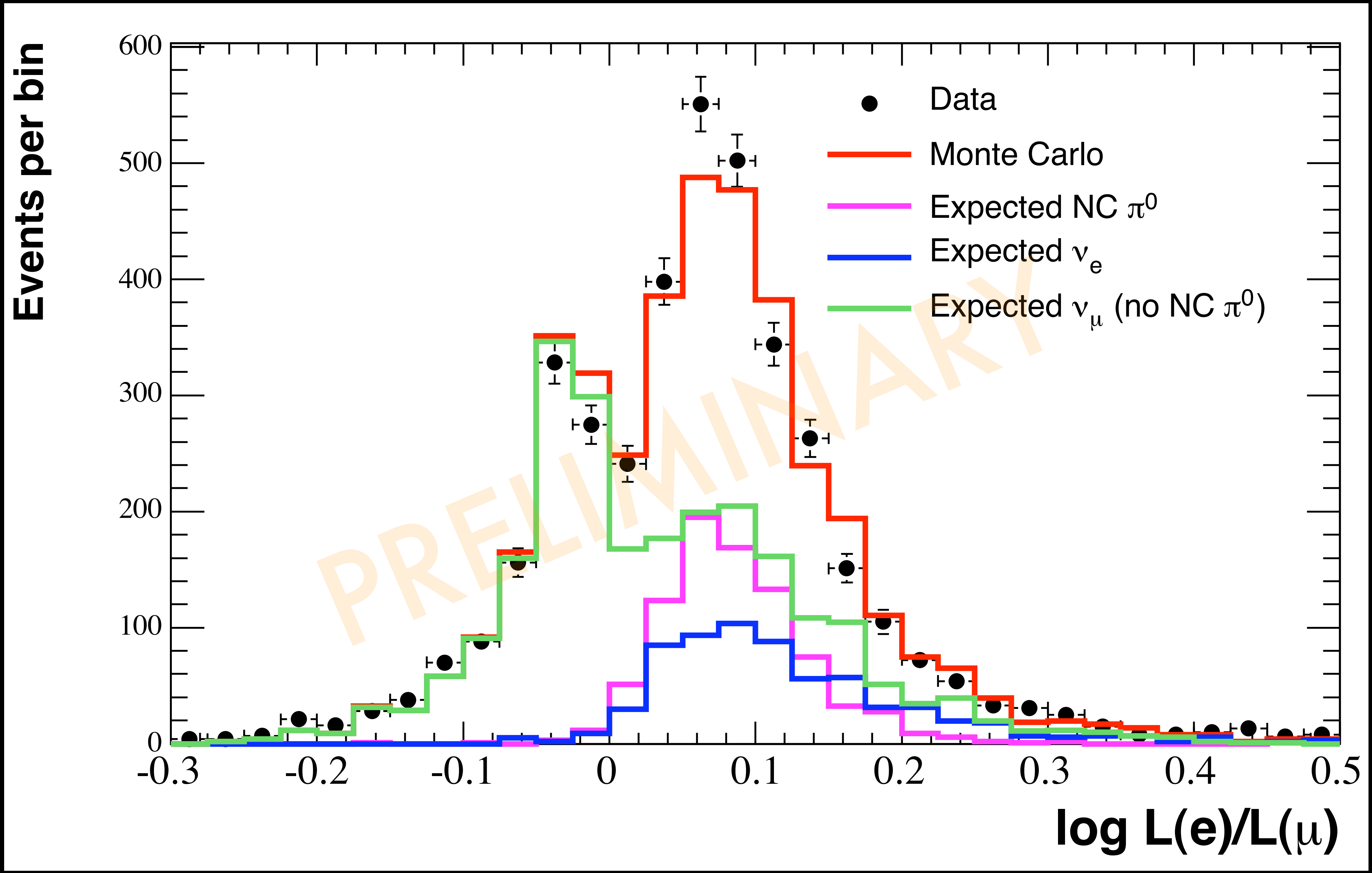




PID on NUMI neutrinos

- MiniBooNE is an off-axis detector for NuMI!
- Better yet, the far off-axis position enhances the fraction of ν_e in the NuMI events
- These events aren't blind → we can use them to test the behavior of the PID algorithm on real $\nu_{e.}$

NuMI neutrinos in MiniBooNE



- Clear separation of electrons from muons
- A separate variable distinguishes electrons from π^0

Expected oscillation candidates at MiniBooNE

(for a sample set of cuts oriented toward a counting analysis)

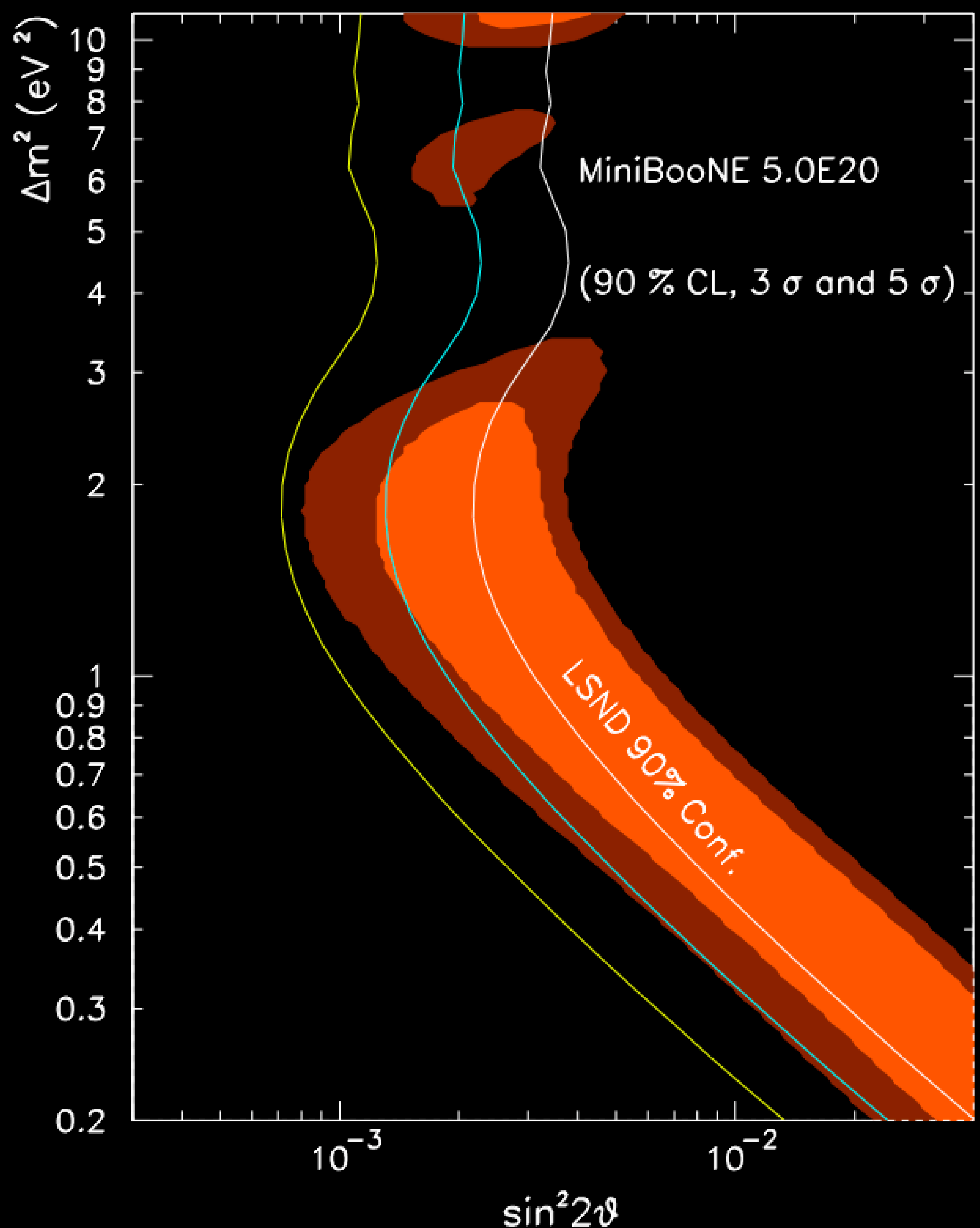
PROCESS	ALL EVENTS	AFTER SELECTION
NEUTRAL CURRENT π^0	55000	145
NC RADIATIVE Δ DECAY	540	40
ν_μ QUASIELASTIC	275000	5
OTHER ν_μ	~500000	25
INTRINSIC ν_e	1250	175
OSCILLATION SIGNAL	750	150
SIGNAL/BACKGROUND		150/390=0.38

If LSND correct

For 5×10^{20} protons on target

Energy fitting analysis is more sensitive.

MiniBooNE Sensitivity



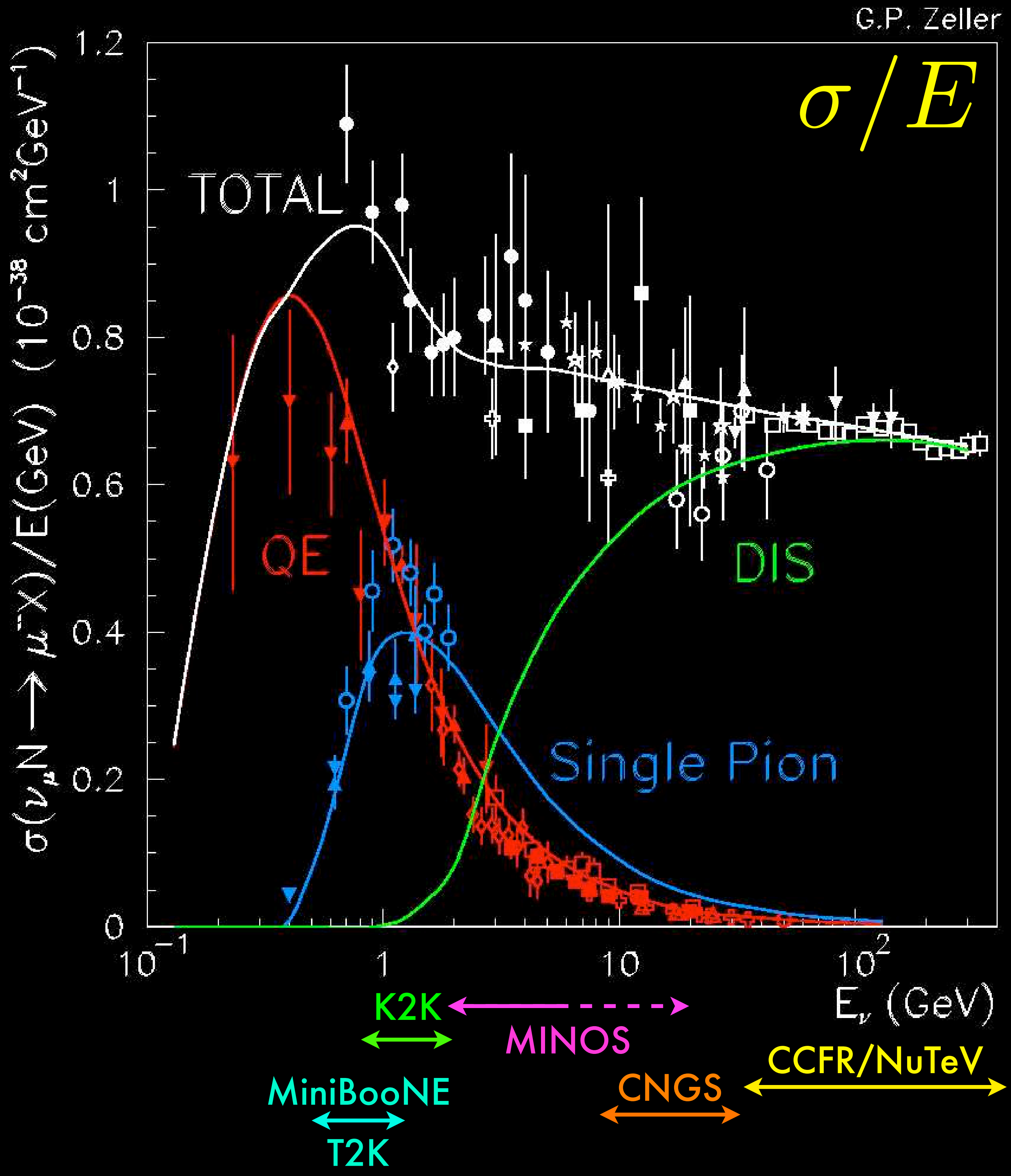
- Expected limit curves assuming $5 \cdot 10^{20}$ protons on target (and no signal)

We are getting very close to being able to unblind the analysis.

Neutrino Cross-Sections

- Many new results coming out here in a field where data have been lacking:
  - Quasielastic
  - Resonant/coherent meson production
  - Deep inelastic scattering
- Many processes are being measured for the first time
- K2K and MiniBooNE are doing most of the current work
- Next step at the Booster: SciBooNE

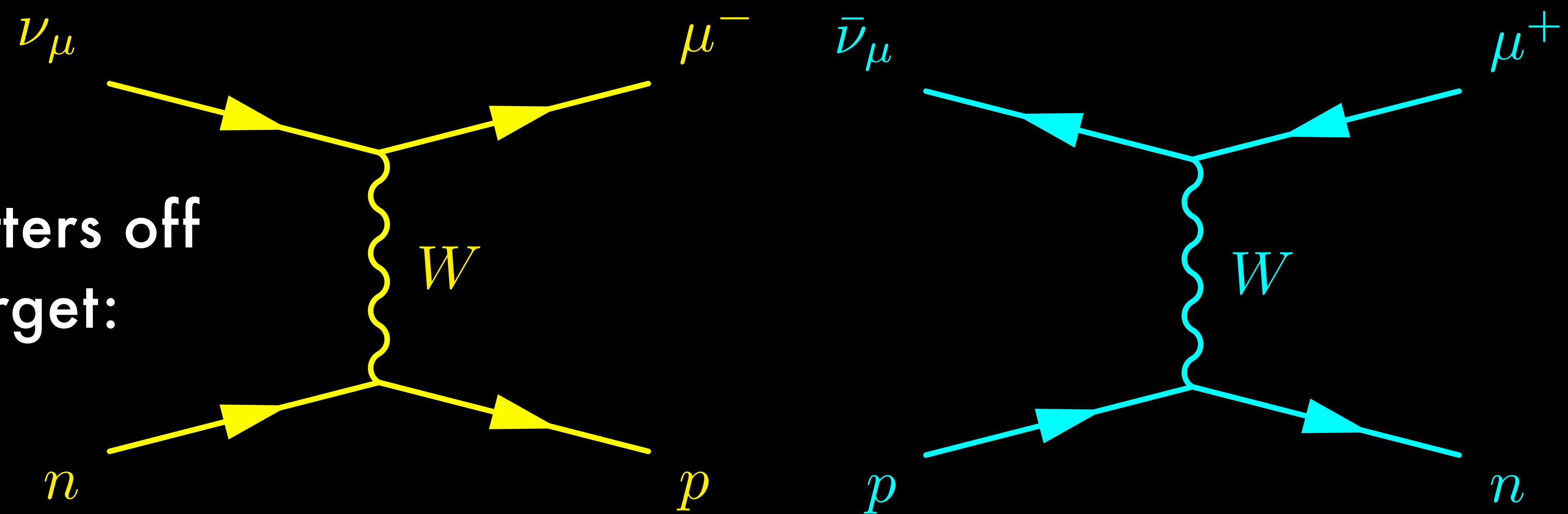
Why Cross-Sections?



- Present and near future oscillation experiments operate in an energy region where several processes overlap
- Signal and background cross-sections both contribute to systematic errors
- Oscillation experiments cover a wide range of energies
- Existing data very sparse, especially in exclusive channels in needed energy ranges.

Quasielastic Scattering

Neutrino scatters off nucleon in target:

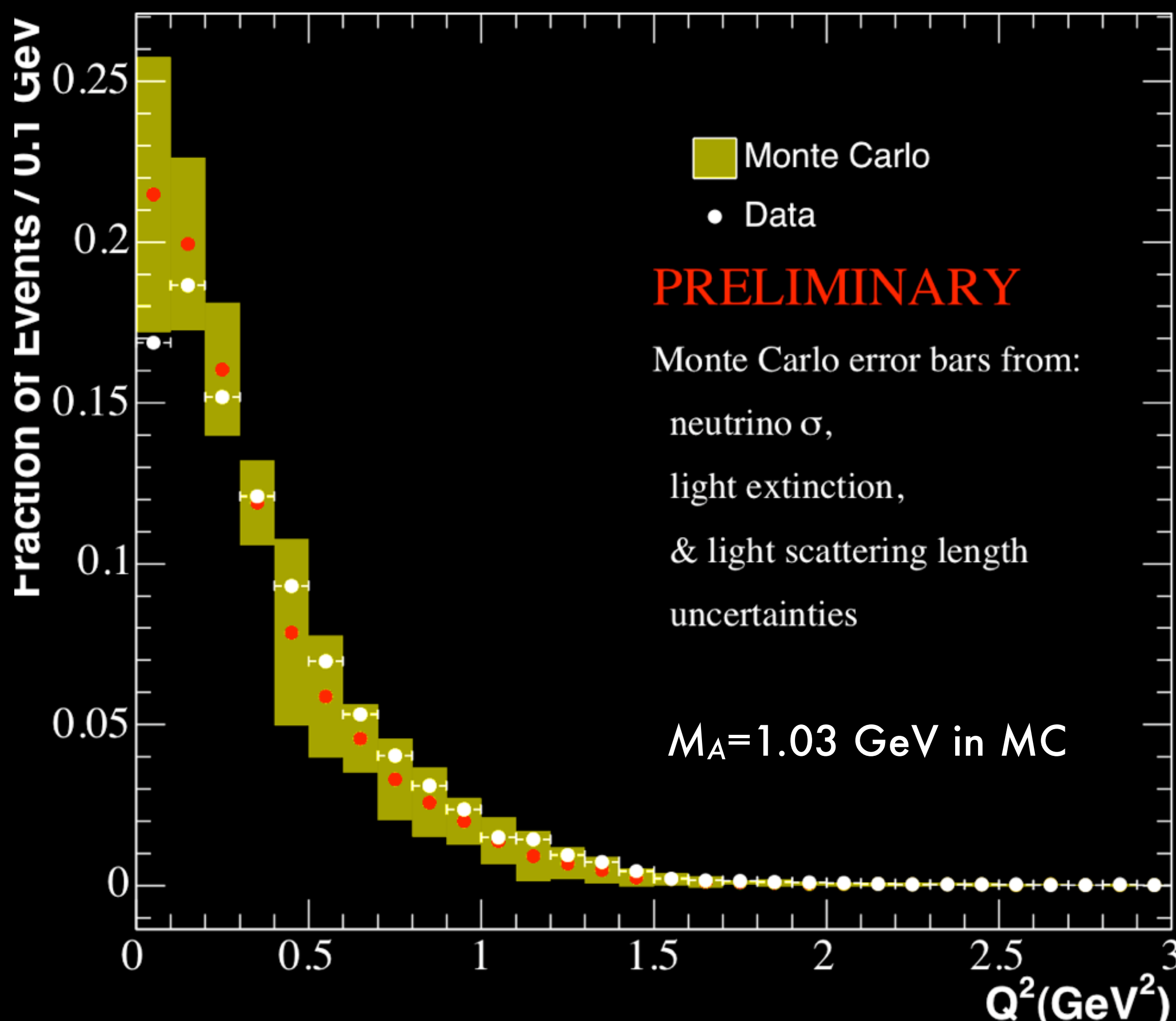


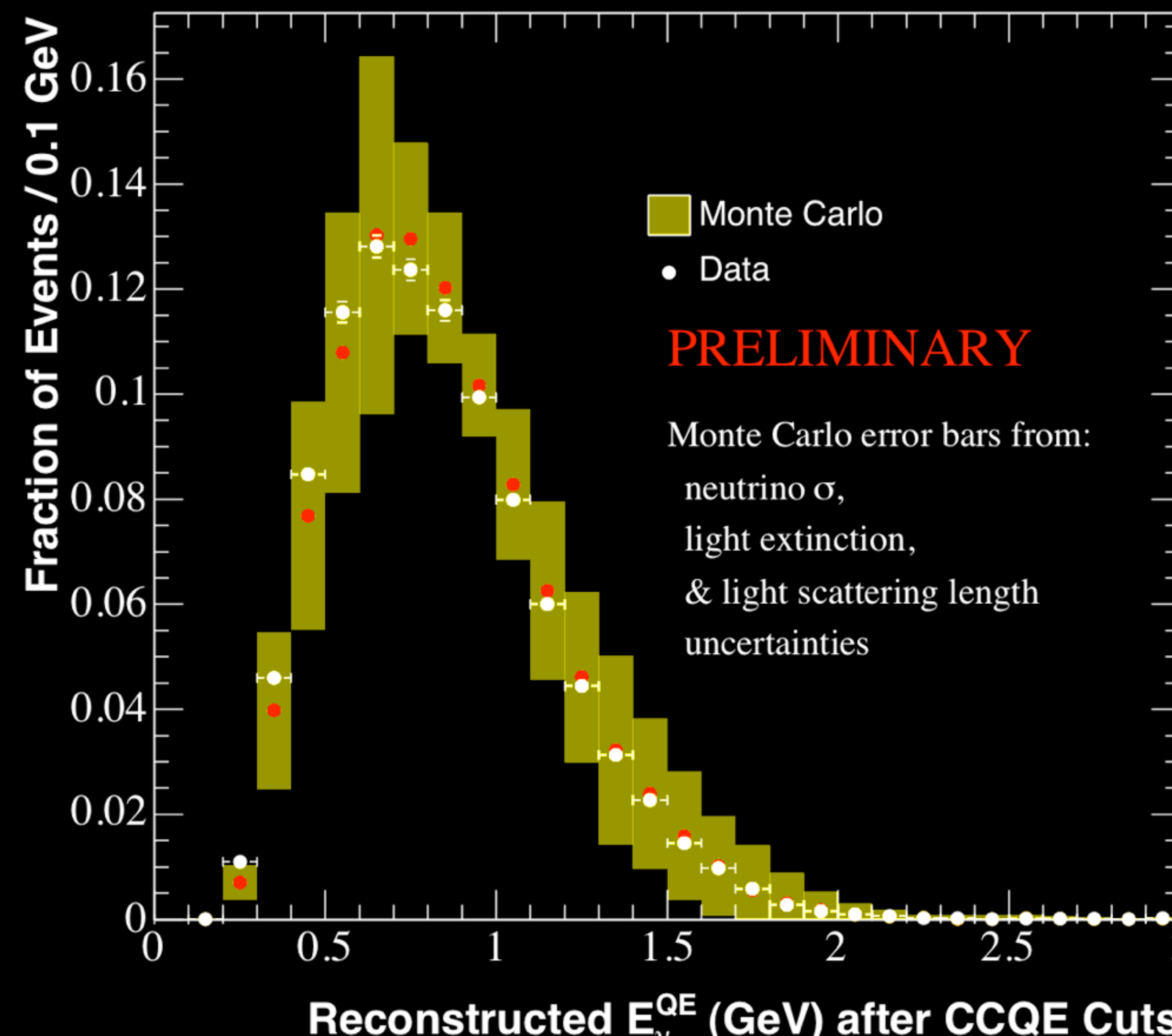
- Golden signal mode for oscillation searches: clean events; neutrino energy can be calculated given known neutrino direction:

$$E_\nu = \frac{m_N E_\mu - \frac{1}{2} m_\mu^2}{m_N - E_\mu + p_\mu \cos\theta_\mu}; \qquad Q^2 = -2E_\nu(E_\nu - p_\mu \cos\theta_\mu) + m_\mu^2$$

- (Correction for m_n-m_p, binding energy, Fermi motion of target nucleon)
- Nucleus may break up
- Final state nucleon not excited: no resonance, no pion, no (hard) gamma
- Physics to measure: axial form factor F_A, parametrized by M_A (axial mass)

MiniBooNE QE results



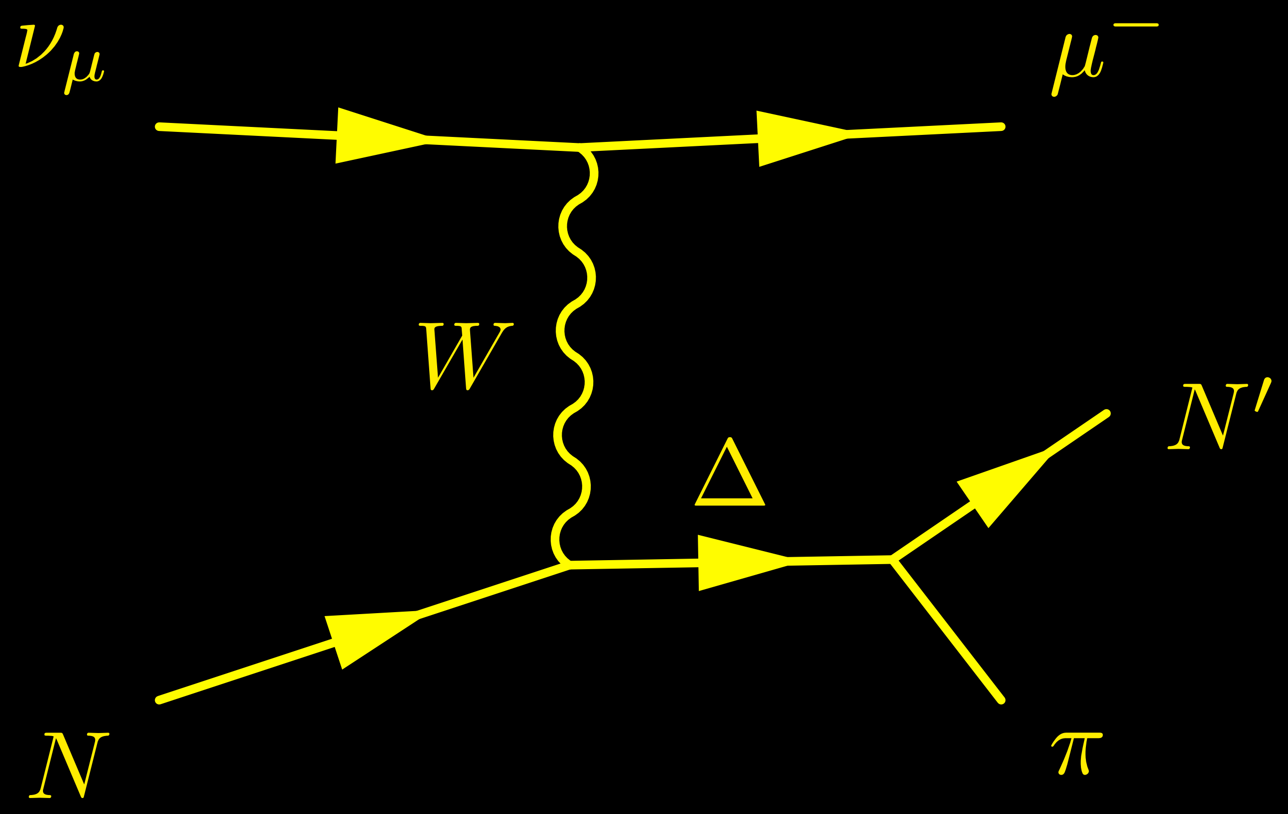


- Data/MC disagreement at low Q^2 similar to K2K
- Fits better with higher M_A
- New results will be shown soon

Pion production

- About a third of neutrino interactions at 1 GeV
- Two production modes for nuclear targets:
  - Nucleon resonance: $\nu_\mu + N \;\rightarrow\; \mu^- + \Delta \;\rightarrow\; \mu^- + \pi^+ + N'$
  - Coherent nuclear: $\nu_\mu + A \;\rightarrow\; \mu^- + \pi^+ + A$
  - Analogous neutral-current π^0 modes too.
- D. Rein and L. M. Sehgal, *Nucl. Phys.* **B223** 29 (1983) is standard for describing cross-section, kinematics
- MiniBooNE, K2K making first measurements in this energy range on nuclear targets

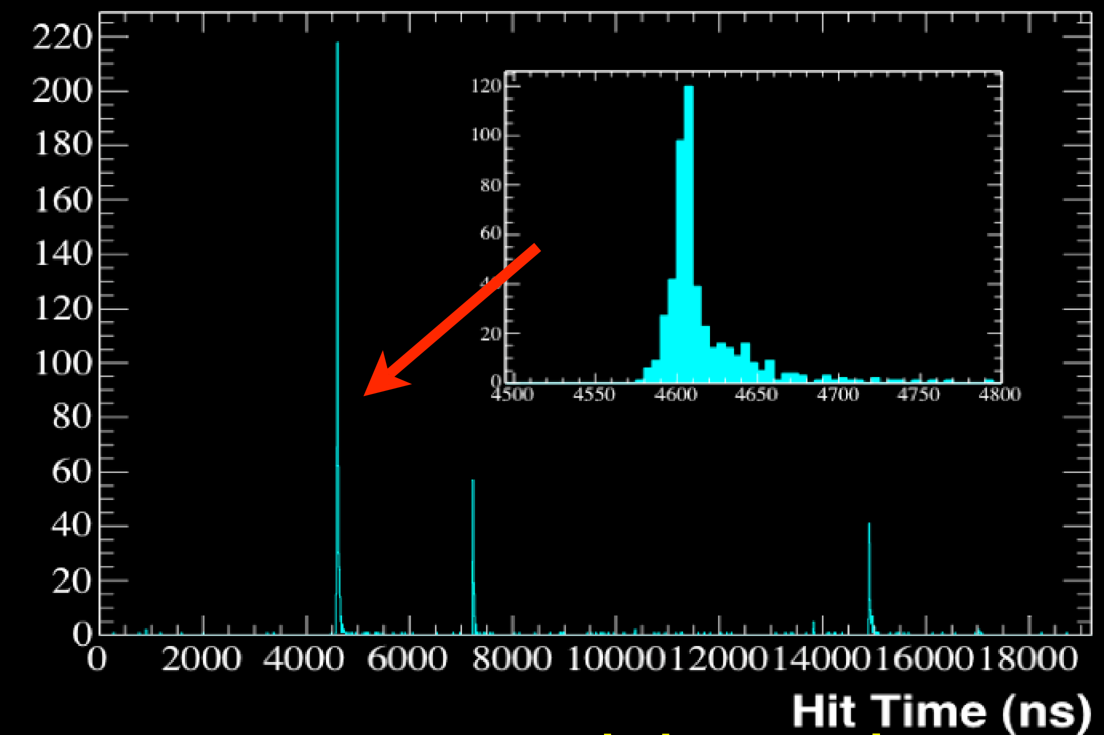
Charged-current π^+ production



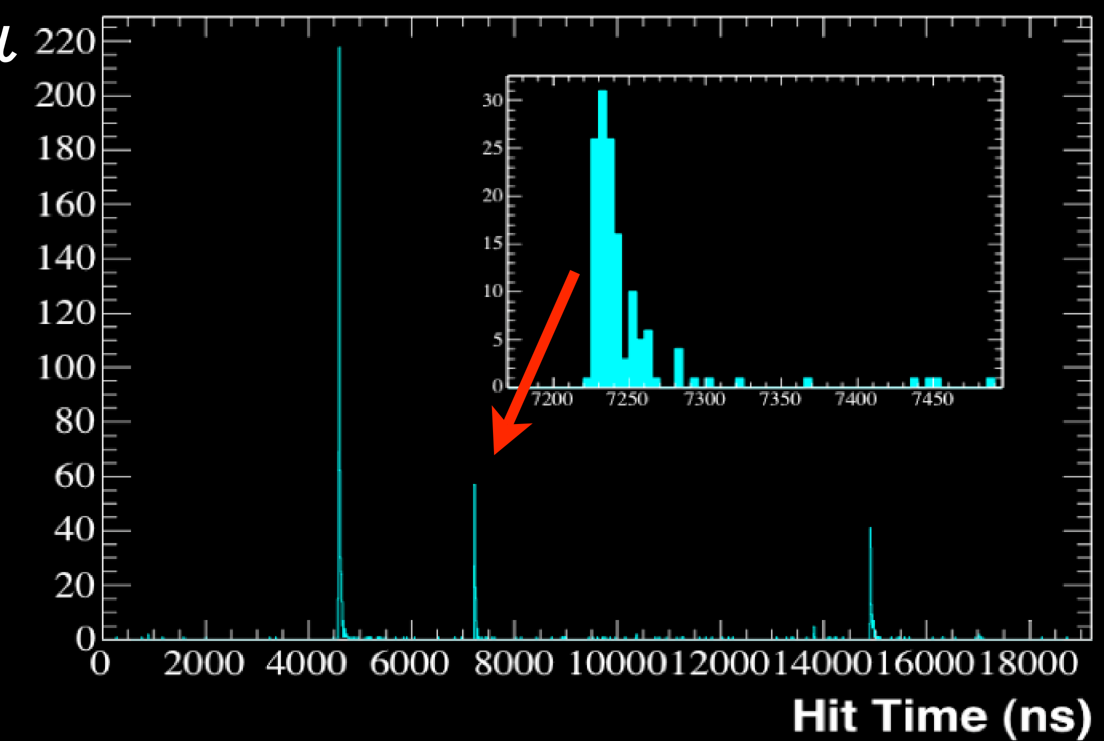
- Second highest rate process in MiniBooNE (behind quasielastics); largest background to QE measurement.
- As with NC process, expected resonant (above diagram) and coherent channels.

MiniBooNE Charged-current π^+ analysis

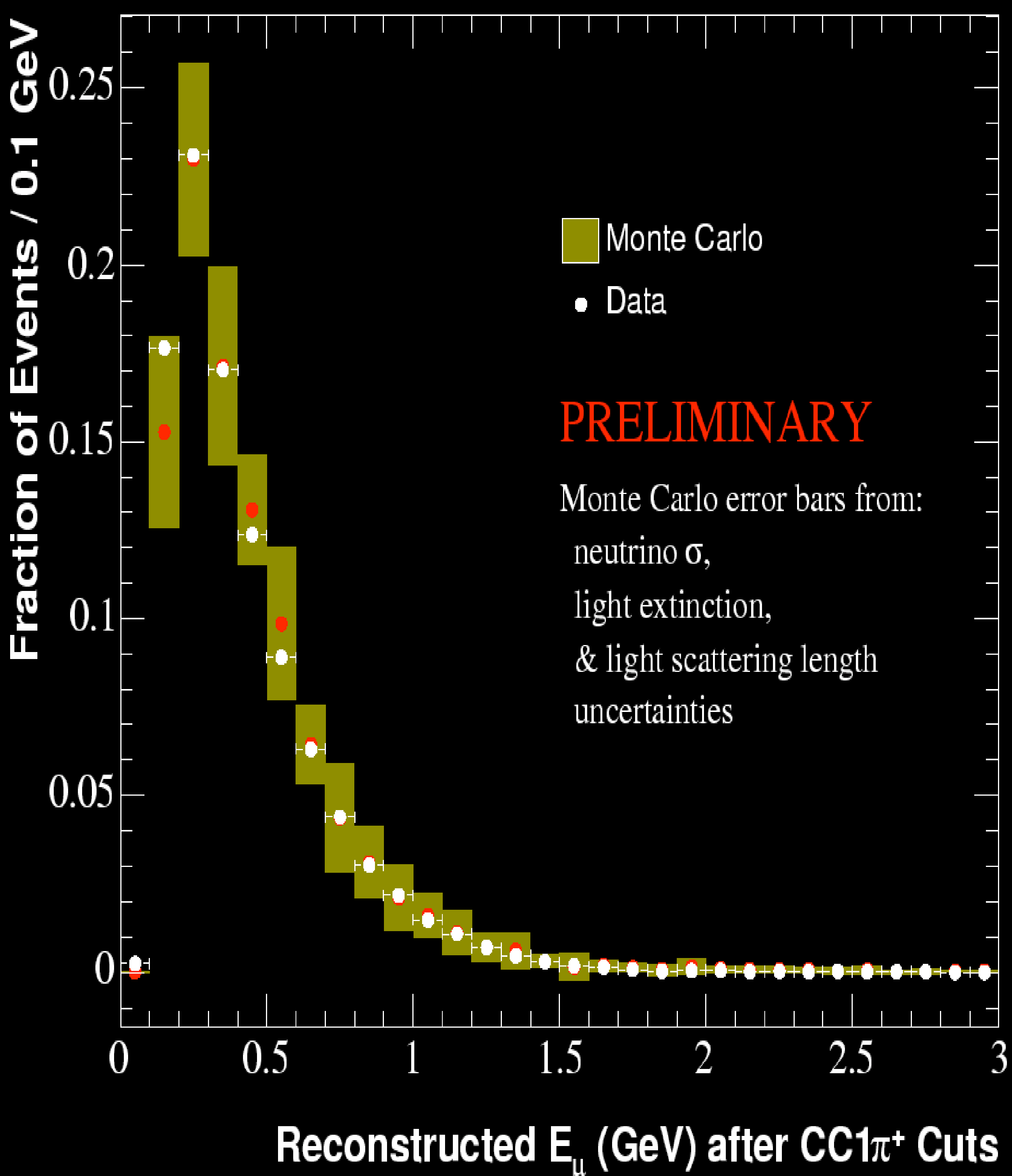
- Final state has a nucleon, muon, and pion.
- Generally, pion is sub-Cherenkov threshold, so MiniBooNE fitter reconstructs only the muon.
- Both muon and $\pi \rightarrow \mu$ leave stopped-μ decay electron signatures in detector
- This is an unusual enough signature that these events can be isolated well even without particle ID.

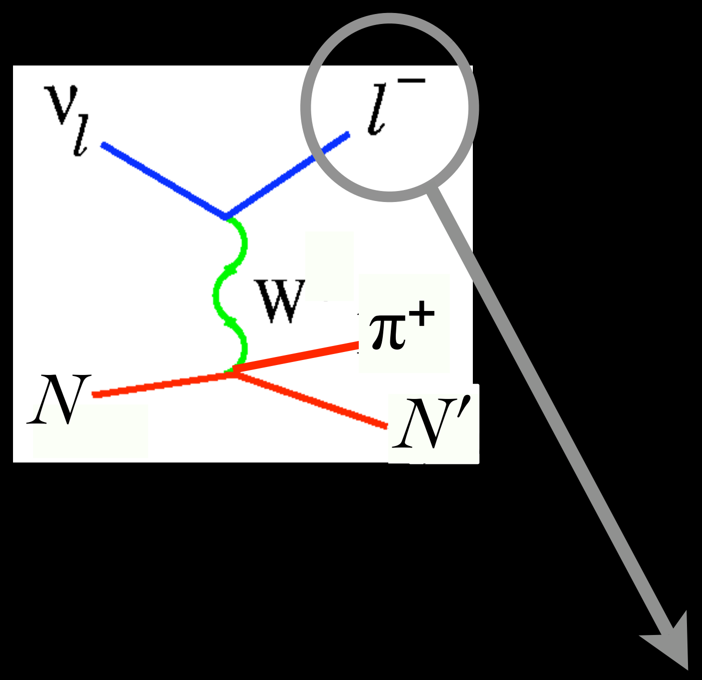


Primary event and decay electrons separated in time



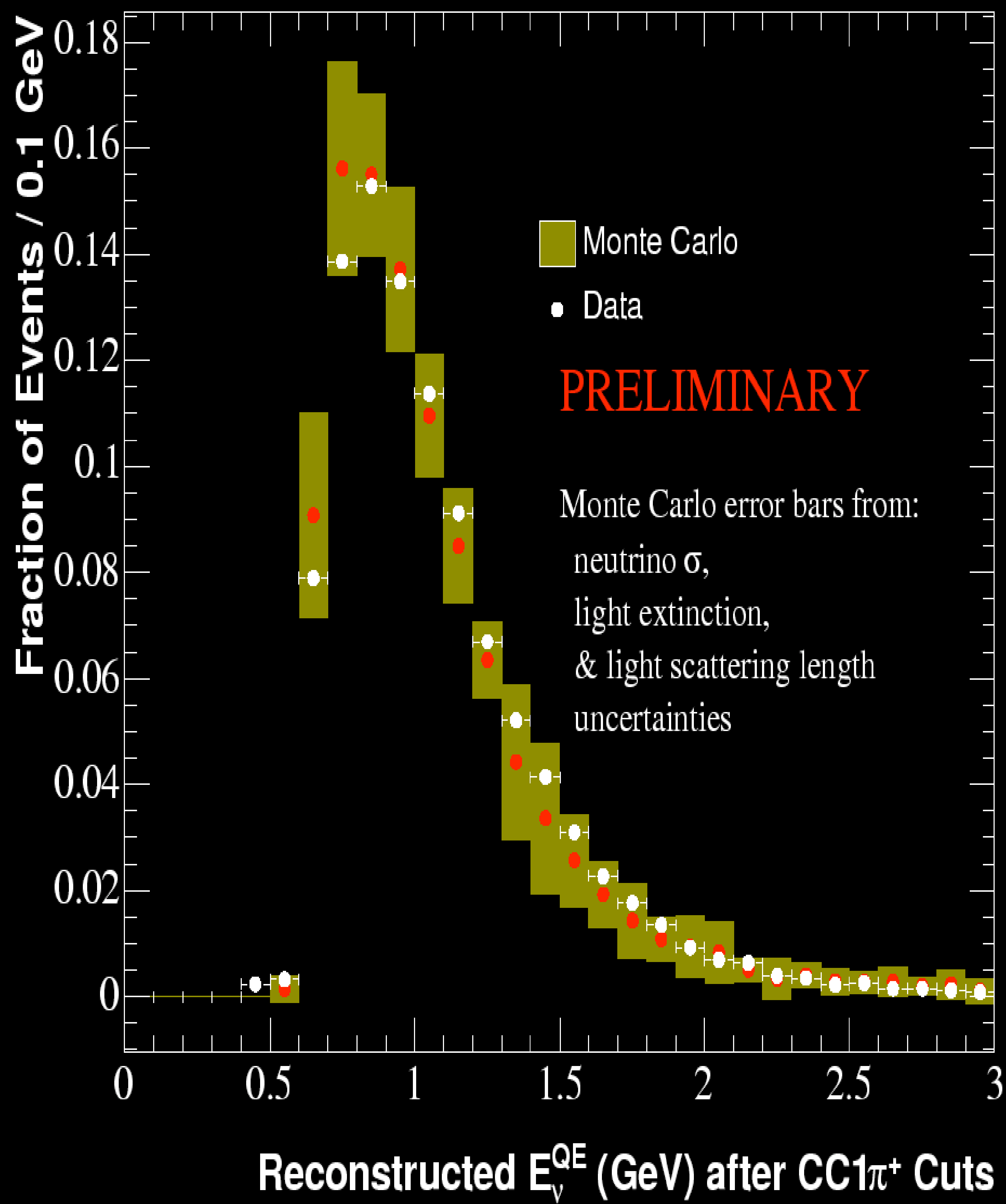
MiniBooNE charged-current π^+ analysis

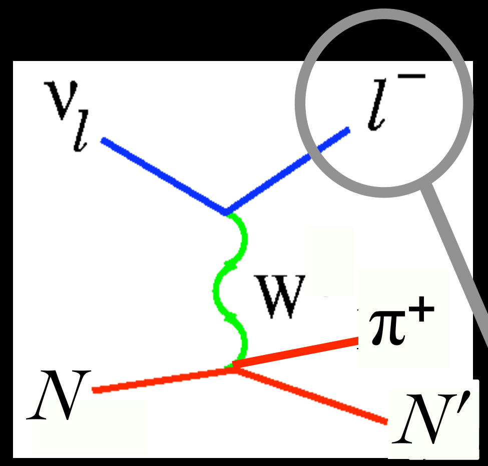




- Measure visible energy, lepton direction from fit to Cherenkov ring *only* (avoid scintillation light from pion, nucleon)

MiniBooNE charged-current π^+ analysis





- Use lepton energy, momentum and direction (from known neutrino beam) to reconstruct a "quasielastic energy" assuming a recoil mass:

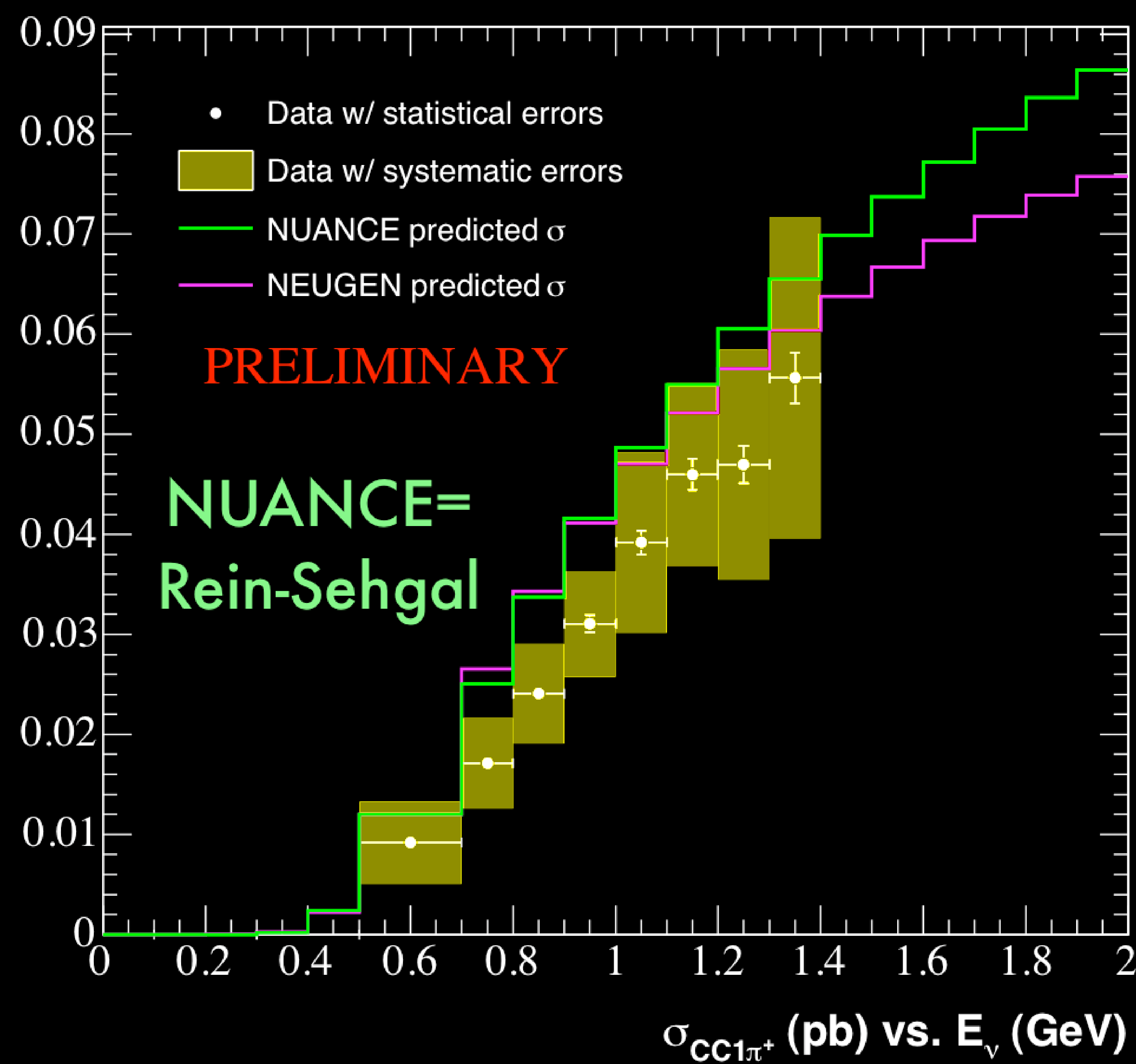
$$E_\nu^{QE} = \frac{1}{2}\frac{2M_p E_l - m_l^2 + (m_\Delta^2 - m_P^2)}{M_p - E_l + \sqrt{(E_l^2 - m_l^2)}\cos\theta_l}$$

- In this case, recoil mass is 1232 MeV (Δ^{++} mass), vs. proton mass for true quasielastics

- This method gives ~20% resolution on neutrino energy (compared to 10% for CCQE)

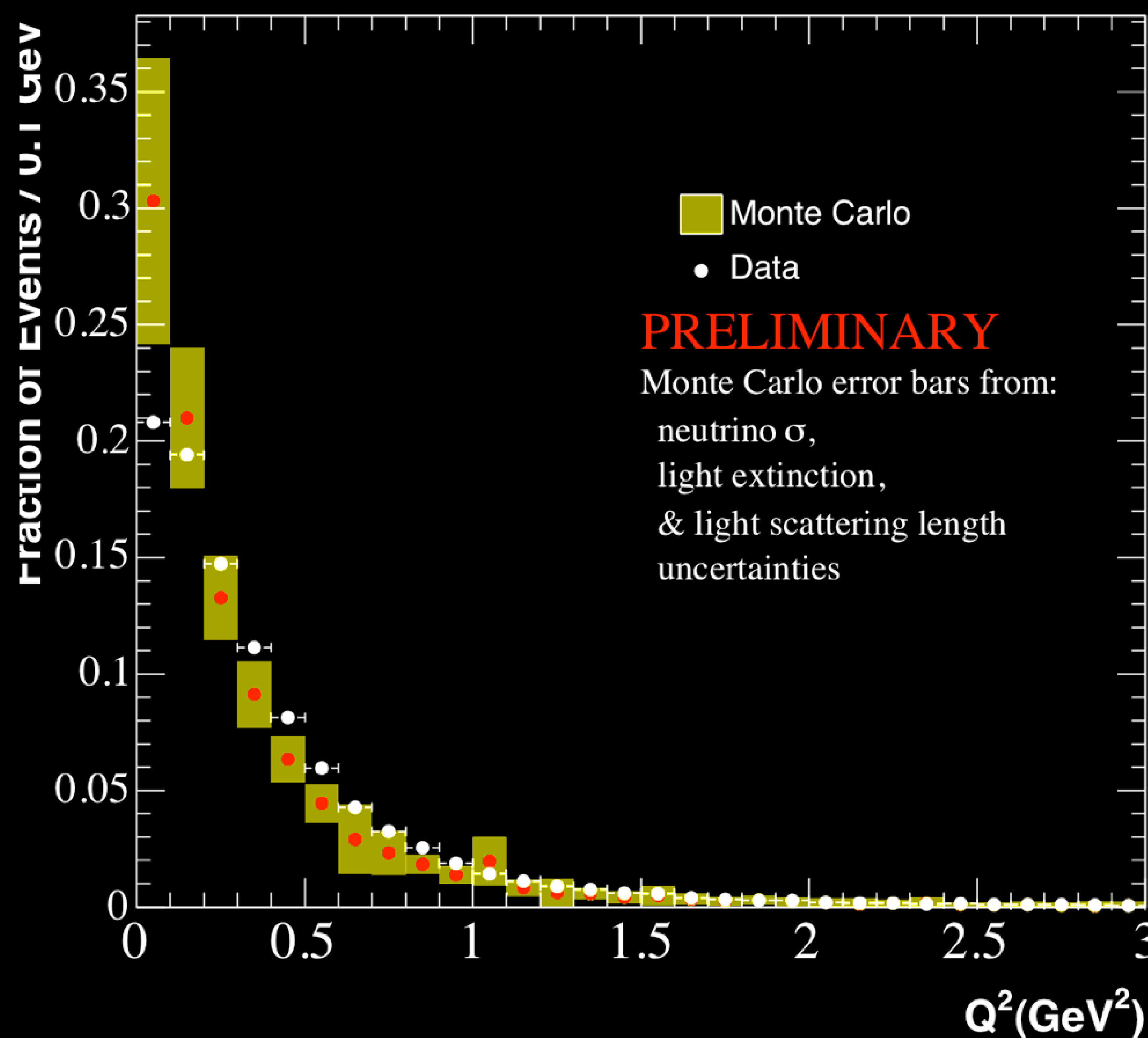
MiniBooNE charged-current π^+ analysis

- Normalized to quasielastics
- Comparison is to common event generators

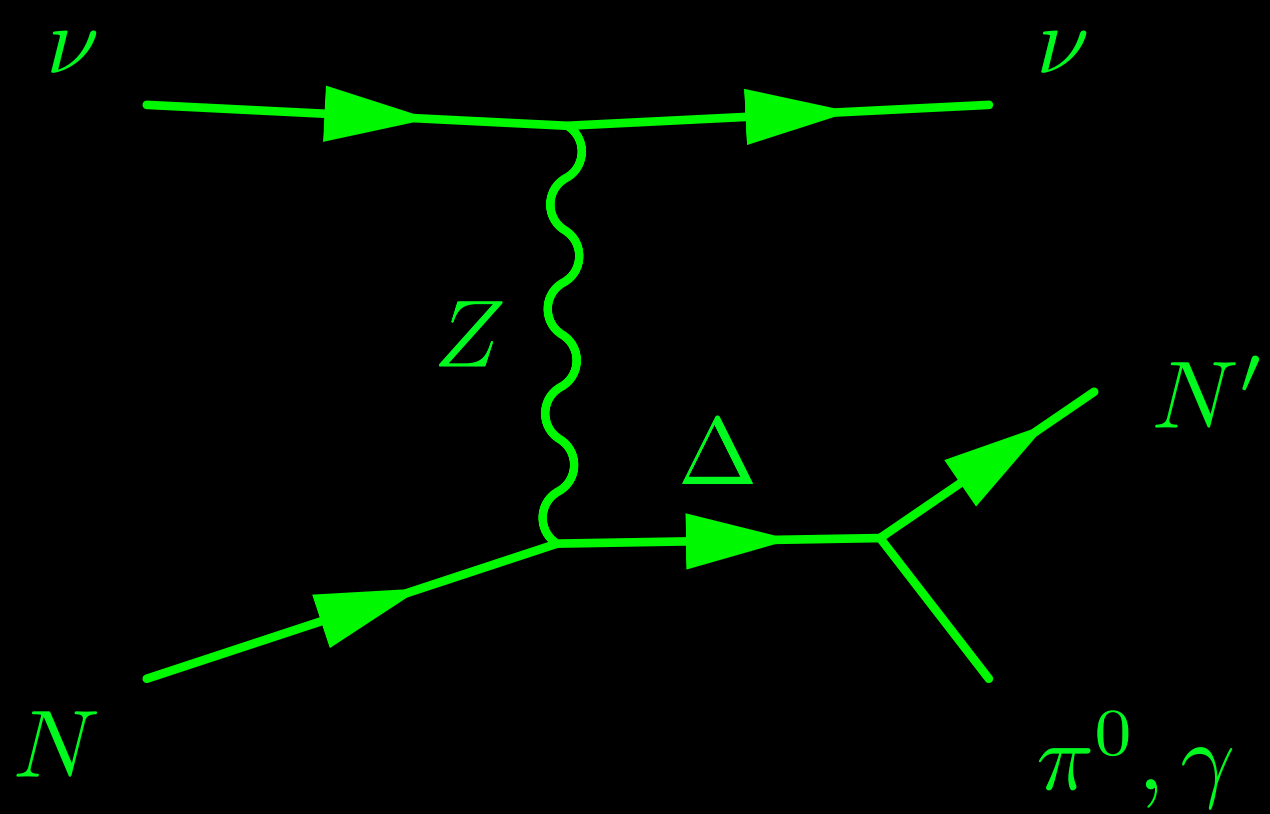


MiniBooNE charged-current π^+ analysis

- Reconstructed Q^2 for charged current single pion candidates.
- Note deficit in low Q^2 (small muon angle) region vs. Rein-Sehgal model. Coherent production is clearly lower than expected. (This is consistent with K2K).

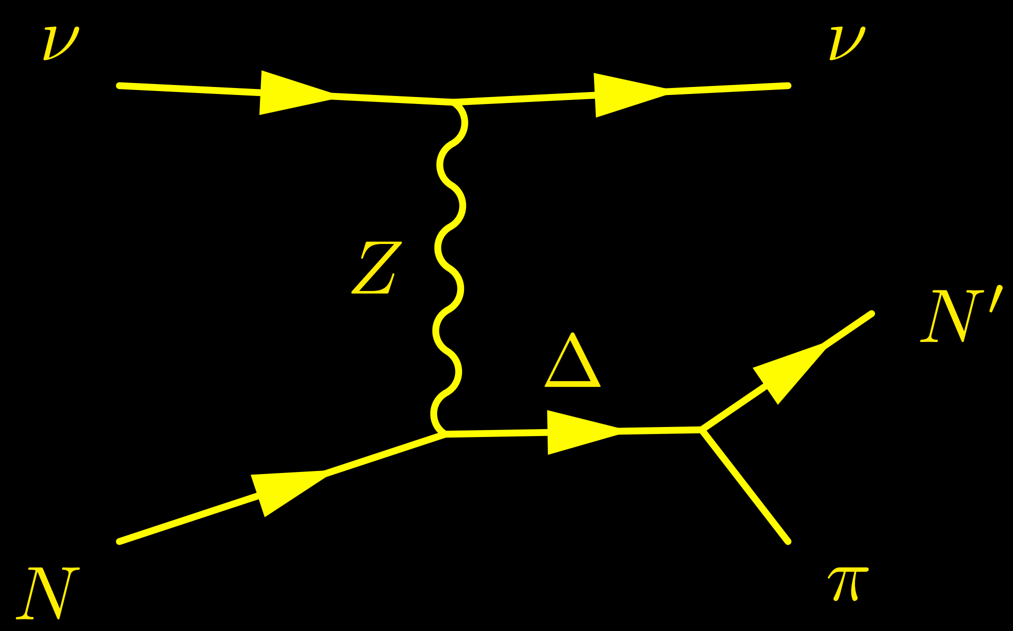


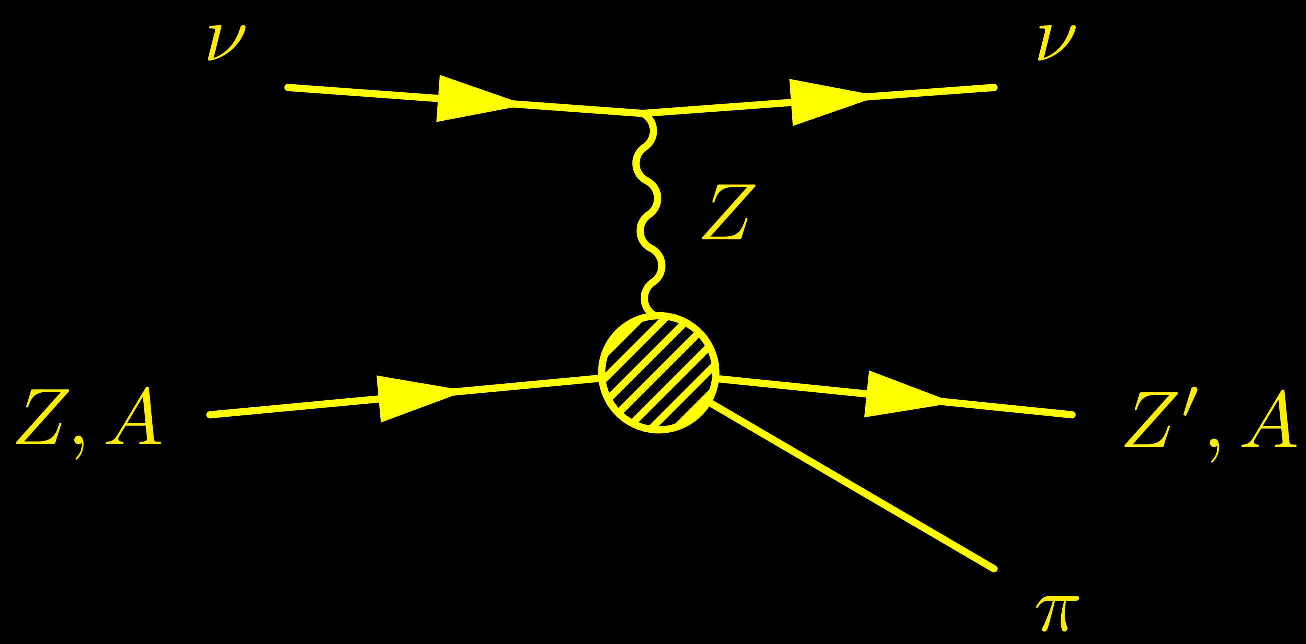
Neutral-current resonance/ π^0 production



- Of interest to oscillation searches primarily because π^0 and radiative Δ decay represent major backgrounds to ν_e appearance searches.
- Radiative Δ decay (BR $\sim$1%) is an irreducible background for detectors without fine-grained tracking!

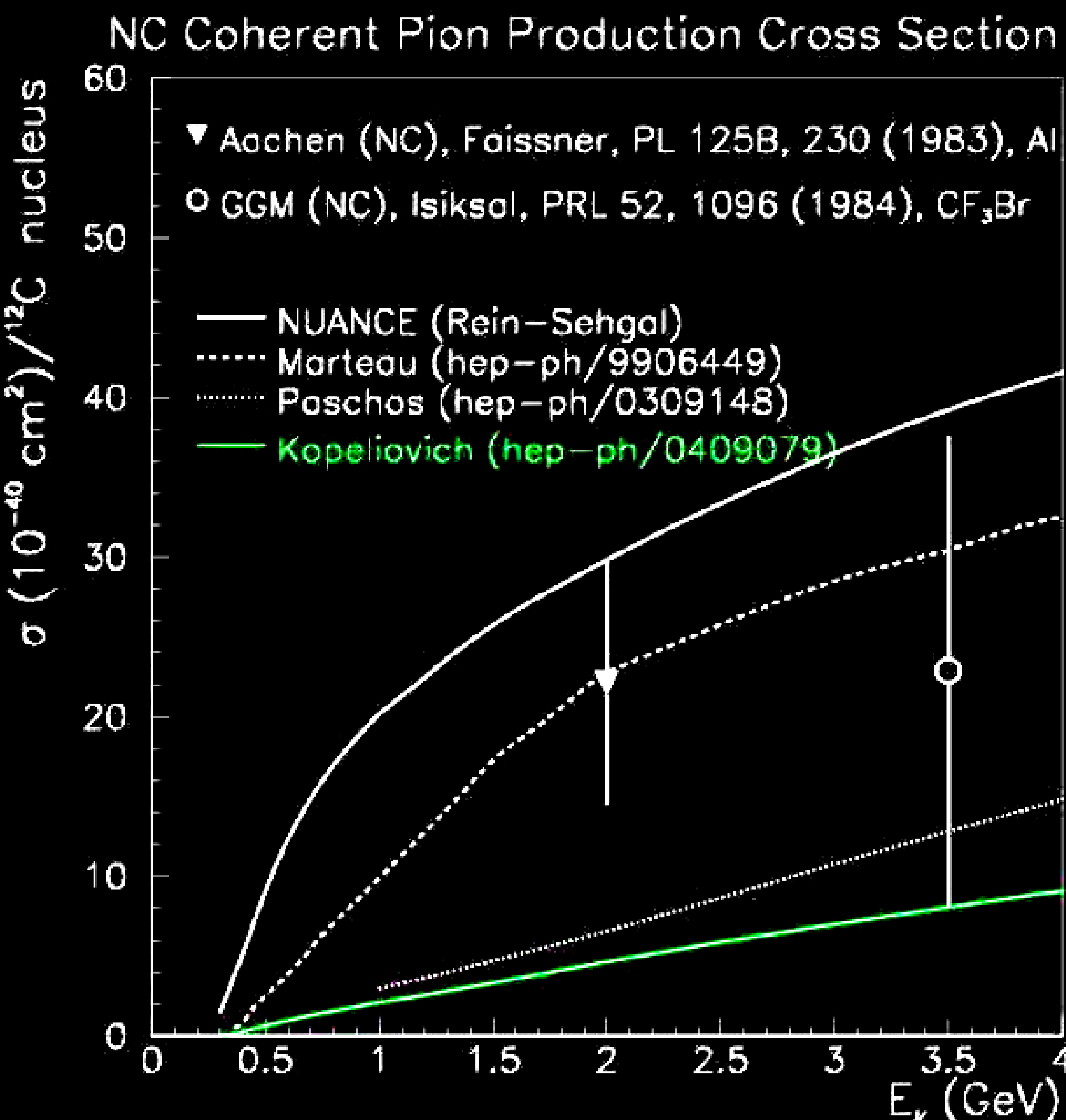
Resonant vs. Coherent π^0



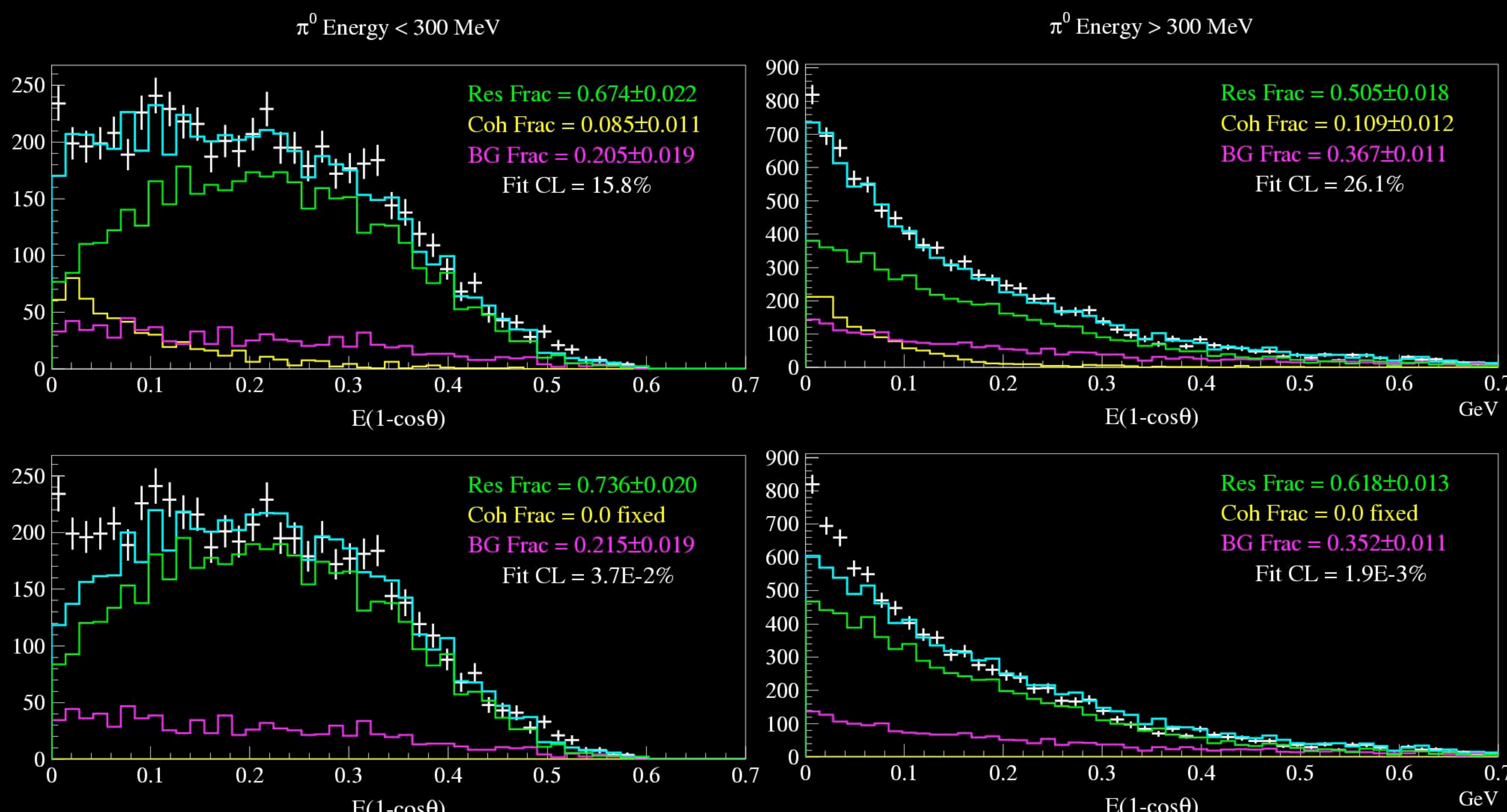


- Neutral current π^0 production can proceed through nucleon resonance or coherent nuclear processes. Coherent is thought to represent 5-20% of the rate.
- Coherent events have low Q^2, therefore should have forward π^0. Coherent events have no outgoing nucleon.

Previously published coherent π^0 production measurements



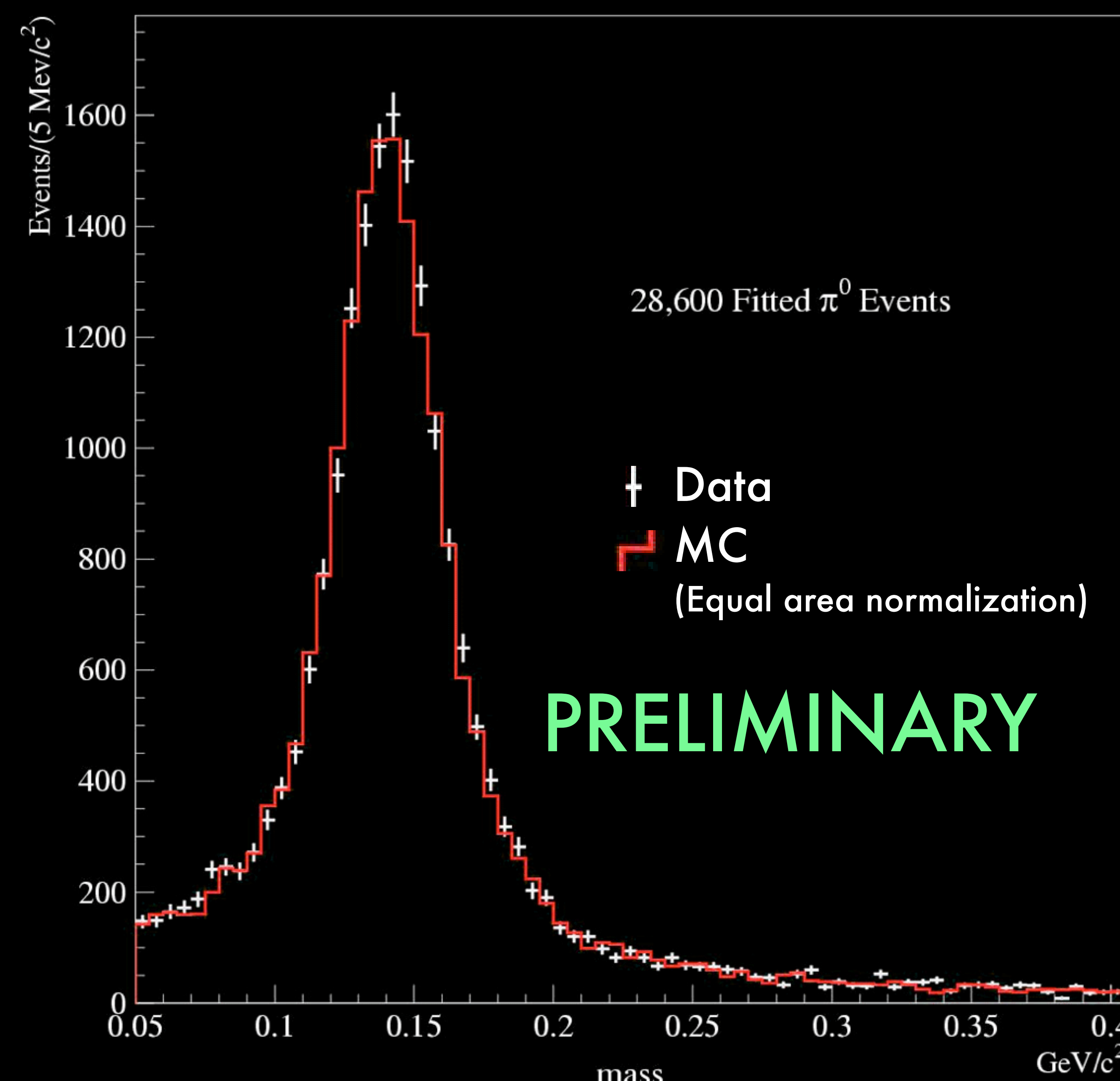
Resonant vs. Coherent π^0



- MiniBooNE data favor >10% of π^0 coherent
- Strongly disfavor zero coherent

MiniBooNE π^0 *measurement*

- Cuts require good π^0 particle ID likelihood, no evidence of muon decay
- Two-ring fit allows extraction of $\gamma\gamma$ invariant mass
- Sample purity is 90% for all π^0 modes, 70% for resonant+coherent
- Extracted yield is 28600 events for full oscillation run



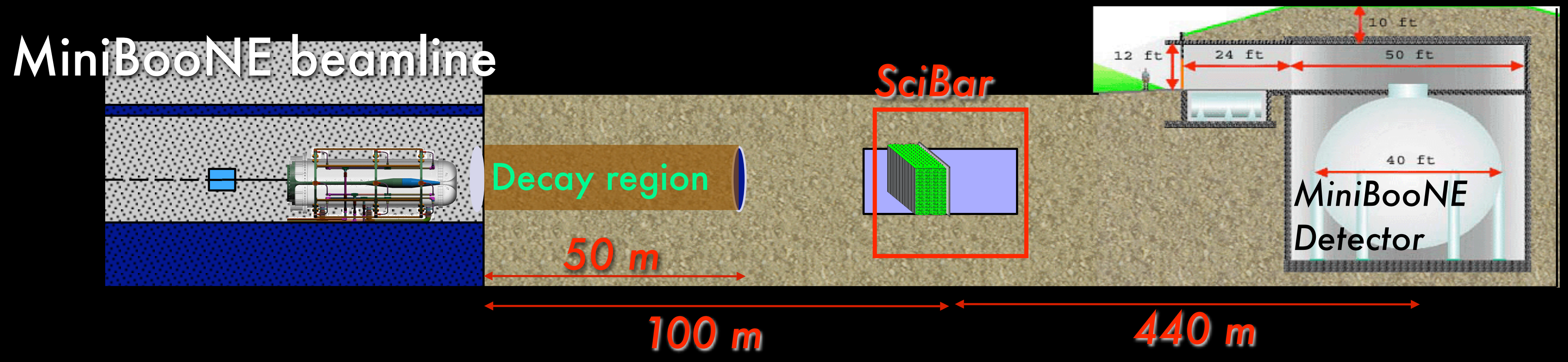
What's up with coherent?

- Both MiniBooNE and K2K see evidence for coherent neutral pion production in NC events, as expected
- However, both see no evidence for coherent charged current pion production!
- New Rein-Sehgal paper (hep-ex/0606185) suggests this may be due to destructive interference in the case of charged current interactions because of the finite muon mass.

Cross-sections

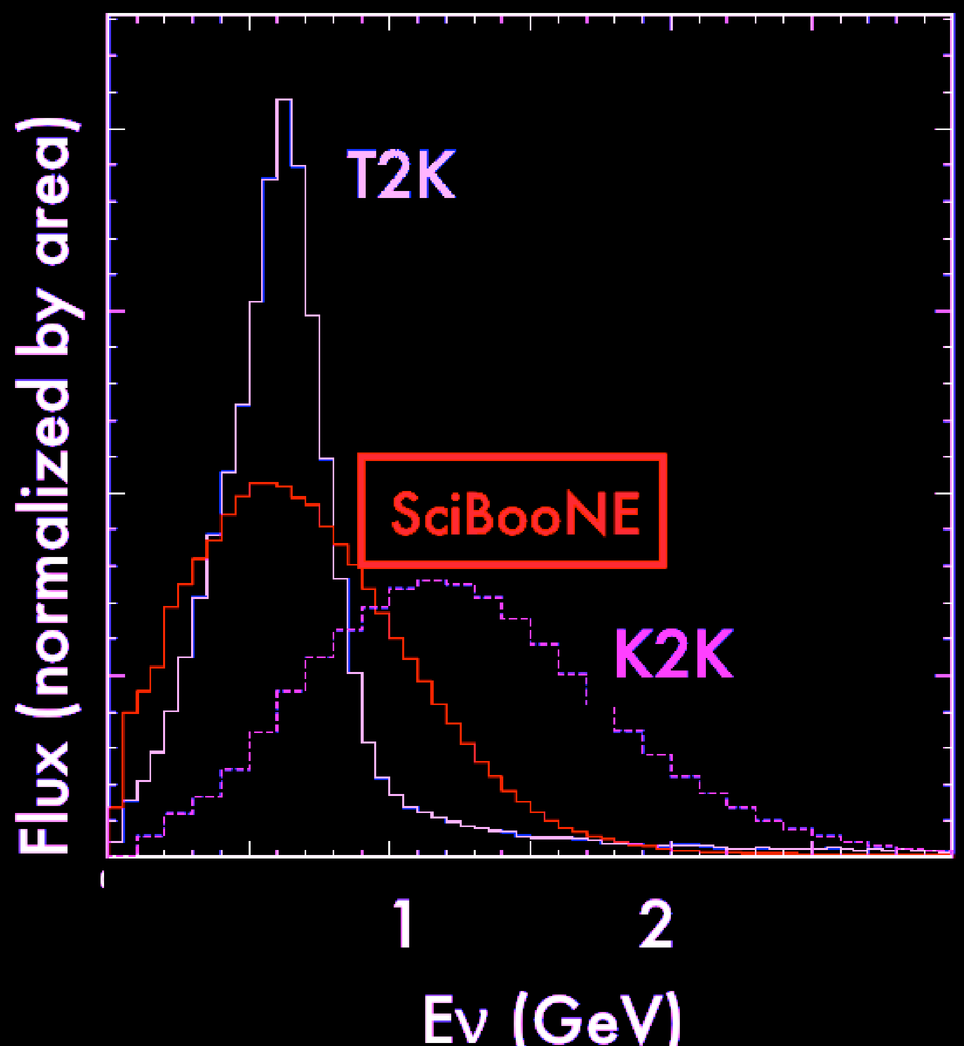
- MiniBooNE expects to publish cross-section results in the next several months for charged pions, neutral pions, and quasielastics
- Antineutrino measurements: data taking underway
- Next step: SciBooNE (new detector in the same beam)

FNAL E954: SciBooNE



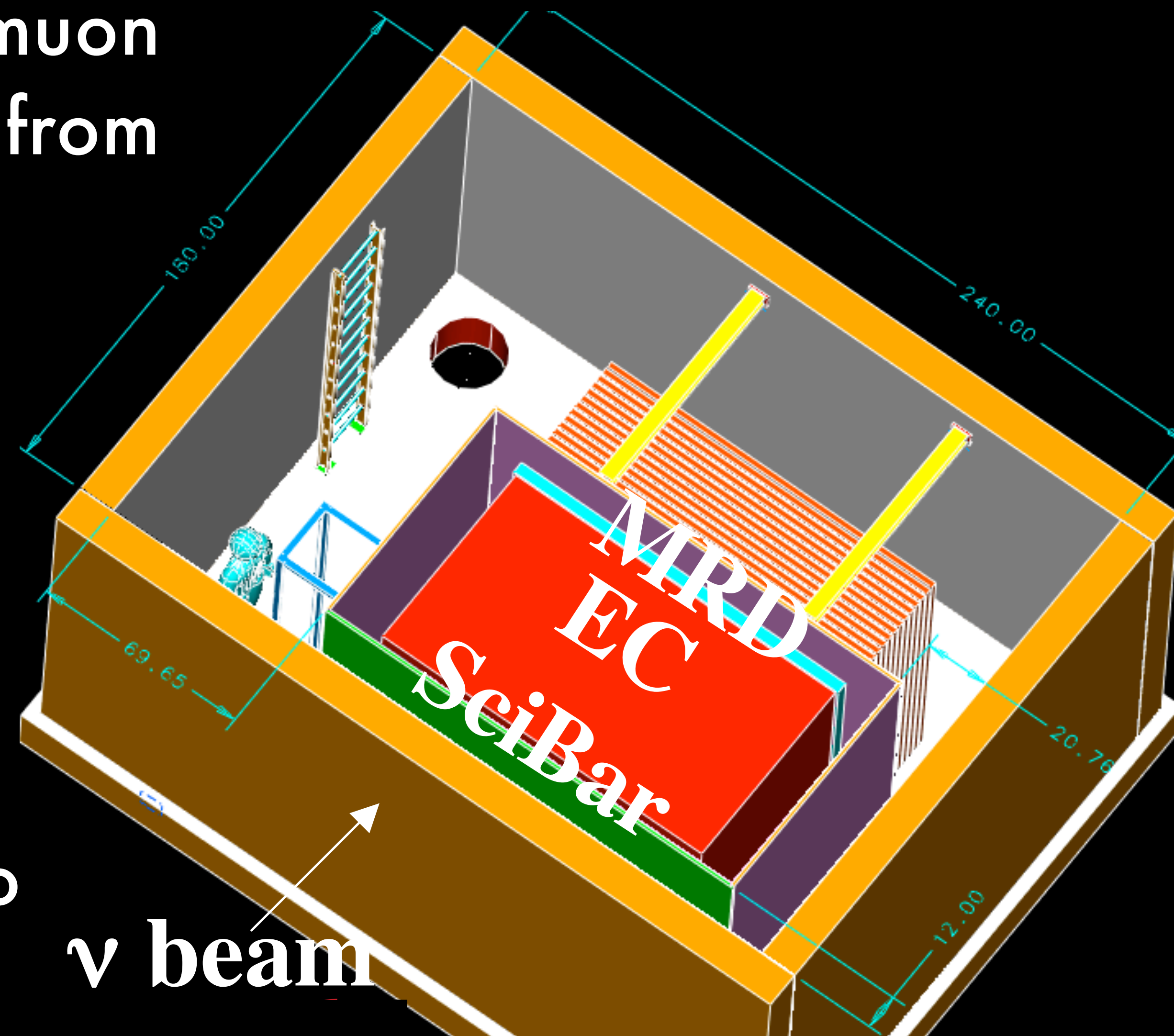
- Bring the K2K SciBar detector to Fermilab, insert it in a new enclosure in the MiniBooNE neutrino beam at a baseline of 100 m.

- SciBooNE sees nearly entire flux of T2K (and of course MiniBooNE)



SciBooNE

- SciBar and ECAL from KEK; muon range detector built at FNAL from old components
- centimeter-scale tracking resolution
- Construction bid awarded
- Data collection in 2007:
  - 0.5×10^{20} p.o.t. in neutrino mode
  - 1.5×10^{20} in antineutrino



MiniBooNE talks at NBI

- The MiniBooNE Beam MC and hadron production fits: Kendall Mahn
- Constraining kaons using high energy neutrinos: Kendall Mahn
- Little Muon Counter results: Martin Tzanov
- Antineutrino data: changeover experience and first data: Morgan Wascko