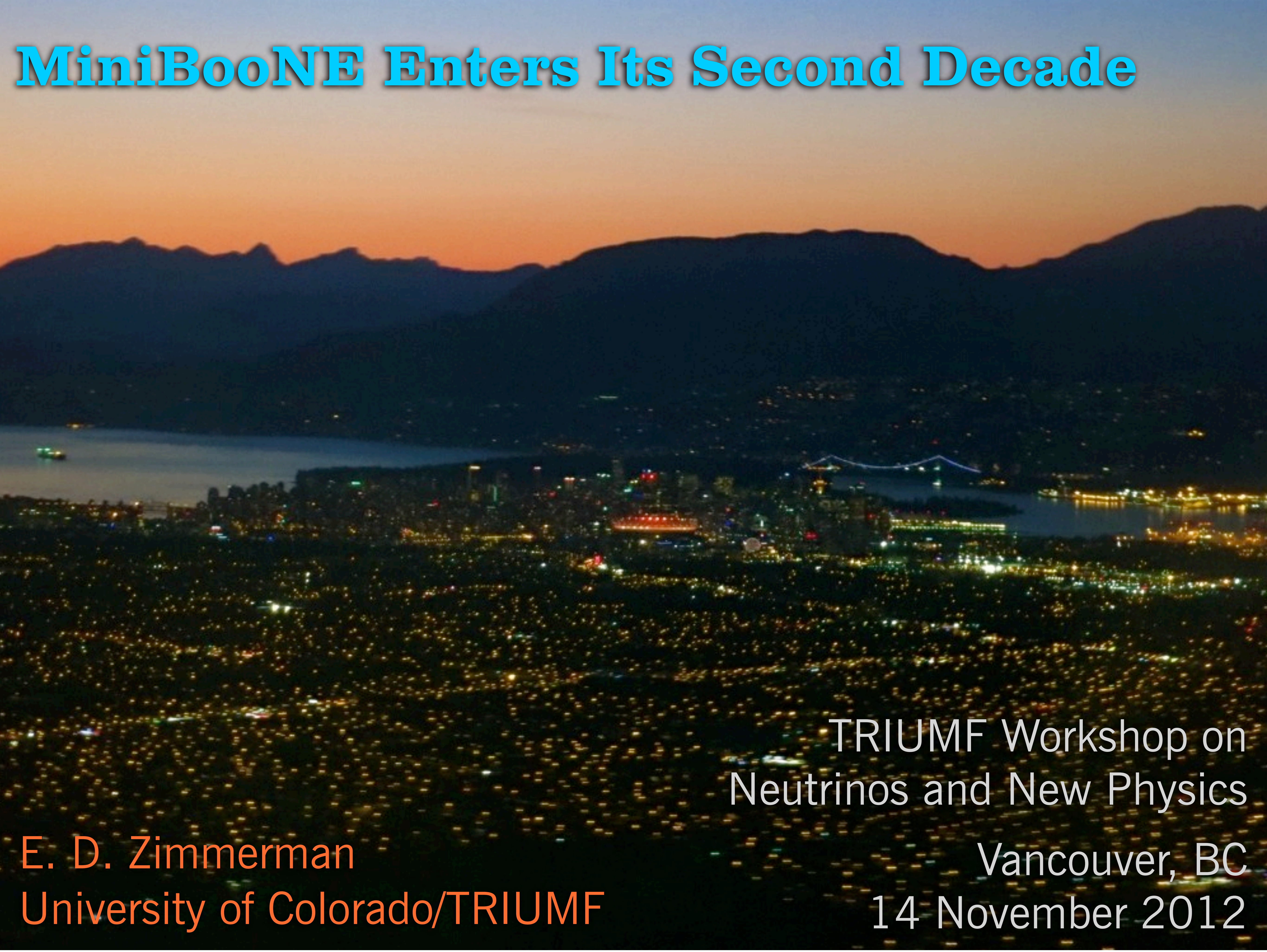


# MiniBooNE Enters Its Second Decade

E. D. Zimmerman
University of Colorado/TRIUMF

TRIUMF Workshop on
Neutrinos and New Physics

Vancouver, BC
14 November 2012

# Short-Baseline Neutrino Physics at MiniBooNE

- MiniBooNE
- Neutrino cross-sections
  - Hadron production channels
  - Quasielastic scattering (if time)
- Oscillation physics
  - Antineutrino Oscillations
  - MiniBooNE-SciBooNE joint result (if time)

# Motivating MiniBooNE: LSND

## Liquid Scintillator Neutrino Detector

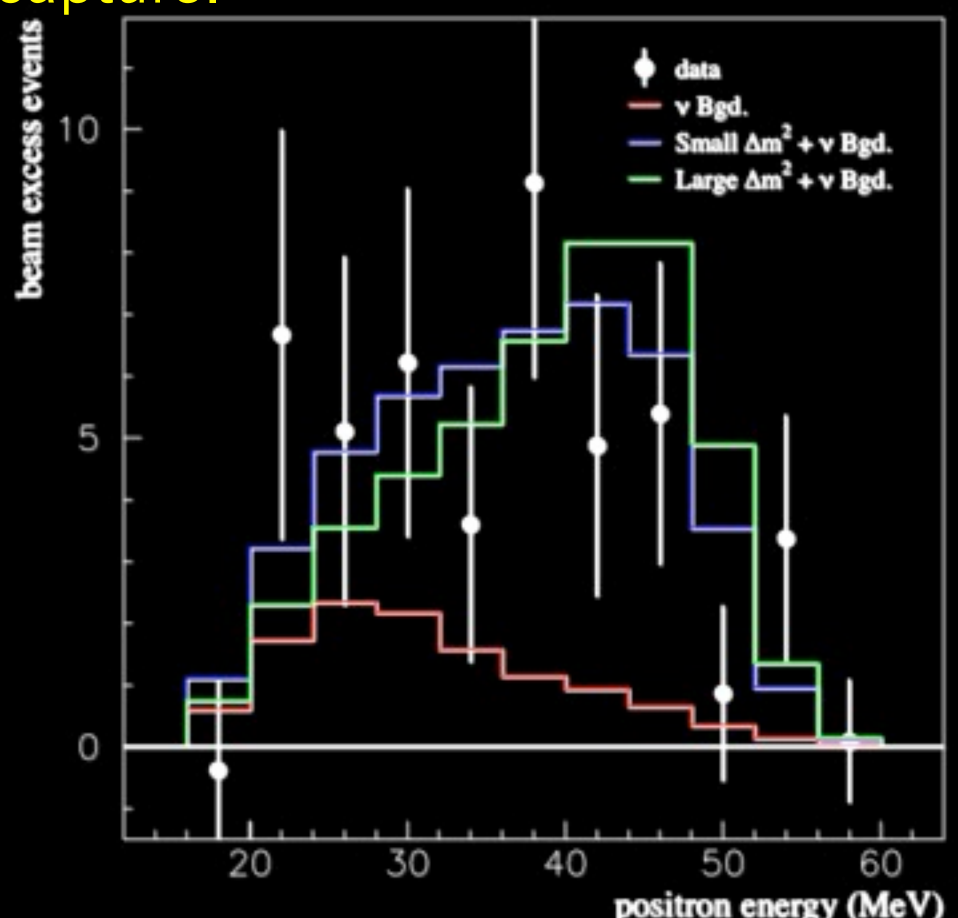
- Stopped $\pi^+$ beam at Los Alamos LAMPF produces $\nu_e$, $\nu_\mu$, $\overline{\nu}_\mu$ but no $\overline{\nu}_e$ (due to $\pi^-$ capture).

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

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

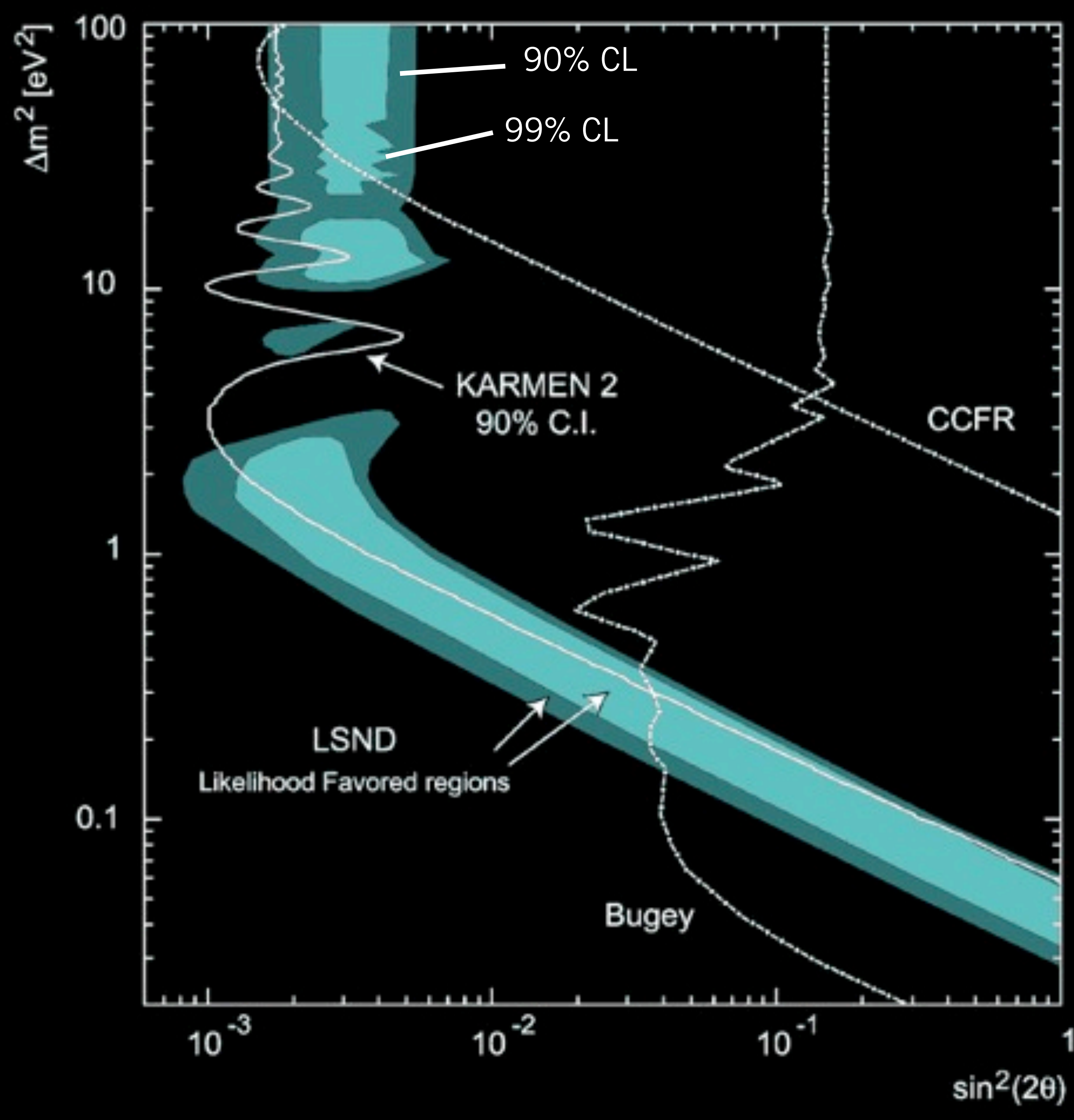
- Look for delayed coincidence of positron and neutron capture.
- Major background non-beam (measured, subtracted)
- 3.8 standard dev. excess above background.
- Oscillation probability:

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



# 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.



# 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:

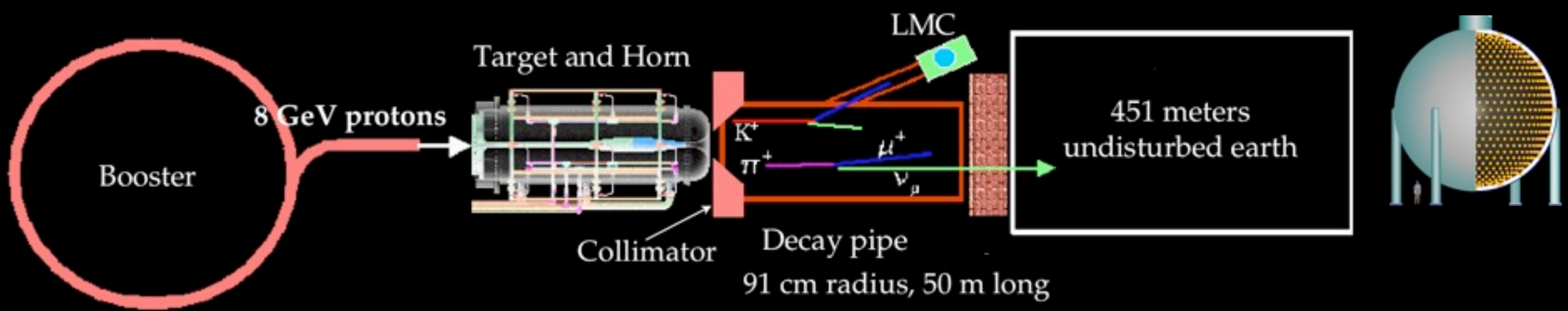
$$\nu_e + n \rightarrow e^- + p$$

- Dominant backgrounds to oscillation:
  - Intrinsic $\nu_e$ 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

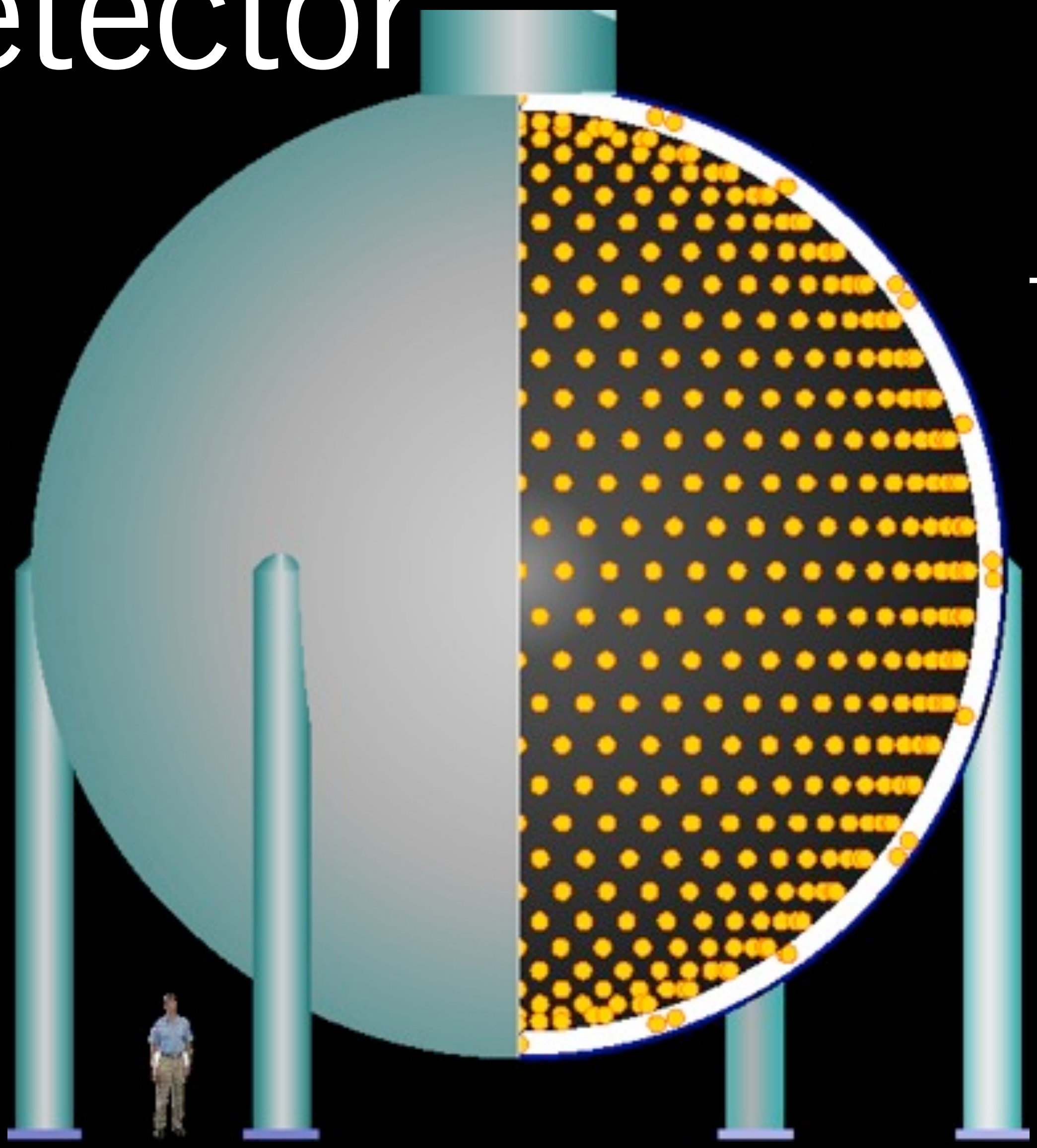
    Neutral current resonance:
    $\Delta \rightarrow \pi^0 \rightarrow \gamma\gamma$ or $\Delta \rightarrow n\gamma$, mis-ID as $e$

# MiniBooNE Beamline




- 8 GeV primary protons come from Booster accelerator at Fermilab
- Booster provides about 5 pulses per second, $5\times10^{12}$ protons per 1.6 $\mu$s 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 - 2012: Antineutrino mode
    - (Interrupted by short Fall 2007 - April 2008 neutrino running for SciBooNE)
- Present analyses use:
    - $\geq$5.7E20 protons on target for neutrino analyses
    - 11.3E20 protons on target for antineutrino analyses
    - Over one million neutrino interactions recorded: by far the largest data set in this energy range

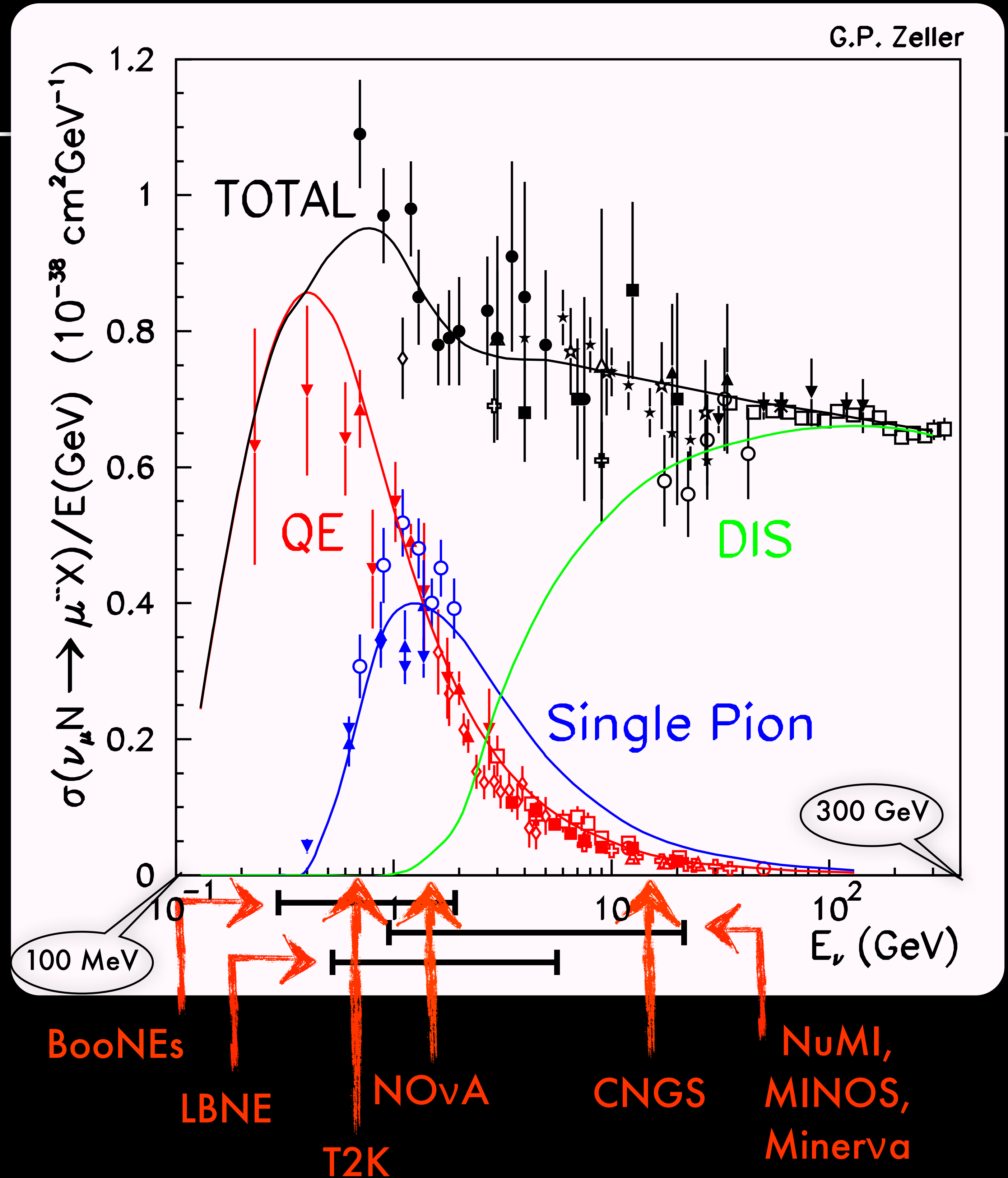
# Neutrino scattering cross-sections

- 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!)

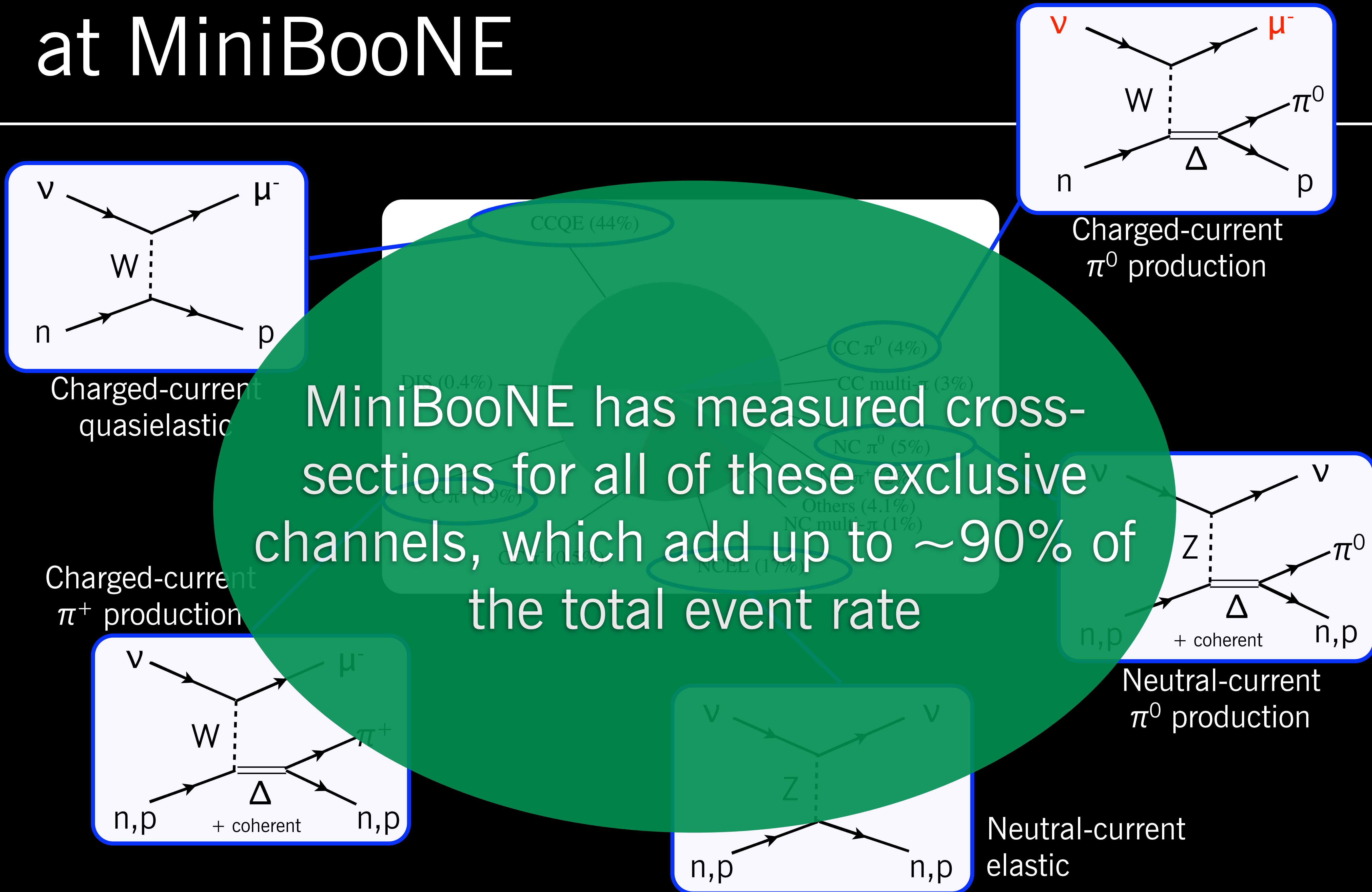
# Scattering cross-sections for $\nu_\mu$

The state of knowledge of $\nu_\mu$ 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; almost no data available.



# Dominant interaction channels at MiniBoONE




MiniBooNE has measured cross-sections for all of these exclusive channels, which add up to ~90% of the total event rate

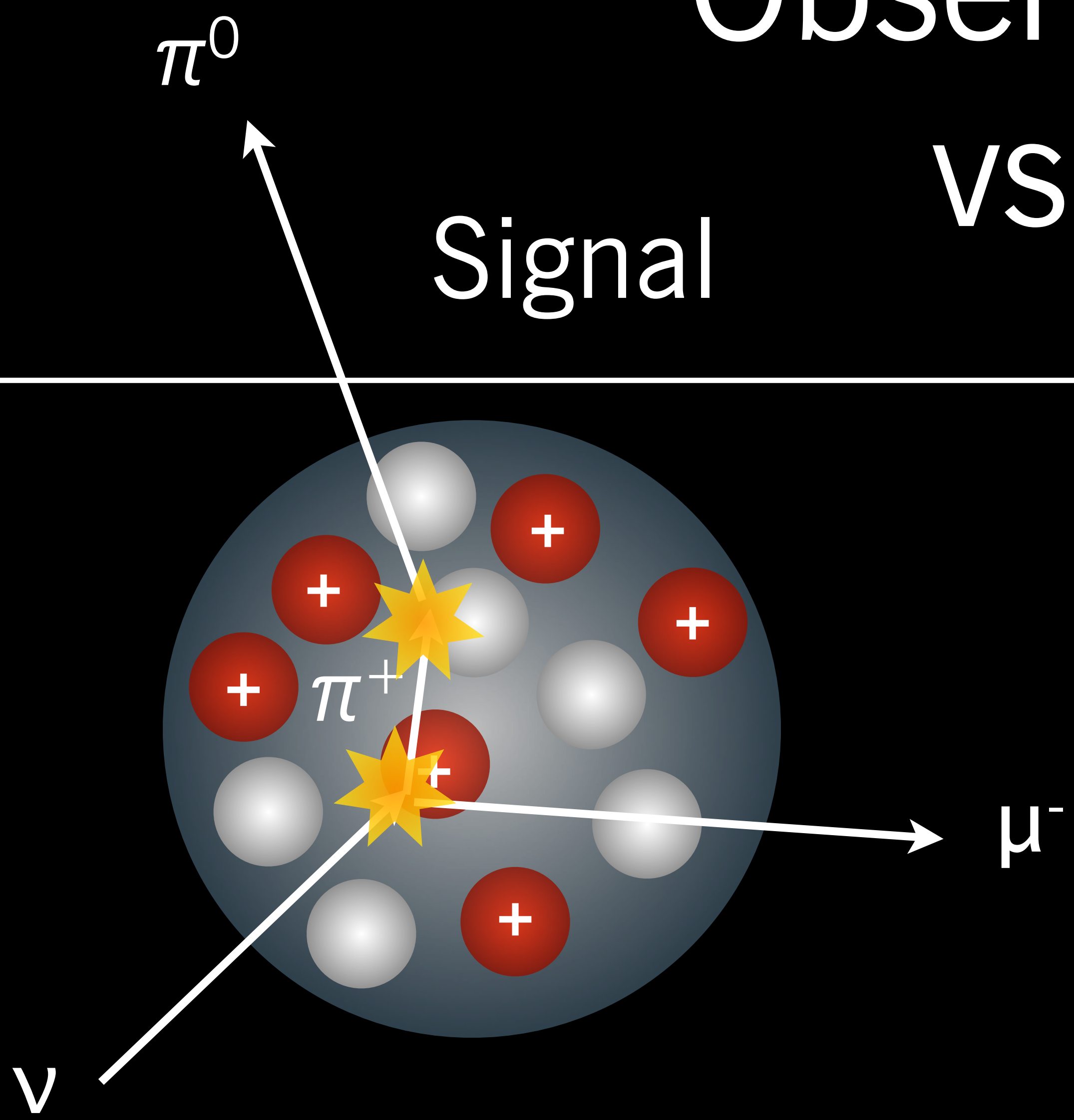
# MiniBooNE cross-section measurements

- ~~NC $\pi^0$~~
- CC $\pi^0$
- CC $\pi^+$
- CC Quasielastic
- ~~NC Elastic~~
- CC Inclusive (new!)

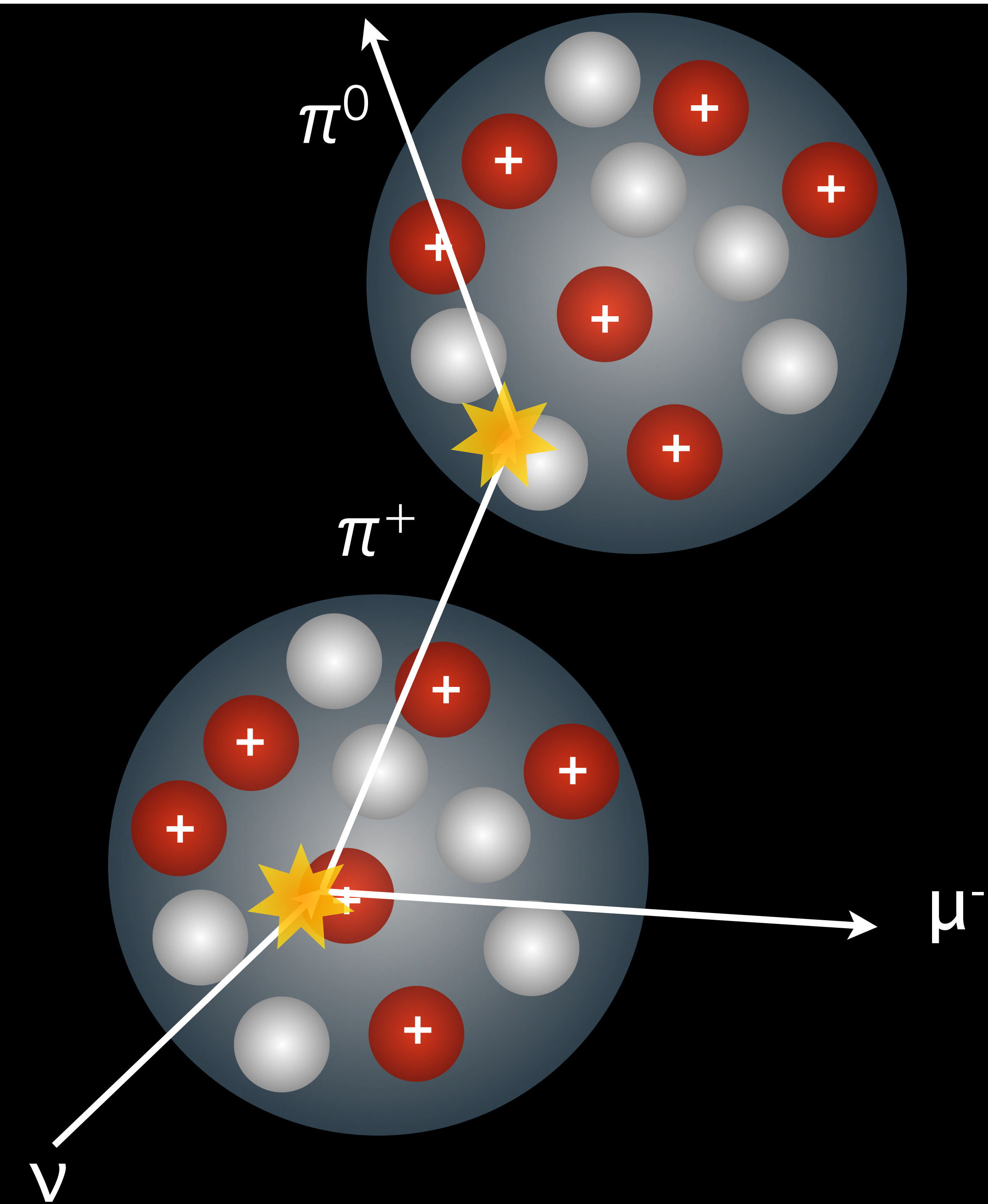
Due to limited time, only discussing a few topics here.

# “Observable” signal vs tank $\pi^0$

## Signal

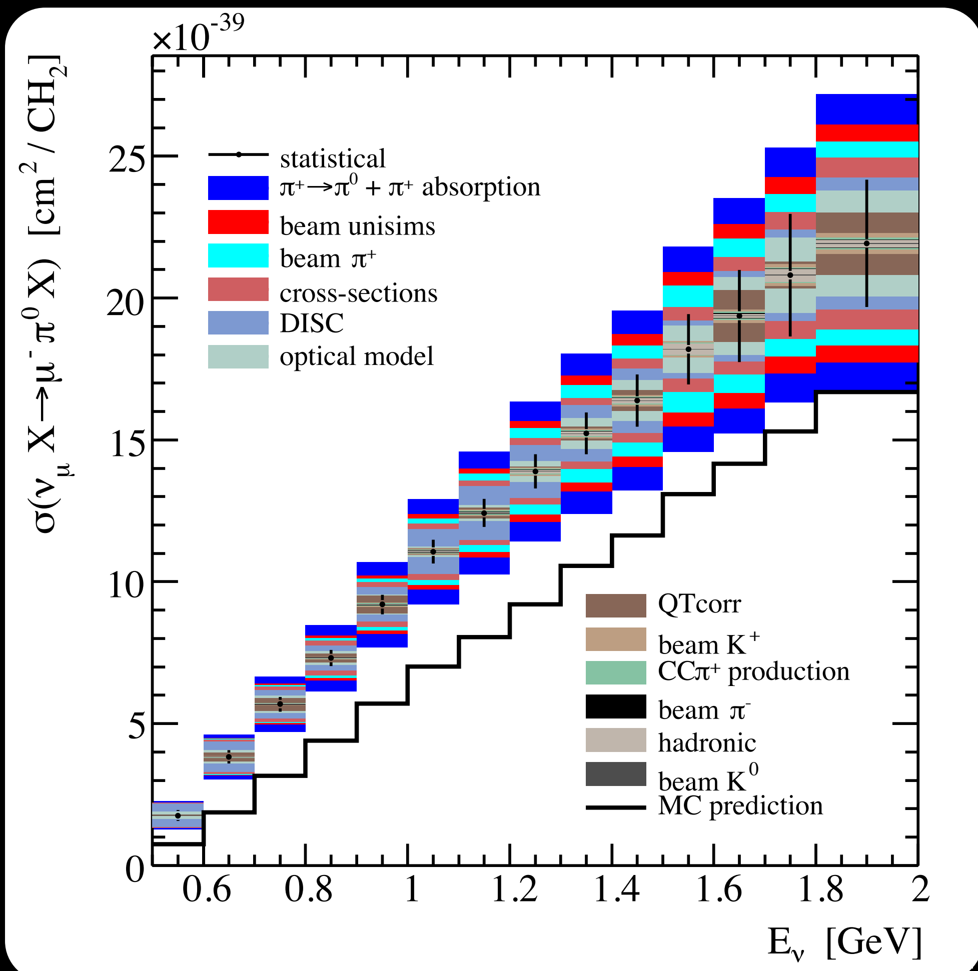


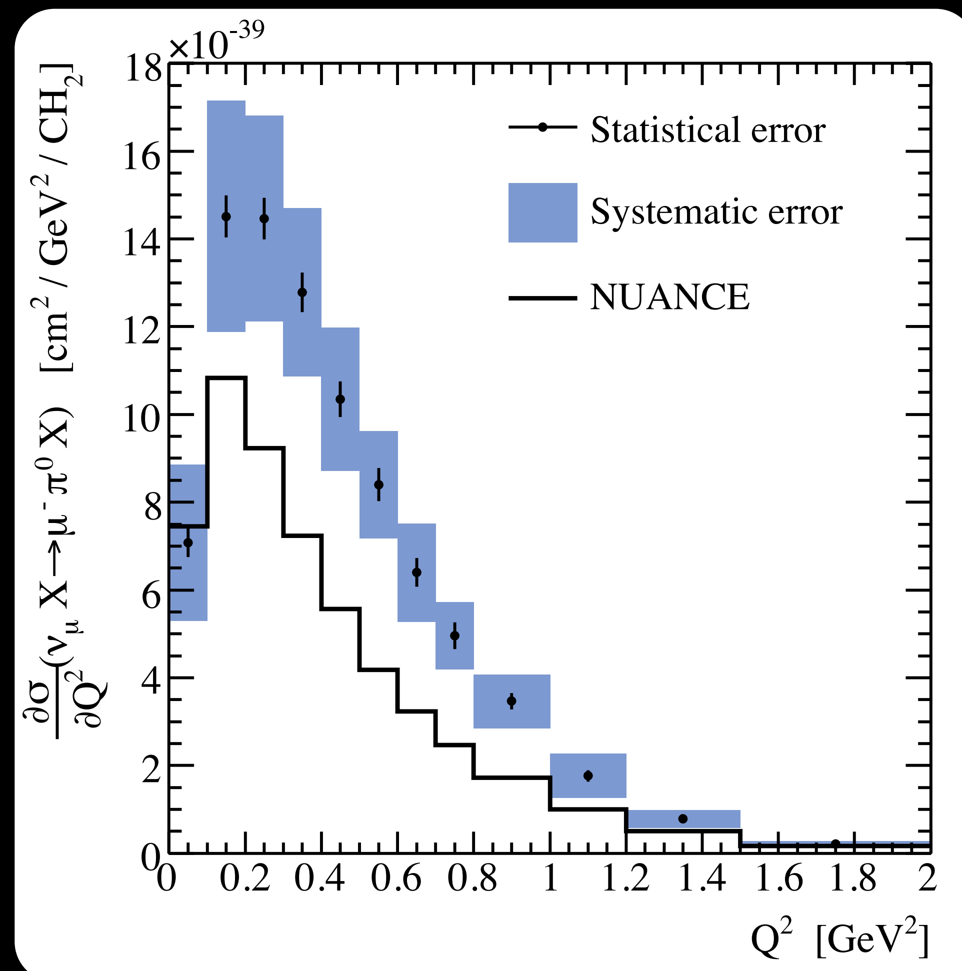

## Tank $\pi^0$




- $\pi^0$ from charge exchange within the target nucleus is considered **signal**.
- Charge exchange with *other* nuclei constitutes a **background**.
- We **include** FSI pion production to remove model dependence; **exclude** tank $\pi^0$ to remove detector dependence.

# Measured observable CC$\pi^0$ cross-section



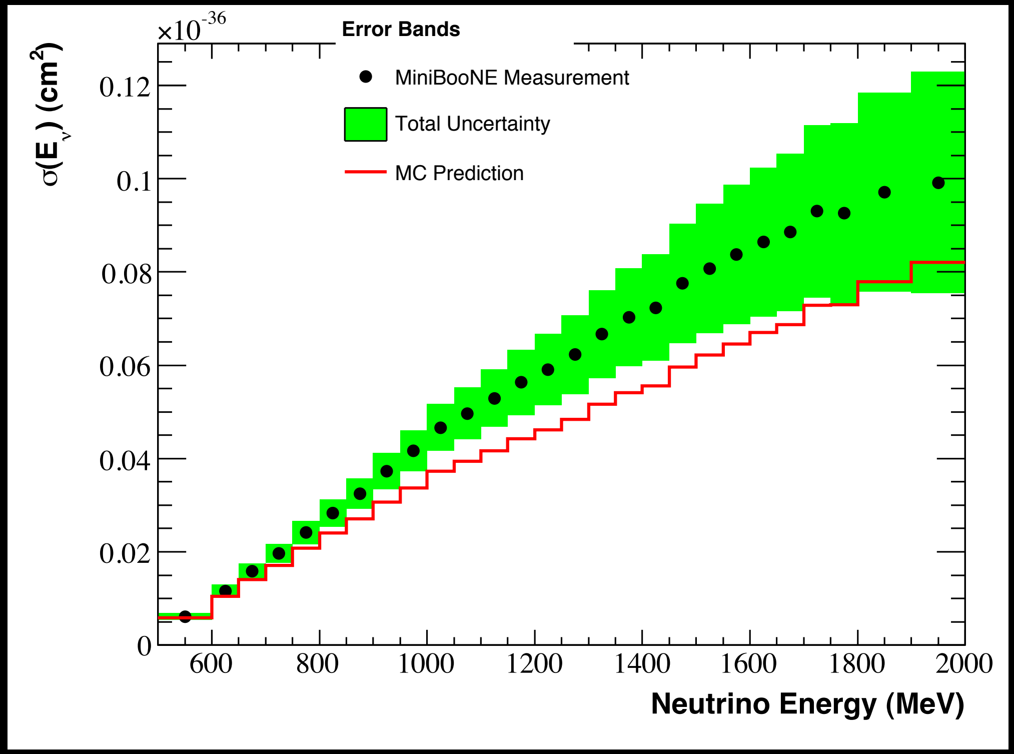

Additionally, we measure differential cross-sections vs:

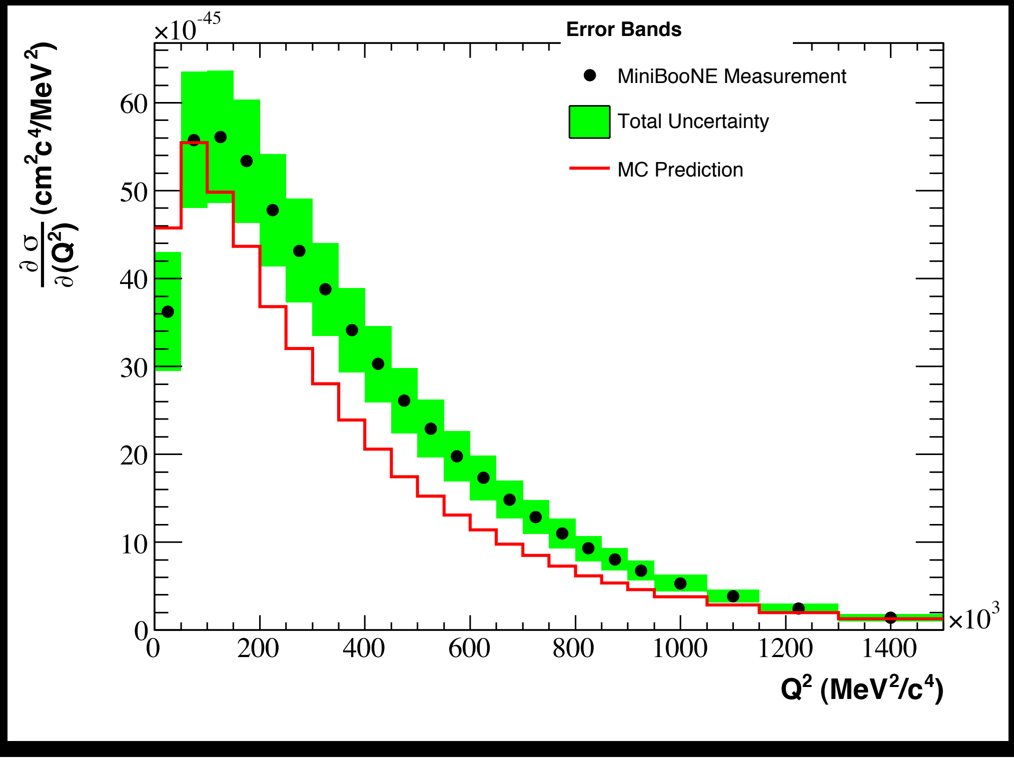
- $\theta_\mu$
- $\theta_\pi$
- $E_\mu$
- $E_\pi$

- The dominant error is $\pi^+$ 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

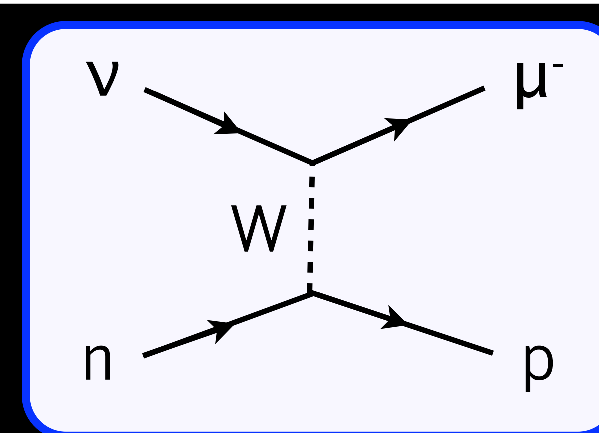
# Measured observable charged-current $\pi^+$ cross-sections

- 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.



# Charged-current quasielastic scattering (CCQE)



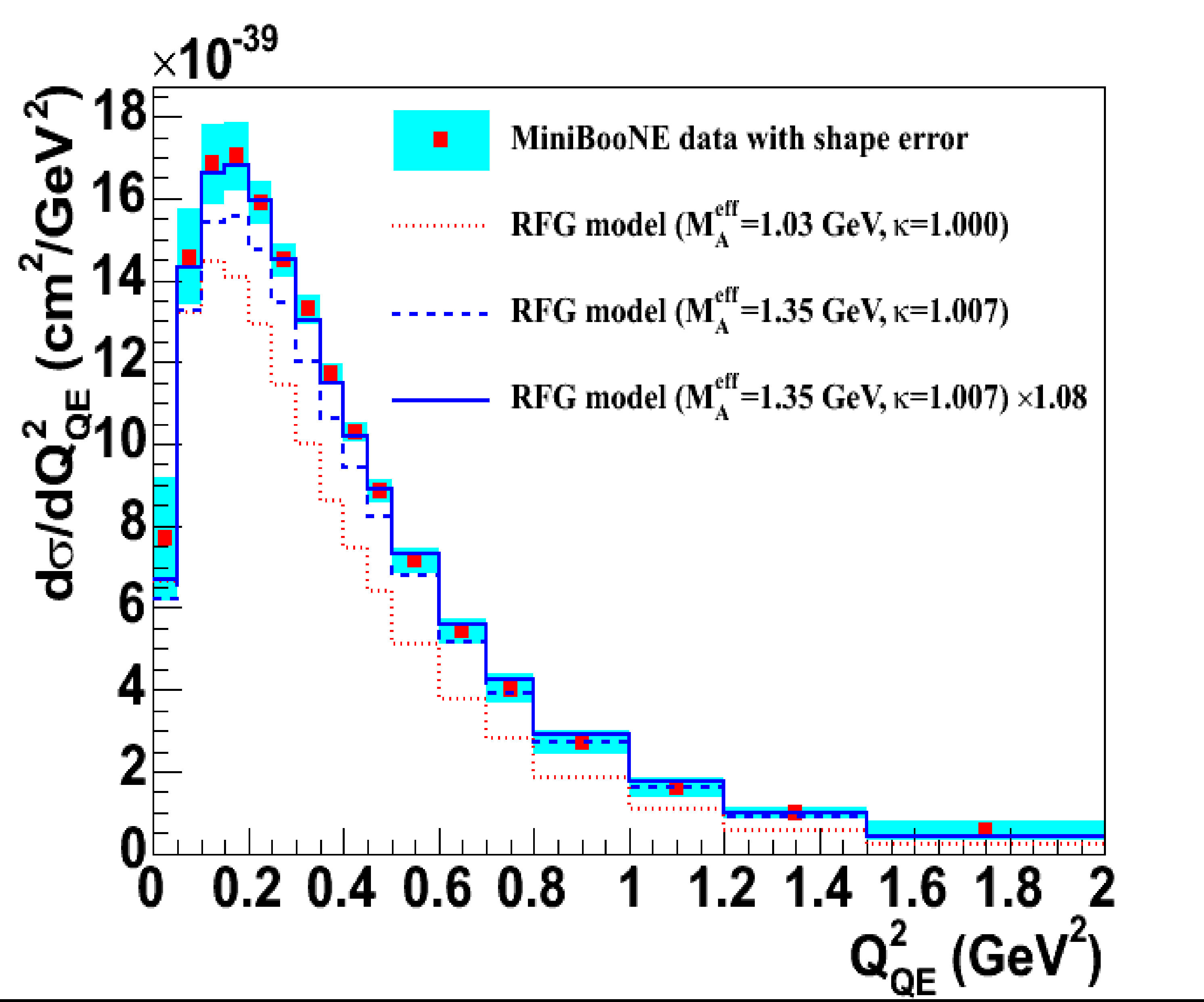

- Lepton vertex well understood
- Nucleon vertex parametrized with 2 vector form factors $F_{1,2}$ and one axial vector form factor $F_A$
- Use relativistic Fermi gas model of nucleus; $F_{1,2}$ come from electron scattering measurements
- Generally assume dipole form of $F_A$; only parameter is axial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

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

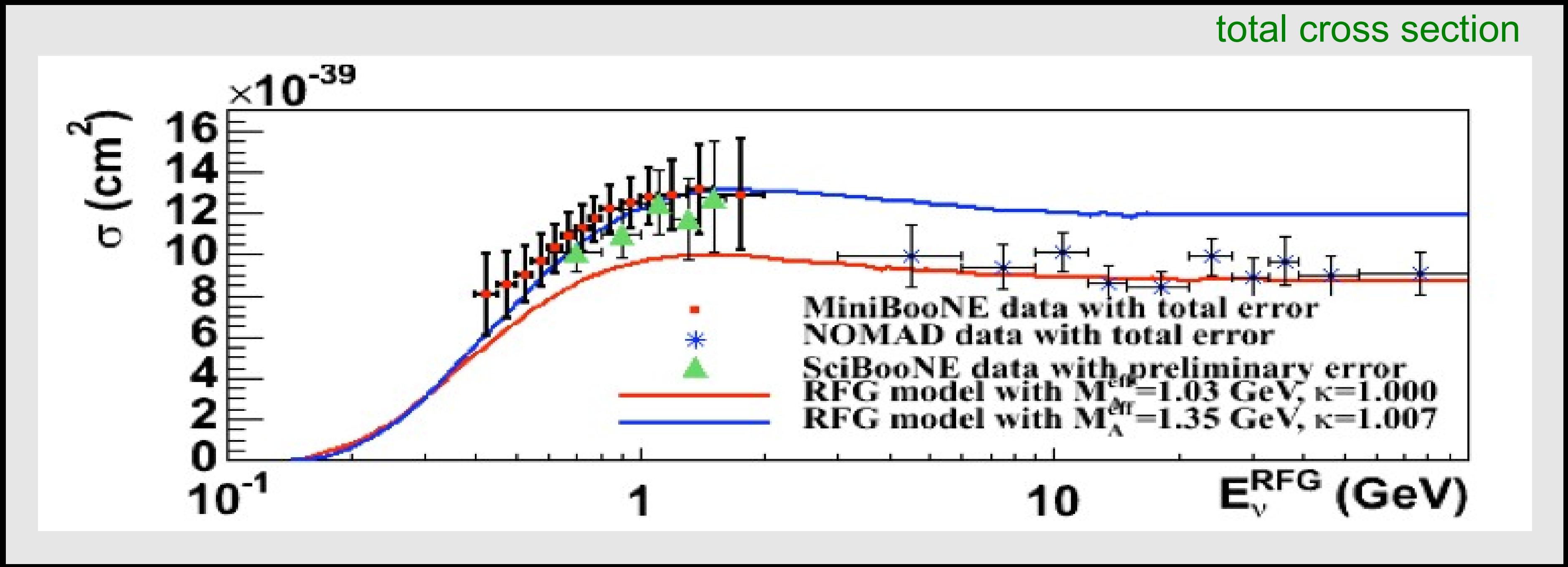
# CCQE fit results: $Q^2$ dependence

- 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 overall event rate (to within normalization error).

Flux-integrated single differential cross section ($Q^2_{QE}$):

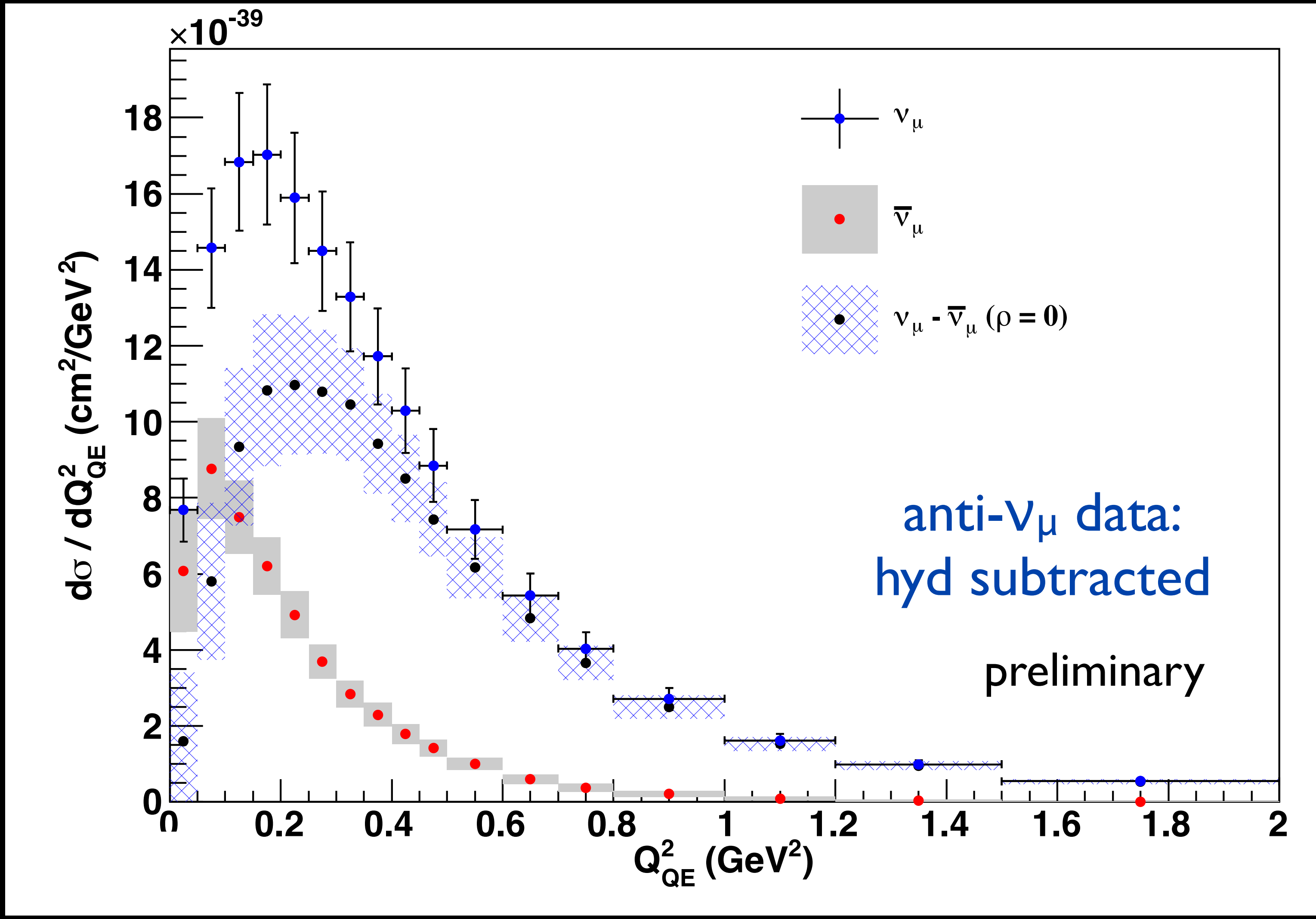


# Comparisons to other experiments (carbon targets)



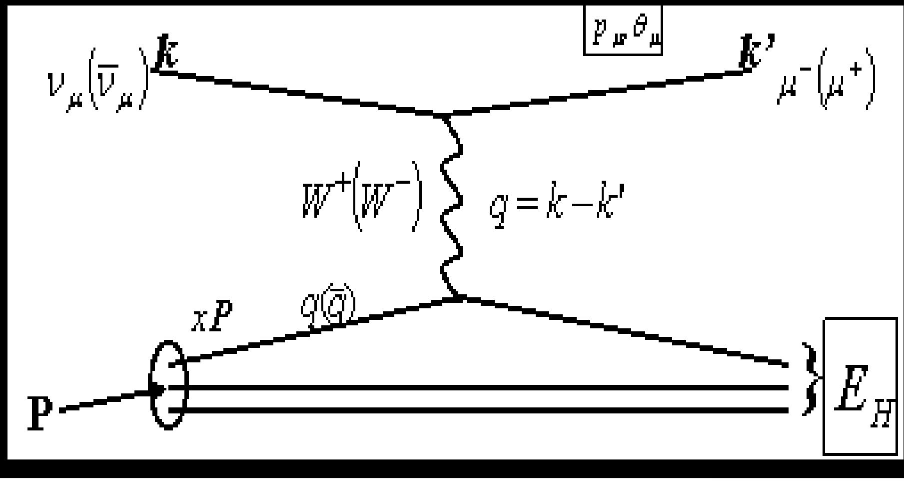

- Our data (and SciBooNE) appear to prefer higher $M_A$ than NOMAD, but the disagreement is not very significant.
- Note that:
  - Our errors are systematic-dominated and grow at highest energies
  - NOMAD allowed maximum of two tracks in event: in principle, different processes may contribute to the two experiments' samples
- Possible explanation for what appears to be higher $M_A$: two-nucleon correlations: Martini *et al.,* PRC 80, 065501 (2009) and (new) Martini, Ericson, Chanfray 1121.1523

# New: antineutrino CCQE




- J. Grange, NuInt 2012 talk

# Charged-current inclusive




Can't we just add CCQE, CC$\pi^+$ and CC$\pi^0$?

- Yes, we can add the cross sections, but we'll be adding the systematics as well.
- Complicated model-dependent correlations: each of the exclusive channels is a background for the others (both experimentally and through FSI model).
- We report observable pion production, but nucleon-level CCQE. So adding the cross-sections doesn't include all events properly.

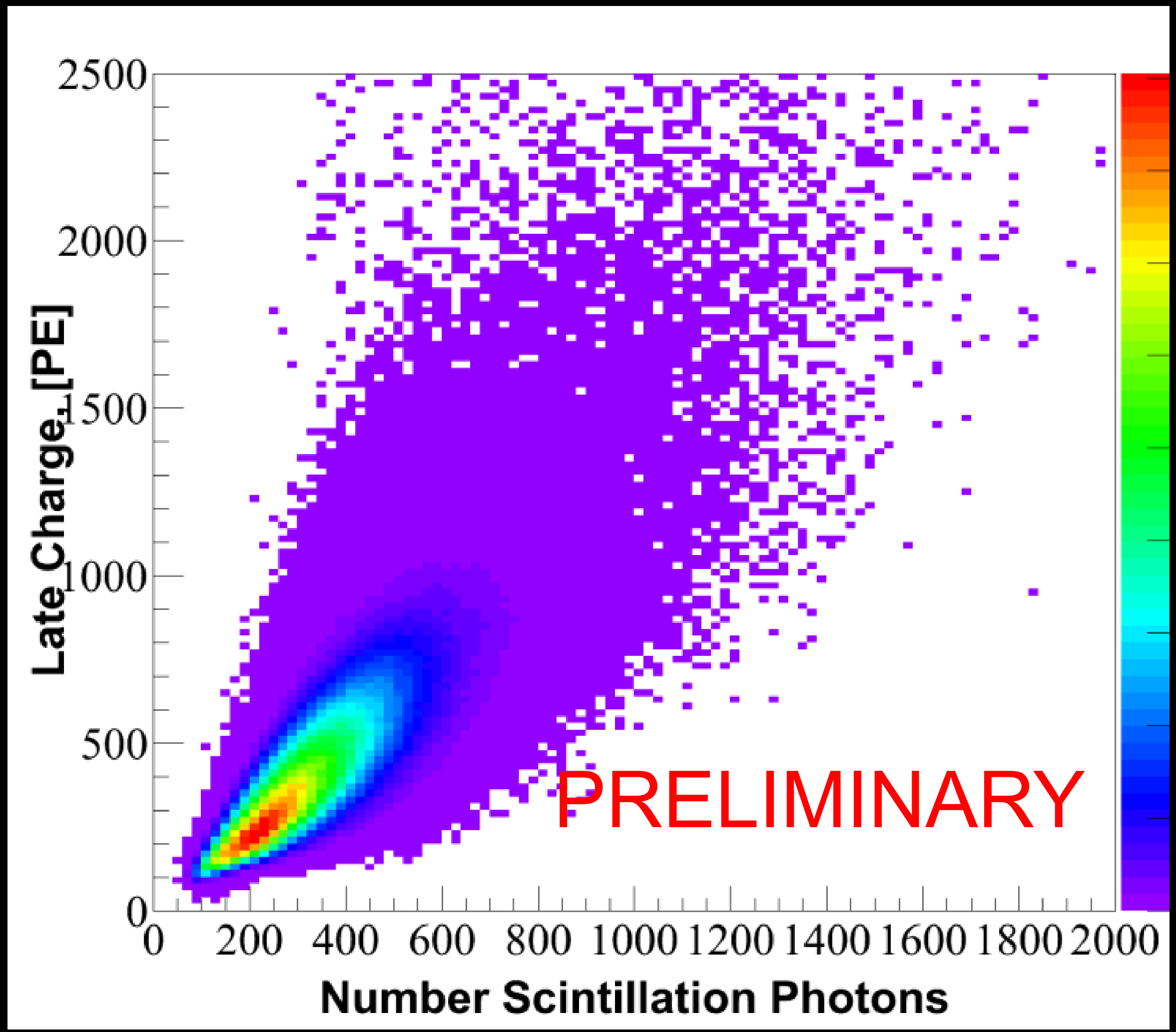
# CC Inclusive event selection

- Events are tagged by at least one Michel electron,
- Veto and Containment – Maximum of five veto hits in all subevents,
- Minimum PMT hits in the first subevent to remove beam unrelated backgrounds.
- Fiducial Volume - Reconstructed vertex within 5m radius.
- Event rates at the generator level:
  - CCQE: 52%; CC$\pi^+$: 34%;
  - CC$\pi^0$: 5%; Other CC: 3%;
  - NC: 3%; antineutrino: 1%.
- FSI changes the fractions of different event topologies. Data events after cuts 344k. 96% purity.

# MiniBooNE as a calorimeter

- Need a measure of the total energy in an event, not just muon momentum
- Get muon kinematics from 2-track likelihood fit: allowing second ring reduces bias in events where there is a second (or more) charged track.
- Small scintillation component of natural mineral oil yields “late” light in event. Use total late light as a measure of neutrino energy.
- Fully reconstructs lepton vertex: no assumptions about target mass

MiniBooNE MC

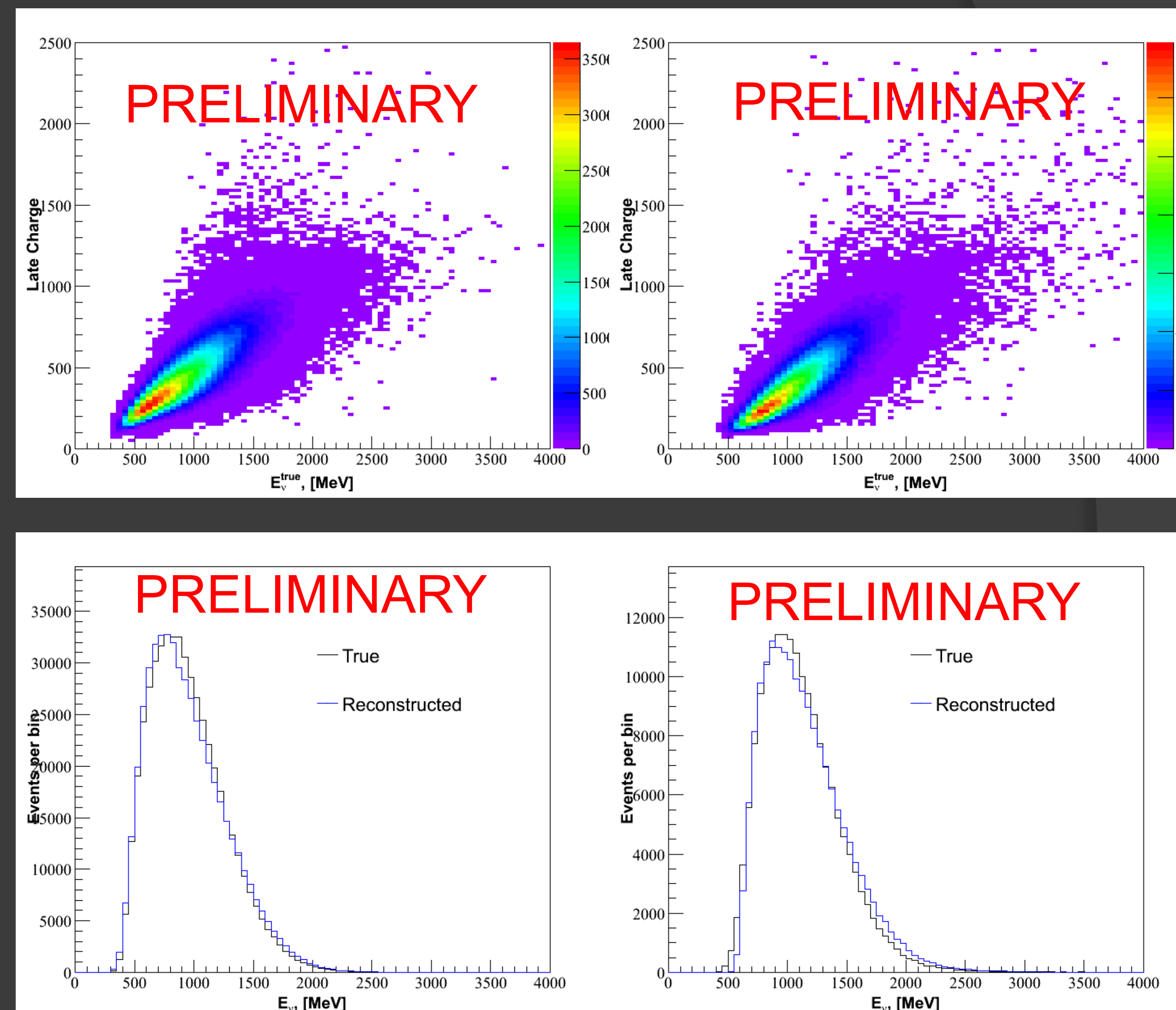


# Neutrino Energy Reconstruction Performance

Neutrino energy reconstruction is obtained from the late light charge which is linearly correlated with the true neutrino energy.

The parameters of the reconstruction come from a linear fit to both CCQE and $CC\pi^+$ enhanced samples. the slope parameter is the same in both cases while the Intercept is different.

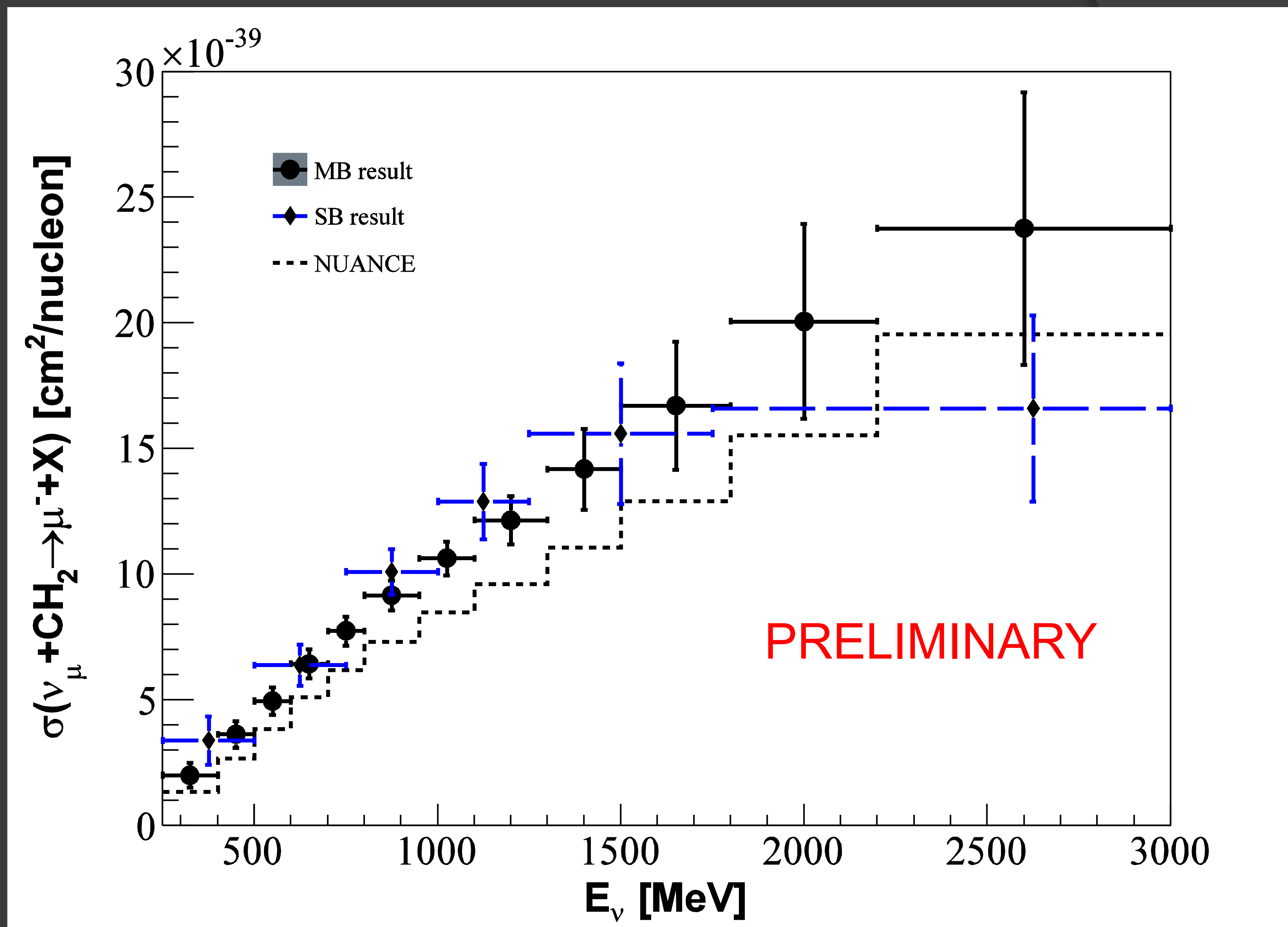
Energy reconstruction resolution is about 18%.




CCQE

$CC\pi+$

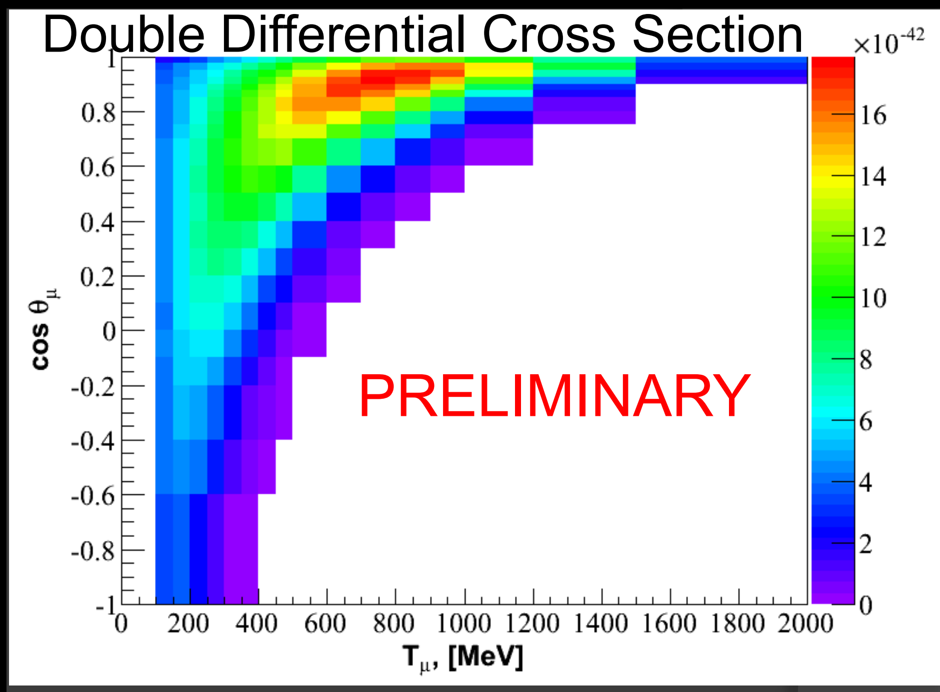
# MiniBooNE CC inclusive total cross-section vs. energy

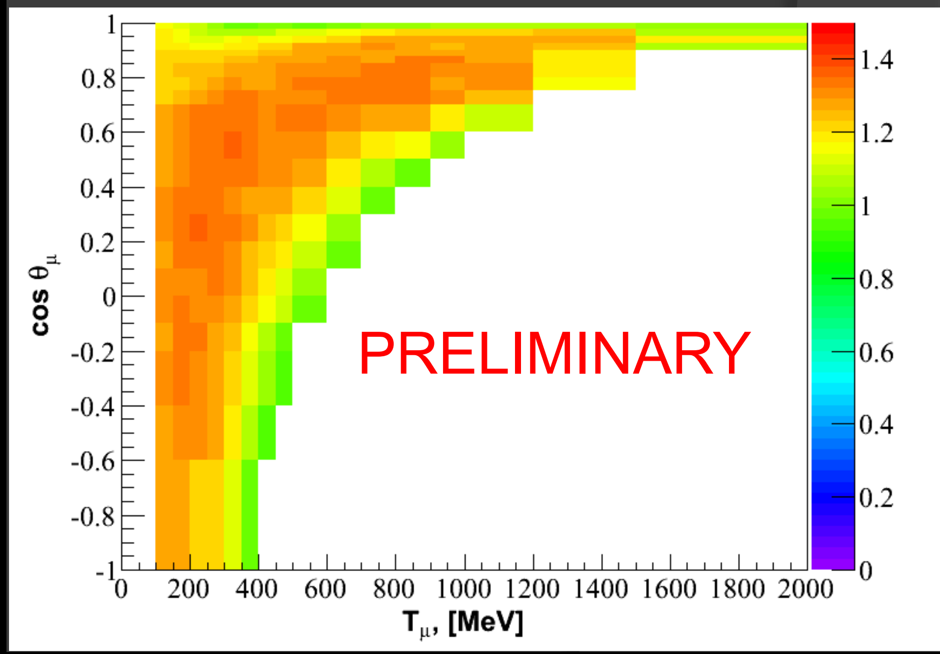



*SciBooNE CC Inclusive paper - Phys. Rev. D 83, 012005 (2011)*

# CC inclusive cross-sections in muon kinematics

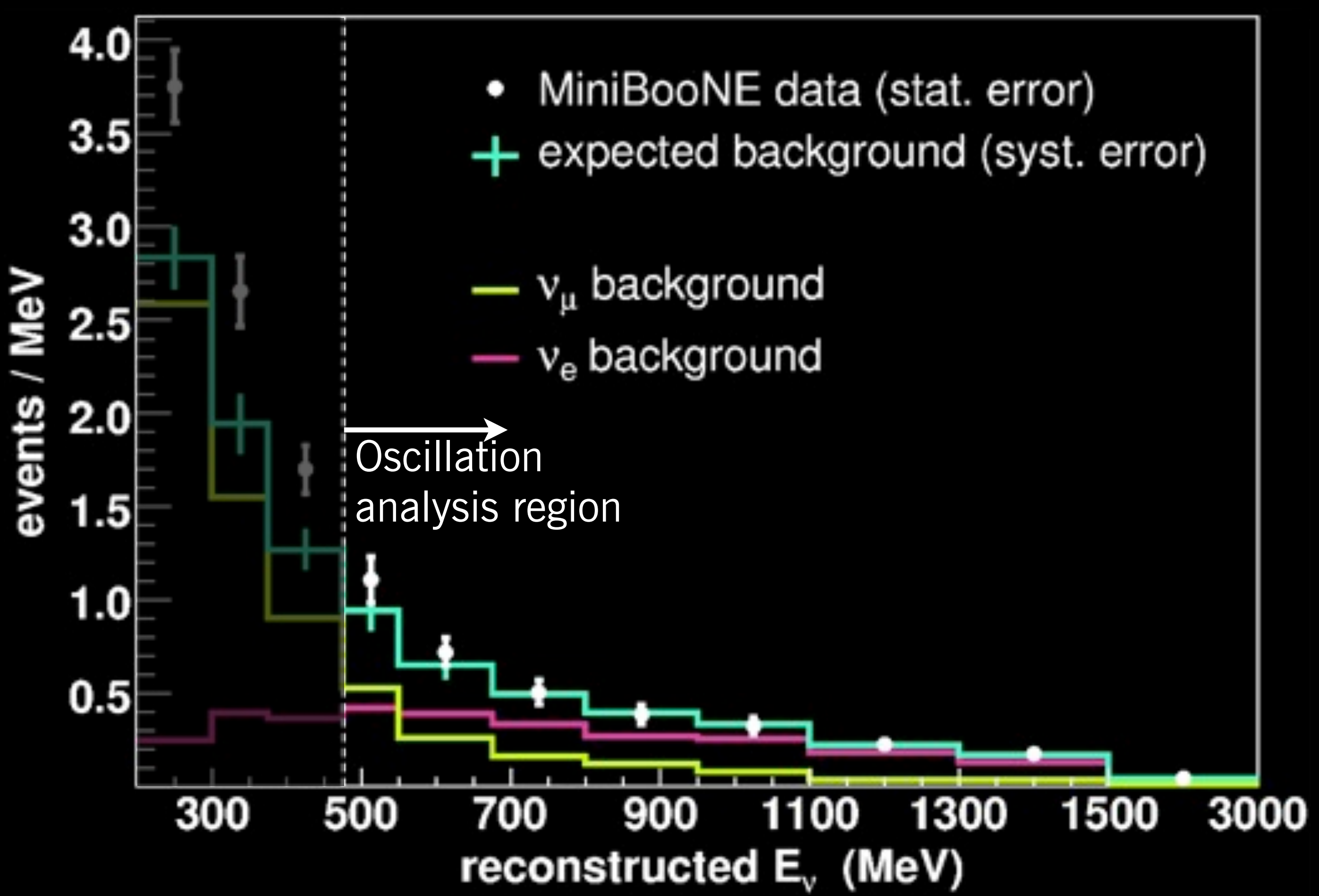
- Top plot shows the flux integrated double differential cross section in muon kinematics $d^2\sigma/dT_\mu d\cos\theta_\mu$.
- Double-differential cross-section
- Bottom plot shows the ratio with the model (NUANCE).
- Model: Fermi gas model (Smith-Moniz) with $M_A^{QE} = 1.23$ GeV, $\kappa=1.019$, Rein-Seghal $M_A^{res}$.
- Working on this cross-section as function of neutrino energy



# 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 $\nu_e$ or single photon production

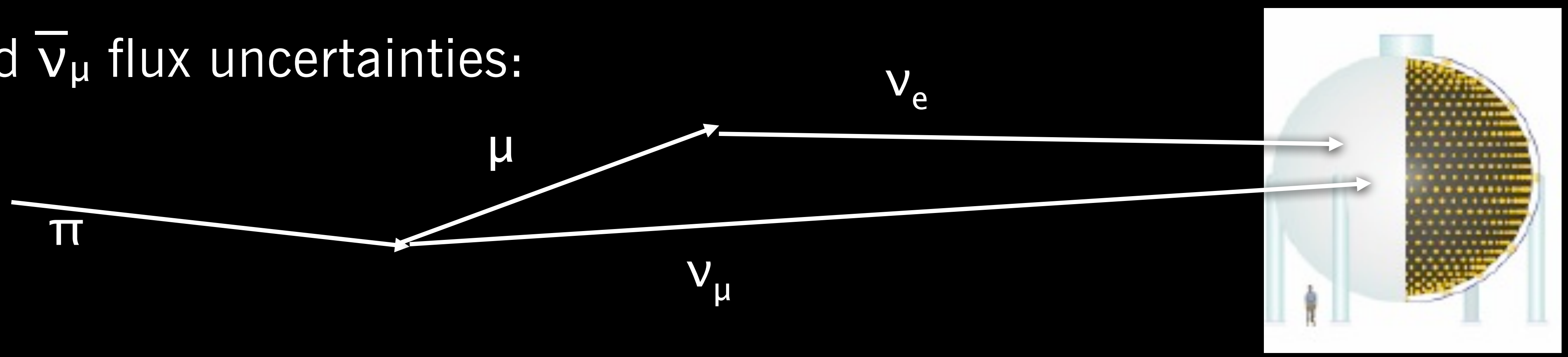



Oscillation search: *Phys.Rev.Lett*.**98**:231801 (2007)
Low-E excess: *Phys.Rev.Lett*.**102**:101802 (2009)

# 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)

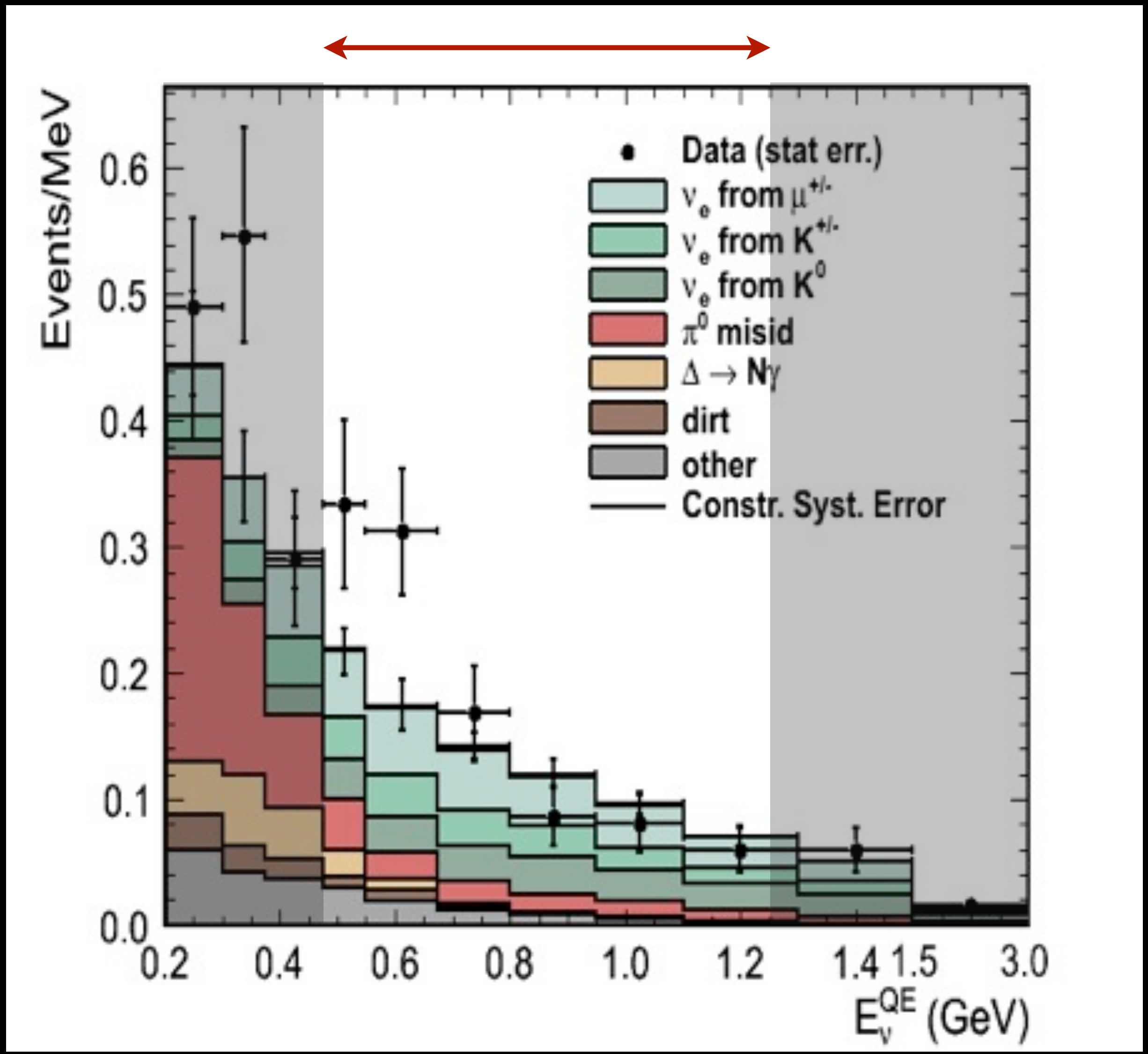
# Antineutrino Oscillations

- LSND was primarily an antineutrino oscillation search; need to verify with antineutrinos as well due to potential *CP*-violating explanations
- Antineutrino oscillation search suffers from lower statistics than in neutrino mode due to lower production and interaction cross-sections
- Also, considerable neutrino contamination $(22 \pm 5)\%$ in antineutrino event sample (e-print 1102.1964 [hep-ex])
- However, now have twice the protons on target compared to neutrino mode

# Data in antineutrino oscillation search: 2010 result with 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 $\bar{\nu}$ beam

475-1250 MeV
oscillation-sensitive region

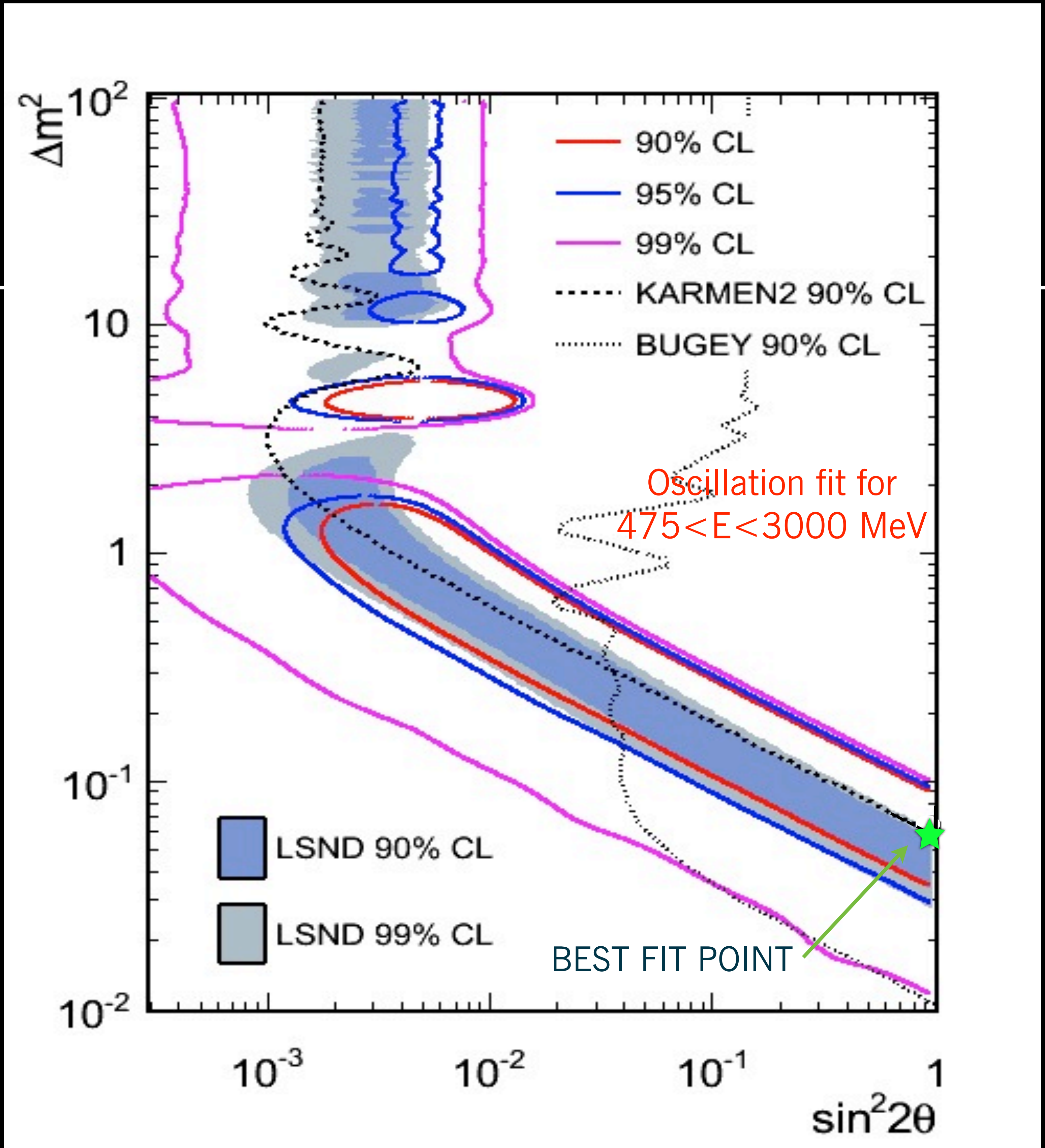



•*Phys. Rev. Lett. 105, 181801 (2010)*

# Electron antineutrino appearance oscillation result from 2010

- 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)*



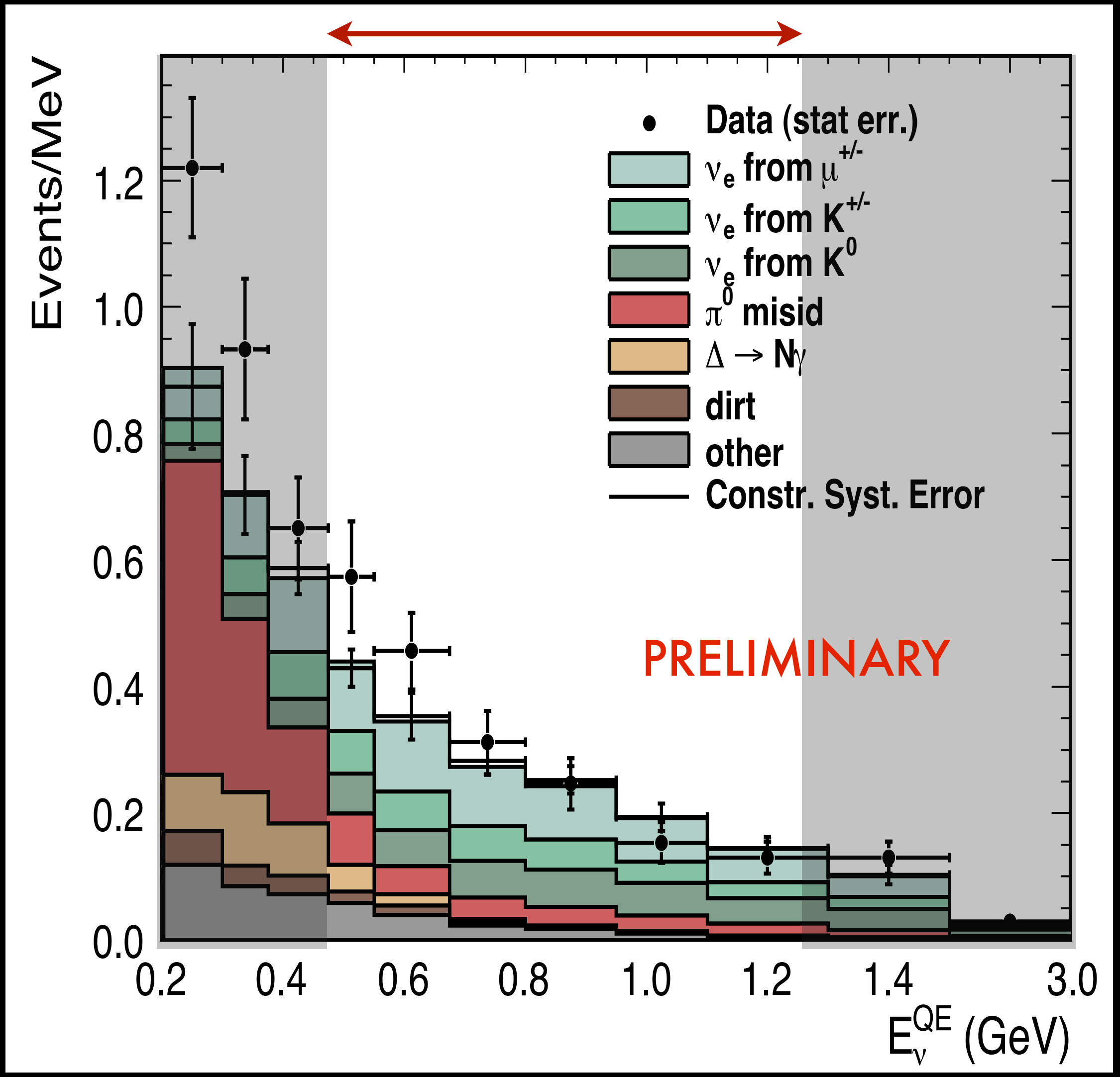
# Updated antineutrino data: full 11.3E20 POT

- Analysis is very nearly unchanged; double the statistics
- Most significant changes:
  - New constraint on neutrino flux from $K^+$ decays from SciBooNE result (e-print 1105.2871 [hep-ex]). Reduces this component of background by 3%; error by factor of 3
  - In-situ measurement of neutrino contamination in antineutrino beam: Phys.Rev.D81 072005 (2011).
- Other systematic errors, constrained by MiniBooNE data, shrink fractionally due to higher statistics in control samples:
  - Pion-decay neutrino normalization factors
  - Dirt neutrino background
  - Neutral-current $\pi^0$ production

# Updated antineutrino data: 11.3E20 POT

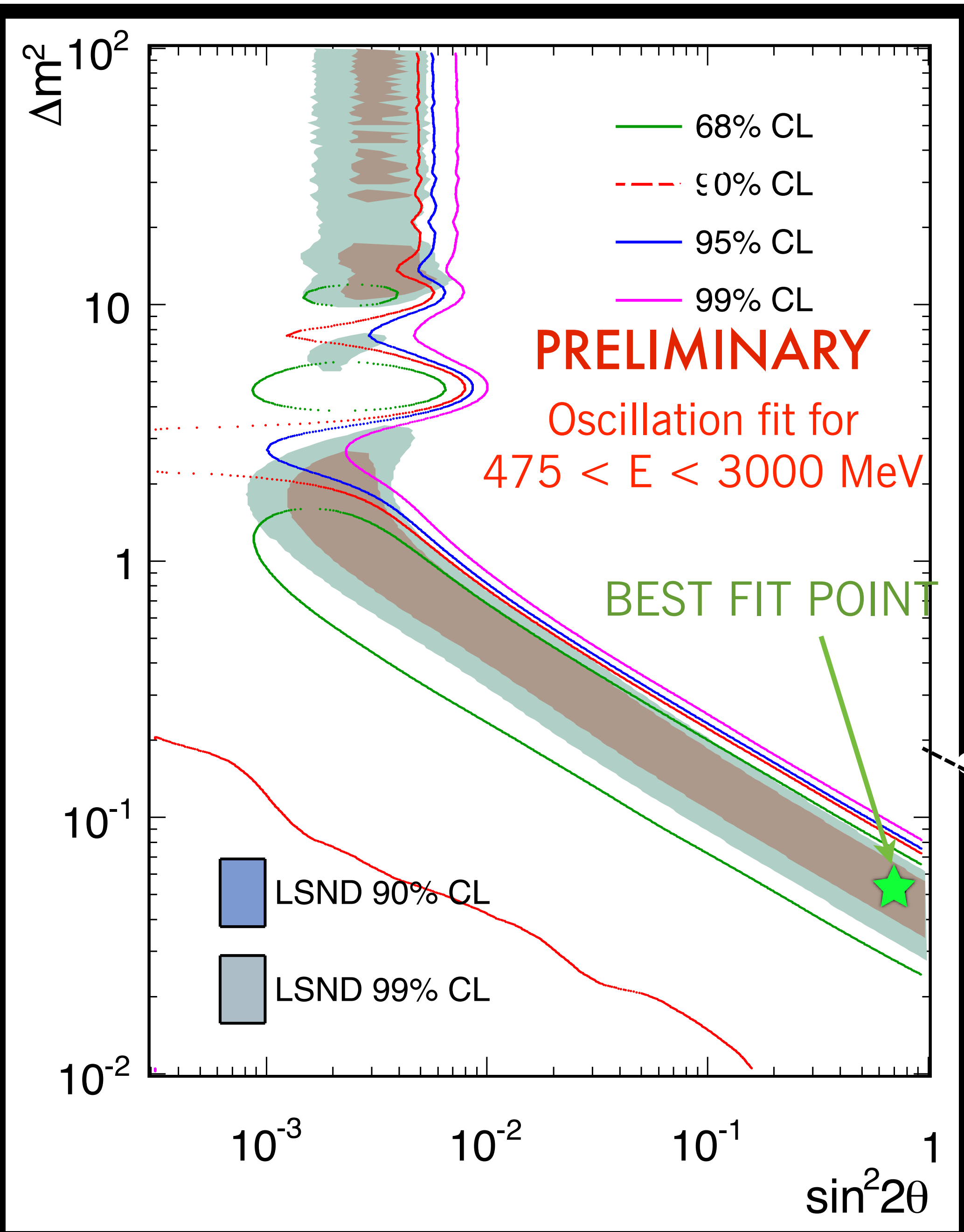
- 475 MeV < E < 1250 MeV:
  - 200.8±17.9(syst) expected after fit constraints
  - 221 observed; excess 20.1±22.8 (total)
  - Raw “one-bin” counting excess significance 0.88σ
- Excess in oscillation-sensitive region is reduced somewhat with new data; low-energy excess is more significant and resembles neutrino-mode data

475-1250 MeV
oscillation-sensitive region



# Updated electron antineutrino appearance oscillation results

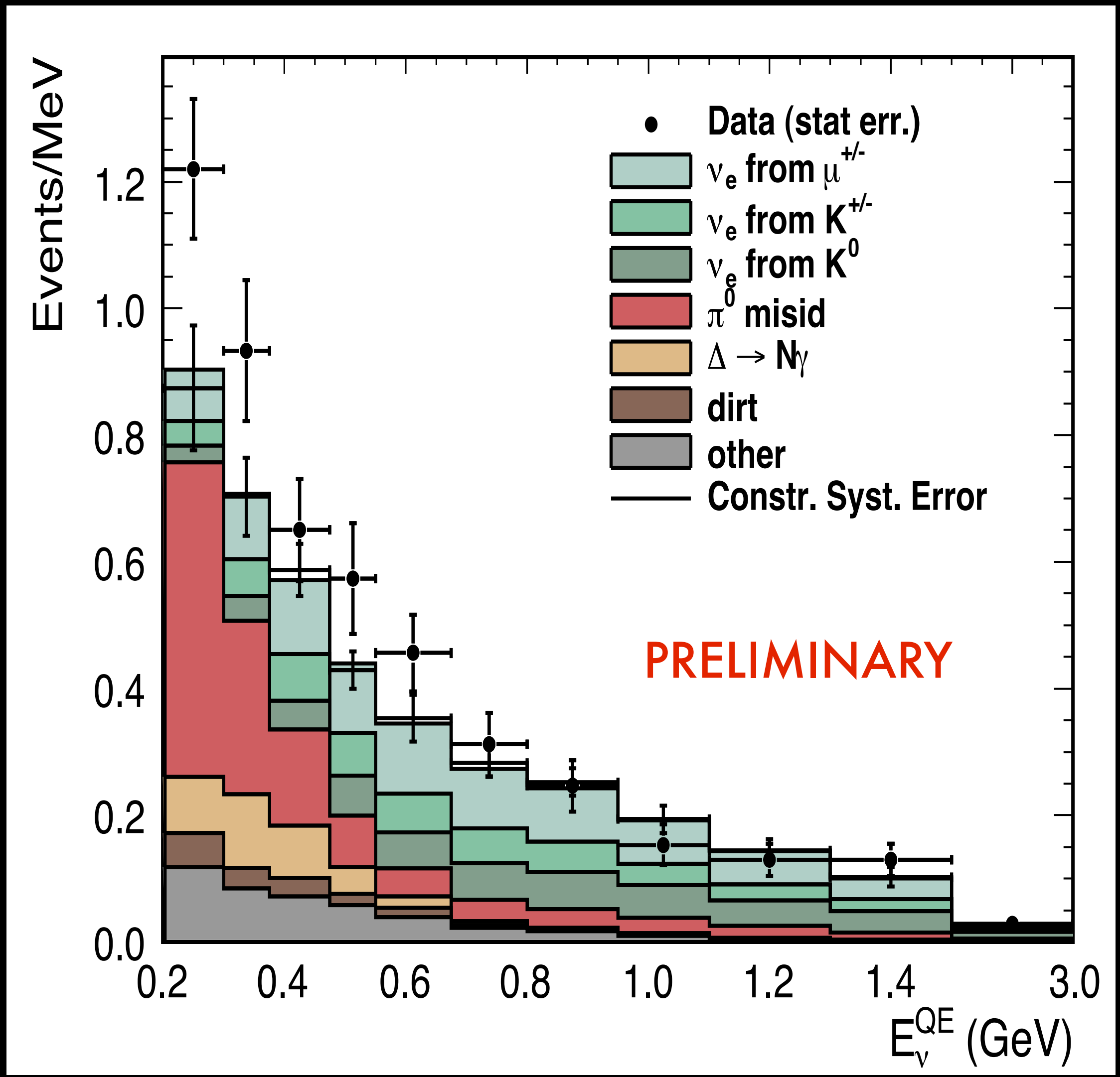
- Results for **11.3E20 POT**
- Maximum likelihood fit for *simple two-neutrino model*
- Oscillation hypothesis preferred to background-only at 91.4% confidence level.
- E>475 bins only:
  - $P_{\chi 2}$(null)= 24.6%
  - $P_{\chi 2}$(best fit)= 49.2%
- Still consistent with LSND, though evidence for LSND-like oscillations no longer as strong




Primary test of LSND

# The full energy range

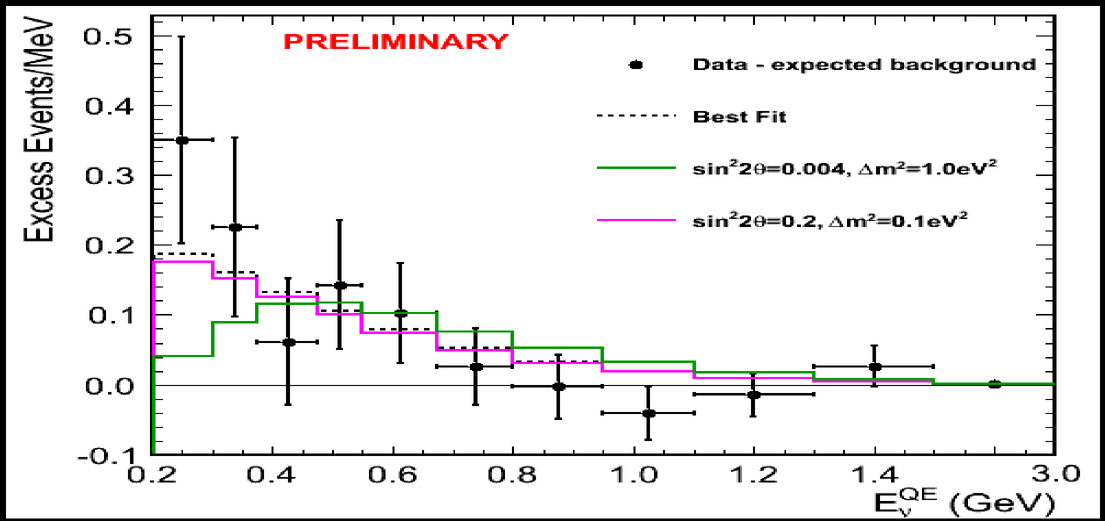
- Low-energy excess is now more prominent; excess above background in 200<E<475 MeV is 58.1±21.6 events.
- Full E<1250 range: excess is 78.2±30.8

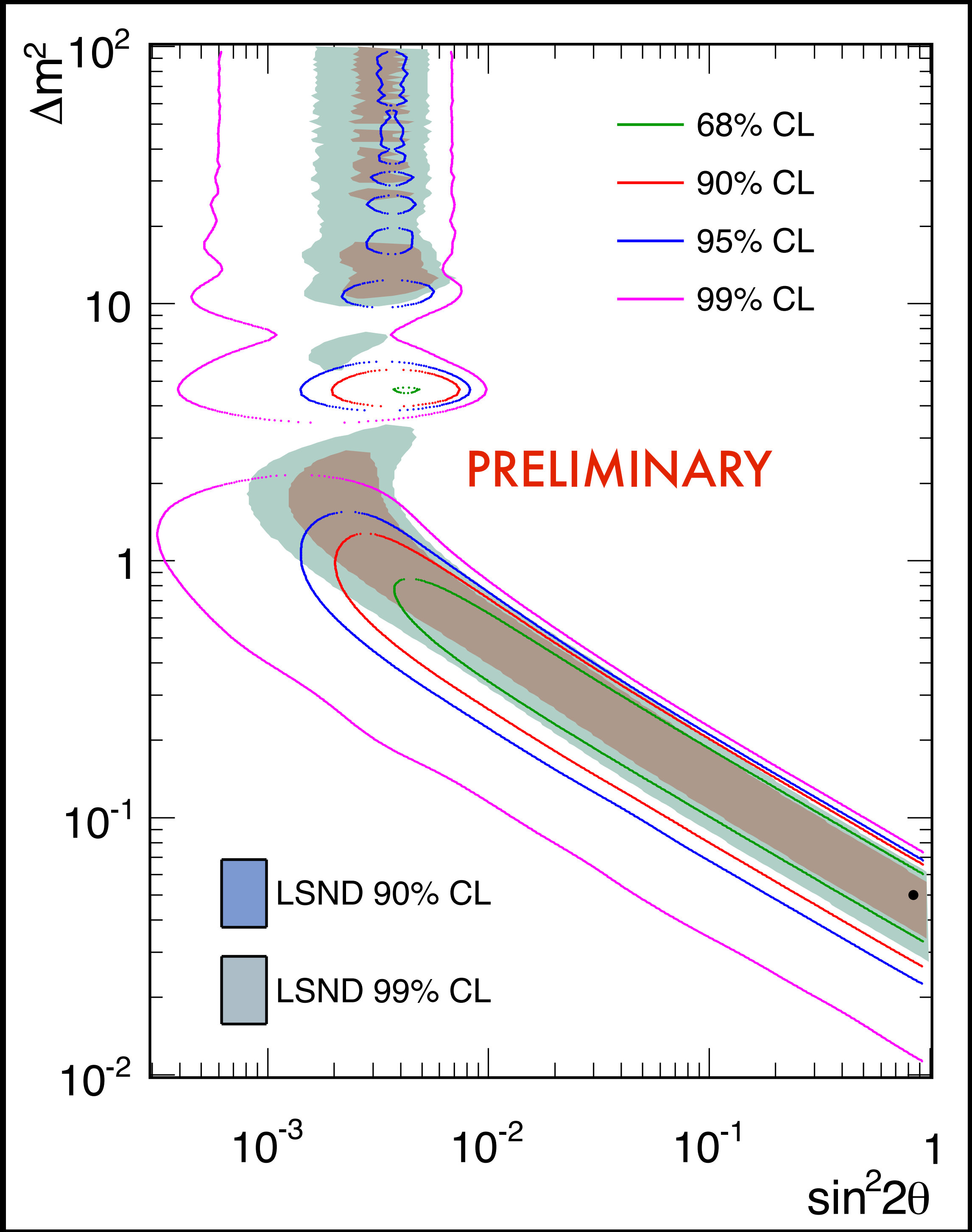


# Oscillation fits: full energy range

- Results for **11.3E20 POT**
- Maximum likelihood fit for *simple two-neutrino model*
- Oscillation hypothesis preferred to background-only at 99.5% confidence level.
- Fit over all bins:
  - $P_{\chi 2}$(null)= 5.4%
  - $P_{\chi 2}$(best fit)= 67.1%

This is not our primary test of LSND, due to known low-energy excess: can't be interpreted as a pure antineutrino fit



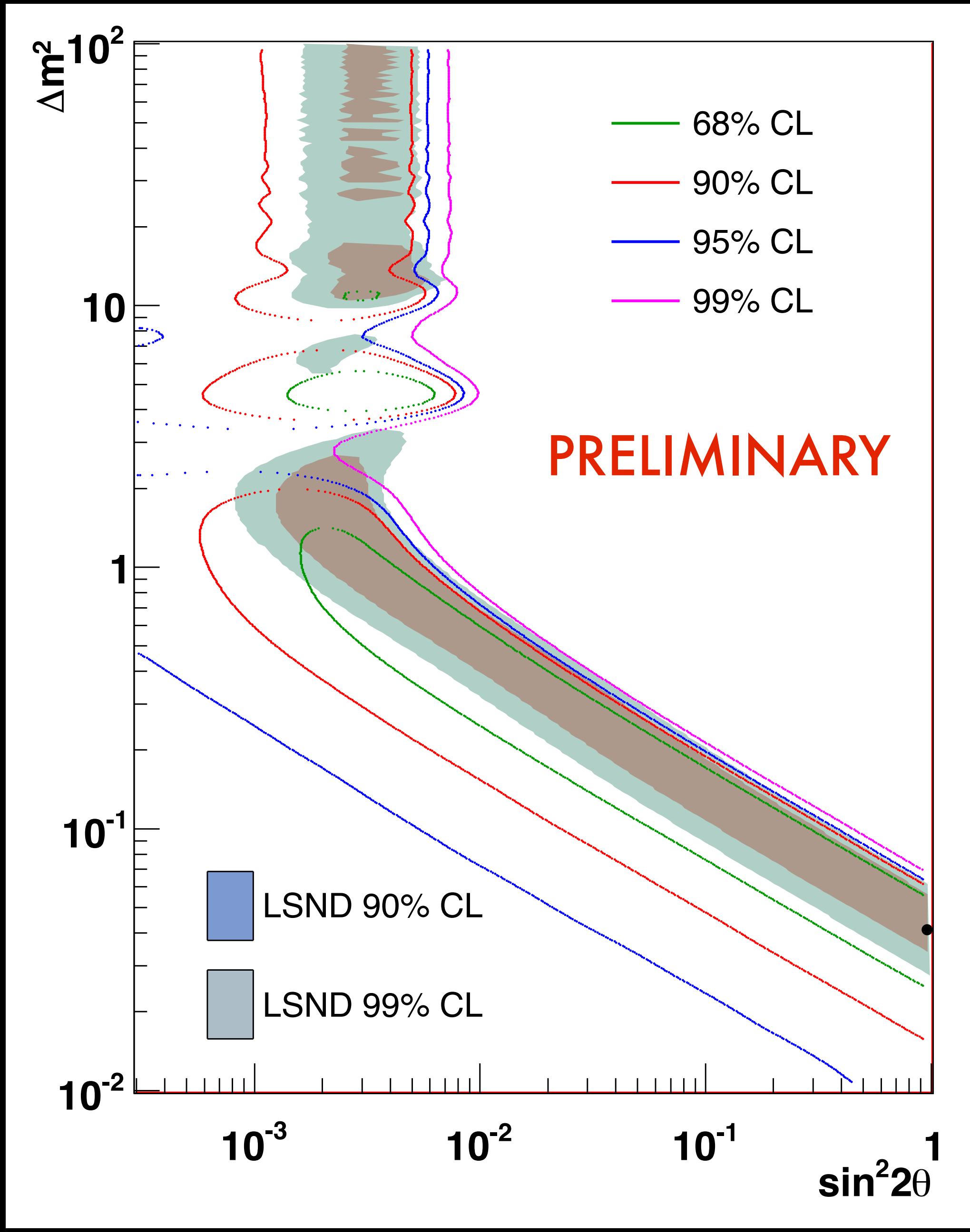



# Low-energy excess: how does it scale?

- Excess above background in 200<E<475 MeV is 58.1±21.6 events. Scaling from what is observed in neutrino mode, can test various hypotheses.
- Expect if it scales with...
  - Total background: 63
  - Neutrino contamination only: 21
  - $\Delta \to N\gamma$ decays: 50
  - Dirt: 59
  - Protons on target (neutrals in secondary beam): 210
  - $K^+$ in secondary beam: 84
  - NC $\pi^0$: 61
  - Inclusive CC: 75

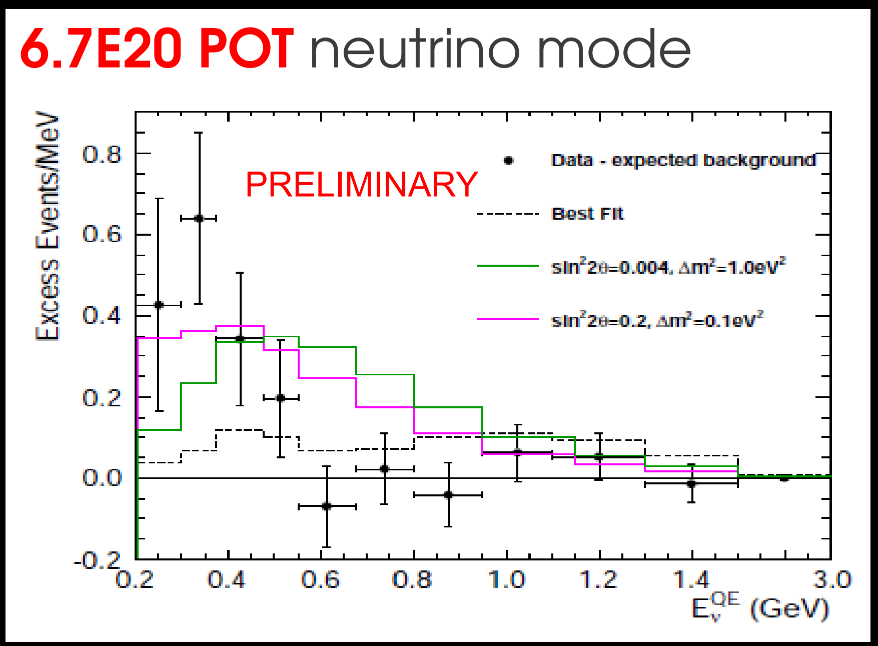
# Another way to fit: subtract low-E excess expected from neutrinos

- In principle, we are trying to fit for $\bar{\nu}$ oscillations only, with expected contributions from $\nu$ 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 96.2% confidence level.
- Fit over all bins: $P_{\chi 2}$(null)=15.6%; $P_{\chi 2}$(best fit)=54.3%



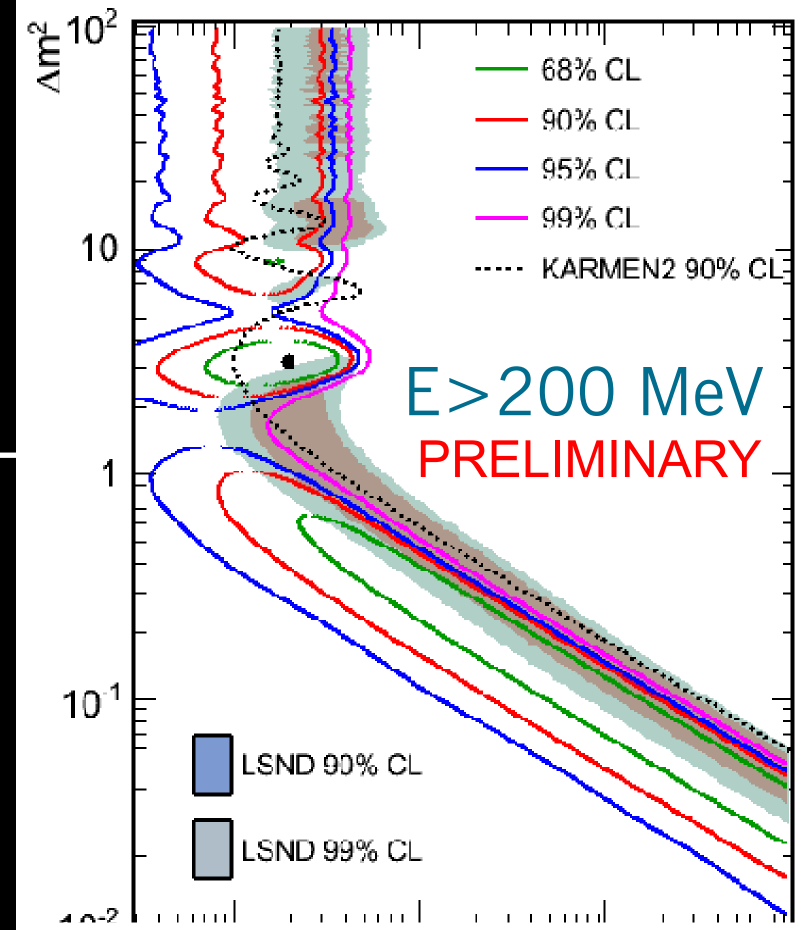
# Going back to full neutrino data, fits including low-energy region

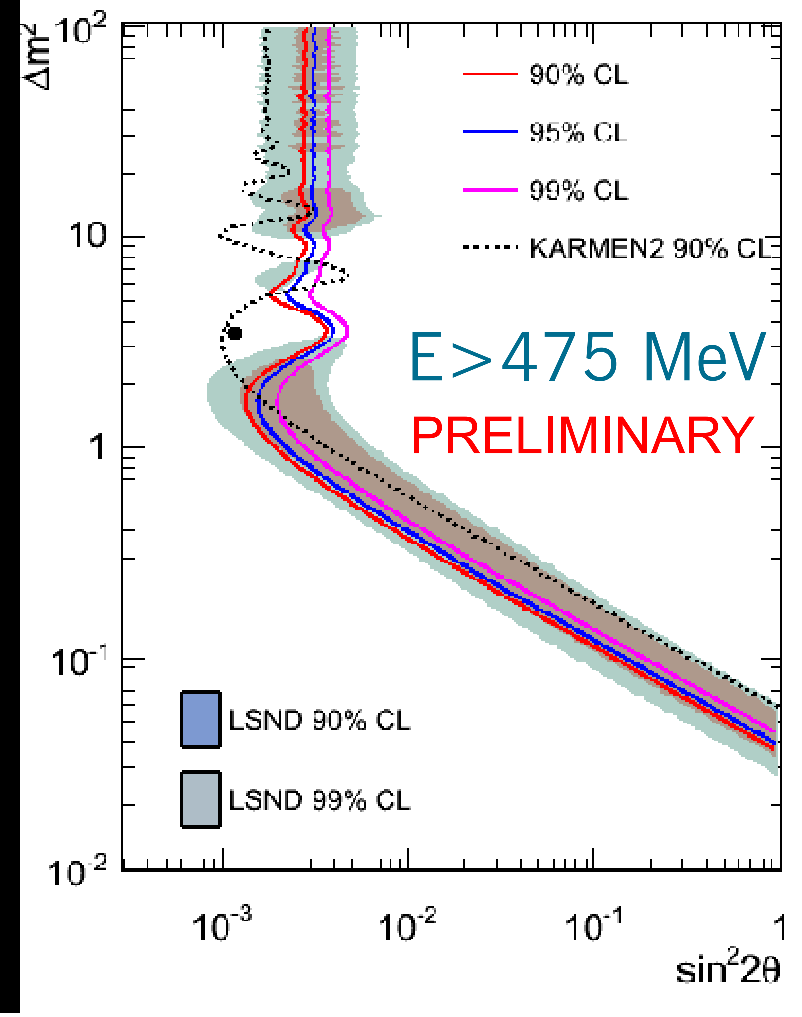
| ν mode | E > 200 MeV | E > 475 MeV |
|---|---|---|
| $\chi^2$(null) | 22.81 | 6.35 |
| Prob(null) | 0.5% | 36.6% |
| $\chi^2$(bf) | 13.24 ⟷ | 3.73 |
| Prob(bf) | 6.12% | 42.0% |




- Excess in 200-475: 124.8 ± 41.1
- Excess in 475-1250: 21.5 ± 34.9
- Some tension in fits between low- and high-energy regions

arxiv:1207.4809



# Further Neutrino/Antineutrino Running: Worthwhile?

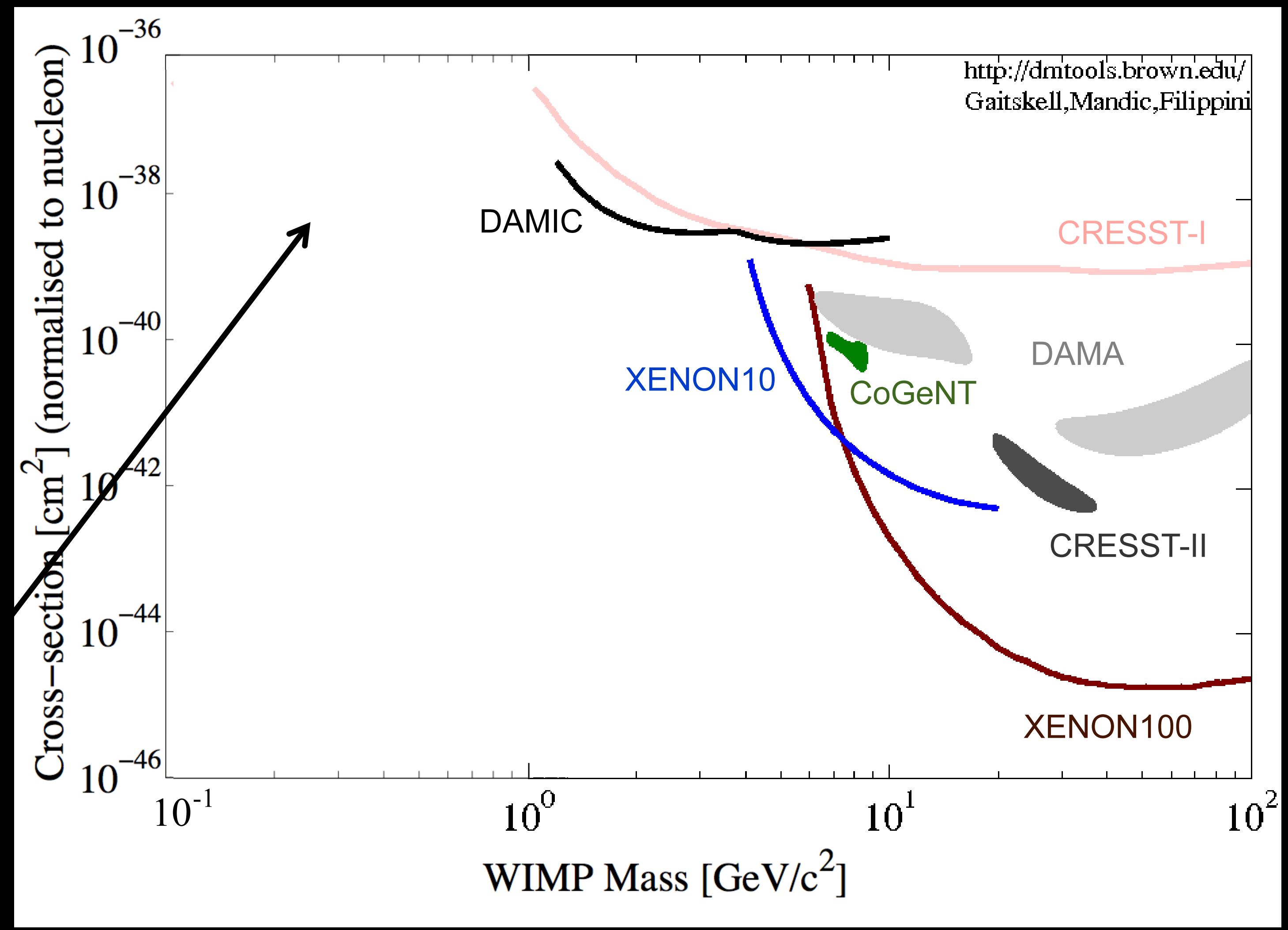
- The Booster Neutrino Beam will be used again for MicroBooNE and possibly other projects. Is it worth taking more MiniBooNE data with the current detector to increase statistics?
  - Neutrino mode: probably not. We are reaching systematic limits.
  - Antineutrino mode: possibly. We are still statistics limited, but many years would be required to double the data set.
- There are possible new configurations that would address some systematic issues.

# Future Possibilities for MiniBooNE

- MircoBooNE starts running on the BNB in early 2014 in neutrino mode.
- FNAL accelerator shutdown ends early 2013.
- $\sim$1 year opportunity for MB to run in whatever mode we dictate (WIMP search in beam off target mode). Proposal submitted to 2012 PAC.
- When MicroBooNE runs in neutrino mode, MB can run concurrently.
- Studying possibility of adding scintillator to separate backgrounds from oscillation signal. LOI submitted to 2012 PAC.

# World Data on Low-Mass Spin-Independent WIMP Scattering

- Traditional underground direct detection experiments run out of sensitivity below ~1 GeV. It turns out MB can probe this region. See PAC proposal for theory and experiment details:
- http://www.fnal.gov/directorate/program_planning/Oct2012Public/P-1032_MiniBooNE_proposal_2012.pdf



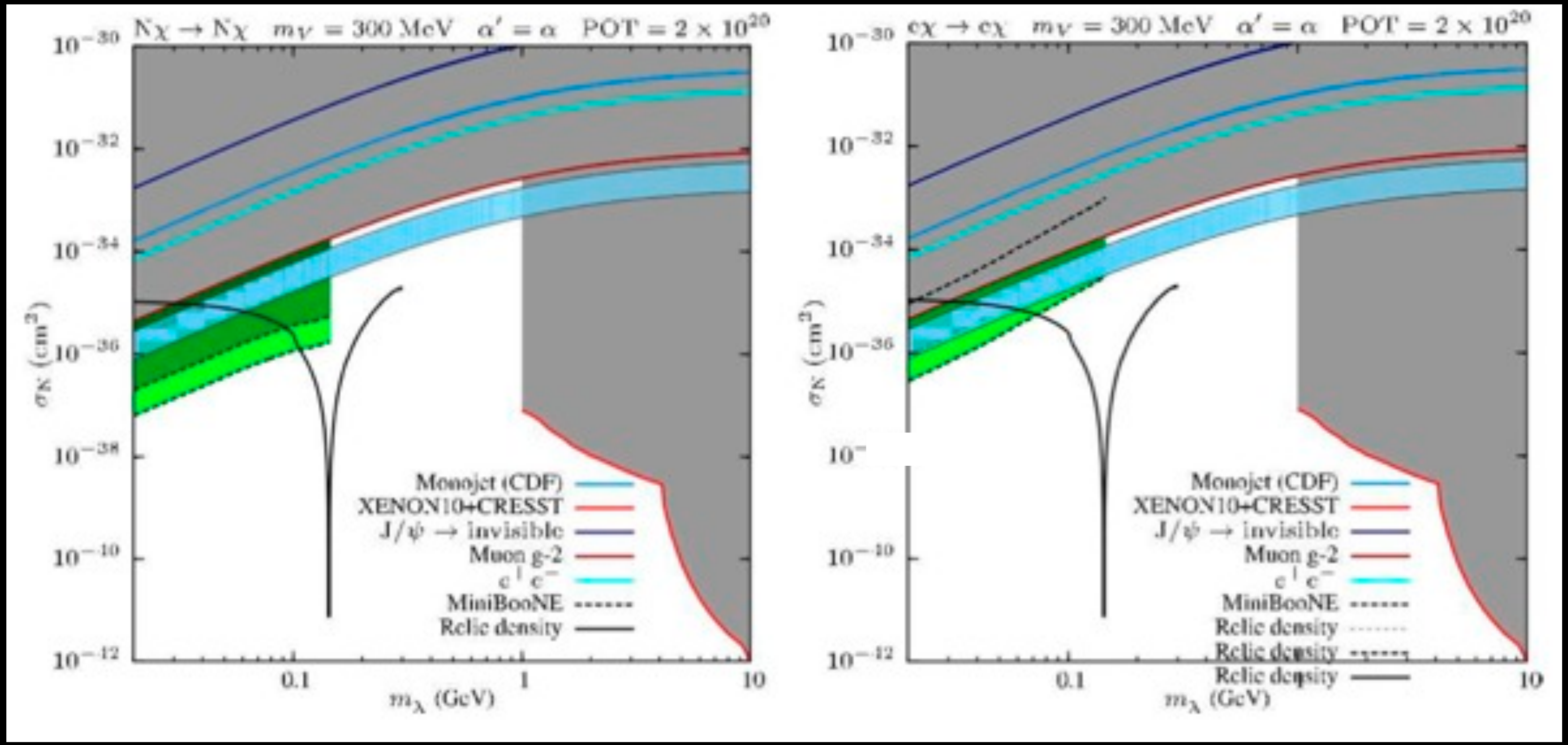
# WIMP search with off-target beam

- Idea: let primary beam bypass target and horn, and strike steel beam absorber directly
- $\pi^0$ and η produced by protons in the iron quickly decay and then couple to WIMPs
- Charged mesons are absorbed in the iron before decaying, which significantly reduces the neutrino flux (backgrounds to WIMP search) by a factor of 42.
- WIMPs scatter off nucleons or electrons (to first order looks like neutrino elastic scattering).

# MiniBooNE WIMP Sensitivities

WIMP cross section
vs
WIMP mass

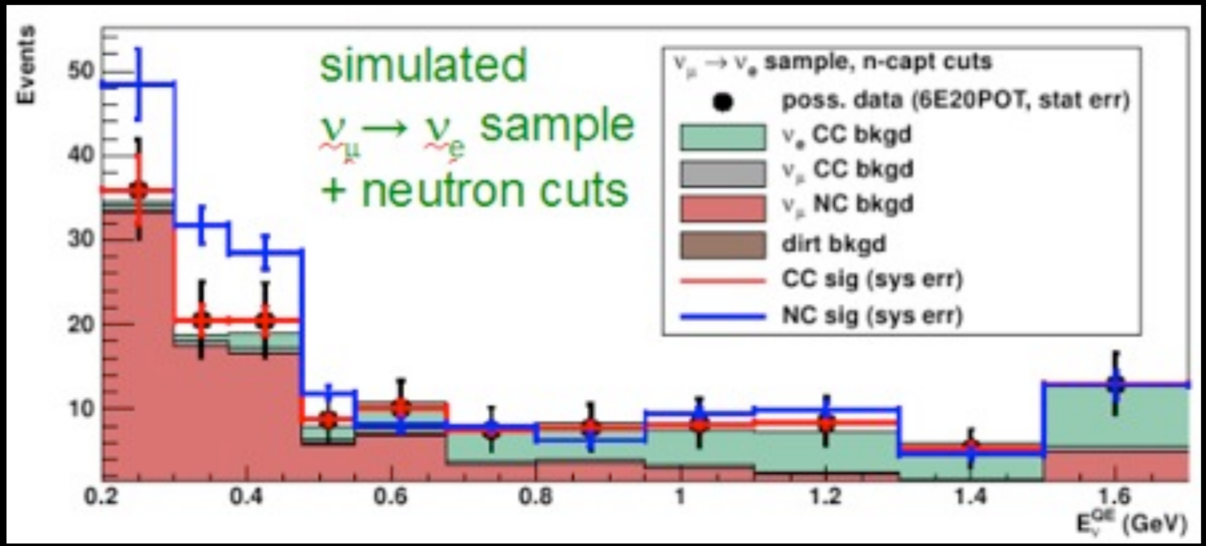
**WIMP-Nucleon Scattering** **WIMP-Electron Scattering**

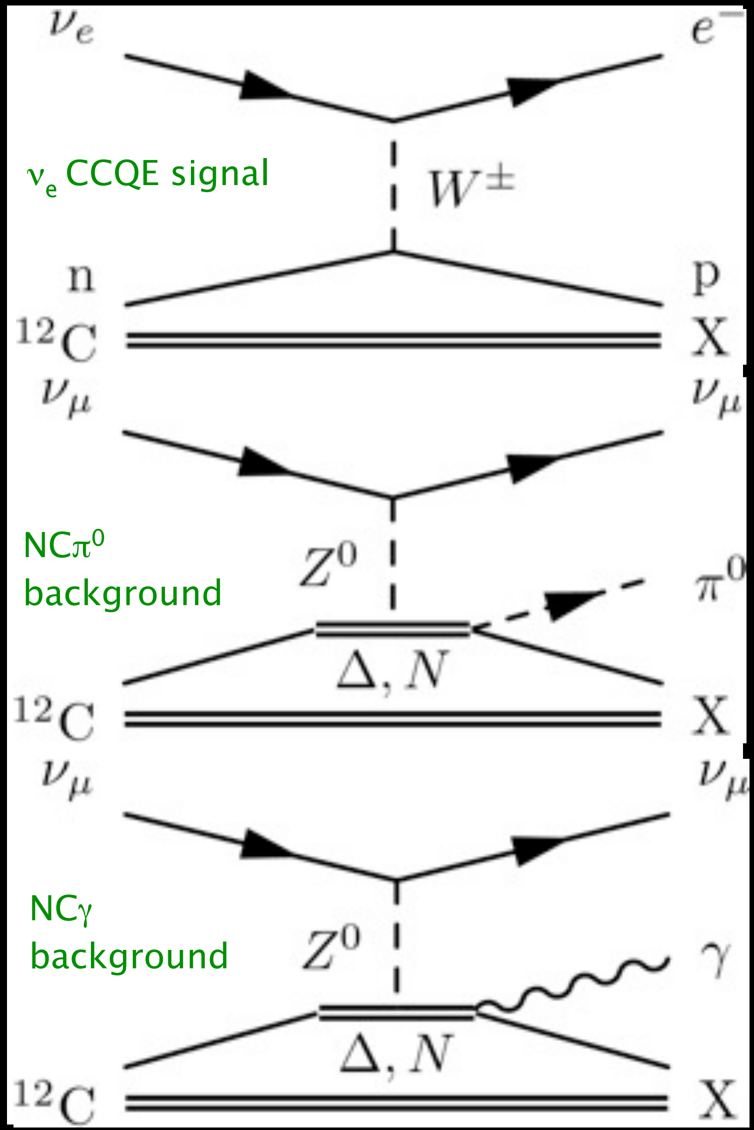



- WIMPs scatter off nucleons or electrons (to first order looks like neutrino elastic scattering).
- Number of WIMP events detected in MiniBooNE:
  - Dark Green: >1000
  - Green: 10-1000
  - Light Green: 1-10 → After all cuts, can achieve close to this region
- Light blue band is muon g-2 signal in Vector portal WIMP model.
- Solid black line is where WIMP relic density matches observation

# MiniBooNE Scintillator Option

- Test NC backgrounds: Add scintillator to enable detection of 2.2 MeV n-capture photons for an enhanced $\nu_\mu \rightarrow \nu_e$ search at low energy.
    - CC oscillation signal events have very few neutrons: 1% (at 200MeV) → 10% (1 GeV)
    - NC backgrounds have ~50% neutrons
    - can measure these neutron fractions with νμ events
- Plan: add scintillator, redo oscillation search with 6E20POT and n-capture analysis
- Will reduce systematic erorrs on NC backgrounds



# 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 $\nu_e$ and $\bar{\nu}_e$ excesses above background are 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 in high-energy range is reduced compared to 2010
  - Antineutrino results still statistics-limited; MiniBooNE may accumulate more data after shutdown, perhaps in different configuration.