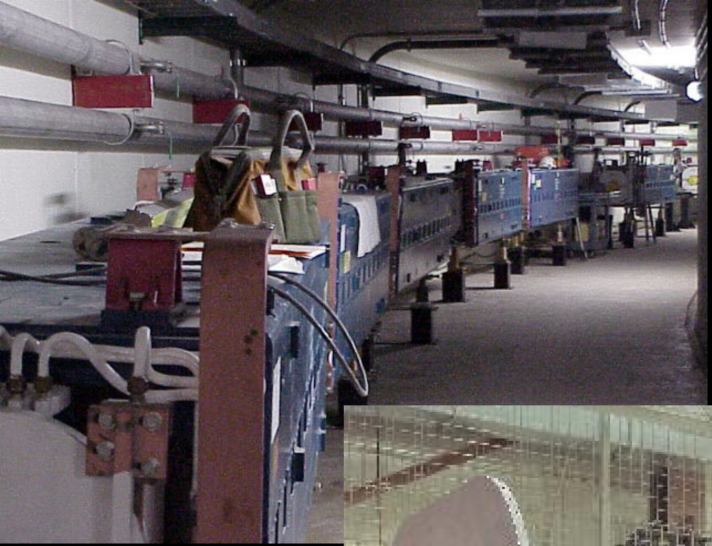
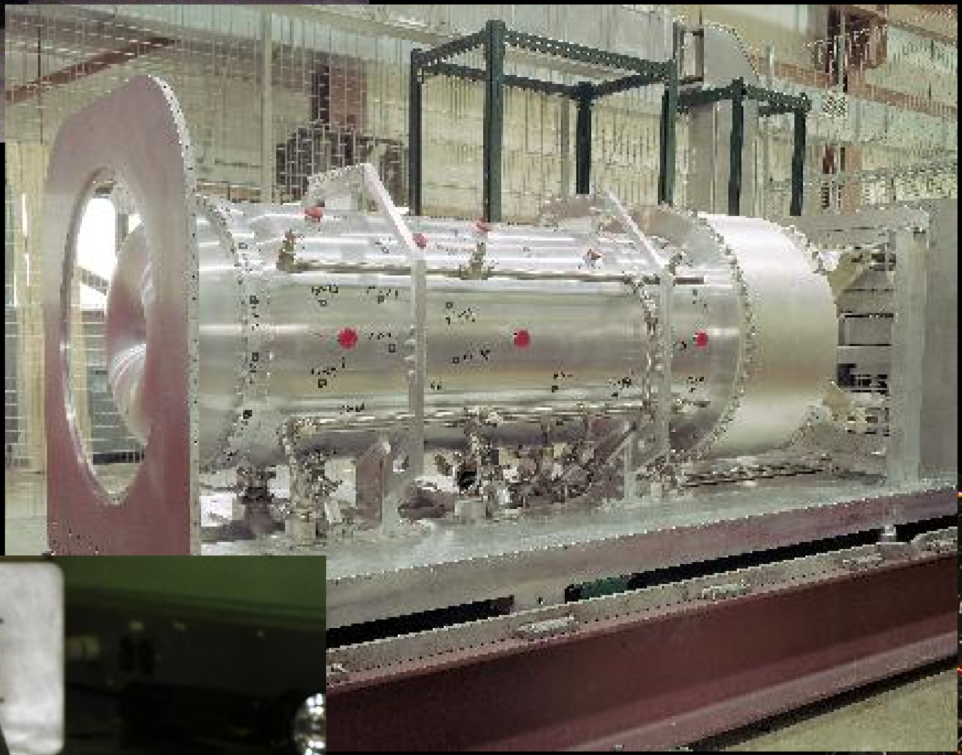
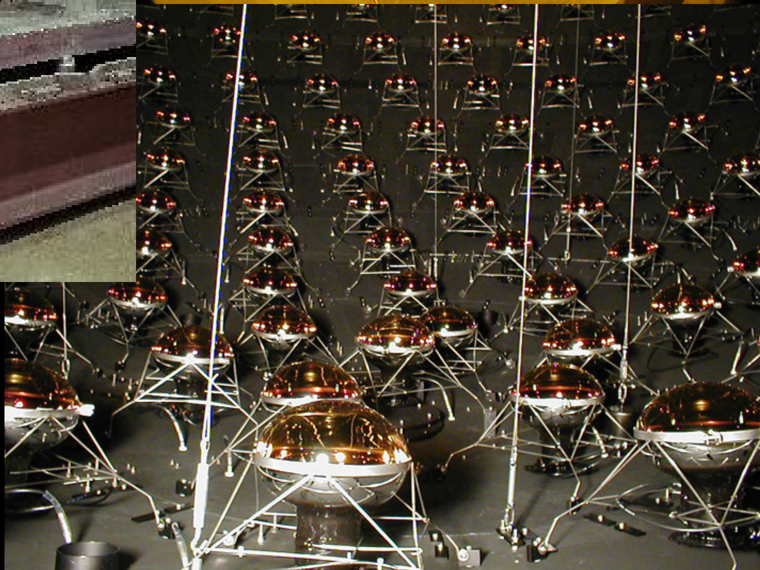
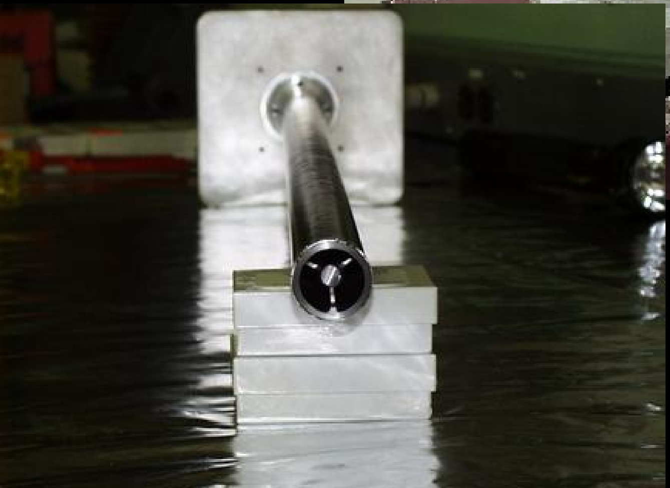
Oscillation Results from MiniBooNE

Chris Polly, Univ. of Illinois









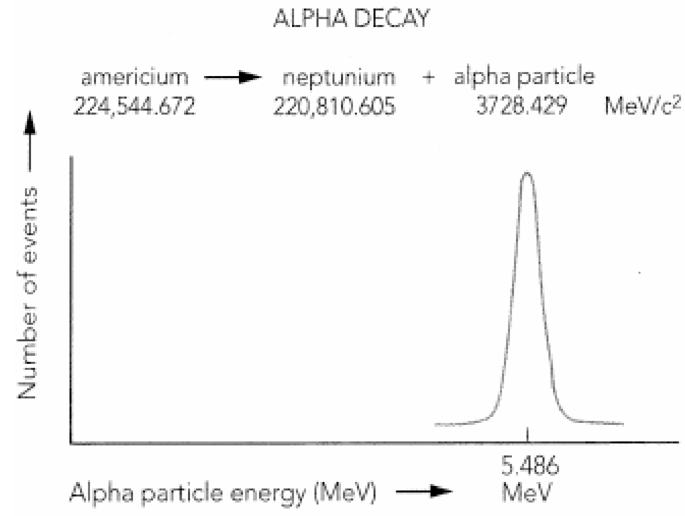
Long ν history of solving data-driven mysteries

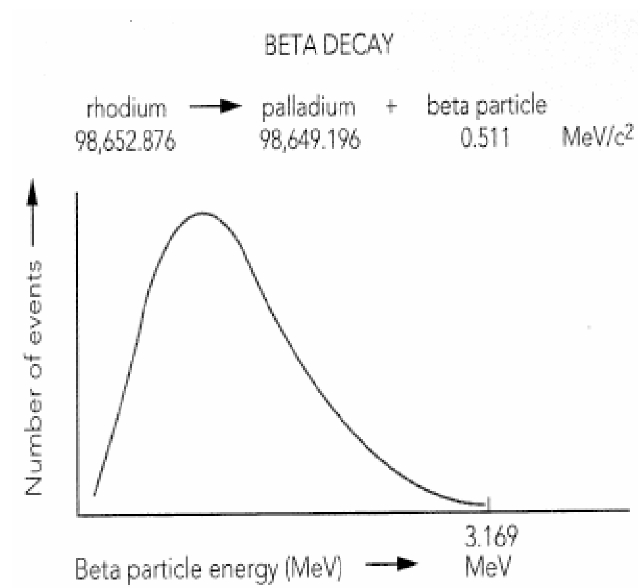
- Starting with the original mystery of the continuous nature of the β decay spectrum

Detective Pauli

"Dear Radioactive Ladies and Gentlemen, …as a desperate remedy to save the principle of energy conservation in beta decay,…I propose the idea of a neutral particle of spin half" W. Pauli 1929

"I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do." W. Pauli 1929

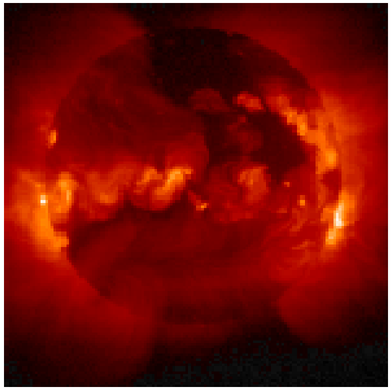


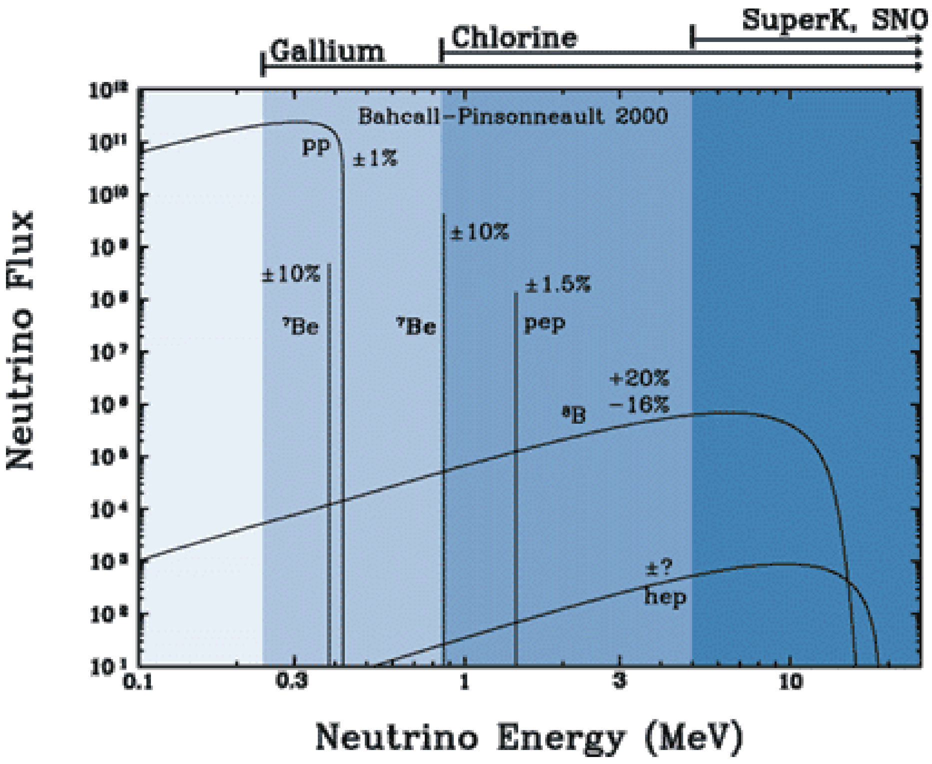


☆ And so the neutrino was 'discovered'!

Starting in the 1960's solar ν mystery arises

- The sun is fueled by fusion reactions
  - $4\,^1H + 2e^- \rightarrow {}^4He + 2\nu_e + 6\gamma$
  - More reaction chains follow...
- Neutrinos are produced copiously
  - Note all ν_e have E_ν below ~10MeV

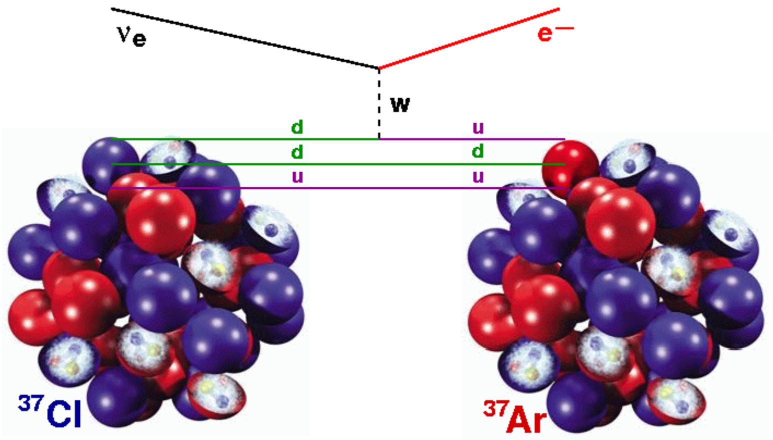




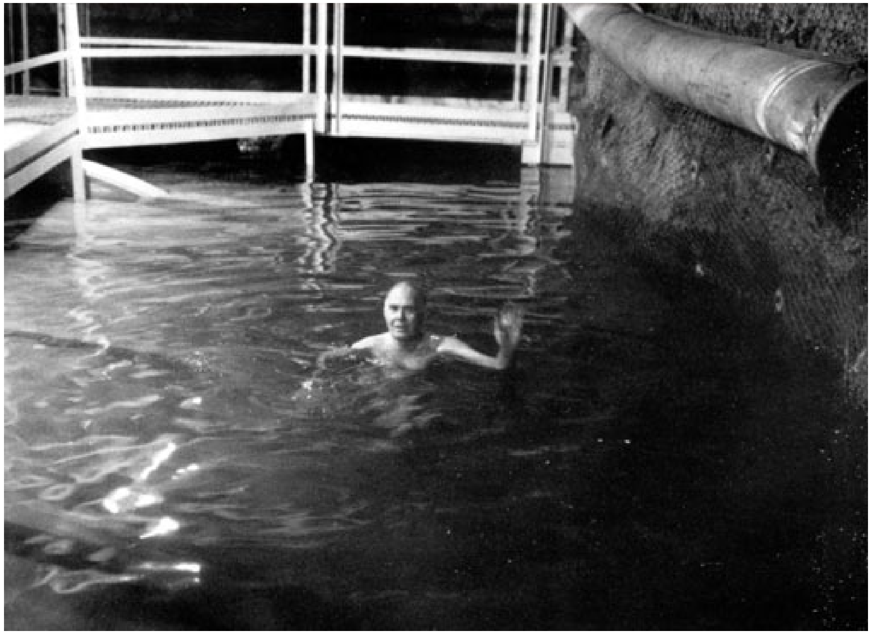
☆ Ray Davis sets out to measure solar ν's for the first time.

Ray Davis' Experiment at Homestake

- Used a large vat of dry cleaning solution to look for Argon from inverse beta decay



☆ Found 1/3 of the ν_e from sun compared to Bahcall's prediction!



- Remained mired in controversy for 30 years. Do we understand fusion? Is the experiment correct? Could it be new physics, e.g. Pontecorvo's oscillations?

Pontecorvo first to point out possible ν mixing

- Back in 1957, Pontecorvo pointed out that if ν's have mass, then it could be the case that the mass eigenstates were not identical to the weak

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

- Sounds a little far-fetched, but similar to kaon mixing where it was already known that the weak and strong (mass) eigenstates differed
- Neutrino mixing is a direct result:

$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta \sin^2 (1.27 \Delta m^2 \frac{L}{E})$$

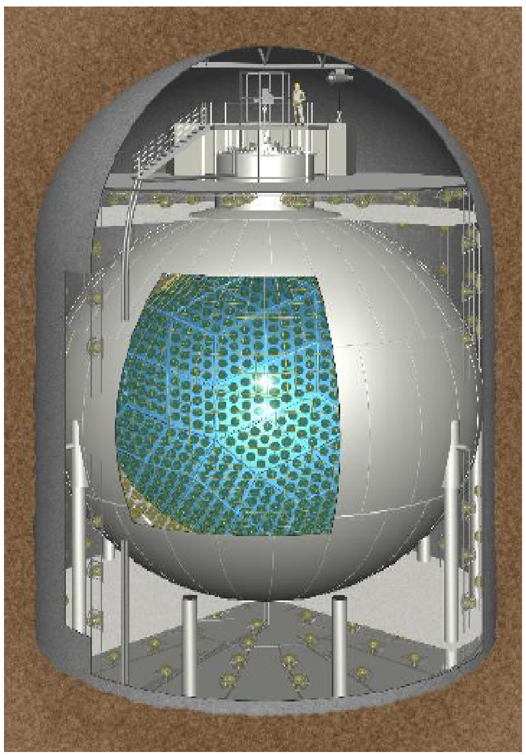
☆ By measuring the mixing, the mass differences of the neutrino can be inferred!

Bruno Pontecorvo

"At present this is highly speculative– there is no experimental evidence for neutrino oscillations..." D.J. Griffiths (1995), *Introduction to Quantum Mechanics*

Definitive proof via systematically different expts

- **SNO:** Definitive proof of solar mixing
  - Measured same disappearance signal as Davis
  - Also measured NC total xsec consistent with Bahcall's expected total ν flux

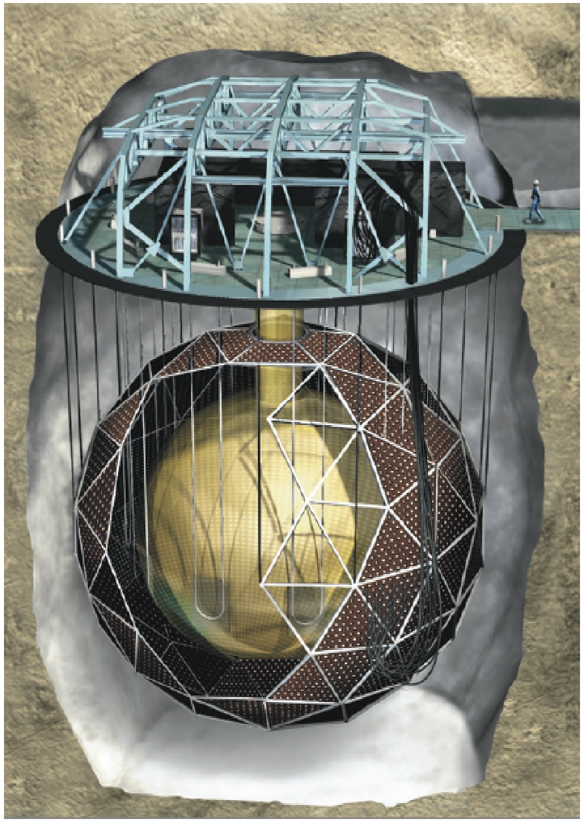


NCD phase:

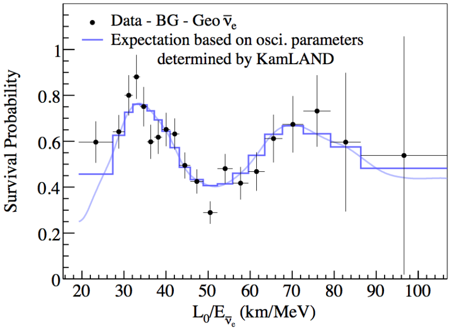
$\Delta m_{21} = (8 \pm 0.3)\ 10^{-5}\ \mathrm{eV}^2$

$\theta_{12} = (33.8 \pm \mathbf{1.4})^\circ$

☆ Latest results, including 3rd phase of SNO, see Ryan Martin talk, this conference!

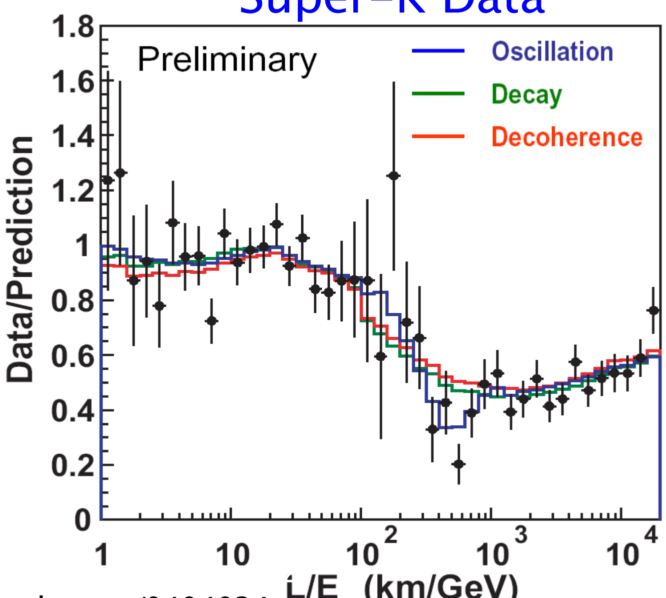


- **Kamland:** Confirmation of the physics
  - Ind. ν source, reactor vs. solar
  - Confirms anti-ν_e behave like ν_e



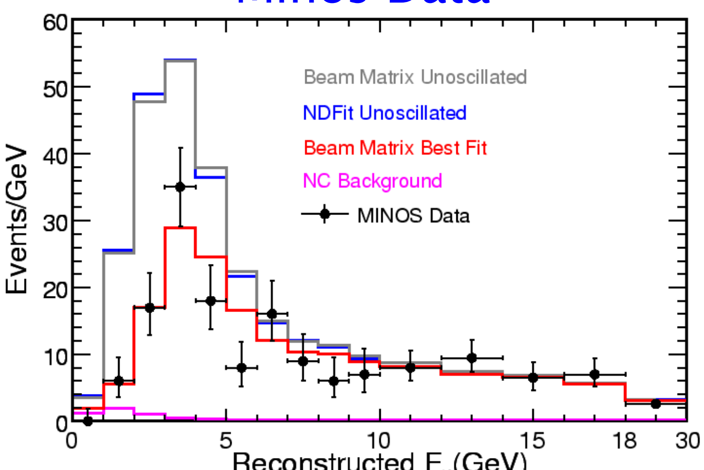
Similarly compelling story in atmospheric sector

Super-K Data

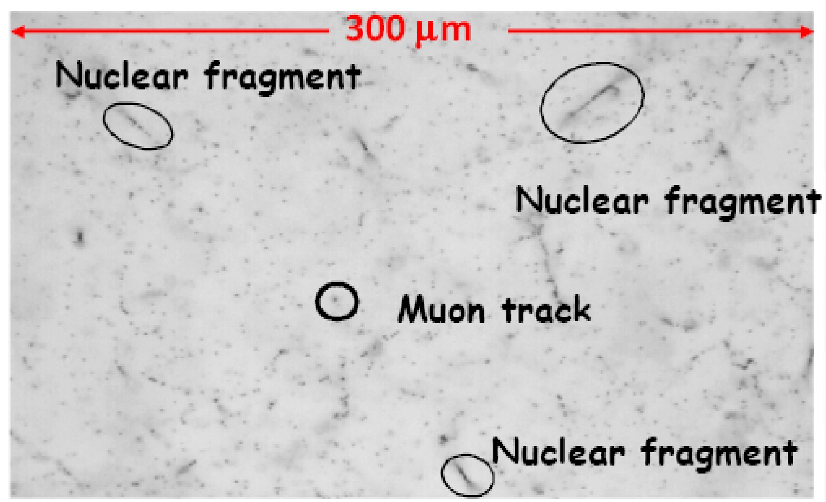


hep-ex/0404034

Minos Data



- **Super-K:** New mixing found in atmospheric ν_μ
  - found 1/2 as the upward ν_μ as downward
  - $\Delta m_{23}^2 \sim 2\times10^{-3}$ eV^2, $\sin^2(2\theta_{23}) \sim 1.0$
- **K2K:** Confirms Super-K
  - accelerator vs. cosmic source
  - much smaller L, confirms L/E invariance
- **MINOS:** Entering the precision era
- **OPERA:** Looking to confirm $\nu_\mu \to \nu_\tau$



☆ Emulsion from OPERA, see talk by Guillame Lutter, this conference!

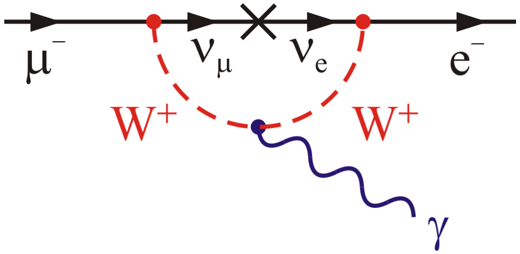
So where do we stand with many mysteries solved?

- Now know neutrinos have mass and weak /mass eigenstates differ
- SM has a much richer ν sector

neutrino mixing (mass→weak)

$$U_{PMNS} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} = \begin{bmatrix} 0.8 & 0.5 & <0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{bmatrix}$$

Source of CLFV in SM



$BR(\mu \to e\gamma) < 10^{-52}$

$BR(\mu N \to eN) < 10^{-54}$

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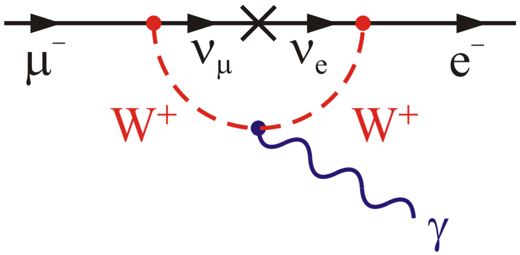

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quark mixing (strong/mass→weak)

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} = \begin{bmatrix} 0.974 & 0.225 & 0.004 \\ 0.226 & 0.973 & 0.041 \\ 0.009 & 0.041 & 0.999 \end{bmatrix}$$

(PDG 2008)

- Why is the PMNS matrix so different from CKM?

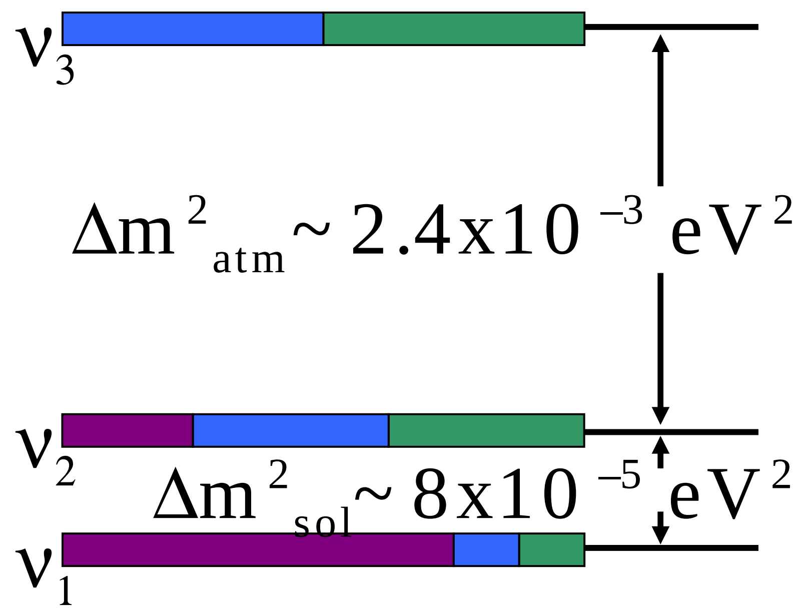
☆ MORE MYSTERIES!!!

Open questions from the mixing matrix...

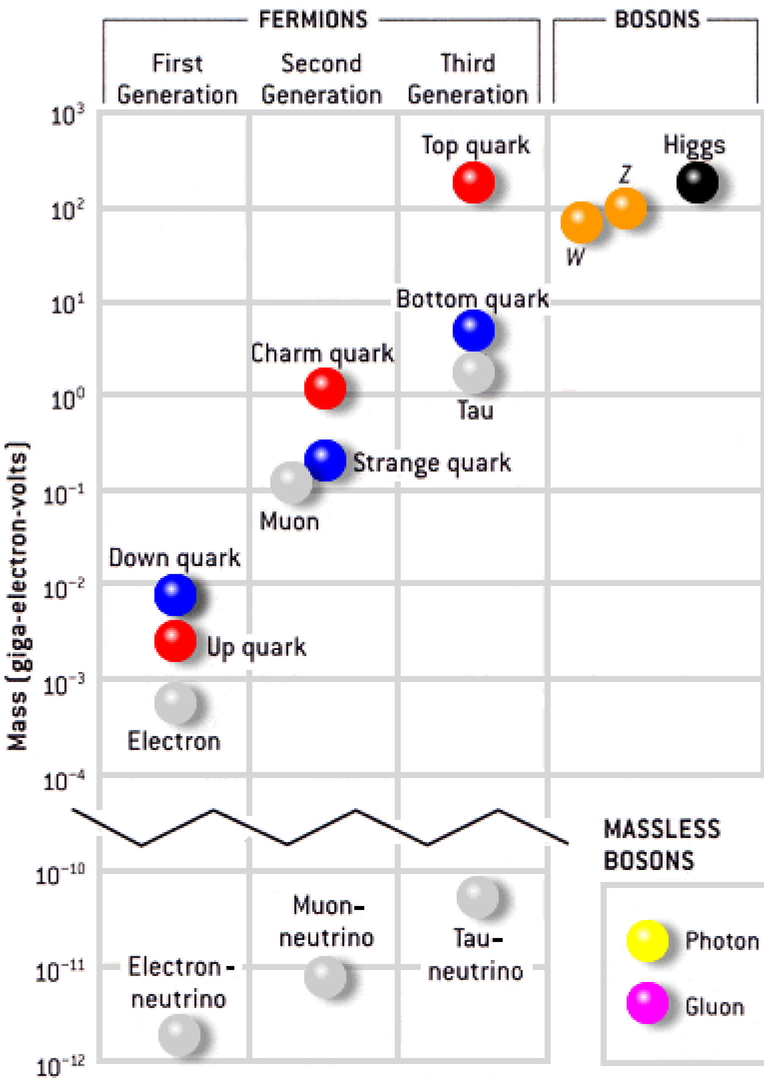
neutrino mixing (mass→weak)

$$U_{PMNS} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} = \begin{bmatrix} 0.8 & 0.5 & <0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{bmatrix} \approx U_{TBM} = \begin{bmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \\ \sqrt{1/6} & -\sqrt{1/2} & \sqrt{1/2} \end{bmatrix}$$

- At 1st order mixing is tribimaximal, why?
- What is causing the PMNS symmetry?
- How big is the U_{e3} component? Zero if consistent with tribimaximal.
- Is there still enough room for CP violation in the ν sector for leptogenesis?
- Unitarity?



Even more basic questions...



Shamelessly stolen from *Scientific American*

- Why is the ν mass so small?
- What is the absolute mass scale?
- Is the hierarchy normal or inverted?
- Are ν's Dirac or Majorana?
- Are there right-handed partners?
- Sterile neutrinos at any mass scale?

☆ Many experiments/theories out there seeking answers right now. Too many to discuss and still have time for MiniBooNE.

So many questions, even Bob Seger is curious!!

Tomorrow (lyrics)

They say the sun is gonna grow someday.

It's gonna get real close and burn us all up...

...I can't promise you tomorrow. No one has the right to lie.

You can beg and steal and borrow. It won't save you from the sky.

Let me see a show of hands.
Tell me the truth now.

What happens if neutrinos have mass?

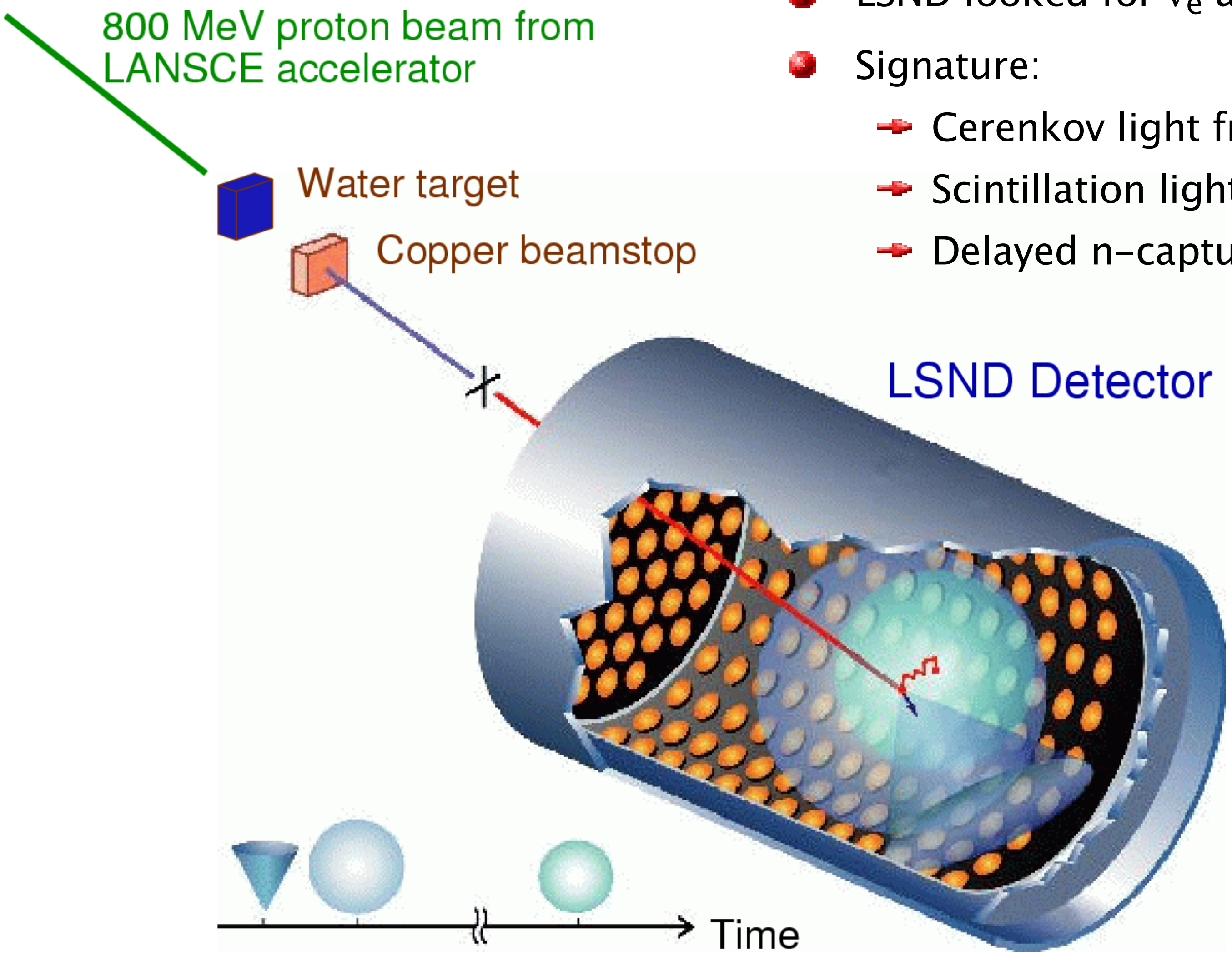
I can't tell you about tomorrow.

I'm as lost as yesterday. In between your joy and sorrow,

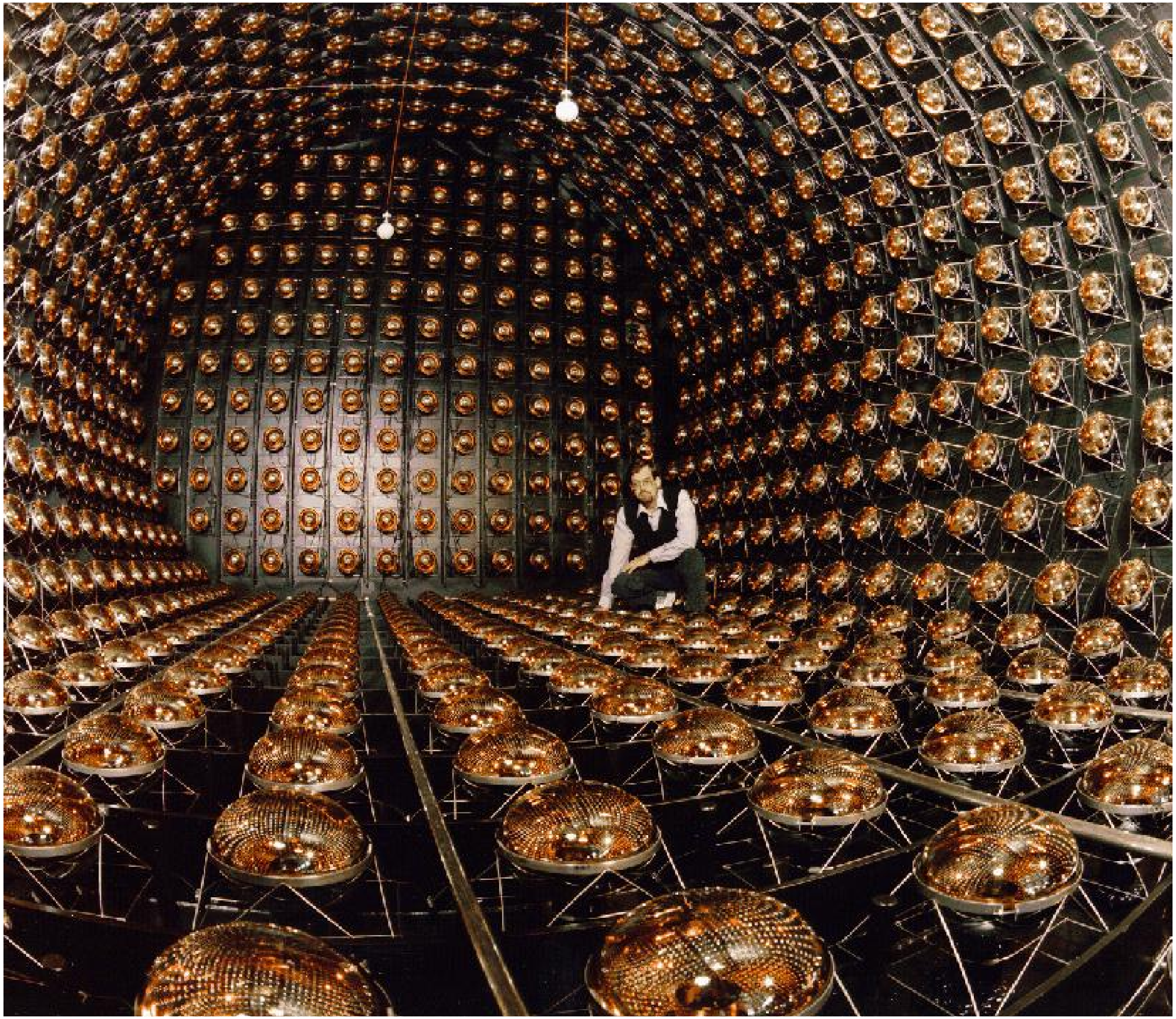
I suggest you have your say: Here's to the little things...

A more recent mystery...LSND

- LSND looked for $\overline{\nu}_e$ appearing in a $\overline{\nu}_\mu$ beam
- Signature:
  - Cerenkov light from e^+ (CC)
  - Scintillation light from nuclear recoil
  - Delayed n-capture (2.2 MeV)



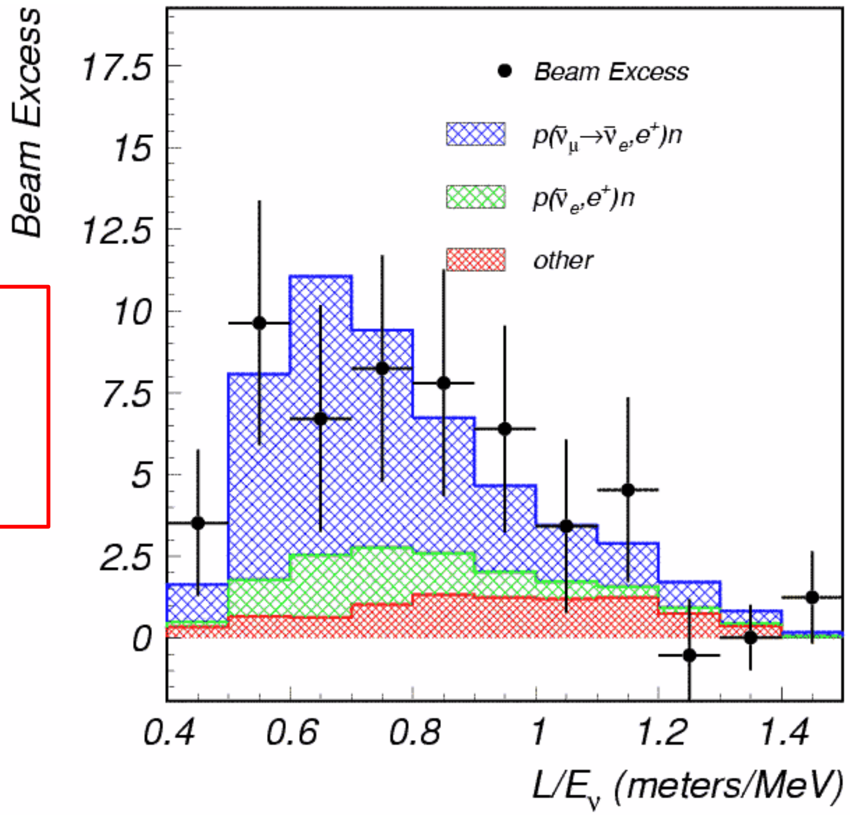
Picture of LSND photomultipliers (used later in MB)



MiniBooNE's motivation...LSND

- LSND found an excess of $\overline{\nu}_e$ in $\overline{\nu}_\mu$ beam
- Signature: Cerenkov light from e^+ with delayed n-capture (2.2 MeV)
- Excess: 87.9 ± 22.4 ± 6.0 (3.8σ)
- Under a 2ν mixing hypothesis:

$$P(\overline{\nu}_\mu \to \overline{\nu}_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\ L\,\Delta m^2}{E}\right)$$
$$= 0.245 \pm 0.067 \pm 0.045\ \%$$



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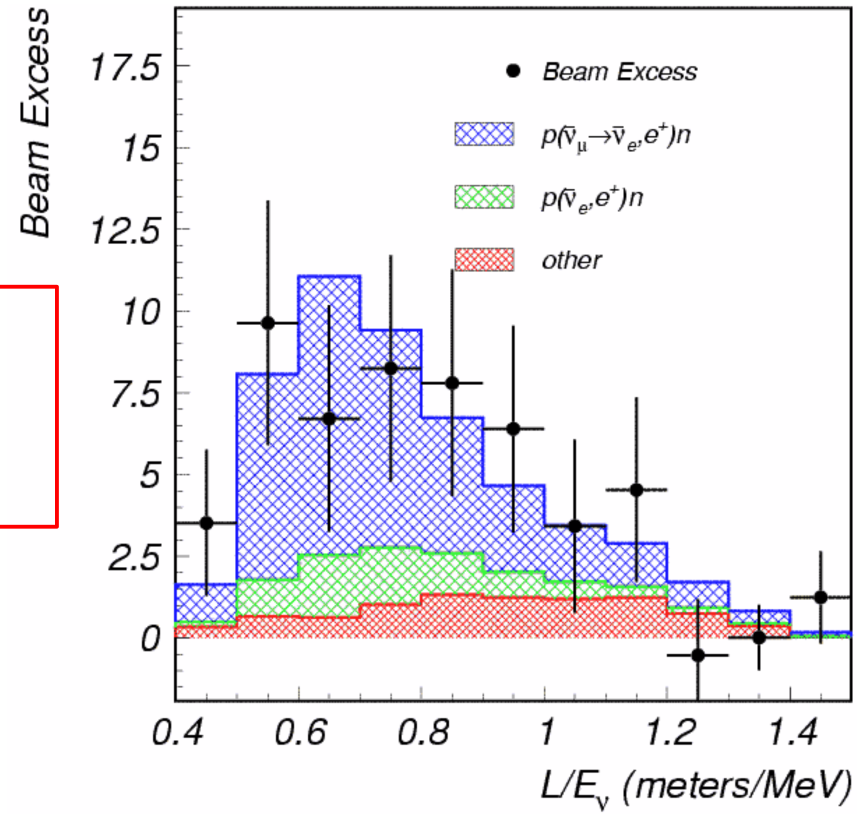
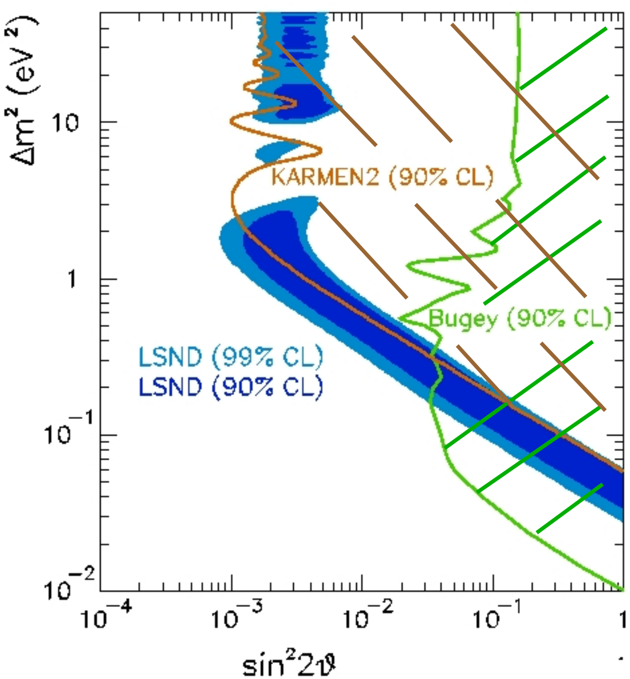
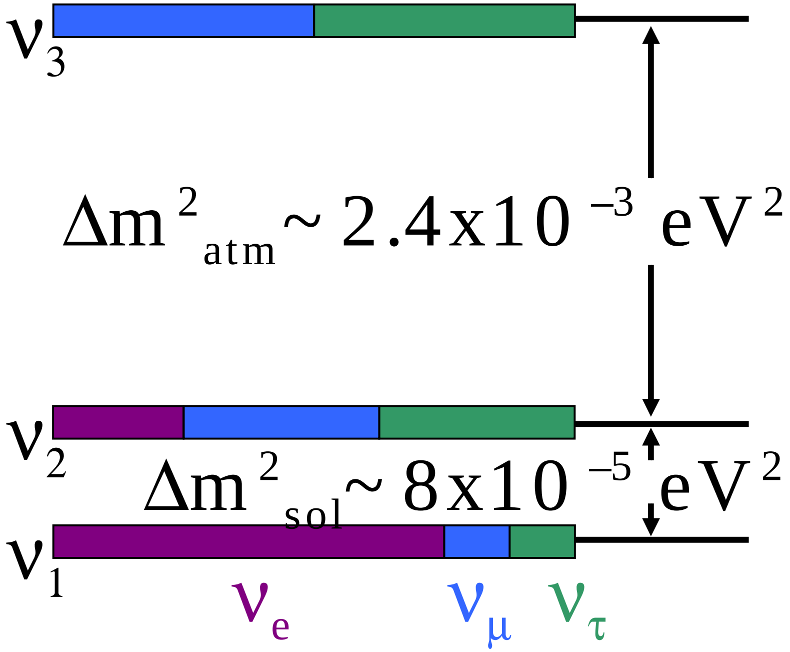




- Other experiments, i.e. Karmen and Bugey, have ruled out portions of the LSND signal
- MiniBooNE was designed to cover the entire LSND allowed region

Interpreting the LSND signal



- The other two measured mixings fit conveniently into a 3-neutrino model
- With $\Delta m_{13}^2 = \Delta m_{12}^2 + \Delta m_{23}^2$, the LSND $\Delta m^2 \sim 1\ eV^2$ does not fit
- 'Simplest' explanation...a 4th neutrino

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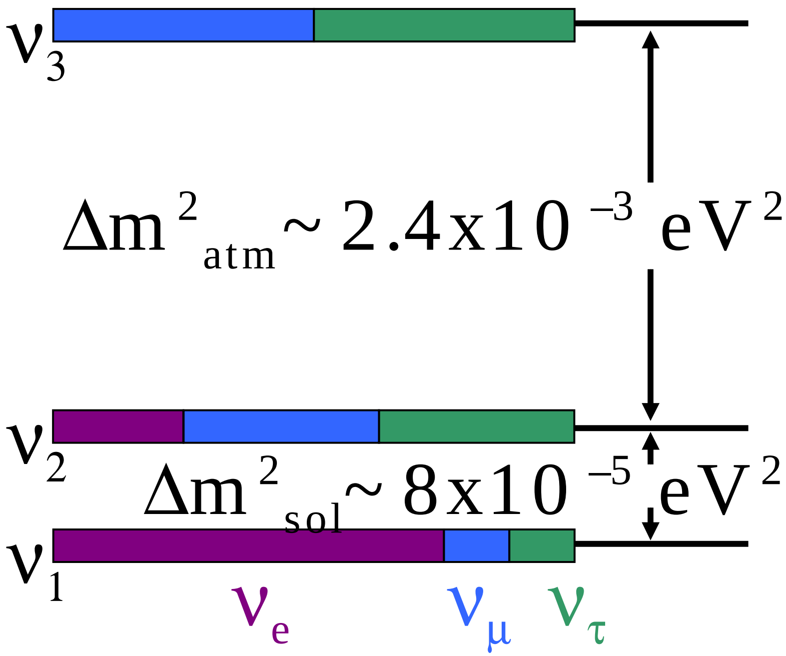

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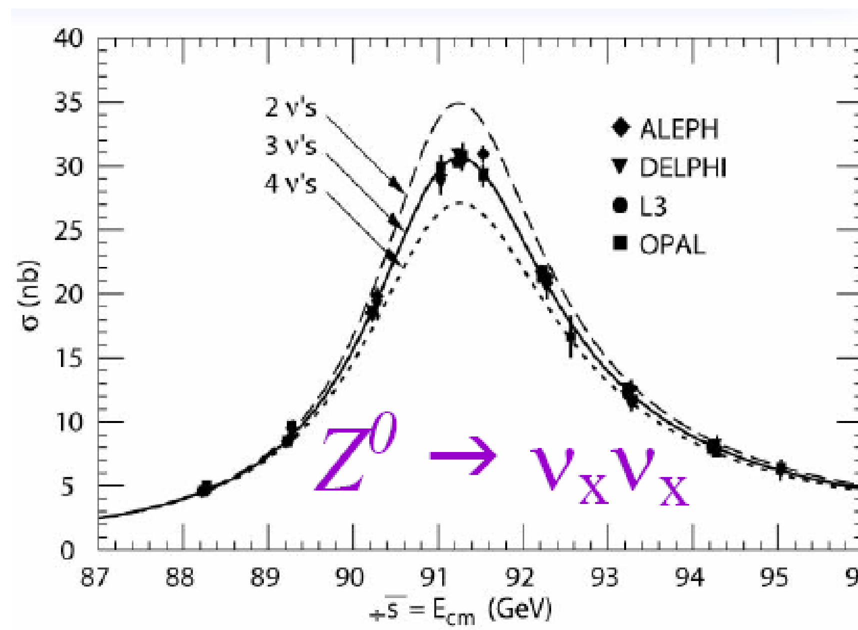
- Width of the Z implies 2.994 + 0.012 light neutrino flavors
- Requires 4th neutrino to be 'sterile' or an even more exotic solution
  - Sterile neutrinos *hep-ph/0305255*
  - Neutrino decay *hep-ph/0602083*
  - Lorentz/CPT violation *PRD(2006)105009*
  - Extra dimensions *hep-ph/0504096*



The MiniBooNE Collaboration

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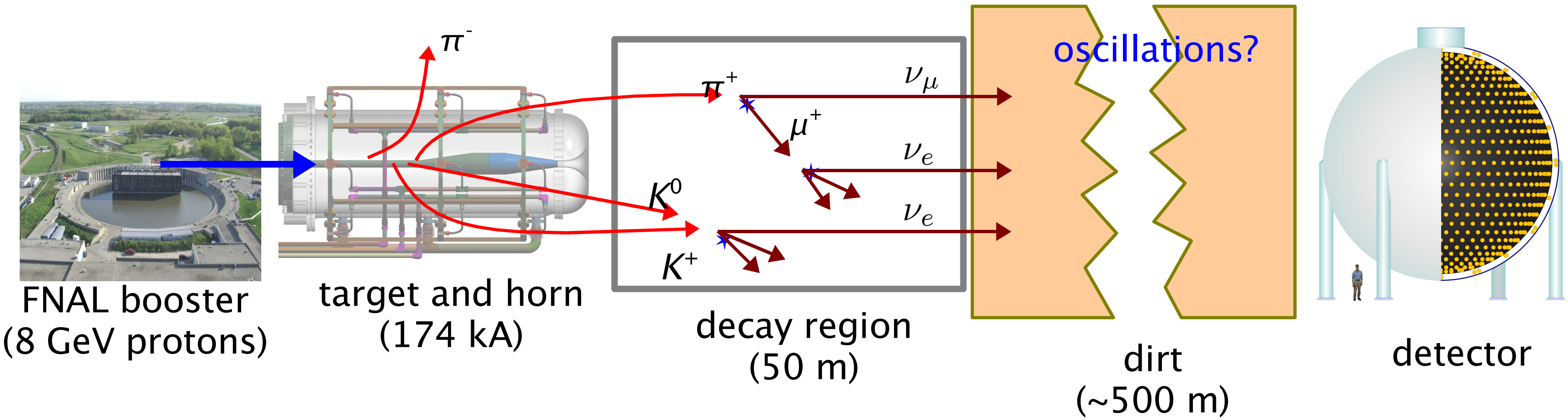
~80 physicists from ~18 institutions

OUTLINE

- Part 1: Recap of the analysis method and '07 ν_e result
- Part 2: Analysis updates, emphasis on ν_e–like excess at low energy
- Part 3: New results from anti–ν run (including ν_μ disappearance)

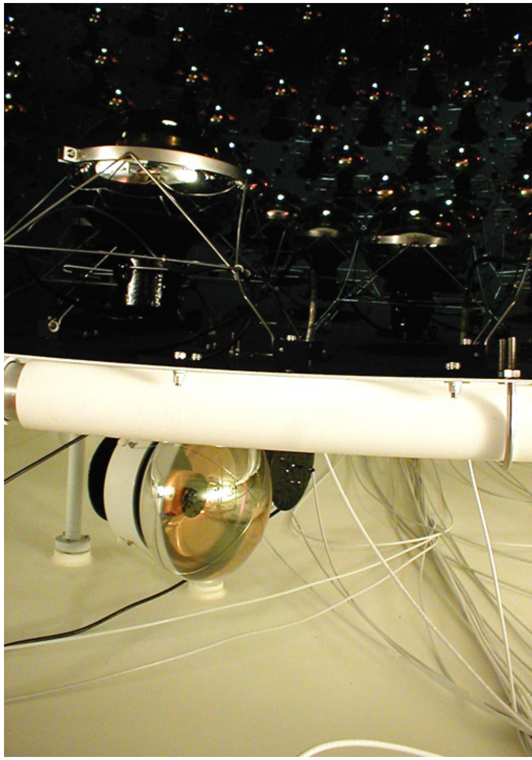
The MiniBooNE design strategy...must make ν_μ



- Start with 8 GeV proton beam from FNAL Booster
- Add a 174 kA pulsed horn to gain a needed x 6
- Requires running ν (not anti-ν like LSND) to get flux
- Pions decay to ν with E_ν in the 0.8 GeV range
- Place detector to preserve LSND L/E:

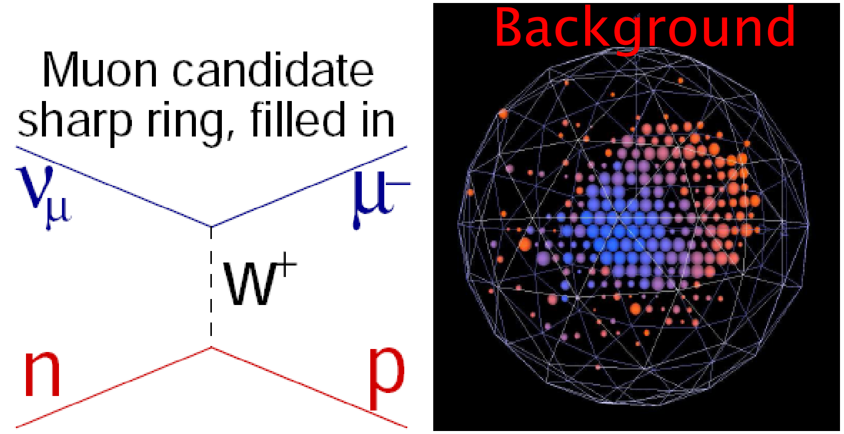
  MiniBooNE: (0.5 km) / (0.8 GeV)
  LSND: (0.03 km) / (0.05 GeV)

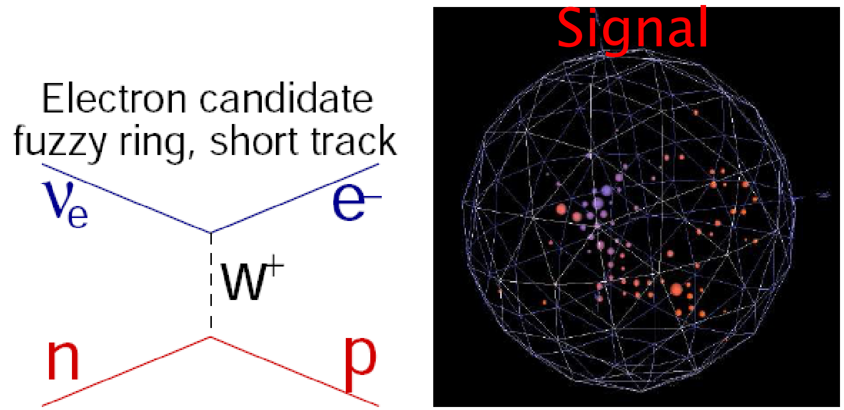
- Detect ν interactions in 800T pure mineral oil detector
  - 1280 8” PMTs provide 10% coverage of fiducial volume
  - 240 8” PMTs provide active veto in outer radial shell

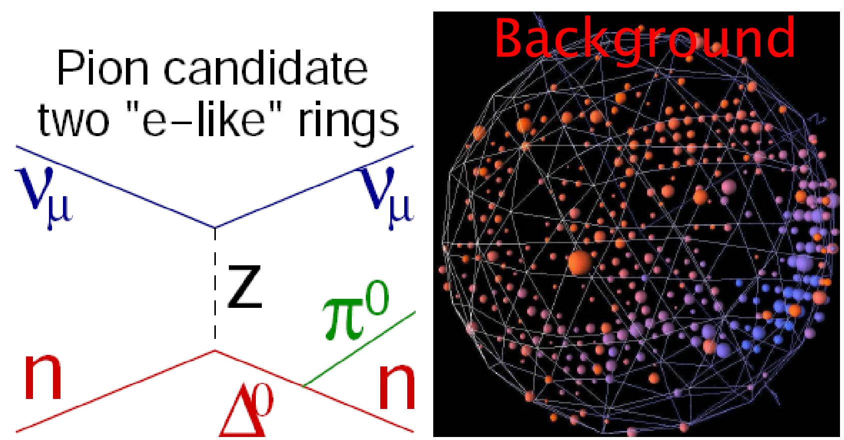


Key points about the signal

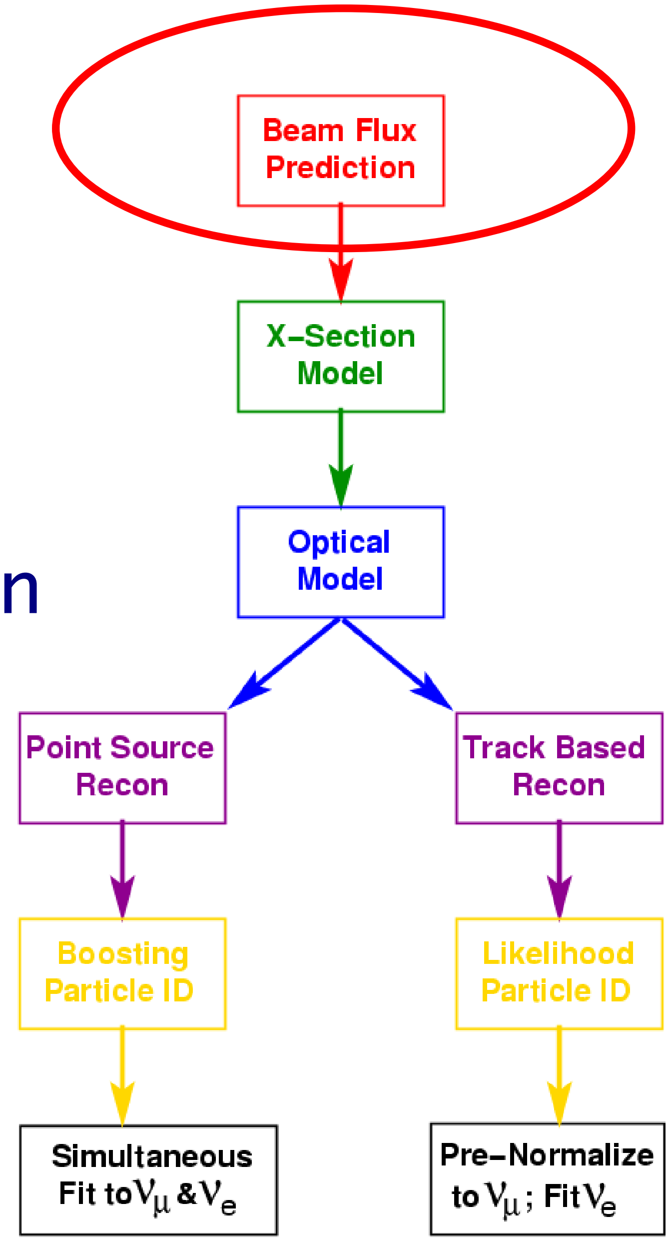
- LSND oscillation probability is < 0.3%
- After cuts, MiniBooNE has to be able to find ~300 ν_e CCQE interactions in a sea of ~150,000 ν_μ CCQE
- Intrinsic ν_e background
  - Actual ν_e produced in the beamline from muons and kaons
  - Irreducible at the event level
  - E spectrum differs from signal
- Mis-identified events
  - ν_μ CCQE easy to identify, i.e. 2 “subevents” instead of 1. However, lots of them.
  - Neutral-current (NC) π^0 and radiative Δ are more rare, but harder to separate
  - Can be reduced with better PID
- Effectively, MiniBooNE is a ratio meas. with the ν_μ constraining flux X cross-section





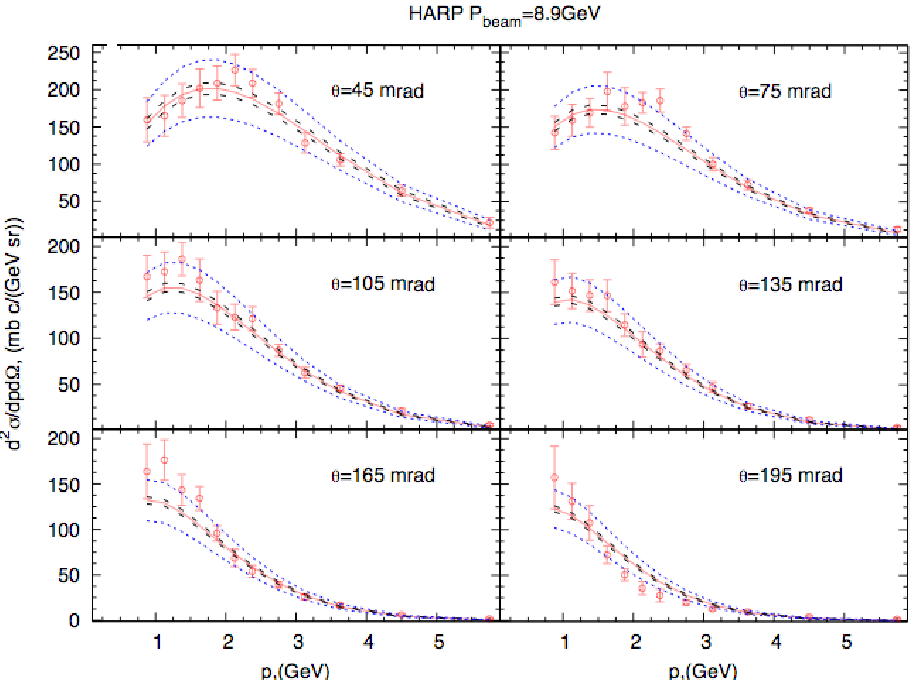


Analysis Chain: Flux Prediction



Meson production at the target

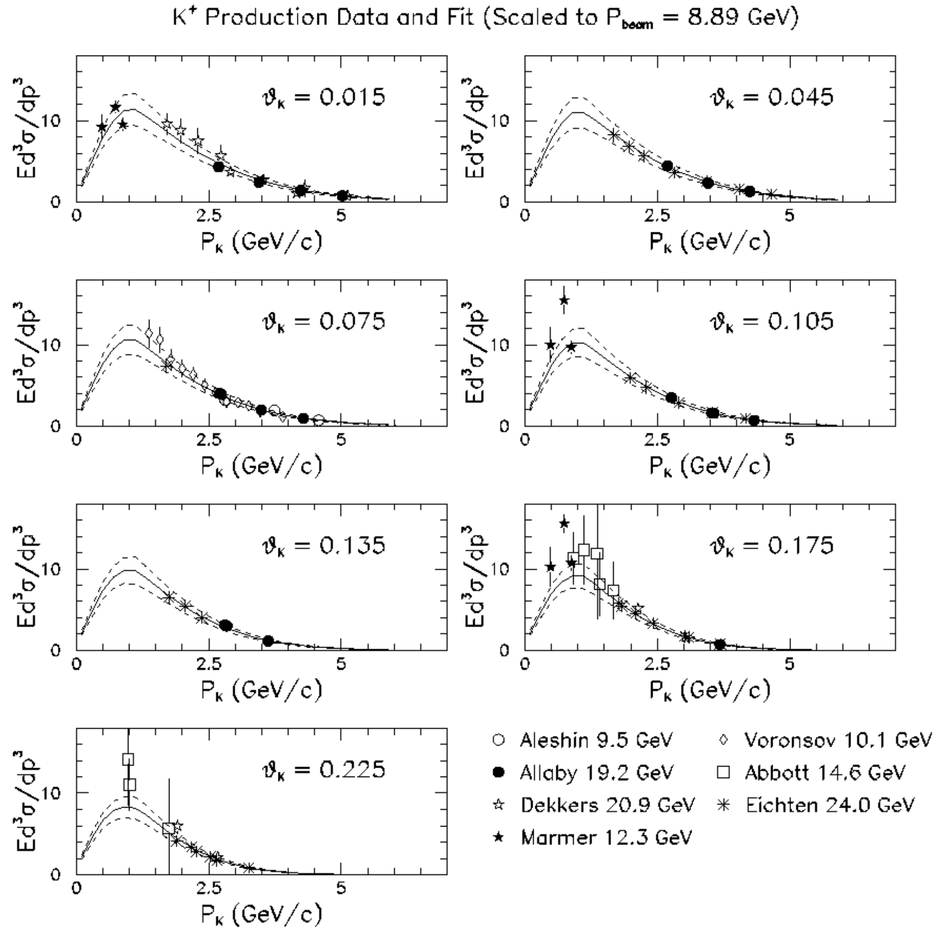
Pions:



HARP collaboration, hep-ex/0702024

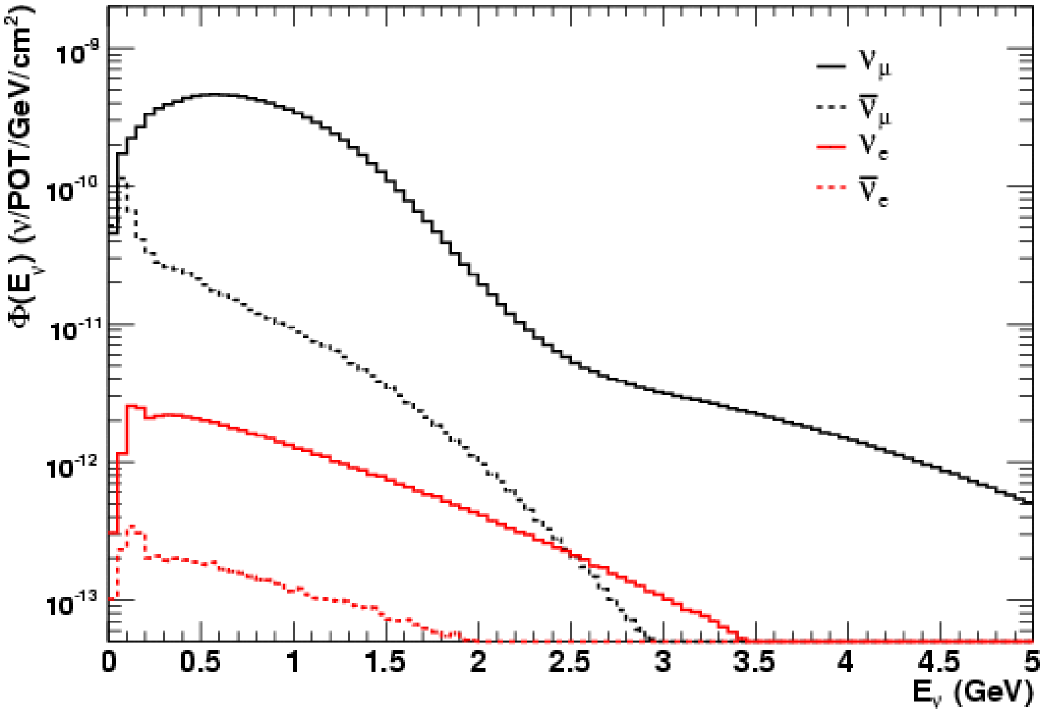
- MiniBooNE members joined the HARP collaboration
  - 8 GeV proton beam
  - 5% λ Beryllium target
- Data were fit to Sanford-Wang parameterization for '07 analysis

Kaons:



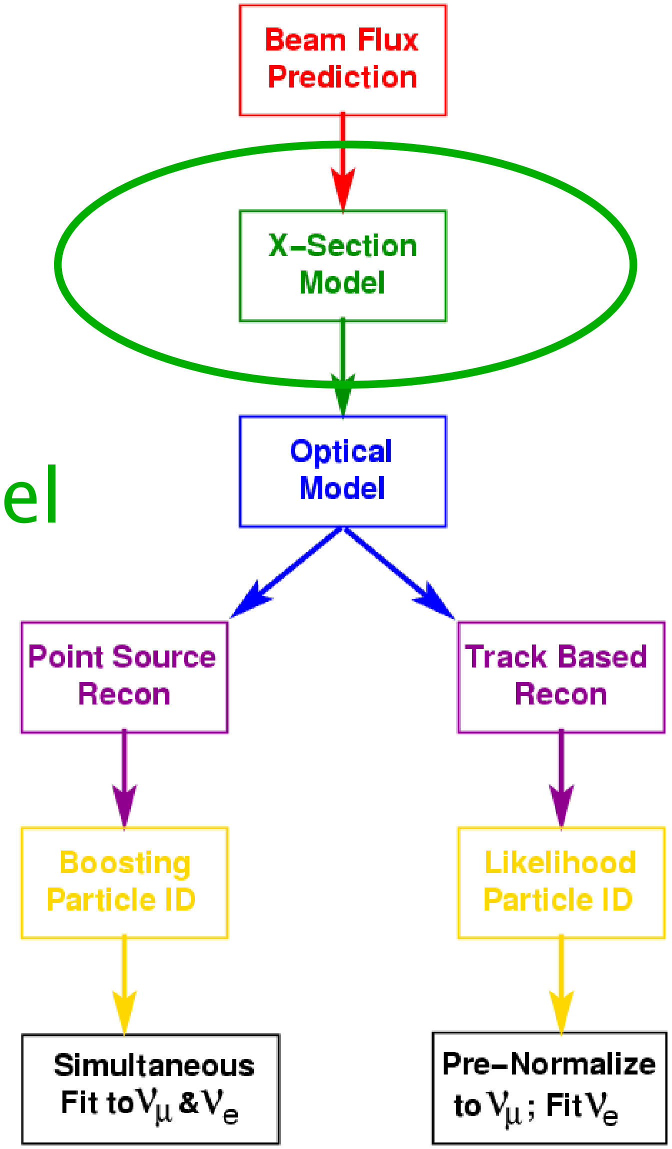
- Kaon data taken on multiple targets in 10-24 GeV range
- Fit to world data using Feynman scaling
- 30% overall uncertainty assessed

Final neutrino flux estimation



- Flux intersecting MB detector (not cross-section weighted)
- Intrinsic contamination ν_e/ν_μ = 0.5%
  - $\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$ (52%)
  - $K^+ \to \pi^0 e^+ \nu_e$ (29%)
  - $K^0 \to \pi e \nu_e$ (14%)
  - Other (5%)
- Wrong-sign $\bar{\nu}_\mu$ content: 6%

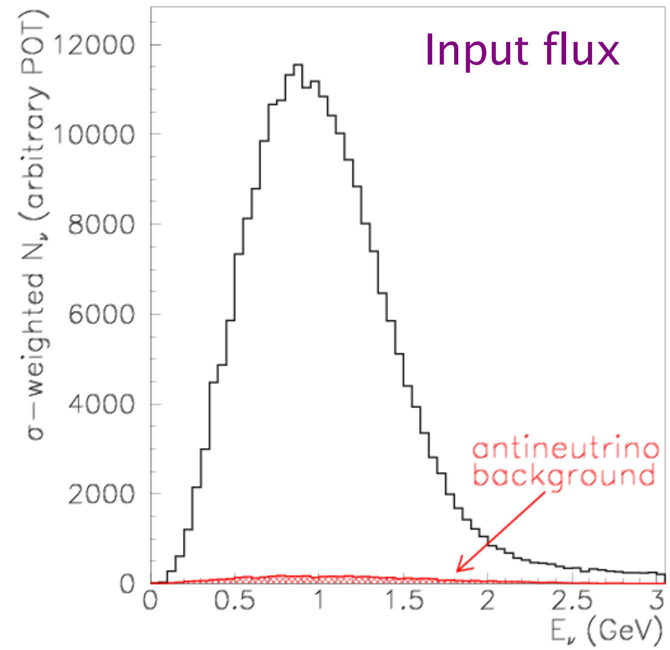
Analysis Chain: X−Section Model

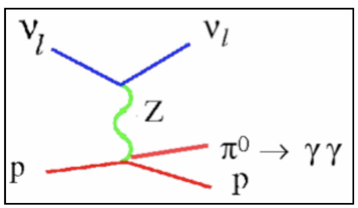


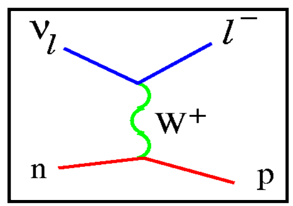
Nuance Monte Carlo

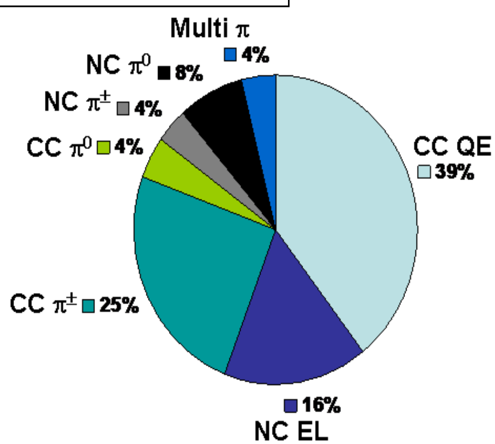
D. Casper, NPS, 112 (2002) 161

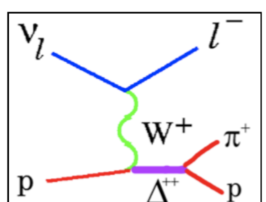
- Comprehensive generator, covers entire E_ν range
- Predicts rates and kinematics of specific ν interactions from input flux
- Expected interaction rates in MiniBooNE (before cuts) shown below
- Based on world data, ν_μ CC shown below right

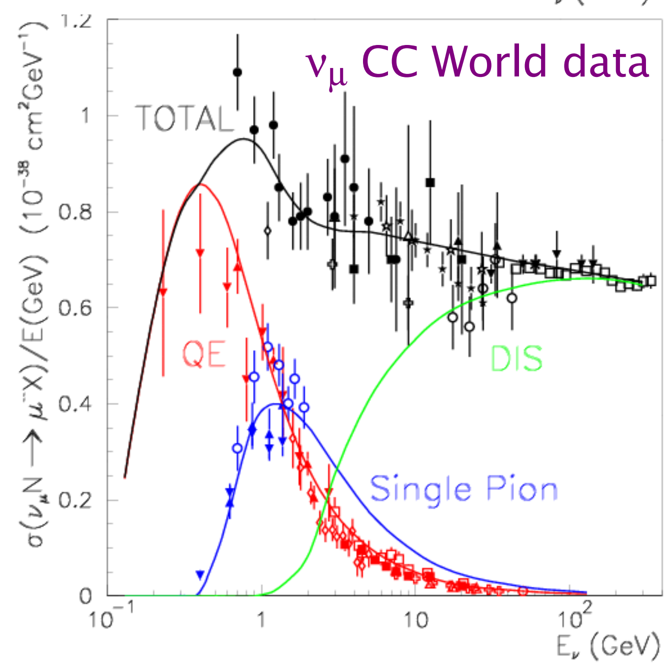








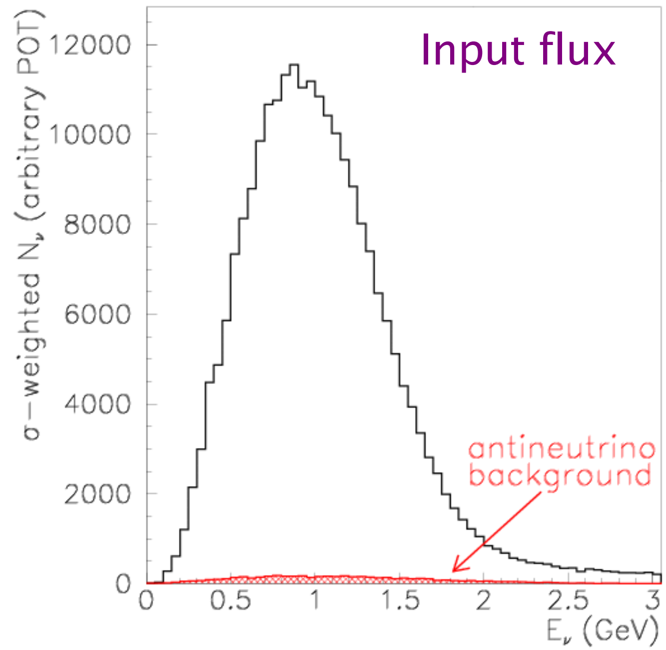


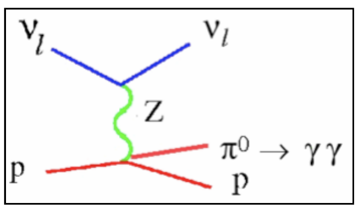


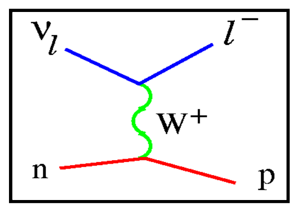
Nuance Monte Carlo

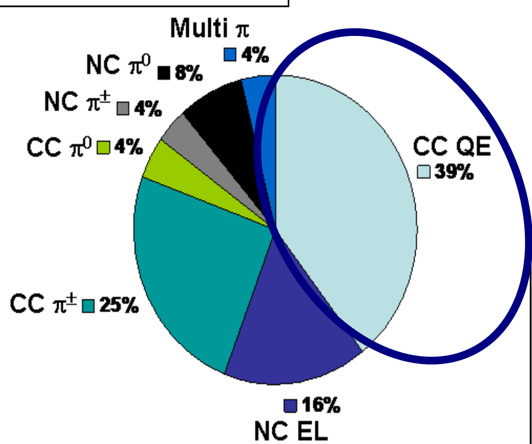
D. Casper, NPS, 112 (2002) 161

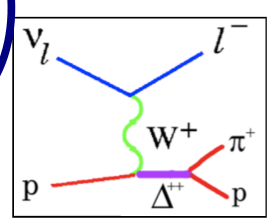
- Comprehensive generator, covers entire E_ν range
- Predicts rates and kinematics of specific ν interactions from input flux
- Expected interaction rates in MiniBooNE (before cuts) shown below
- Based on world data, ν_μ CC shown below right
- Also tuned on internal data

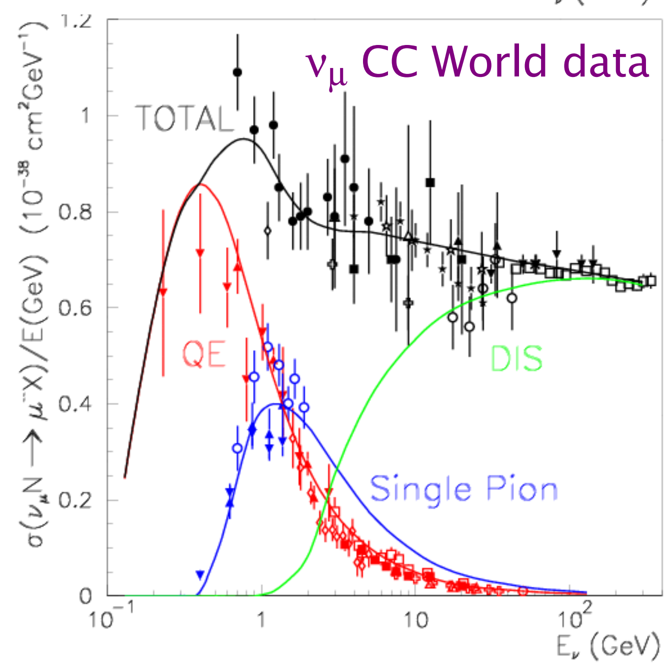




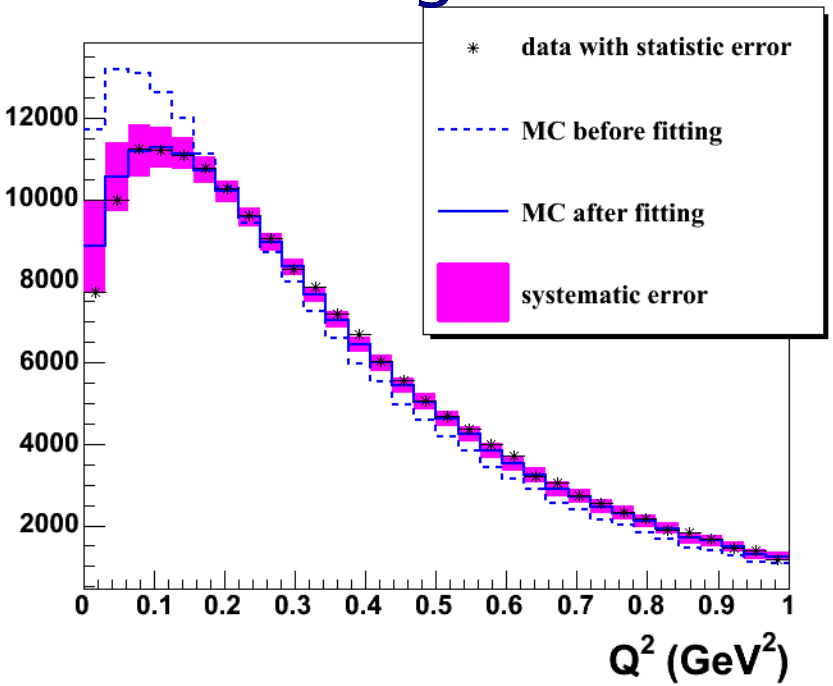




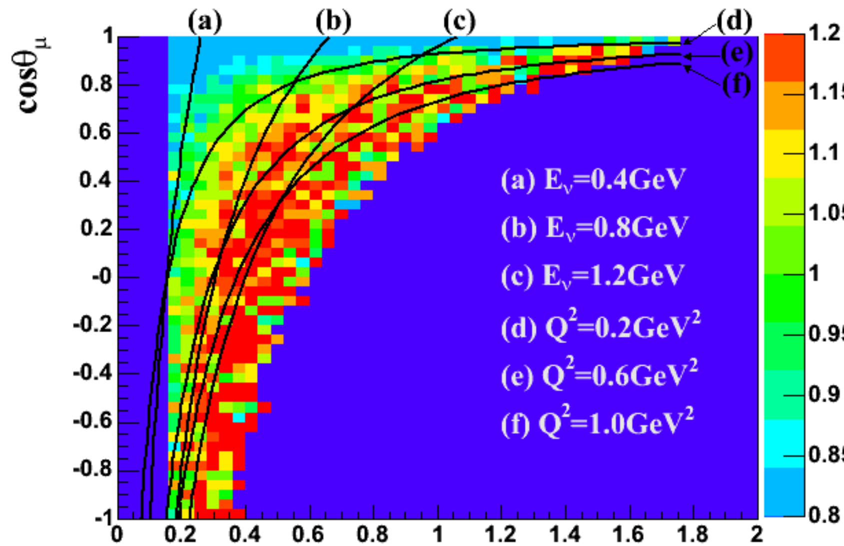




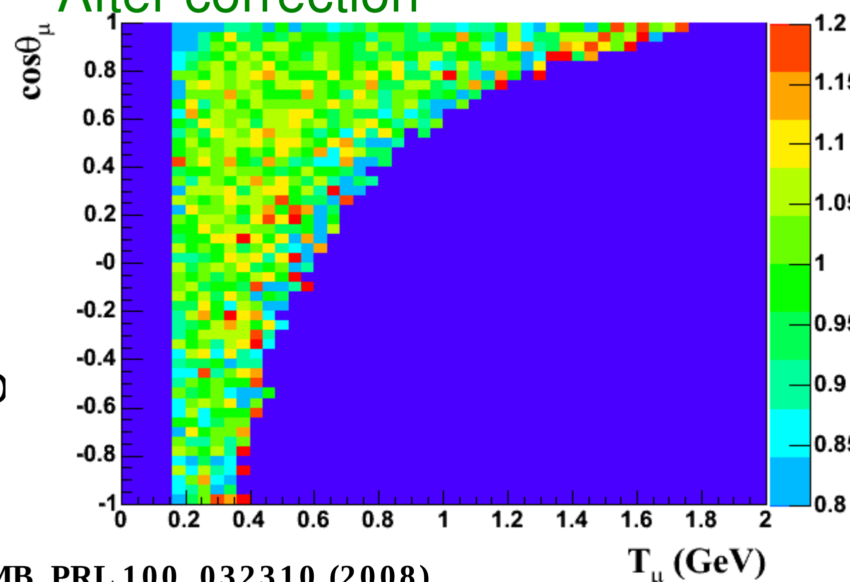
Tuning Nuance on internal ν_μ CCQE data



Before correction



After correction



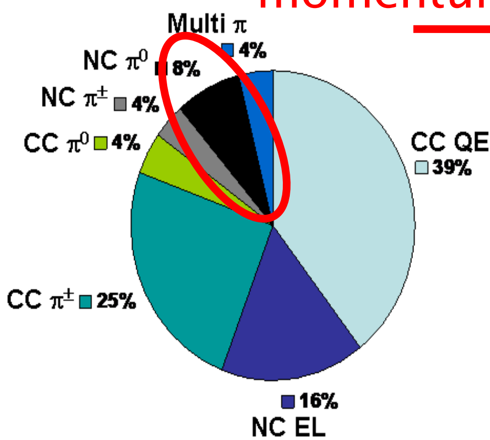
- Poor agreement in Q^2
- From Q^2 fits to MB ν_μ CCQE data extract:
  - M_A^{eff} -- effective axial mass
  - κ -- Pauli Blocking parameter
- Beautiful agreement after Q^2 fit, even in 2D
- Ability to make these 2D plots is unique due to MiniBooNE's high statistics

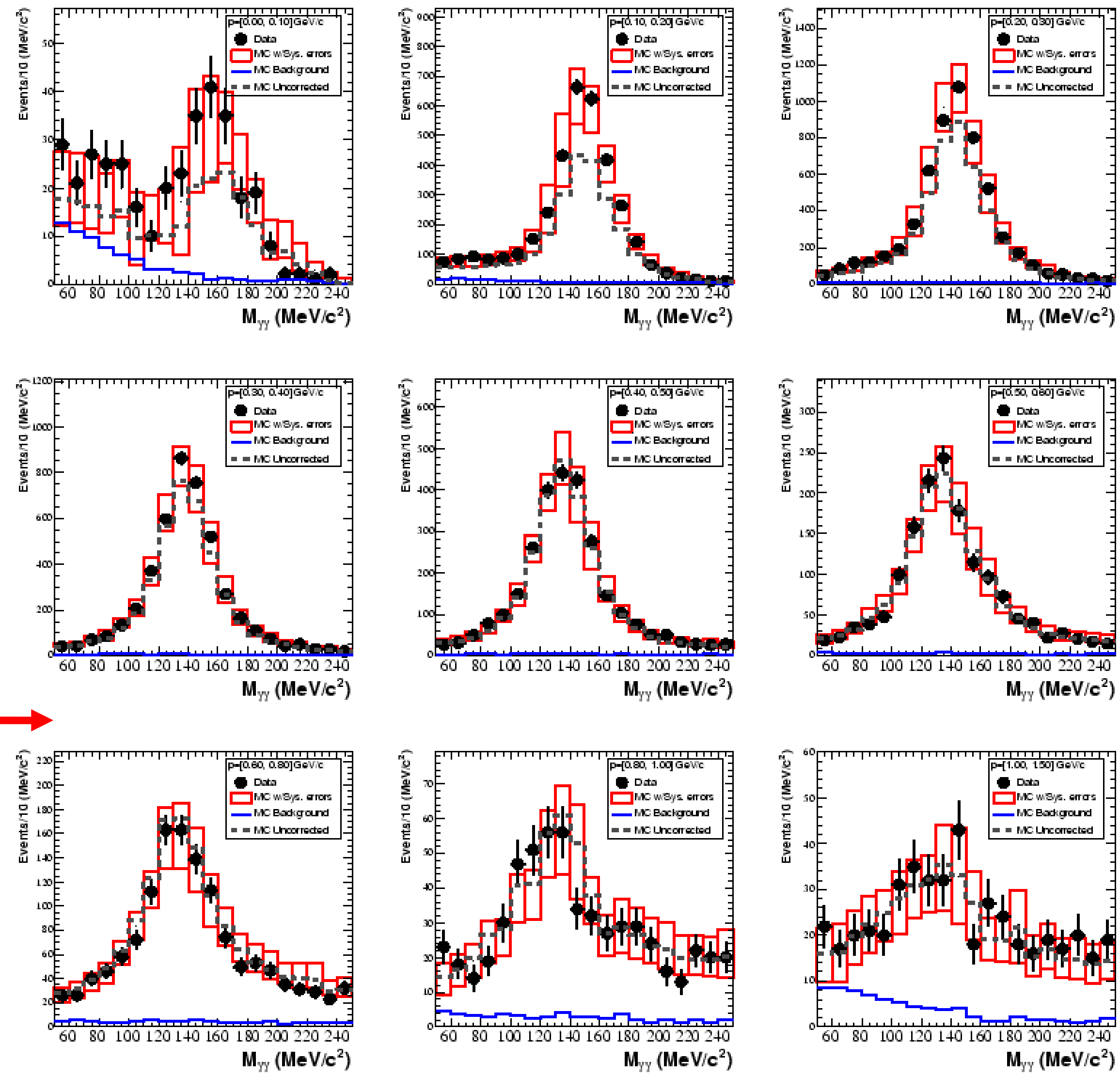
MB, PRL 100, 032310 (2008)

Tuning Nuance on internal NC π^0 data

- NC π^0 important background
- 97% pure π^0 sample (mainly $\Delta \rightarrow N\pi^0$)
- Measure rate as function of momentum
- Default MC underpredicts rate at low momentum
- $\Delta \rightarrow N\gamma$ also constrained

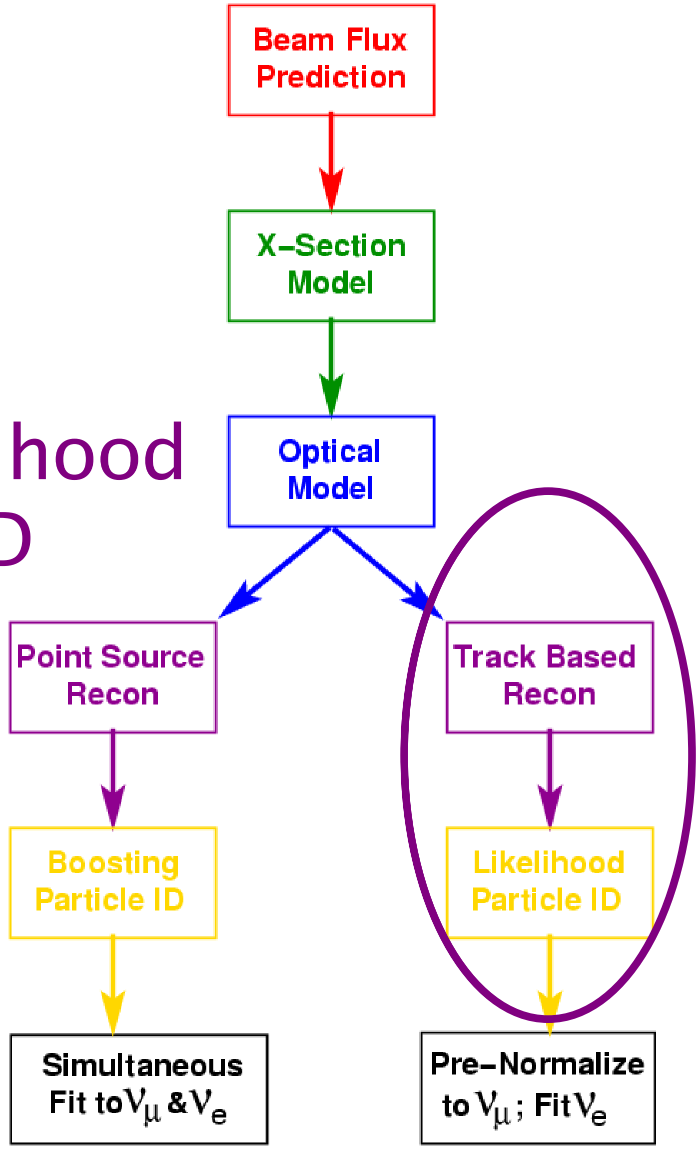
Invariant mass distributions in momentum bins





MB, Phys Lett B. 664, 41 (2008)

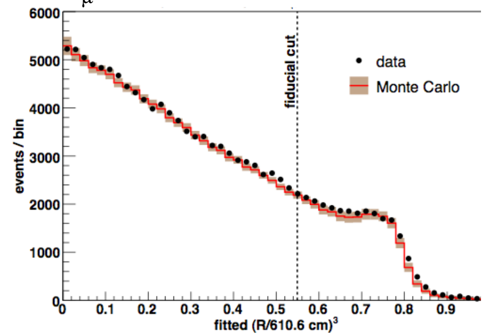
Analysis Chain: Track-Based Likelihood Reconstruction and Particle ID

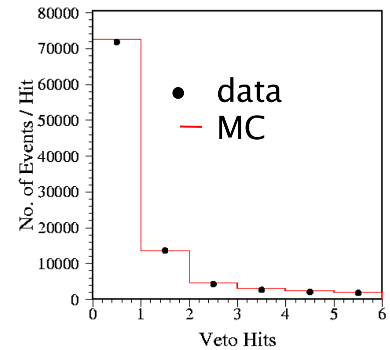


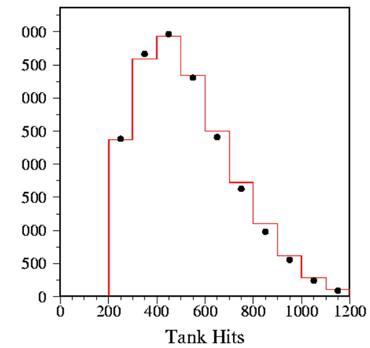
TBL Analysis: Separating e from μ

- Analysis pre-cuts
  - Only 1 subevent
  - Veto hits < 6
  - Tank hits > 200
  - Radius < 500 cm

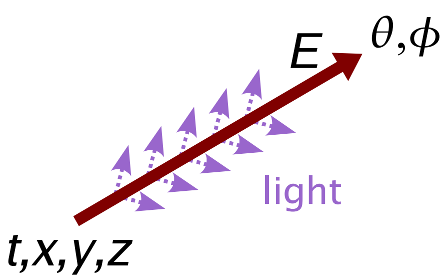
ν_μ CCQE events (2 subevent)

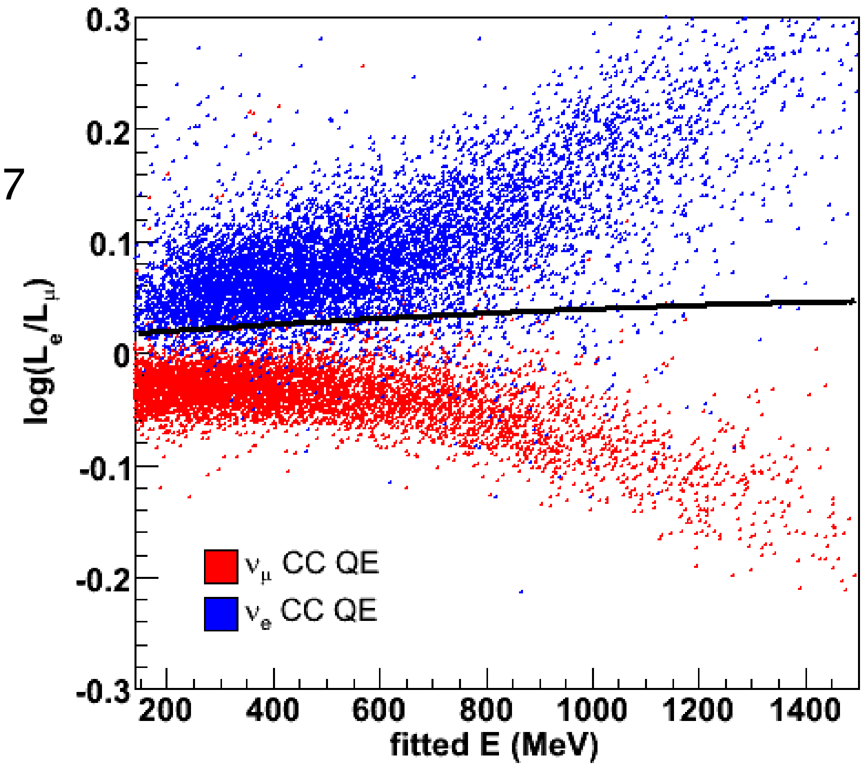






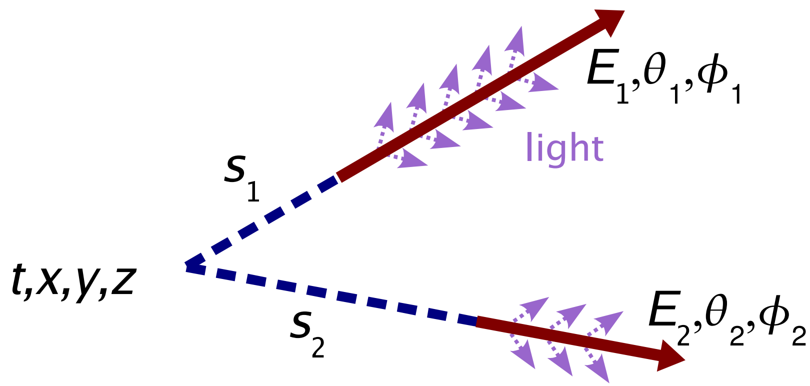
- Event is a collection of PMT-level info (q,t,x)
- Form sophisticated Q and T pdfs, and fit for 7 track parameters under 2 hypotheses
  - The track is due to an electron
  - The track is coming from a muon

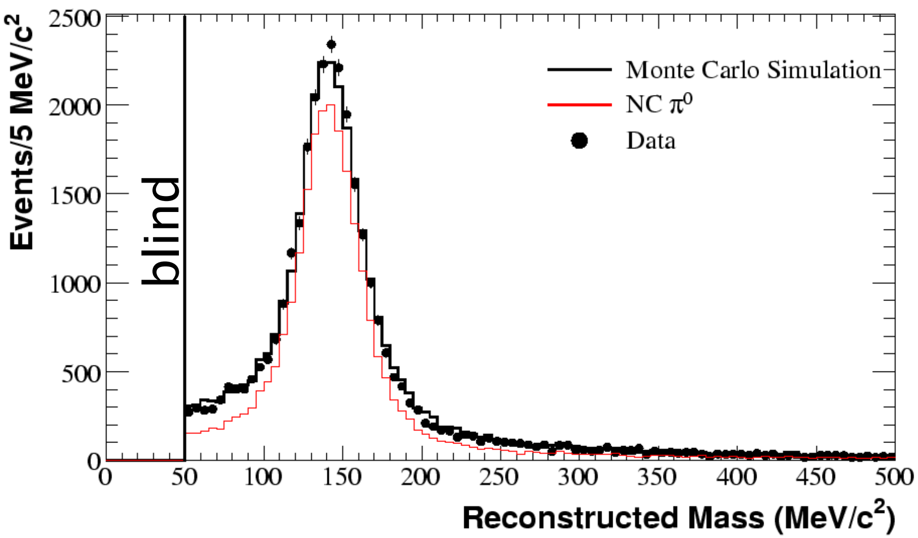


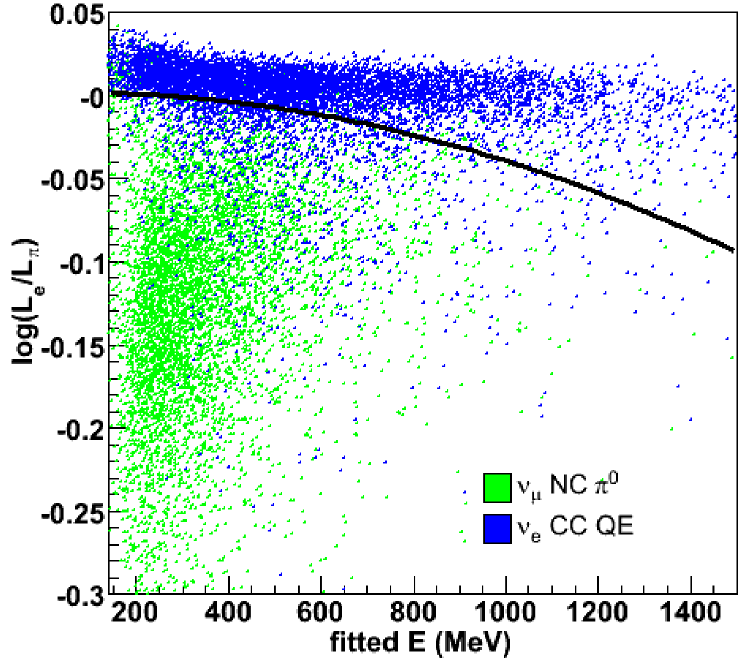


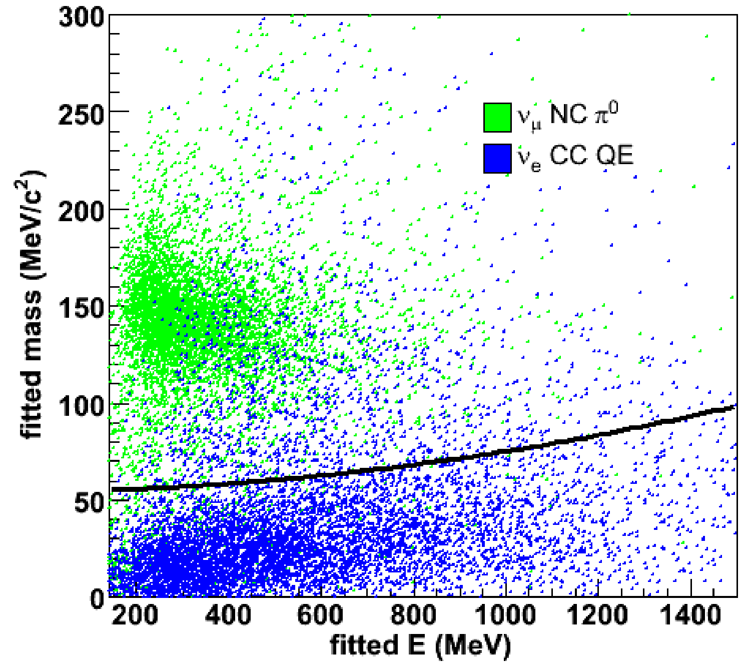
Separating e from π^0

- Extend fit to include two e-like tracks
- Very tenacious fit...8 minutes per event
- Nearly 500k CPU hours used

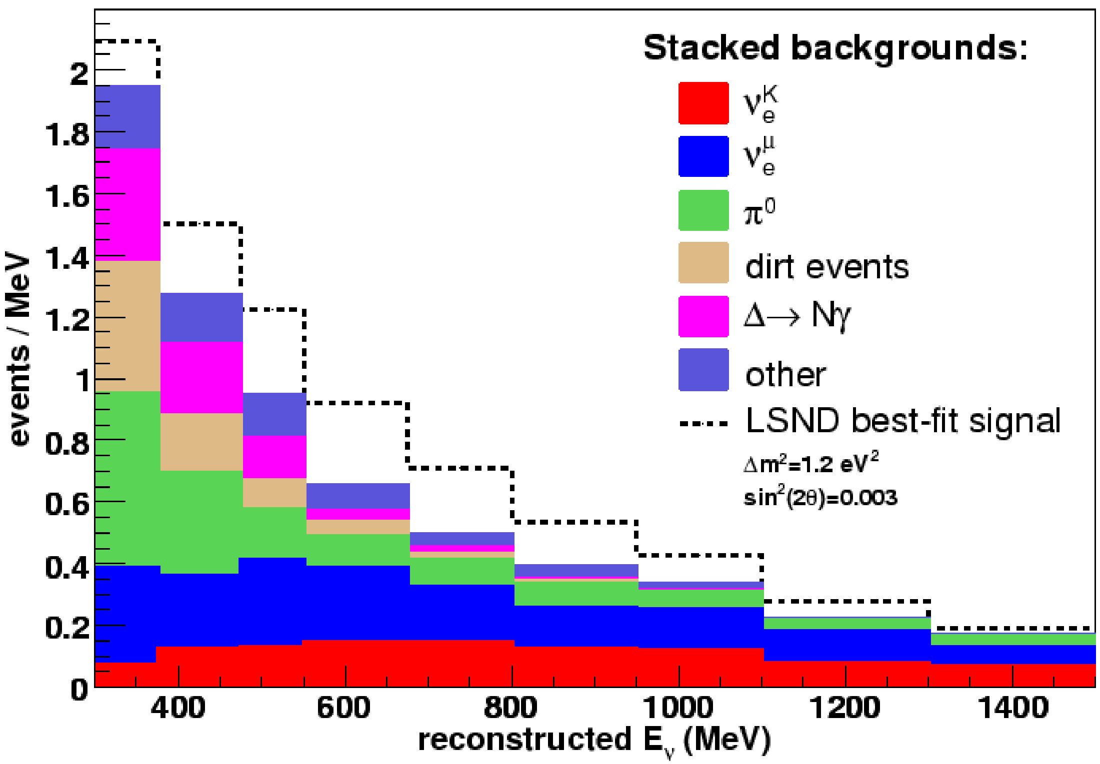








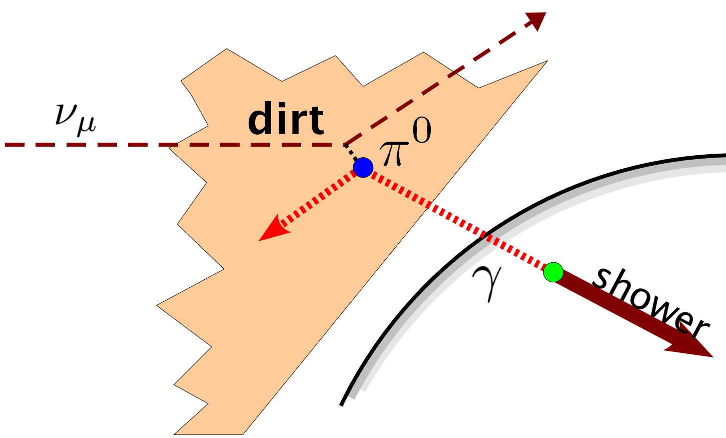
TBL Analysis: Expected event totals

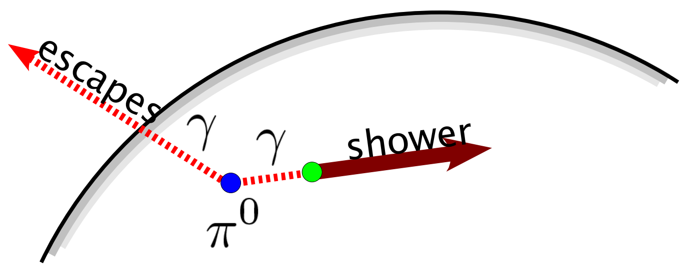


475 MeV – 1250 MeV

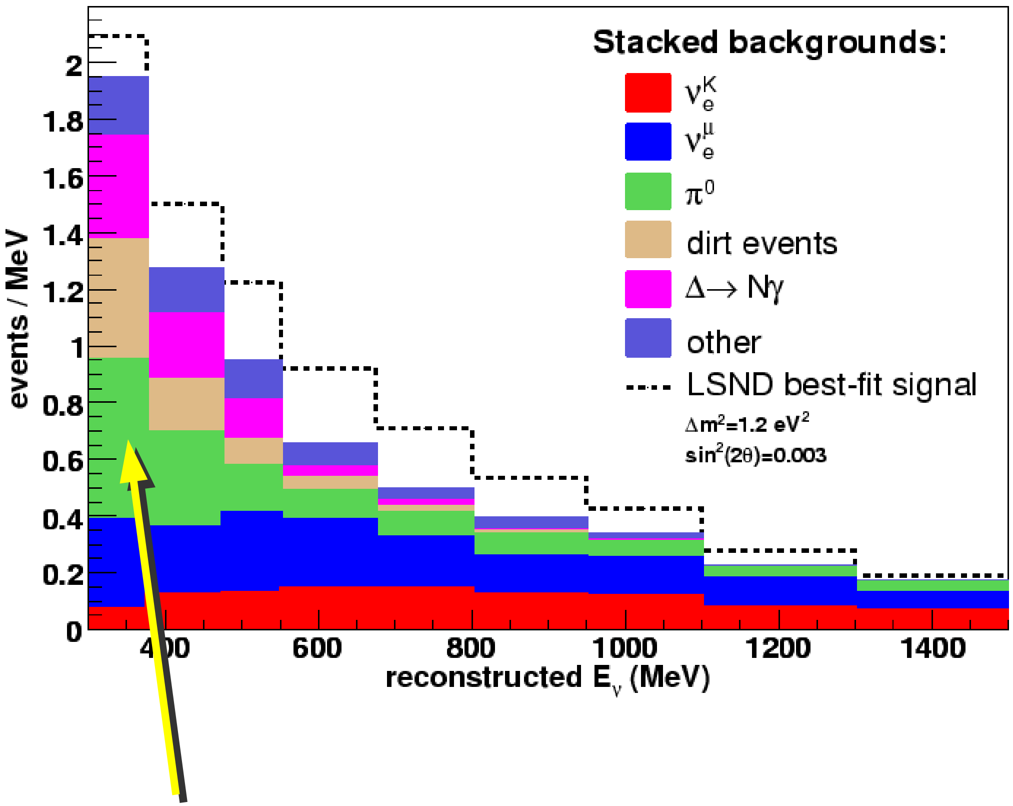
ν_e^K	94
ν_e^μ	132
π^0	62
dirt	17
$\Delta \to N\gamma$	20
other	33
total	358

LSND best-fit $\nu_\mu \to \nu_e$ 126





In situ background constraints: NC π^0



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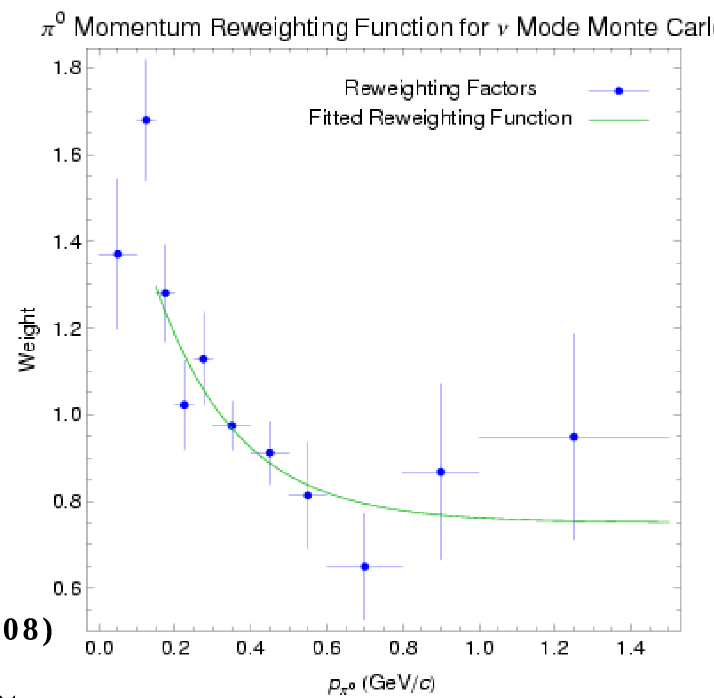
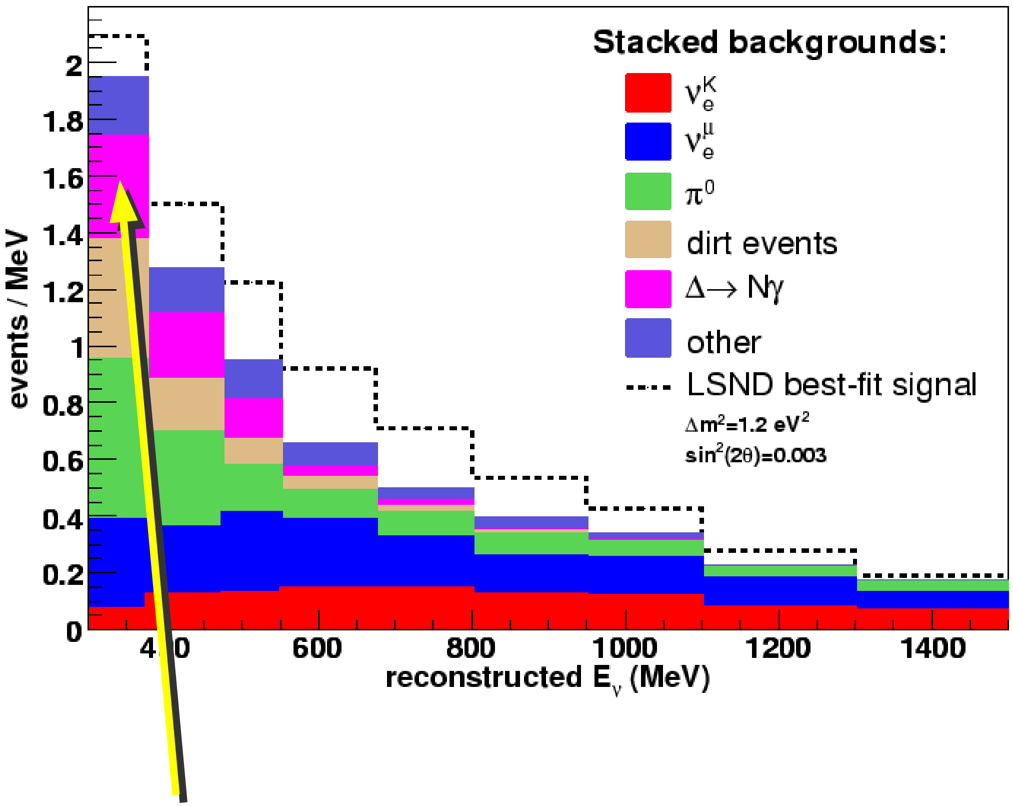


- Reconstruct majority of π^0 events
- Error due to extrapolation uncertainty into kinematic region where 1 γ is missed due to kinematics or escaping the tank
- Overall < 7% error on NC π^0 bkgs

MB, Phys Lett B. 664, 41 (2008)

In situ background constraints: Δ→Nγ



475 MeV – 1250 MeV	
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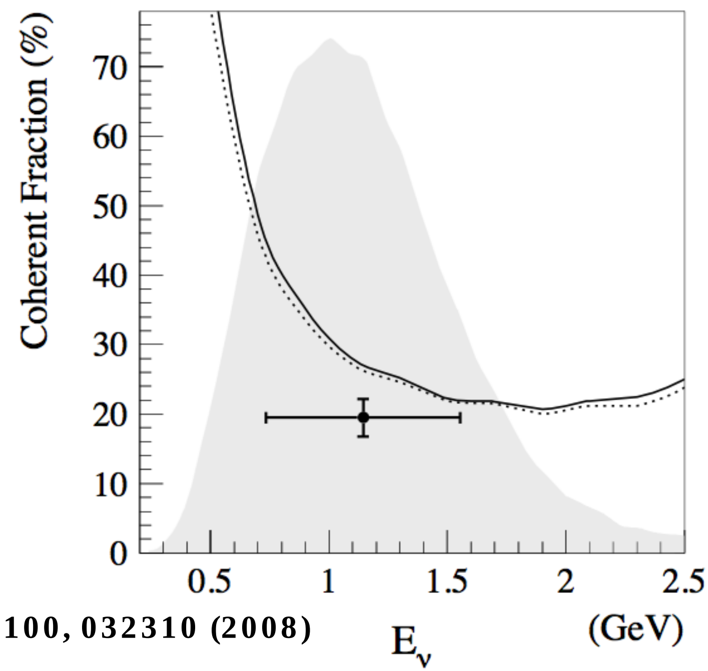
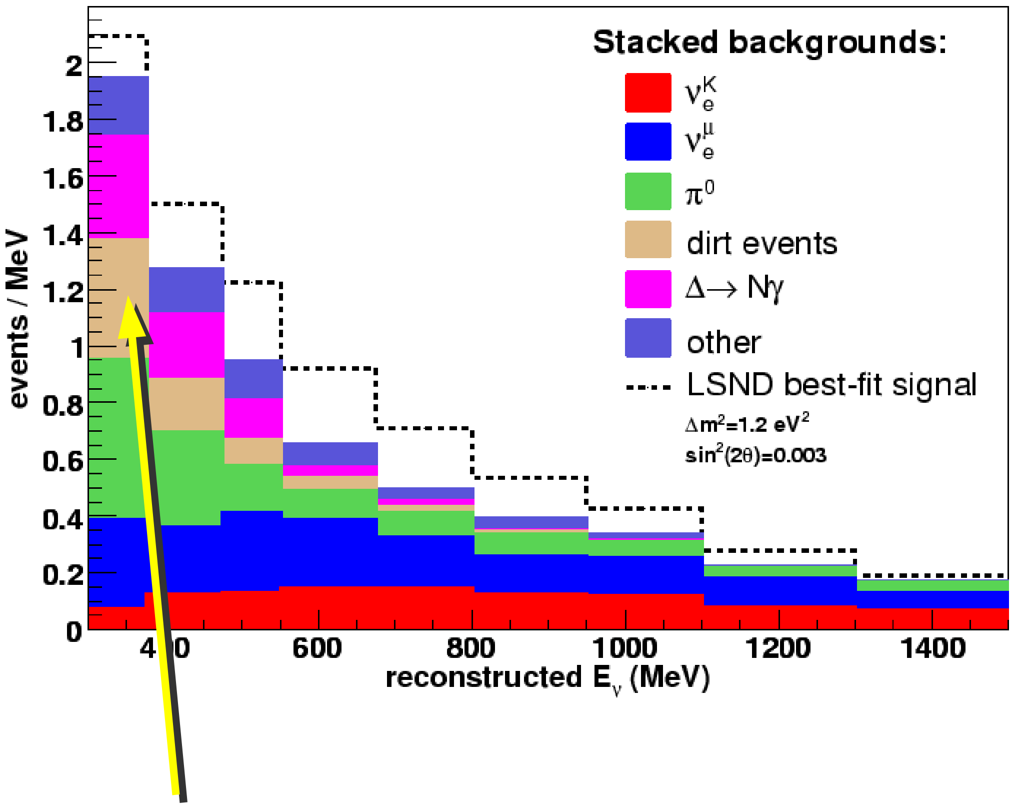
π^0	62
dirt	17
Δ→Nγ	20
other	33
total	358

- About 80% of our NC π^0 events come from resonant Δ production
- Constrain Δ→Nγ by measuring the resonant NC π^0 rate, apply known branching fraction to Nγ, including nuclear corrections



MB, PRL 100, 032310 (2008)

In situ background constraints: Dirt



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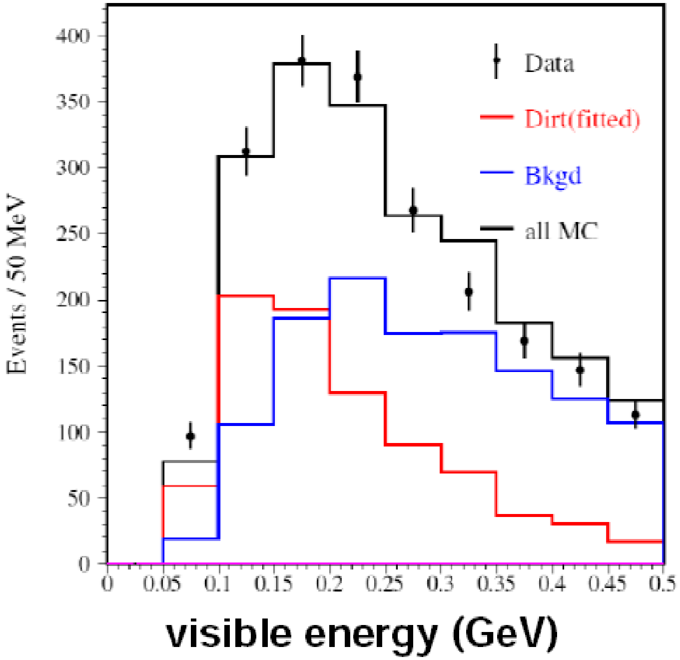
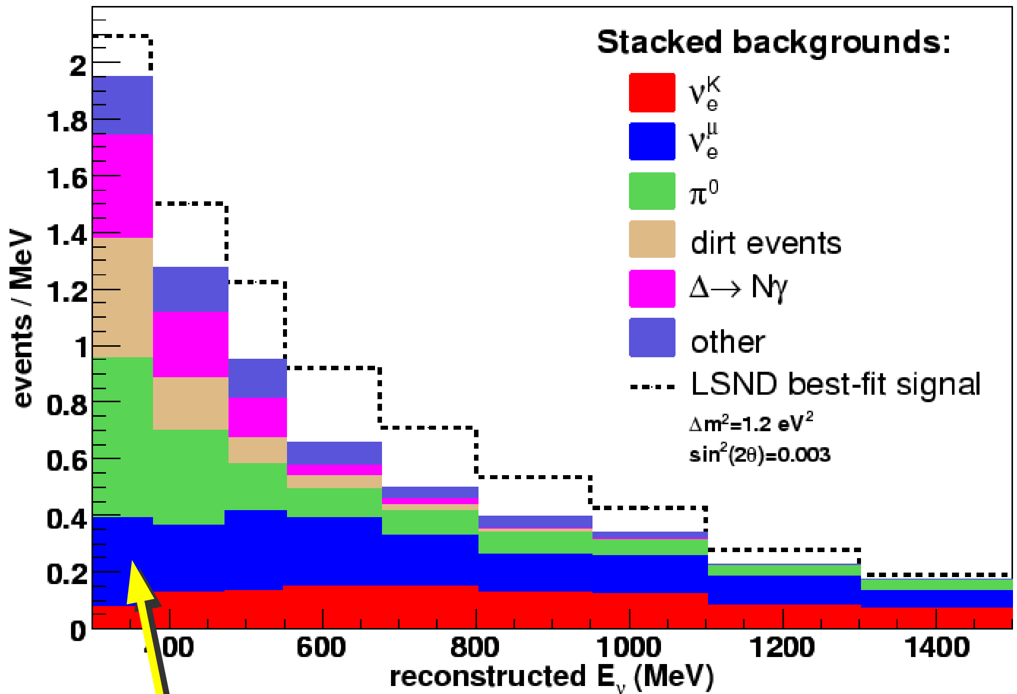


- Come from ν events int. in surrounding dirt
- Pileup at high radius and low E
- Fit dirt-enhanced sample to extract dirt event rate with 10% uncertainty

In situ background constraints: Muon ν_e



475 MeV – 1250 MeV

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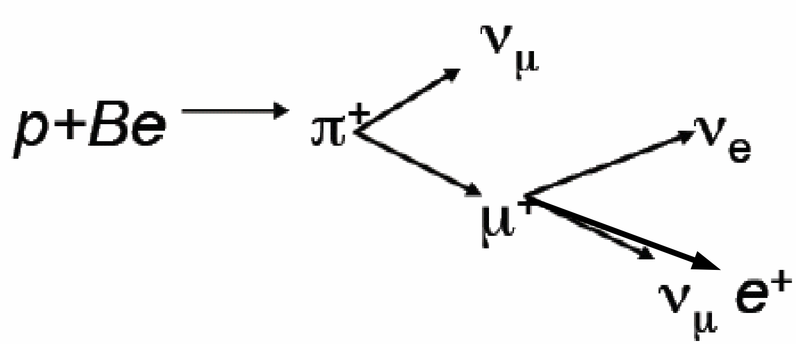
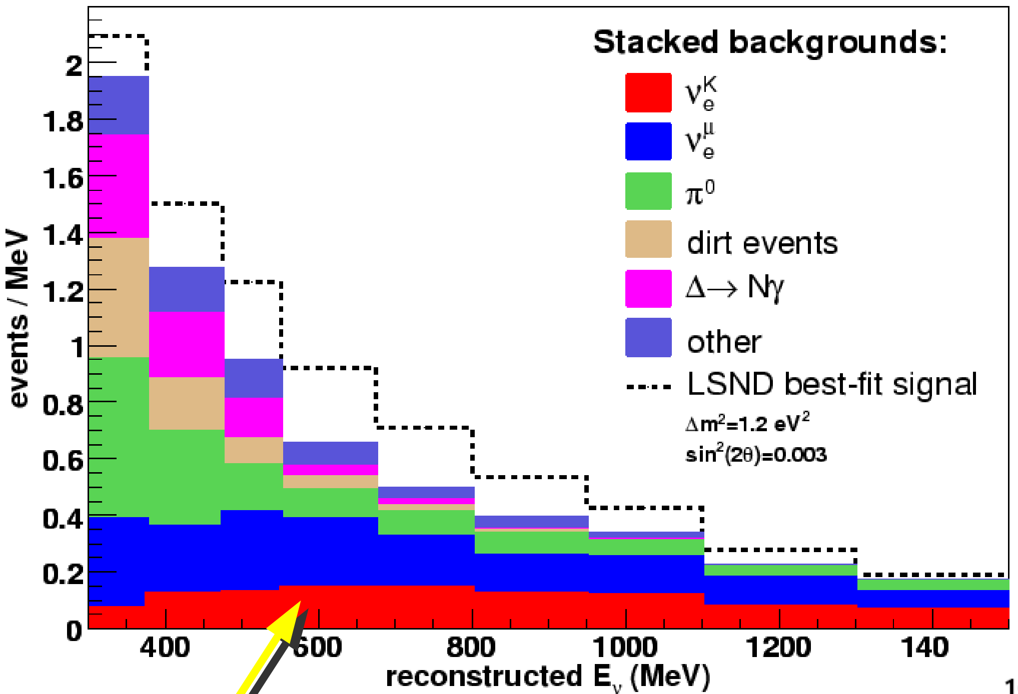
other	33
total	358

- Intrinsic ν_e from μ^+ originate from same π^+ as the ν_μ CCQE sample
- Measuring ν_μ CCQE channel constrains intrinsic ν_e from π^+



In situ background constraints: Kaon ν_e



475 MeV – 1250 MeV

ν_e^K	94
ν_e^μ	132
π^0	62
dirt	17
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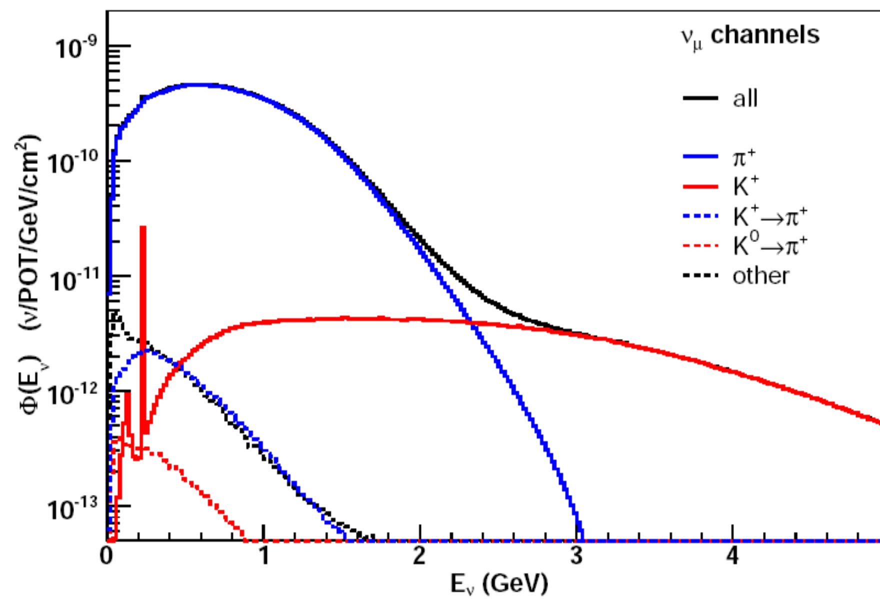
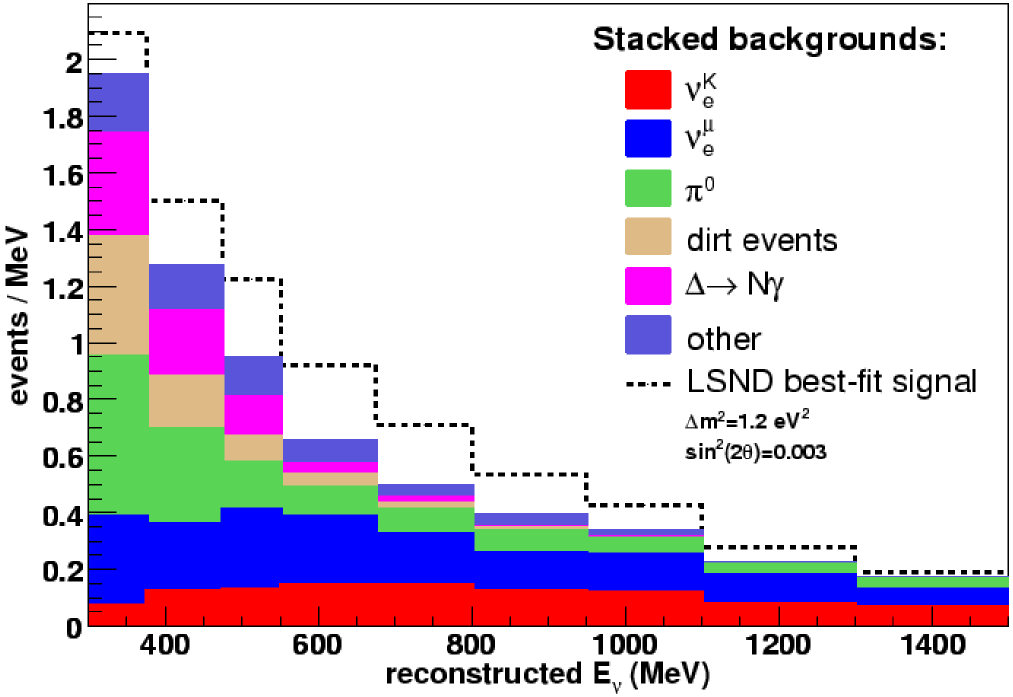
other	33
total	358

- At high energy, ν_μ flux is dominated by kaon production at the target
- Measuring ν_μ CCQE at high energy constrains kaon production, and thus intrinsic ν_e from K^+



In situ background constraints



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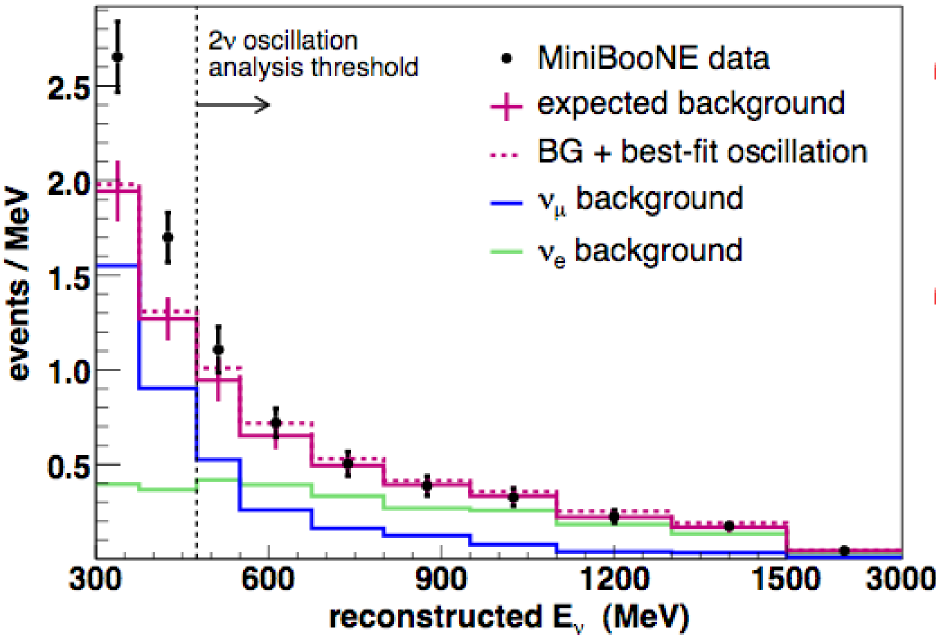
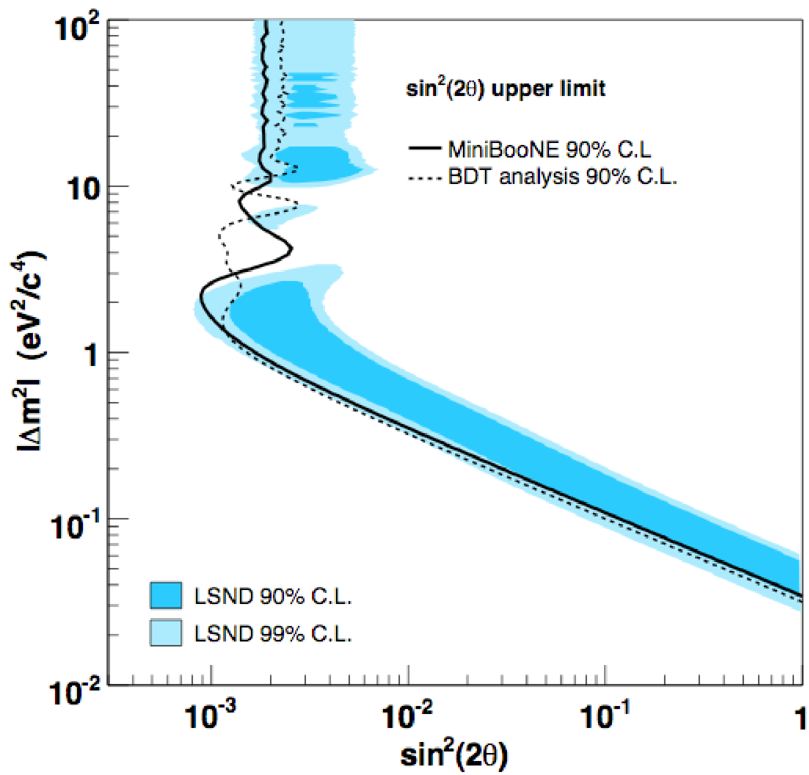
☆ In the end, every major source of background can be internally constrained by MB at various levels.

2007 Data/fit result after unblinding...



- No sign of an excess in the analysis region (where the LSND signal should have highest significance for the 2ν mixing hypothesis)
- Visible excess at low E



- What does it all mean? There are a few possibilities...
  - Some problem with LSND, e.g. mis-estimated background?
  - Difference between neutrinos and antineutrinos?
  - The physics causing the excess in LSND doesn't scale with L/E?
    - Low E excess in MB related?

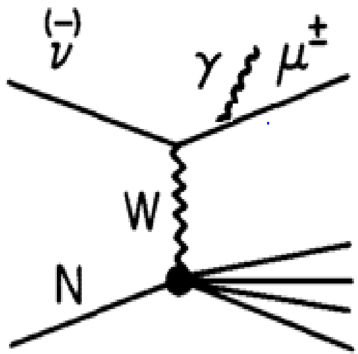
Part 2: Exploring the Low E Excess

The low E excess has fueled much speculation...

Commonplace

- Muon bremsstrahlung

(Bodek, 0709.4004)

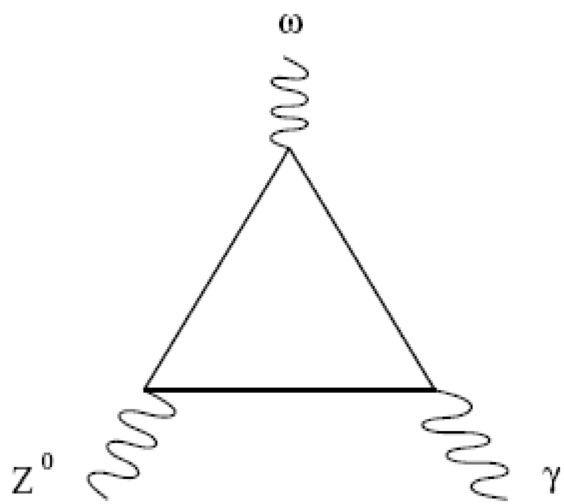


- Easy to study in MB with much larger stats from events with a Michel tag
- Proved negligible with MB data in 0710.3897

SM, but odd

- Anomaly-mediated γ

(Harvey, Hill, Hill, 0708.1281)

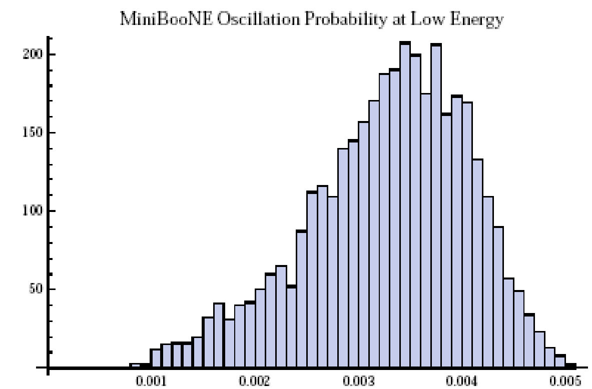


- Still under study, nuc. effects neglected, δg_ω
- Has to contribute...how much?

Beyond the SM

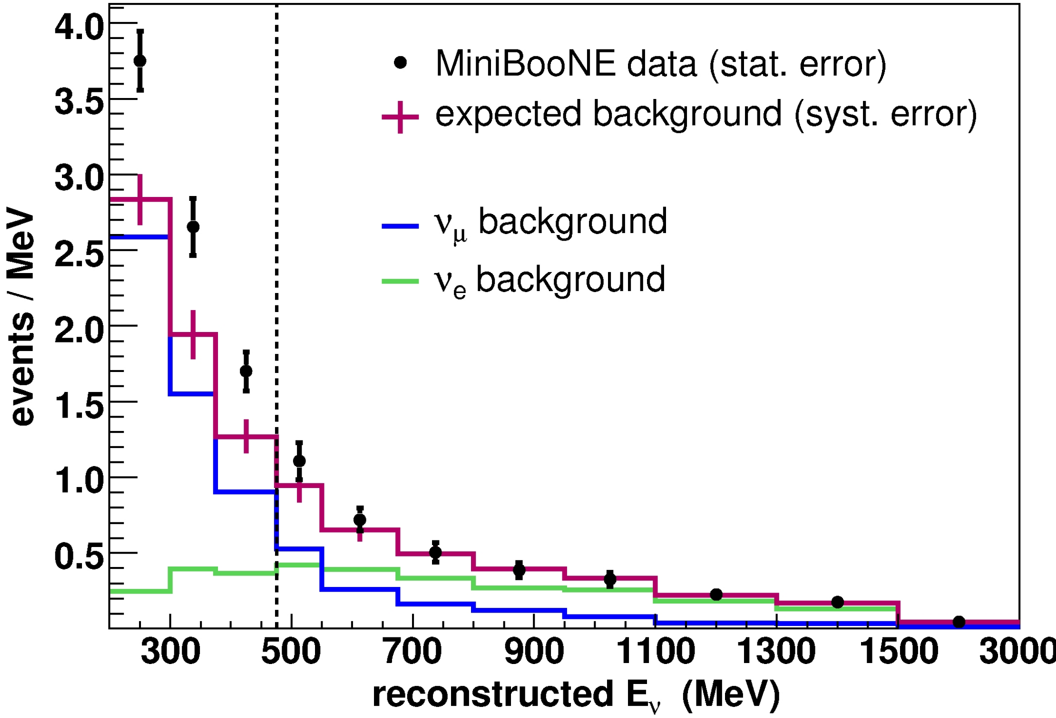
- New gauge boson

(Nelson, Walsh,0711.1363)



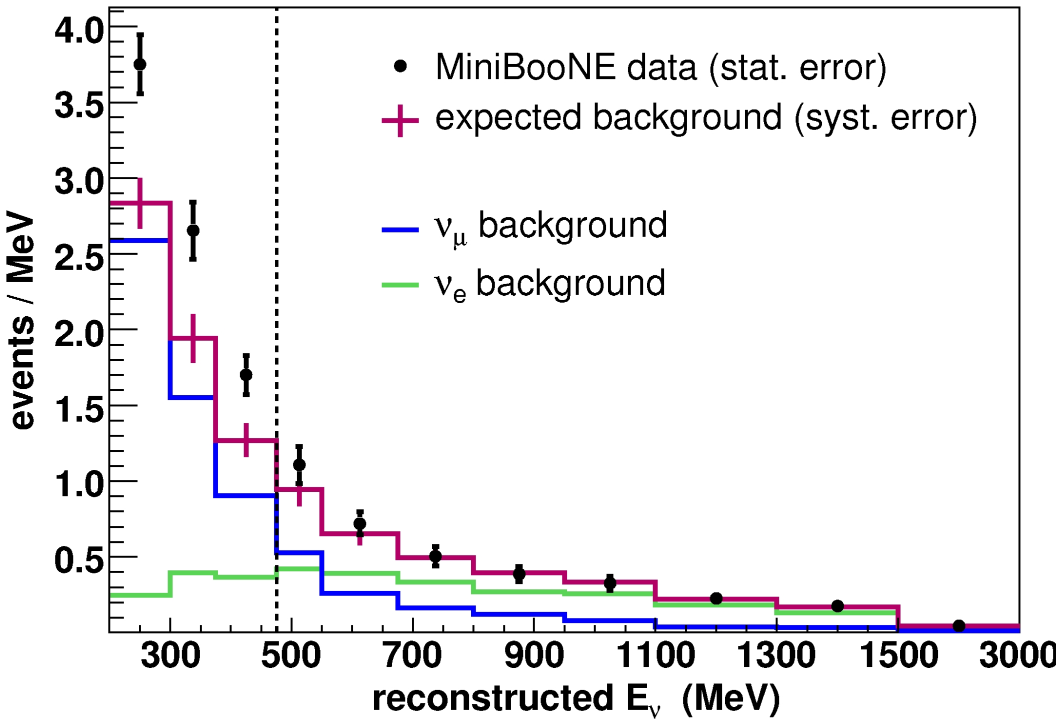
- Can accommodate LSND and MiniBooNE
- Firm prediction for anti-neutrinos

Extending the analysis to lower energies



- Original excess quoted in initial oscillation PRL 98, 231801 (2007)
  - 475–1250 MeV, 22 ± 40, 0.6σ
  - 300–475 MeV, 96 ± 26, 3.7σ
- In summer 2007 extended analysis down to 200 MeV
  - 200–300 MeV, 92 ± 37, 2.5σ
- Combined significance with proper systematic correlations
  - 200–475 MeV, 188 ± 54, 3.5σ

Extending the analysis to lower energies



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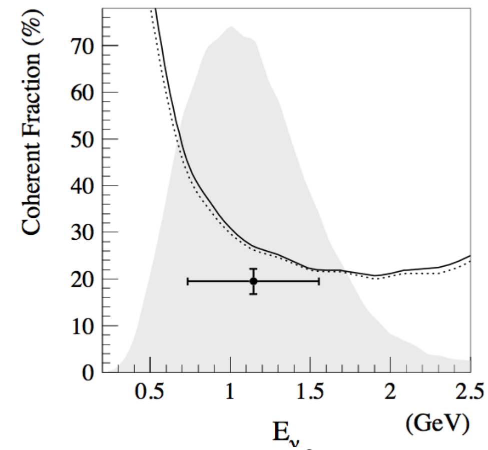
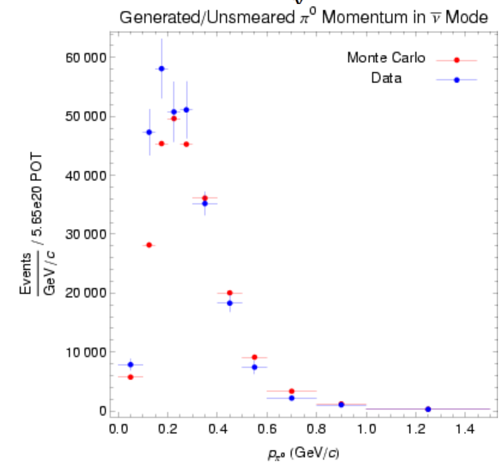
  - 200–475 MeV, 188 ± 54, 3.5σ

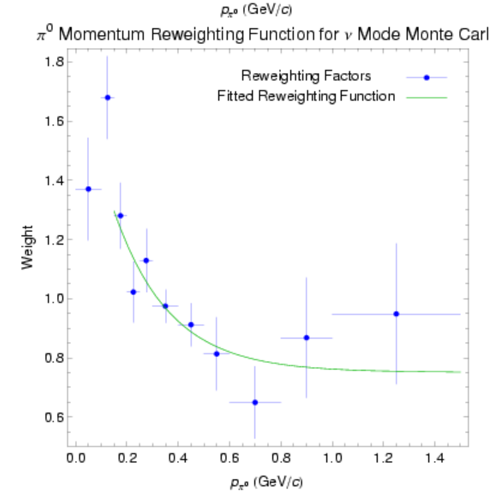
- Since this result a comprehensive (> 1 year) review of bkgs/errors with an emphasis at low E was performed...detailed updates to follow

Updates with minimal impact

- With the ν_e appearance result published and the unexpected excess at low E, we decided to go back and perform a comprehensive re-analysis of all aspects of the analysis
  - General review of all aspects
  - Add improvements that had been put on hold
  - Emphasis on the low E region
- Improvements that had no measurable impact:
  - Better pion flux determination using spline fit to HARP data instead of Sanford-Wang parameterization
  - Flux errors calculated subject to HARP error matrix
  - Implemented MB *in situ* measure of resonant/coherent pion production
  - Completely independent re-analysis of π^0 backgrounds
  - Complete combinatorial treatment of $\Delta \to N\gamma$ branching ratio allowing for pion re-interactions in struck nucleus
  - Added 15% more newly-acquired ν data



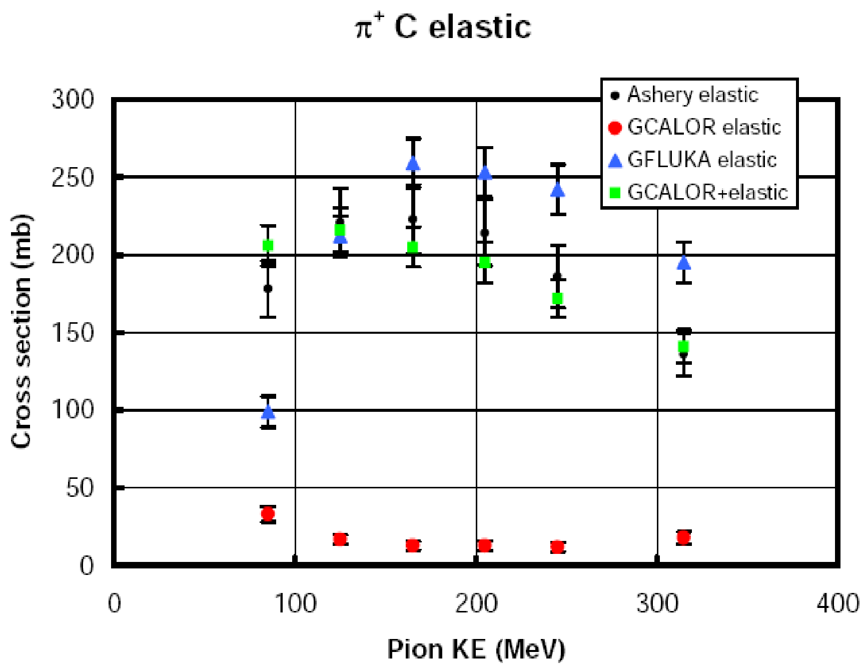




Hadronic bkgs/errors in ν interactions

ADDITIONAL HADRONIC PROCESSES:

- Charged π – C elastic scattering
  - Found $\pi^{\pm}$ elastic scattering to be nearly absent in GCALOR
  - Possibility that NC $\pi^{\pm}$ have more scattering ⇒ making Cerenkov ring look more e-like
- Radiative π^{-} capture
  - π^{-} capture is in GCALOR, but missing radiative branching fraction (<2%, ~100MeV gamma)
- $\pi^{\pm}$ induced Δ->Nγ in mineral oil
  - Abs/cex allowed in GCALOR, but radiative γ branch missing
  - Not as dangerous as in struck nucleus, since π propagates for some time and can give multiple rings

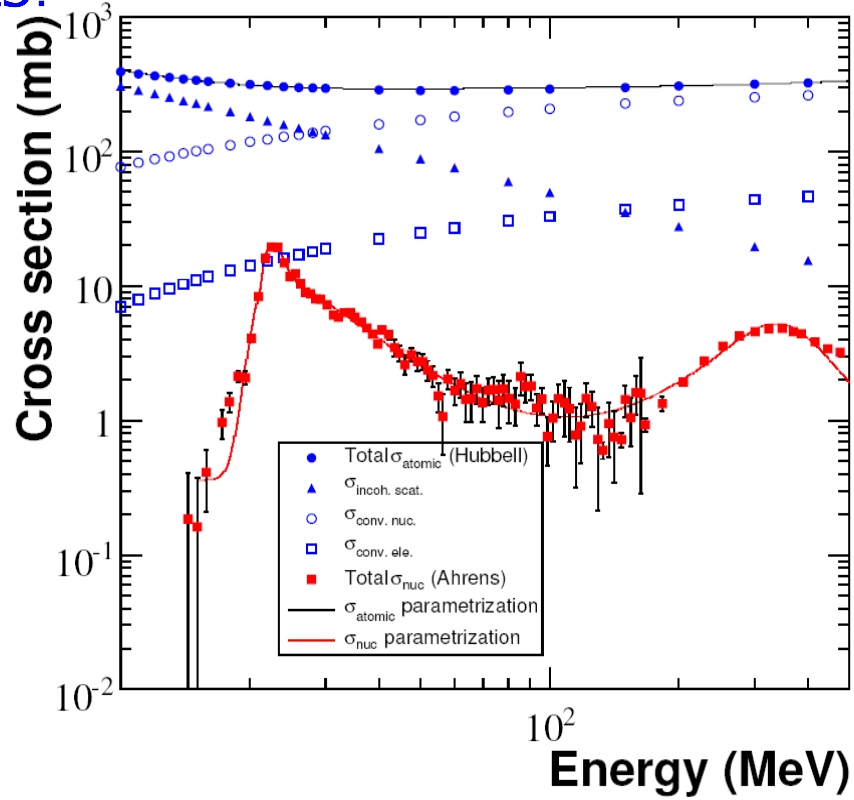


☆ None of these processes contributed a significant number of bkg events

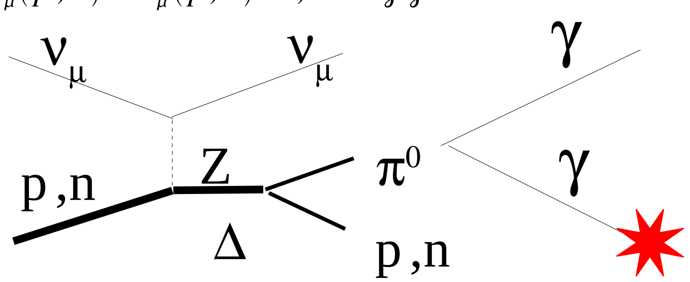
Hadronic bkgs/errors in ν interactions

ADDITIONAL HADRONIC PROCESSES:

- Photonuclear interactions
  - Absent in GEANT3
  - Can delete a γ in a NC pi0 interactions, thus creating a single e-like ring
  - 40,000 NC pi0 interactions
  - Well-known cross-section, in fact in GEANT4 which allowed for cross-check
  - Uncertainties enter via final states
- Only missing hadronic process found to contribute significantly



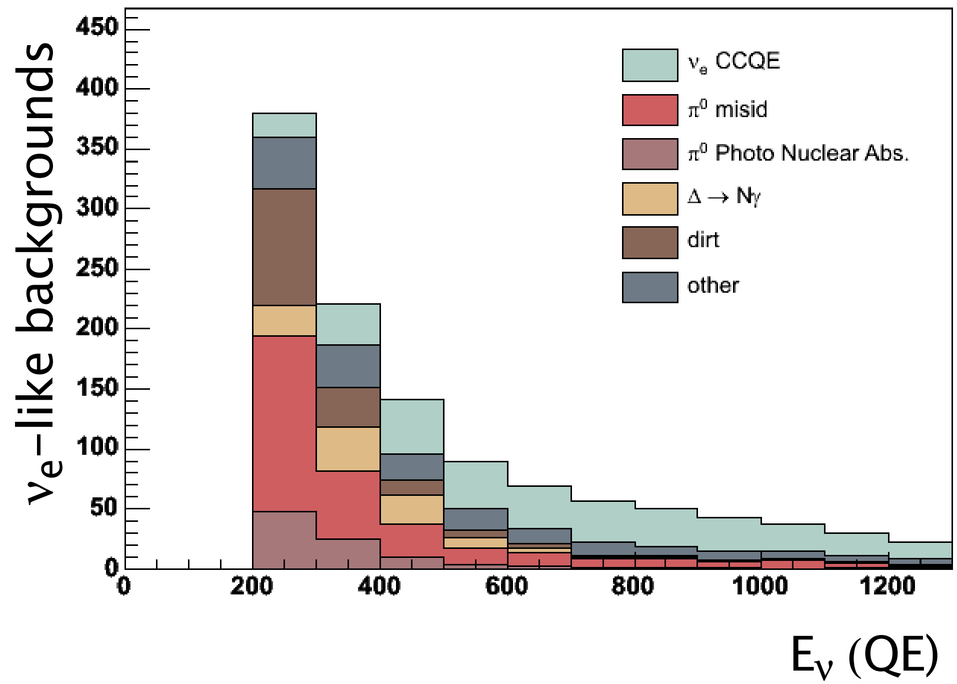
$$\nu_\mu(p,n) \rightarrow \nu_\mu(p,n)\pi^0, \pi^0 \rightarrow \gamma\gamma$$



Hadronic bkgs/errors in ν interactions

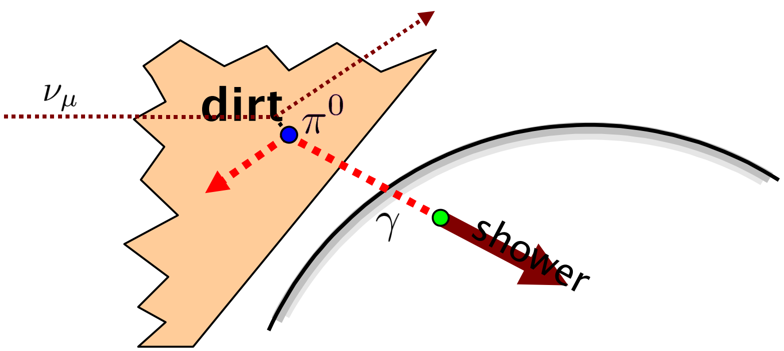
ADDITIONAL HADRONIC PROCESSES:

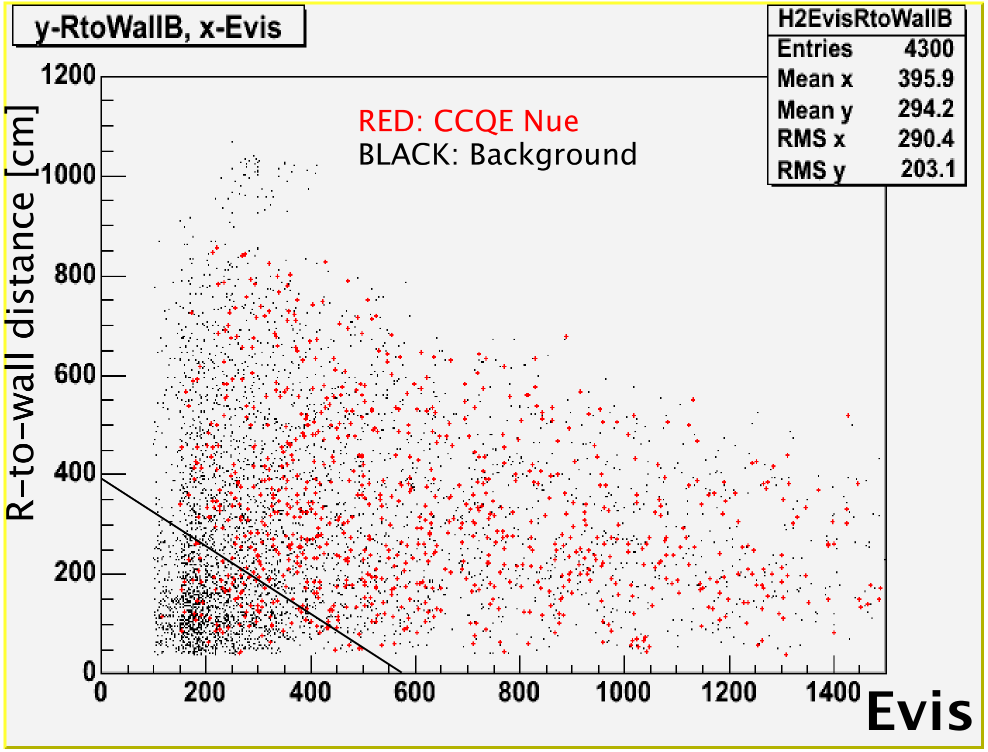
- Photonuke bottom line:
  - Additional p0 mis-id due to all modified hadronic processes (dominated by PN)
    - 200-300 MeV, ~40 events
    - 300-475 MeV, ~20 events
    - 475-1250 MeV, ~1 event
  - Additional systematic error negligible relative to other errors



Additional cut to remove dirt events

- Dirt backgrounds tend to come from γ that sneak through the veto and convert in tank $\Rightarrow$ pile up at high radius
- Don't carry full ν energy $\Rightarrow$ pile up at low visible energy
- Define R-to-wall cut, distance back to wall along reconstructed track direction
- Apply 2d cut as shown

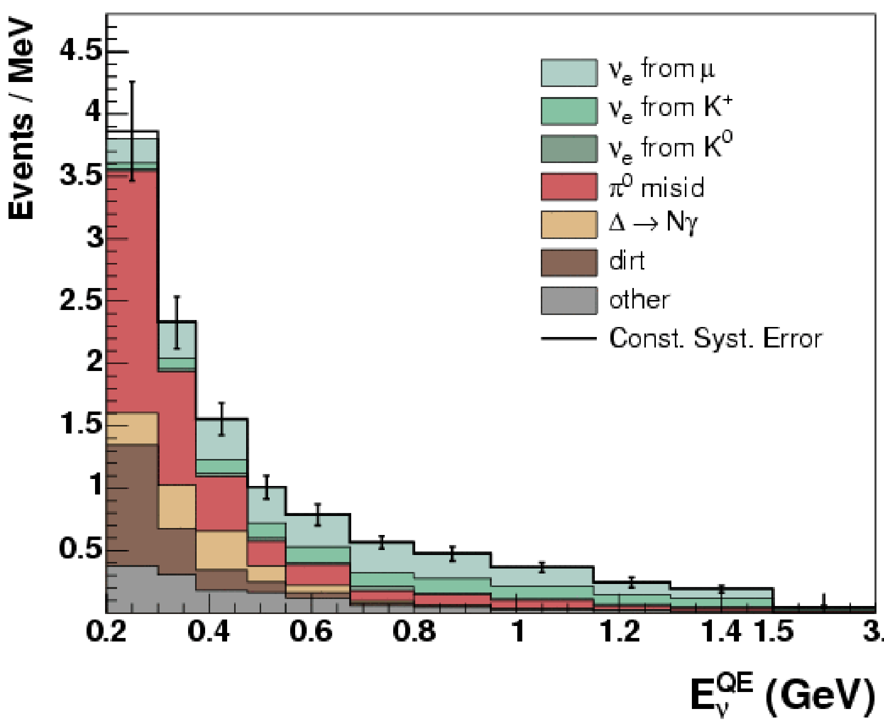




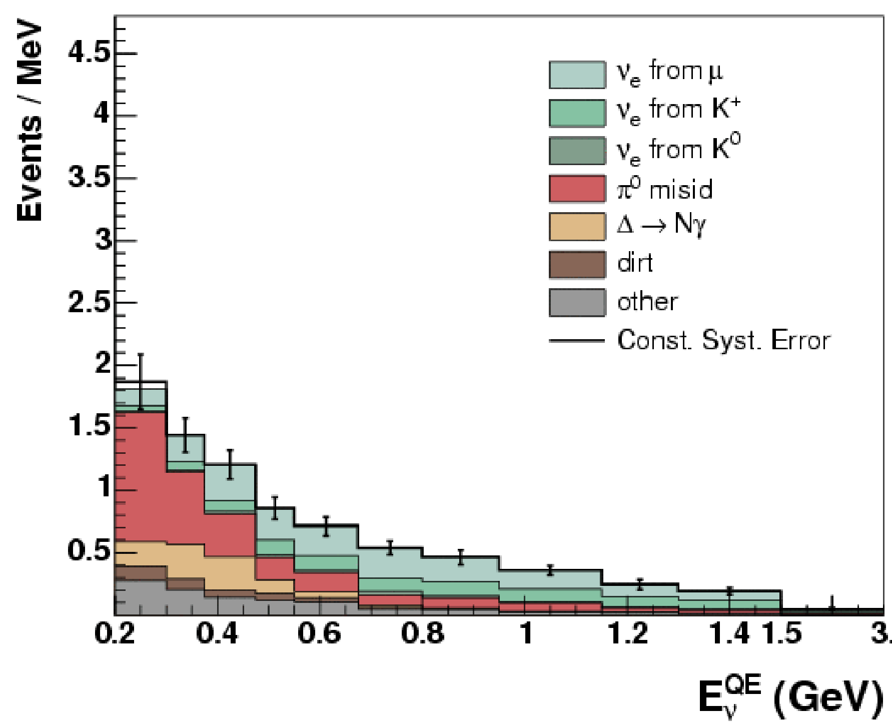
Additional cut to remove dirt events

- Dirt cut bottom line: Removes ~85% of the dirt backgrounds at low energy

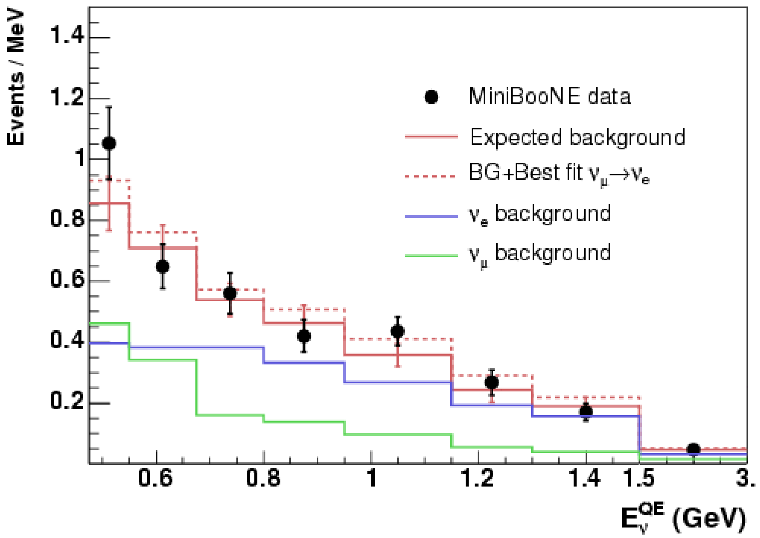
No DIRT cuts

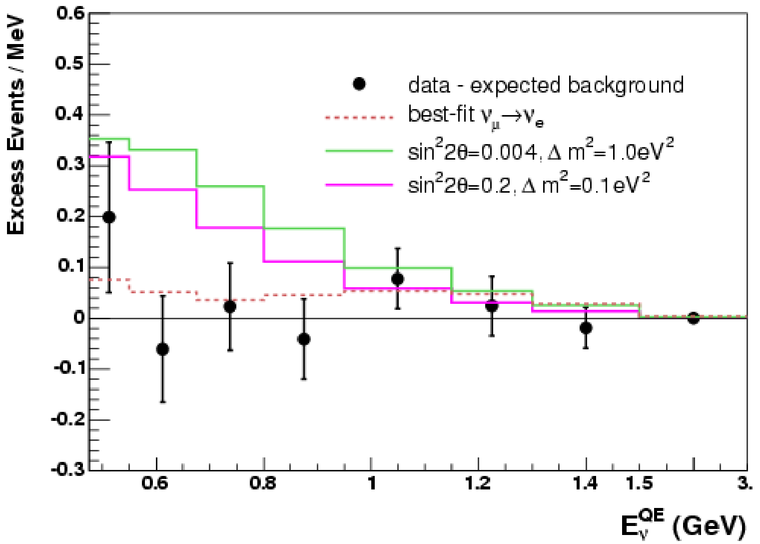


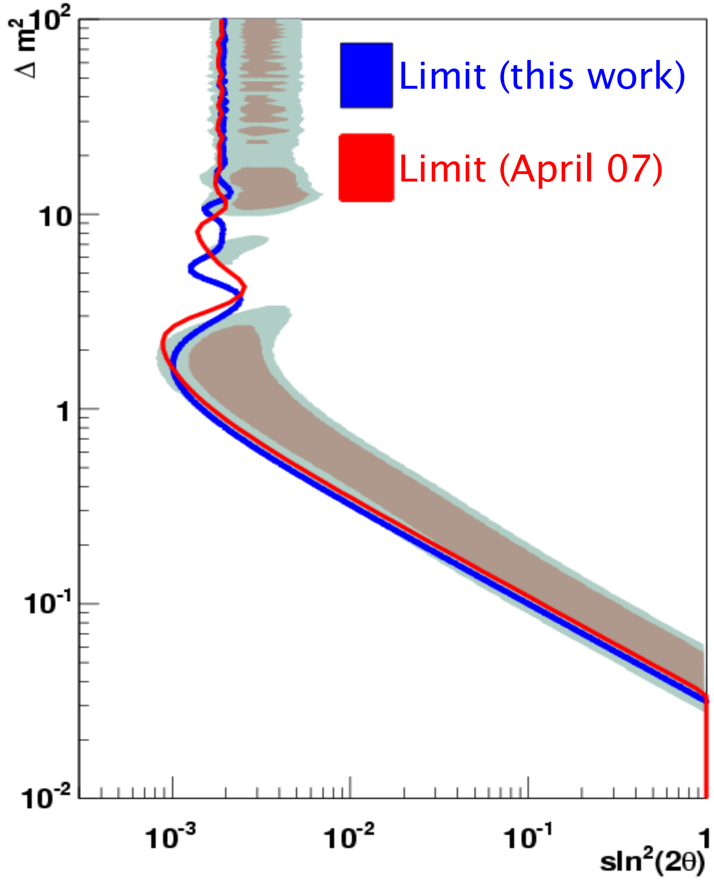
With DIRT Cuts



Full update: Impact on oscillation analysis







☆ Little impact on primary oscillation analysis!

Full update: Compare update stages

Event Sample	Original (April 07)	Updated Analysis	Add New Data	Add Dirt Cut
200 – 300 MeV				
Data	375	368	427	232
Background	283 ± 37	332.4 ± 38.9	386.0 ± 44.3	186.8 ± 26.0
Excess	92 ± 37	35.6 ± 38.9	41.0 ± 44.3	45.2 ± 26.0
Significance	2.5σ	0.9σ	0.9σ	1.7σ
300 – 475 MeV				
Data	369	364	428	312
Background	273 ± 26	282.9 ± 28.3	330.0 ± 31.8	228.3 ± 24.5
Excess	96 ± 26	81.1 ± 28.3	98.0 ± 31.8	83.7 ± 24.5
Significance	3.7σ	2.9σ	3.1σ	3.4σ
200 – 475 MeV				
Data	744	732	855	544
Background	556 ± 54	615.3 ± 58.0	716.1 ± 66.2	415.2 ± 43.4
Excess	188 ± 54	116.7 ± 58.0	138.9 ± 66.2	128.8 ± 43.4
Significance	3.5σ	2.0σ	2.1σ	3.0σ
475 – 1250 MeV				
Data	380	369	431	408
Background	358 ± 40	356.0 ± 33.3	412.7 ± 37.6	385.9 ± 35.7
Excess	22 ± 40	13.0 ± 33.3	18.3 ± 37.6	22.1 ± 35.7
Significance	0.6σ	0.4σ	0.5σ	0.6σ

FINAL

- Divided into 4 major rows based on energy range
- Columns separate analysis updates
  - Original
  - All update except new data and dirt cut
  - Add new data
  - Add new dirt cut

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Part 3: New antineutrino results

Anti-neutrino analysis...rates down

- Simple matter of switching horn polarity
- Analysis for anti-neutrinos nearly identical to neutrino mode
- Biggest problem: Overall reduction in rate

ν channel	events
all channels	895k
CC quasielastic	375k
NC elastic	165k
CC π^+	200k
CC π^0	33k
NC π^0	53k
NC $\pi^{+/-}$	30k
CC/NC DIS, multi-π	39k

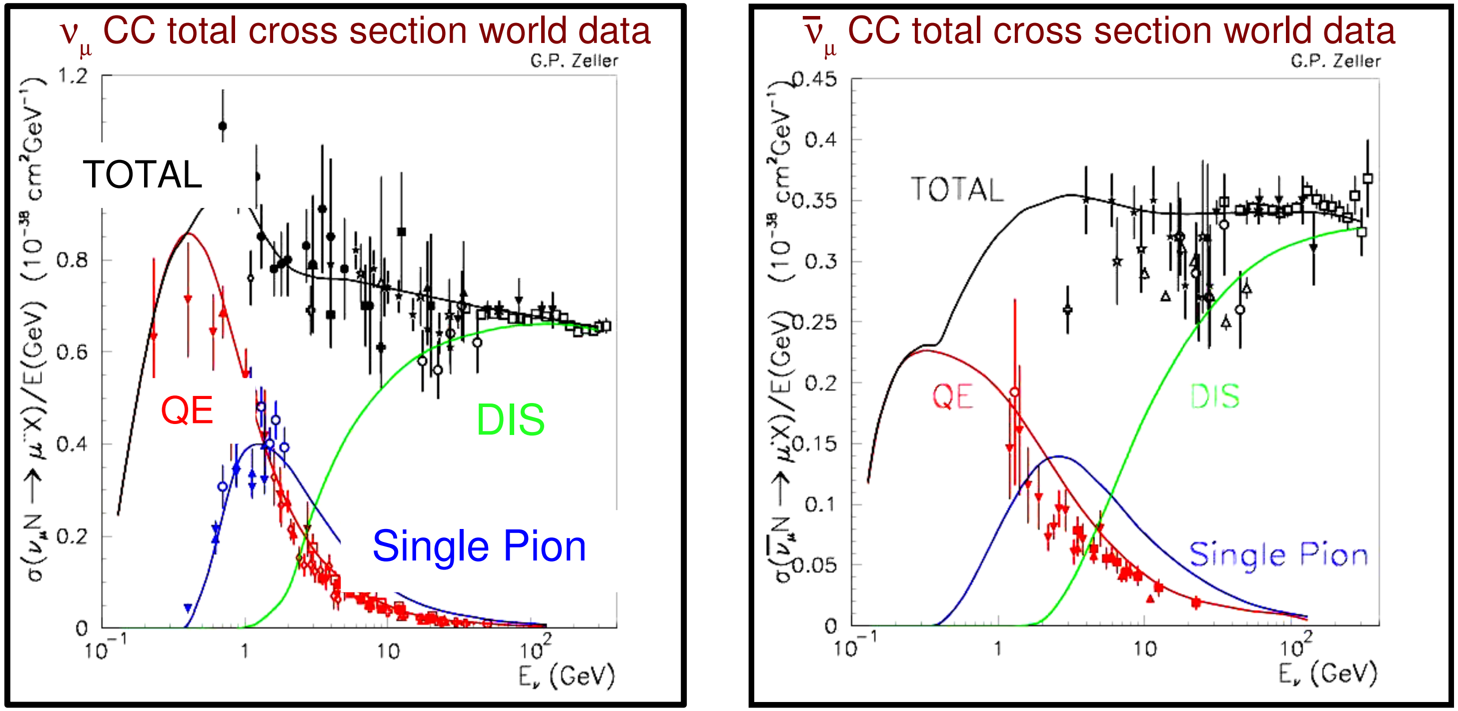
6.6×10^{20} POT
ν mode

$\bar{\nu}$ channel	events
all channels	83k
CC quasielastic	37k
NC elastic	16k
CC π^-	14k
CC π^0	2.6k
NC π^0	7.6k
NC $\pi^{+/-}$	2.8k
CC/NC DIS, multi-π	2.9k

3.4×10^{20} POT
$\bar{\nu}$ mode

- With about half of the POT delivered in nubar mode, the overall number of CCQE events is down by close to an order of magnitude...still useful
  - Check part of LSND phase space with an antineutrino beam
  - Useful comparison of low E anomalous region
  - Cross-section measurements (very relevant for T2K)

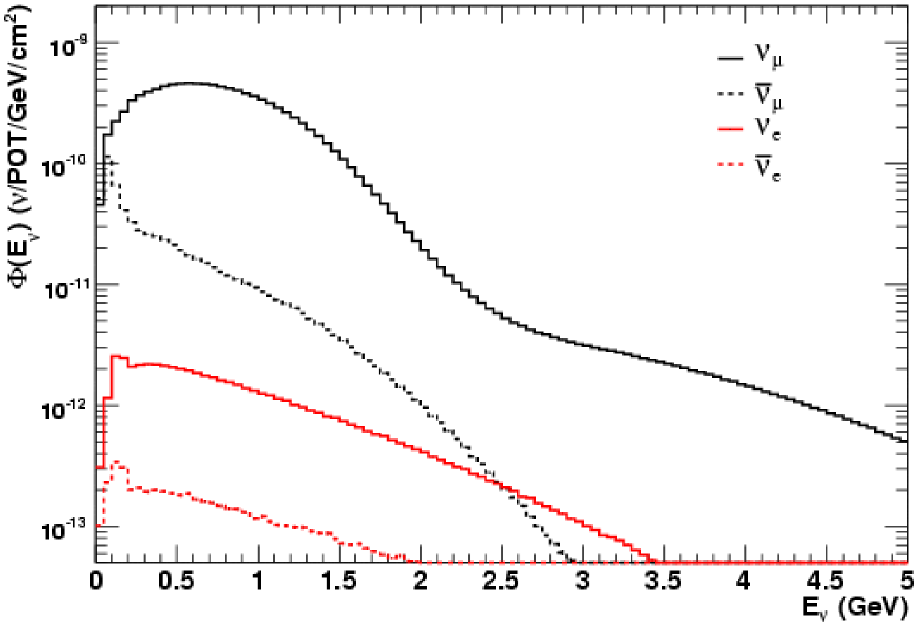
Rate down partially due to cross-section



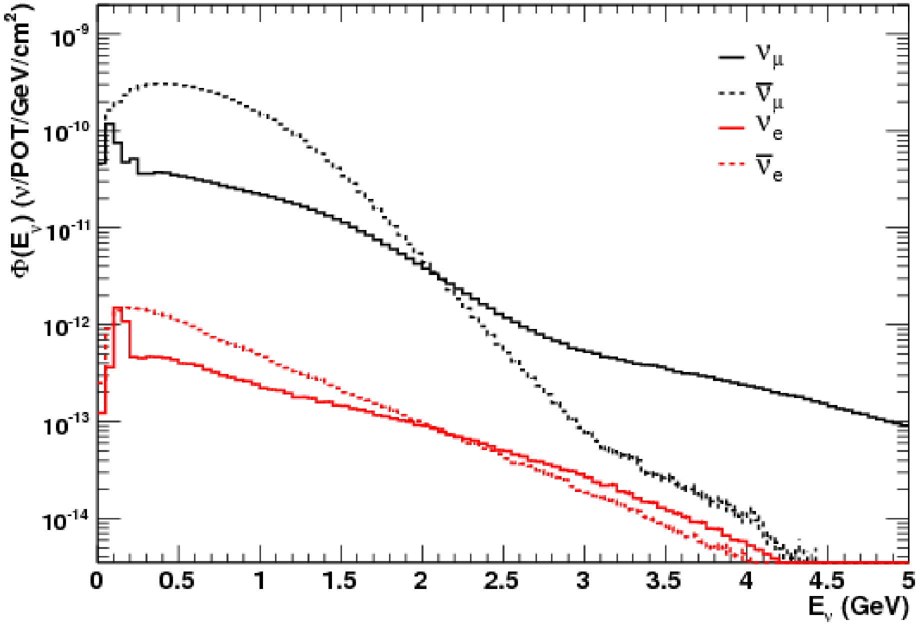
- Recall signal channel is charged-current quasi-elastic ν_e interactions

Rate also down due to π^-/π^+ flux

ν mode flux (focus π^+)



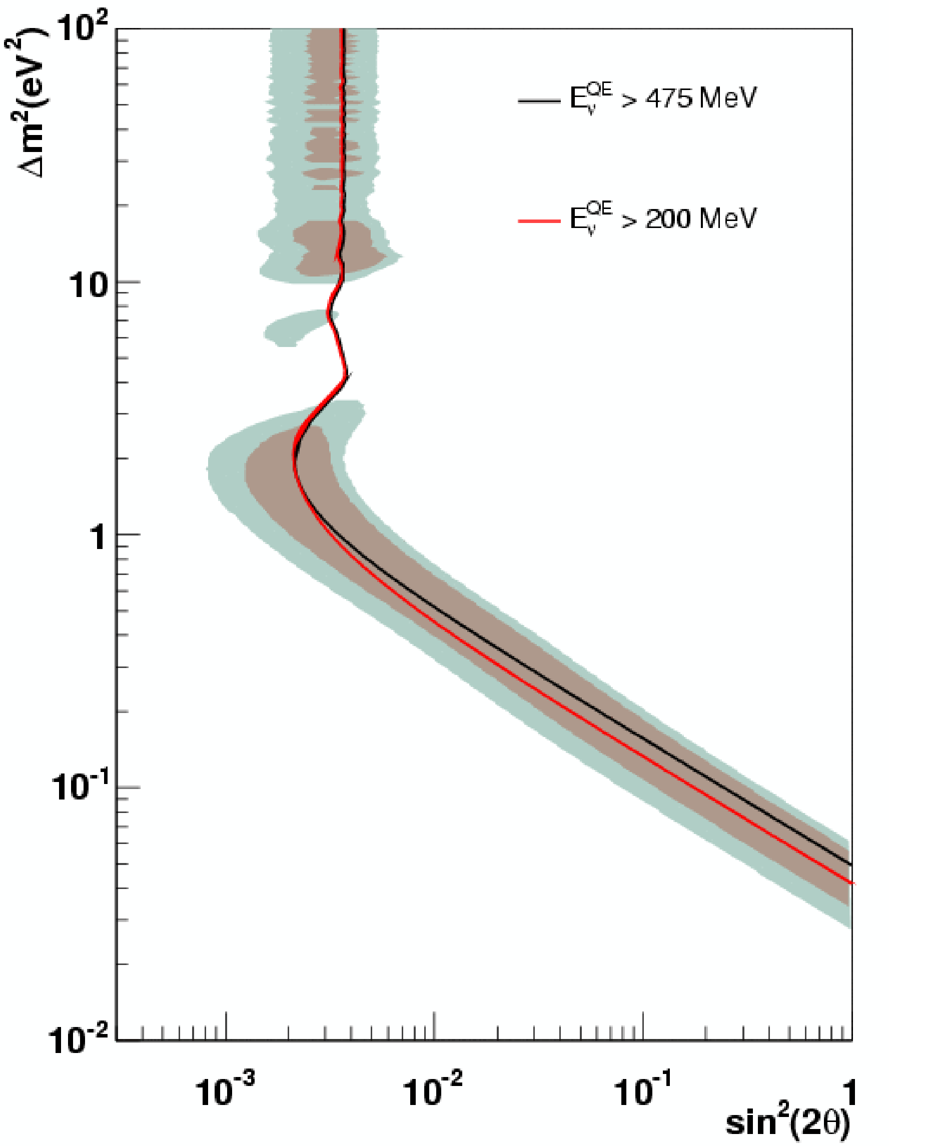
$\bar{\nu}$ mode flux (focus π^-)



- Overall flux is also down
- Second complication: Wrong-sign component is much larger
  - 6% anti-ν_μ in ν beam…18% ν_μ in anti-ν_μ beam
  - WS component further amplified to 30% in nubar mode due to xsec

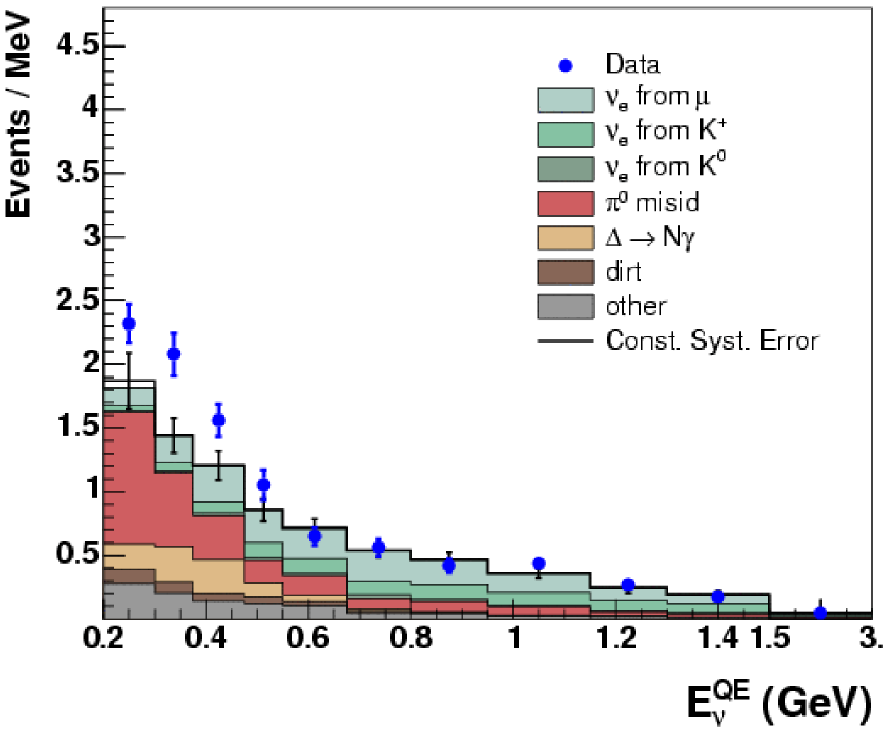
Projected sensitivity (90% CL) to anti-ν oscillation

- Important point, only anti-ν are assumed to oscillate in this analysis
- Already know WS component ν_μ do not oscillate from ν mode result (at least above 475 MeV)
- Due to low E excess in neutrino mode, analysis is performed with and without 475 MeV cut in E_ν(QE)
- Cover > half of LSND 90% CL

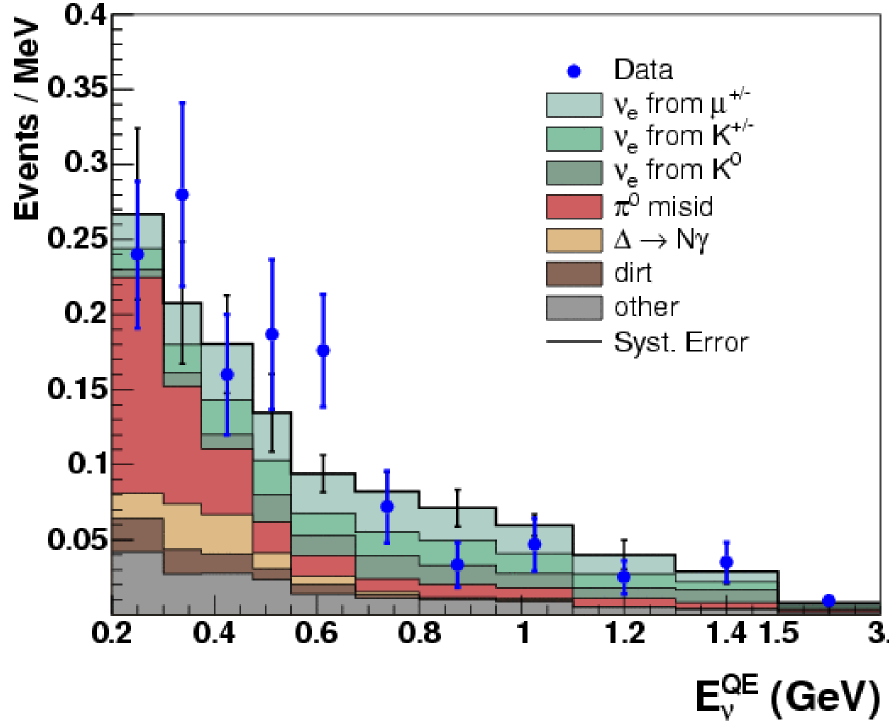


Recently unblinded anti-ν data...NEW RESULTS

ν mode 6.6e20 POT



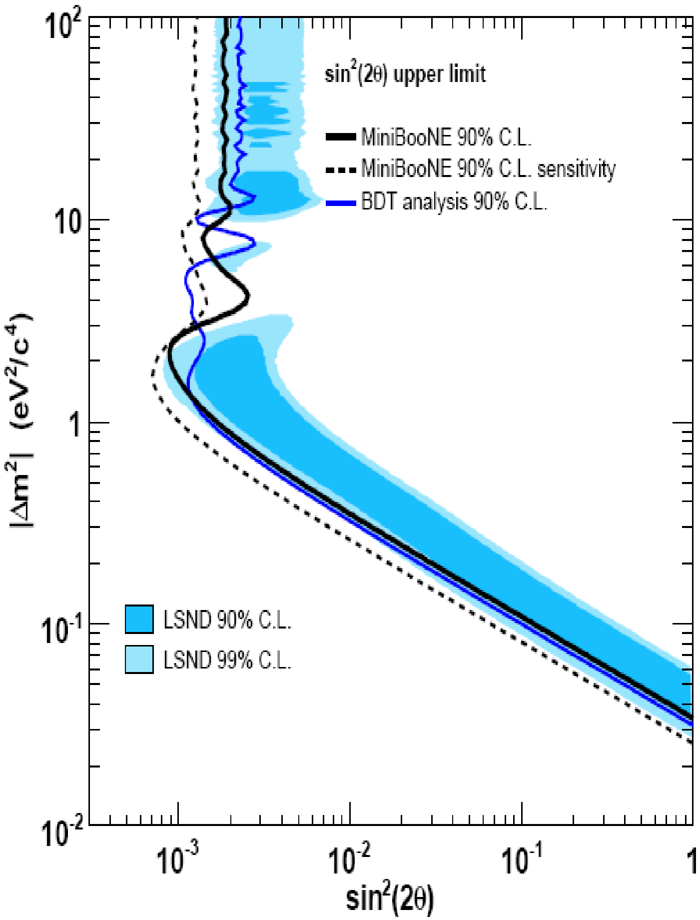
ν̄ mode 3.4e20 POT



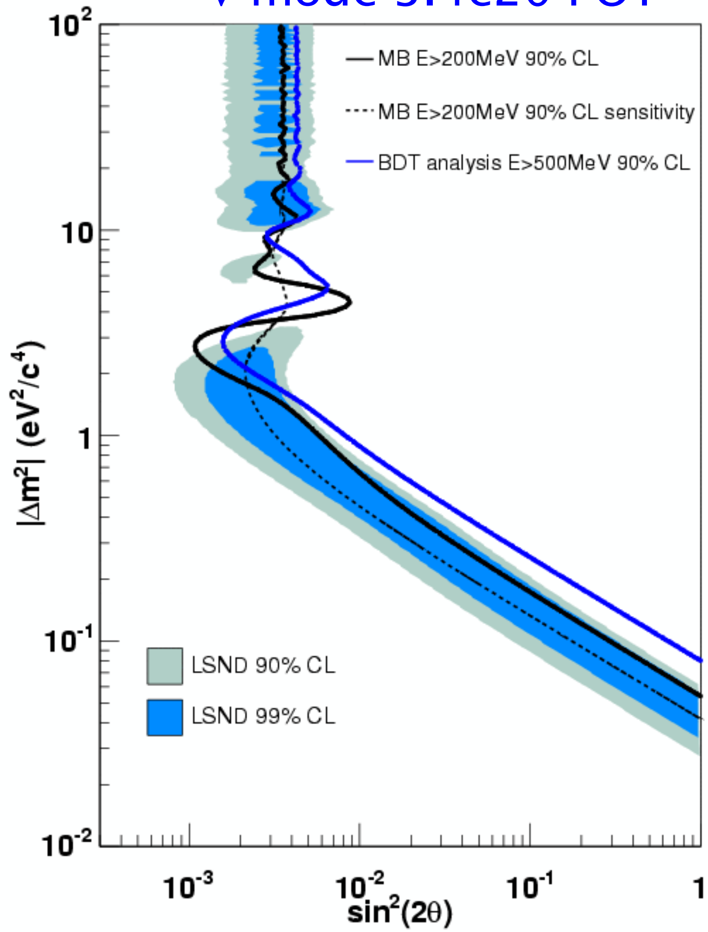
- Unblinded Nov, first presented in Dec, some interesting observations...
  - Backgrounds actually very similar
  - Role of stat error can be seen in blue errors plotted on data, especially relative to systematic errors in black plotted on MC
  - Good agreement...even at low energy

Comparing limits and sensitivities to 2ν mixing

ν mode 6.6e20 POT

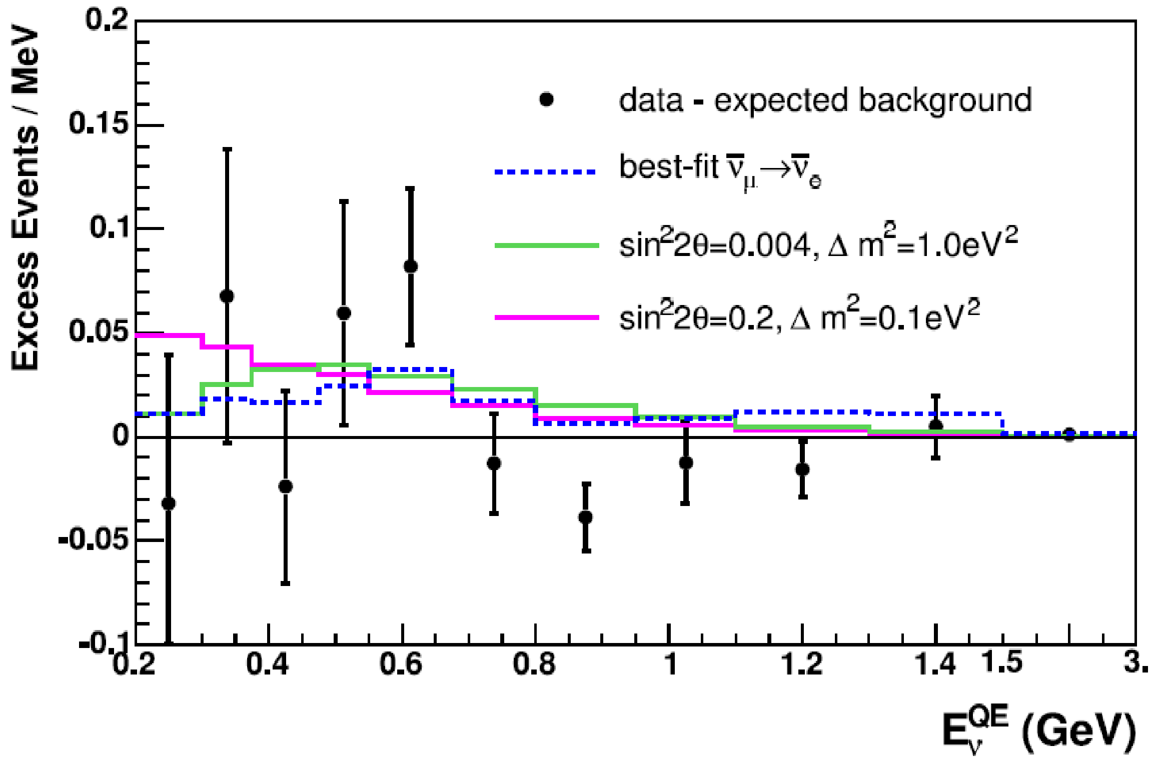


$\bar{\nu}$ mode 3.4e20 POT



- Fit prefers to add some signal making limit curve shift to right relative to sensitivity.
- Nearly all of LSND and the null hypothesis included at 90% CL

Data–MC prediction versus energy (nubar)



- Counting exp. only has a 3.2 event excess above 475 MeV, where LSND's best fit would predict 12.6 events
- However, fit performed with a systematic covariance matrix that allows some normalization freedom
- $\chi 2$ minimized by putting in a small signal that better matches shape of wiggle

Fit Range	dof	$\chi^2_{(null)}$	$\chi^2_{(LSND)}$
> 200 MeV	17	20.2	18.2
> 475 MeV	14	17.9	15.9

☆ LSND best fit parameters slightly preferred over null!

Event excesses in various regions

E_ν^{QE} range (MeV)		$\bar{\nu}$ mode (3.386e20 POT)	ν mode (6.486e20 POT) [paper to be submitted to PRL]
200-300	Data	24	232
	MC ± sys+stat (constr.)	27.2 ± 7.4	186.8 ± 26.0
	Excess (σ)	-3.2 ± 7.4 (-0.4σ)	45.2 ± 26.0 (1.7σ)
300-475	Data	37	312
	MC ± sys+stat (constr.)	34.3 ± 7.3	228.3 ± 24.5
	Excess (σ)	2.7 ± 7.3 (0.4σ)	83.7 ± 24.5 (3.4σ)
200-475	Data	61	544
	MC ± sys+stat (constr.)	61.5 ± 11.7	415.2 ± 43.4
	Excess (σ)	-0.5 ± 11.7 (-0.04σ)	128.8 ± 43.4 (3.0σ)
475-1250	Data	61	408
	MC ± sys+stat (constr.)	57.8 ± 10.0	385.9 ± 35.7
	Excess (σ)	3.2 ± 10.0 (0.3σ)	22.1 ± 35.7 (0.6σ)

- Simple exercise, if the low E excess had scaled with total bkg, how many events should we have seen in anti-ν mode?
  - 200-475, should have observed 19 events on top of 61.5 bkg
  - With stat error only that means 2.4 σ downward fluctuation
  - Not quite right, need fully correlated systematic analysis, compare various bkg hypotheses

Initial study of low E compatibility

Maximum χ^2 probability from fits to ν and $\bar{\nu}$ excesses in 200-475 MeV range	Stat Only	Correlated Syst	Uncorrelated Syst
Same ν,$\bar{\nu}$ NC	0.1%	0.1%	6.7%
NC π^0 scaled	3.6%	6.4%	21.5%
POT scaled	0.0%	0.0%	1.8%
Bkgd scaled	2.7%	4.7%	19.2%
CC scaled	2.9%	5.2%	19.9%
Low-E Kaons	0.1%	0.1%	5.9%
ν scaled	38.4%	51.4%	58.0%

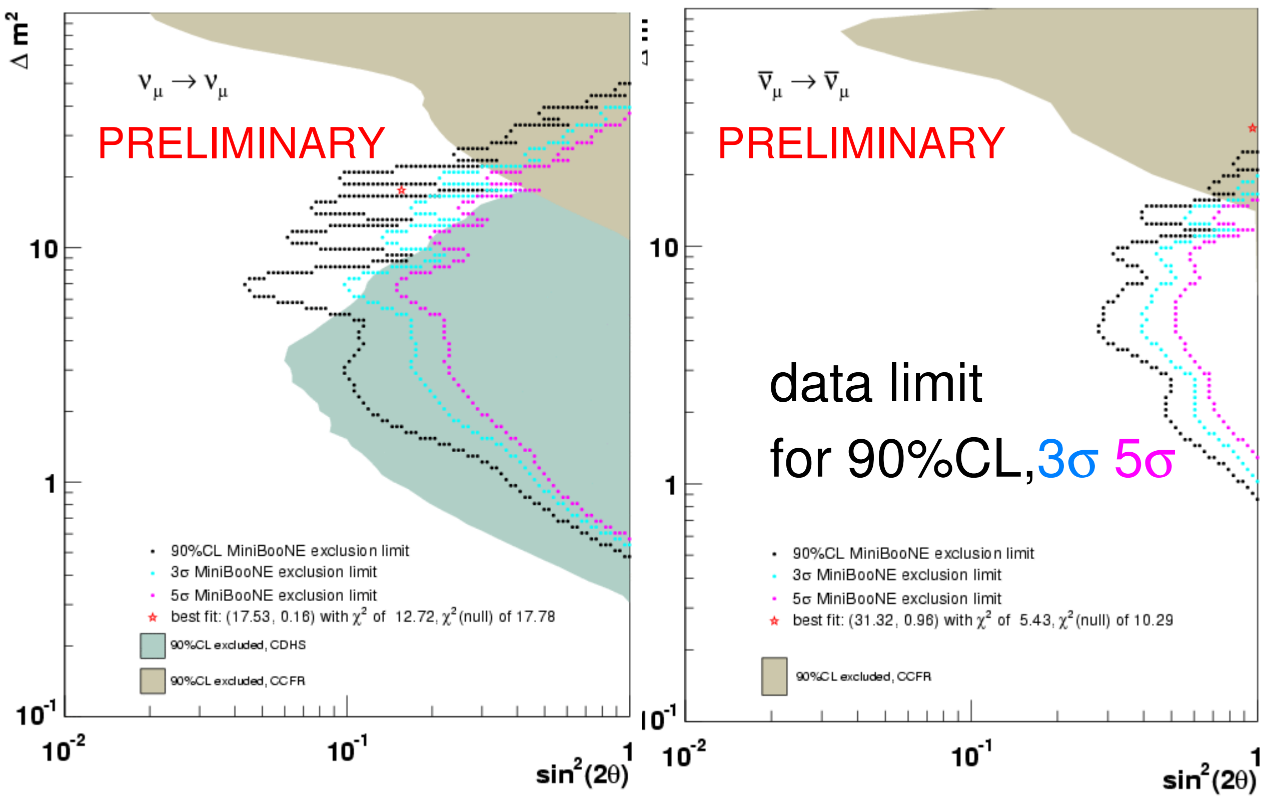
Preliminary

- Main idea: Ignore what we think we know about various backgrounds and ask how compatible the low E region is under various signal/bkg hypothesis
- All correlated systematic errors have to be handled properly
  - Work in progress, but final result has to be bracketed between 100% corr. and uncorr.
- Examples:
  - Low E Kaons: If the excess at low E was due to misestimating the kaon production in the beam, then nubar mode should also see an excess.
  - Axial anomaly falls under first row
  - ν-scaled most compatible, but this is really just a statement that there is only 30% ν_μ in the anti-ν_μ beam

A word on ν_μ disappearance? NEW RESULTS

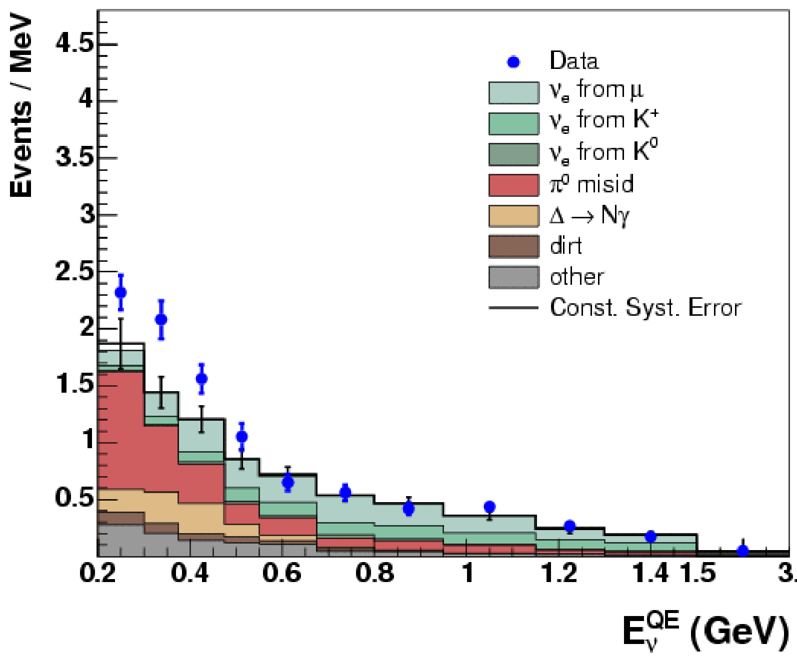
- Harder than ν_e appearance since you have to dead reckon flux and cross-section
- Also know ν_μ rate is 30% (1.5σ) larger than expectation (before M_A fits)
- Solution: perform a shape only fit to a 2ν mixing hypothesis
- Resulting limits shown below...will greatly improve with SciBooNE near detector data

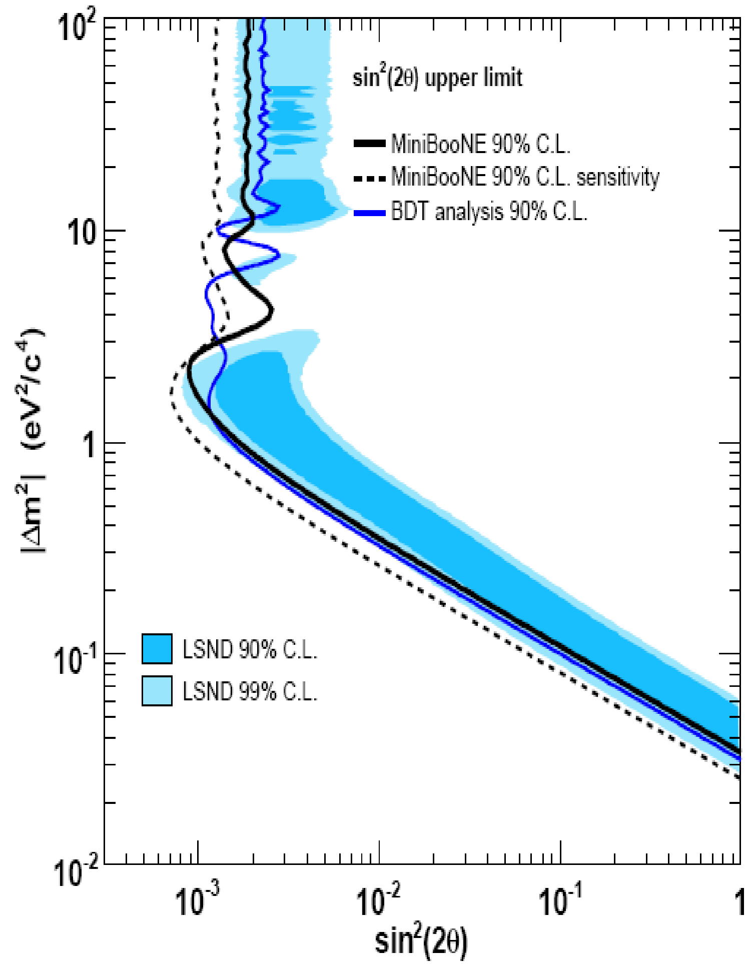
ν mode 5.6e20 POT $\bar{\nu}$ mode 3.4e20 POT



MiniBooNE Conclusions: ν mode

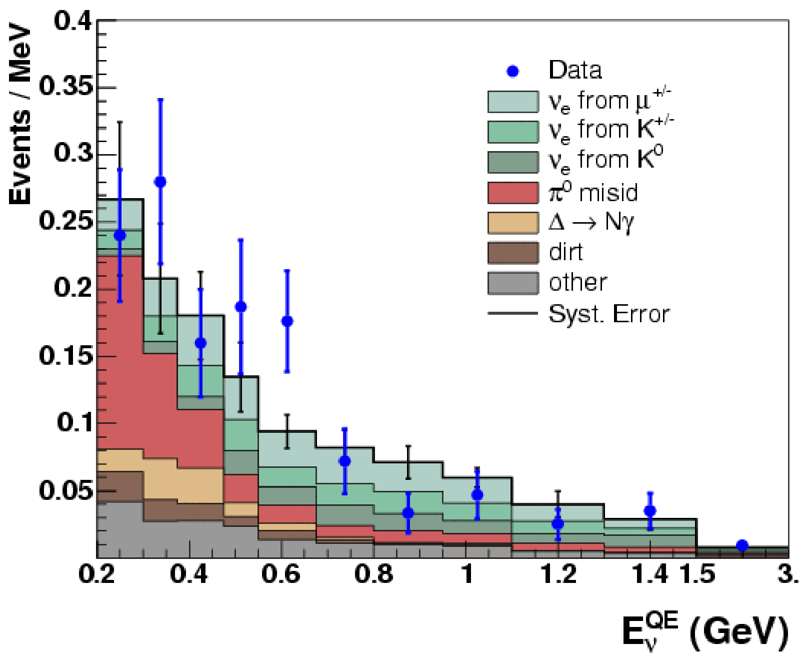
- A comprehensive review of all bkgs and errors completed (emphasis at low E)
  - No change to the analysis above 475 MeV
  - Excess at low E energy reduced but still >3.0σ significant
- Assuming ν behave like anti-ν, L/E invariant models for LSND are ruled out, including simple oscillations, and 3+1 sterile models

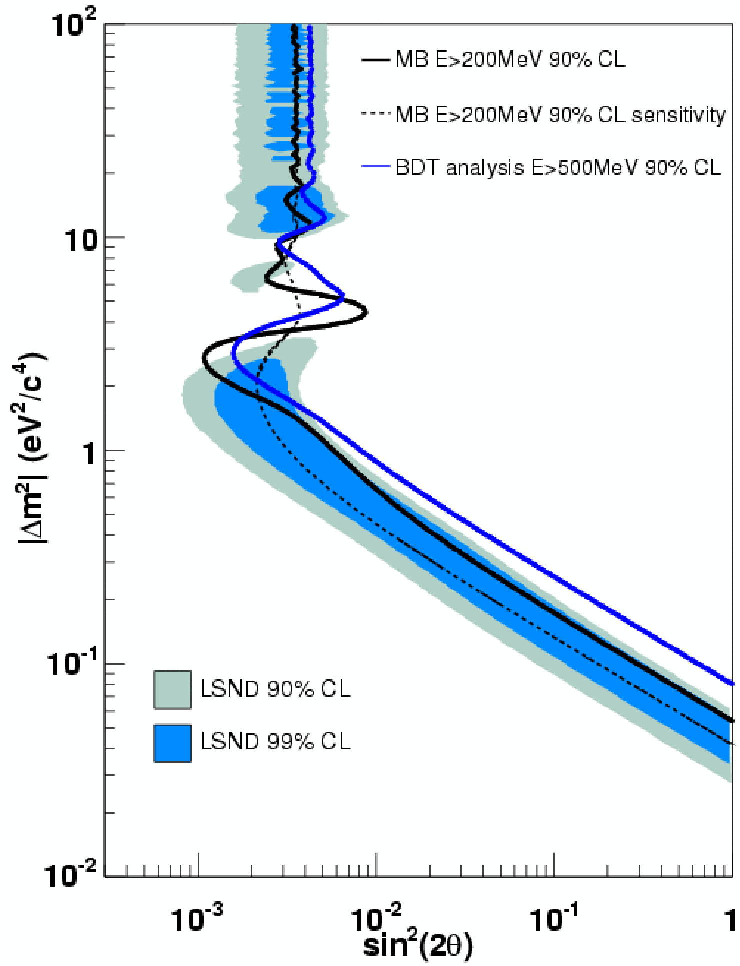




MiniBooNE Conclusions: anti-ν mode

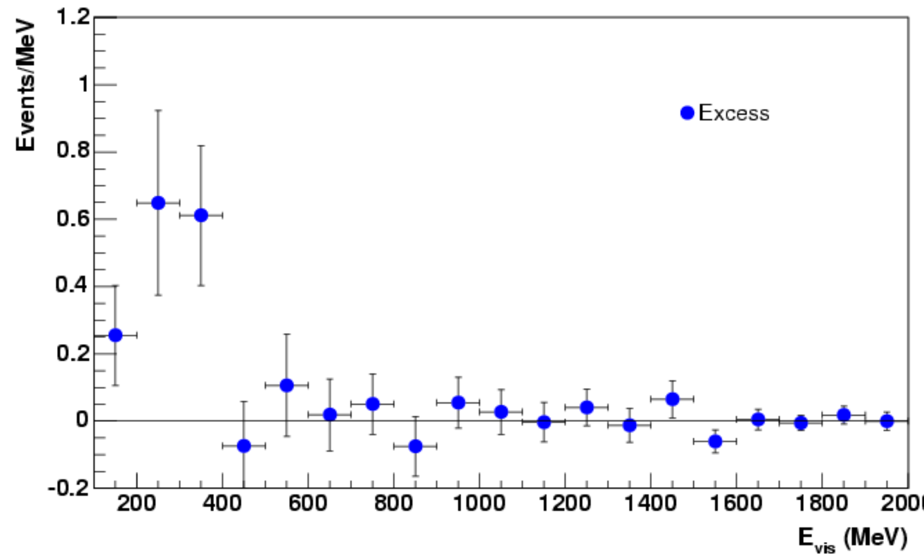
- No statistical significant excess above 475
  - Shape of data-mc prefers a small signal
  - LSND best fit slightly preferred over null
  - Both LSND best fit and null within 90% CL
  - Need more data
- LSND alive and well with regard to anti-n result

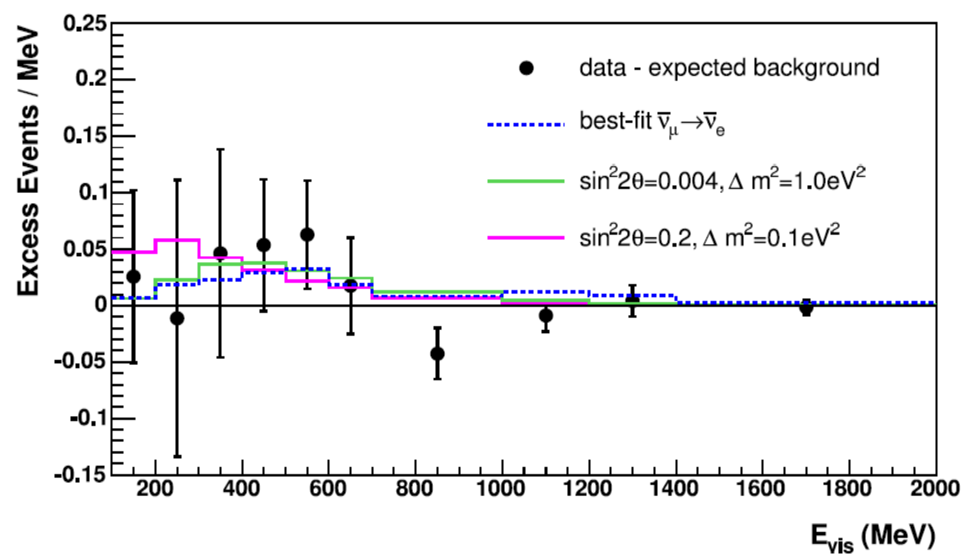




MiniBooNE Conclusions: ν vs. anti−ν

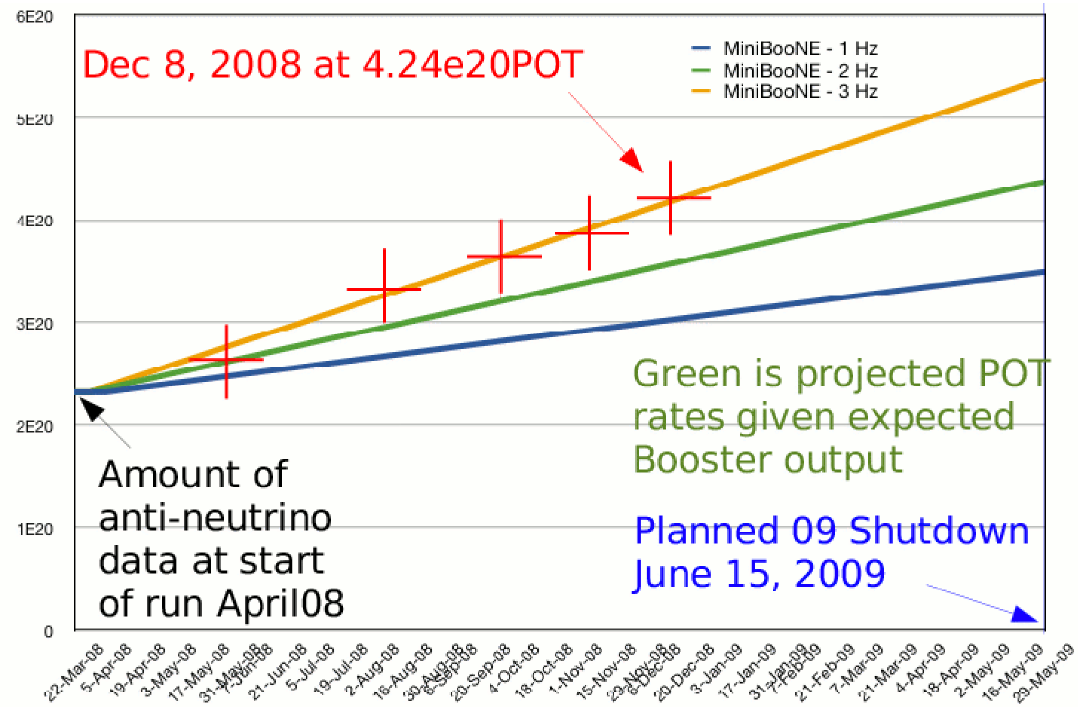
- Very curious that there is no sign of excess at low E in anti−ν data
  - Excess in visible E in plots on right
  - ν mode excess is 6σ statistically significant (3σ with systematics)
  - Many conventional possibilities, e.g. missed bkgs, axial anomaly, low E kaon production, ruled out
- Has ramifications for T2K
  - T2K uses same energy n beam
  - Looks for ν_e appearance
  - If θ_{13} nonzero, will want to compare ν to anti−ν running for CP violation





Looking forward....

Projected Luminosity at MiniBooNE

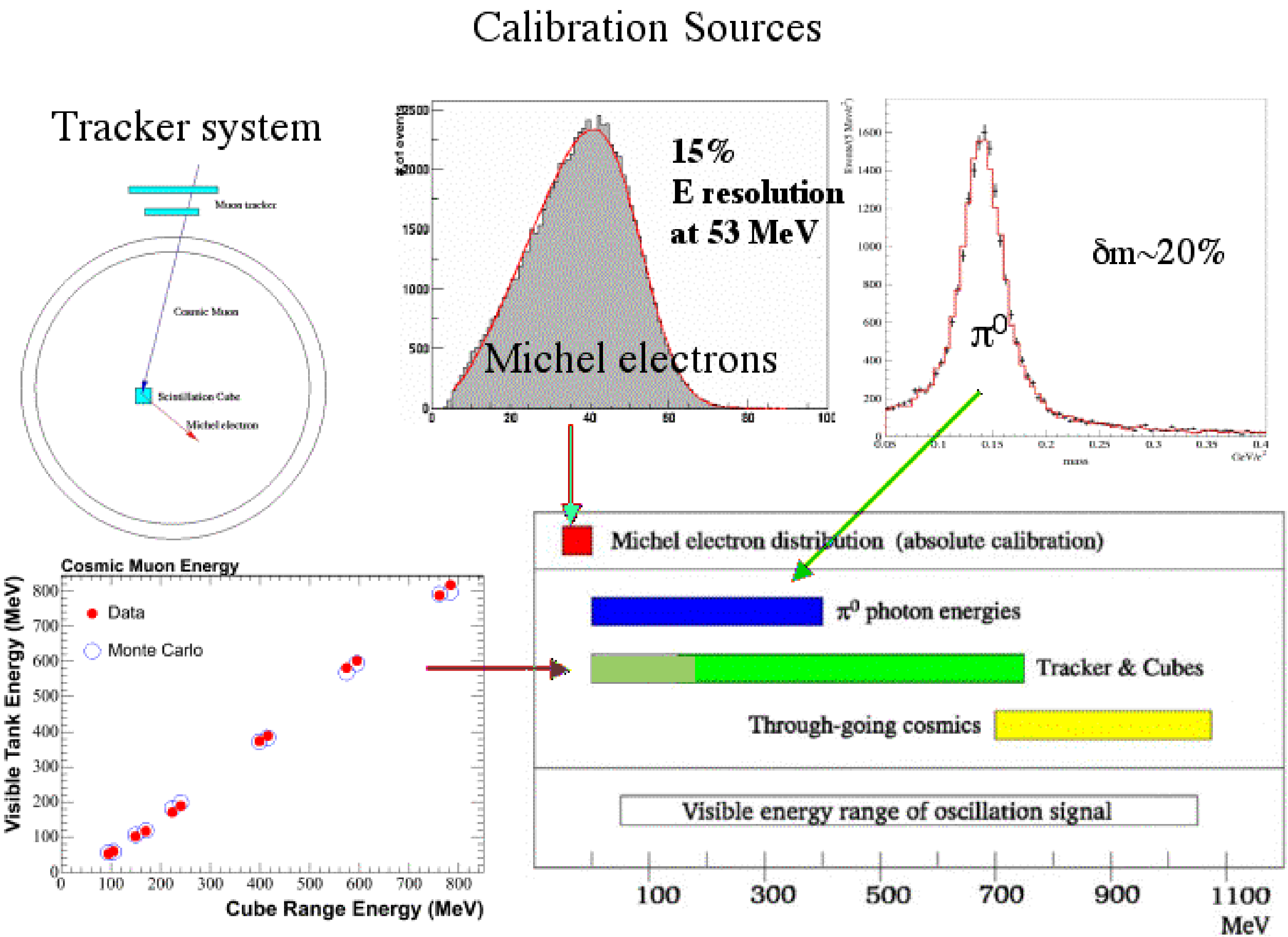


- **OscSNS**
  - MB-like near/far detectors at Oak Ridge
  - Relative to LSND
    - x5 detector mass
    - x1000 lower duty cycle
    - x2 n flux
    - x10 lower DIF background

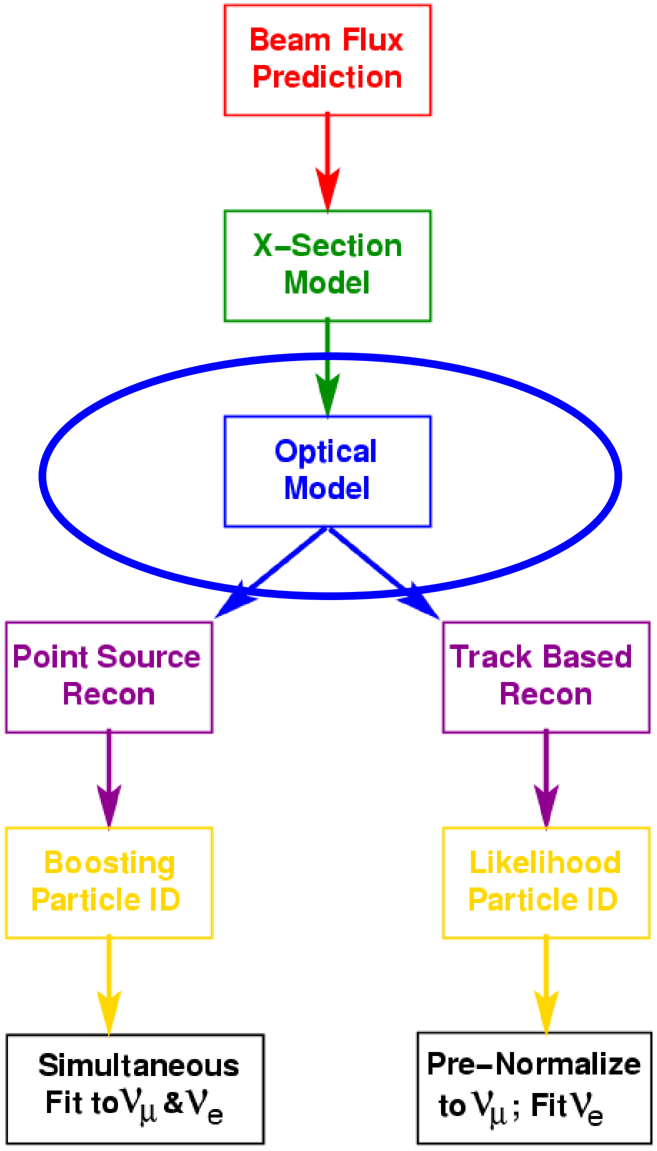
- **MiniBooNE**
  - Will increase anti-ν mode stats by 50% by shutdown, 5e20 POT
  - Proposal in to PAC last week to double nubar stats to 1e21 POT
    - 2.5 years of running without change in program planning or Booster upgrades
- **SciBooNE**
  - Finished with 1e20 POT in both ν and anti-ν mode
    - Will improve ν_μ disappearance
    - Not clear they can contribute to low E analysis, reconstruction typically limited to >500 MeV
- **MicroBooNE**
  - Valuable liquid Ar R&D to be constructed in 8 GeV ν beam
    - Approved
    - Can distinguish electron from γ
    - Expecting 40-50 evts at low E

Extra slides

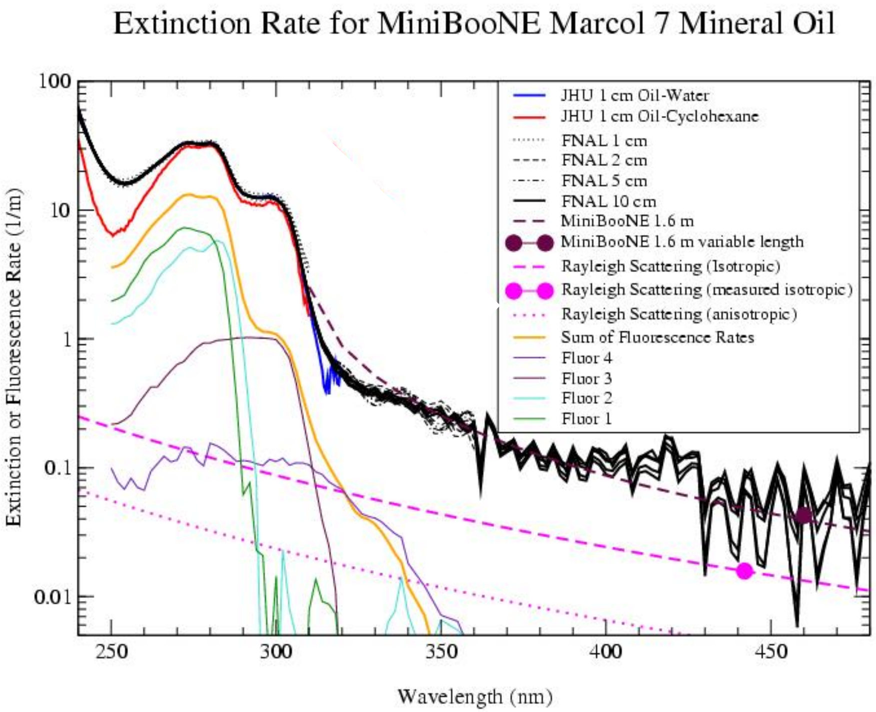
Calibration sources span various energies

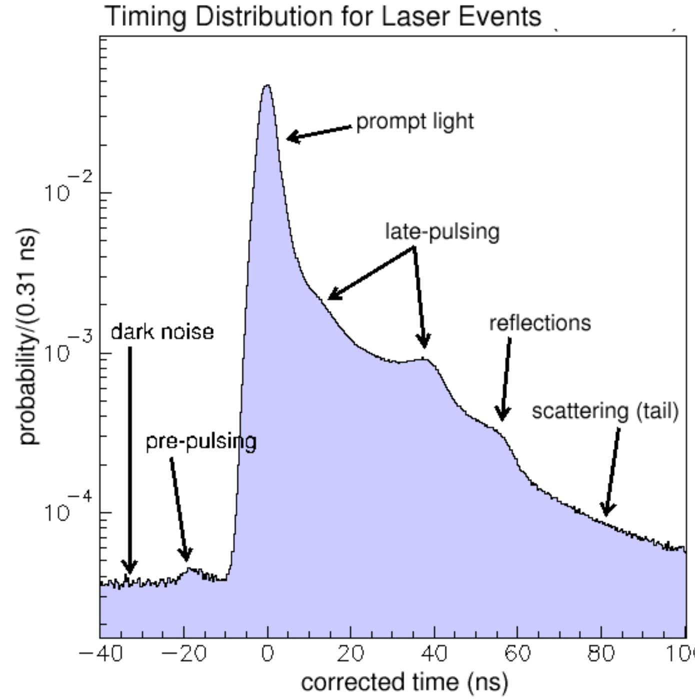


Optical Model



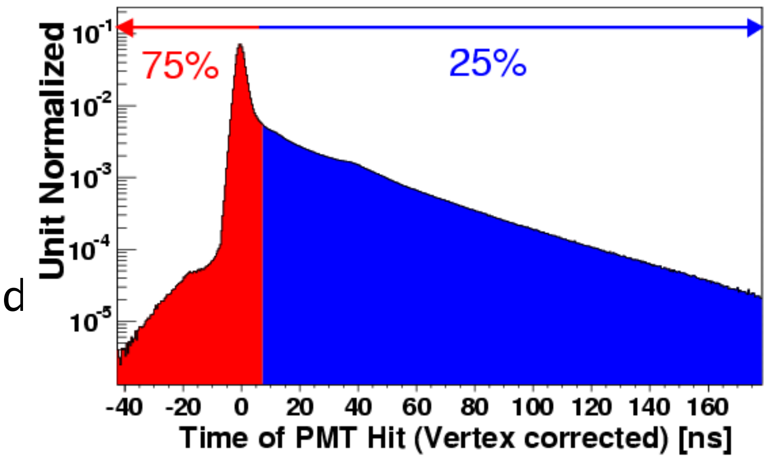
Light propagation in the detector



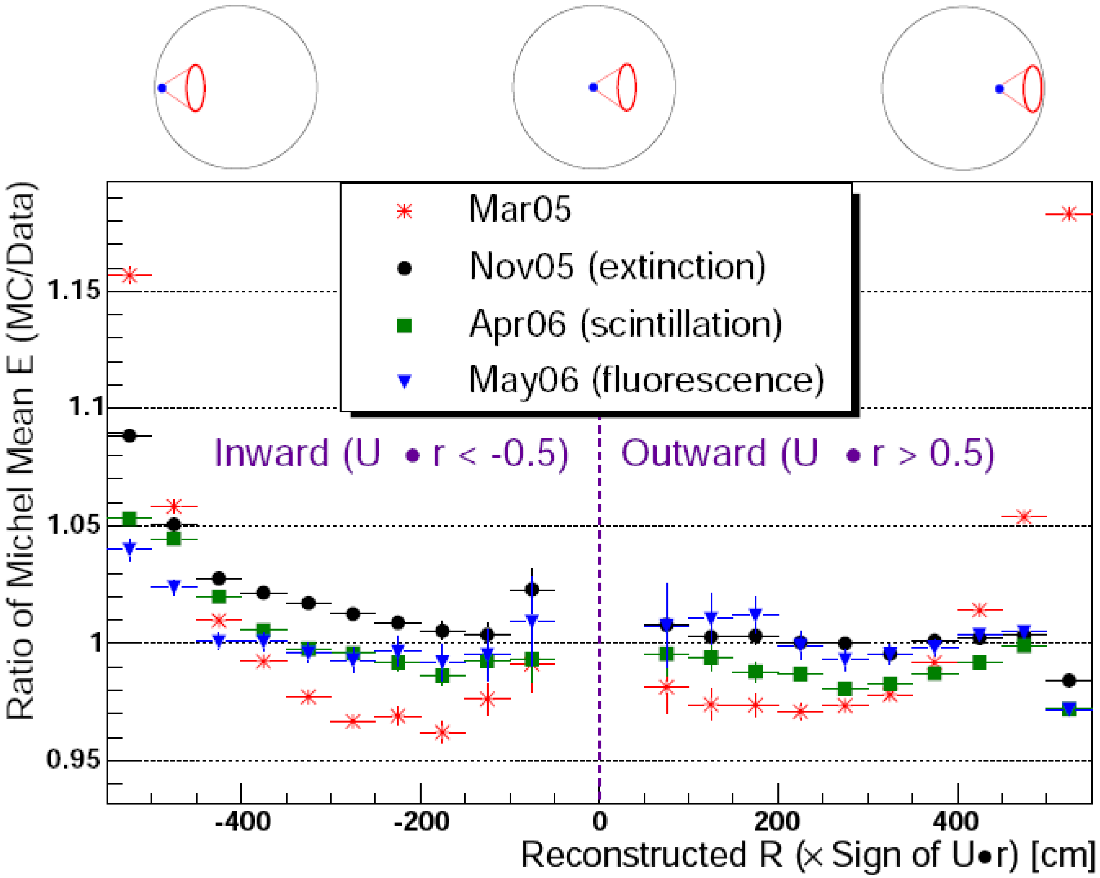


- Optical model is very complex
  - Cerenkov, scintillation, fluorescence
  - PMT Q/t response
  - Scattering, reflection, prepulses
- Overall, about 40 non-trivial parameters
- Started with benchtop measurements, refined via *in situ* tuning. Data/MC agreement critical (esp. for Boosted Decision Tree)

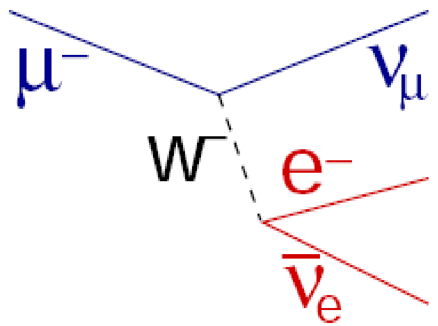
Michel electron t distribution



Tuning the optical model

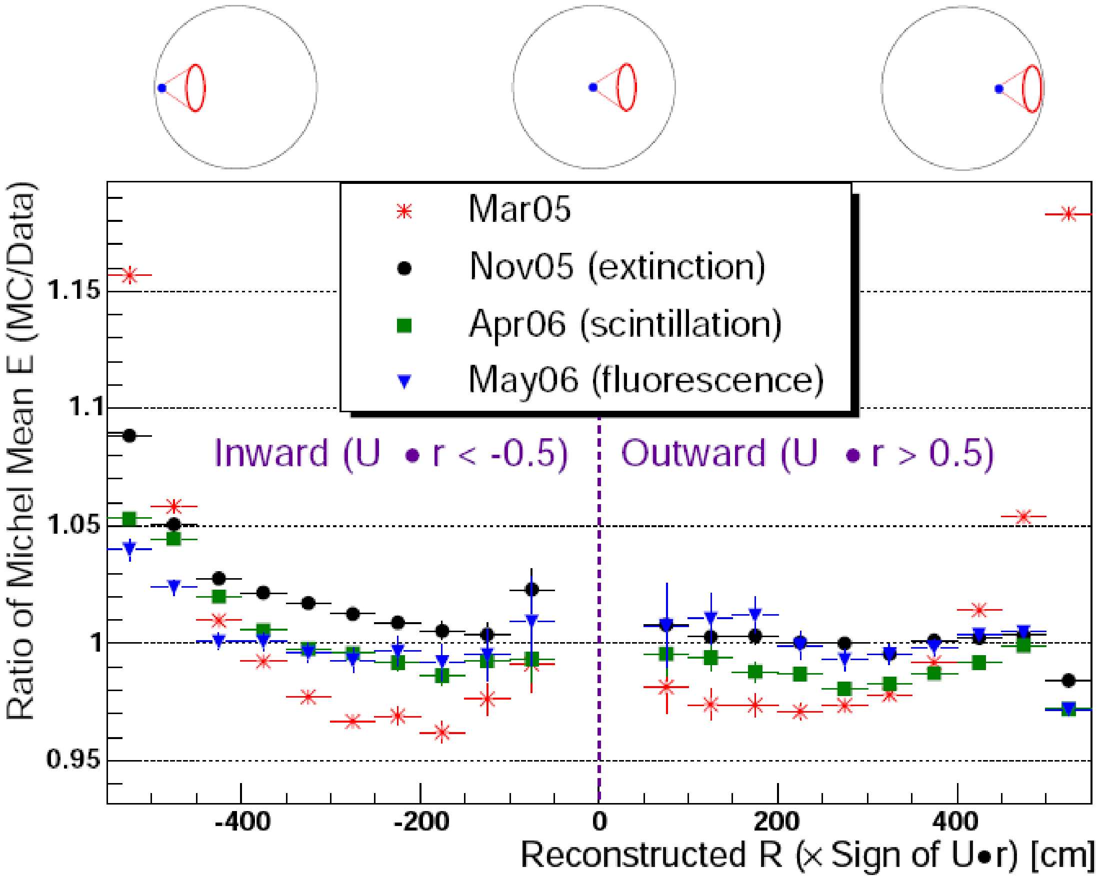


- Decay e– from cosmic muons are a great calibration source
  - Electrons, like the signal
  - E<50 MeV, fast to simulate
  - Uniformly populate all R



- Refining the OM: Basic idea
  - Define n–dimensional hypercube (n~40) of allowed underlying parameter ranges
  - Throw random darts (~100,000) in that space and run 5–10k MC Michel samples
  - Compute a χ^2 for an ensemble of topology–based variables
  - Shrink allowed parameter space down to a remaining hyper–ellipse

Tuning the optical model



- Decay e– from cosmic muons are a great calibration source
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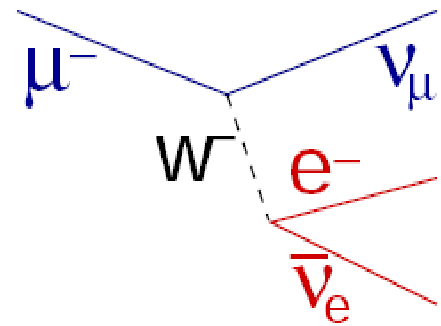
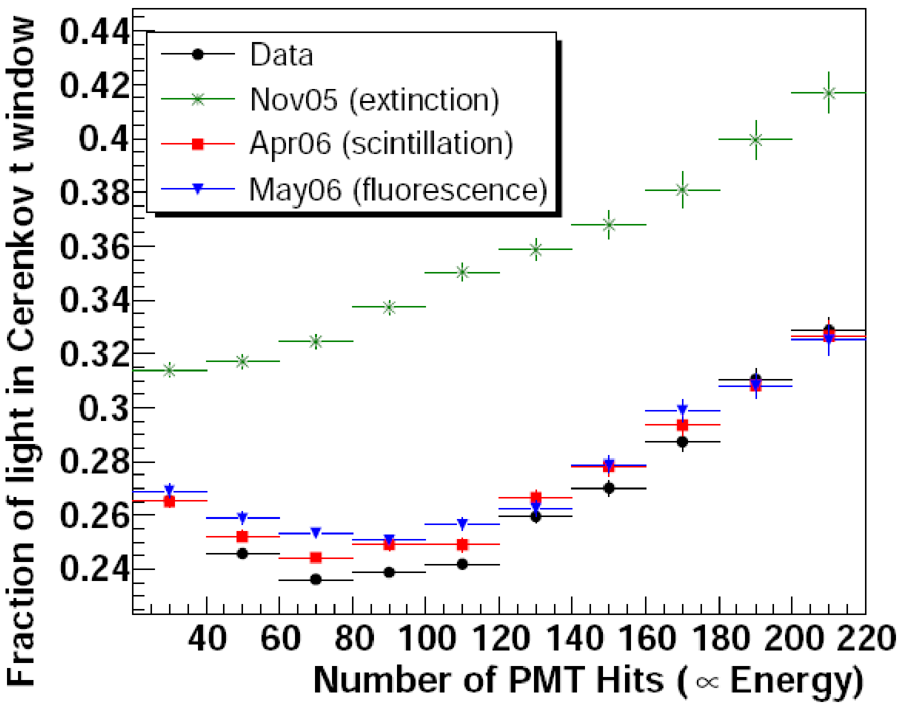
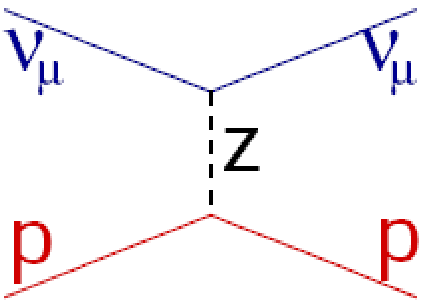


- Benefits are two–fold
  - Center of ellipse defines improved OM
  - Extent of ellipse defines systematic error
    - Can later throw random darts in remaining hyper–ellipse, produce full neutrino samples and fits (much more CPU intensive) to extract errors

Breaking the UVF/scintillation degeneracy

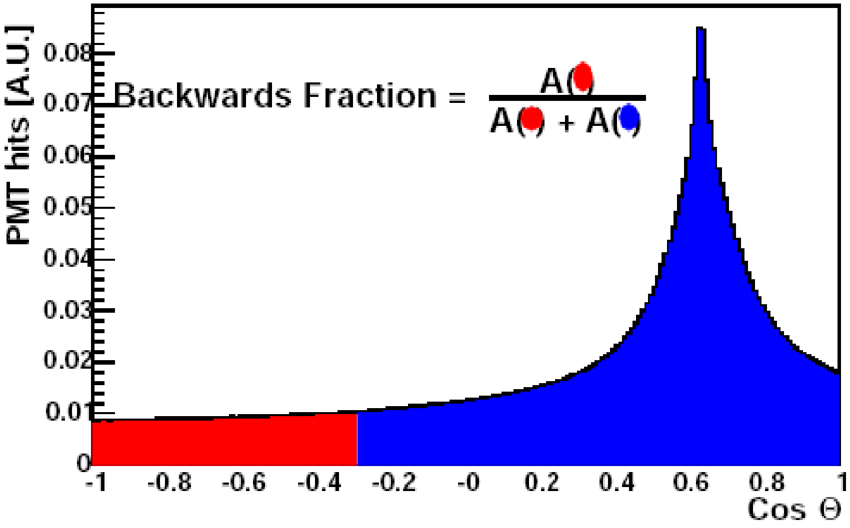


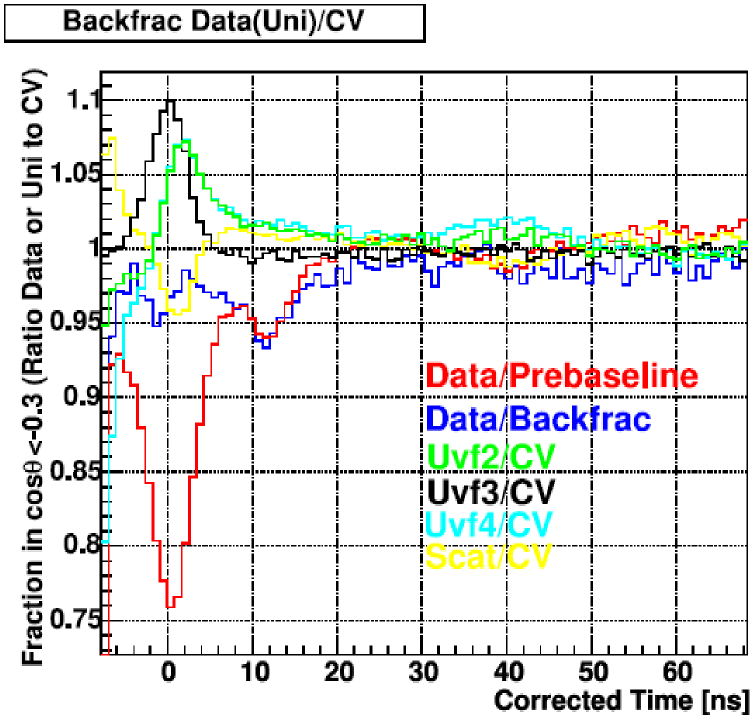
- In general, tried to avoid tuning OM with neutrino sampes
- One exception...NC elastic
  - NC elastic not a significant bkg to signal
  - Sub-Cerenkov p provides direct measure of scintillation amplitude



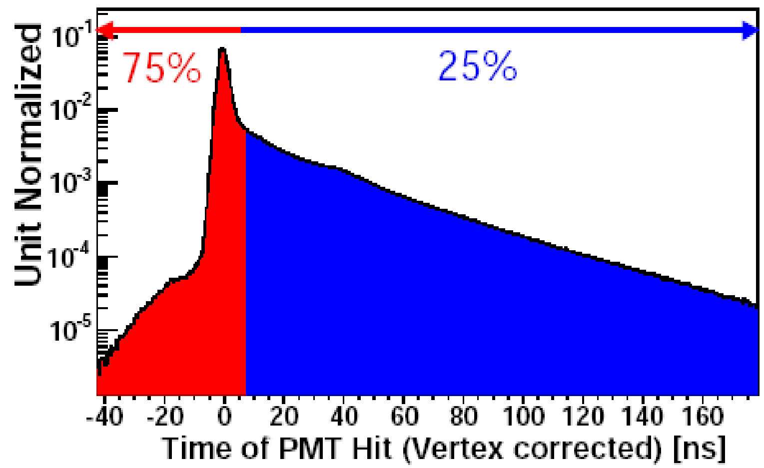
- Important due to degeneracy in original OM
  - Ability of Cerenkov in UV region to absorb and re-emit in visible was not well-measured
  - Means that isotropic, late light in Michel e- could either be due to UV Cerenkov light fluorescence or due to direct excitation due to charged-particle passage

Final step in tuning the optical model



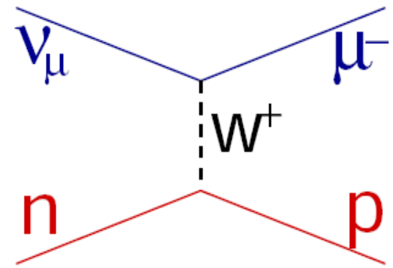


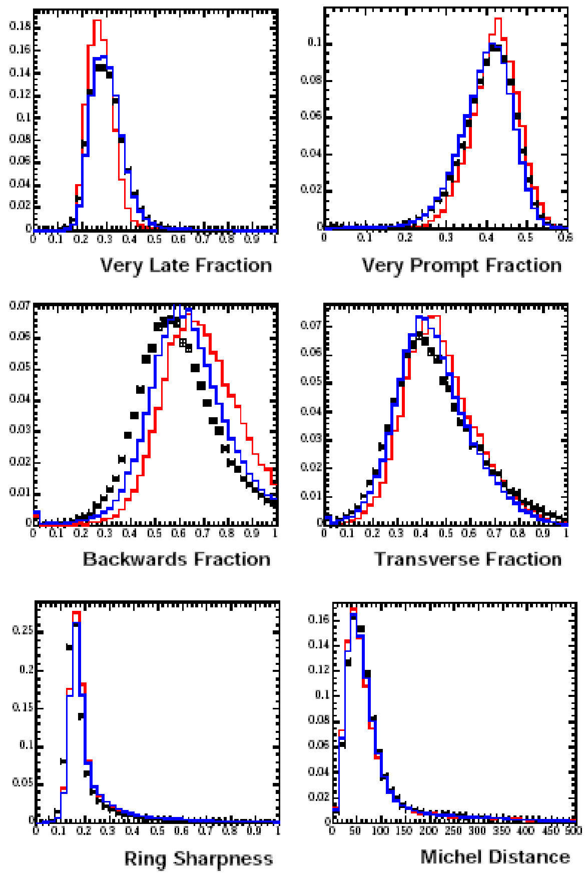
- With the scintillation amplitude fixed from the NC elastic data...could now tune the UVF parameters with the Michels
- Look at the fraction of light on the tank wall behind the Cerenkov cone as a function of corrected time
- Adjusted UVF amplitudes to get amount of isotropic light correct

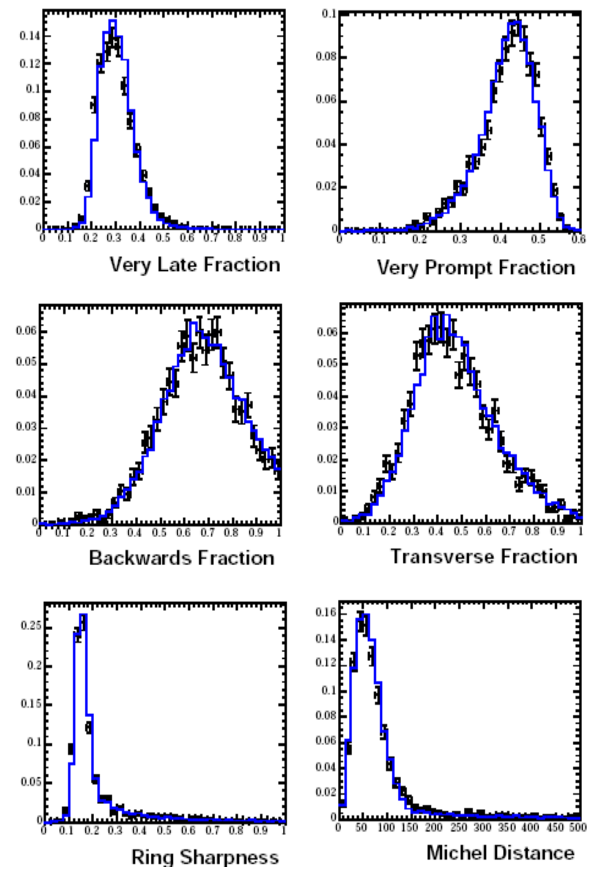


Impact of OM tuning on ν samples

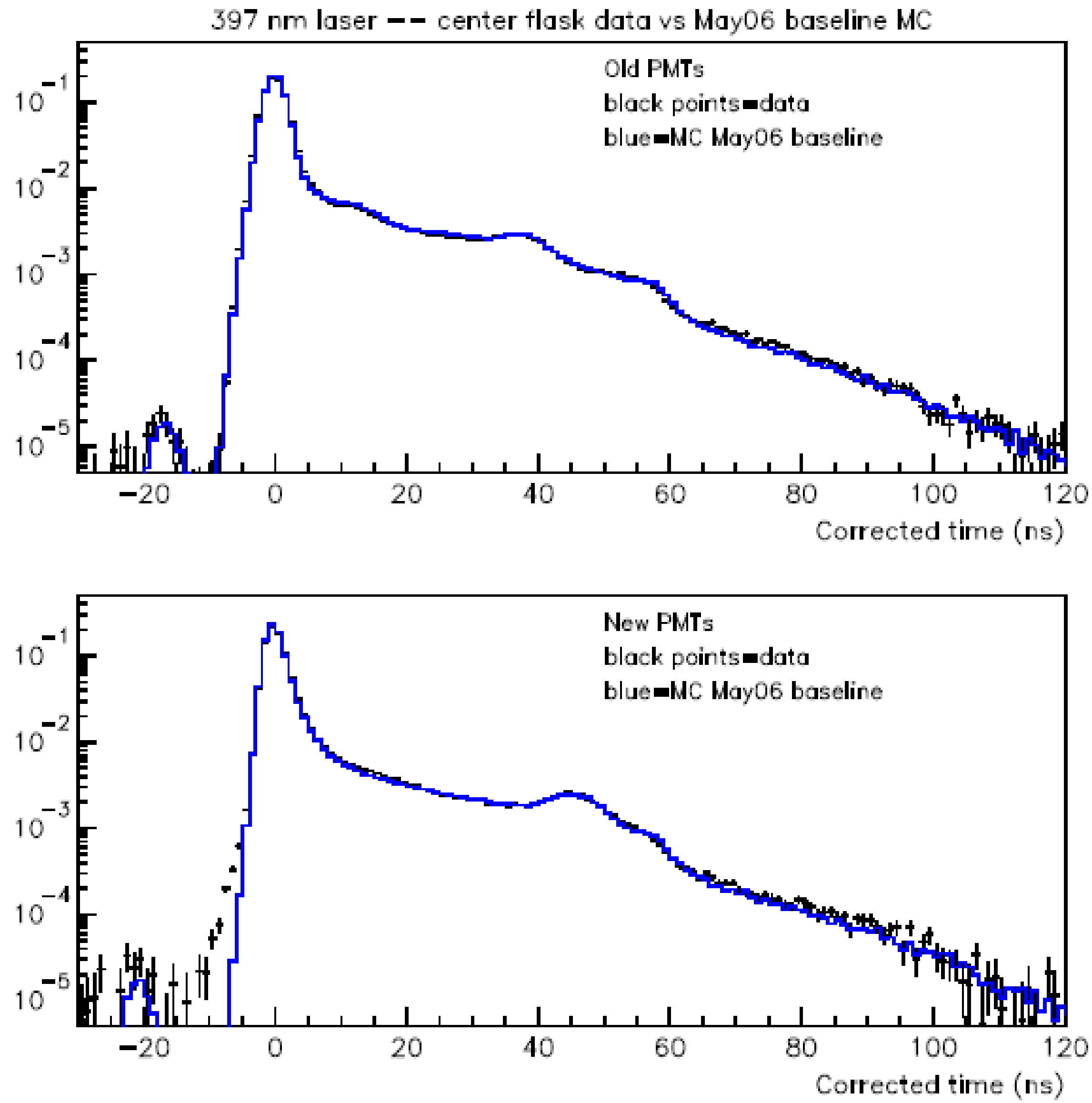
- 6 variables below used in Fisher discriminant to isolate ν_μ CCQE
- Various stages of tuning shown on left (red Nov05, blue May06). Final OM shown on right.







Laser timing distributions (old and new PMTs)



Full update: Background event breakdown

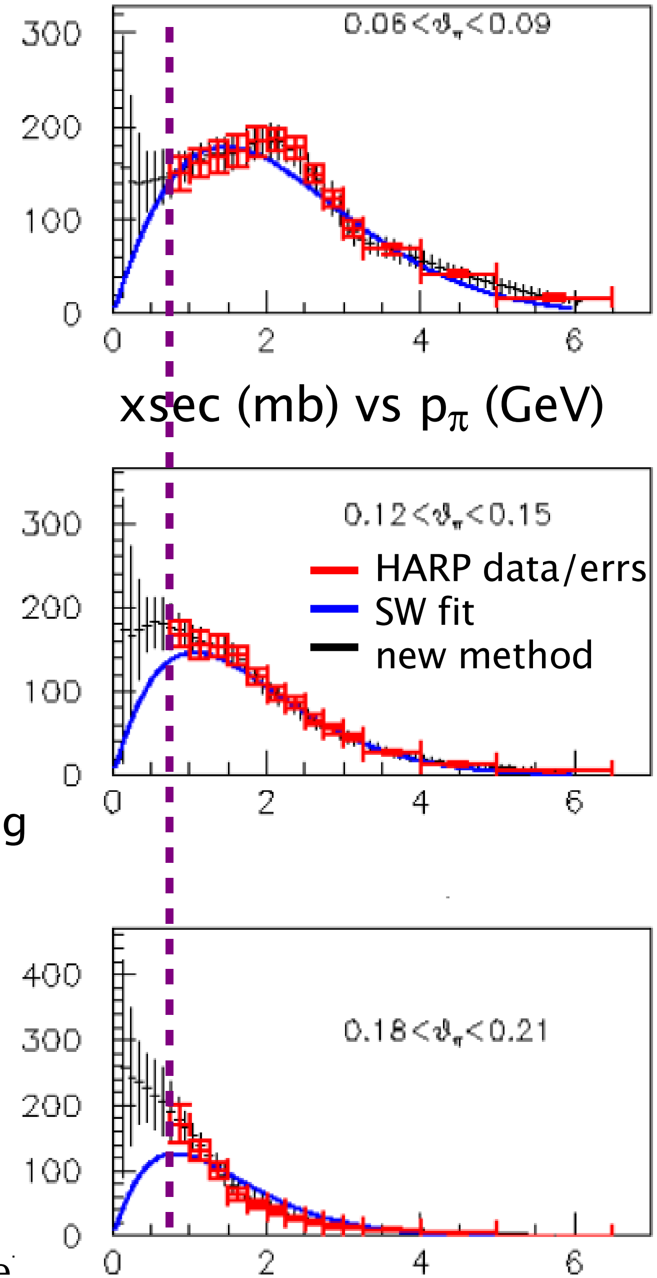
Process	200 − 300	300 − 475	475 − 1250
ν_μ CCQE	9.0	17.4	11.7
$\nu_\mu e \to \nu_\mu e$	6.1	4.3	6.4
NC π^0	103.5	77.8	71.2
NC $\Delta \to N\gamma$	19.5	47.5	19.4
Dirt Events	11.5	12.3	11.5
Other Events	18.4	7.3	16.8
ν_e from μ Decay	13.6	44.5	153.5
ν_e from K^+ Decay	3.6	13.8	81.9
ν_e from K^0_L Decay	1.6	3.4	13.5
Total Background	186.8 ± 26.0	228.3 ± 24.5	385.9 ± 35.7

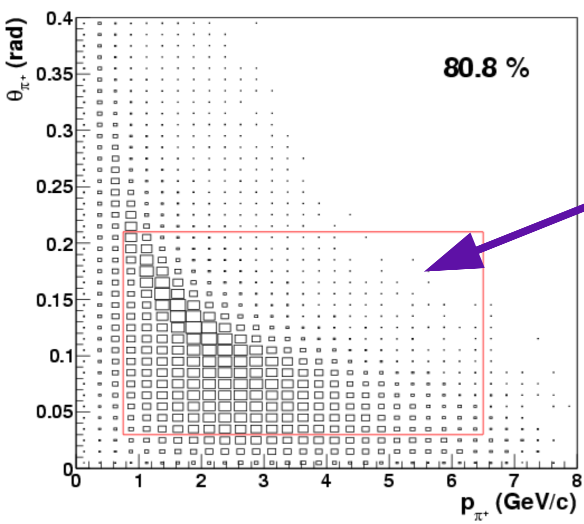
- Above 475 MeV still dominated by intrinsic ν_e
- At low E transitions to NC π^0 and Δ->$N\gamma$ dominated bkgs

Update #1: Treatment of π flux errors

OLD METHOD:

- Fit HARP/E910 data to SW parameterization.
  - Use SW fit as central value (CV) MC
  - Use covariance matrix governing SW parameters in χ^2 fit to assess error
- Problem: poor χ^2 due to SW parameterization not fully describing data at HARP's precision
- Old Sol'n: inflate HARP error until χ^2 accept.
- Turns HARP's ~7% error into ~15%





81% of ν flux crossing MB covered by HARP

Update #1: Treatment of π flux errors

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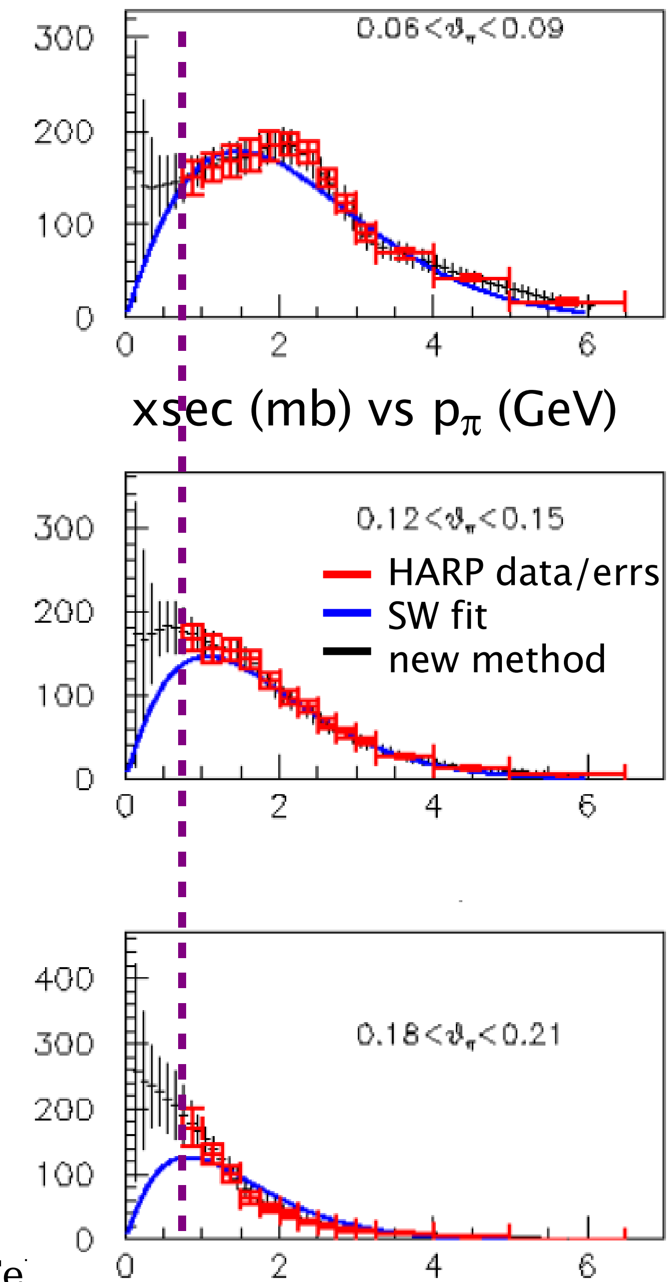
- Old Sol'n: inflate HARP error until χ^2 accept.
- Turns HARP's ~7% error into ~15%

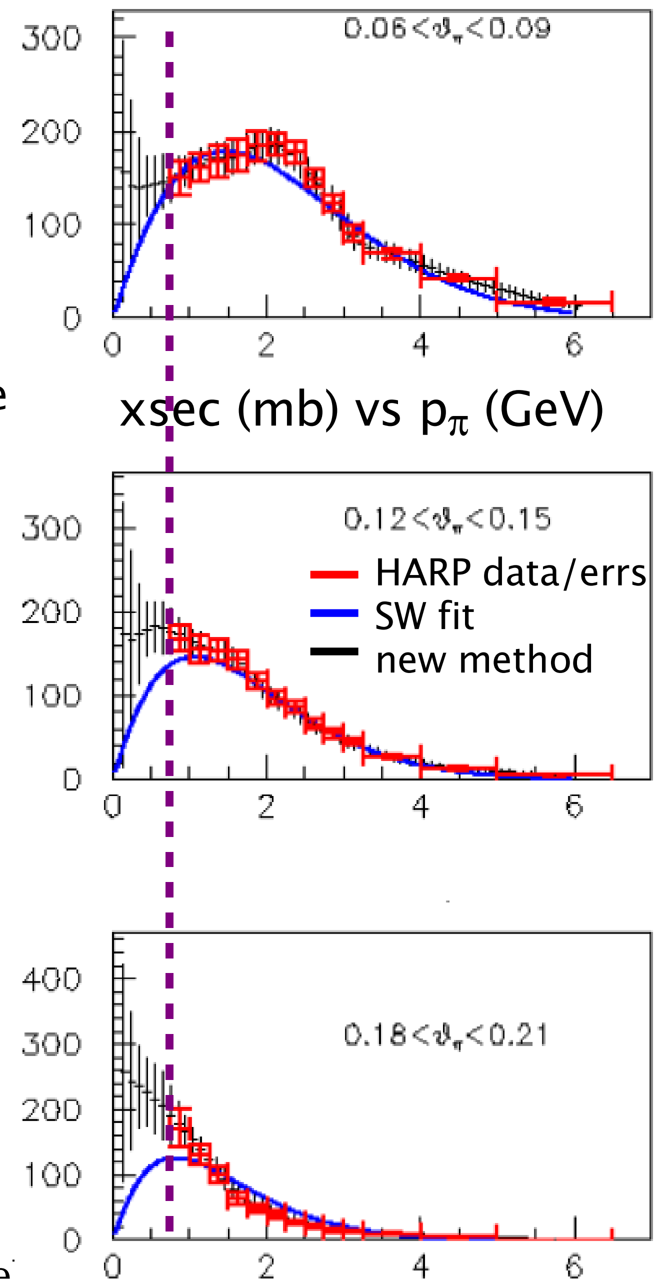
- Sounds dumb, but...
  - Getting a good 2-dim parameterization in (p_π, θ) not as easy as you might think
  - More importantly, in the ν_e appearance analysis the π flux is heavily constrained from the *in situ* ν_μ measurement



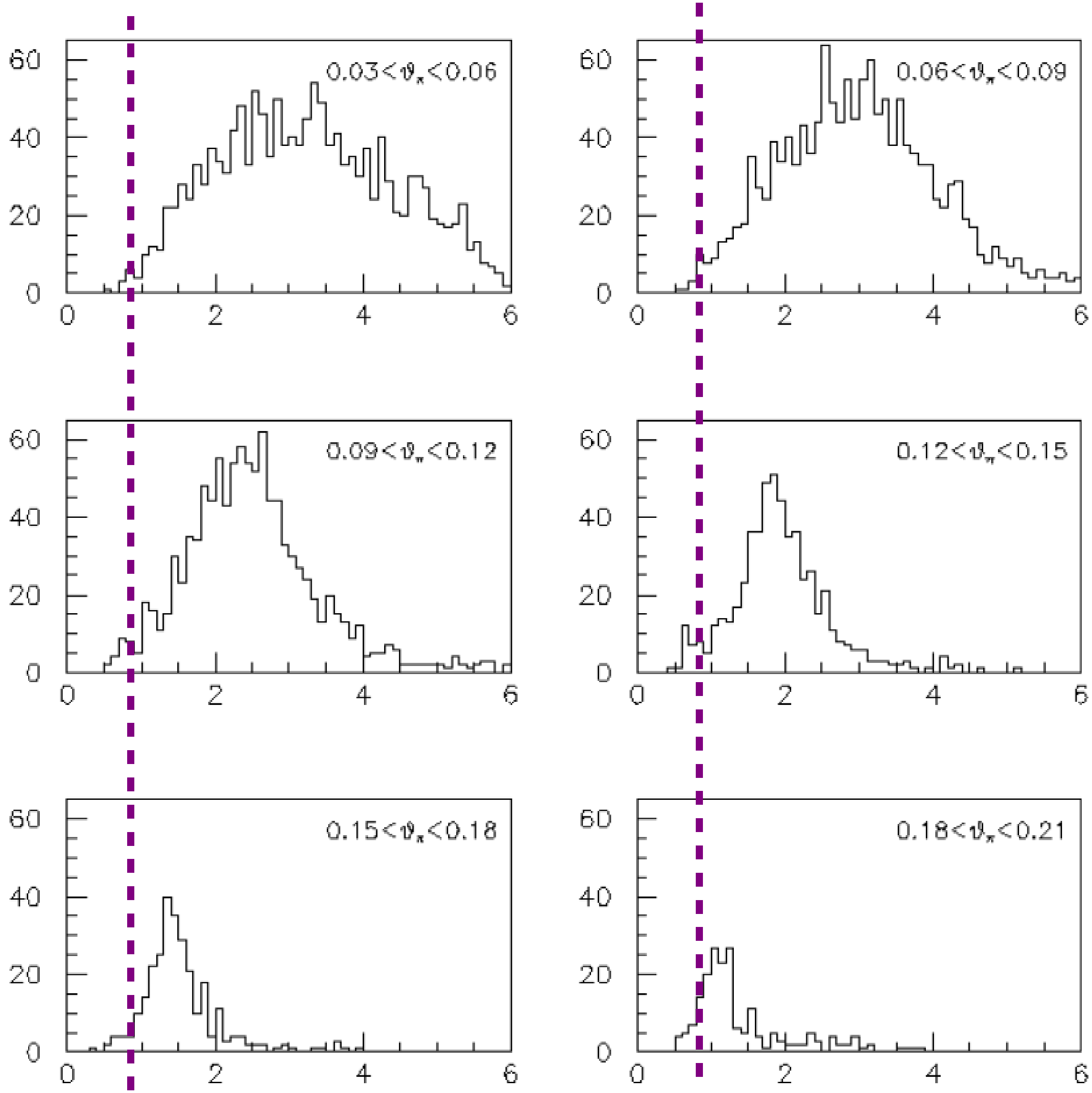
Update #1: Treatment of π flux errors

NEW METHOD:

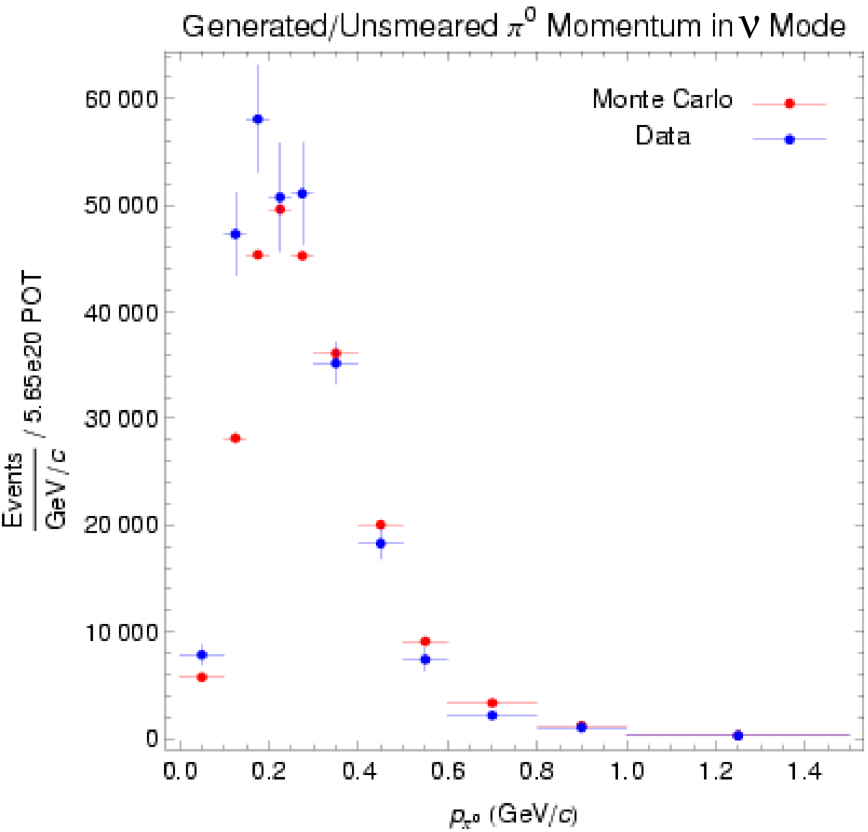
- Forget SW, use HARP data and fit with spline interpolation
- Vary HARP data with their own covariance matrix to produce flux systematic error
- Update #1 bottom line: No impact on ν_e appearance
  - Largest diff at low p_π ,not much ν flux hitting det, further deweighted by cross-sections
  - Still have additional 5% in errors coming from horn modeling + secondary interactions
  - Errors outside of HARP measurement region actually larger by taking covariance about old SW as 1σ error



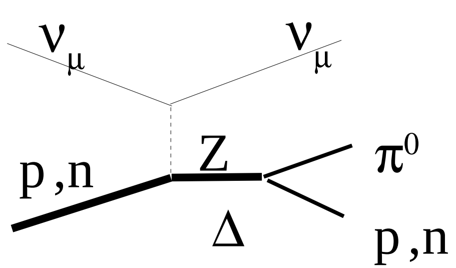
Parent π kinematics -> make ν_e-like bkgs



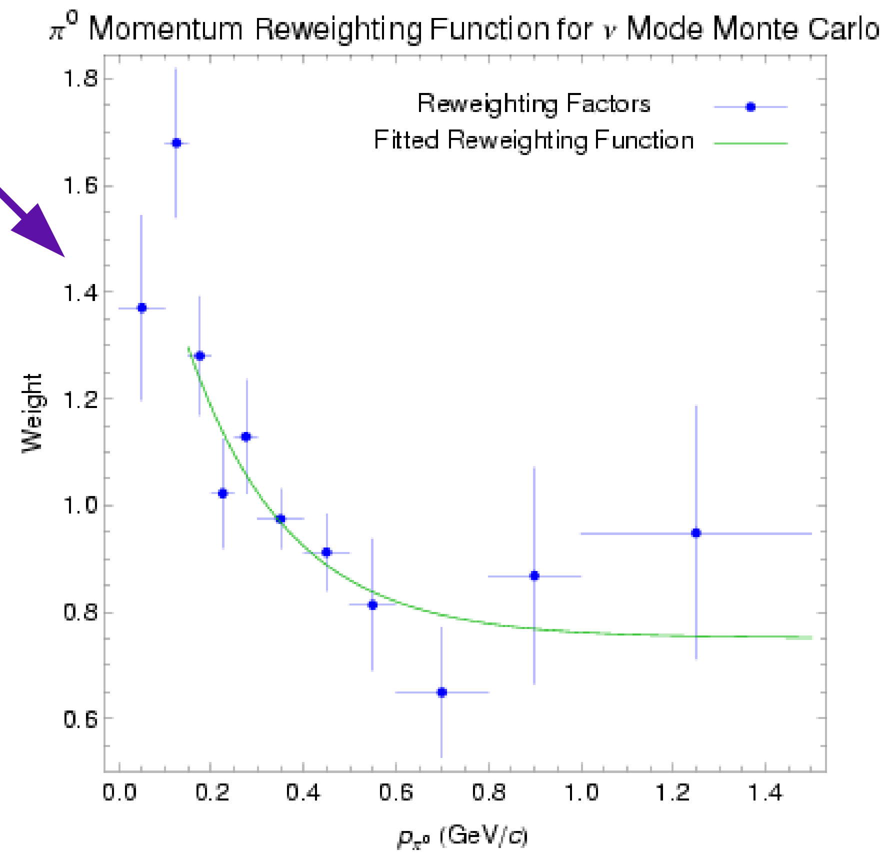
Update #2: Improved π^0/radiative Δ analysis



$\nu_\mu(p,n) \rightarrow \nu_\mu(p,n)\pi^0, \pi^0 \rightarrow \gamma\gamma$

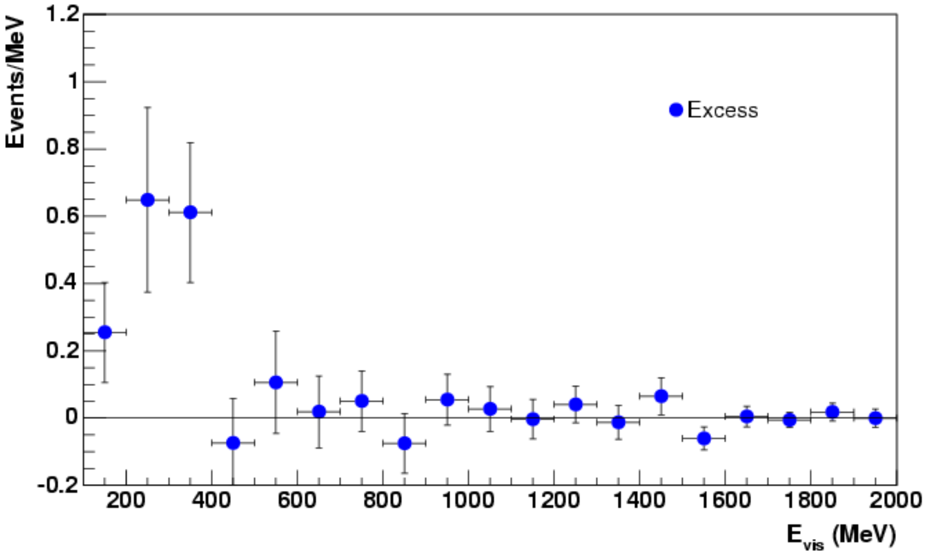


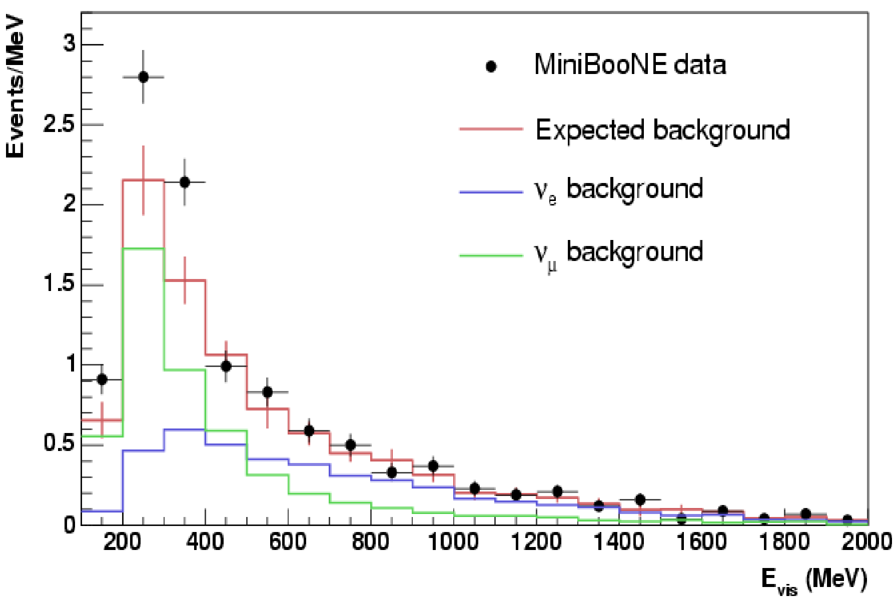
- Complete re-extraction of π^0 weights
  - Independent code, improved unsmearing technique, 11 bins, consistent with old result
  - Fit over 9 bins in p_π to smooth reweighting function



Full update: Visible energy distribution

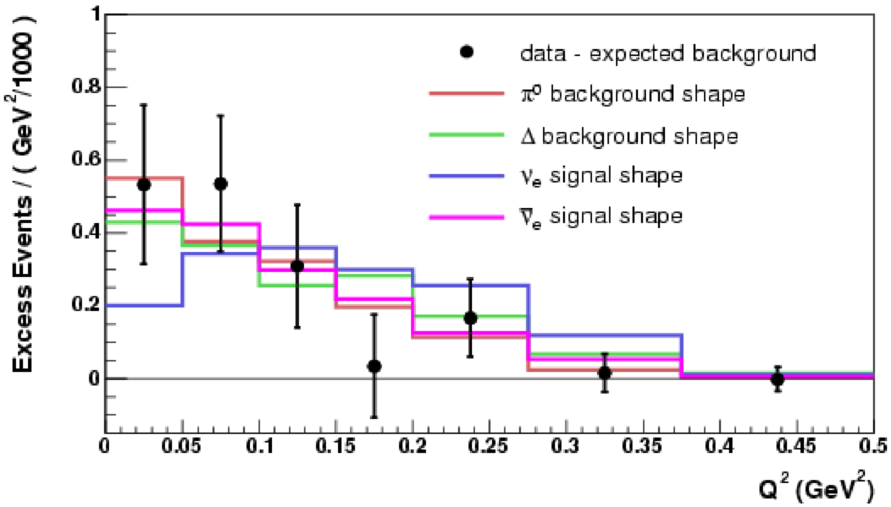
- Visible energy interesting to look at in case excess is not really due to ν_e CCQE
- Can see excess is more consistent with ν_μ mis-ID than intrinsic ν_e.
- Excess piles up below 400 MeV, analysis threshold set at 140 MeV Evis

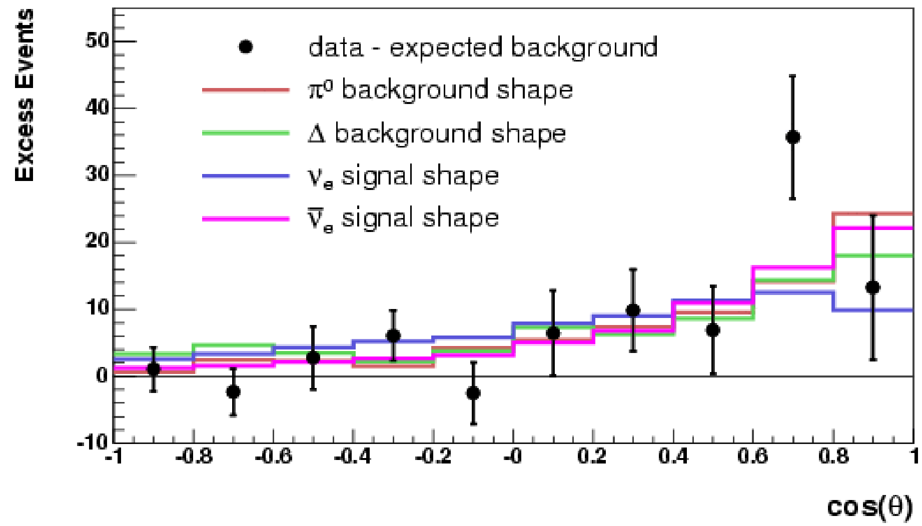




$$E_\nu^{QE} = \frac{1}{2}\frac{2M_pE_\mu - m_\mu^2}{M_p - E_\mu + \sqrt{(E_\mu^2 - m_\mu^2)}\cos\theta_\mu}$$

Full update: Q^2 and cos θ

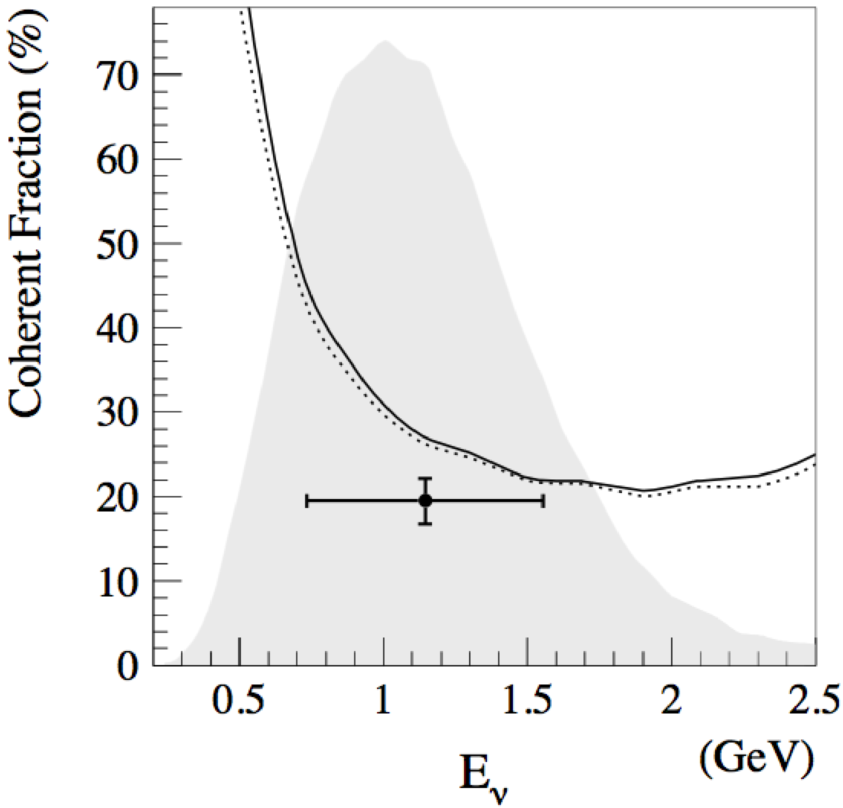


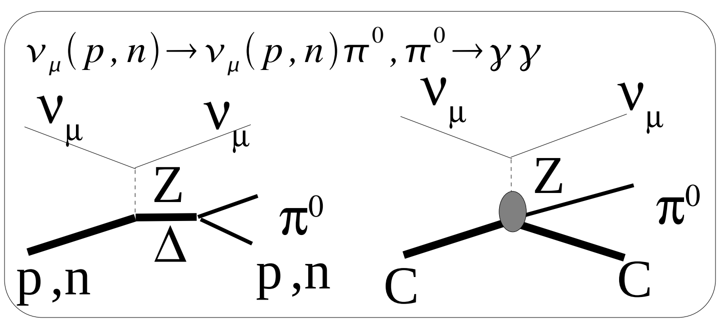


- Excess events plotted versus Q^2 and cos θ...hope was that shapes would favor a particular explanation.
- χ^2 are from a shape only fit, internal constraints on absolute production ignored
  - No smoking gun
  - Most favored is expected excess shape from anti-ν_e, but would require MC prediction off by x 65
  - NC π^0 next most-favored, but measured to better than 10%

Process	χ^2(cos θ)/9 DF	$\chi^2(Q^2)$/6 DF	Mult. Factor
NC π^0	13.46	2.18	2.0
$\Delta \to N\gamma$	16.86	4.46	2.7
$\nu_e C \to e^- X$	14.58	8.72	2.4
$\bar{\nu}_e C \to e^+ X$	10.11	2.44	65.4

Update #2: Improved π^0/radiative Δ analysis





- Applied *in situ* measurement of the coherent/resonant production rate
  - Coherent event kinematics more forward
  - Coherent fraction reduced by 35% (from RS)
- Improvements to $\Delta\text{->}N\gamma$ bkg prediction
  - Coh/res π^0 fraction measured more accurately, $\Delta\text{->}N\gamma$ rate tied to res π^0
  - Old analysis, π created in struck nucleus not allowed to reinteract to make new Δ
  - Complete combinatorial derivation based on branching ratios (Γ_γ, Γ_{π^0}) and the pion escape probability (ε)

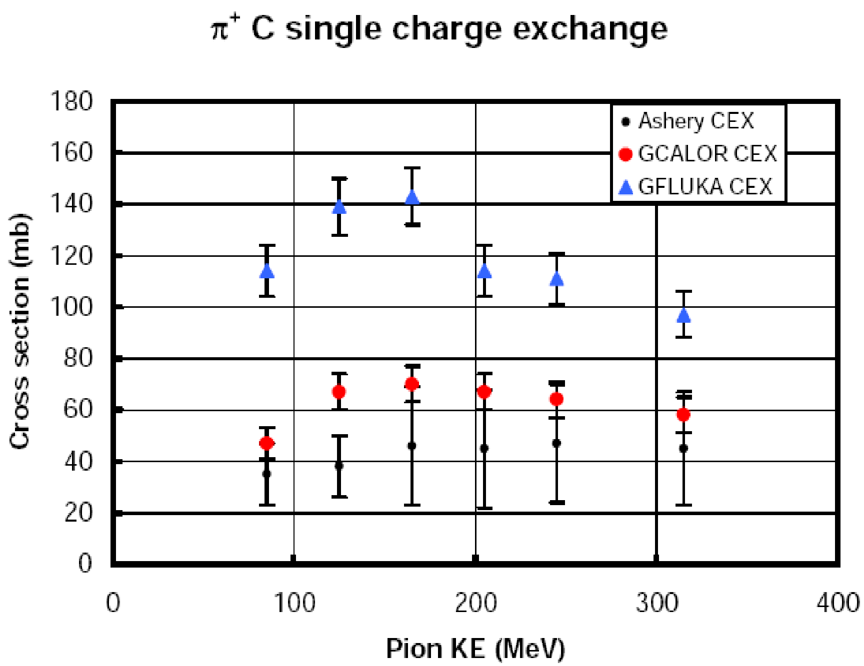
$$\frac{N_C(\Delta \to N\gamma)}{N_C(\Delta \to N\pi^0)} = \frac{3\Gamma_\gamma}{2\Gamma_{\pi^0}\varepsilon}$$

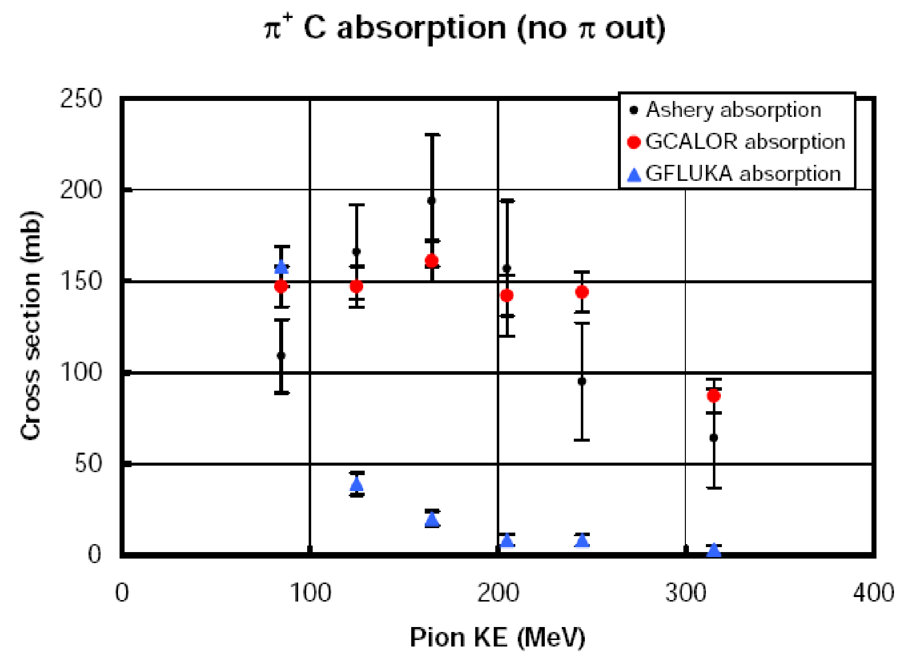
  - Error on $\Delta\text{->}N\gamma$ bkg increased from 9 to 12%
- Update #2 bottom line: Overall, produces a small change in ν_e appearance bkgs

Hadronic bkgs/errors in ν interactions

OLD HADRONIC PROCESSES/ERRORS:

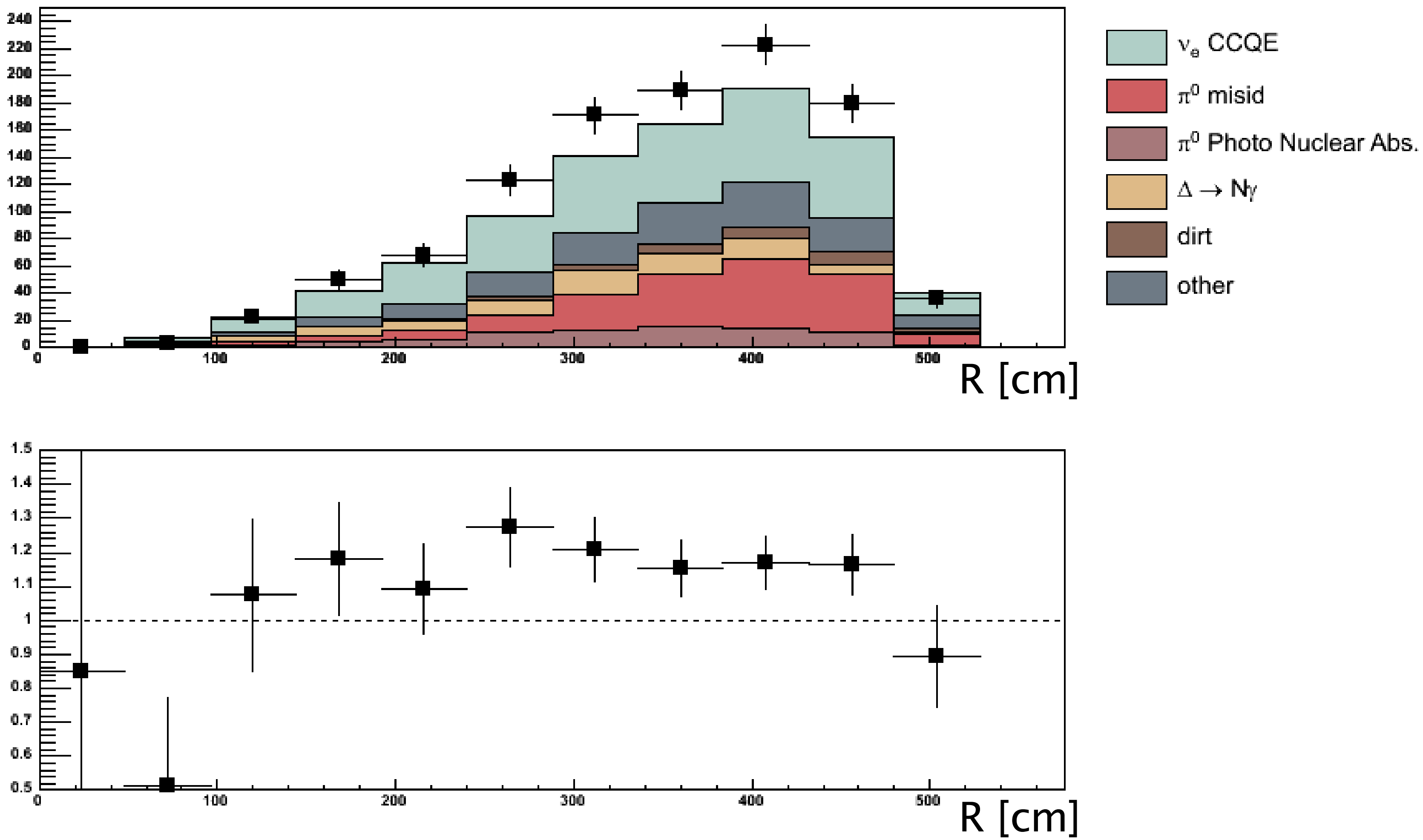
- Mainly due to charged π absorption and charge exchange in the mineral oil, analogous to the same processes in the struck nucleus
- Use GEANT3 MC with GCALOR instead of GFLUKA default
  - better π abs/cex handling (error=max{Ashery error,Ashery-GCALOR})
  - better neutron scattering
- Cross-check: Accounting for cex/abs differences GCALOR & GFLUKA give same result for ν_e appearance bkgs





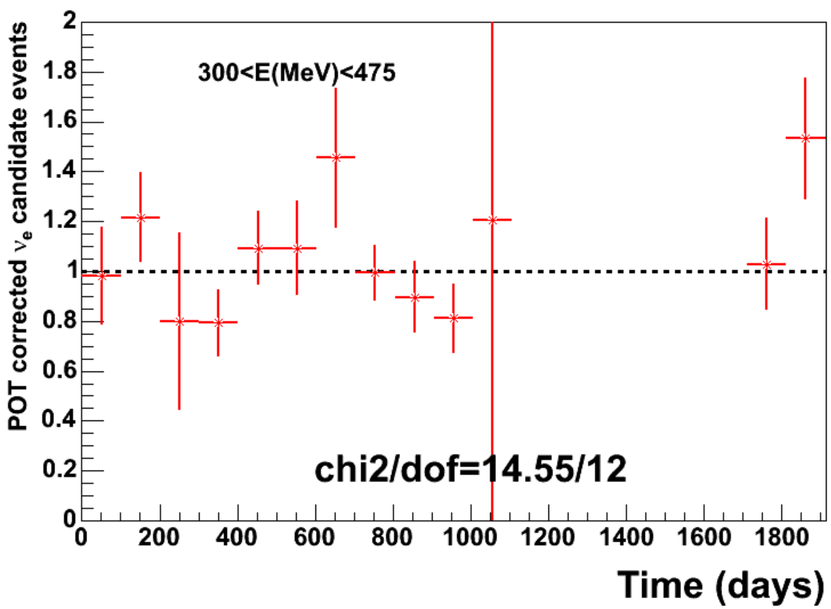
Update #4: Additional cut to remove dirt events

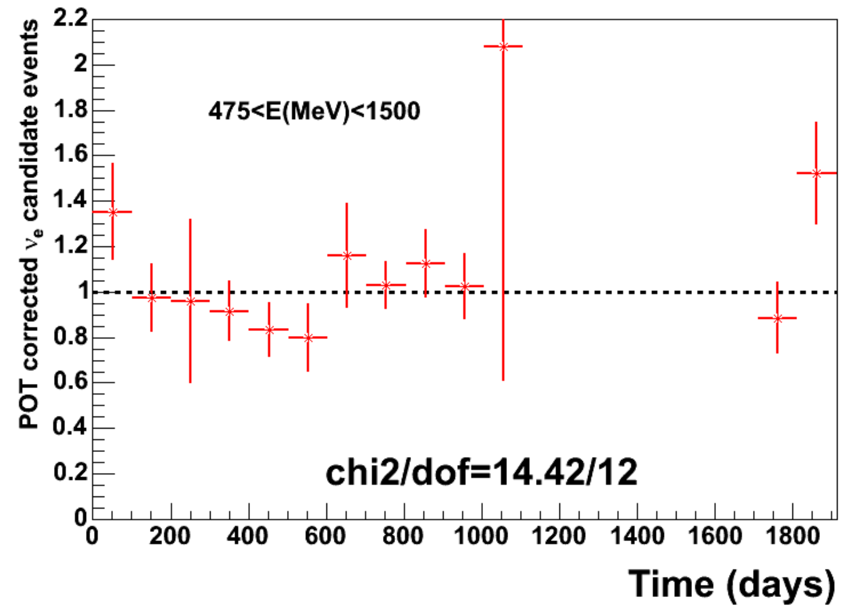
- Consistency-check: look at radial distribution after dirt cut applied
  - Uniform excess throughout tank



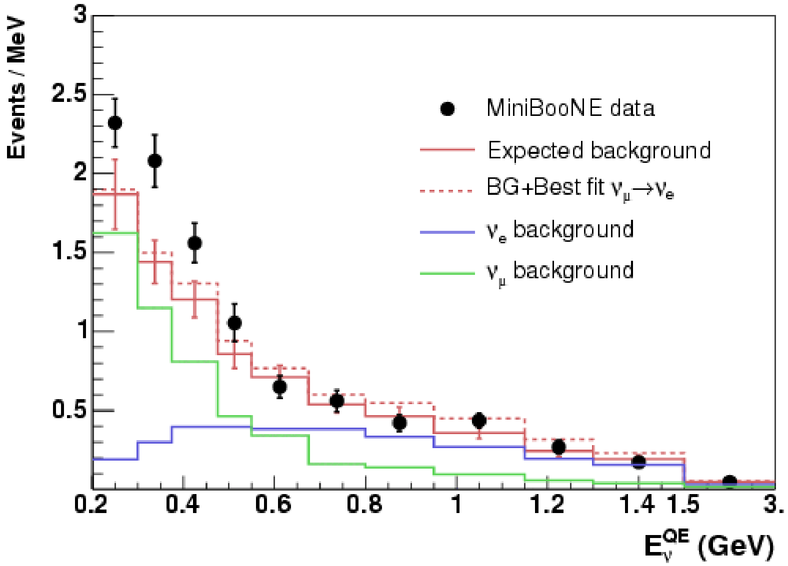
Update #5: New data

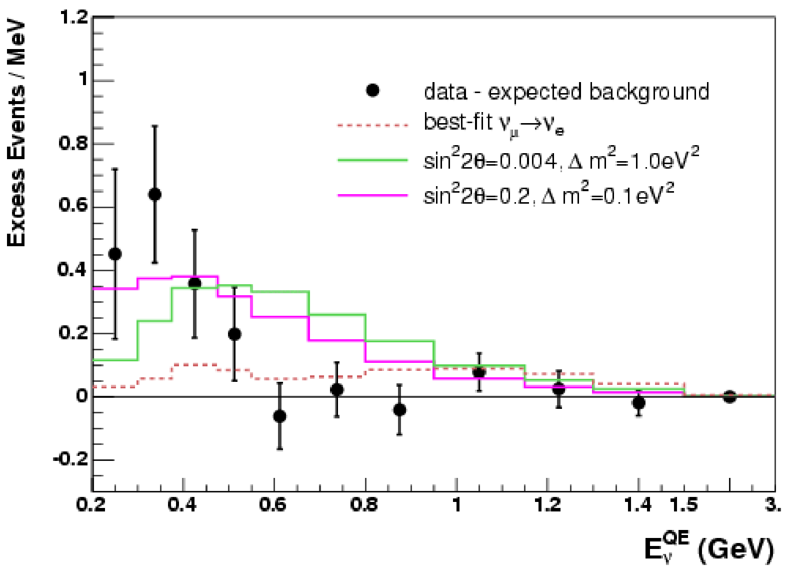
- Extra 0.83E20 POT during combined MiniBooNE/SciBooNE ν running
  - ν_e–like events per POT evenly distributed throughout duration of run
- Update #5 bottom line: ν_e–like event rate slightly higher for new data, but perfectly acceptable





Full update: Extend 2ν fit to low E





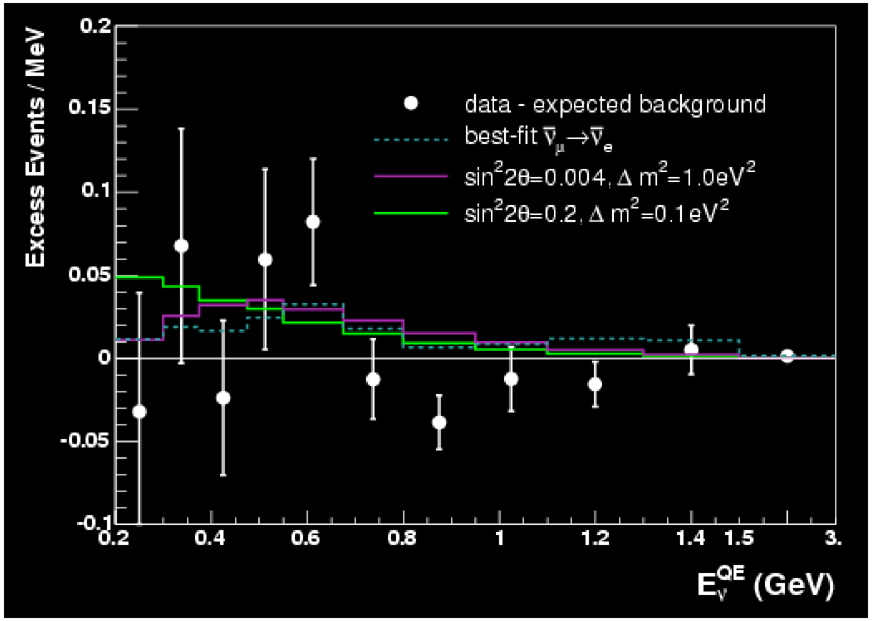
	E_ν>475 MeV	E_ν>200 MeV
Null fit χ^2 (prob.):	9.1(91%)	22.0(28%)
Best fit χ^2 (prob.):	7.2(93%)	18.3(37%)

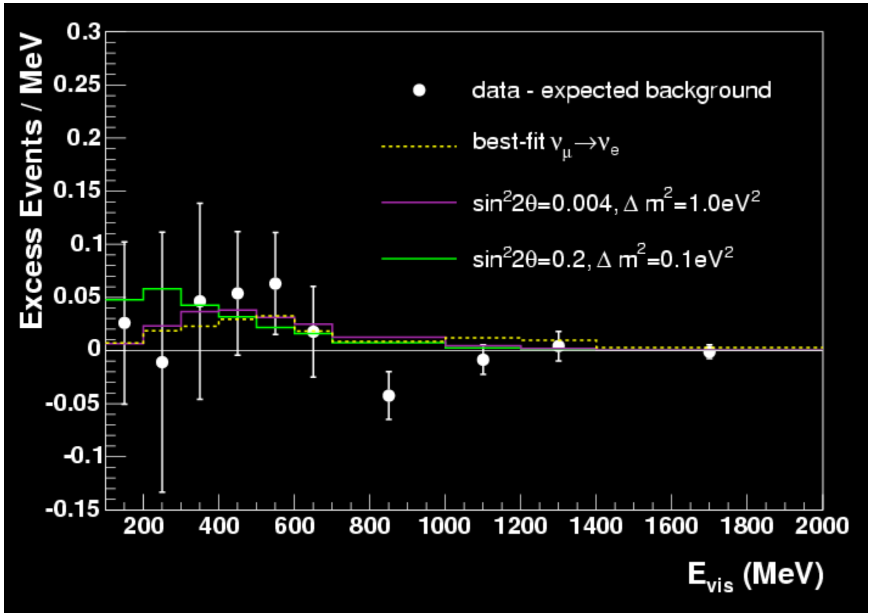
- Adding 3 bins to fit causes chi^2 to increase by 11 (expected 3)
- Can see the problem…the best 2ν fit that can be found does not describe the low E excess.

Background event breakdown nubar mode

N_{events}	200-475 MeV	475-1250 MeV
intrinsic ν_e	17.74	43.23
from $\pi^{\pm}/\mu^{\pm}$	8.44	17.14
from $K^{\pm}$, K^0	8.20	24.88
other ν_e	1.11	1.21
mis-id ν_μ	42.54	14.55
CCQE	2.86	1.24
NC π^0	24.60	7.17
Δ radiative	6.58	2.02
Dirt	4.69	1.92
other ν_μ	3.82	2.20
Total bkgd	60.29	57.78
LSND best fit	4.33	12.63

Data–MC prediction versus energy (nubar)





- Best fit is not very different from LSND oscillations, easily within large error bars.

Systematic error comparison

Source	$\bar{\nu}$ mode uncer. (%)		ν mode uncer. (%)	
E_ν^{QE} range (MeV)	*200-475*	*475-1100*	*200-475*	*475-1100*
Flux from π^+/μ^+ decay	0.4	0.7	1.8	2.2
Flux from π^-/μ^- decay	3.3	2.2	0.1	0.2
Flux from K^+ decay	2.3	4.9	1.4	5.7
Flux from K^- decay	0.5	1.1	-	-
Flux from K^0 decay	1.5	5.7	0.5	1.5
Target and beam models	1.9	3.0	1.3	2.5
ν cross section	6.4	12.9	5.9	11.9
NC π^0 yield	1.7	1.6	1.4	1.9
Hadronic interactions	0.5	0.6	0.8	0.3
External interactions (dirt)	2.4	1.2	0.8	0.4
Optical model	9.8	2.8	8.9	2.3
Electronics & DAQ model	9.7	3.0	5.0	1.7
Total (unconstrained)	*16.3*	*16.2*	*12.3*	*14.2*

Chi2 values

E_ν^{QE} fit	χ^2_{null}(dof) χ^2-prob	χ^2_{null}(dof)* χ^2-prob	$\chi^2_{best\text{-}fit}$(dof)* χ^2-prob	$\chi^2_{LSND\ best\text{-}fit}$(dof) χ^2-prob
> 200 MeV	24.51(19) 17.7%	20.18(17) 26.5%	18.18(17) 37.8%	20.14(19) 38.6%
> 475 MeV	22.19(16) 13.7%	17.88(14) 21.2%	15.91(14) 31.9%	17.63(16) 34.6%

(*Covariance matrix approximated to be the same everywhere by its value at best fit point)