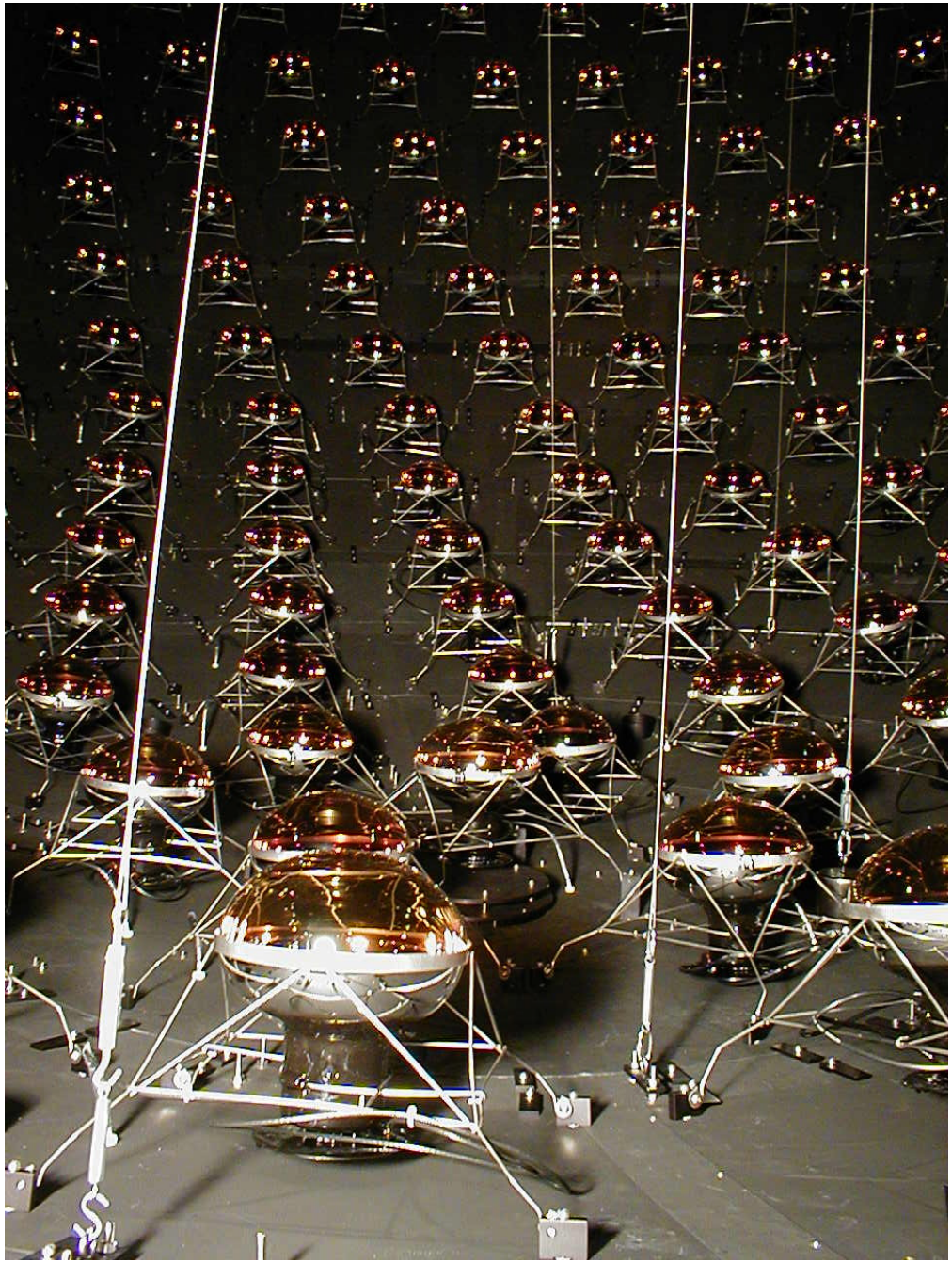


A Search for $\nu_\mu \rightarrow \nu_e$ Oscillations at $\Delta m^2 > 0.1$ eV^2

Ryan Patterson

FNAL Users' Meeting 2008

Neutrino Oscillations

- non-zero neutrino mass allows for lepton flavor changing physics
- mass eigenstates ≠ flavor eigenstates: $$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$ $$\alpha = (e, \mu, \tau)$$
- flavor composition of the neutrino can change as it propagates:

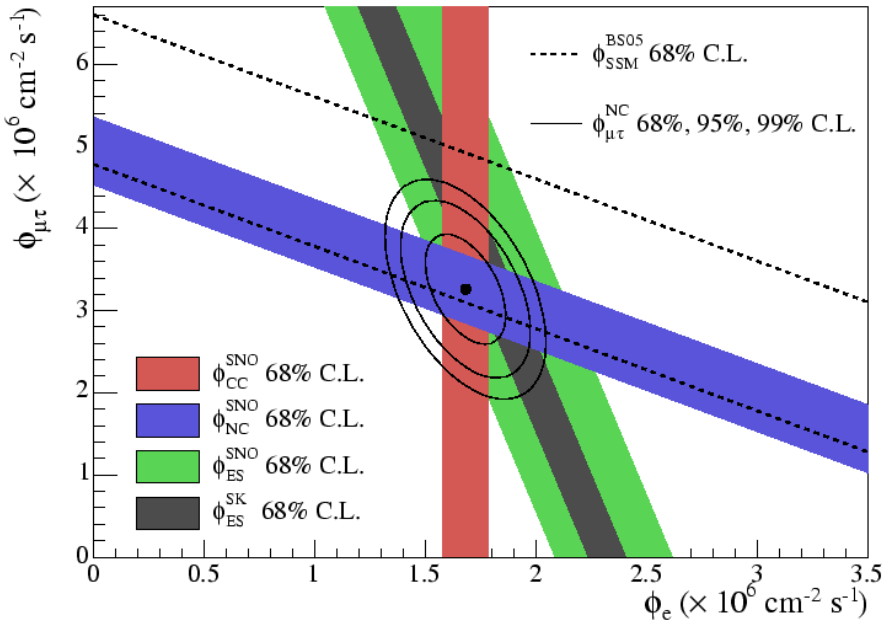
$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(L)\rangle|^2$$

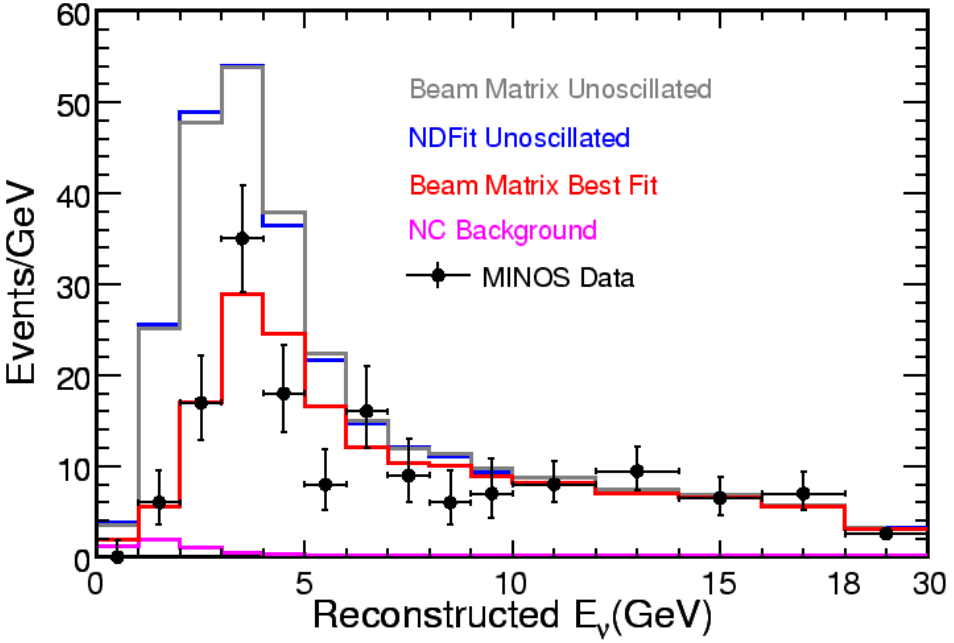
$$= \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2[1.27\Delta m^2_{ij}L/E]$$

$$+2\sum_{i>j} \Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2[2.54\Delta m^2_{ij}L/E]$$

- two neutrino case: $P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$

$$\left(1.27,\ 2.54 \text{ in units of } \frac{\text{GeV}\cancel{c^4}}{\text{eV}^2\text{km}}\right)$$





- solar, reactor experiments:
  $\Delta m_{12}^2 \sim 8\times10^{-5}$ eV^2
- atmospheric, accelerator experiments:
  $\Delta m_{23}^2 \sim 2\times10^{-3}$ eV^2

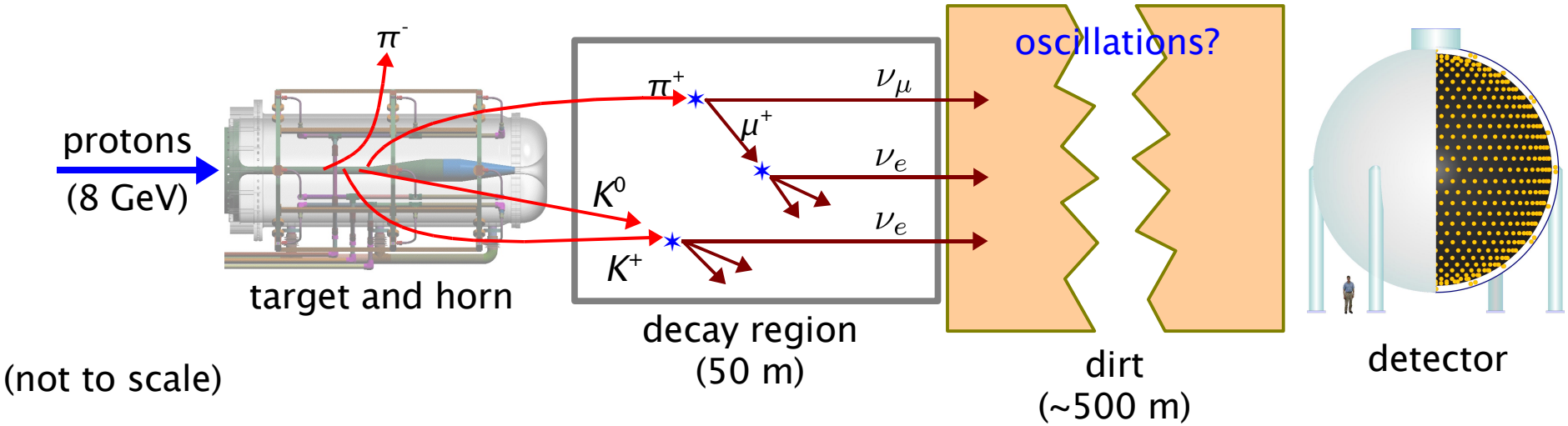
well established

- LSND:
  $\Delta m^2 \sim 1$ eV^2

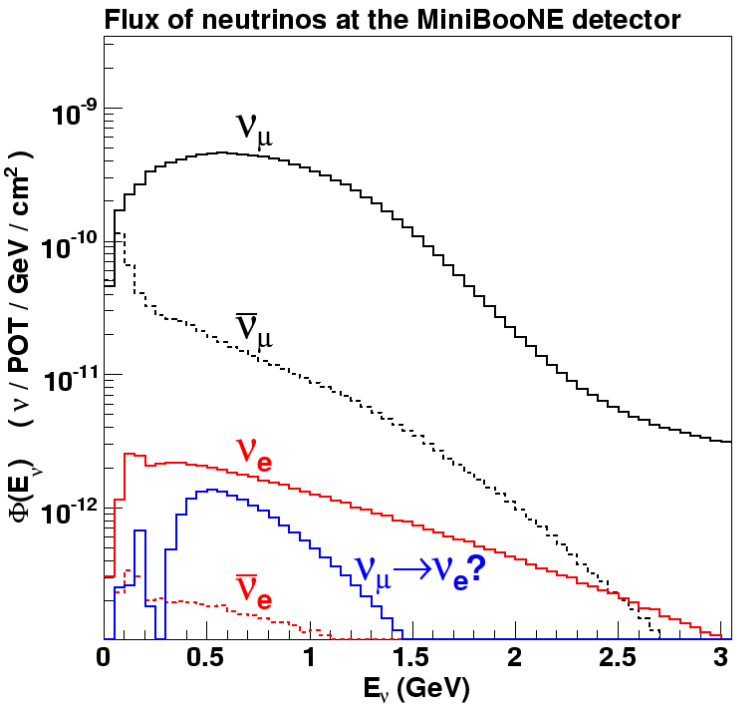
unconfirmed
(enter MiniBooNE)

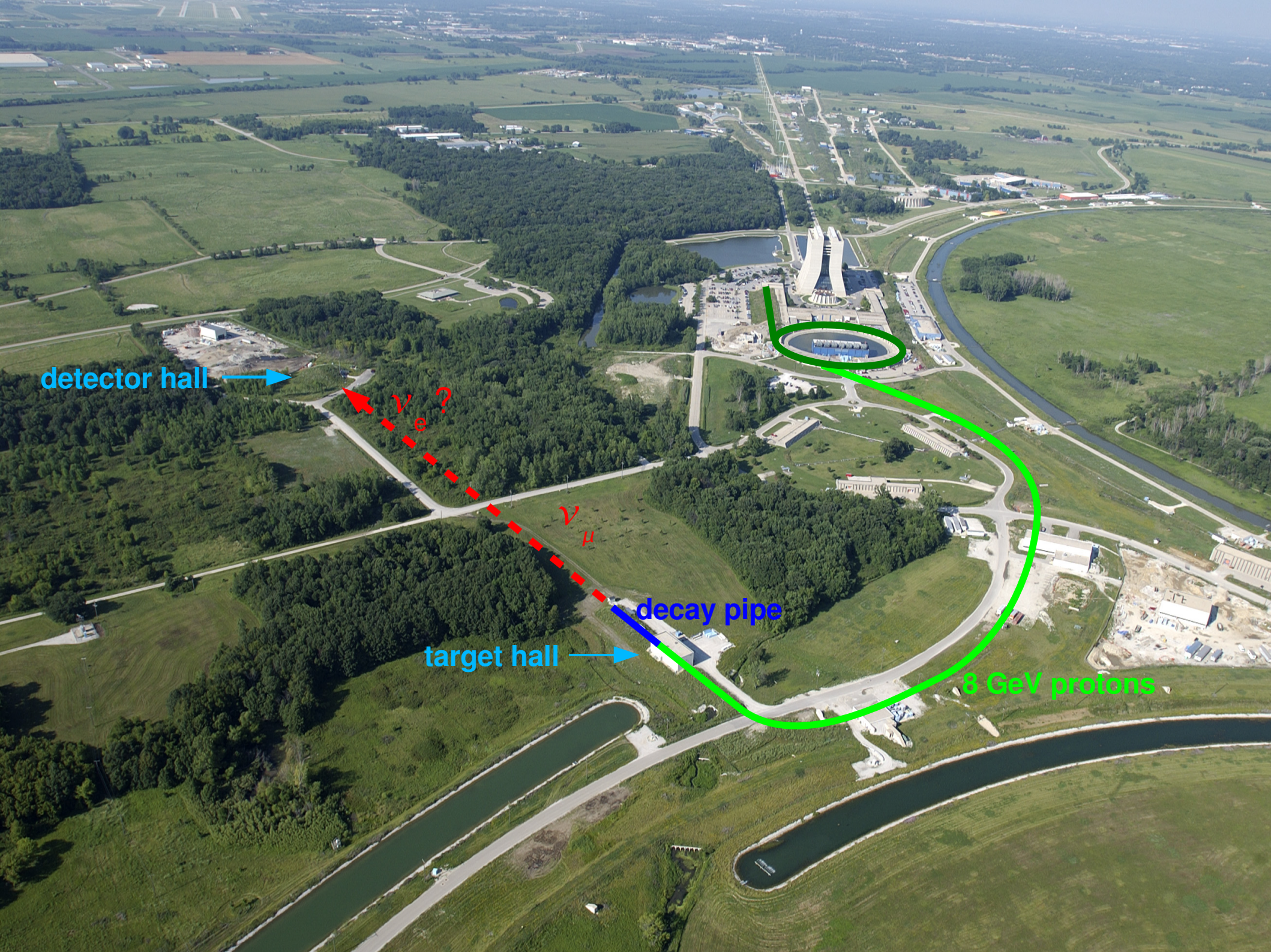
Incompatible with three-neutrino model
⇒ new physics needed to accommodate LSND (sterile states, CPT violation?)

MiniBooNE

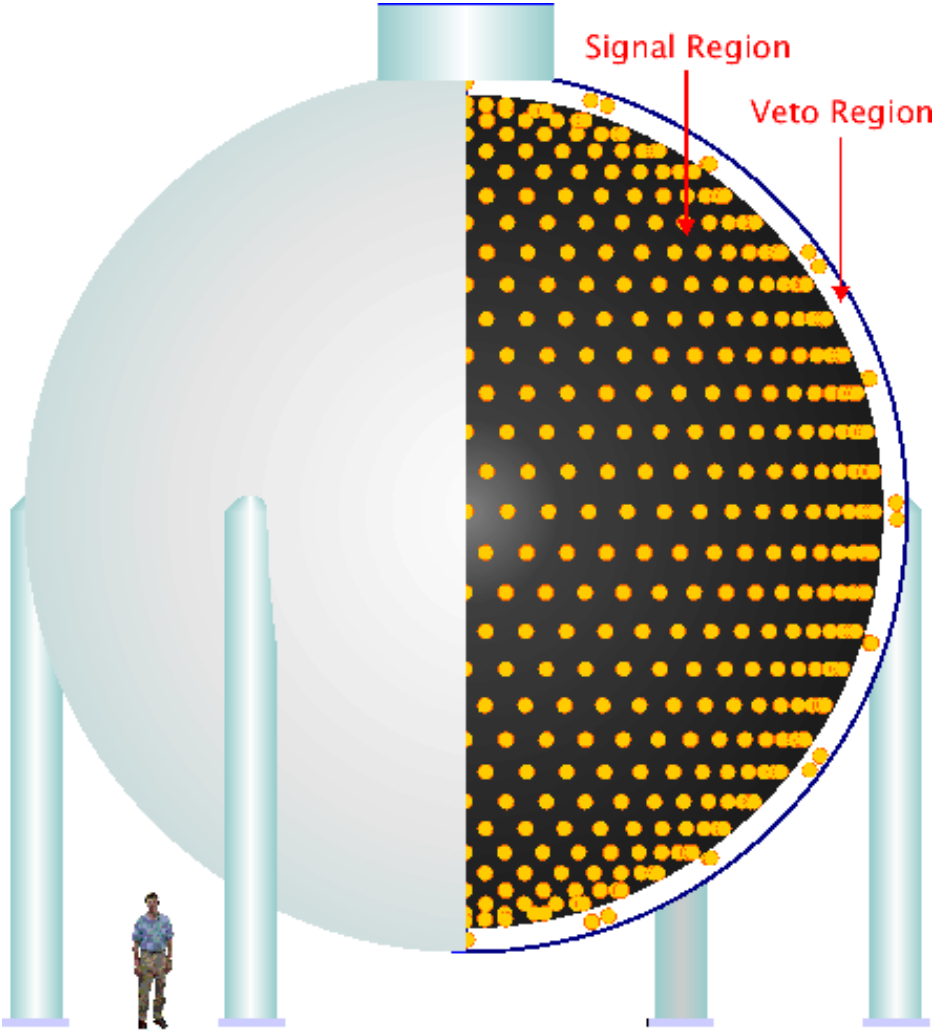


- ~0.8 GeV ν_μ beam (0.6% intrinsic ν_e)
- L/E:
  MiniBooNE: (0.5 km) / (0.8 GeV)
  LSND: (0.03 km) / (0.05 GeV)
- 1.7M neutrino events collected during run
- Looking for a few hundred excess ν_e CC events

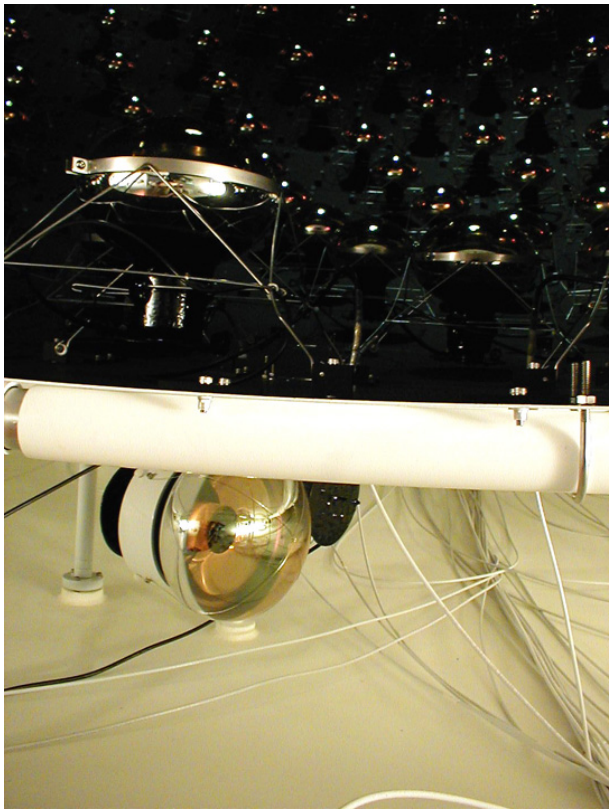



detector hall
ν_e ?
ν_μ
decay pipe
target hall
8 GeV protons

Detector



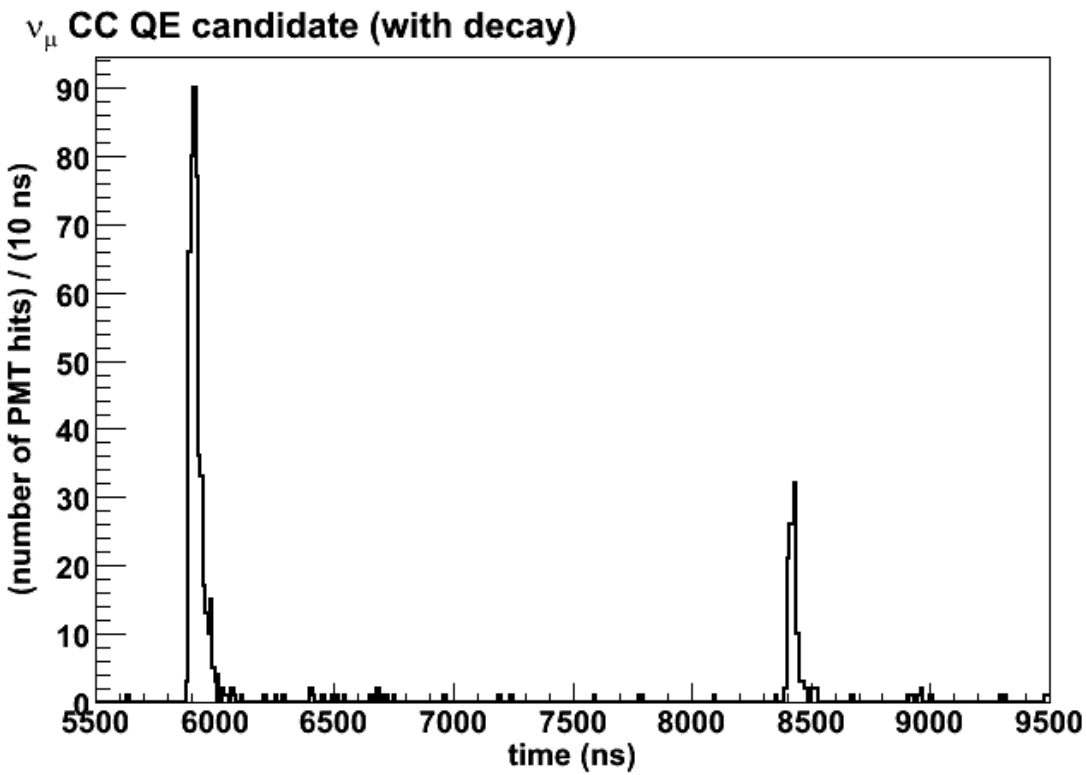
- 12 m sphere filled with
  800 tons of mineral oil
- inner main region: 1280 PMTs
- outer veto region: 240 PMTs
- laser flasher calibration system



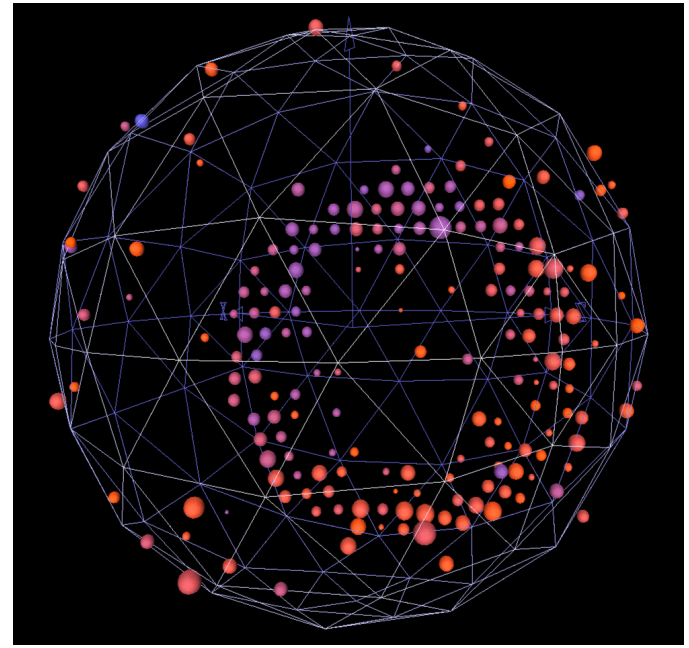
veto | main

MiniBooNE events

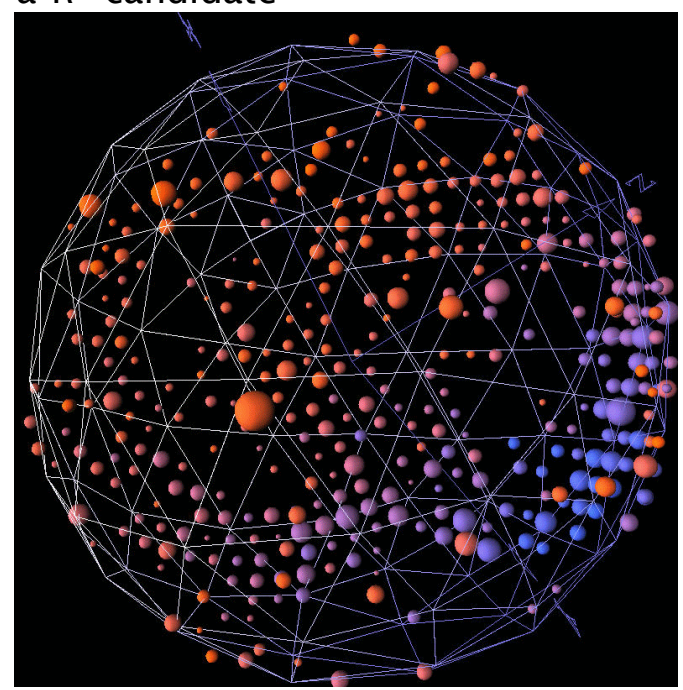
- PMT activity clustered in time = “event”
- Below:
  PMT “hits” (any PMT signal above threshold) for a muon followed by its decay electron

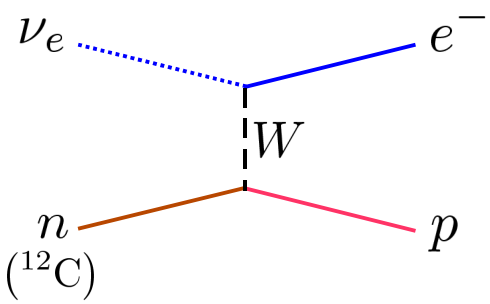


a muon candidate



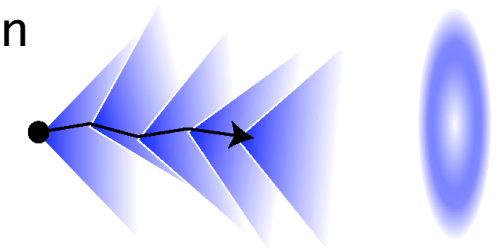
a π^0 candidate

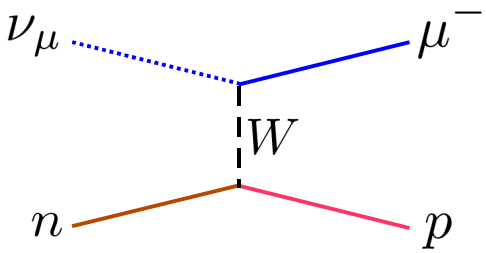




signal and
intrinsic ν_e background

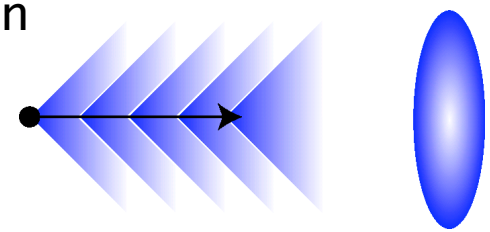
electron

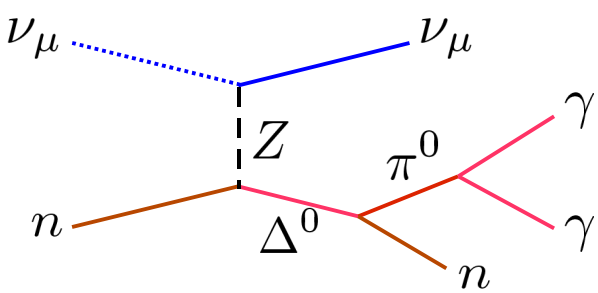




single muon ring
(μ decay-at-rest tags
~80% of these)

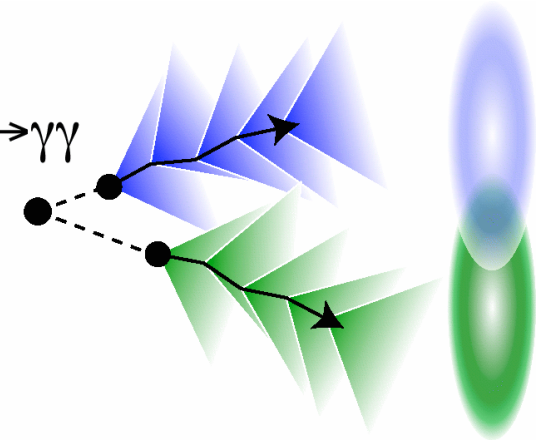
muon

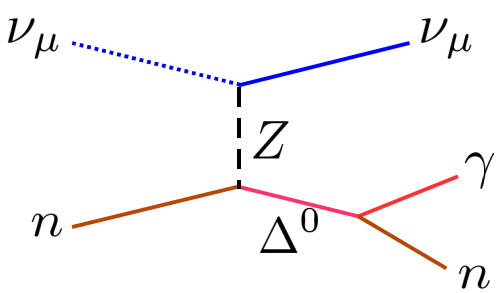




NC $\pi^0 \rightarrow \gamma\gamma$
(can look like one ring)

$\pi^0 \rightarrow \gamma\gamma$





NC $\Delta \rightarrow N\gamma$
(approximately irreducible)

Maximum likelihood reconstruction

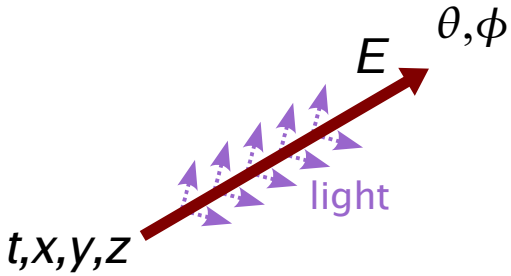
- Form likelihood for PMT signals (charge and time) under different hypotheses:

  (1) e track

  (2) μ track

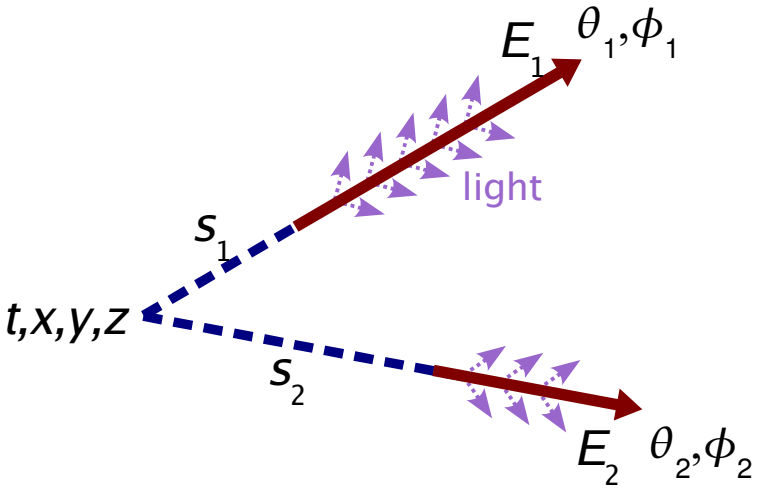
  (3a) two γ tracks with mass=M_{π^0}

  (3b) two γ tracks with any mass



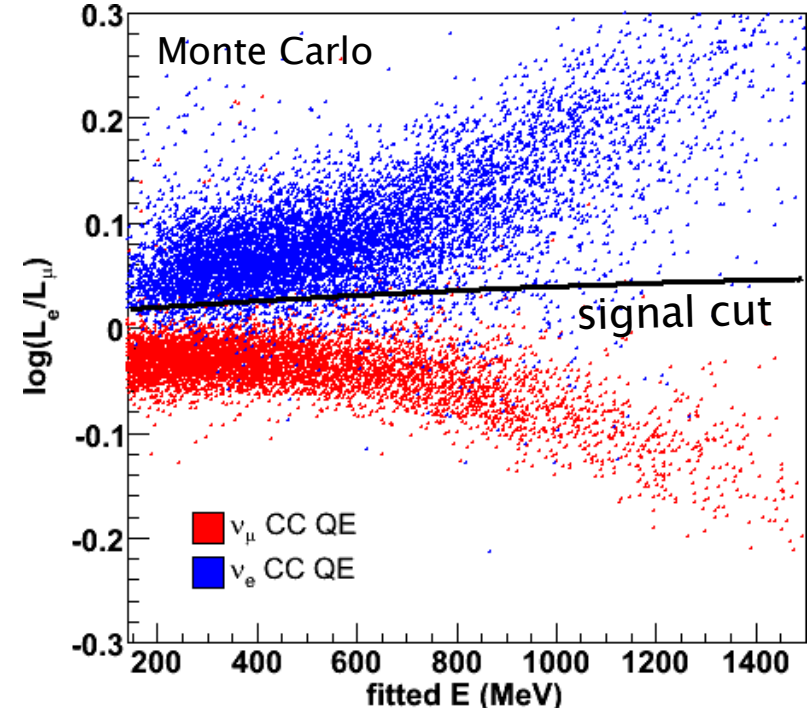
- Maximize likelihood to extract track parameters, and...

- Likelihood ratios provide particle identification



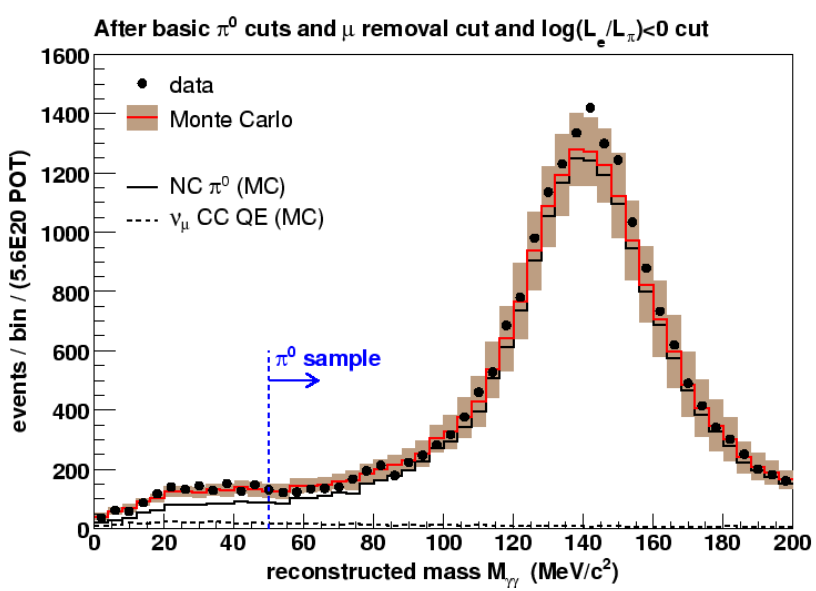
μ or e?

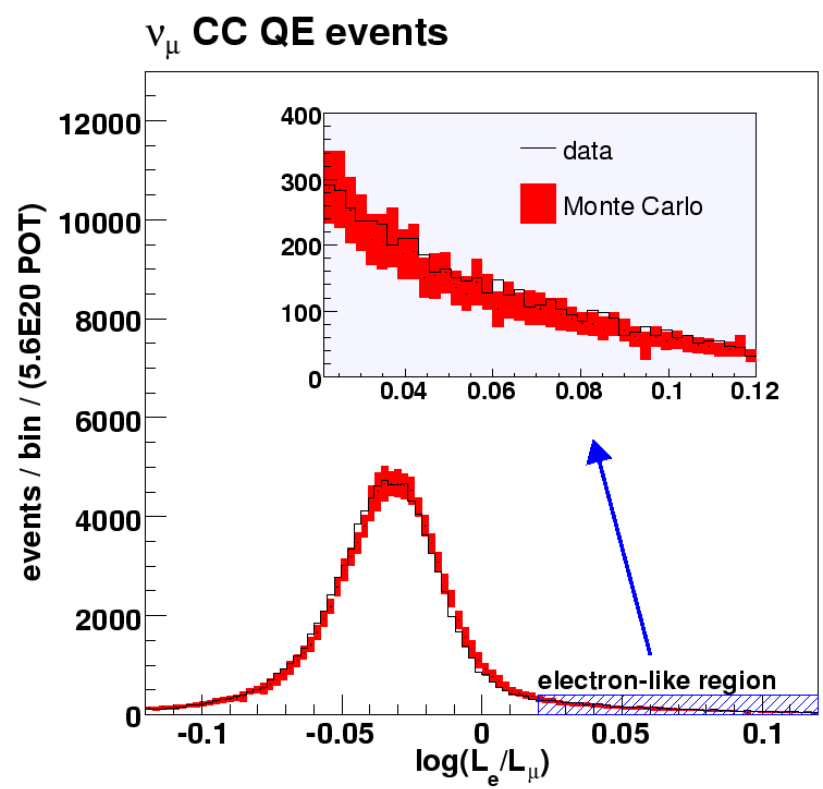
- positive (negative) **$\log(L_e/L_\mu)$** favors the e (μ) hypothesis
- >90% efficient for signal
- check simulation with tagged μ sample



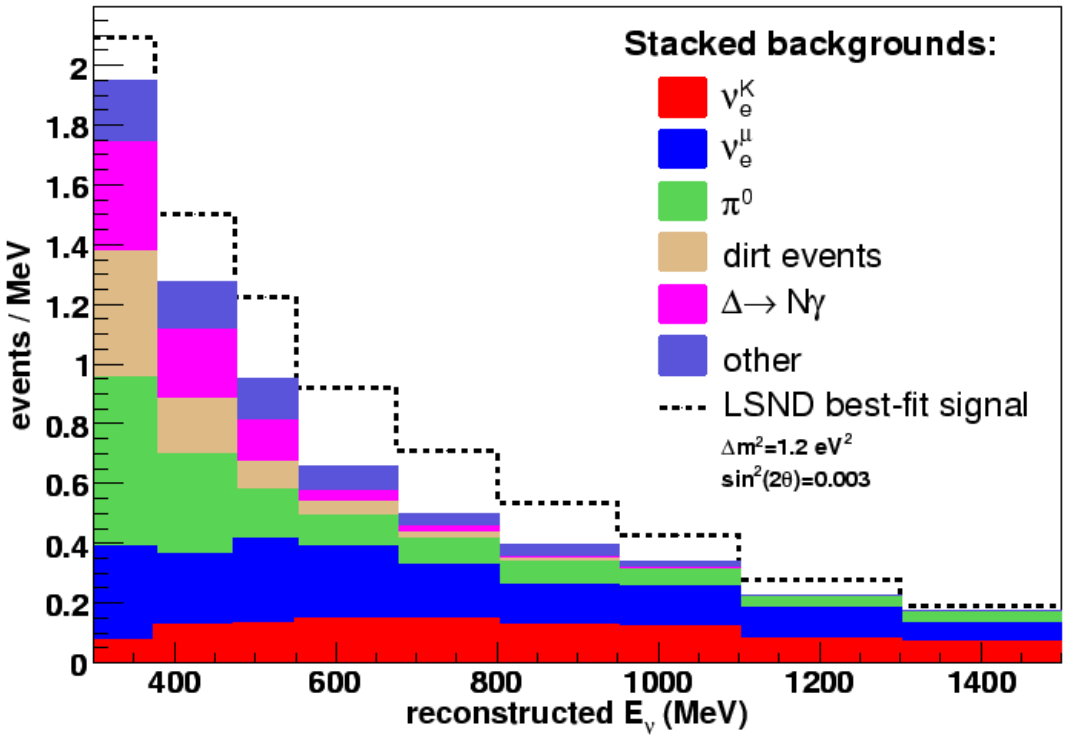
π^0 or e?

- Also use reconstructed invariant mass to identify π^0 events





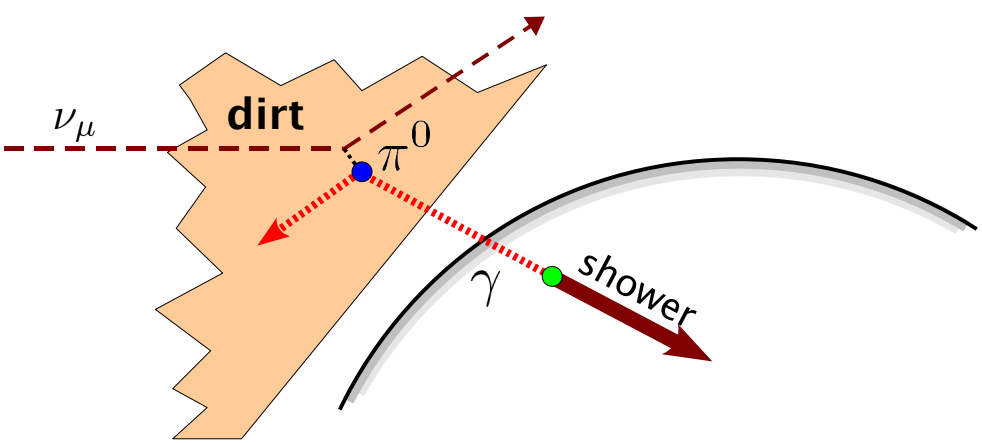
Expected events



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	$358 \pm 19 \pm 35$

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



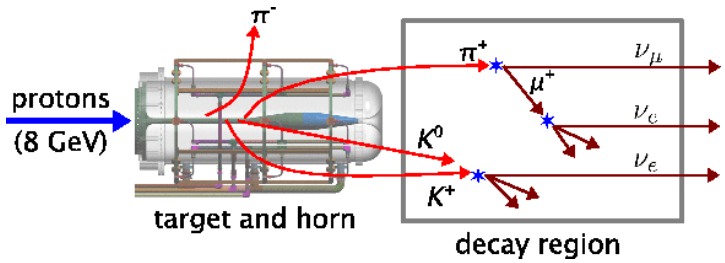
BG predictions come from:

dead reckoning

and

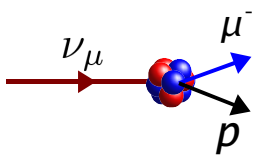
MiniBooNE event samples

Dead reckoning



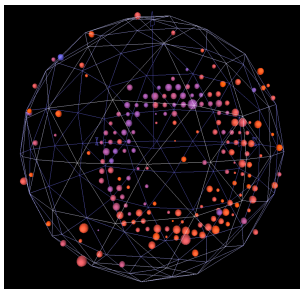
1. Flux prediction

   pion, kaon production and secondary interaction cross sections from world data (including MB target at HARP/CERN)



2. Neutrino interactions

   Nuance event generator (D. Casper) with a few MiniBooNE mods

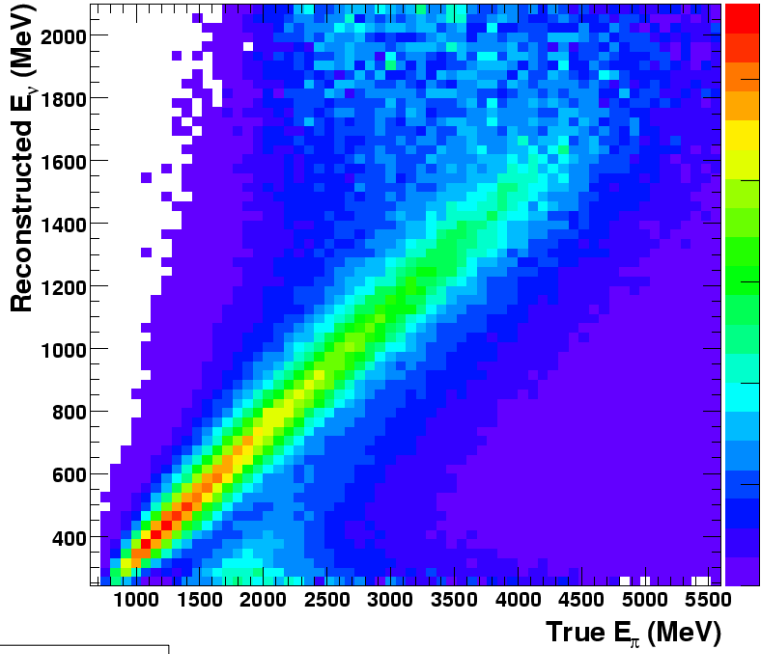


3. Detector simulation (particle/photon tracking, electronics)

   Extensive simulation of optical photons; bench-top and *in situ* measurements

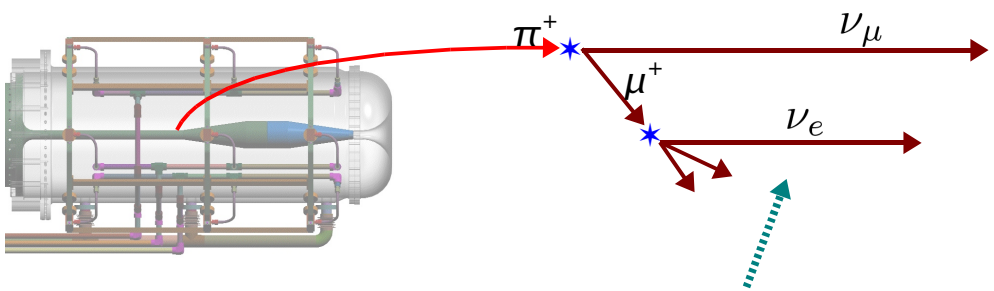
Constraints from ν_μ CC quasi-elastic events

- ν_e signal
- ν_μ CC backgrounds
- ν_e events from $\pi^+ \rightarrow \mu^+ \rightarrow \nu_e$



A measure of the ν_μ E_ν spectrum...

... is a measure of the π^+ spectrum...



... which provides the $\pi^+ \rightarrow \mu^+ \rightarrow \nu_e$ flux.

geometry selects forward decays

E_ν-to-E_π relation ~linear (above)

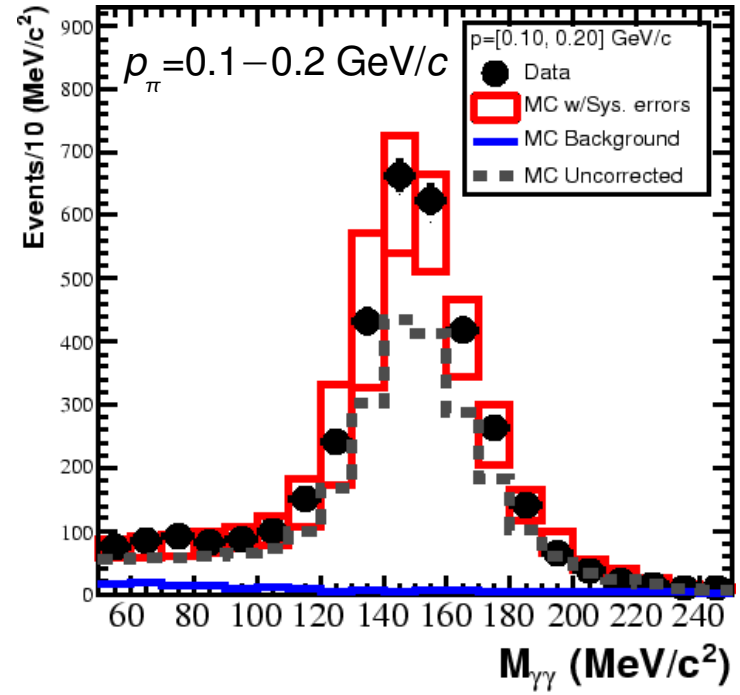
rate systematic errors pushed to higher order

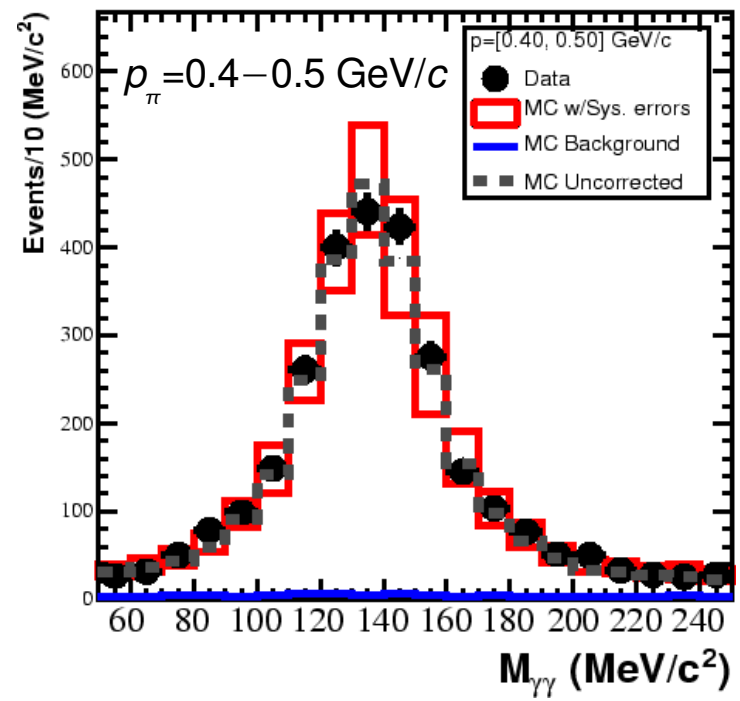
Constraints from NC π^0 events

- 90%+ pure π^0 sample (mainly $\Delta \rightarrow N\pi^0$)
- measure & correct π^0 rate as function of momentum

Invariant mass distribution for two momentum bins →

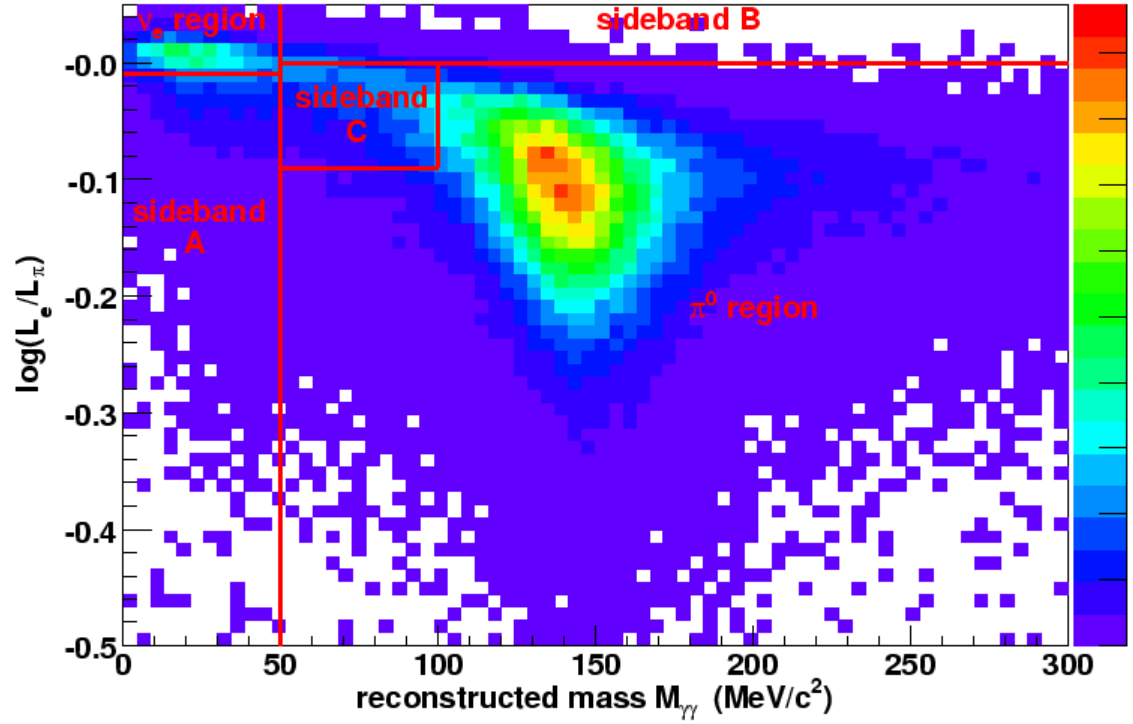
$\Delta \rightarrow N\gamma$ also constrained (though to a lesser extent)

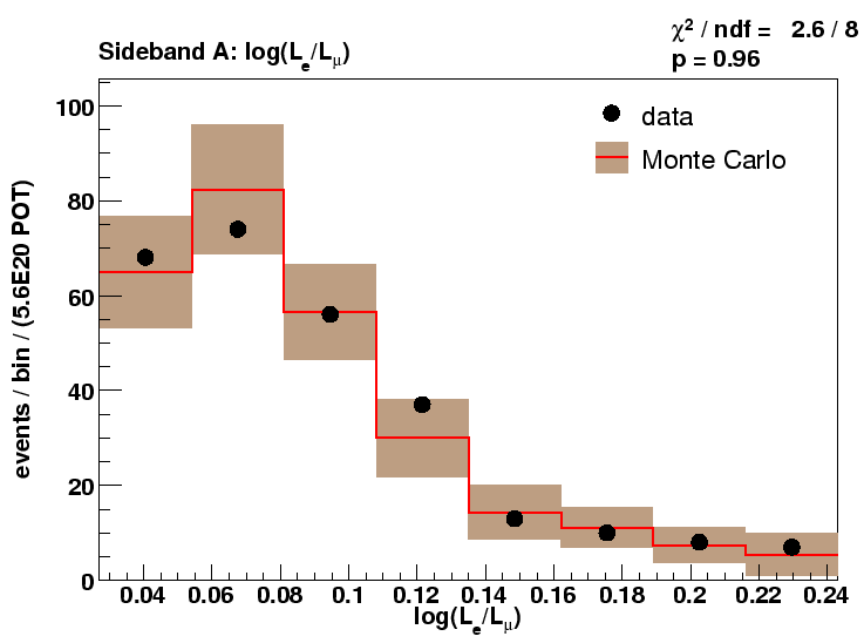


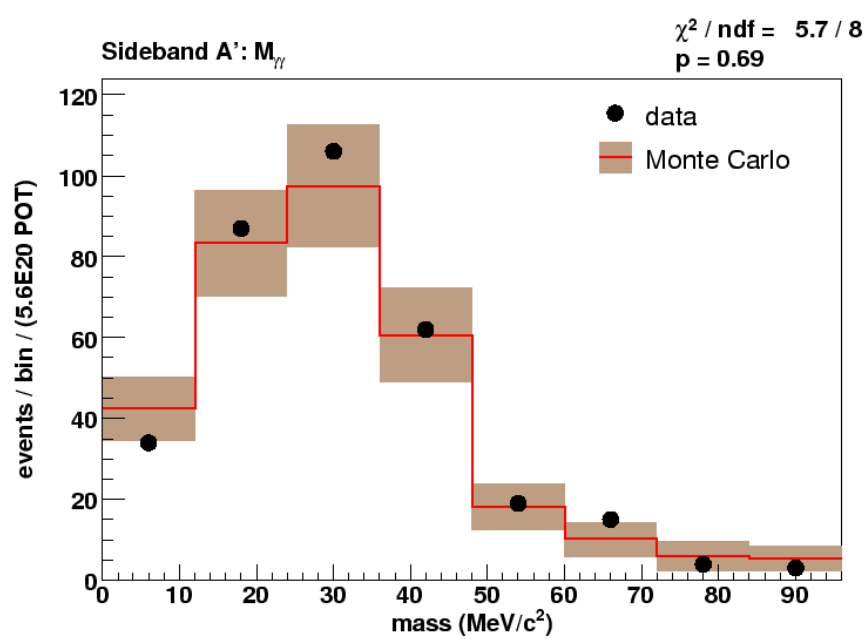


Sideband checks

- Look at data/MC agreement for near-signal events [good]
- Can't check ν_e region directly
- Test full signal extraction procedure on "sideband C" [similar stats]

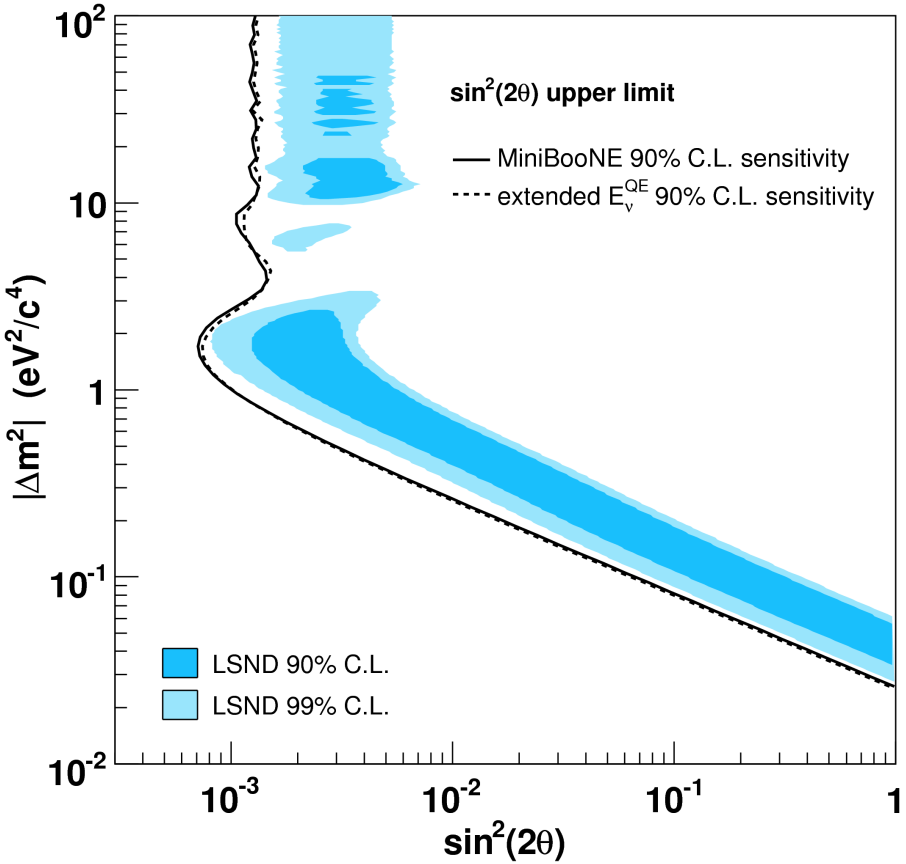






Blind χ^2 checks of signal region

- Perform oscillation fit and look at χ^2 for many distributions
- Everything checked out fine except one distribution (visible energy)
- Eventual way forward: remove very lowest energies from analysis
  300–3000 MeV → 475–3000 MeV
- No loss in sensitivity to LSND-like oscillations →
- All tests now okay; look at result



Counting only

(E_ν from 475–1250 MeV)

Expected: 358 ± 19(stat) ± 35(syst) events

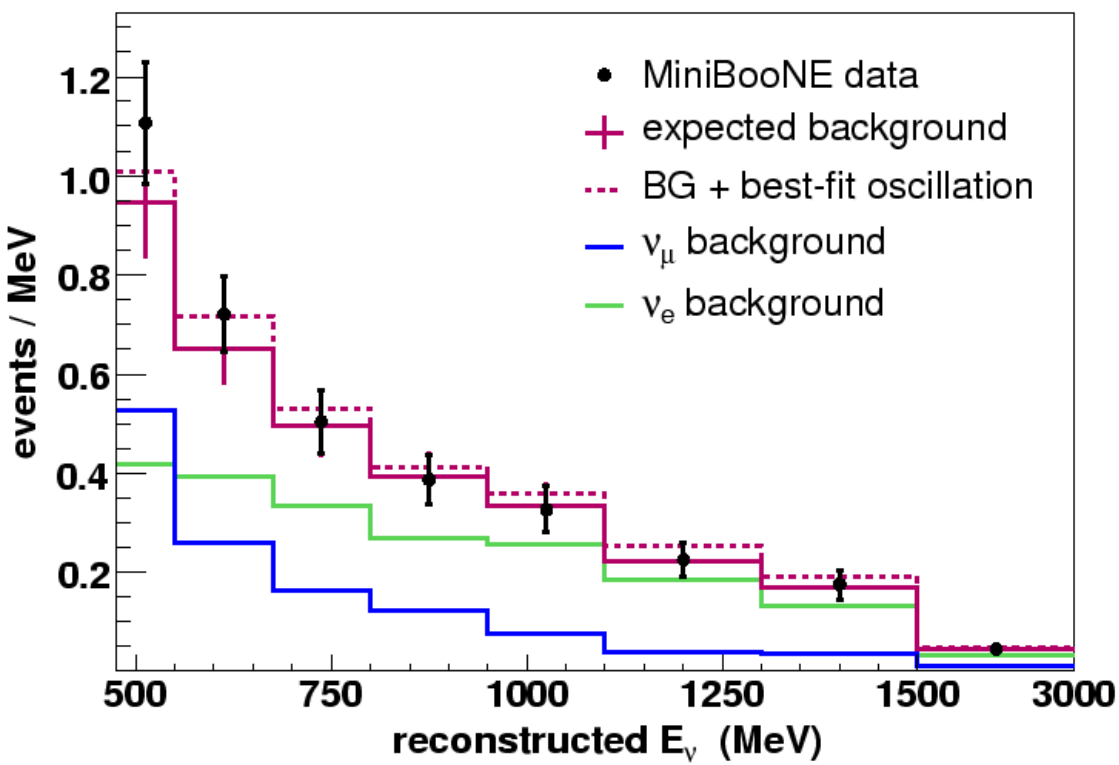
Observed: 380 events

Deviation: 0.55σ

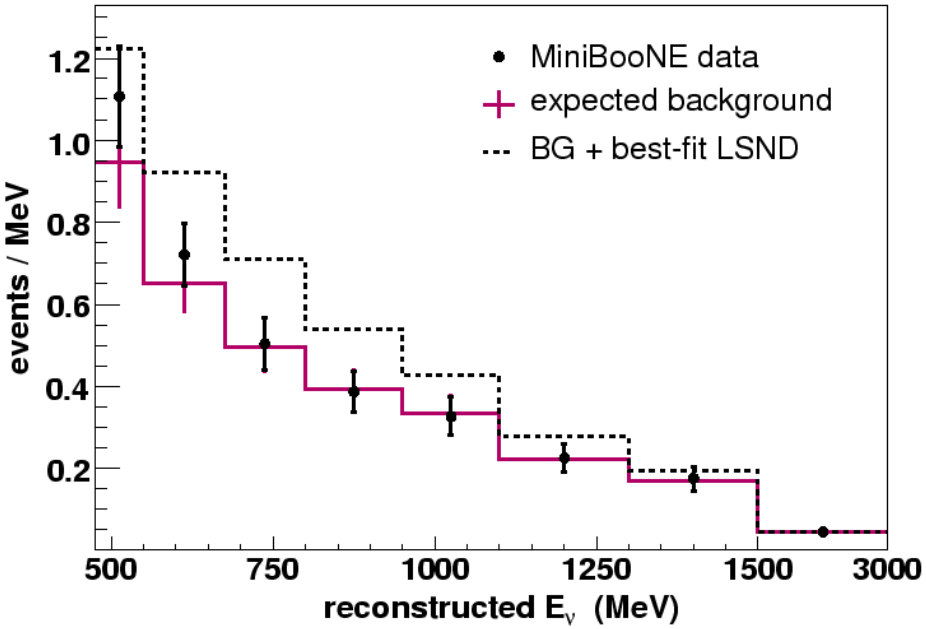
Energy fit

Best fit:

- $\sin^2 2\theta = 1.1\times10^{-3}$
- $\Delta m^2 = 4.1\ eV^2/c^4$
- $\chi^2_{null} - \chi^2_{best} = 0.83$

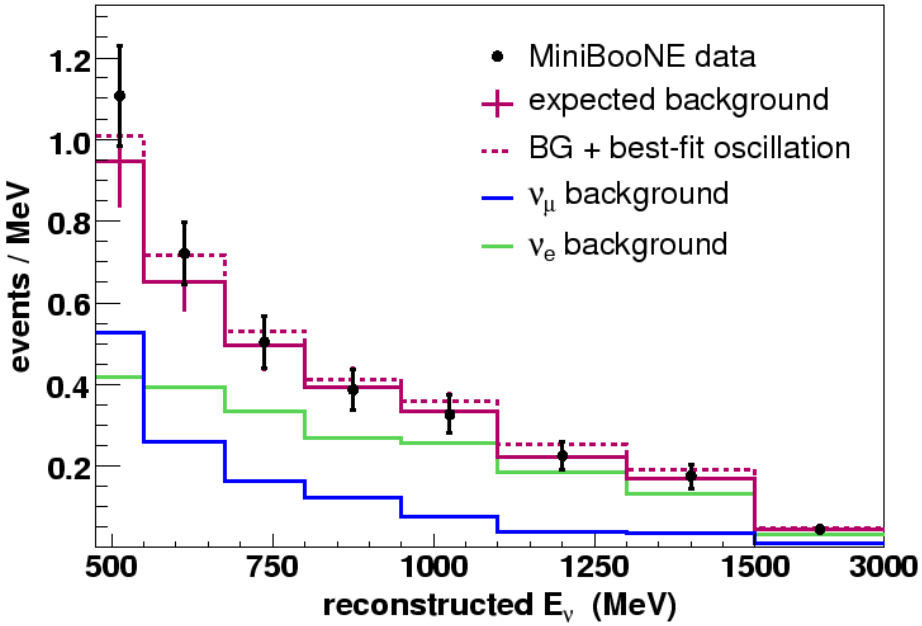


Comparing with LSND best fit



Best fit parameters from **LSND**:

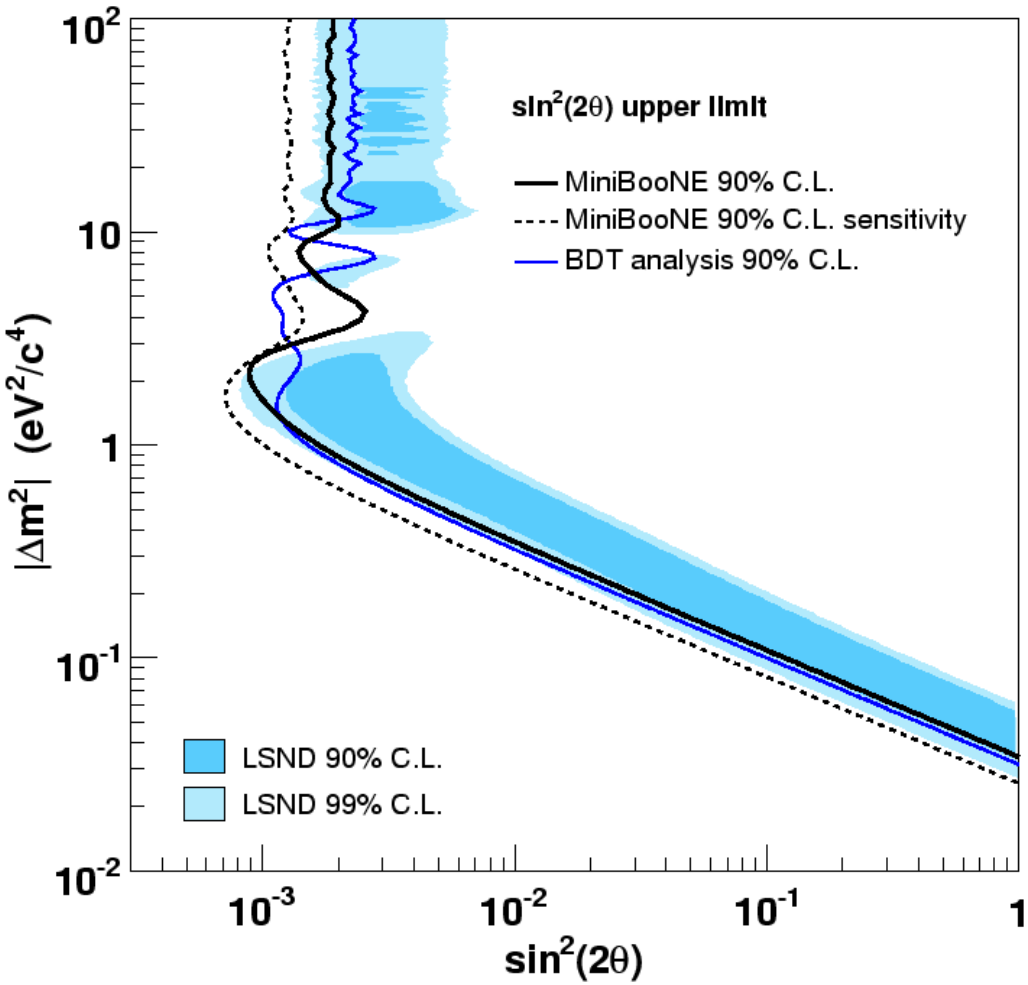
- $\chi^2_{\text{LSND}} - \chi^2_{\text{best MB}} = 13.7$



(from previous page)

- $\chi^2_{\text{null}} - \chi^2_{\text{best MB}} = 0.83$

Limit curve:



PRL **98**, 231801 (2007)

Quasi-independent 2nd analysis gives consistent limit

Summary

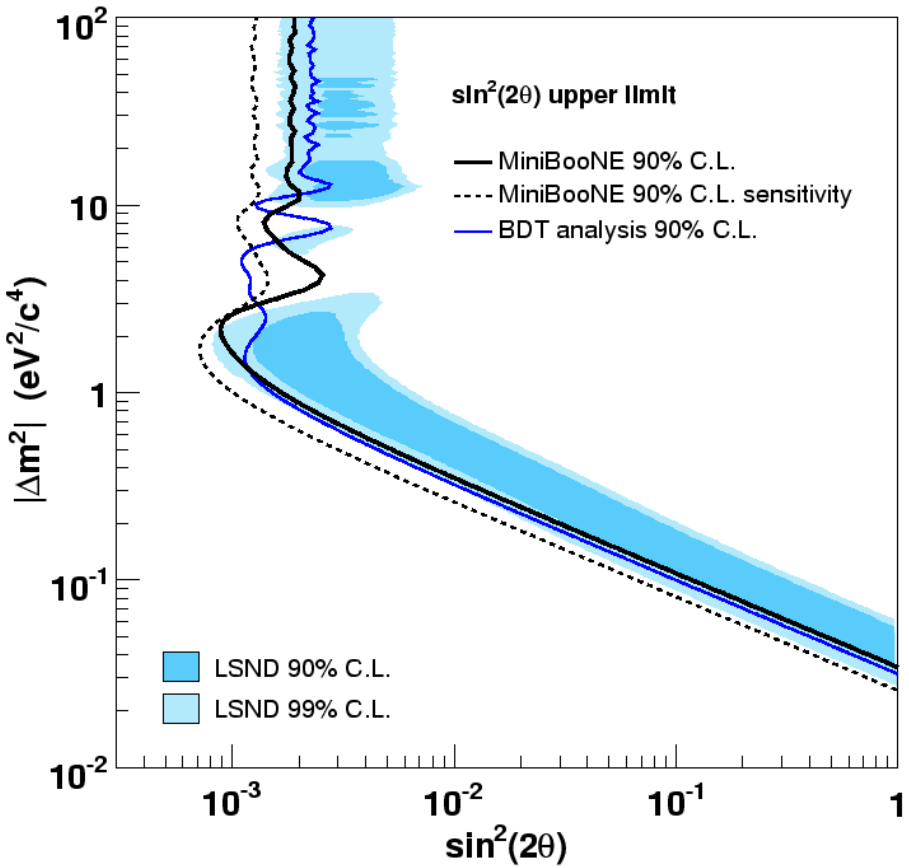
- Blind analysis with full MiniBooNE neutrino data set

- No significant excess seen in analysis region:

  Expected:
  358 ± 19(stat) ± 35(syst) events

  Observed:
  380 events

- Most of LSND-allowed region excluded at 90% C.L. →



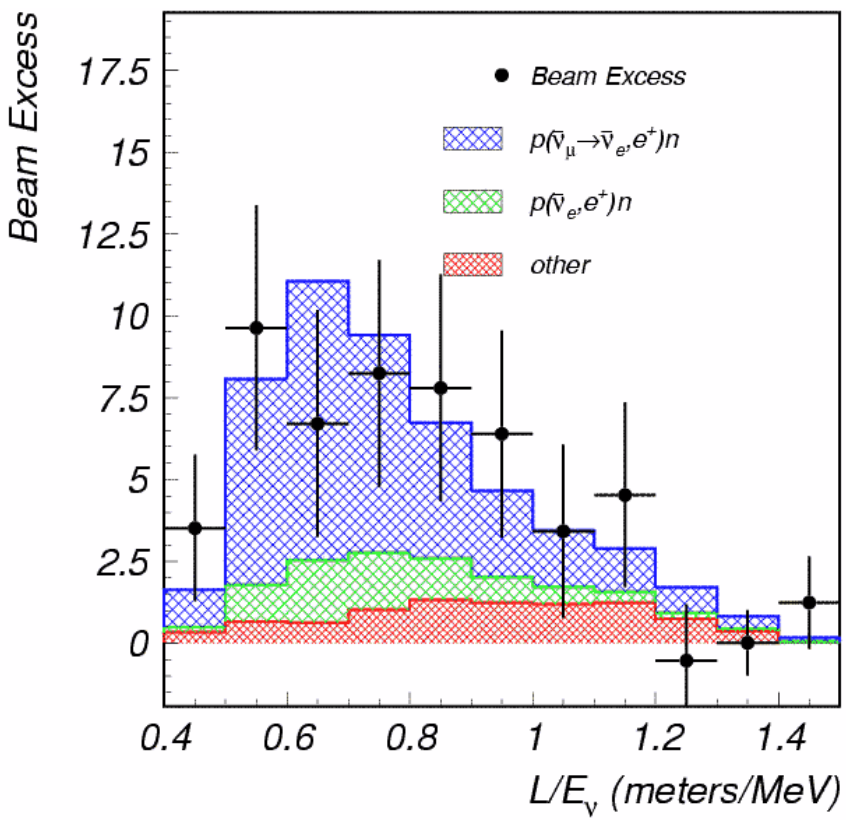
Result of lots of hard work by the MiniBooNE collaboration.

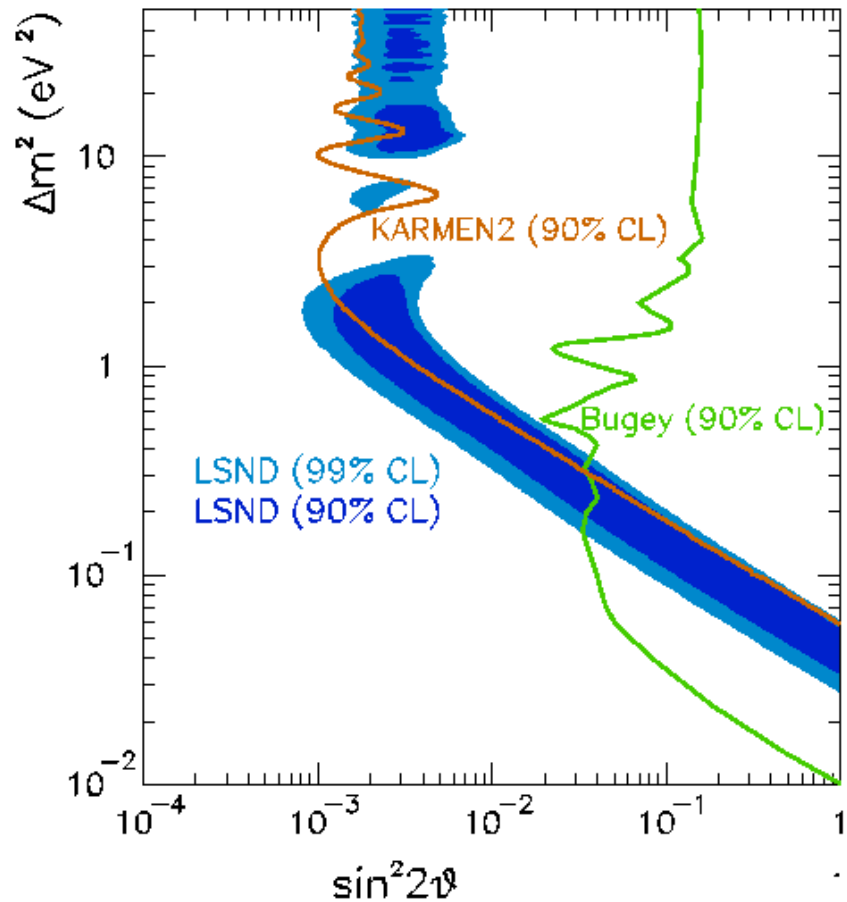
My sincere thanks to all of you!

Backups

LSND signal

- observed excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam
- *signature*: Cherenkov light from e^+ with delayed *n* capture (2.2 MeV)
- excess: 87.9 ± 22.4 ± 6.0



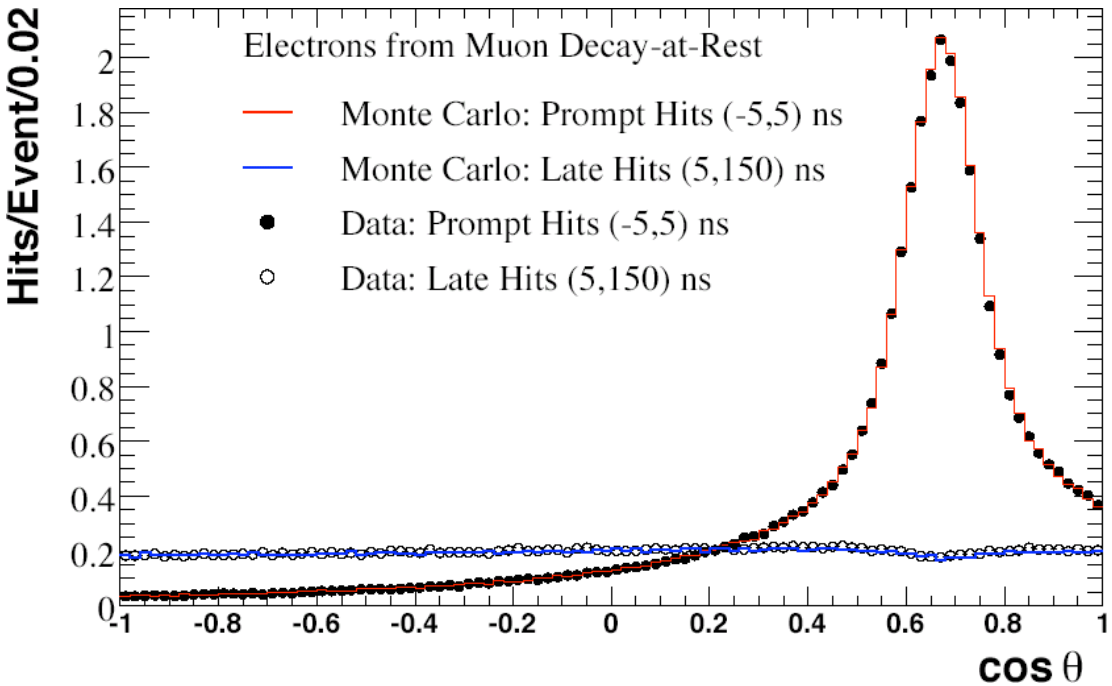


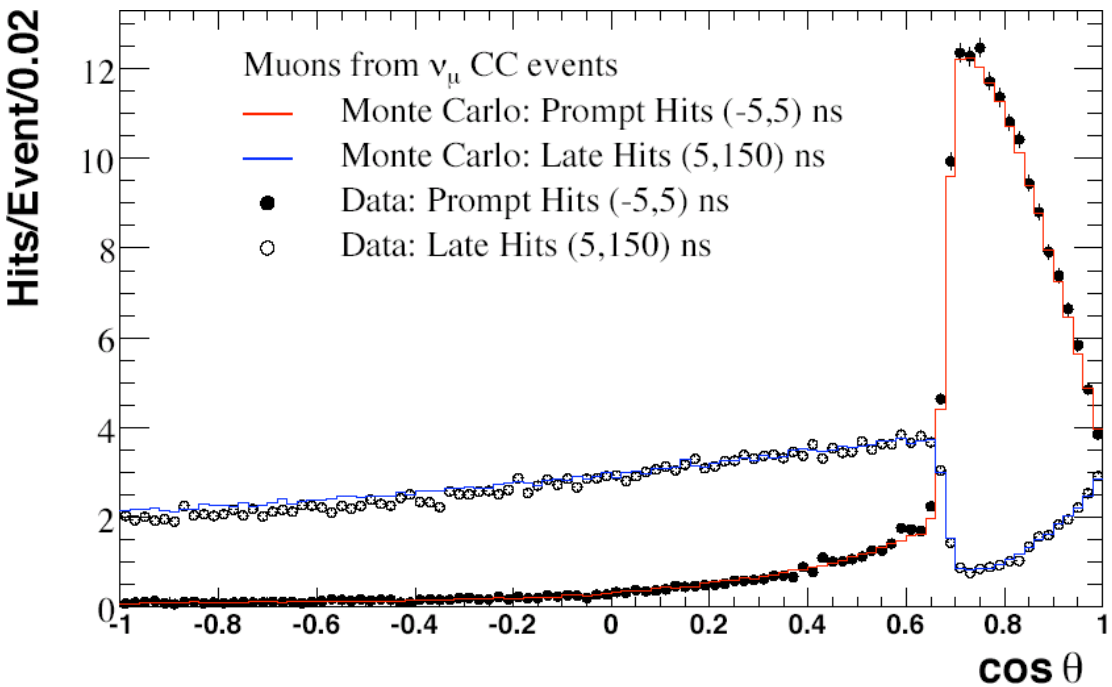
- consistent with two-neutrino osc.:

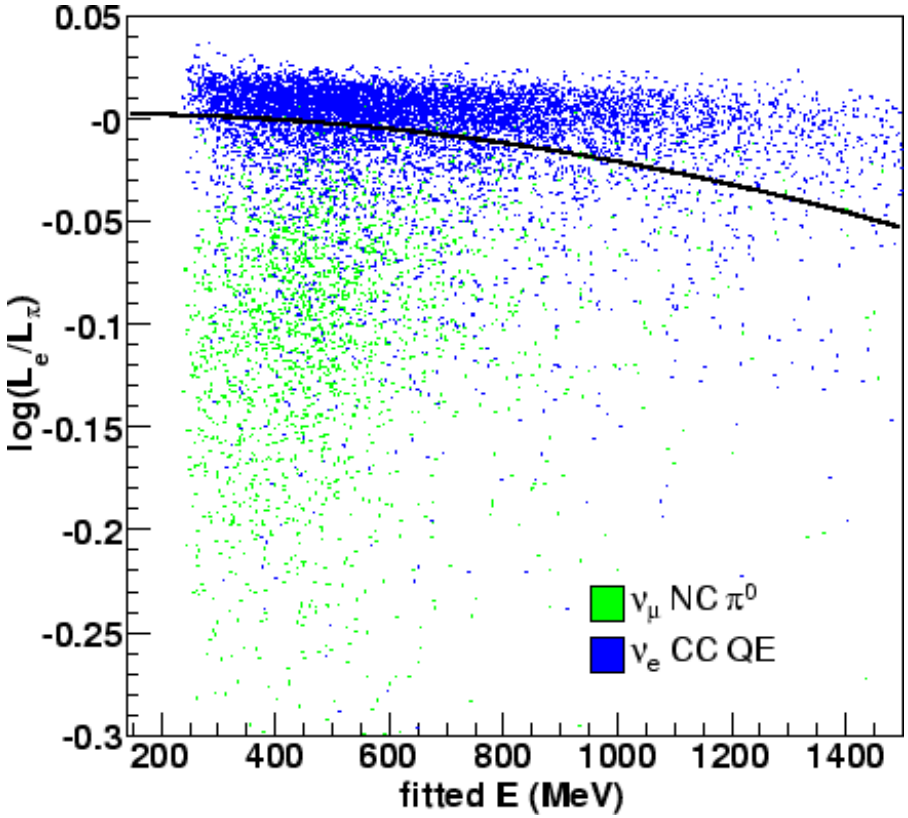
$$0.1\ \mathrm{eV}^2 < \Delta m^2 < 10\ \mathrm{eV}^2$$

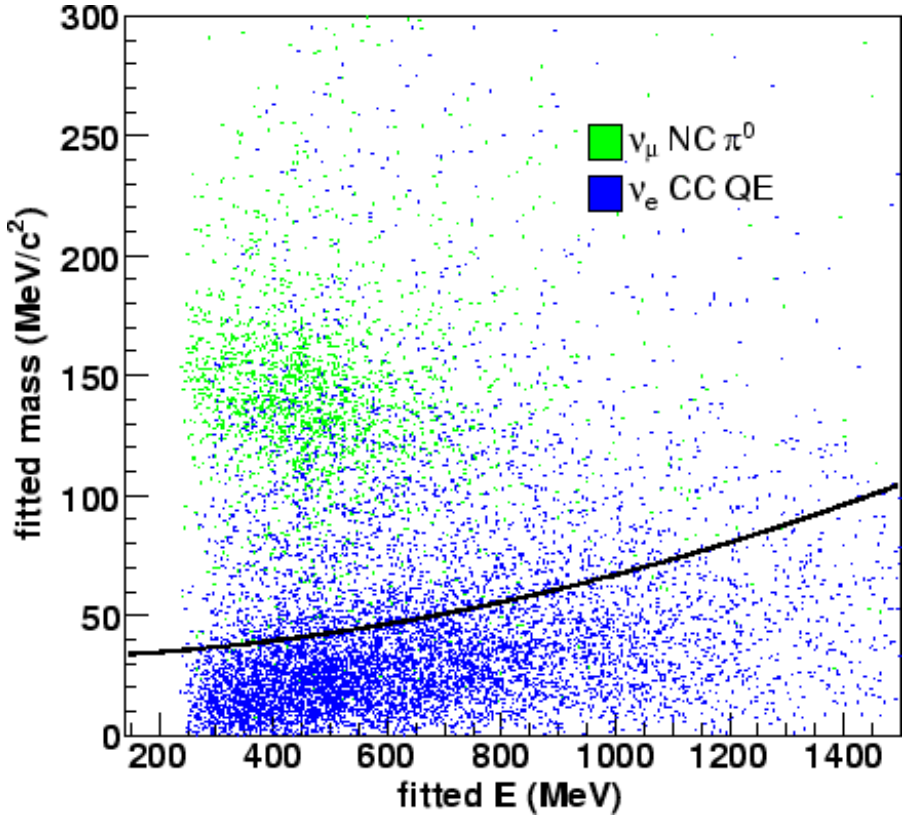
$$0.001 < \sin^2(2\theta) < 0.04$$

- oscillation probability: ~0.003

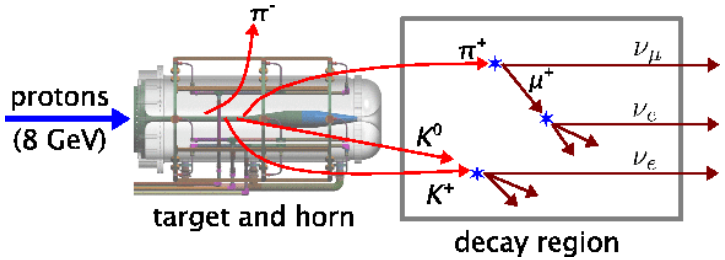

Electrons from Muon Decay-at-Rest
Monte Carlo: Prompt Hits (-5,5) ns
Monte Carlo: Late Hits (5,150) ns
Data: Prompt Hits (-5,5) ns
Data: Late Hits (5,150) ns
Hits/Event/0.02
cos θ


Muons from ν_μ CC events
Monte Carlo: Prompt Hits (-5,5) ns
Monte Carlo: Late Hits (5,150) ns
Data: Prompt Hits (-5,5) ns
Data: Late Hits (5,150) ns
Hits/Event/0.02
cos θ


0.05
-0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
log(L_e/L_π)
200
400
600
800
1000
1200
1400
fitted E (MeV)
ν_μ NC π^0
ν_e CC QE


300
250
200
150
100
50
0
fitted mass (MeV/c^2)
200
400
600
800
1000
1200
1400
fitted E (MeV)
ν_μ NC π^0
ν_e CC QE

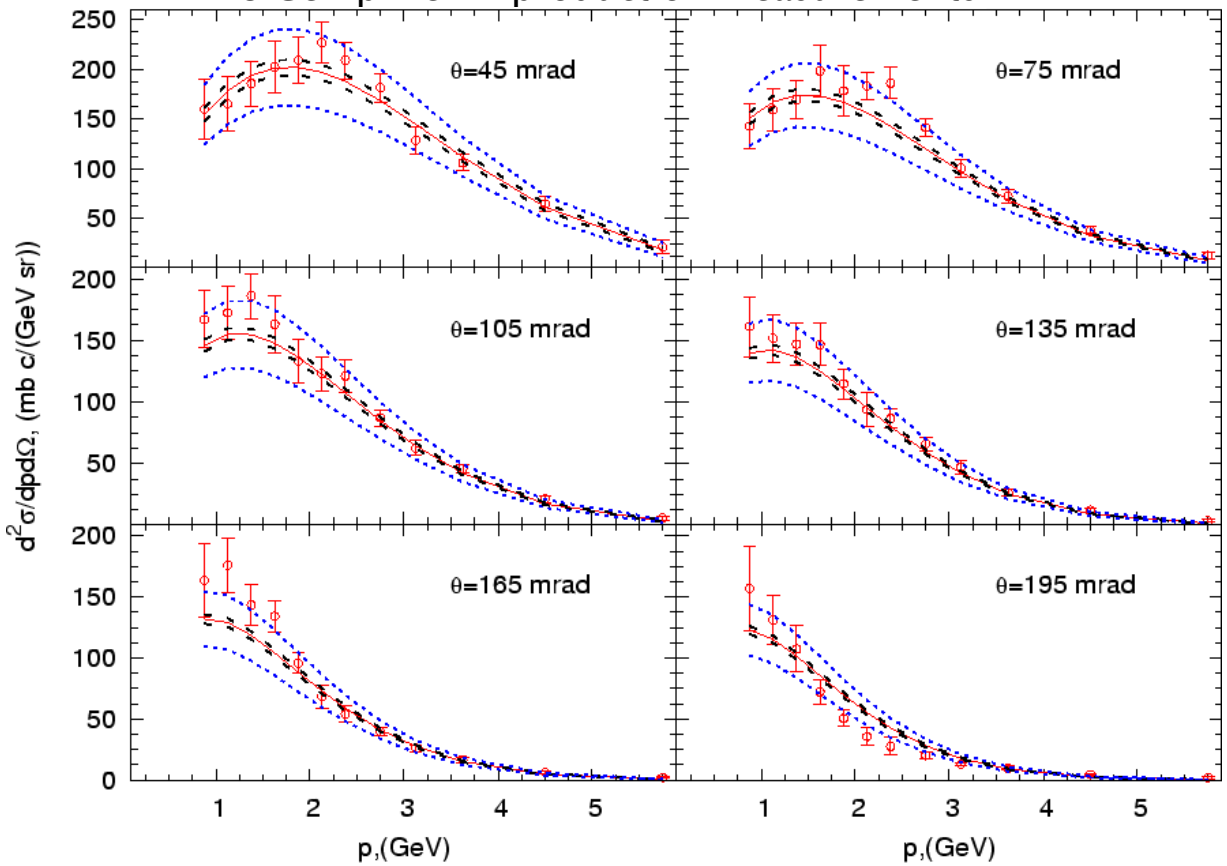
The simulation chain (1)



Neutrino flux

- GEANT4 implementation of beam components
- secondary particle production, propagation, decay
- Hadronic cross sections tuned on external data

HARP 8 GeV p-Be π^+ production measurements



Pion production in p-Be:

HARP (8 GeV, see left)

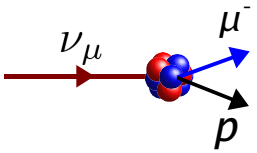
BNL E910 (6/12 GeV)

Kaon production

data sets at 9.5-24 GeV

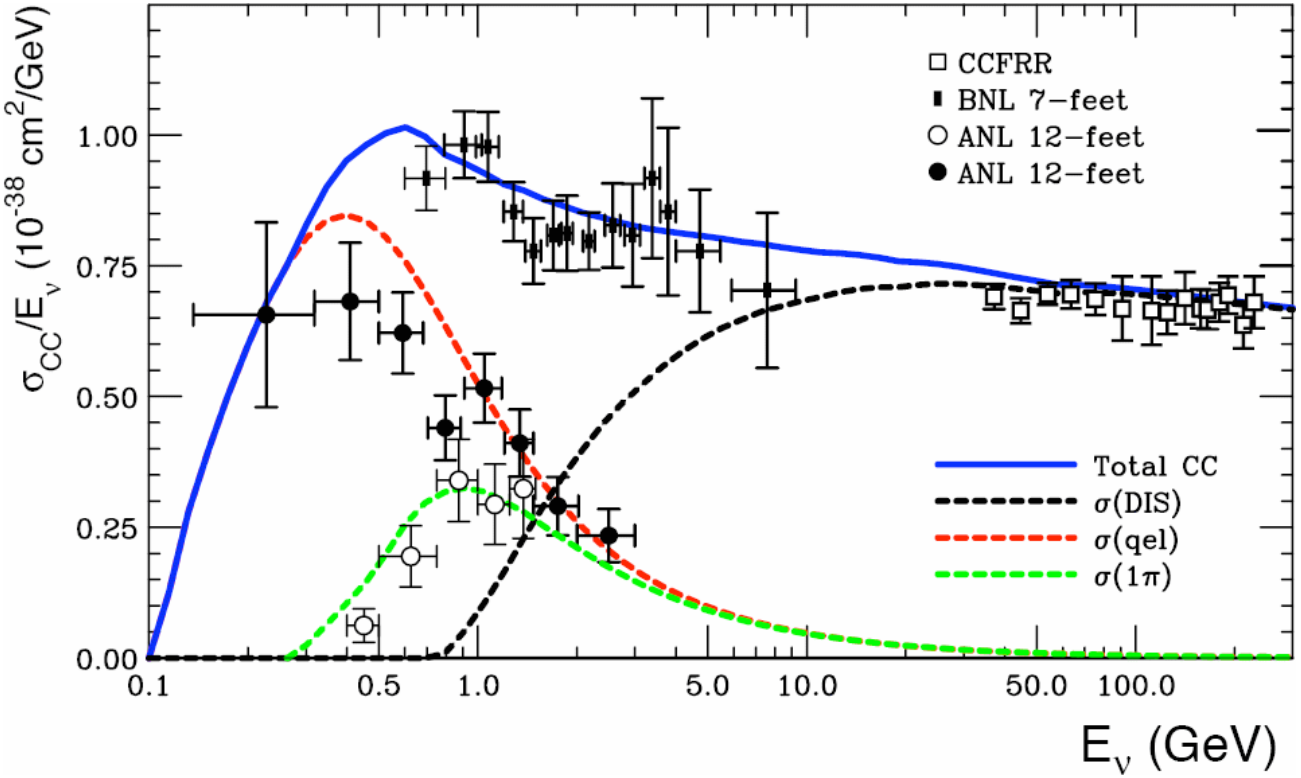
BNL E910 12 GeV (K^0)

The simulation chain (2)

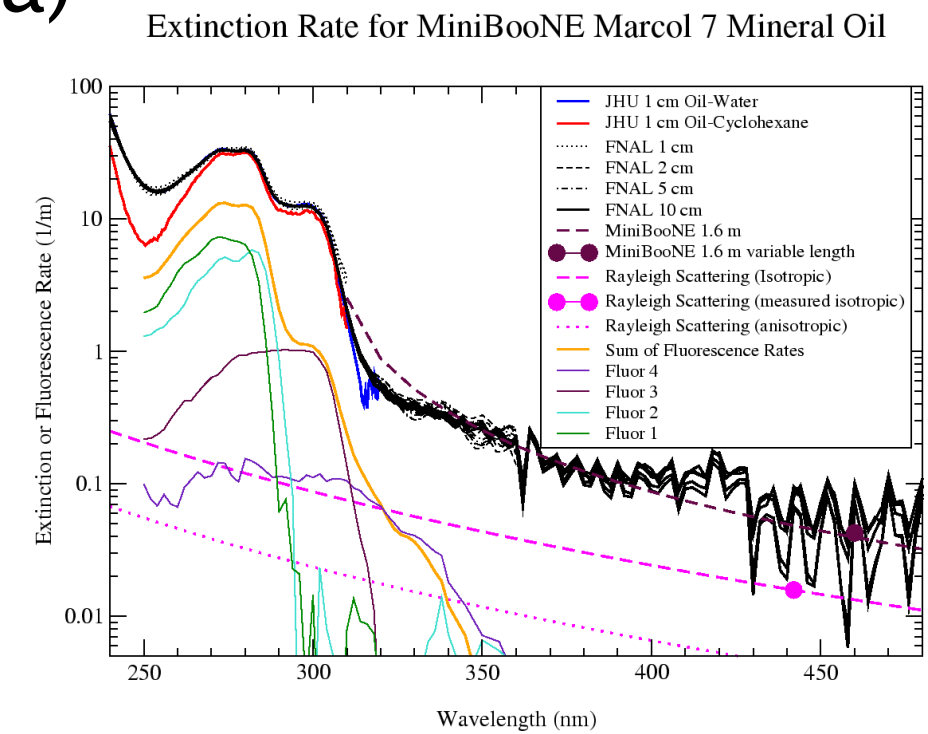


Neutrino cross sections

- **Nuance** event generator
- used elsewhere in community
- tuned on external & MiniBooNE data



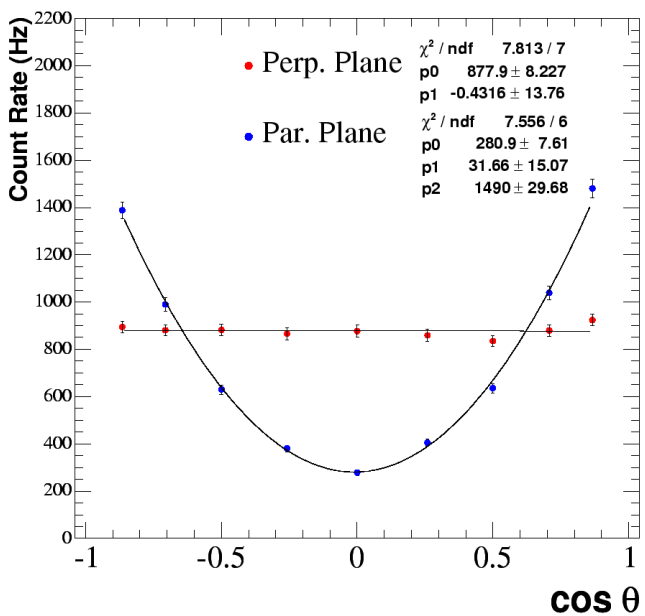
The simulation chain (3a)

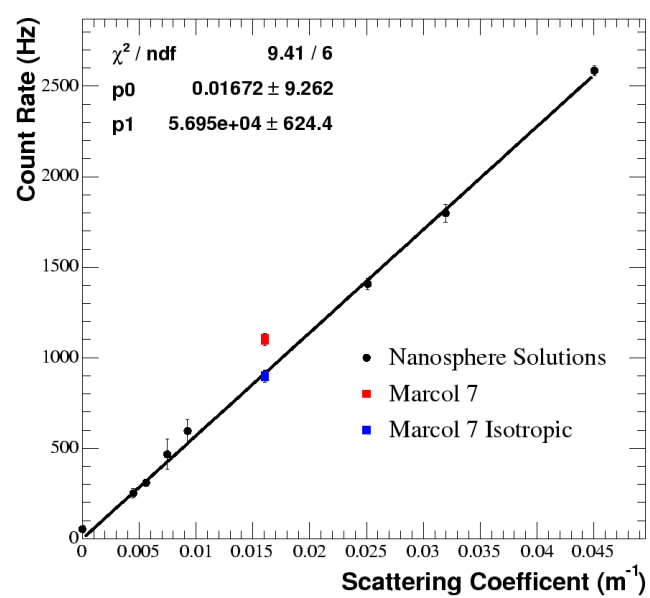


Detector

- GEANT3
- particle propagation/decay
- optical photons:
  - Cher. & scint.
  - production/propagation
  - absorption
  - Rayleigh/Raman scattering
  - fluorescence

precision scattering measurements →

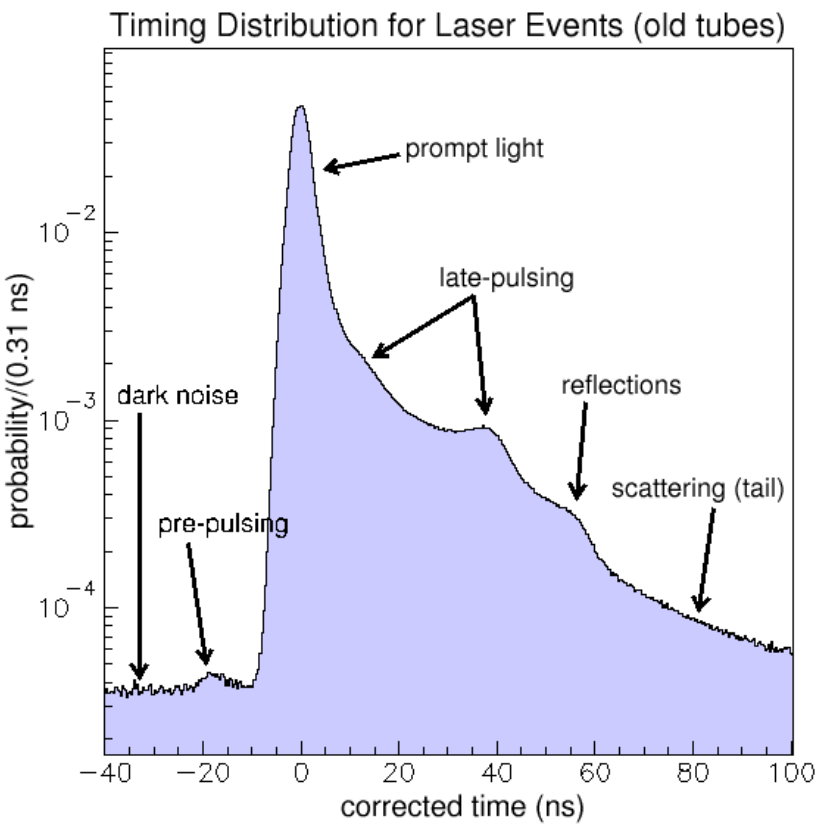




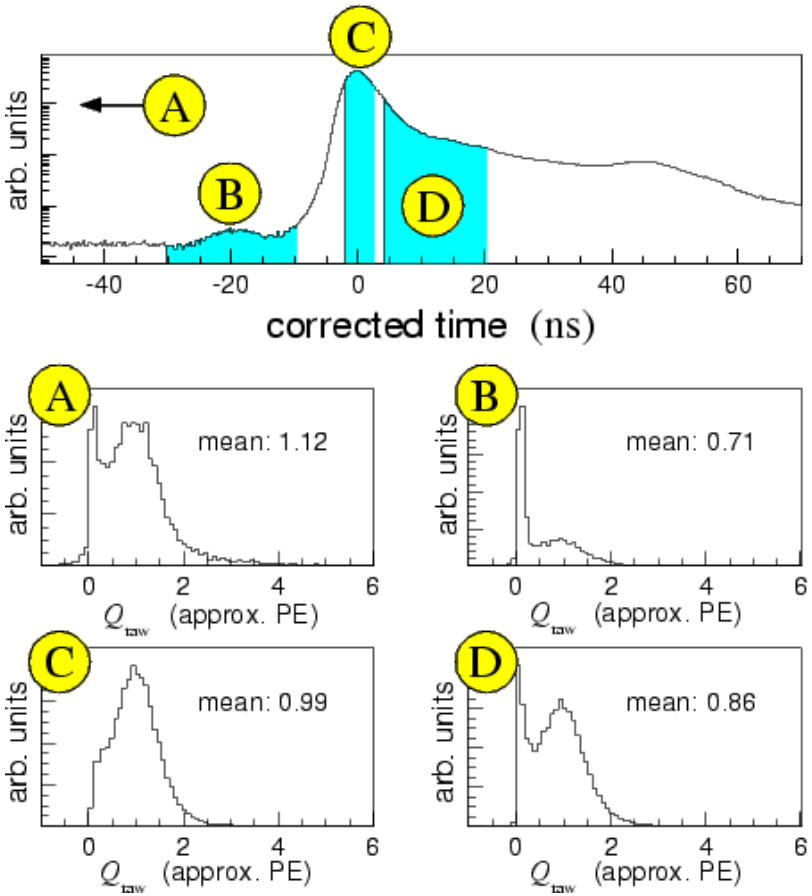
The simulation chain (3b)

PMTs and electronics

- angular efficiencies
- time response (below)
- Q/T correlations (right)
- discriminator slew



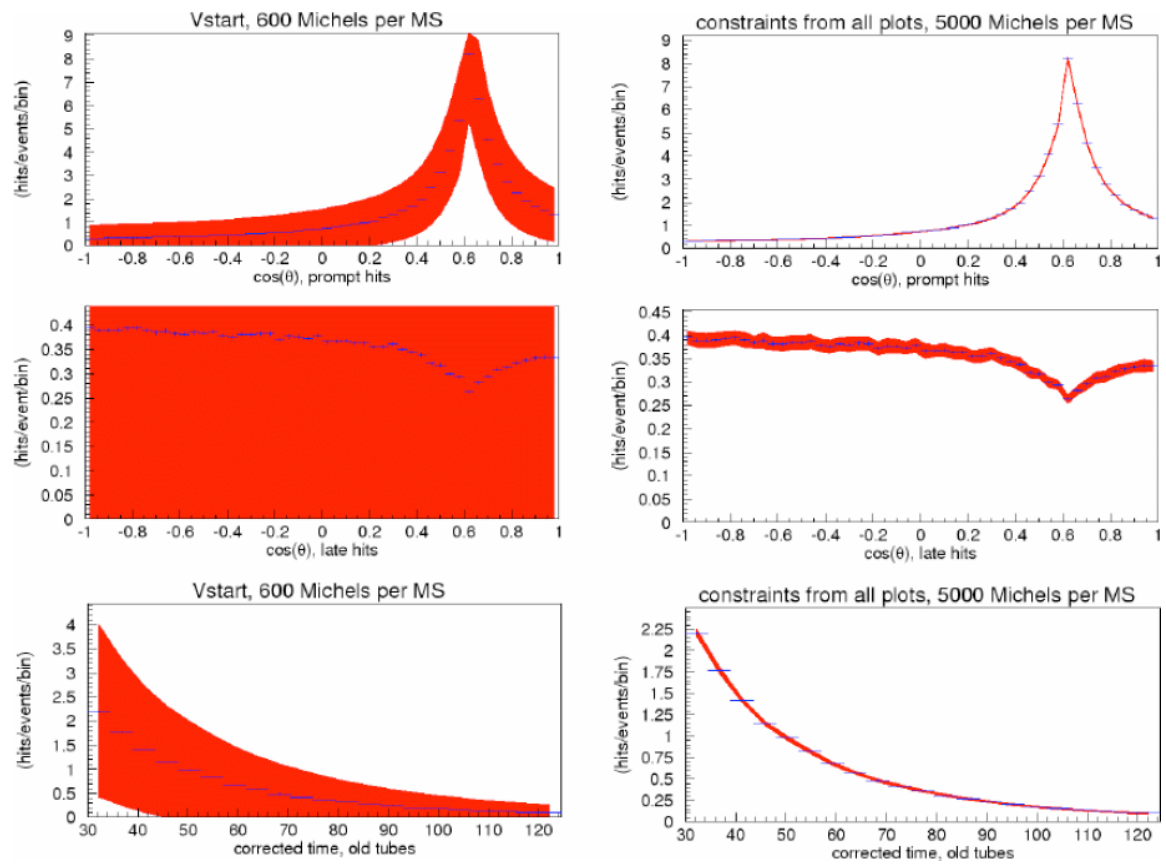
Single-photoelectron charge distributions in time slices



Constraining the optical photon model

- external measurements essential
- **finish with μ decay events (low-energy electrons)**
  (~unlimited supply and fast to simulate)

- use a Monte Carlo method to reduce uncertainty:
- compare data/MC events in relevant distributions for many allowed models
- de-weight disallowed regions of model space
- NC elastic events help out with scintillation

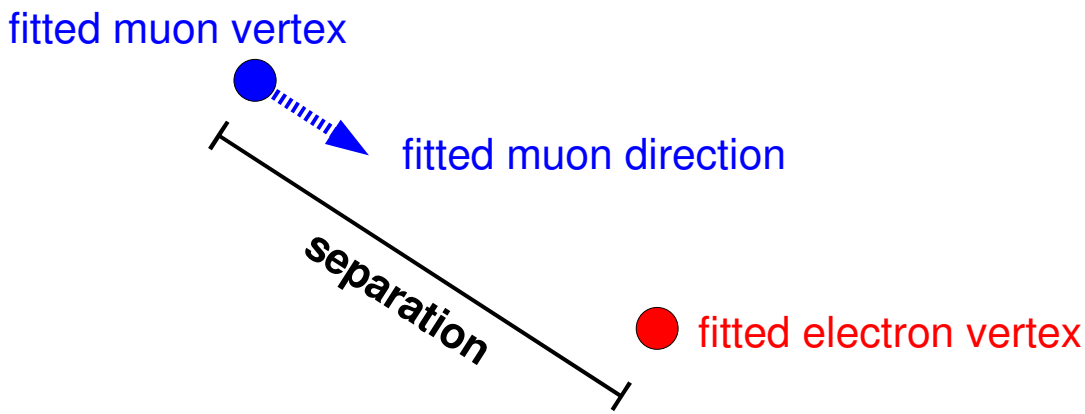


starting uncertainties in three of the distributions

(near) ending uncertainties

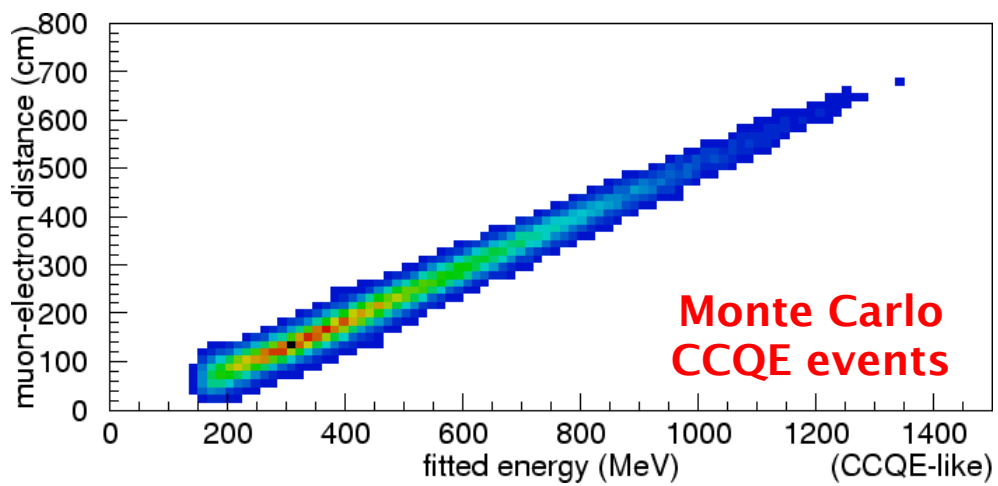
Obtaining a ν_μ CC QE sample:

- require μ decay-at-rest tag
- require consistency between fitted μ energy and μ-e separation

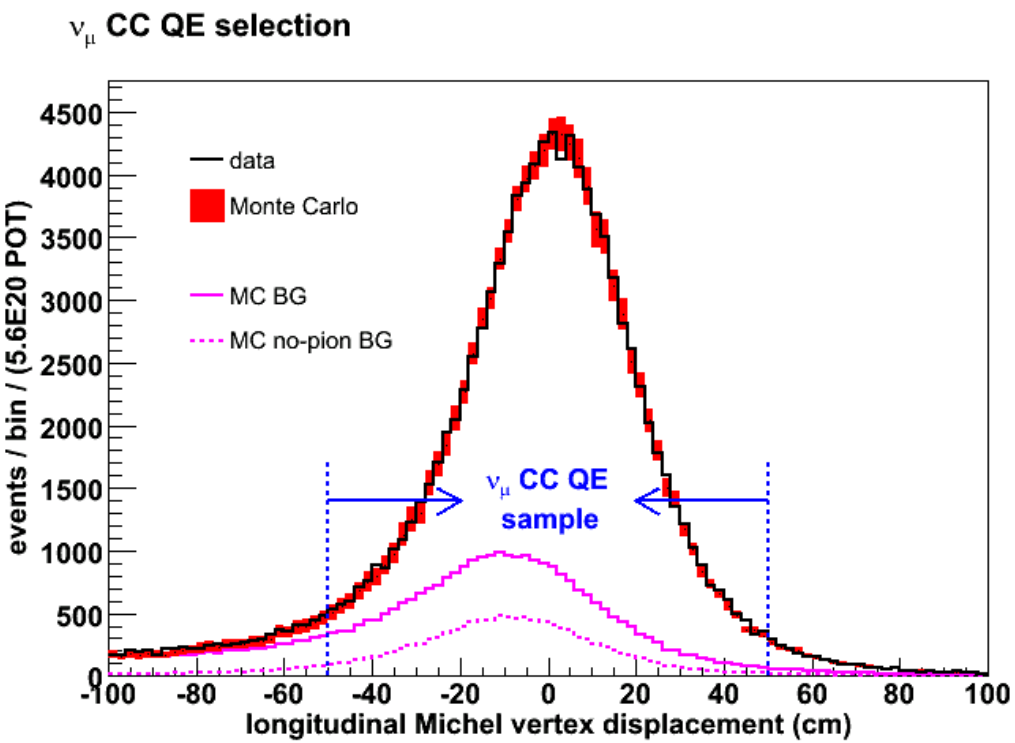


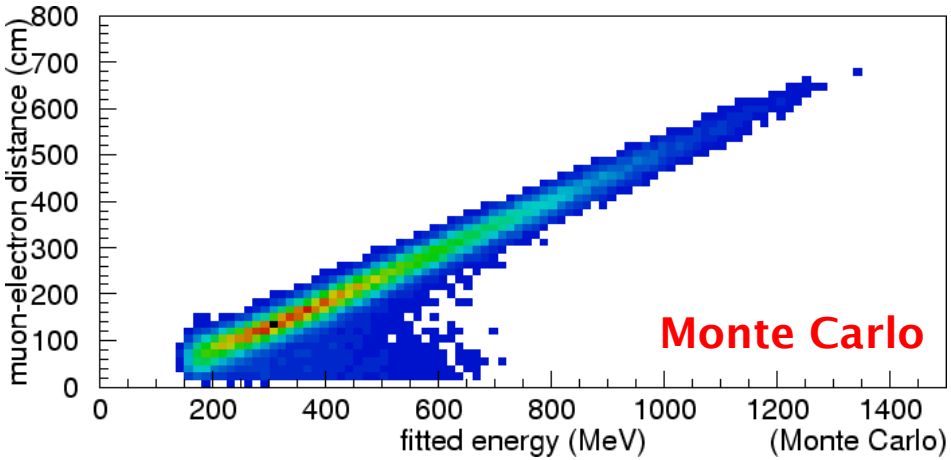
simulated $\nu_\mu n \rightarrow p\mu^-$
$\hookrightarrow e^-$

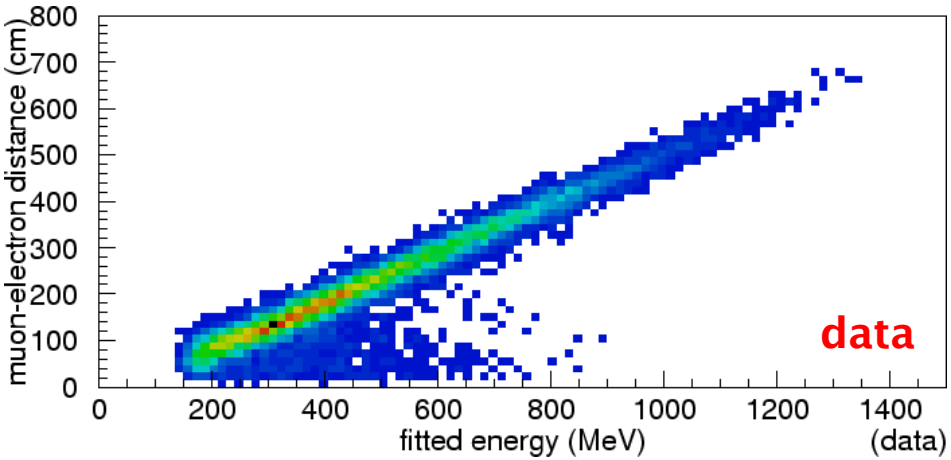
~linear relation between separation and energy



- select events near swath
- 100k events
- (below) Monte Carlo and data before this cut

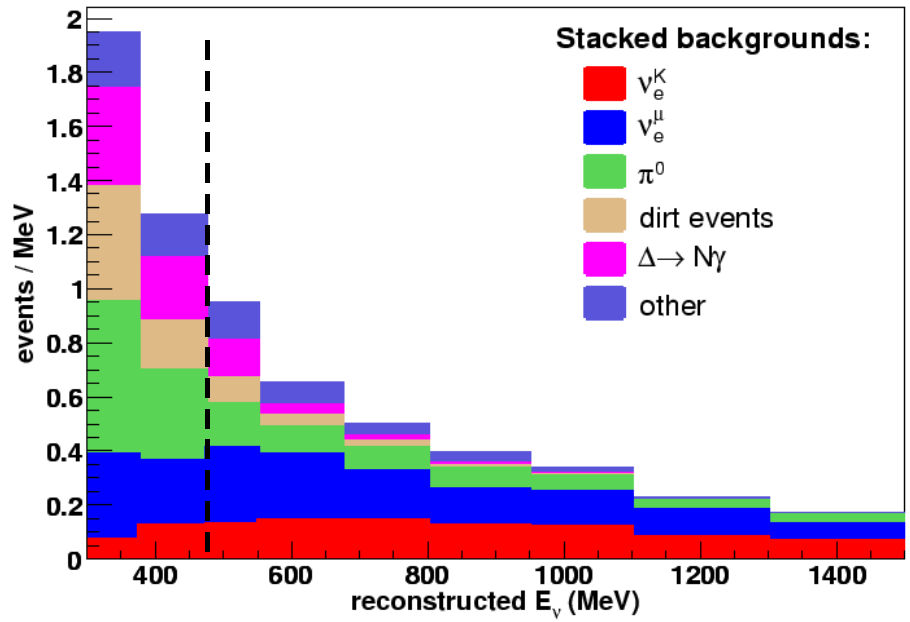


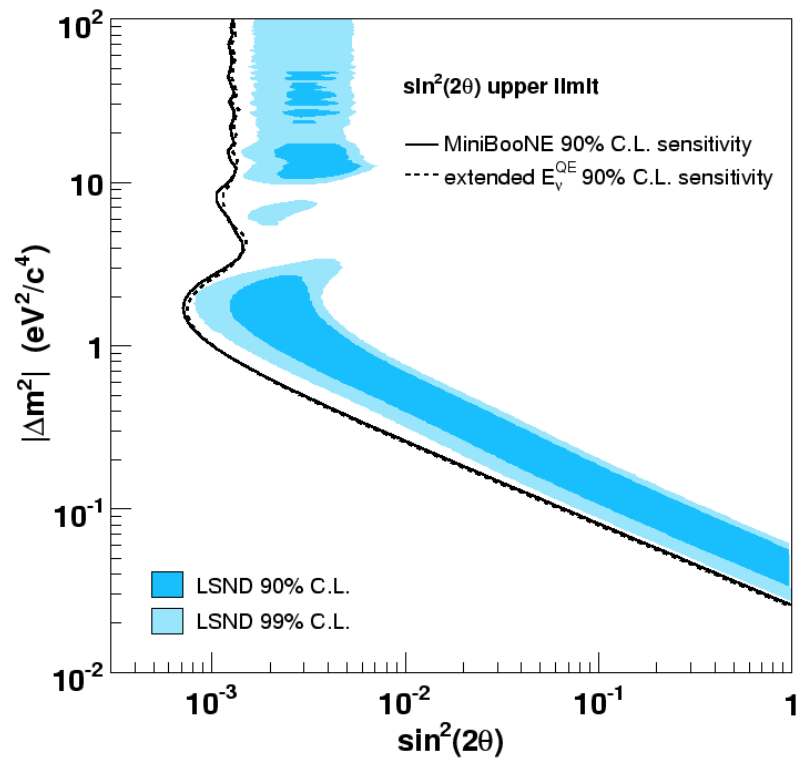


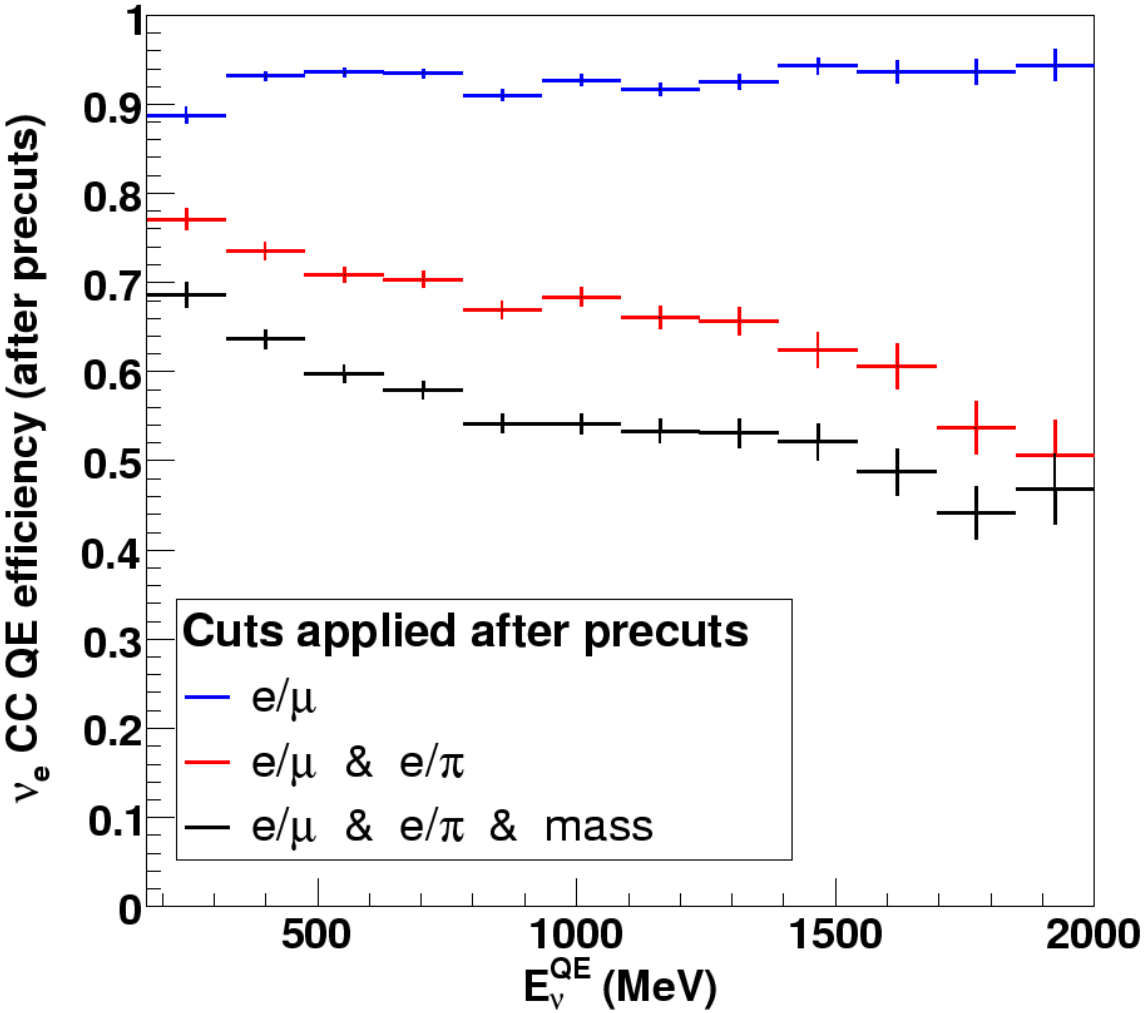


Blind χ^2 Tests:

- Fit ν_e sample for oscillations (but don't look at answer)
- Test data/MC agreement accounting for the (unknown) best-fit signal
- All quantities looked great, except $E_{visible}$: χ^2 probability of 1%
- Apparent low energy problem
  $\Rightarrow$ raise E_ν^{QE} threshold to 475 MeV
- Repeat all data/MC comparisons [all good]
  $\Rightarrow$ proceed with unblinding...



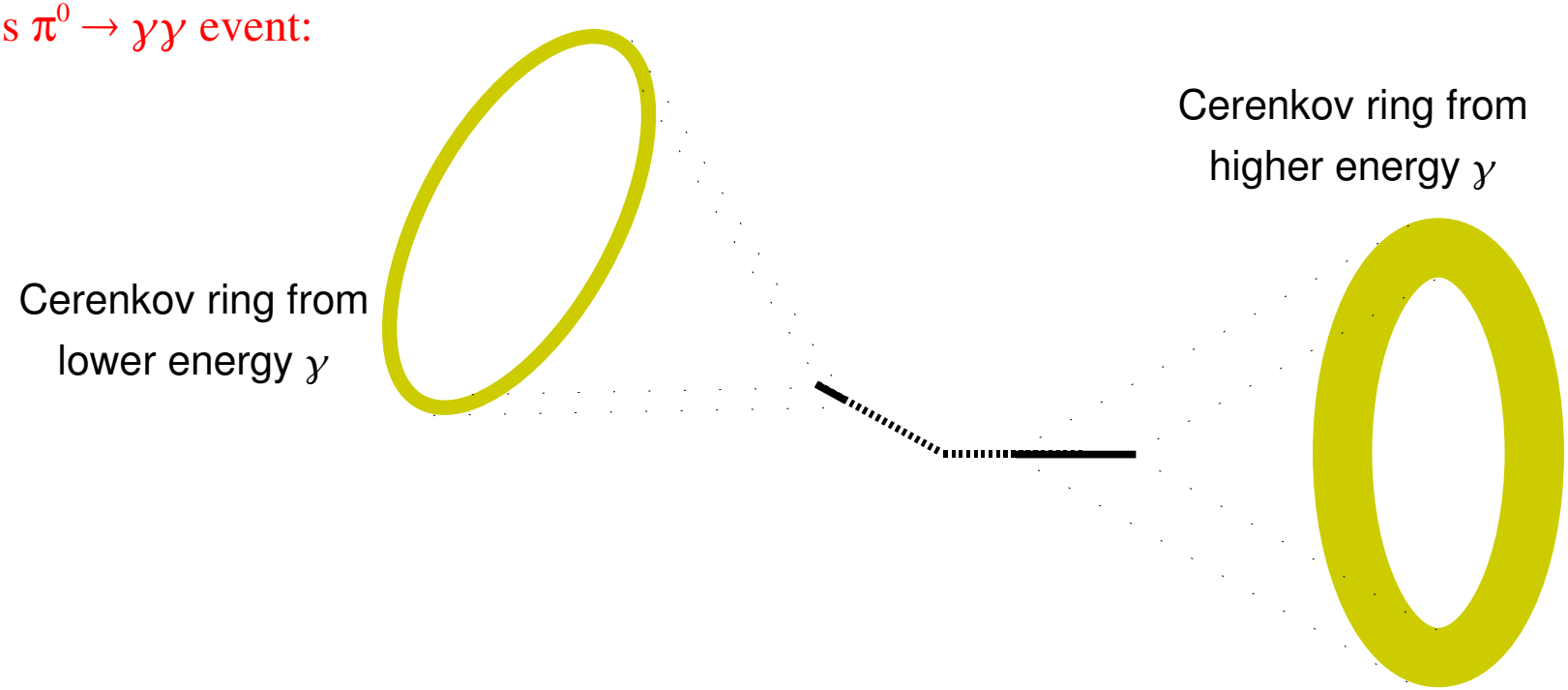



Cuts applied after precuts
e/μ
e/μ & e/π
e/μ & e/π & mass
ν_e CC QE efficiency (after precuts)
E_ν^{QE} (MeV)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
500
1000
1500
2000

Fitting $\nu_\mu N \rightarrow \pi^0 N$

- π^0 events are our largest reducible background
- Fitting these requires turning the 7-parameter fit into a 12-parameter fit.
- The larger likelihood space has many local minima. For example:

Take this $\pi^0 \rightarrow \gamma\gamma$ event:



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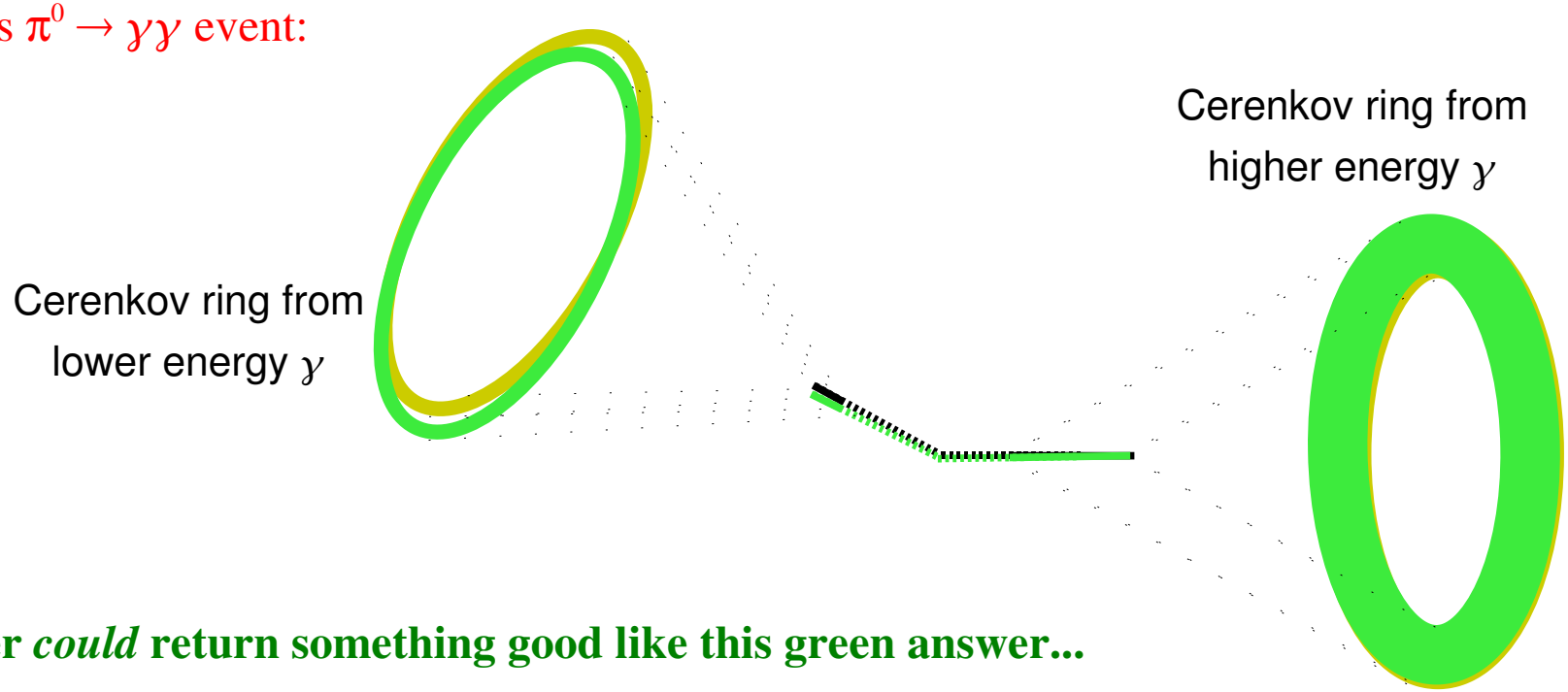
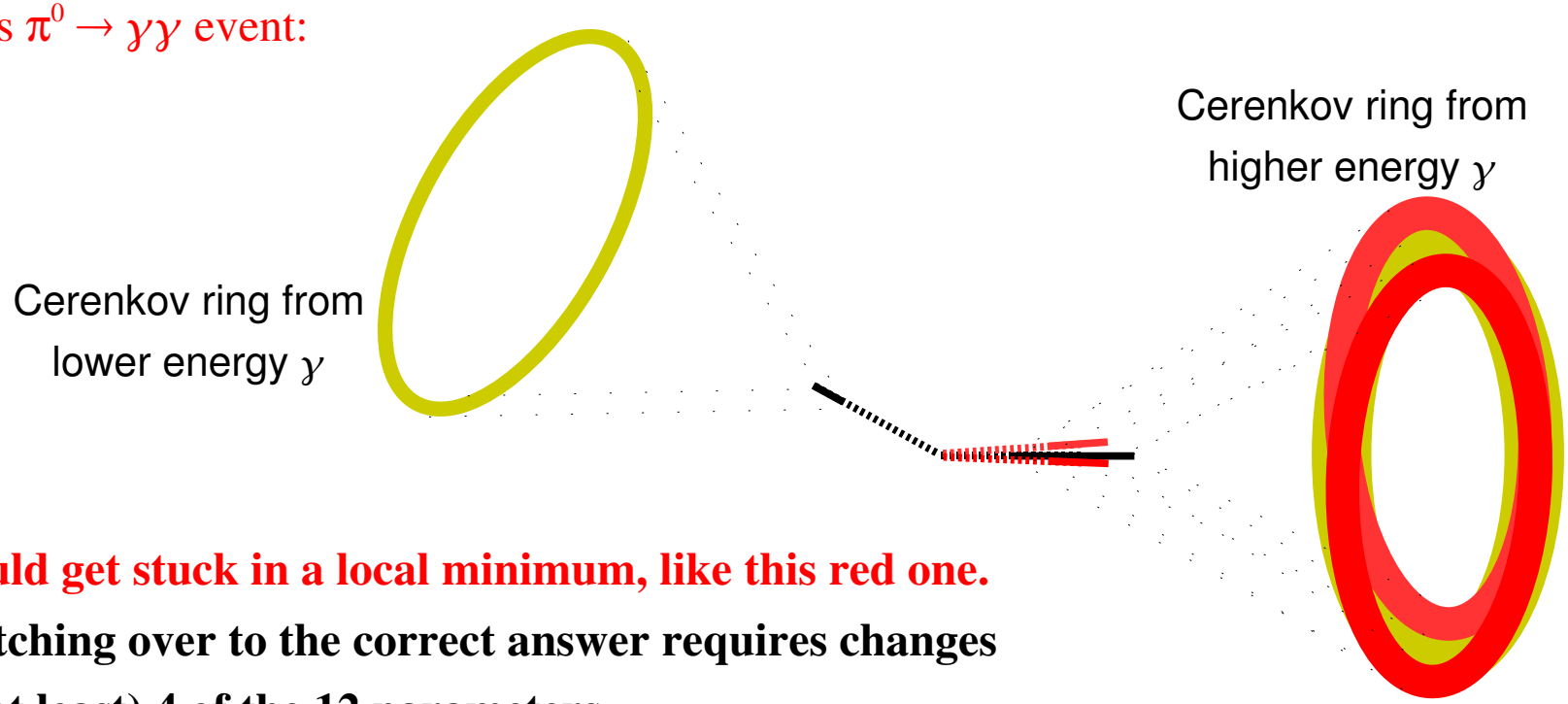


The fitter *could* return something good like this green answer...

Fitting $\nu_\mu N \rightarrow \pi^0 N$

- π^0 events are our largest reducible background
- Fitting these requires turning the 7-parameter fit into a 12-parameter fit.
- The larger likelihood space has many local minima. For example:

Take this $\pi^0 \rightarrow \gamma\gamma$ event:



Or it could get stuck in a local minimum, like this red one.

- **Switching over to the correct answer requires changes in (at least) 4 of the 12 parameters.**

Eliminating non-beam events

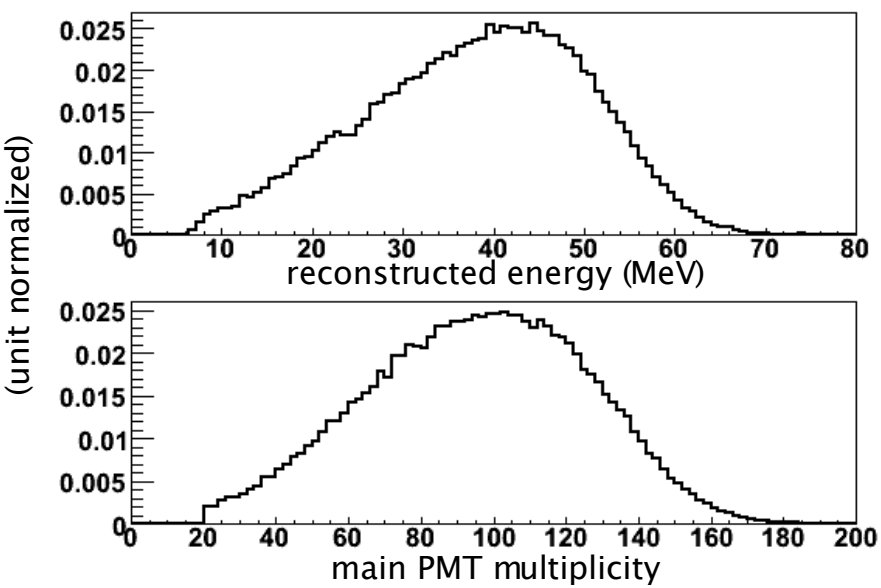
- near-surface detector:

  10kHz cosmic ray μ
  4kHz μ DAR (53 MeV endpoint)

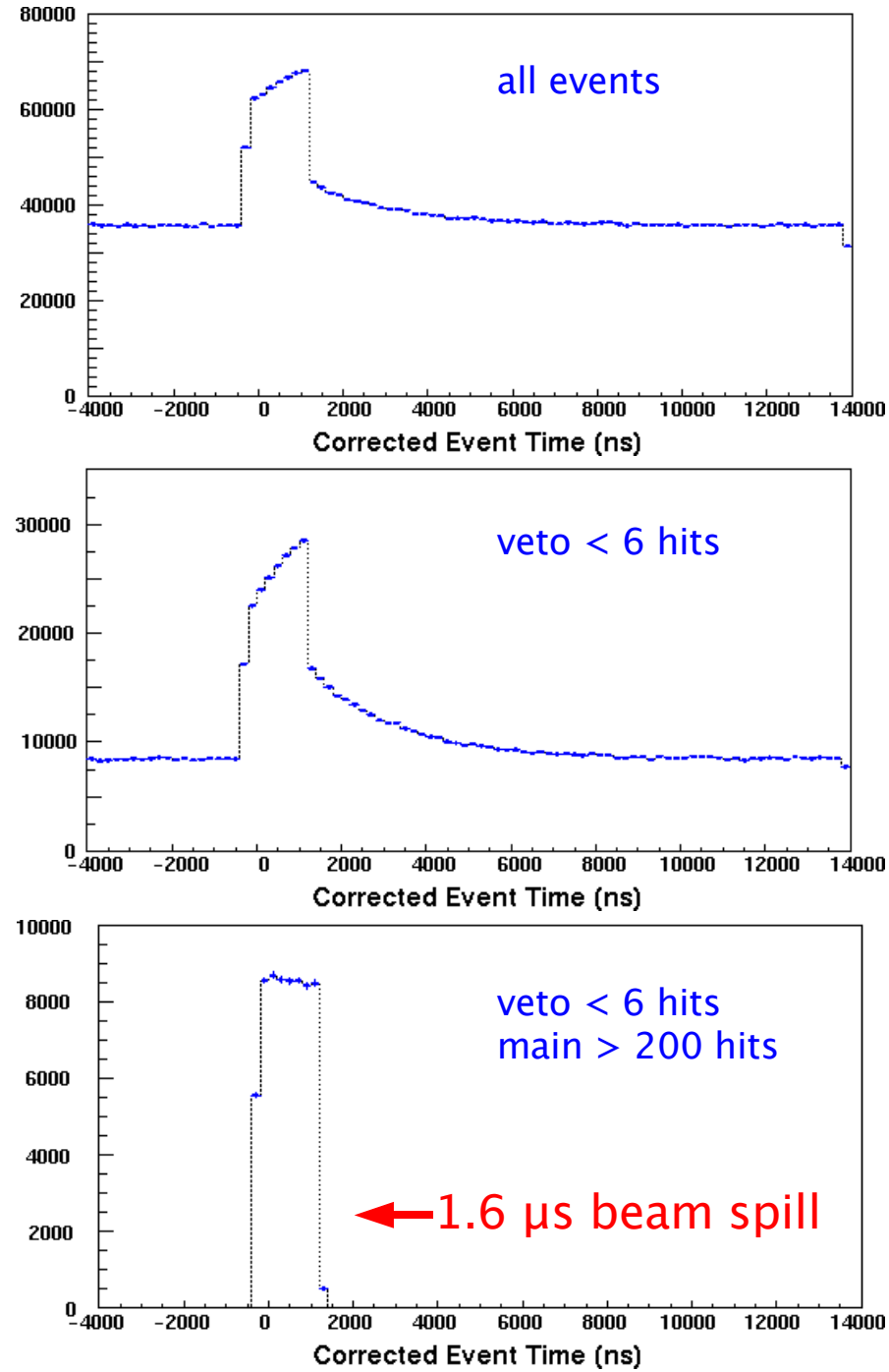
- veto and main PMT multiplicity cuts:

  fewer than 6 veto PMTs hit
  more than 200 main PMTs hit

Electrons from μ decay-at-rest

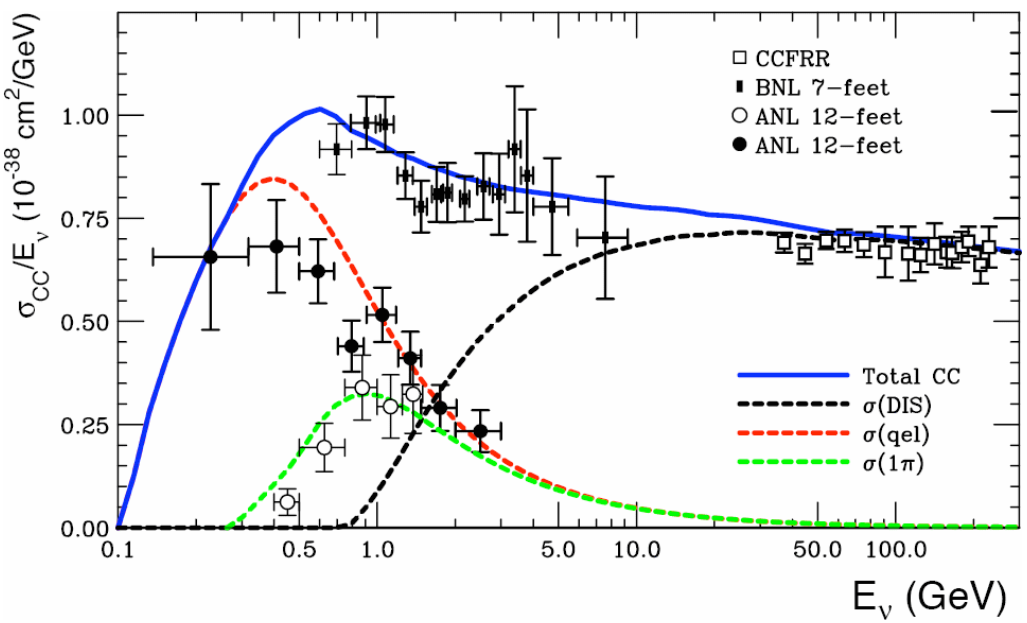


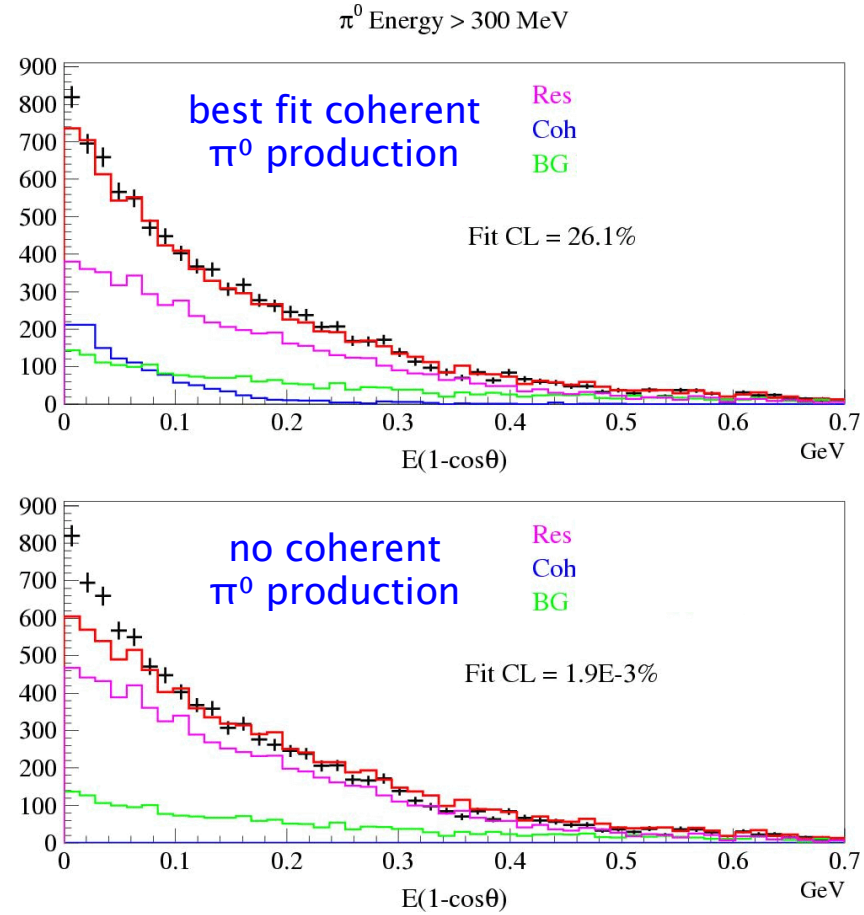
Event times relative to beam arrival



ν+C/H cross sections

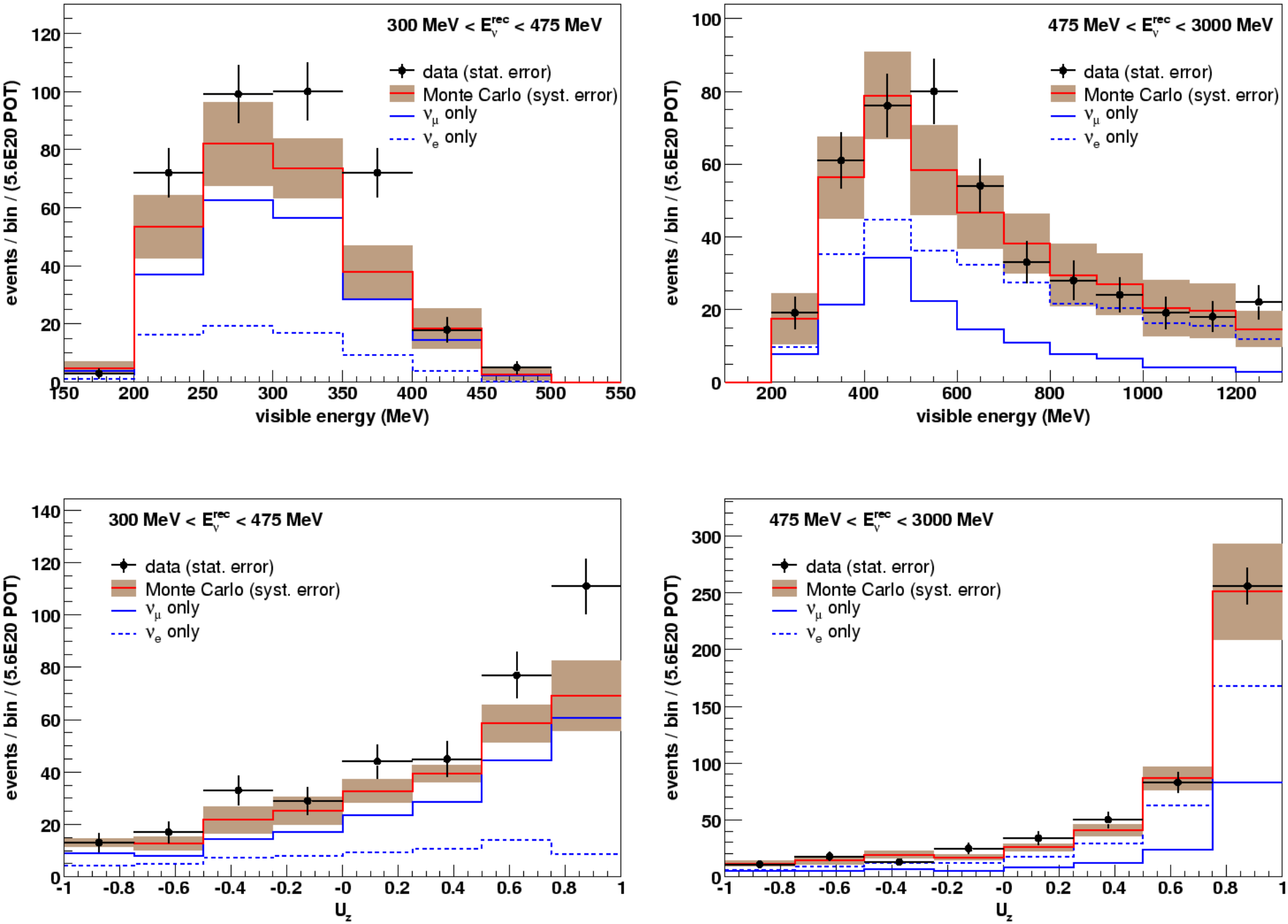
- **Nuance** event generator
- comprehensive XS simulation
- used elsewhere in community
- tuned on external, internal data

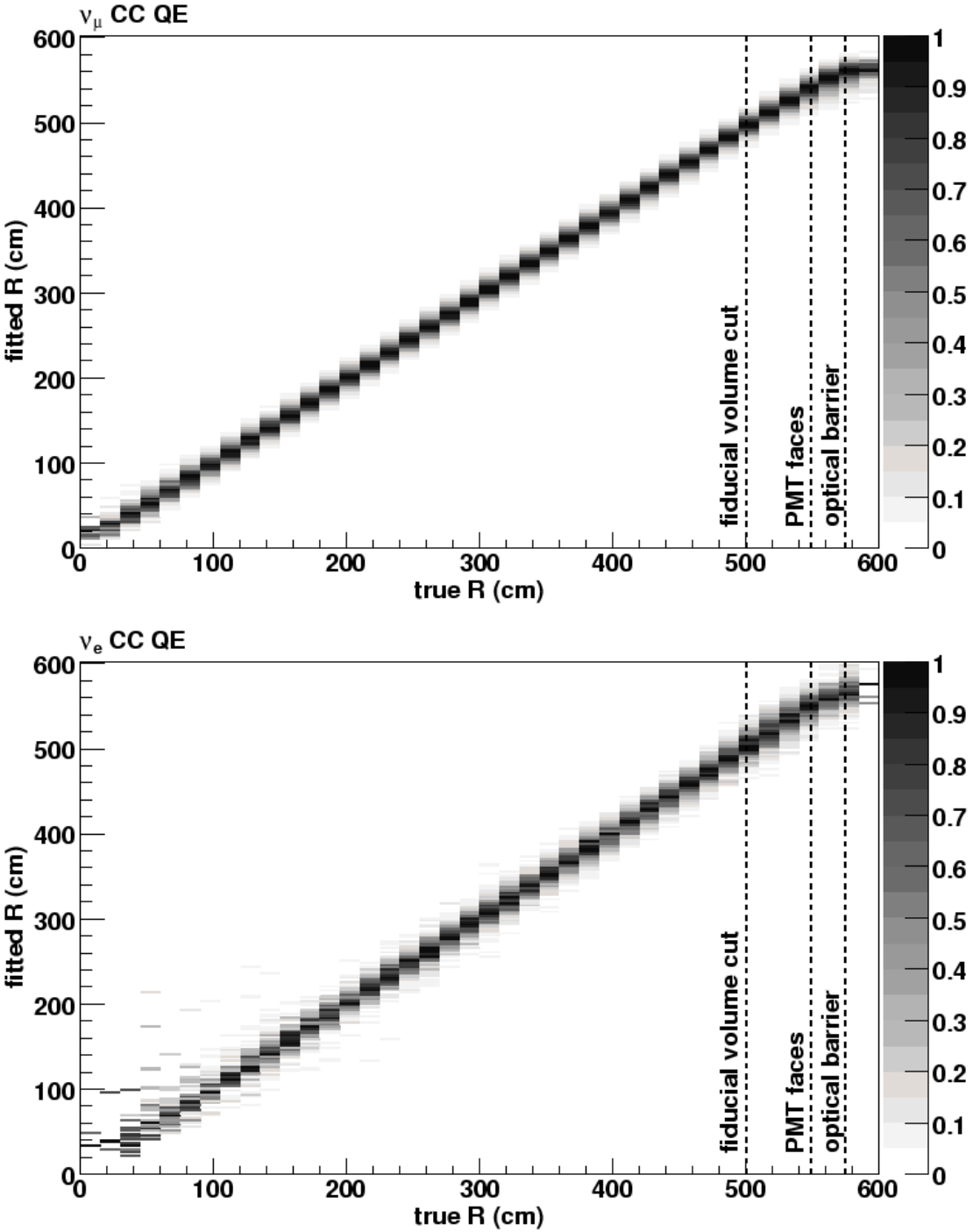




above: ν C → ν C π^0
(coherent π^0 production)

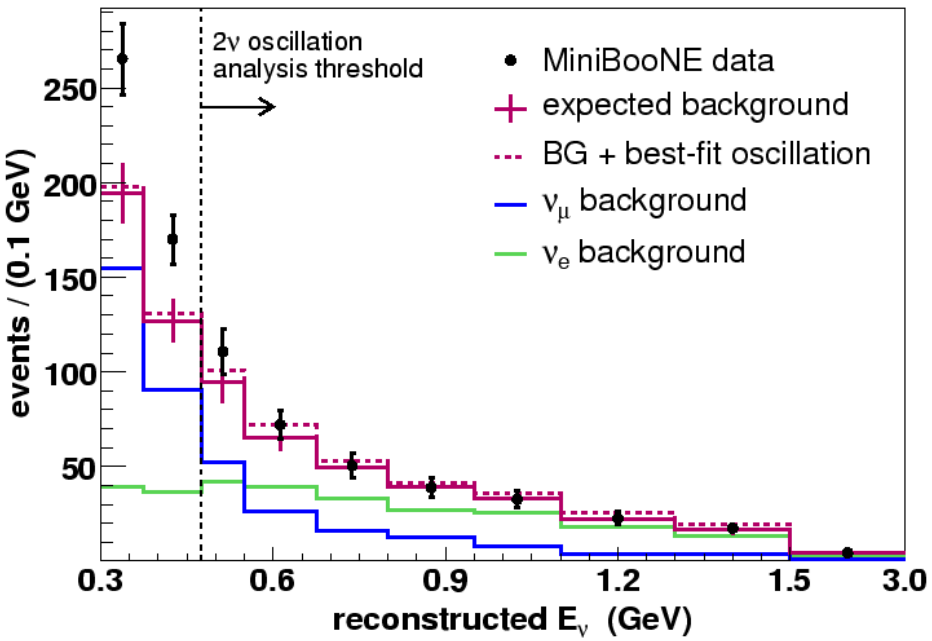
left: various external CC measurements

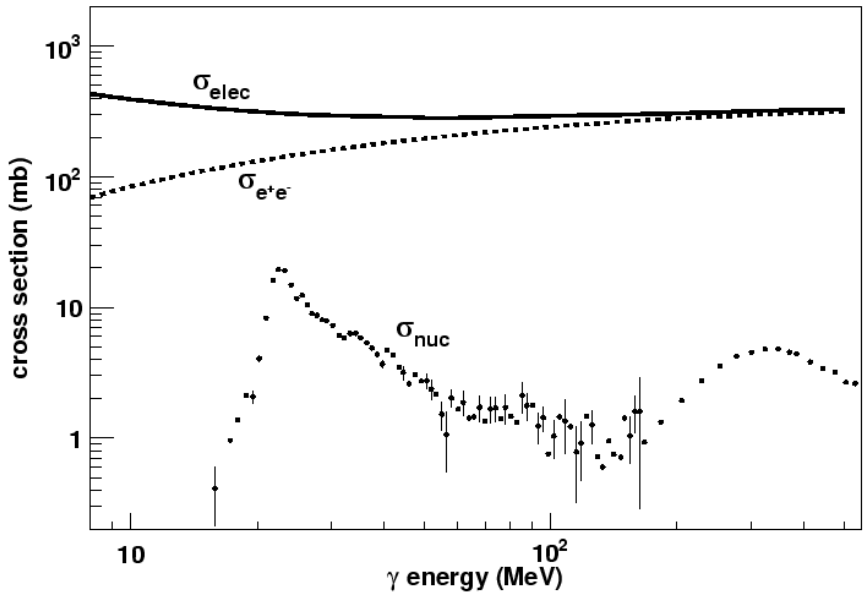

300 MeV < E_ν^{rec} < 475 MeV
475 MeV < E_ν^{rec} < 3000 MeV
data (stat. error)
Monte Carlo (syst. error)
ν_μ only
ν_e only
events / bin / (5.6E20 POT)
visible energy (MeV)
U_z

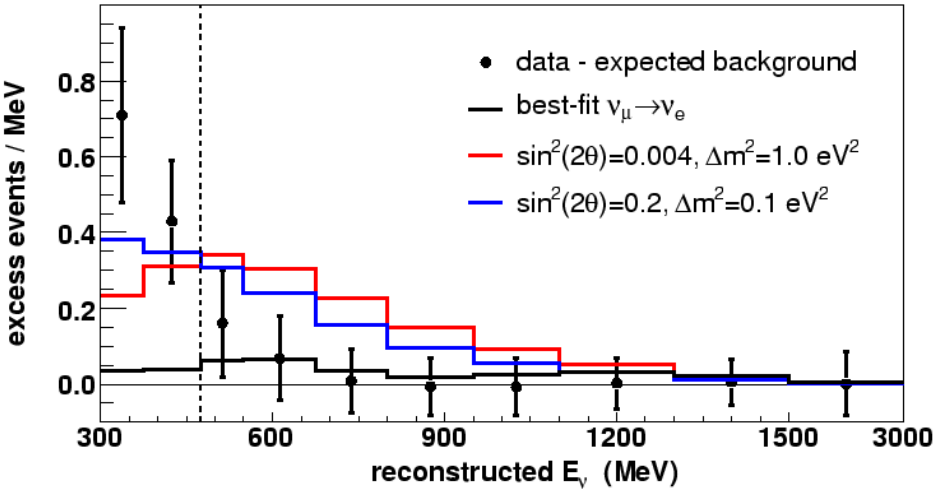

ν_μ CC QE
fitted R (cm)
true R (cm)
fiducial volume cut
PMT faces
optical barrier
ν_e CC QE
fitted R (cm)
true R (cm)
fiducial volume cut
PMT faces
optical barrier

A look below the E_ν threshold

- Indeed, a discrepancy at low energy
- Does not follow a two-neutrino oscillation shape
- Photonuclear absorption explains 20%–40% of the excess (originally absent from the simulation)
- ν-γ interaction at finite baryon density
  Harvey, Hill, and Hill, PRL **99** 261601 (2007)
- Still under investigation







Measuring the NC π^0 rate

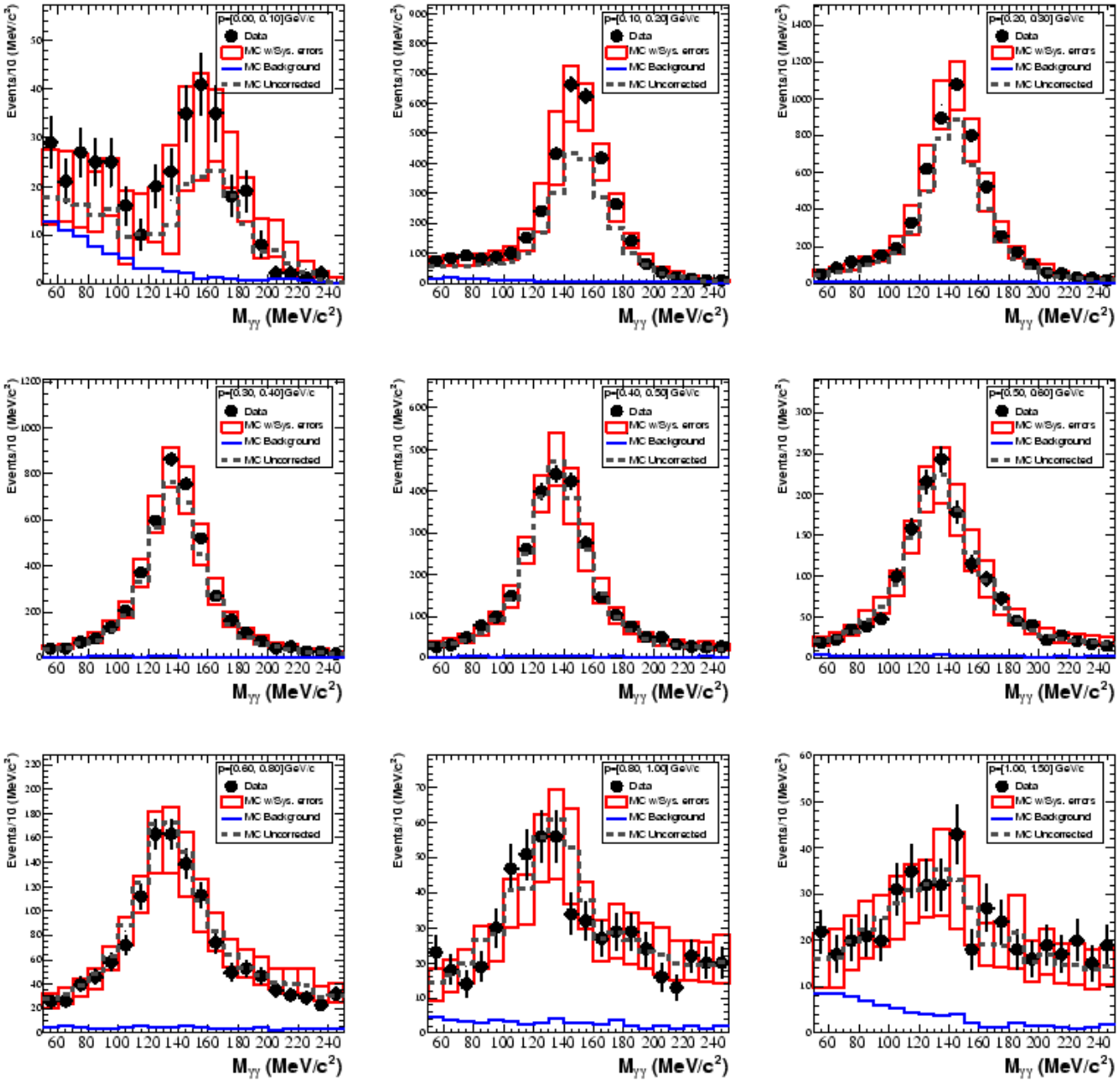
90%+ pure π^0 sample (mainly $\Delta \rightarrow N\pi^0$)

measure rate as function of momentum

default MC underpredicts rate at low momentum

analysis reaches 1.5 GeV

Invariant mass distributions in momentum bins



$\Delta \rightarrow N\gamma$ also constrained (though to a lesser extent)