Neutrino interactions
and stories, 1995-2015

Outline:
- LSND
- MiniBooNE
- Future

Rex Tayloe
Indiana U.

Motivated by the study of ν-oscillations, much has been learned over last 20 years about ν-interactions, through beautiful data provided by the LSND and MiniBooNE experiments.

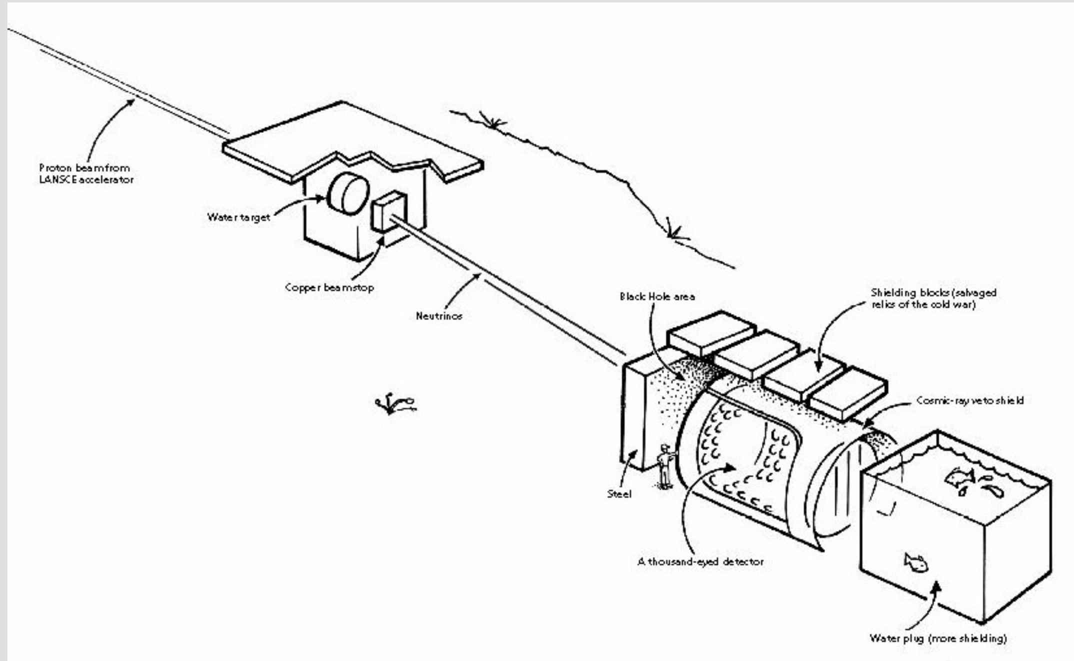
At:

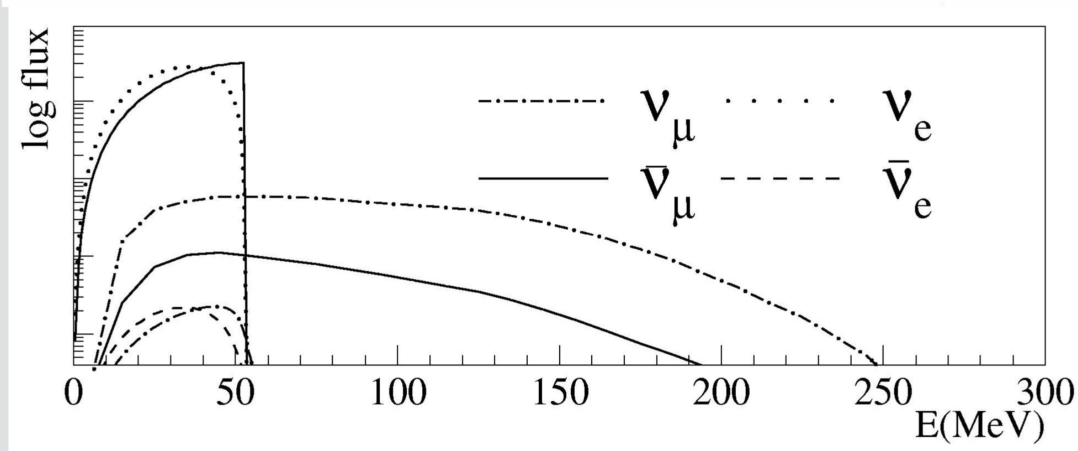
- $E\nu$ ~ 10-1000MeV,
- on Carbon
- over all angles/kinematics
- charged-, neutral-current
- elastic, inelastic, resonant…

adding greatly to understanding of these processes for ν-oscillations.
(and just because it is interesting physics !)

LSND Experiment:

- at LAMPF, 1993-1998
- 800 MeV protons on ν-target
- DAR and DIF ν
- detector 30 m downstream
- liquid scintillator (CH_2)
- 1220, 8” PMTs
- reconstruction:
    - charged particles/photons via scint and Cerenkov
    - muon decays (μ->eνν)
    - neutrons via delayed capture (np -> dγ)





LSND Experiment:

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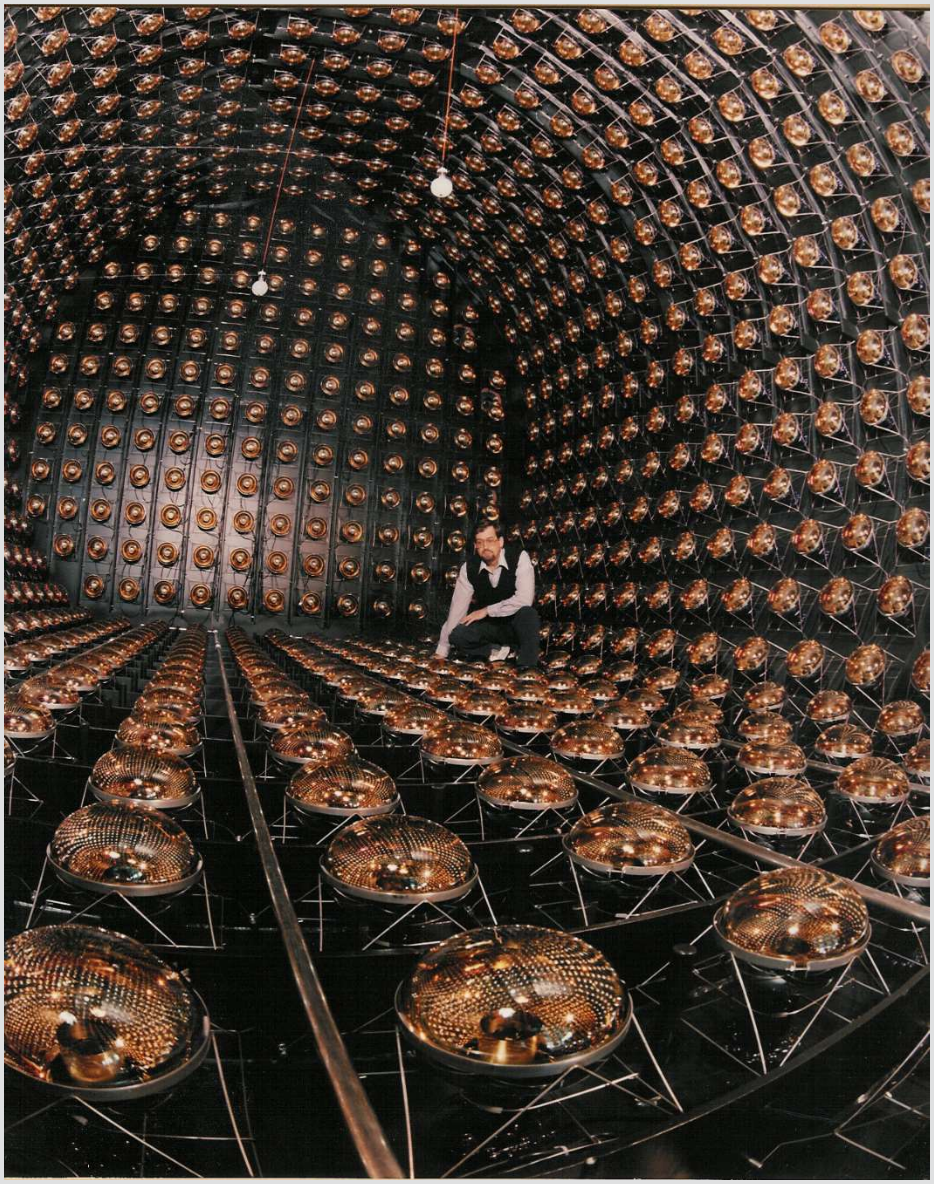
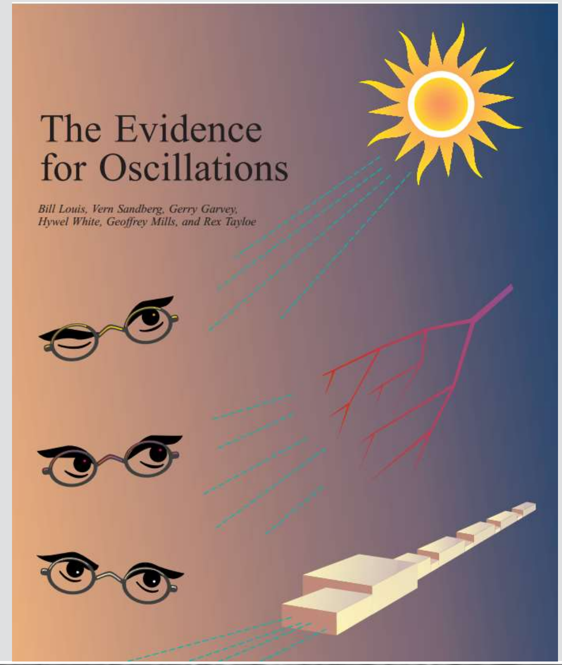


LA Science 25, 1997



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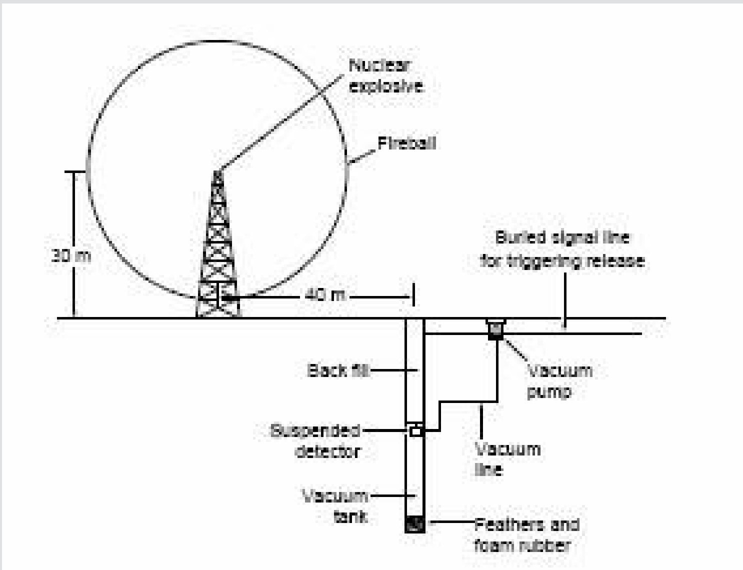
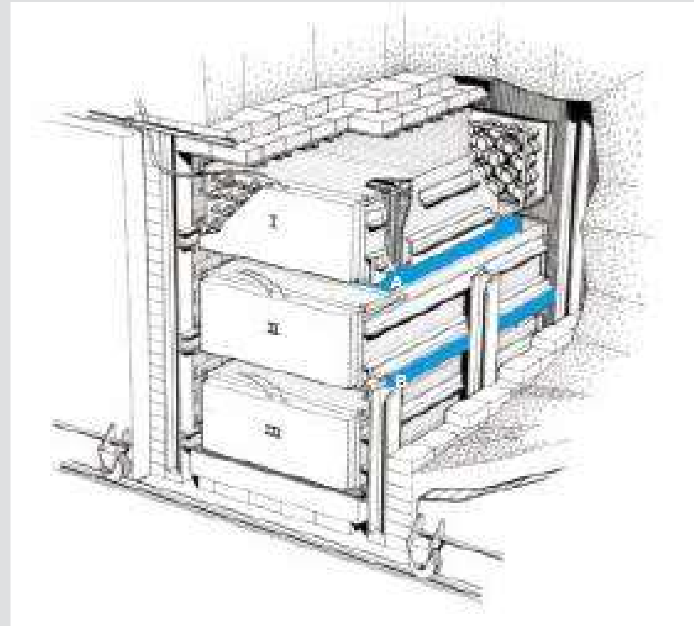
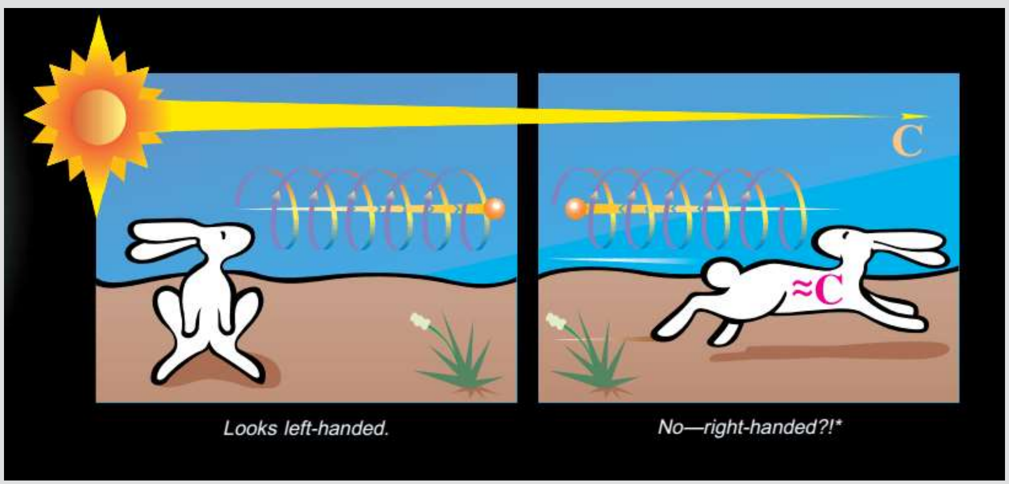
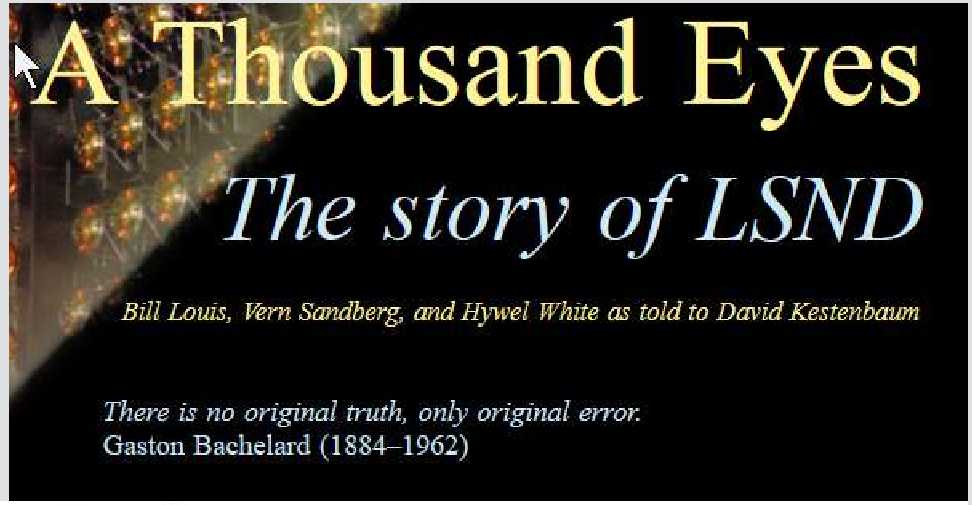






LA Science 25, 1997



David Kestenbaum

Correspondent

David Kestenbaum is a correspondent for NPR, covering science, energy issues and, most recently, the global economy for NPR's multimedia project Planet Money. David has been a science correspondent for NPR since 1999. He came to journalism the usual way — by getting a Ph.D. in physics first.

In his years at NPR, David has covered science's discoveries and its darker side, including the Northeast blackout, the anthrax attacks and the collapse of the New

LSND cross section measurements

$^{12}C(\nu_e, e^-)^{12}N_{g.s.}$

$^{12}C(\nu_e, e^-)^{12}N^*$

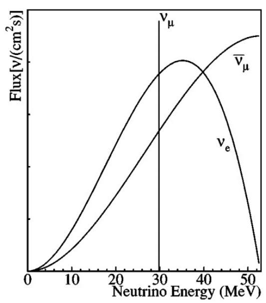


FIG. 1. Flux shape of neutrinos from pion and muon decay at rest.

PHYSICAL REVIEW C, VOLUME 64, 065501

Measurements of charged current reactions of ν_e on ^{12}C

L. B. Auerbach,[8] R. L. Burman,[5] D. O. Caldwell,[3] E. D. Church,[1] J. B. Donahue,[5] A. Fazely,[7] G. T. Garvey,[5] R. M. Gunasingha,[7] R. Imlay,[6] W. C. Louis,[5] R. Majkic,[8] A. Malik,[6] W. Metcalf,[6] G. B. Mills,[5] V. Sandberg,[5] D. Smith,[4] I. Stancu,[1,*] M. Sung,[6] R. Tayloe,[5,†] G. J. VanDalen,[1] W. Vernon,[2] N. Wadia,[6] D. H. White,[5] and S. Yellin[3]

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via β- dk:

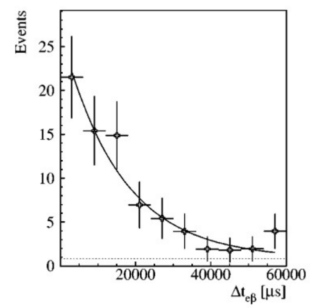

FIG. 9. The distribution of time differences between the electrons and β in the exclusive sample of $^{12}C(\nu_\mu, \mu^-)^{12}N_{g.s.}$ is compared with the expected β lifetime. The dotted line shows the calculated accidental contribution.

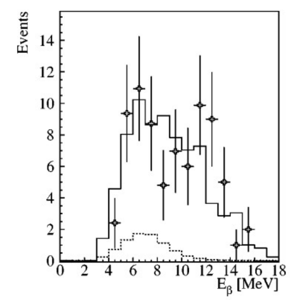

FIG. 11. The distribution of β energy from the exclusive sample of $^{12}C(\nu_\mu, \mu^-)^{12}N_{g.s.}$. The dashed line shows the estimated accidental contribution. The solid line shows the expected shape (including the accidental contribution) from the Monte Carlo simulation, normalized to the data.

id e+/-:

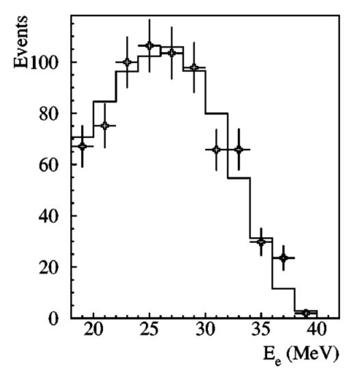

FIG. 6. The observed and expected (solid line) energy distributions for electrons from $^{12}C(\nu_e, e^-)^{12}N_{g.s.}$.

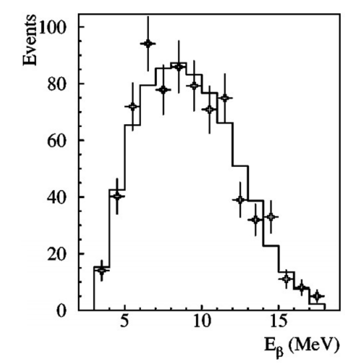

FIG. 10. Observed and expected (solid line) e^+ energy distribution for the $^{12}C(\nu_e, e^-)^{12}N_{g.s.}$ sample.

LSND cross section measurements

$^{12}C(\nu_e, e^-)^{12}N_{g.s.}$

$^{12}C(\nu_e, e^-)^{12}N^*$

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TABLE V. Measurements and theoretical predictions of the flux averaged cross section for the process $^{12}C(\nu_e, e^-)^{12}N_{g.s.}$.

Experiment	
LSND	$(8.9 \pm 0.3 \pm 0.9) \times 10^{-42}$ cm^2
LSND(previous) [3]	$(9.1 \pm 0.4 \pm 0.9) \times 10^{-42}$ cm^2
*E*225 [1]	$(10.5 \pm 1.0 \pm 1.0) \times 10^{-42}$ cm^2
KARMEN [2]	$(9.1 \pm 0.5 \pm 0.8) \times 10^{-42}$ cm^2
Theory	
Donnelly [5]	9.4×10^{-42} cm^2
Fukugita *et al.* [4]	9.2×10^{-42} cm^2
Kolbe *et al.* [7]	8.9×10^{-42} cm^2
Mintz *et al.* [28]	8.0×10^{-42} cm^2

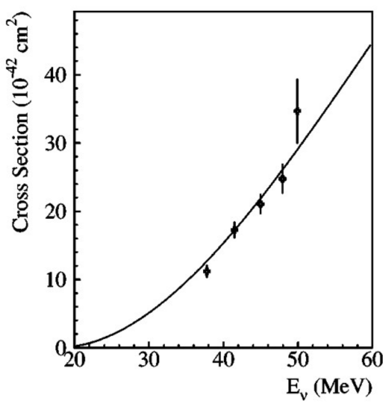

FIG. 11. The measured and expected (solid line) cross section for the process $^{12}C(\nu_e, e^-)^{12}N_{g.s.}$.

TABLE IX. Measurements and theoretical predictions of the flux averaged cross section for the process $^{12}C(\nu_e, e^-)^{12}N^*$.

Experiment	
LSND	$(4.3 \pm 0.4 \pm 0.6) \times 10^{-42}$ cm^2
LSND(previous) [3]	$(3.7 \pm 0.6 \pm 0.6) \times 10^{-42}$ cm^2
*E*225 [1,36]	$(3.6 \pm 2.0) \times 10^{-42}$ cm^2
KARMEN [32]	$(5.1 \pm 0.6 \pm 0.5) \times 10^{-42}$ cm^2
Theory	
Kolbe *et al.* [6]	6.3×10^{-42} cm^2
Kolbe *et al.* [7]	5.5×10^{-42} cm^2
Hayes *et al.* [9]	4.1×10^{-42} cm^2

LSND cross section measurements

$$\nu_\mu + {}^{12}\mathrm{C} \rightarrow \mu^- + {}^{12}\mathrm{N}_{\mathrm{g.s.}}$$

$$\nu_\mu + {}^{12}\mathrm{C} \rightarrow \mu^- + X$$

PHYSICAL REVIEW C **66**, 015501 (2002)

Measurements of charged current reactions of ν_μ on ^{12}C

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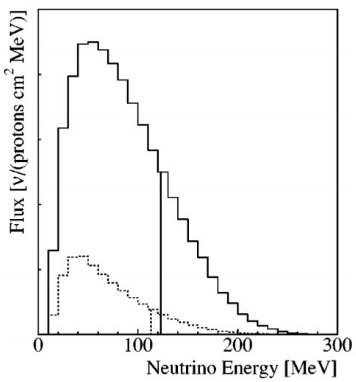


FIG. 2. The solid line shows the flux shape of ν_μ from π^+ decay in flight. The dashed line shows the $\bar{\nu}_\mu$ flux from π^- decay in flight for the same integrated proton beam. The muon production threshold energy for each spectrum is shown by a vertical line.

id μ:

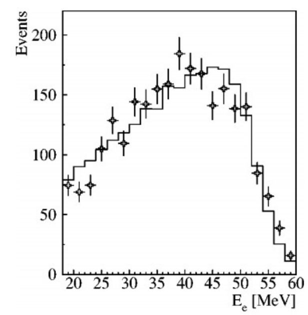
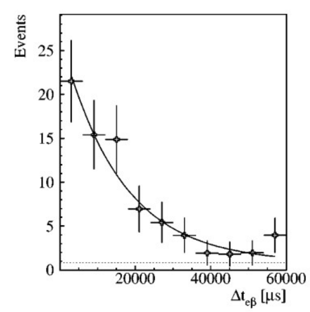


FIG. 4. The observed energy distribution of electrons from μ^- decay for the inclusive sample, $^{12}\mathrm{C}(\nu_\mu,\mu^-)X$. The histogram shows the expected energy distribution of Michel electrons from Monte Carlo simulation.

id Ngs via β- dk:



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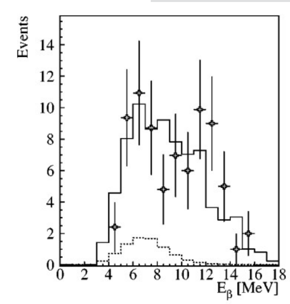

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LSND cross section measurements

$$\nu_\mu + {}^{12}\mathrm{C} \rightarrow \mu^- + {}^{12}\mathrm{N}_{\mathrm{g.s.}}$$

$$\nu_\mu + {}^{12}\mathrm{C} \rightarrow \mu^- + X$$

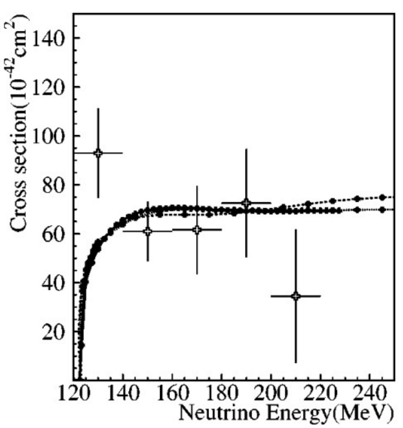


FIG. 14. The measured cross section for the process ${}^{12}\mathrm{C}(\nu_\mu,\mu^-){}^{12}\mathrm{N}_{\mathrm{g.s.}}$ compared with three theoretical calculations obtained from Ref. [32].

TABLE V. Beam-excess events, background, efficiency, neutrino flux, and flux-averaged cross section for the exclusive reaction ${}^{12}\mathrm{C}(\nu_\mu,\mu^-){}^{12}\mathrm{N}_{\mathrm{g.s.}}$.

Corrected beam excess events	77.8 ± 8.9
$\bar{\nu}_\mu + {}^{12}\mathrm{C} \rightarrow \mu^+ + {}^{12}\mathrm{B}_{\mathrm{g.s.}}$	2.7 ± 0.5
Accidental e^+ background	8.2 ± 0.8
$\nu_\mu + {}^{12}\mathrm{C} \rightarrow \mu^- + {}^{12}\mathrm{N}_{\mathrm{g.s.}}$	66.9 ± 9.0
Efficiency	$16.3 \pm 1.2\%$
ν_μ flux ($E_\nu >$ 123.1 MeV)	2.03×10^{12} cm^{-2}
$\langle\sigma\rangle$ measured	$(5.6 \pm 0.8 \pm 1.0) \times 10^{-41}$ cm^2
$\langle\sigma\rangle$ theory	
Engel *et al.* [32]	6.4×10^{-41} cm^2
Kolbe *et al.* [9]	7.0×10^{-41} cm^2
Volpe *et al.* [10]	6.5×10^{-41} cm^2
Hayes and Towner [11]	5.6×10^{-41} cm^2

TABLE VI. Beam-excess events, background, efficiency, neutrino flux, and flux-averaged cross section for the inclusive reaction ${}^{12}\mathrm{C}(\nu_\mu,\mu^-){}^{12}X$.

Corrected beam excess events	2464 ± 50
$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$	217 ± 35
$\bar{\nu}_\mu + {}^{12}\mathrm{C} \rightarrow \mu^+ + X$	71 ± 35
$\nu_\mu + {}^{13}\mathrm{C} \rightarrow \mu^- + X$	24 ± 12
$\nu_\mu + {}^{12}\mathrm{C} \rightarrow \mu^- + X$	2152 ± 56
Efficiency	$(27.7 \pm 1.9)\%$
ν_μ flux ($E_\nu >$ 123.1 MeV)	2.03×10^{12} cm^{-2}
$\langle\sigma\rangle$ measured	$(10.6 \pm 0.3 \pm 1.8) \times 10^{-40}$ cm^2
Theory	
Kolbe *et al.* [9]	17.5×10^{-40} cm^2
Volpe *et al.* [10]	15.2×10^{-40} cm^2
Hayes and Towner [11]	13.8×10^{-40} cm^2

next, MiniBooNE

MB proposal cross section chapter was a bit… terse

A proposal for an experiment to measure $\nu_\mu \to \nu_e$ oscillations and ν_μ disappearance at the Fermilab Booster: BooNE

December 7, 1997

Chapter 9

Non-oscillation Neutrino Physics with MiniBooNE

With the MiniBooNE detector and FNAL Booster neutrino source, a plethora of nuclear and particle physics using the neutrino as a probe could be investigated. These topics include the role of strangeness in the proton, the behavior of the axial vector mass and coupling constant in nuclear matter, the helicity structure of the weak neutral current, and the neutrino magnetic moment.

The large-mass MiniBooNE detector along with the intense Booster neutrino source will create unprecedented neutrino reaction rates at these energies. The number of expected events for several interesting channels are listed in Table 9.1. These numbers are calculated assuming one year of running (2×10^7 s) at each polarity at an average rate of 2.5×10^{13} protons/s. The fiducial detector contains of 1.9×10^{31} CH_2 molecules and all particle ID efficiencies are assumed to be 50%.

The list below outlines some of the interesting physics that may be investigated with MiniBooNE. Several of the channels (namely, $\nu_\mu C \to \mu^- N$ and $\nu_\mu C \to \nu_\mu \pi^0 X$) will need to be understood thoroughly for neutrino oscillation background estimates. The others, while not potential backgrounds, have the possibility of yielding exciting physics. More detailed feasibility studies are currently underway.

- Neutrino-Nucleon Elastic Scattering and a Measurement of G_s

  The $\nu p \to \nu p$ and $\nu n \to \nu n$ reactions (where ν is a ν_μ or a $\bar{\nu}_\mu$) offer the possibility of extracting G_s, the strange quark axial form factor of the nucleon. The ratio of neutrino elastic scattering events producing a proton to those producing a neutron on the isoscalar carbon nucleus is a sensitive measure of G_s and dependent only weakly upon the F_2^s form factor[65]. More exactly, if this ratio is measured for both antineutrinos and neutrinos, G_s and F_2^s are separable[66]. A precision measurement of this ratio will be difficult with MiniBooNE due to the difficulty of separating neutrons and protons and perhaps a dedicated experiment closer to the neutrino source would be required. However, it may be possible to extract information on the strange form factors through the neutral-current/charge-current neutrino-antineutrino asymmetry[67]. This method is currently under study.

- Neutrino Charged-Current Scattering

  The $\nu_\mu {}^{12}C \to \mu^{-\,12}N$ and $\bar{\nu}_\mu {}^{12}C \to \mu^{+\,12}B$ reactions will be measured to high precision with MiniBooNE. An attempt will be made to measure M_A, the axial-vector dipole mass, by comparing the two as a function of Q^2, which allows a separation of the free protons from the bound protons in the $\bar{\nu}_\mu$ channel.

- Neutral-Current π^0 Production

123

Table 9.1: Expected number of detected events in 1 year of running at each horn polarity for selected neutrino channels in the MiniBooNE detector.

ν_μ reaction	events	$\bar{\nu}_\mu$ reaction	events
$\nu_\mu C \to \mu^- N$	510,000	$\bar{\nu}_\mu C \to \mu^+ B$	150,000
$\nu_\mu e \to \nu_\mu e$	130	$\bar{\nu}_\mu e \to \bar{\nu}_\mu e$	60
$\nu_\mu C \to \mu^- \pi^0 X$	65,000	$\bar{\nu}_\mu C \to \mu^+ \pi^0 X$	21,000
$\nu_\mu n,p \to \nu_\mu n,p$	72,000	$\bar{\nu}_\mu n,p \to \bar{\nu}_\mu n,p$	18,000

A measure of $\nu_\mu C \to \nu_\mu \pi^0 X$ is a sensitive probe of the structure of the weak neutral-current. Significant gains in precision will be achieved over previous experiments in this energy region. This will enable a test of the standard model prediction of the helicity structure of the weak neutral-current.

- Neutrino-Electron Neutral-Current Scattering

  By measuring the $\nu_\mu e^- \to \nu_\mu e^-$ cross section and its behavior at low-Q^2, we will search for evidence of a magnetic moment of the muon-neutrino. If the neutrino is a Majorana particle (and CPT holds) the neutrino must have no magnetic moment. Thus, a measurement of a non-vanishing magnetic moment is proof that the neutrino is a Dirac particle. This is a difficult measurement due to the small cross section for this process, however, an non-zero magnetic moment could be of relevance in the solar neutrino problem.

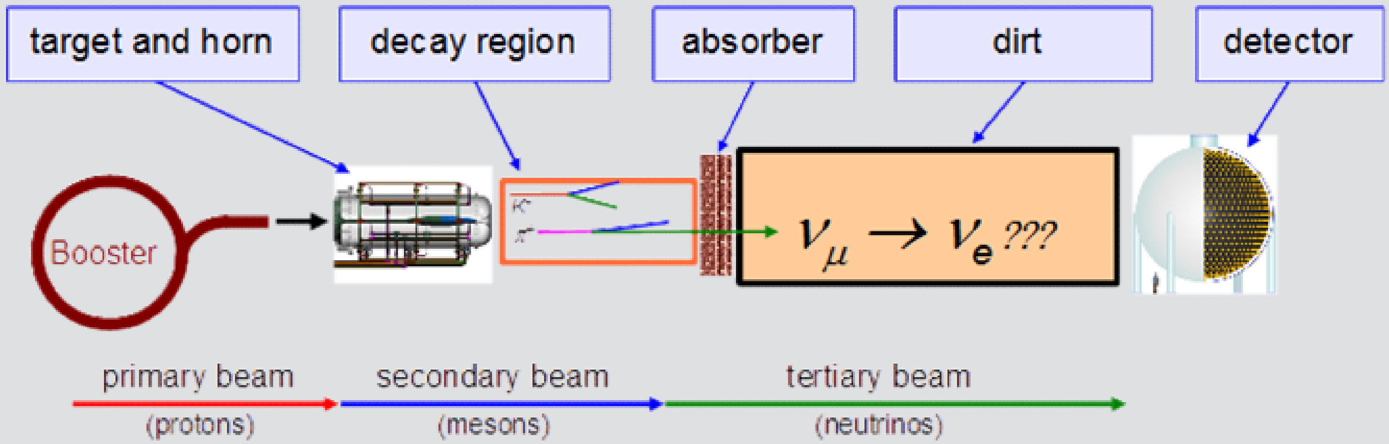
MiniBooNE…

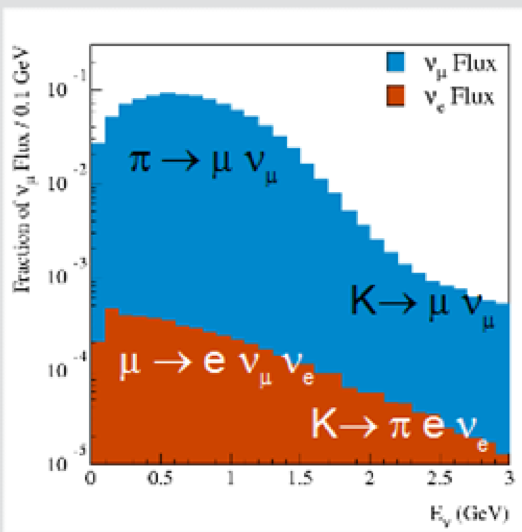
.. fortunately cross section results output was high..

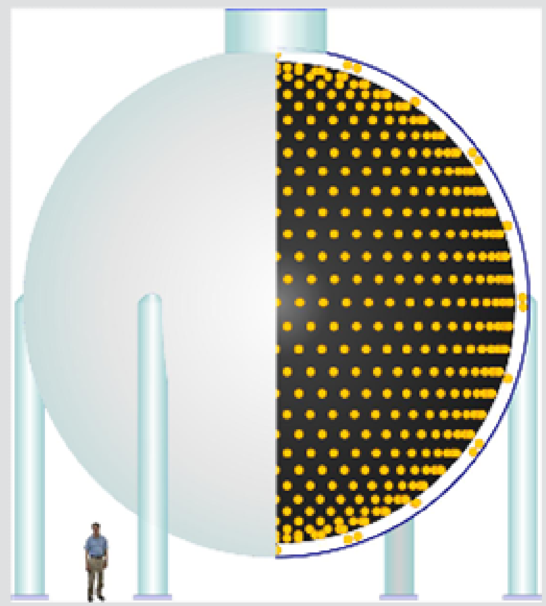
4. **First Measurement of the Muon Neutrino Charged Current Quasielastic Double Differential Cross Section**
(365) MiniBooNE Collaboration (A.A. Aguilar-Arevalo (Mexico U., CEN) *et al.*). Feb 2010. 21 pp.
Published in **Phys.Rev. D81 (2010) 092005**
FERMILAB-PUB-10-046-E
DOI: 10.1103/PhysRevD.81.092005
e-Print: **arXiv:1002.2680 [hep-ex] | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; OSTI Information Bridge Server; Fermilab Library Server (fulltext available); Fermilab Today Result of the Week
Detailed record - Cited by 365 records 250+

- **Refereed publications by the MiniBooNE Collaboration:**
  - A.A. Aguilar-Arevalo et al., Measurement of the Antineutrino Neutral-Current Elastic Differential Cross Section, arXiv:1309.7257, Phys. Rev. D91, 012004 (2015), Data Release
  - A.A. Aguilar-Arevalo et al., First Measurement of the Muon Antineutrino Double Differential Charged Current Quasi-Elastic Cross Section, arXiv:1301.7067, Phys. Rev. D88, 032001 (2013), Result of the Week, Data Release
  - G. Cheng et al., "Dual Baseline search for Muon Antineutrino Disappearance at $0.1<\Delta m^2<100eV^2$", arXiv:1208.0322, Phys. Rev. D86, 052009 (2012), Result of the Week
  - A.A. Aguilar-Arevalo et al., "Improved Search for ν_μ to ν_e; and $\bar{\nu}_\mu$ to $\bar{\nu}_e$; Oscillations in the MiniBooNE Experiment", arXiv:1303.2588, Phys. Rev. Lett. 110, 161801 (2013), Result of the Week
  - A.A. Aguilar-Arevalo et al., "A Combined ν_μ to ν_e; and $\bar{\nu}_\mu$ to $\bar{\nu}_e$; Oscillation Analysis of the MiniBooNE Excess", arXiv:1207.4809, Data release
  - A.A. Aguilar-Arevalo et al., "Test of Lorentz and CPT Violation with Short Baseline Neutrino Oscillation Excesses", arXiv:1109.3480 [hep-ex], submitted to Phys. Lett. B.
  - K.B.M. Mahn et al., "Dual Baseline Search for muon neutrino disappearance at $0.5\ eV^2< \Delta m^2 < 40\ eV^2$", arXiv:1106.5685 [hep-ex], Phys. Rev. D85, 032007 (2012)
  - A.A. Aguilar-Arevalo et al., "Measurement of the Neutrino Component of an Anti-Neutrino Beam Observed by a Non-Magnetized Detector", arXiv:1102.1964 [hep-ex], Phys. Rev. D84, 072005 (2011)
  - A.A. Aguilar-Arevalo et al., "Measurement of Neutrino-Induced Charged-Current Charged Pion Production Cross Sections on Mineral Oil at $E_\nu \sim 1$ GeV", arXiv:1011.3572 [hep-ex], Phys. Rev. D83, 052007 (2011), Data release
  - A.A. Aguilar-Arevalo et al., "Measurement of ν_μ Induced Charged Current Neutral Pion Production Cross-Sections on Mineral Oil at $E_\nu \in 0.5$-2.0 GeV", arXiv:1010.3264 [hep-ex], Phys. Rev. D83, 052009 (2011), Data release
  - A.A. Aguilar-Arevalo et al., "Measurement of the Neutrino Neutral-Current Elastic Differential Cross Section", arXiv:1007.4730 [hep-ex], Phys. Rev. D82, 092005 (2010), Data release
  - A.A. Aguilar-Arevalo et al., "Event Excess in the MiniBooNE Search for Muon Antineutrino to Electron Antineutrino Oscillations", arXiv:1007.1150 [hep-ex], Phys. Rev. Lett. 105 181801 (2010), Result of the Week, Press
  - A.A. Aguilar-Arevalo et al., "First Measurement of the Muon Neutrino Charged Current Quasielastic Double Differential Cross Section", arXiv:1002:2680 [hep-ex], Phys. Rev. D81, 092005 (2010), Result of the Week, Data release
  - A.A. Aguilar-Arevalo et al., "Measurement of ν_μ and $\bar{\nu}_\mu$ induced neutral current single π^0 production cross sections on mineral oil at $E_\nu \sim O(1\ GeV)$", arXiv:0911.2063 [hep-ex], Phys. Rev. D81, 013005 (2010), Result of the Week, Data release
  - A.A. Aguilar-Arevalo et al., "A Search for Core-Collapse Supernovae using the MiniBooNE Neutrino Detector", arXiv:0910.3182 [hep-ex], Phys. Rev. D81, 032001 (2010), Result of the Week
  - A.A. Aguilar-Arevalo et al., "Measurement of the ν_μ CC pi+/QE Cross Section Ratio on Mineral Oil in a 0.8 GeV Neutrino Beam", arXiv:0904.3159 [hep-ex], Phys. Rev. Lett. 103, 081801 (2009)
  - A.A. Aguilar-Arevalo et al., "A Search for Electron Anti-Neutrino Appearance at the $\Delta m^2 \sim 1\ eV^2$ Scale", arXiv:0904.1958 [hep-ex], Phys. Rev. Lett. 103, 111801 (2009), Result of the Week, Data release
  - A.A. Aguilar-Arevalo et al., "A Search for Muon Neutrino and Anti-Neutrino Disappearance in MiniBooNE", arXiv:0903.2465 [hep-ex], Phys. Rev. Lett. 103, 061802 (2009), Data release
  - A.A. Aguilar-Arevalo et al., "Unexplained Excess of Electron-Like Events From a 1 GeV Neutrino Beam", arXiv:0812.2243 [hep-ex], Phys. Rev. Lett. 102, 101802 (2009), Data release
  - P. Adamson et al., "First Measurement of ν_μ and ν_e Events in an Off-Axis Horn-Focused Neutrino Beam", arXiv:0809.2447 [hep-ex], Phys. Rev. Lett. 102, 211801 (2009)
  - A.A. Aguilar-Arevalo et al., "The MiniBooNE Detector", arXiv:0806.4201 [hep-ex], Nucl. Instr. Meth. A599 (2009) 28-46
  - A.A. Aguilar-Arevalo et al., "The Neutrino Flux Prediction at MiniBooNE", arXiv:0806.1449 [hep-ex], Phys. Rev. D79, 072002 (2009), Data release
  - A.A. Aguilar-Arevalo et al., "Compatibility of high Δm^2 ν_e and $\nu_e$bar Neutrino Oscillation Searches", arXiv:0805.1764 [hep-ex], Phys. Rev. D78, 012007 (2008)
  - A.A. Aguilar-Arevalo et al., "First Observation of Coherent π^0 Production in Neutrino Nucleus Interactions with $E_\nu<2$ GeV", arXiv:0803.3423 [hep-ex], Phys. Lett. B664, 41 (2008)
  - A.A. Aguilar-Arevalo et al., "Constraining Muon Internal Bremsstrahlung As A Contribution to the MiniBooNE Low Energy Excess", arXiv:0710.3897 [hep-ex]
  - A.A. Aguilar-Arevalo et al., "Measurement of Muon Neutrino Quasi-Elastic Scattering on Carbon", arXiv:0706.0926 [hep-ex], Phys. Rev. Lett. 100, 032301 (2008)
  - A.A. Aguilar-Arevalo et al., "A Search for Electron Neutrino Appearance at the $\Delta m^2 \sim 1\ eV^2$ Scale", arXiv:0704.1500 [hep-ex], Phys. Rev. Lett. 98, 231801 (2007), Press release, Data release

MiniBooNE experiment, overview







LSND cross section measurements

- MiniBooNE results (from CH2)
  (PRL100, 0323021, '08)

- Q^2 spectrum of data, compared to "world average model" (dashed)
  - event excess at $Q^2 > 0.2$ GeV^2
  - also event deficit at $Q^2 < 0.2$ GeV^2

- could not get satisfactory fit (at low Q^2 with only M_A so had to add new parameter κ that increases Pauli-blocking of outgoing nucleon

- shape-only fit of Q^2 distribution yielded:

$$M_A^{\rm eff} = 1.23 \pm 0.20 \text{ GeV},$$

$$\kappa = 1.019 \pm 0.011.$$

PRL 100, 032301 (2008) PHYSICAL REVIEW LETTERS week ending 25 JANUARY 2008

Measurement of Muon Neutrino Quasielastic Scattering on Carbon

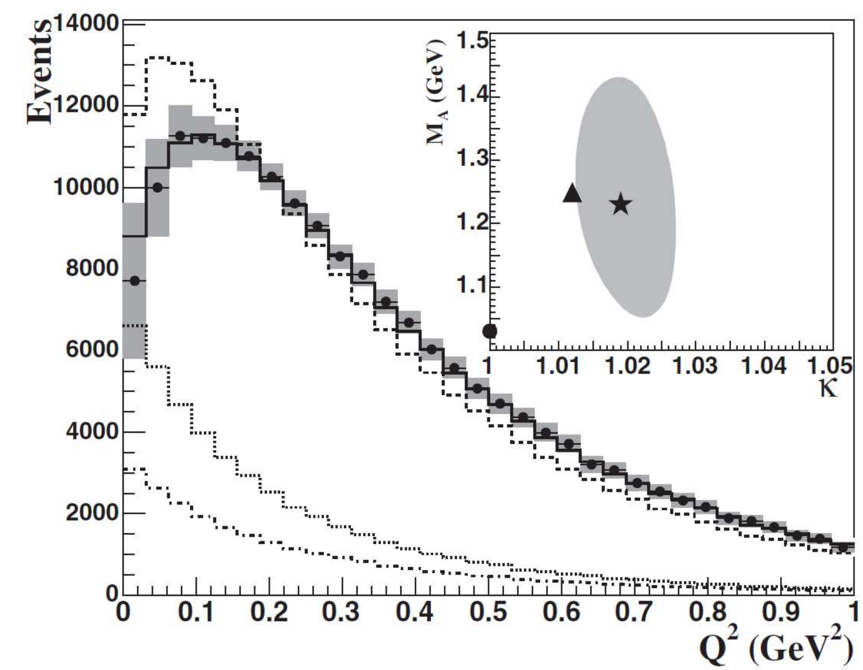
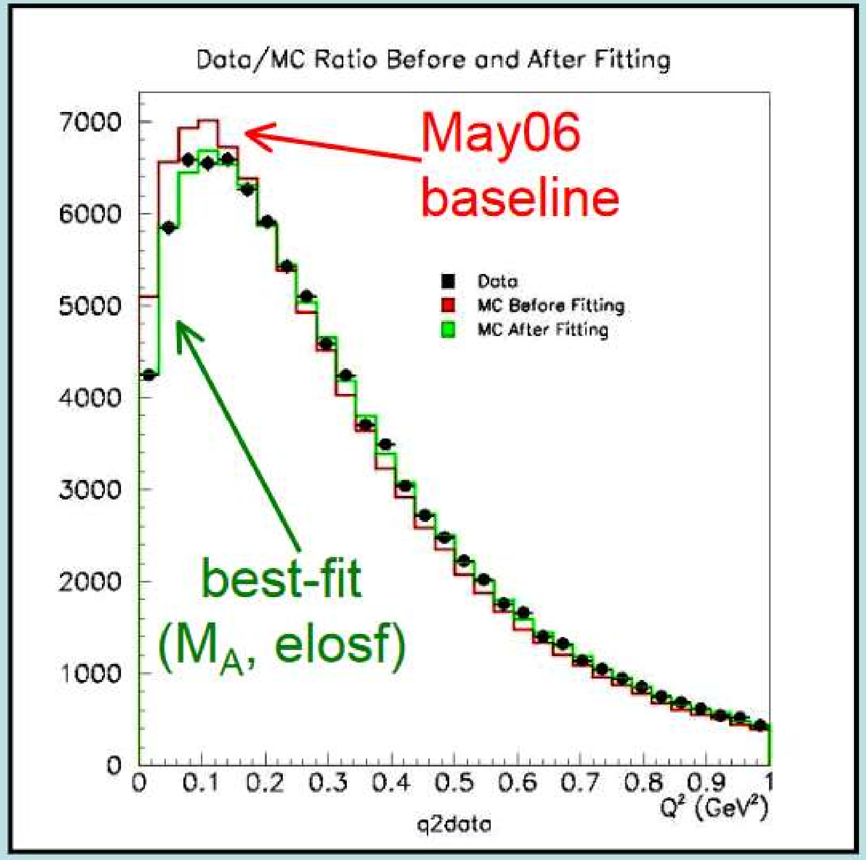


FIG. 2. Reconstructed Q^2 for ν_μ CCQE events including systematic errors. The simulation, before (dashed curve) and after (solid curve) the fit, is normalized to data. The dotted curve (dot-dashed curve) shows backgrounds that are not CCQE (not "CCQE-like"). The inset shows the 1σ C.L. contour for the best-fit parameters (star), along with the starting values (circle), and fit results after varying the background shape (triangle).

κ , "kappa", ("elosf")



Sam Zeller, 11/02/06

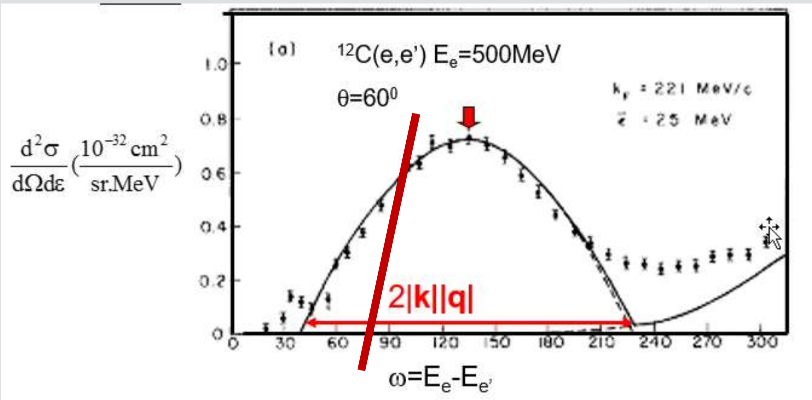
ASPECTS of the FERMI GAS MODEL AS IMPLEMENTED in NUANCE

G. GARVEY

OCT. 2006

Rex, Teppei and Sam has shown that a less than 1% increase in εloSF has a remarkable effect on bringing the low Q^2 QE data into line and allowing more reasonable values of p_F, E_b and M_A.

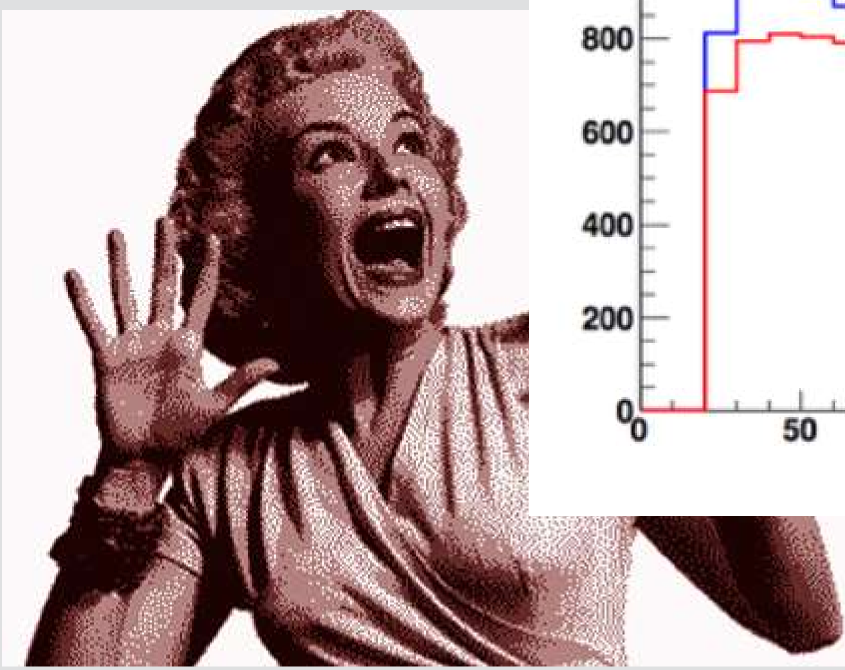
εloSF is a bound on the initial energy of the struck nucleon (momentum?) such that with a given momentum transfer **q** it can exceed the Fermi Energy and thereby participate in QE scattering.

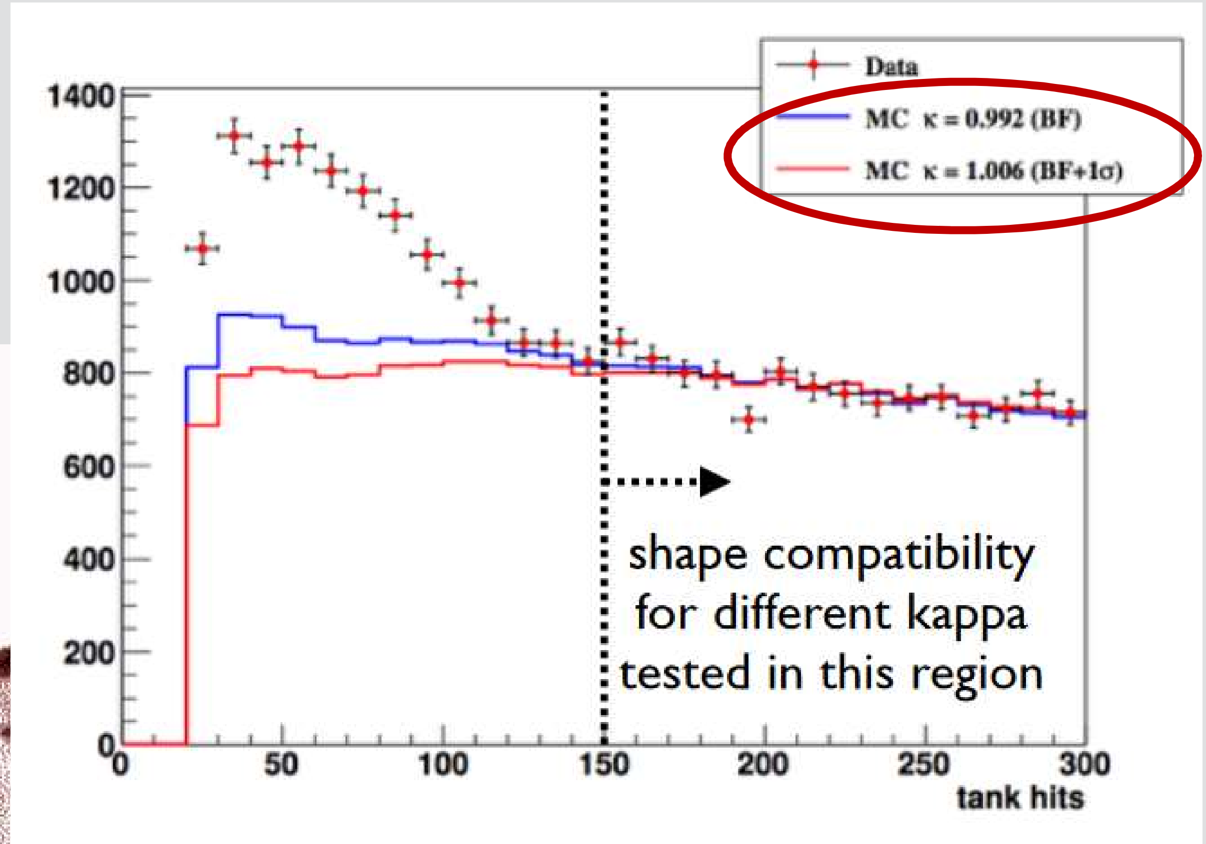


I will continue to work on this but you should not be anxious about it. The remedy that Rex et al found looks harmless, works well and should be employed.

κ , “kappa”, (“elosf”)

κ , it wont die!





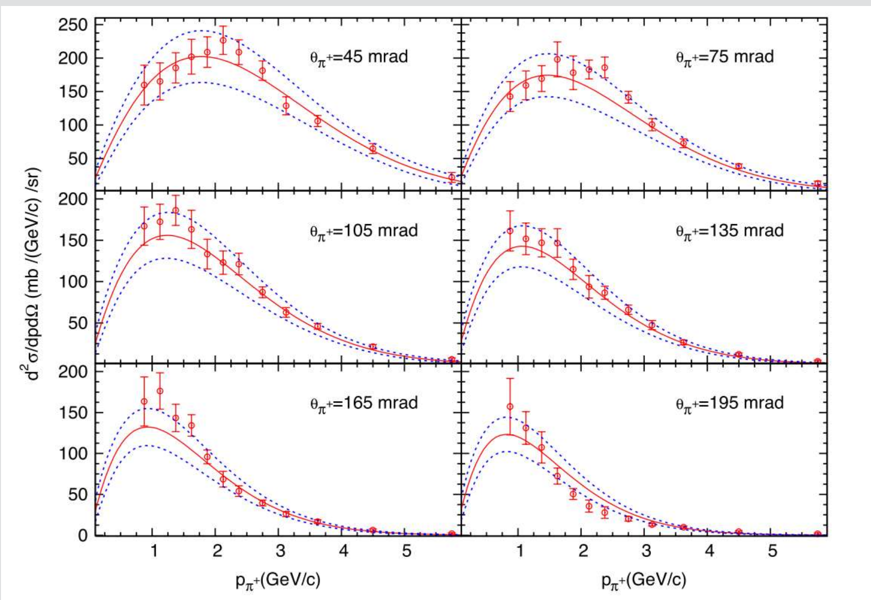
MiniBooNE, cross section measurements

need a flux prediction,
not normed to CCQE xsection…

PHYSICAL REVIEW D **79,** 072002 (2009)

Neutrino flux prediction at MiniBooNE

HARP measurements



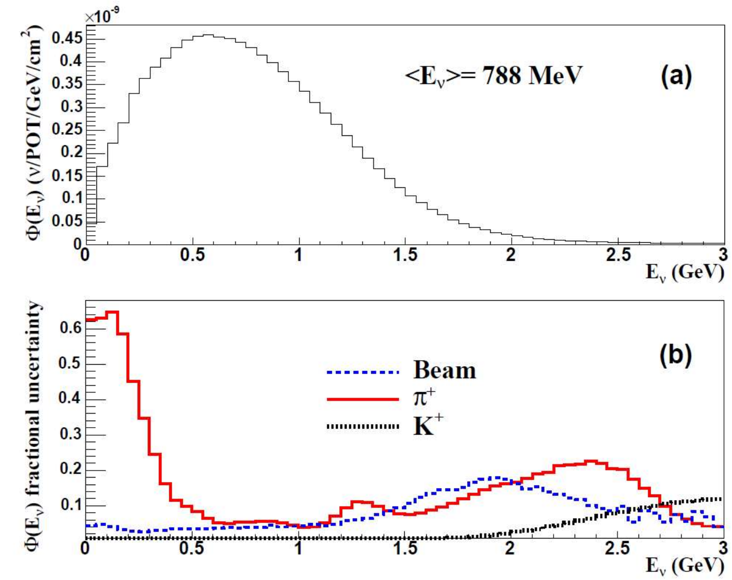


FIG. 2: (color online) Predicted ν_μ flux at the MiniBooNE detector (a) along with the fractional uncertainties grouped into various contributions (b). The integrated flux is 5.16×10^{-10} ν_μ/POT/cm^2 ($0 < E_\nu < 3$ GeV) with a mean energy of 788 MeV. Numerical values corresponding to the top plot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

MiniBooNE, CCQE xsection

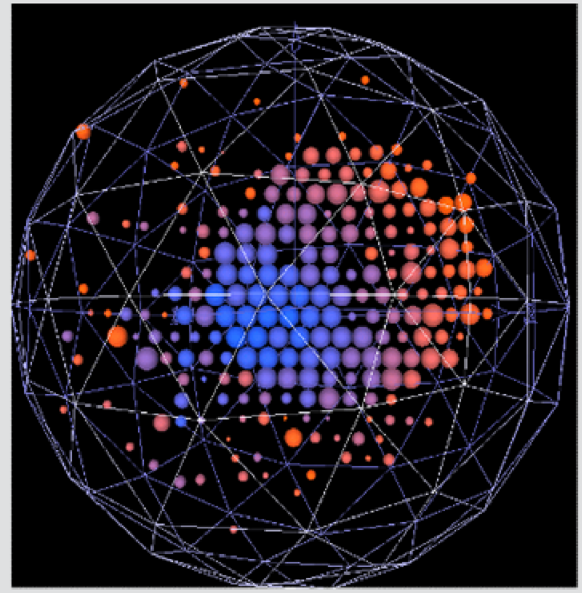
- charged particles in MB create cherenkov (and some scintillation) light

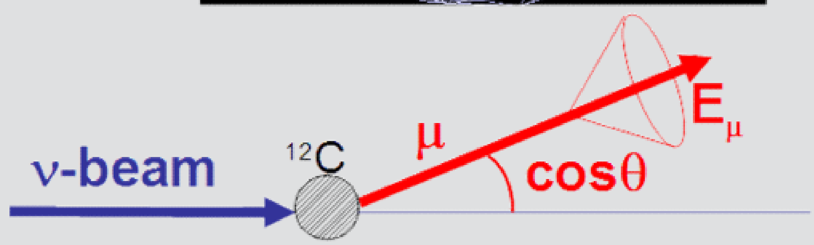
- tracks reconstructed (energy, direction, position) with likelihood method utilizing time, charge of PMT hits (NIM, A 608 (2009), pp. 206-224)

- in addition, muon, pion decays are seen by recording PMT info for 20μs around 2μs beam spill

- In this analysis, all observables are formed from muon energy (E_{μ}) and muon scattering angle (θ_{μ})

- Energy of the neutrino E_{ν}^{QE} and 4-momentum transfer Q^2_{QE} can be reconstructed by these 2 observables, under the assumption of CCQE interaction with bound neutron at rest ("QE assumption")

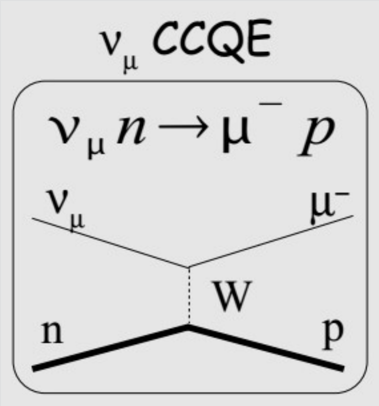




$$E_{\nu}^{QE} = \frac{2(M'_n)E_{\mu} - ((M'_n)^2 + m_{\mu}^2 - M_p^2)}{2 \cdot [(M'_n) - E_{\mu} + \sqrt{E_{\mu}^2 - m_{\mu}^2}\cos\theta_{\mu}]}, \quad (1)$$

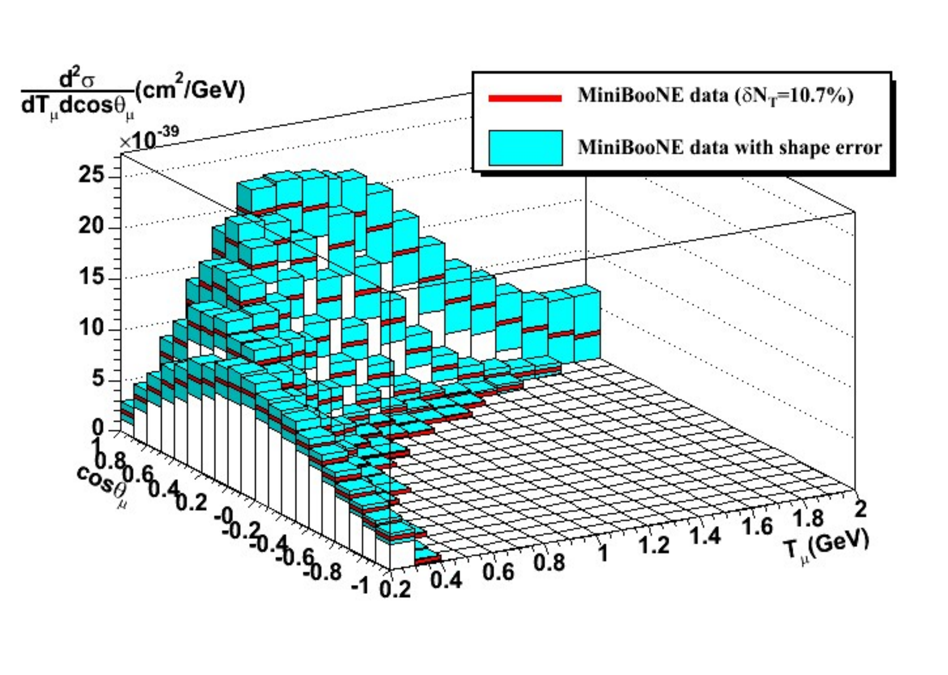
$$Q^2_{QE} = -m_{\mu}^2 + 2E_{\nu}^{QE}(E_{\mu} - \sqrt{E_{\mu}^2 - m_{\mu}^2}\cos\theta_{\mu}), \quad (2)$$

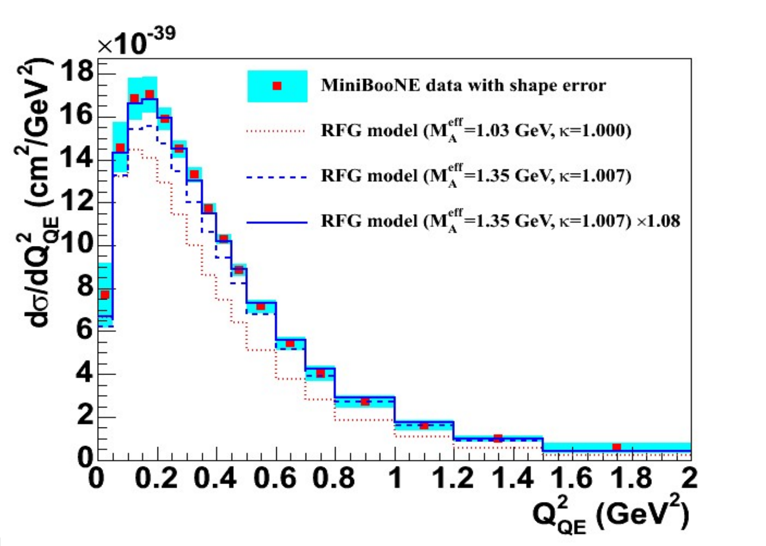
MiniBooNE, CCQE xsection, results



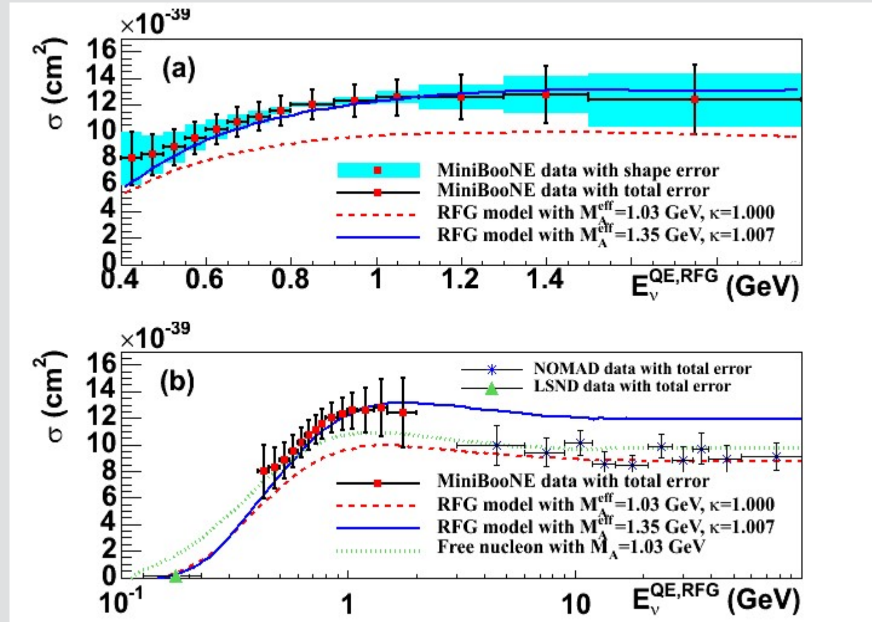
integrated protons on target		5.58×10^{20}
energy-integrated ν_μ flux		2.90×10^{11} ν_μ/cm^2
CCQE candidate events		146070
CCQE efficiency ($R < 550$ cm)		26.6%
background channel	events	fraction
NCE	45	$< 0.1\%$
$CC1\pi^+$	26866	18.4%
$CC1\pi^0$	3762	2.6%
$NC1\pi^\pm$	535	0.4%
$NC1\pi^0$	43	$< 0.1\%$
other ν_μ	328	0.2%
all non-ν_μ	1977	1.4%
total background	33556	23.0%

TABLE III: Summary of the final CCQE event sample including a breakdown of the estimated backgrounds from individual channels. The fraction is relative to the total measured sample. The channel nomenclature is defined in Table I.





MiniBooNE, CCQE xsection, results



Thanks, Gerry!

PHYSICAL REVIEW D **81,** 092005 (2010)

First measurement of the muon neutrino charged current quasielastic double differential cross section

A. A. Aguilar-Arevalo,[13] C. E. Anderson,[18] A. O. Bazarko,[15] S. J. Brice,[7] B. C. Brown,[7] L. Bugel,[5] J. Cao,[14] L. Coney,[5] J. M. Conrad,[12] D. C. Cox,[9] A. Curioni,[18] Z. Djurcic,[5] D. A. Finley,[7] B. T. Fleming,[18] R. Ford,[7] F. G. Garcia,[7] G. T. Garvey,[10] J. Grange,[8] C. Green,[7,10] J. A. Green,[9,10] T. L. Hart,[4] E. Hawker,[3,10] R. Imlay,[11] R. A. Johnson,[3] G. Karagiorgi,[13] P. Kasper,[7] T. Katori,[9,12] T. Kobilarcik,[7] I. Kourbanis,[7] S. Koutsoliotas,[2] E. M. Laird,[15] S. K. Linden,[18] J. M. Link,[17] Y. Liu,[14] Y. Liu,[1] W. C. Louis,[10] K. B. M. Mahn,[5] W. Marsh,[7] C. Mauger,[10] V. T. McGary,[12] G. McGregor,[10] W. Metcalf,[11] P. D. Meyers,[15] F. Mills,[7] G. B. Mills,[10] J. Monroe,[5] C. D. Moore,[7] J. Mousseau,[8] R. H. Nelson,[4] P. Nienaber,[16] J. A. Nowak,[11] B. Osmanov,[8] S. Ouedraogo,[11] R. B. Patterson,[15] Z. Pavlovic,[10] D. Perevalov,[1] C. C. Polly,[7] E. Prebys,[7] J. L. Raaf,[3] H. Ray,[8,10] B. P. Roe,[14] A. D. Russell,[7] V. Sandberg,[10] R. Schirato,[10] D. Schmitz,[5] M. H. Shaevitz,[5] F. C. Shoemaker,[15,*] D. Smith,[6] M. Soderberg,[18] M. Sorel,[5,†] P. Spentzouris,[7] J. Spitz,[18] I. Stancu,[1] R. J. Stefanski,[7] M. Sung,[11] H. A. Tanaka,[15] R. Tayloe,[9] M. Tzanov,[4] R. G. Van de Water,[10] M. O. Wascko,[11,‡] D. H. White,[10] M. J. Wilking,[4] H. J. Yang,[14] G. P. Zeller,[7] and E. D. Zimmerman[4]

(MiniBooNE Collaboration)

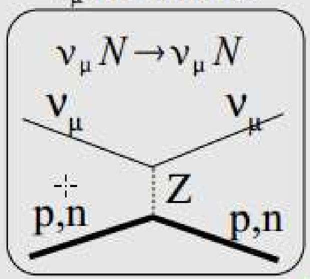
MiniBooNE NC elastic results

differential cross section:

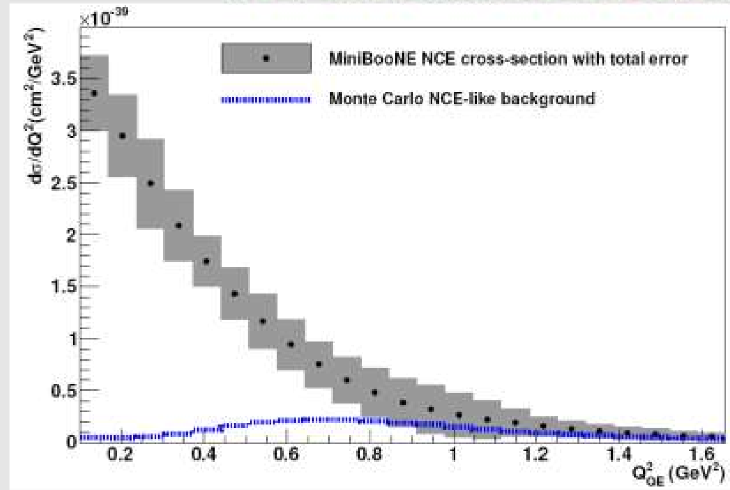
- from an absolute fit to proton KE distribution

- $M_A = 1.39 \pm 0.11$ GeV

ν_μ NC elastic



NCel differential cross section

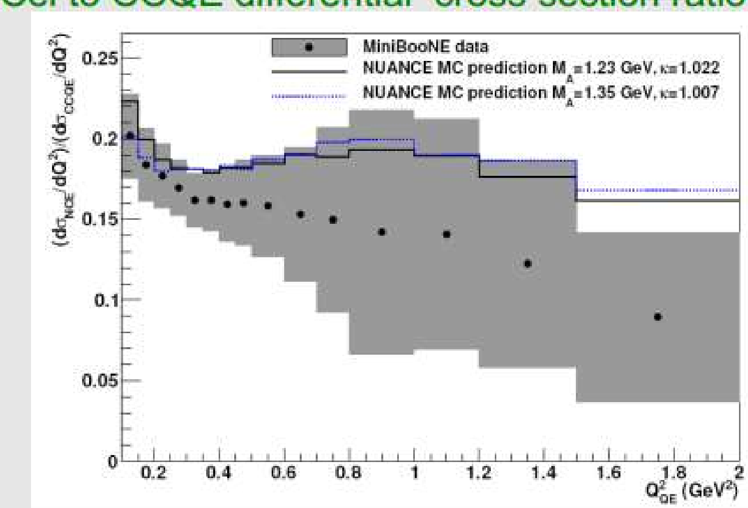


NCel to CCQE differential cross section ratio:

- flux error cancels between the 2 channels

- ratio is consistent with RFG model. So no discrepency in NCel compared to CCQE

NCel to CCQE differential cross section ratio



also nubar versions of CCQE/NCE

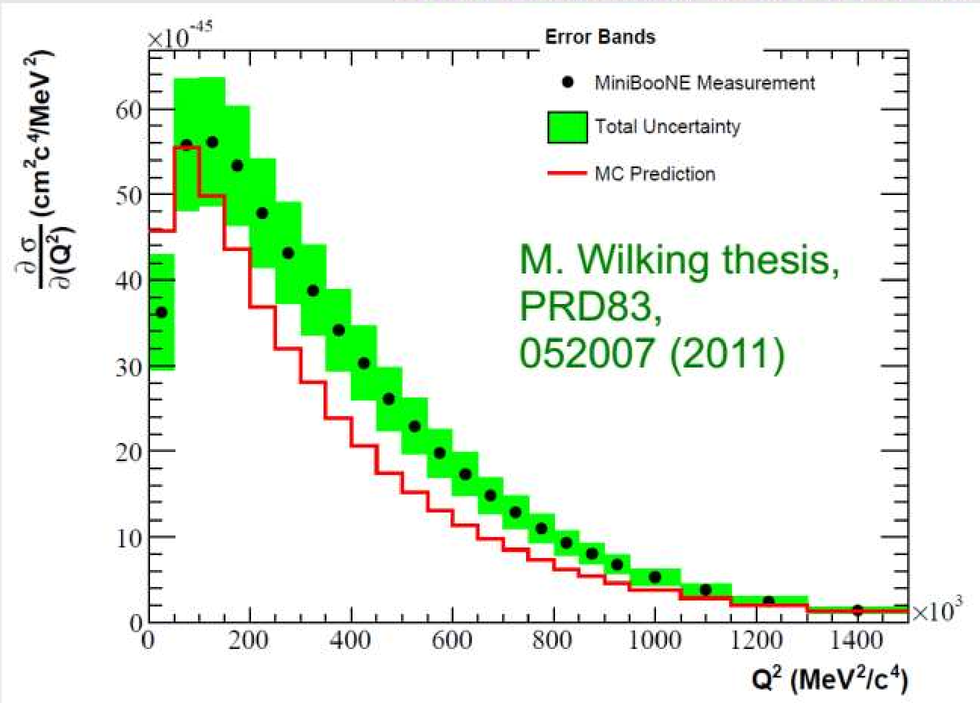
CCπ production

CCπ^+, π^0 differential cross sections from MiniBooNE:

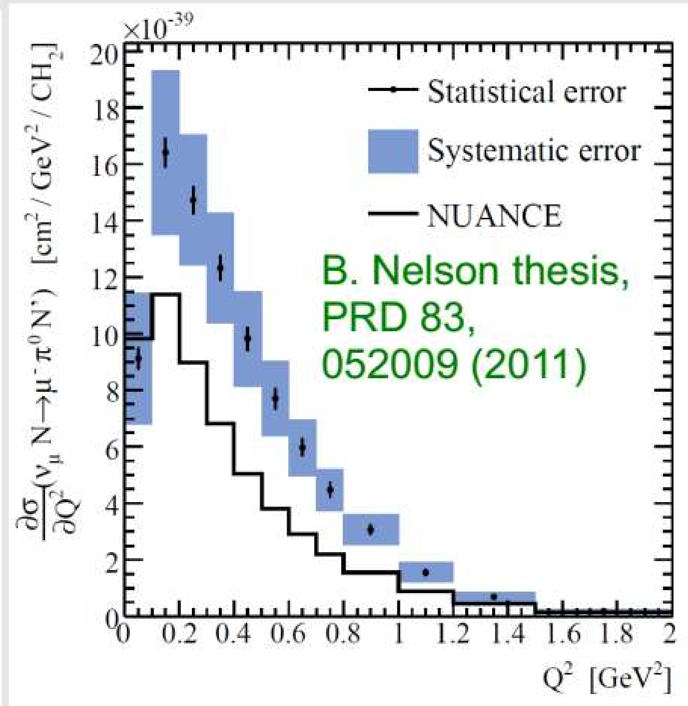
$$\nu_\mu + p(n) \rightarrow \mu + \Delta^{+(+)} \rightarrow \mu + p(n) + \pi^+$$
$$\nu_\mu + A \rightarrow \mu + A + \pi^+$$

- in a variety of kinematic variables
- model independent, absolutely norm'd
- will guide models of pion production including coherent piece (also from SciBooNE, see Waskco talk)

CCπ^+ differential cross sections

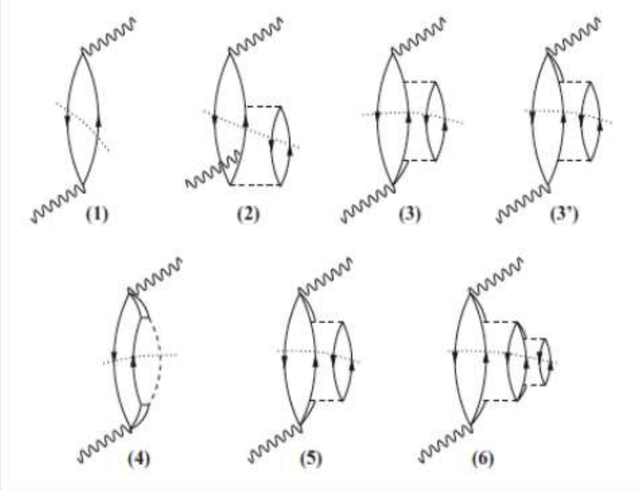


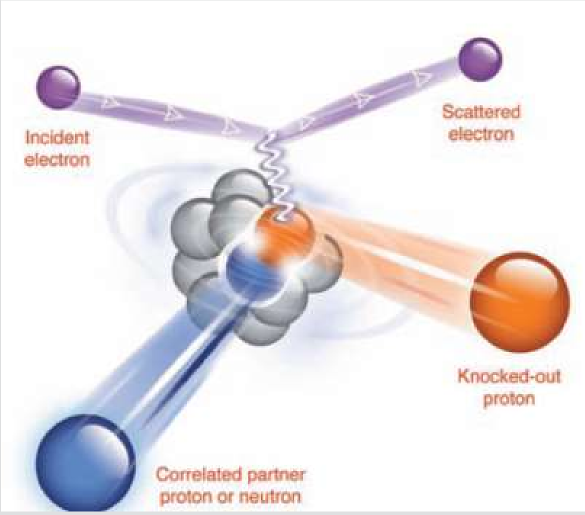
CCπ^0 differential cross section



MB cross sections, summary

- ν charged-current (CC) quasielastic (CCQE)
  - detection and normalization signal for oscillations
  - charged-current axial formfactor
- ν neutral-current (NC) elastic (NCel)
  - predicted from CCQE excepting NC contributions to axial form factor (strange quarks)
- ν CC production of π^+, π^0
  - background (and perhaps signal) for oscillations
  - insight into models of neutrino pion production via nucleon resonances and via coherent production
- ν CC inclusive scattering
  - should be understood together with exclusive channels
  - ~independent of final state details
- ν NC production of neutral pions
  - very important oscillation background
  - complementary to CC pion production



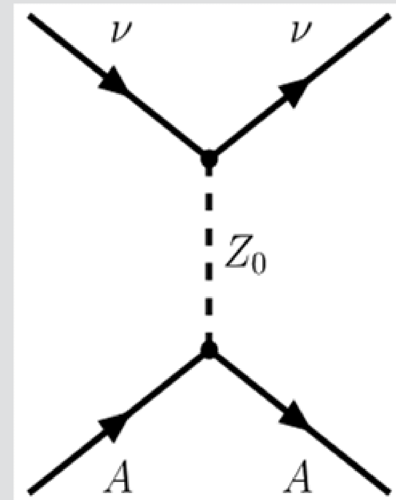


and anti-neutrinos!

Coherent Elastic ν-Nucleus Scattering:

"CEvNS":

Coherent Elastic ν-Nucleus Scattering: νA→νA

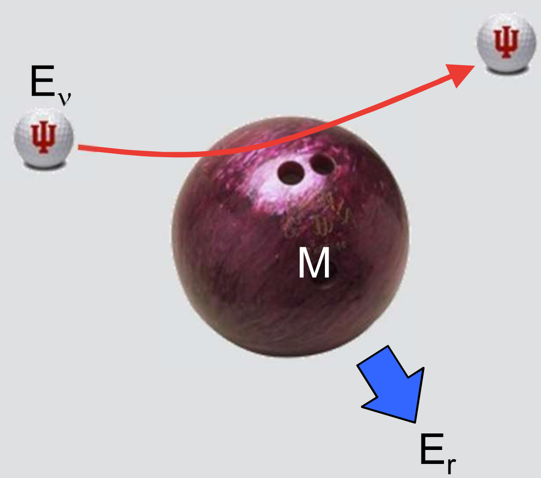


Neutrino scatters with low momentum transfer coherently, elastically from entire nucleus. For large nucleus, R_N~few fm, and:

$$E_\nu \lesssim \frac{hc}{R_N} \cong 50 \text{ MeV}$$

.. but recoil energy is quite small:

$$E_r^{\text{max}} \simeq \frac{2E_\nu^2}{M} \simeq 50 \text{ keV}$$

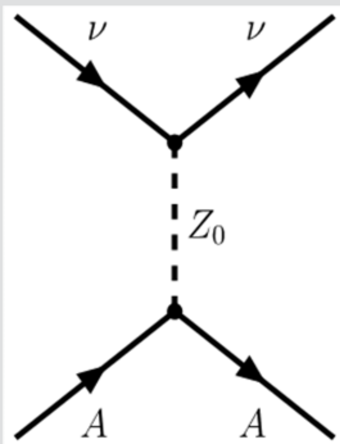


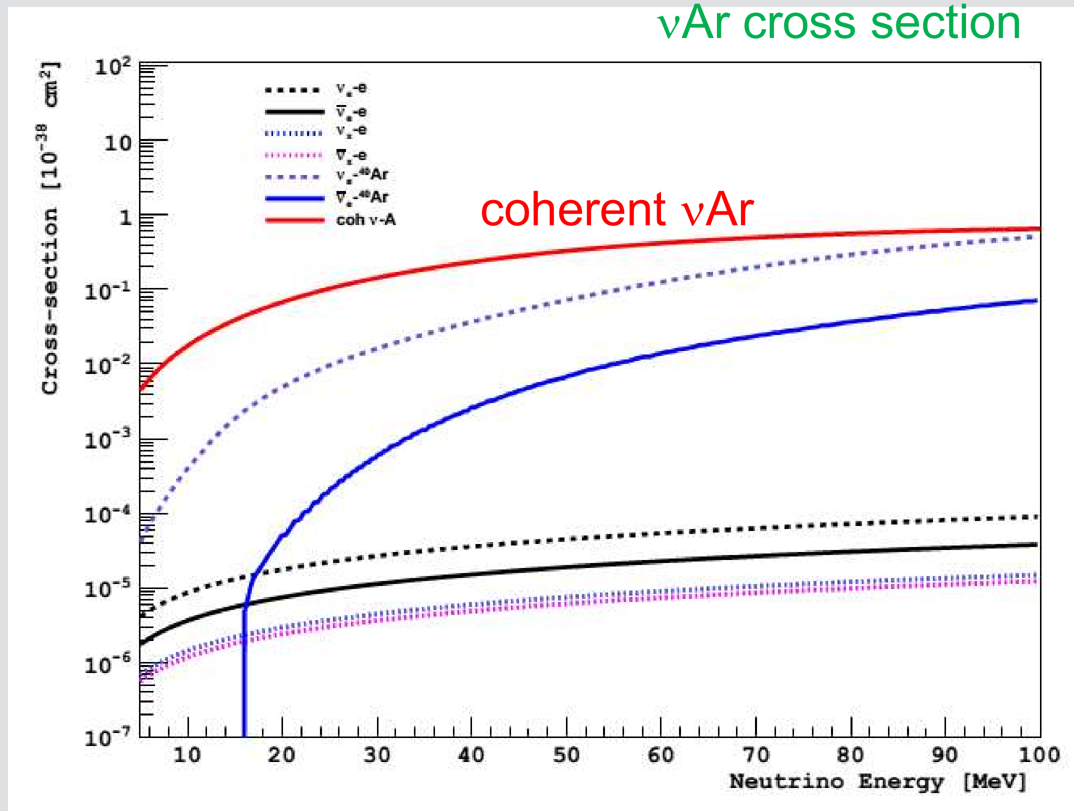
The CEvNS process has yet to be observed…

Coherent Elastic ν-Nucleus Scattering:

- Cross section is large…

in fact largest ν channel
at O(10 MeV) on heavier nuclei,
eg Ar





- and has distinctive

N^2 dependence

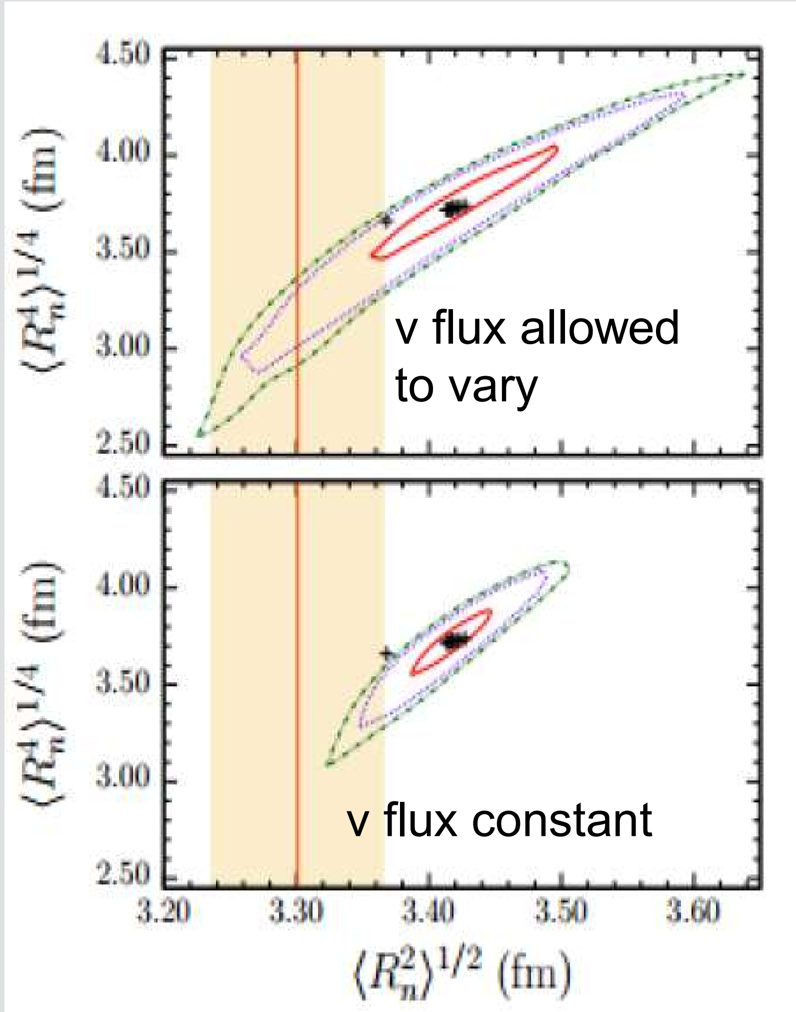
$$\frac{d\sigma}{dE} = \frac{G_F^2}{4\pi}[(1-4\sin^2\theta_w)Z-(A-Z)]^2 M\left(1-\frac{ME}{2E_\nu^2}\right)F(Q^2)^2$$

Coherent Elastic ν-Nucleus Scattering:

- SM Test
- Irreducible DM WIMP background
- Astrophysics
- Non Standard Interactions
- Nuclear Form Factors/Structure
  - Fit recoil spectrum shape to measure $F(Q^2)$
  - One isotope can measure ν flux
  - With two isotopes (e.g. Ar/Xe), ratio of recoil spectra removes flux uncertainty

$$\frac{d\sigma}{dE} = \frac{G_F^2}{4\pi}[(1-4\sin^2\theta_w)Z-(A-Z)]^2 M\left(1-\frac{ME}{2E_\nu^2}\right)F(Q^2)^2$$

Ar-C scattering



K. Patton et al, Phys. Rev. C86, 024612 (2012)

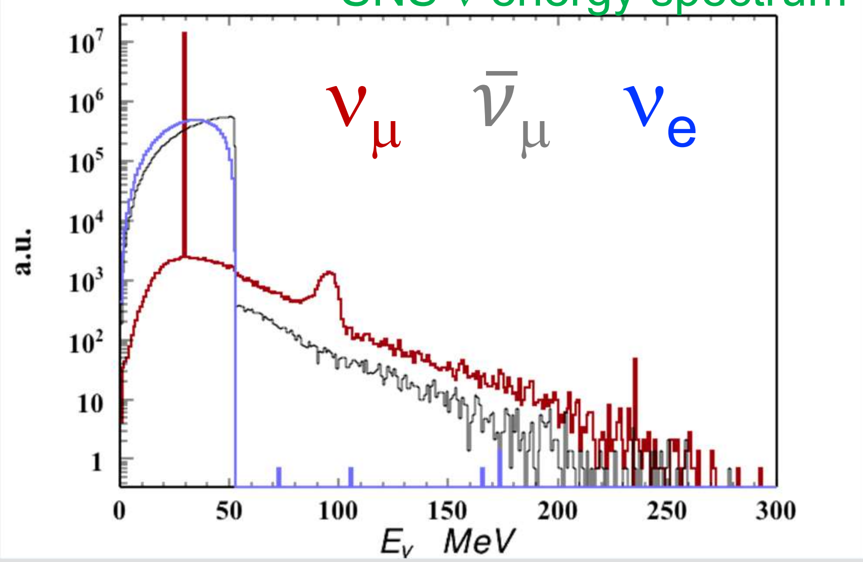
COHERENT experiment at SNS/ORNL

ORNL SNS is also an…

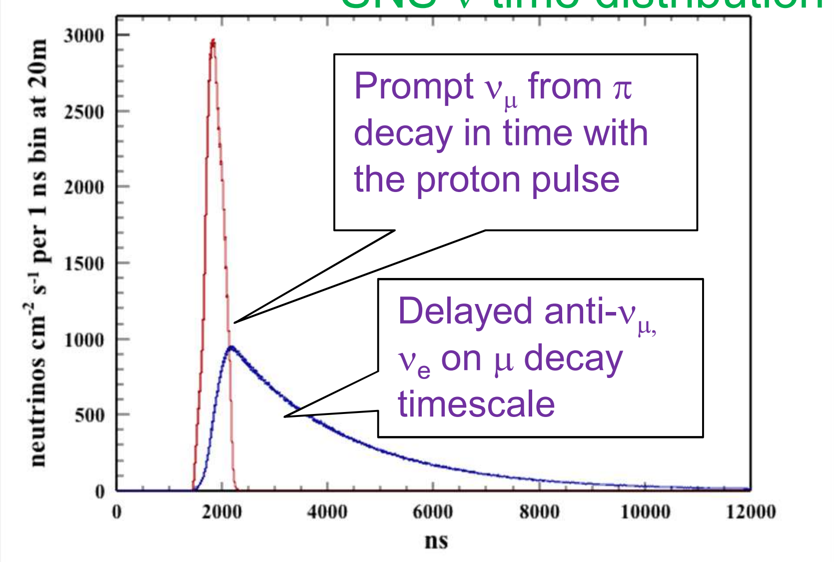
- intense (~1MWatt, 0-50 MeV)..
- pulsed (60 Hz, 600ns spill time)…

..ν source

SNS ν energy spectrum

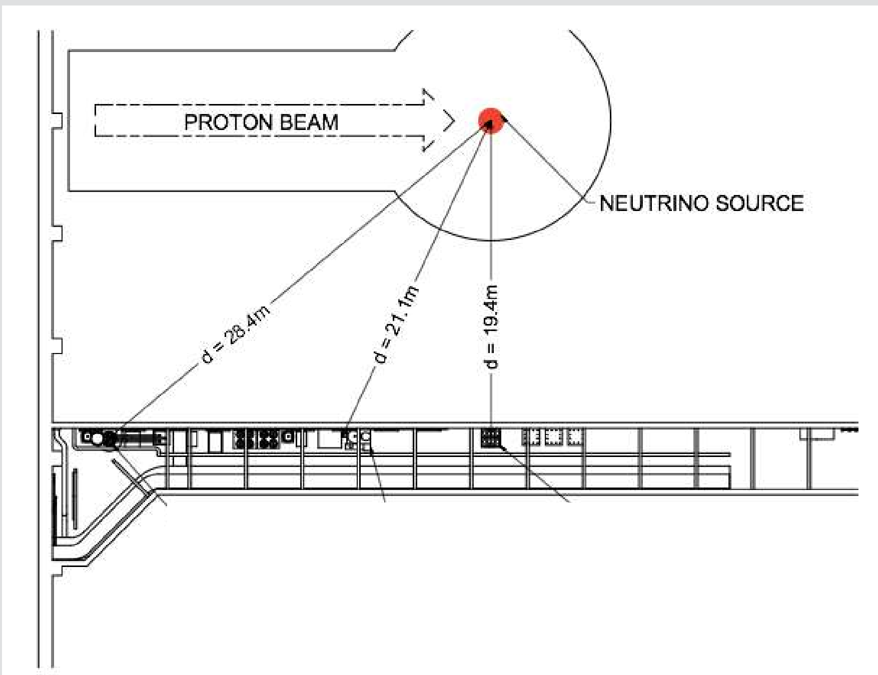


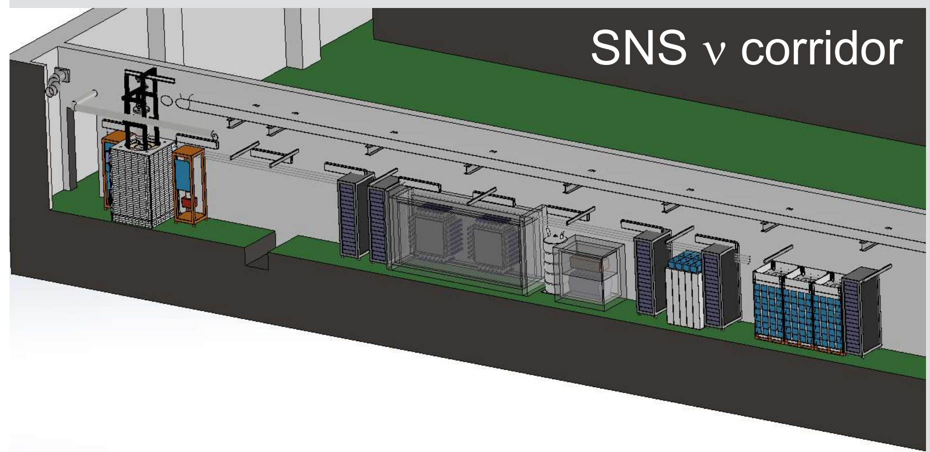
SNS ν time distribution



COHERENT experiment at SNS/ORNL

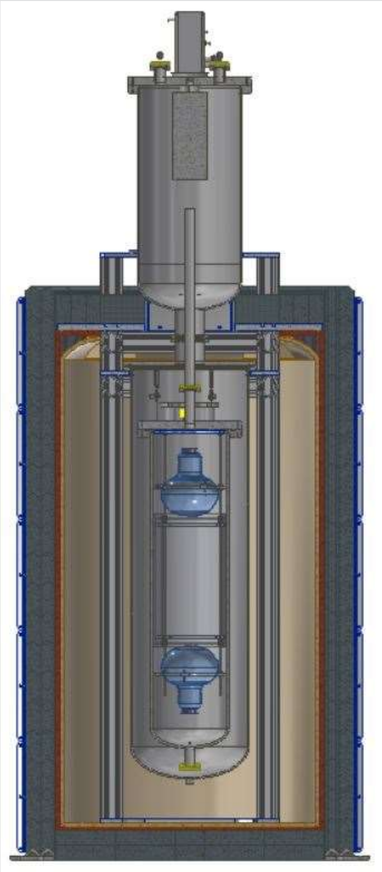
- a low-background experimental area has been acquired for COHERENT
- 20-29 m from target

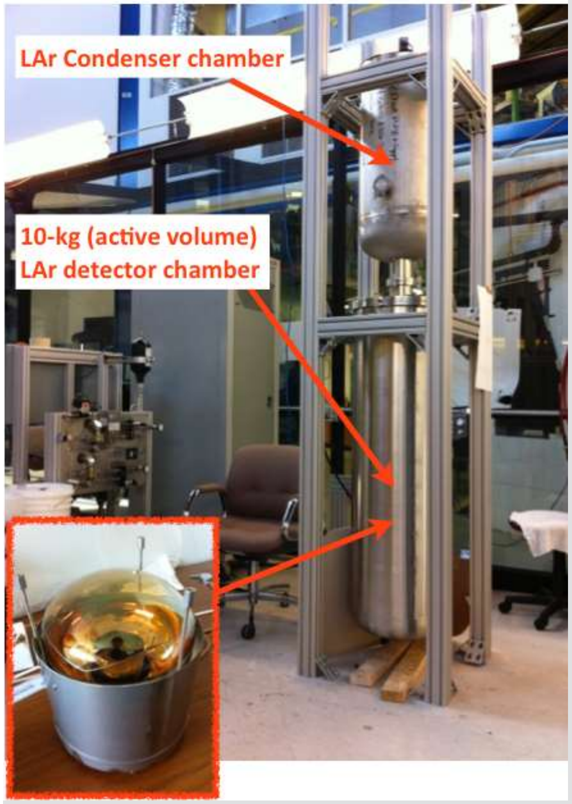




LAr for COHERENT

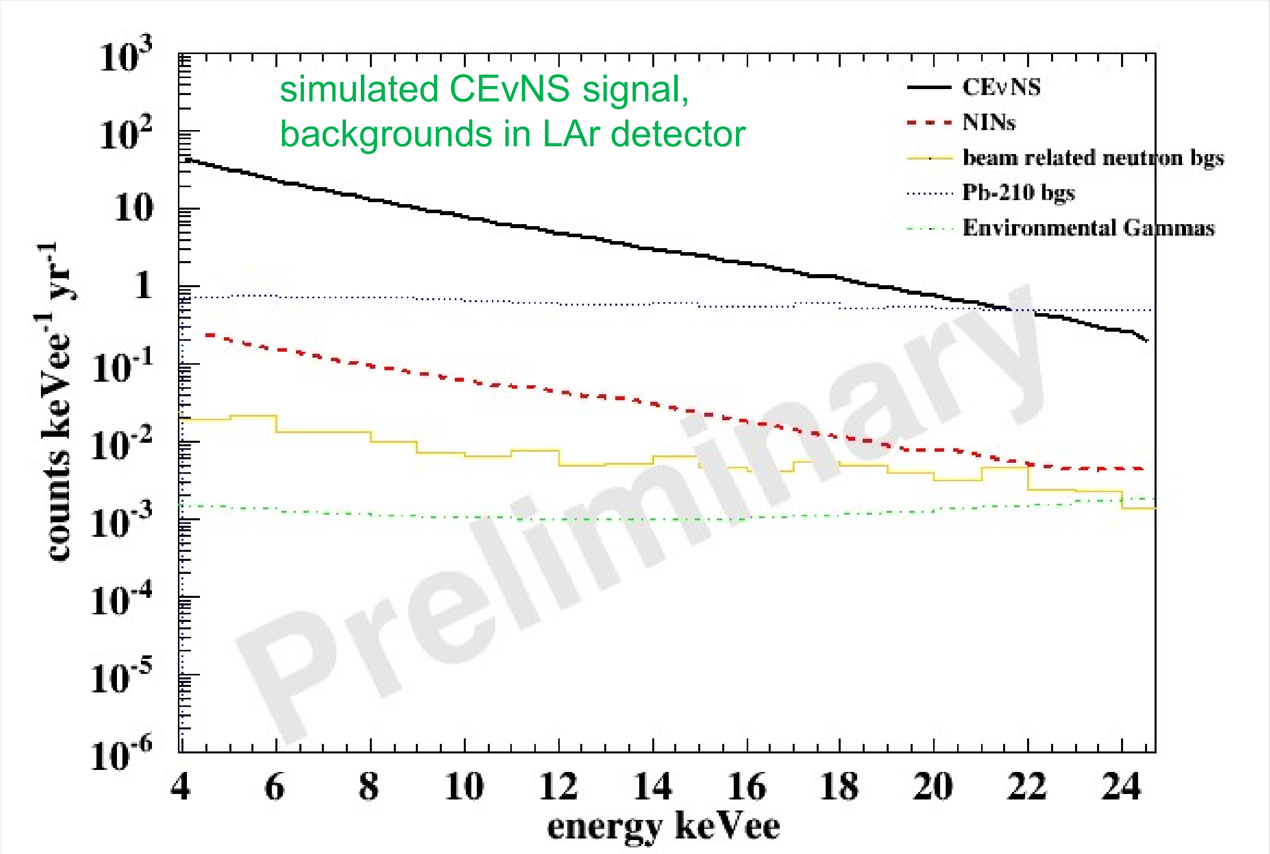
- Single-phase scintillation detector built by J. Yoo, etal at Fermilab for CEvNS effort
- 35-kg fiducial volume
- Readout: 2 × Hamamatsu R5912-02MOD PMT (8” cryogenic, high-gain)
- Excellent nuclear-/electron-recoil PSD demonstrated by miniCLEAN
- SCENE has measured quenching factors[1]
- ^{39}Ar controllable with PSD and duty factor
- Pb, Cu, H2O shielding structure
- Currently being installed at SNS





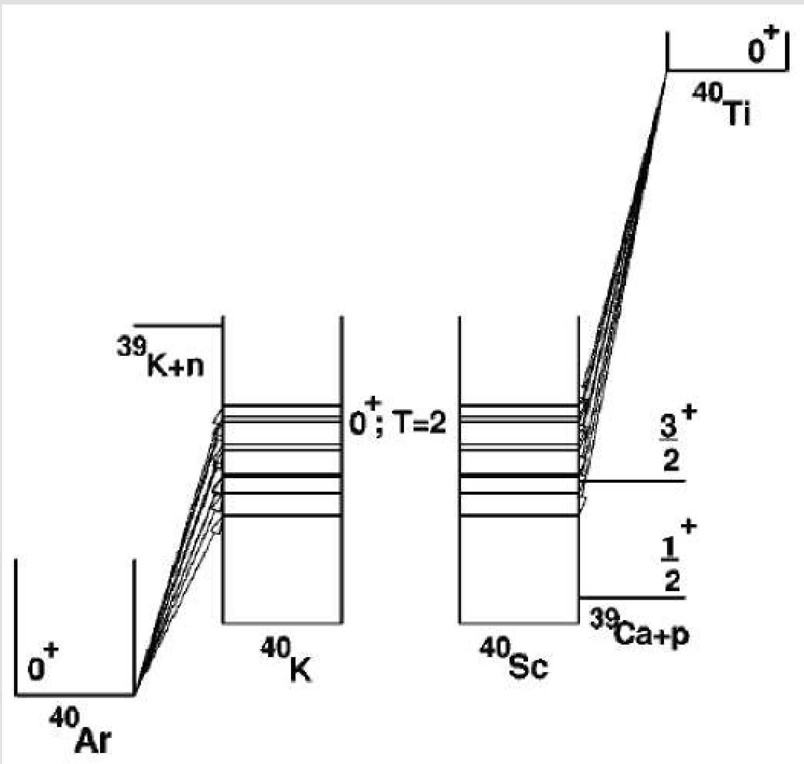
[1]H. Cao et al., SCENE Collaboration, *Phys. Rev.* **D91** (2015) 092007. arXiv:1406.4825 [physics.ins-det].

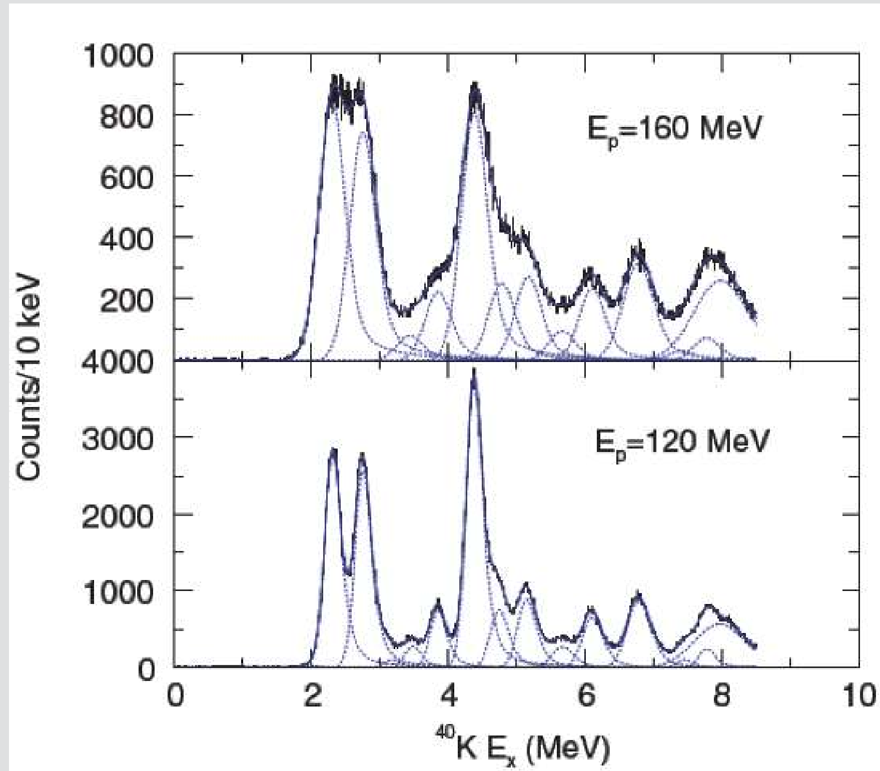
COHERENT experiment at SNS/ORNL



COHERENT experiment at SNS/ORNL

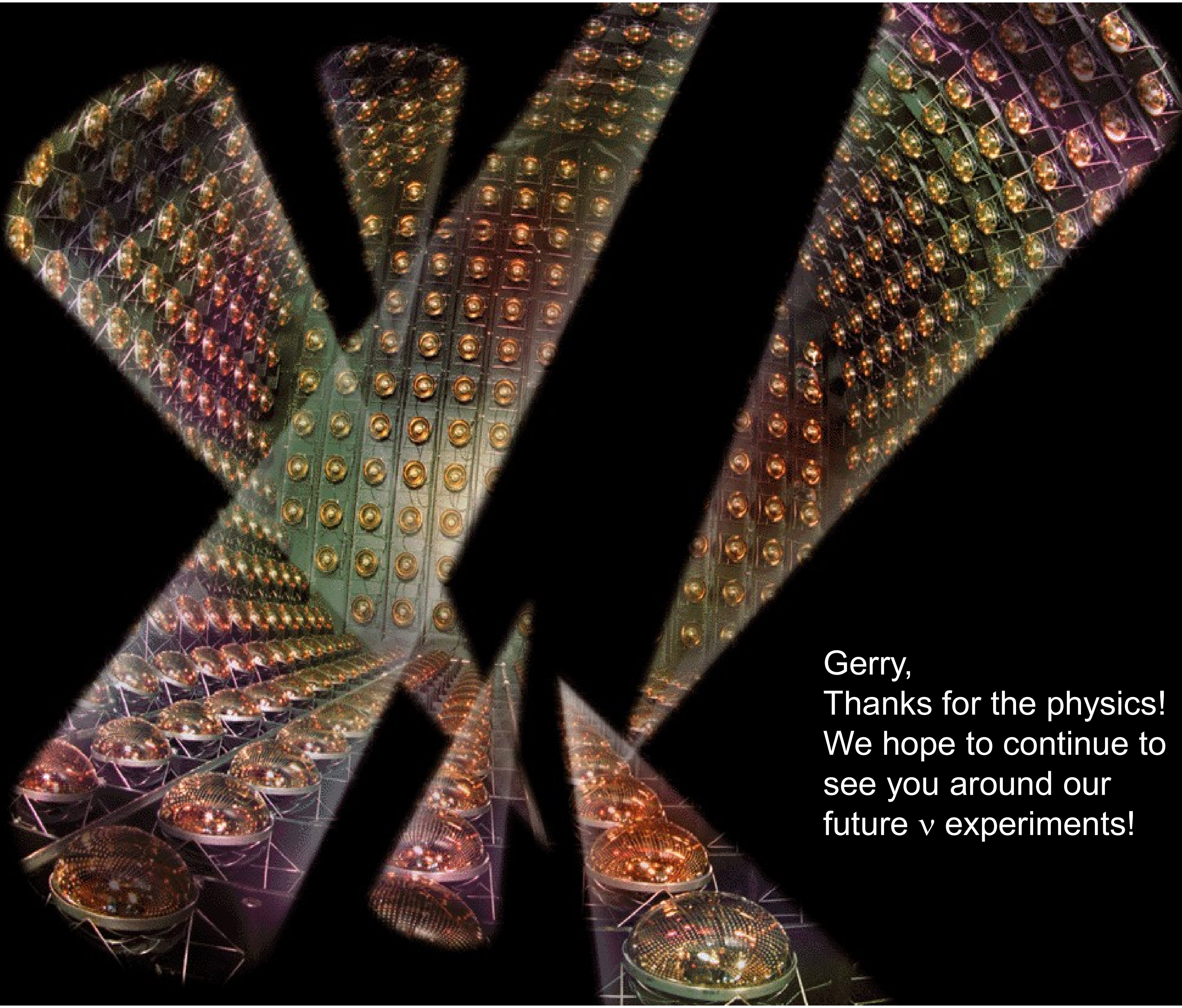
Low-E ν ^{40}Ar xsections, perhaps



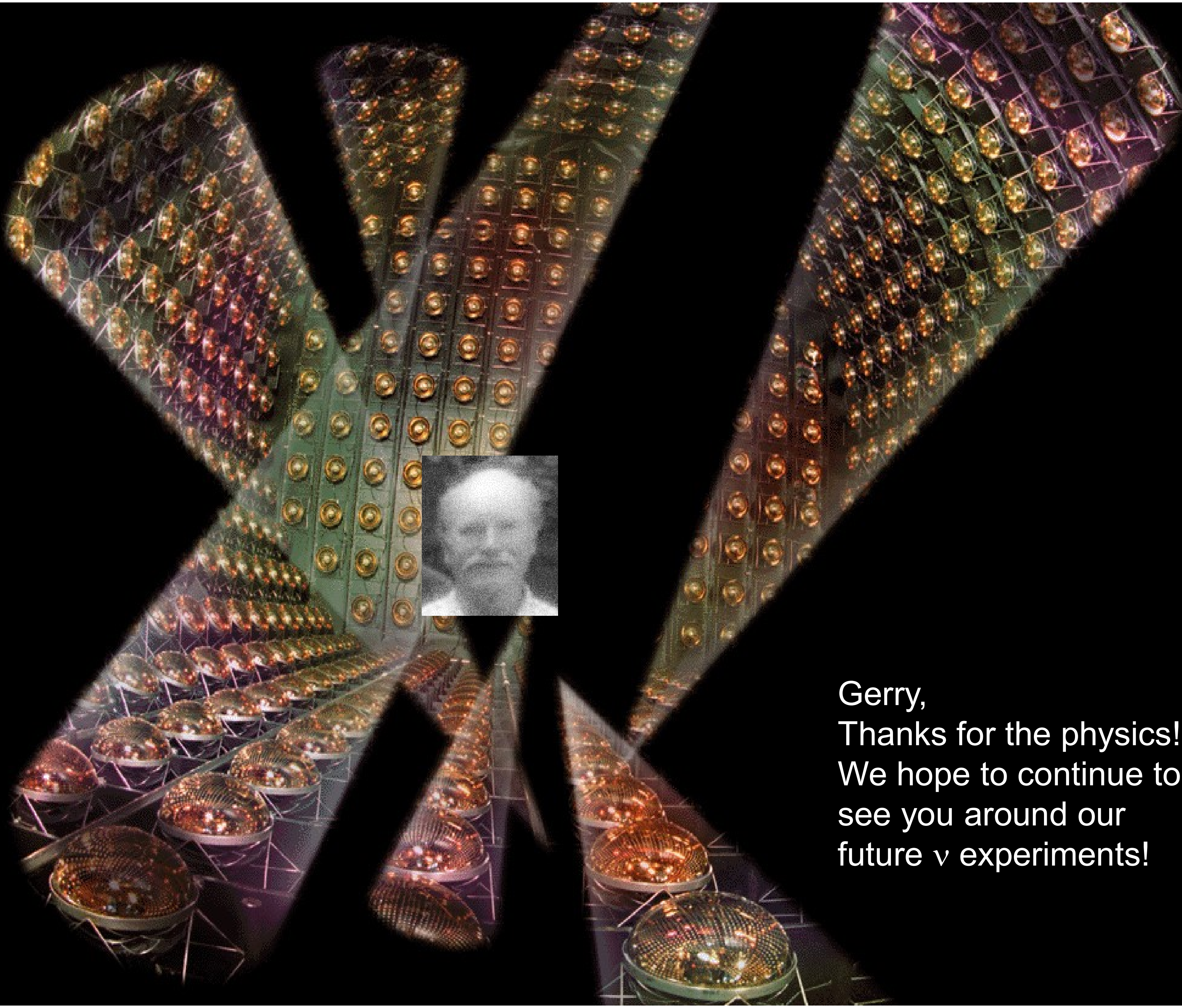


COHERENT experiment at SNS/ORNL

currently installed and filling. Running starts next week.



Gerry,
Thanks for the physics!
We hope to continue to see you around our future ν experiments!



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