SHORT-BASELINE NEUTRINO PHYSICS AT MiniBooNE

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Short-Baseline Neutrino Physics at MiniBooNE

- MiniBooNE
- Neutrino cross-sections
  - Hadron production channels
- Oscillation physics
  - Antineutrino Oscillations
  - MiniBooNE-SciBooNE joint result

Motivating MiniBooNE: LSND
Liquid Scintillator Neutrino Detector

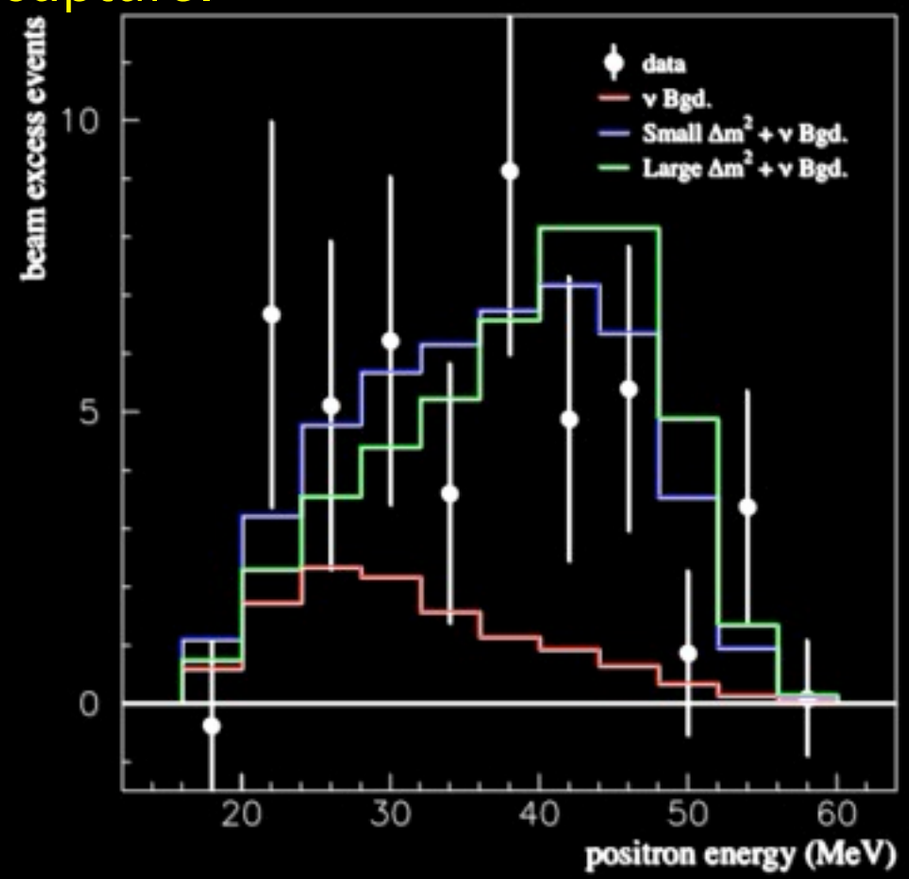
- Stopped π^+ beam at Los Alamos LAMPF produces ν_e, ν_μ, $\overline{\nu}_\mu$ but no $\overline{\nu}_e$ (due to π^- capture).

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

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

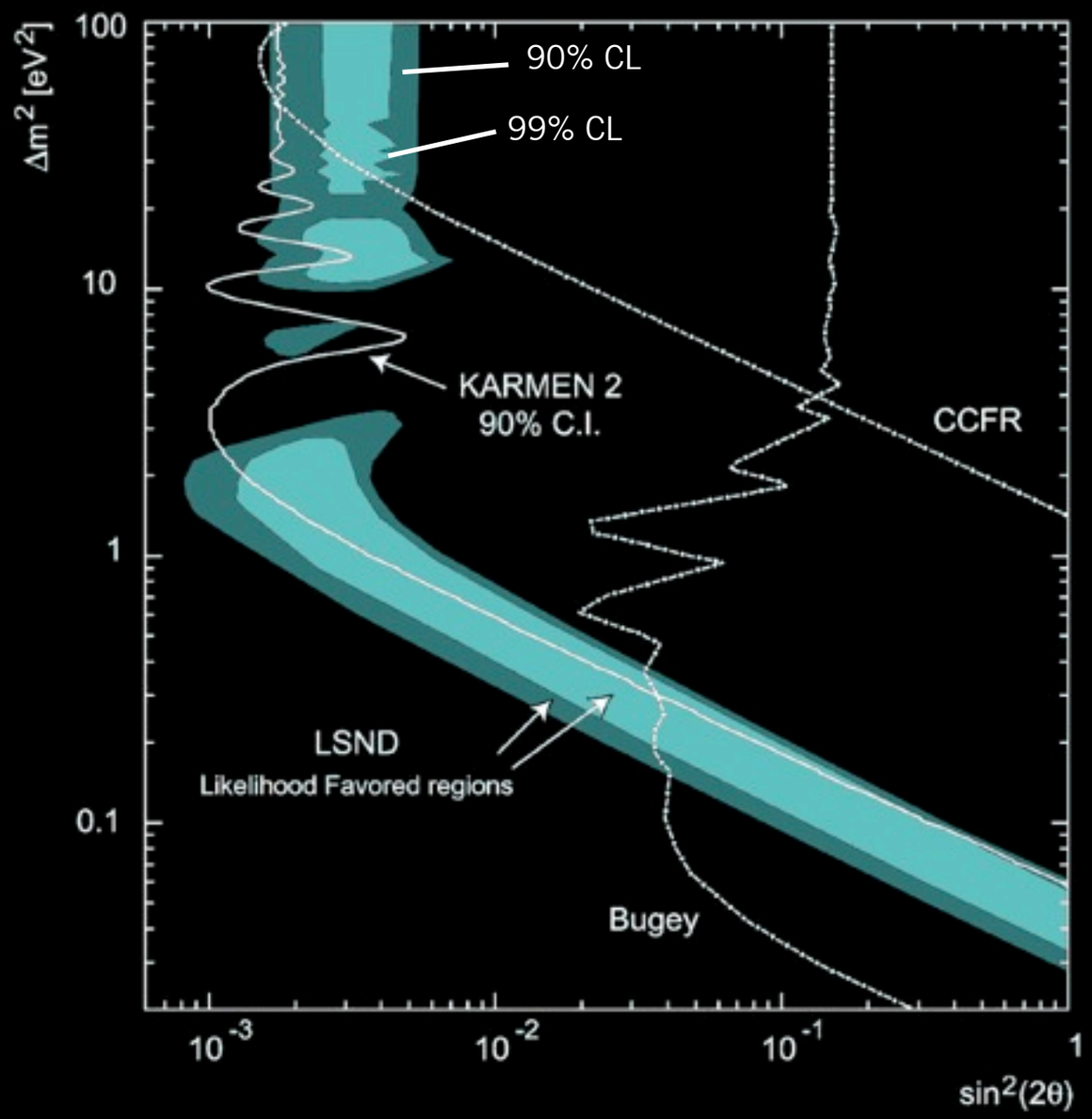
- Look for delayed coincidence of positron and neutron capture.
- Major background non-beam (measured, subtracted)
- 3.8 standard dev. excess above background.
- Oscillation probability:

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



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

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!
- Current ideas out there:
  - An experiment or two is wrong
  - Sterile neutrino sector: extra masses and mixing angles

MiniBooNE: E898 at Fermilab

- Purpose is to test LSND with:
  - Higher energy
  - Different beam
  - Different oscillation signature
  - Different systematic effects
- 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

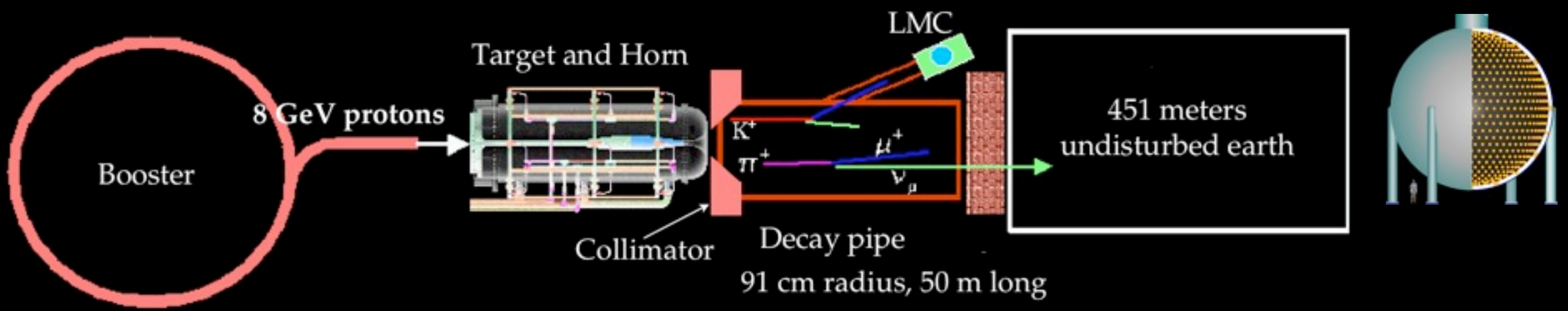
    $\pi \rightarrow \mu \rightarrow \nu_e$ in beam

    $K^+ \rightarrow \pi^0 e^+ \nu_e$, $K^0_L \rightarrow \pi^0 e^\pm \nu_e$ in beam
  - Particle misidentification in detector

    Neutral current resonance:

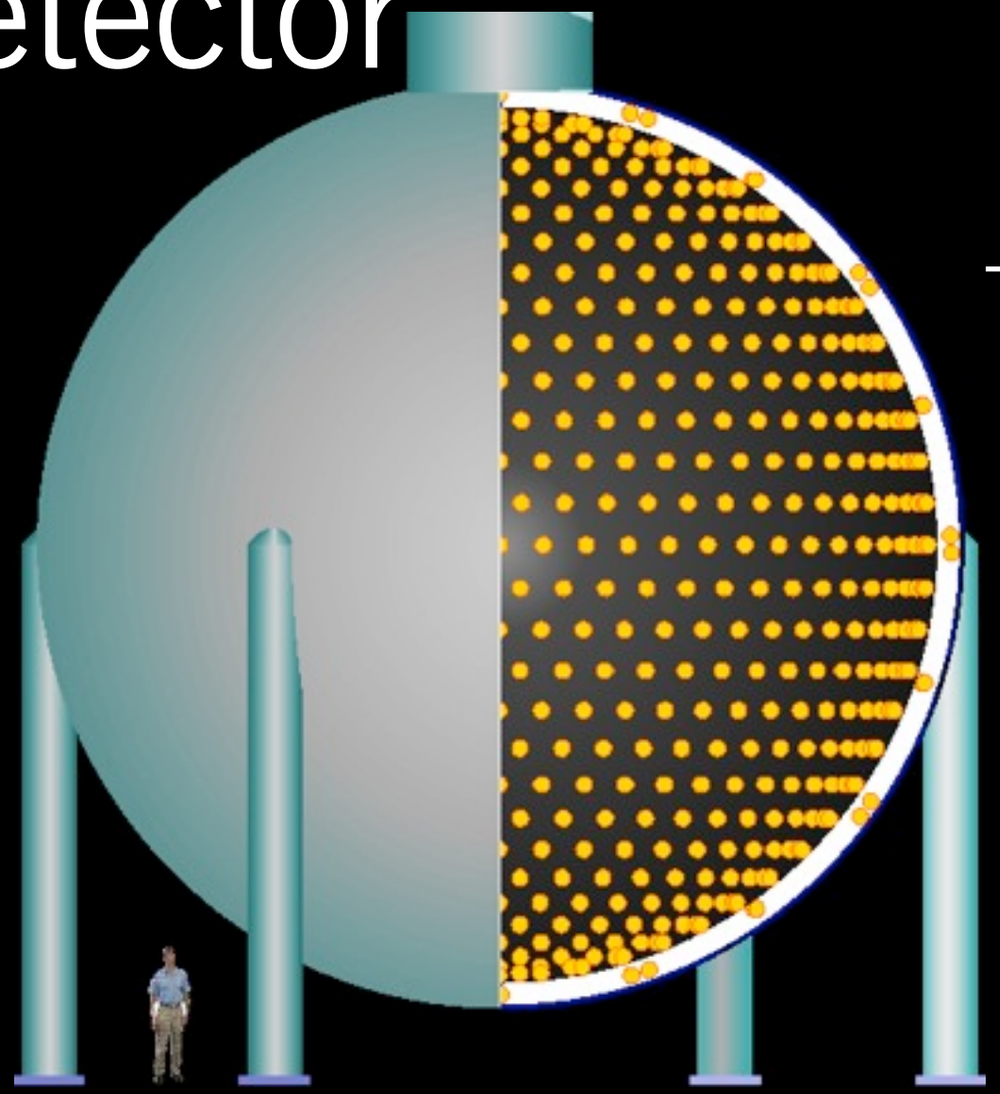
    $\Delta \rightarrow \pi^0 \rightarrow \gamma\gamma$ or $\Delta \rightarrow n\gamma$, mis-ID as e

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

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 for SciBooNE)
- Present analyses use:
  - ≥5.7E20 protons on target for neutrino analyses
  - 5.66⇒**8.58**E20 protons on target for antineutrino analyses **(Updated on data collected up to May 2011)**
  - Over one million neutrino interactions recorded: by far the largest data set in this energy range

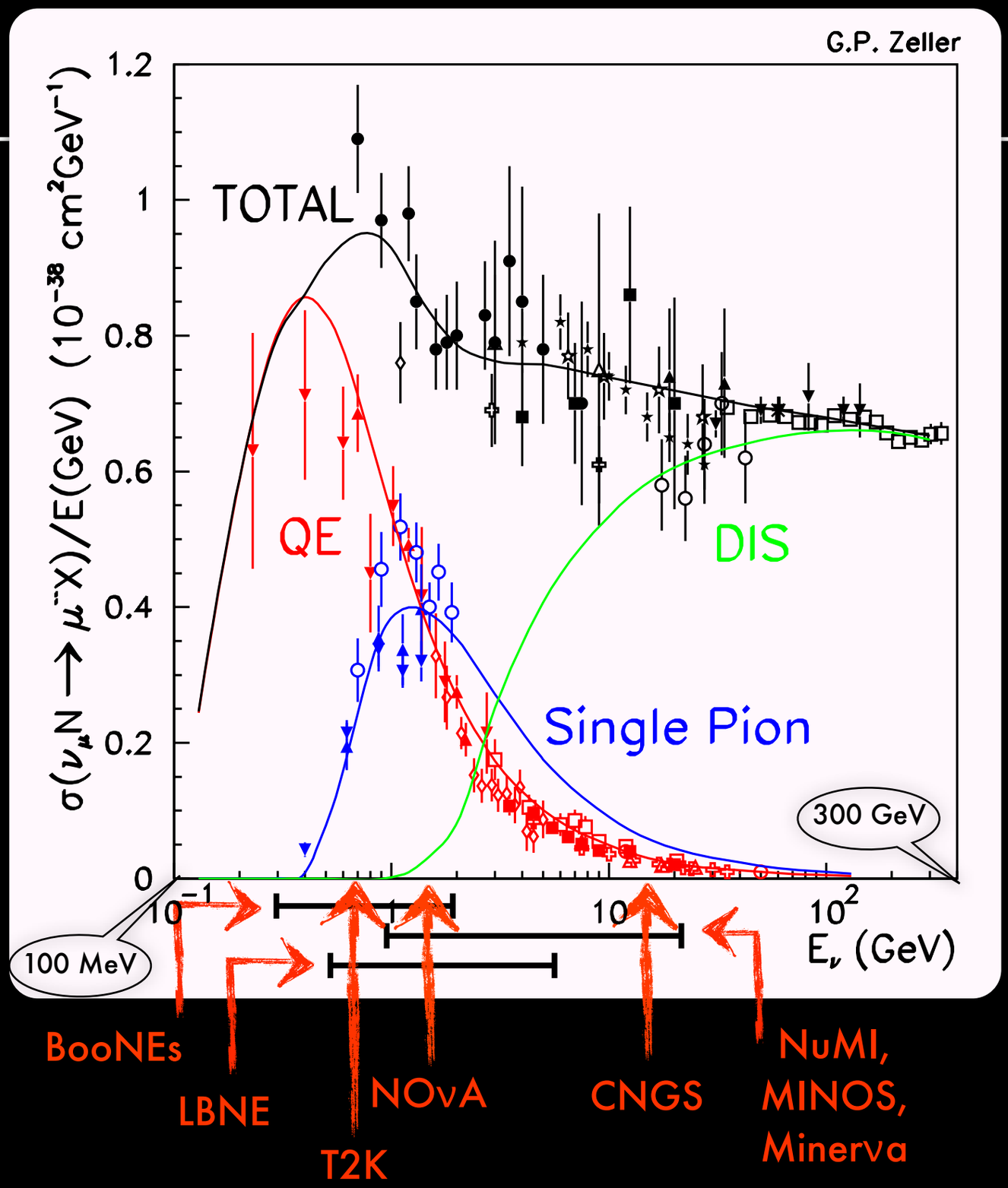
Neutrino scattering cross-sections

- 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!)

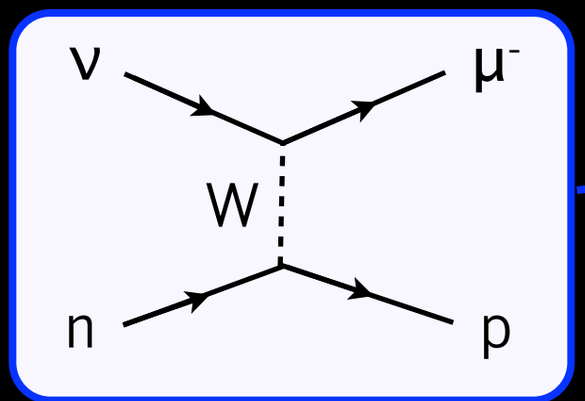
Scattering cross-sections for ν_μ

- 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.

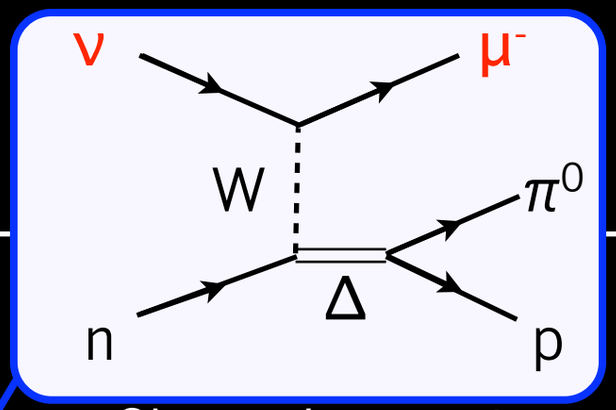
The state of knowledge of ν_μ interactions before the current generation of experiments:



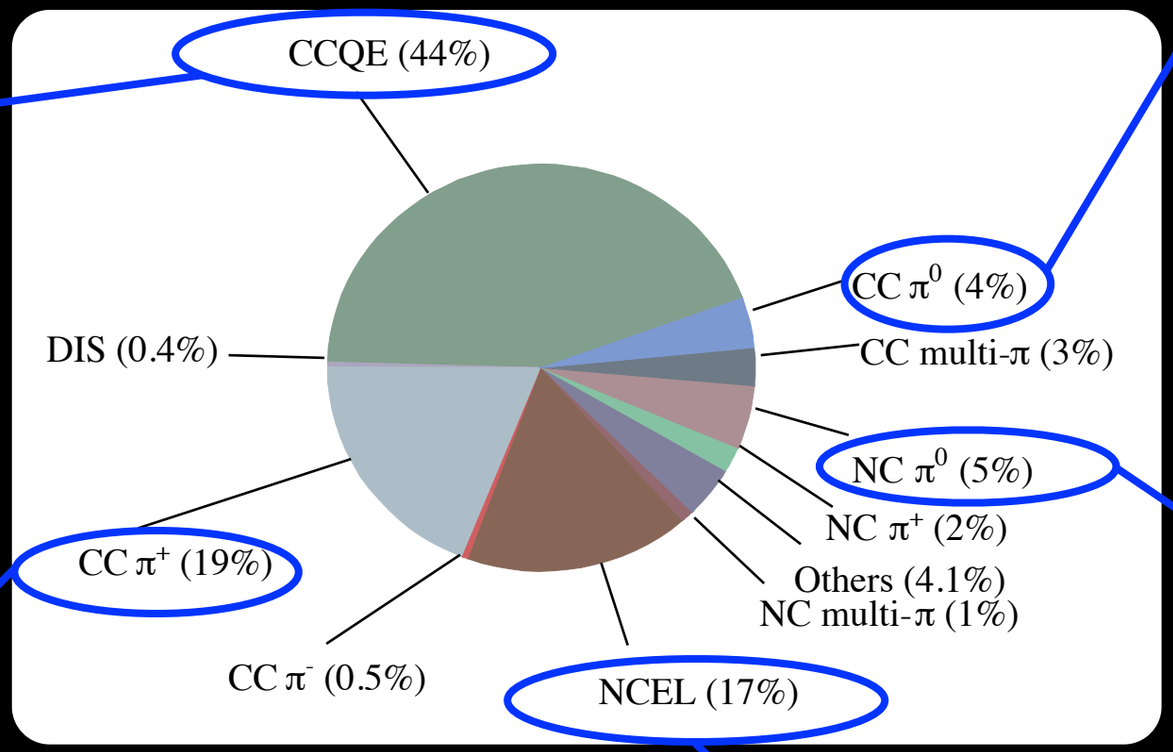
Dominant interaction channels at MiniBooNE

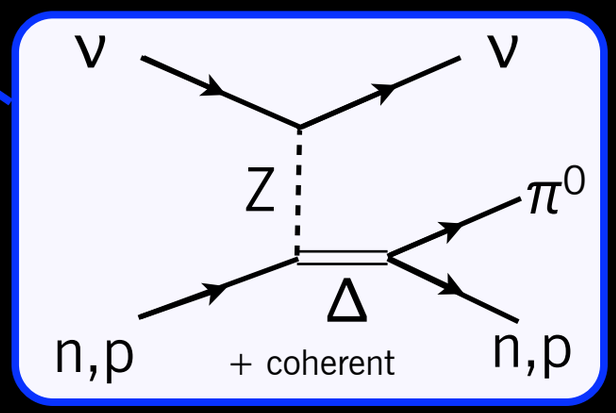


Charged-current quasielastic



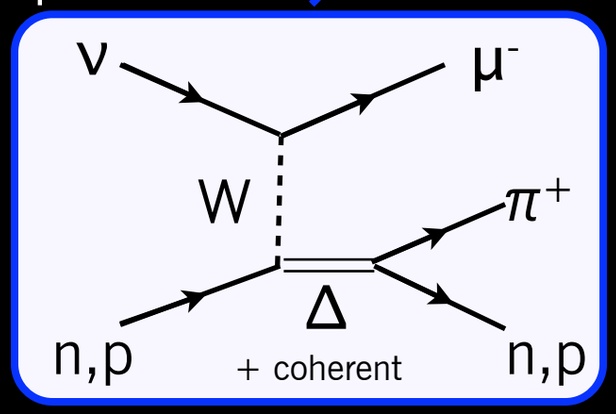
Charged-current π^0 production

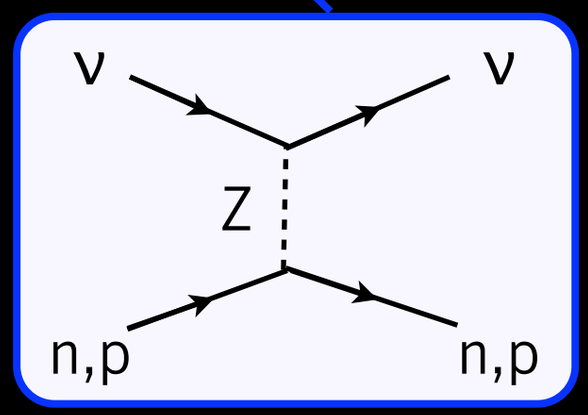




Neutral-current π^0 production

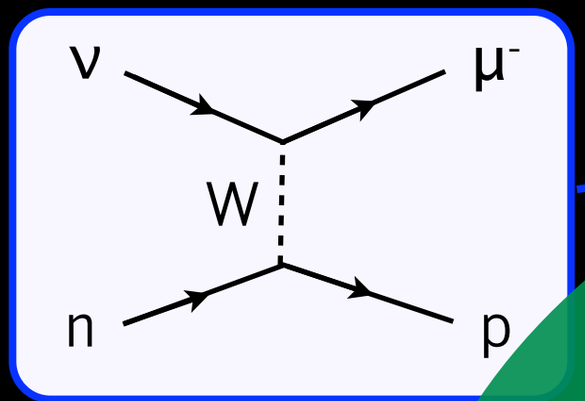
Charged-current π^+ production



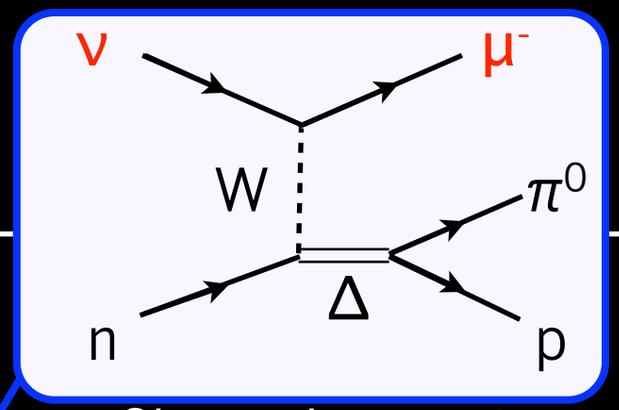


Neutral-current elastic

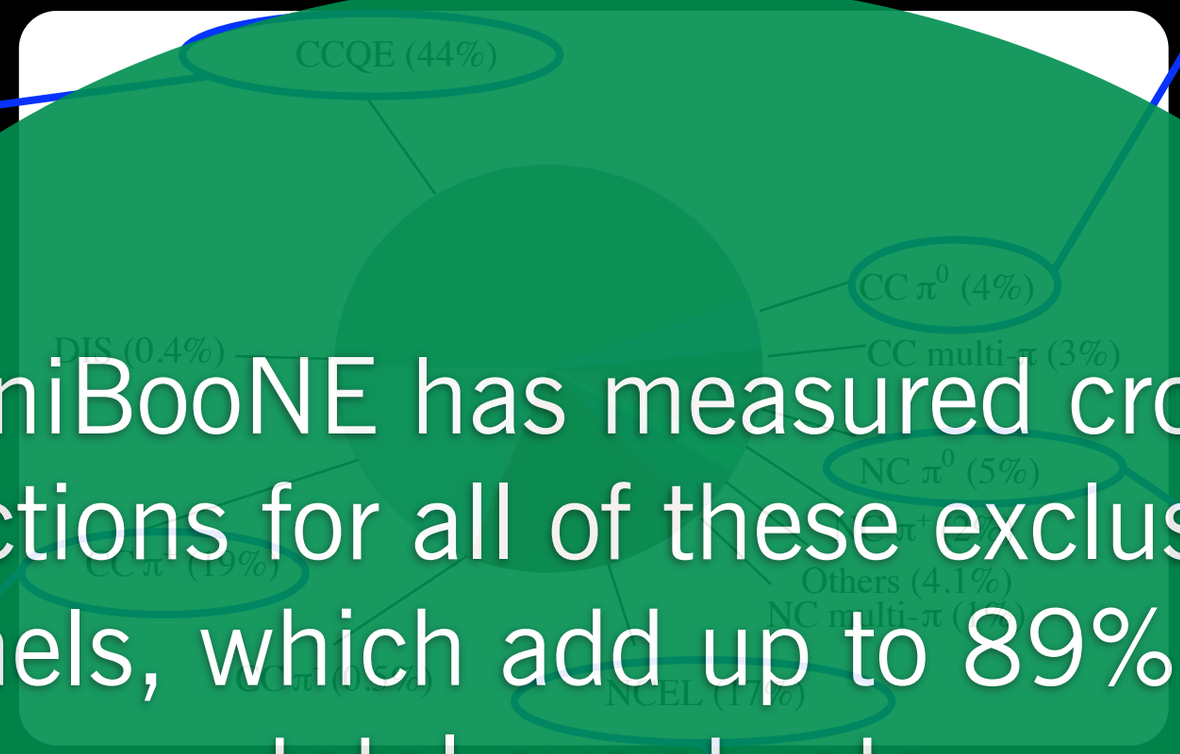
Dominant interaction channels at MiniBooNE



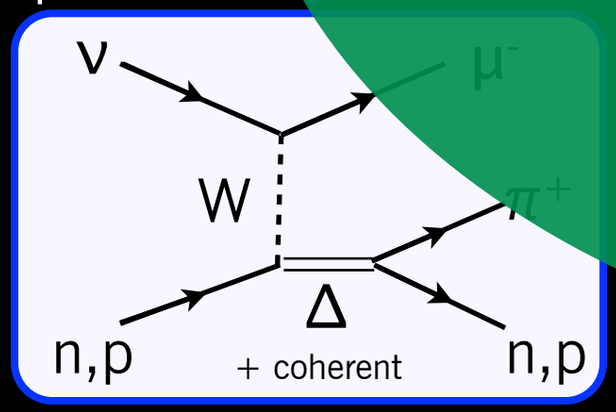
Charged-current quasielastic



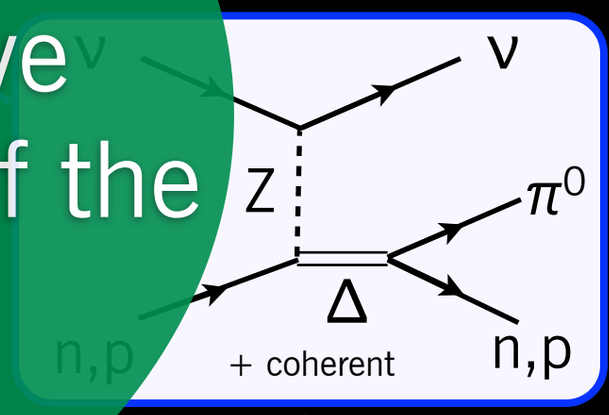
Charged-current π^0 production



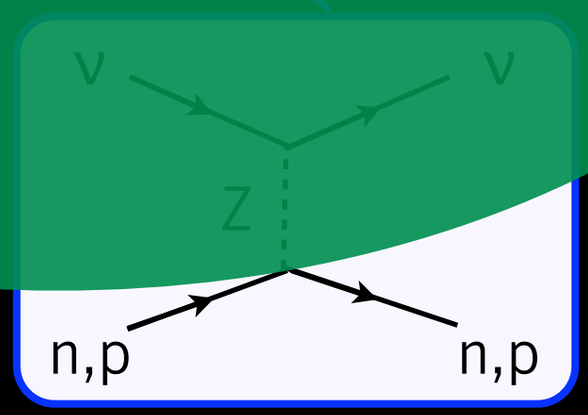
MiniBooNE has measured cross-sections for all of these exclusive channels, which add up to 89% of the total event rate



Charged-current π^+ production



Neutral-current π^0 production

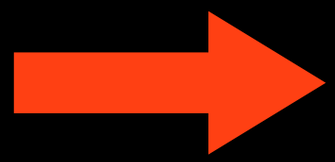


Neutral-current elastic

MiniBooNE cross-section measurements

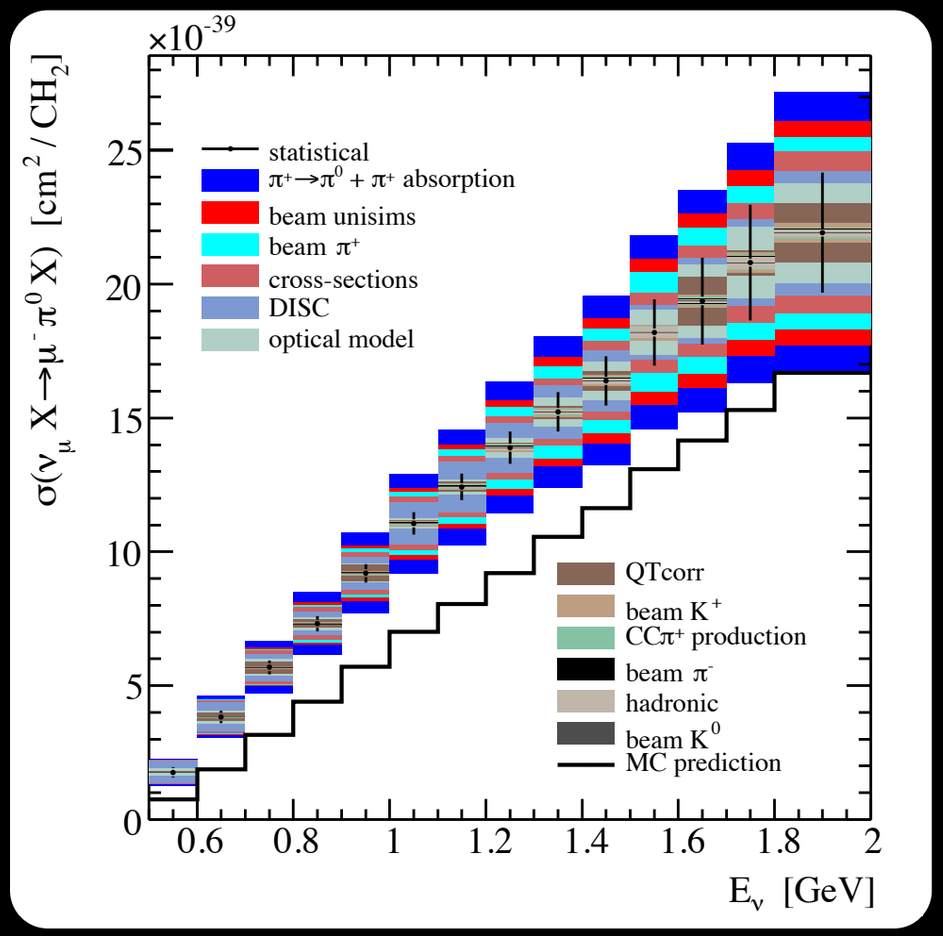
- ~~NC π^0~~
- CC π^0
- CC π^+
- ~~CC Quasielastic~~
- ~~NC Elastic~~
- ~~CC Inclusive~~

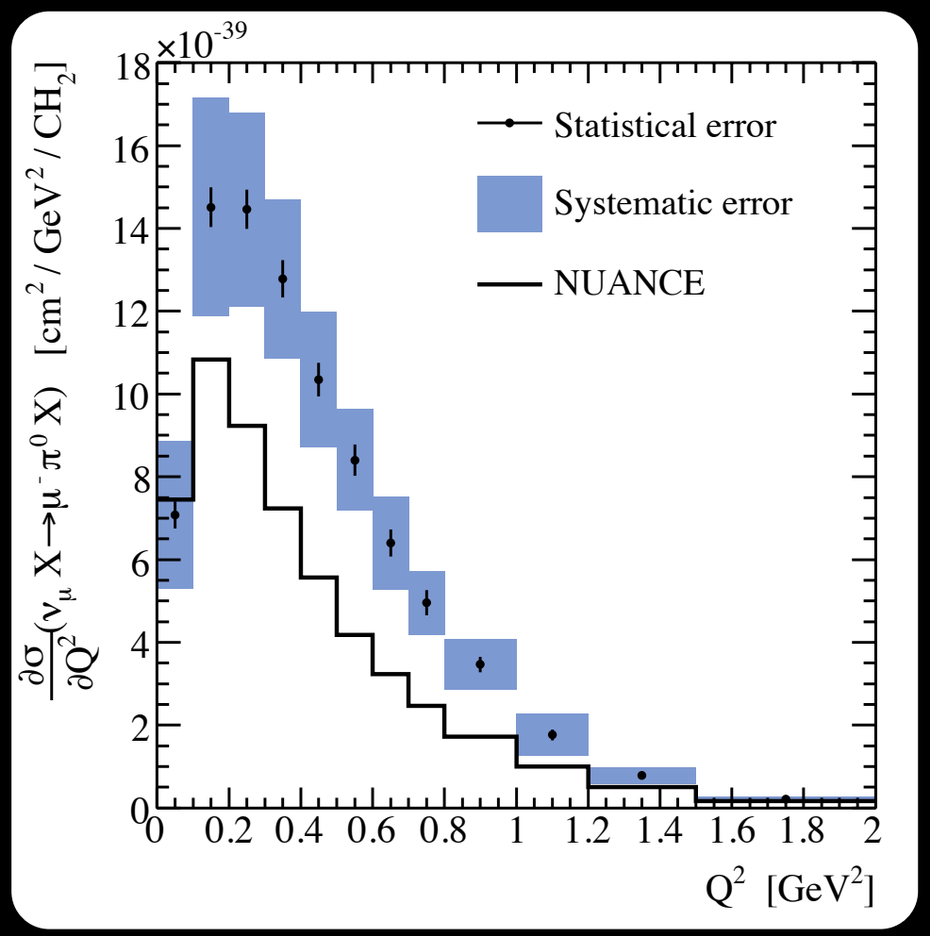
Due to limited time, only discussing a few topics here.



See plenary talk by G. Zeller

Measured observable CCπ^0 cross-section





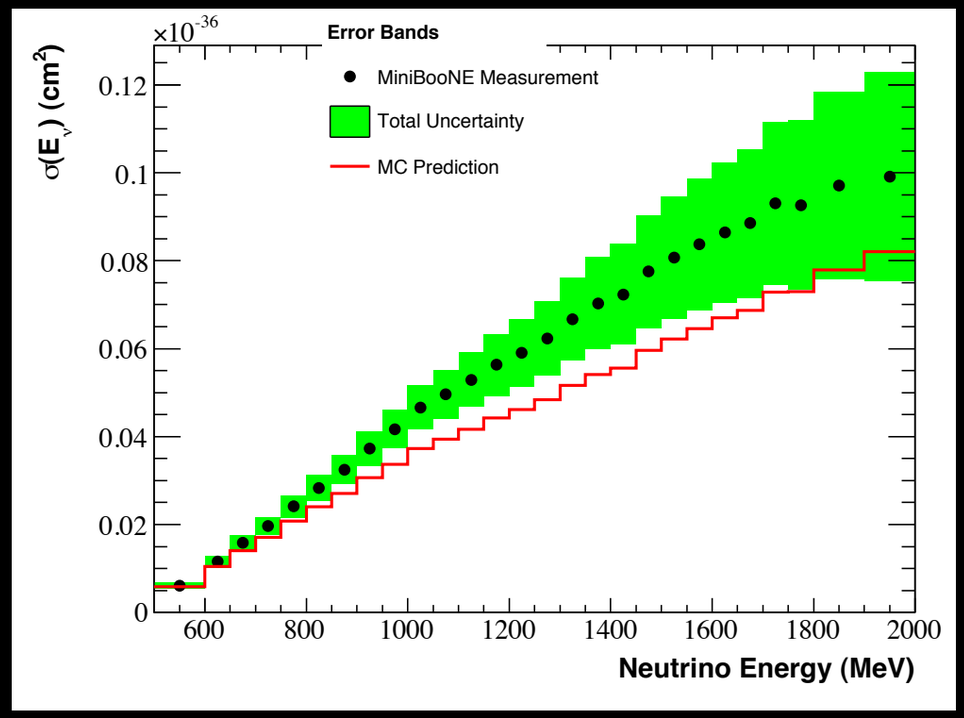
Additionally, we measure differential cross-sections vs:

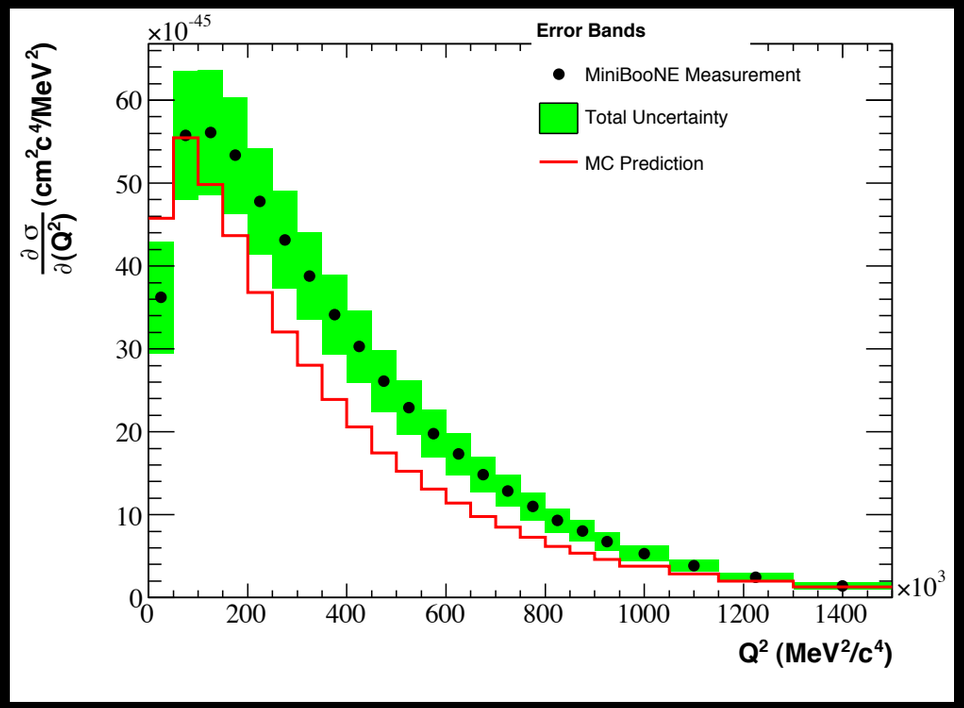
- θ_μ
- θ_π
- E_μ
- E_π

- 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.
- Phys.Rev.D83:052009,2011

Measured observable charged-current π^+ cross-sections

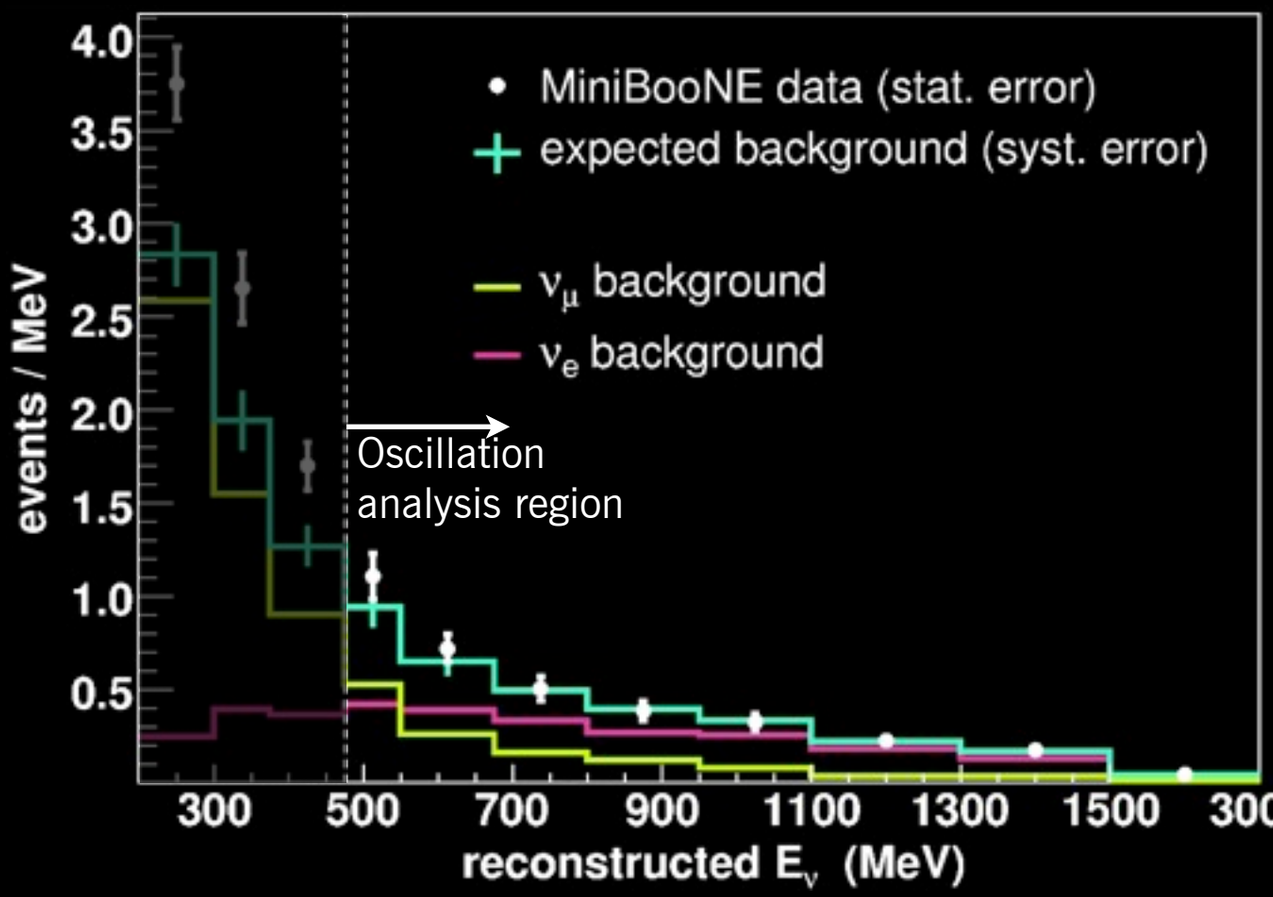
- Differential cross sections (flux averaged):
  - $d\sigma/dQ^2$, $d\sigma/dE_\mu$, $d\sigma/d\cos\theta_\mu$, $d\sigma/d(E_\pi)$, $d\sigma/d\cos\theta_\pi$:
- Double Differential Cross Sections
  - $d^2\sigma/dE_\mu d\cos\theta_\mu$, $d^2\sigma/dE_\pi d\cos\theta_\pi$
- Data Q^2 shape differs from the model
- Phys.Rev.D83:052007,2011.





Neutrino Oscillations: 2007 result

- Search for ν_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



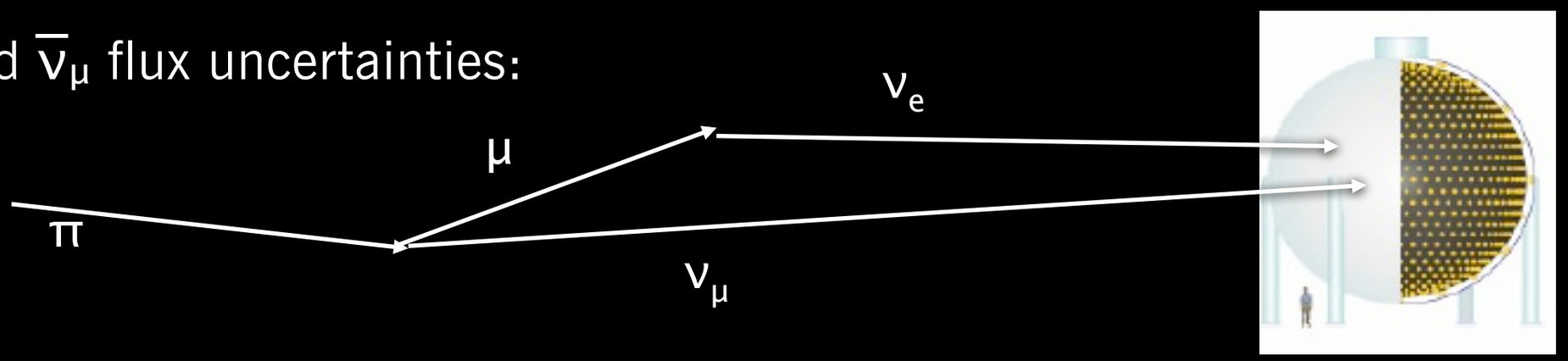
Oscillation search: *Phys.Rev.Lett*.**98**:231801 (2007)
Low-E excess: *Phys.Rev.Lett*.**102**:101802 (2009)

Antineutrino Oscillations

- LSND was primarily an antineutrino oscillation search; need to verify with antineutrinos as well due to potential *CP*-violating explanations
- Published analysis has 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 (22±5)% in antineutrino event sample (e-print 1102.1964 [hep-ex])

Oscillation Fit Method

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

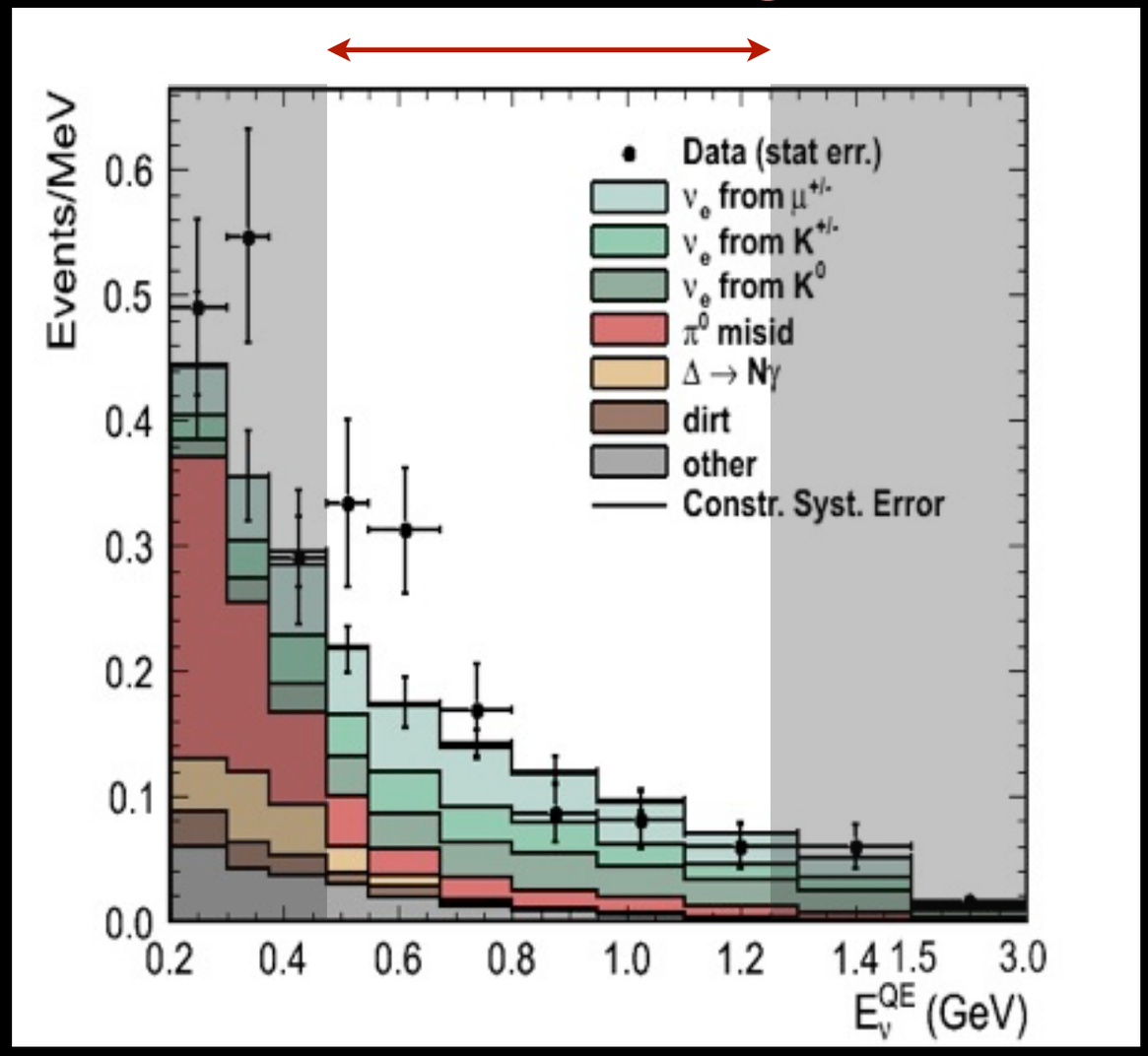


  - Cross section uncertainties (assume lepton universality)
- Background modes -- estimate before constraint from $\bar{\nu}_\mu$ data (constraint changes background by about 1%)
- Systematic error on background ≈10% (energy dependent)

Data in antineutrino oscillation search: published 5.66E20 POT

- 475 MeV < E < 1250 MeV:
  - 99.1±9.8(syst) expected after fit constraints
  - 120 observed; excess 20.9±13.9 (total)
  - Raw “one-bin” counting excess significance is 1.5σ
- Also saw small excess at low energy, consistent with neutrino mode excess if attributed to neutrino contamination in $\overline{\nu}$ beam

475-1250 MeV
oscillation-sensitive region

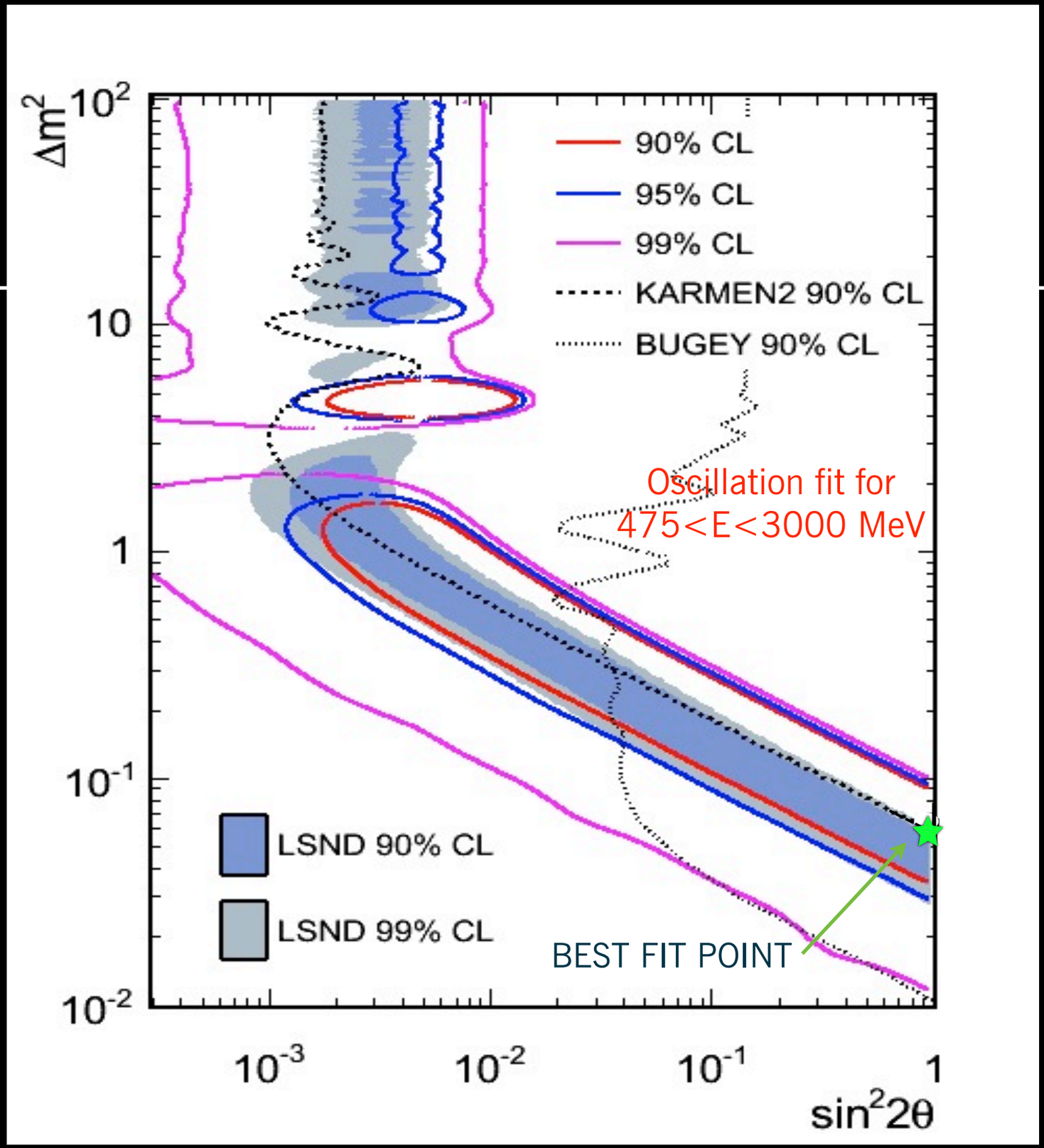


•*Phys. Rev. Lett. 105, 181801 (2010)*

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)*

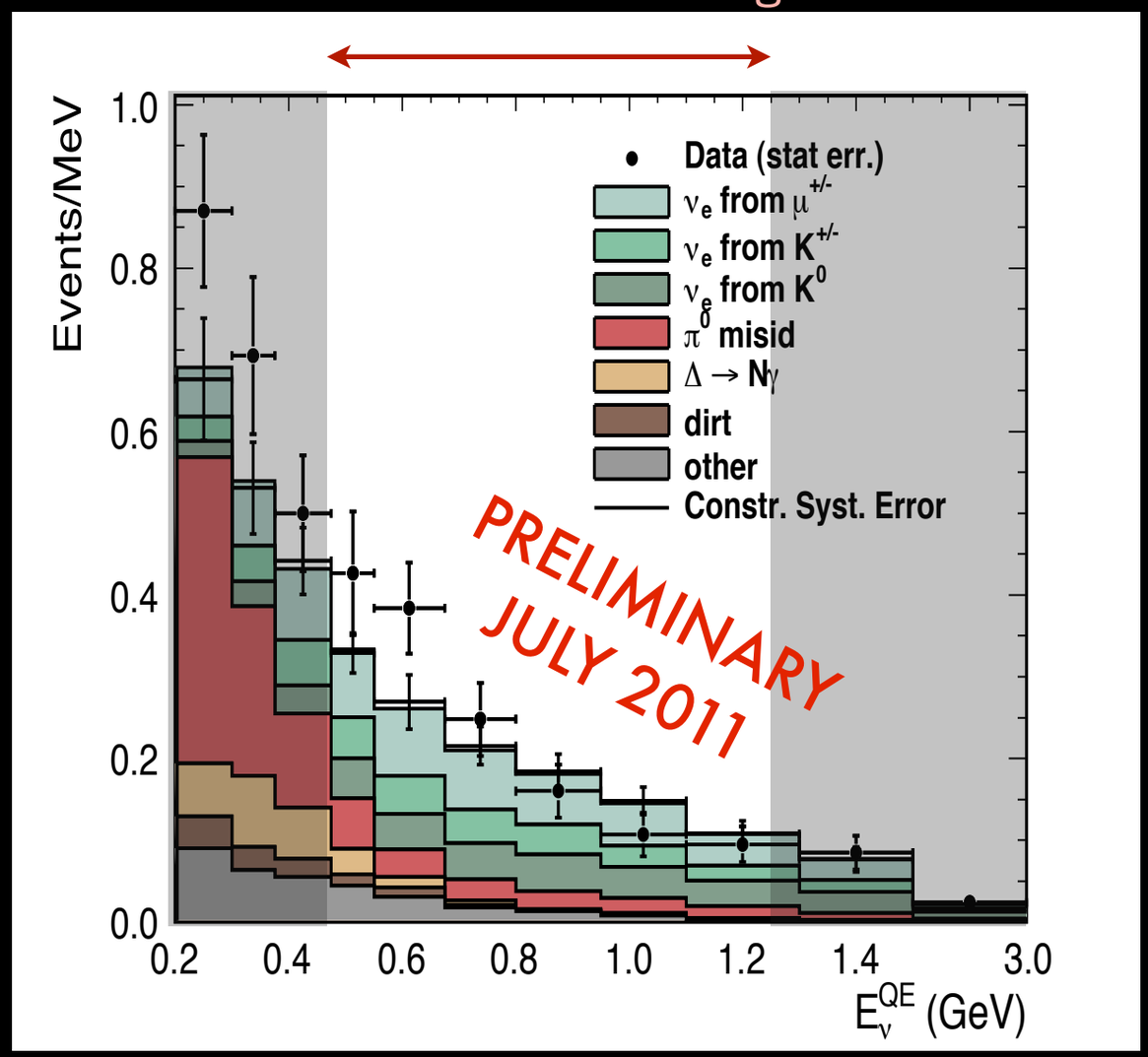


Updated antineutrino data: 8.58E20 POT

- Analysis is very nearly unchanged; 52% more statistics
- Most significant change: new constraint on neutrino flux from K^+ decays from SciBooNE result (e-print 1105.2871 [hep-ex], accepted by *Phys. Rev. D.,* in press)
  - Reduces this component of background by 3%; error by factor of 3
- Other systematic errors, constrained by MiniBooNE data, shrink slightly due to higher statistics in control samples:
  - Pion-decay neutrino normalization factors
  - Dirt neutrino background
  - Neutral-current π^0 production

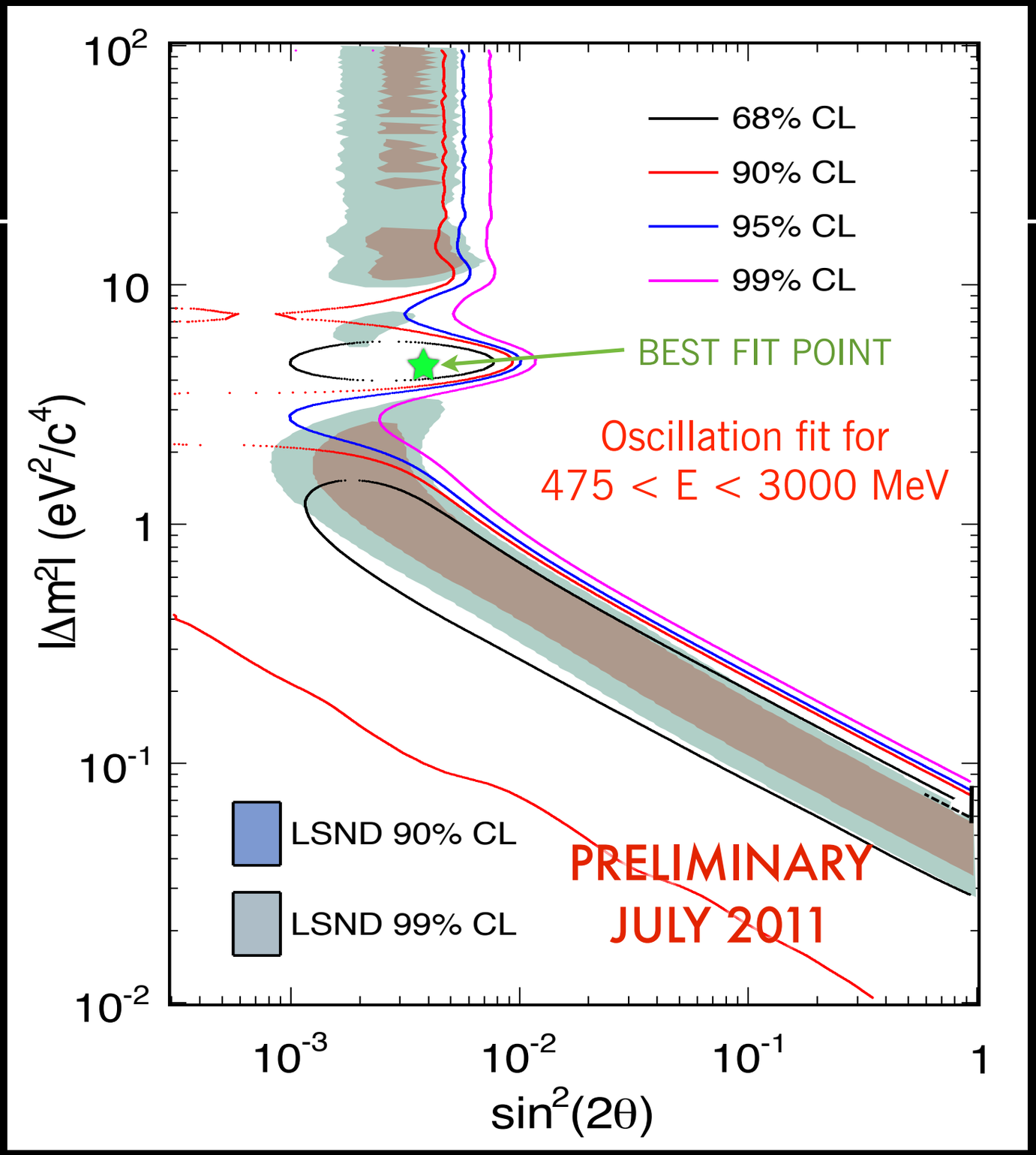
Updated antineutrino data: 8.58E20 POT

- 475 MeV < E < 1250 MeV:
  - 151.7±15.0(syst) expected after fit constraints
  - 168 observed; excess 16.3±19.4 (total)
  - Raw “one-bin” counting excess significance 0.84σ
- Excess in oscillation-sensitive region is reduced somewhat with new data; low-energy excess is more significant and resembles neutrino-mode data



Updated electron antineutrino appearance oscillation results

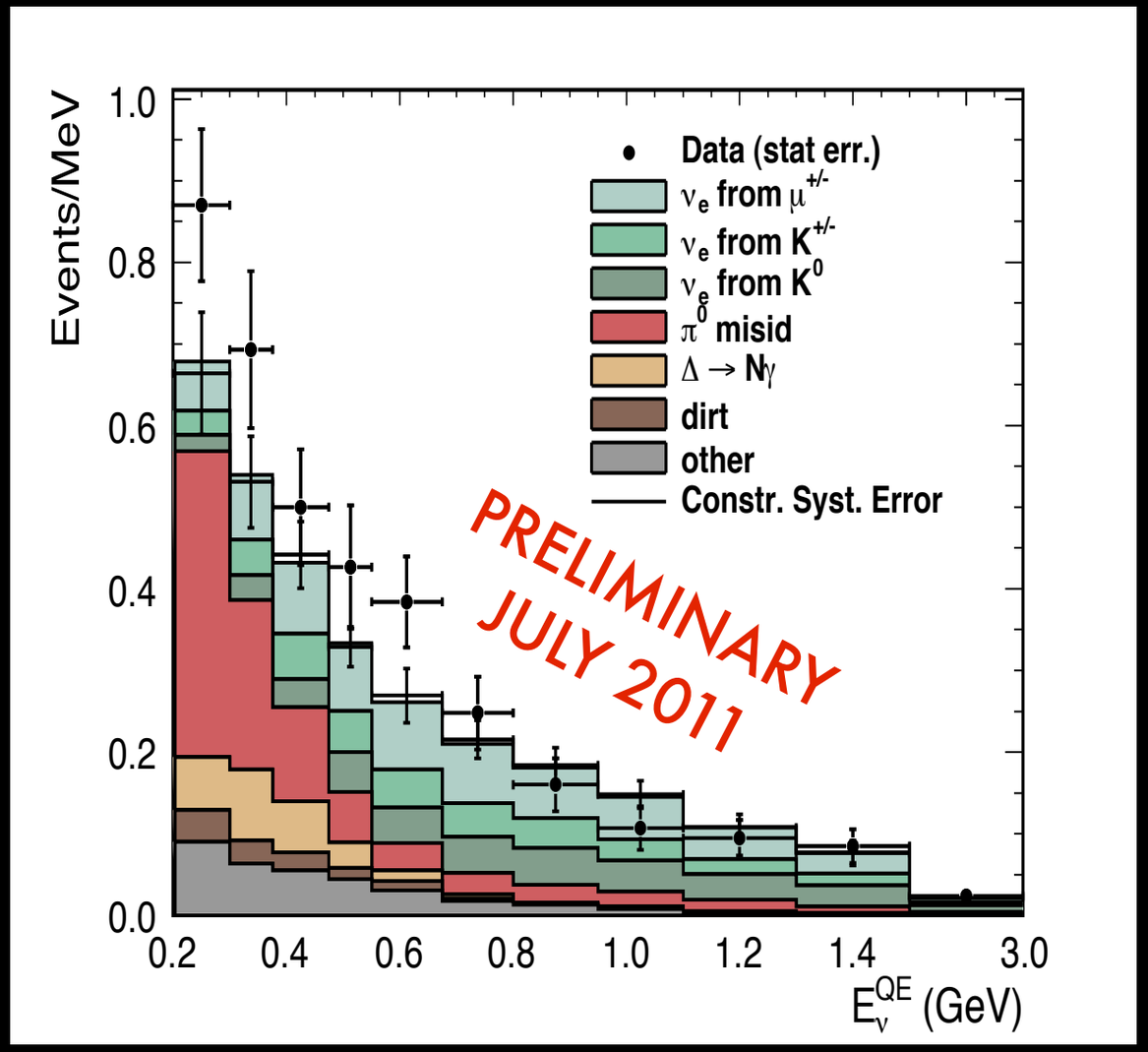
- Results for **8.58E20 POT**
- Maximum likelihood fit for *simple two-neutrino model*
- Oscillation hypothesis preferred to background-only at 91.1% confidence level.
- Signal bins only:
  - $P_{\chi 2}$(null)= 14.9%
  - $P_{\chi 2}$(best fit)= 35.5%
- Still consistent with LSND, though evidence for LSND-like oscillations no longer as strong



Primary test of LSND

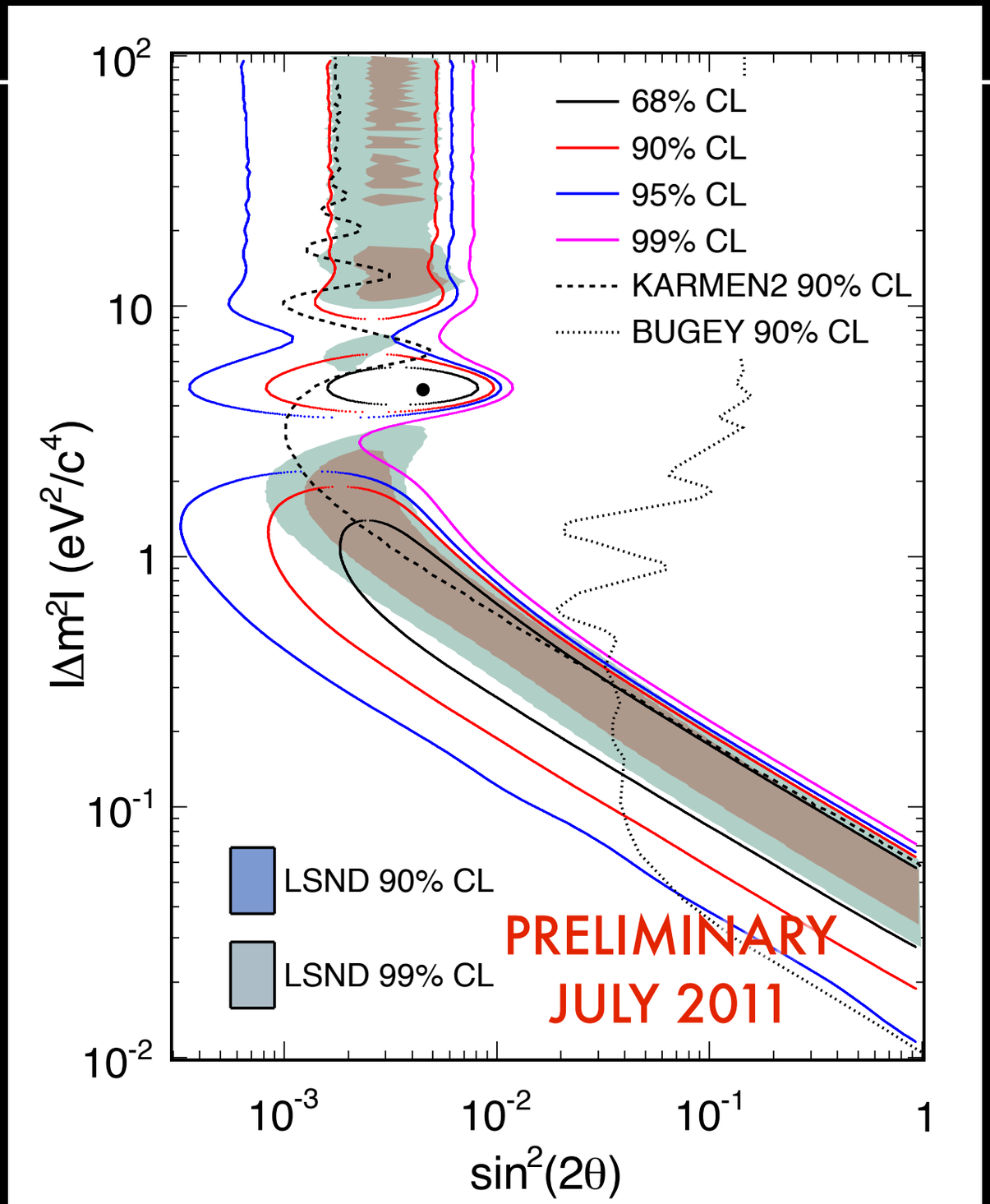
The full energy range

- Low-energy excess is now more prominent; excess above background in 200<E<475 MeV is 38.6±18.5 events.
- Full energy range: excess is 57.7±28.5



Oscillation fits: full energy range

- Results for **8.58E20 POT**
- Maximum likelihood fit for *simple two-neutrino model*
- Oscillation hypothesis preferred to background-only at 97.6% confidence level.
- Fit over all bins:
  - $P_{\chi 2}$(null)= 10.1%
  - $P_{\chi 2}$(best fit)= 50.7%
- This is not our primary test of LSND, due to known low-energy excess: can't be interpreted as a pure antineutrino fit

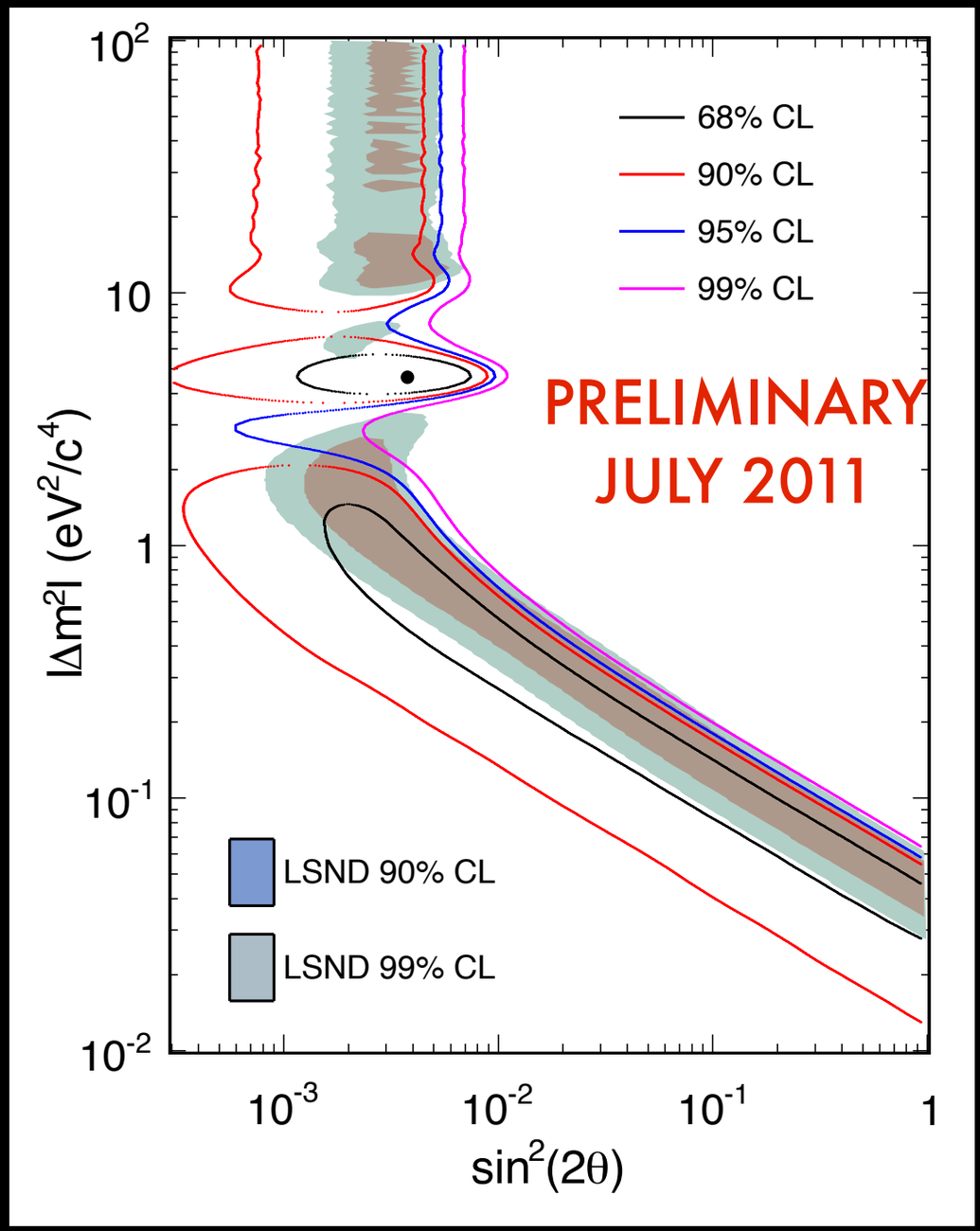


Low-energy excess: how does it scale?

- Excess above background in 200<E<475 MeV is 38.6±18.5 events. Scaling from what is observed in neutrino mode, can test various hypotheses.
- Expect if it scales with...
  - Total background: 50
  - Neutrino contamination only: 17
  - $\Delta \rightarrow N\gamma$ decays: 39
  - Dirt: 46
  - Protons on target (neutrals in secondary beam): 165
  - K^+ in secondary beam: 67
  - NC π^0: 48
  - Inclusive CC: 59

Another way to fit: subtract low-E excess expected from neutrinos

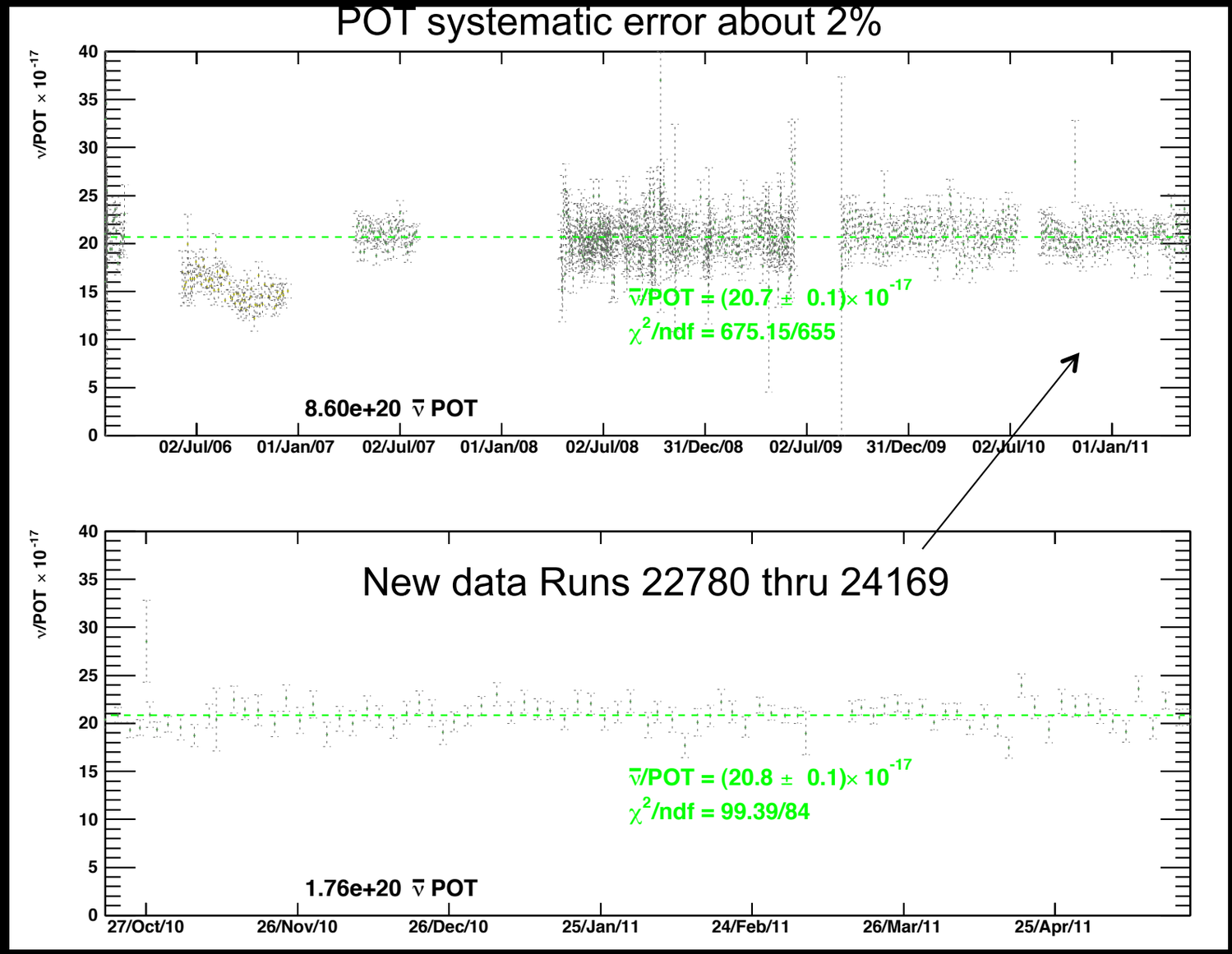
- In principle, we are trying to fit for $\bar{\nu}$ oscillations only, with expected contributions from ν subtracted as background
- However, neutrino contribution to low-energy excess isn't in background simulation since its explanation is unknown
- We can assume it scales with total neutrino-induced event rate in each bin, and subtract it out when fitting for antineutrino oscillations.
- Oscillation hypothesis preferred to background-only at 94.2% confidence level.
- Fit over all bins: $P_{\chi 2}$(null)=28.3%; $P_{\chi 2}$(best fit)=76.5%



Consistency of new and old data

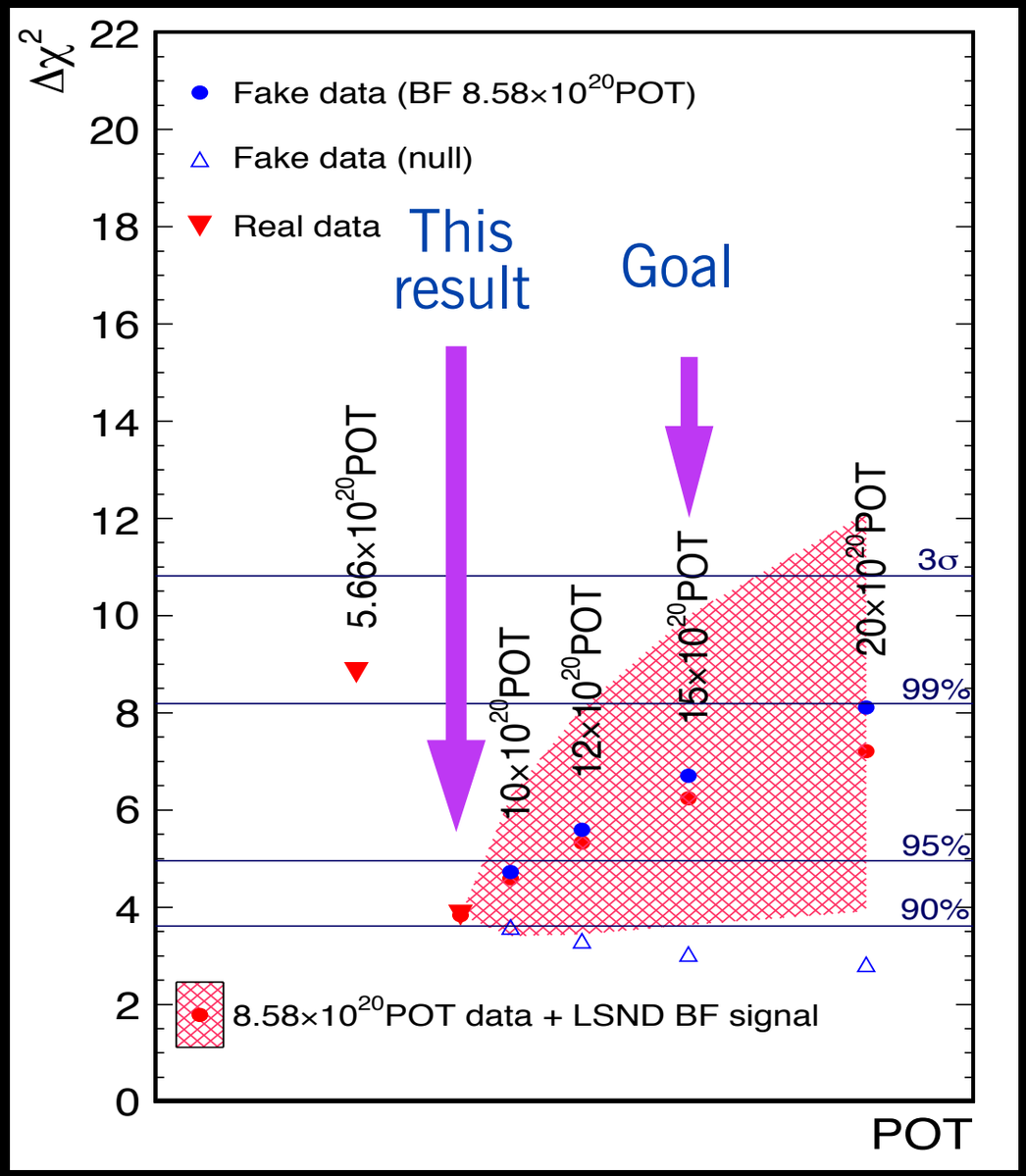
- Statistical tests on data sets:
  - K-S tests performed across all data sets; no anomalous results
- Beam/detector stability:
  - Horn and target have been in use since 2004
  - Monitoring of primary beam and neutrino events/POT shows no change over the data collection period except for known beam absorber failure in 2006
- No evidence for any significant change in either flux or detector

Antineutrino candidates vs. protons on target

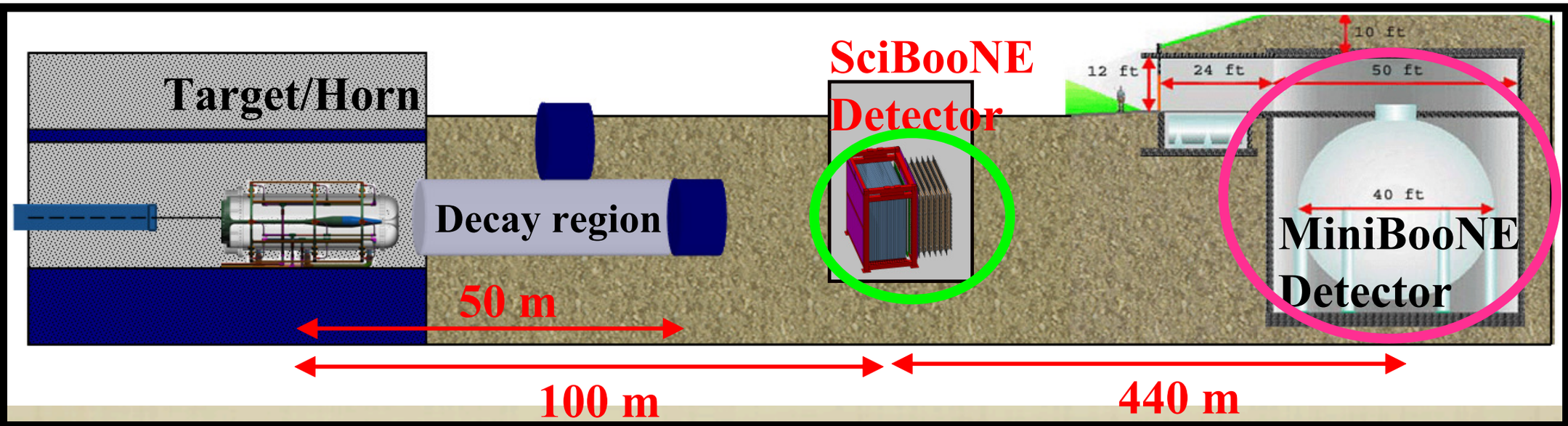


Future sensitivity in $\bar{\nu}$ data

- MiniBooNE has requested a total of 1.5×10^{21} POT in antineutrino mode. Data collection will continue through spring 2012 (at least).
- Sensitivity to LSND at 2-3 sigma for expected full data set: hashed region shows possible region (68% C.L.) of future results assuming LSND best-fit signal
- Systematics limit approaches above 2×10^{21} POT

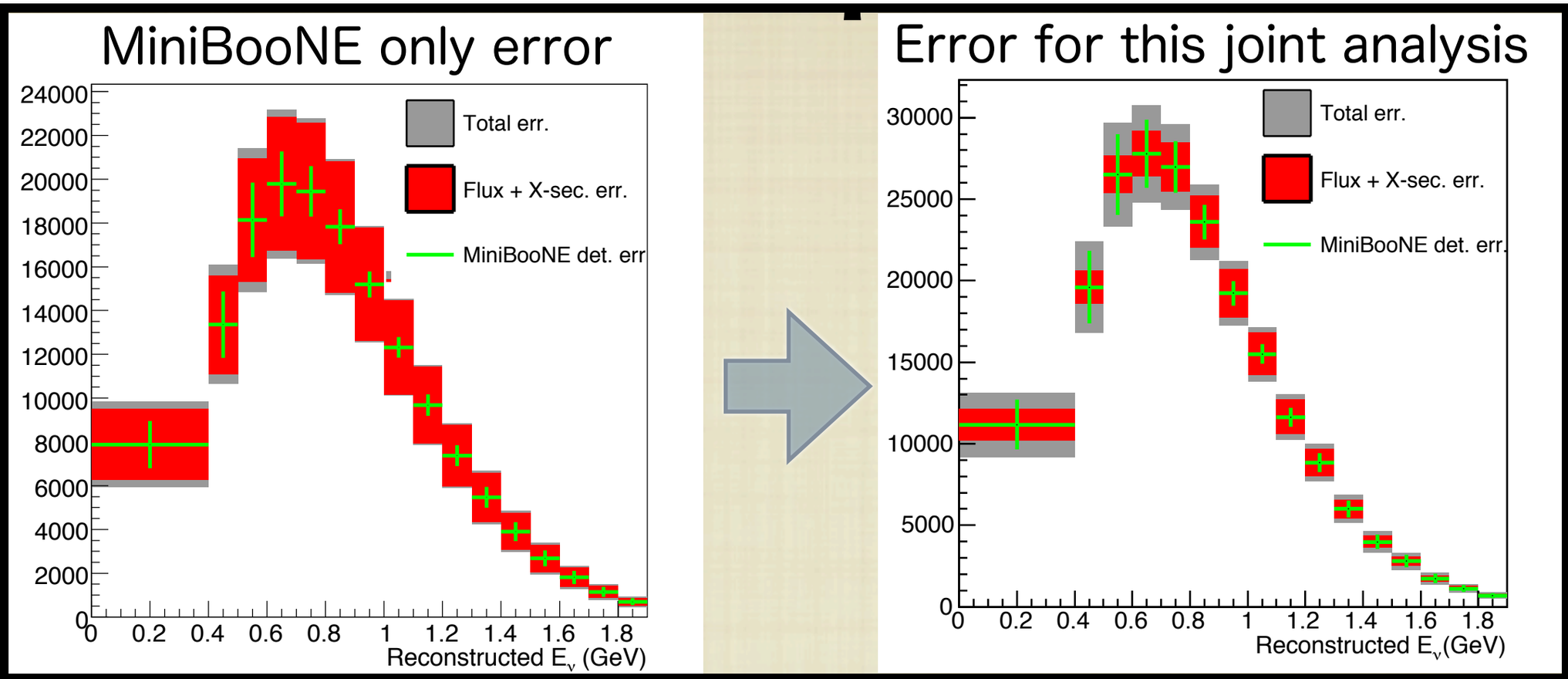


Muon neutrino disappearance with SciBooNE as near detector



- SciBooNE: Scintillating bar detector (originally from K2K) was in the BooNE beamline in 2007-08 to measure cross-sections
- Can also be used as a near detector for MiniBooNE
- New result this summer: ν_μ disappearance search using both detectors
- Mean baseline: 76m (SciBooNE), 520m (MiniBooNE): oscillation probabilities differ significantly for $0.5 < \Delta m^2 < 30\ eV^2$

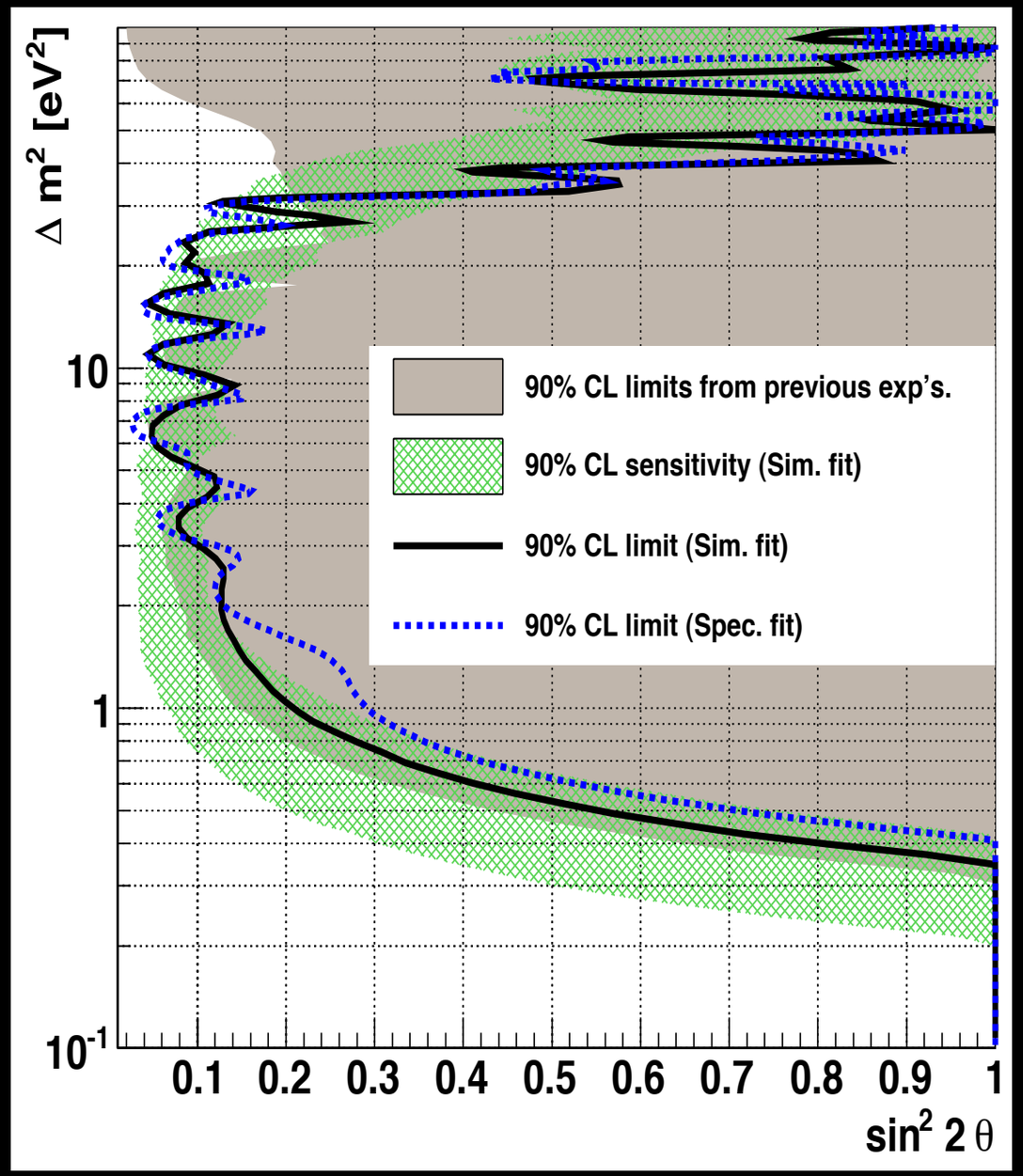
SciBooNE constraint reduces error at MiniBooNE



- Flux errors become 1-2% level: negligible for this analysis
- Cross-section errors reduced, but still significant due to different kinematic acceptance.

SciBooNE-MiniBooNE ν_μ disappearance result

- No evidence for oscillations
- Limit is better than other experiments in 10-30 eV^2 region
- e-print 1106.5685 [hep-ex]
- Analysis of antineutrino mode is underway



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 $\overline{\nu}_e$ excesses above background are emerging in both neutrino mode and antineutrino mode in MiniBooNE
  - Newest data update: excess is mostly at low energy, as with neutrinos.
  - Antineutrino data are still consistent with LSND; significance of oscillation signal is reduced
  - 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.

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See also: M. Shaevitz plenary talk tomorrow