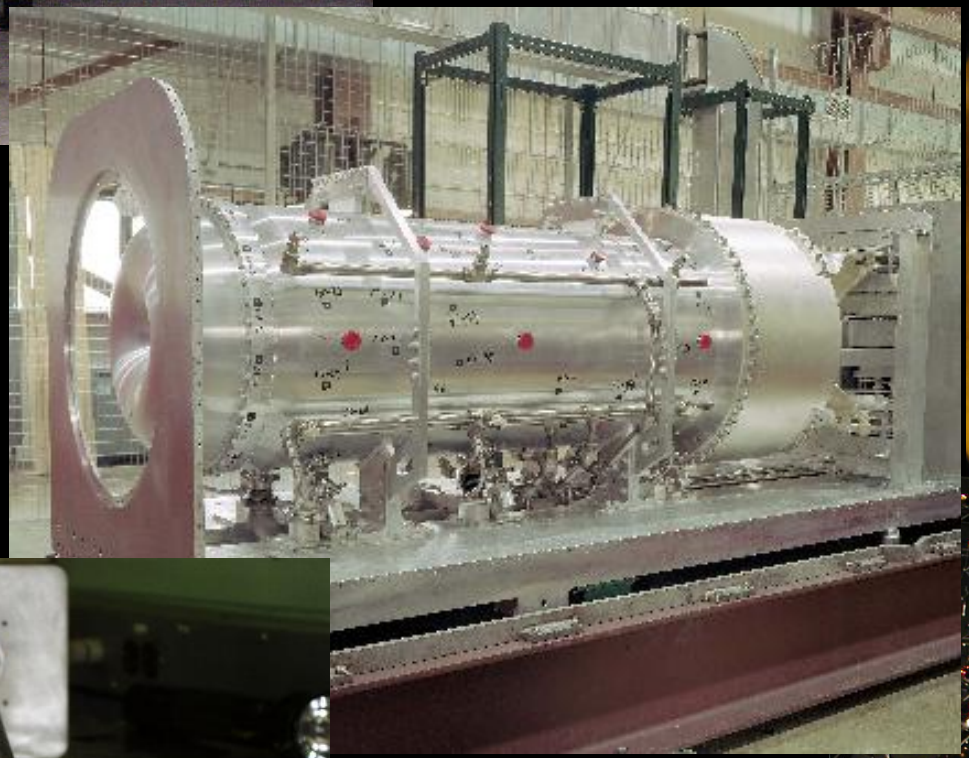
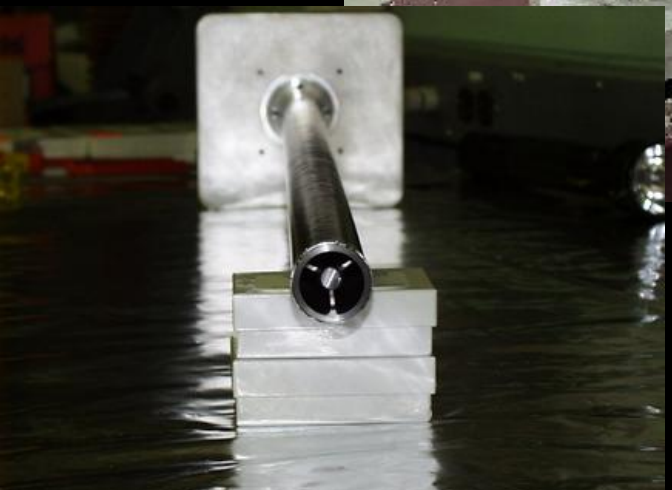
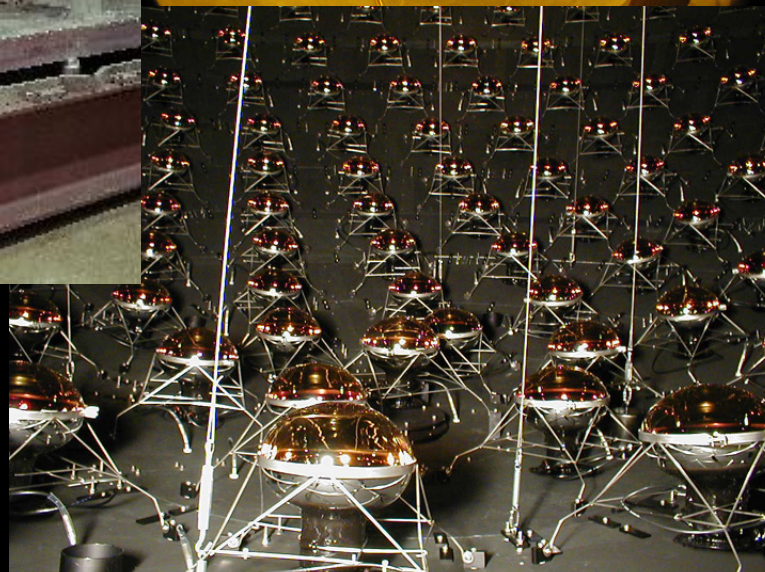
Oscillation Results from MiniBooNE

Chris Polly, Univ. of Illinois







The MiniBooNE Collaboration

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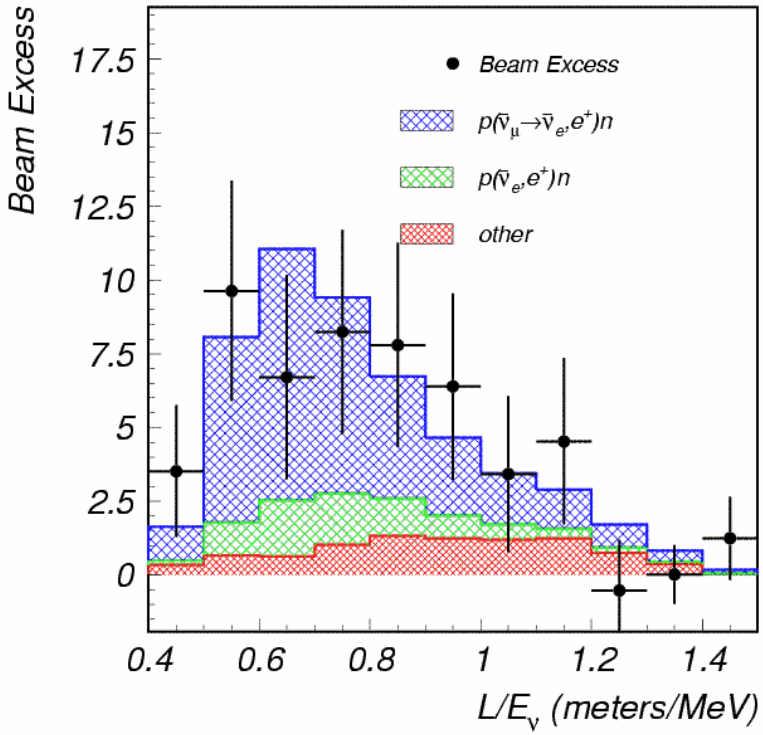
~80 physicists from ~18 institutions

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)

MiniBooNE's Motivation: The LSND signal



- LSND found an excess of $\overline{\nu}_e$ in $\overline{\nu}_\mu$ beam
- 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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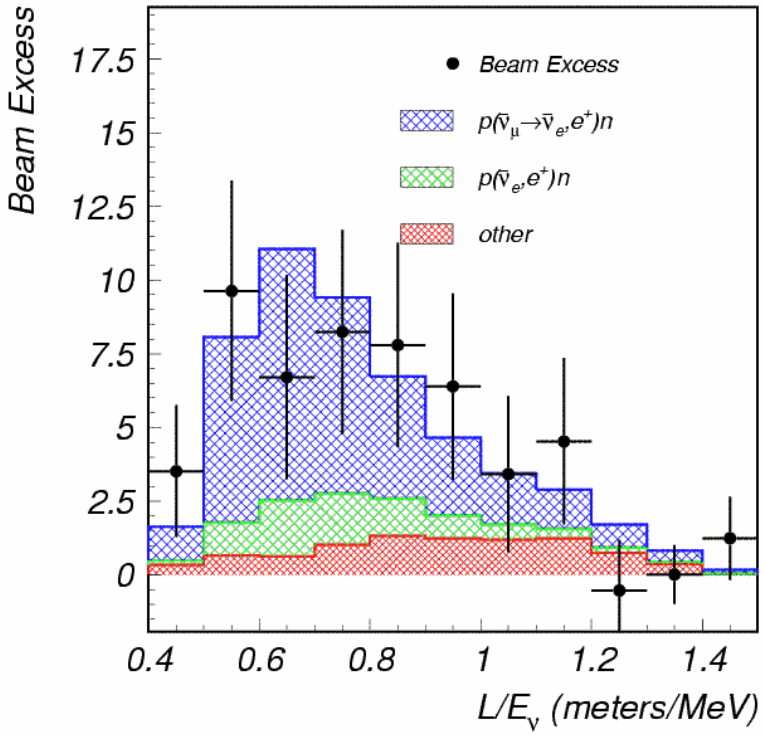

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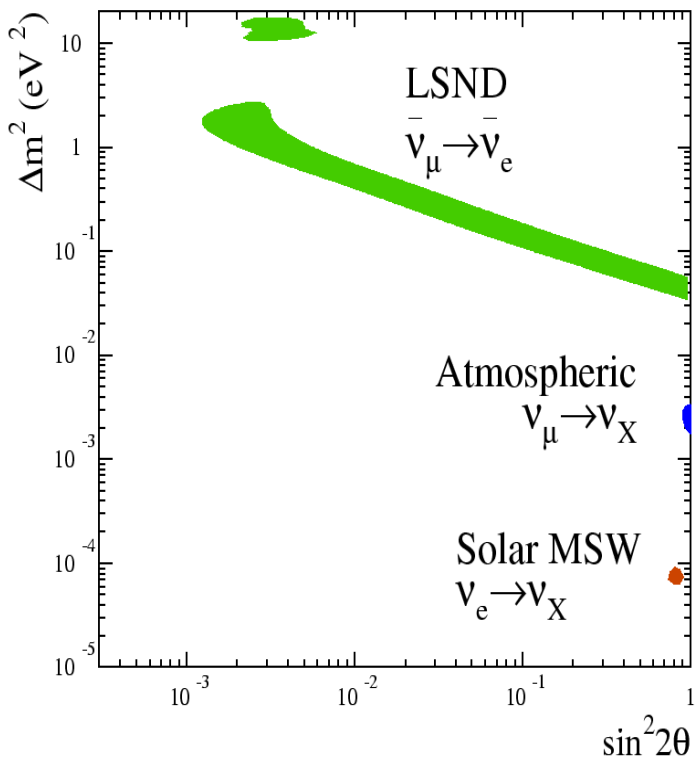
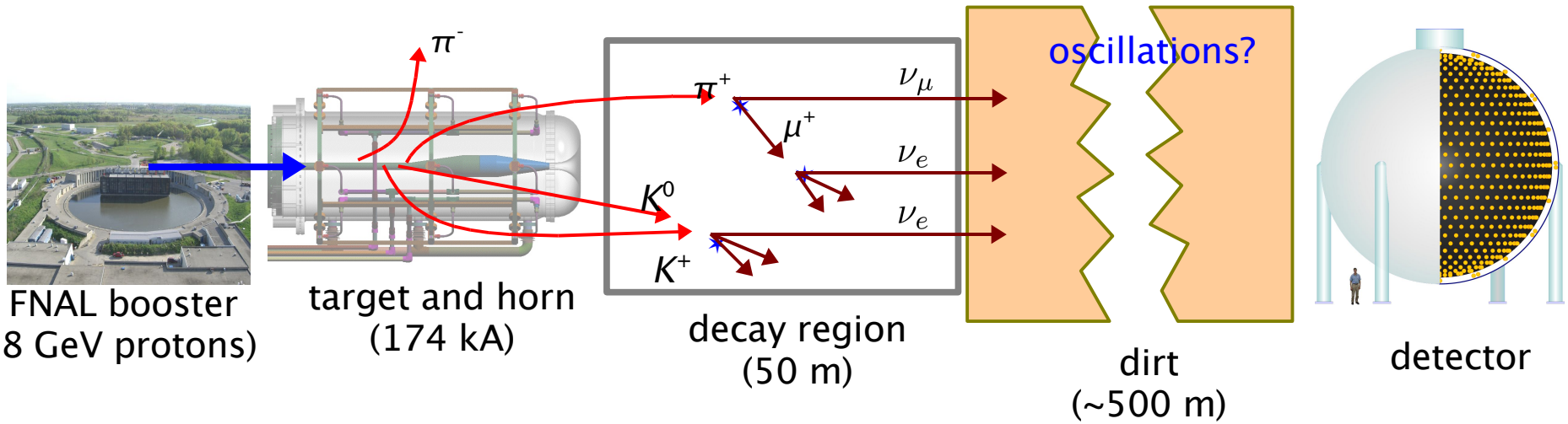


- $\Delta m^2 \sim 1$ eV^2 impossible with only 3ν
- Requires extraordinary physics!
  - Sterile neutrinos *hep-ph/0305255*
  - Neutrino decay *hep-ph/0602083*
  - Lorentz/CPT viol. *PRD(2006)105009* (T. Katori, A. Kostelecky, R. Tayloe)
  - Extra dimensions *hep-ph/0504096*
- Unlike atmos and solar...LSND unconfirmed

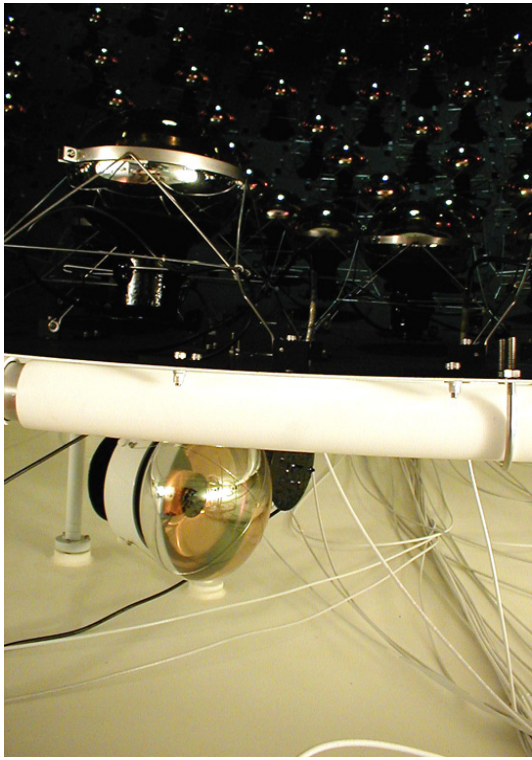
The MiniBooNE design strategy...must make ν_μ



- 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:

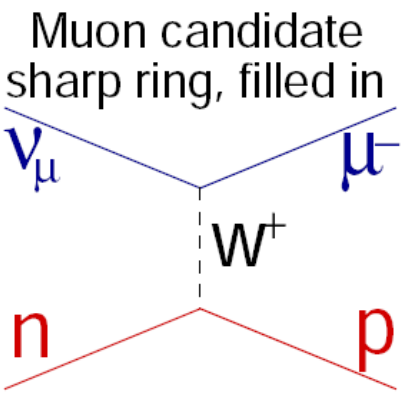
  MiniBooNE: (0.5 km) / (0.8 GeV)

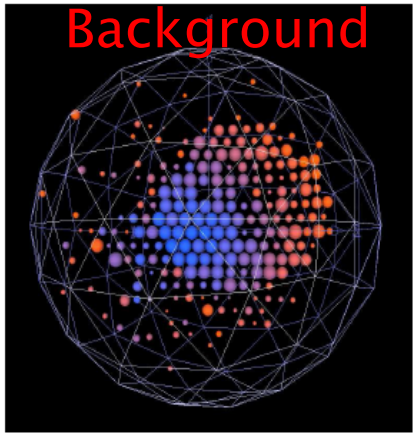
  LSND: (0.03 km) / (0.05 GeV)
- Detect ν interactions in 800T pure mineral oil detector
  - 1280 8" PMTs provide 10% coverage of fiducial volume
  - 240 8" PMTs provide active veto in outer radial shell

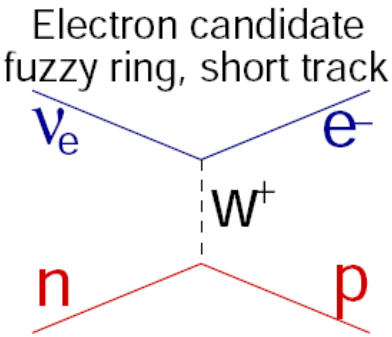


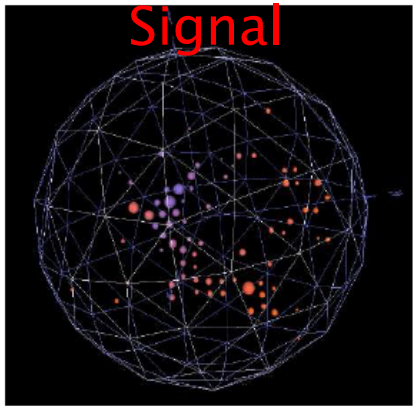
Key points about the signal

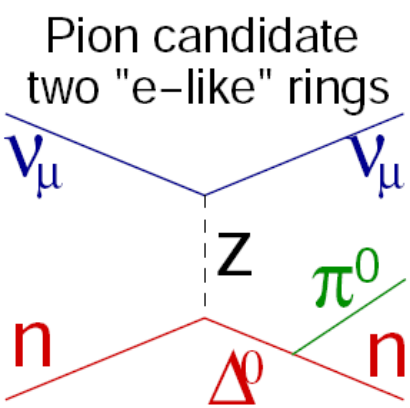
- LSND oscillation probability is < 0.3%
- After cuts, MiniBooNE has to be able to find ~300 ν_e CCQE interactions in a sea of ~150,000 ν_μ CCQE
- Intrinsic ν_e background
  - Actual ν_e produced in the beamline from muons and kaons
  - Irreducible at the event level
  - E spectrum differs from signal
- 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

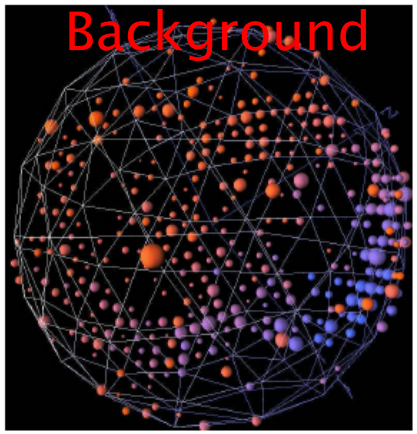




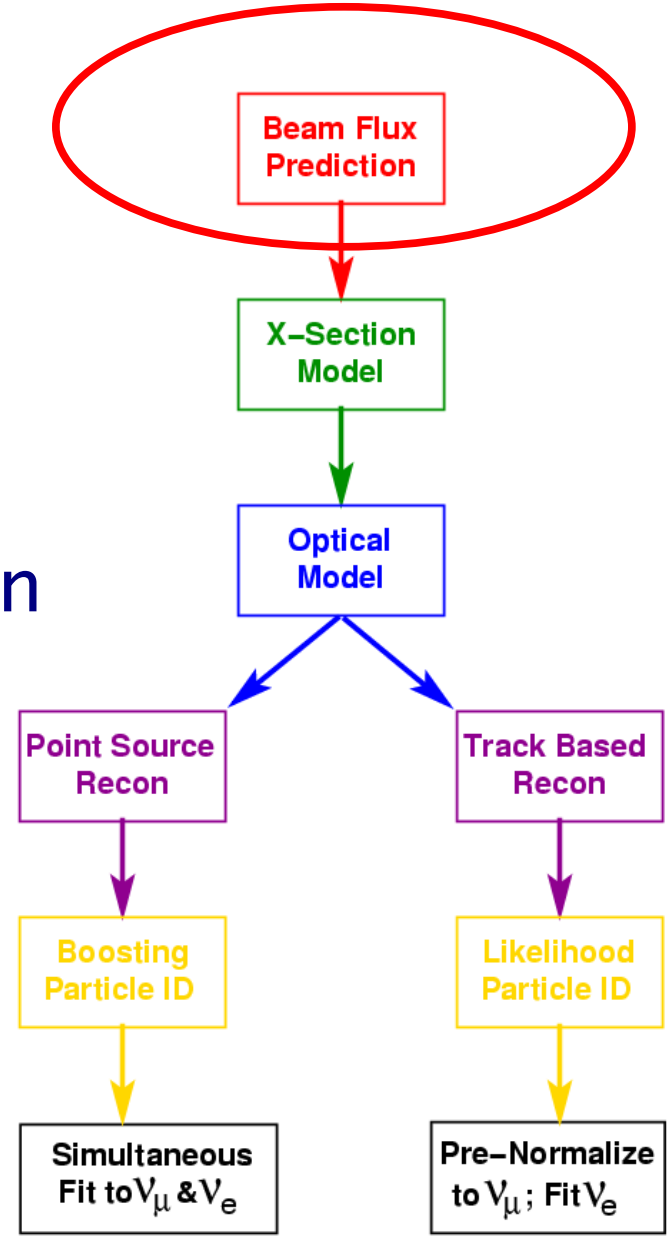






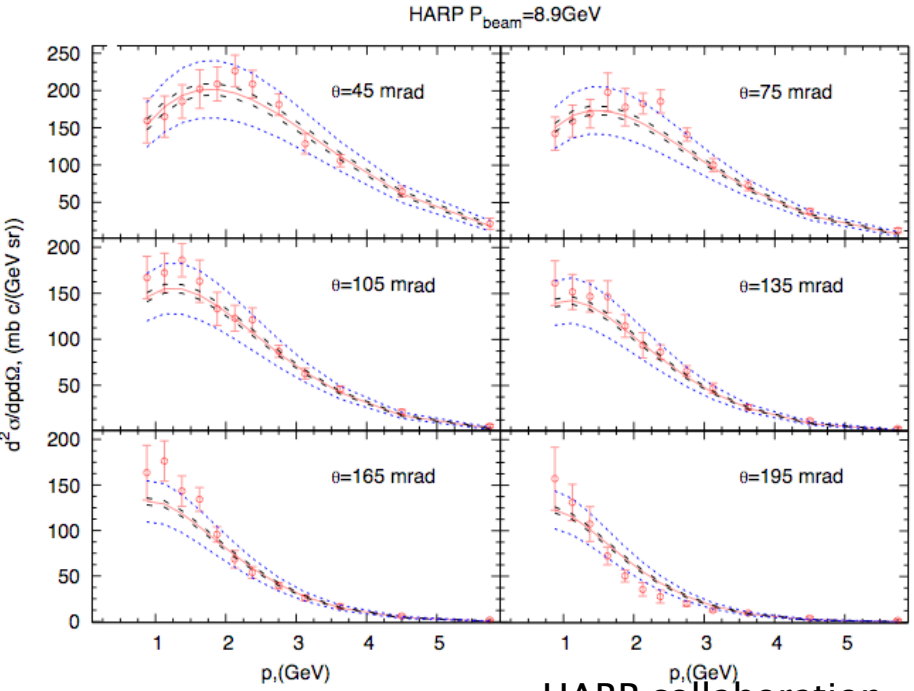


Analysis Chain: Flux Prediction



Meson production at the target

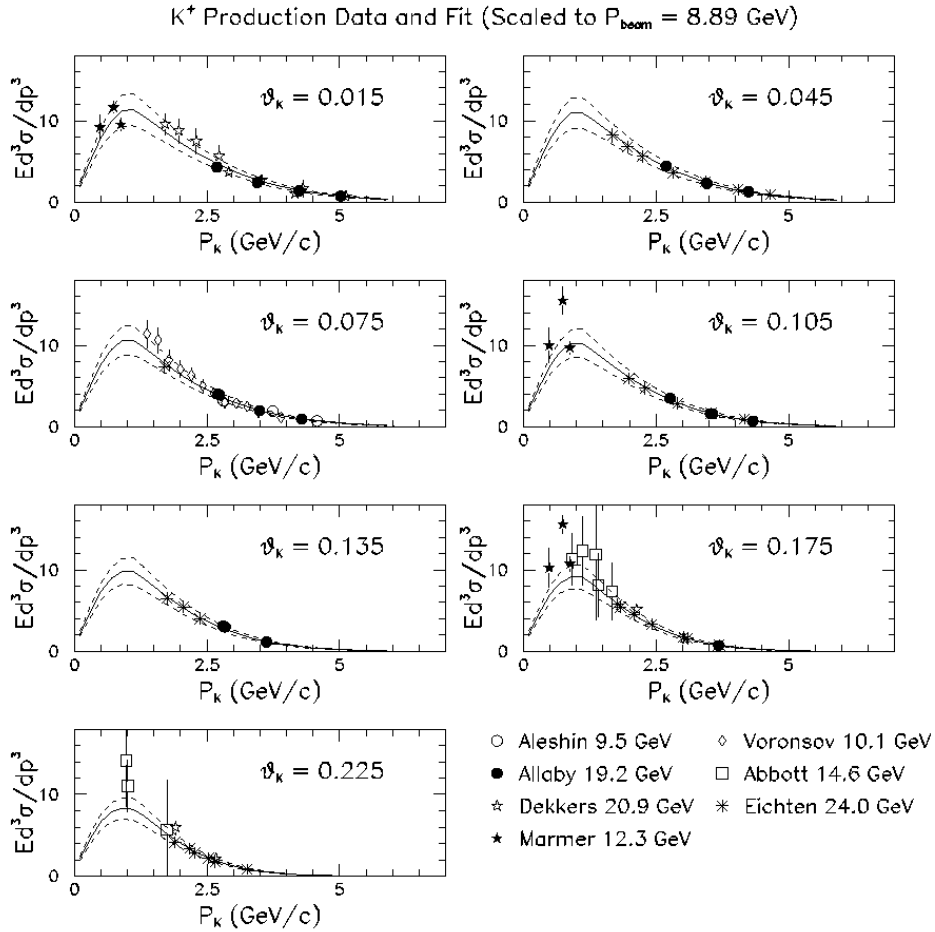
Pions:



HARP collaboration, hep-ex/0702024

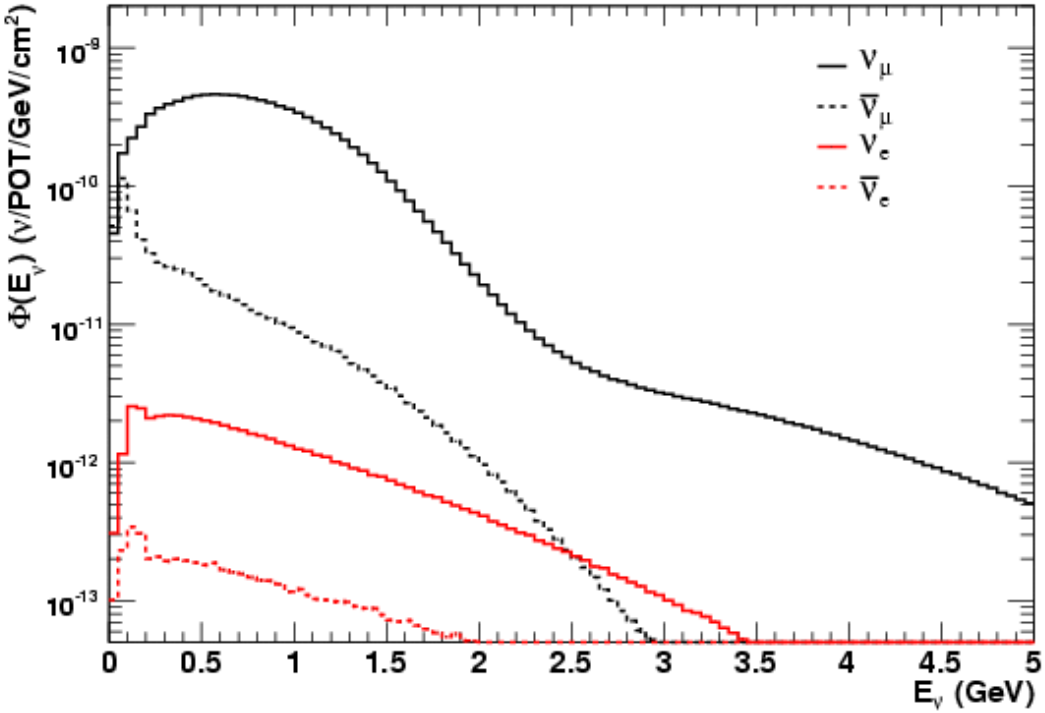
- MiniBooNE members joined the HARP collaboration
  - 8 GeV proton beam
  - 5% λ Beryllium target
- Data were fit to Sanford-Wang parameterization for '07 analysis

Kaons:



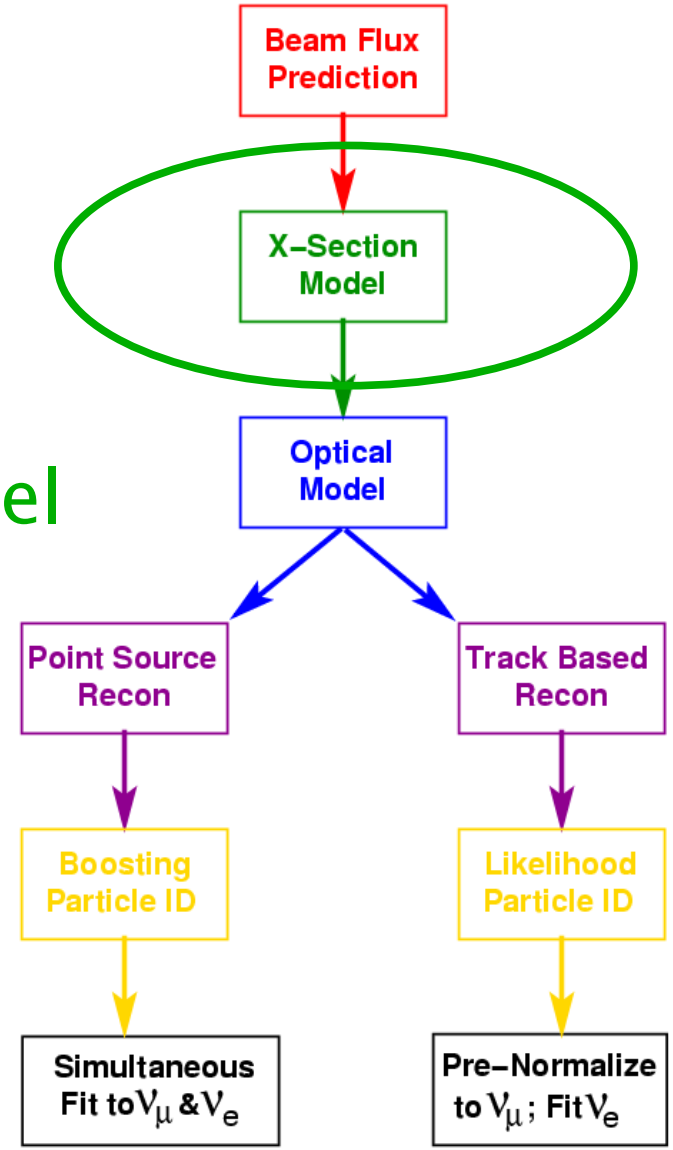
- Kaon data taken on multiple targets in 10-24 GeV range
- Fit to world data using Feynman scaling
- 30% overall uncertainty assessed

Final neutrino flux estimation



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

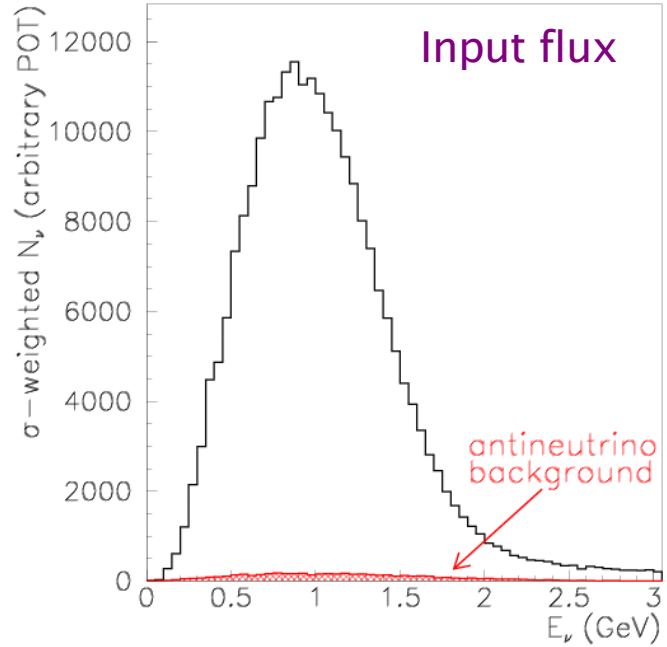
Analysis Chain: X-Section Model

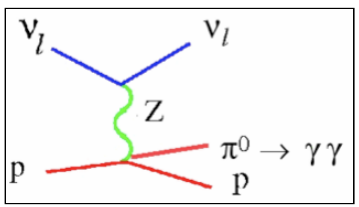


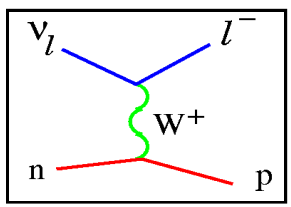
Nuance Monte Carlo

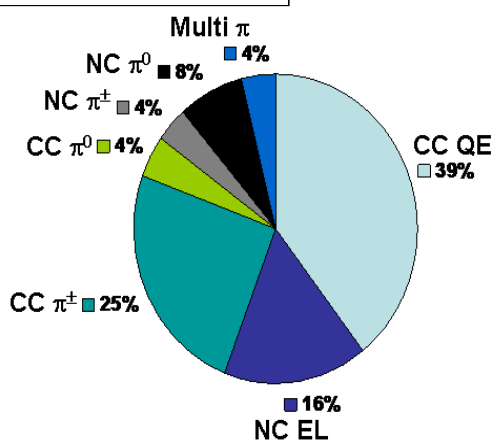
D. Casper, NPS, 112 (2002) 161

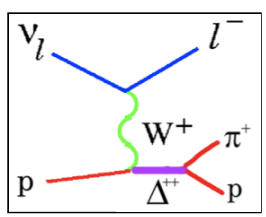
- Comprehensive generator, covers entire E_ν range
- Predicts rates and kinematics of specific ν interactions from input flux
- Expected interaction rates in MiniBooNE (before cuts) shown below
- Based on world data, ν_μ CC shown below right

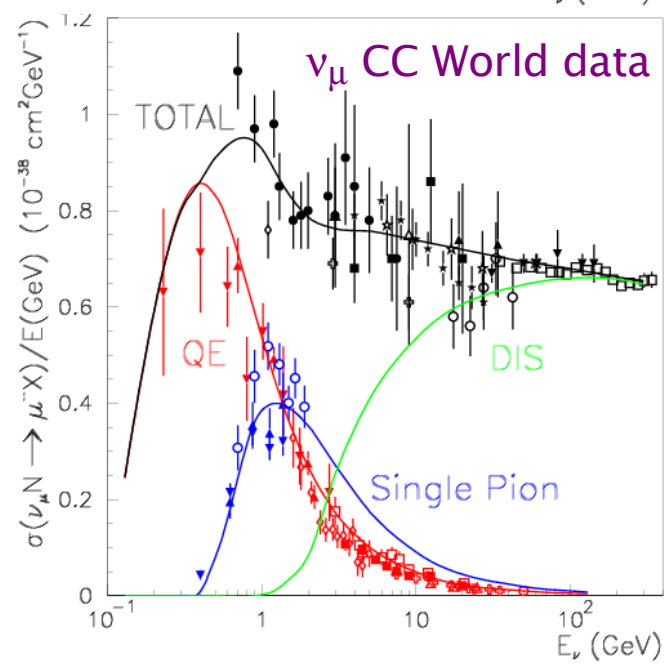








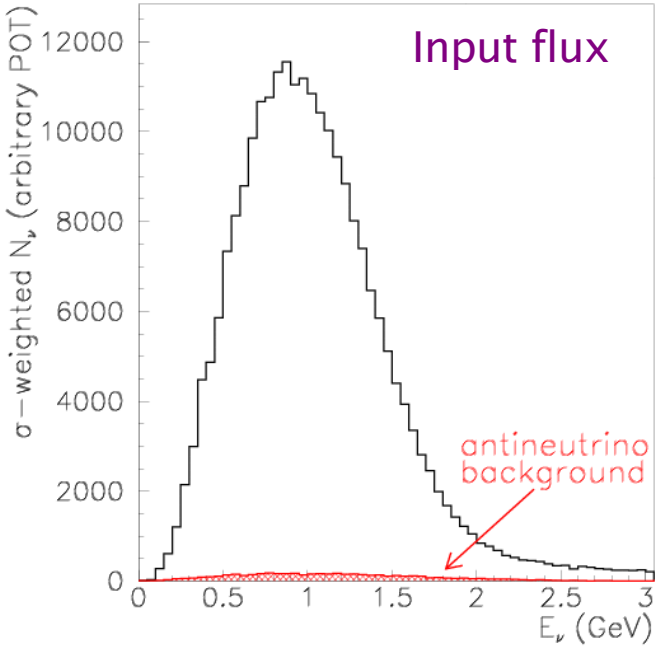


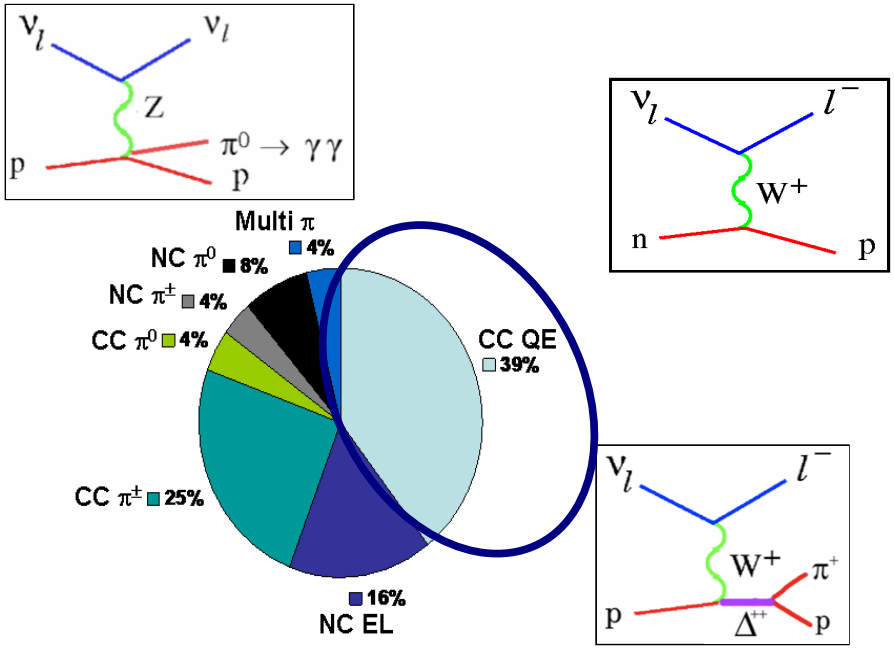


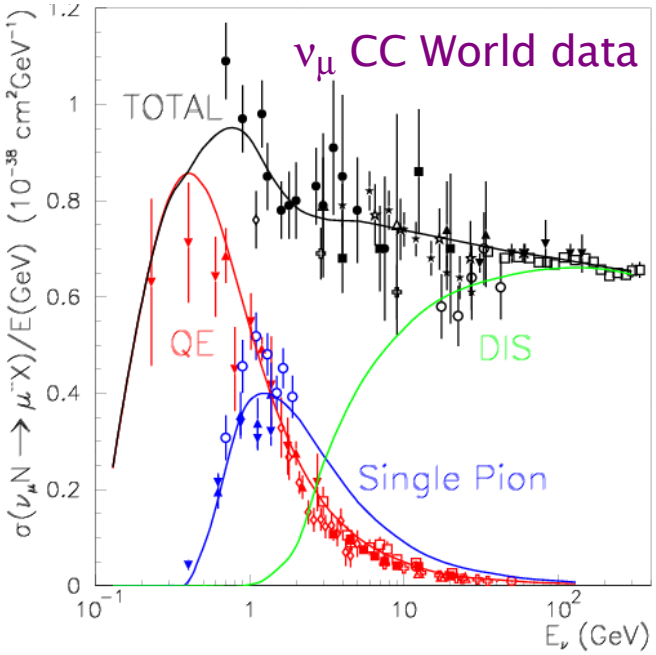
Nuance Monte Carlo

D. Casper, NPS, 112 (2002) 161

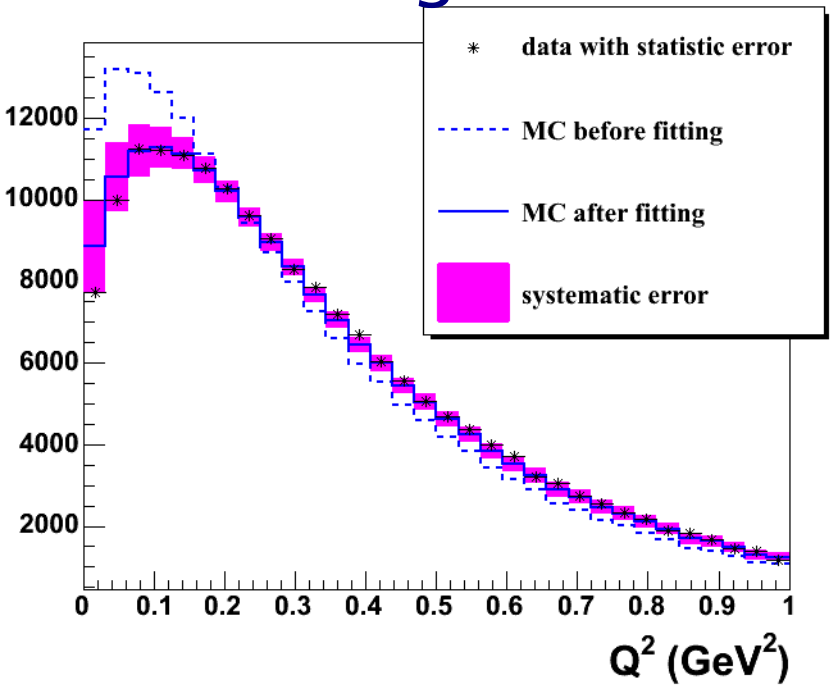
- Comprehensive generator, covers entire E_ν range
- Predicts relative rate and kinematics of specific ν interactions from input flux
- Expected interaction rates in MiniBooNE (before cuts) shown below
- Based on world data, ν_μ CC shown below right
- Also tuned on internal data



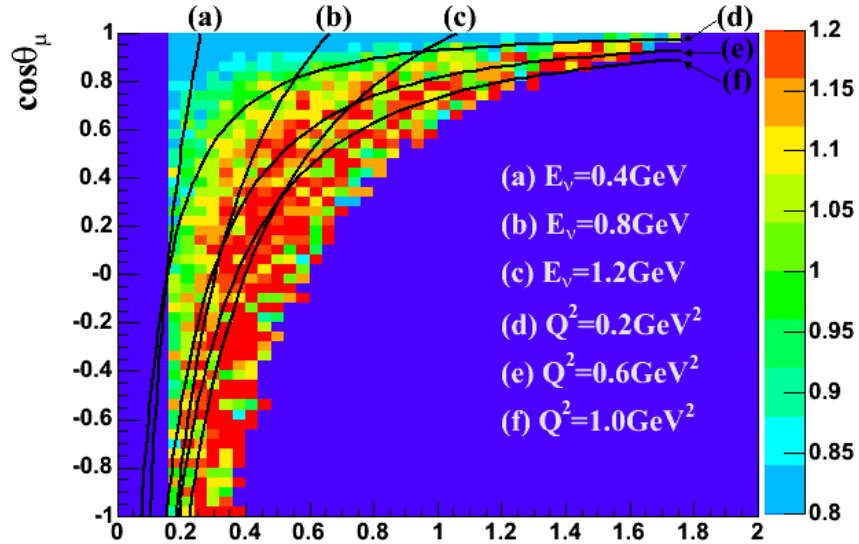




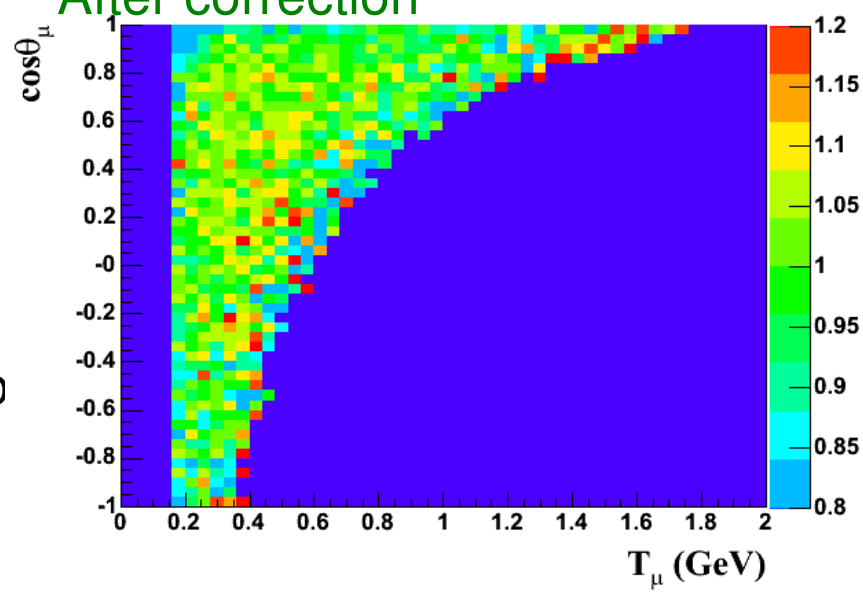
Tuning Nuance on internal ν_μ CCQE data



Before correction



After correction

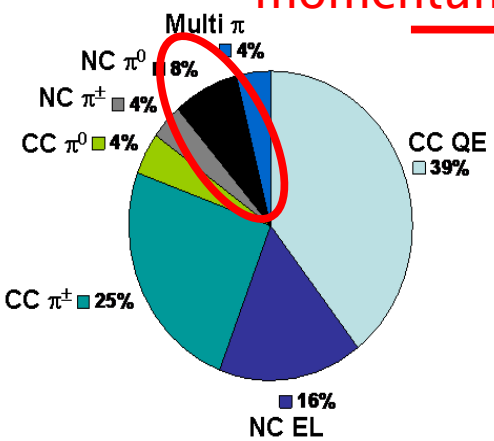


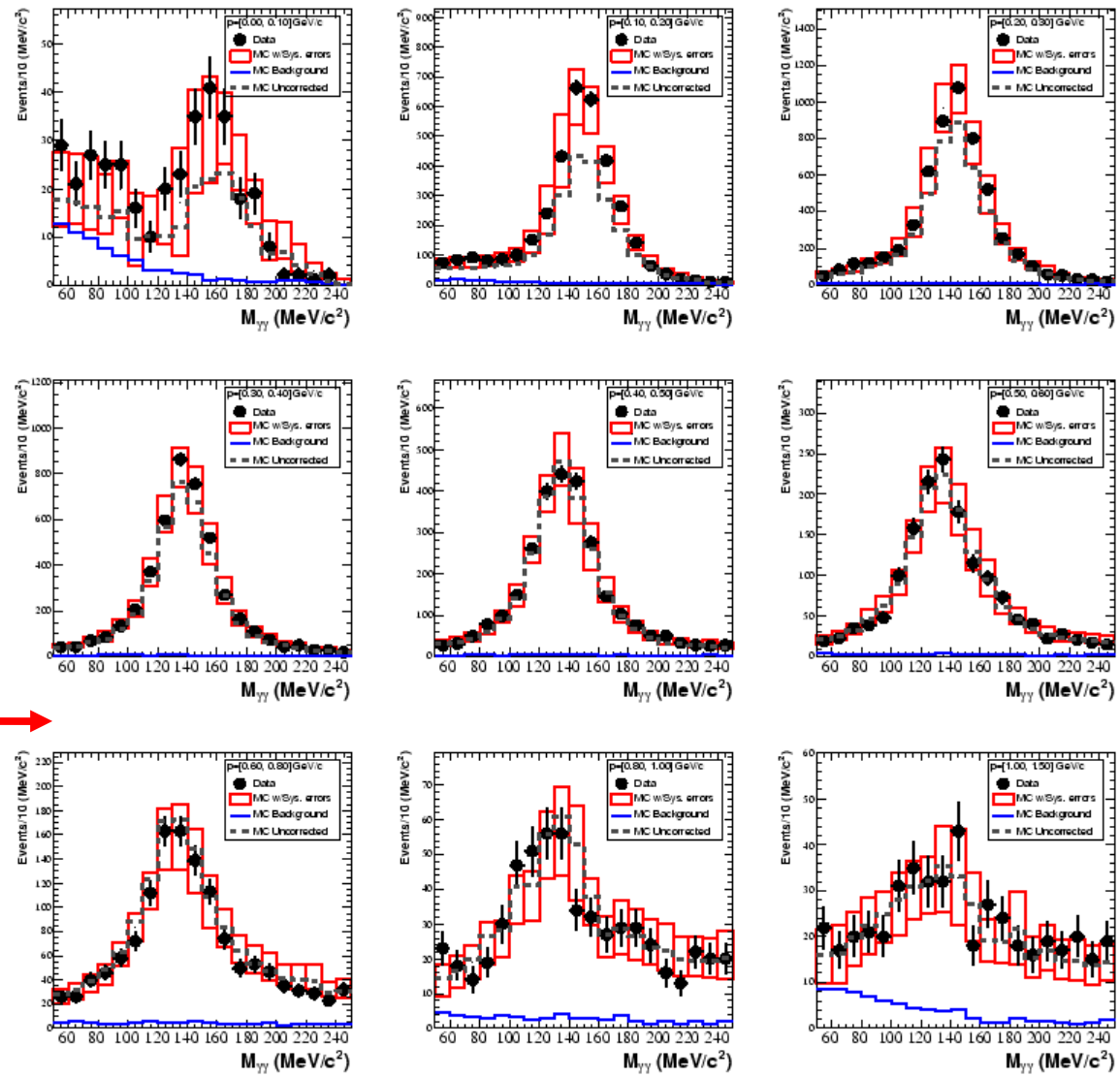
- Poor agreement in Q^2
- From Q^2 fits to MB ν_μ CCQE data extract:
  - M_A^{eff} -- effective axial mass
  - κ -- Pauli Blocking parameter
- Beautiful agreement after Q^2 fit, even in 2D
- Ability to make these 2D plots is unique due to MiniBooNE's high statistics

Tuning Nuance on internal NC π^0 data

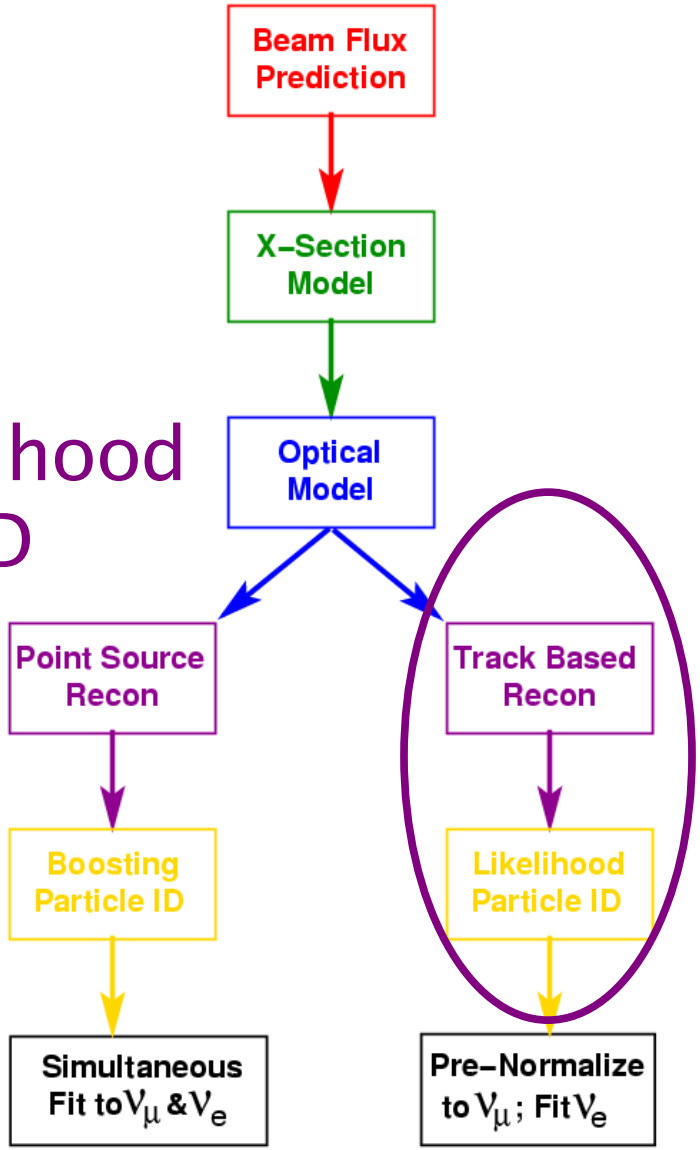
- NC π^0 important background
- 97% pure π^0 sample (mainly $\Delta \rightarrow N\pi^0$)
- Measure rate as function of momentum
- Default MC underpredicts rate at low momentum
- $\Delta \rightarrow N\gamma$ also constrained

Invariant mass distributions in momentum bins





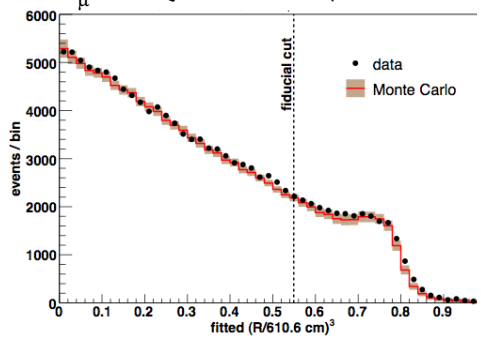
Analysis Chain: Track-Based Likelihood Reconstruction and Particle ID

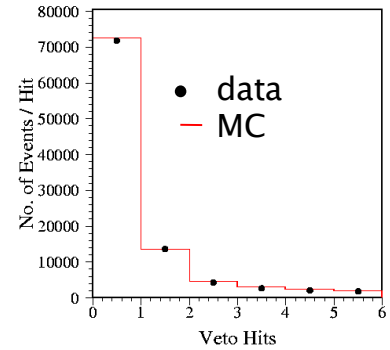


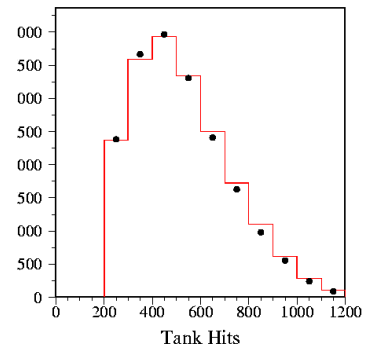
TBL Analysis: Separating e from μ

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

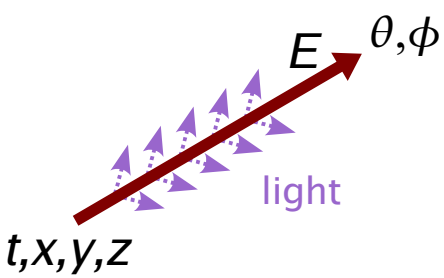
ν_μ CCQE events (2 subevent)

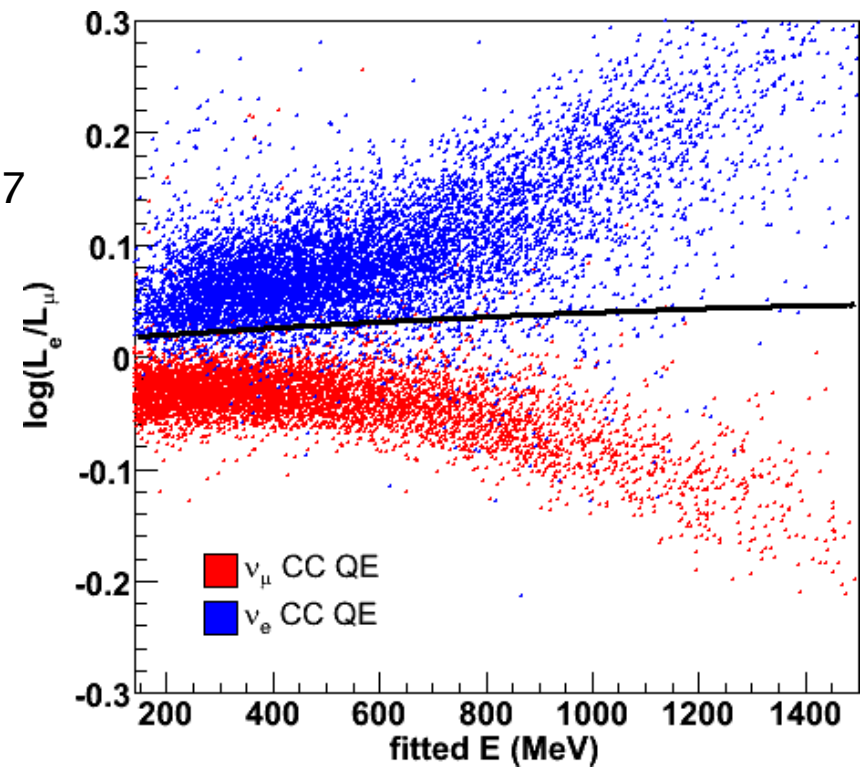






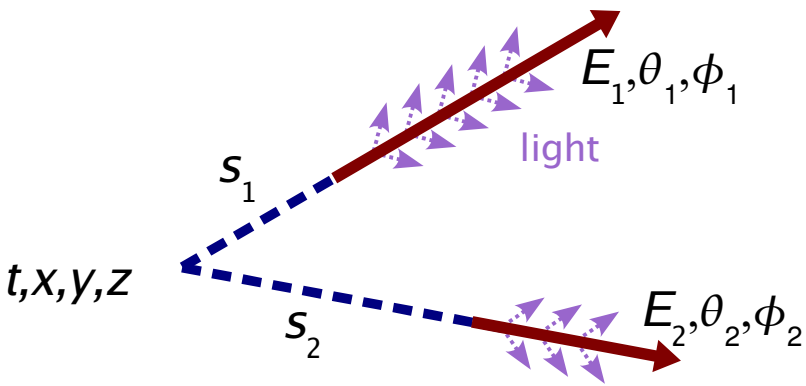
- Event is a collection of PMT-level info (q,t,x)
- Form sophisticated Q and T pdfs, and fit for 7 track parameters under 2 hypotheses
  - The track is due to an electron
  - The track is coming from a muon

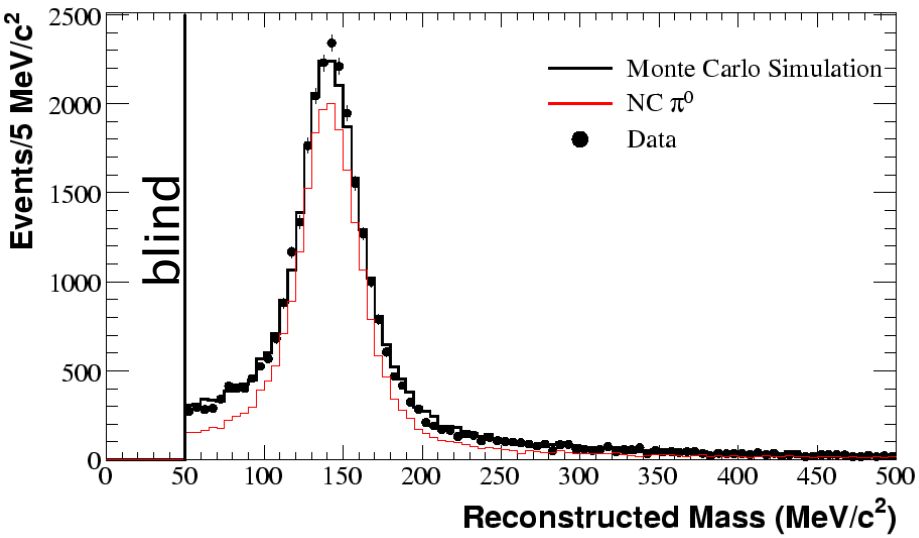


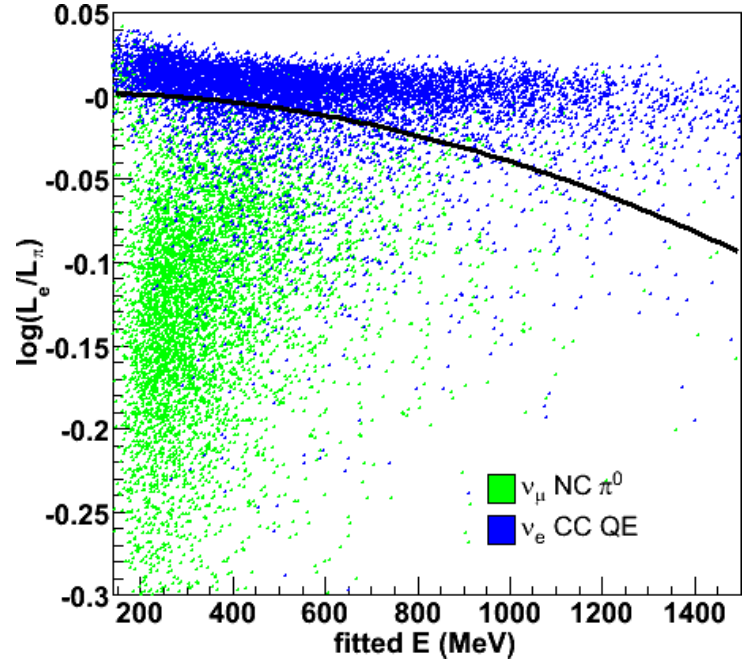


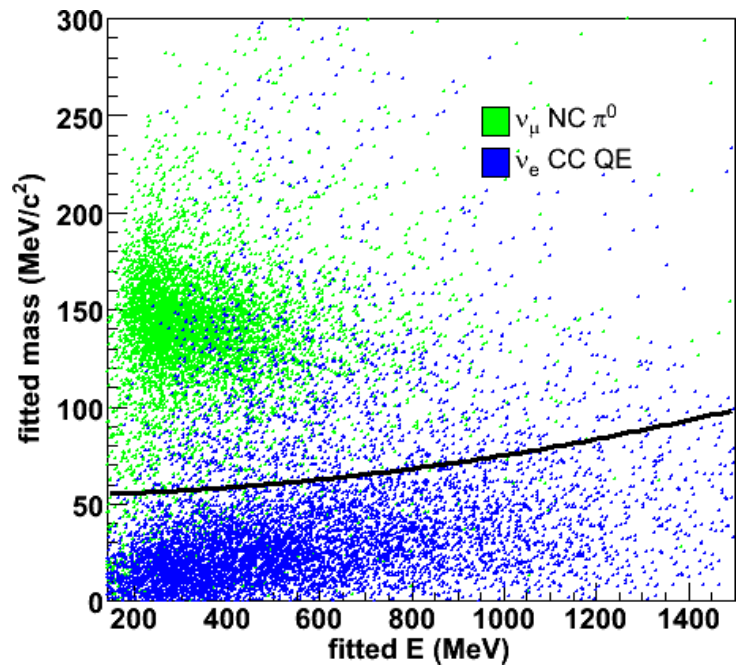
Separating e from π^0

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

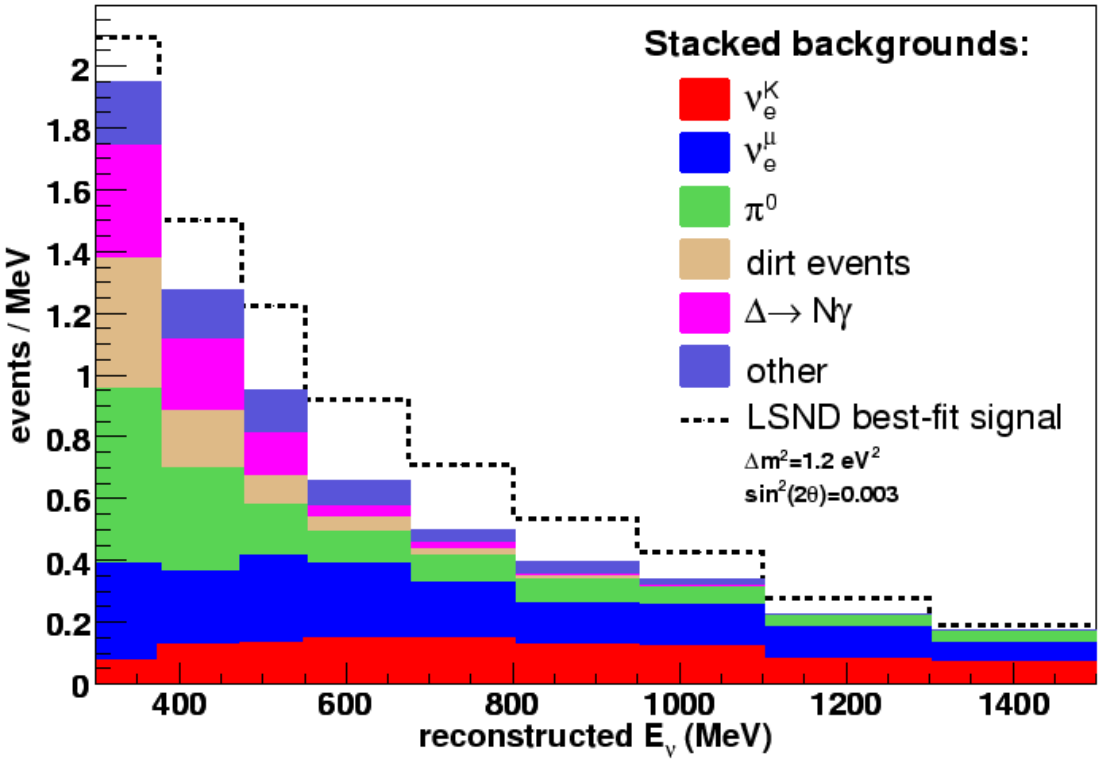








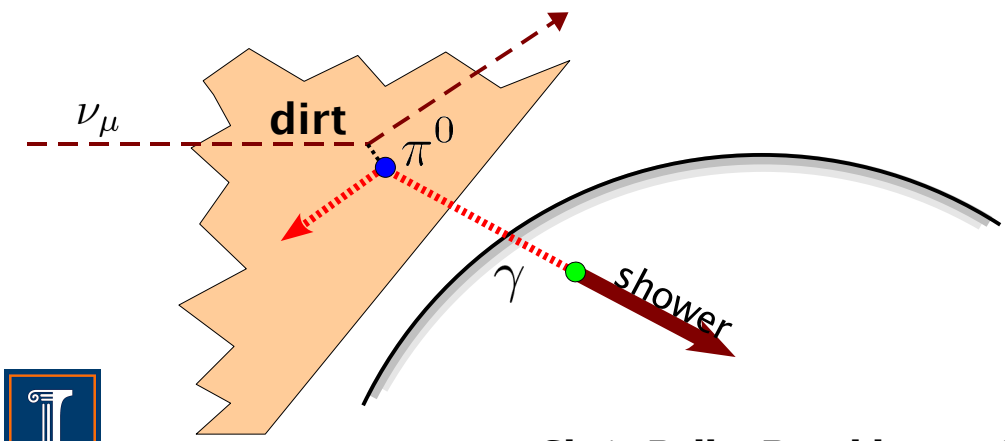
TBL Analysis: Expected event totals

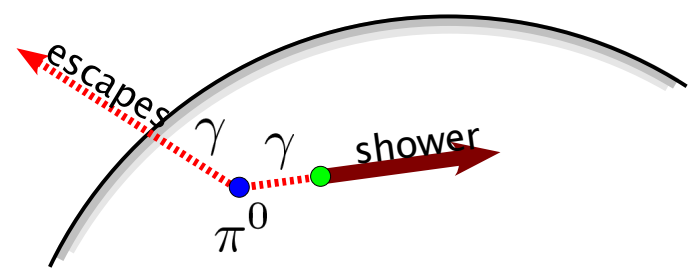


475 MeV – 1250 MeV

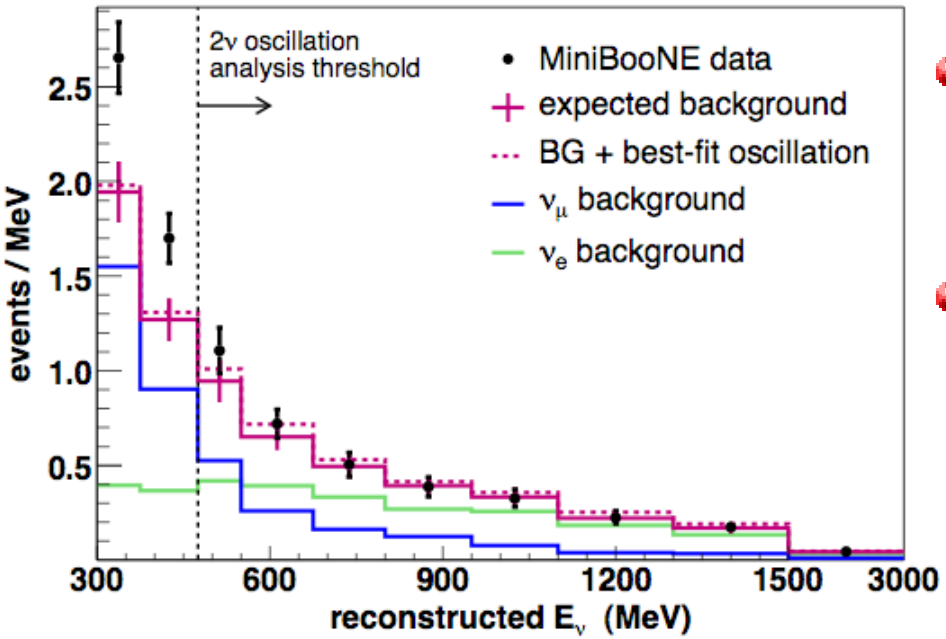
ν_e^K	94
ν_e^μ	132
π^0	62
dirt	17
$\Delta \rightarrow N\gamma$	20
other	33
total	358

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

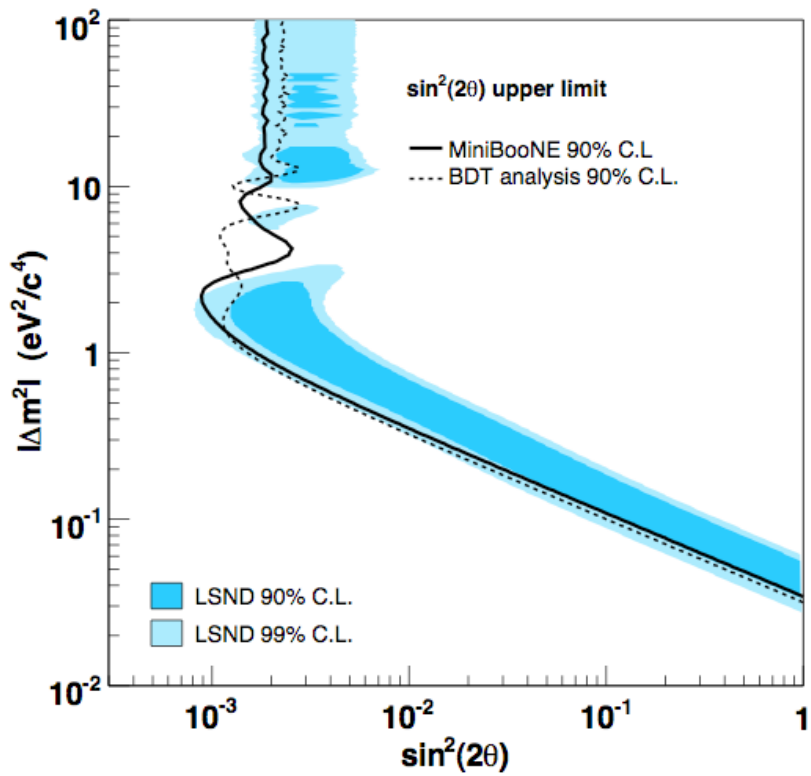




Data/fit result after blind analysis complete...



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



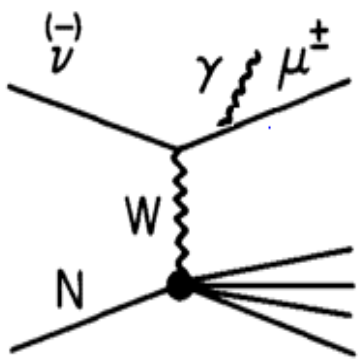
- What does it all mean? There are a few possibilities...
  - Some problem with LSND, e.g. mis-estimated background?
  - Difference between neutrinos and antineutrinos?
  - The physics causing the excess in LSND doesn't scale with L/E?
    - Low E excess in MB related?

Part 2: Exploring the Low E Excess

The low E excess has fueled much speculation...

Commonplace

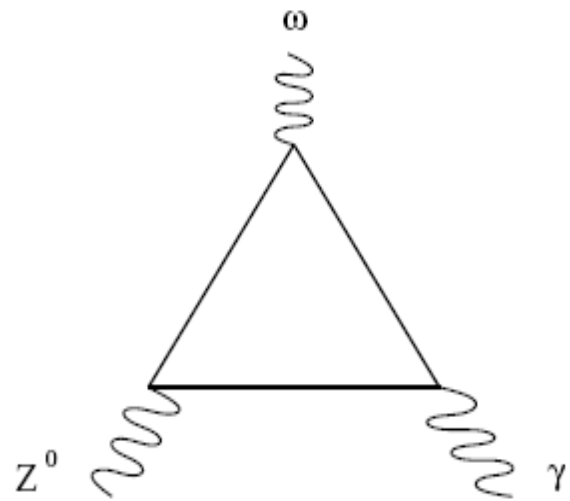
- Muon bremsstrahlung
  (Bodek, 0709.4004)



- 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

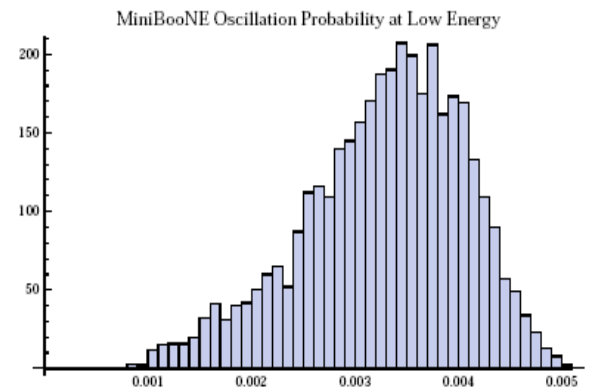
- Anomaly-mediated γ
  (Harvey, Hill, Hill, 0708.1281)



- Still under study, nuc. effects neglected, δg_{ω}
- Has to contribute...how much?

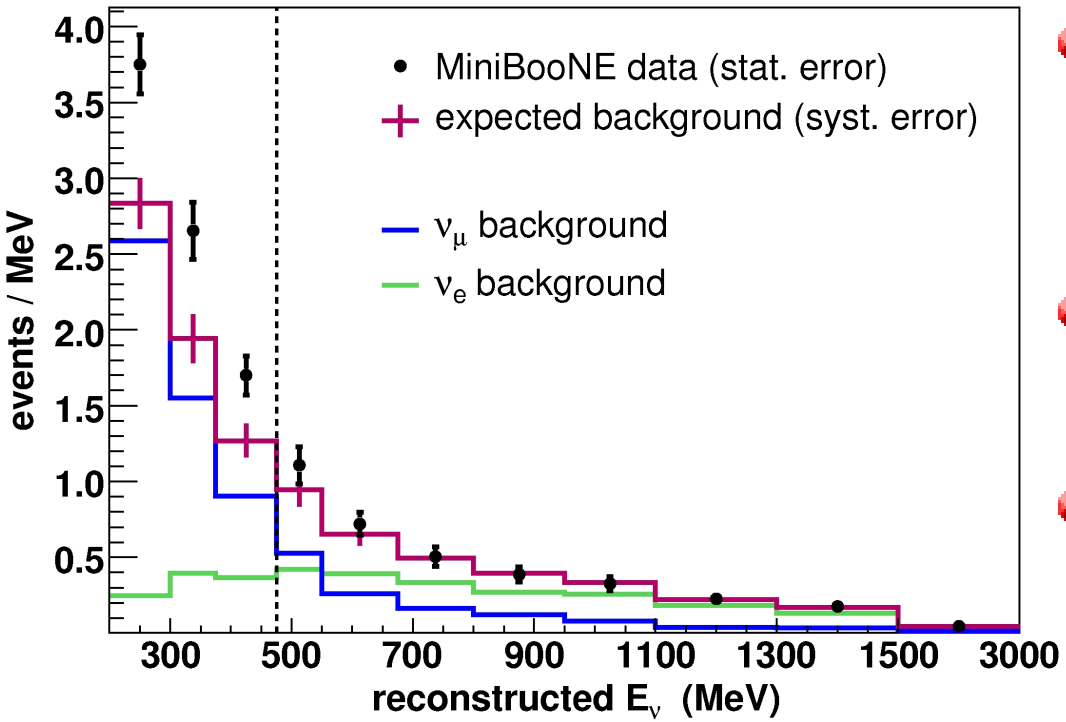
Beyond the SM

- New gauge boson
  (Nelson, Walsh,0711.1363)



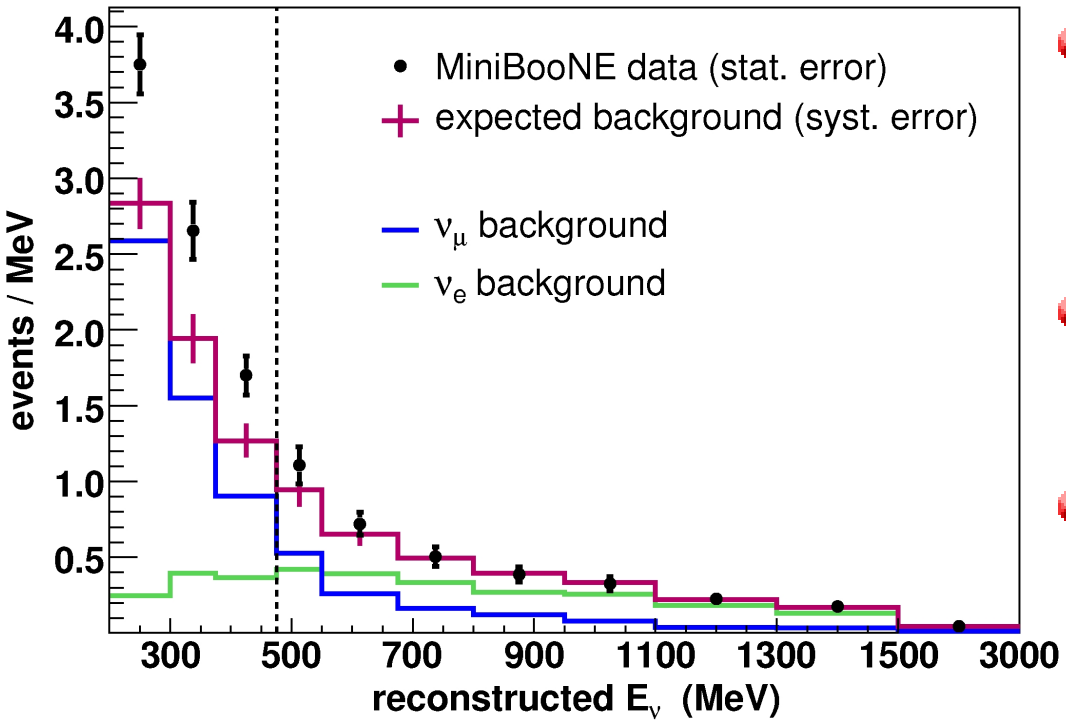
- Can accommodate LSND and MiniBooNE
- Firm prediction for anti-neutrinos

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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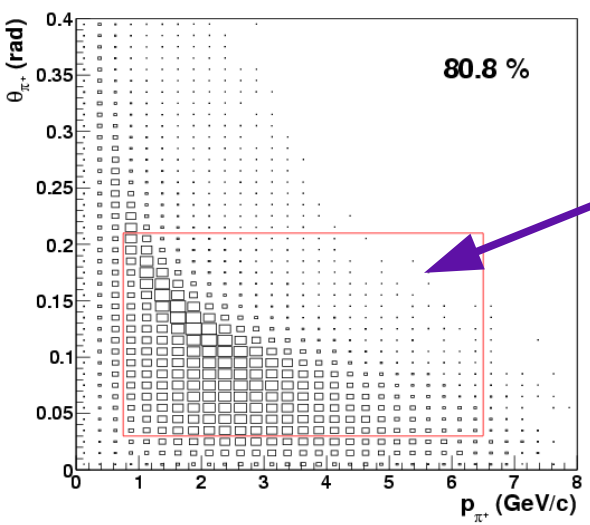
- Since this result a comprehensive review bkgs/errors with an emphasis at low E was performed...detailed updates to follow

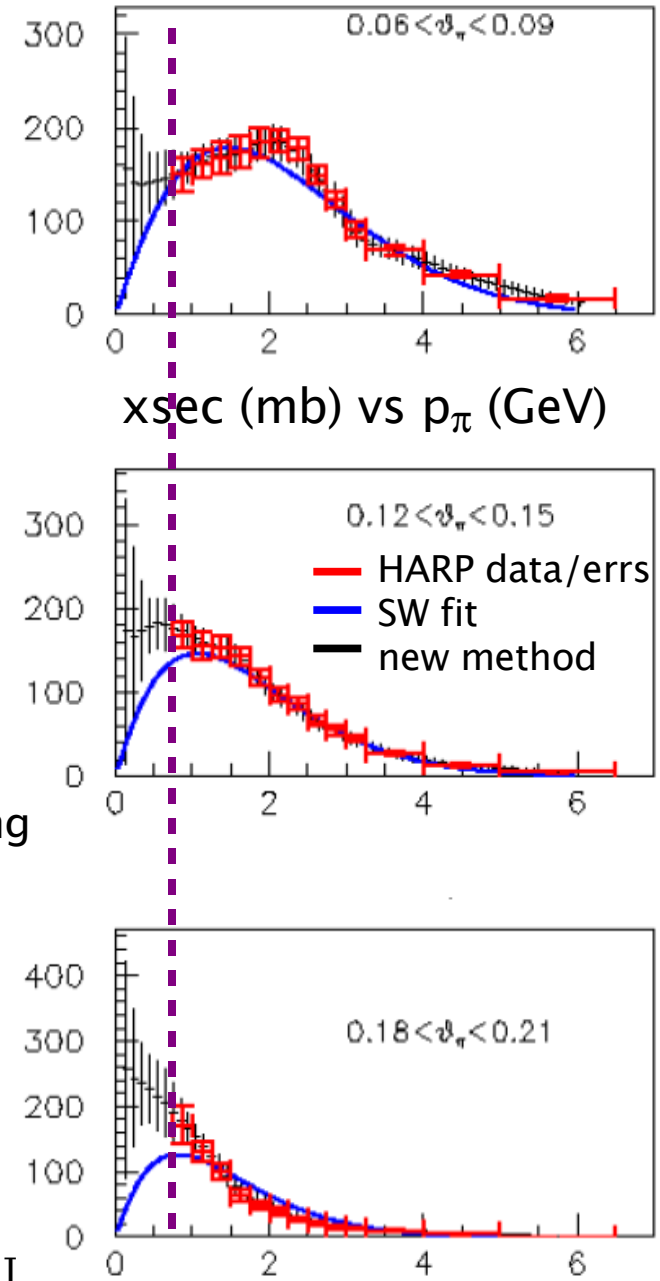
Update #1: Treatment of π flux errors

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



xsec (mb) vs p_π (GeV)

Update #1: Treatment of π flux errors

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- Fit HARP/E910 data to SW parameterization.
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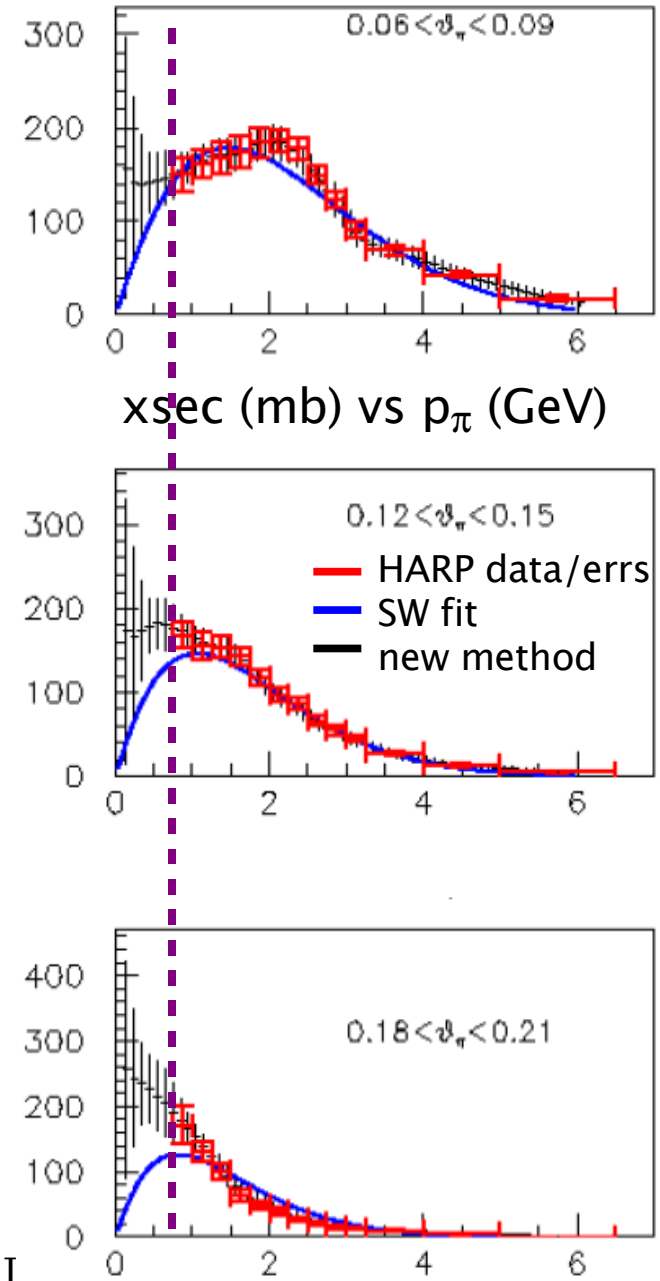
- Old Sol'n: inflate HARP error until χ^2 accept.
- Turns HARP's ~7% error into ~15%

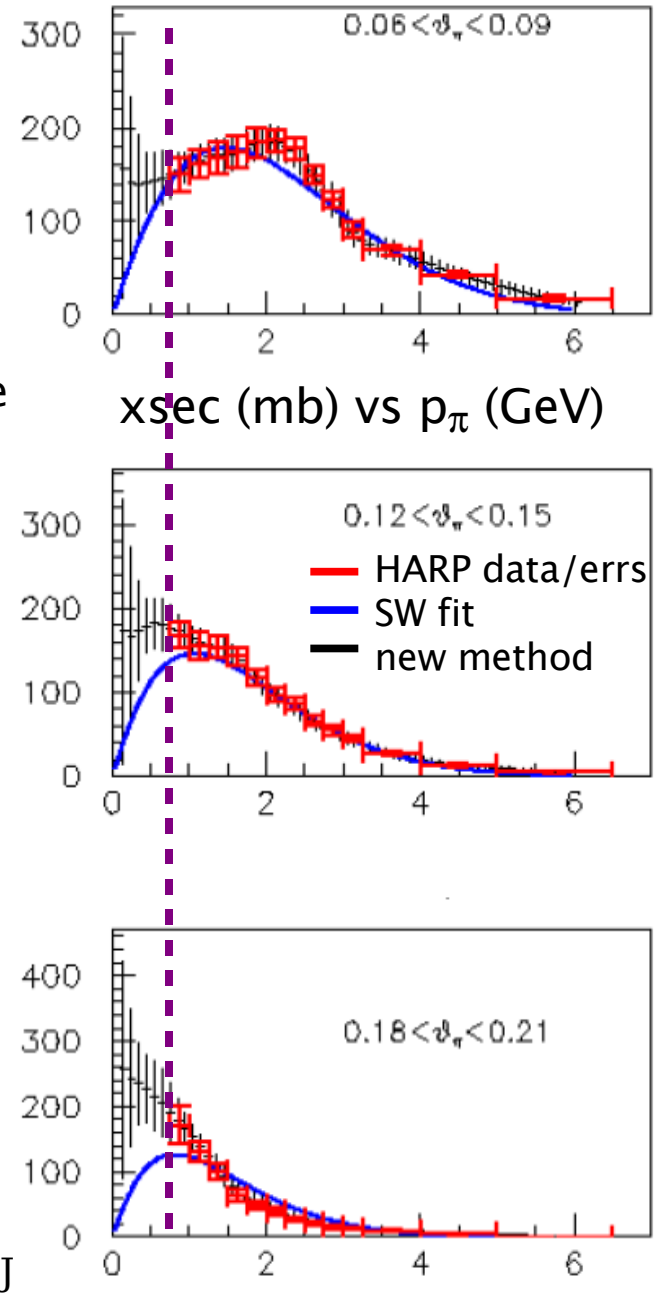
- Sounds dumb, but...
  - Getting a good 2-dim parameterization in (p_π,θ) not as easy as you might think
  - More importantly, in the ν_e appearance analysis the π flux is heavily constrained from the *in situ* ν_μ measurement



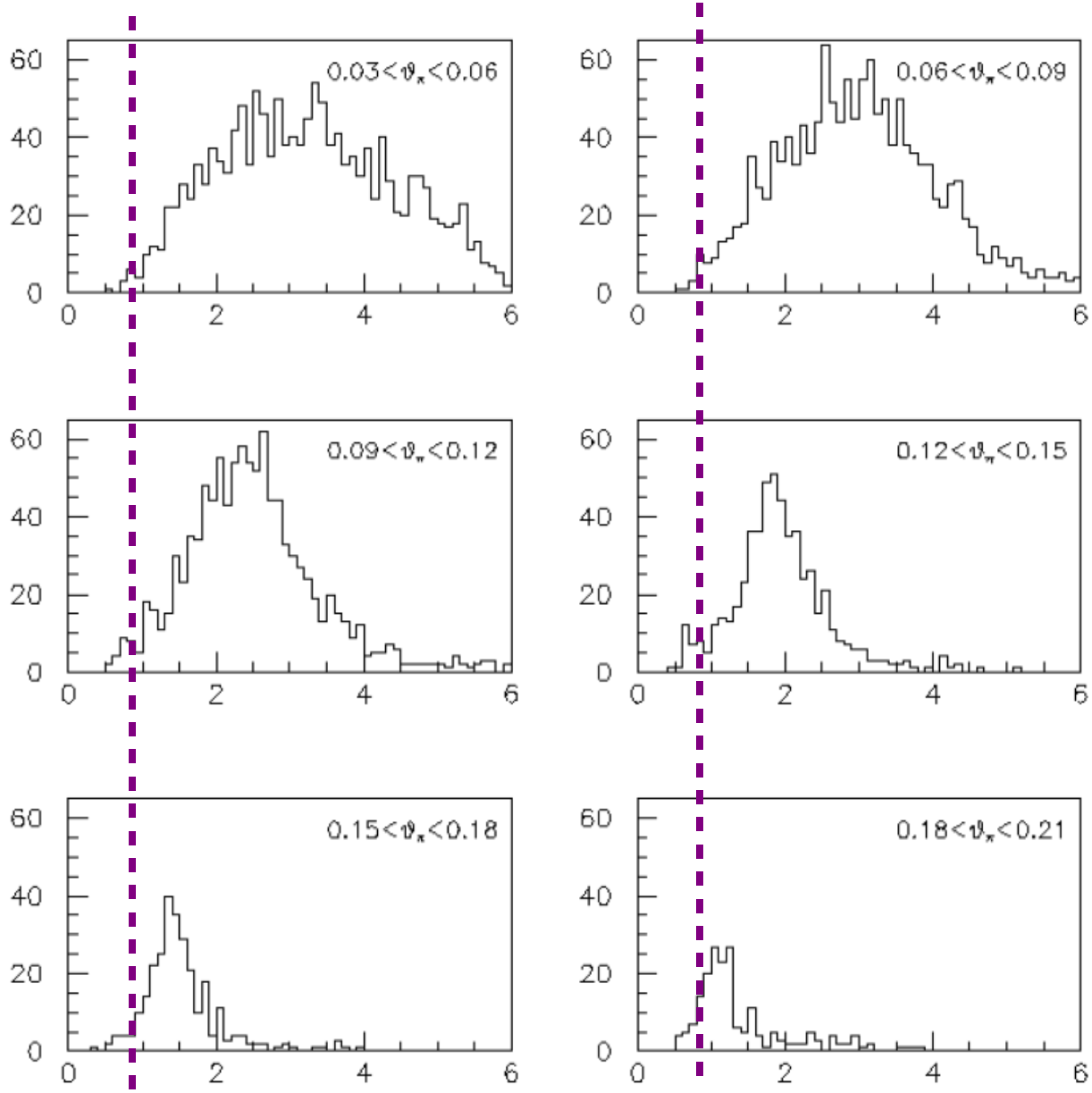
Update #1: Treatment of π flux errors

NEW METHOD:

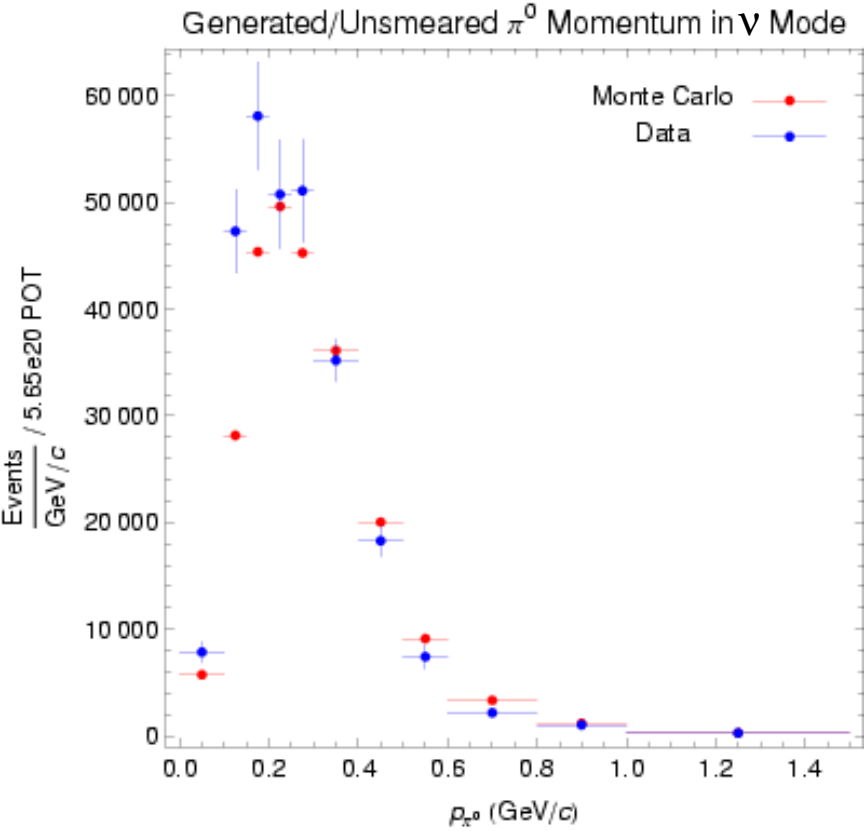
- Forget SW, use HARP data and fit with spline interpolation
- Vary HARP data with their own covariance matrix to produce flux systematic error
- Update #1 bottom line: No impact on ν_e appearance
  - Largest diff at low p_π ,not much ν flux hitting det, further deweighted by cross-sections
  - Still 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



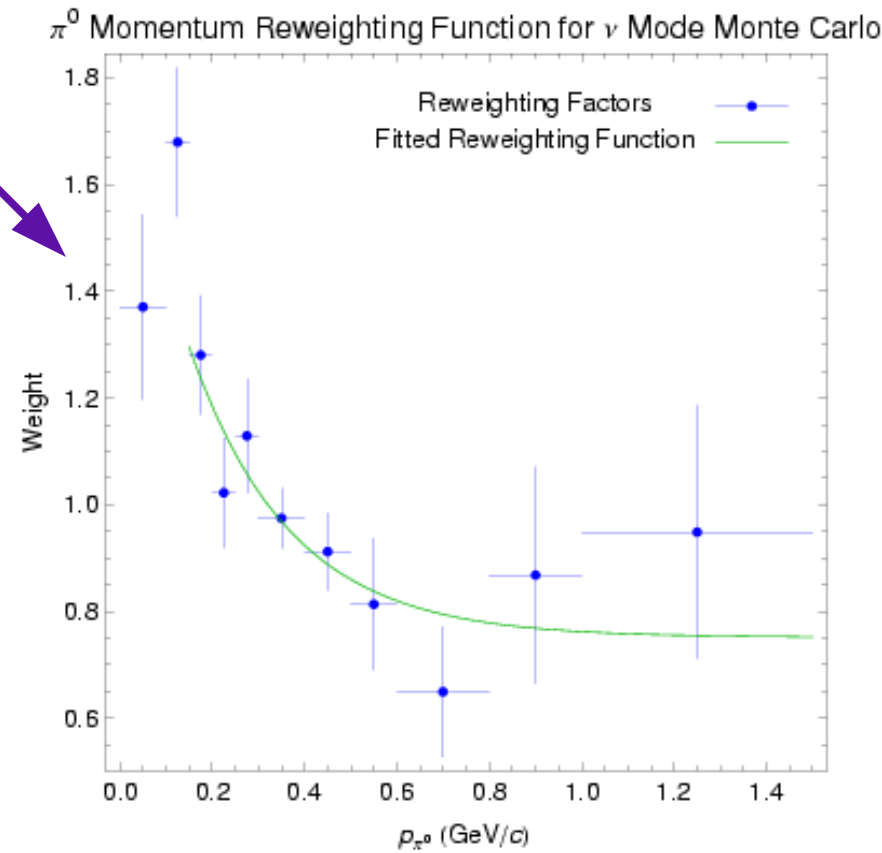
Parent π kinematics -> make ν_e-like bkgs



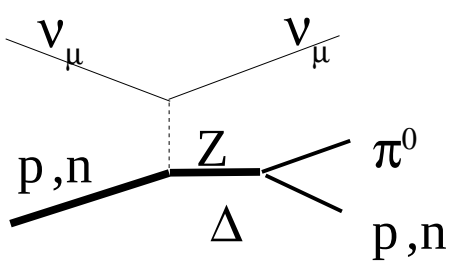
Update #2: Improved π^0/radiative Δ analysis



- 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



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



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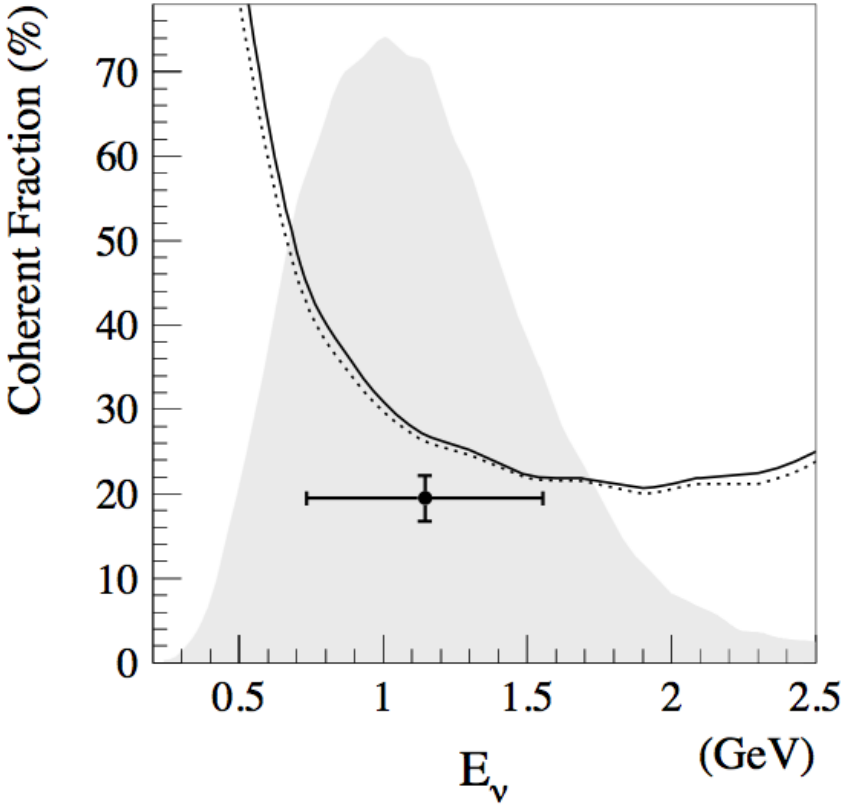
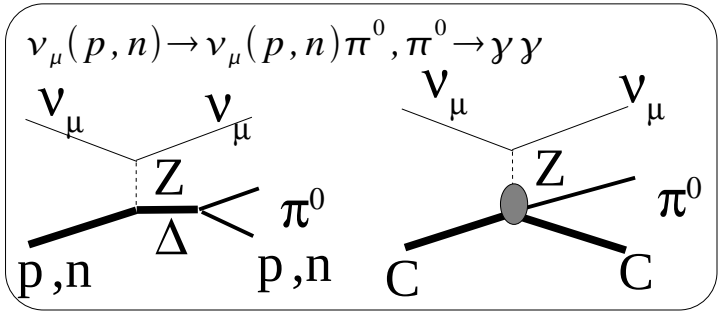




- Applied *in situ* measurement of the coherent/resonant production rate
  - Coherent event kinematics more forward
  - Coherent fraction reduced by 35% (from RS)
- Improvements to $\Delta \rightarrow N\gamma$ bkg prediction
  - Coh/res π^0 fraction measured more accurately, $\Delta \rightarrow N\gamma$ 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)

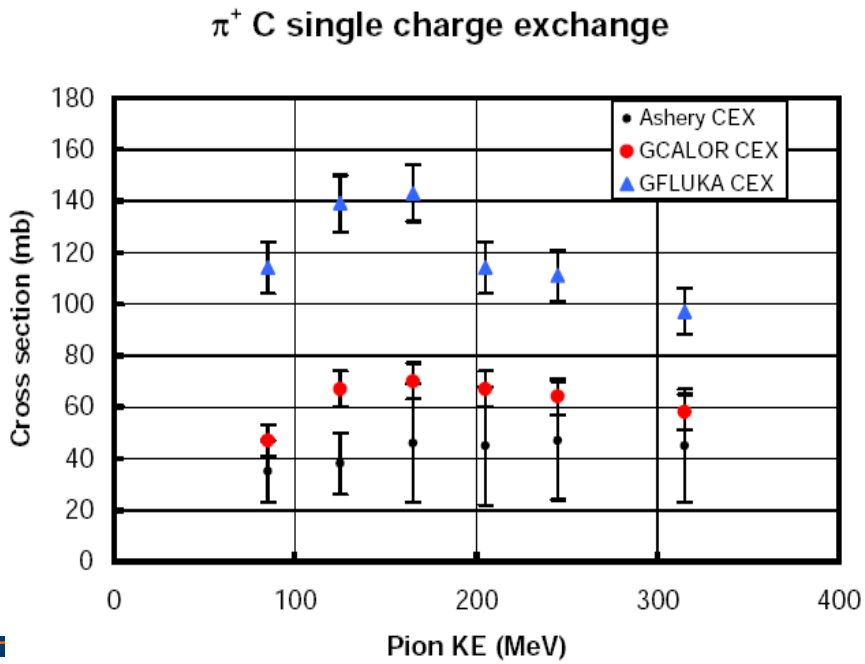
$$\frac{N_C(\Delta \rightarrow N\gamma)}{N_C(\Delta \rightarrow N\pi^0)} = \frac{3\Gamma_\gamma}{2\Gamma_{\pi^0}\varepsilon}$$

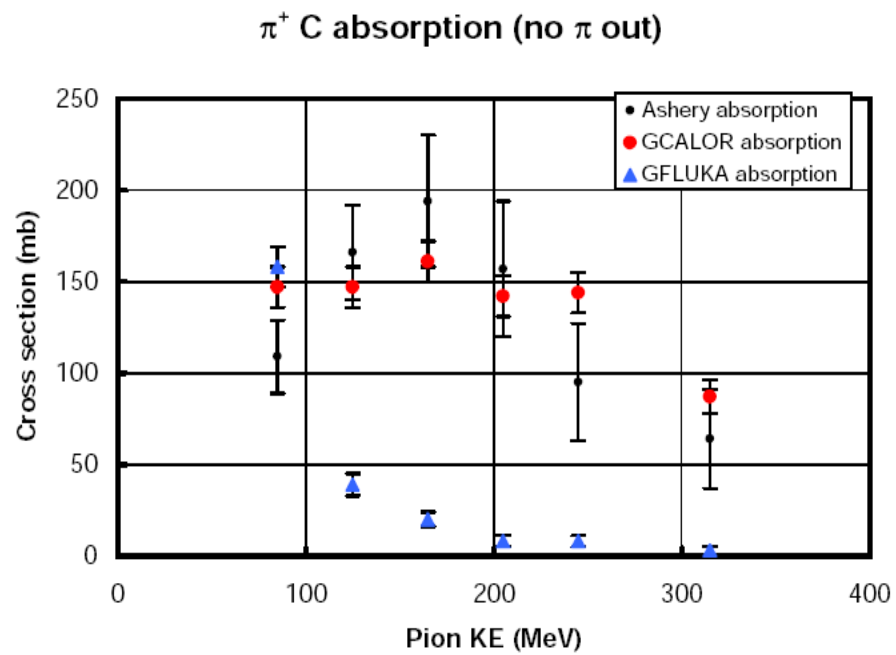
  - Error on $\Delta \rightarrow N\gamma$ bkg increased from 9 to 12%
- Update #2 bottom line: Overall, produces a small change in ν_e appearance bkgs

Update #3: 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

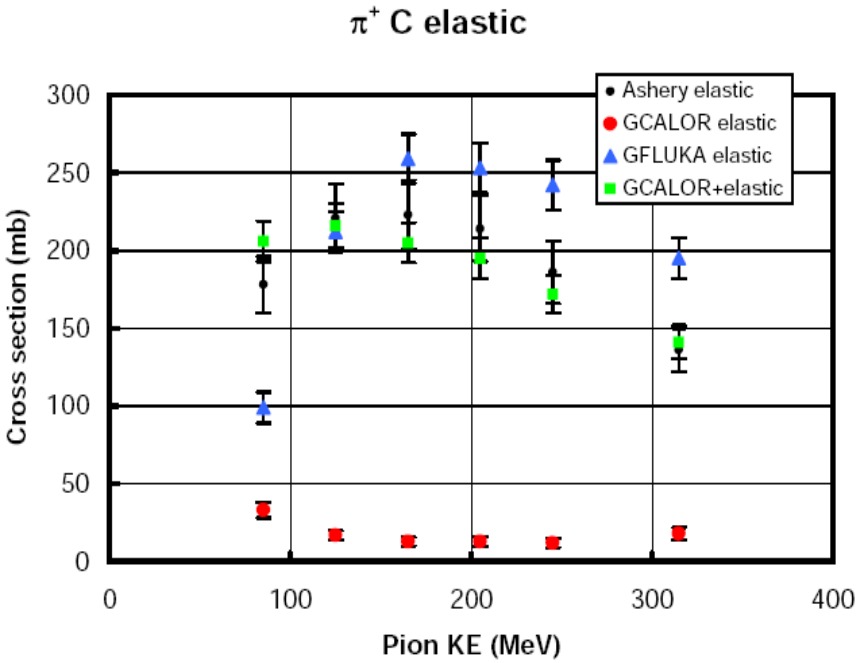




Update #3: Hadronic bkgs/errors in ν interactions

ADDITIONAL HADRONIC PROCESSES:

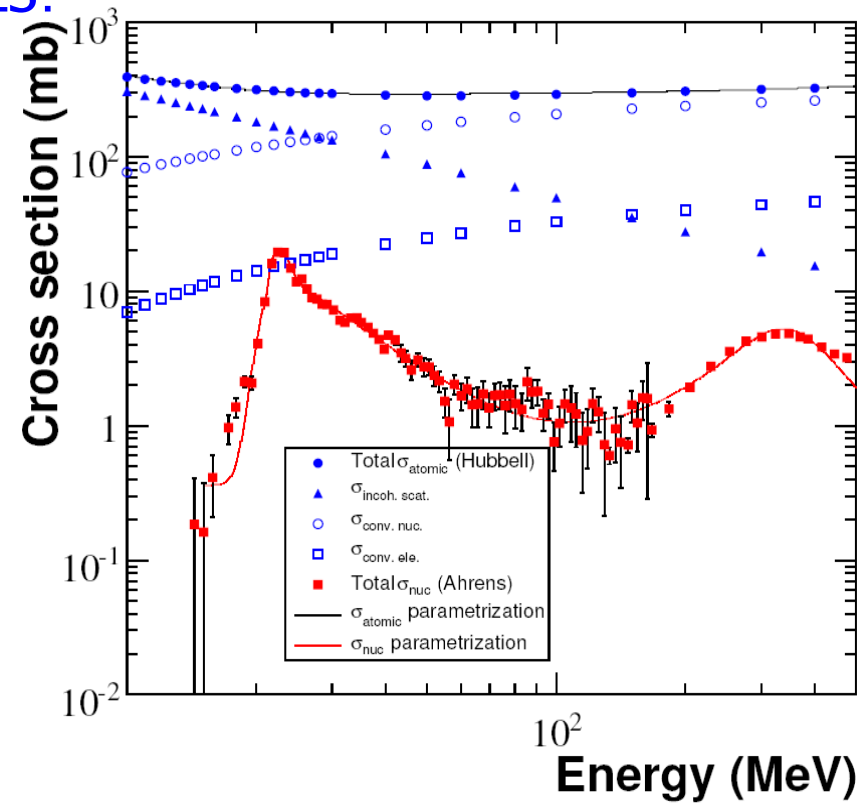
- Charged $\pi - C$ elastic scattering
  - Found $\pi^{\pm}$ elastic scattering to be nearly absent in GCALOR
  - Possibility that NC $\pi^{\pm}$ have more scattering ⇒ making Cerenkov ring look more e-like
- Radiative π^- capture
  - π^- capture is in GCALOR, but missing radiative branching fraction (<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.



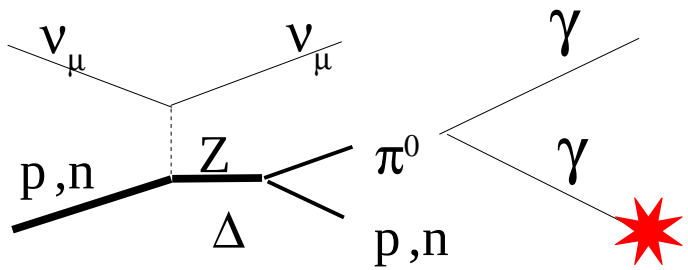
Update #3: Hadronic bkgs/errors in ν interactions

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 hadronic process found to contribute significantly



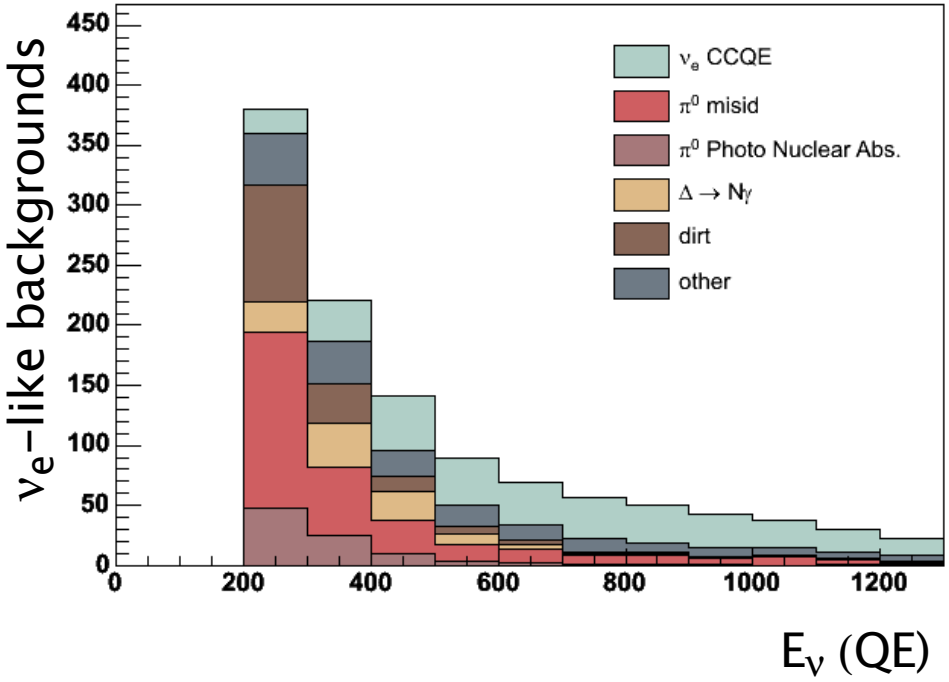
$$\nu_\mu(p,n) \rightarrow \nu_\mu(p,n)\pi^0, \pi^0 \rightarrow \gamma\gamma$$



Update #3: Hadronic bkgs/errors in ν interactions

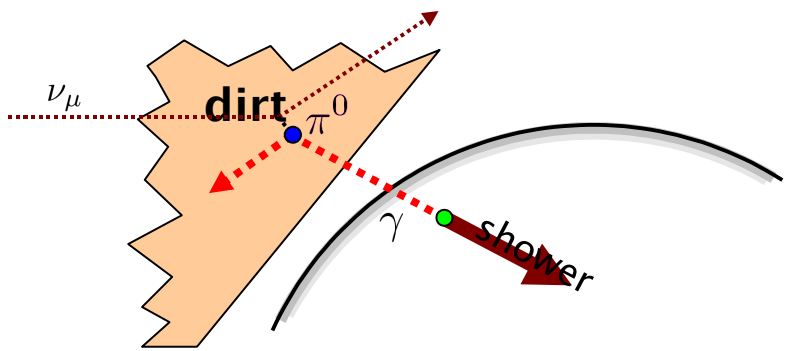
ADDITIONAL HADRONIC PROCESSES:

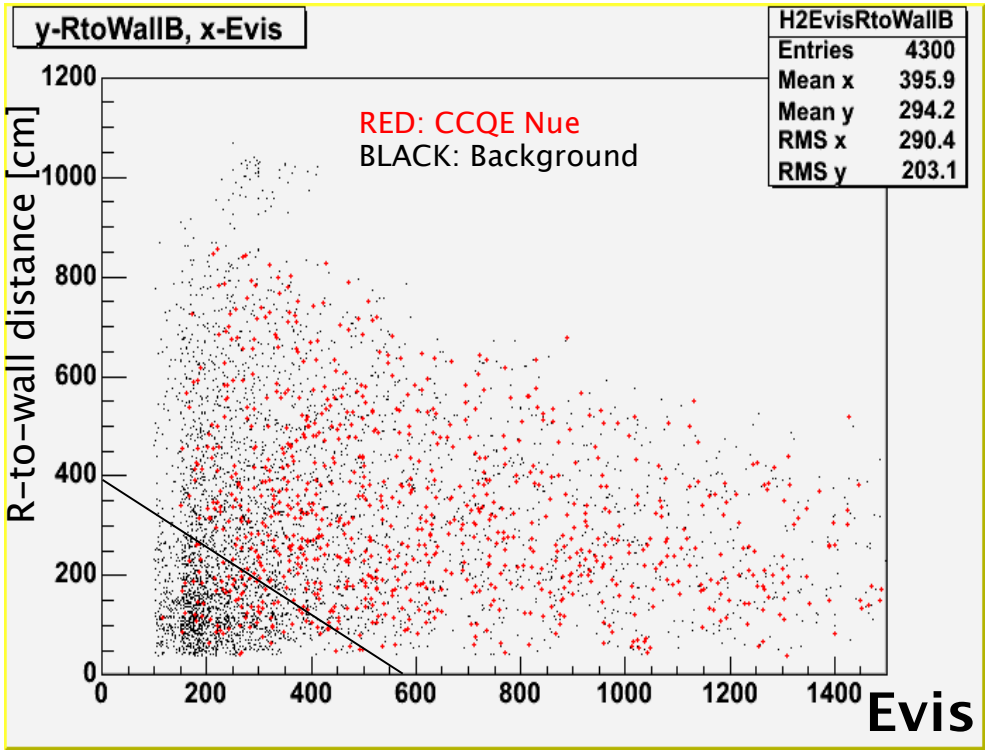
- Update #3 bottom line:
  - Additional p0 mis-id due to all modified hadronic processes (dominated by PN)
    - 200-300 MeV, ~40 events
    - 300-475 MeV, ~20 events
    - 475-1250 MeV, ~1 event
  - Additional systematic error negligible relative to other errors



Update #4: 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

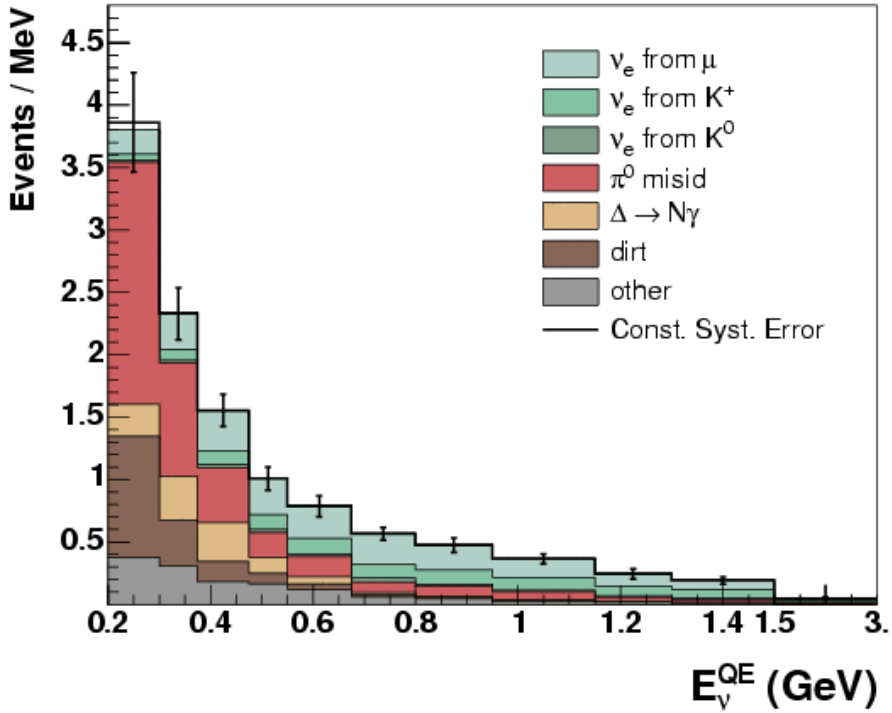




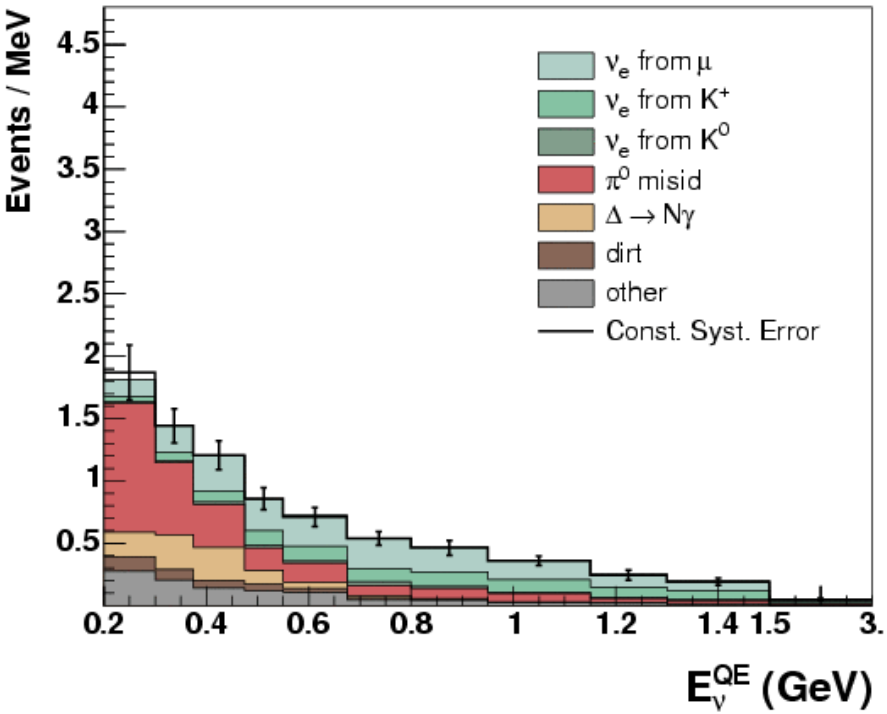
Update #4: Additional cut to remove dirt events

- Update #4 bottom line: Removes ~85% of the dirt backgrounds at low energy

No DIRT cuts

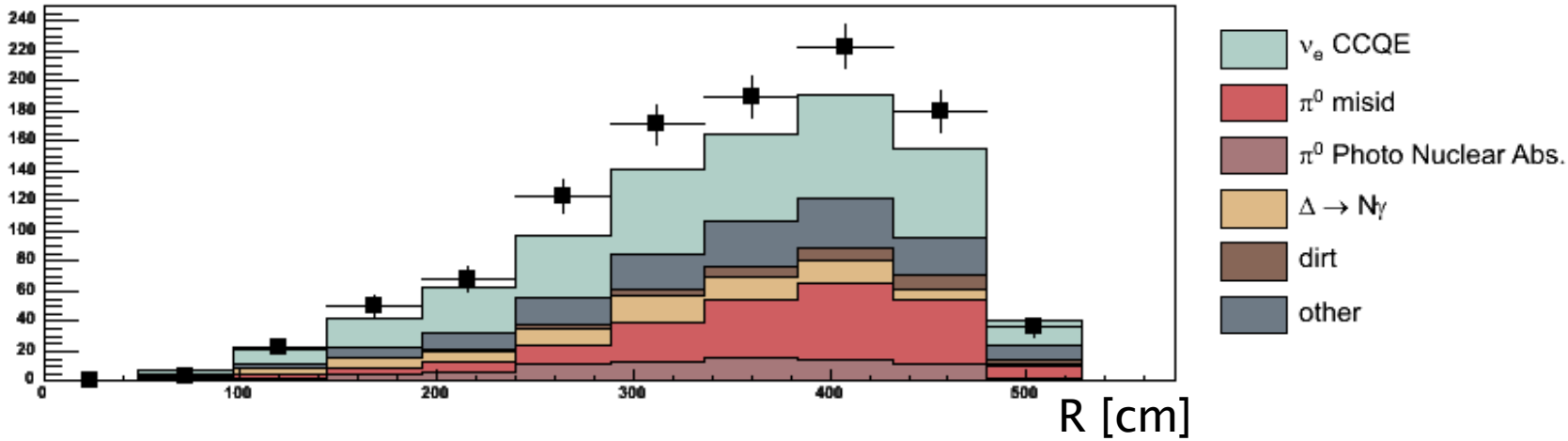


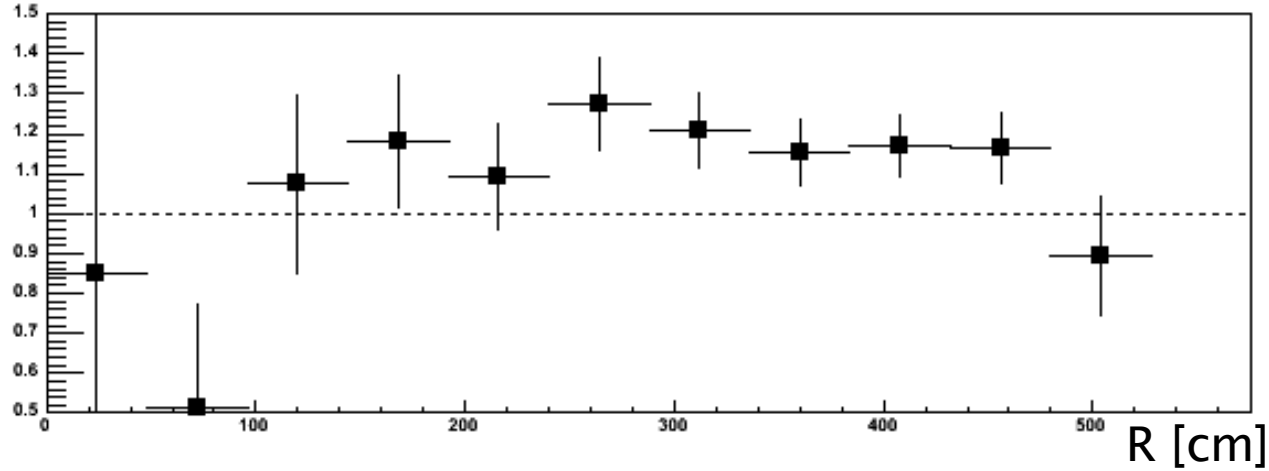
With DIRT Cuts



Update #4: Additional cut to remove dirt events

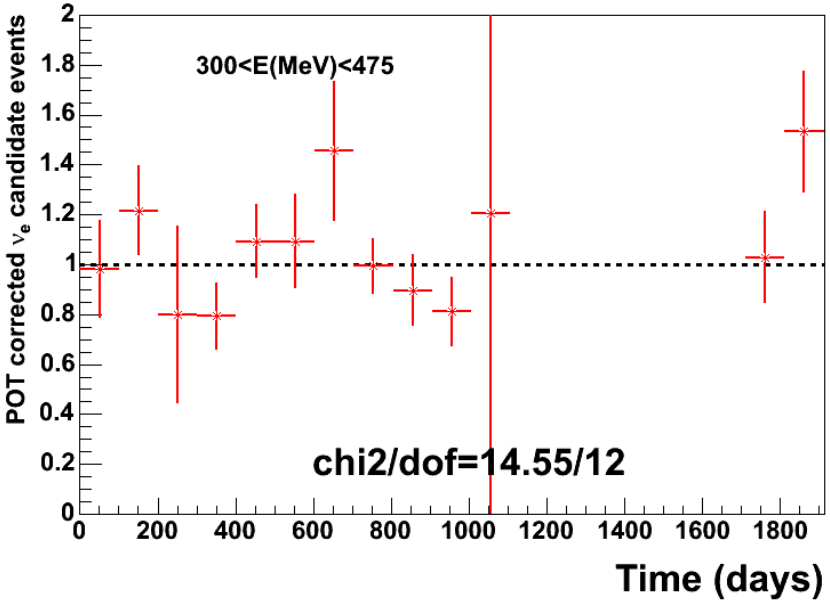
- Consistency-check: look at radial distribution after dirt cut applied
  - Uniform excess throughout tank

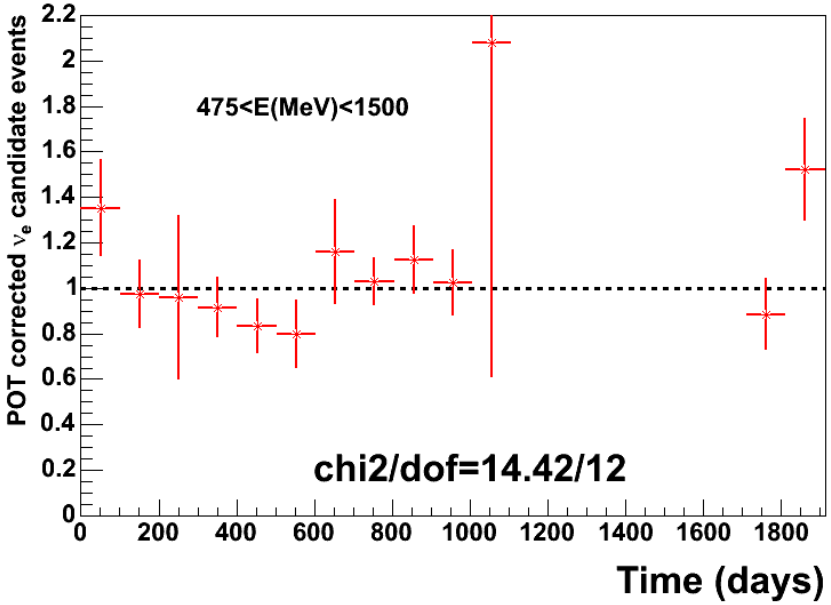




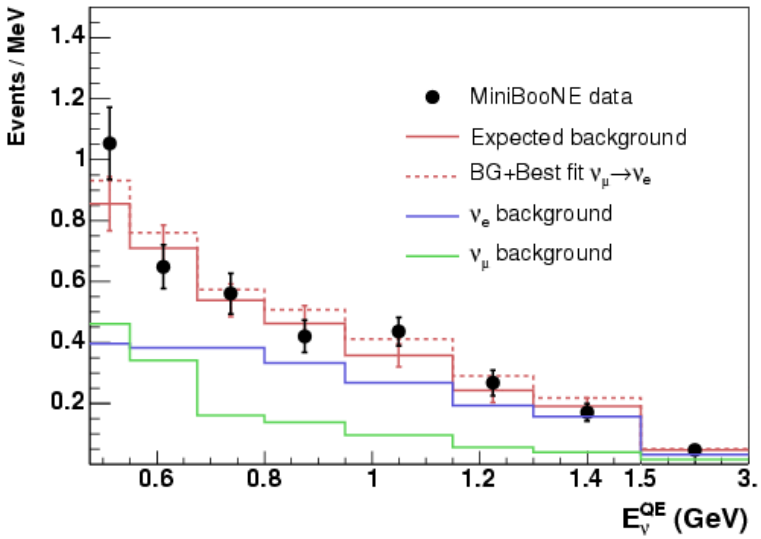
Update #5: New data

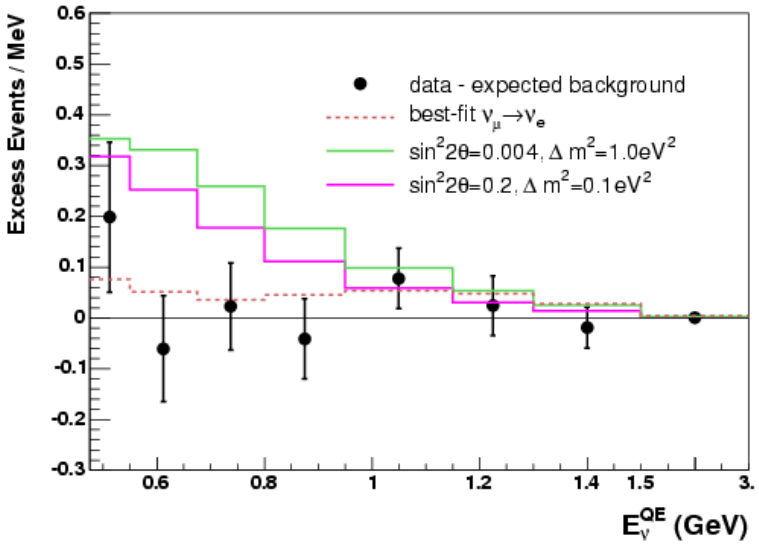
- Extra 0.83E20 POT during combined MiniBooNE/SciBooNE ν running
  - ν_e-like events per POT evenly distributed throughout duration of run
- Update #5 bottom line: ν_e-like event rate slightly higher for new data, but perfectly acceptable

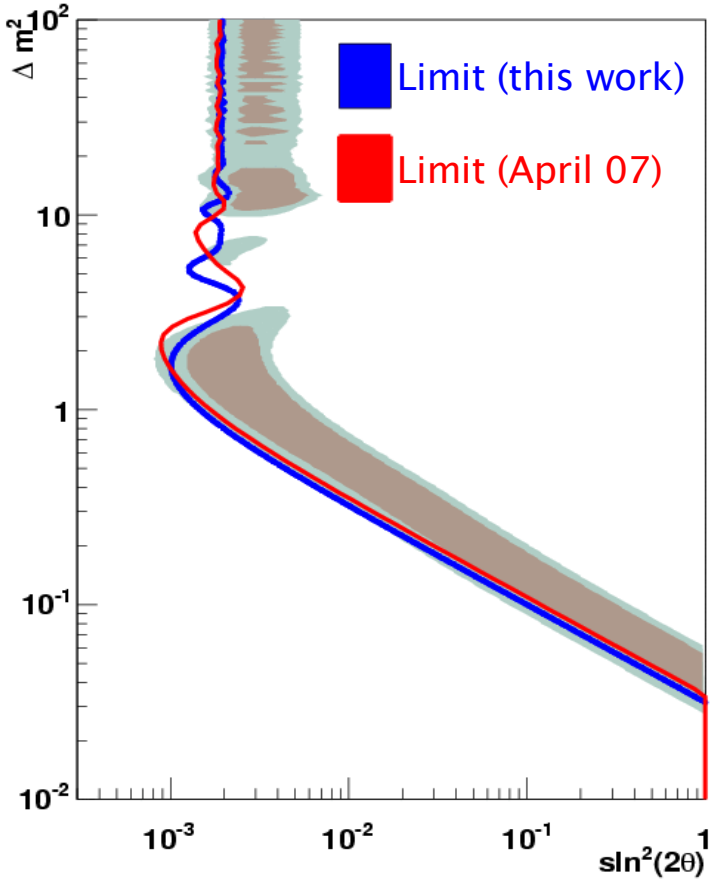




Full update: Impact on oscillation analysis

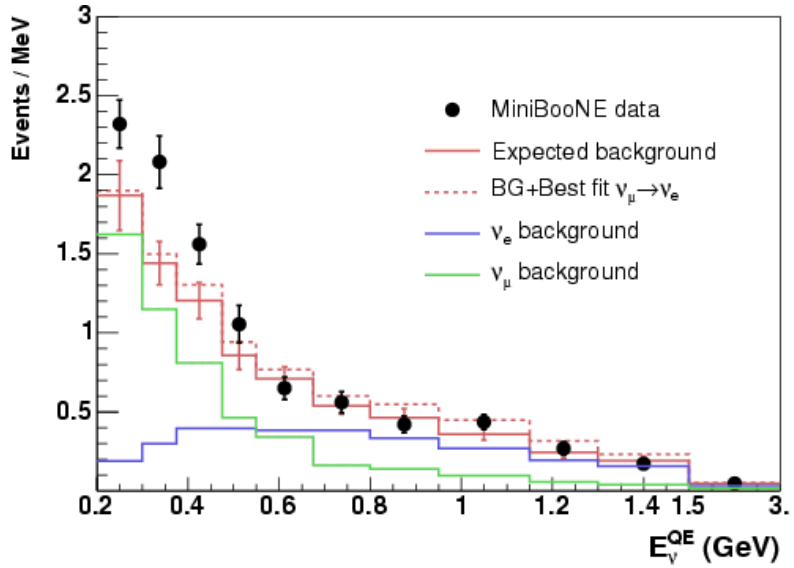




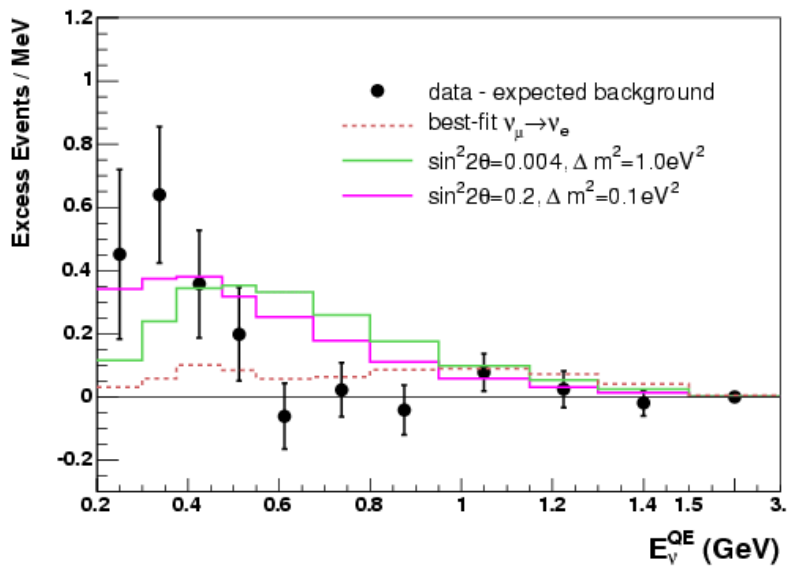


- Little impact on primary oscillation analysis!

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.

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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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

- In 475–1250 MeV, excess is small/stable through all updates
- In 200–475 MeV, excess significance reduced due to additional hadronic bkgs, compensated by reduction in dirt background
- Original 3.7σ excess in 300–475 remains a 3.4σ effect after a comprehensive review

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
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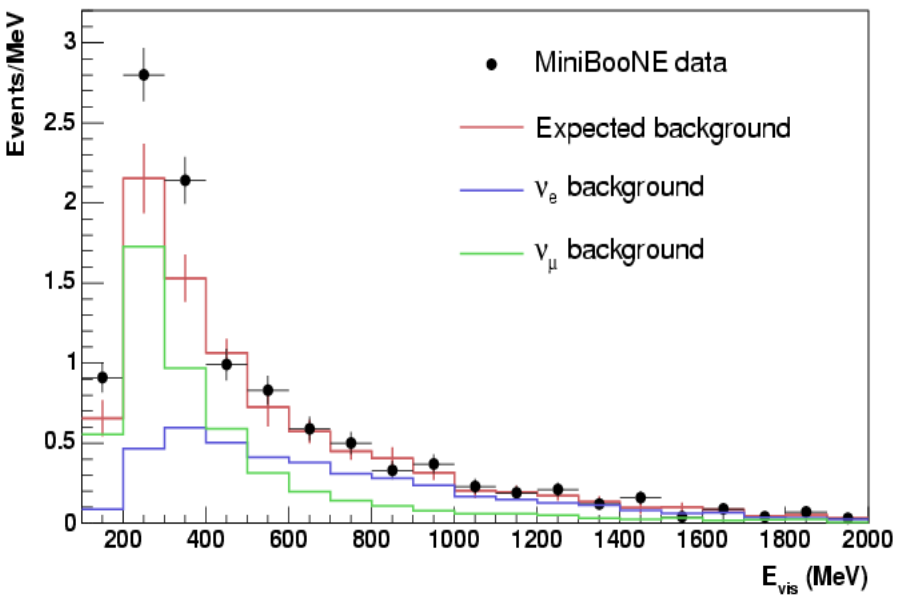
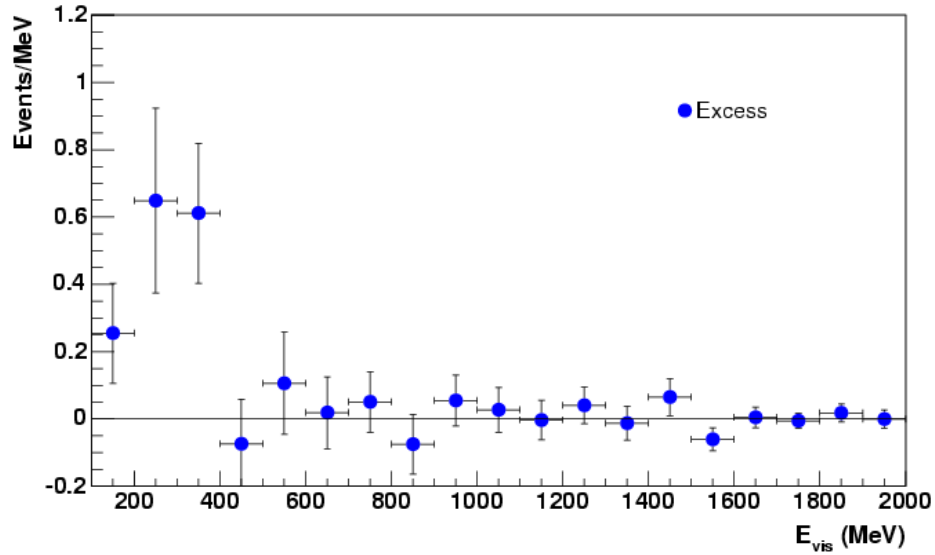
Full update: Visible energy distribution

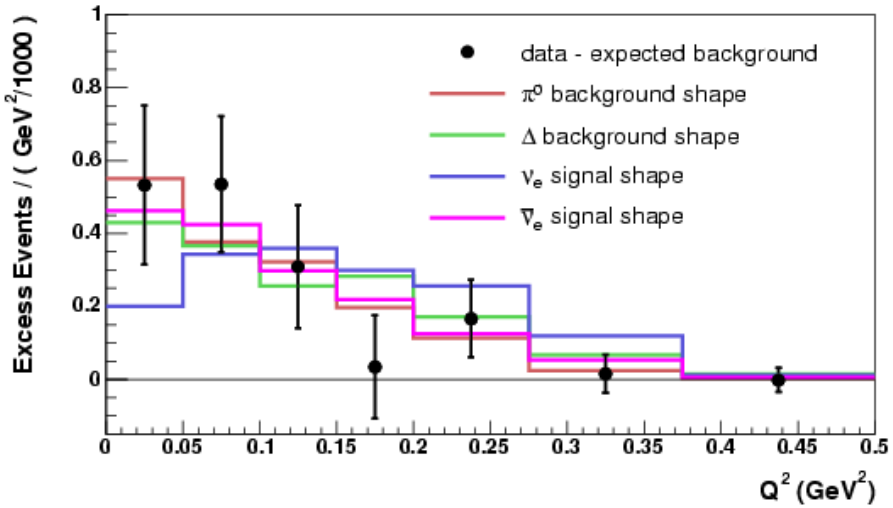
- Visible energy interesting to look at in case excess is not really due to ν_e CCQE
- Can see excess is more consistent with ν_μ mis-ID than intrinsic ν_e.
- Excess piles up below 400 MeV, analysis threshold set at 140 MeV Evis

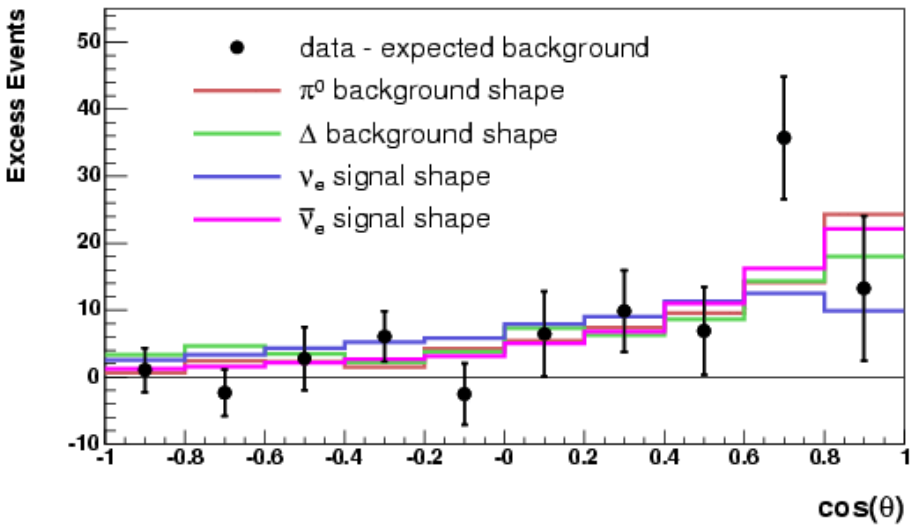




$$E_\nu^{QE} = \frac{1}{2}\frac{2M_pE_\mu - m_\mu^2}{M_p - E_\mu + \sqrt{(E_\mu^2 - m_\mu^2)}\cos\theta_\mu}$$

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
$\Delta \rightarrow N\,\gamma$	16.86	4.46	2.7
$\nu_e\, C \rightarrow e^- X$	14.58	8.72	2.4
$\bar{\nu}_e\, C \rightarrow e^+ X$	10.11	2.44	65.4

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

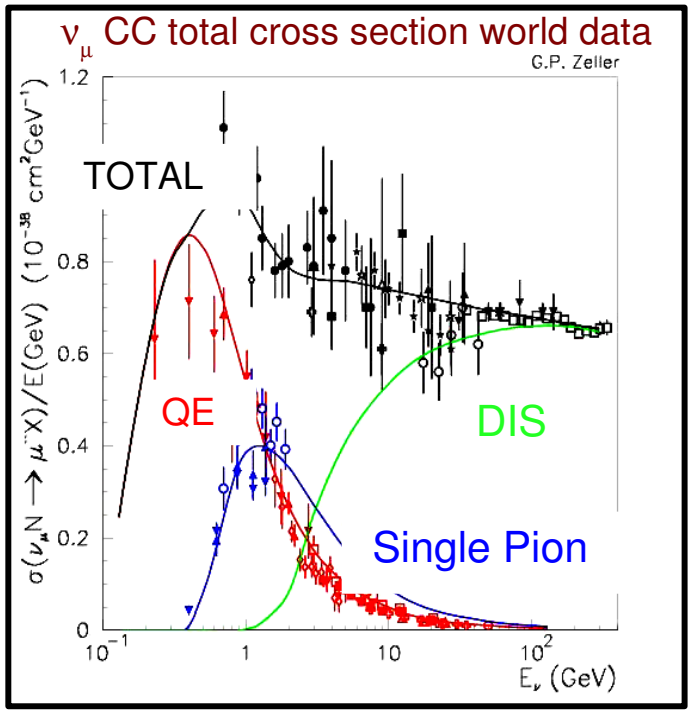
6.6×10^{20} POT
ν mode

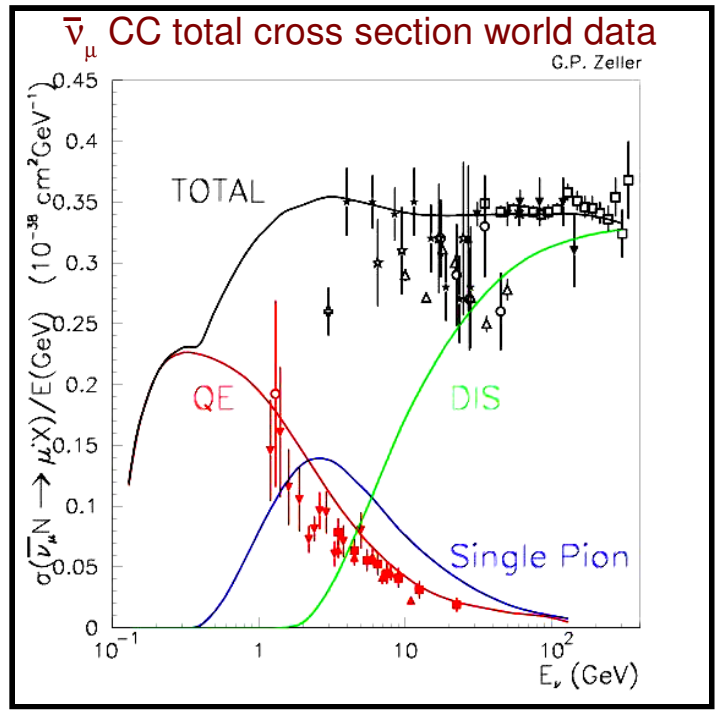
$\bar{\nu}$ channel	events
all channels	83k
CC quasielastic	37k
NC elastic	16k
CC π^-	14k
CC π^0	2.6k
NC π^0	7.6k
NC $\pi^{+/-}$	2.8k
CC/NC DIS, multi-π	2.9k

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

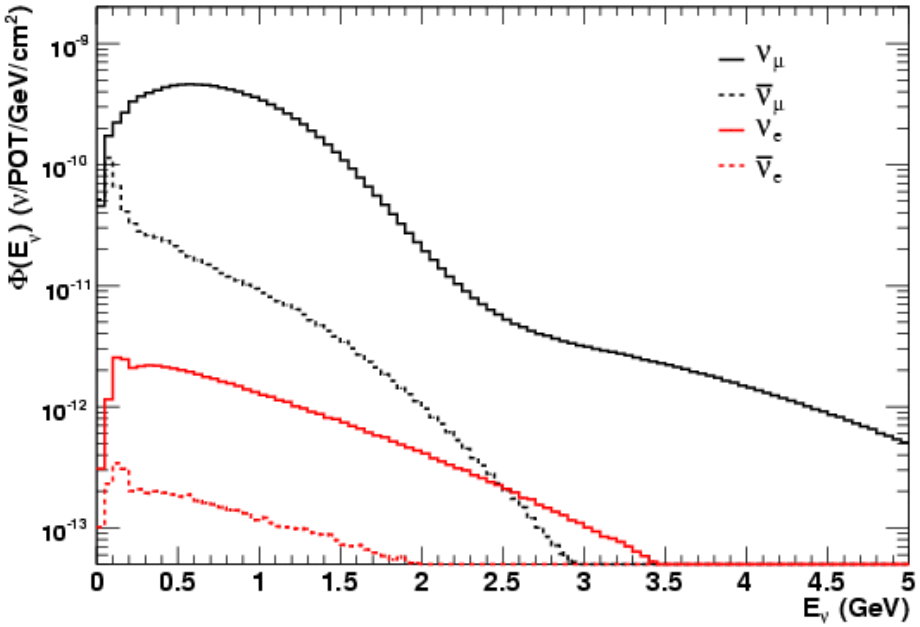




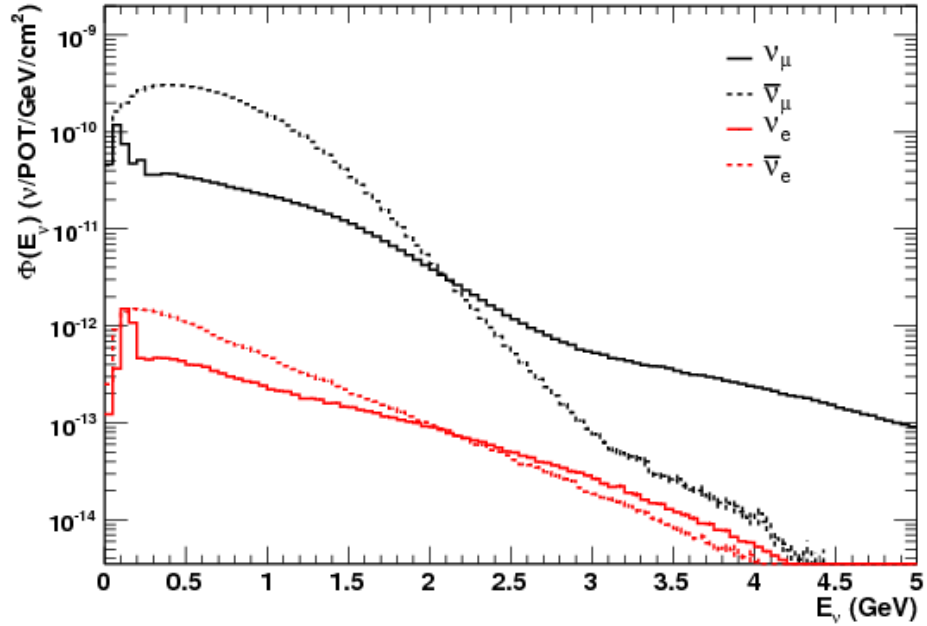
- Recall signal channel is charged-current quasi-elastic ν_e interactions

Rate also down due to π^-/π^+ flux

ν mode flux (focus π^+)



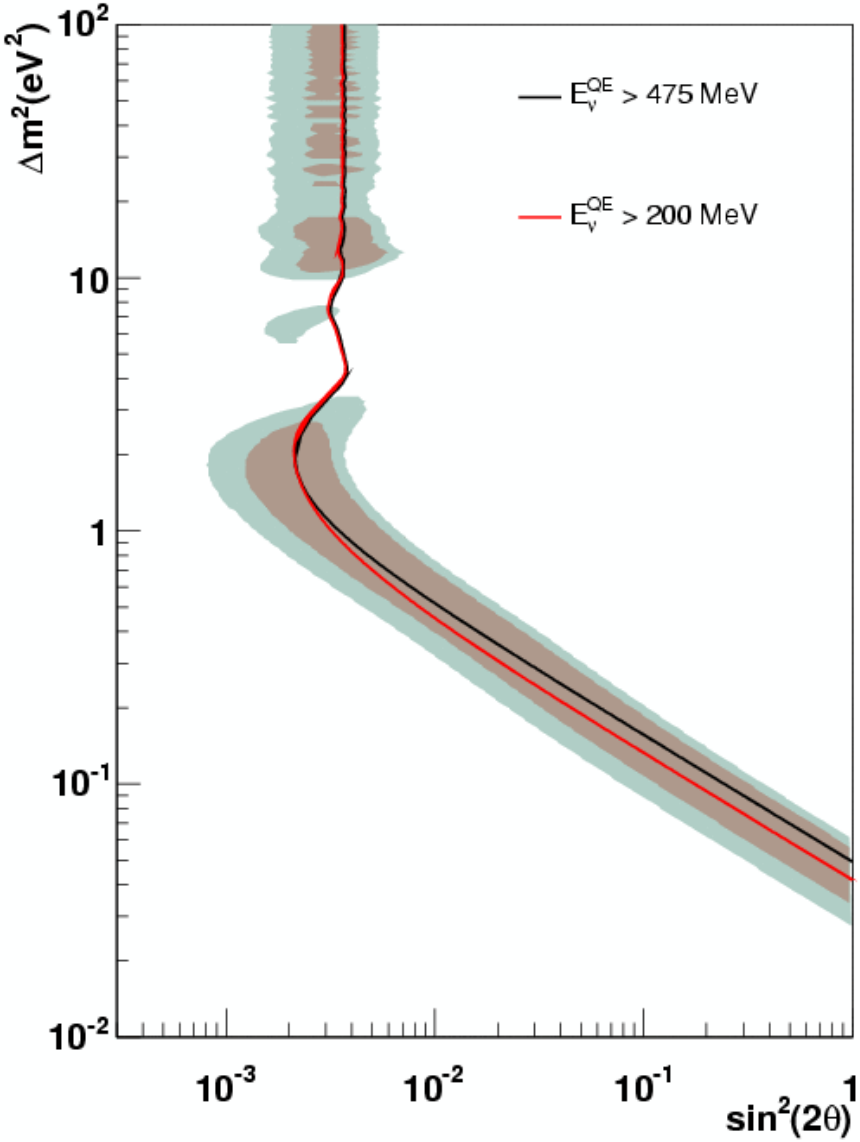
$\bar{\nu}$ mode flux (focus π^-)



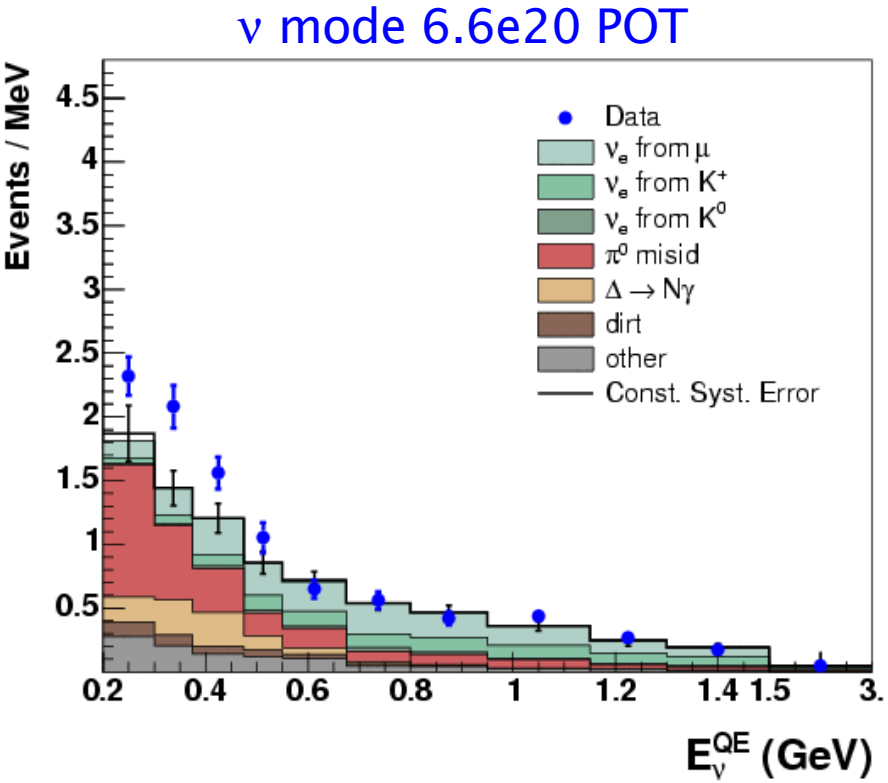
- Overall flux is also down
- Second complication: Wrong-sign component is much larger
  - 6% anti-ν_μ in ν beam...18% ν_μ in anti-ν_μ beam
  - WS component further amplified to 30% in nubar mode due to xsec

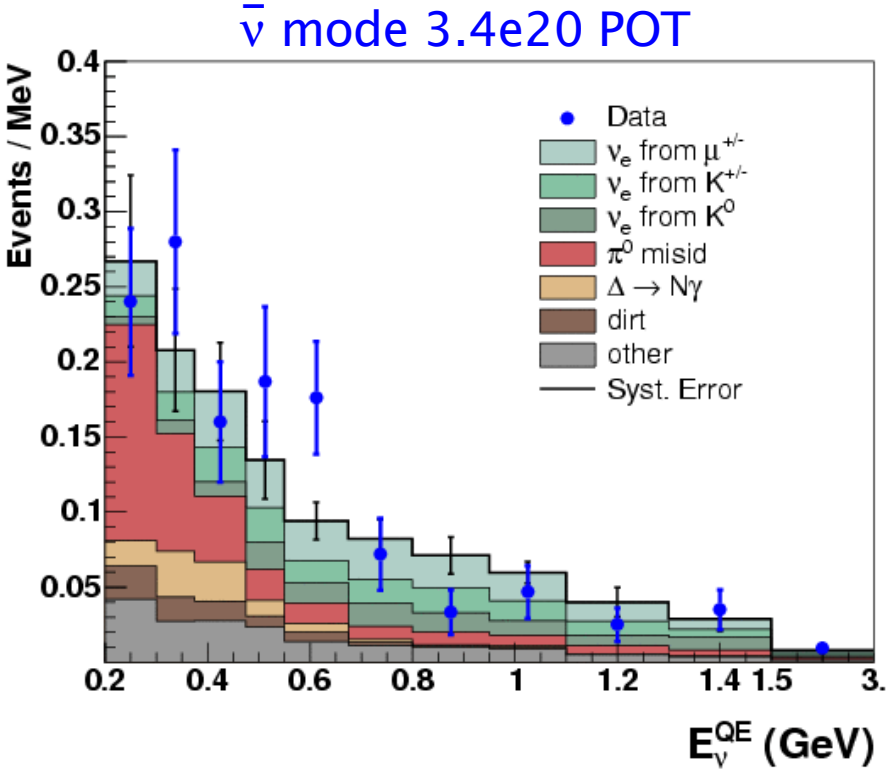
Projected sensitivity (90% CL) to anti-ν oscillation

- Important point, only anti-ν are assumed to oscillate in this analysis
- Already know WS component ν_μ do not oscillate from nu mode result
- 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



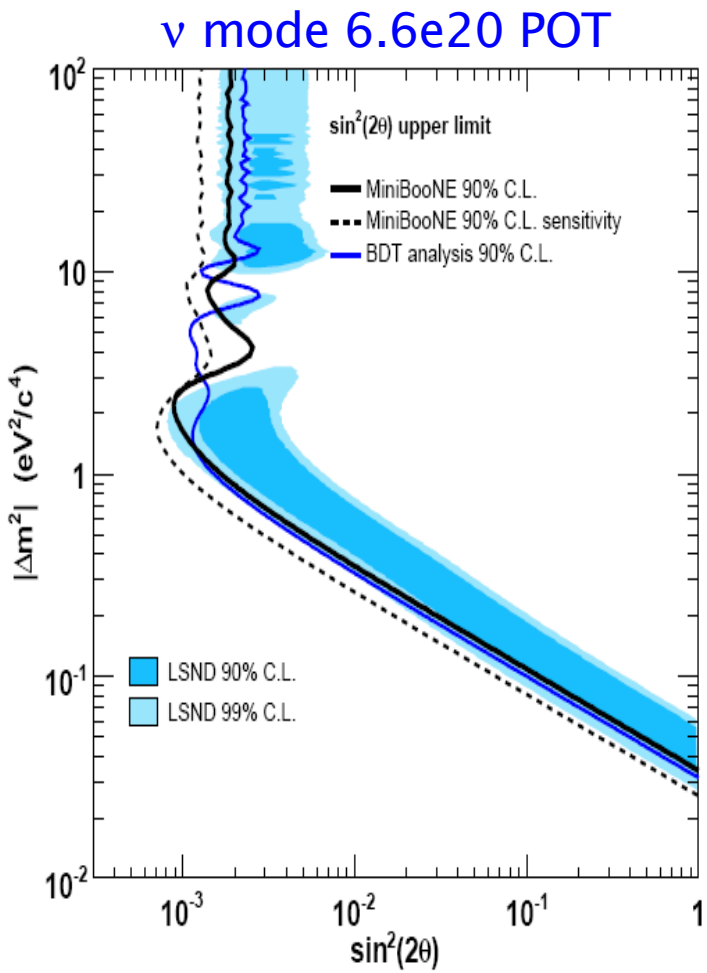
Recently unblinded anti-ν data...NEW RESULTS

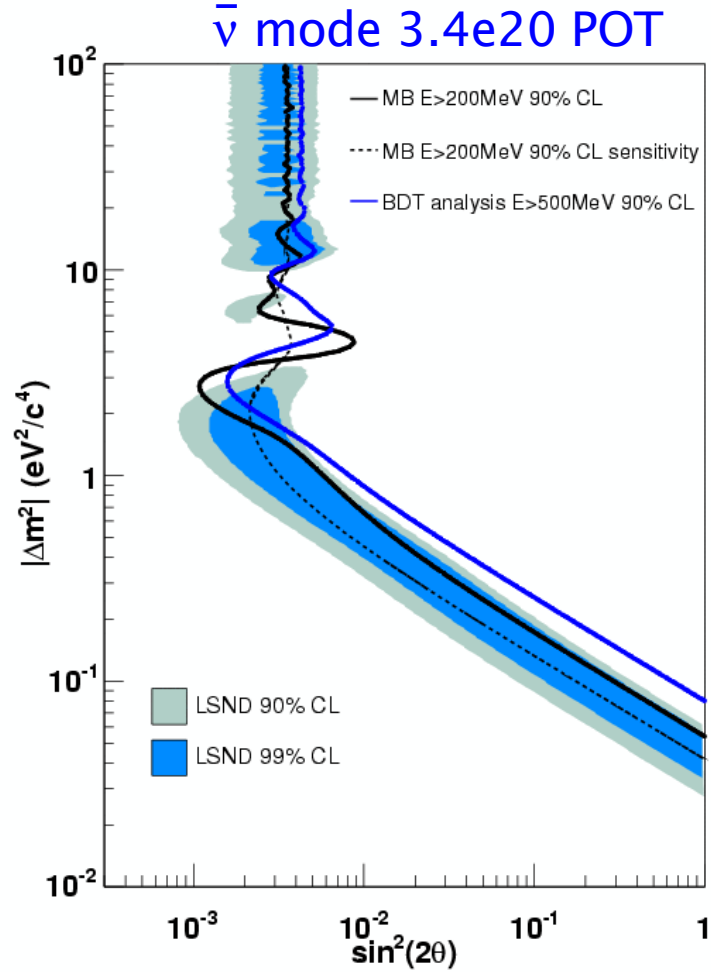




- Number of interesting observations here...
  - Backgrounds actually very similar
  - Role of stat error can be seen in blue errors plotted on data, especially relative to systematic errors in black plotted on MC
  - Good agreement...even at low energy

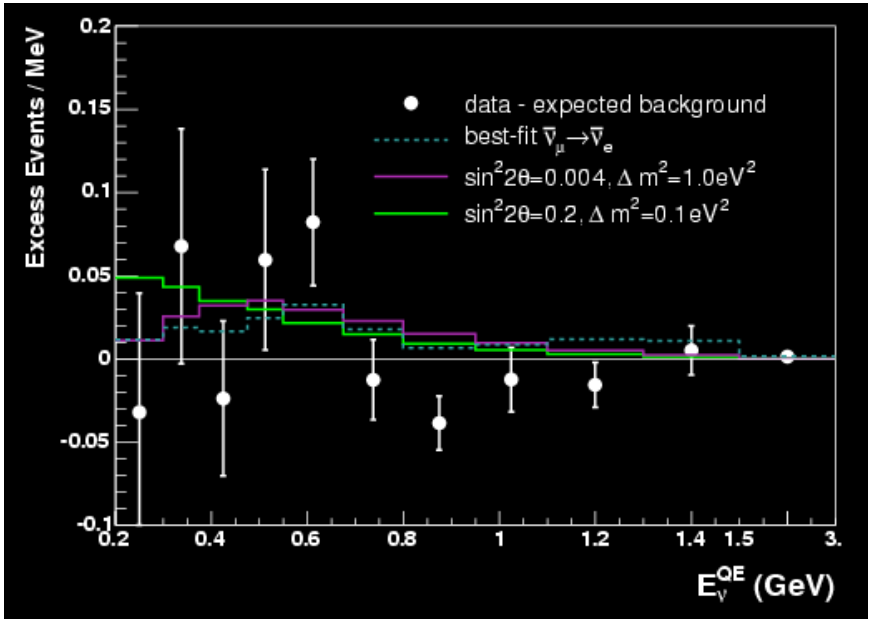
Comparing limits and sensitivities to 2ν mixing

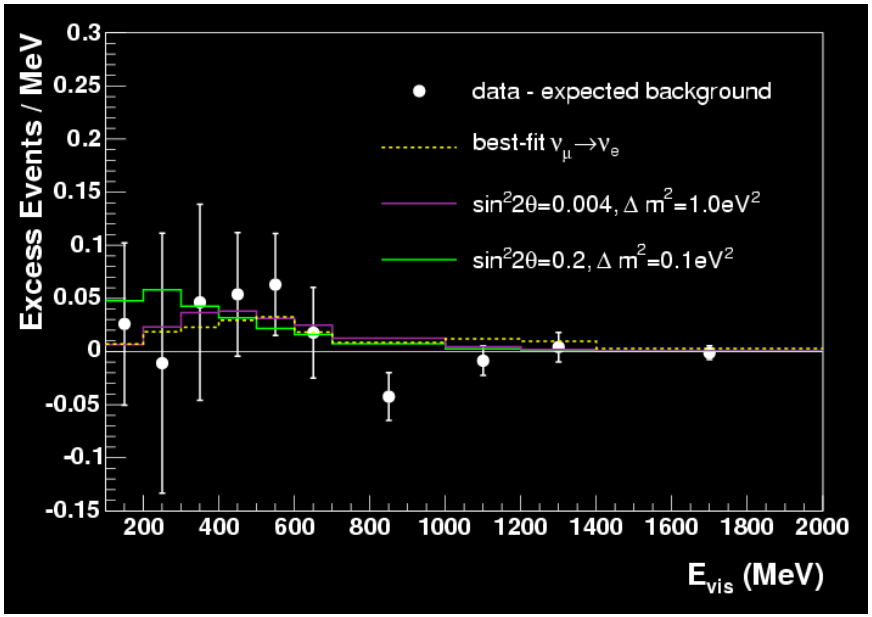




- Fit prefers to add some signal making limit curve shift to right relative to sensitivity.
- Nearly all of LSND and the null hypothesis included at 90% CL

Data-MC prediction versus energy (nubar)





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

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

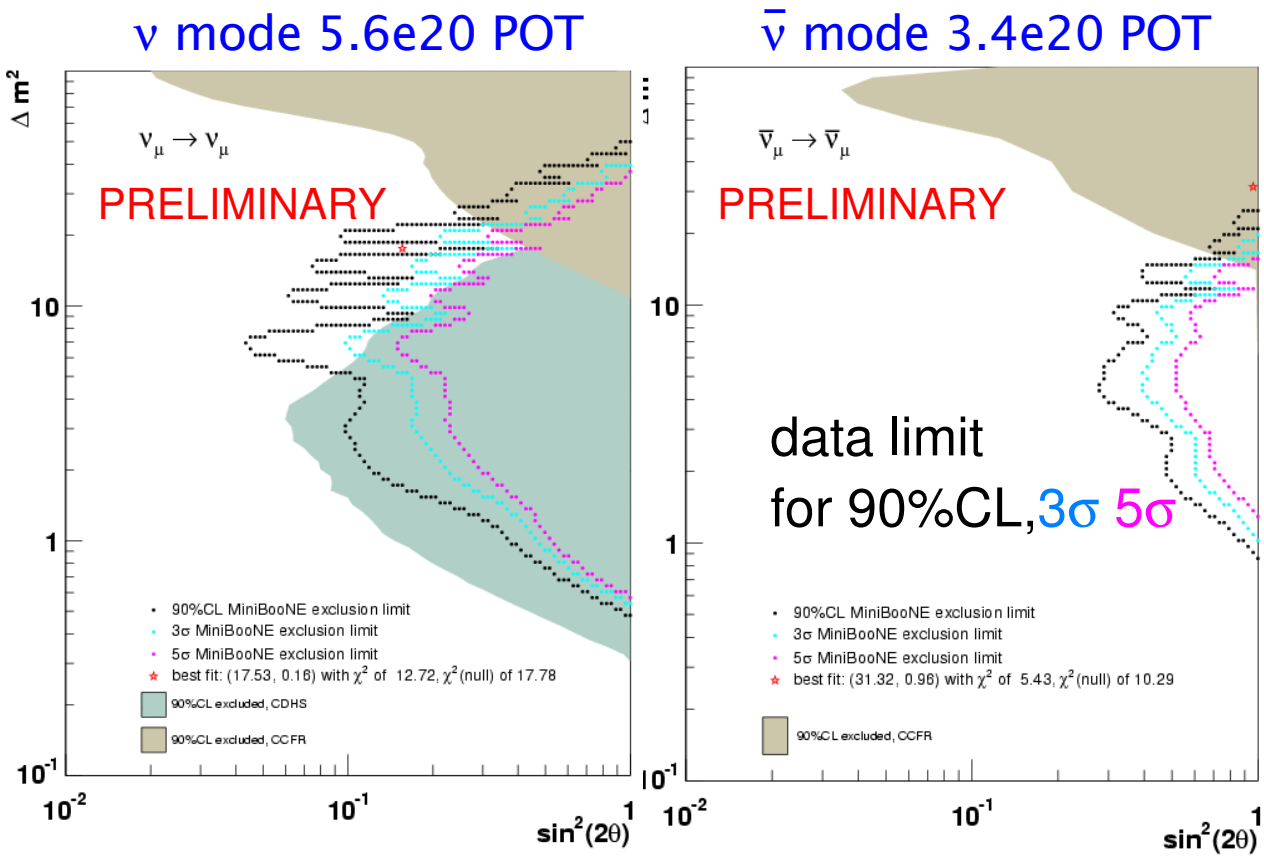
	Stat Only	Correlated Syst	Uncorrelated Syst
Same $\nu,\bar{\nu}$ NC	0.1%	0.1%	6.7%
NC π^0 scaled	3.6%	6.4%	21.5%
POT scaled	0.0%	0.0%	1.8%
Bkgd scaled	2.7%	4.7%	19.2%
CC scaled	2.9%	5.2%	19.9%
Low-E Kaons	0.1%	0.1%	5.9%
ν scaled	38.4%	51.4%	58.0%

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
  - That work is in progress, but the final result has to be bracketed between 100% correlated and uncorrelated.
- 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

What about 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



Conclusions and references

- Summary
  - A comprehensive review of all bkgss 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
  - First results with a predominantly antineutrino beam presented
    - No sign of excess at low energy
    - Under 2ν mixing hypothesis fit results inconclusive
    - No evidence for ν_μ disappearance
- For more info on MiniBooNE see
  - *Unexplained Excess of Electron-like Events from a 1 GeV Neutrino Beam*, **Submitted to PRL [arXiv:0812.2243]**
  - *First Measurement of ν_μ and ν_e Events in an Off-axis Horn-focused Neutrino Beam*, **Submitted to PRL [arXiv:0809.2446]**
  - *Measurement of Muon Neutrino Quasi-Elastic Scattering on Carbon*, **PRL 100, 032310 (2008)**
  - *First Observation of Coherent π^0 Production in Neutrino Nucleus Interactions with En<2 GeV*, **Phys Lett B. 664, 41 (2008) [arXiv:0803:3423]**
  - *Compatibility of High Δm^2 ν_e and Anti-ν_e Neutrino Oscillations Searches*, **Phys. Rev D 78, 012007 (2008) [arXiv:0805:1764]**
  - *The Neutrino Flux Prediction at MiniBooNE*, **Accepted by PRD [arXiv:0806:1449]**
  - *The MiniBooNE Detector*, **Accepted by NIM A [arXiv:0806.4201]**
- Papers on the immediate horizon
  - Anti-ν_e appearance
  - CCpi+/CCQE ratio measurement
  - ν_μ disappearance in MiniBooNE

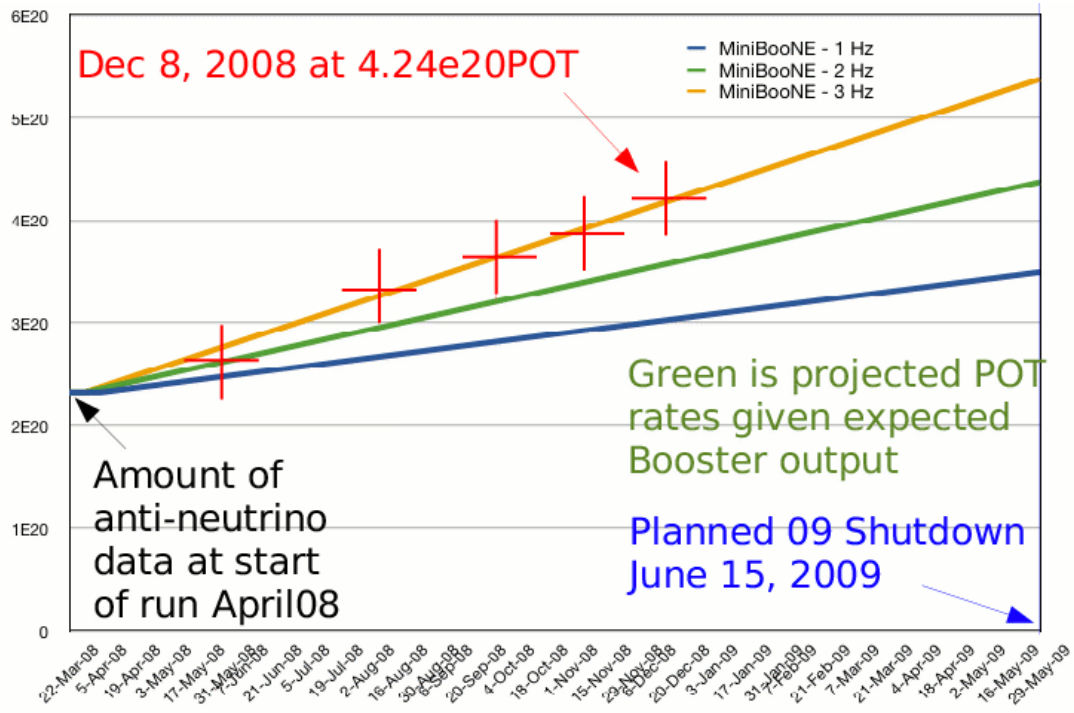
Extra slides

Full update: Background event breakdown

Process	$200-300$	$300-475$	$475-1250$
ν_μ CCQE	9.0	17.4	11.7
$\nu_\mu e \rightarrow \nu_\mu e$	6.1	4.3	6.4
NC π^0	103.5	77.8	71.2
NC $\Delta \rightarrow N\gamma$	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_L^0 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->Nγ dominated bkgs

Projected POT



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

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)