A Standard Model explanation for the excess of electron-like events in MiniBooNE

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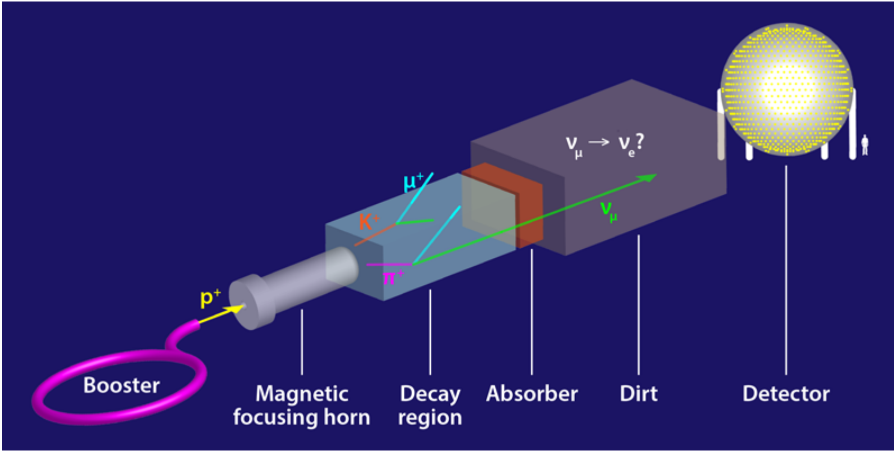
- MiniBooNE/LSND anomaly: $\nu_\mu \to \nu_e$ oscillations?
- excess of electron-like events (4.5 - 5 σ)
- excess is in 200-500MeV (Δ resonance region)
- $e^\pm/\gamma$ separation problem
- number of γ's (from NC) from number of registered π^0's
- A2 experiment (real photons 40-1600 MeV) $\gamma + A \to \pi^0 + X$
- π^0 escape factor from nuclei is unaffected by its production channel (via photon or Z boson)
- significantly lowering the number of unexplained electron-like events at MB
- predictions for SBN program at FNAL
- predictions for bound nucleon decay in nuclei (C,O,Ar)


$\nu_\mu \to \nu_e$?
μ^+
K^+
π^+
ν_μ
p^+
Booster
Magnetic focusing horn
Decay region
Absorber
Dirt
Detector

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Editors' Suggestion   Featured in Physics

Significant Excess of Electronlike Events in the MiniBooNE Short-Baseline Neutrino Experiment

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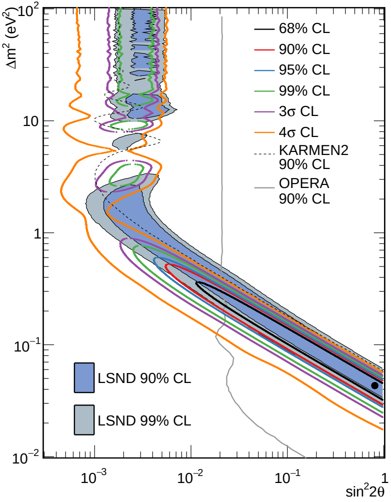
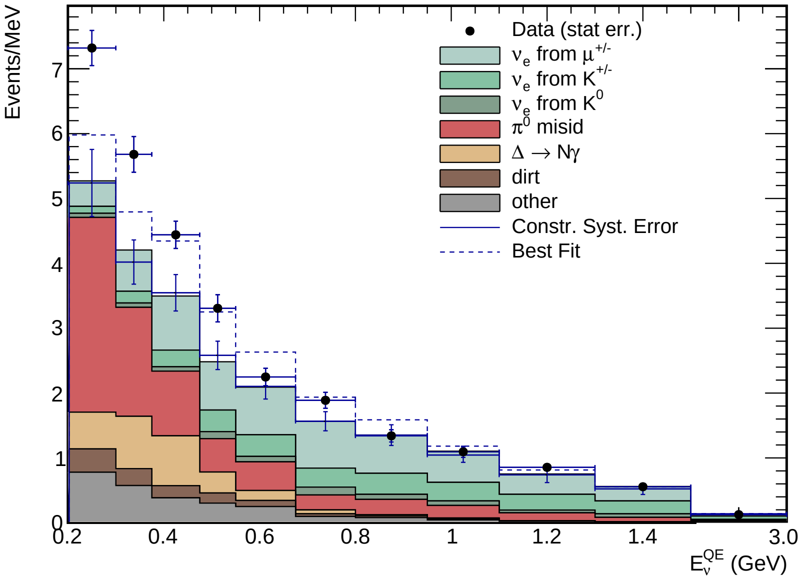
The MiniBooNE experiment at Fermilab reports results from an analysis of ν_e appearance data from 12.84×10^{20} protons on target in neutrino mode, an increase of approximately a factor of 2 over previously reported results. A ν_e charged-current quasielastic event excess of 381.2 ± 85.2 events (4.5σ) is observed in the energy range $200 < E_\nu^{\rm QE} < 1250$ MeV. Combining these data with the $\bar{\nu}_e$ appearance data from 11.27×10^{20} protons on target in antineutrino mode, a total ν_e plus $\bar{\nu}_e$ charged-current quasielastic event excess of 460.5 ± 99.0 events (4.7σ) is observed. If interpreted in a two-neutrino oscillation model, $\nu_\mu \to \nu_e$, the best oscillation fit to the excess has a probability of 21.1%, while the background-only fit has a χ^2 probability of 6×10^{-7} relative to the best fit. The MiniBooNE data are consistent in energy and magnitude with the excess of events reported by the Liquid Scintillator Neutrino Detector (LSND), and the significance of the combined LSND and MiniBooNE excesses is 6.0σ. A two-neutrino oscillation



MiniBooNE (2006.16883) allowed regions for a combined neutrino mode and antineutrino mode.

2006.16883, MiniBooNE update



2006.16883	MiniBooNE update	
Process	Neutrino Mode	Antineutrino Mode
ν_μ & $\bar{\nu}_\mu$ CCQE	107.6 ± 28.2	12.9 ± 4.3
NC π^0	732.3 ± 95.5	112.3 ± 11.5
NC $\Delta \to N\gamma$	251.9 ± 35.2	34.7 ± 5.4
External Events	109.8 ± 15.9	15.3 ± 2.8
Other ν_μ & $\bar{\nu}_\mu$	130.8 ± 33.4	22.3 ± 3.5
ν_e & $\bar{\nu}_e$ from $\mu^\pm$ Decay	621.1 ± 146.3	91.4 ± 27.6
ν_e & $\bar{\nu}_e$ from $K^\pm$ Decay	280.7 ± 61.2	51.2 ± 11.0
ν_e & $\bar{\nu}_e$ from K^0_L Decay	79.6 ± 29.9	51.4 ± 18.0
Other ν_e & $\bar{\nu}_e$	8.8 ± 4.7	6.7 ± 6.0
Unconstrained Bkgd.	2322.6 ± 258.3	398.2 ± 49.7
Constrained Bkgd.	2309.4 ± 119.6	400.6 ± 28.5
Total Data	2870	478
Excess	560.6 ± 119.6	77.4 ± 28.5
0.26% (LSND) $\nu_\mu \to \nu_e$	676.3	100.0

MiniBooNE esttimates the number of photons (due to the NC $\nu_\mu + A \to \nu_\mu + \gamma + X$) from registered number of π^0's
for free nucleons

$$Br(\Delta^{+/0} \to p/n + \gamma) = (6 \pm 0.5)10^{-3}$$

$$Br(\Delta^{+/0} \to p/n + \pi^0) \simeq 2/3$$

Thus the probability to have produced a photon per produced π^0 is

$$\frac{\Gamma^{\gamma}(\Delta^{+/0})}{\Gamma^{\pi^0}(\Delta^{+/0})} \simeq (9 \pm 0.75)10^{-3}$$

On BooNE official web page there are only two documents (both are PhD thesises) were discussed suppression of π^0 rate.

Janet Conrad was a spokesperson for MB and her PhD student's dissertation it was assumed only 10% suppression of π^0 rate
In page 153 on
https : //www – boone.fnal.gov/publications/Papers/georgiak_thesis.pdf

and in page 65 of
https : //www – boone.fnal.gov/publications/Papers/ranjan_thesis.pdf
it is written that they consider 20% absorption

here is similar to the reconstruction in reference [24], but with a different time offset applied.

The $\Delta \to N + \gamma$ background is determined from the NC π^0 event sample [29], which has contributions from Δ production in ^{12}C (52.2%), Δ production in H_2 (15.1%), coherent scattering on ^{12}C (12.5%), coherent scattering on H_2 (3.1%), higher-mass resonances (12.9%), and non-resonant background (4.2%). The fraction of Δ decays to π^0 is 2/3 from the Clebsch-Gordon coefficients, and the probability of pion escape from the ^{12}C nucleus is estimated to be 62.5%. The Δ radiative branching fraction is 0.60% for ^{12}C and 0.68% for H_2 after integraton over all the invariant mass range, where the single gamma production branching ratio increases below the pion production threshold. With these values, the ratio of single gamma events to NC π^0 events, R, can be estimated to be

$$R = 0.151 \times 0.0068 \times 1.5 + 0.522 \times 0.0060 \times 1.5/0.625 = 0.0091.$$

Note that single gamma events are assumed to come entirely from Δ radiative decay. The total uncertainty on this ratio is 14.0% (15.6%) in neutrino (antineutrino) mode. This estimate of $R = 0.0091 \pm 0.0013$ agrees fairly well with theoretical calculations of the single gamma event rate [31].

The intrinsic ν_e background comes almost entirely from muon and kaon decay-in-flight in the beam decay pipe. MiniBooNE ν_μ CCQE event measurements [28] constrain the size and energy dependence of the intrinsic ν_e background from muon decay, while the intrinsic ν_e

- π^0 escape factor from nucleus (Carbon)
- non resonance contribution (add to Δ resonance)
- coherent photon production
- higher resonance contribution (very small)

A2 collaboration at the Mainz MAMI accelerator
photon beam has a very well known energy, flux and polarisation
enrange 40-1603 MeV

$$\gamma + A \rightarrow$$

A is nucleon/nucleus

B. Krusche
Photoproduction of mesons from nuclei: In-medium properties of hadrons, Prog. Part. Nucl. Phys. **55**, 46 (2005)

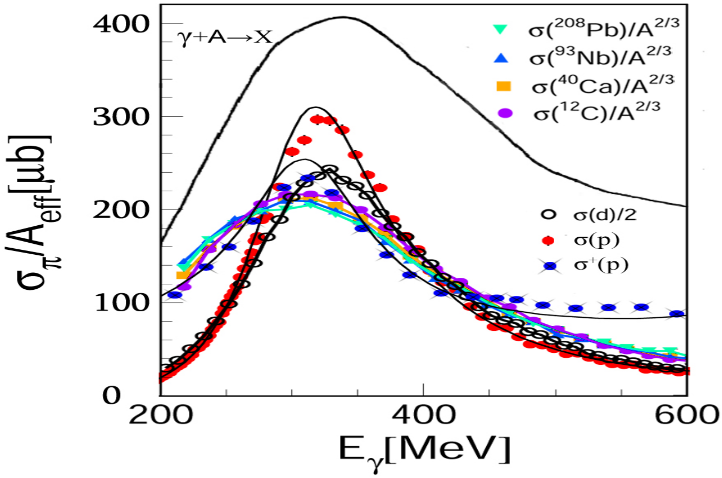


Figure: Plots from A2. Inclusive π^0 production cross sections $\gamma + A \to \pi^0 + X$, A_{eff}=1 for proton, A_{eff}=2 for deuteron and $A_{eff} = A^{2/3}$ for nuclei. σ^+ is the cross section of $\gamma + p \to n + \pi^+$. $\gamma + A \to X$ is (per nucleon) photo-absorption cross section on nuclei, A_{eff}=A.

According to the A2 collaboration the π^0 photo-production on nuclei scales as $A^{2/3}$

$$\frac{N_{\pi^0}^{\mathrm{FSI}}}{N_{\pi^0}^{0}} = \frac{\sigma_{\mathrm{FSI}}(\gamma + {}^{A}\mathcal{N} \to \pi^0 + X)}{\sigma_0(\gamma + {}^{A}\mathcal{N} \to \pi^0 + X)} \simeq \frac{A^{2/3}}{A} = A^{-1/3}$$

thus π^0 escape factor from carbon is about $12^{-1/3} \sim 43\%$ instead of 62.5%

$$R^{\Delta} = \frac{1.496}{43/62.5 + 0.496} 0.9\% = 1.25x0.9\%$$

As it is well known the pion-nucleus interaction cross section is proportional to the surface area of the nucleus, $A^{2/3}$.
By contrast the total photon absorption cross section on the nucleus is proportional to its volume and scales as A . Meanwhile the photons created in Δ decays will leave the nucleus, and that cross section will be proportional to the atomic number of the nucleus,A, volume of the nucleus.
Thus we conclude that the ratio of photon to π^0 production via a Δ resonance in nuclei is proportional to $A^{1/3}$.

Serot and Zhang PhysRevC.86.035502 (2012)

$\sigma(10^{-42}\mathrm{cm}^2)$	only Δ (f)	$\nu = 1$ (f)	Nonresonant (f)	Only Δ (b)	$\nu = 1$ (b)	Nonresonant (b)
$p, p\gamma$	1.89	2.49	0.60	0.98	1.50	0.52
$n, n\gamma$	1.89	2.25	0.36	0.97	1.24	0.24

Table: Total cross sections averaged over number of proton or nucleon for NC photon production in neutrino–^{12}C scattering at $E_\nu = 0.5$ GeV. Here $E_\gamma \geqslant 0.15$ GeV for both types of scattering. In the nuclear scattering, $r_s = r_v$=1.

$$R^{\Delta+N} = 1.4x1.25x0.9\% = 1.75x0.9\%$$

BUT contact term problem! Which is very large at high energy.
10% increase due to the non-resonant contribution,

E. Wang, L. Alvarez-Ruso, and J. Nieves, Phys.Lett. B740, 16 (2015),
ν mode E_ν= (0.3 - 0.475) MeV

$$R^{\Delta+N+coh+N^*} \simeq 1.25x(1+0.1+0.13+0.02)x0.9\% \sim 1.6x0.9\%$$

e-like events excess at MiniBooNE is 560.6 $\pm$ 119.6, which is 4.7 σ.

R=1.6x0.9%, e-like events excess is increasing to 409.5.

560.6 -251.9x0.6=409.5, which is 3.4 σ

for R=1.8x0.9%

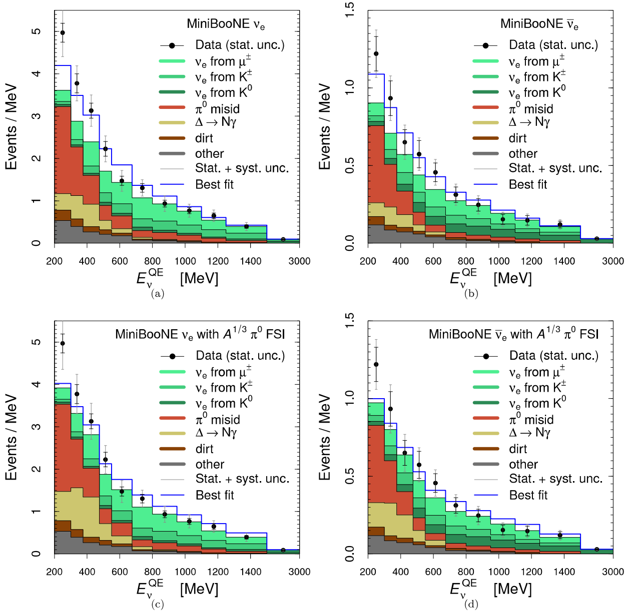
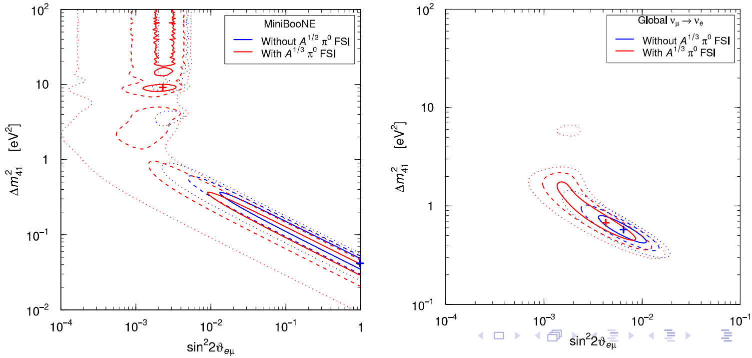
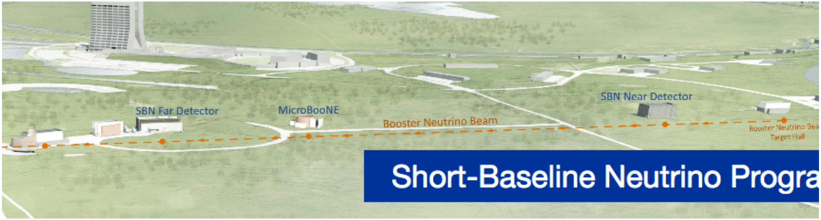


FIG. 1. Comparison of a reproduction of the MiniBooNE event histograms in (a) neutrino and (b) antineutrino mode from Refs. [2, 15] with our versions (c) and (d), which include the effect of $A^{1/3}$ π^0 FSI.


MiniBooNE
Without $A^{1/3}$ π^0 FSI
With $A^{1/3}$ π^0 FSI
Δm^2_{41} [eV^2]
$\sin^2 2\vartheta_{e\mu}$
Global $\nu_\mu \to \nu_e$
Without $A^{1/3}$ π^0 FSI
With $A^{1/3}$ π^0 FSI
Δm^2_{41} [eV^2]
$\sin^2 2\vartheta_{e\mu}$

for ^{12}C π^0 rate suppressed $12^{1/3} \simeq 2.3$

In
T. Leitner, O. Buss, U. Mosel and L. Alvarez-Ruso,
PoS NUFACT 08, 009 (2008)
Similar value, 2.4(for π^0 rate suppression factor), was briefly reported in section 3.3 without strong statement/conclusion in that section and in the paper.
Outgoing π^0 momentum? All π^0 or only with $P_{\pi^0} > 200$ MeV ?



Liquid argon TPC detectors are able to distinguish photons from electrons (or positrons).
Short Baseline Neutrino experiments at FNAL (SBND, microBooNE and ICARUS), π^0 escape factor is about 30 % ($40^{1/3} \simeq 3.4$)

proton decay

$$p \to e^+ \pi^0$$

WC ^{16}O $16^{1/3} \simeq 2.5$

Argon ^{40}Ar $40^{1/3} \simeq 3.4$

Conclusion

The reduced neutral pion production rate, plus nonresonant and coherent photon production
would yield at about 60% more photons as previously expected, thus significantly lowering the number of unexplained electron-like events at MiniBooNE

For SBN program:
At argon detectors π^0 escape factor is about 30%.

THANK YOU