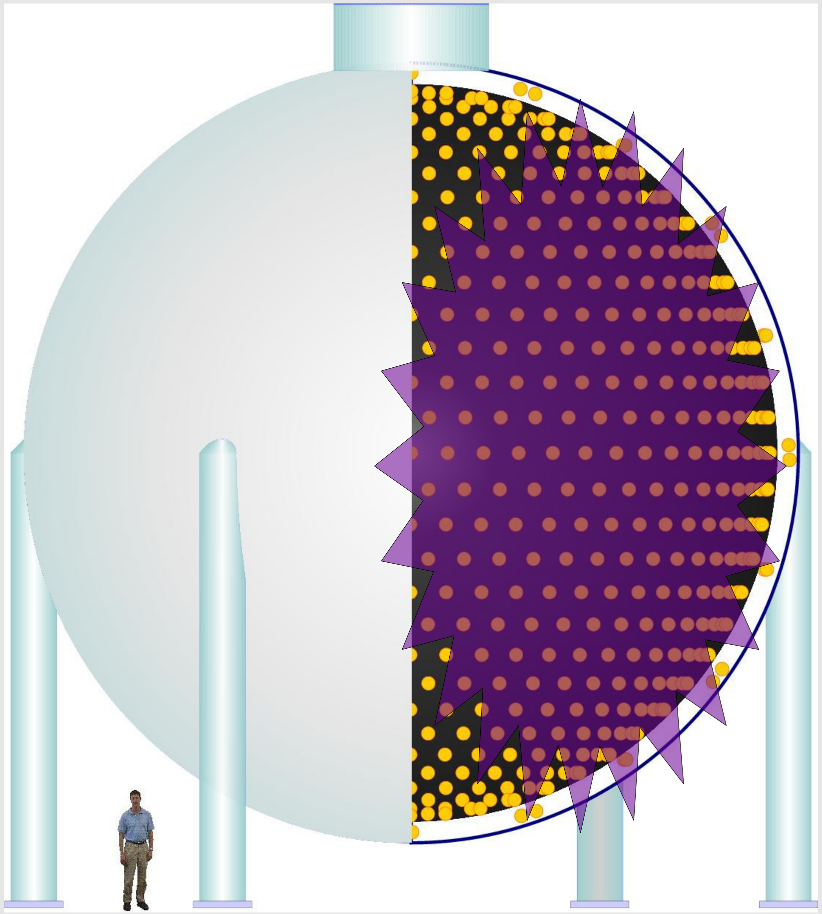
P-1033: A proposal for future running of MiniBooNE with scintillator: "MiniBooNE+"

"A new investigation of $\nu_\mu \rightarrow \nu_e$ oscillations with improved sensitivity in an enhanced MiniBooNE experiment"



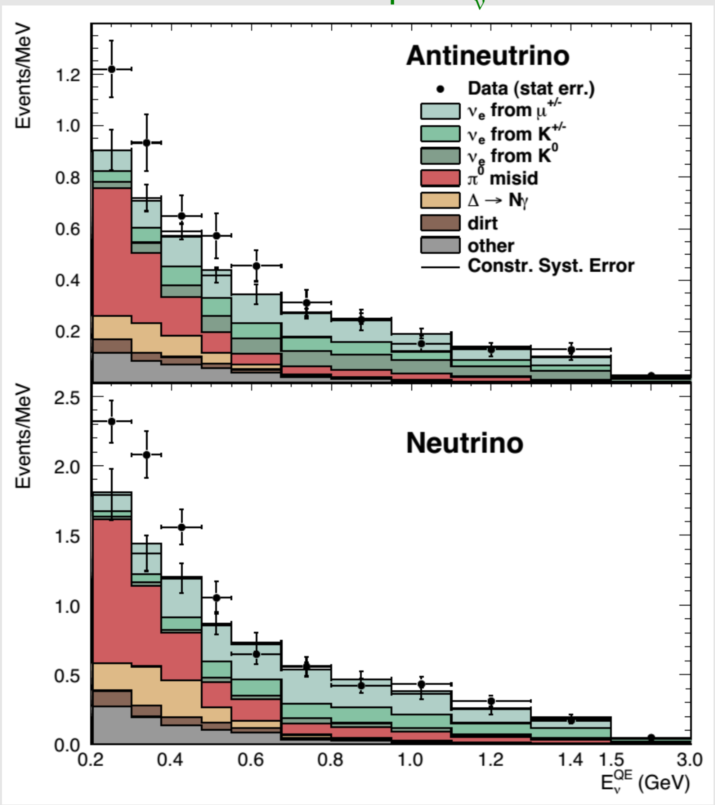
Outline:
- Motivation/Overview
- Physics
- Increasing scintillation
- Reconstruction/analysis
- Sensitivity
- Plans/request/summary

Note: Some new/updated results obtained since the proposal was submitted are presented here.

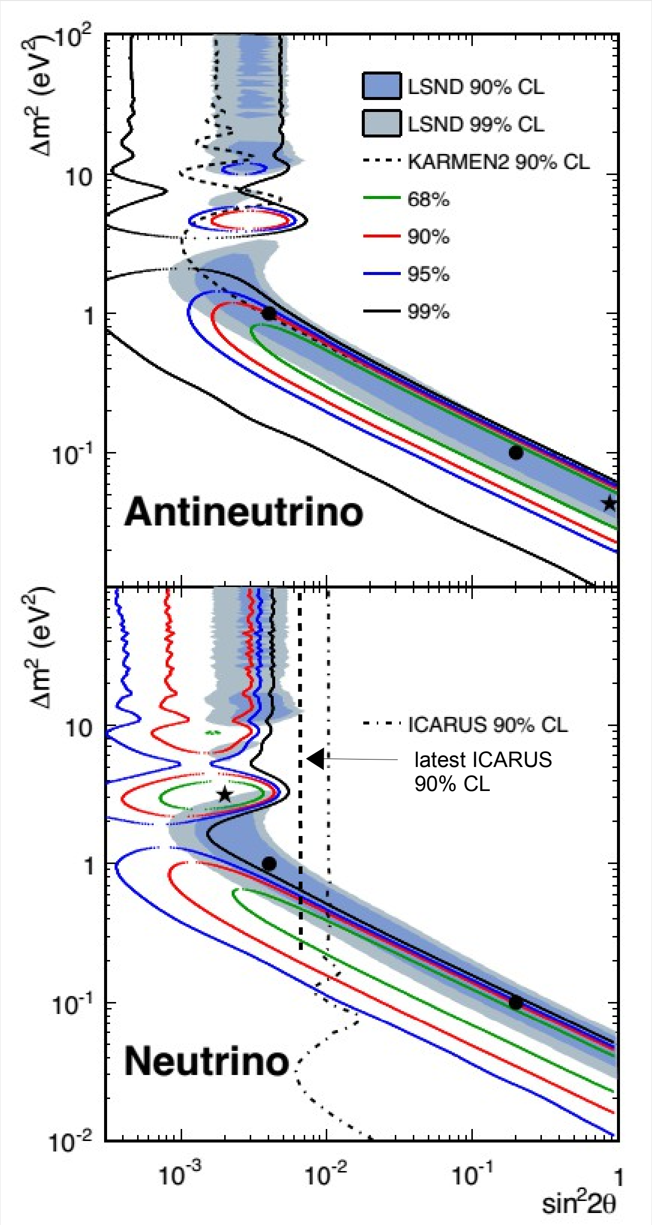
Motivation: MiniBooNE oscillation excess:

- The combined $\nu/\bar{\nu}$ data set yields combined excess of 240.3 ± 62.9 events (3.8σ), consistent with LSND result.

oscillation sample E_ν distributions



oscillation fit regions



-Requires multiple sterile ν for satisfactory fit.

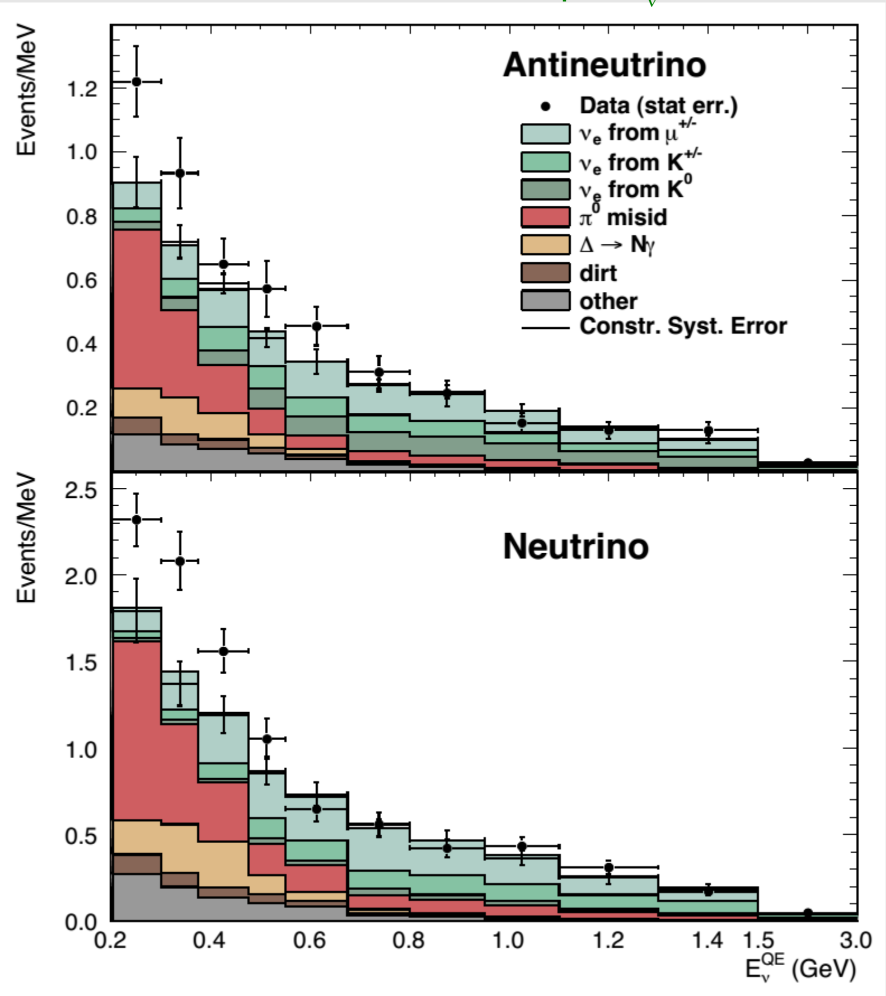
-Excess at low-energy where $NC\gamma$ and $NC\pi^0$ dominate, should examine these carefully!

MiniBooNE oscillation NC backgrounds:

- To explain the MB excess at low energy with NC backgrounds, would need to increase the MB background calcs by...
  - ~x2 for NCπ^0 background
  - ~x3 for NCγ background
  - or some combination...

The current error estimate on these backgrounds are ~10% in the low-E bins (0.2-0.55 GeV)

oscillation sample E_ν distributions



MiniBooNE oscillation NC backgrounds:

- Both NCγ and NCπ^0 are constrained with additional MB measurements.
  - NCπ^0 directly measured in MB
  - NCγ constrained to NCπ^0 (due to dominance of Δ , $\Delta \rightarrow N\gamma$)

- Recent theoretical calculations show reasonable agreement with MB calculations

[13] J. A. Harvey, C. T. Hill and R. J. Hill, Phys. Rev. Lett. **99**, 261601 (2007) [arXiv:0708.1281 [hep-ph]].

[14] R. J. Hill, Phys. Rev. D **81**, 013008 (2010) [arXiv:0905.0291 [hep-ph]].

[15] R. J. Hill, Phys. Rev. D **84**, 017501 (2011) [arXiv:1002.4215 [hep-ph]].

[16] J. Jenkins and T. Goldman, Phys. Rev. D **80**, 053005 (2009) [arXiv:0906.0984 [hep-ph]].

[17] B. D. Serot and X. Zhang, arXiv:1110.2760 [nucl-th].

[18] B. D. Serot and X. Zhang, Phys. Rev. C **86**, 015501 (2012) [arXiv:1206.3812 [nucl-th]].

[19] X. Zhang and B. D. Serot, Phys. Rev. C **86**, 035504 (2012) [arXiv:1208.1553 [nucl-th]].

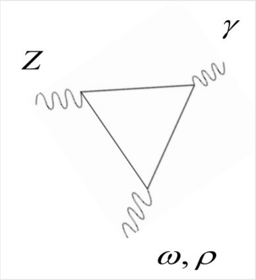
[20] X. Zhang and B. D. Serot, Phys. Rev. C **86**, 035502 (2012) [arXiv:1206.6324 [nucl-th]].

[21] X. Zhang and B. D. Serot, Phys. Lett. B **719**, 409 (2013) [arXiv:1210.3610 [nucl-th]].

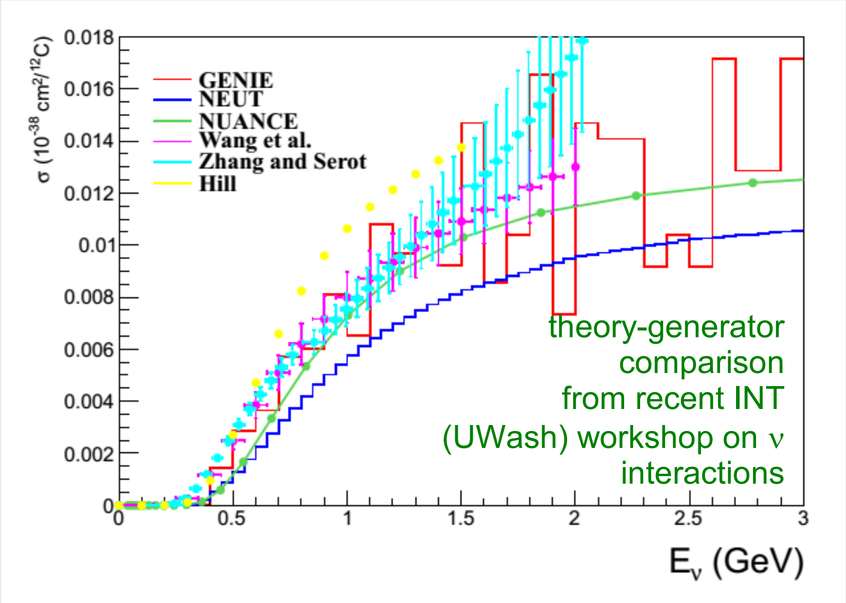
[22] L. Alvarez-Ruso, J. Nieves and E. Wang, arXiv:1304.2702 [nucl-th].

[23] E. Wang, L. Alvarez-Ruso and J. Nieves, arXiv:1311.2151 [nucl-th].

- and concensus that these terms: should be small and Δ production does indeed dominate as MB assumes...
- however, this should be exp tested!



NCγ production cross section



- The MB calculation is in green above, “NUANCE”
- Agreement within ~20% at MB flux peak with most models.

MiniBooNE+: Overview

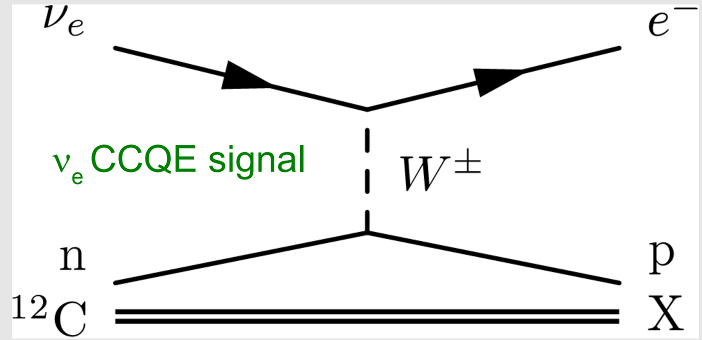
We propose the addition of scintillator to MiniBooNE to enable reconstruction of 2.2 MeV n-capture photons for an enhanced $\nu_\mu \rightarrow \nu_e$ search at low energy.

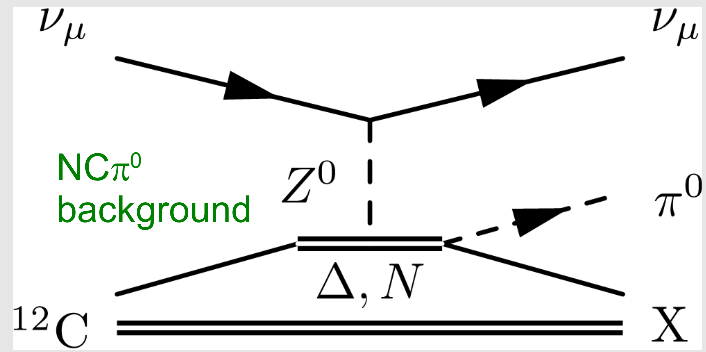
The n-capture (np→dγ) signal will enable separation of CC oscillation signal events from NC backgrounds for an improved test of the low-energy MiniBooNE oscillation excess.

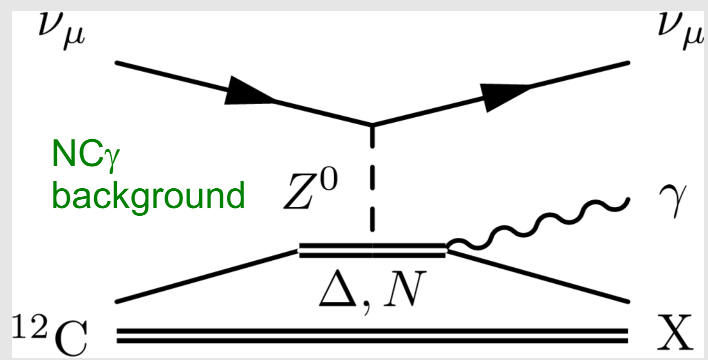
Other physics made possible:

- p to n ratio in NC elastic scattering (Δs)
- measurement of $\nu_\mu C \rightarrow \mu^- N_{g.s.}$
- a test of QE assumption in neutrino energy reconstruction

We are requesting approval for MiniBooNE+ which requires 6.5×10^{20} protons on target. The Δs measurement and calibration of the oscillation event neutron fraction can be obtained with 2×10^{20} protons on target providing an early test of the viability of the new oscillation measurement along with a physics result. We request to begin this new phase of running in mid-2014, concurrently with the MicroBooNE experiment.







Physics: $\nu_\mu \rightarrow \nu_e$ search with NC veto

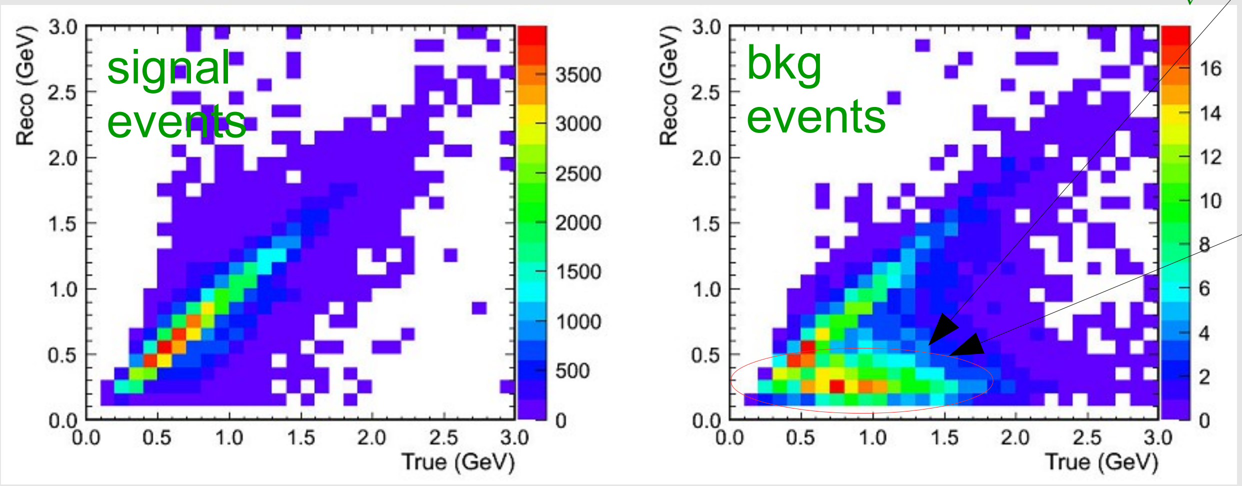
Require oscillation candidates to contain 0 n-capture events.
If event excess (at low energy) is:

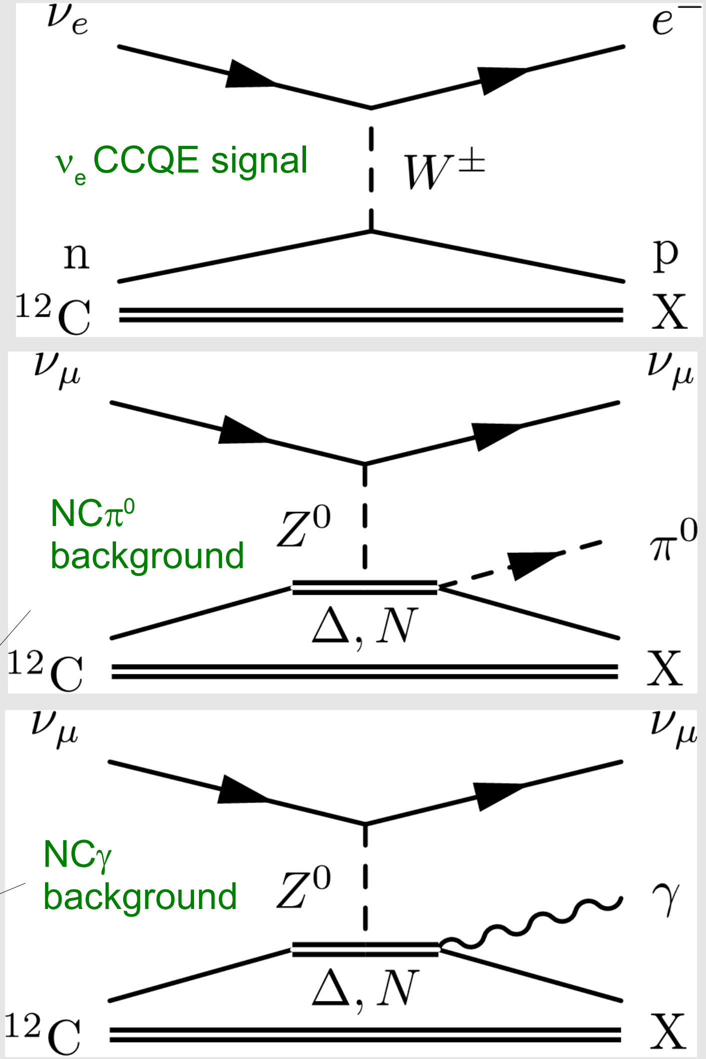
- CC oscillations: excess will maintain since it is mostly CCQE (with only 10% neutrons)

- NC background: excess will be greatly reduced since it will contain 50% neutrons. This is because of dominance of NC Δ with equal branch to p/n decay

Additionally, NC backgrounds come from higher true neutrino, are incorrectly reconstructed with QE assumption.

true vs reconstructed E_ν





More physics opportunities

NC elastic scattering:

- MiniBooNE has measured ν – nucleon NC elastic scattering in both ν and $\bar{\nu}$ channels.
- Addition of scintillator allows for n/p separation and measurement of Δs (s-quark contribution to nucleon spin) via:

$$R(NCp/NCn)=\frac{\sigma(\nu_\mu p\rightarrow\nu_\mu p)}{\sigma(\nu_\mu n\rightarrow\nu_\mu n)}$$

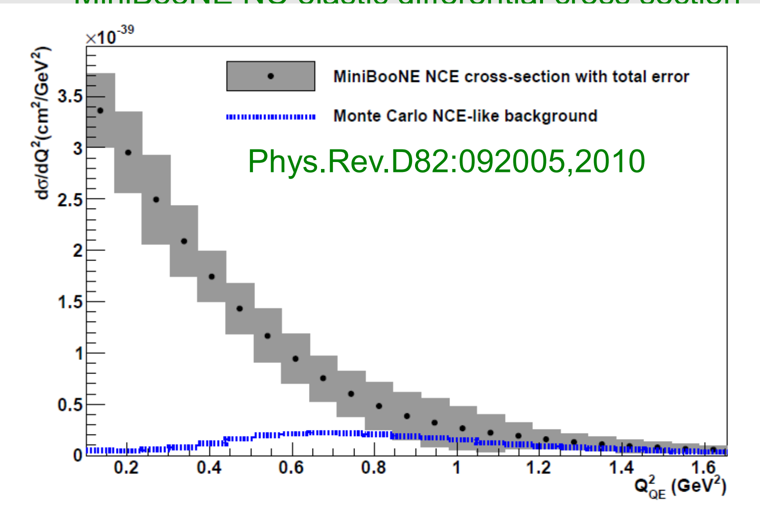
$$\frac{d\sigma}{dQ^2}(\nu N\rightarrow\nu N)\propto(-\tau_z G_A+G_A^s)^2$$

$$G_A^s(Q^2=0)=\Delta s$$

$$\Delta\Sigma=\Delta u+\Delta d+\Delta s$$
$$\Delta q=q\uparrow-q\downarrow+\bar{q}\uparrow-\bar{q}\downarrow$$

for more input to ongoing proton spin puzzle.

MiniBooNE NC elastic differential cross section



- Measurement of $\nu_\mu C\rightarrow\mu^- N_{g.s.}$
  - tagged with $N_{g.s.}$ β decay (~15MeV endpoint, enabled with scintillator)
  - cross section known to ~2% near threshold allows a low-E flux test

- Test of E_ν^{QE} in ν energy reconstruction
  - addition of scintillator will allow total energy of event to be measured and compared with E_ν^{QE}, the current method of reconstruction that assumes quasielastic ν–nucleon scattering.

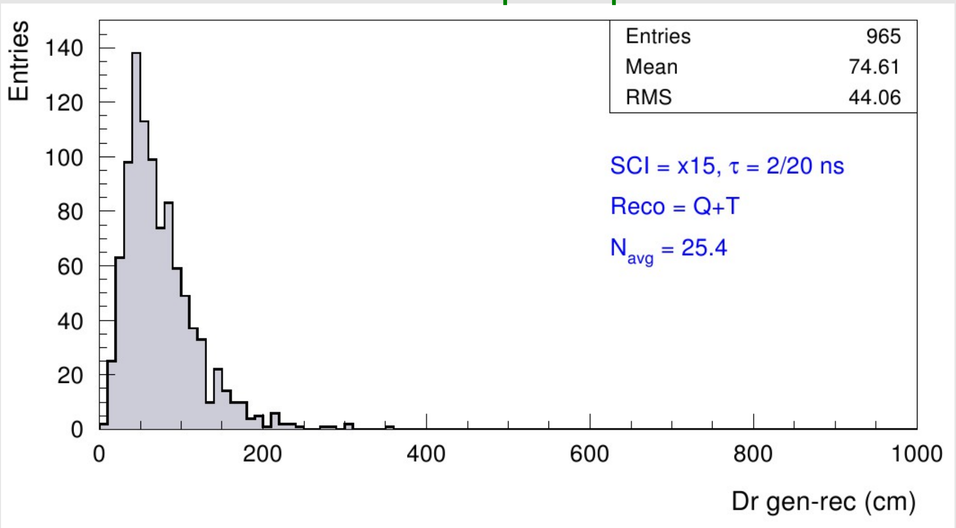
Adding scintillator

We have studied n-capture ($np \rightarrow d\gamma$(2.2MeV), $\tau \sim 186\mu s$), in MB+ with a range of scintillator concentrations.

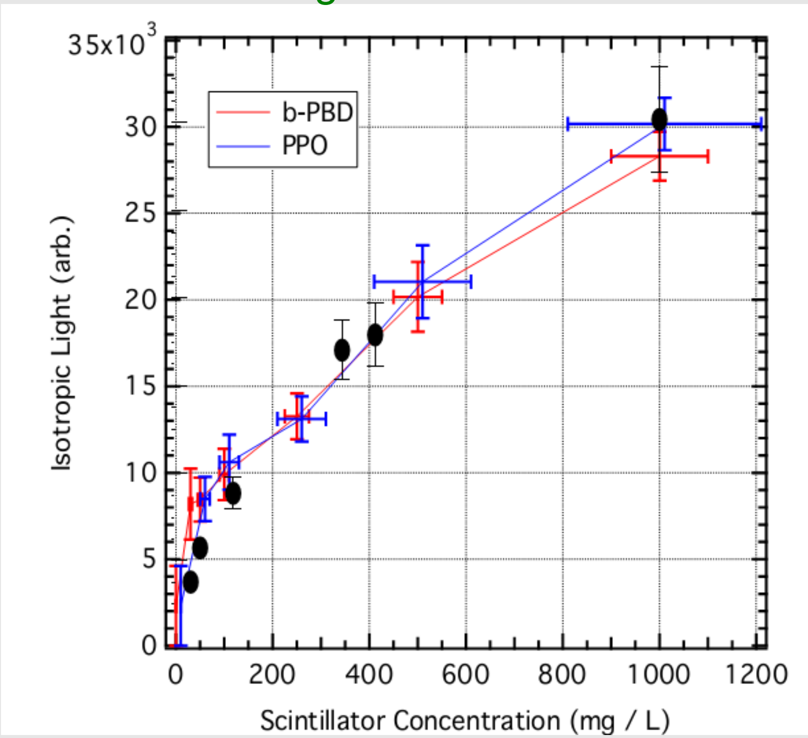
For good n-capture ID, need x15 scintillation as compared to current.

From MC studies combined with lab tests, determined that 300kg of PPO (~$75k) added to 800 tons MiniBooNE mineral oil (0.3g/l) will increase light to desired level.

n-capture position resolution



scint. light vs scint. concentration



A 5σ test of MiniBooNE excess

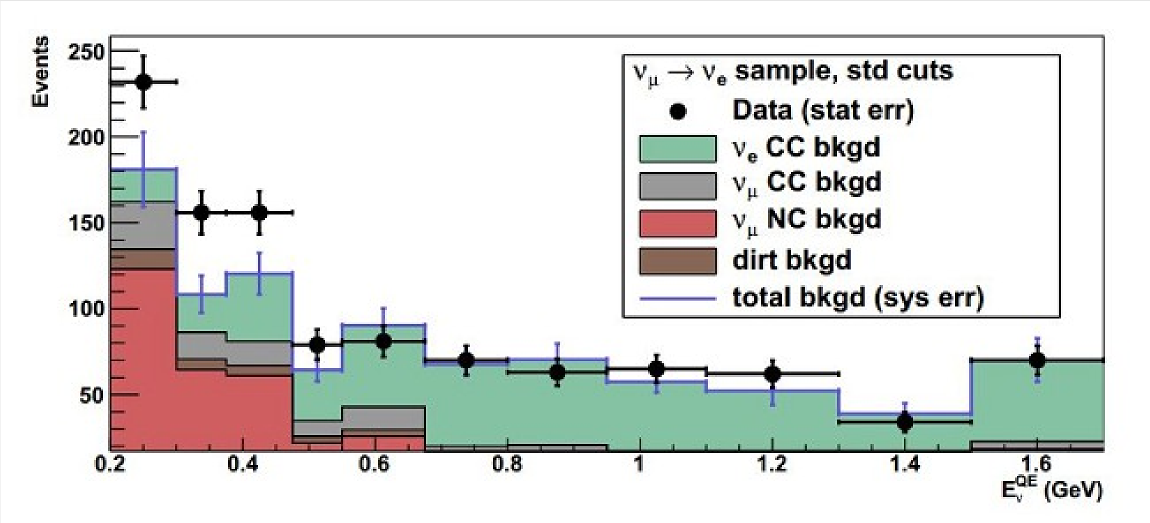
To obtain a 5σ test of the MB oscillation excess

Need lower background and
lower systematic error on background.

(Statistical error is relatively small
in this sample)

Rerun the oscillation search
with MB+

neutrino oscillation sample E_ν distributions



- Concentrate on low energy region (~0.2-0.55GeV) where excess exists
- Require:
  - 6.5E20POT (same sample size) as previous run
  - approximately same (prompt) π^0 rejection as for existing analysis
  - n-capture veto to reduce background, mainly NC π^0 , NC γ
  - reduction in systematic error on background

A 5σ test: background reduction

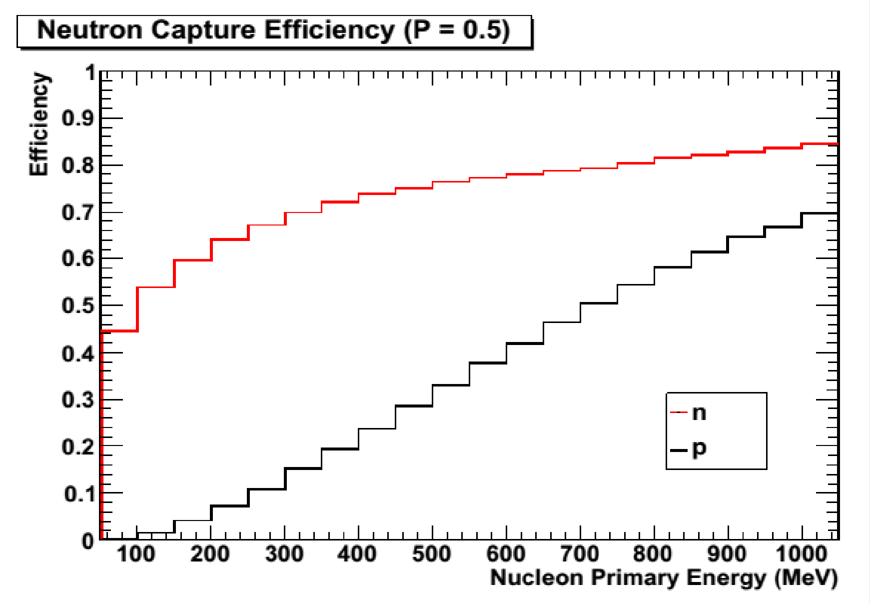
neutrino oscillation sample E_ν distributions (from Zhang, private commun.)

E_{QE}(GeV)	[0.2 , 0.3]	[0.3 , 0.475]	[0.475 , 1.25]
coh	1.5 (2.9)	6.0 (9.2)	2.1 (8.0)
inc	12.8 (14.1)	27.7 (31.1)	14.4 (23.2)
inc(n)	5.2 (5.9)	12.5 (14.3)	6.4 (10.9)
H	4.1 (4.4)	10.6 (11.6)	4.6 (6.3)
Total	17.6 (21.4)	42.1 (51.9)	19.3 (37.5)
n/tot	0.30 (0.28)	0.30 (0.28)	0.33 (0.30)
MiniBN	19.5	47.3	19.4
Excess	42.6 ± 25.3	82.2 ± 23.3	21.5 ± 34.9

To obtain a 5σ test of the MB oscillation excess:

Use n-capture veto to reduce dominant backgrounds, NC π^0 , NC γ

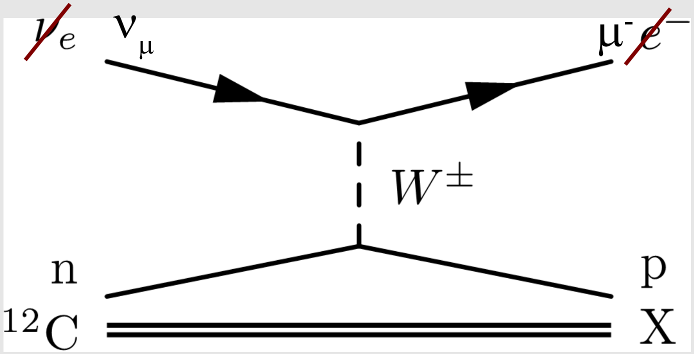
- Simulated neutron production in oscillation search with NUANCE model (and checked with theory estimates)
- Used MCNP to simulate n/p transport in detector.
- **Result:**
  - NC backgrounds decreased by 30% (compared to MB search)

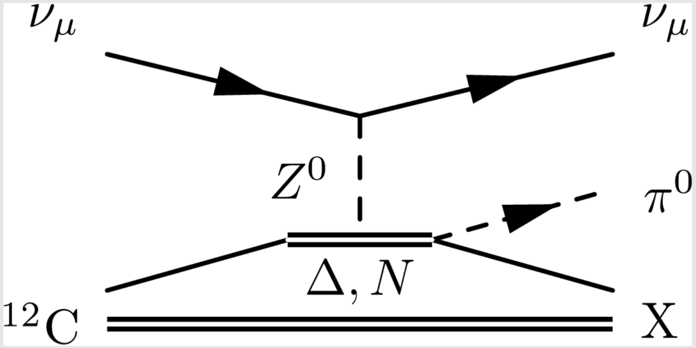


A 5σ test: systematic error reduction

To obtain a 5σ test of the MB oscillation excess:

Use n-capture calibration method to reduce systematic on dominant backgrounds, NC π^0, NC γ





- For ν_e CCQE interactions, can measure n-fraction in ν_μ CCQE events

- For ν_μ NC backgrounds, ν_μ NCπ^0 events (with well-identified) π^0 will be used

Provides measured n-fraction for both CC signal and NC background, bin-bin in reconstructed ν energy. Includes final state effects.

- Result:
- Systematic on NC backgrounds decreased by x2 (compared to MB search)

Event reconstruction

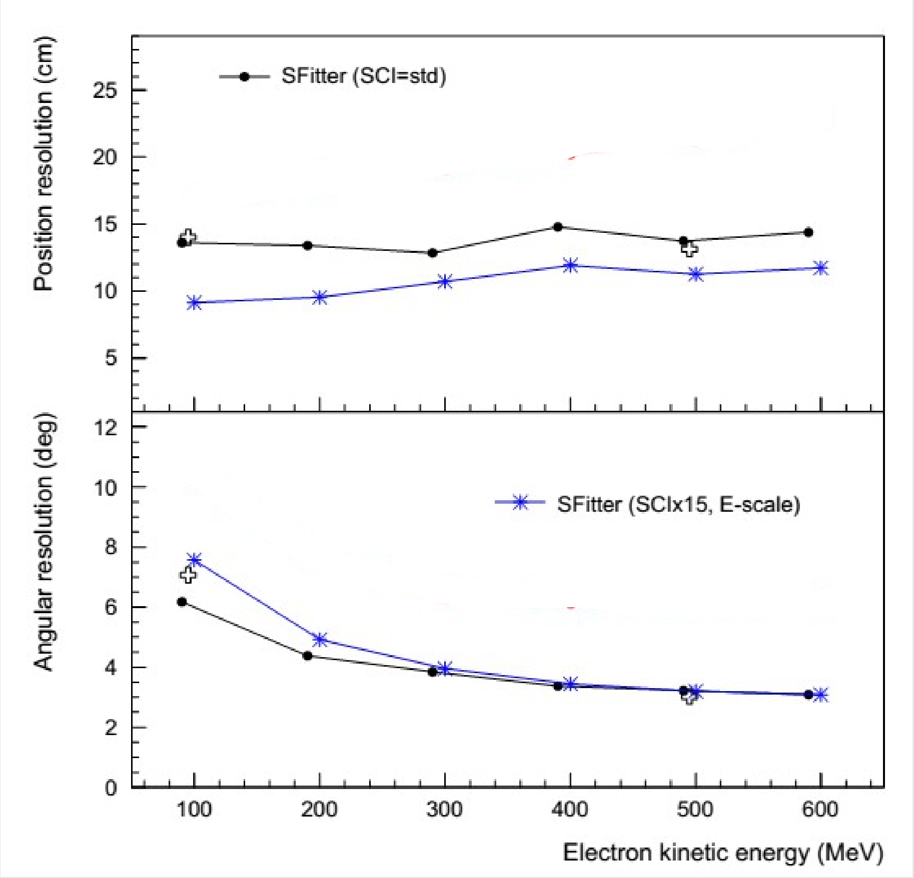
electron reconstruction study from MC

To obtain a 5σ test of the MB oscillation excess:

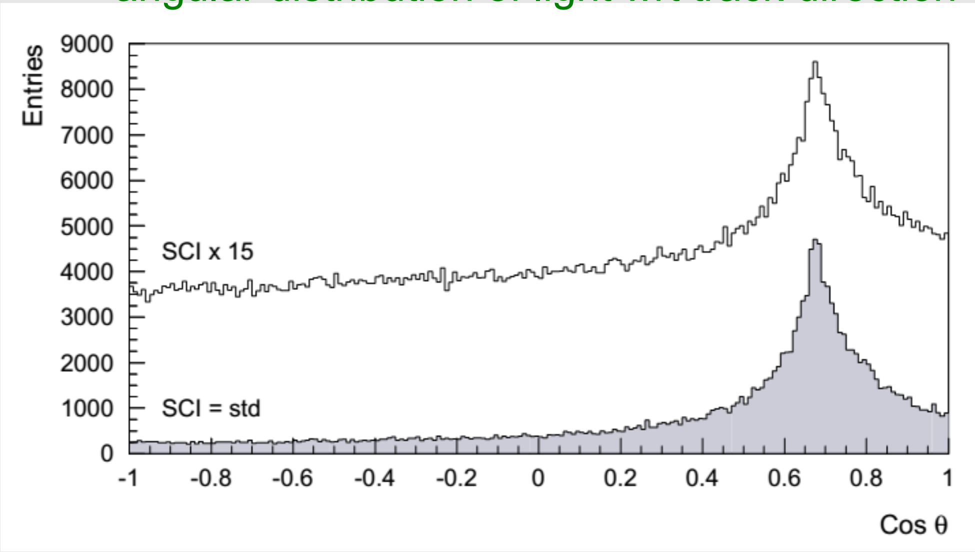
Require good reconstruction of e, μ, π^0
to conduct oscillation search with scintillator.

Studies with single particle and ν events (from NUANCE) with x15 scintillation show that electron reconstruction is still good, up to ~700MeV, with only moderate tuning.

- Cerenkov rings are still quite distinct, even with extra (isotropic) scintillation light.



angular distribution of light wrt track direction

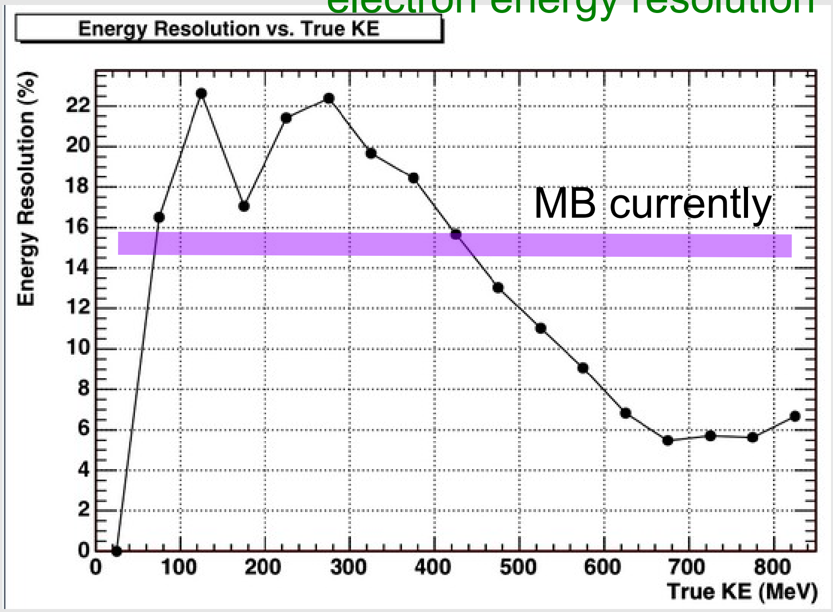


Event reconstruction

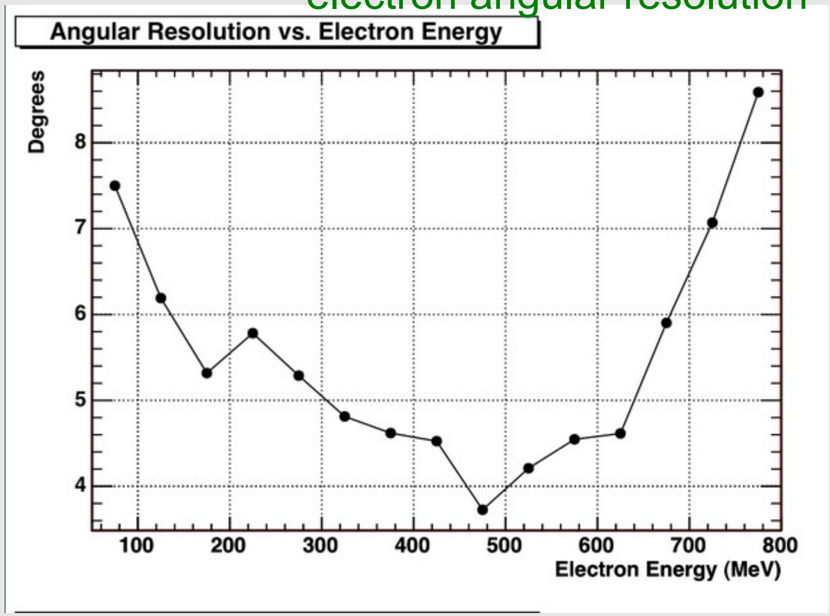
Also require good reconstruction of e, μ, π^0 to conduct oscillation search with scintillator.

Update since proposal submitted: Energy resolution good up to ~700MeV (electron energy). Compare to ~flat 15% in MB.

electron energy resolution



electron angular resolution



Aside:
- electron reconstruction degrades above ~700MeV.

This will set our reach in E_ν^{QE} to ~700MeV.

A 5σ test of MiniBooNE excess

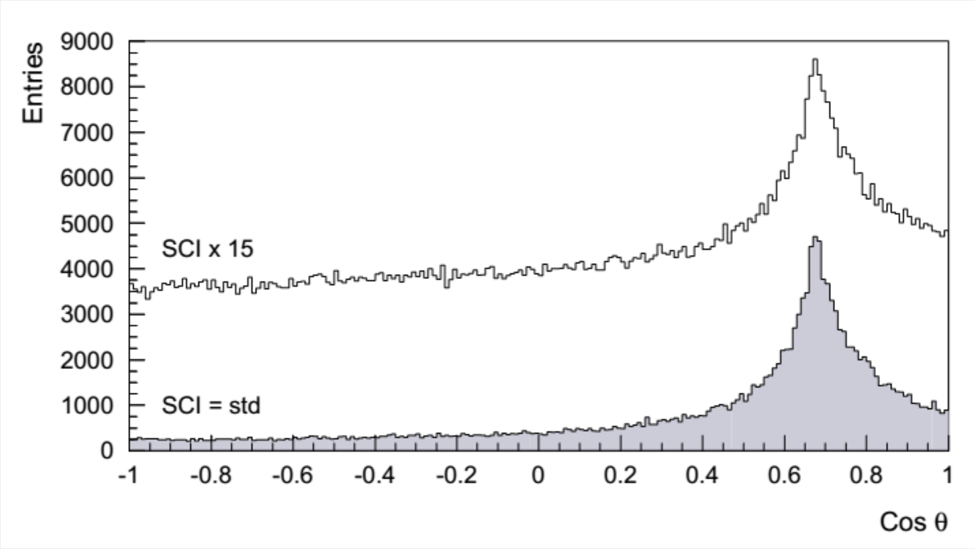
So 1 ring performance of MB+ (x15 scint) good....
Therefore... π^0 ID should be as good

(1 ring resolvable so 2 should be,
albeit harder minimization problem).

That was status for submission of proposal
work on π^0 ID has continued over last month.

Reminder:
In current MB, π^0 contamination is
~1% with ~50% electron efficiency

angular distribution of light wrt track direction



Event reconstruction: 5σ sensitivity with MB+

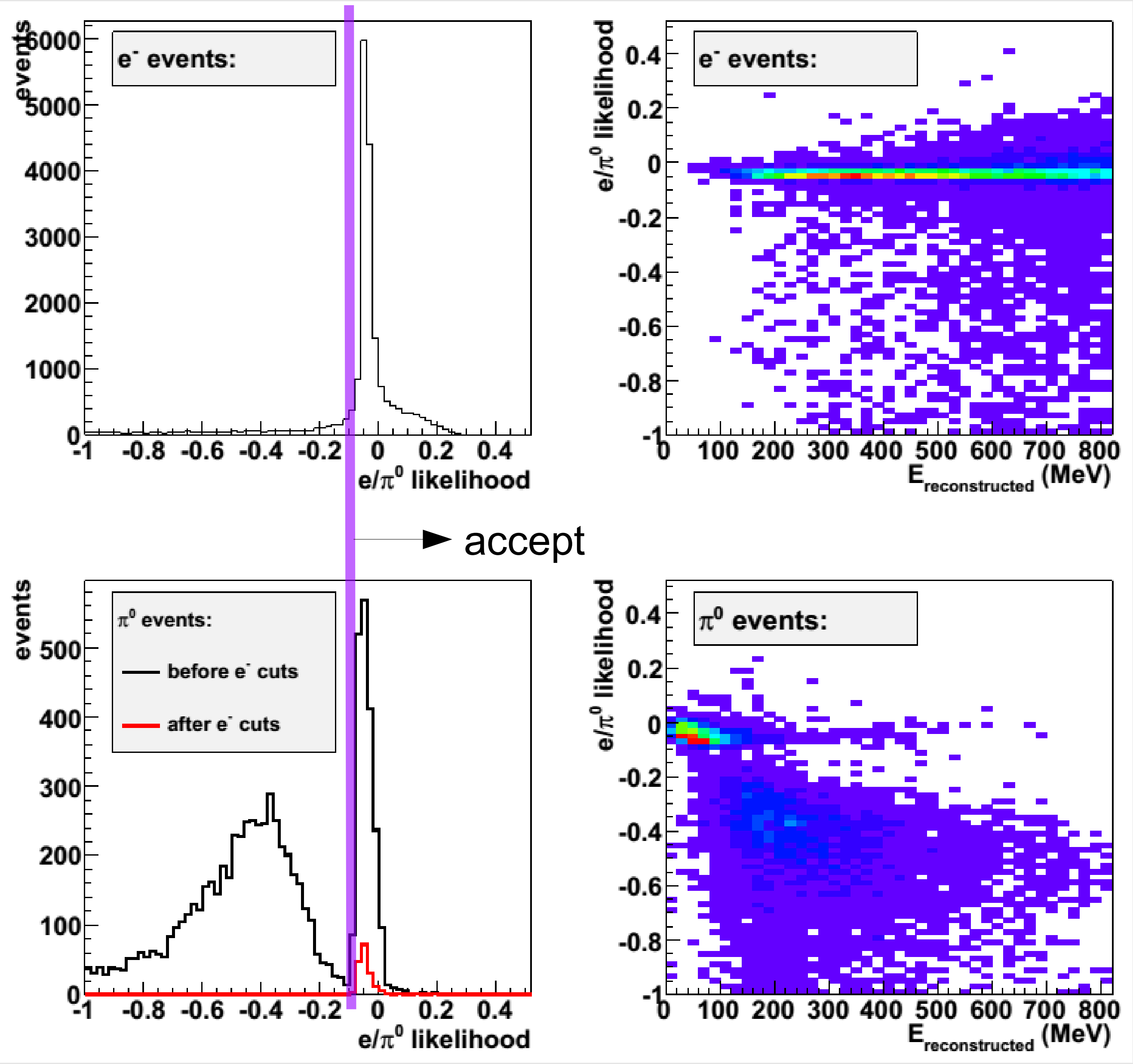
New results on, π^0 fitting...
Update since proposal submitted:

electron events:

π^0 events:
apply electron cuts: visible energy, π^0 mass, e/π^0 likelihood

π^0 contamination: 1.8%
w/electron efficiency ~44%

e/π^0 discrimination will work in MB+ at level required!



Event reconstruction: 5σ sensitivity with MB+

Oscillation events and errors

- In low E region (0.2-0.55GeV)
- 6.5E20POT,
- approximately same reconstruction efficiency and prompt π^0 rejection as for current analysis.
- NC background reduction of 30% via n-capture veto
- systematic error reduction of ~x2 via ν_μ NC calibration measurement

=> 5σ test of MB ν_e appearance result!

	current	MB+
	no n-veto	with n-veto
background	479.3	380.7
statistical error	21.9	19.5
systematic error	50.5	19.0
relative systematic error	10.5%	5.0%
total error	54.0	27.3
data events	623.0	520.0
excess events	143.7	139.3
# σ	2.7	5.1

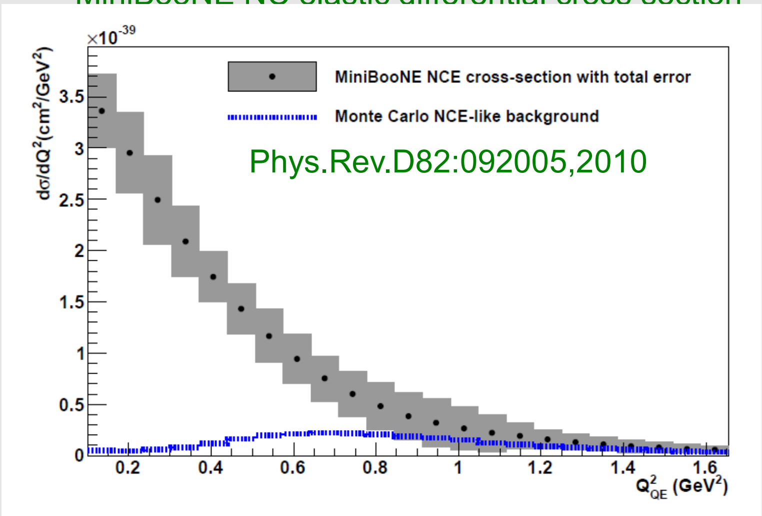
Δs measurement:

Simulation of a 2E20POT measurement of NCelastic scattering:

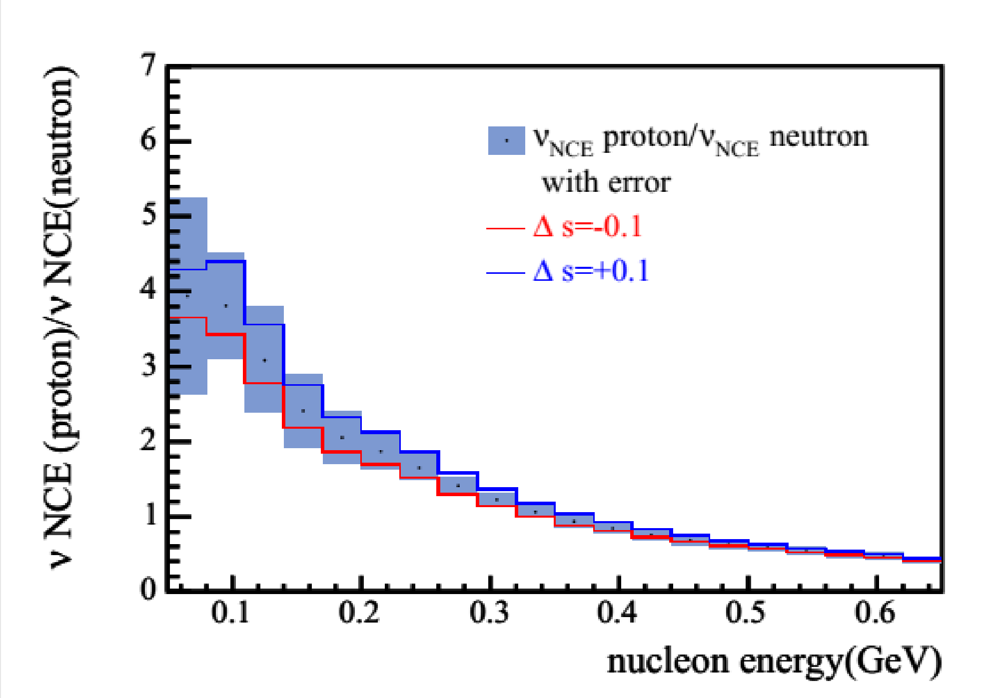
- R(p/n) in NCelastic events with (integrated) 12.5% error
→ Δs to ±0.06

Competitive with DIS results which claim (very model dependent) ± 0.03.

MiniBooNE NC elastic differential cross section



NC elastic proton/neutron ratio



MB+: low energy protons...

Detector (light) response to low-energy nucleons is greatly enhanced with scintillator.
Will improve the NCelastic measurement as well as possible future Dark Matter searches:

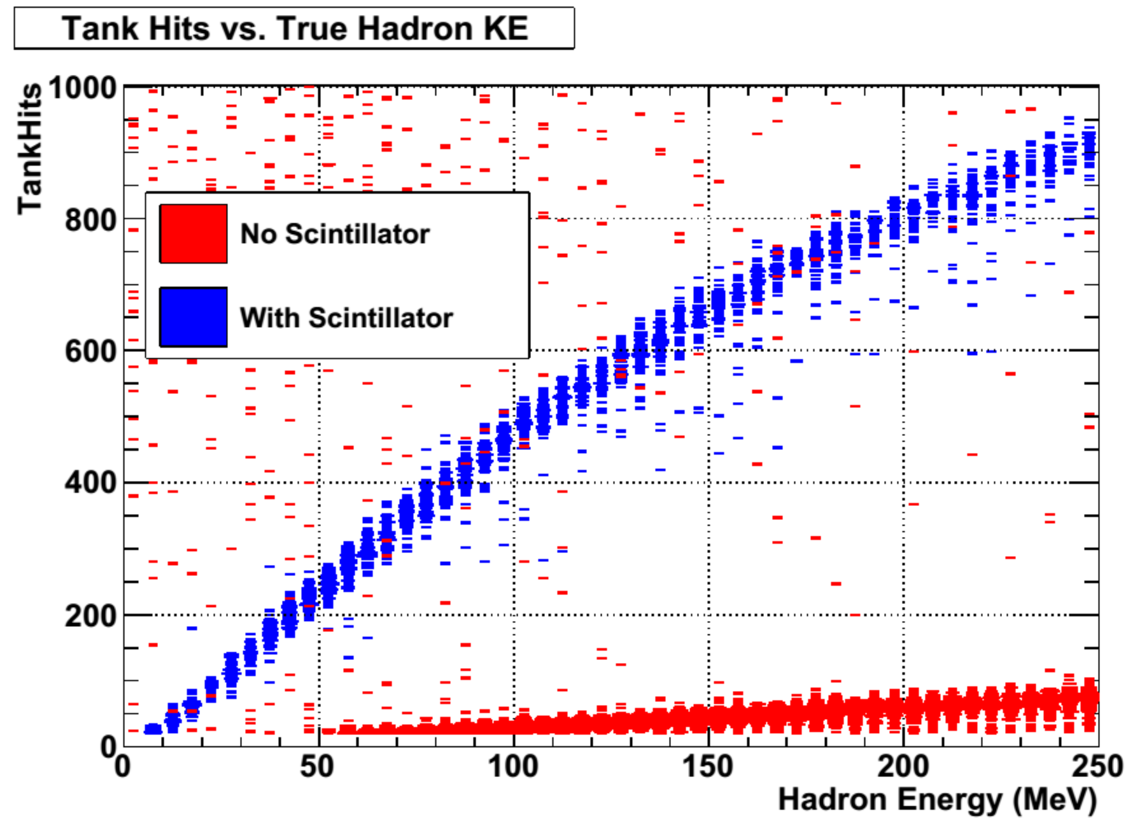


Figure 12: Distribution of PMT hits as function of proton energy in NC elastic scattering events for standard and ×15 scintillator.

MiniBooNE+ and MicroBooNE

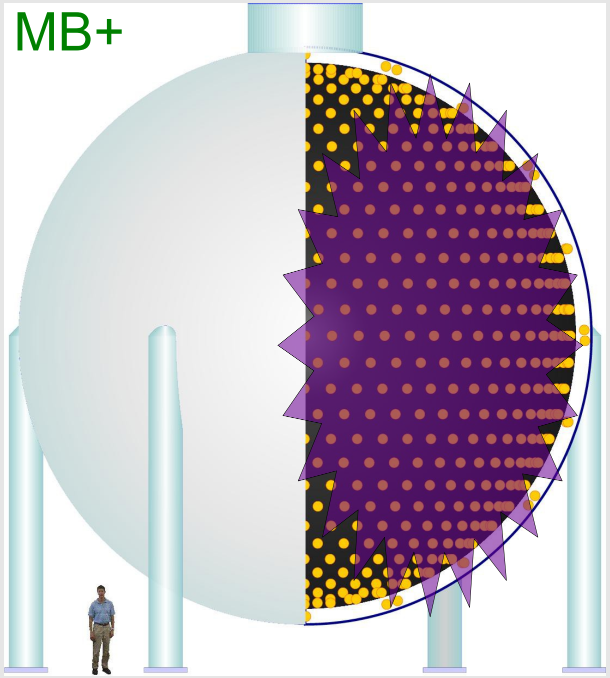
This would be a complementary effort to that of MicroBooNE which also has a goal of understanding MB excess...

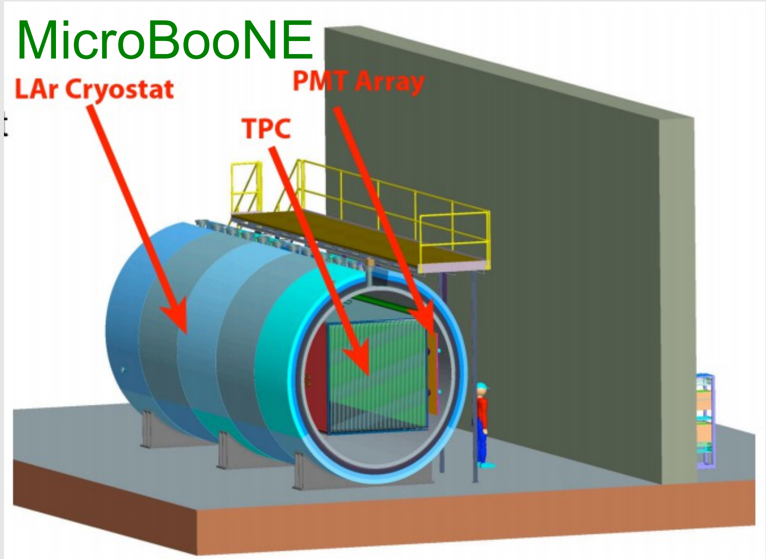
- MicroBooNE goal is to differentiate CC/NC via γ/e separation.
  MB+ will focus on nucleons, in particular neutrons with no energy threshold

- MicroBooNE will have precision tracking, but low event counts.
  MB+ Cerenkov/calormetric reconstruction, higher event rates.

- MiniBooNE larger fiducial volume and concurrent running may help with external beam-related ("dirt") backgrounds, especially neutrons.

- Important to keep an 800ton CH_2 detector running in the BNB as event rates will be higher than any of new/proposed LAR devices. Could be quite valuable to understand any changes in beam.





Physics results:

Continuing with momentum of MiniBooNE, MB+ will provide important physics output in next 3 years.

MiniBooNE has published 31 papers with >2500 citations on oscillations, cross sections.

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31 papers found, 31 of them citeable (published or arXiv)

Citation summary results	Citeable papers	Published only
Total number of papers analyzed:	31	31
Total number of citations:	2,513	2,513
Average citations per paper:	81.1	81.1
Breakdown of papers by citations:		
Renowned papers (500+)	0	0
Famous papers (250-499)	2	2
Very well-known papers (100-249)	6	6
Well-known papers (50-99)	8	8
Known papers (10-49)	10	10
Less known papers (1-9)	3	3
Unknown papers (0)	2	2
h_{HEP} index [?]	21	21

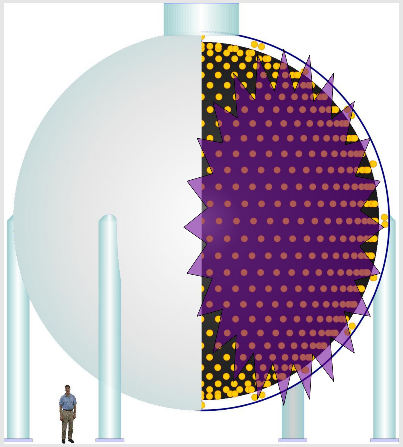
MB+ commissioning/run plan

This proposed measurement requires 6.5E20POT.

Assuming that 2E20POT/year available on Booster neutrino beamline (concurrent with MicroBooNE).

If we are approved, we will:
- Continue with reconstruction/simulation analysis and make plan for 3yrs more data.
- Fire up lab for scintillator mixing and tests ($25k, funding obtained).
- Procure PPO ($75k, funding obtained)
- Continue to run MB without scintillator for ~1 month in summer 2014, after microBooNE turns on.
- Start MB scintillator incremental mixing, full concentration ~3months later.

- Produce NCelastic and n-fraction calibration measurements after ~2E20POT
- If all looks well, proceed for 4E20POT (~2more years)
- Run 2E20POT/yr 2014-2016 concurrently with MicroBooNE.



MB+ collaboration:

As made evident by current test run
and our recent analysis work
for this (and dark matter) proposals.
The MiniBooNE+ collaboration is
ready for the challenge!

The existance of working simulations
and analysis code (from MiniBooNE)
will help greatly.

Additionally, approval for MB+ will
allow the collaboration to be
further strengthened.

A Proposal for

MiniBooNE+: A new investigation of $\nu_\mu \rightarrow \nu_e$ oscillations with improved sensitivity in an enhanced MiniBooNE experiment

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December 19, 2013

Summary

MiniBooNE+ will provide an exiting new near-term research opportunity at Fermilab for a modest additional investment.

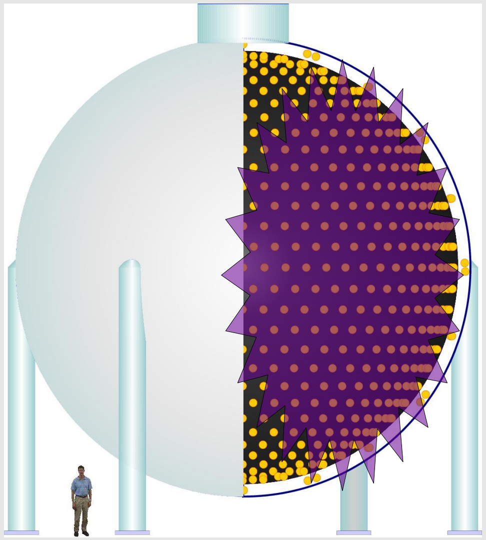
Enables these physics topics:

- A 5σ test of low-energy ν oscillation excess,
- nucleon spin structure measurement, Δs, via NC elastic scattering,
- measurement of $\nu_\mu C \to \mu^- N_{g.s.}$ and low-energy flux test,
- test of the quasielastic assumption in ν energy reconstruction.

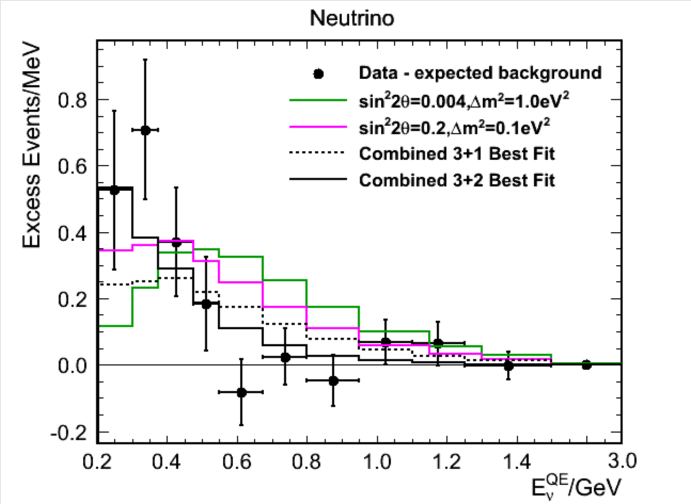
These will come with associated publications and 4-6 Ph.D. theses.

Exciting new physics, results in timely manner.

We are requesting approval for MiniBooNE+ which requires 6.5×10^{20} *protons on target. The* Δs *measurement and calibration of the oscillation event neutron fraction can be obtained with* 2×10^{20} *protons on target providing an early test of the viability of the new oscillation measurement along with a physics result. We request to begin this new phase of running in mid-2014, concurrently with the MicroBooNE experiment.*

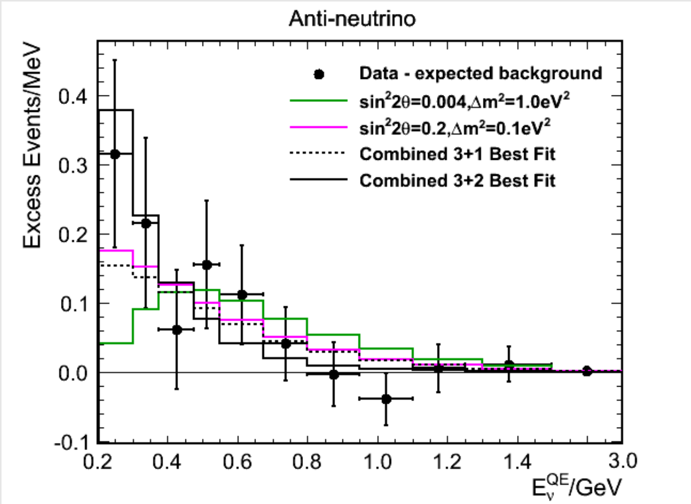


Backup slides



6.7e20 POT neutrino mode

ν mode	E > 200 MeV	E > 475 MeV
χ^2(null)	22.81	6.35
Prob(null)	0.5%	36.6%
χ^2(bf)	13.24	3.73
Prob(bf)	6.12%	42.0%



11.3e20 POT anti-neutrino mode

$\bar{\nu}$ mode	E > 200 MeV	E > 475 MeV
χ^2(null)	16.3	7.59
Prob(null)	5.8%	26.4%
χ^2(bf)	4.76	3.23
Prob(bf)	67.5%	50.2%