MiniBooNE Update

44th Fermilab User's Meeting

Joe Grange

University of Florida

Outline

- MiniBooNE review
- Physics results in the last year
  - Oscillations
  - Cross sections
    - Neutrinos
    - Anti-neutrinos
- Summary and outlook

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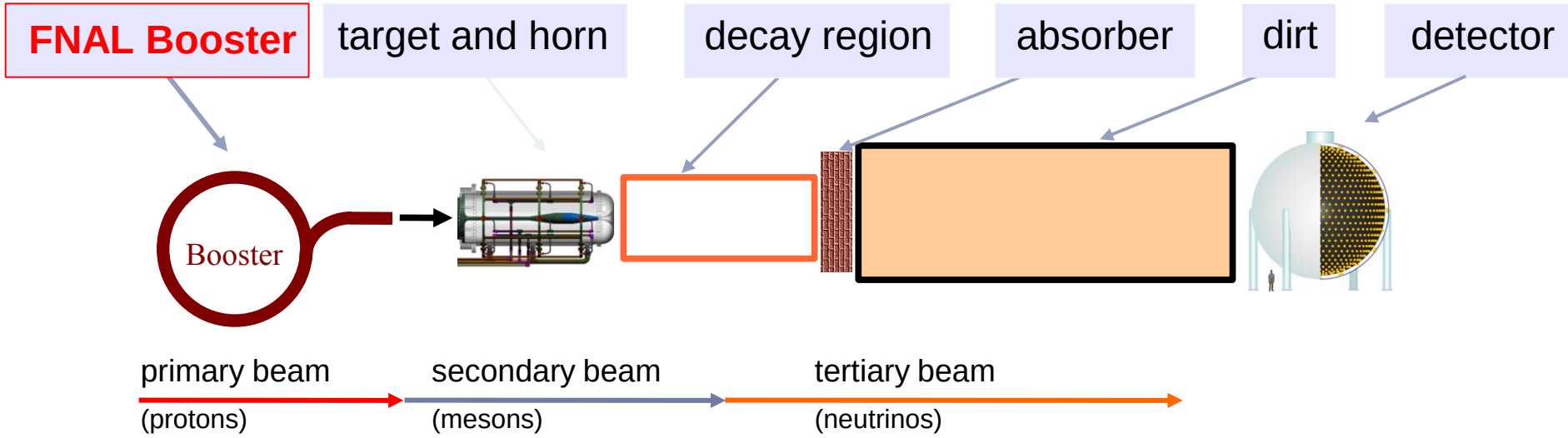
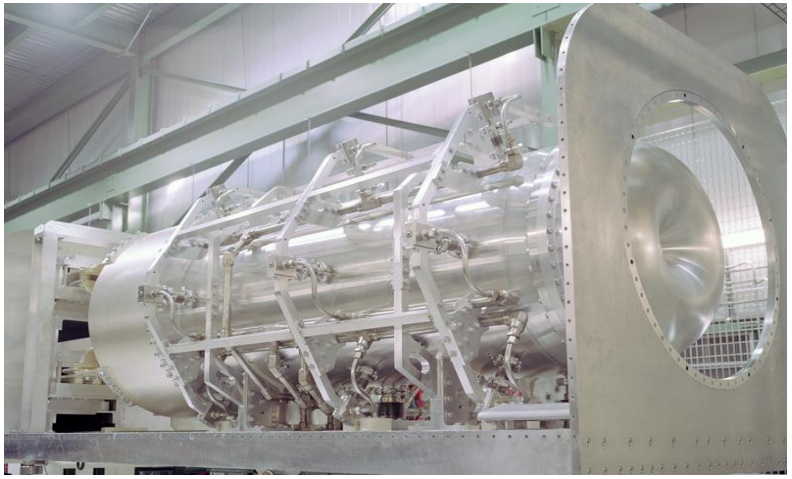
Booster Neutrino Beam

8.9 GeV/c momentum protons extracted from Booster, steered toward a beryllium target in bunches of 5×10^{12} at a maximum rate of 5 Hz

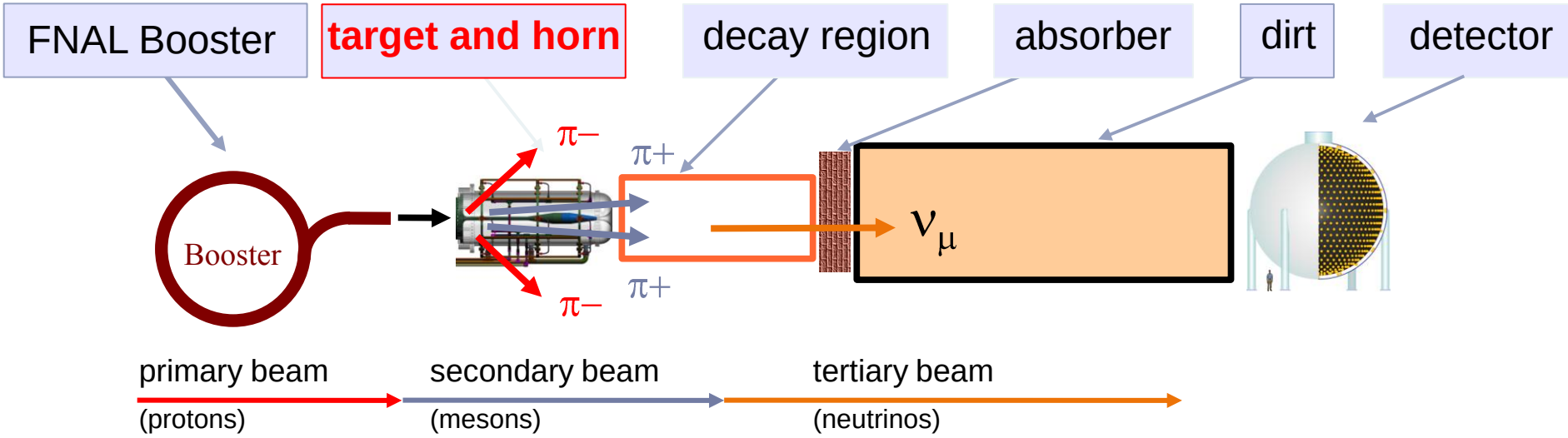


Booster Neutrino Beam



Magnetic horn with reversible polarity focuses either neutrino or anti-neutrino parent mesons

("neutrino" vs "anti-neutrino" mode)

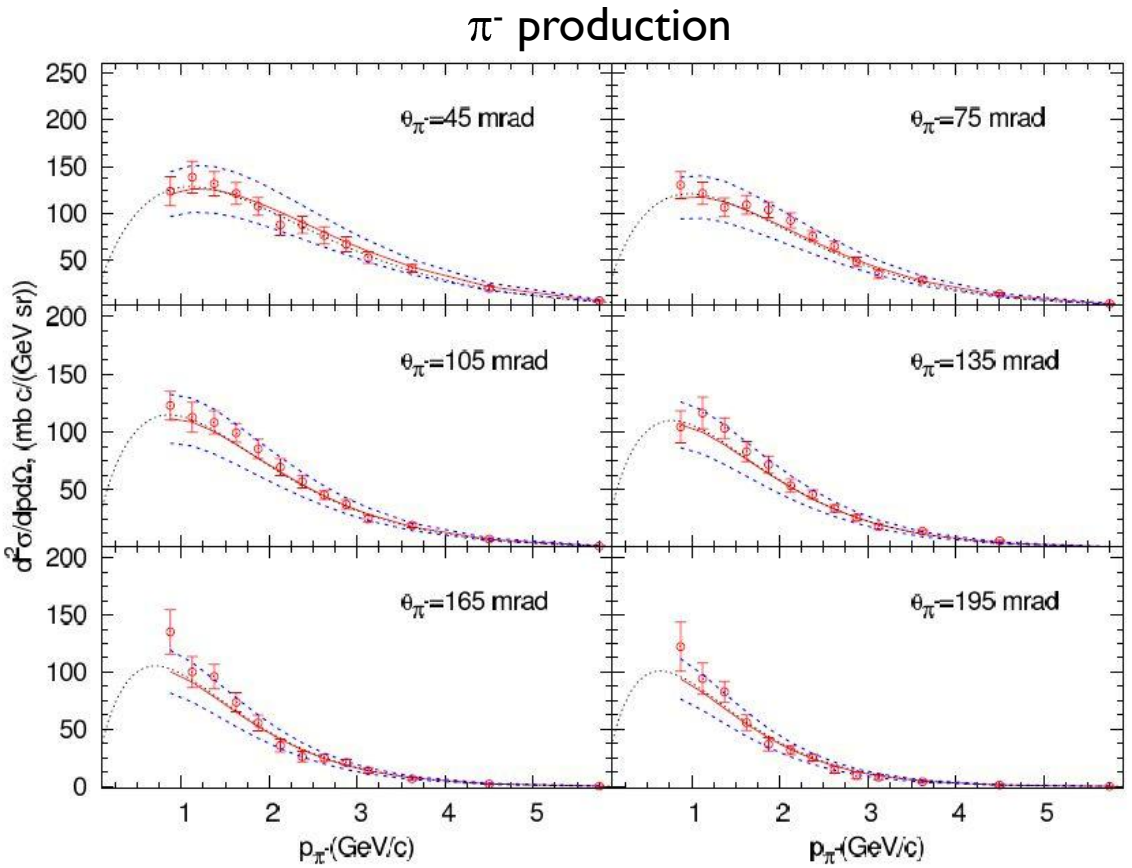


Neutrino Flux

- Flux prediction based exclusively on external data - no *in situ* tuning
- Dedicated π production data taken by HARP collaboration, measured 8.9 GeV/c

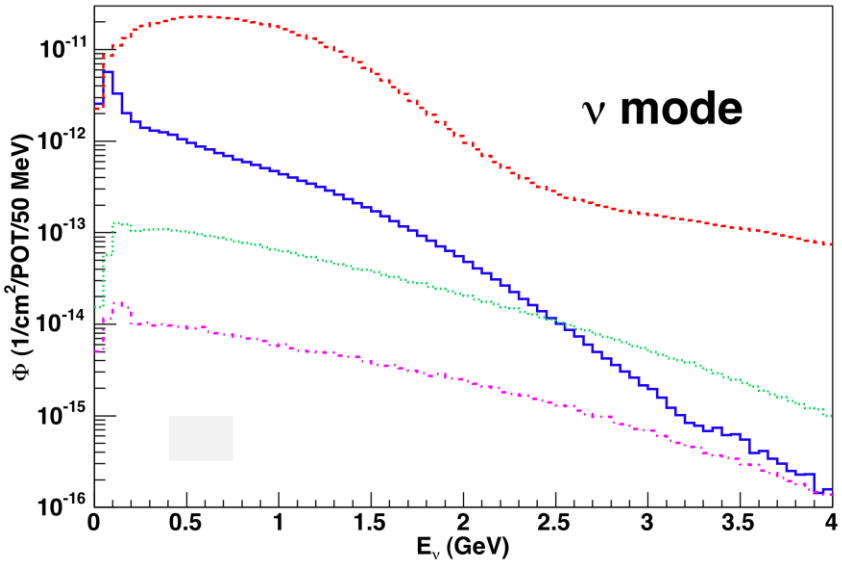
$$p + \mathrm{Be} \rightarrow \pi^{\pm} + X$$

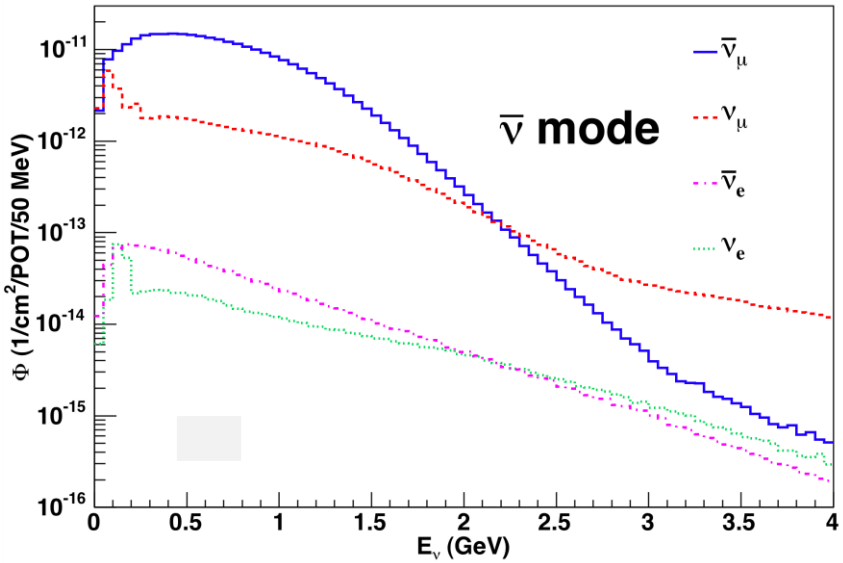
on MiniBooNE replica target



HARP collaboration,
Eur. Phys. J. C **52** 29 (2007)

Neutrino Flux



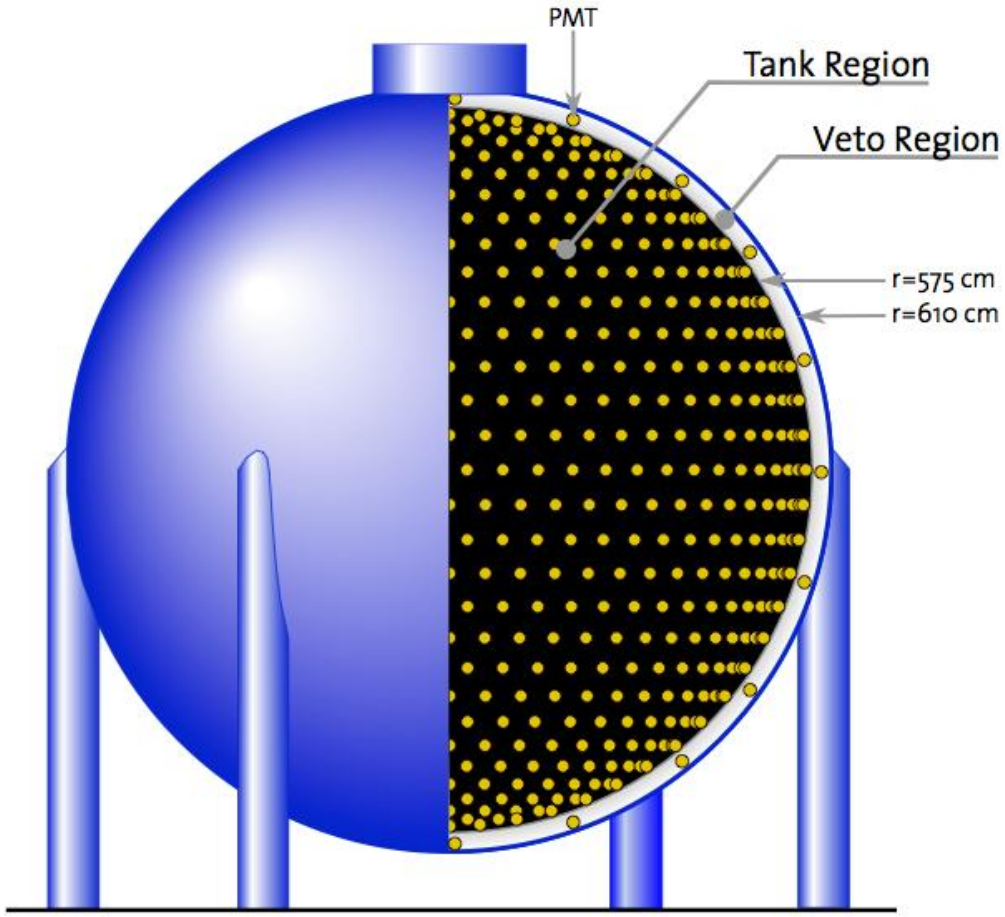


MiniBooNE collaboration,
Phys. Rev. D **79**, 072002 (2009)

- Combining HARP data with detailed Geant4 simulation gives the flux prediction at the MiniBooNE detector for positive and negative focusing horn polarities

Detector

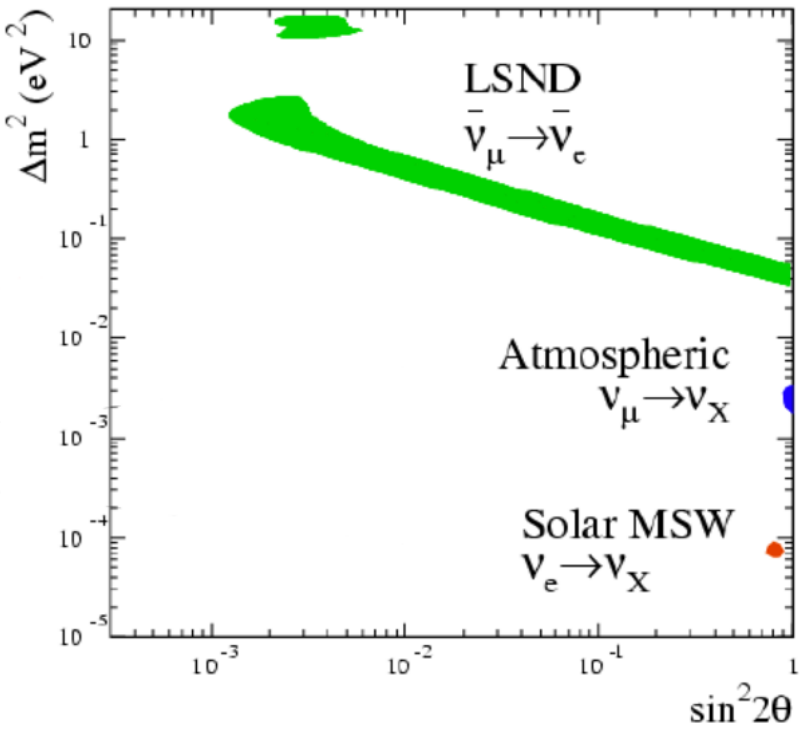
- 6.1m radius Cherenkov detector houses 800 tons of undoped mineral oil, 1520 PMTs in two regions
  - Inner signal region
  - Outer veto region (35 cm thick)



Nucl. Instr. Meth. A599, 28 (2009)

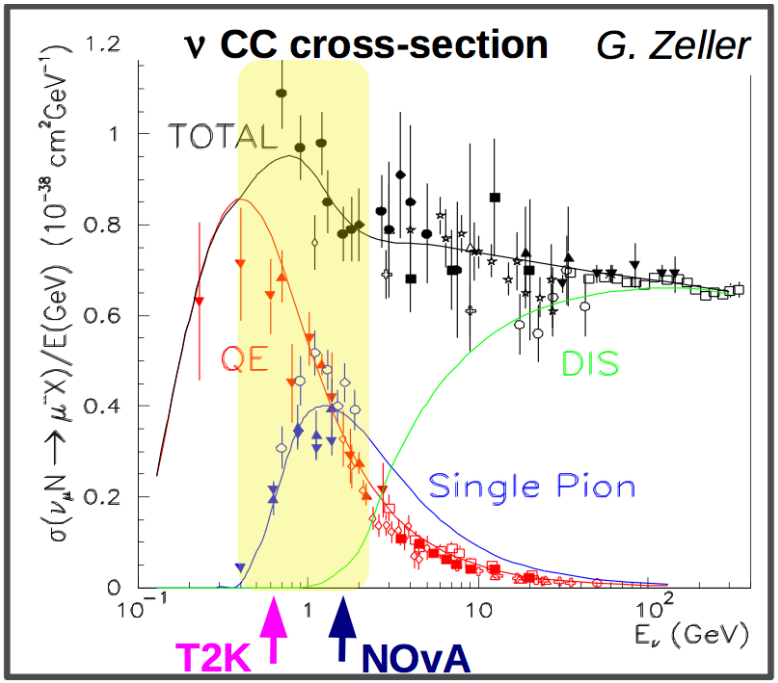
Physics Goals 1

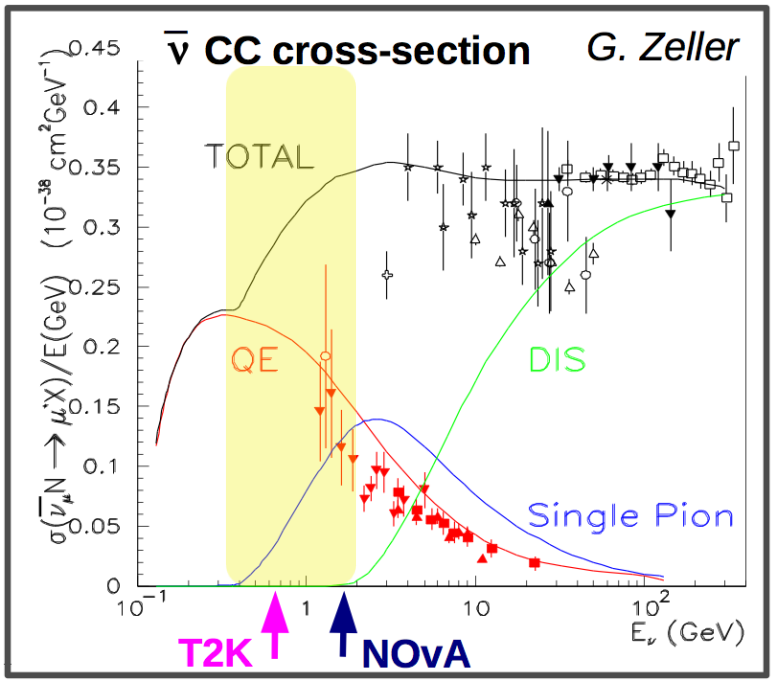
- Primarily a neutrino oscillation experiment
  - Testing anomalous LSND result of $\bar{\nu}_e$ appearance in $\bar{\nu}_\mu$ beam
- MiniBooNE probes the LSND oscillation region with different backgrounds and systematic errors



Physics Goals 2

Pre-MiniBooNE σ's

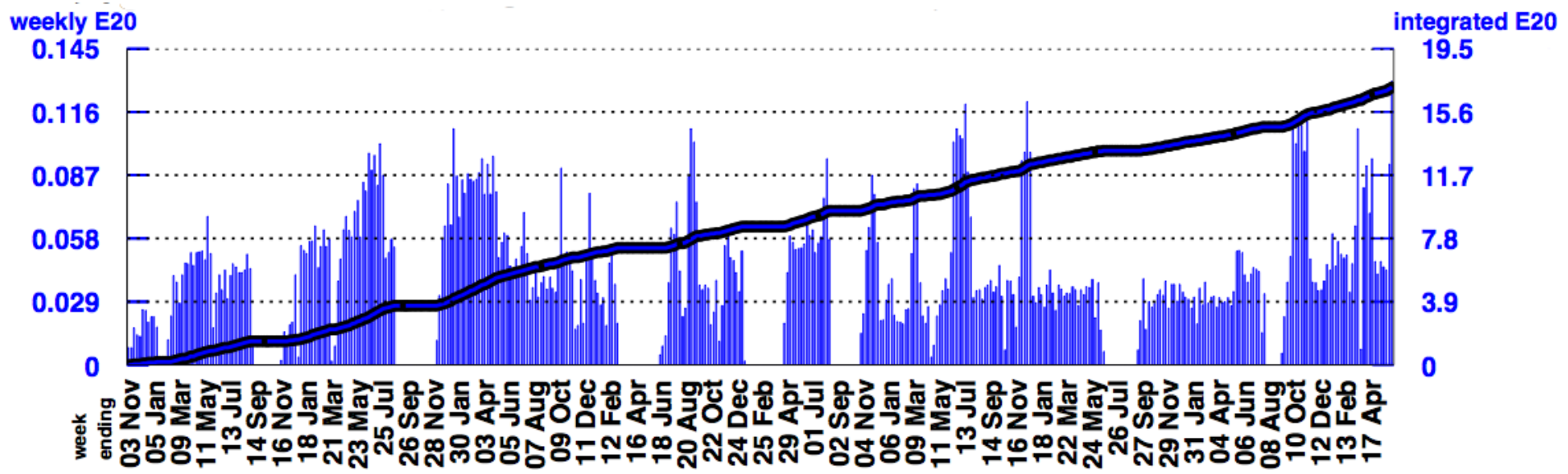




- Cross sections at MiniBooNE energy sparsely measured
- No sub-GeV $\bar{\nu}_\mu$ cross sections
  - Vital for future ~~CP~~ studies

- Recent results suggest these cross sections are more interesting than we thought! (later)

A BooNE of Data



Number of Protons on Target

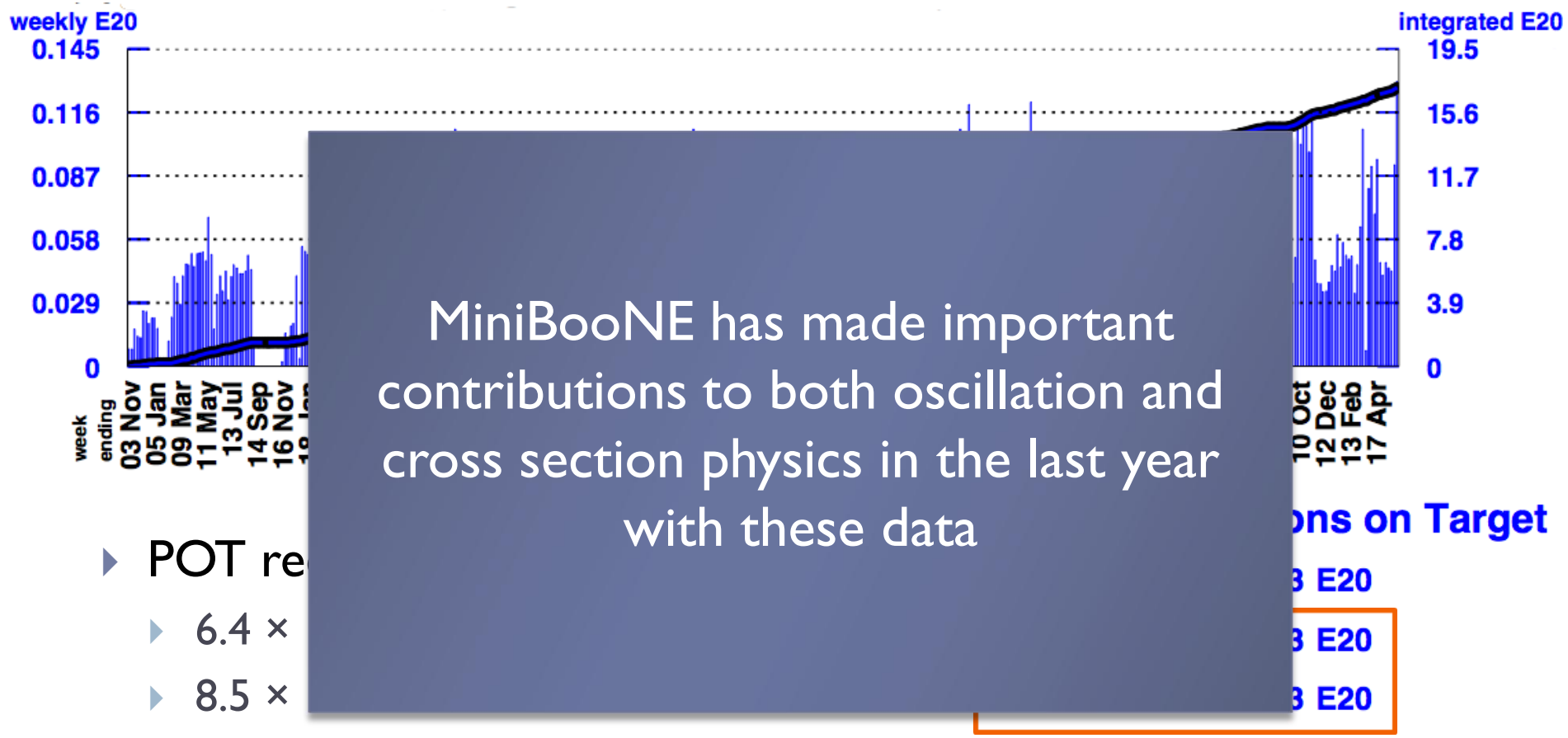
To date 17.1283 E20

Largest week: 0.13 E20

Latest week: 0.13 E20

- POT received from Booster:
  - 6.4×10^{20} in ν mode
  - 8.5×10^{20} in $\bar{\nu}$ mode
- **Thank you to accelerator division!**

A BooNE of Data



MiniBooNE has made important contributions to both oscillation and cross section physics in the last year with these data

- POT re
  - 6.4 ×
  - 8.5 ×
- **Thank you to accelerator division!**

- MiniBooNE review
- Physics results in the last year
  - Oscillations
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    - Neutrinos
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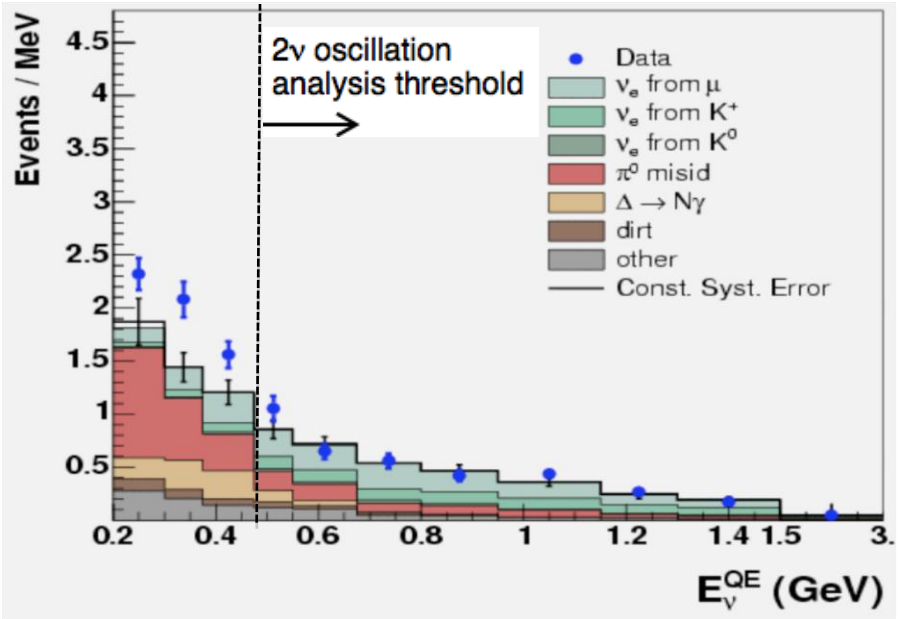
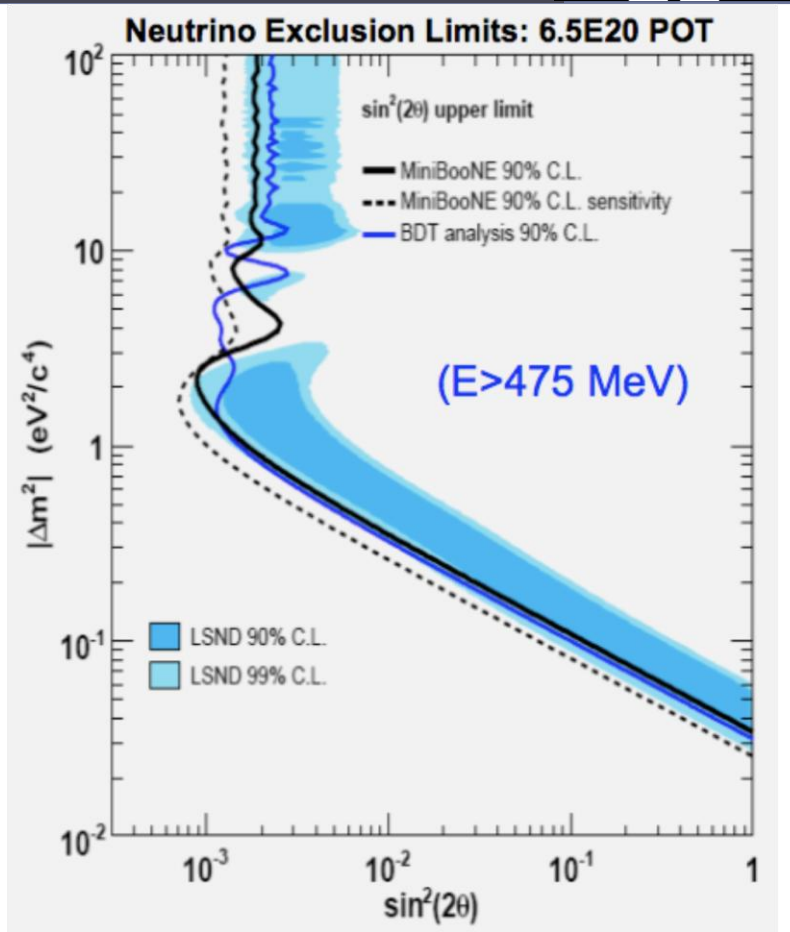
$\nu_\mu \rightarrow \nu_e$ Appearance Reminder

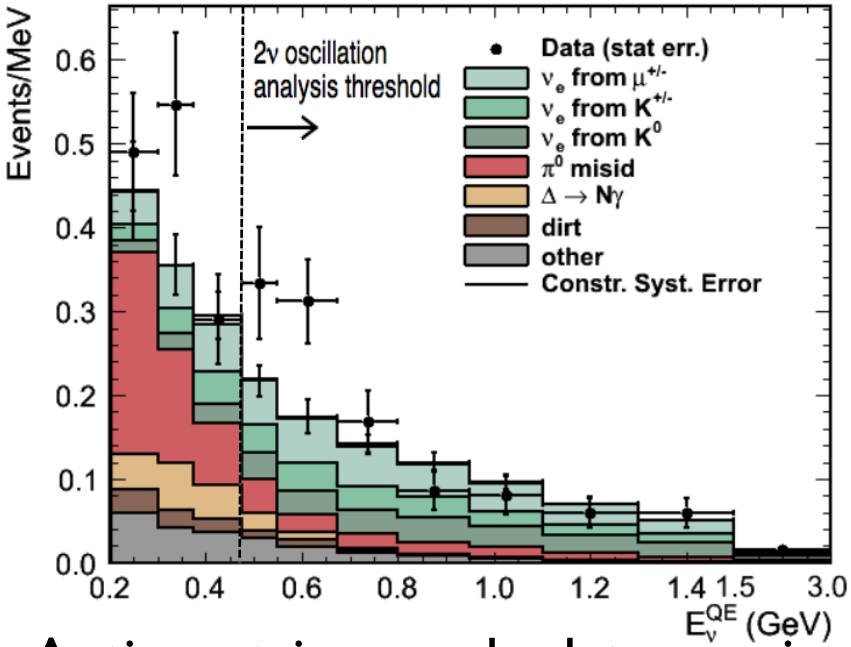


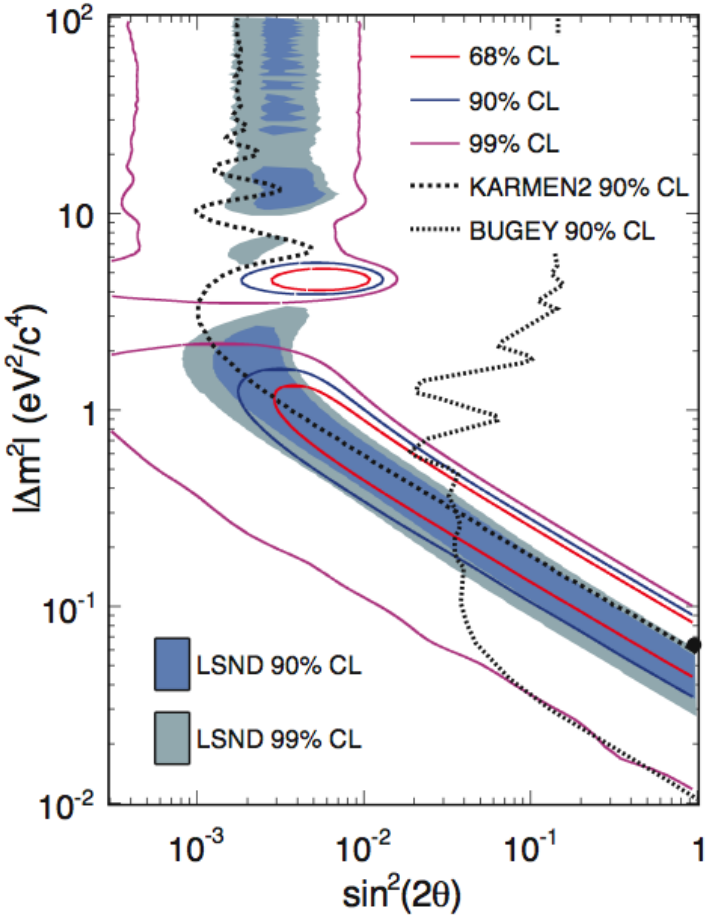


Phys. Rev. Lett. **98**, 231801 (2007)

- Neutrino-mode appearance analysis does not confirm LSND two-neutrino oscillation interpretation
  - assuming CP conservation
- Unexplained low-energy excess (3σ) observed

$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ Appearance (2010)





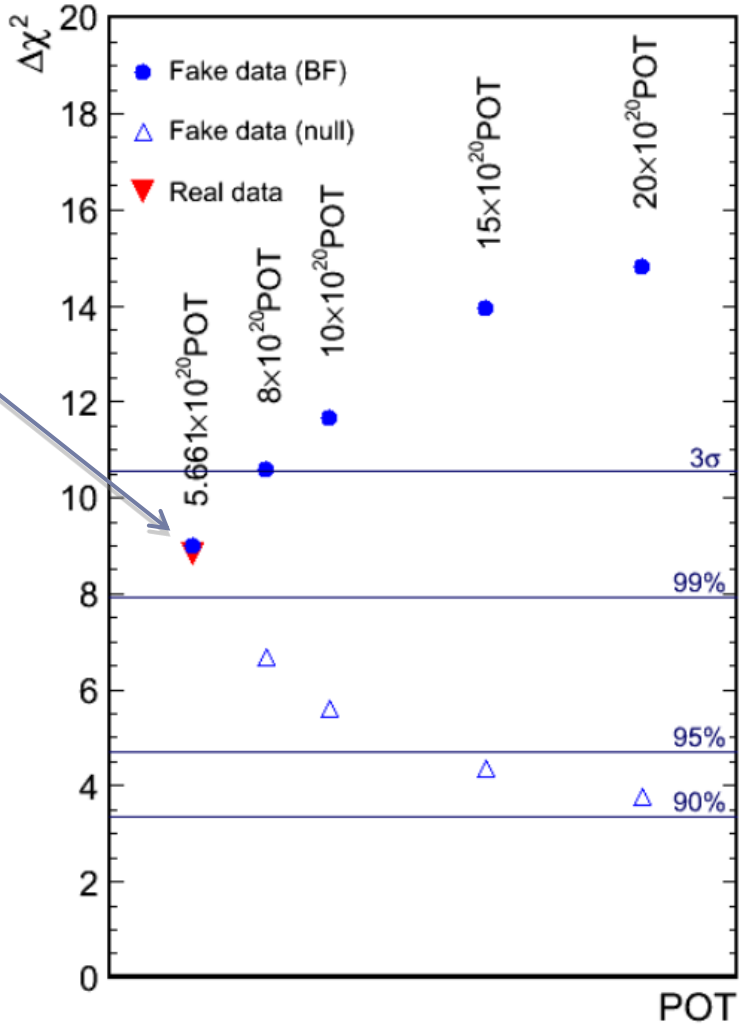
- Anti-neutrino mode data consistent with LSND signal (!)
  - probability of 0.5% for background-only hypothesis

Ph.D. thesis, G. Karagiorgi, MIT
Phys. Rev. Lett. **105**, 181801 (2010)

- Constrains explanations of low-energy excess

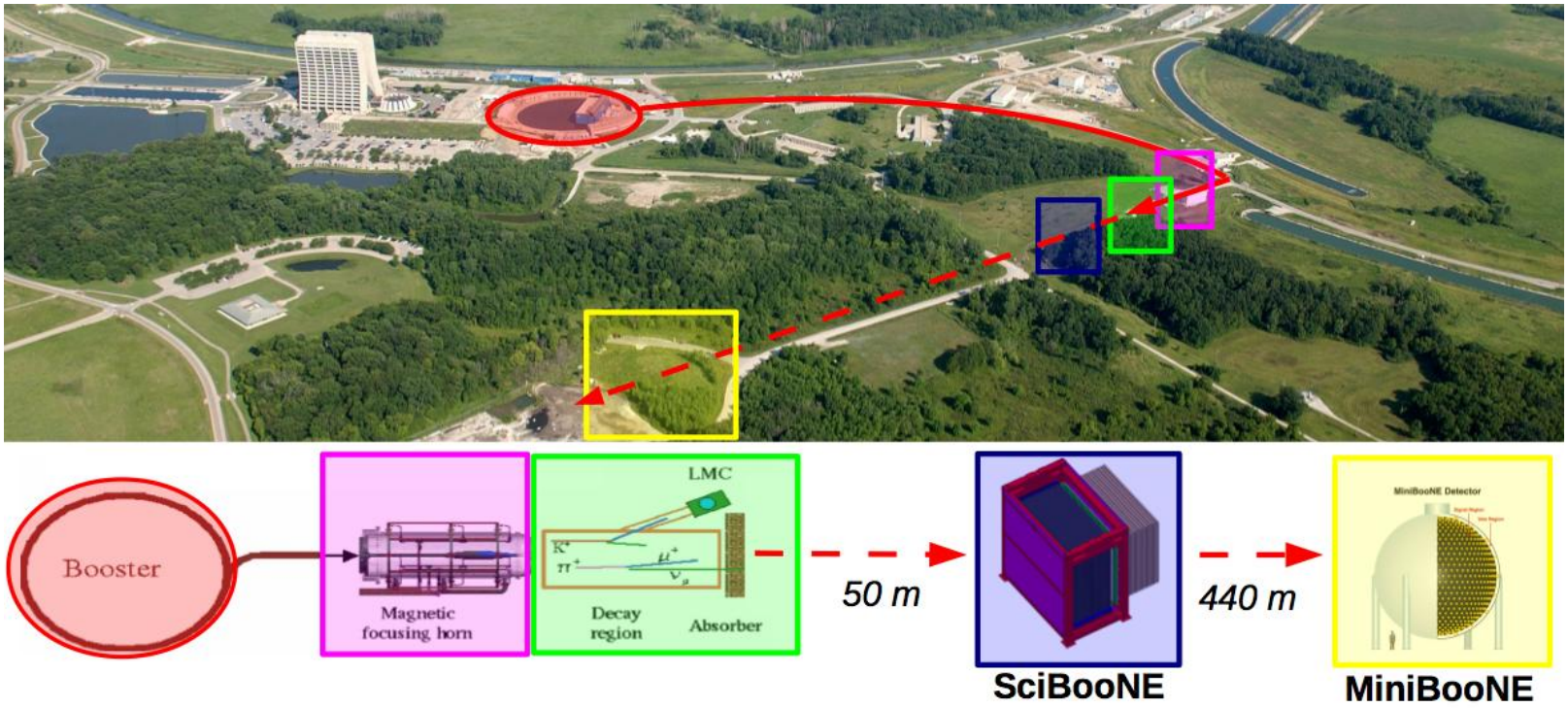
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Future Sensitivity

- Recent anti-neutrino appearance result based on 5.66 × 10^{20} POT
- Expect update this year with ~8.5 × 10^{20} POT
  - x 1.5 statistics
- ~10 x 10^{20} POT by 2012 shutdown
  - x 2 statistics



Joint MiniBooNE-SciBooNE ν_μ Disappearance Analysis

- SciBooNE a fine-grained tracking detector 50m downstream of proton target in same ν beam

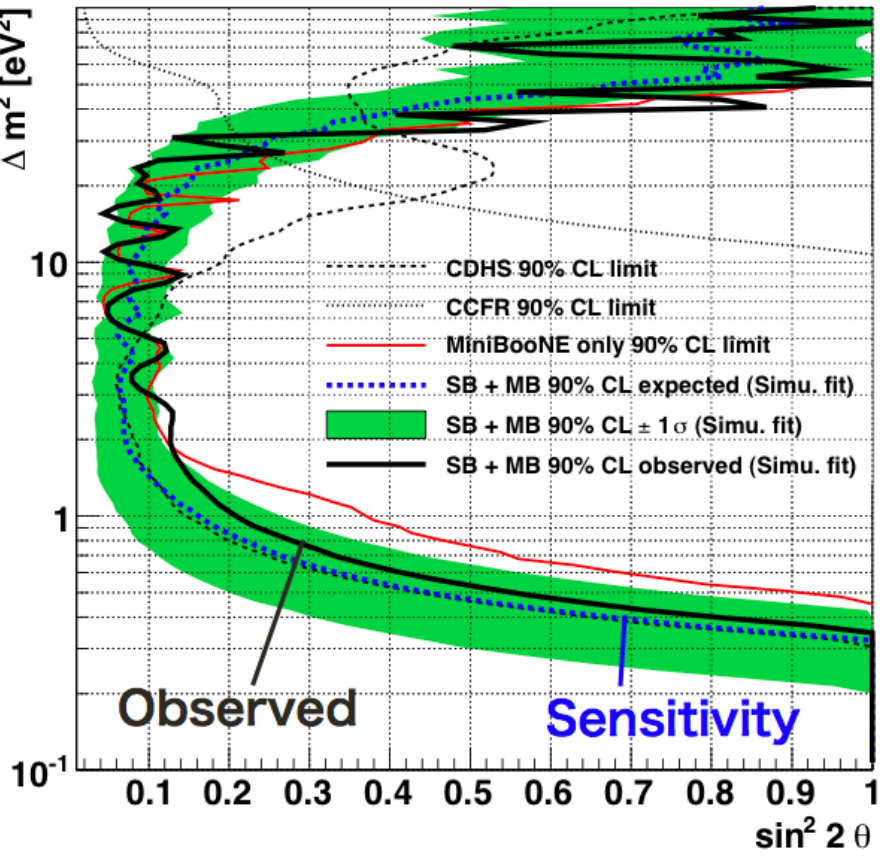


- Can use SciBooNE-MiniBooNE as a two-detector osc expt!

Joint MiniBooNE-SciBooNE ν_μ Disappearance Analysis

- By comparing rate and shape information in ν_μ CC interactions between the two detectors, set limits for ν_μ disappearance
  - world's strongest limit at $10 < \Delta m^2\ (eV^2) < 30$
- Constrains $\nu_\mu \rightarrow \nu_e$ oscillations as well as other, more exotic models
  - extra dimensions, ~~CPT~~
- See Y. Nakajima's 4/29/11 FNAL Wine & Cheese seminar

  Paper in draft
- Forthcoming $\overline{\nu}_\mu$ disappearance analysis



- SBNW11 last month, featured > 100 participants from 44 institutions

  https://indico.fnal.gov/conferenceDisplay.py?ovw=True&confId=4157
- Featured presentations, discussions on recent oscillation hints in MiniBooNE region
  - reactor $\bar{\nu}_e$ disappearance?

    Phys. Rev. D **83**, 073006 (2011)
  - gallium anomaly

    Phys. Rev. D **82**, 053005 (2010)
  - cosmology

    Phys. Rev. Lett **105**, 181301 (2010)
  - global 3+N fits

    C. Ignarra, SBNW11

- MiniBooNE review
- Physics results in the last year
  - Oscillations
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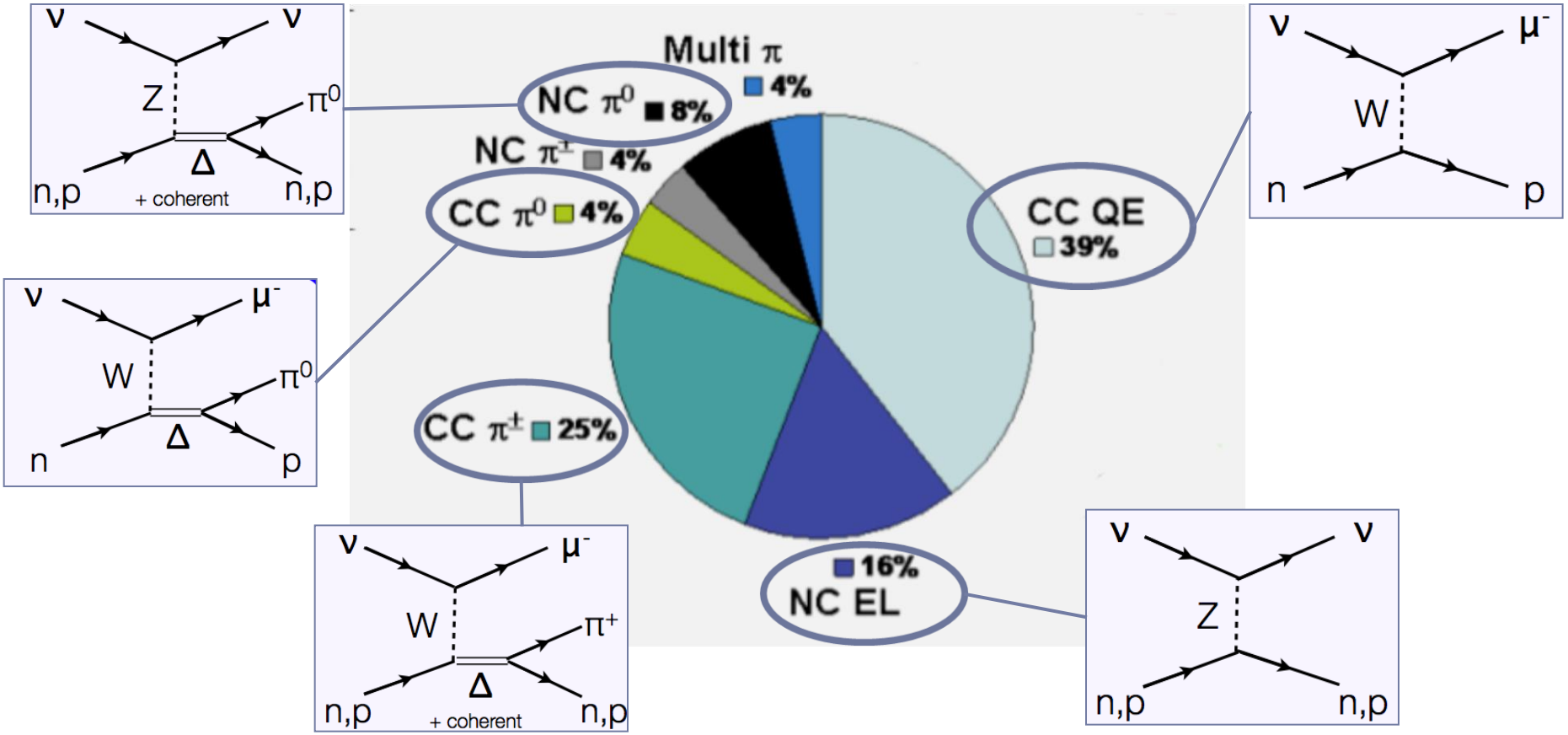
- MiniBooNE has analyzed and published 90% of neutrino-mode data collected (unprecedented statistics), most in the last year!



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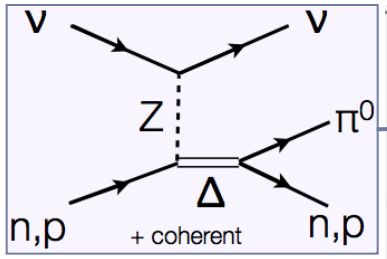
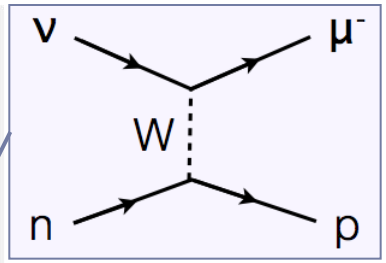
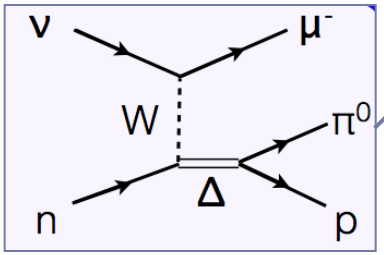
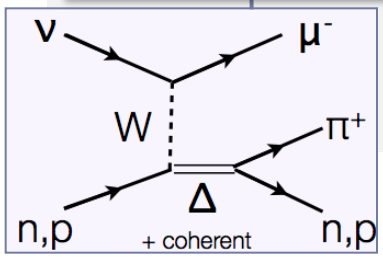
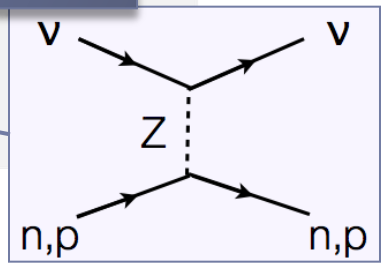




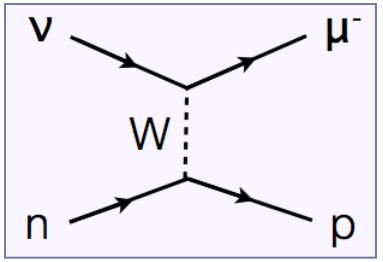




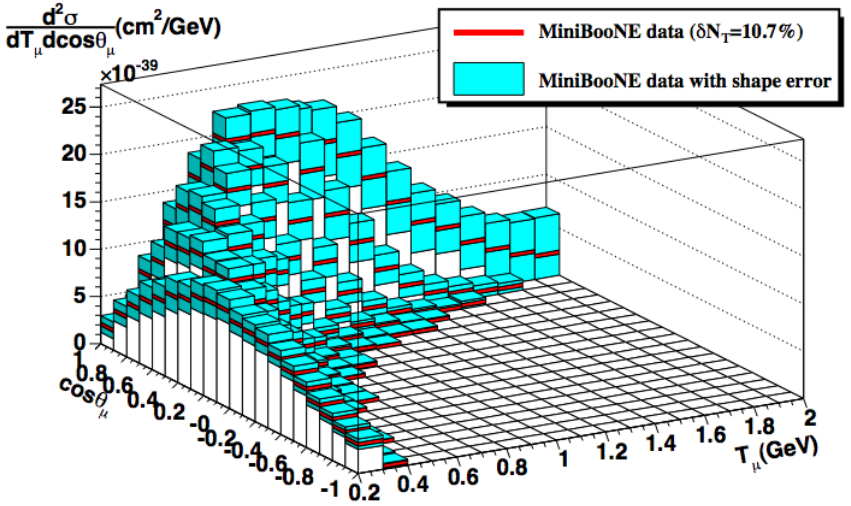


Data pushed into measurements as differential as possible - this allows for the most complete extraction of information

- Charged-current quasi-elastic channel typically used for osc measurements
  - simple event multiplicity
  - can recover E_ν with only lepton reconstruction

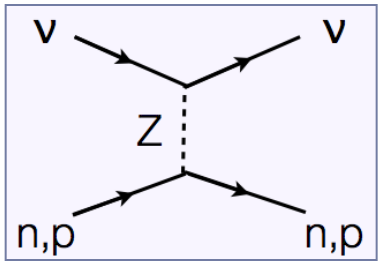


- Measured quantities:
  - $\sigma(E_\nu)$
  - $d\sigma/dQ^2$
  - $d^2\sigma/dT_\mu d\theta_\mu$ (model independent!)

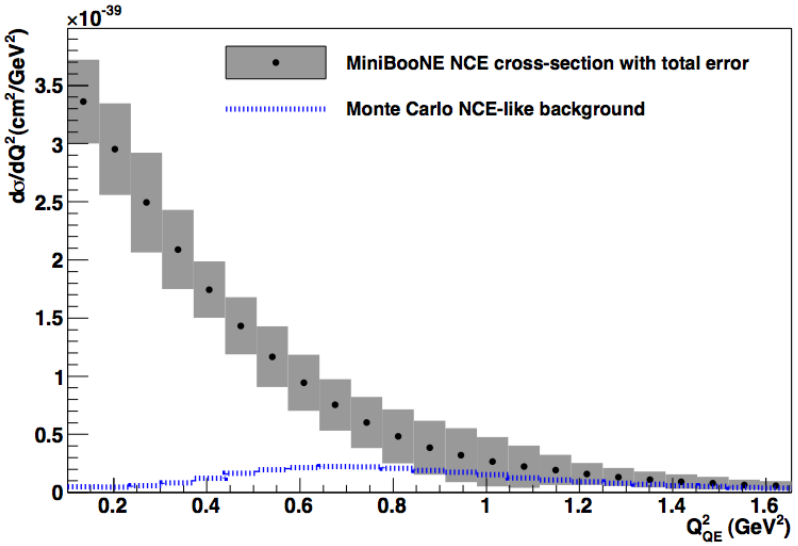


Ph.D. thesis, T. Katori, Indiana University
Phys. Rev. D. **81**, 092005 (2010)

- Neutral current elastic process probes similar formalism as charged-current quasi-elastic
  - sensitive to structure of both nucleon types



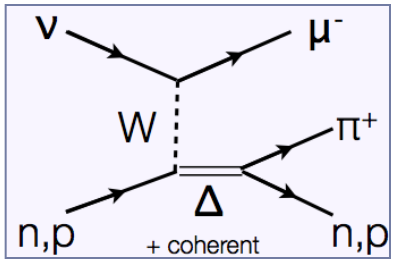
- Protons fitter developed, reconstructs protons above Cherenkov threshold (T_p > 350 MeV)



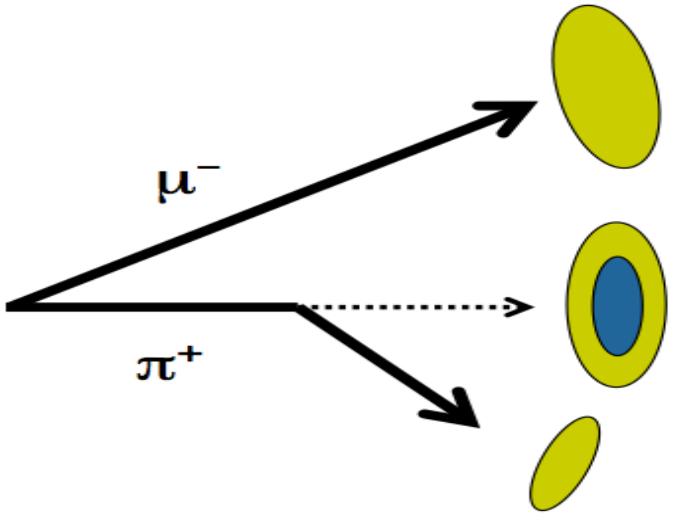
- Measured quantities:
  - $d\sigma/dQ^2$
  - Δs, strange quark contribution to nucleus

Ph.D. thesis, D. Perevalov, University of Alabama
Phys. Rev. D. **82**, 092005 (2010)

- Crucial channel for ν_μ disappearance measurements
  - can bias CCQE signal if π^+ lost



- First tracking of charged pions in a Cherenkov detector!

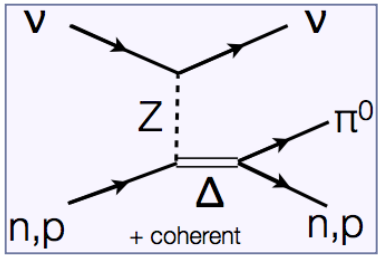


- Measured quantities:
  - $\sigma(E_\nu)$, $d\sigma/dQ^2$, $d\sigma/dT_\mu$, $d\sigma/d\theta_\mu$, $d\sigma/dT_\pi$, $d\sigma/d\theta_\pi$, $d^2\sigma/dT_\mu d\theta_\mu$, $d^2\sigma/dT_\pi d\theta_\pi$ (many firsts)

Ph.D. thesis, M. Wilking, University of Colorado
Phys. Rev. D. **83**, 052007 (2011)

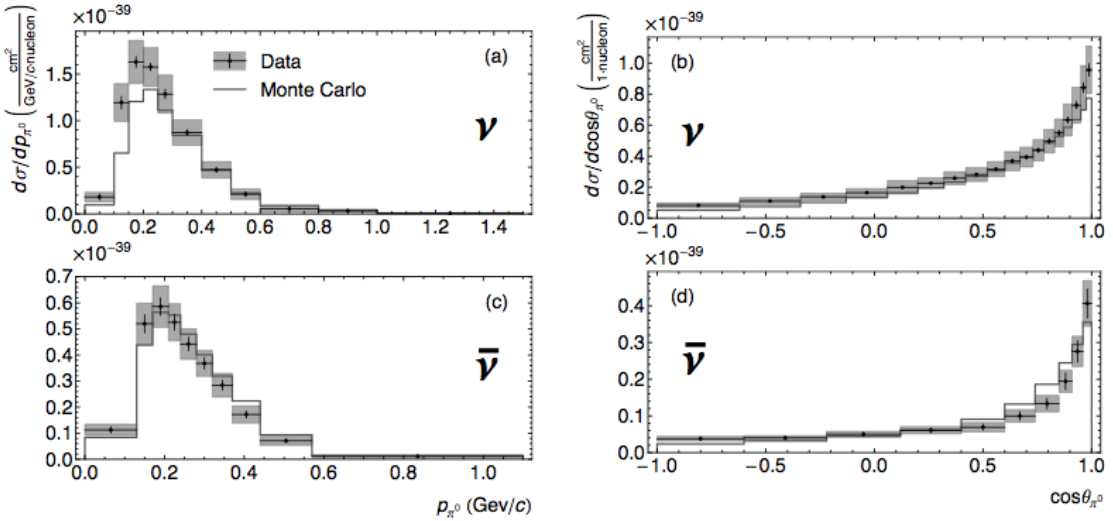
Neutral-Current $1\pi^0$

- Background measurement for ν_e appearance analysis
  - NCπ^0 signature electron-like if lose γ



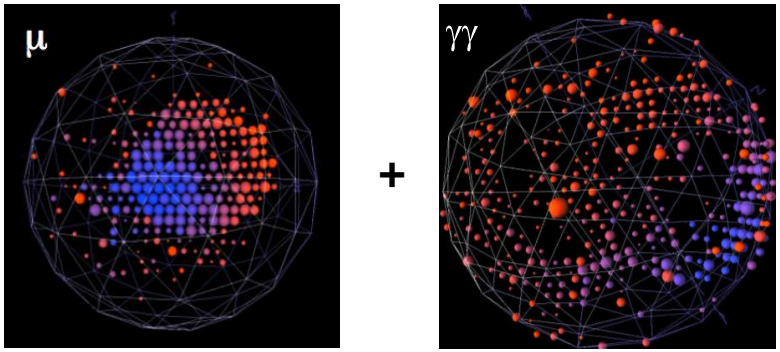
- Valuable input for θ_{13} Cherenkov-based measurements
  - T2K, LBNE

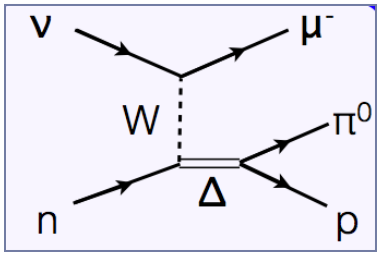
- Measured quantities:
  - $d\sigma/dp_\pi$, $d\sigma/d\theta_\pi$ (for both ν, $\bar{\nu}$ data)

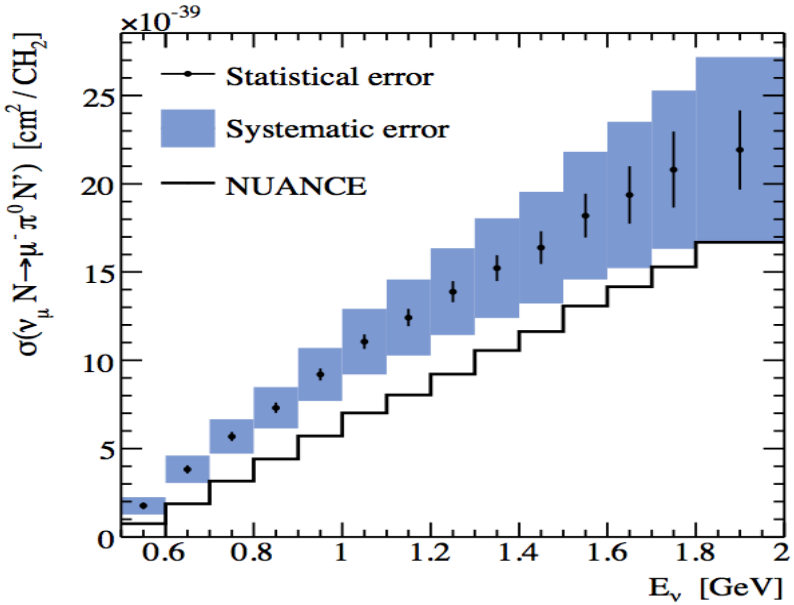


Ph.D. thesis, C. Anderson, Yale University
Phys. Rev. D. **81**, 013005 (2010)

- Custom 3-ring fitter developed to reconstruct both μ, π^0
- Resonant-only process
- Measured quantities:
  - $\sigma(E_\nu)$, $d\sigma/dQ^2$, $d\sigma/dT_\mu$, $d\sigma/dp_\pi$, $d\sigma/d\theta_\mu$, $d\sigma/d\theta_\pi$ (many firsts)



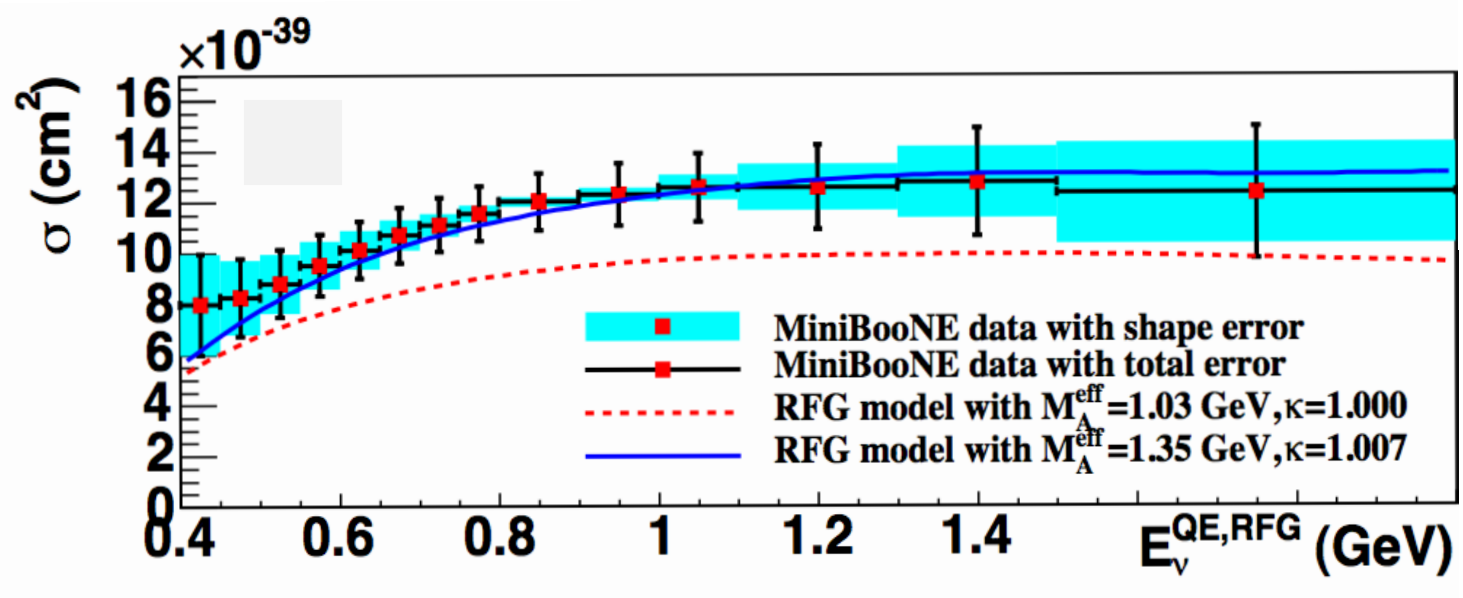




Ph.D. thesis, R. Nelson, University of Colorado
Phys. Rev. D. **83**, 052009 (2011)

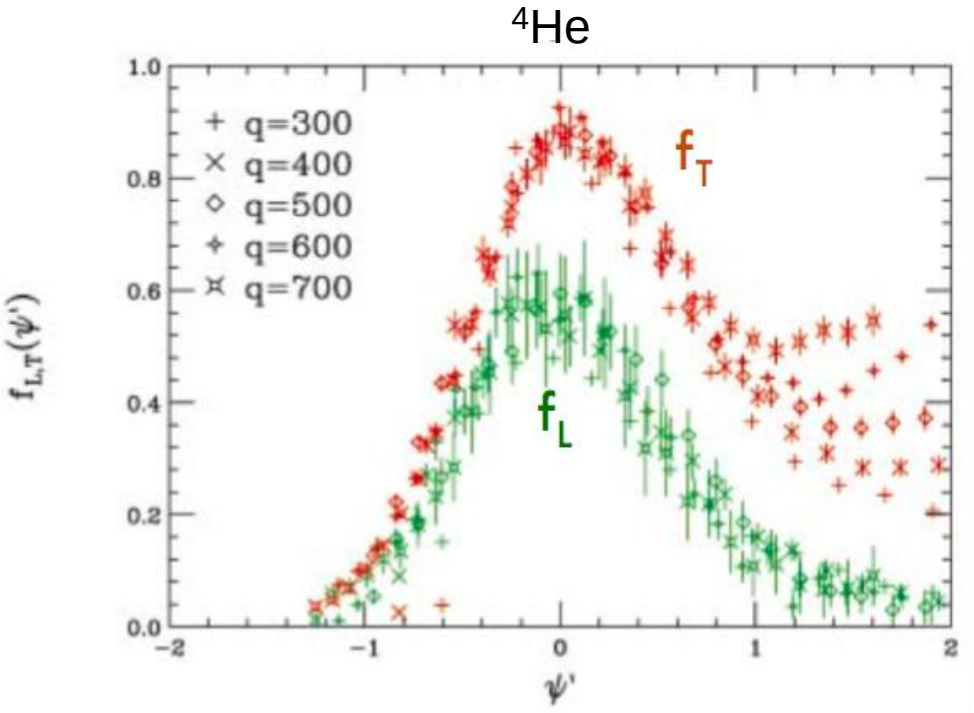
An Aside: Cross Section Interpretations

- CCQE σ results ~30% higher than expected!



- Simulation: Fermi gas model, combines **bare nucleon** physics with binding energy, Pauli blocking
  - No other considerations for nuclear effects

- e^- scattering data: **transverse** response function significantly enhanced for nuclear targets, fully described by short-range correlations and 2-body currents



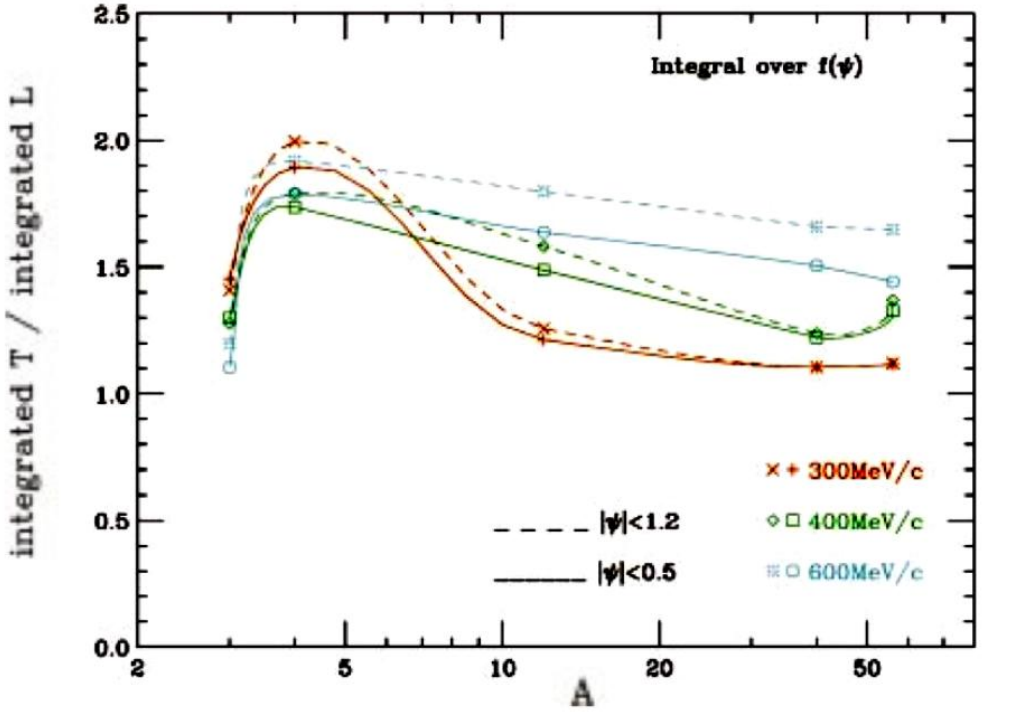
$$\psi' = \psi'(\omega, q)$$

- $f_{L,T}(\psi')$: superscaling variable, looking for A, **q** dependence
- Simulation takes $f_L = f_T$ (!)
- Consistent with MB σ's exceeding free nucleon case

Phys. Rev. C. **65**, 024002 (2002)

- Enhancement **has** to exist in ν scattering σ's as well
  - *At least* for the vector piece of QE channel

- Open questions:
  - axial enhancement?
  - resonance enhancement?
- Very active area to describe ν interactions consistent with these effects
  - Phys. Rev. C **80**, 065001 (2009)
  - Phys. Rev. C **83**, 045501 (2011)
- Anti-neutrinos provide an important test!



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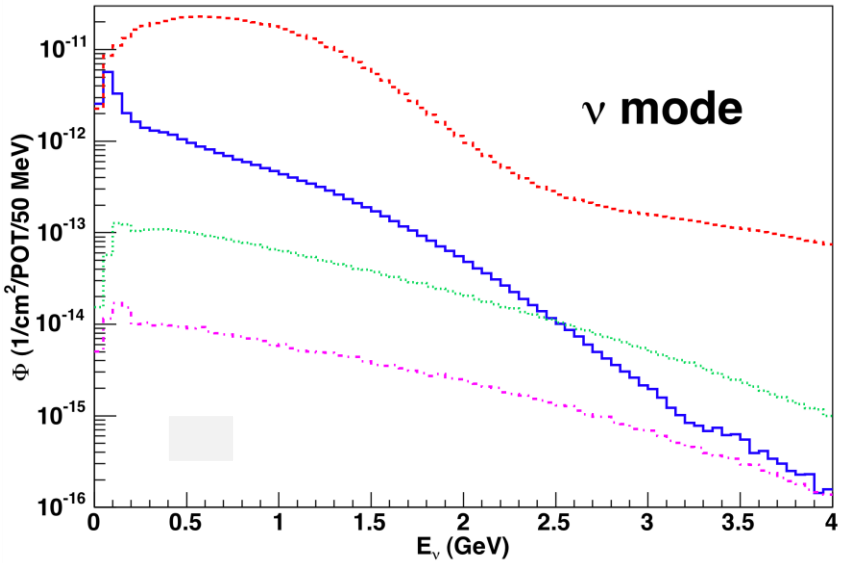
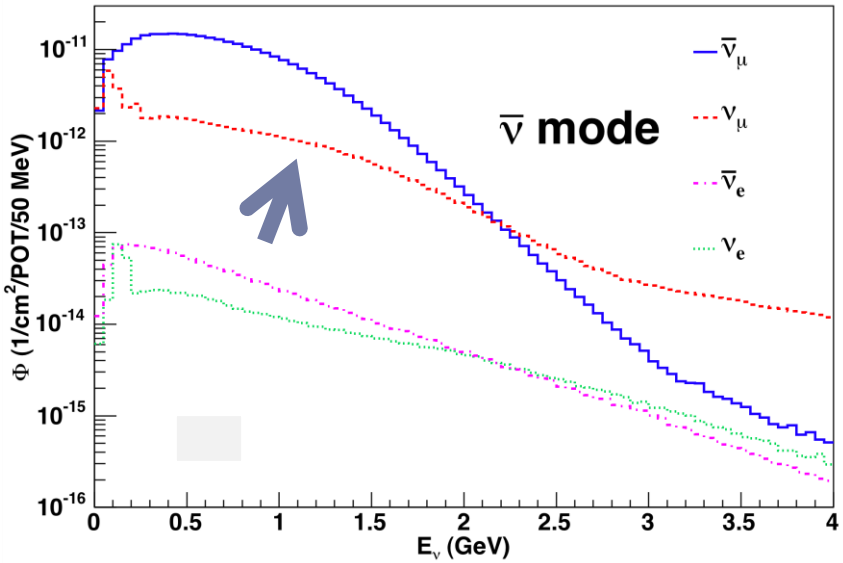
Neutrino Flux Revisited





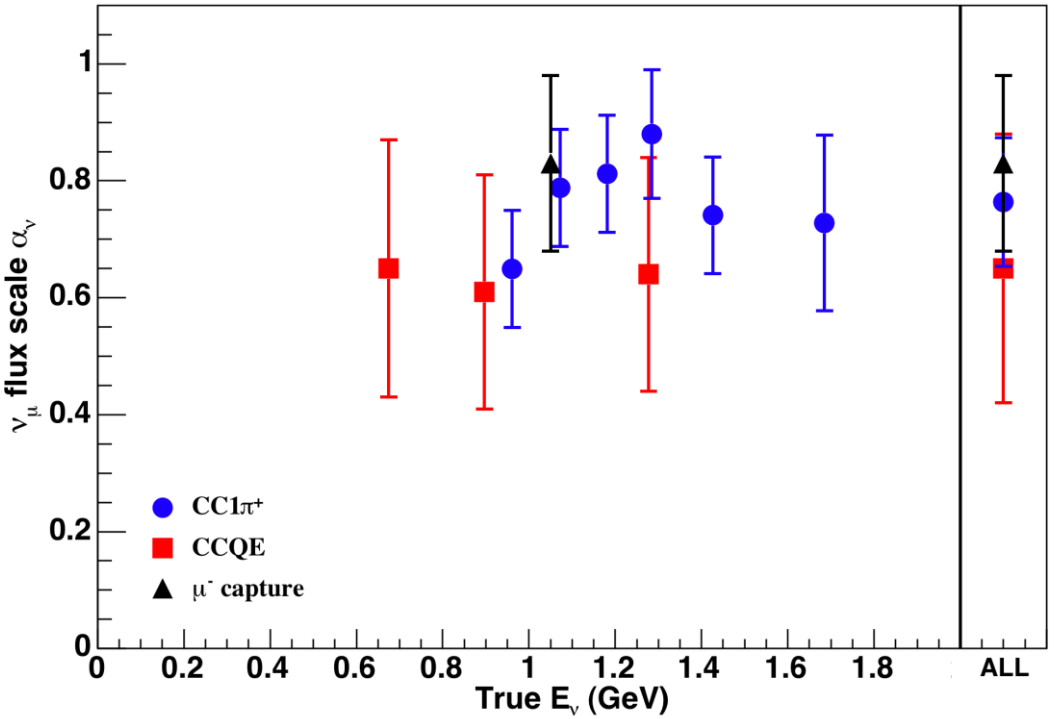
MiniBooNE collaboration,
Phys. Rev. D **79**, 072002 (2009)

- Significant neutrino content in anti-neutrino beam
- Detector not magnetized; cannot separate contribution based on μ charge

Neutrino Flux Revisited

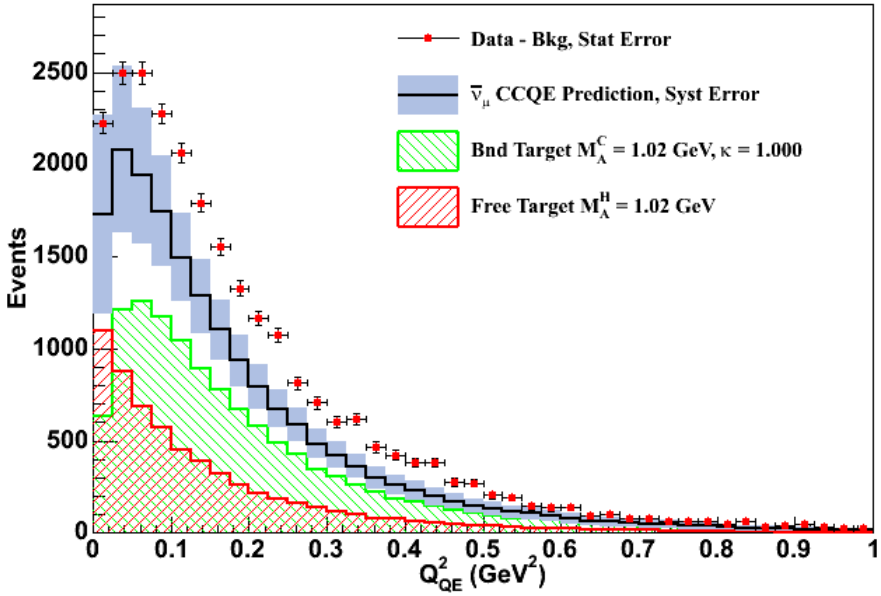
- First measurement of neutrino contribution to anti-neutrino beam with non-magnetized detector
- 3 **independent, complementary** measurements
  - μ^+/μ^- angular distribution
  - π^- capture
  - μ^- capture
- Demonstration of techniques for other non-magnetized detectors looking for ~~CP~~
  - NOνA, T2K, LBNE, etc.

arxiv: 1102.1964 [hep-ex]
Submitted to Phys. Rev. D

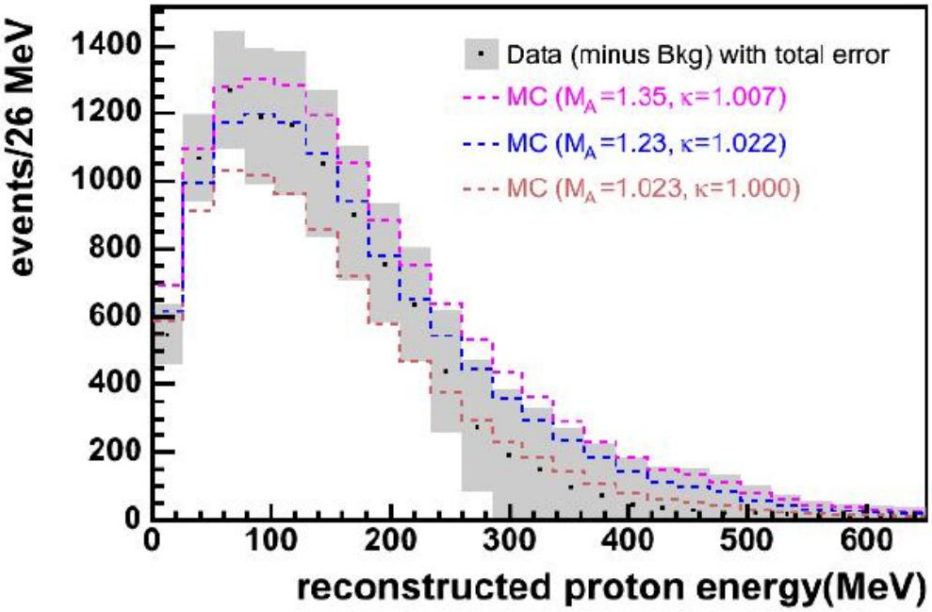


- Background-subtracted CCQE and NC Elastic:

J. Grange, NuInt11



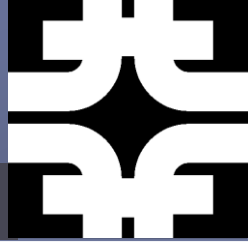
R. Dharmapalan, NuInt11



- Data favors some models of axial enhancement over others

- MiniBooNE review
- Physics results in the last year
  - Oscillations
  - Cross sections
    - Neutrinos
    - Anti-neutrinos
- Summary and outlook

Summary and Outlook: Oscillations



- MiniBooNE $\bar{\nu}_e$ appearance analysis is consistent with LSND signal
  - expect update with 50% more statistics this year!
- Joint SciBooNE-MiniBooNE ν_μ disappearance analysis provides world's strongest limits for $10 < \Delta m^2\ (eV^2) < 30$
  - corresponding $\bar{\nu}_\mu$ analysis underway
- These analyses will provide a critical test of an oscillation region where hints have recently been appearing…

$$\Delta m^2 \sim 1\mathrm{eV}^2 : \bar{\nu}_\mu \longrightarrow \bar{\nu}_e, \bar{\nu}_x ?$$

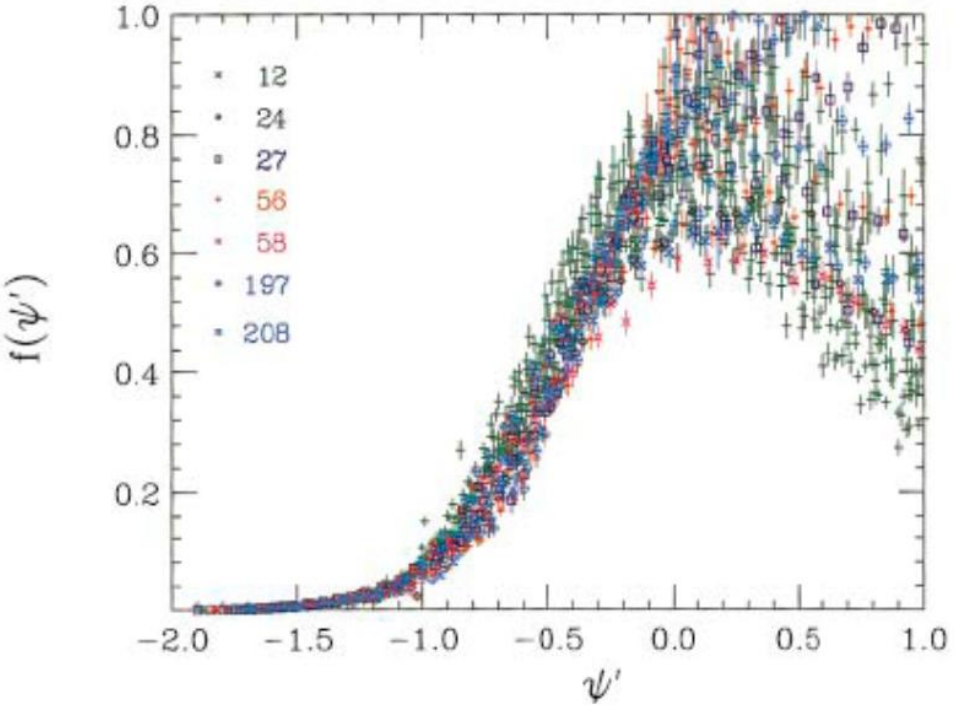
- In the previous year MiniBooNE has turned ~ 90% of ν-mode data collected into cross sections
  - most analyses have more statistics than all previous measurements *combined*!
  - wealth of statistics exploited to make model-independent differential measurements
- Significant excess over free-nucleon prediction in CCQE channel observed
  - consistent with previously-overlooked e^- scattering data
  - anti-neutrino cross sections will provide a test of the details in the upcoming year

Thanks for your attention!

- Recent MiniBooNE graduates
  - **R. H. Nelson**, "A Measurement of Neutrino-Induced Charged-Current Neutral Pion Production" Ph.D thesis, University of Colorado, 2010
  - **G. Karagiorgi**, "Searches for New Physics at MiniBooNE: Sterile Neutrinos and Mixing Freedom", Ph.D thesis, MIT, 2010
  - **C. E. Anderson**, "Measurement of Muon Neutrino and Antineutrino Induced Single Neutral Pion Production Cross Sections", Ph.D thesis, Yale University, 2010

BACKUP

- "Super Scaling": can scaling results be applied from 1 nucleus to another?



Phys. Rev. C38, 1801(1988),
Phys. Rev. C60, 065502 (1999)

$$\psi = \frac{m_N}{k_F}\left(\lambda\sqrt{1+\tau^{-1}} - \kappa\right)$$

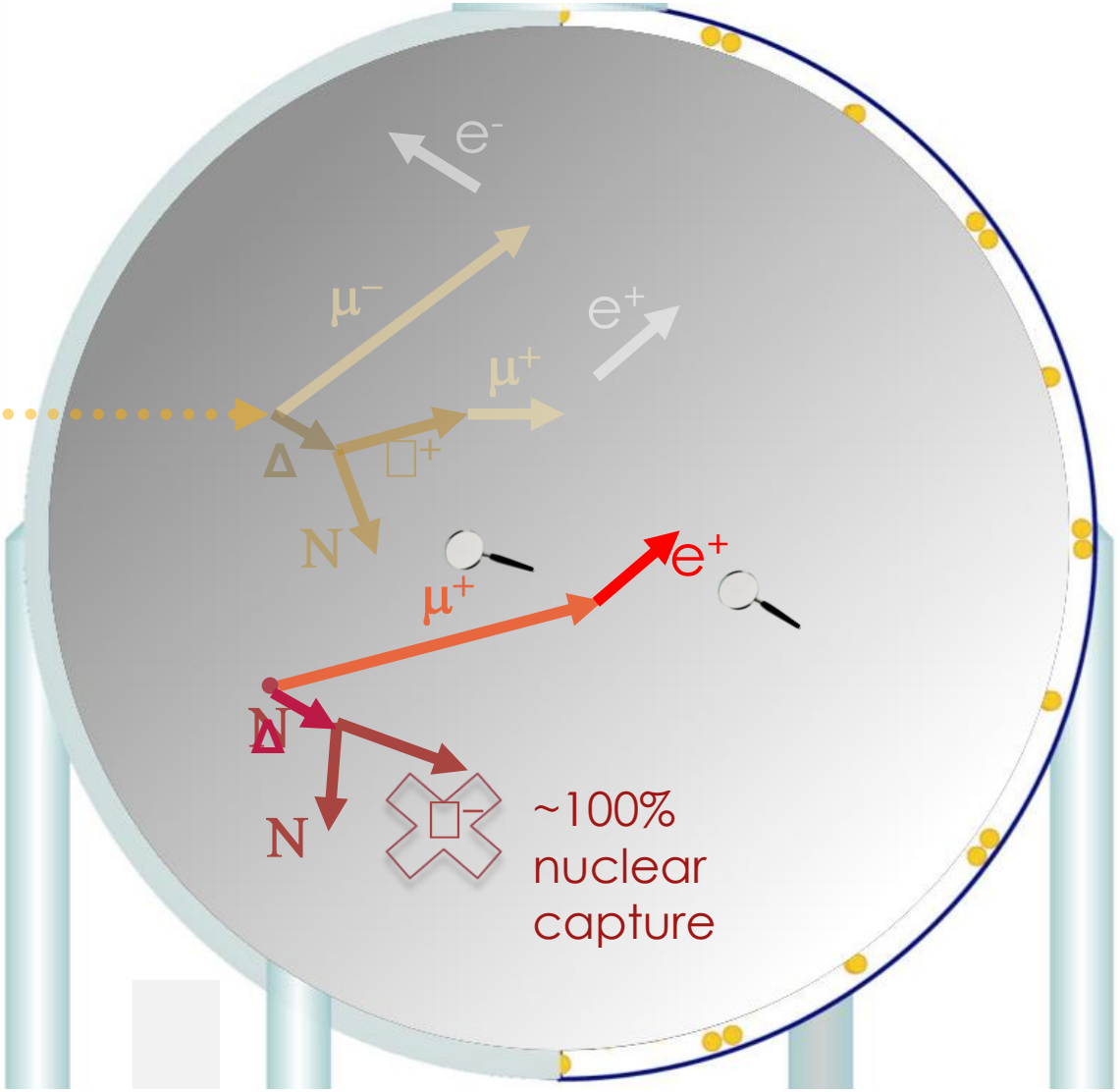
$$\lambda = \frac{\omega}{2m_N};\quad \tau = \frac{Q^2}{4m_N^2};\quad \kappa = \frac{q}{2m}$$

- Scales approximately linearly for different nuclear targets and $\psi < 0$
- Divergent for $\psi > 0$

Single π Sample, Anti-neutrino Mode

* The neutrino induced resonance channel leads to three leptons above Cherenkov threshold
  1. Primary muon
  2. Decay electron
  3. Decay positron

Single π Sample, Anti-neutrino Mode

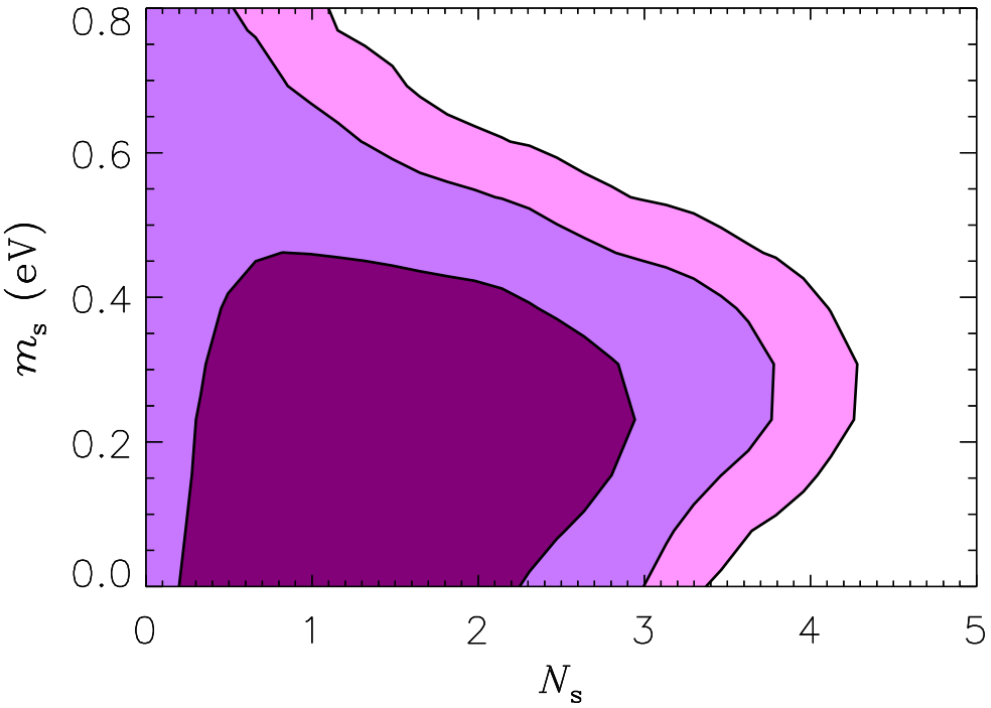


- Due to nuclear □⁻ capture, the corresponding anti-neutrino interaction has only two:
  1. Primary muon
  2. Decay positron

- Cosmology data prefers extra degrees of freedom afforded by extra ν species

- N_s: number of thermalized sterile neutrinos

PRL 105, 181301 (2010)

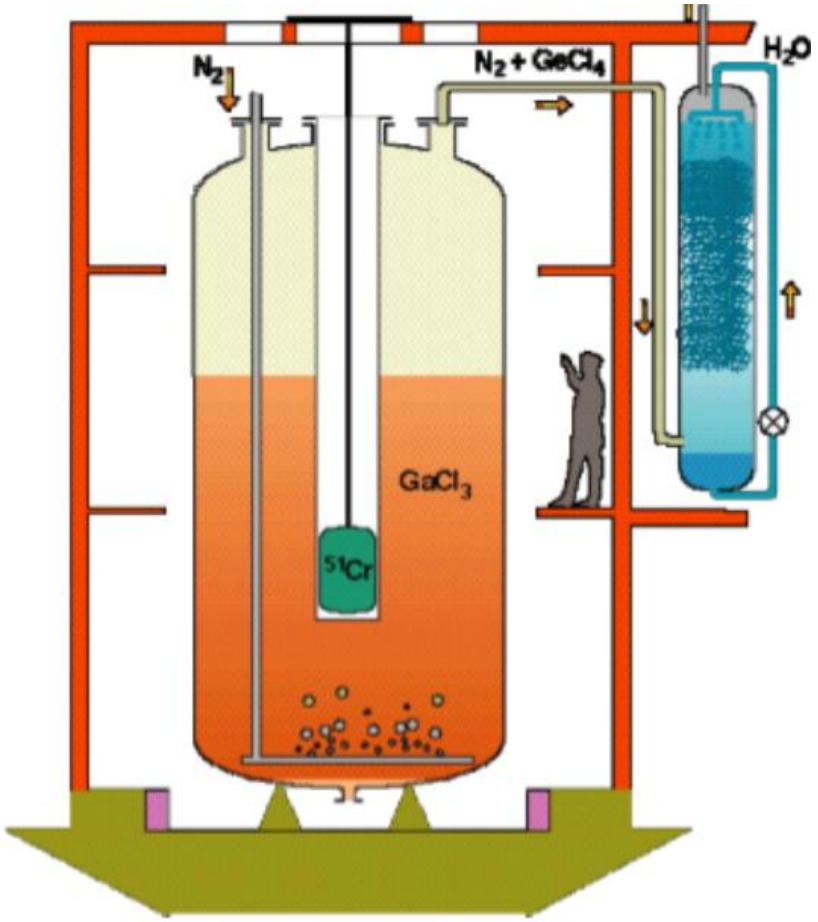


- Other analyses: effective number of ν species
  - $N_{eff} = 4.34^{+0.86}_{-0.88}$ (68% CL) arxiv:1001.4538
  - $N_{eff} = 4.78^{+1.86}_{-1.79}$ (95% CL) JCAP **1007**, 022 (2010)

- GALLEX and SAGE radiochemical experiments combined for 4 calibration runs with MCi source
  - counted $^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$
  - all 4 runs observed event deficit, with improved flux prediction
    $R = (obs/pred) = 0.86 \pm 0.06\ (1\sigma)$

PRD **83**: 073006 (2011)

- ν_e disappearance?



GALLEX

Single π Production Summary

- Many differential measurements world's firsts

- A total of 16 measurements!
- ✳ = presented as a function of neutrino energy.
- Least model dependent results!

Measurement\Mode	NCπ⁰	CCπ⁰	CCπ⁺
$\sigma(E_\nu)$		✓	✓
$d\sigma/dQ^2$		✓	✓✳
$d\sigma/dp_\pi$	✓	✓	✓✳
$d\sigma/d\cos\theta_\pi$	✓	✓	✓✳
$d\sigma/dT_\mu$		✓	✓✳
$d\sigma/d\cos\theta_\mu$		✓	✓✳
$d^2\sigma/dT_\mu d\cos\theta_\mu$			✓
$d^2\sigma/dT_\pi d\cos\theta_\pi$			✓

R. Nelson, NuInt11

By requiring (μ-only/μ+e)^{data} = (μ-only/μ+e)^{MC} and normalization to agree in the μ+e sample we can calculate a ν_μ flux scale α_ν and a rate scale $\alpha_{\bar{\nu}}$

$$\frac{\mu}{\mu+e}^{\text{data}} = \left(\frac{\alpha_\nu \, \nu^\mu + \alpha_{\bar{\nu}} \, \bar{\nu}^\mu}{\alpha_\nu \, \nu^{\mu+e} + \alpha_{\bar{\nu}} \, \bar{\nu}^{\mu+e}} \right)^{\text{MC}}$$

Predicted neutrino content in the μ+e sample, for example

By requiring (μ-only/μ+e)^{data} = (μ-only/μ+e)^{MC} and normalization to agree in the μ+e sample we can calculate a ν_μ flux scale α_ν and a rate scale $\alpha_{\bar{\nu}}$

$$\frac{\mu}{\mu+e}^{\text{data}} = \left(\frac{\alpha_\nu \, \nu^\mu + \alpha_{\bar{\nu}} \, \bar{\nu}^\mu}{\alpha_\nu \, \nu^{\mu+e} + \alpha_{\bar{\nu}} \, \bar{\nu}^{\mu+e}} \right)^{\text{MC}}$$

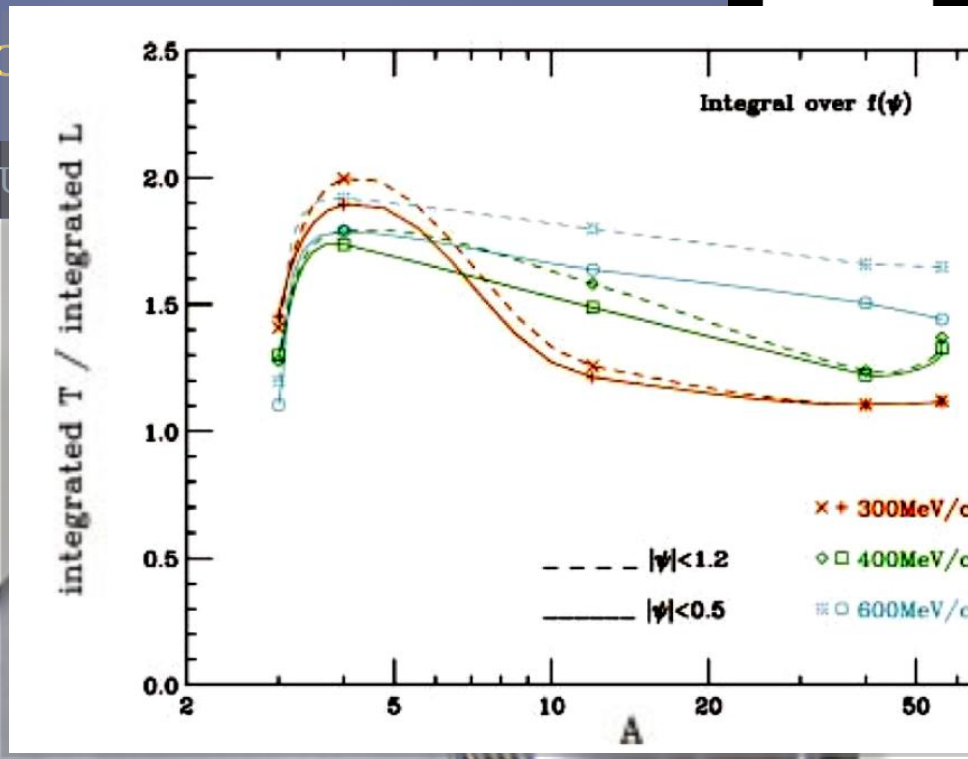
Results:

$$\alpha_\nu = 0.86 \pm 0.14$$

$$\alpha_{\bar{\nu}} = 1.09 \pm 0.23$$

PRELIMINARY

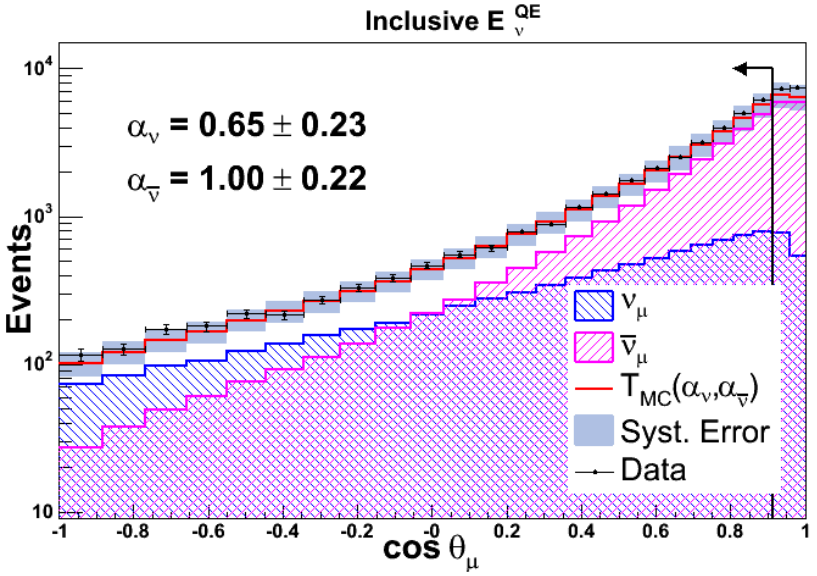
- Electron scattering time capsule?



- No…

μ^+/μ^- Angular Fits

- Results indicate the ν_μ flux is over-predicted by ~30%
- Fit also performed in bins of reconstructed energy; consistent results indicate flux spectrum shape is well modeled



$E_{\bar\nu}^{QE}$(MeV)	α_ν	$\alpha_{\bar\nu}$
< 600	0.65 ± 0.22	0.98 ± 0.18
600 - 900	0.61 ± 0.20	1.05 ± 0.19
> 900	0.64 ± 0.20	1.18 ± 0.21
Inclusive	0.65 ± 0.23	1.00 ± 0.22