Neutrino Physics at Short Baseline

E. D. Zimmerman
University of Colorado
Boulder, Colorado

XXVI Physics in Collision
Búzios, 6 July 2006

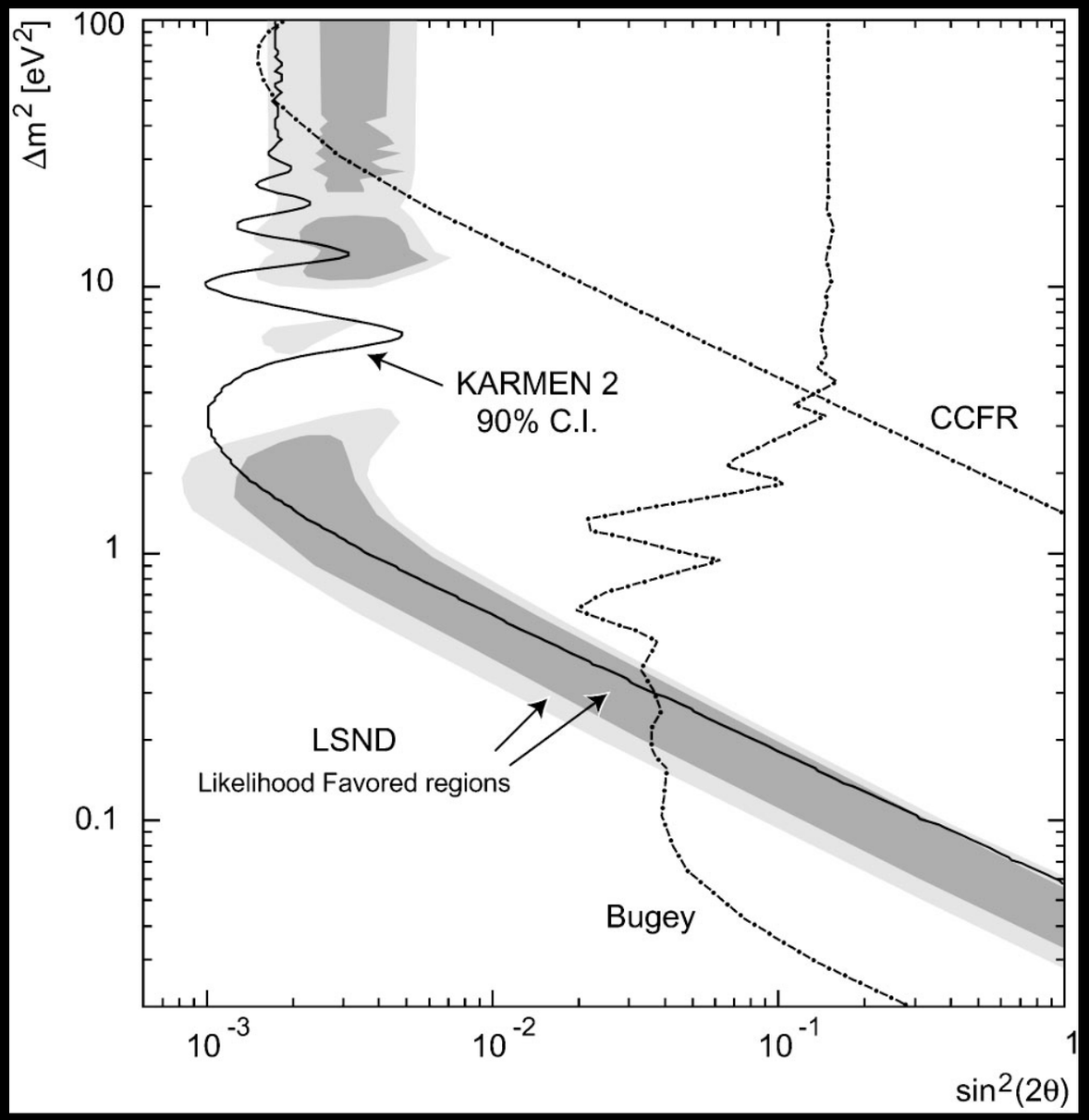
The Amazon from 33,000 feet

Neutrino Physics at Short Baseline

- Oscillations *(The LSND question)*
- Cross-Sections
  - Medium-energy processes *(MiniBooNE, K2K, MINOS)*
    - Quasielastic scattering
    - Resonance and coherent meson production
  - Deep Inelastic Scattering *(E815, MINOS)*
  - Future experiments
    - SciBooNE, MINERνA

Oscillations:The Experimental Picture

- Highest Δm^2 limits:
  Dominated by high energy experiments: CCFR, CDHS, NuTeV, BNL, NOMAD/CHORUS
- Lower Δm^2 limits:
  Reactor experiments (Bugey)
- Moderate Δm^2 and $\sin^2 2\theta$ experiments:
  LSND (positive signal) and KARMEN2 (no signal)



Atmospheric

Solar

LSND concept

(Liquid Scintillator Neutrino Detector)

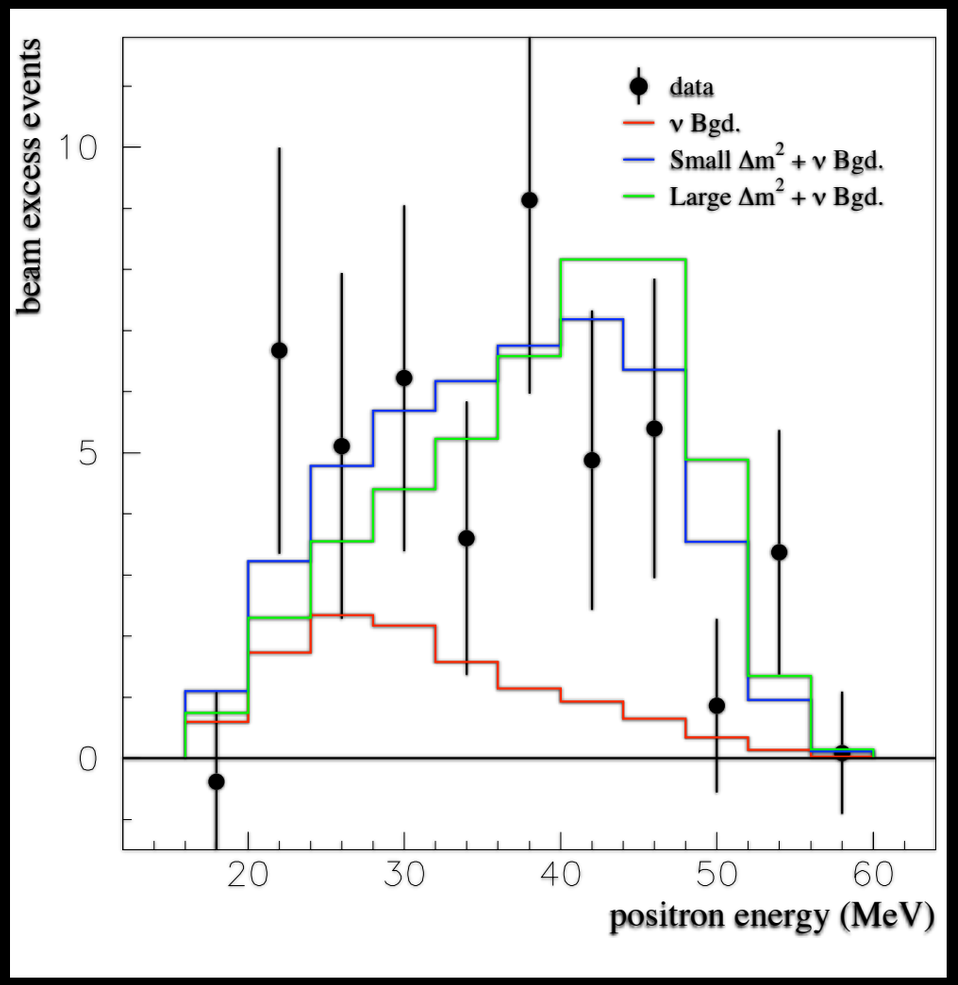
- Stopped π^+ beam at Los Alamos LAMPF produces ν_e, ν_μ, $\bar{\nu}_\mu$ but no $\bar{\nu}_e$ (due to π^- capture).

  Search for $\bar{\nu}_e$ appearance via reaction:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

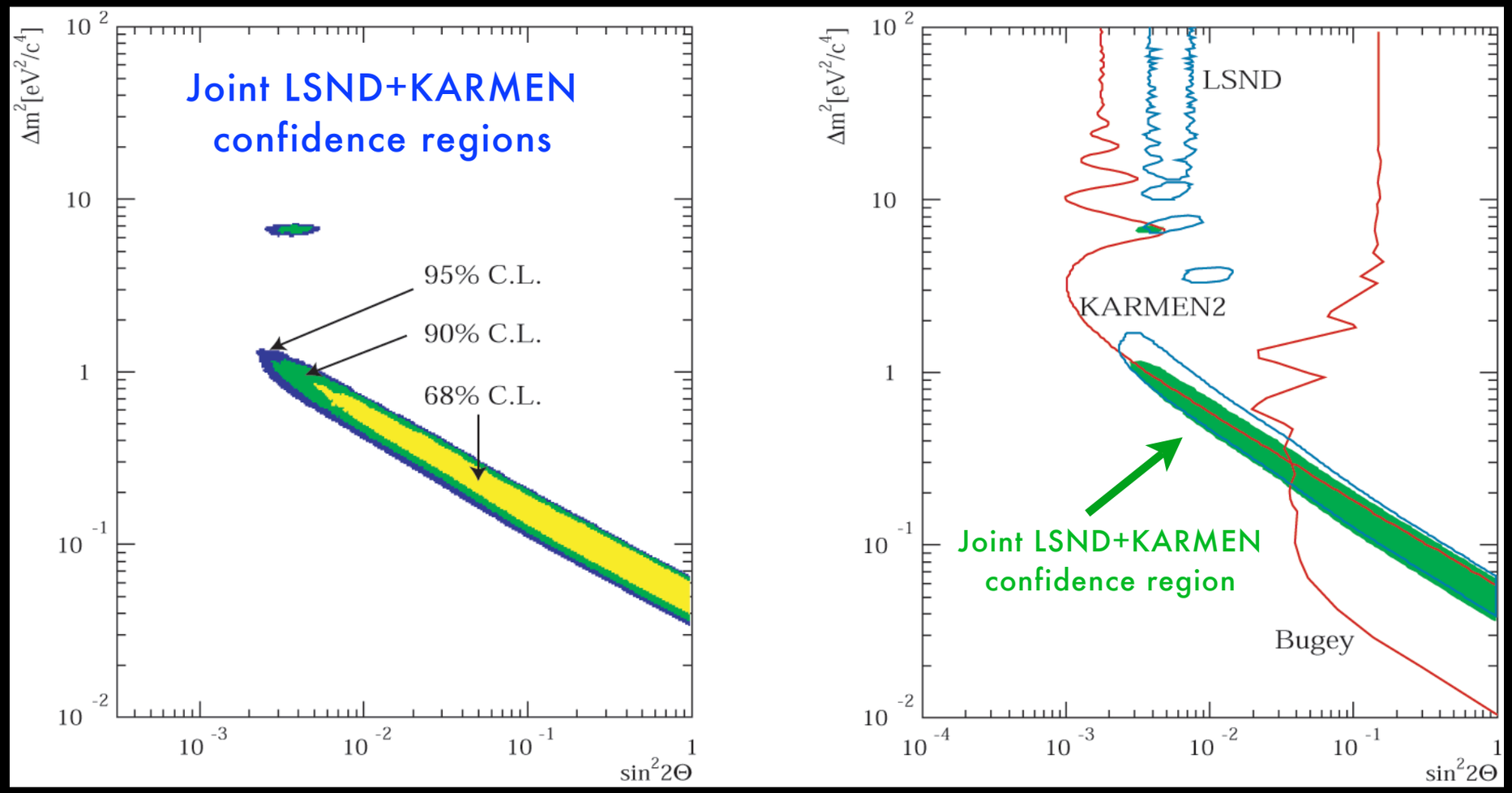
- Neutron thermalizes, captures ➡2.2 MeV γ-ray
- Look for the delayed coincidence.
- Major background non-beam (measured, subtracted)
- 4 standard dev. excess above background.
- Oscillation probability:

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = (2.5 \pm 0.6_{\text{stat}} \pm 0.4_{\text{syst}}) \times 10^{-3}$$



LSND and KARMEN2 compatibility

KARMEN2: similar experiment at RAL (UK), shows no excess above background. KARMEN2 had shorter baseline, so sensitive to higher Δm^2.



E. Church *et al.*, *Phys. Rev.* **D66**, 013001 (2002)

- Combined analysis:
  - Consistency at 64% confidence level
  - Restricted parameter region

The Overall Picture

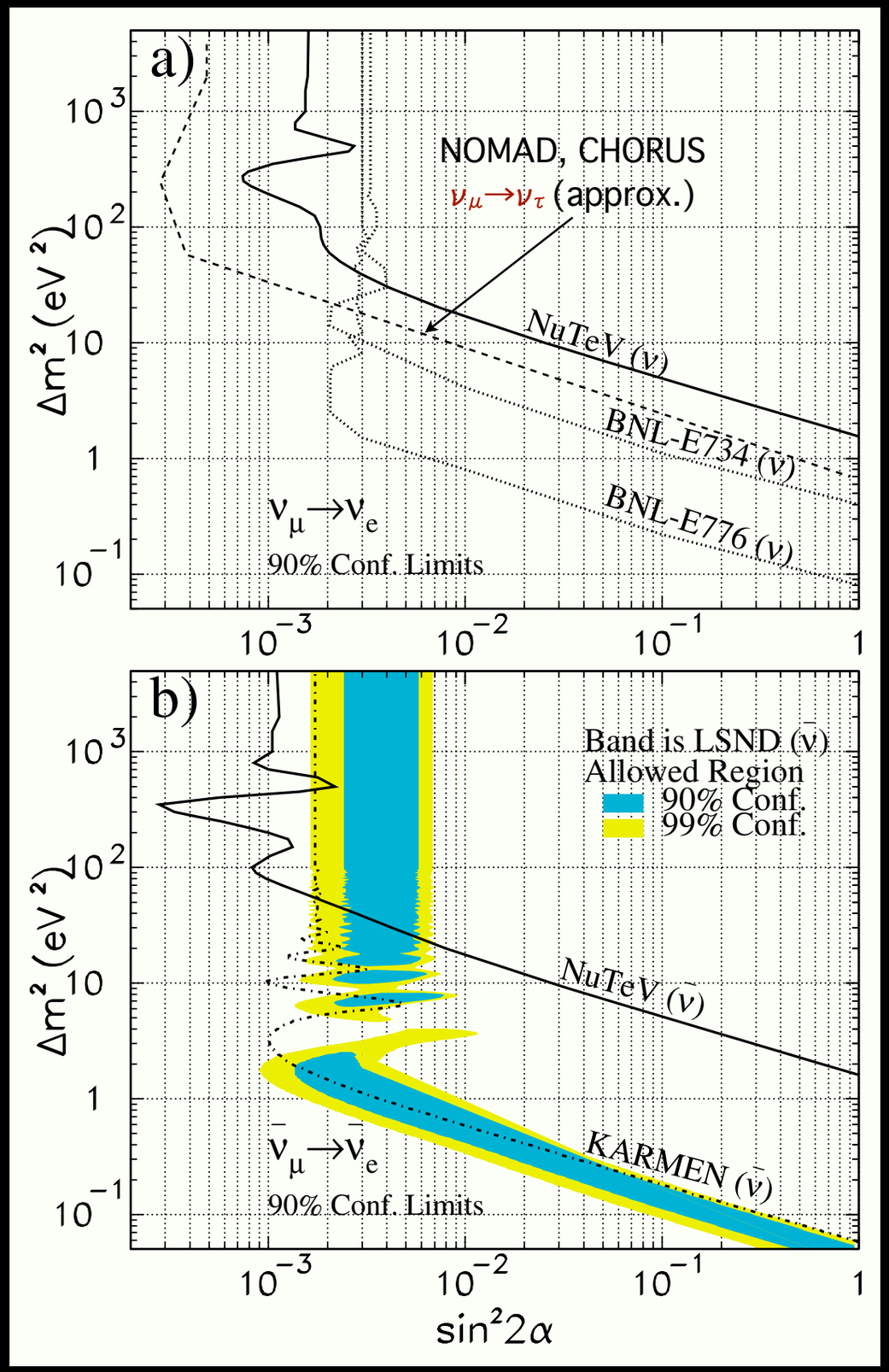
LSND	$\Delta m^2 > 0.1\mathrm{eV}^2$	$\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$
Atmos.	$\Delta m^2 \approx 2 \times 10^{-3}\mathrm{eV}^2$	$\nu_\mu \leftrightarrow \nu_?$
Solar	$\Delta m^2 \approx 10^{-4}\mathrm{eV}^2$	$\nu_e \leftrightarrow \nu_?$

With only 3 masses, can't construct 3 Δm^2 values of different orders of magnitude!

- Is there a fourth neutrino?
  - If so, it can't interact weakly at all because of Z^0 boson resonance width measurements consistent with only three neutrinos.
- We need one of the following:
  - A "sterile" neutrino sector
  - New ideas: CPT violation (excluded?), neutrino decay, mass varying neutrinos, ...
  - Discovery that one of the observed effects is not oscillations

Separating ν and $\bar{\nu}$:

- LSND, KARMEN only antineutrinos
- BNL, NOMAD, CHORUS only neutrinos
- NuTeV does them separately
- Combined results only:
  - CCFR (appearance)
  - CDHS (disappearance)



MiniBooNE at Fermilab

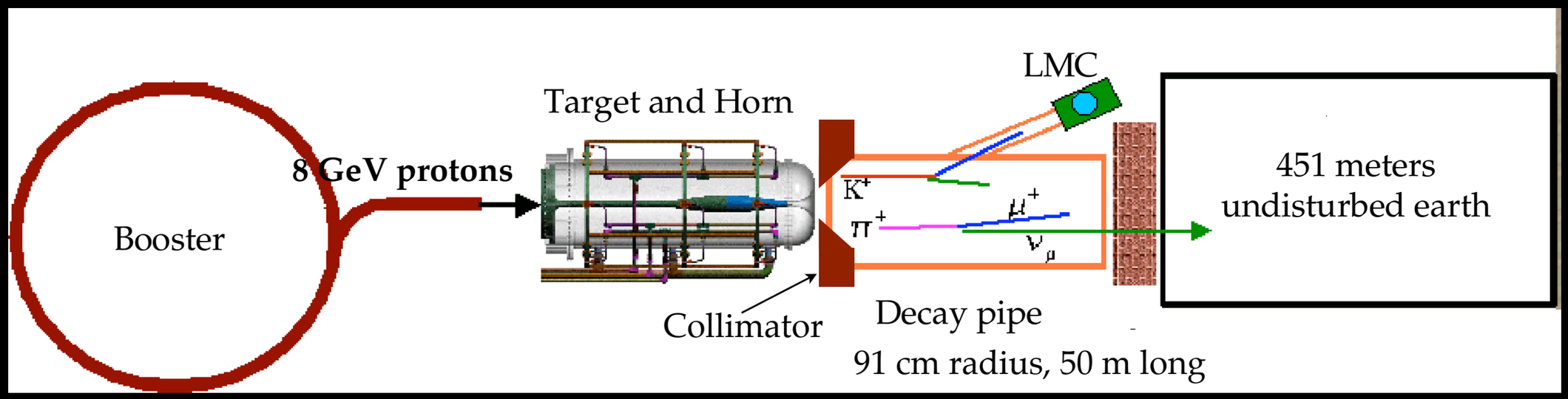
Purpose is to test LSND with:

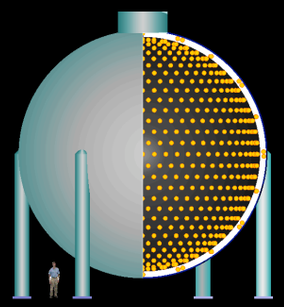
- Higher energy
- Different beam
- x10 statistics
- Different oscillation signature
- Different systematics
- Antineutrino-capable beam

8 GeV primary proton beam from FNAL Booster

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

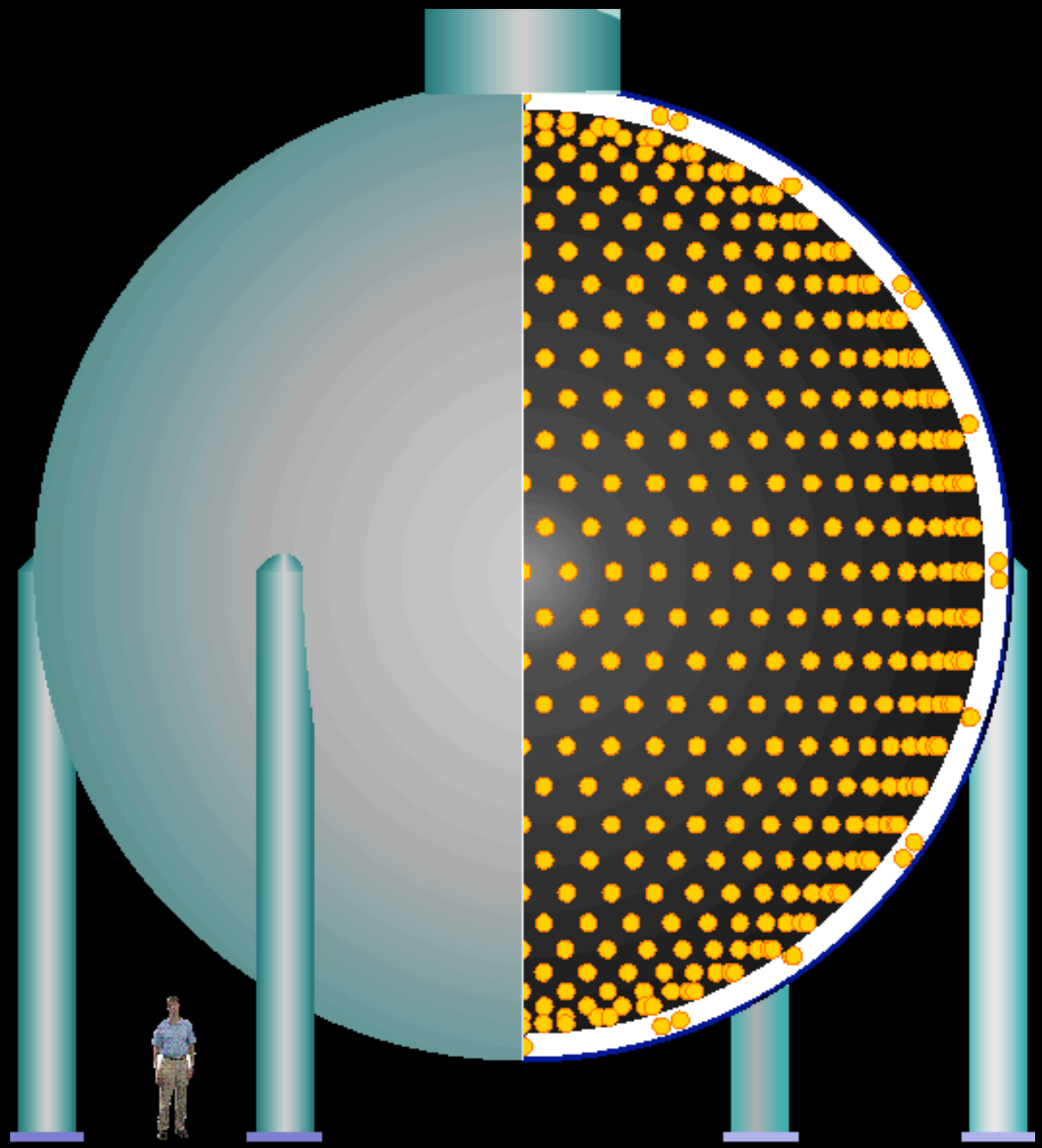
MiniBooNE Beamline

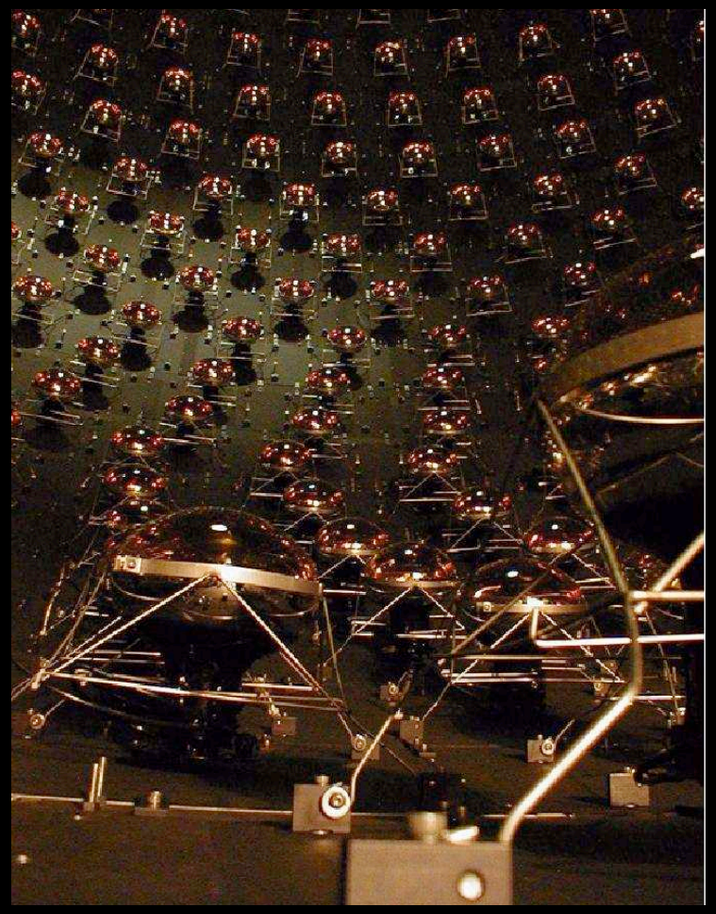




- Cartoon not to scale!
- Booster provides about 5 pulses per second, 5×10^{12} protons per 1.6 μs pulse under optimum conditions

The BooNE neutrino detector





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

Oscillation Signature at MiniBooNE

- Oscillation signature is charged-current quasielastic scattering:

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

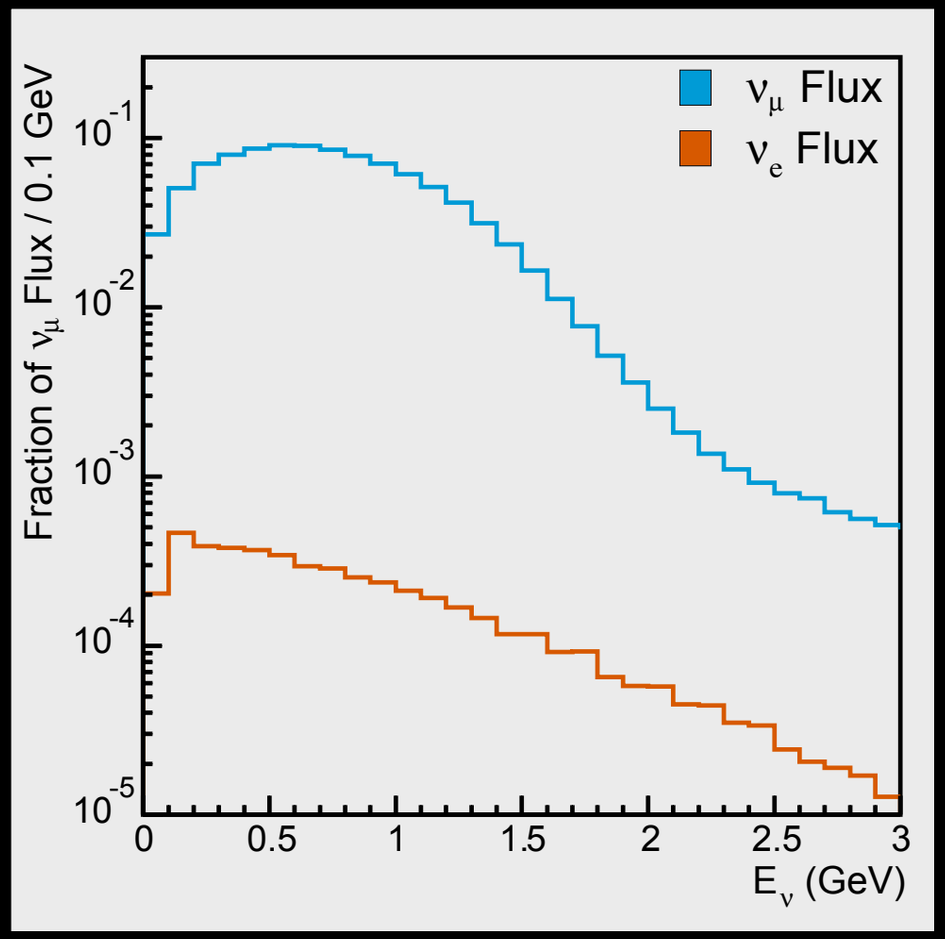
- Backgrounds to oscillation:
  - Intrinsic ν_e in the beam
    $\pi \rightarrow \mu \rightarrow \nu_e$ in beam
    $K^+ \rightarrow \pi^0 e^- \nu_e$, $K_L^0 \rightarrow \pi^0 e^\pm \nu_e$ in beam
  - Particle misidentification in detector
    μ mis-id as e, decay unseen
    π^0 produced in NC, decays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

Oscillation Analysis

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

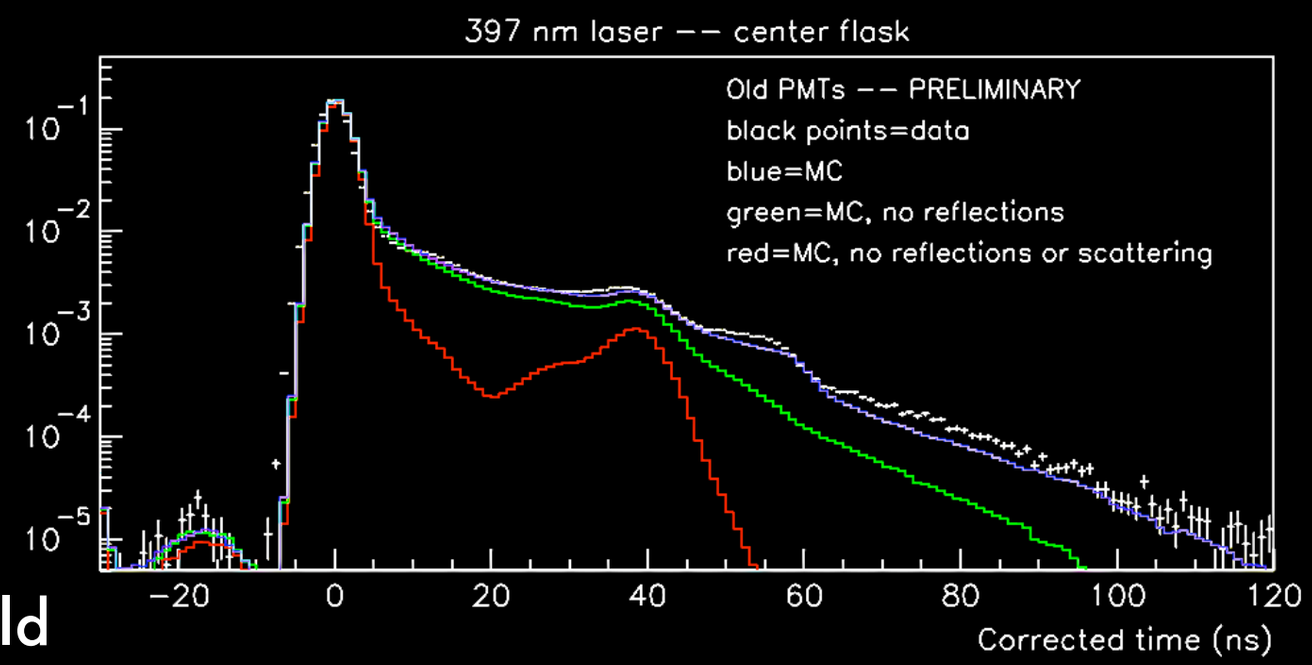
Understanding the neutrino flux

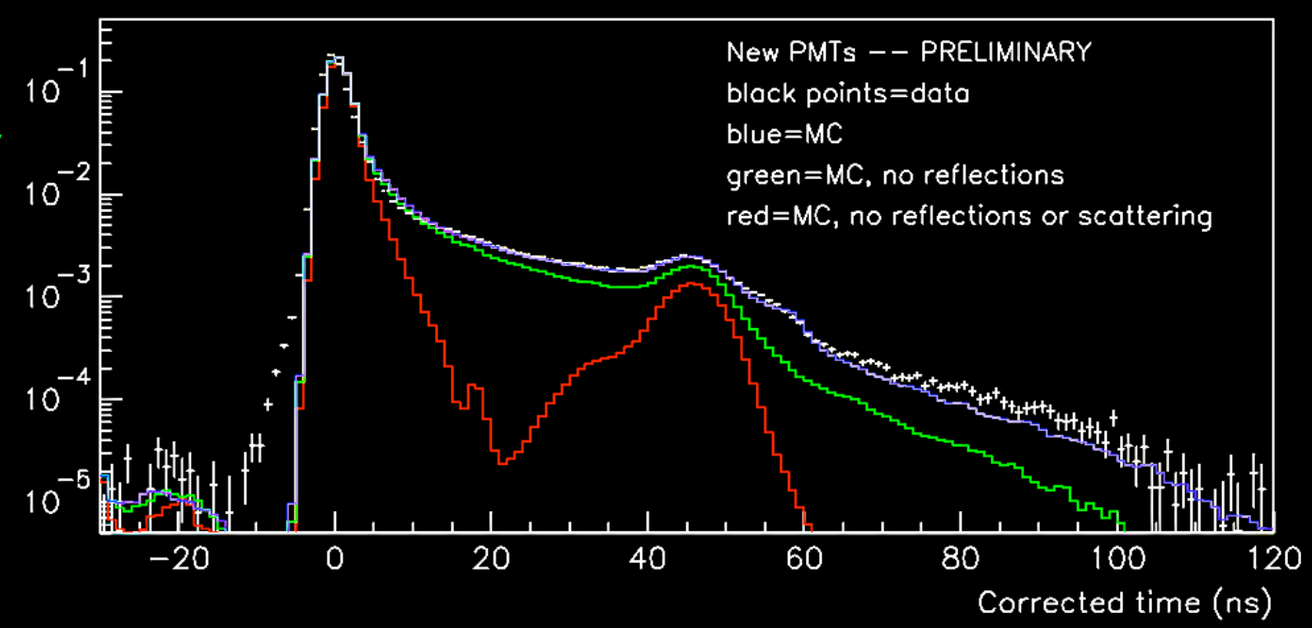
- Primary p-Be interactions:
  - π^+ are produced from a parametrized p-Be cross-section using external measurements including recent results from BNL E910 and HARP.
  - K^+ from external data fit too; agrees well with MARS. Will incorporate internal measurements from dedicated beam monitor, studies of highest-energy neutrinos in detector. HARP data will be coming too.
  - K^0 scaled from K^+
- 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

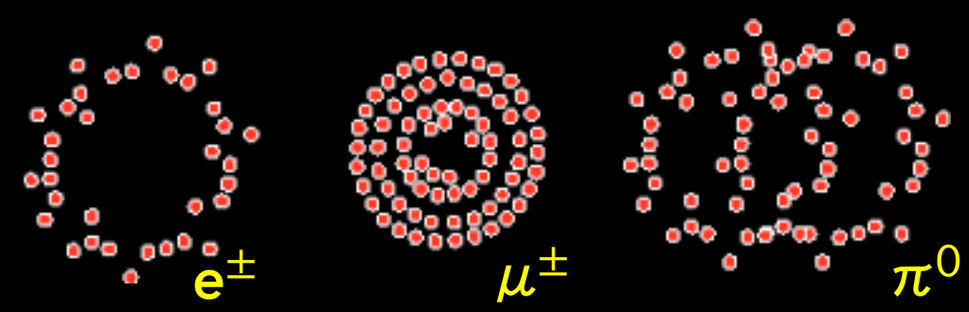
- Cherenkov light production
  - Emitted promptly, in cone
  - $1/\lambda^2$ wavelength distribution
- Scintillation light
  - Emitted isotropically
  - Several lifetimes, emission modes
  - λ = 270-340 nm
  - Particles below Cherenkov threshold still scintillate
- Optical properties of oil, detectors: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

Expected oscillation candidates at MiniBooNE

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

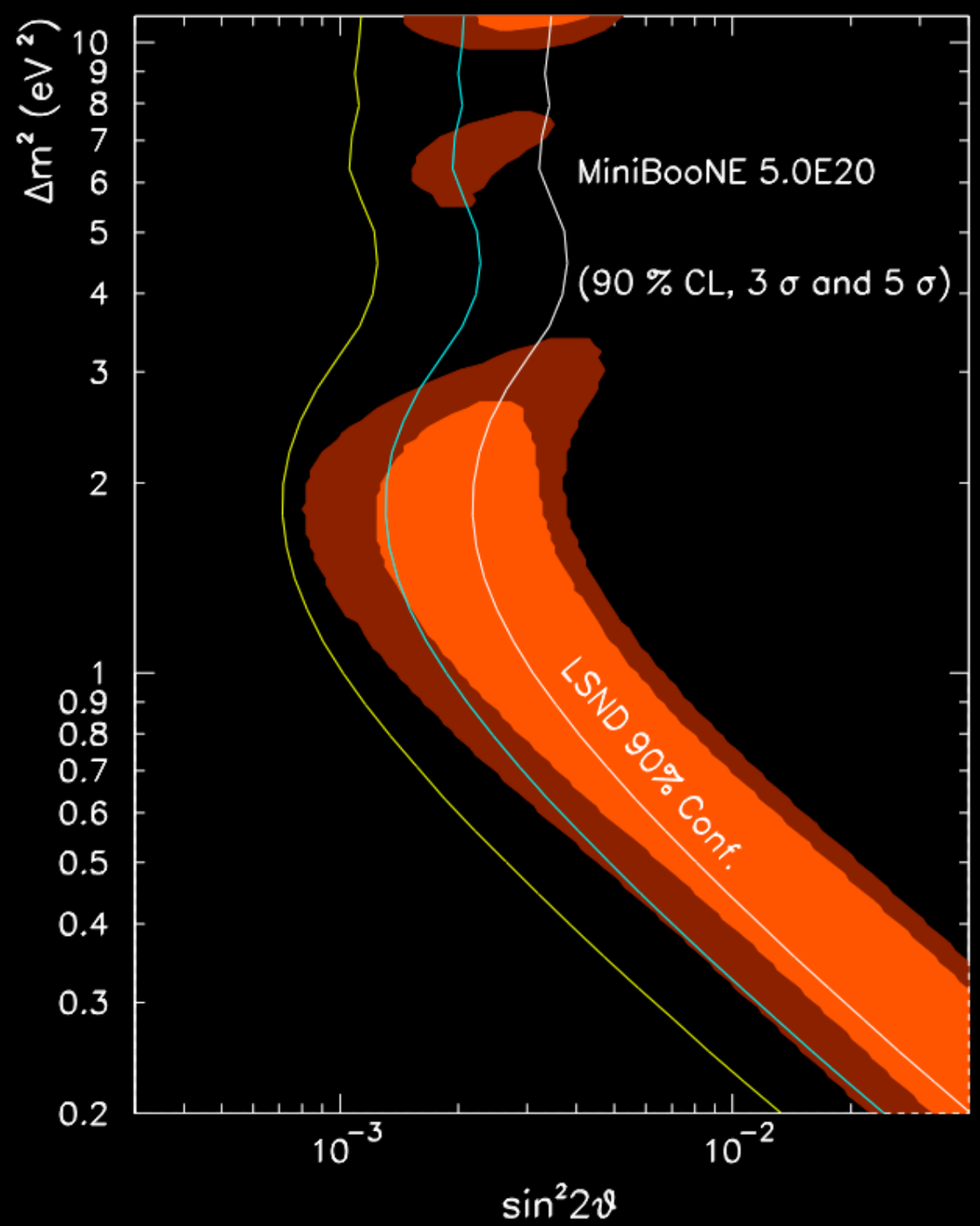
PROCESS	ALL EVENTS	AFTER SELECTION
NEUTRAL CURRENT π^0	55000	145
NC RADIATIVE Δ DECAY	540	40
ν_μ QUASIELASTIC	275000	5
OTHER ν_μ	~500000	25
INTRINSIC ν_e	1250	175
OSCILLATION SIGNAL	750	150
SIGNAL/BACKGROUND		150/390=0.38

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)

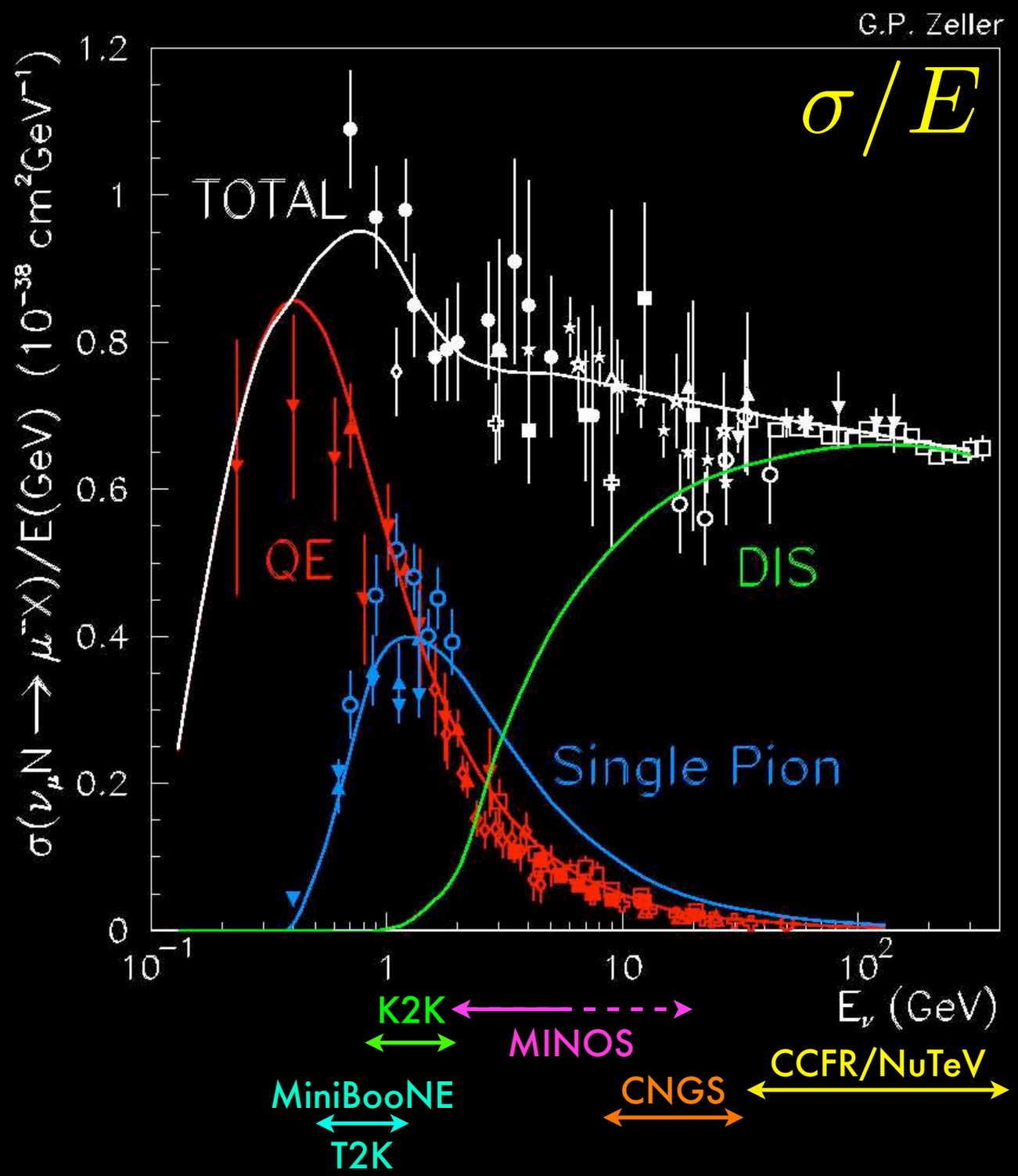
MiniBooNE oscillation analysis progress

- Rapid progress is being made on all aspects, including understanding of:
  - Neutrino Flux
  - Particle ID understanding and performance
  - Optical model of detector is improving rapidly
- ν_e appearance analysis is still blind
  - Potential ν_e candidates are hidden from detailed 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
- Newer experiments are coming

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.

Current cross-section experiments

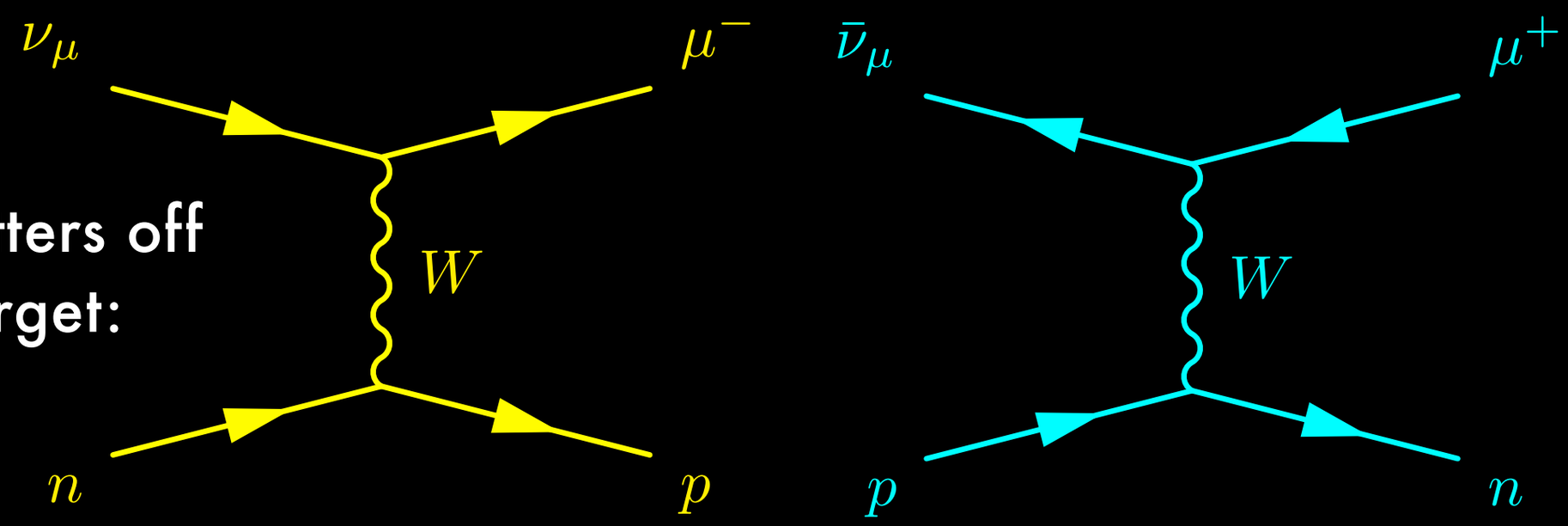
- Mature:
  - CCFR/NuTeV, NOMAD
- Current, rapidly-developing analyses
  - K2K (recent quasielastic, π^+ production)
  - MiniBooNE (recent π^0 and π^+ production)
- Newly collecting data
  - MiniBooNE ($\bar{\nu}$), MINOS
- Near future/construction
  - SciBooNE, MINERνA

Aside: cross-sections doesn't just mean neutrino experiments!

- Proton-nucleus hadron production cross-sections are crucial to understanding our neutrino beams.
- Three current efforts are making huge advances in our knowledge of these cross-sections:
  - BNL E910
  - CERN PS216 (HARP)
  - FNAL E907 (MIPP)

Quasielastic Scattering

Neutrino scatters off nucleon in target:

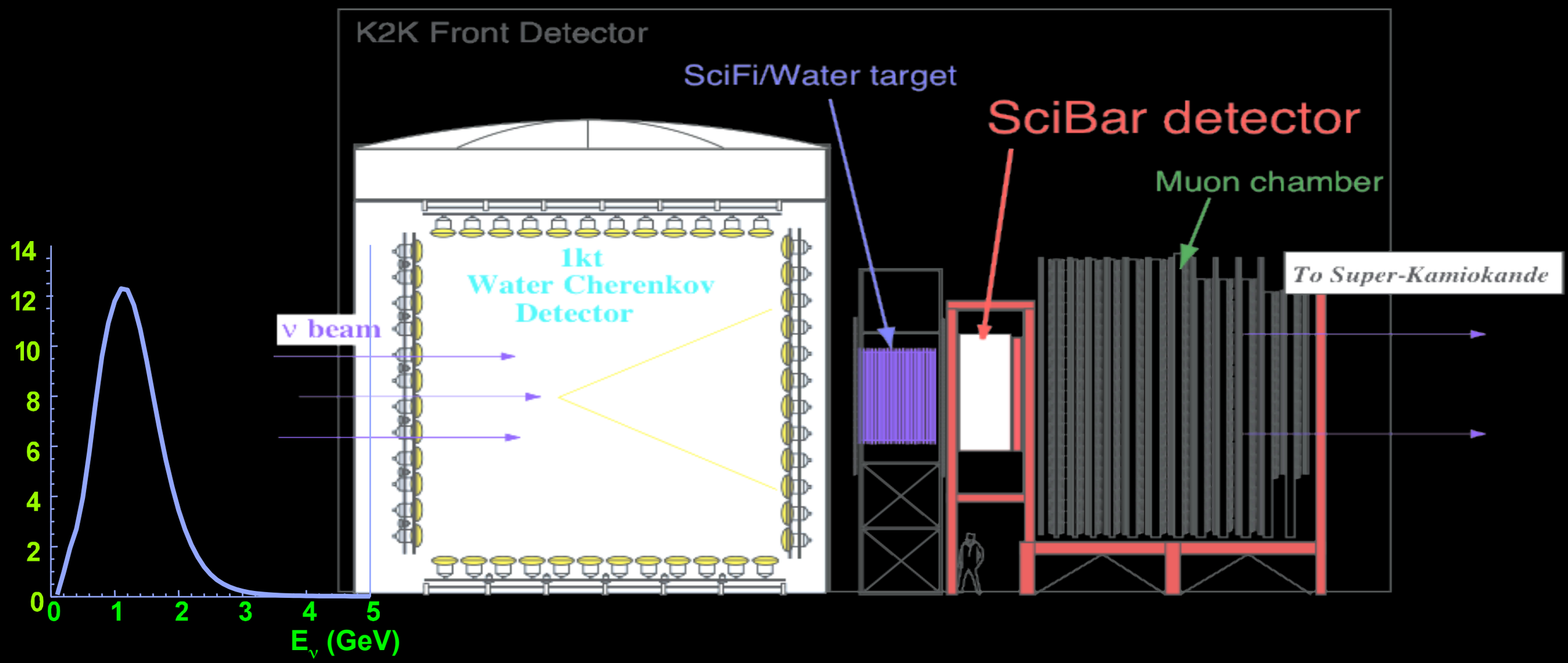


- Golden signal mode for oscillation searches: clean events; neutrino energy can be calculated given known neutrino direction:

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

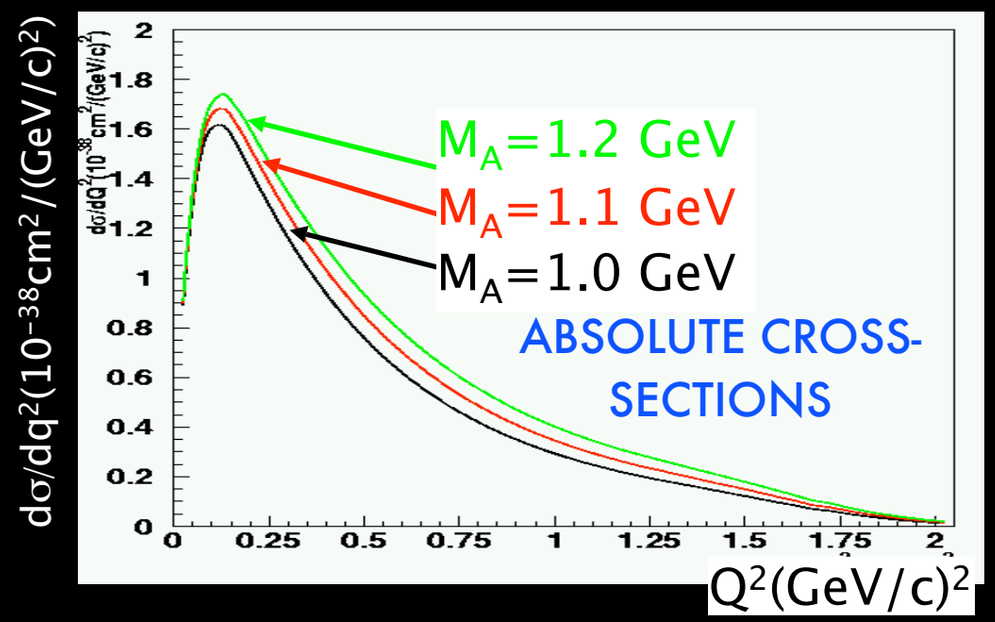
- (Correction for m_n-m_p, binding energy, Fermi motion of target nucleon)
- Nucleus may break up
- Final state nucleon not excited: no resonance, no pion, no (hard) gamma
- Physics to measure: axial form factor F_A, parametrized by M_A (axial mass)

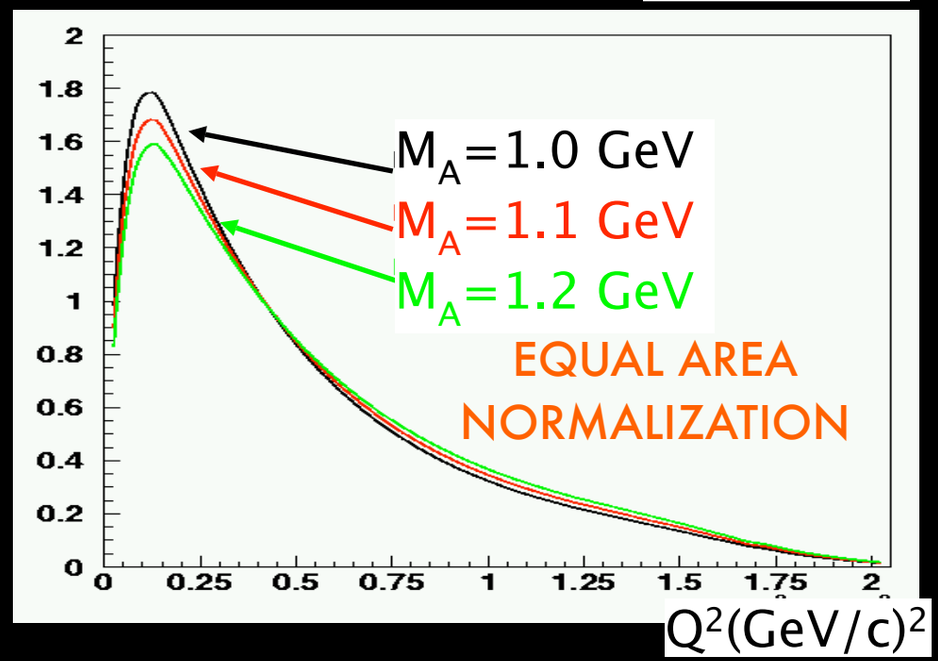
K2K ν_μ Quasielastic Scattering



- Targets available: carbon, water, iron
- Fine-grained detectors often allow proton detection

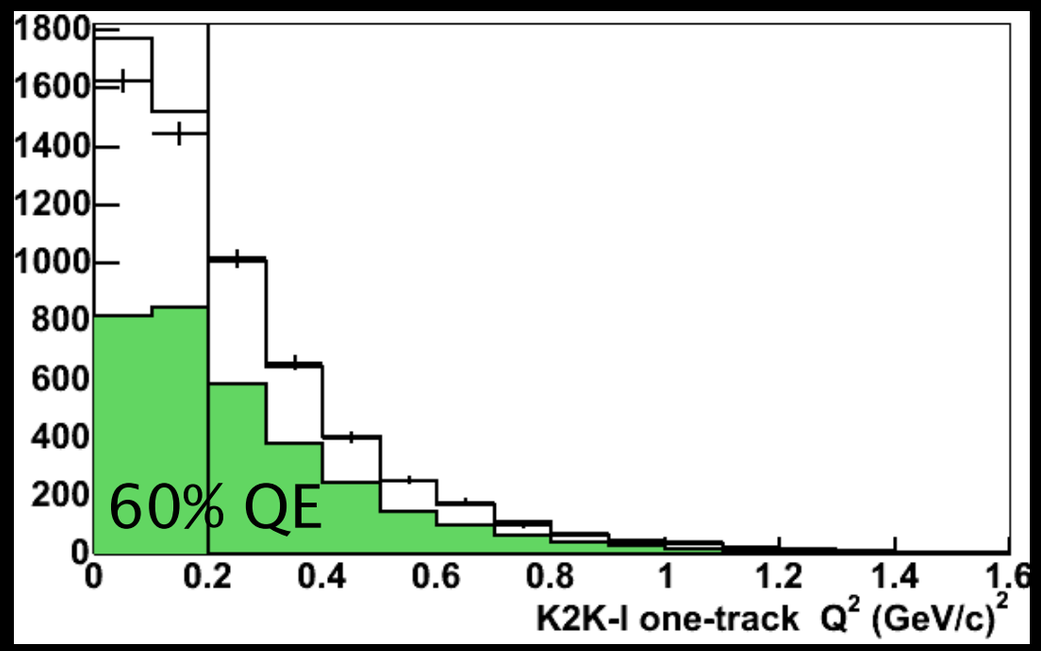
K2K ν_μ Quasielastic Scattering

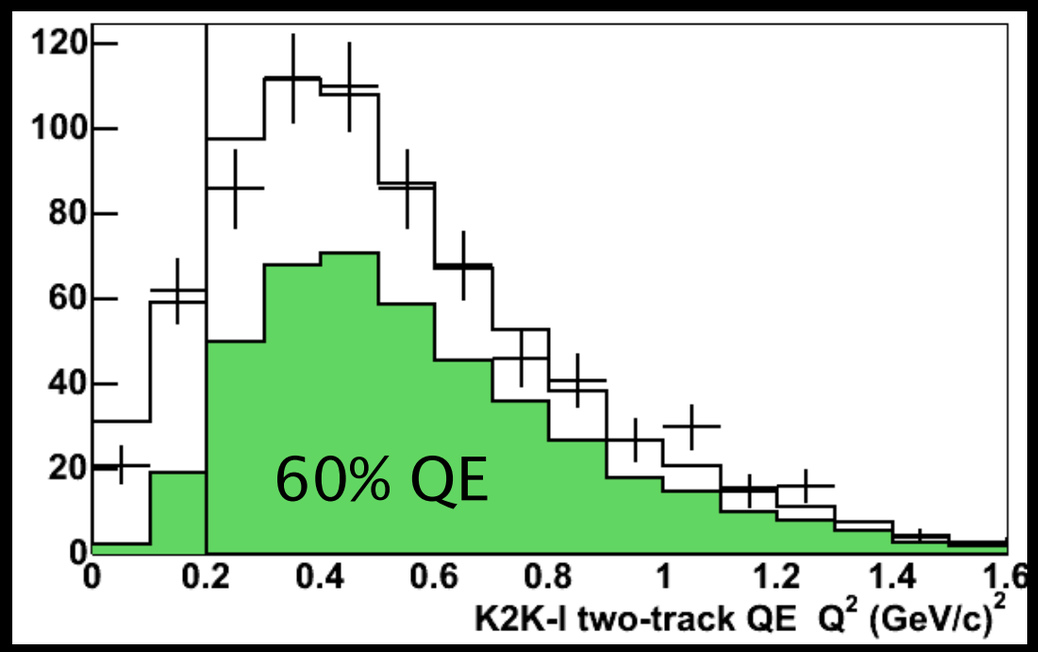




- This analysis uses only shape: in Q^2>0.2 GeV region (avoid model dependence at low Q^2)
- Higher M_A ➡ higher total σ, less peaked at low Q^2

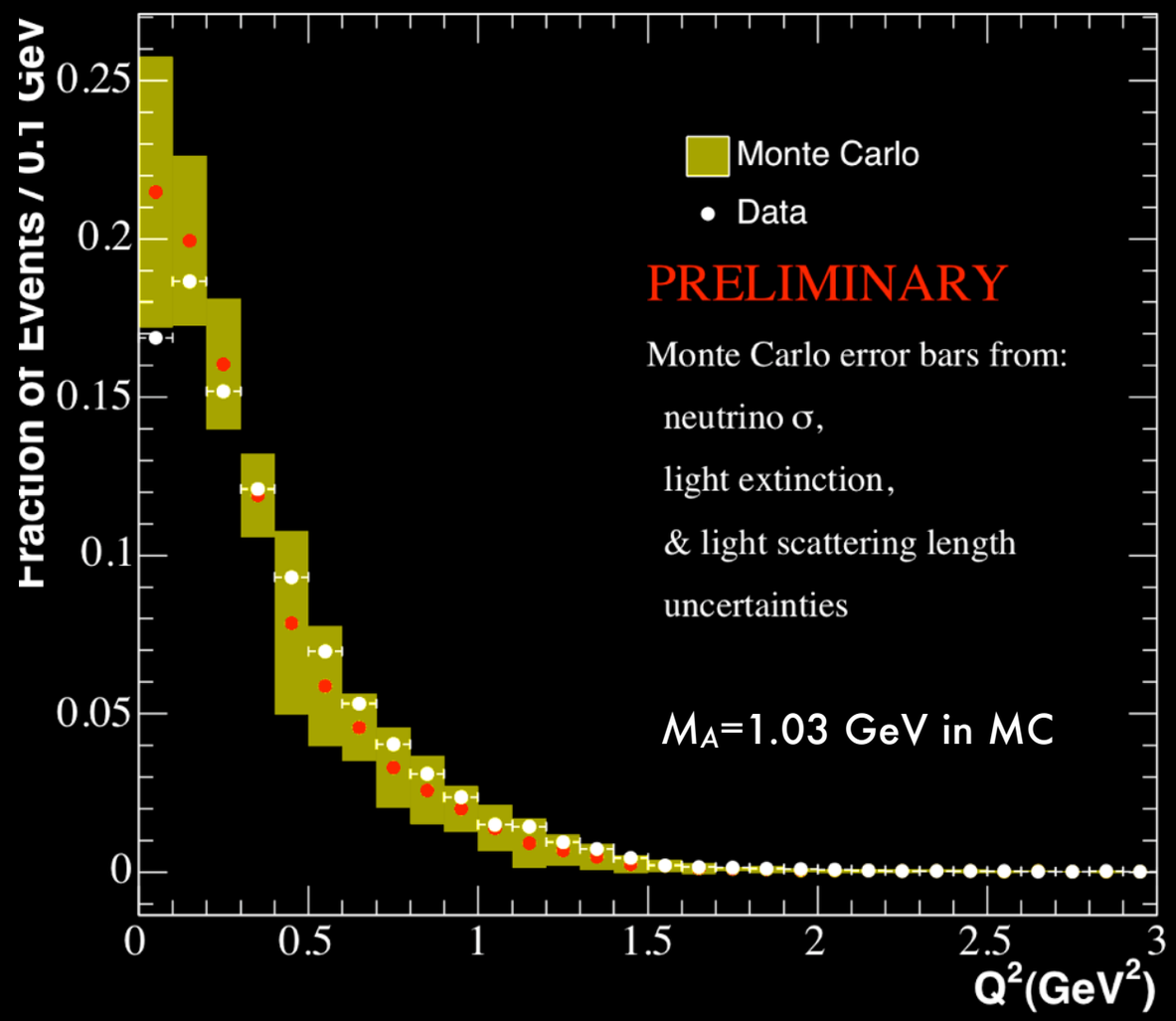
K2K ν_μ Quasielastic Scattering

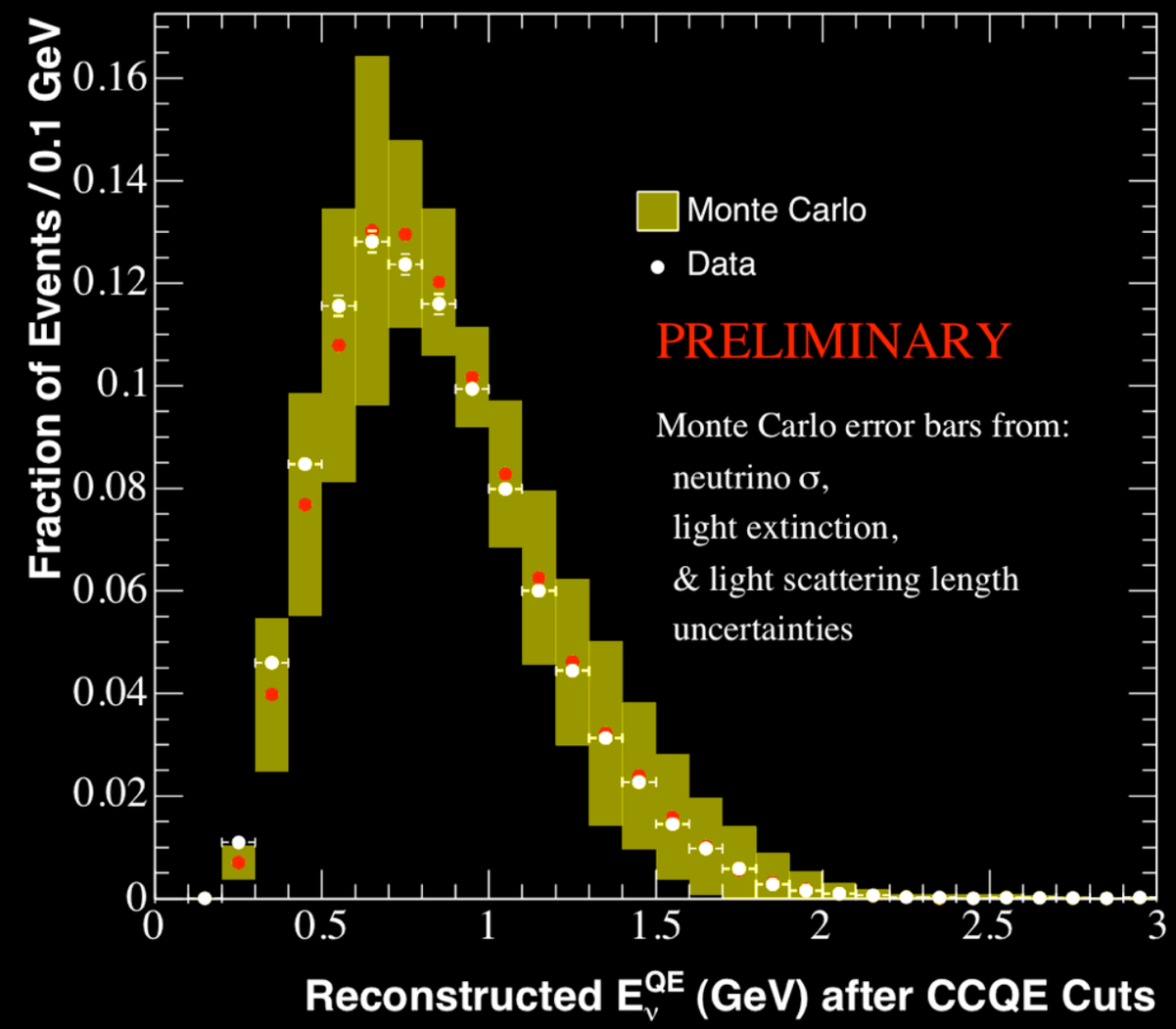




- Q^2 calculated assuming quasielastic interaction
- 60% pure quasielastic sample enables fitting of M_A=1.20±0.12 GeV (oxygen target)
- Previous results with deuterium targets show M_A=1.03±0.03 GeV

MiniBooNE QE results



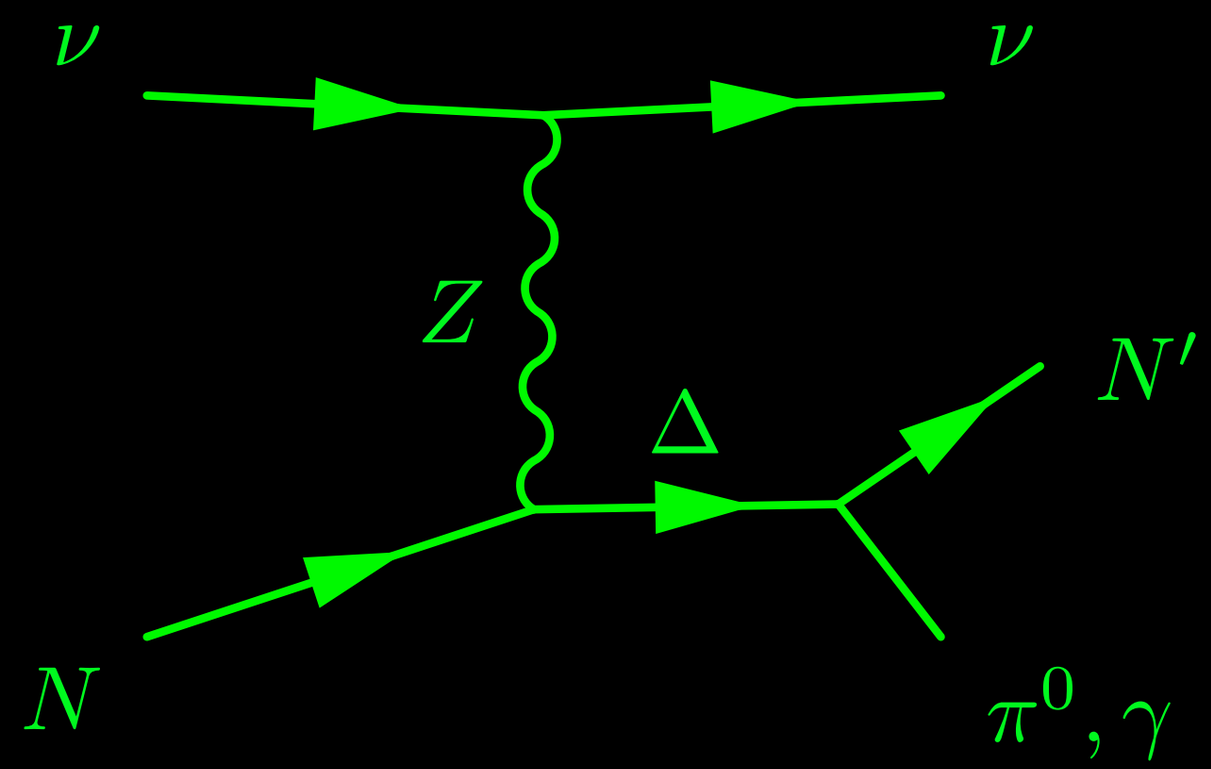


- Data/MC disagreement at low Q^2 similar to K2K
- Fits better with higher M_A
- New results wll be shown in August at NuFact'06

Pion production

- This represents a third of neutrino interactions at 1 GeV! Must understand it to characterize total event rates, backgrounds, etc.
- 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

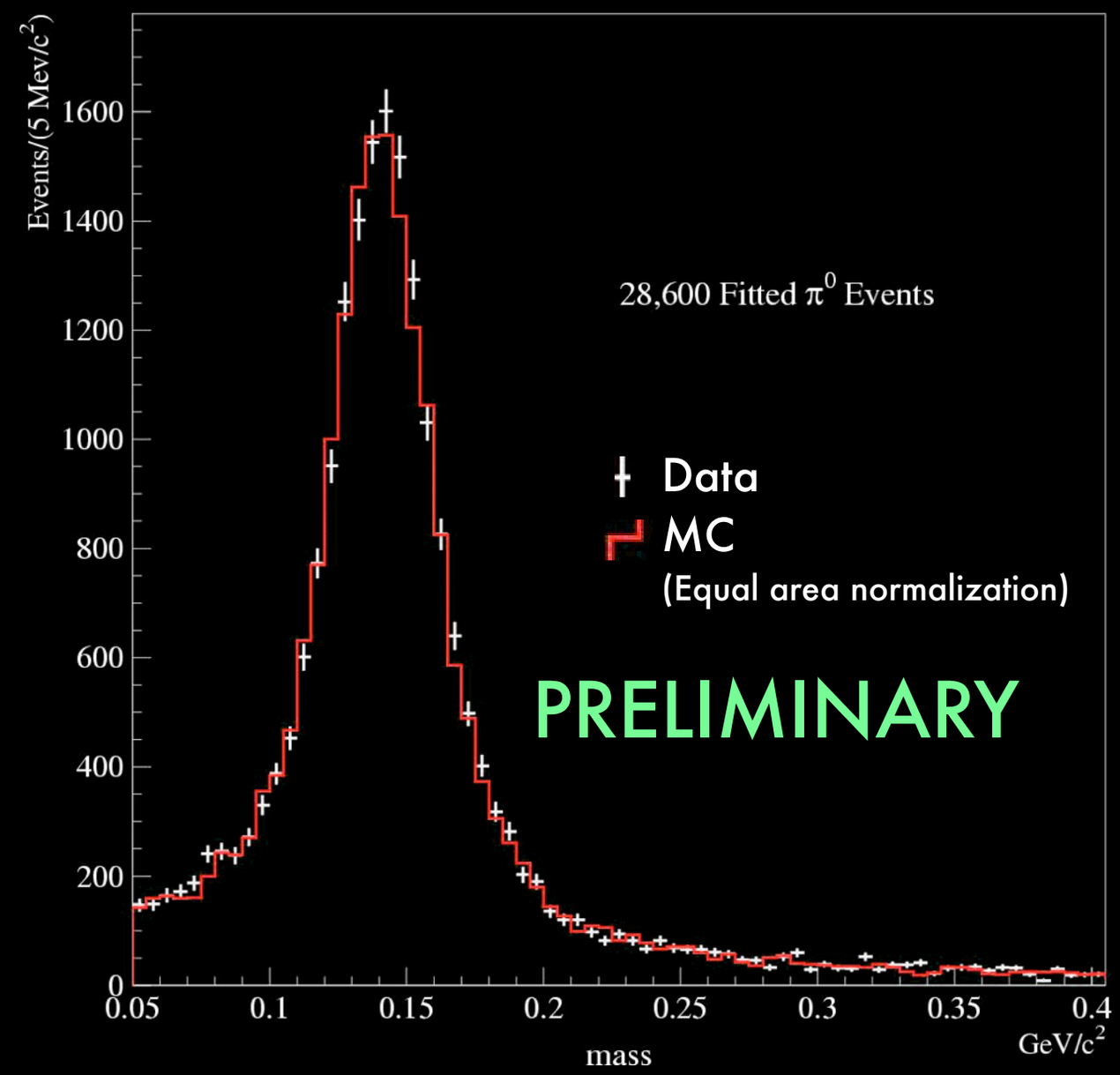
Neutral-current resonance/ π^0 production



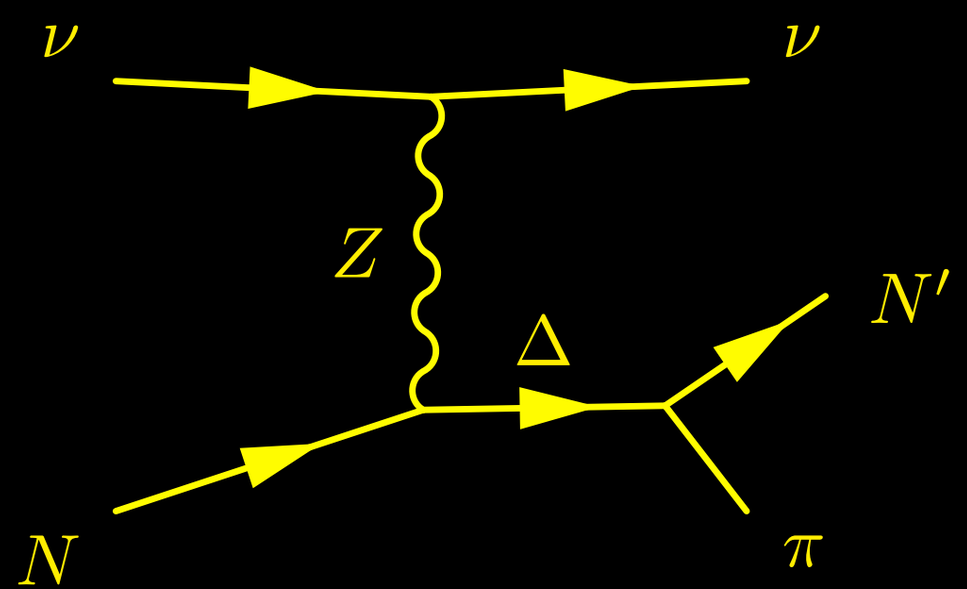
- Of interest to oscillation searches primarily because π^0 and radiative Δ decay represent major backgrounds to ν_e appearance searches.
- Radiative Δ decay (BR $\sim$1%) is an irreducible background for detectors without fine-grained tracking!

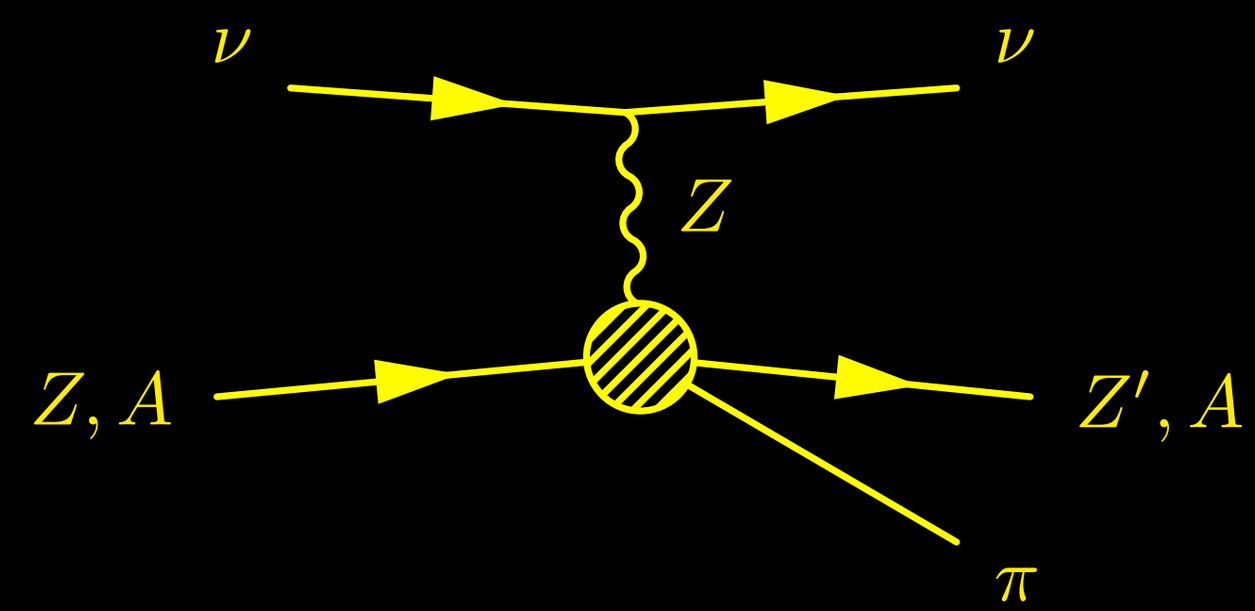
MiniBooNE π^0 measurement

- 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



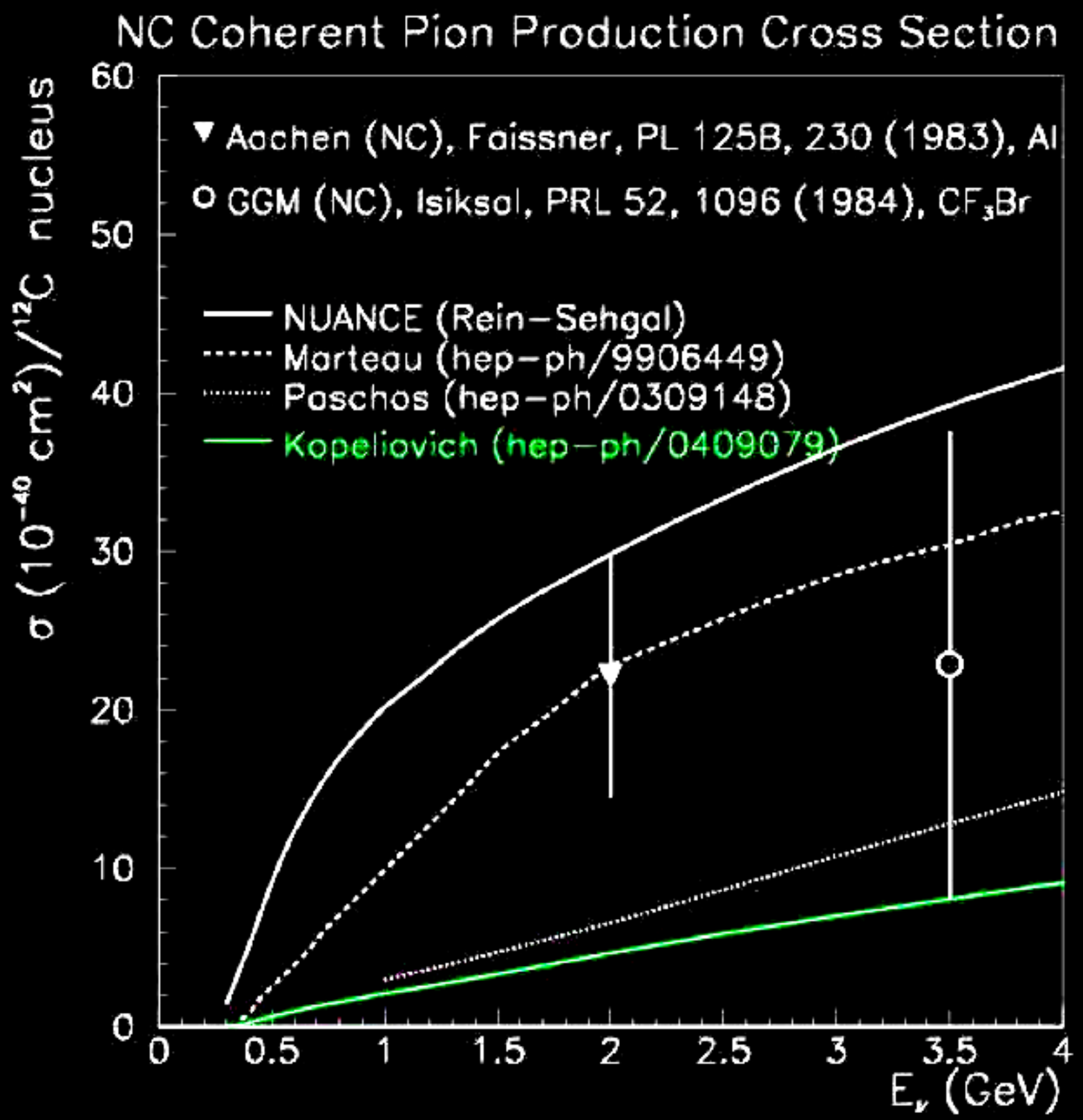
Resonant vs. Coherent π^0



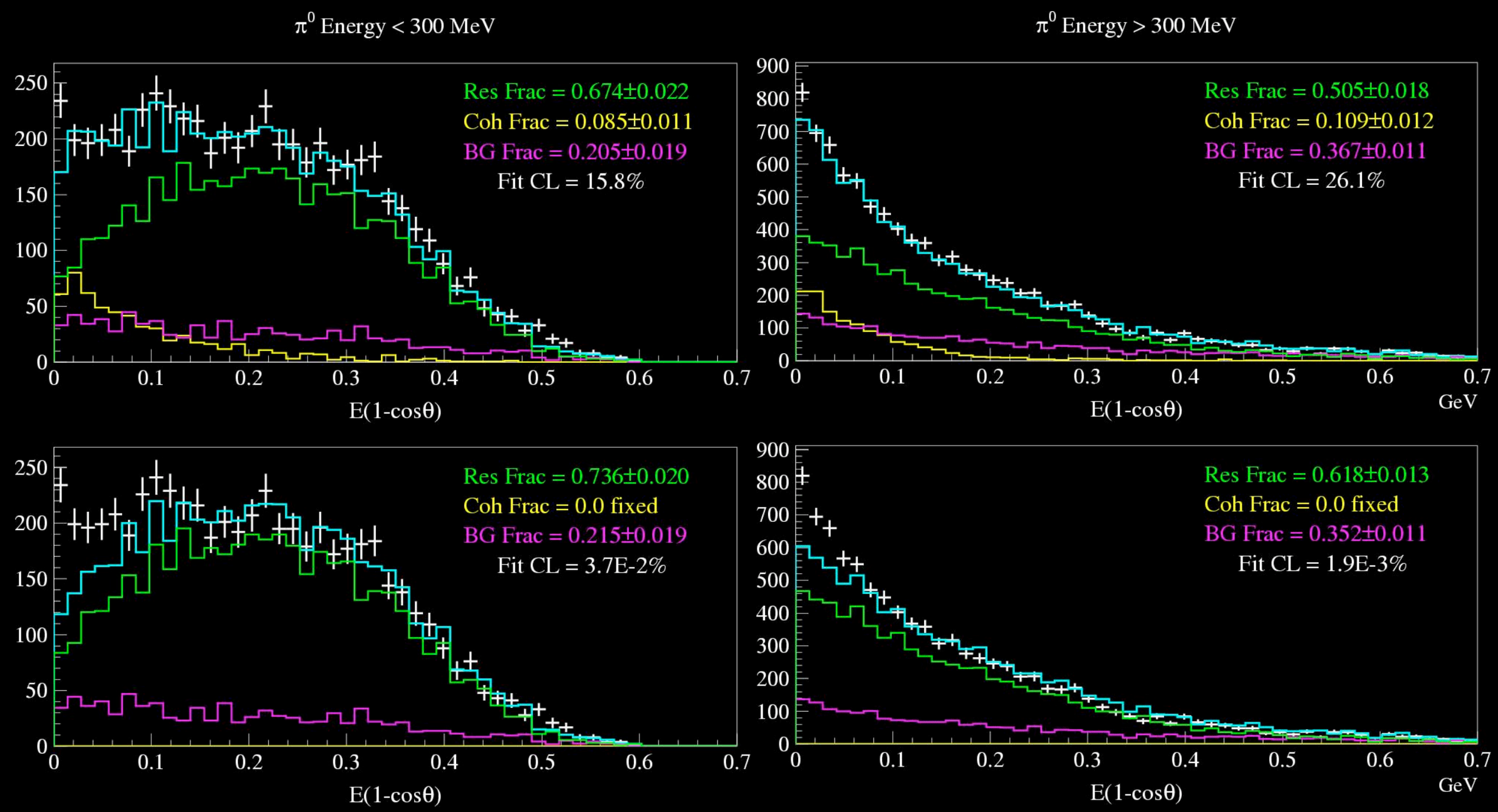


- Neutral current π^0 production can proceed through nucleon resonance or coherent nuclear processes. Coherent is thought to represent 5-20% of the rate.
- Coherent events have low Q^2, therefore should have forward π^0. Coherent events have no outgoing nucleon.

Previously published coherent π^0 production measurements



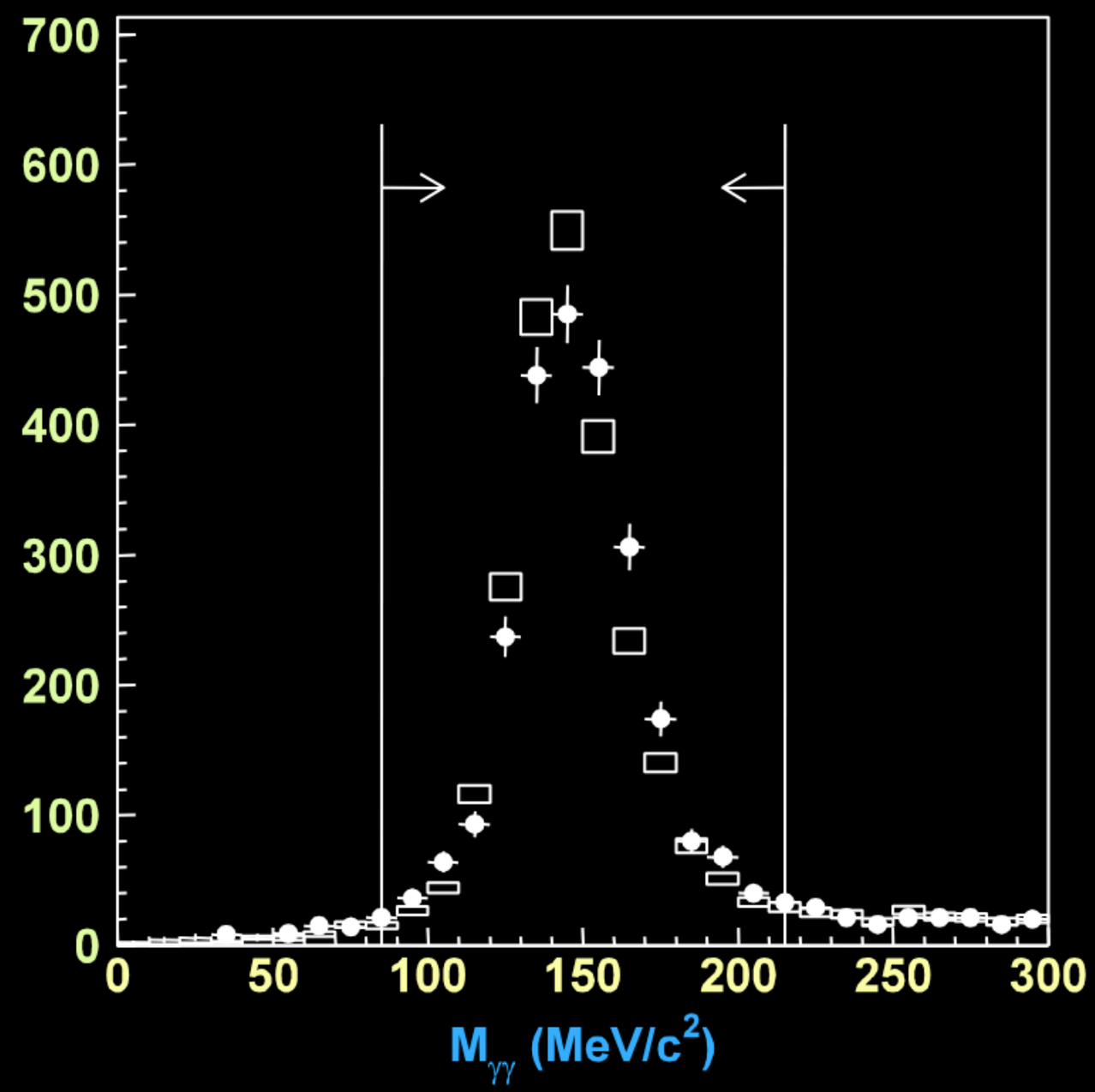
Resonant vs. Coherent π^0



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

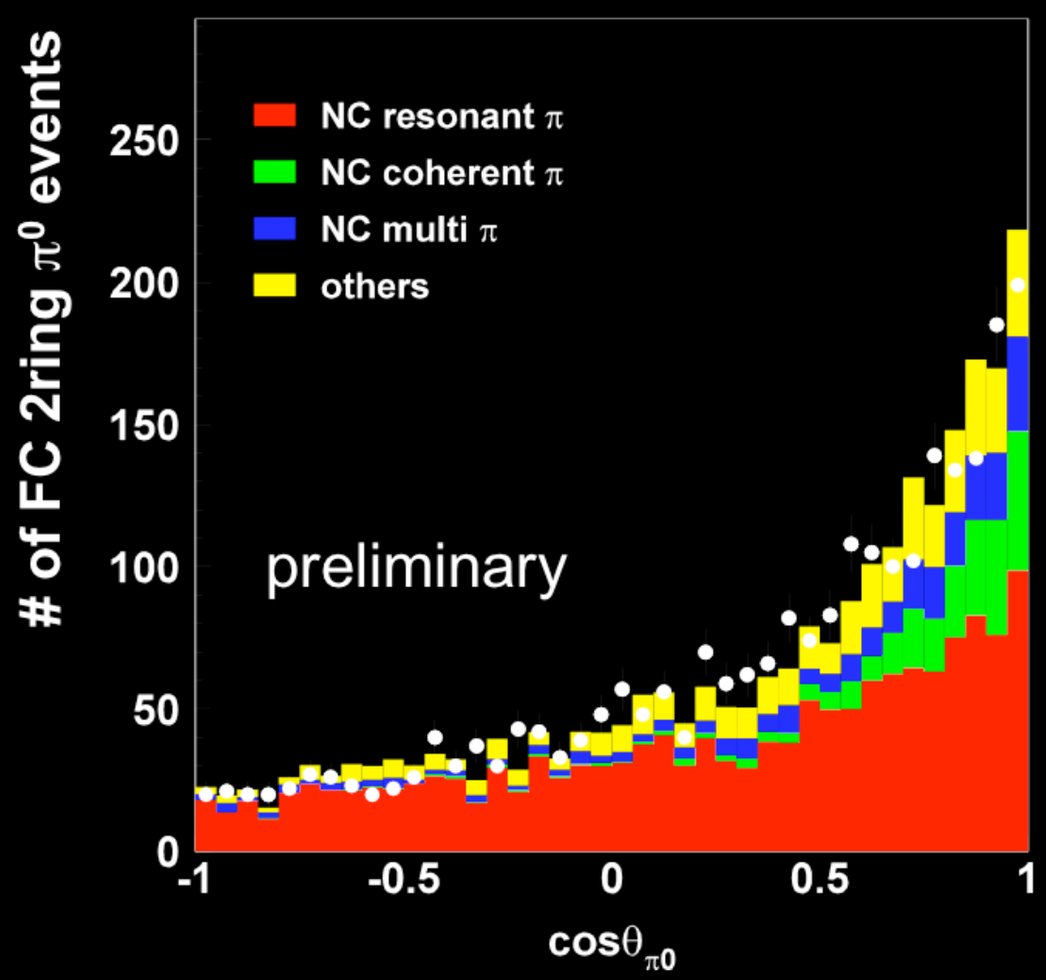
K2K π^0

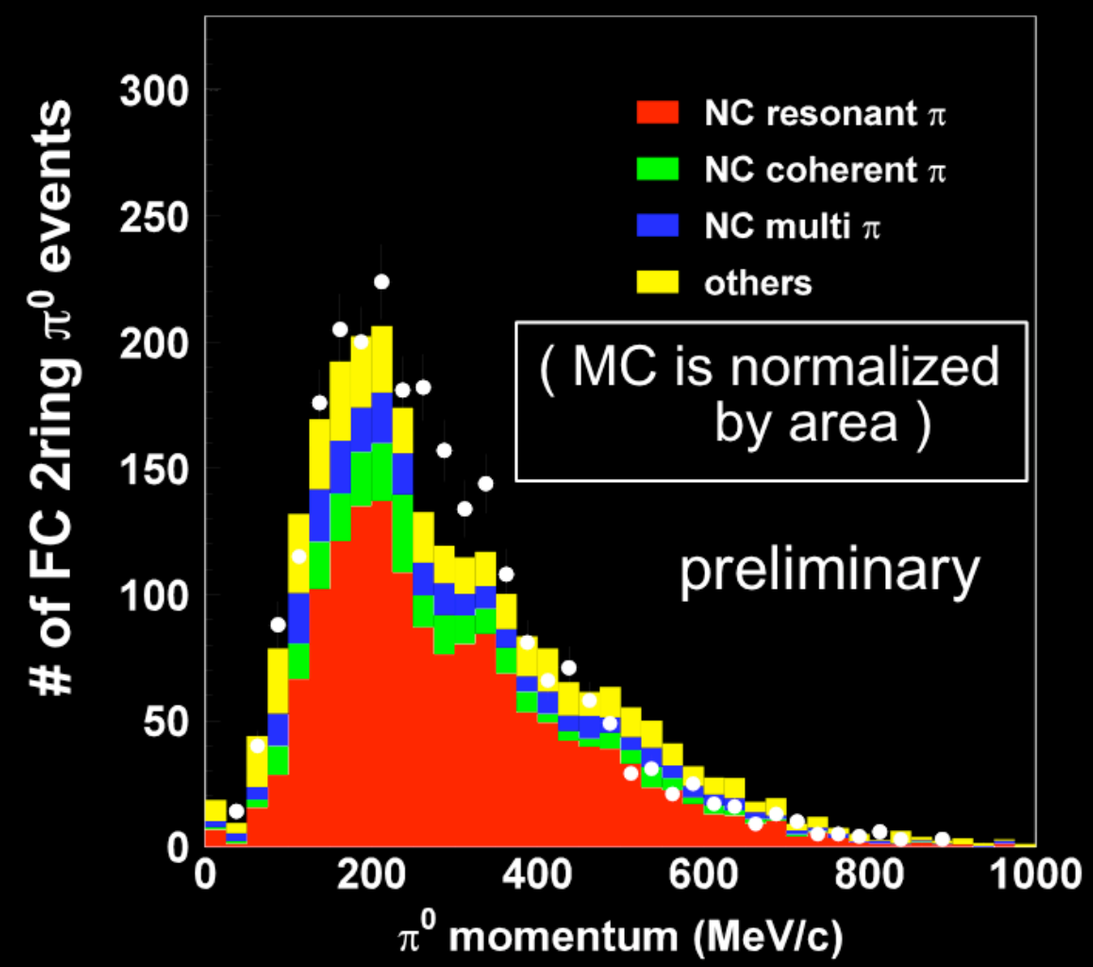
- Analysis from 1kT water Cherenkov detector
- $(NC1\pi^0)/\mu$ ratio on H_2O = $0.064 \pm 0.001(stat) \pm 0.007(syst)$ at $\langle E\nu \rangle \sim 1.3$ GeV
- S. Nakayama *et al.*, *Phys. Lett.* B619 (2005)



K2K

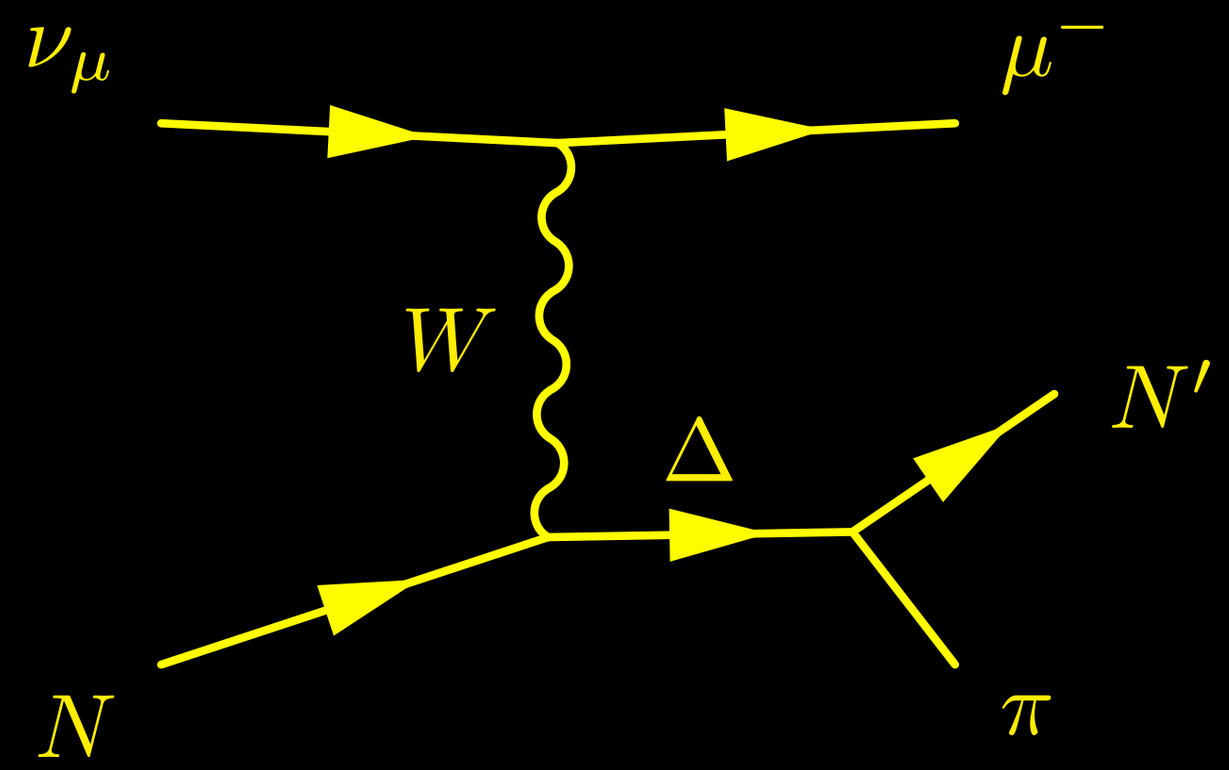
Resonant vs. Coherent π^0





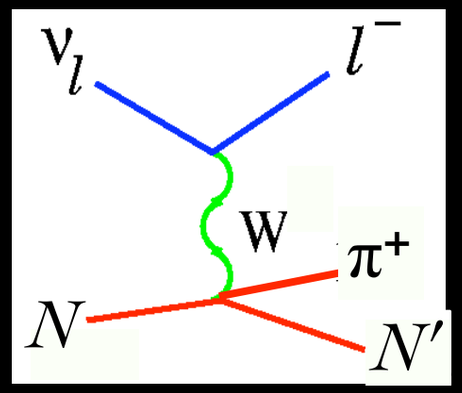
- K2K data also appear to require coherent production

Charged-current π^+ production

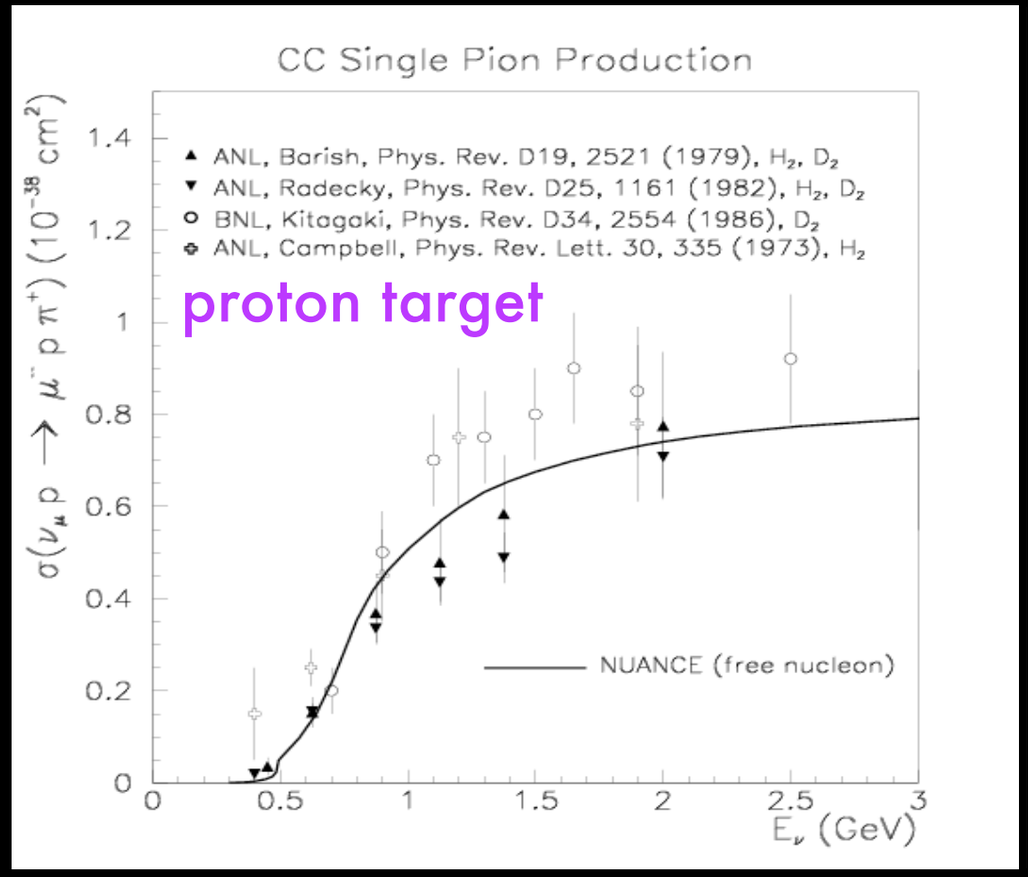


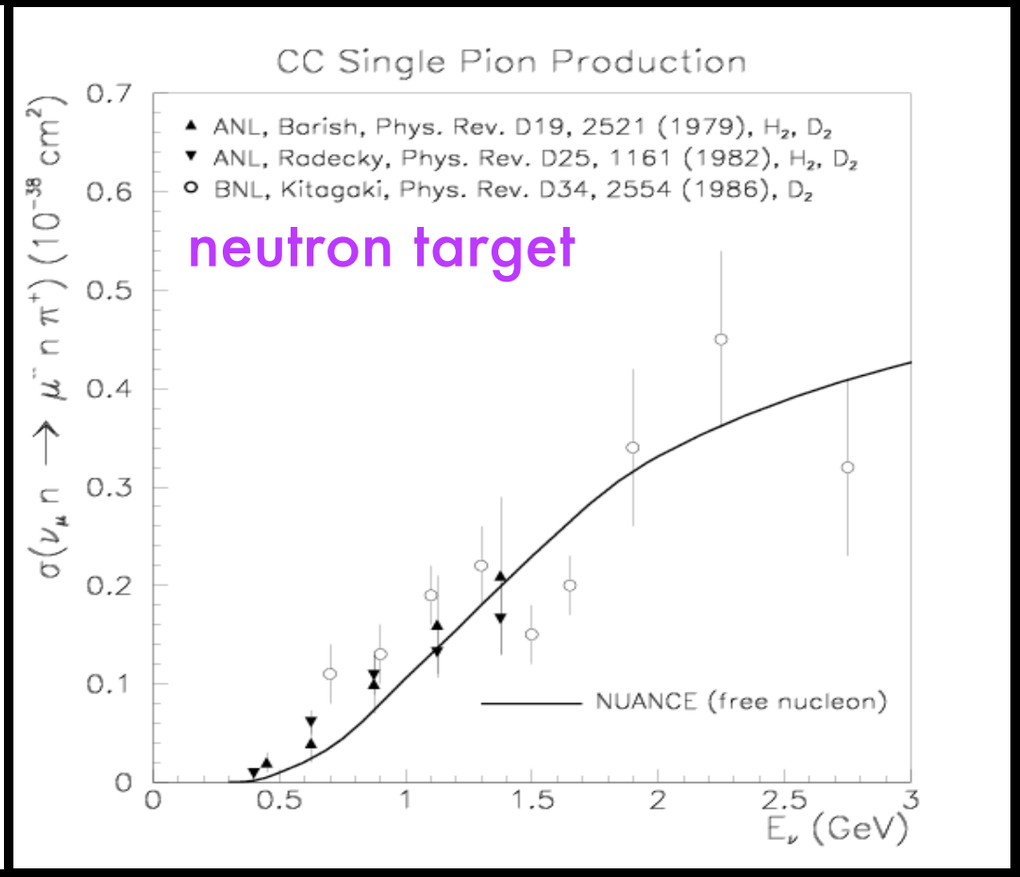
- Second highest rate process in MiniBooNE (behind quasielastics); largest background to QE measurement.
- As with NC process, expected resonant (above diagram) and coherent channels.

Charged-current π^+ production



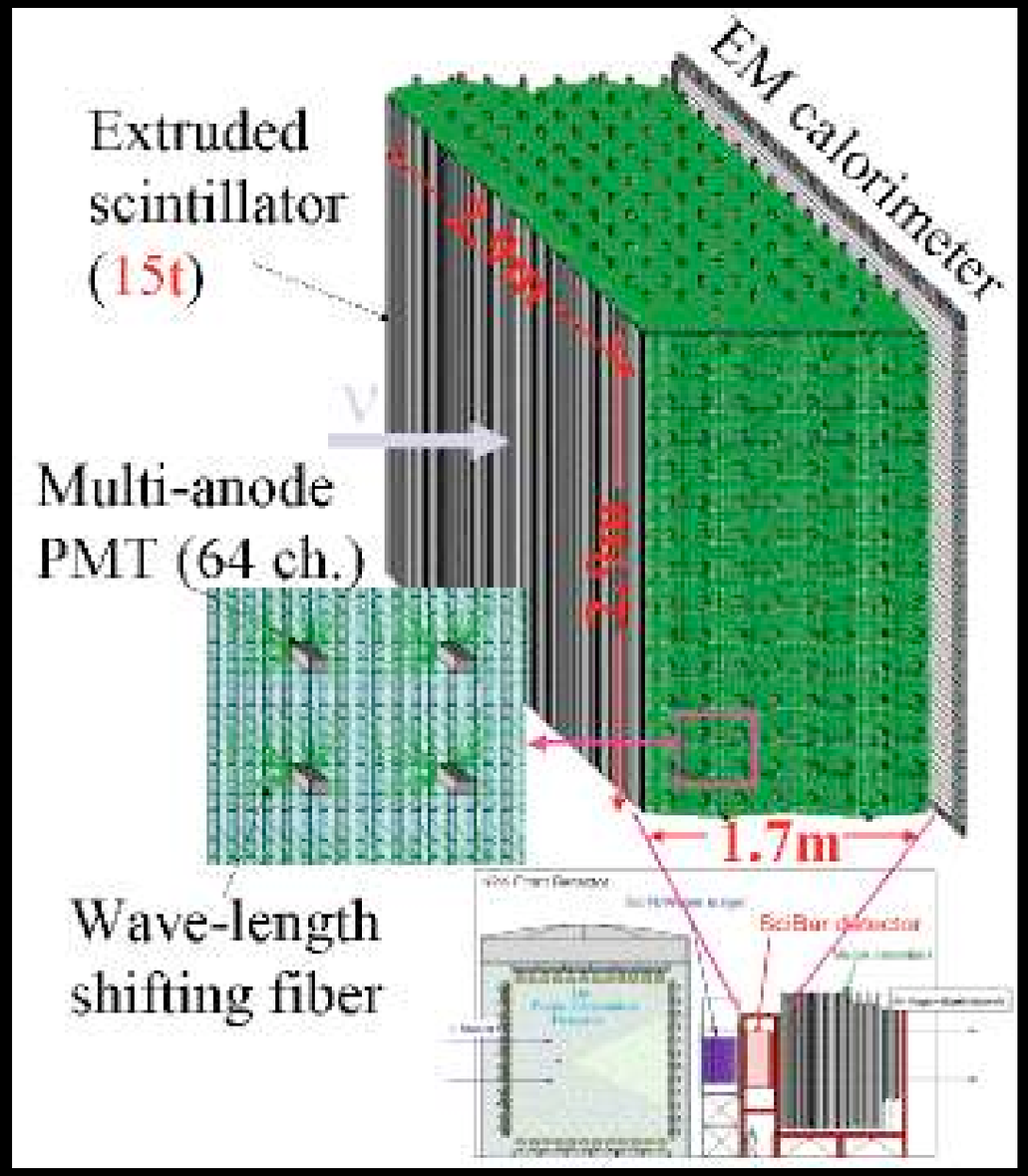
Pre-2005 data set is small:
no nuclear targets below 3 GeV





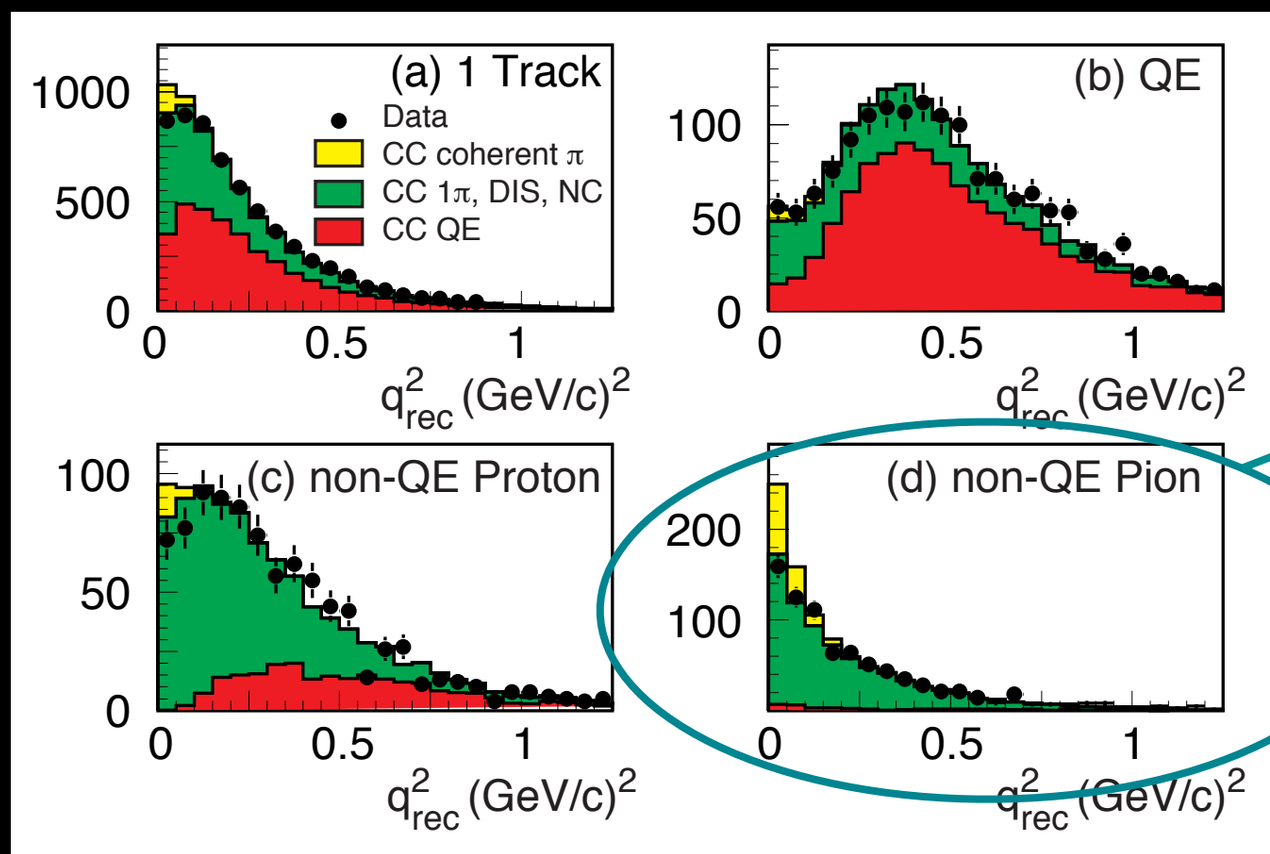
K2K Charged-current π^+ production

- K2K has measured the q^2 distribution of CC π^+ production using the "SciBar" fine-grained scintillation detector at the near detector site.
- The Q^2 distribution distinguishes nucleon resonance (high) from coherent nuclear pion production (low)
- M. Hasegawa *et al.*, *Phys. Rev. Lett.* 95 (2005)

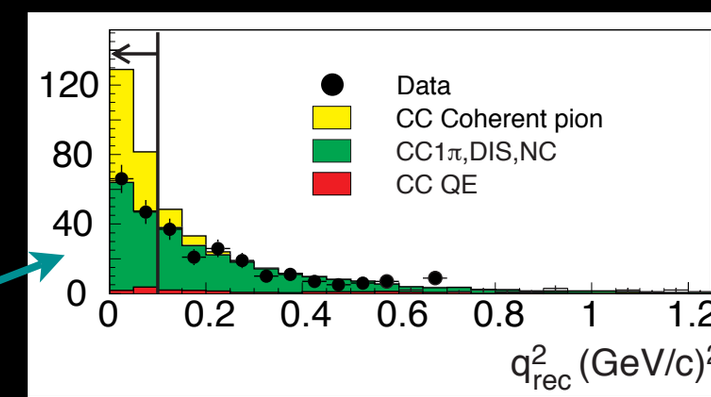


K2K fit to data

All CC events



Remove events with evidence of extra proton



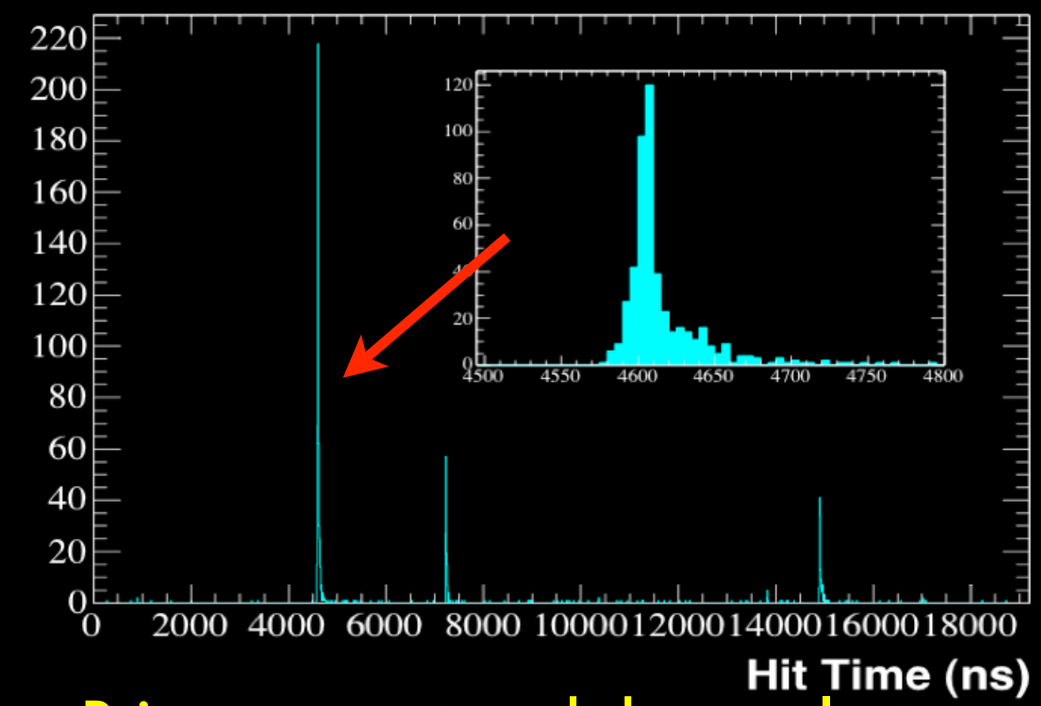
Final coherent candidates (q^2_{rec}<0.1 GeV^2): Data 113; Background 111

- No evidence for coherent pion production!

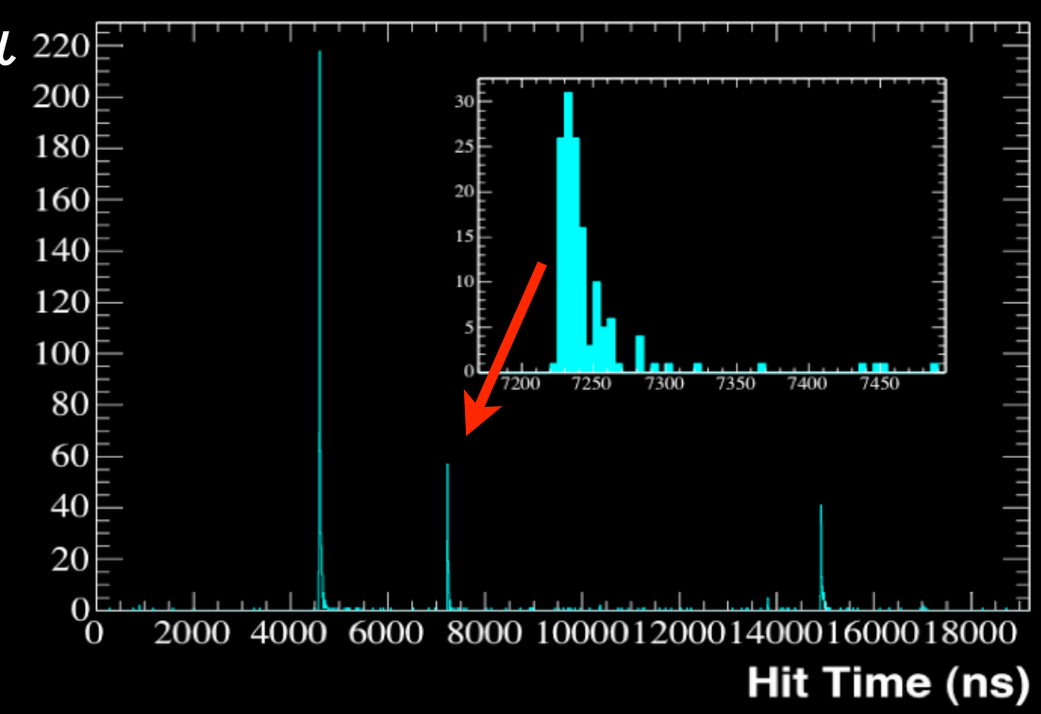
Rein-Seghal prediction for coherent pion production	K2K limit
2.67% of all CC	<0.60% at 90% CL

MiniBooNE Charged-current π^+ analysis

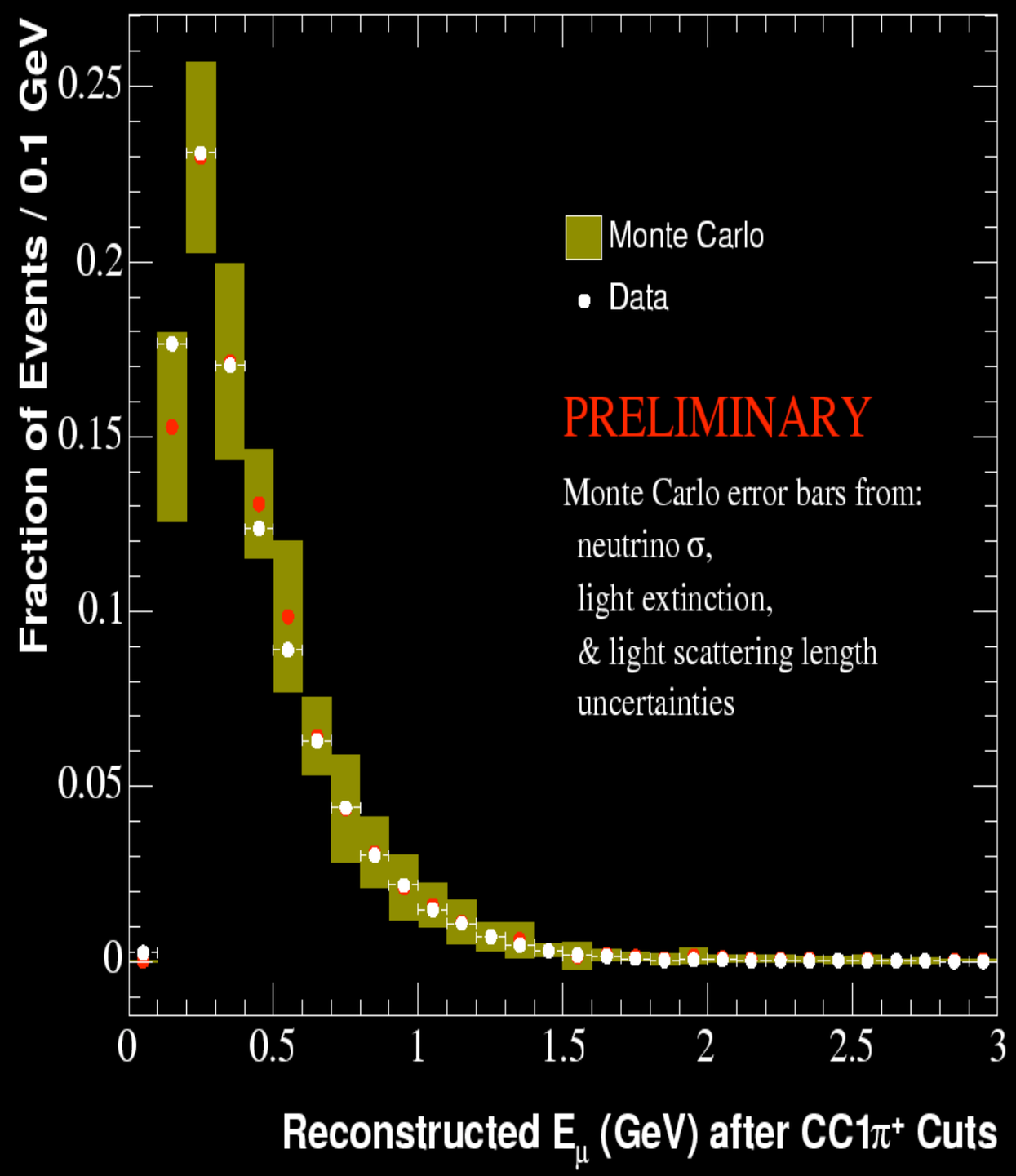
- Final state has a nucleon, muon, and pion.
- Generally, pion is sub-Cherenkov threshold, so MiniBooNE fitter reconstructs only the muon.
- Both muon and $\pi \rightarrow \mu$ leave stopped-μ decay electron signatures in detector
- This is an unusual enough signature that these events can be isolated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

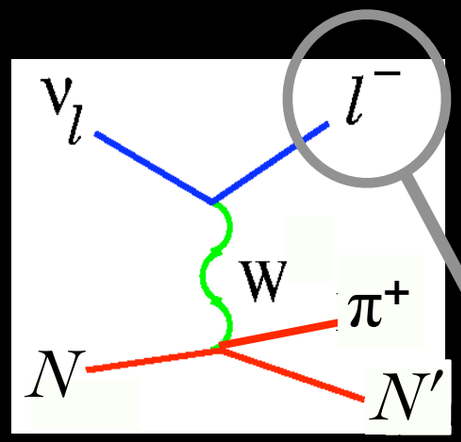


Primary event and decay electrons separated in time



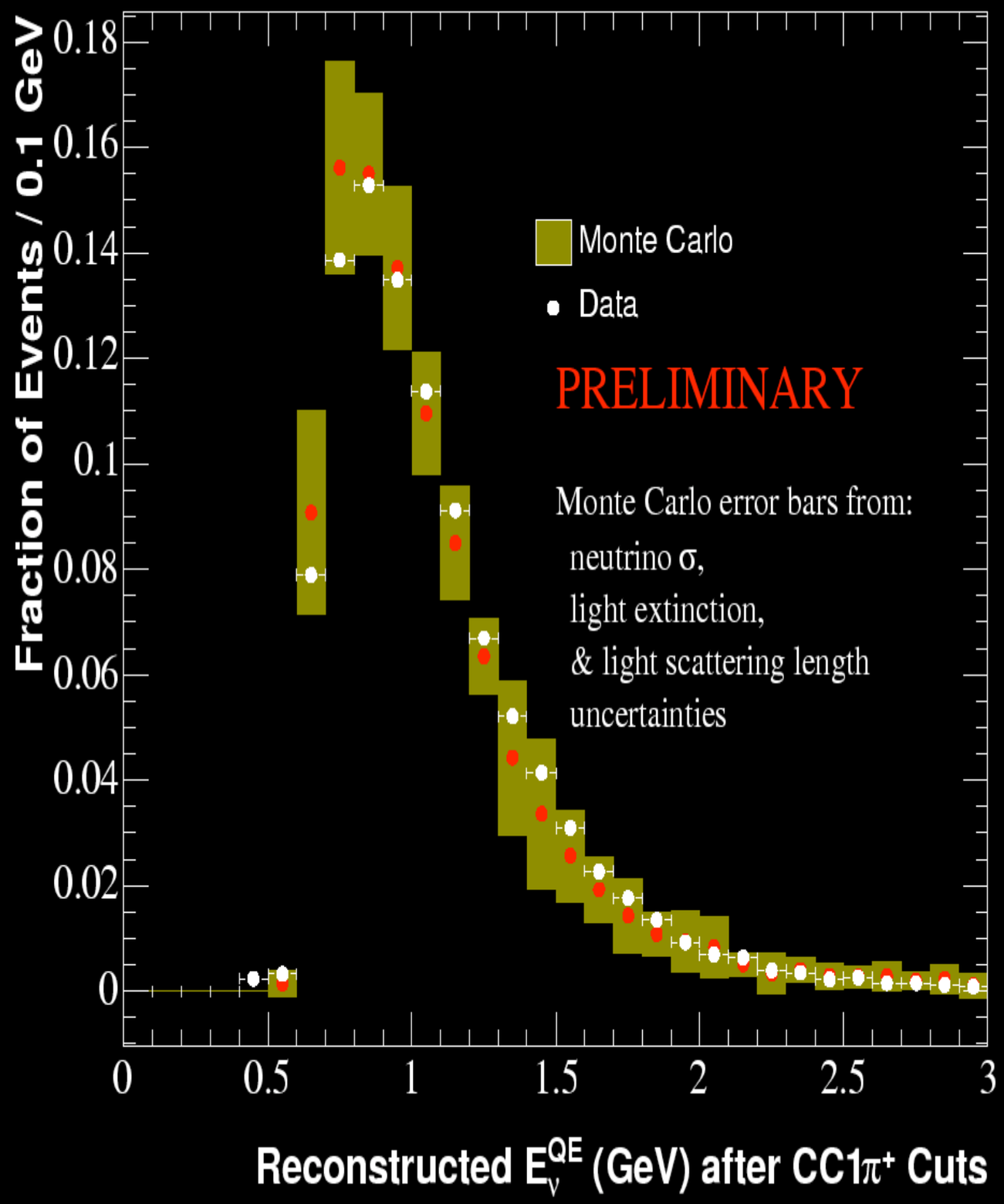
MiniBooNE charged-current π^+ analysis

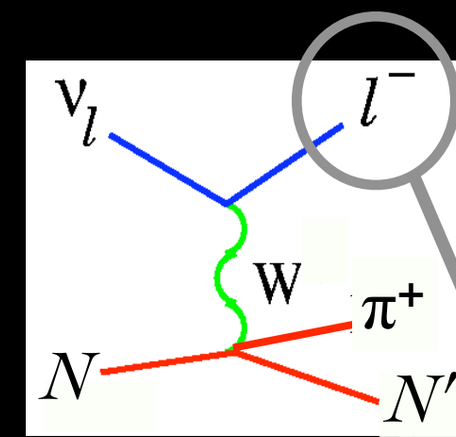




- Measure visible energy, lepton direction from fit to Cherenkov ring *only* (avoid scintillation light from pion, nucleon)

MiniBooNE charged-current π^+ analysis





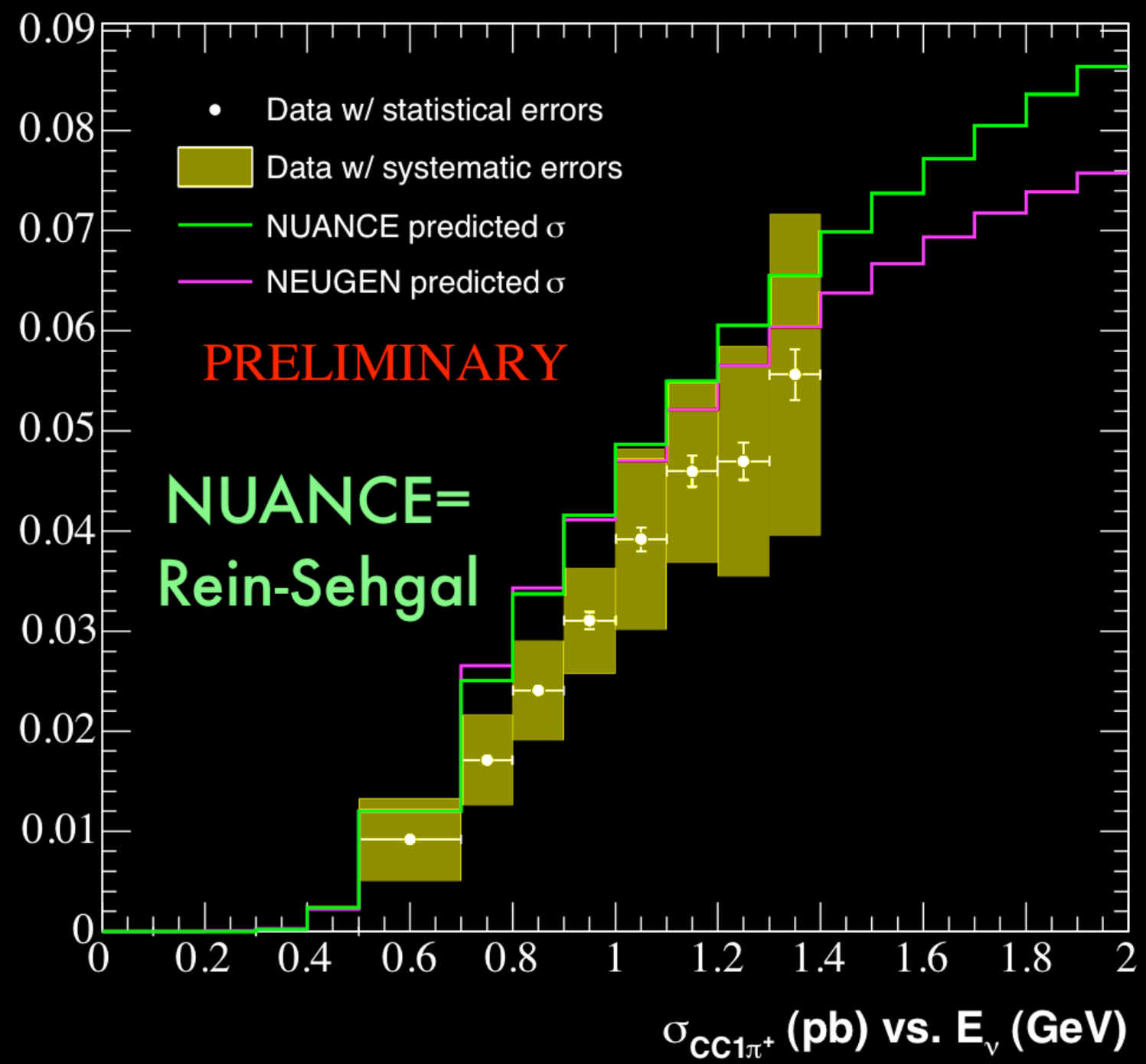
- Use lepton energy, momentum and direction (from known neutrino beam) to reconstruct a "quasielastic energy" assuming a recoil mass:

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

- 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)

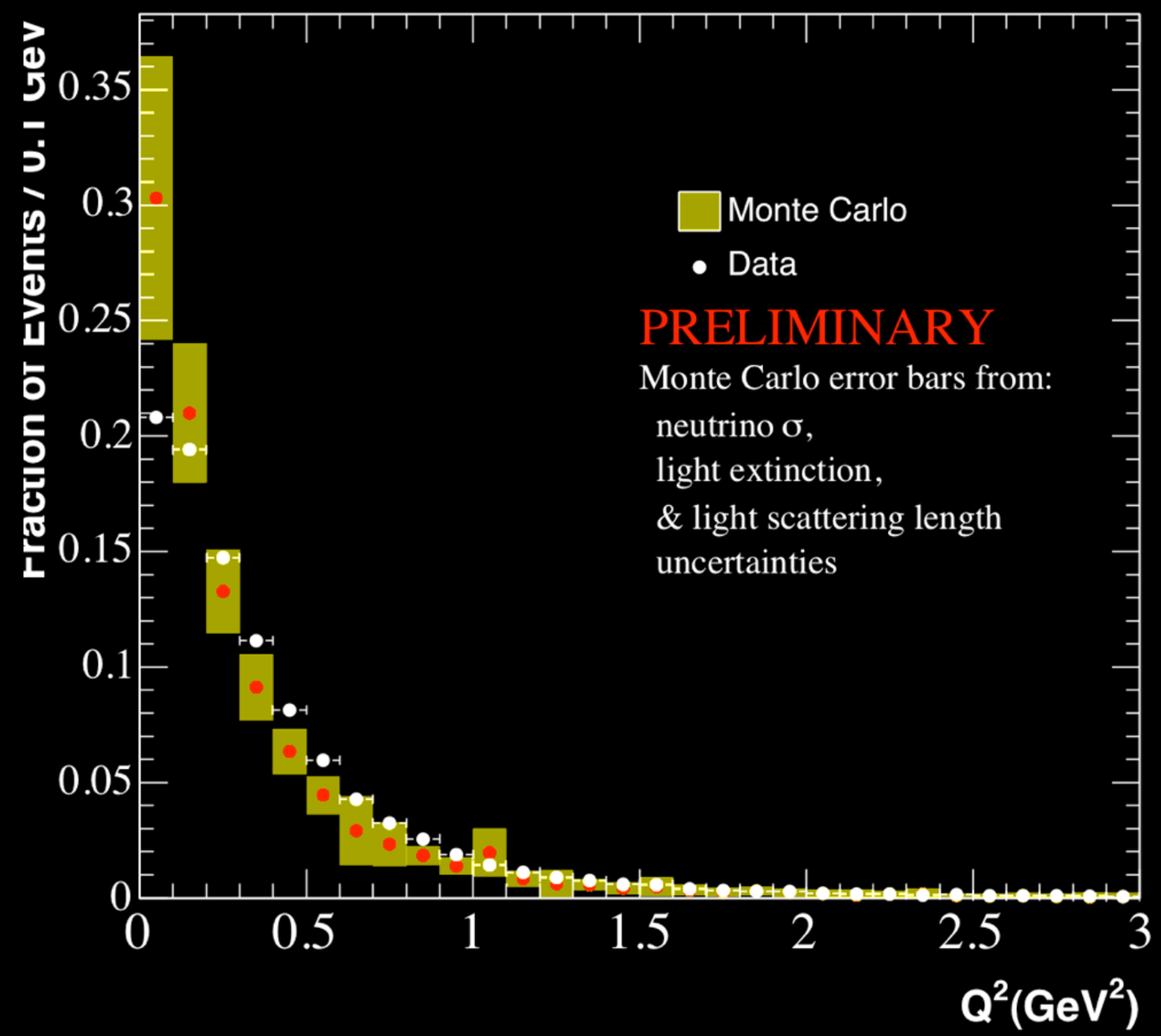
MiniBooNE charged-current π^+ analysis

- Normalized to quasielastics
- Comparison is to common event generators



MiniBooNE charged-current π^+ analysis

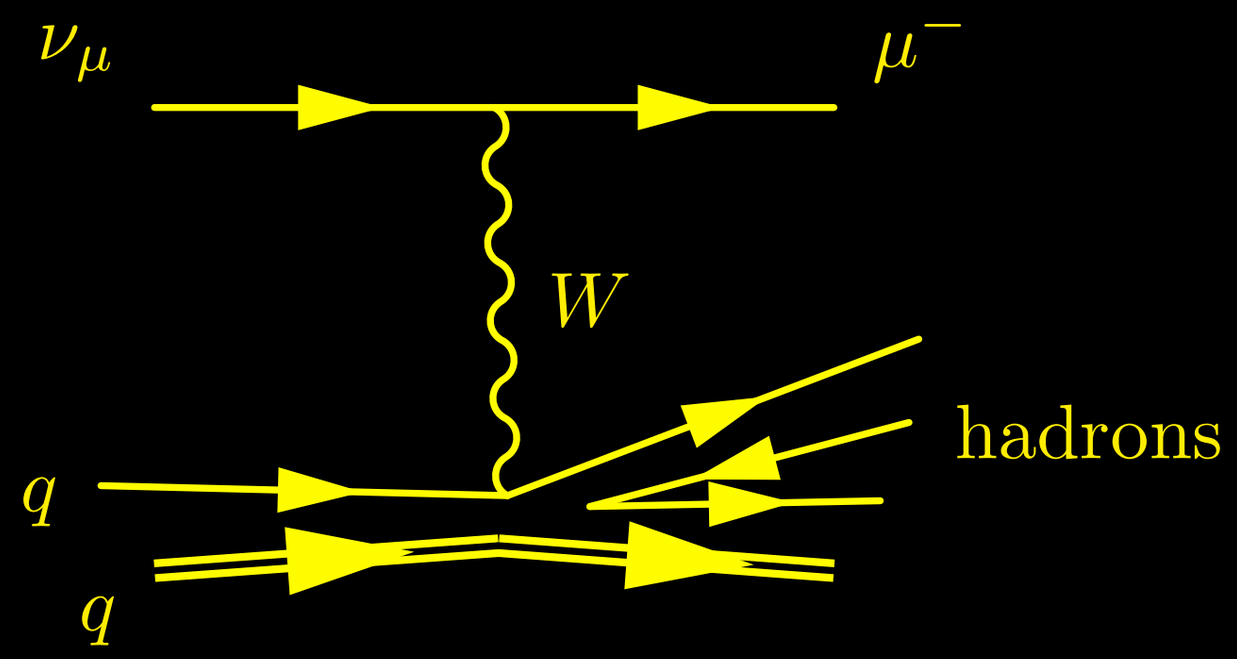
- Reconstructed Q^2 for charged current single pion candidates.
- Note deficit in low Q^2 (small muon angle) region vs. Rein-Sehgal model. Coherent production is clearly lower than expected. (This is consistent with K2K).



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.

Deep Inelastic Scattering



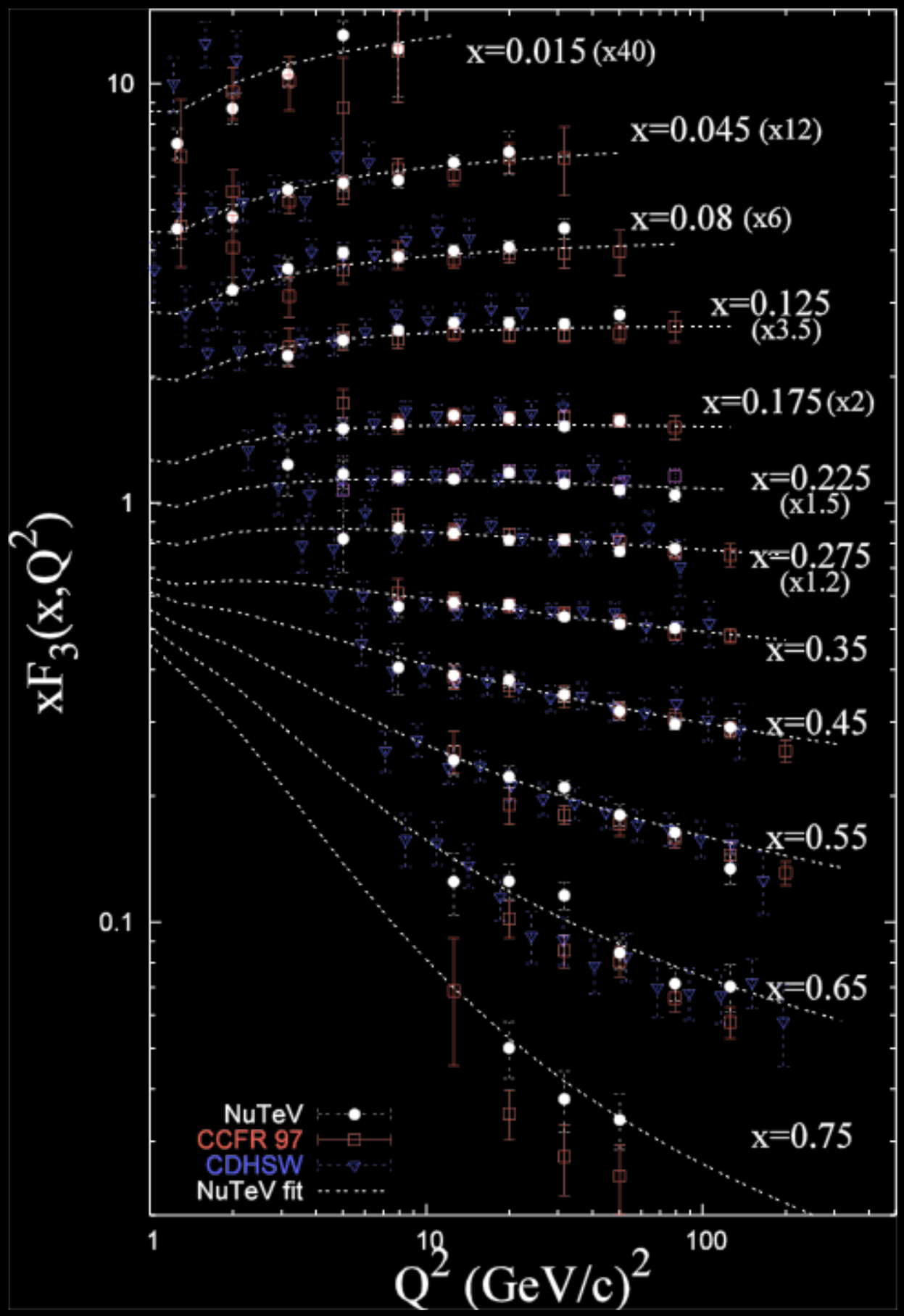
- Dominant interaction channel above few GeV
- Very long history of measurements! Geared toward QCD (structure functions) and electroweak physics.
- Last dedicated experiments in mid-1990s; final results are now coming out.

Nucleon structure functions

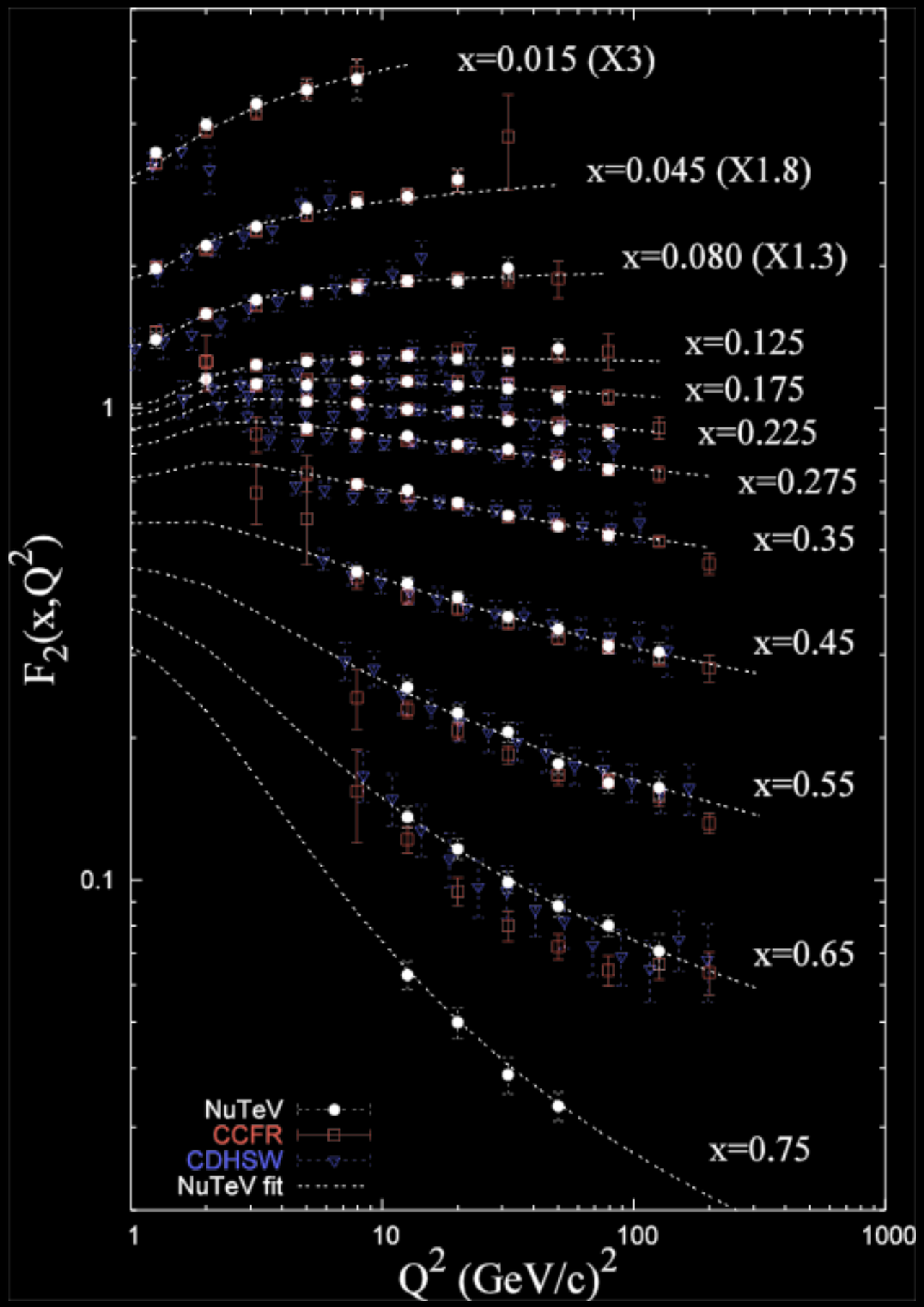
$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}[(1-y-\frac{Mxy}{2E_\nu})F_2^{\nu(\bar{\nu})} + \frac{y^2}{2}2xF_1^{\nu(\bar{\nu})} \pm y(1-\frac{y}{2})xF_3^{\nu(\bar{\nu}}$$

Structure functions: where the theory of QCD meets reality.

- Structure function F_2 has been measured over a wide range of x and Q^2 by charged lepton DIS experiments.
- Neutrino DIS measures the structure functions using different probe (W):
  - provides measurement at medium and high x and low Q^2 where the structure functions are not well known.
  - used to constrain global QCD fits in this region.
  - only neutrino DIS measures the parity-violating structure function xF_3 which represents the valence distribution at high x.

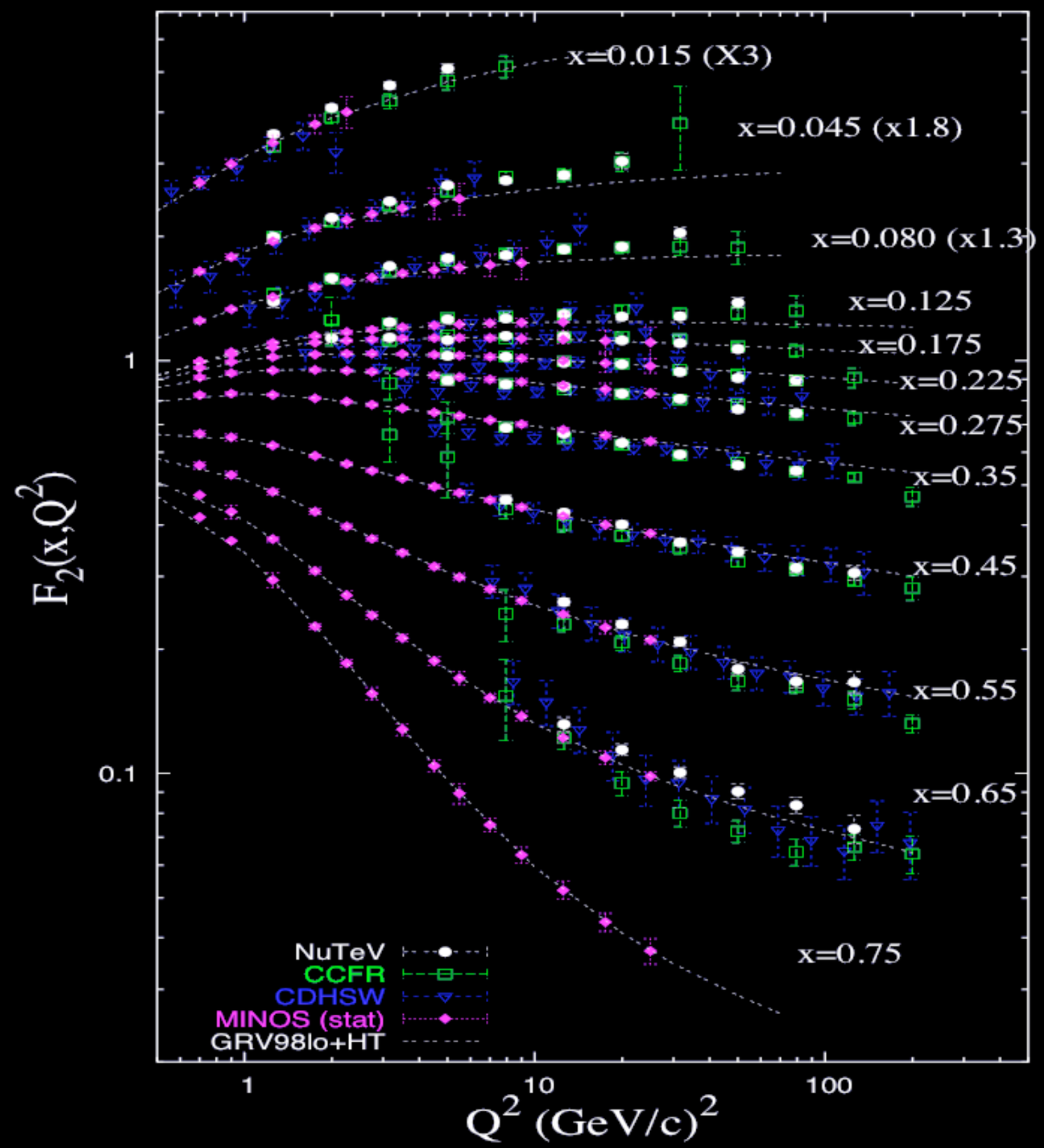


- NuTeV: sign-selected beam allowed separate neutrino and antineutrino measurements with intense, high-purity flux. Iron target.
- CCFR: predecessor experiment without sign selected beam.



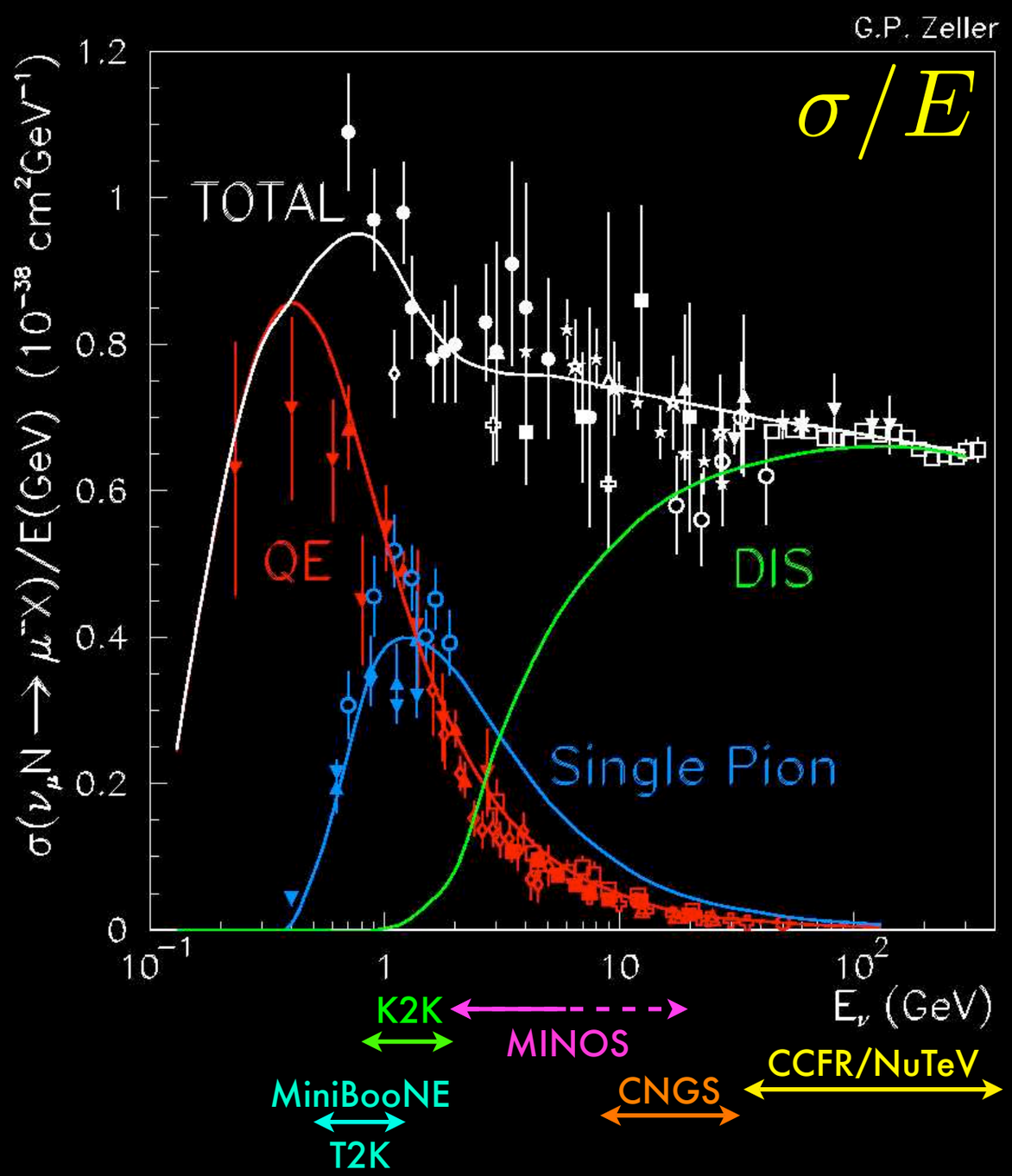
- These results are used in PDF fits to constrain moderate- and high-x behavior
- Very active theoretical industry

Deep Inelastic from MINOS

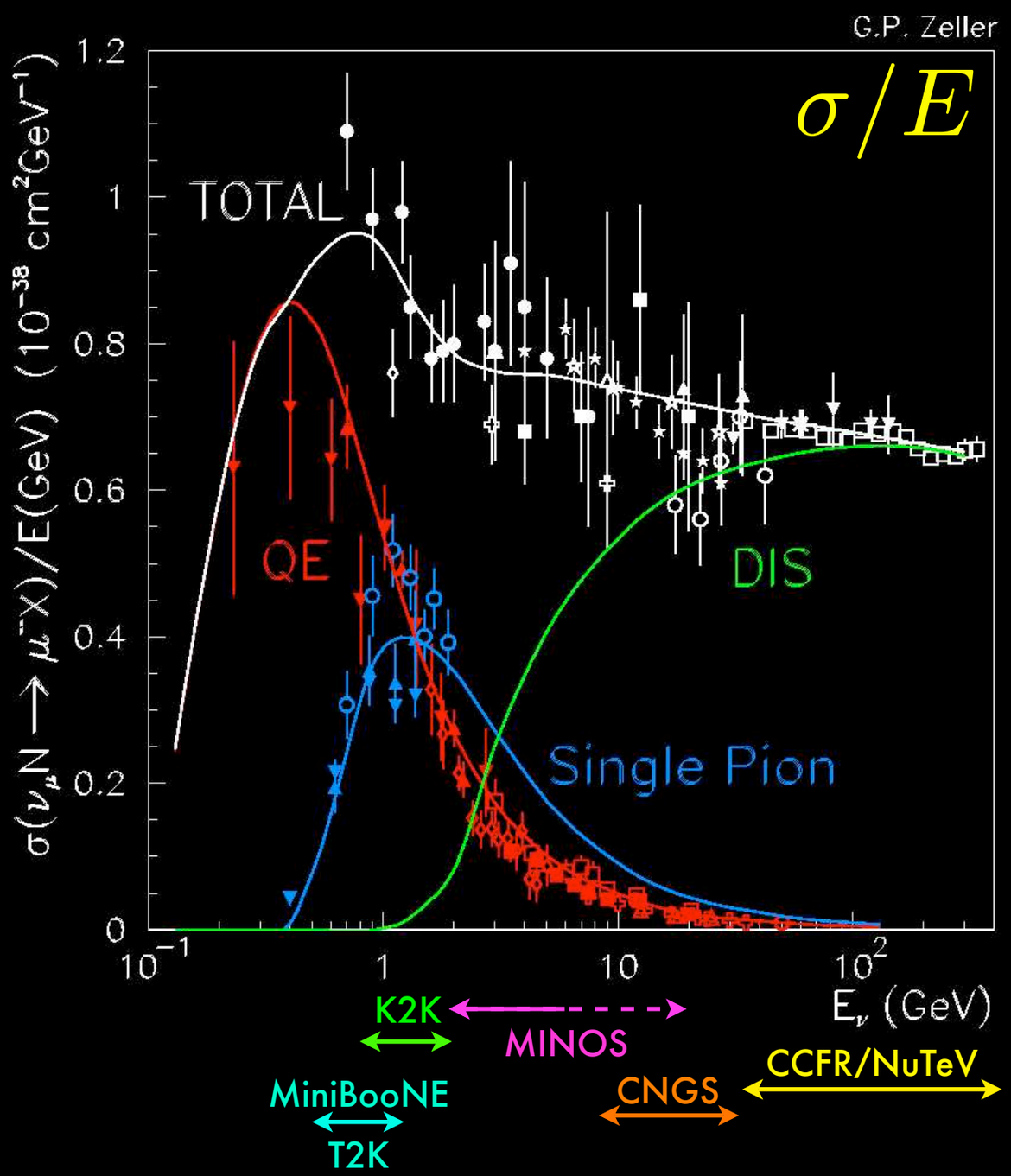


- MINOS will have huge statistics below 30 GeV (where CCFR/ NuTeV MINOS turns off)
- Can fill in much of the low-Q^2 region where existing neutrino data sparse
- Expected statistical errors shown only!

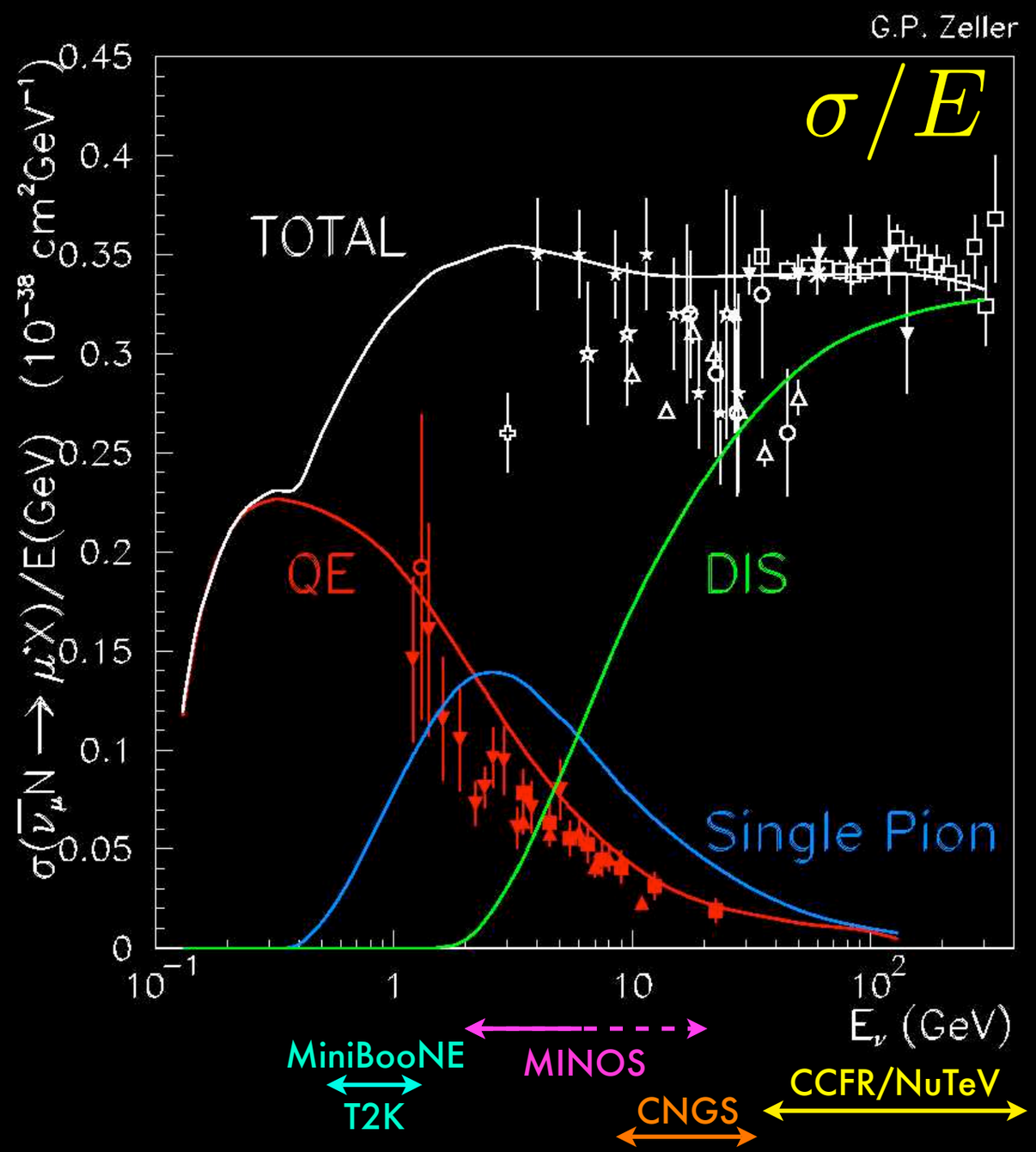
From neutrinos...



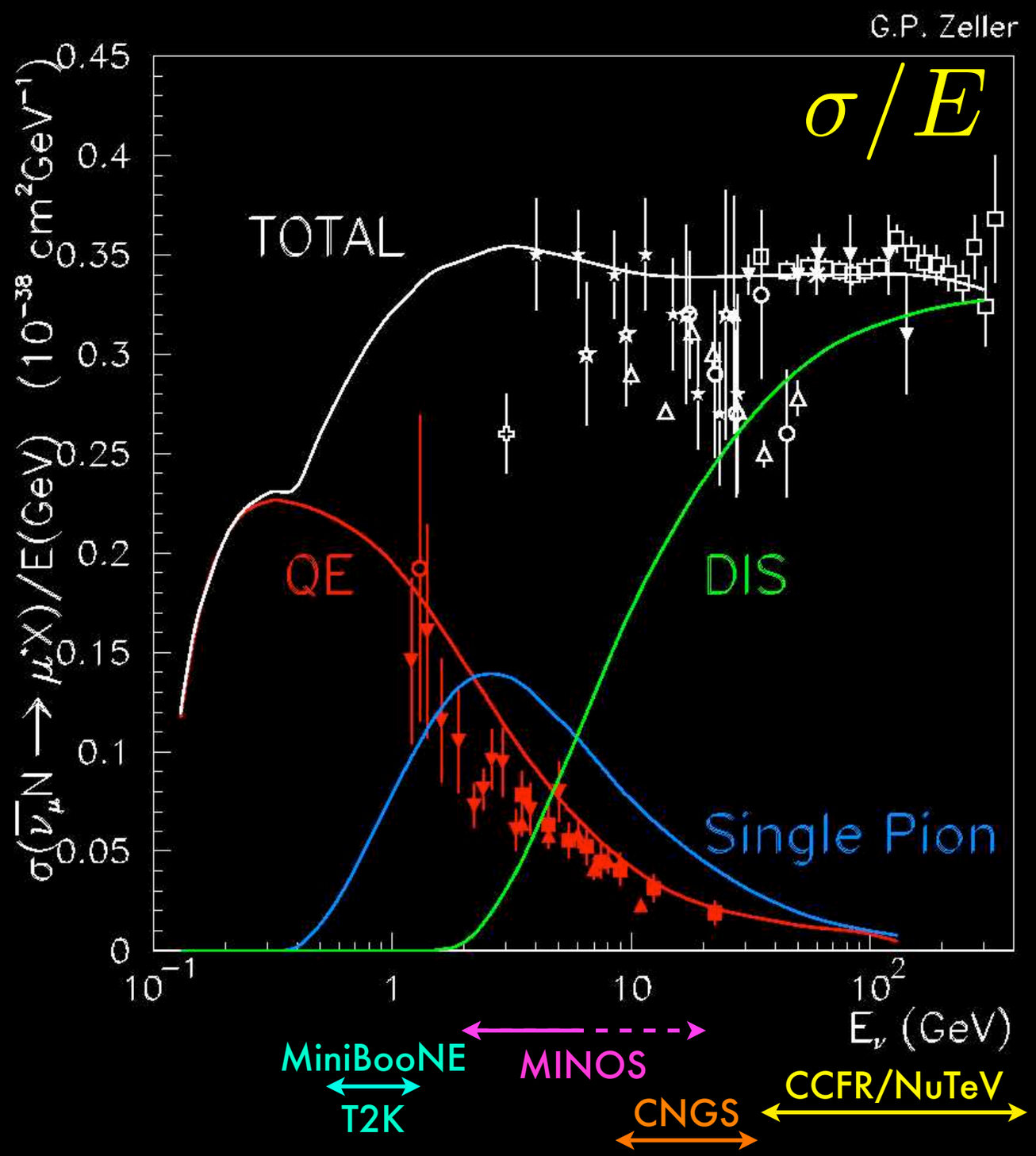
From neutrinos...



...to antineutrinos



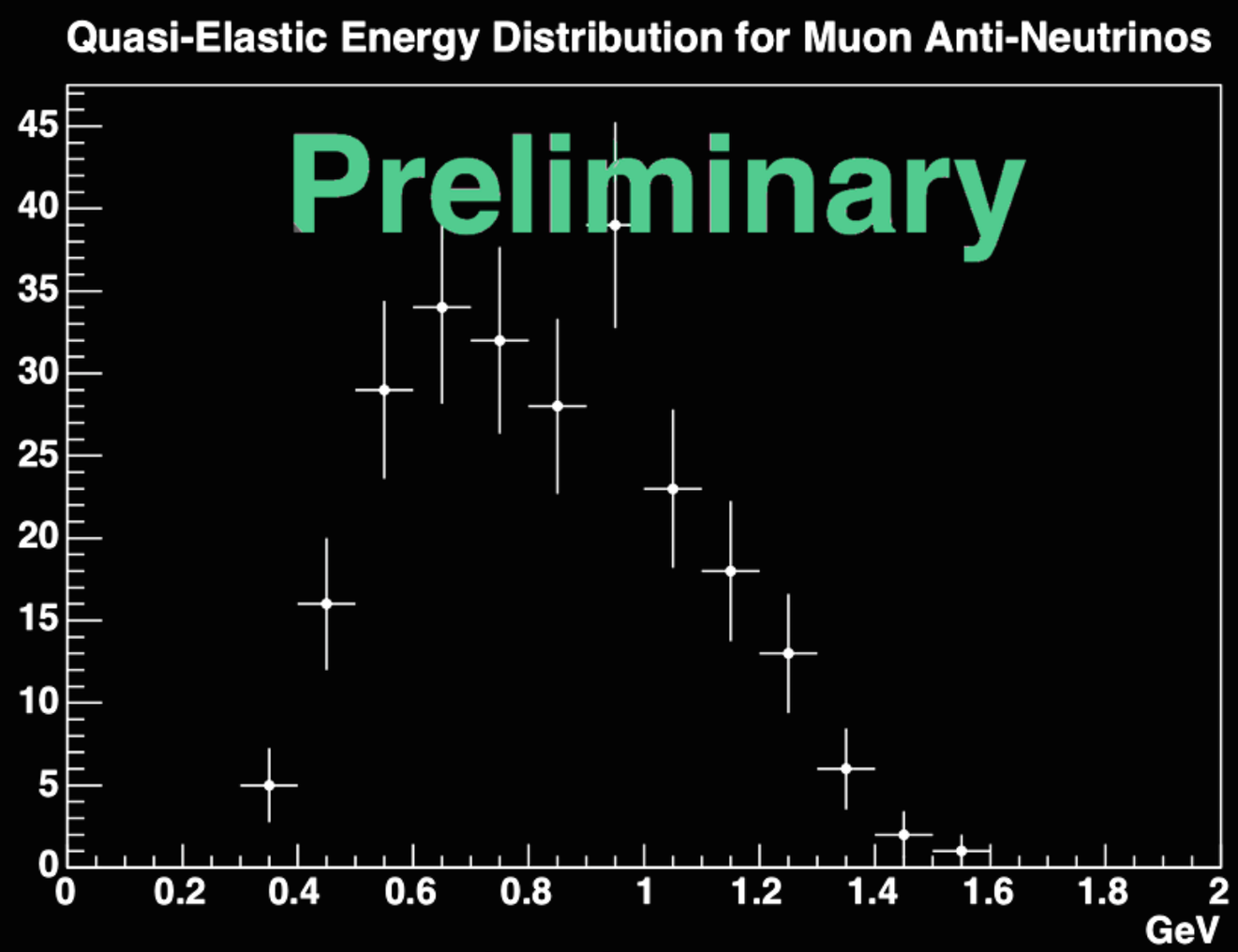
Antineutrino cross-sections



DATA SITUATION EVEN WORSE THAN FOR NEUTRINOS:

- No data at all below 1 GeV or on pion production!
- Need data before antineutrino oscillation searches can get serious
- Also need to evaluate wrong-sign backgrounds in neutrino mode
- MiniBooNE is now running in antineutrino mode and will make some of the first measurements here.

MiniBooNE antineutrinos

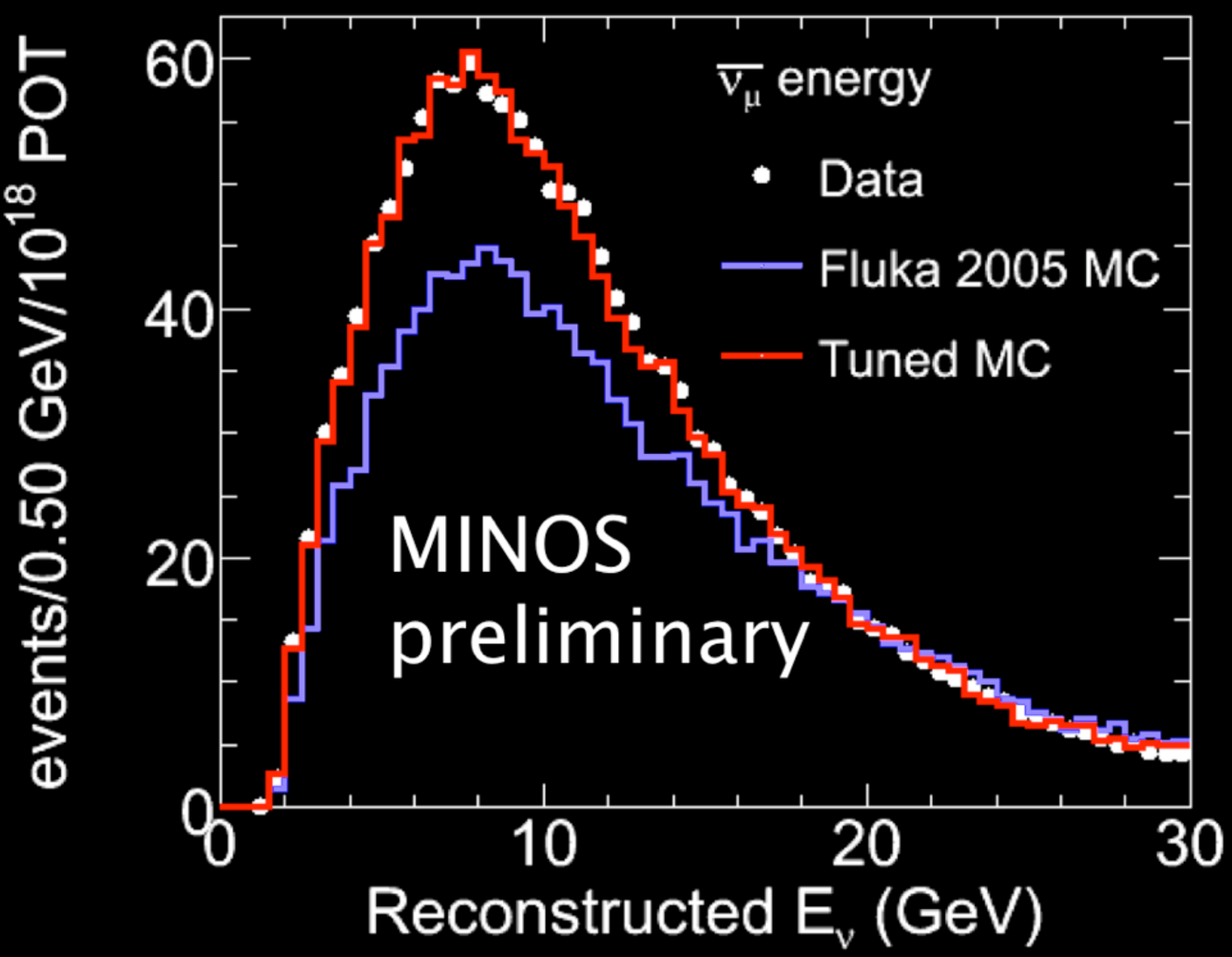


Expected pre-cuts yield,
1 year running (2E20 pot):

$\bar{\nu}$ channel	events
all channels	54k
CC quasielastic	24k
NC elastic	10k
CC π^-	8.9k
CC π^0	1.7k
NC π^0	4.9k
NC $\pi^{+/-}$	1.8k

- MiniBooNE has been running in antineutrino mode (reversed horn polarity) since end 2005.
- First look at antineutrino data
- Reconstructed quasielastic energy for QE candidates in <1 month of data

MINOS antineutrinos

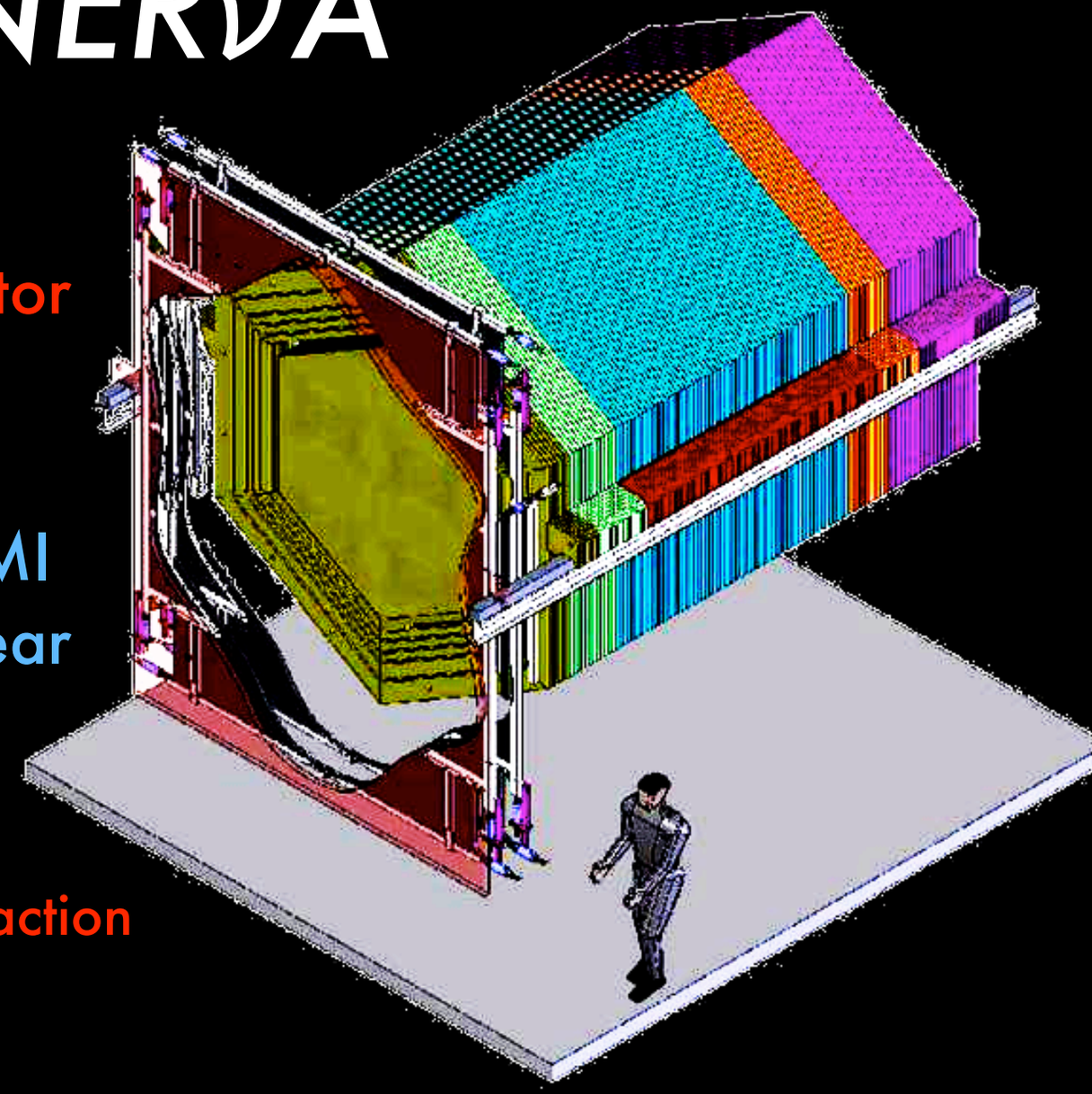


- MINOS has large nubar flux from π^- that miss the horns
- Magnetic field in detector allows muon sign to be measured, so antineutrino charged current events are readily identifiable!
- Can expect major improvements soon to knowledge of cross-sections in 2 < E < 30 GeV range.

Near future experiments

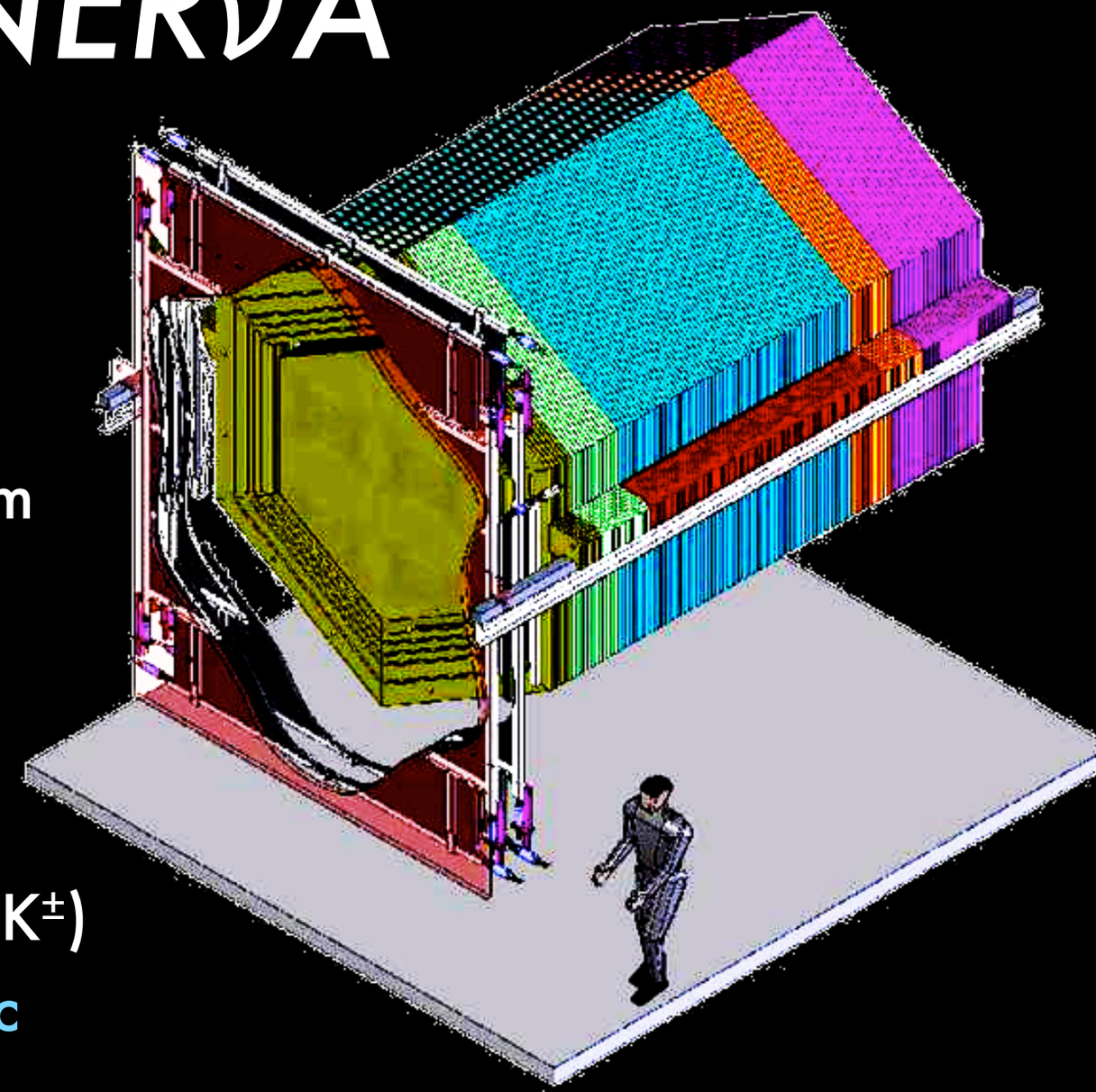
- Understanding neutrino cross-sections now recognized by the field as a critical step in extracting oscillation physics.
- FNAL has now begun a program of dedicated, small experiments to run parasitically in existing neutrino beams:
  - MINERνA (E938)
  - SciBooNE (E954)

FNAL E938: MINERνA



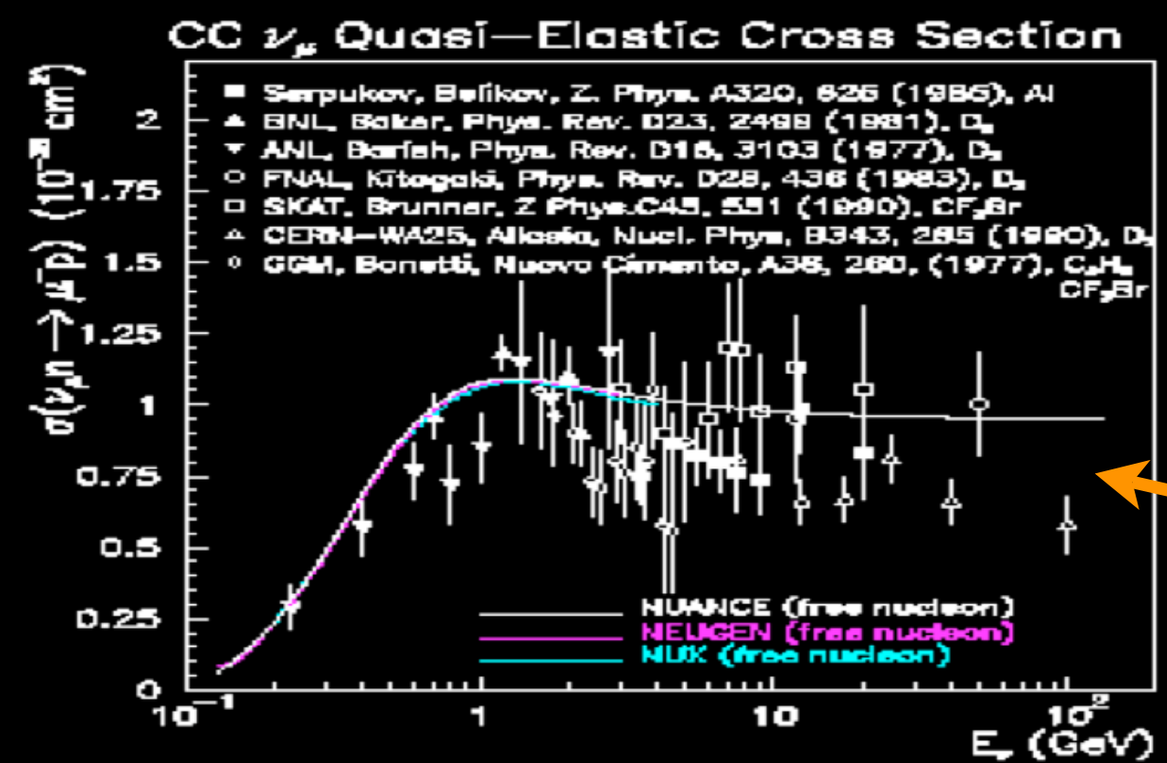
- A compact, fully active neutrino detector designed to study neutrino-nucleus interactions with unprecedented detail
- The detector will be placed in the NuMI beam line upstream of the MINOS Near Detector.
- The NuMI intensity provides
  - Opportunity for precision neutrino interaction measurements
  - Wide range of neutrino energies
- Detector with several different nuclear targets (carbon, iron, lead): allows 1st study of nuclear effects in neutrino interactions!

FNAL E938: MINERνA

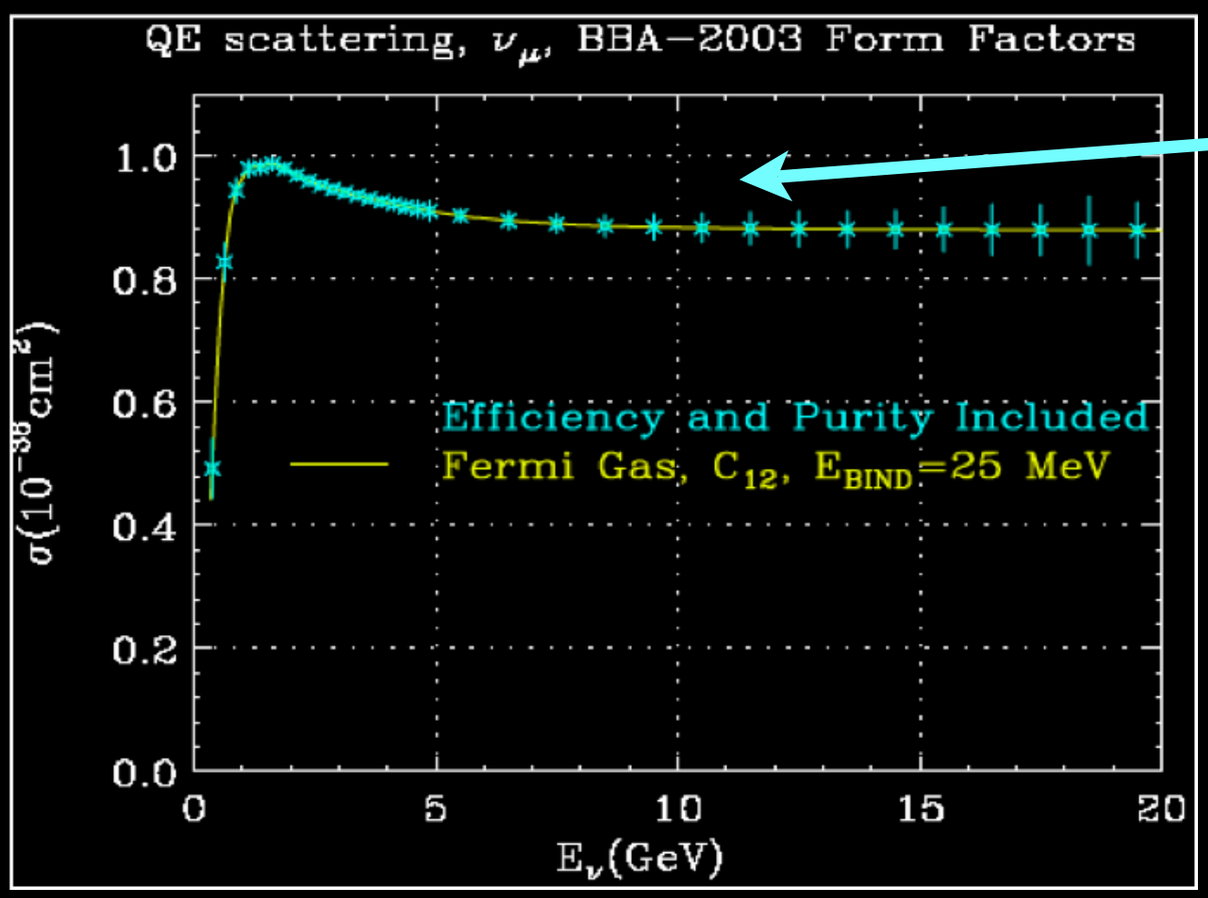


- Active core is segmented solid scintillator
  - Tracking (including low momentum recoil protons and π^0) photon conversion vertices)
  - Particle identification
  - 3 ns (RMS) per hit timing (track direction, identify stopped $K^{\pm}$)
- Core surrounded by electromagnetic and hadronic calorimeters
  - Photon (π^0) & hadron energy measurement
- MINOS Near Detector acts as MINERvA's muon catcher

MINERνA quasielastics



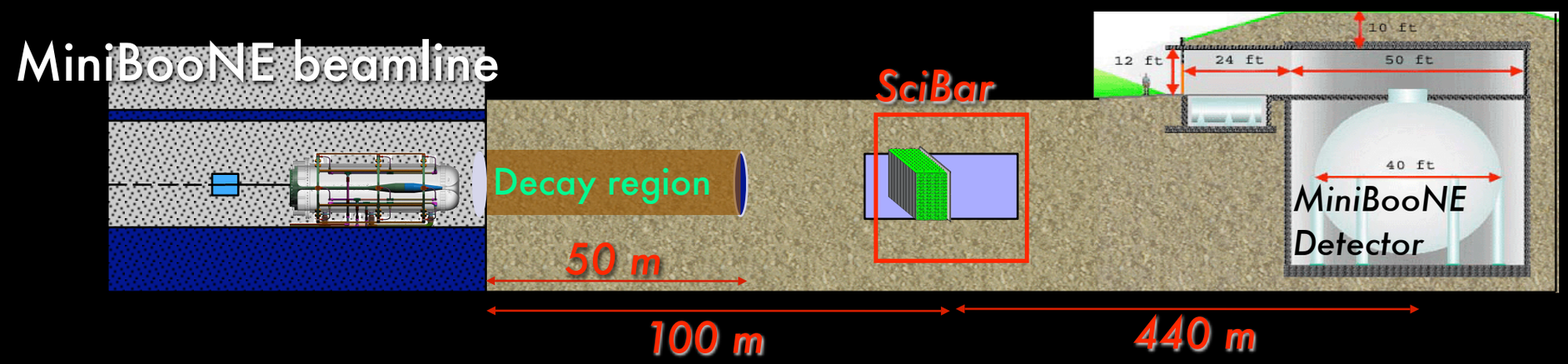
Current measurements



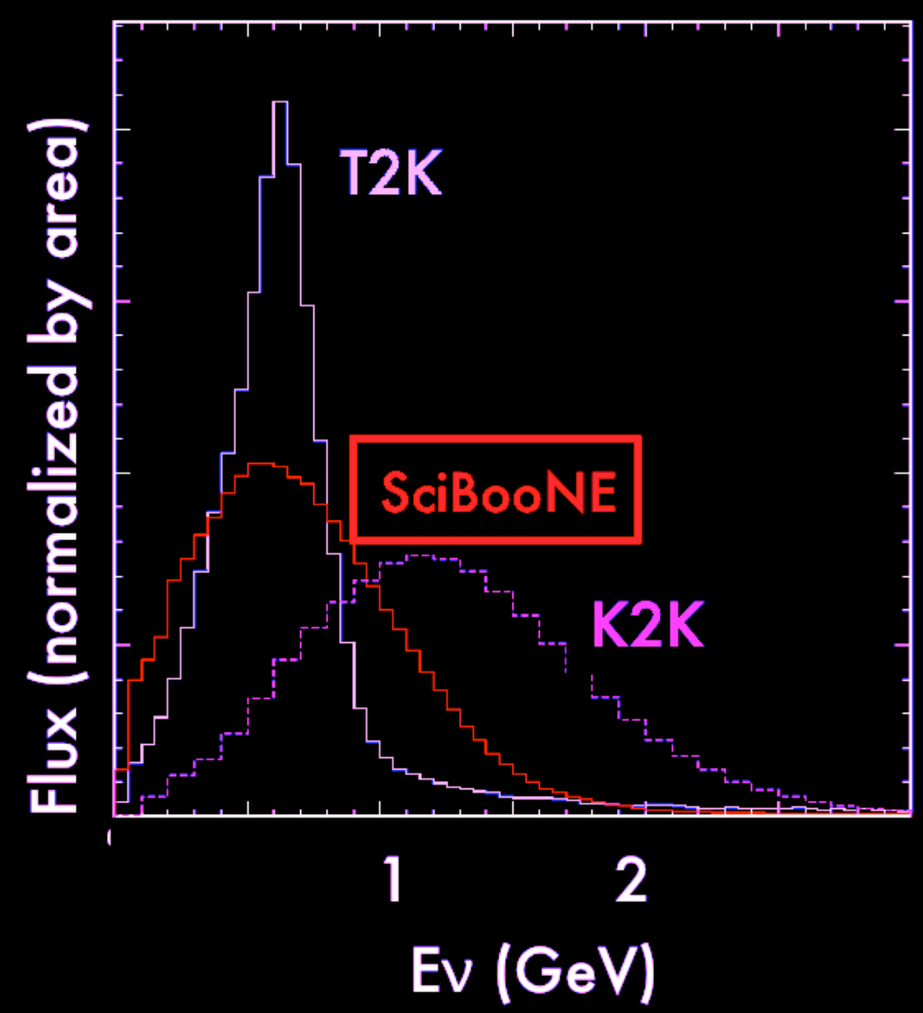
Expected MINERνA sensitivity

- Expect to clean up other processes (coherent/ resonant pion, etc) at similar level pof precision

FNAL E954: SciBooNE

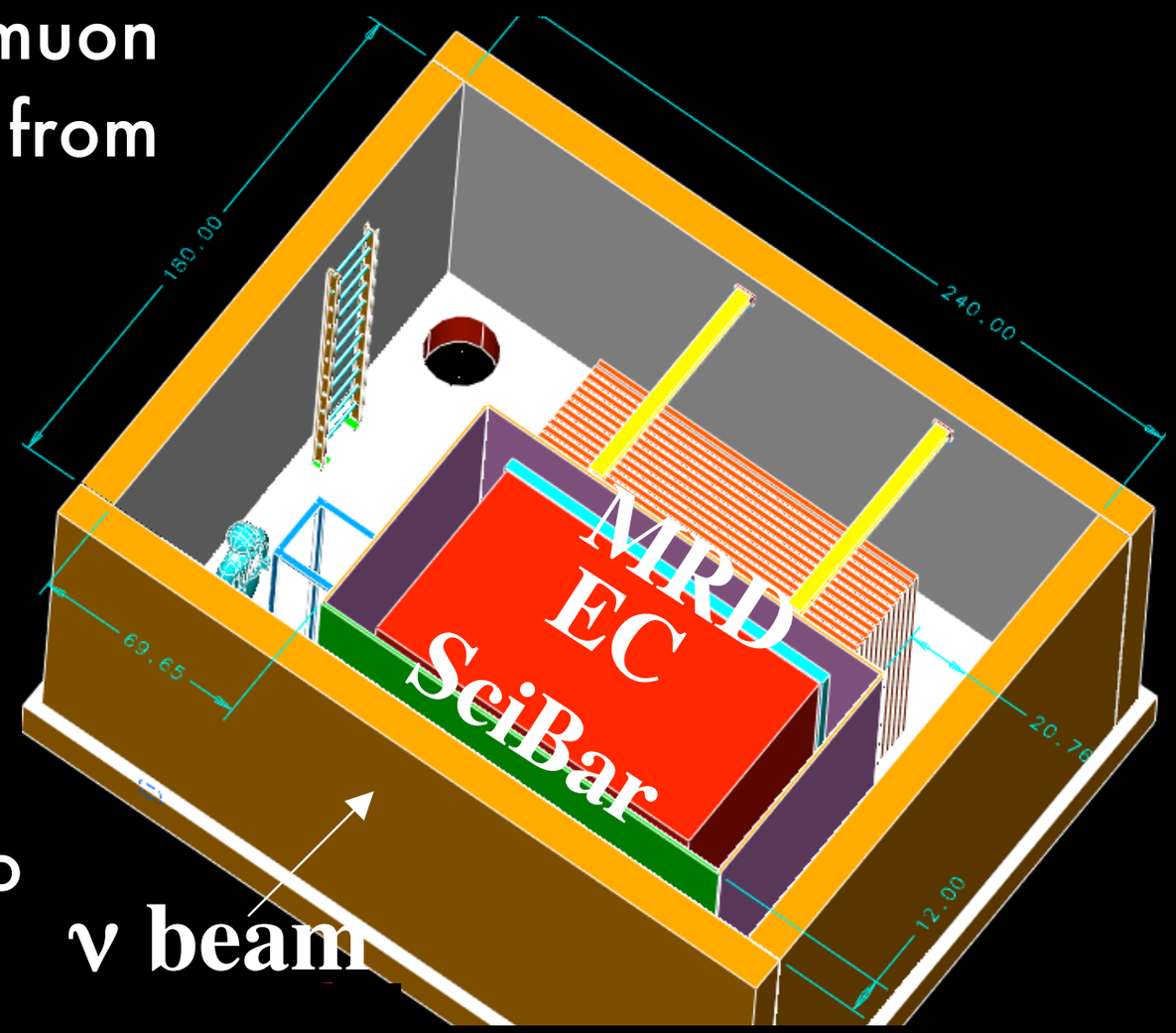


- Bring the K2K SciBar detector to Fermilab, insert it in a new enclosure in the MiniBooNE neutrino beam at a baseline of 100 m.
- SciBooNE sees nearly entire flux of T2K (and of course MiniBooNE)



SciBooNE

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



SciBooNE physics

- Expect 78,000 ν_μ and 40,000 $\bar{\nu}_\mu$ events.
- Measure quasielastic σ and M_A to 5%
- Possibly first measurement of $\bar{\nu}$ quasielastic at $E_\nu < 1$ GeV
- 10% measurements of pion production exclusive channels
- Other, rarer process searches too ($\Delta \to N\gamma$, coherent π, ...)

Wrapping Up

- Short-baseline oscillation physics is approaching denouement with MiniBooNE's resolution of the LSND effect
- Cross-section physics is rich, varied, making rapid progress to allow oscillation experiments to enter a new era of precision