Recent results from MiniBooNE

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NNN'10

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Recent Results from MiniBooNE

- MiniBooNE
- Neutrino cross-sections
  - Quasielastic and elastic scattering
  - Hadron production channels
- Neutrino Oscillations
- Antineutrino Oscillations

Motivating MiniBooNE: LSND

Liquid Scintillator Neutrino Detector

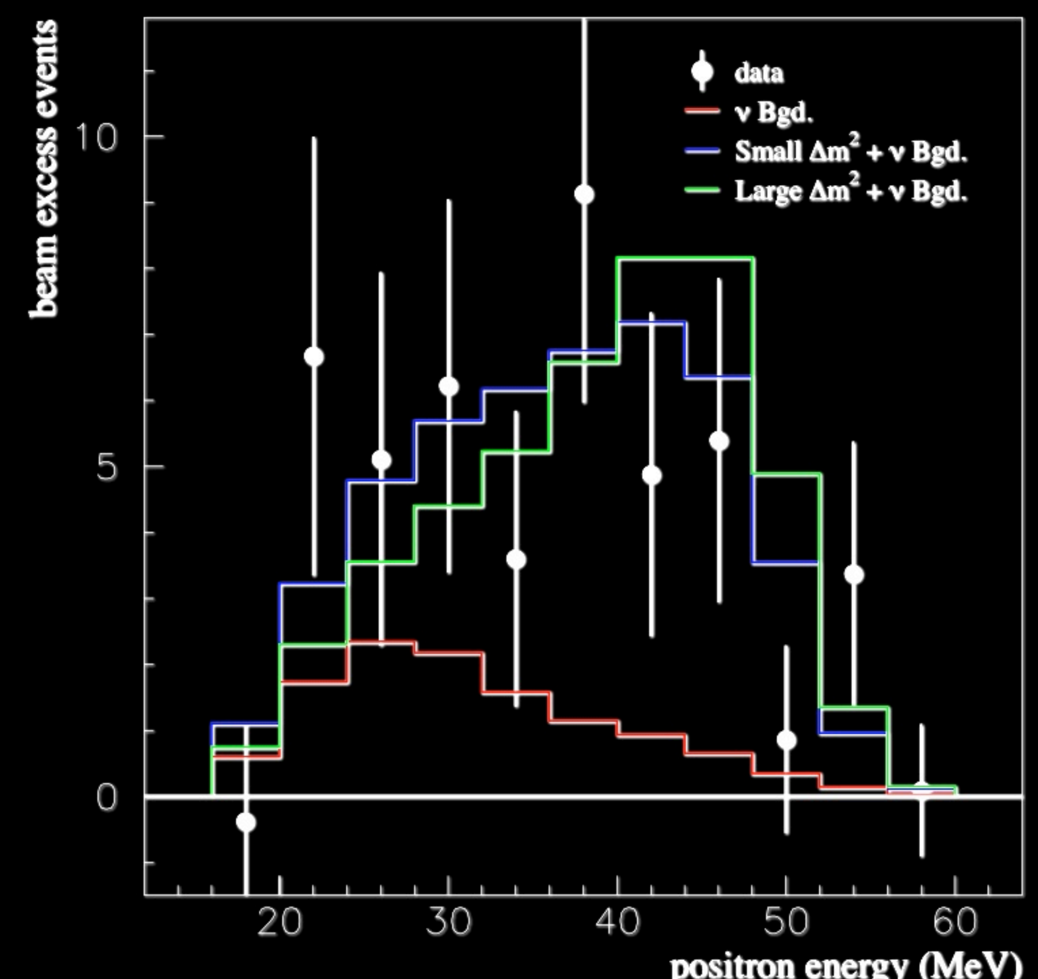
- Stopped π^+ beam at Los Alamos LAMPF produces ν_e, ν_μ, $\bar{\nu}_\mu$ but no $\bar{\nu}_e$ (due to π^- capture).

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

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

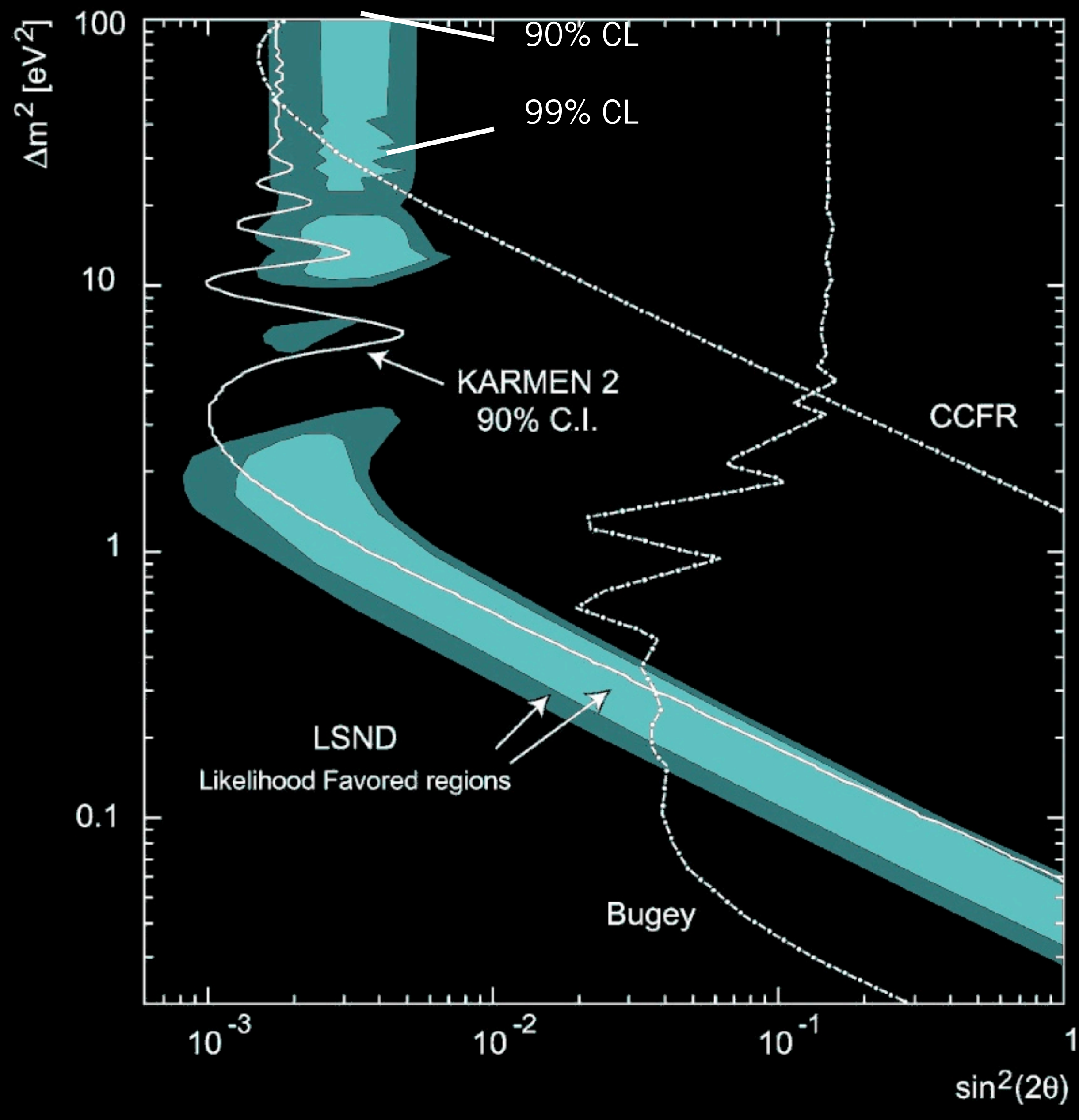
- Neutron thermalizes, captures ➡2.2 MeV γ-ray
- Look for the delayed coincidence.
- Major background non-beam (measured, subtracted)
- 3.8 standard dev. excess above background.
- Oscillation probability:

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



LSND oscillation signal

- LSND “allowed region” shown as band
- KARMEN2 is a similar experiment with a slightly smaller L/E; they see no evidence for oscillations. Excluded region is to right of curve.



The Overall Picture

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

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
  - Discovery that one of the observed effects is not oscillations
  - A new idea

MiniBooNE: E898 at Fermilab

- Purpose is to test LSND with:
    - Higher energy
    - Different beam
    - Different oscillation signature
    - Different systematics
- L=500 meters, E=0.5−1 GeV: same L/E as LSND.

Oscillation Signature at MiniBooNE

- Oscillation signature is charged-current quasielastic scattering:

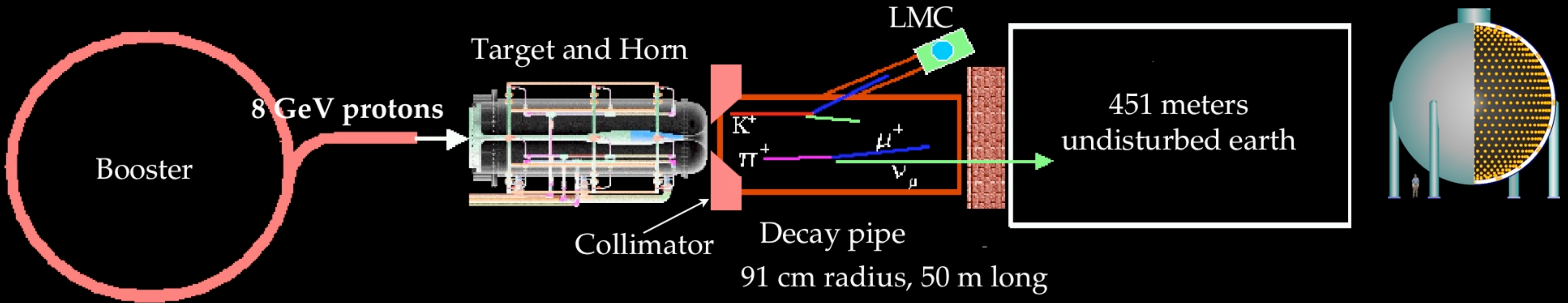
$$\nu_e + n \rightarrow e^- + p$$

- Dominant 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

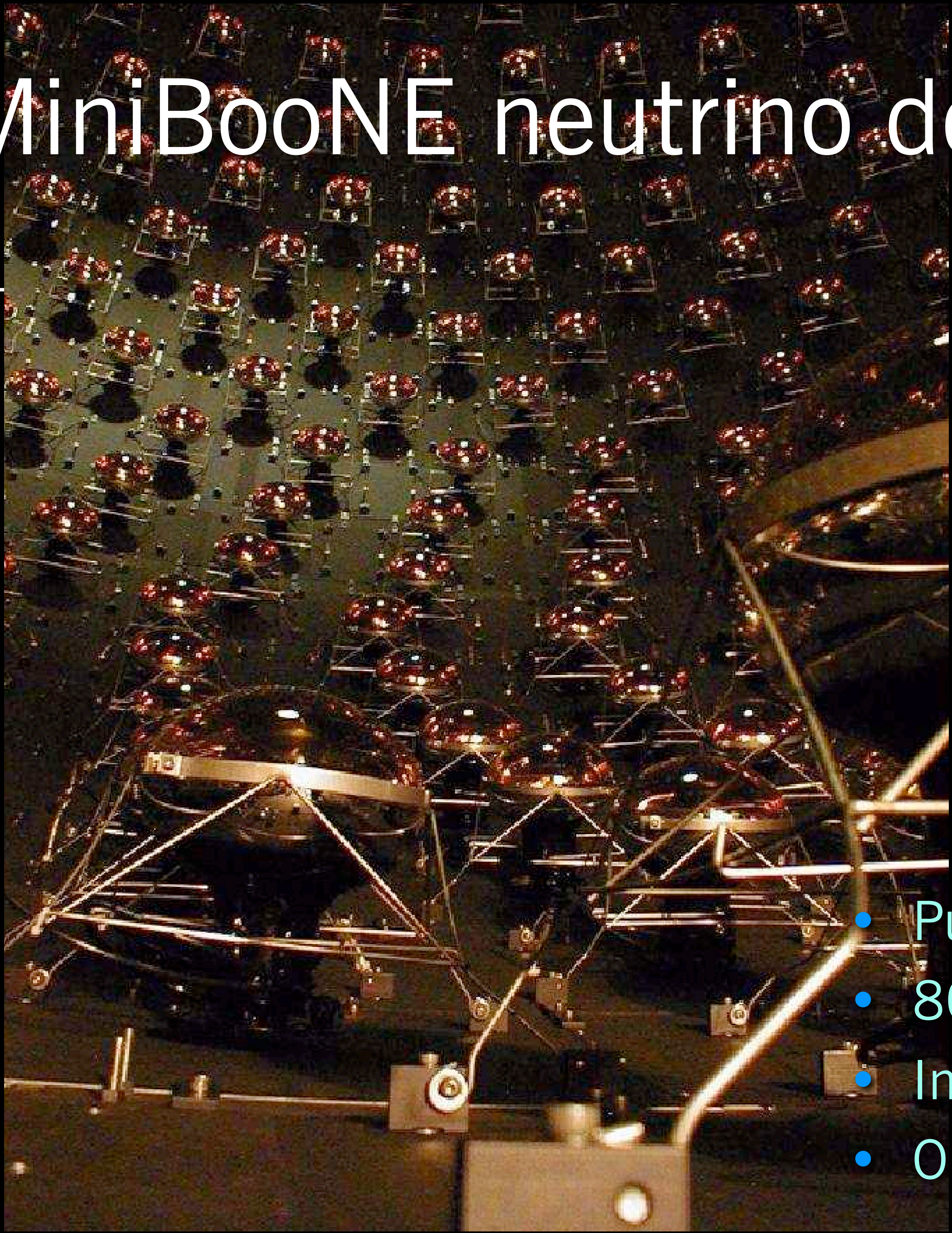
    Neutral current resonance:
    $\Delta \rightarrow \pi^0 \rightarrow \gamma\gamma$ or $\Delta \rightarrow n\gamma$, mis-ID as e

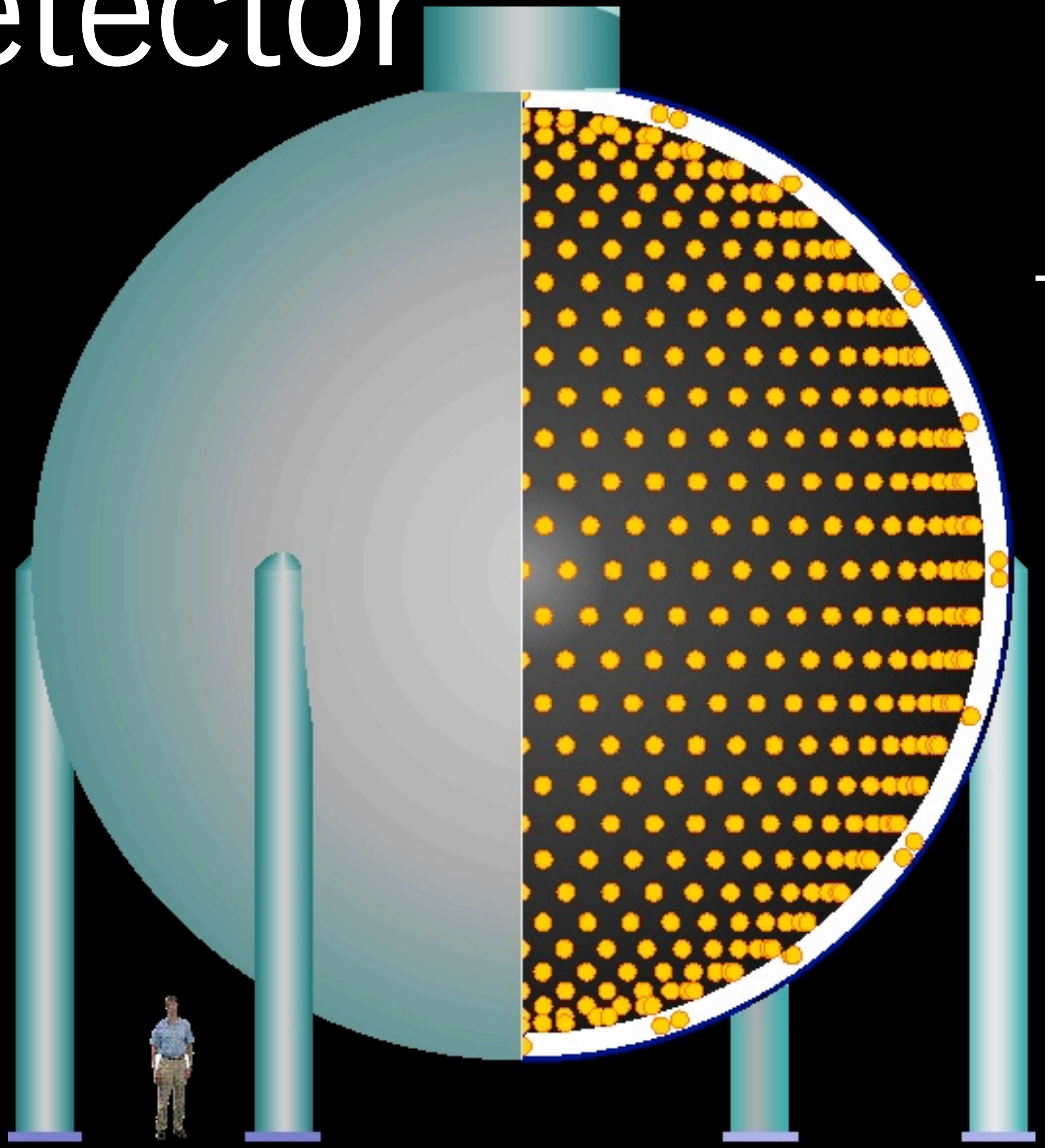
MiniBooNE Beamline



- 8 GeV primary protons come from Booster accelerator at Fermilab
- Booster provides about 5 pulses per second, 5×10^{12} protons per 1.6 μs pulse under optimum conditions
- Beryllium target, single 174 kA horn
- 50 m decay pipe, 91 cm radius, filled with stagnant air

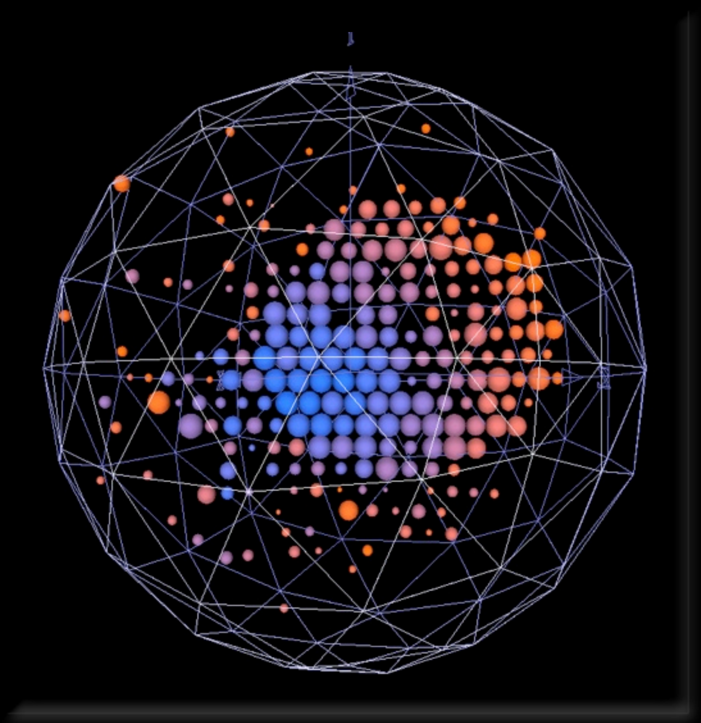
MiniBooNE neutrino detector

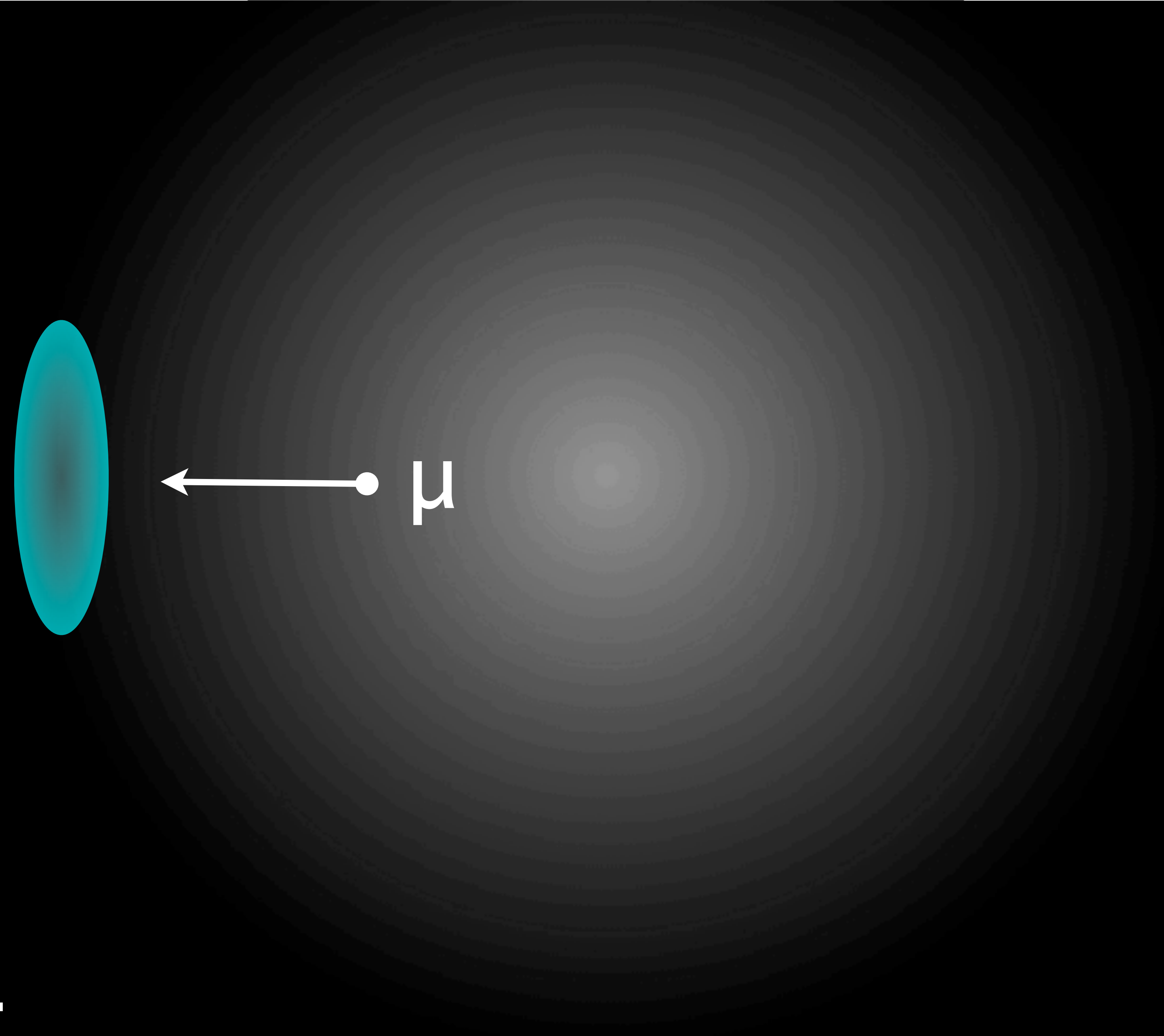




- Pure mineral oil
- 800 tons; 40 ft diameter
- Inner volume: 1280 8" PMTs
- Outer veto volume: 240 PMTs

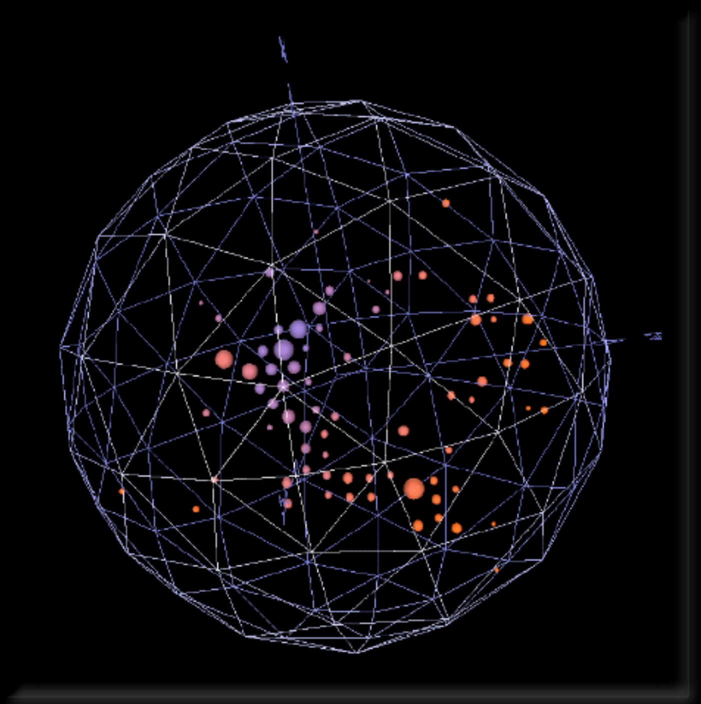
Cherenkov ring characteristics: muons

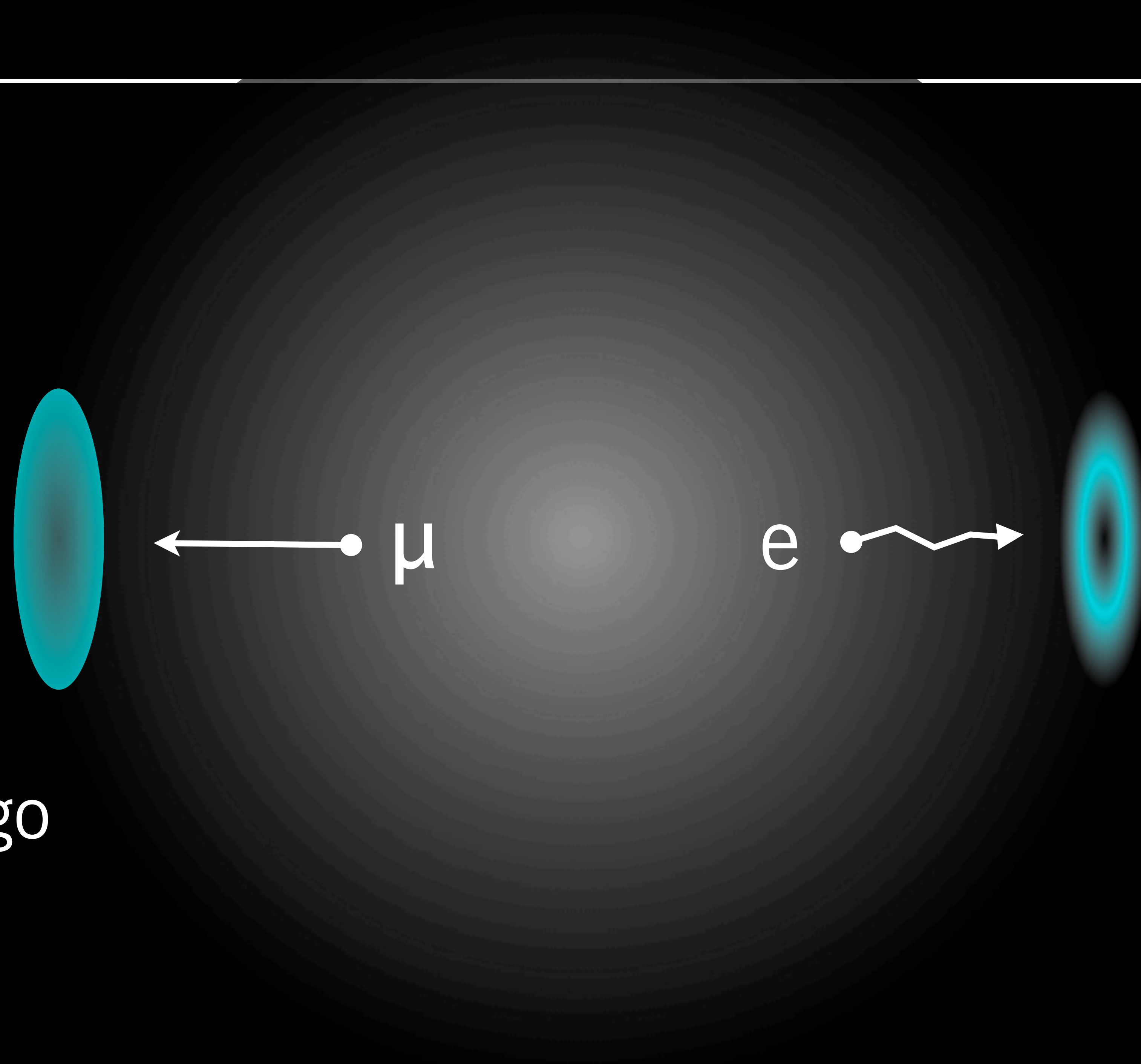




- Muons have sharp filled in Cherenkov rings.

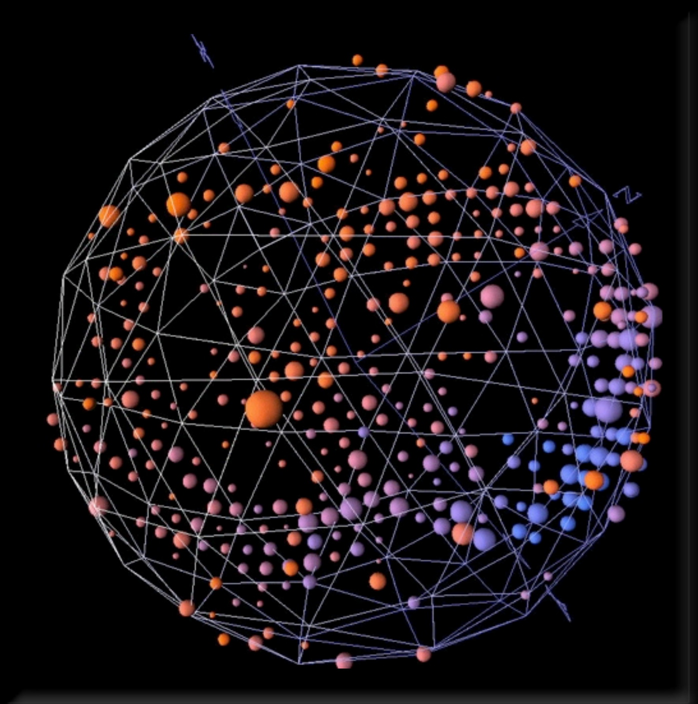
Cherenkov ring characteristics: electrons

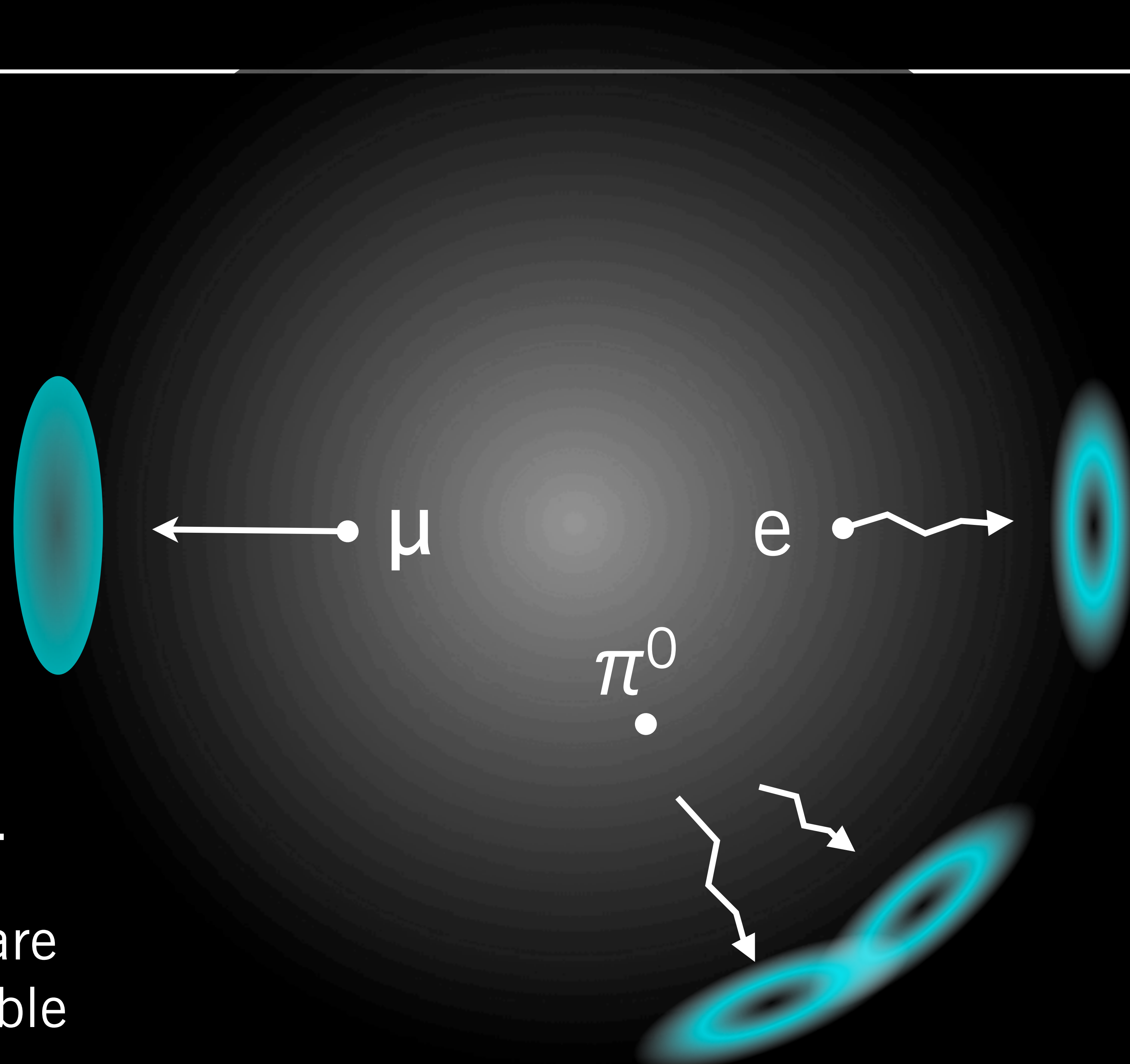




- Electrons undergo more scattering and produce “fuzzy” rings.

Cherenkov ring characteristics: π^0





- π^0 decay to γγ with 99% branching ratio.
- Photon conversions are nearly indistinguishable from electrons.

MiniBooNE's track-based reconstruction

- A detailed analytic model of extended-track light production and propagation in the tank predicts the probability distribution for charge and time on each PMT for individual muon or electron/photon tracks.
- Prediction based on seven track parameters: vertex (x,y,z), time, energy, and direction $(\theta,\varphi)\Leftrightarrow(U_x, U_y, U_z)$.
- Fitting routine varies parameters to determine 7-vector that best predicts the actual hits in a data event
- Particle identification comes from ratios of likelihoods from fits to different parent particle hypotheses

Beam/Detector Operation

- Fall 2002 - Jan 2006: Neutrino mode (first oscillation analysis).
- Jan 2006 - 201?: Antineutrino mode
  - (Interrupted by short Fall 2007 - April 2008 neutrino running)
- Present analyses use:
  - $\geq$5.7E20 protons on target for neutrino analyses
  - 5.66E20 protons on target for antineutrino analyses
  - Over one million neutrino interactions recorded: by far the largest data set in this energy range

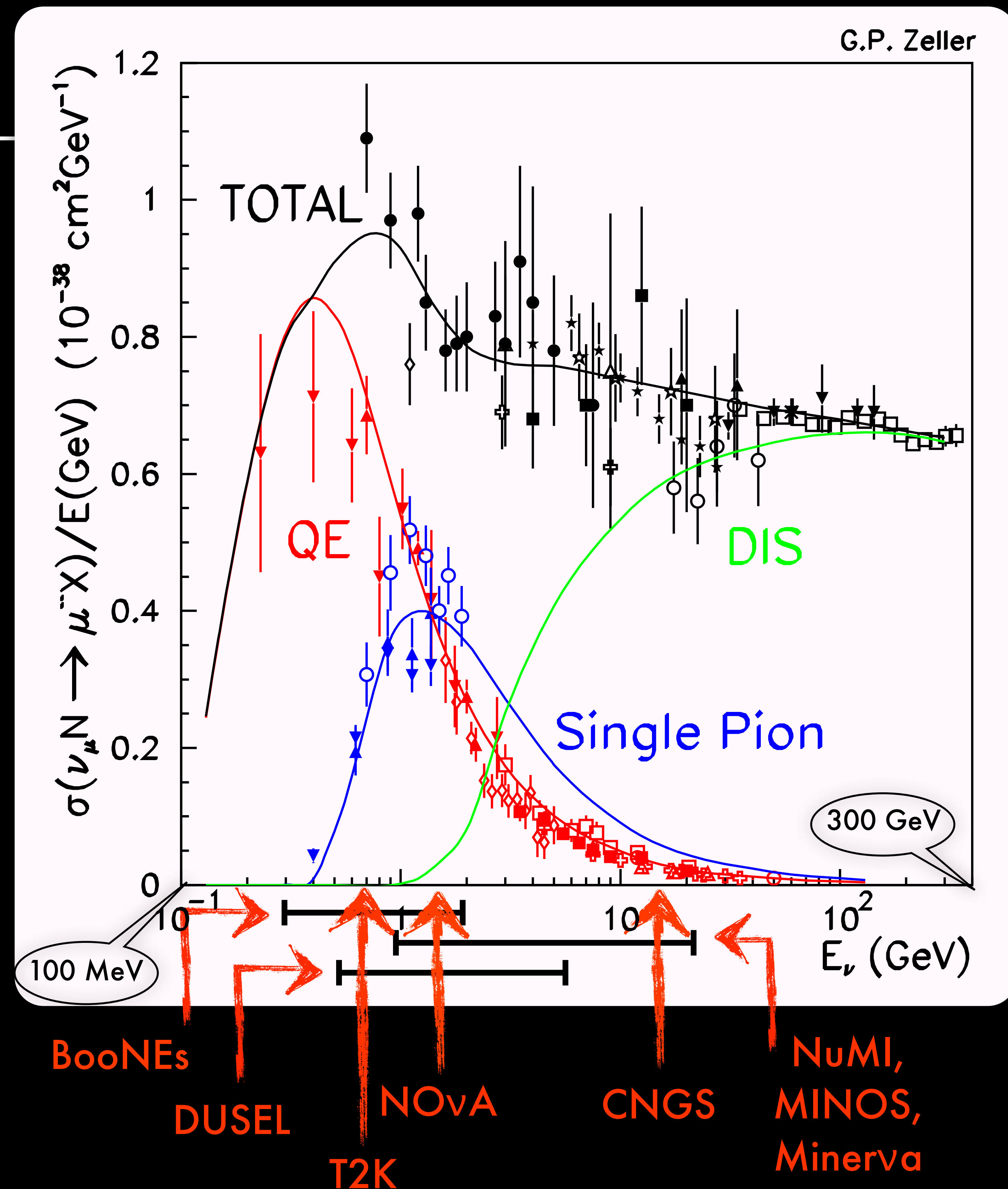
Neutrino scattering cross-sections

- To understand the flavor physics of neutrinos (*i.e.* oscillations), it is critical to understand the physics of neutrino interactions
- This is a real challenge for most neutrino experiments:
    - Broadband beams
    - Large backgrounds to most interaction channels
    - Nuclear effects (which complicate even the definition of the scattering processes!)

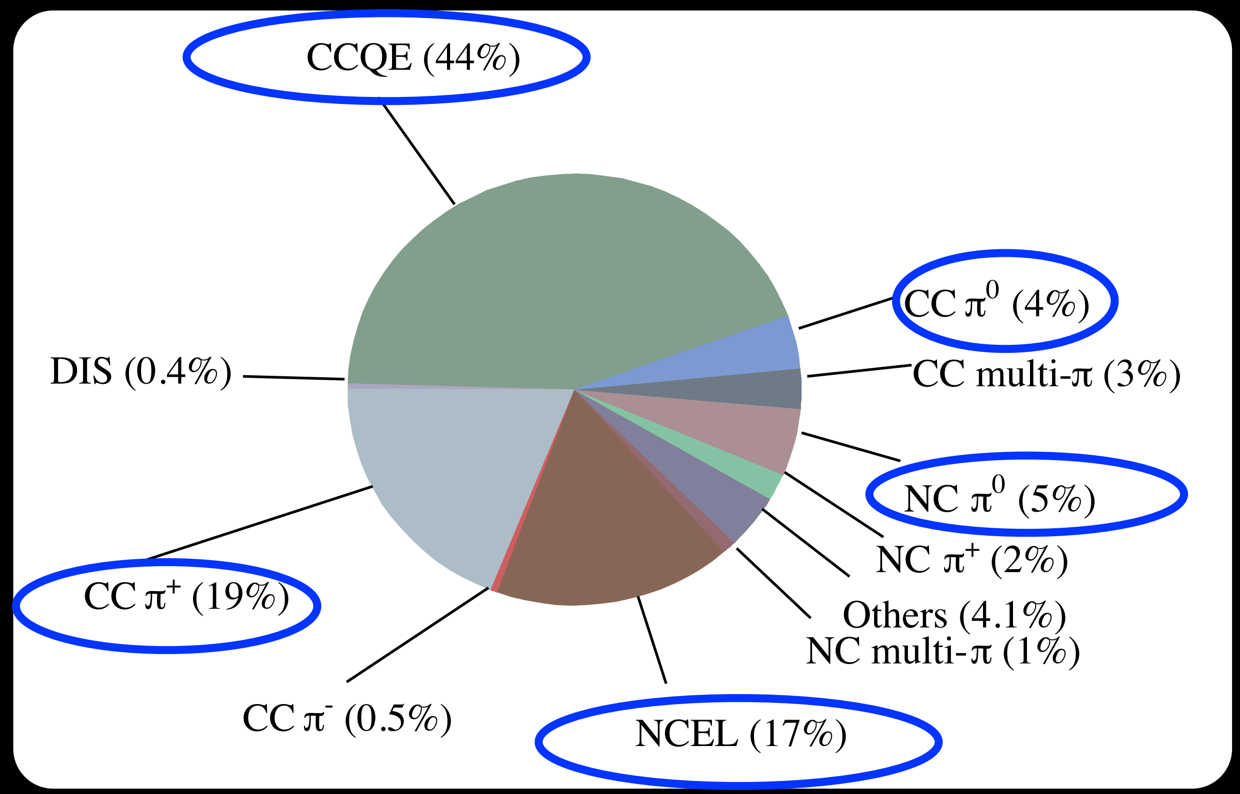
Scattering cross-sections for ν_μ

The state of knowledge of ν_μ interactions before the current generation of experiments:

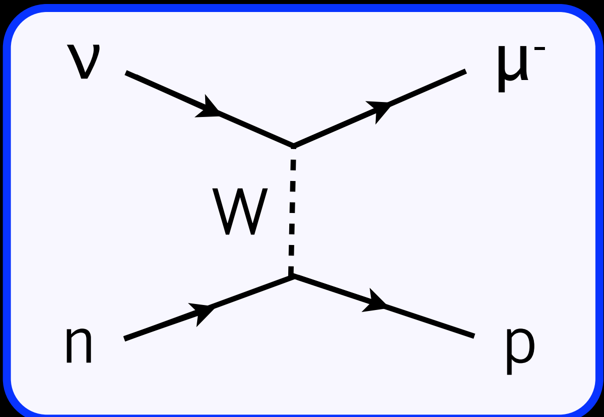
- Lowest energy (E < 500 MeV) is dominated by CCQE.
- Moderate energies (500 MeV < E < 5 GeV) have lots of single pion production.
- High energies (E > 5 GeV) are completely dominated by deep inelastic scattering (DIS).
- Most data over 20 years old, and on light targets (deuterium).
- Current and future experiments use nuclear targets from C to Pb; almost no data available.



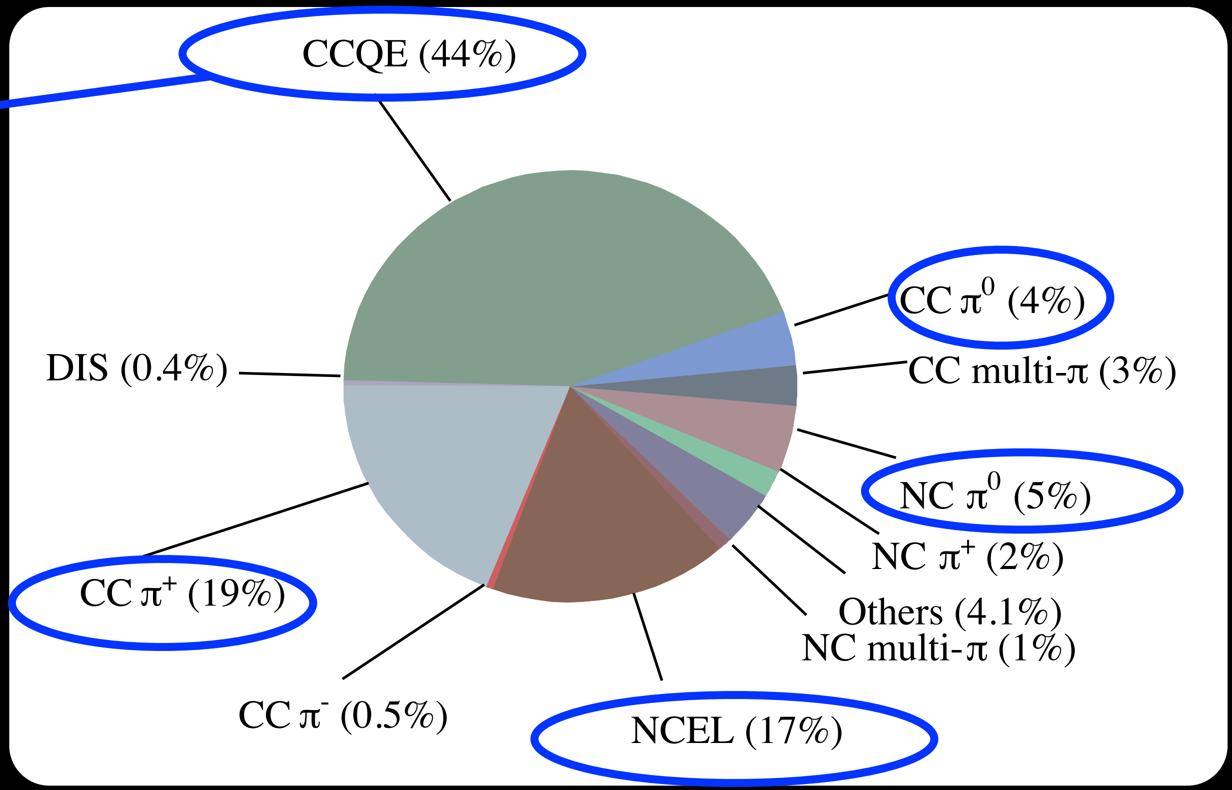
Dominant interaction channels at MiniBooNE



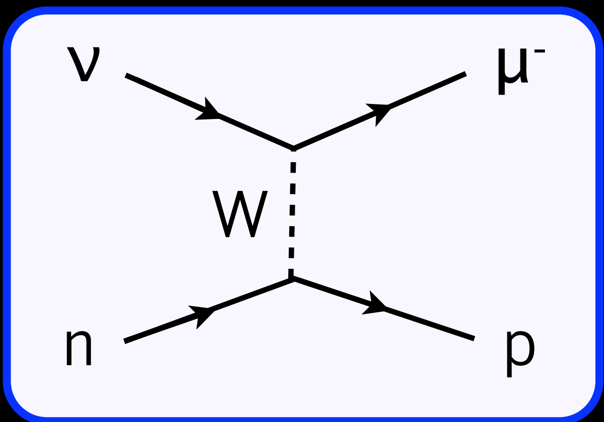
Dominant interaction channels at MiniBooNE



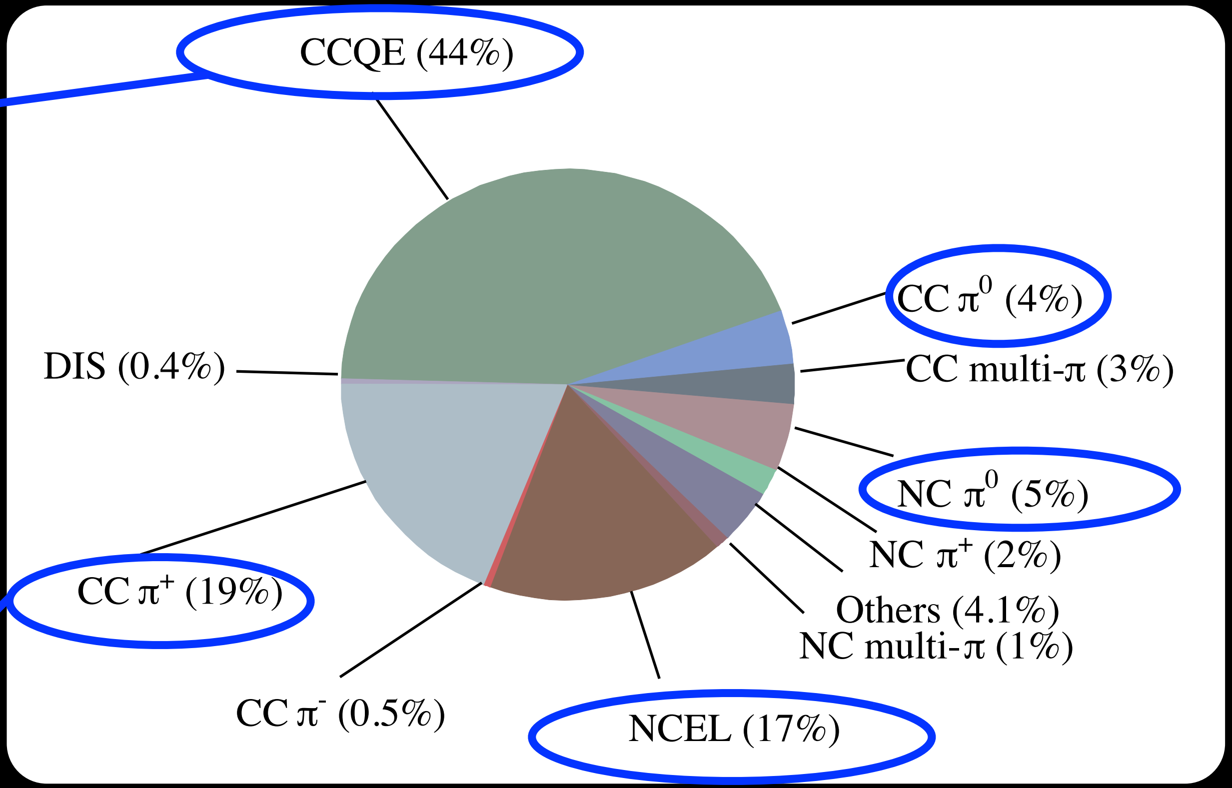
Charged-current quasielastic



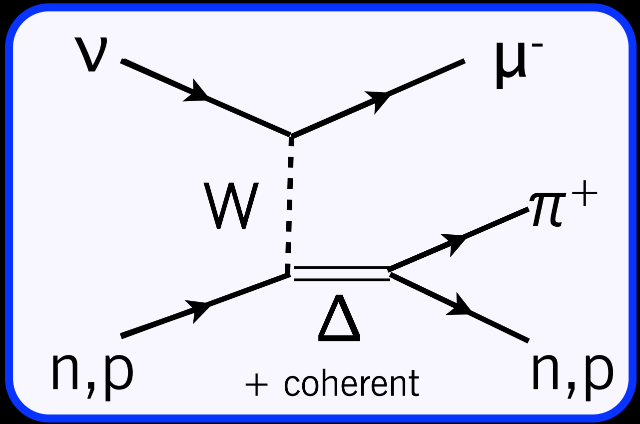
Dominant interaction channels at MiniBooNE



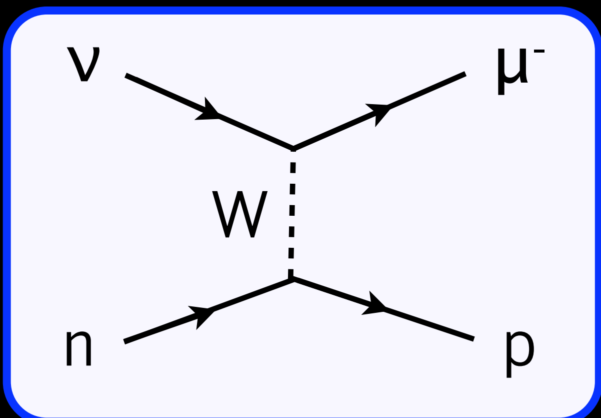
Charged-current quasielastic



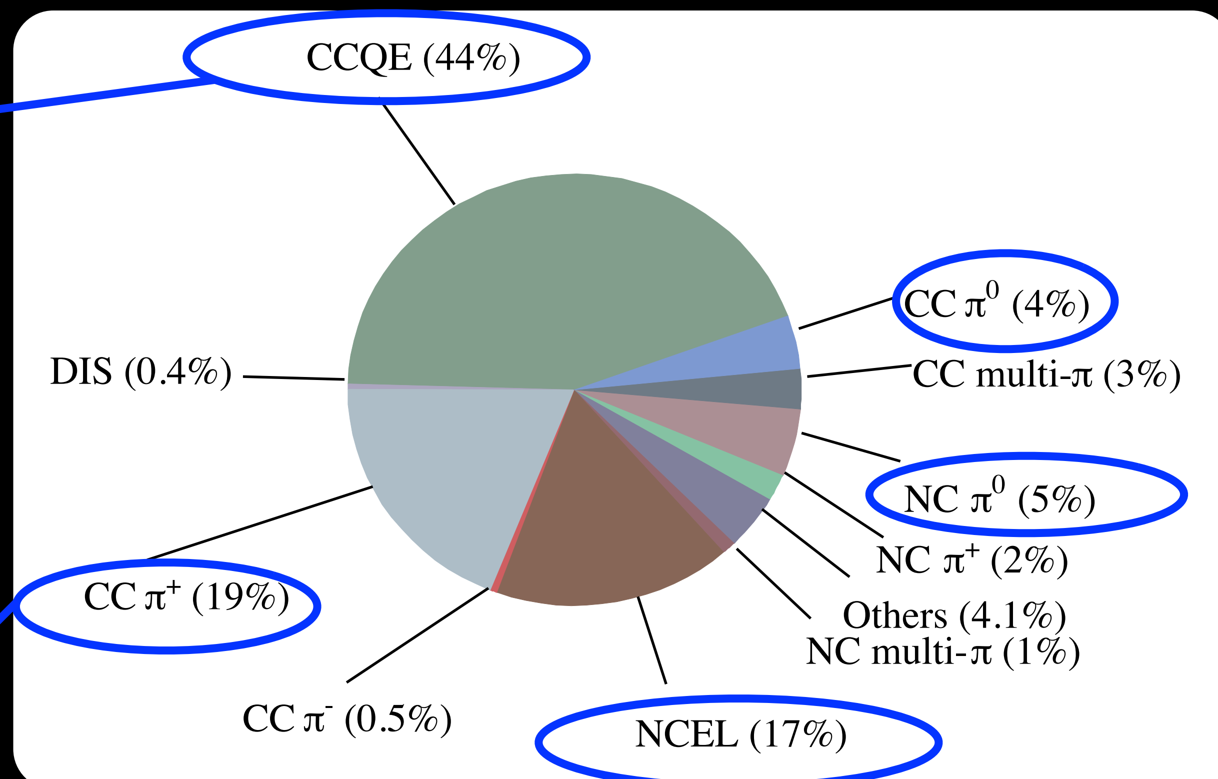
Charged-current π^+ production



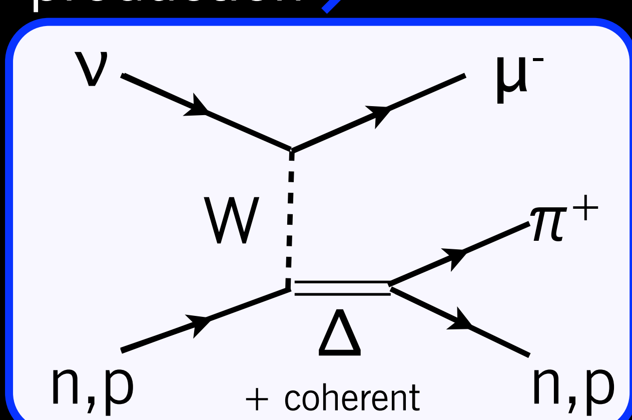
Dominant interaction channels at MiniBooNE

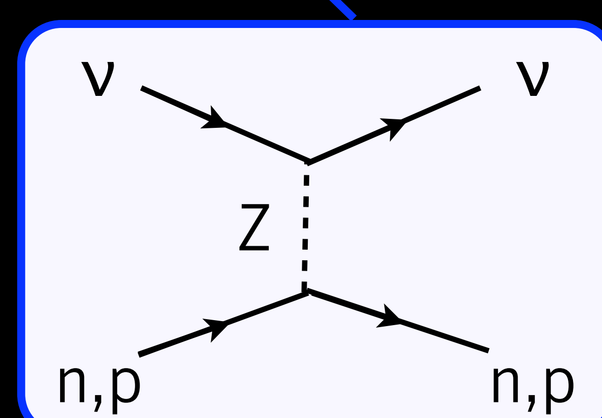


Charged-current quasielastic



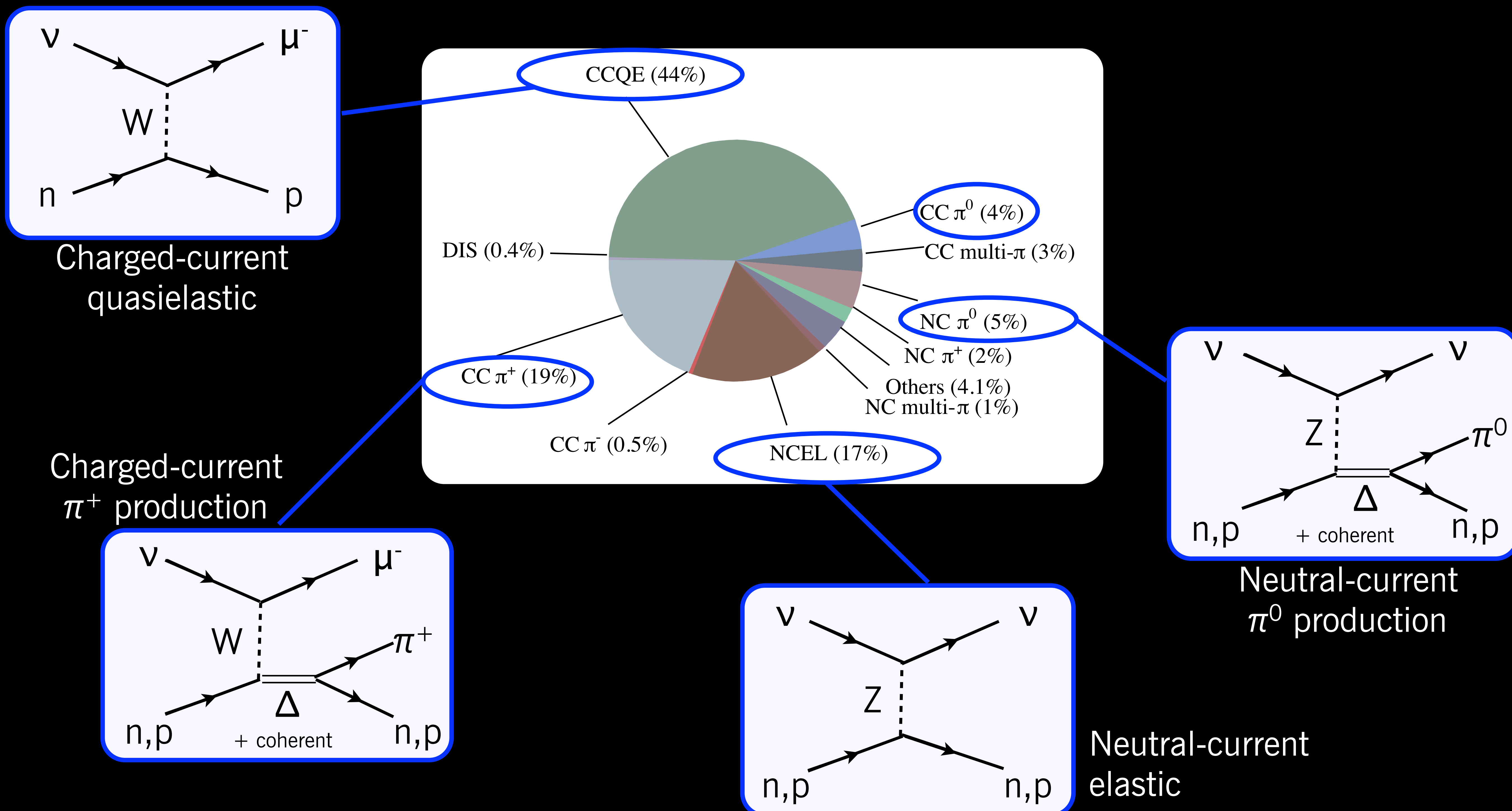
Charged-current π^+ production



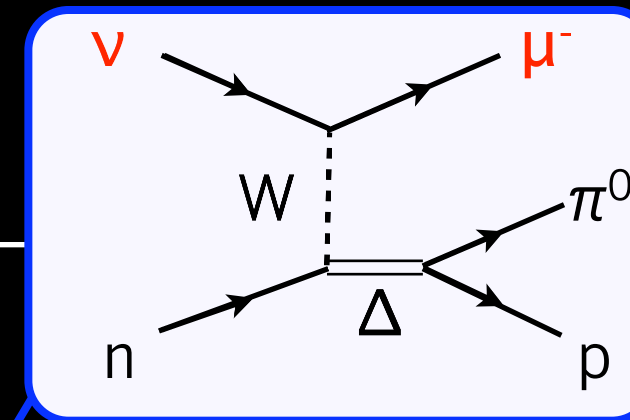


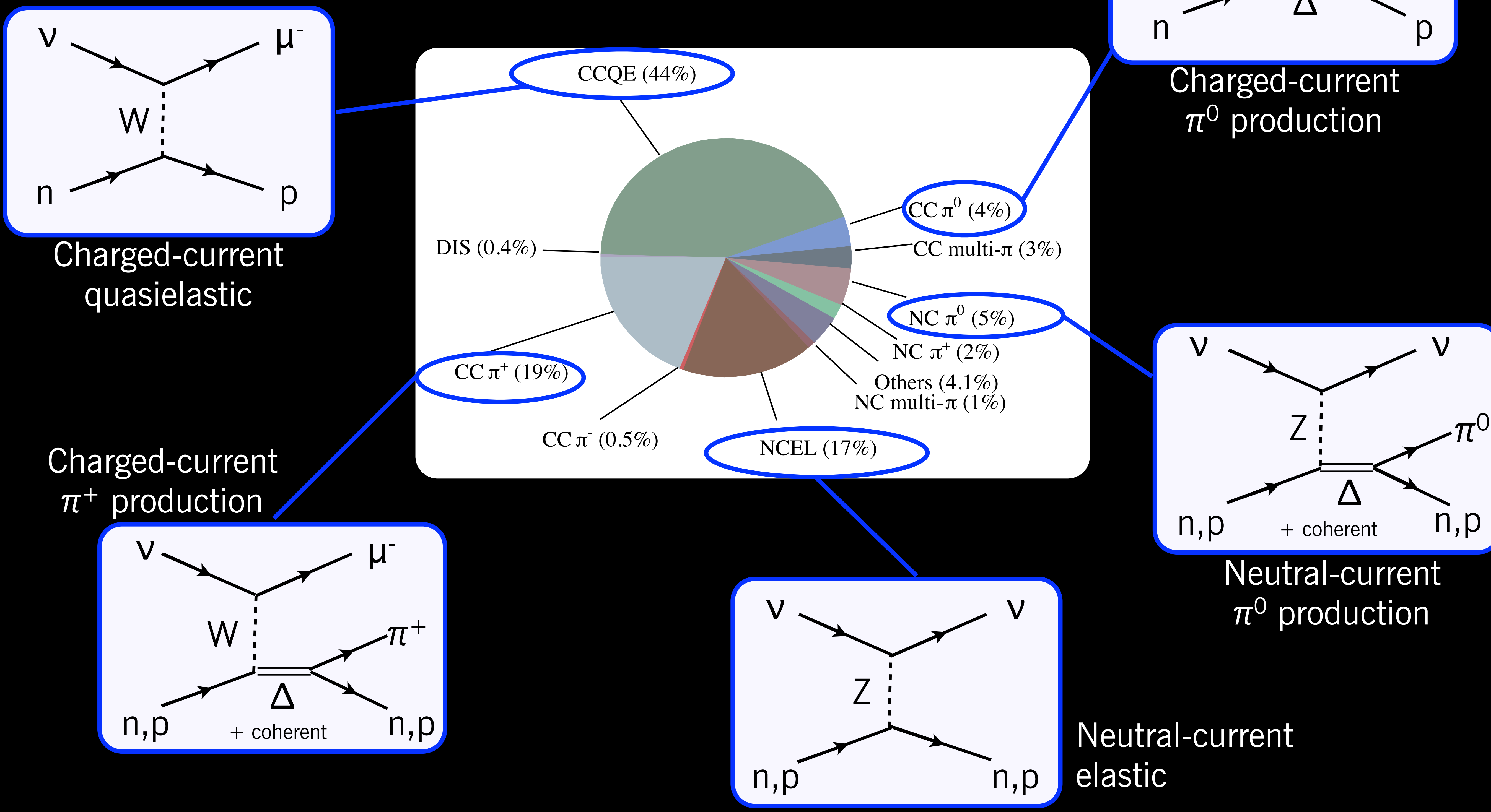
Neutral-current elastic

Dominant interaction channels at MiniBooNE

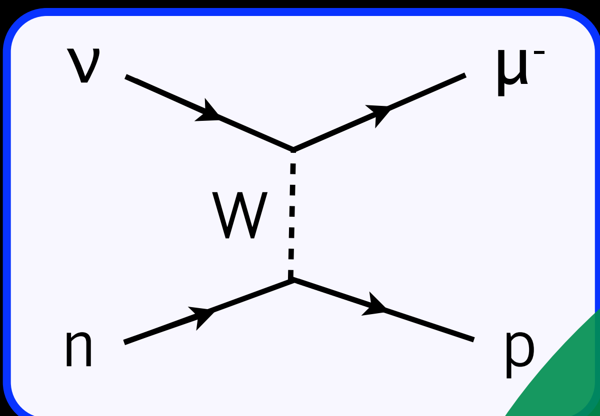


Dominant interaction channels at MiniBooNE

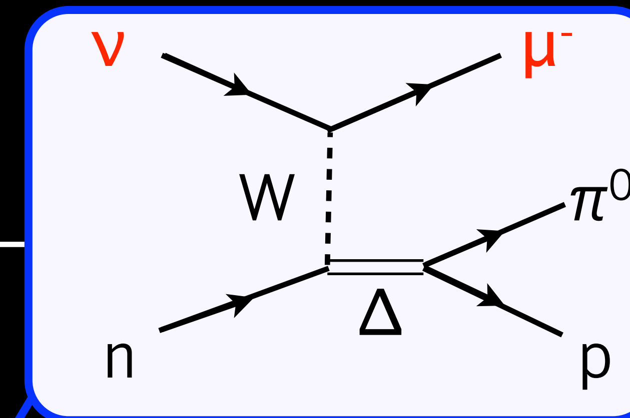




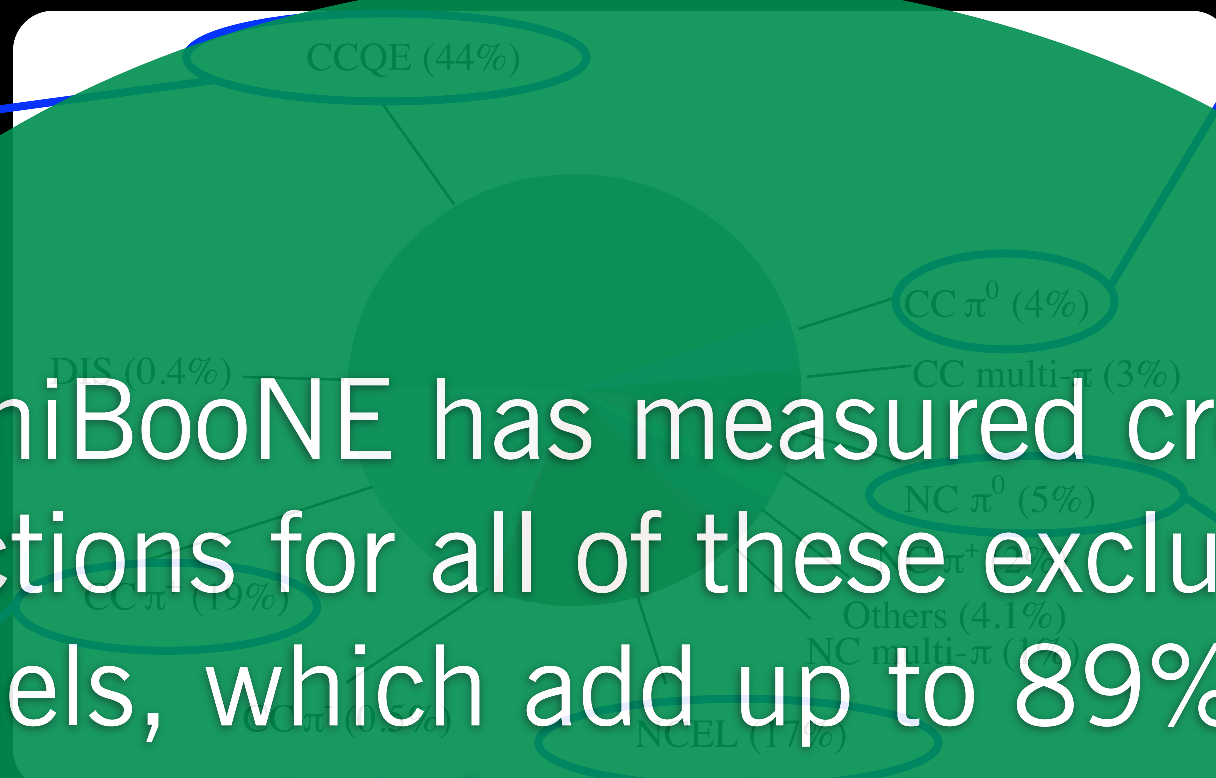
Dominant interaction channels at MiniBooNE



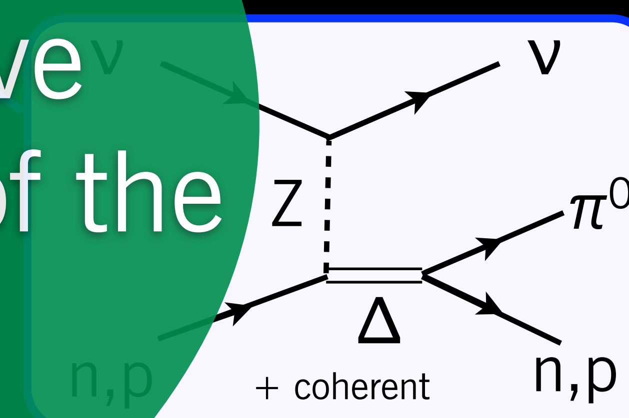
Charged-current quasielastic



Charged-current π^0 production

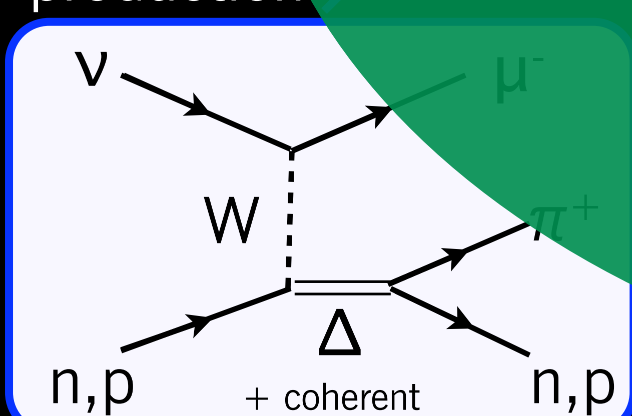


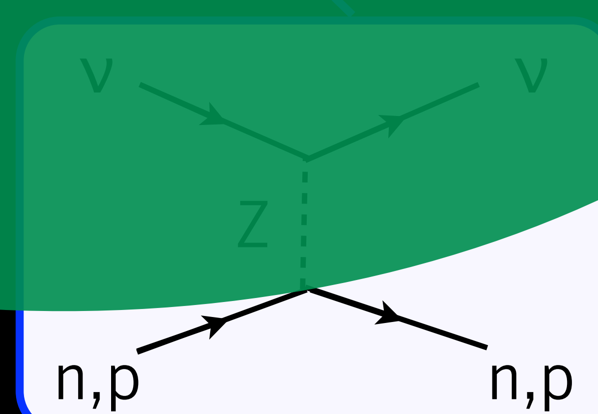
MiniBooNE has measured cross-sections for all of these exclusive channels, which add up to 89% of the total event rate



Neutral-current π^0 production

Charged-current π^+ production





Neutral-current elastic

Critical for measuring cross-sections: well-understood flux

- Detailed MC simulations of target+horn+decay region, using π production tables from dedicated measurements: PRD **79** 072002 (2009).
- ***No flux tuning based on MB data***
- Most important π production measurements from HARP(at CERN) at 8.9 GeV/c beam momentum (as MB), 5% int. length Be target (Eur.Phys.J.C52 (2007)29)
- Error on HARP data (7%) is dominant contribution to flux uncertainty
- Overall 9% flux uncertainty, dominates cross section normalization (“scale”) error

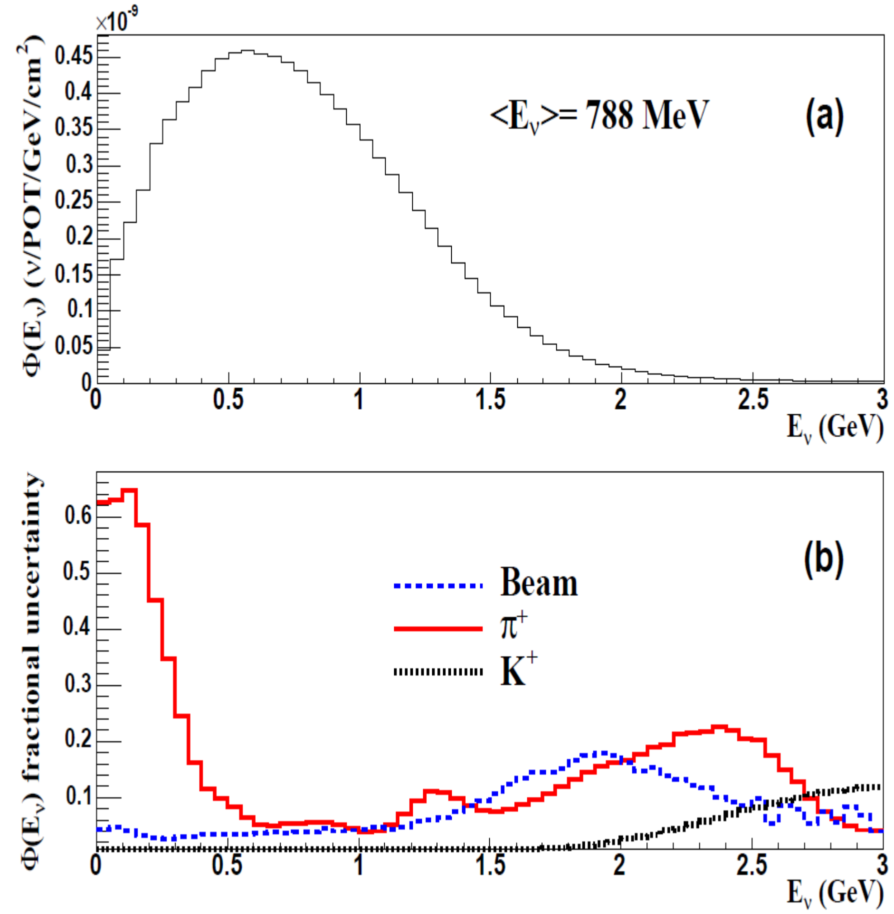
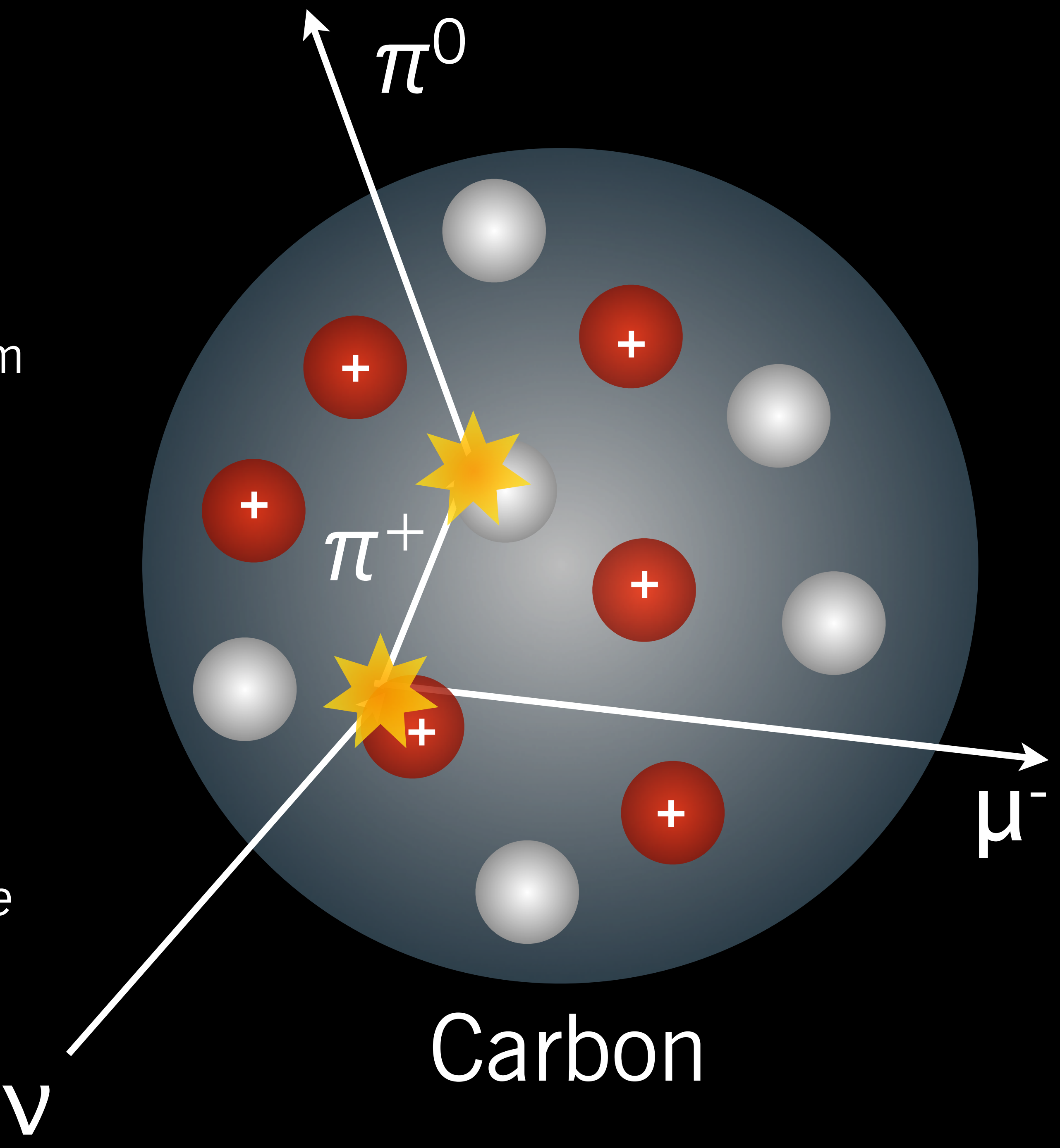


FIG. 2: (color online) Predicted ν_μ flux at the MiniBooNE detector (a) along with the fractional uncertainties grouped into various contributions (b). The integrated flux is 5.16×10^{-10} ν_μ/POT/cm^2 ($0 < E_\nu < 3$ GeV) with a mean energy of 788 MeV. Numerical values corresponding to the top plot are provided in Table V in the Appendix.

A general concern: final state interaction

- The particles that leave the target nucleus are not necessarily the final state particles from the initial neutrino-nucleon interaction.
- True CCπ^+ can be indistinguishable from CCQE (π^+ absorption) or CCπ^0 (charge exchange).
- Experiments only have access to what came out of the nucleus. These are called ***observable events***:
  - An interaction where the target nucleus yields one μ^-, exactly one π^+, and nuclear debris is *observable* CCπ^+, regardless of the initial nucleon-level interaction
- ***Most of our measurements are of observable cross-sections.***



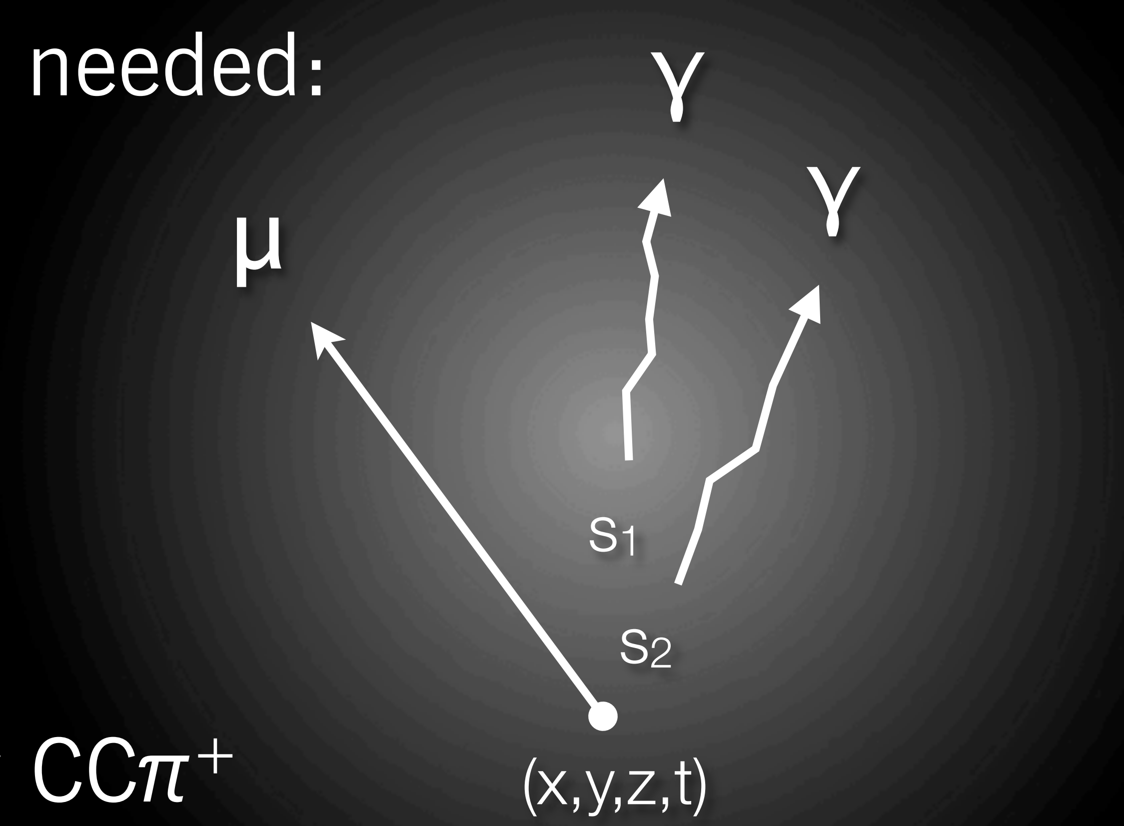
MiniBooNE cross-section measurements

- ~~NC π^0~~
- CC π^0
- CC π^+
- CC Quasielastic
- ~~NC Elastic~~
- ~~CC Inclusive~~

Due to limited time, only discussing charged-current papers here.

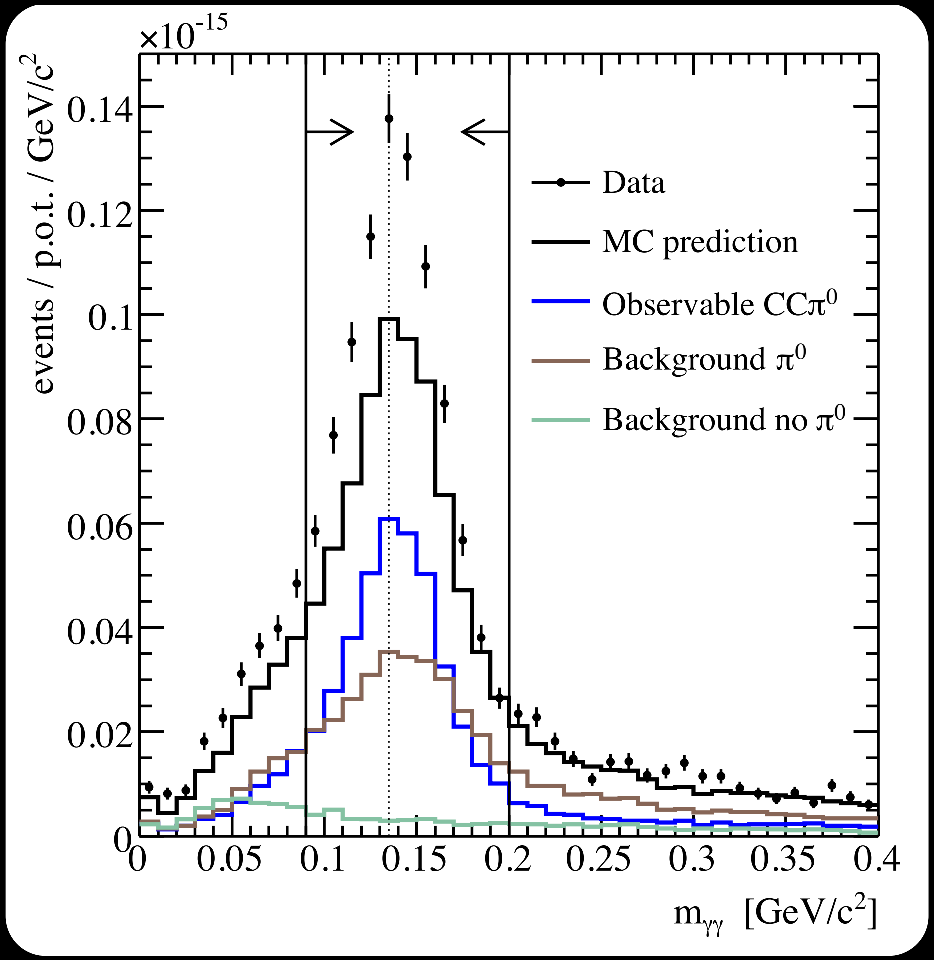
Charged-current π^0 production

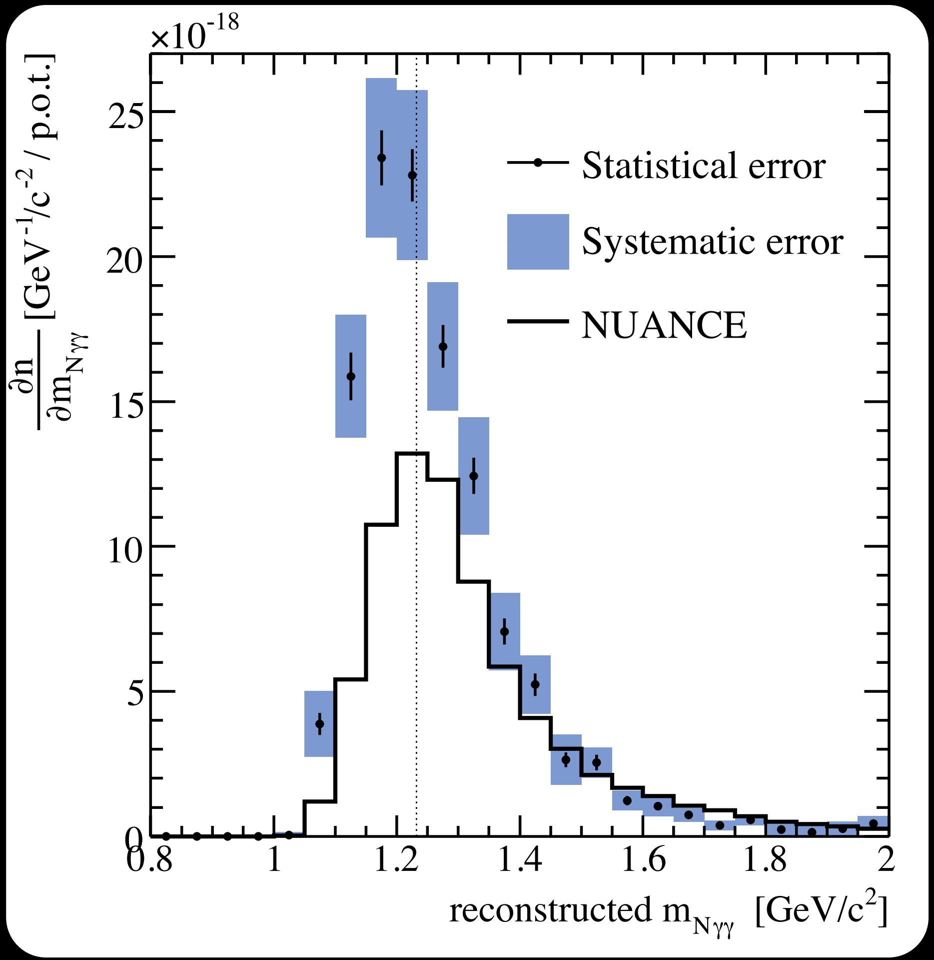
- Least common interaction for which we do exclusive measurement
- Uniquely, proceeds only via resonance: $\nu + n \rightarrow \mu + \Delta \rightarrow \mu + p + \pi^0$
- Challenging 15-parameter, 3-ring fit needed:
  - Event vertex: (x,y,z,t)
  - Muon: (E,θ,φ)
  - 1st photon: (E,θ,φ,s)
  - 2nd photon: (E,θ,φ,s)
- Relatively high backgrounds (mostly CCπ^+ which we measure separately)



Reconstructed signal candidates

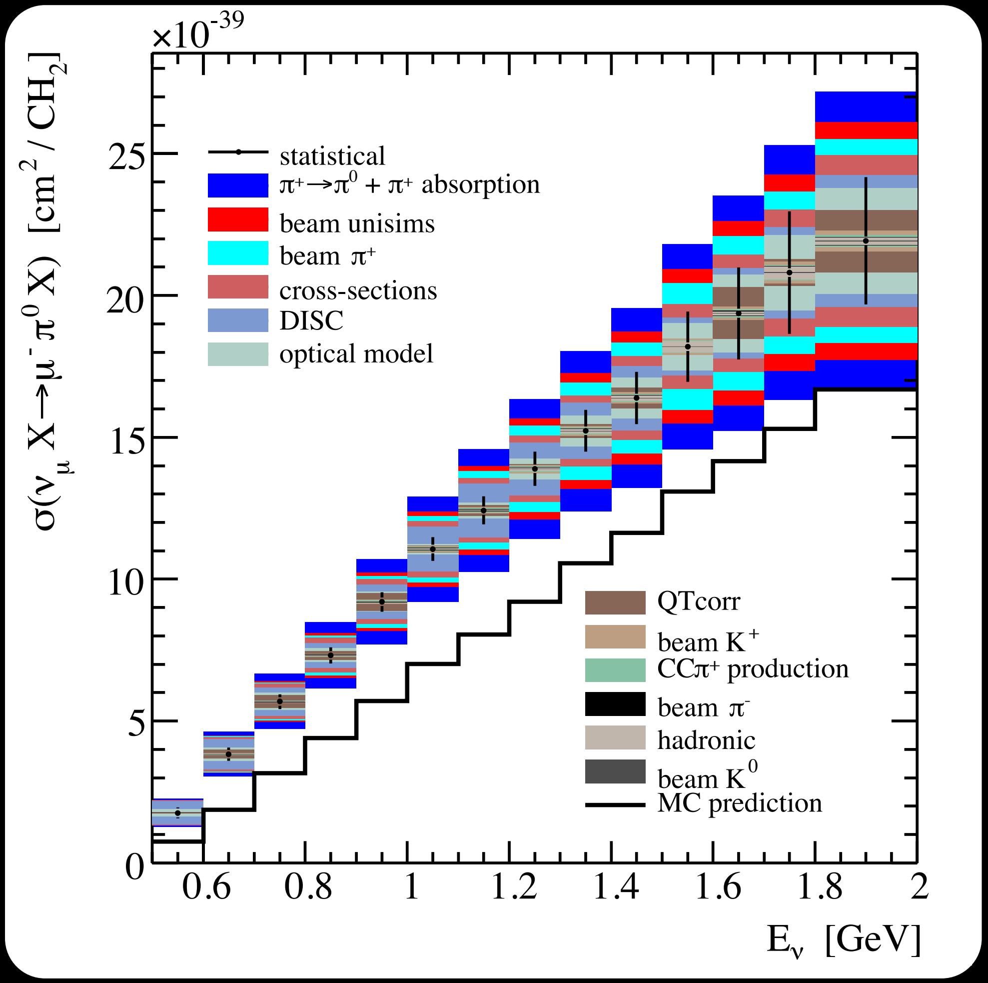
- Two-photon invariant mass $m_{\gamma\gamma}$ allows very effective identification of events with a π^0
- Reconstruction of full event allows observation of Δ resonance

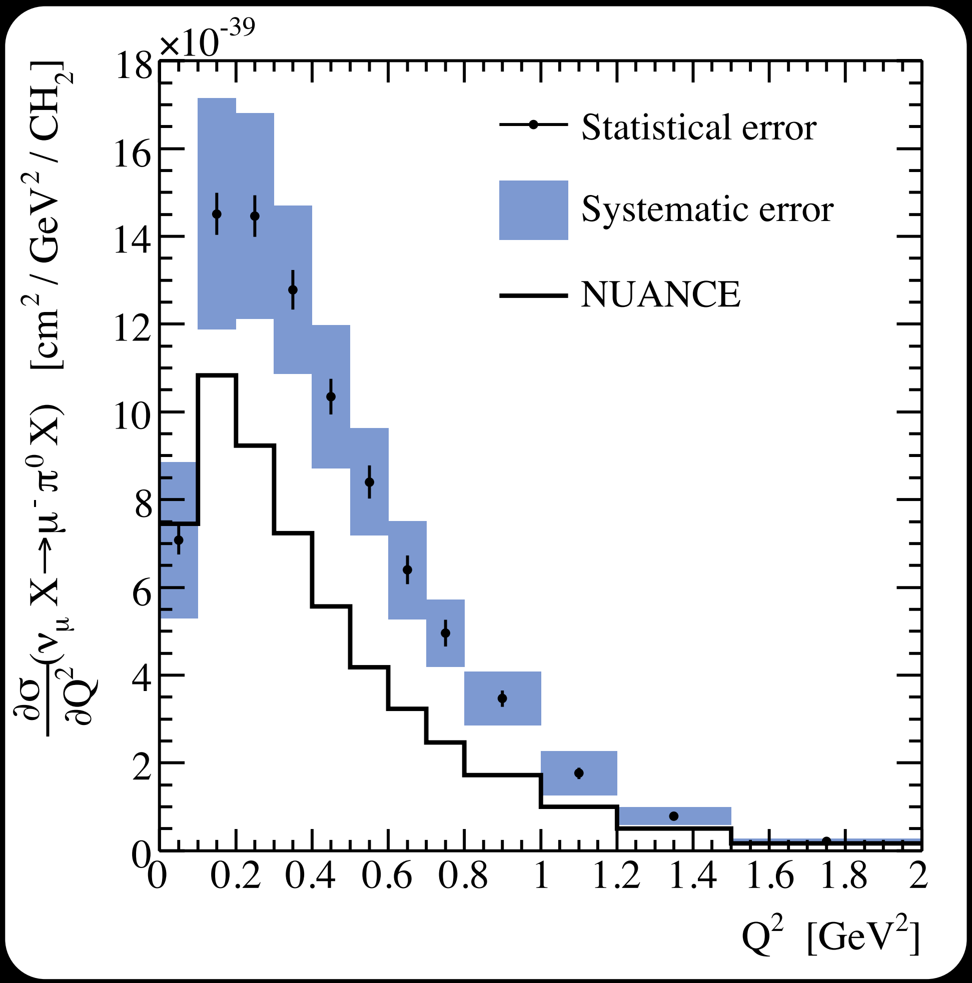




NUANCE is the default MiniBooNE neutrino interaction generator

Measured observable CCπ^0 cross-section





Additionally, we measure differential cross-sections vs:

- θ_μ
- θ_π
- E_μ
- E_π

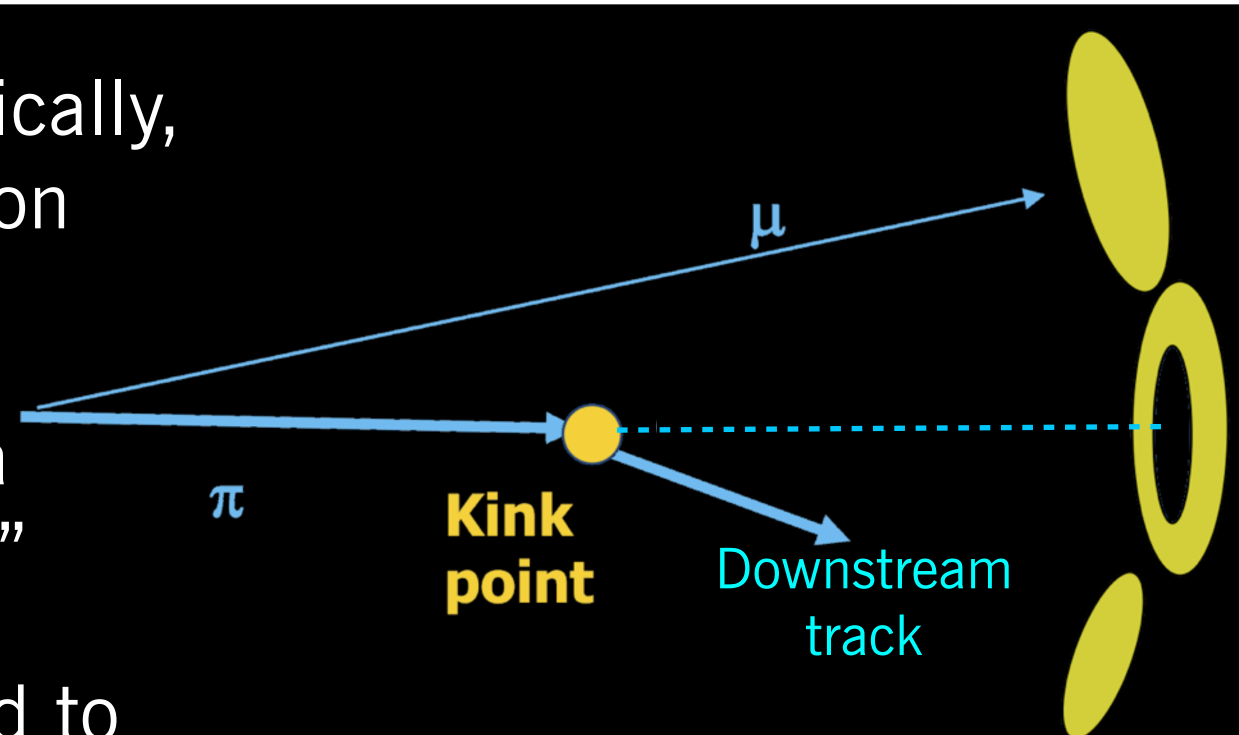
- The dominant error is π^+ charge exchange and absorption in the detector.
- First-ever differential cross-sections on a nuclear target.
- The cross-section is larger than expectation for all energies.
- Submitted to PRD. e-print:1011.3264[hep-ex]

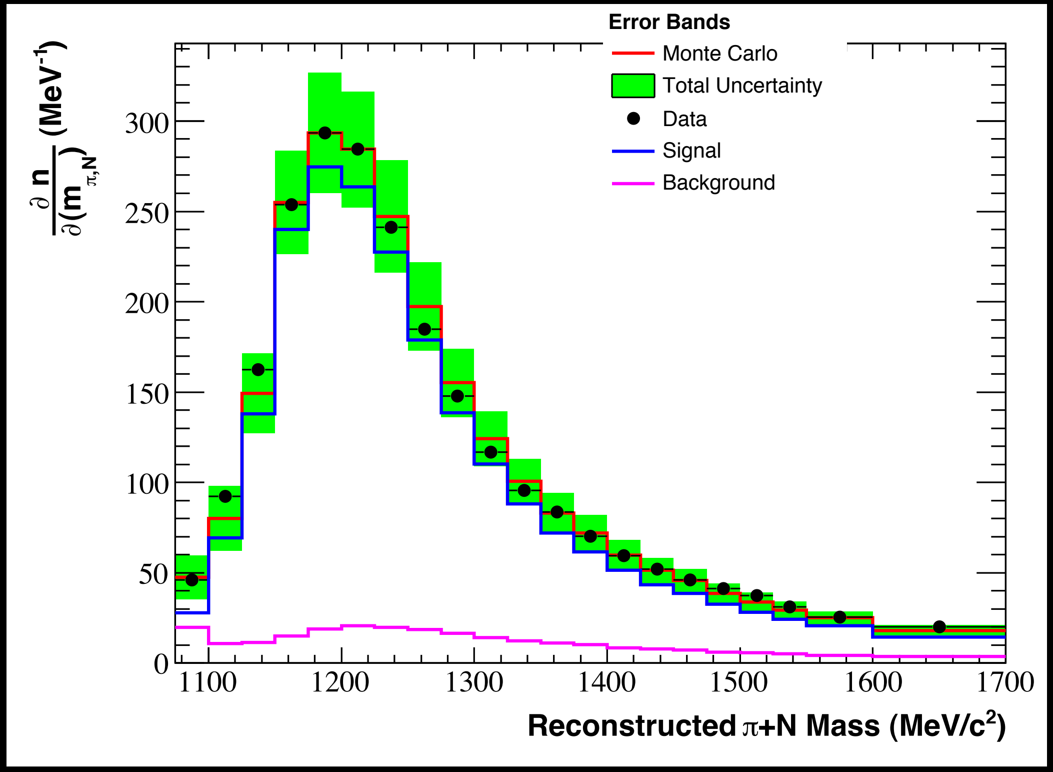
Charged-current π^+ production

- Second-largest interaction channel at MiniBooNE
- Can proceed via resonance $\nu + N \rightarrow \mu + \Delta \rightarrow \mu + N' + \pi^+$ or by coherent nuclear scatter.
- Identified by observation of *two* stopped muon decays after primary event. Unique signature results in purest exclusive sample in MiniBooNE
- Pion reconstruction and μ/π separation are challenging.

Cherenkov ring shapes: π^+

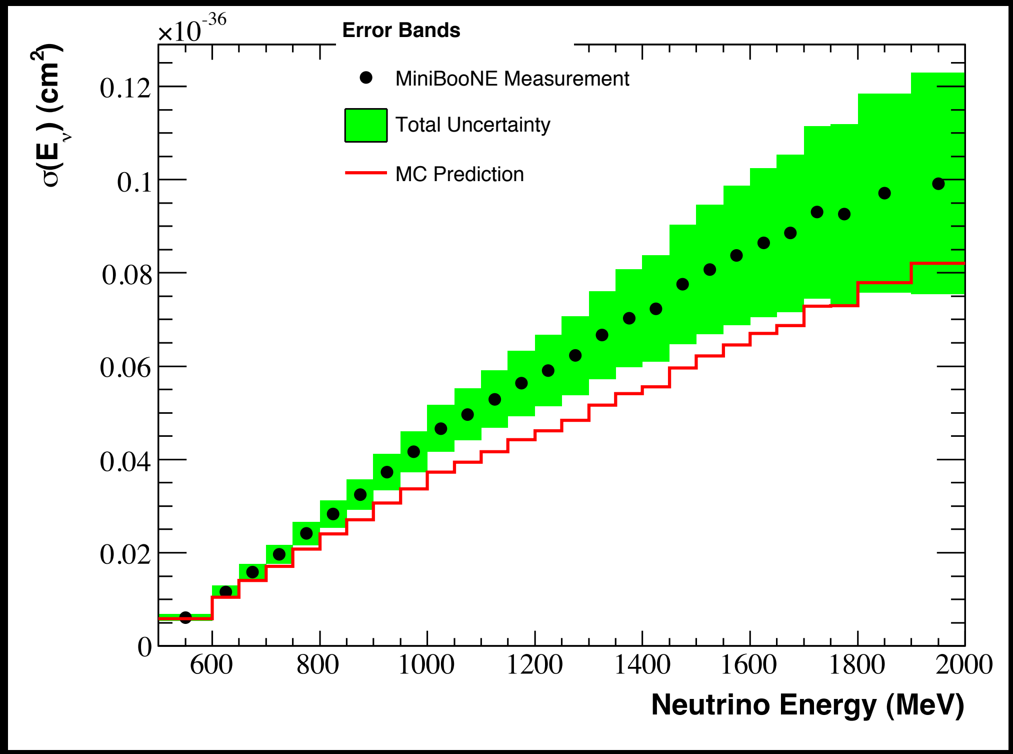
- Pions occasionally interact hadronically, losing energy and changing direction sharply.
- Kinked track produces two rings: a "doughnut" and a "doughnut hole."
- Pion reconstruction fitter developed to searched for the kinked track
- Likelihood identifies the pion
- ~90% purity, ~67,000 events.
- Reconstruction of muon and pion allows Δ mass to be calculated

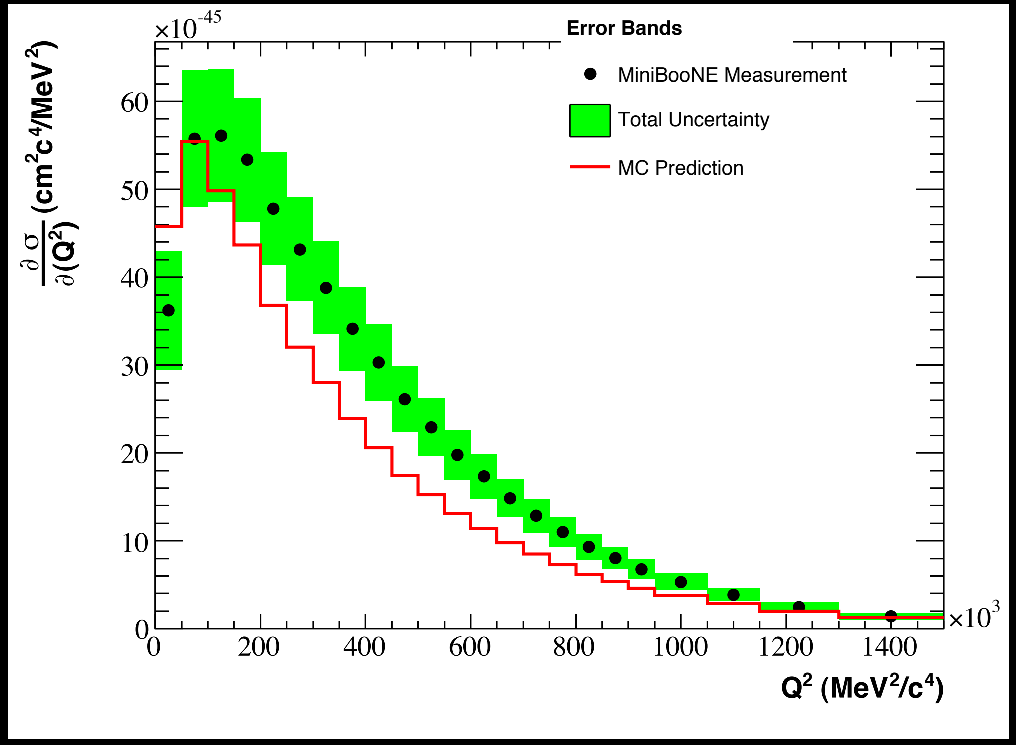




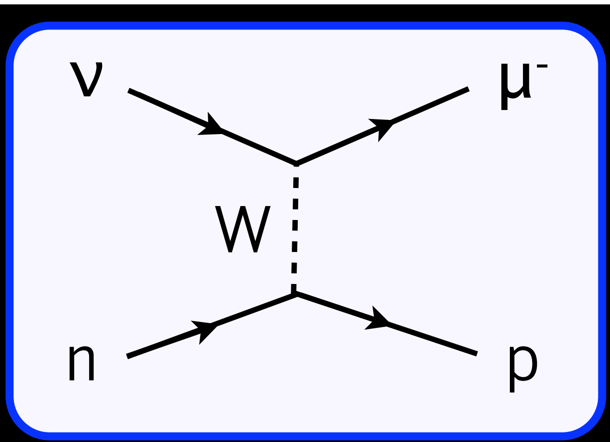
Measured observable charged-current π^+ cross-sections

- Differential cross sections (flux averaged):
  - $d\sigma/dQ^2$, $d\sigma/dE_\mu$, $d\sigma/d\cos\theta_\mu$, $d\sigma/d(E_\pi)$, $d\sigma/d\cos\theta_\pi$:
- Double Differential Cross Sections
  - $d^2\sigma/dE_\mu d\cos\theta_\mu$, $d^2\sigma/dE_\pi d\cos\theta_\pi$
- Data Q^2 shape differs from the model
- Submitted to PRD. e-print: 1011.3572[hep-ex]





Charged-current quasielastic scattering (CCQE)

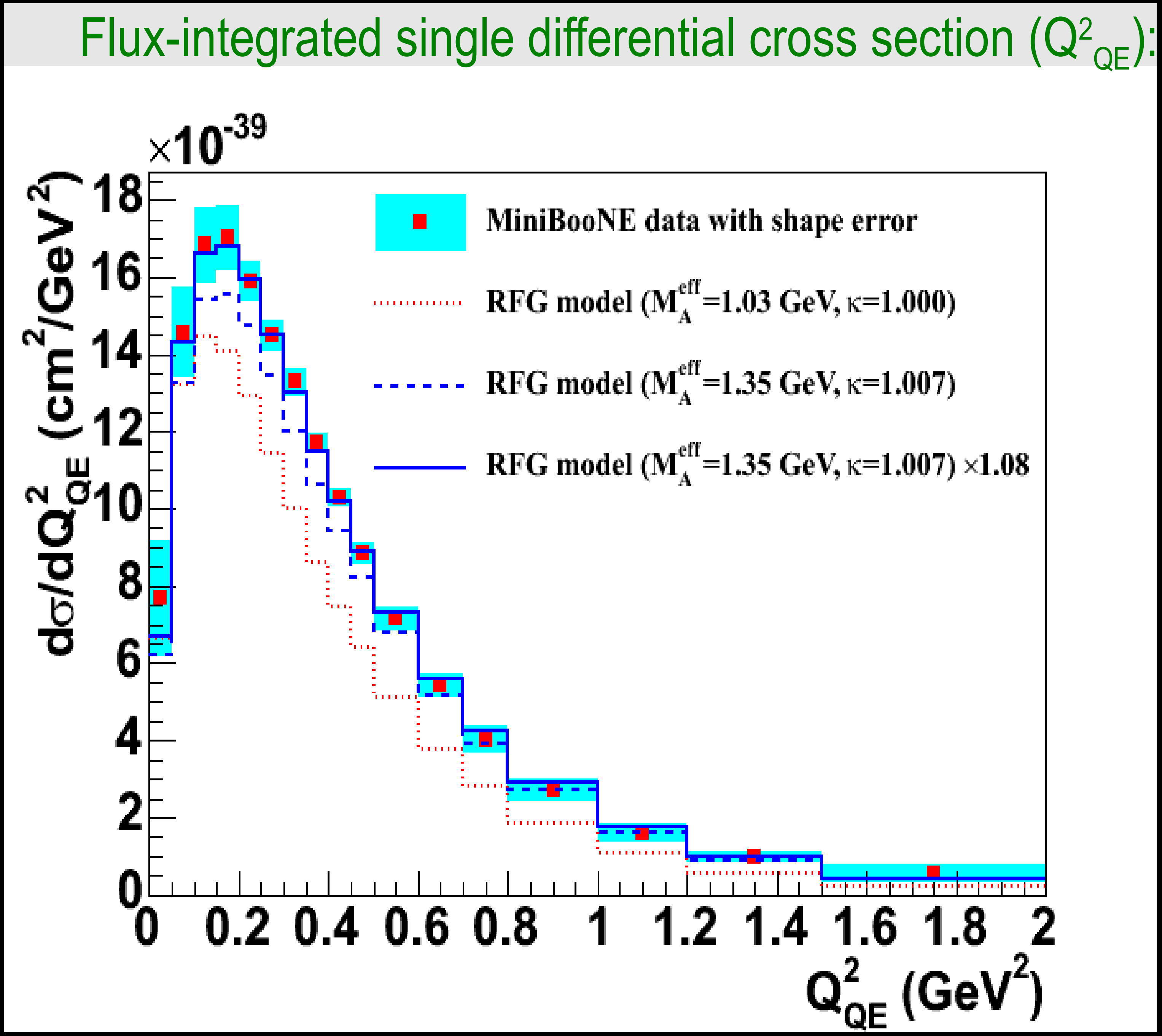


- Lepton vertex well understood
- Nucleon vertex parametrized with 2 vector form factors $F_{1,2}$ and one axial vector form factor F_A
- Use relativistic Fermi gas model of nucleus; $F_{1,2}$ come from electron scattering measurements
- Generally assume dipole form of F_A; only parameter is axial mass m_A extracted from neutrino-deuterium scattering experiments: 2002 average $M_A = 1.026 \pm 0.021$ GeV

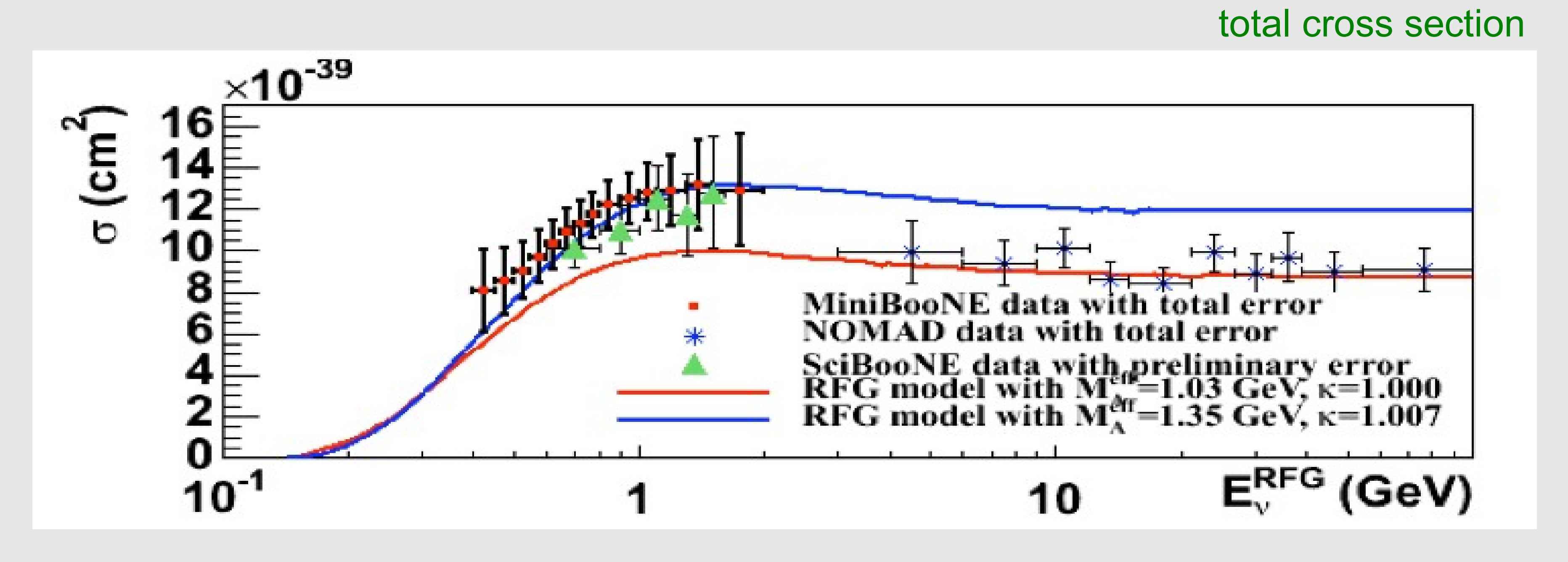
$$F_A(Q^2) = -\frac{g_A}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}$$

CCQE fit results: Q^2 dependence

- Data are compared (absolutely) with CCQE (RFG) model with various parameter values
- We prefer larger m_A compared to D_2 data
- Our CCQE cross-section is 30% above the world-averaged CCQE model (red).
- Model with CCQE parameters extracted from shape-only fit agrees well with over normalization (to within normalization error).



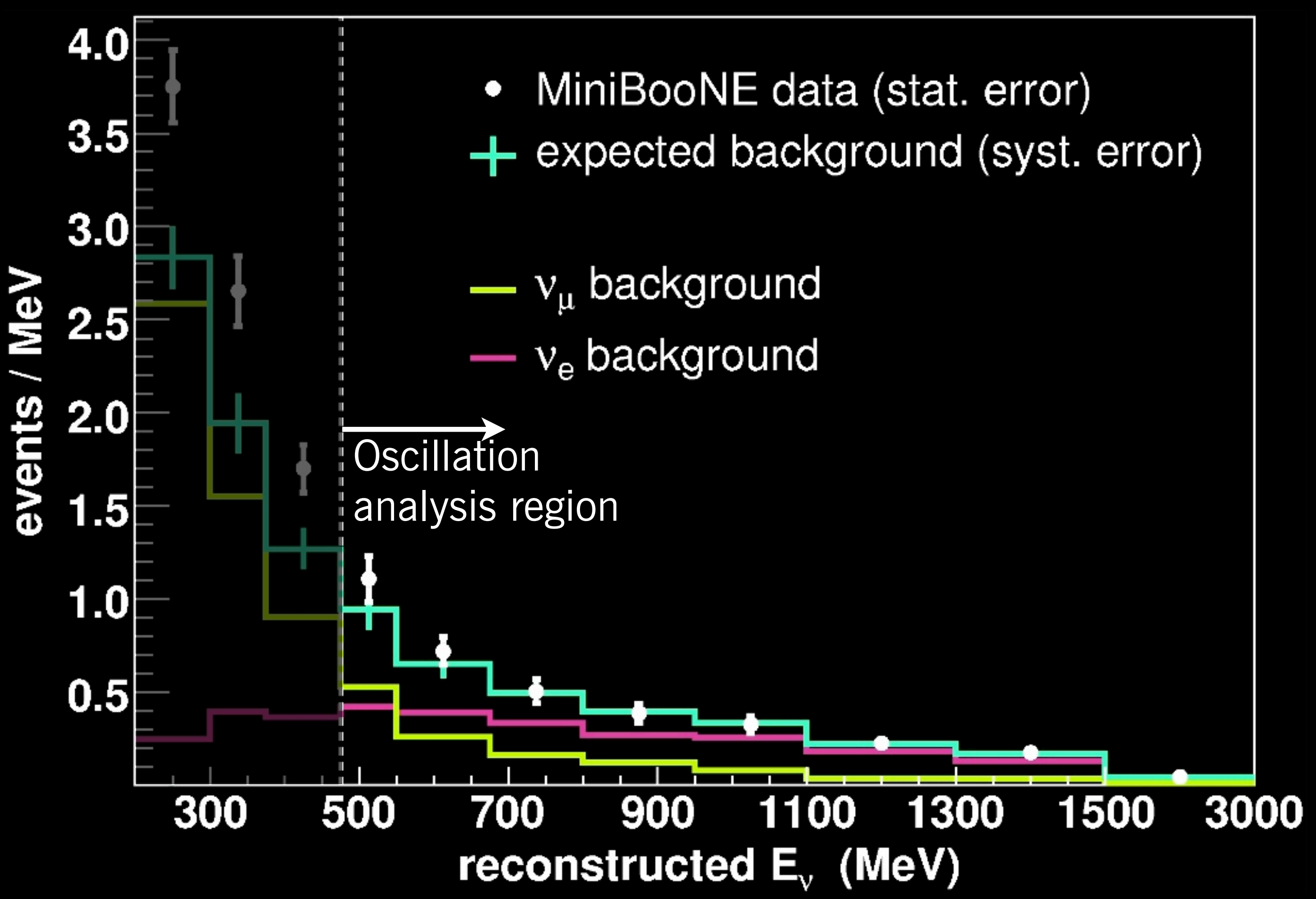
Comparisons to other experiments (carbon targets)



- Our data (and SciBooNE) appear to prefer higher M_A than NOMAD, but the disagreement is not very significant.
- Note that:
  - Our errors are systematic-dominated and grow at highest energies
  - NOMAD allowed maximum of two tracks in event: in principle, different processes may contribute to the two experiments' samples
- Possible explanation for higher M_A: two-nucleon correlations: Martini *et al.*, PRC 80, 065501 (2009)

Neutrino Oscillations: 2007 result

- Search for nu_e appearance in the detector using quasielastic scattering candidates
- Sensitivity to LSND-type oscillations is strongest in 475 MeV < E < 1250 MeV range
- Data consistent with background in oscillation fit range
- Significant excess at lower energies: source unknown, consistent experimentally with either ν_e or single photon production

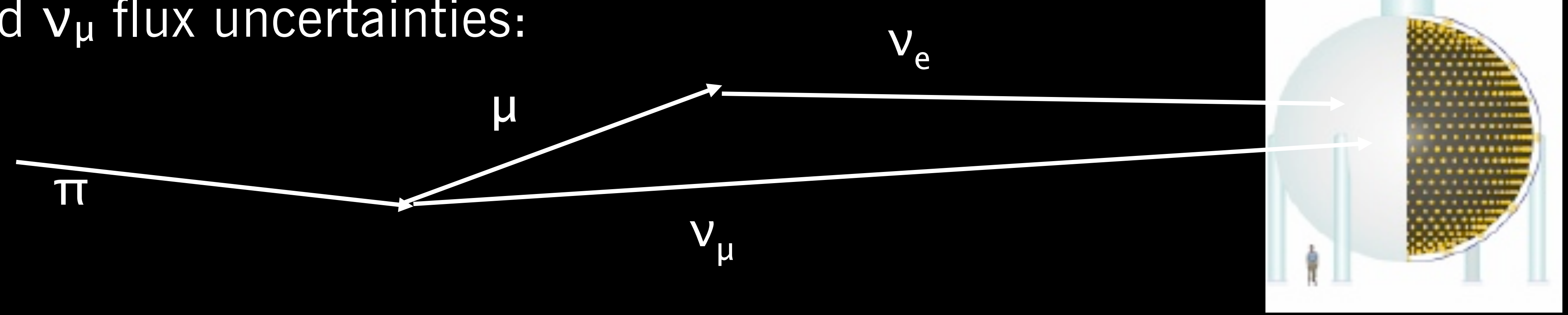


Antineutrino Oscillations

- LSND was primarily an antineutrino oscillation search; need to verify with antineutrinos as well due to potential *CP*-violating explanations
- Now have same number of protons on target in antineutrino vs. neutrino mode, but...
  - Antineutrino oscillation search suffers from lower statistics than in neutrino mode due to lower production and interaction cross-sections
  - Also, considerable neutrino contamination $(20\pm5)\%$ in antineutrino event sample

Oscillation Fit Method

- Simultaneous maximum likelihood fit to
  - $\bar{\nu}_e$ CCQE sample
  - High statistics $\bar{\nu}_\mu$ CCQE sample
- ν_μ CCQE sample constrains many of the uncertainties:
  - $\bar{\nu}_e$ and $\bar{\nu}_\mu$ flux uncertainties:



  - Cross section uncertainties (assume lepton universality)

Antineutrino oscillation search: background sources

- Background modes -- estimate before constraint from $\bar{\nu}_\mu$ data (constraint changes background by about 1%)

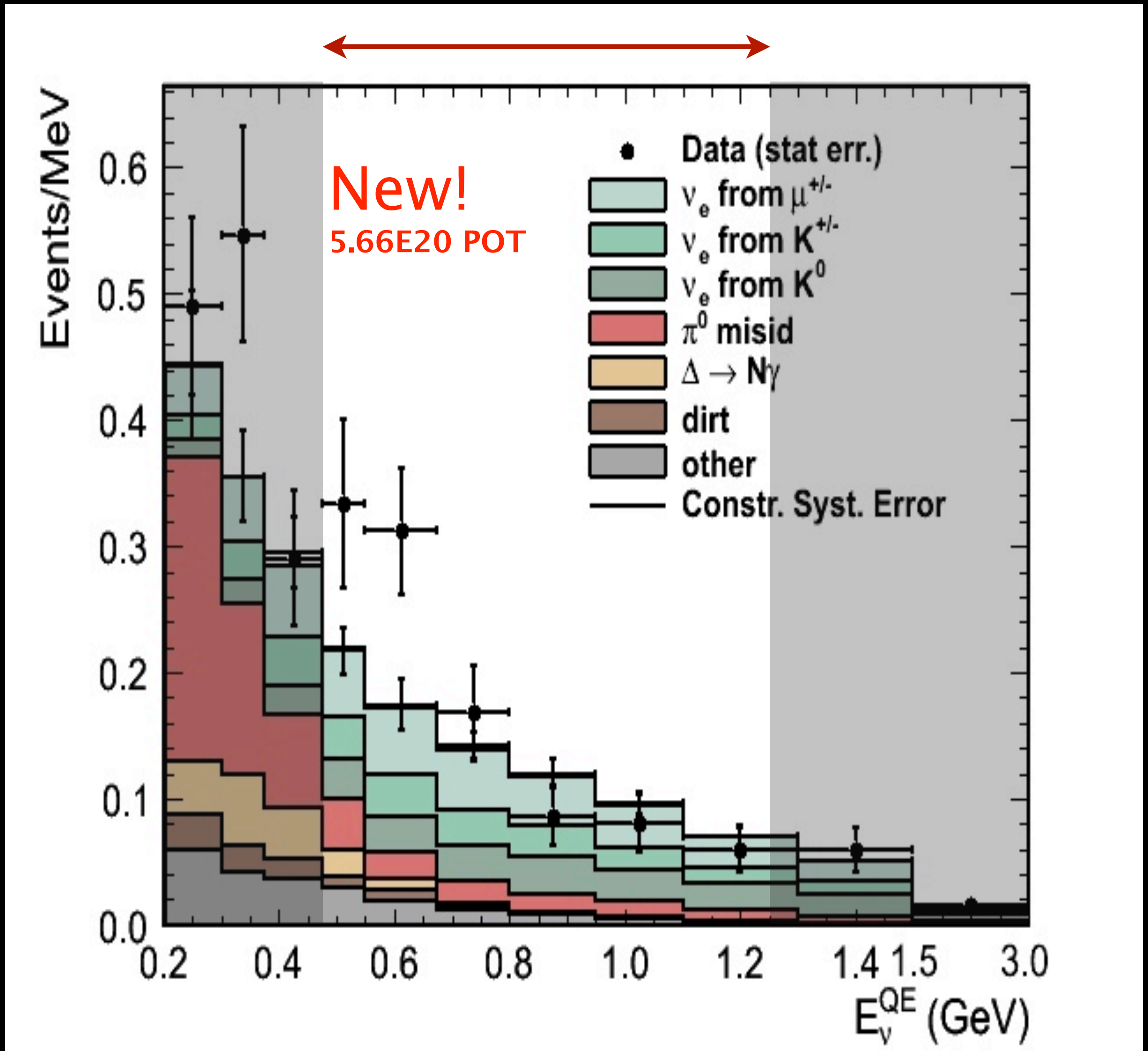
- Systematic error on background ≈10.5% (energy dependent)

Process	200 − 475 MeV	475 − 1250 MeV
$\overset{(-)}{\nu}_\mu$ CCQE	4.3	2.0
NC π^0	41.6	12.6
NC $\Delta \rightarrow N\gamma$	12.4	3.4
External Events	6.2	2.6
Other $\overset{(-)}{\nu}_\mu$	7.1	4.2
$\overset{(-)}{\nu}_e$ from $\mu^\pm$ Decay	13.5	31.4
$\overset{(-)}{\nu}_e$ from $K^\pm$ Decay	8.2	18.6
$\overset{(-)}{\nu}_e$ from K^0_L Decay	5.1	21.2
Other $\overset{(-)}{\nu}_e$	1.3	2.1
Total Background	99.5	98.1
0.26% $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	9.1	29.1

Data in antineutrino oscillation search

- 475 MeV < E < 1250 MeV:
  - 99.1±9.8(syst) expected after fit constraints
  - 120 observed
  - Raw "one-bin" counting excess significance is 1.5σ
- Also see small excess at low energy, consistent with neutrino mode excess if attributed to neutrino contamination in $\bar{\nu}$ beam

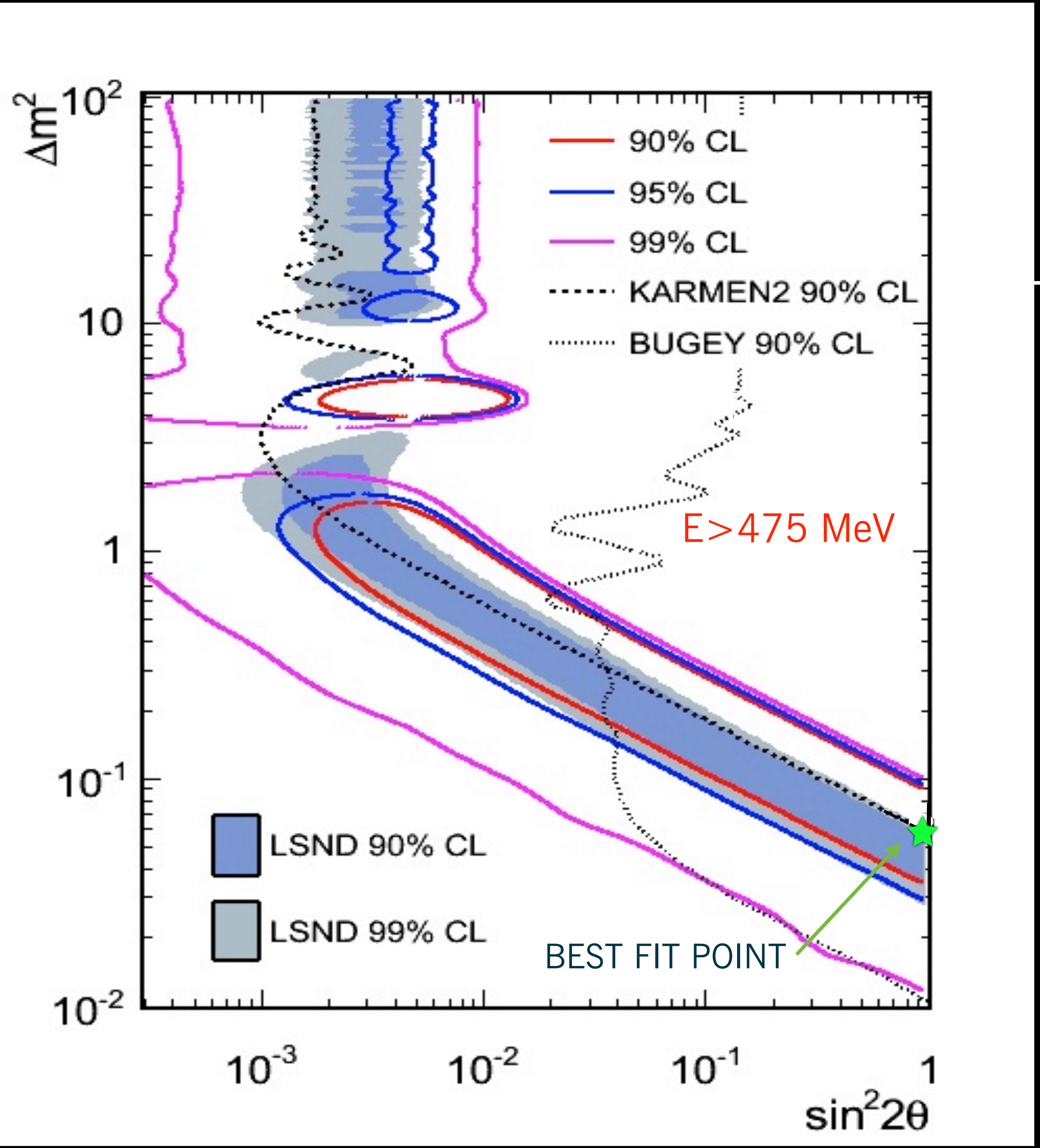
475-1250 MeV
oscillation-sensitive region



Electron antineutrino appearance oscillation results

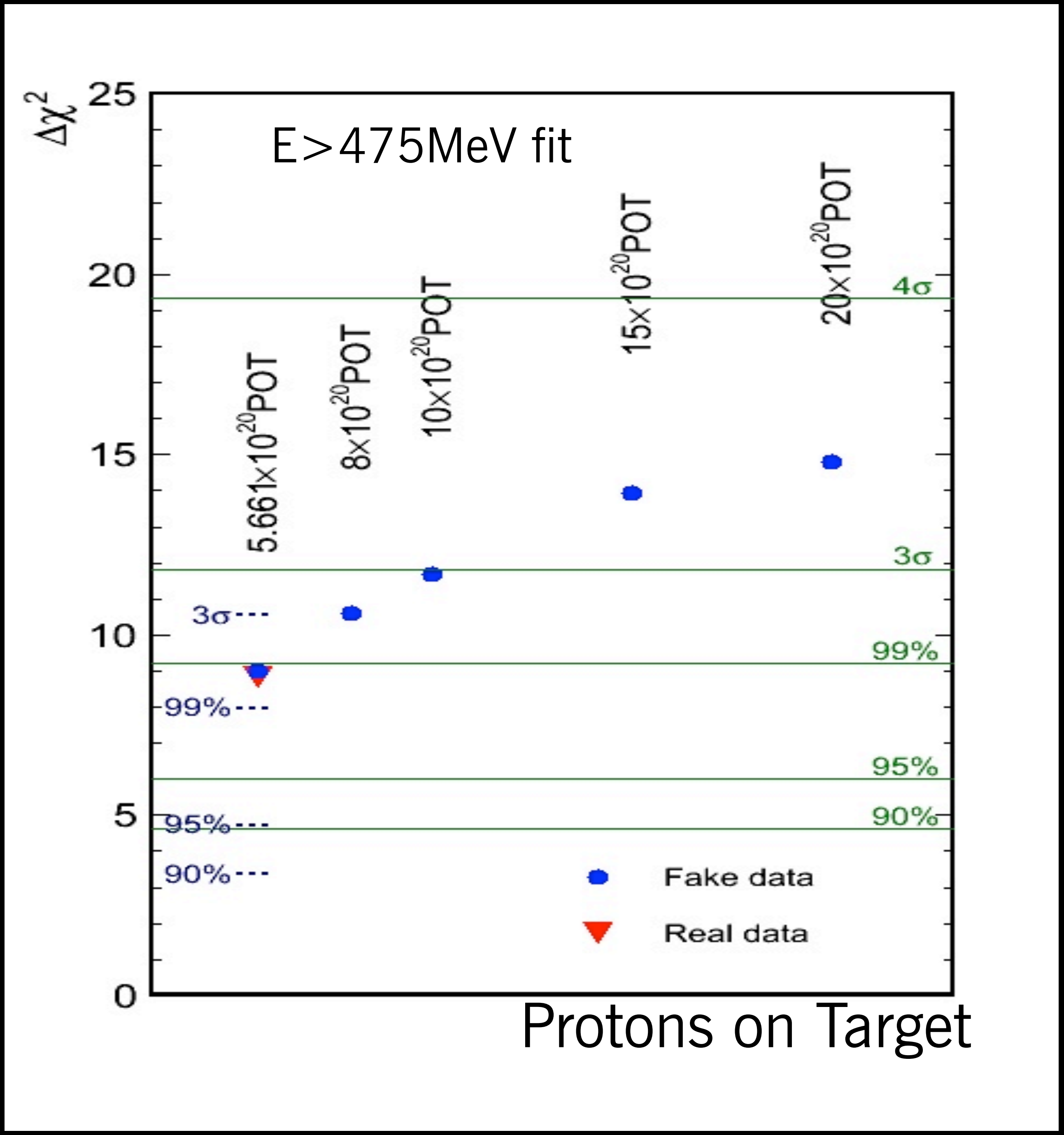
- Results for **5.66E20 POT**
- Maximum likelihood fit for *simple two-neutrino model*
- Oscillation hypothesis preferred to background-only at 99.4% confidence level.
- E>475 avoids question of low-energy excess in neutrino mode.
- Signal bins only:
  - $P_{\chi 2}$(null)= 0.5%
  - $P_{\chi 2}$(best fit)= ~10%

•*Phys. Rev. Lett. 105, 181801 (2010)*



Future sensitivity in $\bar{\nu}$ data

- MiniBooNE has requested a total of 1.5×10^{21} POT in antineutrino mode
- Potential 3σ+ significance assuming best fit signal
- Systematics limit approaches above 2×10^{21} POT
- This run has recently been approved by PAC.



Conclusions

- Cross-sections:
  - MiniBooNE has most precise measurements of top five interaction modes on carbon; only differential and double-differential cross-sections in some modes
  - Some disagreements with most common nuclear models?
- Oscillation searches
  - Significant ν_e and $\bar{\nu}_e$ excesses above background are emerging in both neutrino mode and antineutrino mode in MiniBooNE
  - The two modes do not appear to be consistent with a simple two-flavor neutrino model
  - Antineutrino results still heavily statistics-limited; MiniBooNE plans to accumulate more data until the goal of 1.5×10^{21} protons on target is reached