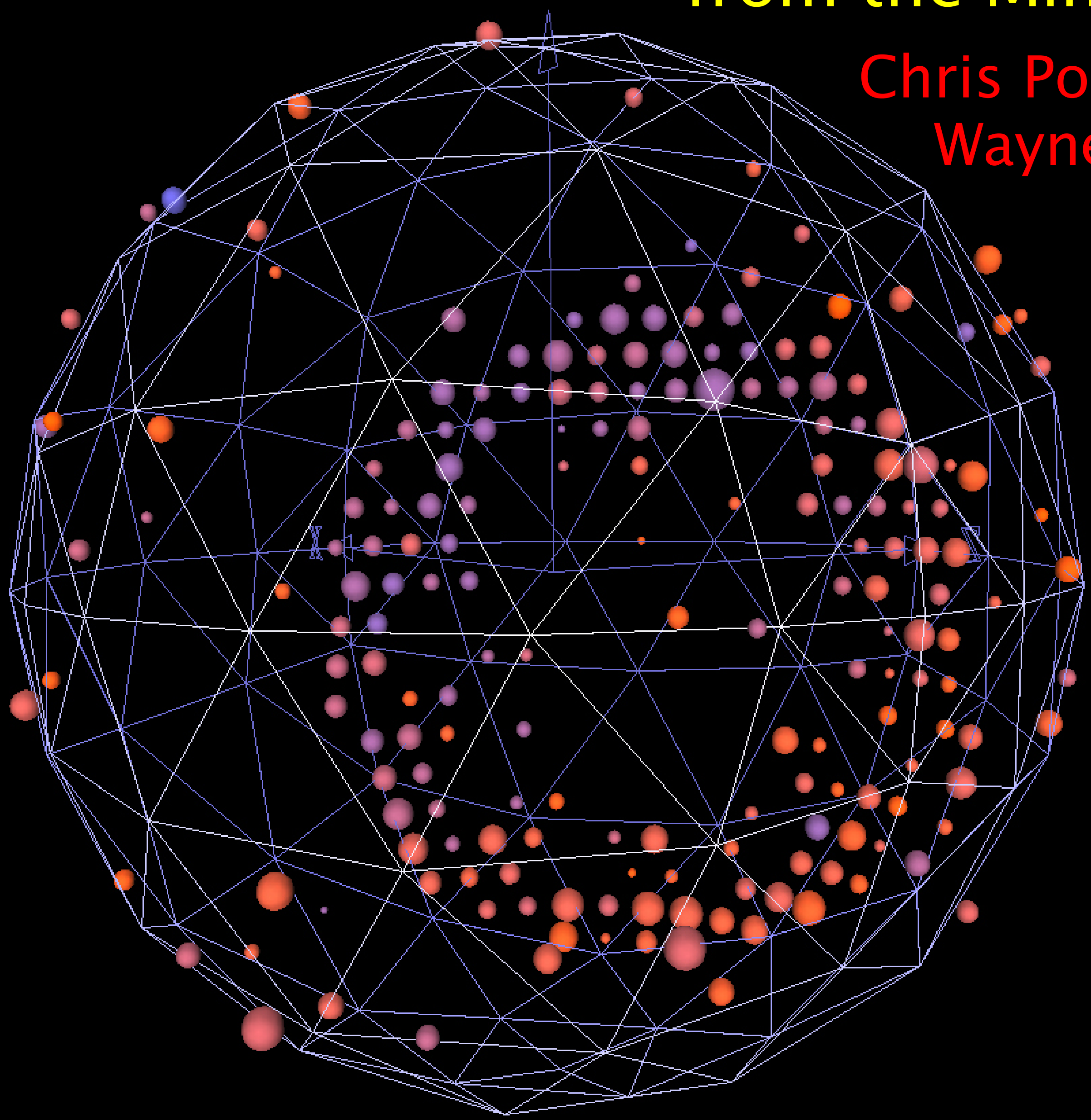
Neutrino Oscillation Results from the MiniBooNE Experiment

Chris Polly, Indiana University

Wayne State Colloquium



The MiniBooNE Collaboration

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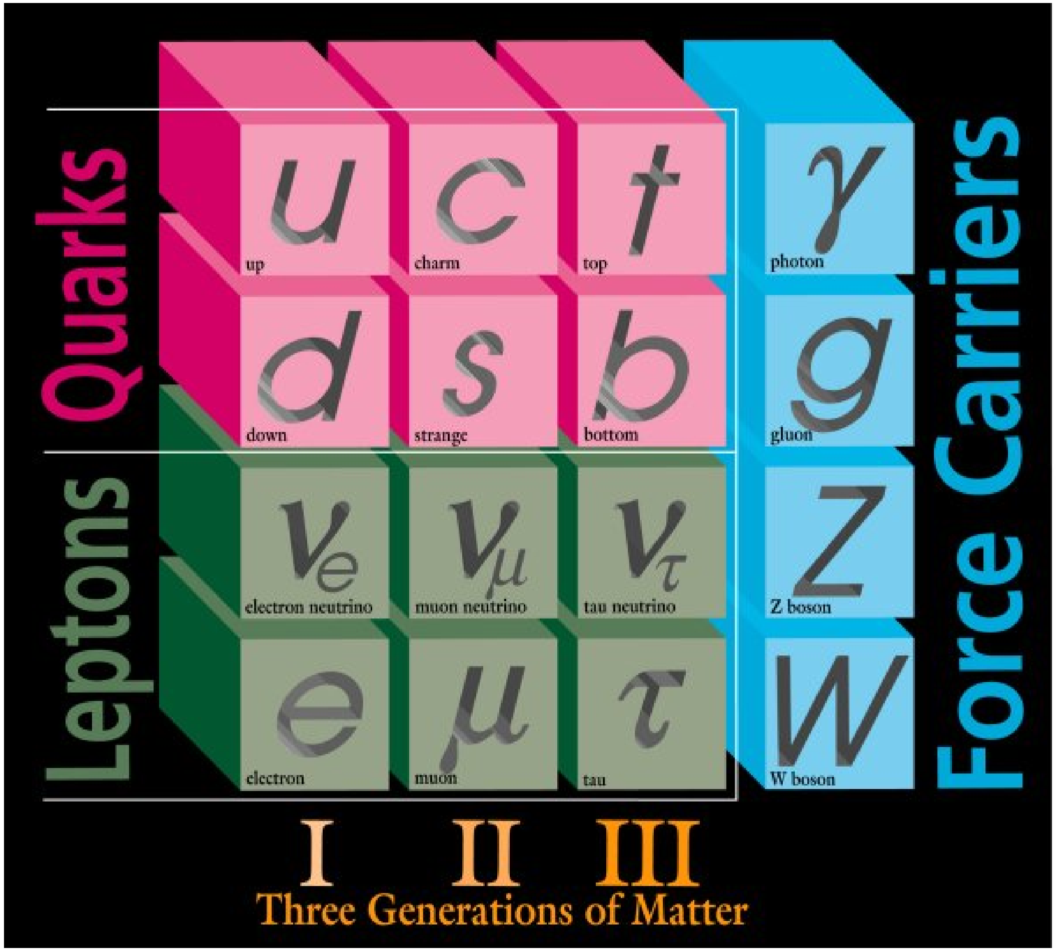
- Talk Outline:
  - Brief introduction to the Standard Model
  - History of the neutrino
  - Neutrino oscillations
  - The LSND oscillation signal
  - Analysis details and results from MiniBooNE

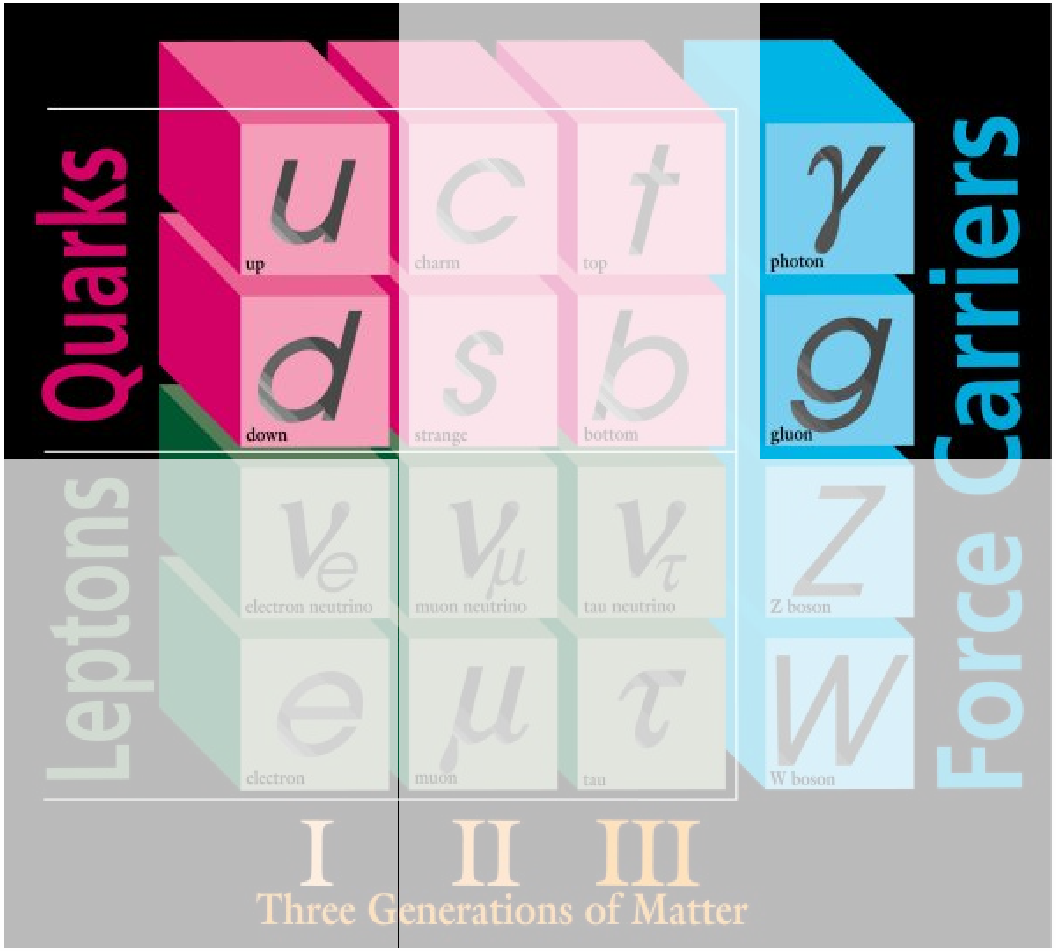
The Standard Model building blocks...



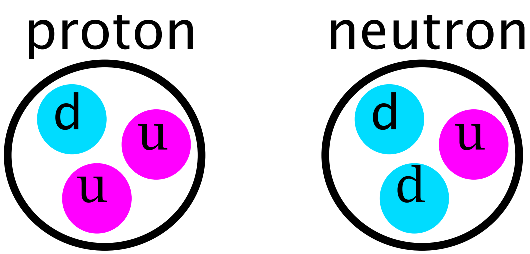
- Force carriers
  - photons (γ) ⇔ electromagnetic
  - gluons (g) ⇔ strong force
  - $W^{\pm}$,Z bosons ⇔ weak force
  - no inclusion of gravity...yet
- Quarks
  - Feel all the forces
  - Other than gluons, only particles that experience the strong force
- Leptons
  - Charged e, μ, τ
    - Feel EM and weak
  - Neutral ν_e, ν_μ, ν_τ
    - Interact ONLY via weak force

✩ Blocks not explicitly shown: every quark and lepton has an antiparticle, actually 8 gluons, 2 W bosons that differ in their +/−1 charge.

From simple rules..incredible complexity



- Glue u (+2/3 charge) and d (−1/3 charge) together via strong force



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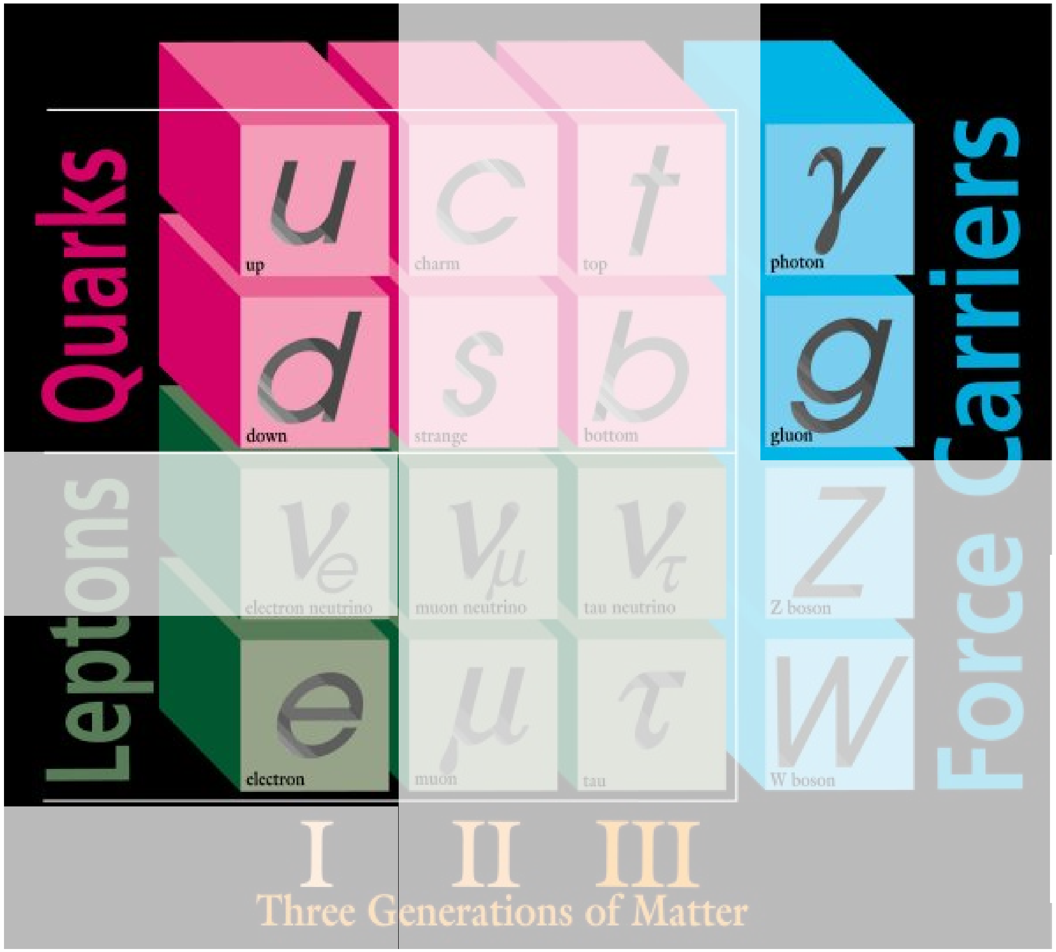

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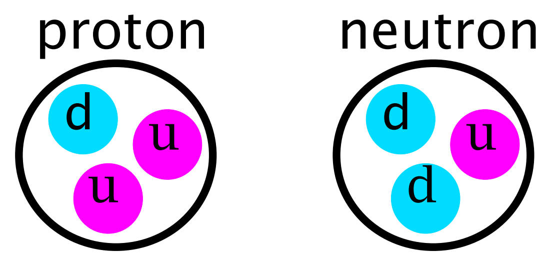
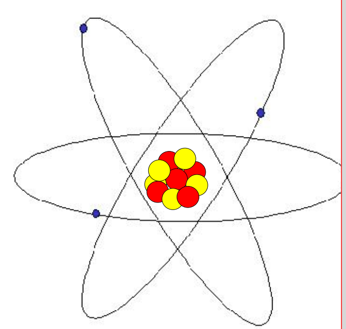
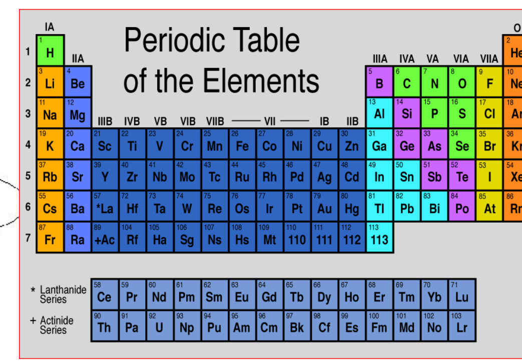


- Combine n, p, and e– and we have nuclear and atomic physics





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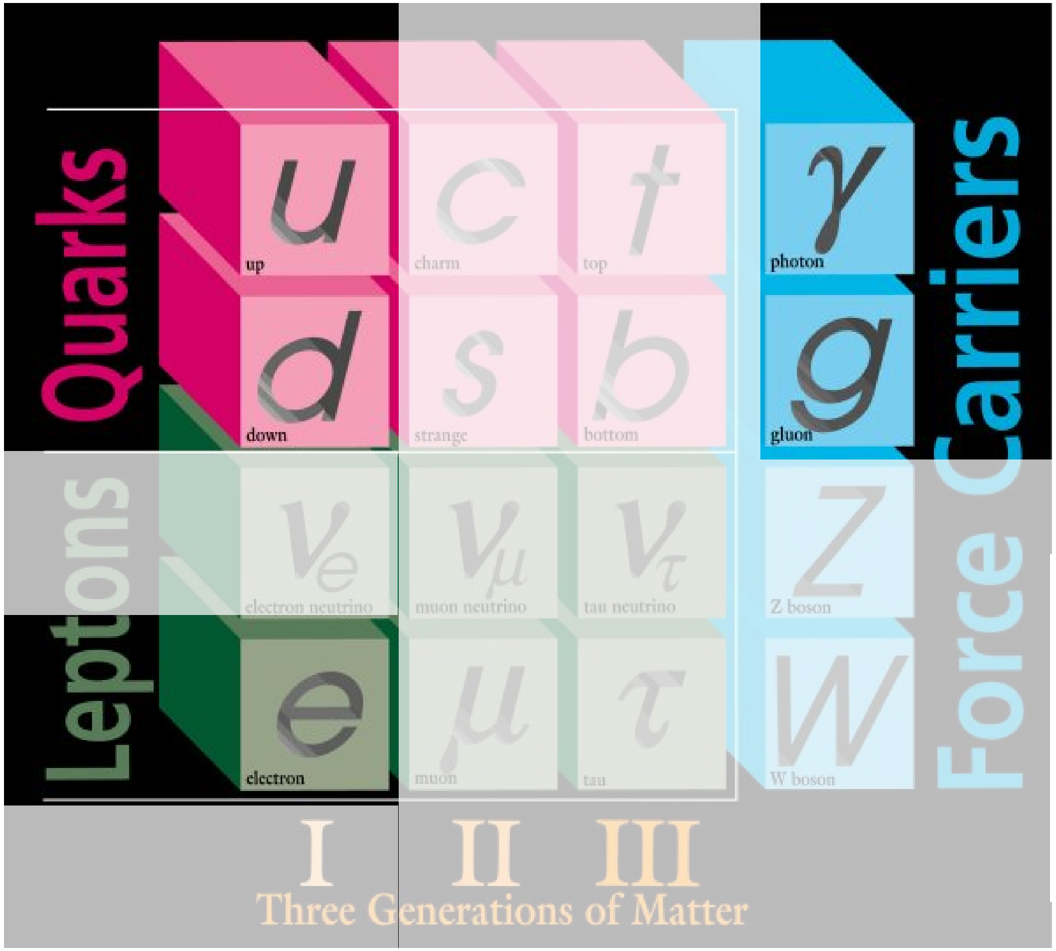

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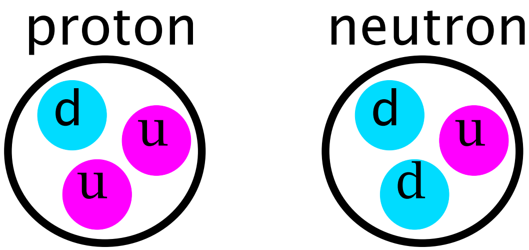

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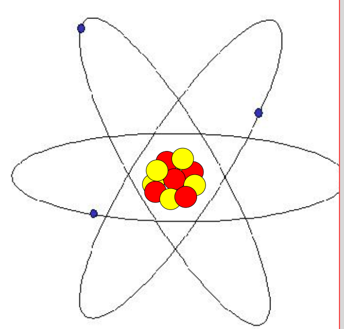
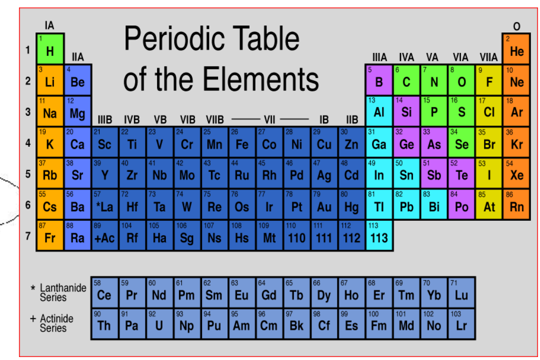
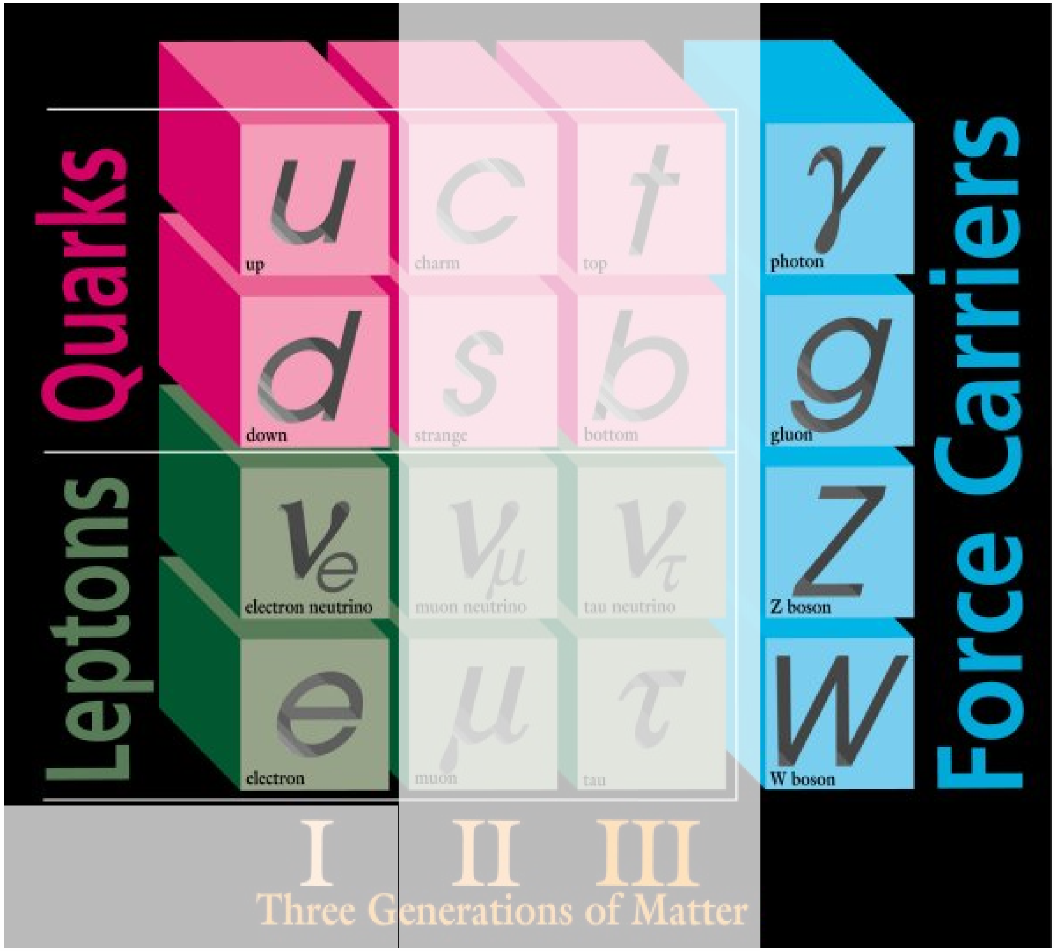


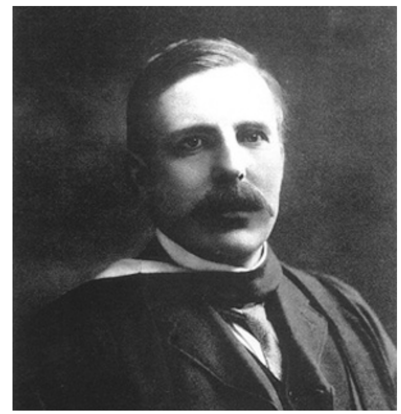


- Better stop here or we'll find ourselves doing chemistry⇒ biology ⇒ debating theology!!!

So where exactly does this weak force and the ν's enter?



- First hint was discovered in what we now call nuclear beta decay
- In the very early 1900's it was first discovered that nuclei could transform by radiation

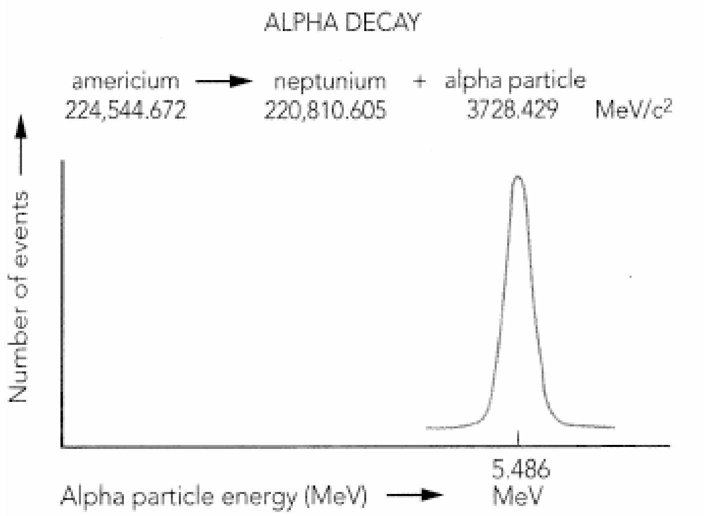
Ernest Rutherford	J.J. Thomson
	
α decay	β decay
Mass of parent nuclei (A) reduced by 4, charge (Z) reduced by 2.	Mass of parent nuclei (A) unchanged, charge (Z) increased by 1.
Po (208,84)->Pb(204,82) + α	C(14,6)->N(14,7) + β

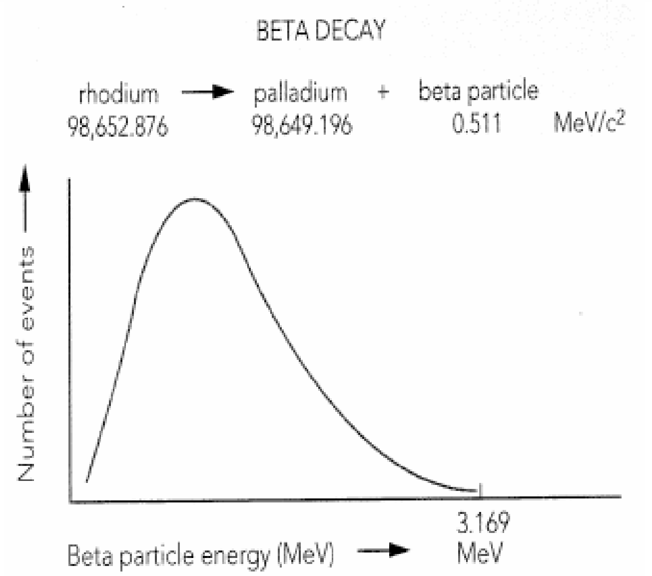
The mystery of the missing energy

- For simple 2-body decay: $M \Rightarrow m_1 + m_2$

  $$E_1 = 0.5\left(M^2 - m_2^2 + m_1^2\right)/M$$

- Emitted α is monoenergetic, but β is not!!!
- Led distinguished luminaries of the day (i.e. Neils Bohr) to postulate violation of energy and momentum conservation





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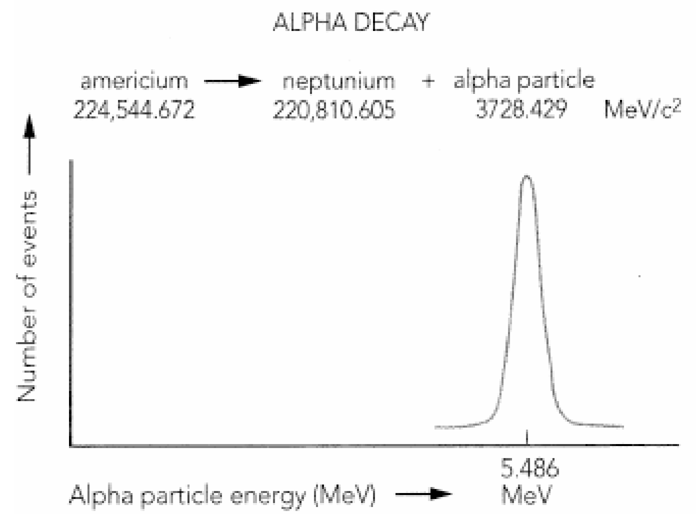
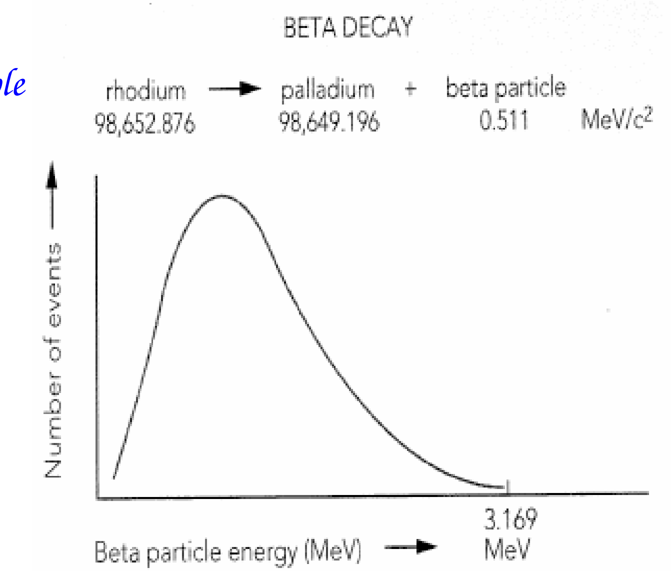


Detective Pauli

"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'!

The mystery of the missing energy

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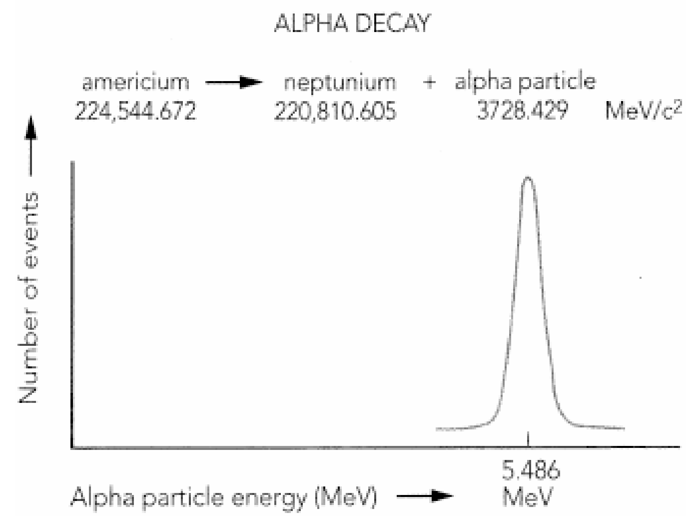

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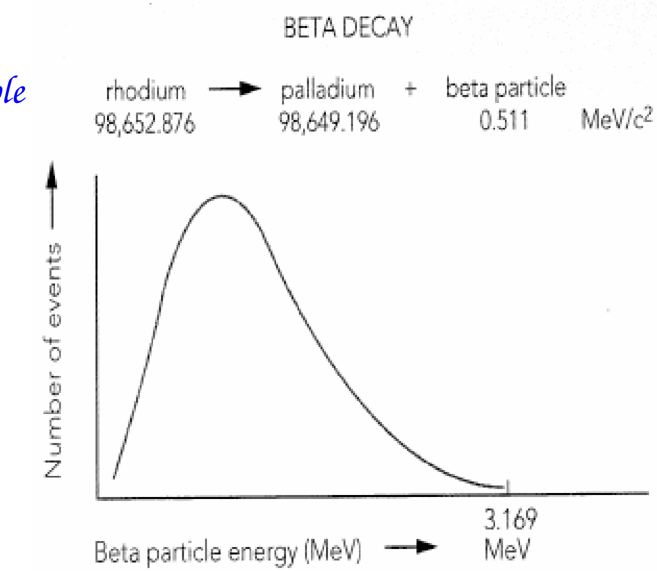
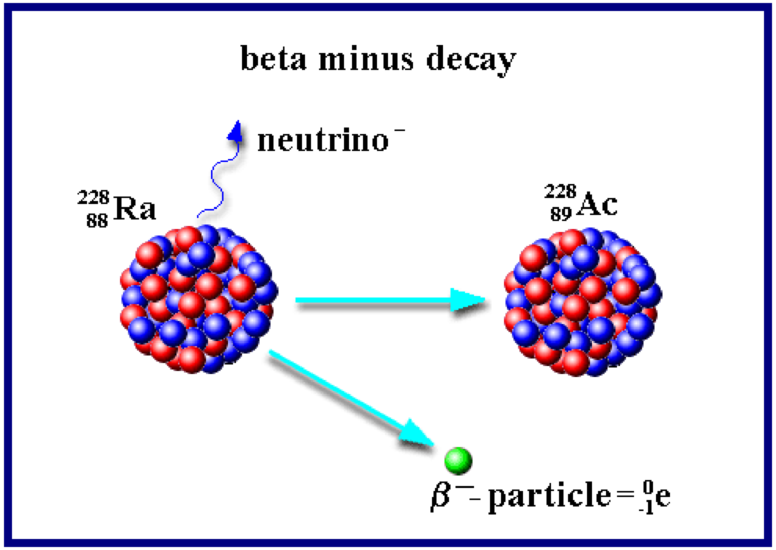


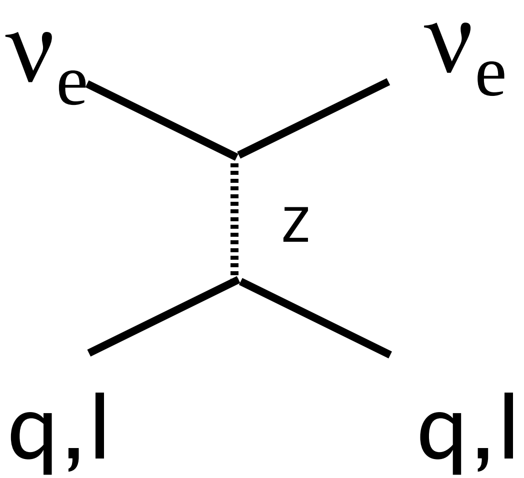
☆ And so the neutrino was hypothesized!

No relation :(

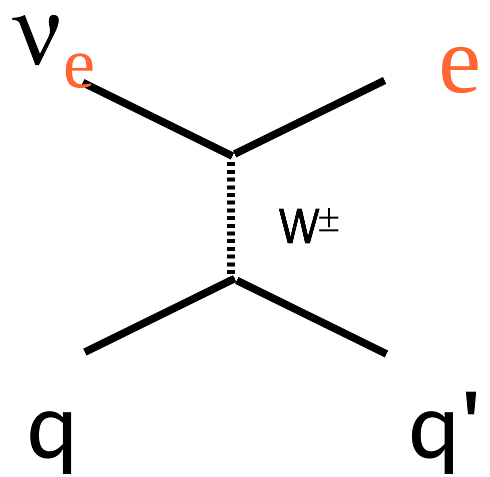
Fast forward to what we know today



- The missing E in beta decay IS carried away by Pauli's phantom particle
- Hard to detect a neutrino directly
  - ν is neutral, no detection via ionization tracks, Cerenkov, etc.
  - Interacts only via the weak force by exchange a Z or W boson.

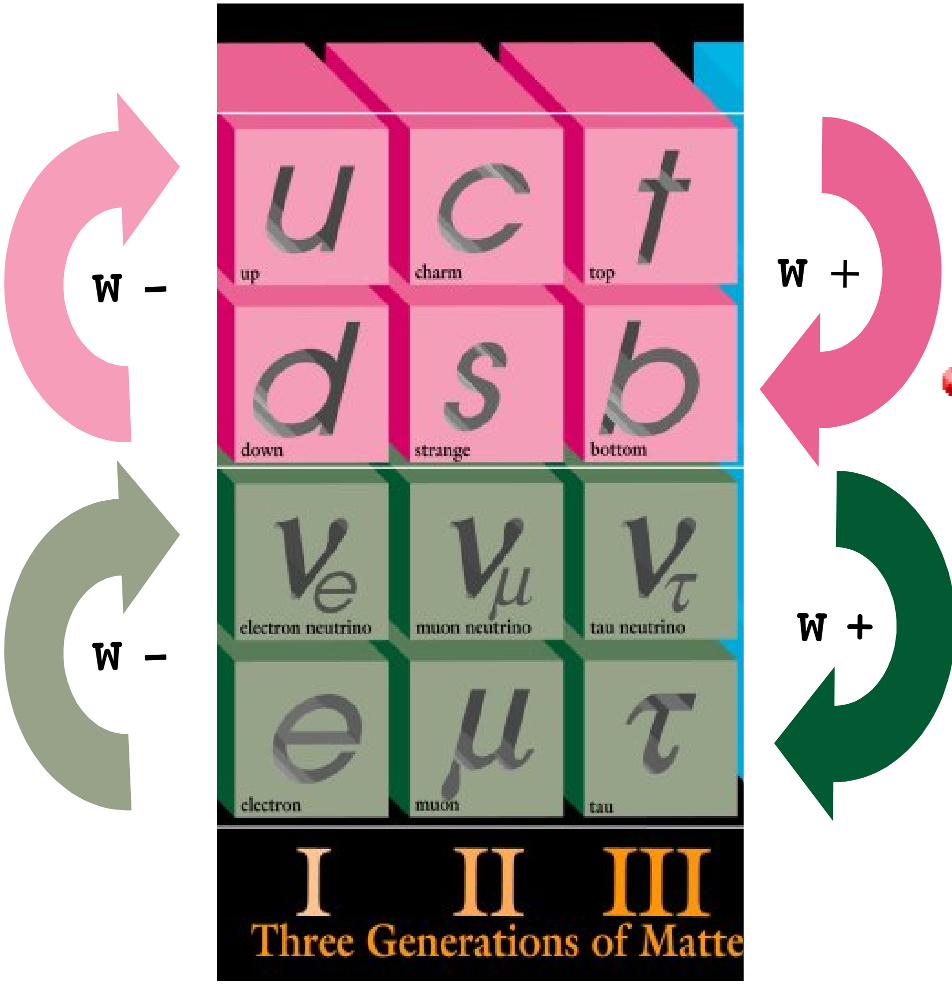


Neutral Current (NC)

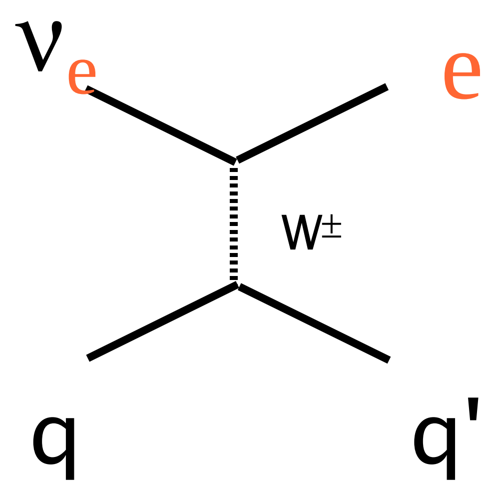


Charged Current (CC)

The weak force...force of transmutation

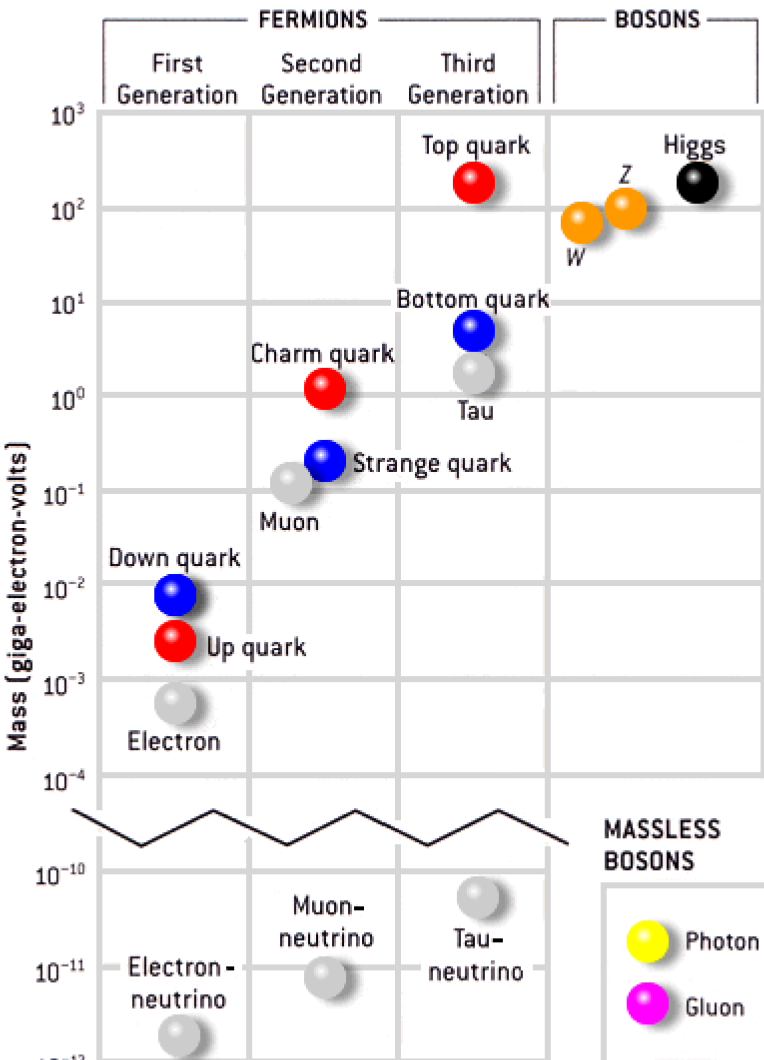


- Makes the weak interaction truly a force of transmutation
  - The CC channel converts ν into their charged alter egos
  - Converts −1/3 charge quarks into +2/3 counterparts
- Incidentally, CC also proves that we have three distinct ν flavors



Charged Current

Neutrino masses are another enigma...



Shamelessly stolen from *Scientific American*

- We know neutrinos are very light
- Direct mass searches yield limits
  - ν_e: tritium decay: m < 3 eV
  - ν_μ: pion decay: m < 0.2 MeV
  - ν_τ: tau decay: m < 18 MeV
  - Compare to hadron masses:
    - pions ~ 140 Mev
    - kaons ~ 500 MeV
    - protons ~ 1 GeV
    - neutrons ~ 1 GeV
- In fact, the Standard Model (c.1995) assumes they are massless

ν masses and Pontecorvo's hypothesis

- 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*

Tomorrow

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?

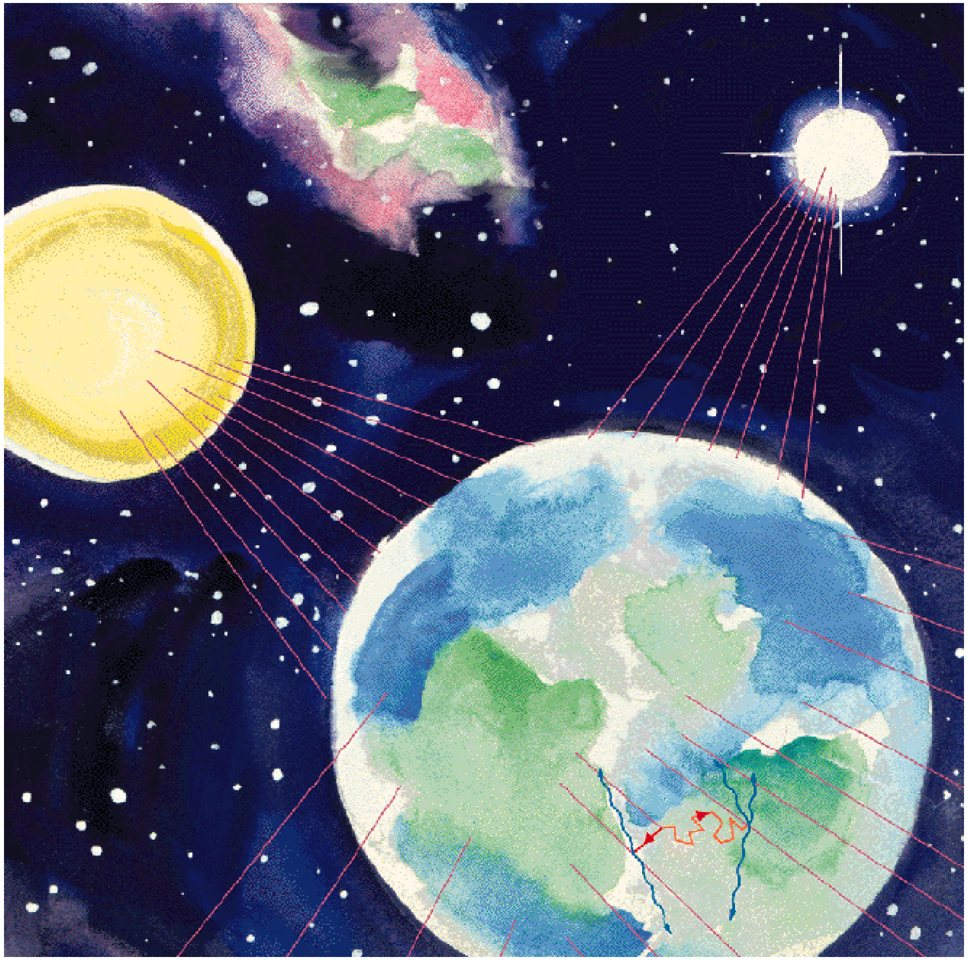
I can't tell you about tomorrow.

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

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

Well Bob, I'm glad you asked...

neutrinos power the sun



neutrinos drive supernovae explosions

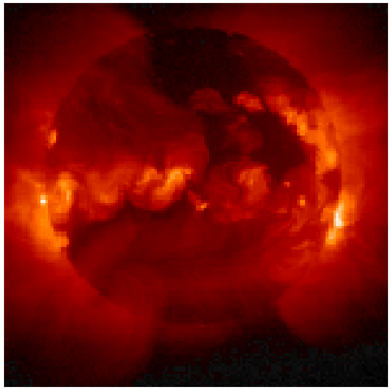
next to photons in the CMB, neutrinos are the most abundant particle in the universe

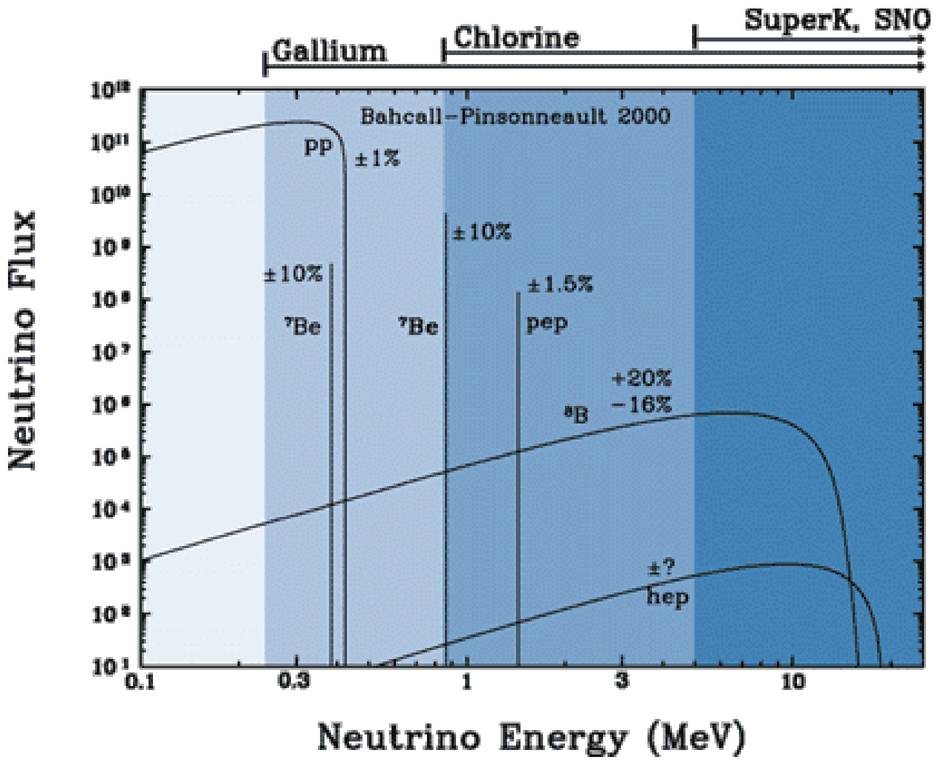
neutrinos are a component of dark matter

Even a tiny mass can change the way the universe works!

A natural source of neutrinos...

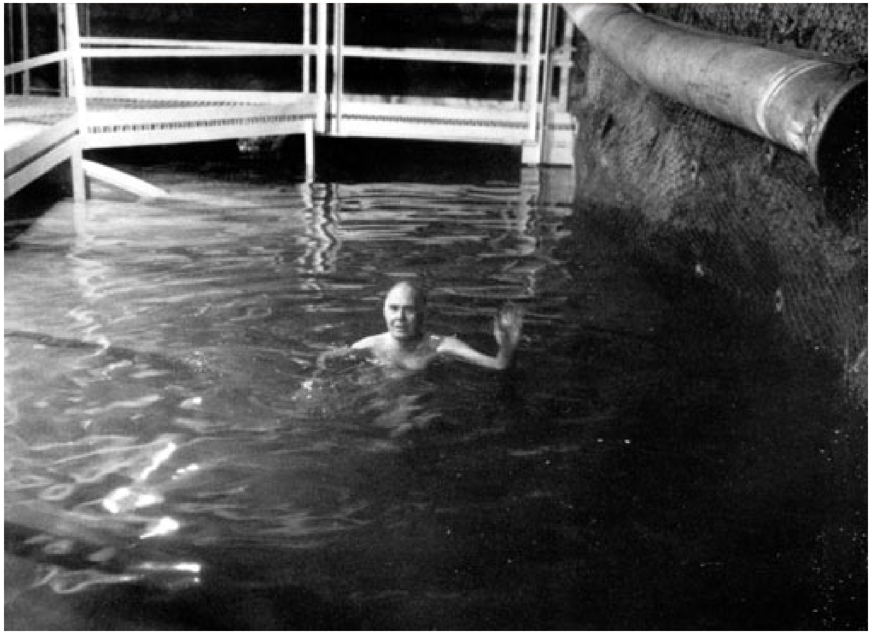
- The sun is fueled by fusion reactions
  - $4\,^1H + 2e^- \rightarrow \,^4He + 2\nu_e + 6\gamma$
  - More reaction chains follow...
- Neutrinos are produced copiously
  - Note all produce ν_e, below ~10MeV





Ray Davis' experiment

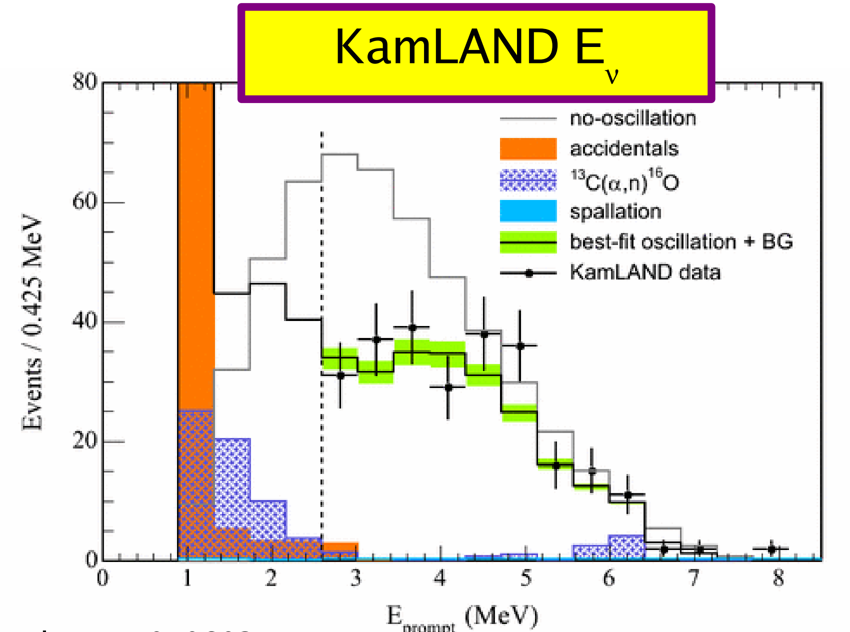
- Ray Davis set out to measure solar ν's
- Used a large vat of dry cleaning solution
- Looking for inverse beta decay (CC) with Chlorine converting to Argon
- Deep underground at Homestake gold mine to get away from cosmic ray background



- First oscillation evidence came in 1968 from Davis' solar ν_e experiment
  - found 1/3 of the expected ν_e from sun
  - disappearance $\nu_e \to \nu_x$
  - $\Delta m_{12}^2 \sim 8\times10^{-5}$ eV^2, $\sin^2(2\theta) \sim 0.8$
- Mired in controversy, do we understand fusion, is the experiment correct, could it be due to neutrino oscillation?

Solar neutrino oscillations

- The Sudbury Neutrino Observatory (SNO) confirmed Ray Davis' findings
  - Could also see CC and NC
    - Deficit in CC channel
    - Exactly right in NC channel!
- KamLAND eperiment used reactor antineutrinos
  - Confirm solar result through spectral distortion!
  - Showed oscillations apply to ν_e and anti-ν_e
- Final solution:
  - Mixing angle $\theta \simeq 32^{\circ}$
  - $\Delta m_{12}^2 \sim 8\times10^{-5}\ eV^2$



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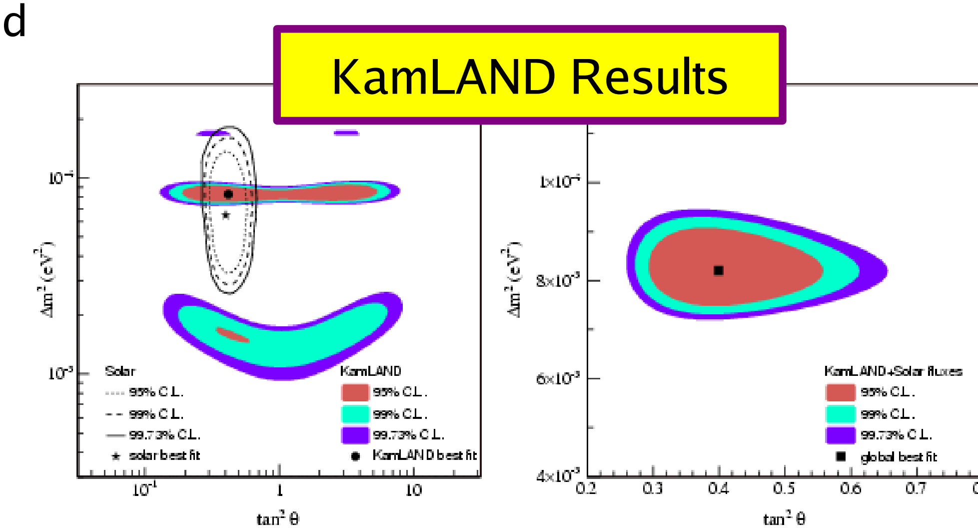
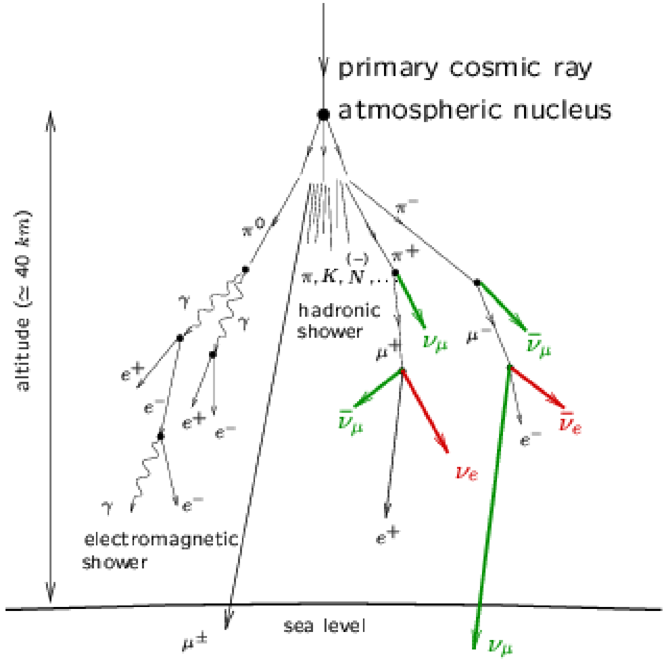
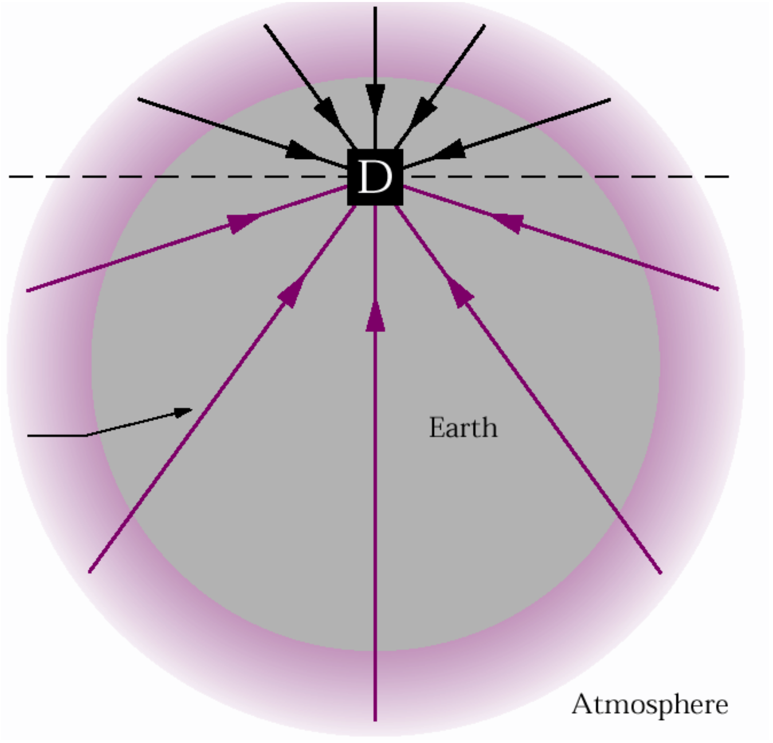


Cosmic ray interactions are a natural source of ν_μ

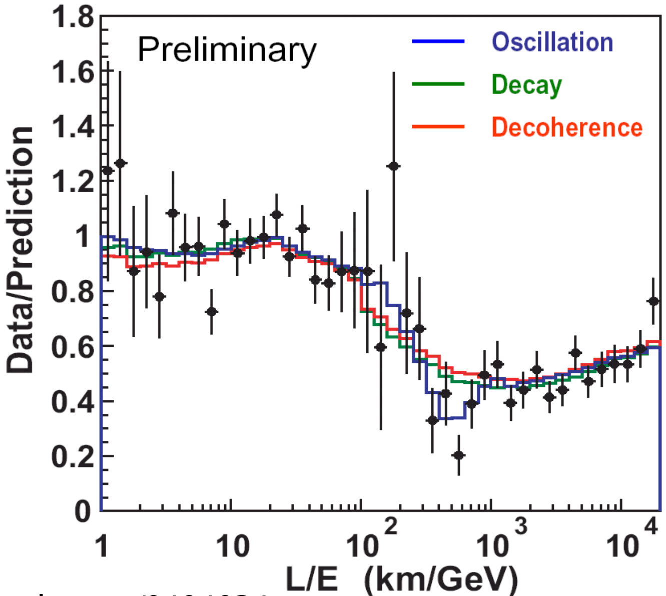


- High energy cosmic ray (primarily protons) generate massive showers
- Relativistically dilated lifetime allows muons to penetrate
- Copious source of ν_μ



- Cannot control the E spectrum
- Can control the baseline, L
  - By looking at the direction the ν_μ comes from, the distance between the detector and the source can be varied

Atmospheric oscillations



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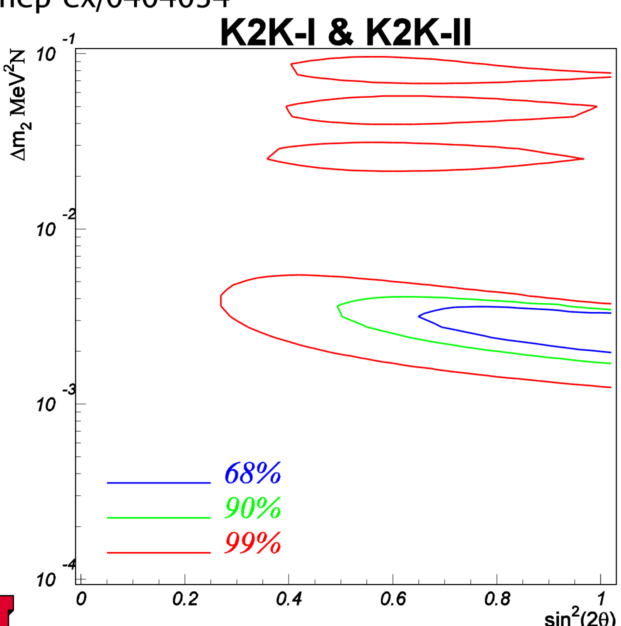
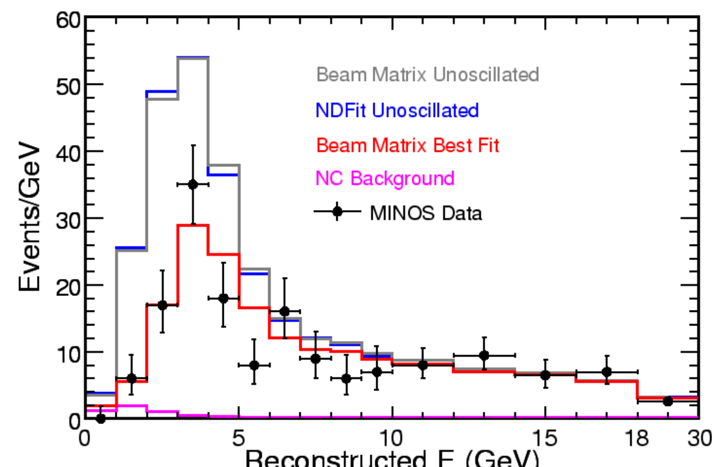
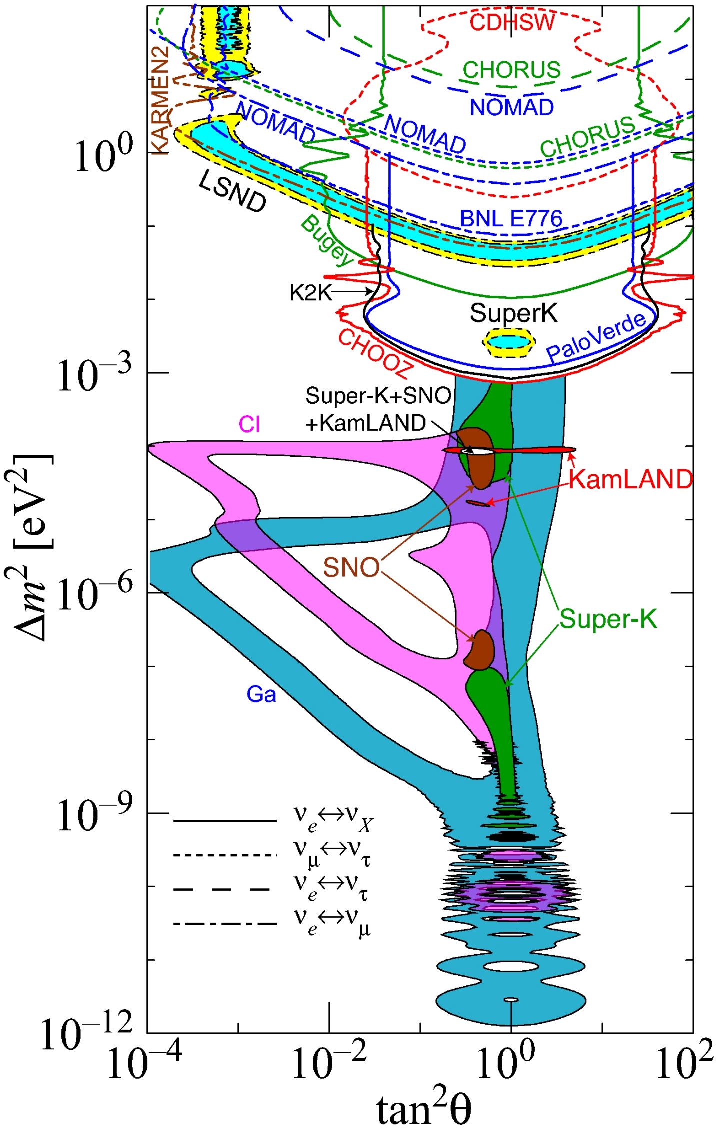


- New mixing found by Super-K through atmospheric ν_μ oscillations
  - mix of anti-ν and ν
  - found 1/2 as the upward ν_μ as downward
  - disappearance $\nu_\mu \rightarrow \nu_x$
  - $\Delta m_{23}^{\ 2} \sim 2\times10^{-3}\ eV^2$, $\sin^2(2\theta) \sim 1.0$
- Confirmed by K2K
  - ν_μ from KEK accelerator to Super-K
  - man-made source confirms the natural
- Confirmed by many other experiments SNO, IMB, Soudan, and most recently MINOS



Summary of ν oscillation searches

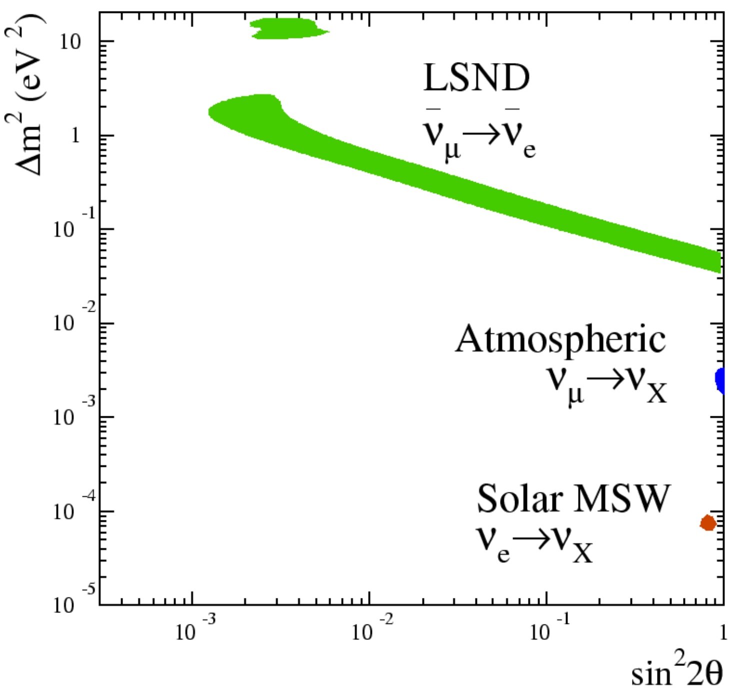


http://hitoshi.berkeley.edu/neutrino

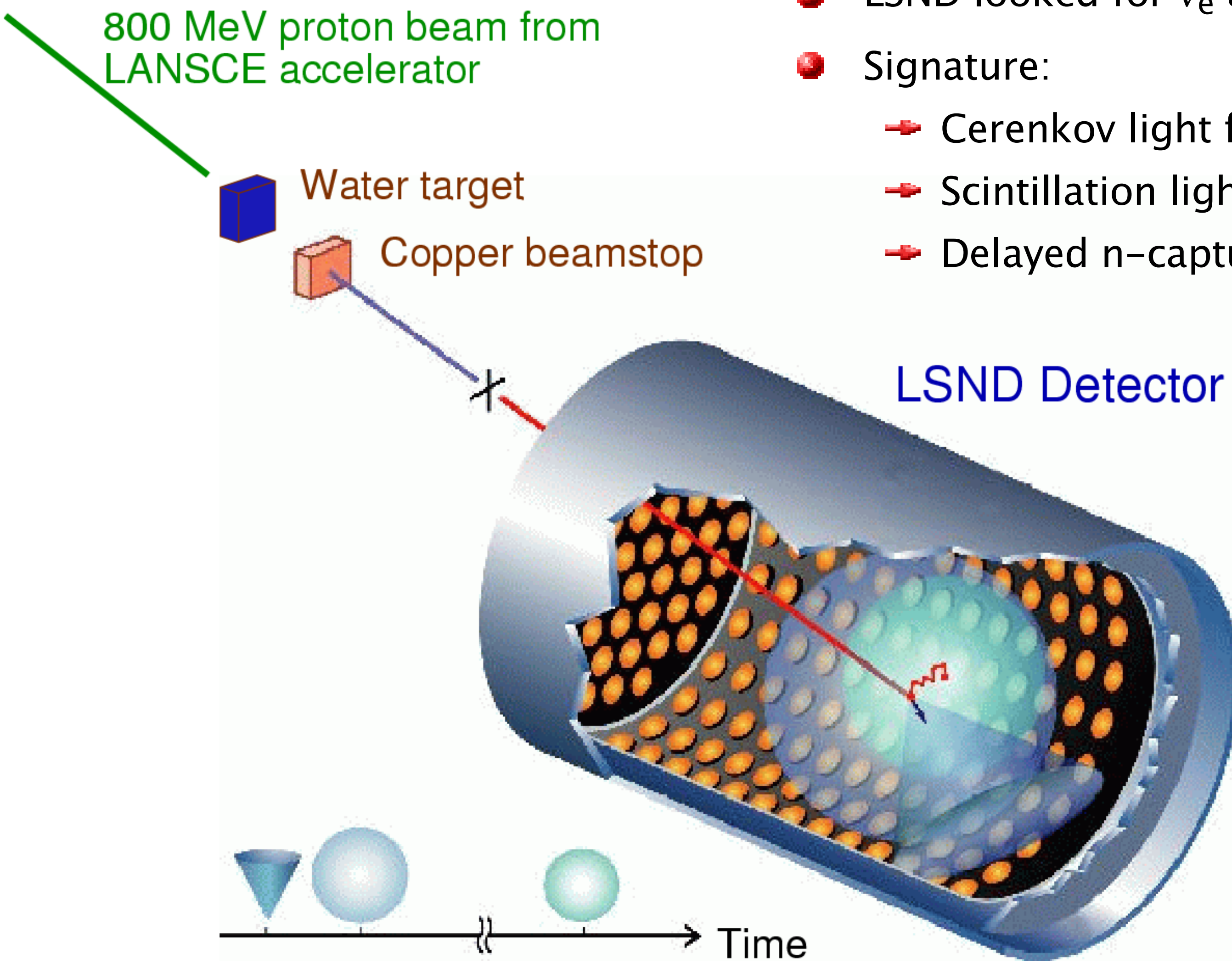
- Can see from the plot on the left how active the ν oscillation industry has been!

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

- Reducing plot on left to experiments that have found a positive oscillation...
  - Well-measured solar and atmospheric
  - One other signal, LSND, which is curiously at a much higher Δm^2

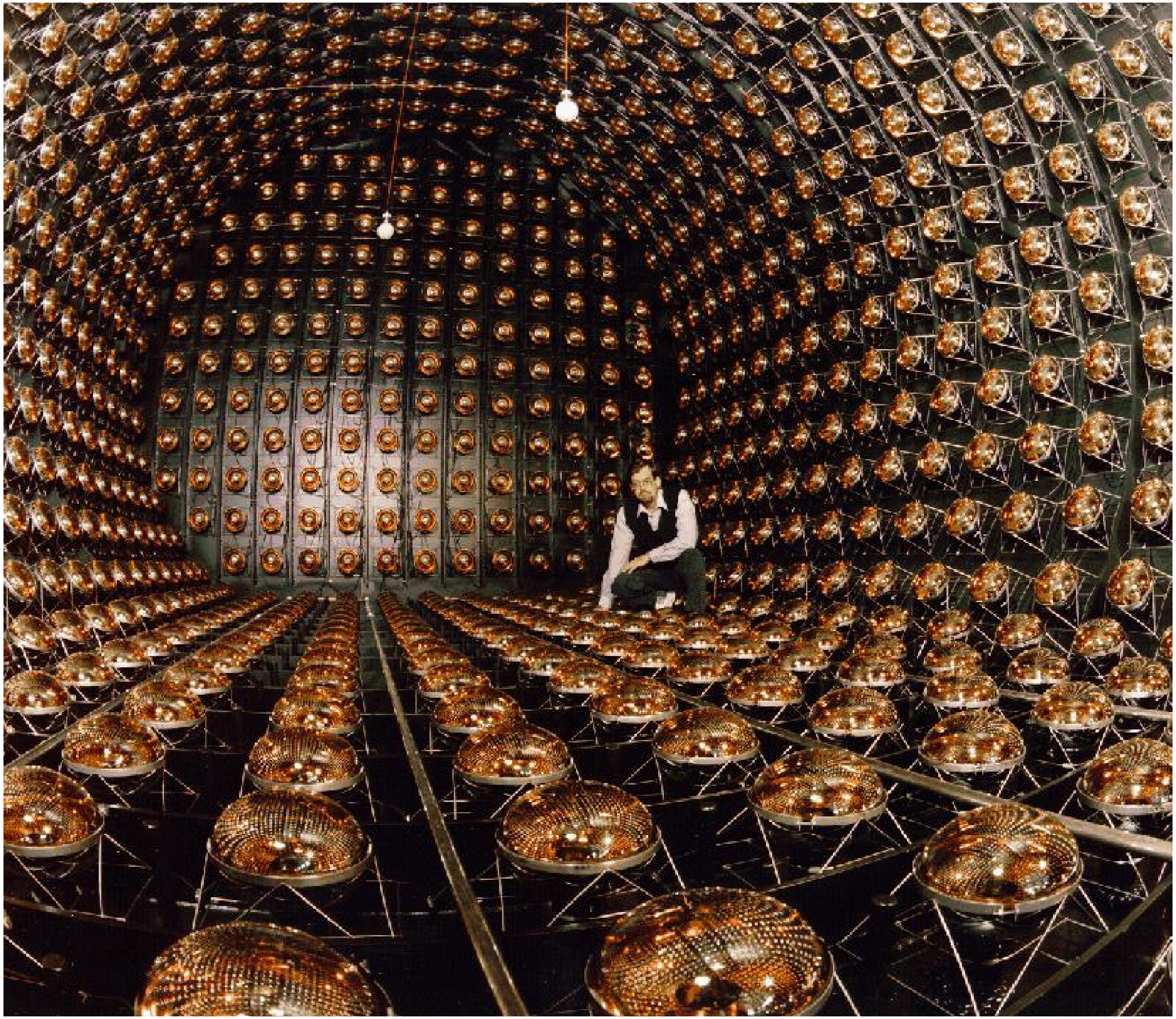


The Liquid Scintillator Neutrino Detector at LANL



- 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)

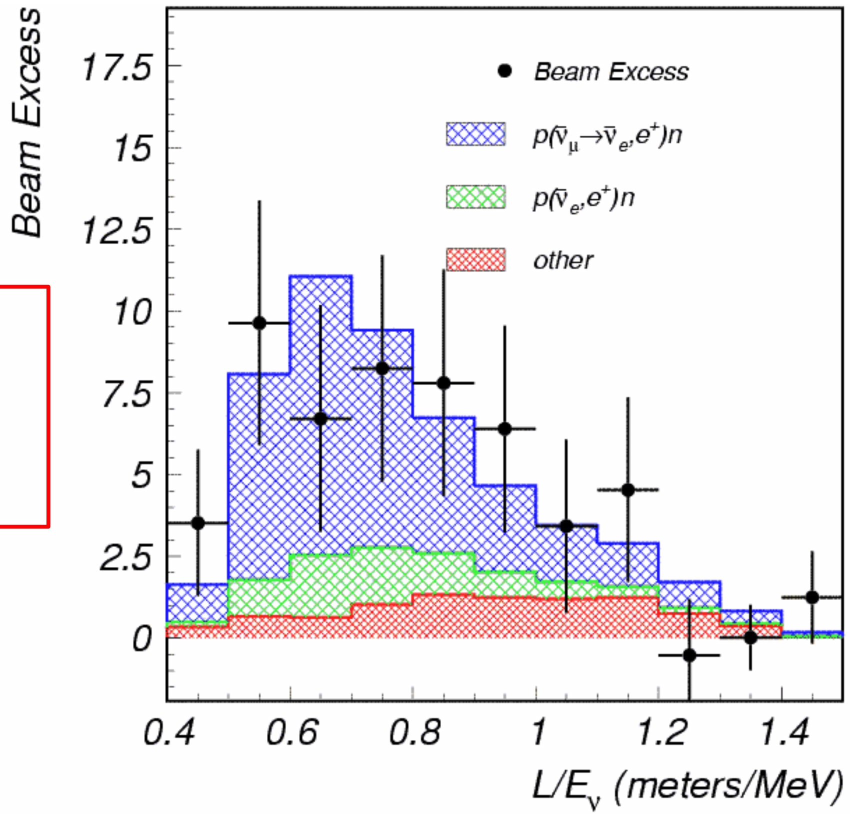
Picture of LSND photomultipliers (used later in MB)



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:

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



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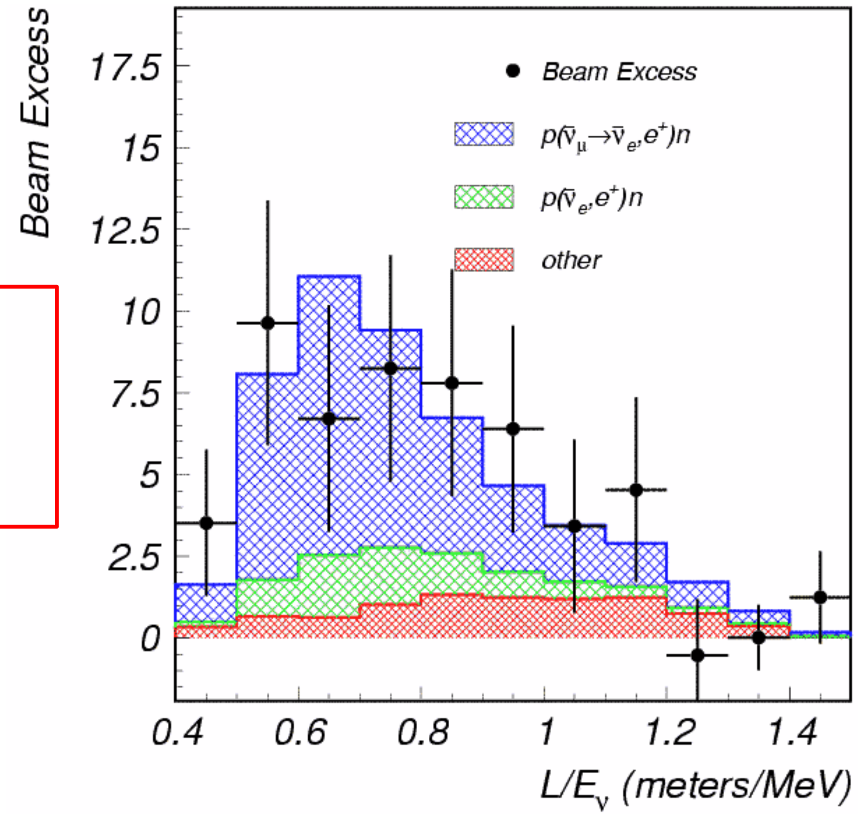
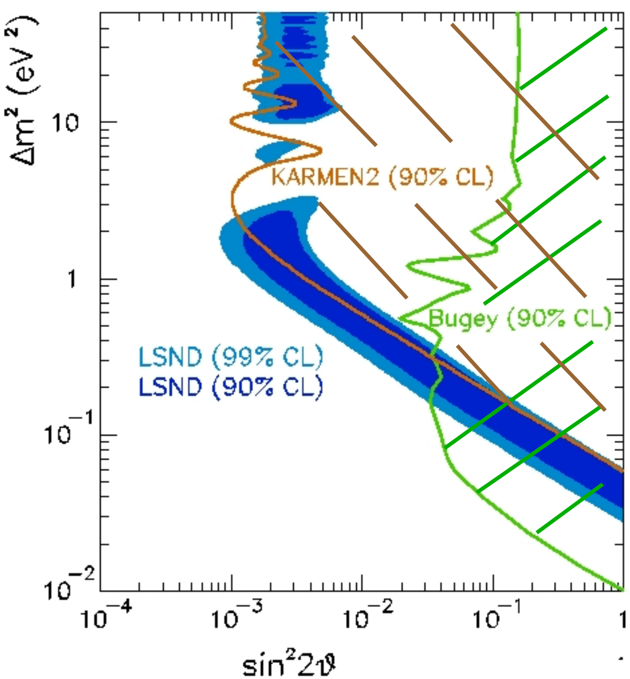
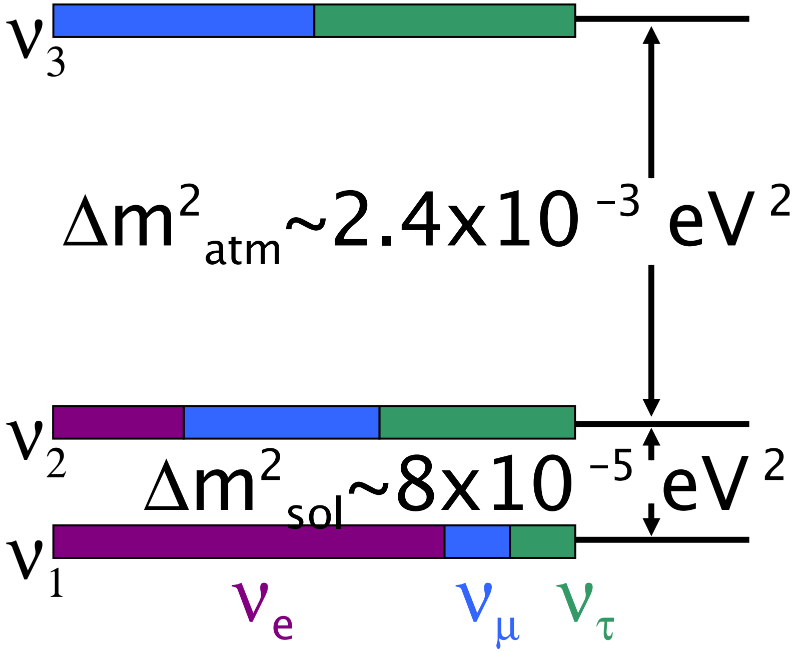
$$= 0.245 \pm 0.067 \pm 0.045\ \%$$





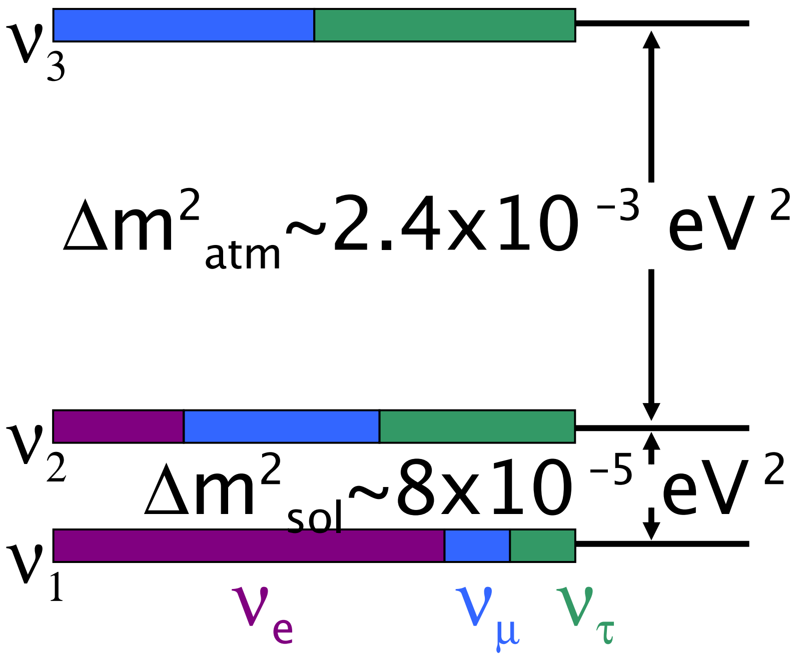
- Other experiments, i.e. Karmen and Bugey, have ruled out portions of the LSND signal
- MiniBooNE was designed to cover the entire LSND allowed region

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

Interpreting the LSND signal



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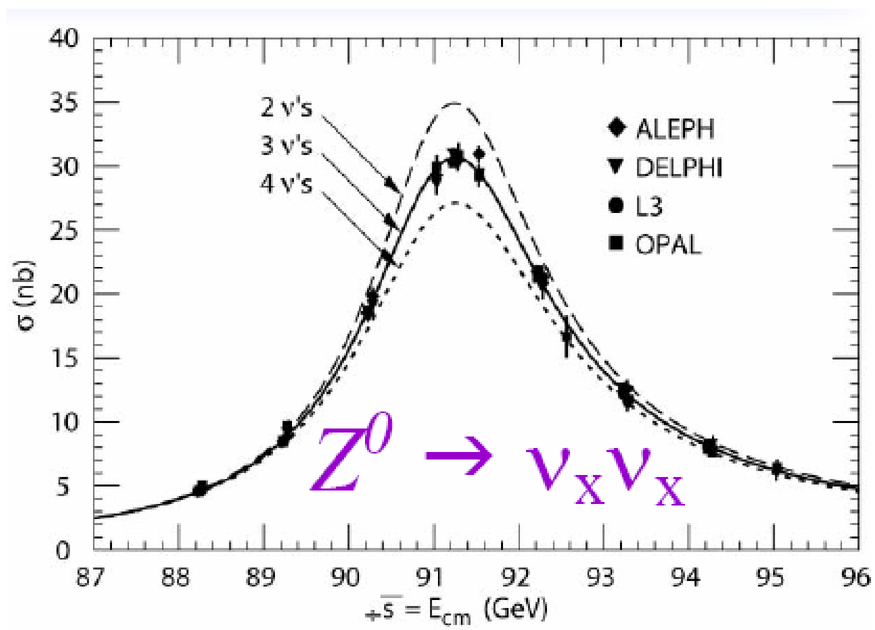
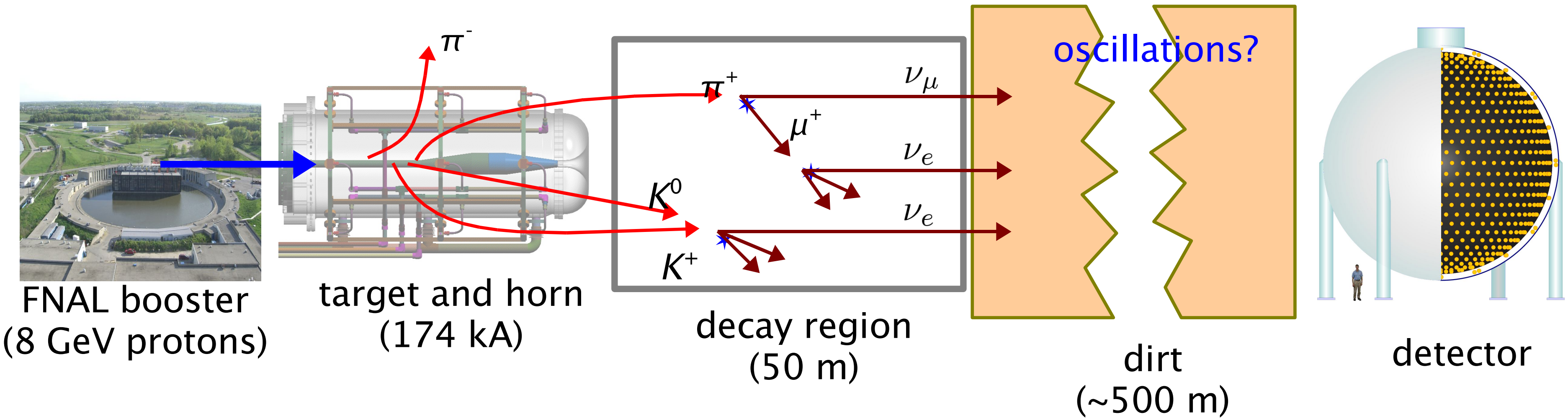
- 'Simplest' explanation...a 4th neutrino

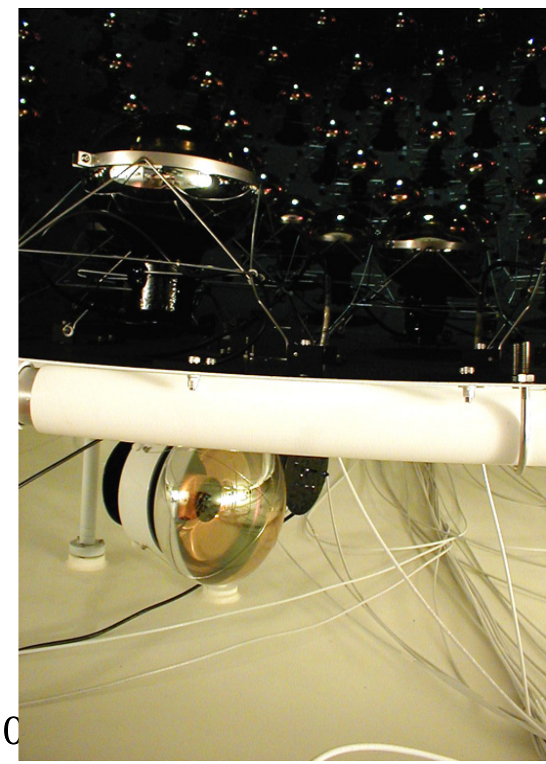
- Width of the Z implies 2.994 + 0.012 light neutrino flavors
- Requires 4th neutrino to be 'sterile' or an even more exotic solution
  - Sterile neutrinos *hep-ph/0305255*
  - Neutrino decay *hep-ph/0602083*
  - Lorentz/CPT violation *PRD(2006)105009*
  - Extra dimensions *hep-ph/0504096*



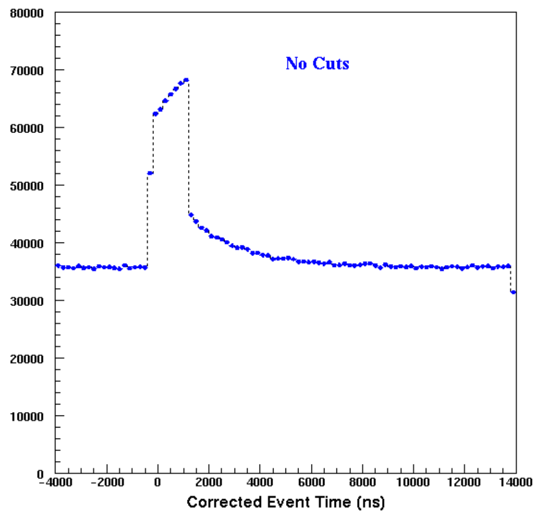
The MiniBooNE design strategy

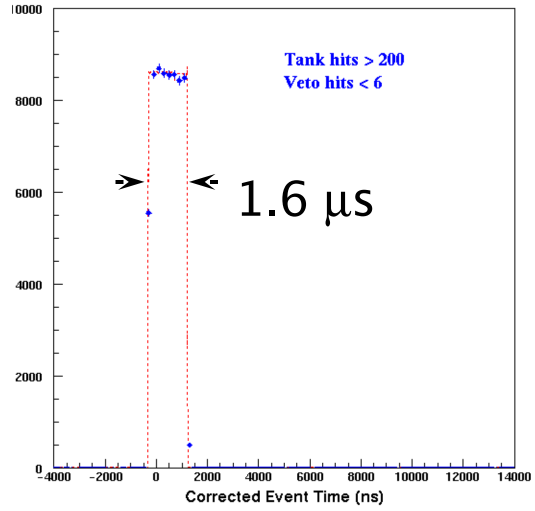


- Start with 8 GeV proton beam from FNAL Booster
- Add a 174 kA pulsed horn to gain a needed x 6
- Requires running ν (not anti–ν) to get flux
- Pions decay to ν with E_ν in the 0.8 GeV range
- Place detector to preserve LSND L/E:
  - MiniBooNE: (0.5 km) / (0.8 GeV)
  - LSND: (0.03 km) / (0.05 GeV)
- Detect ν interations 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



Simple cuts eliminate random backgrounds

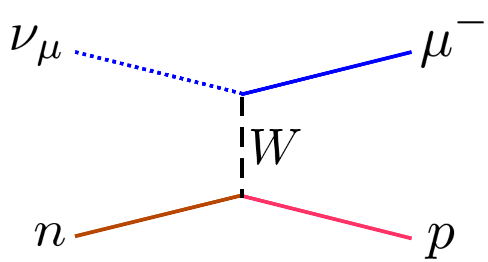


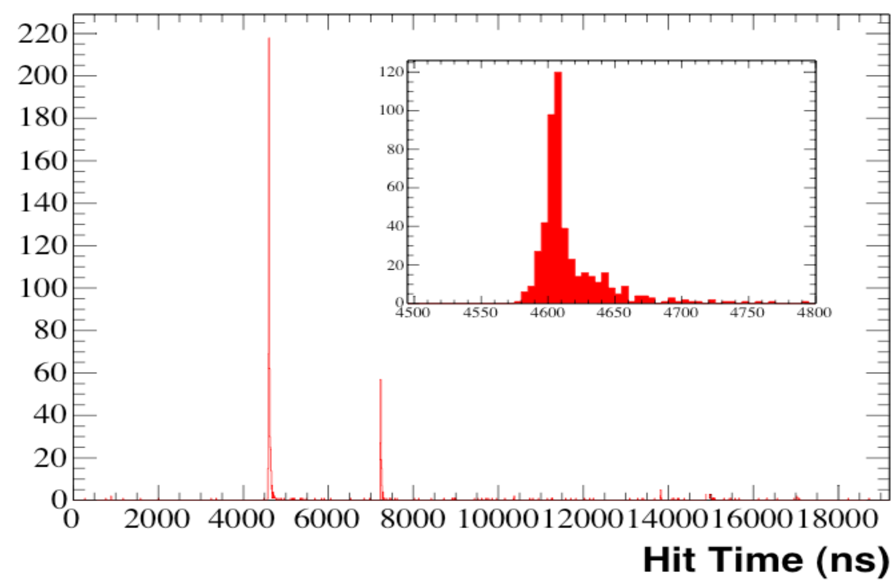


- Left: trigger window, no cuts
- Right: Simple cuts applied PMT hits in veto < 6 and tank > 200 show clean beam window
- Removes cosmic μ and their decay electrons

- Subevent structure (clusters in time) can be used for particle identification (PID)
- 2 subevent time structure expected for most common ν interaction in MB:

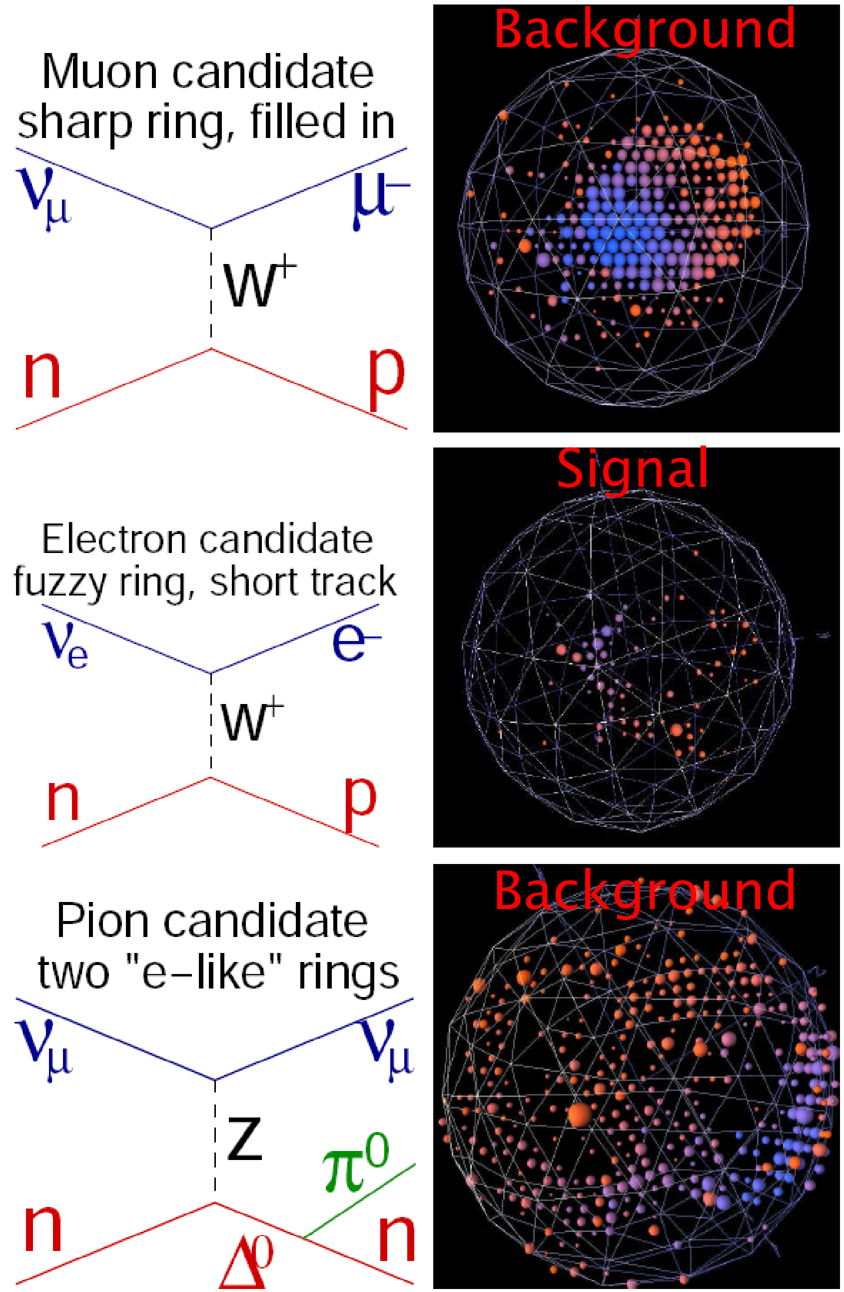
ν_μ CCQE (charged-current quasi-elastic)



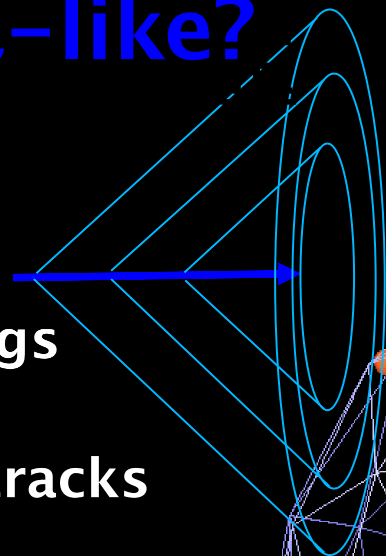


Key points about the signal

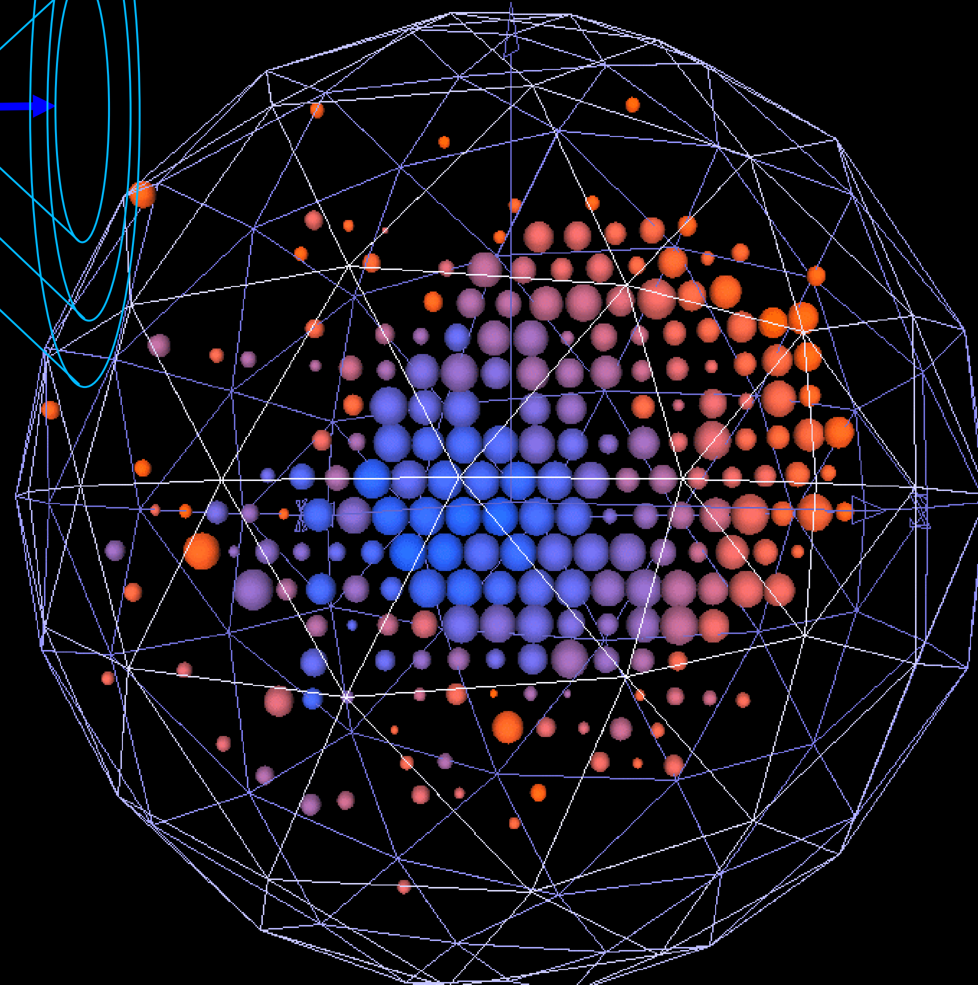
- LSND oscillation probability is < 0.3%
- After cuts, MiniBooNE has to be able to find ~300 ν_e CCQE interactions in a sea of ~150,000 ν_μ CCQE
- Intrinsic ν_e background
  - Actual ν_e produced in the beamline from muons and kaons
  - Irreducible at the event level
  - E spectrum differs from signal
- 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 rarer, but harder to separate
  - Can be reduced with better PID
- MiniBooNE is a ratio measurement with the ν_μ constraining flux X cross-section



Is the ring μ-like?



event displays:
- size: amount of light
- color: detection time



Muons

- **Sharp, clear rings**
- **Long, straight tracks**

Electrons

- Fuzzy rings
- Multiple scattering
  - Radiative processes

Neutral Pions

- Double rings

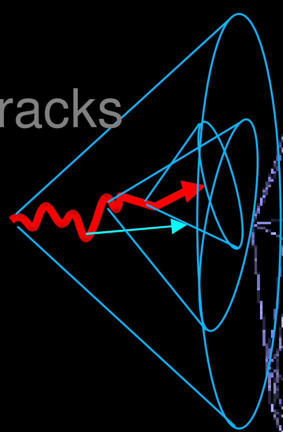
Is the ring e-like?

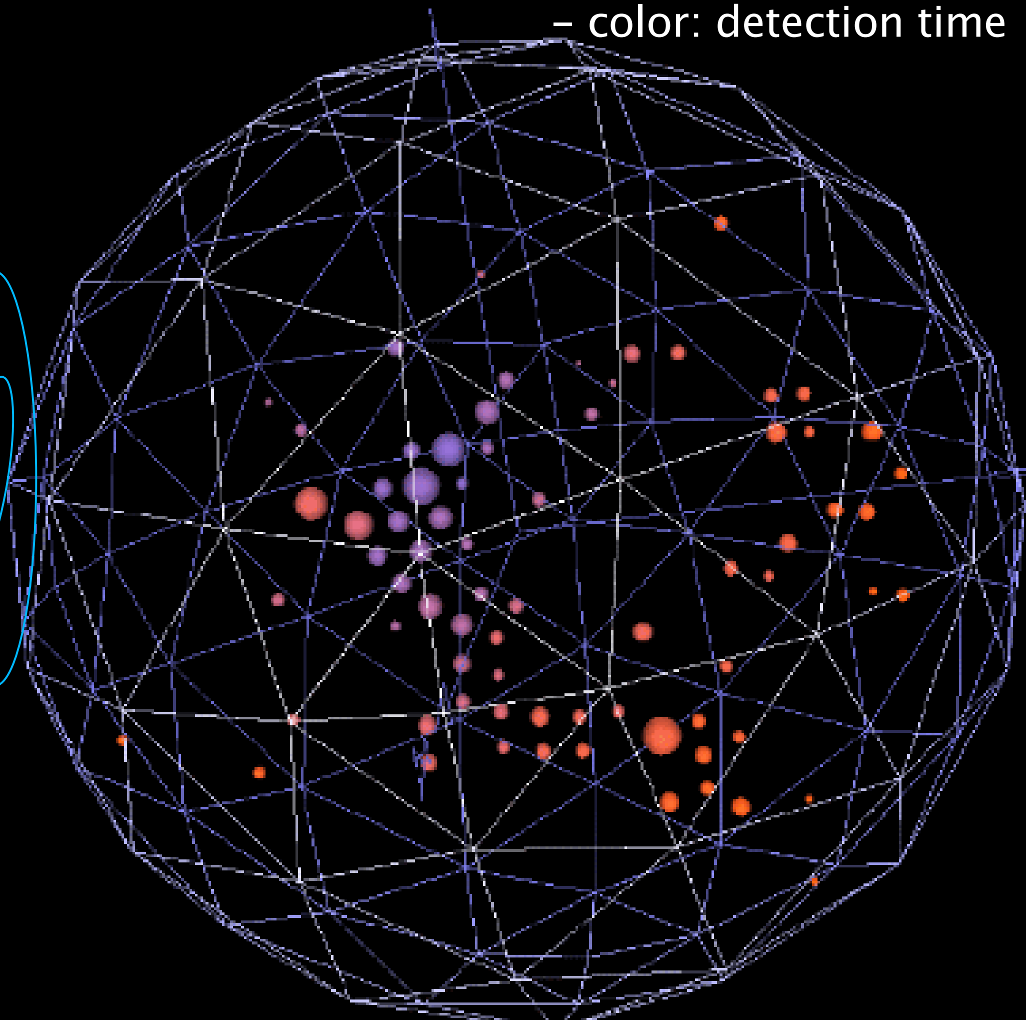
event displays:
- size: amount of light
- color: detection time

Muons

Sharp, clear rings

Long, straight tracks





Electrons

Fuzzy rings

Multiple scattering

Radiative processes

Neutral Pions

How many rings?

event displays:
- size: amount of light
- color: detection time

Muons

Sharp, clear rings

Long, straight tracks

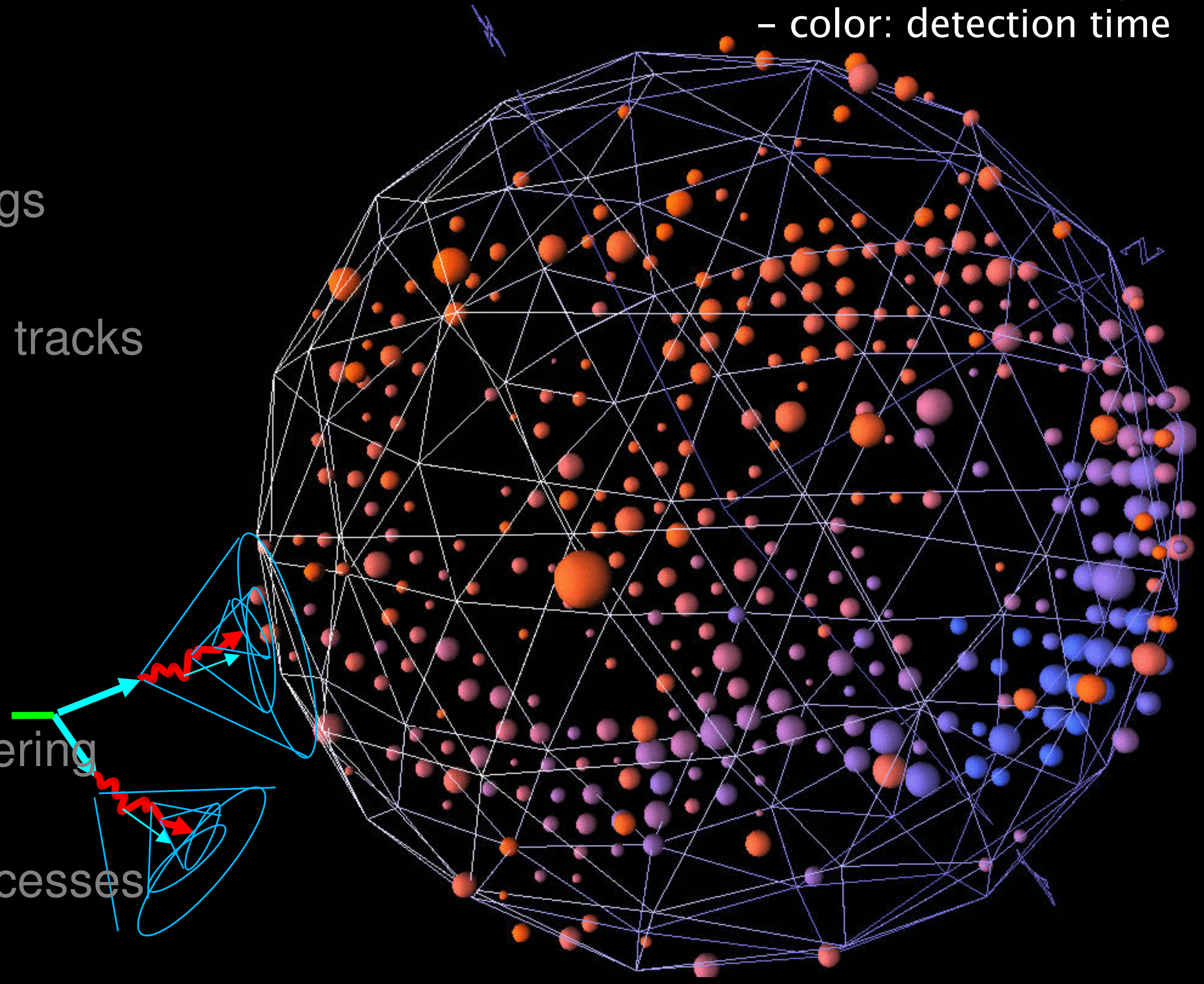
Electrons

Fuzzy rings

Multiple scattering

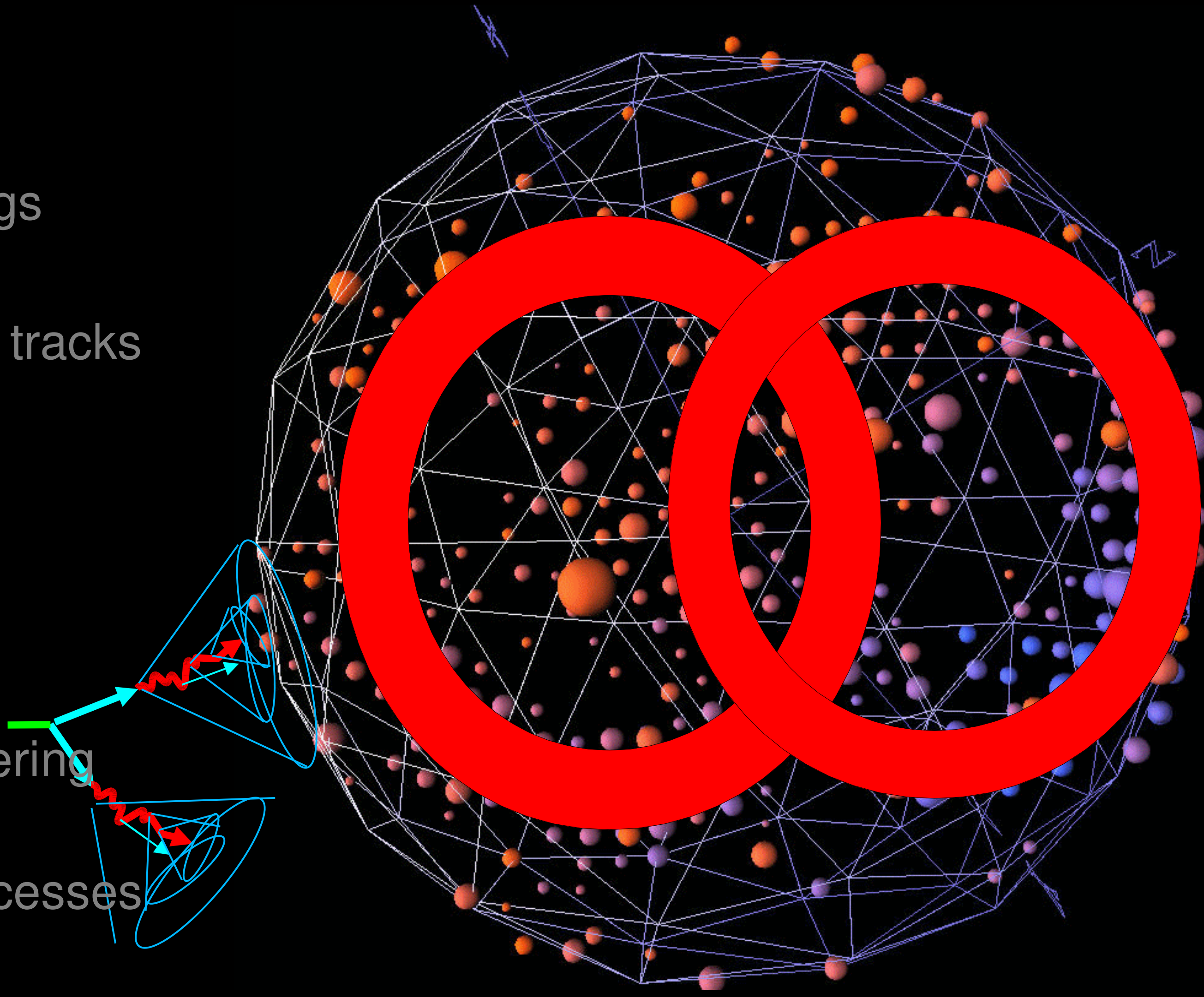
Radiative processes

Neutral Pions



How much Cerenkov?

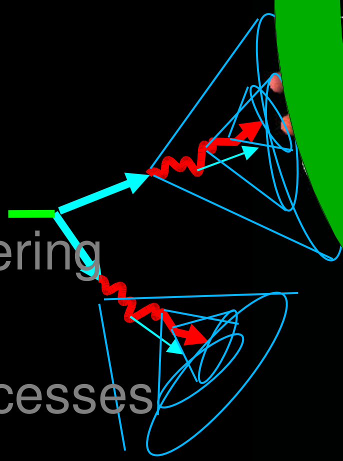
- Muons
  - Sharp, clear rings
    - Long, straight tracks
- Electrons
  - Fuzzy rings
    - Multiple scattering
    - Radiative processes

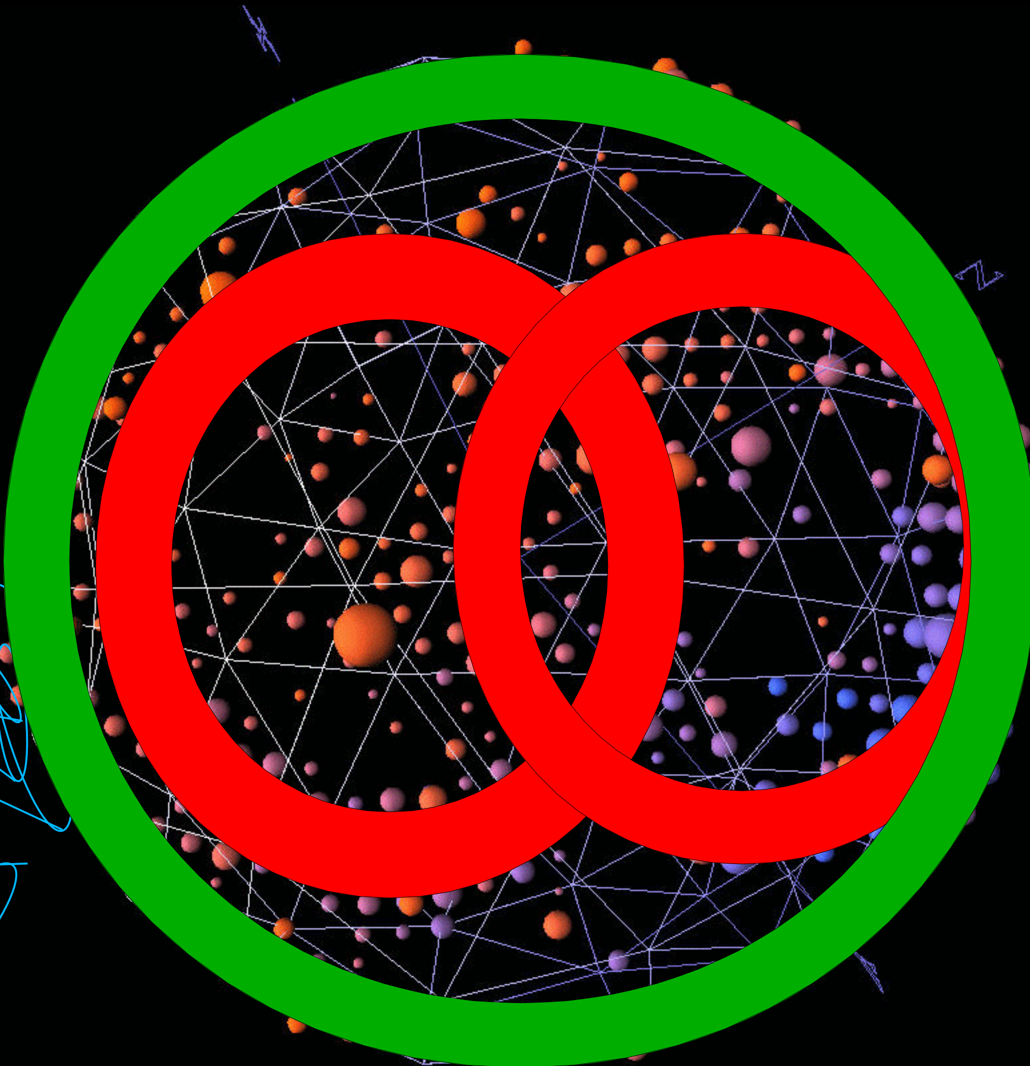


Neutral Pions

How much Cerenkov vs isotropic?

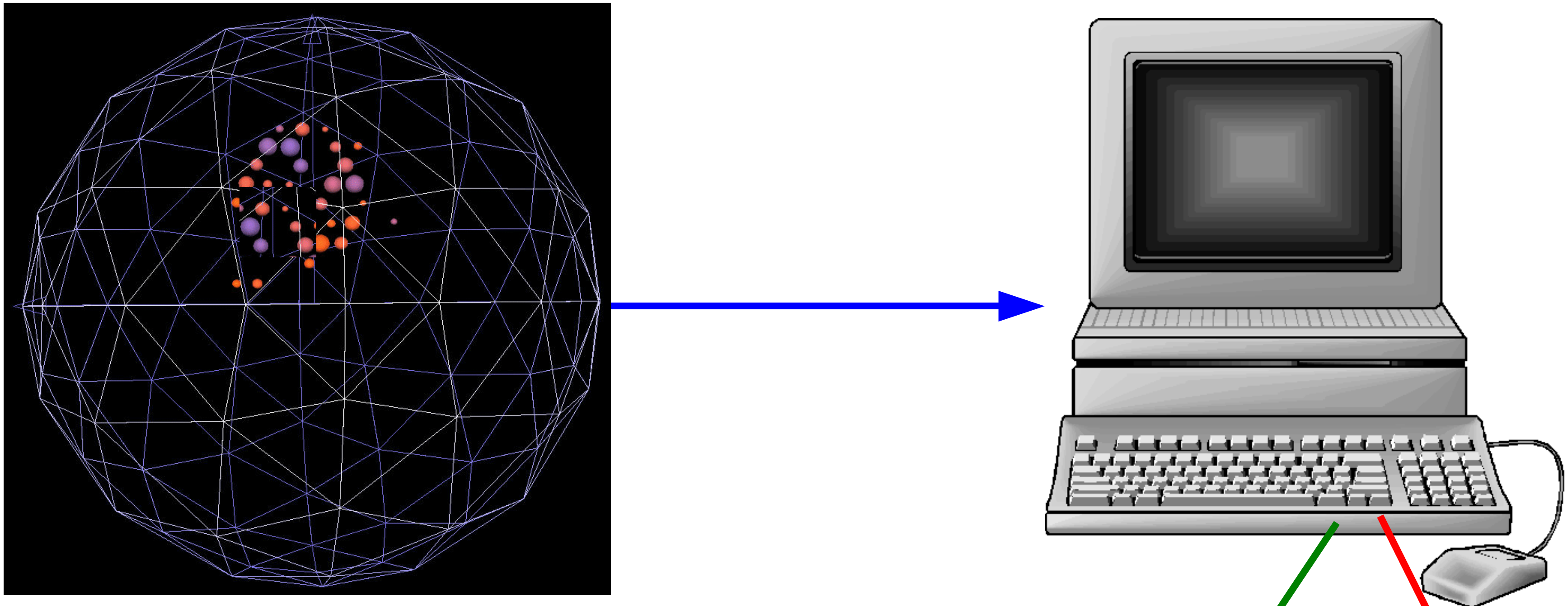
- Muons
  - Sharp, clear rings
    - Long, straight tracks
- Electrons
  - Fuzzy rings
    - Multiple scattering
    - Radiative processes

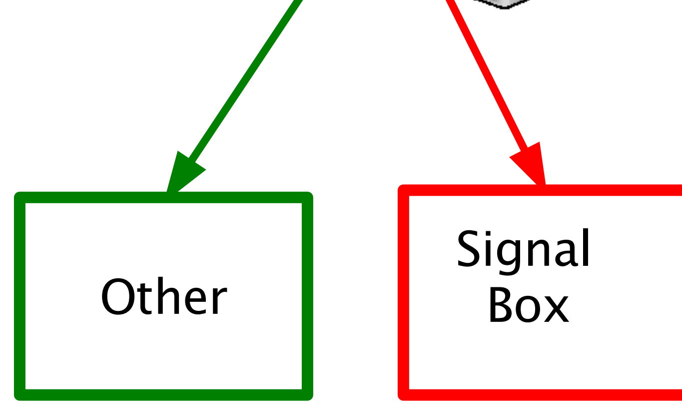




- **Neutral Pions**

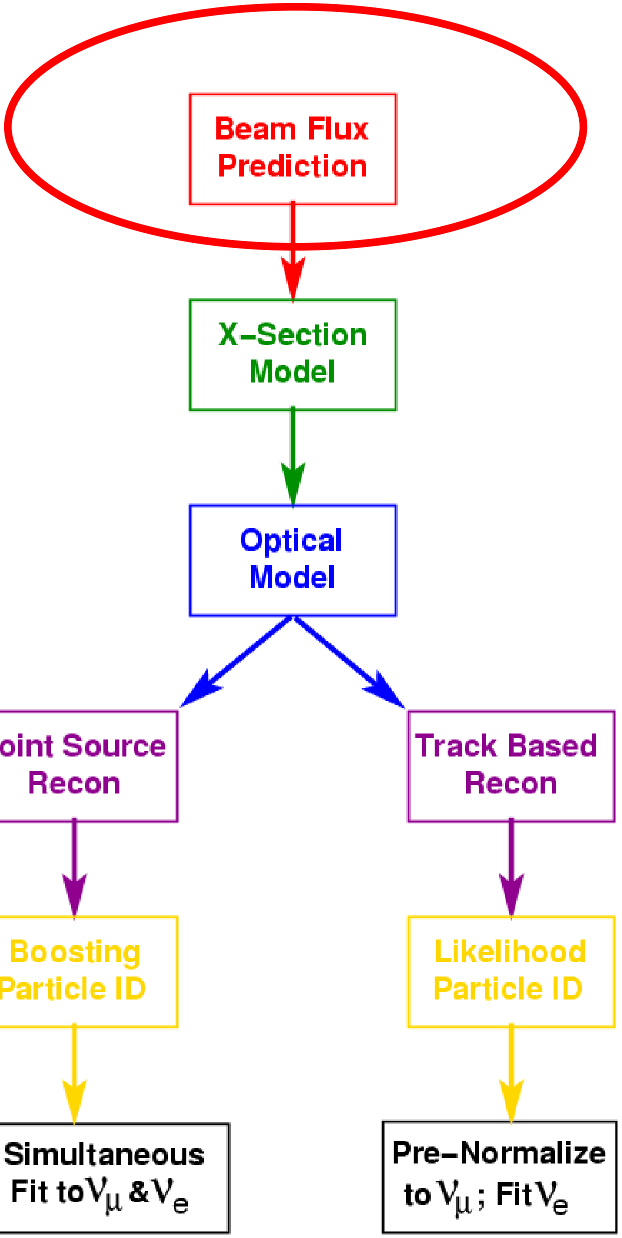
Blind analysis in MiniBooNE





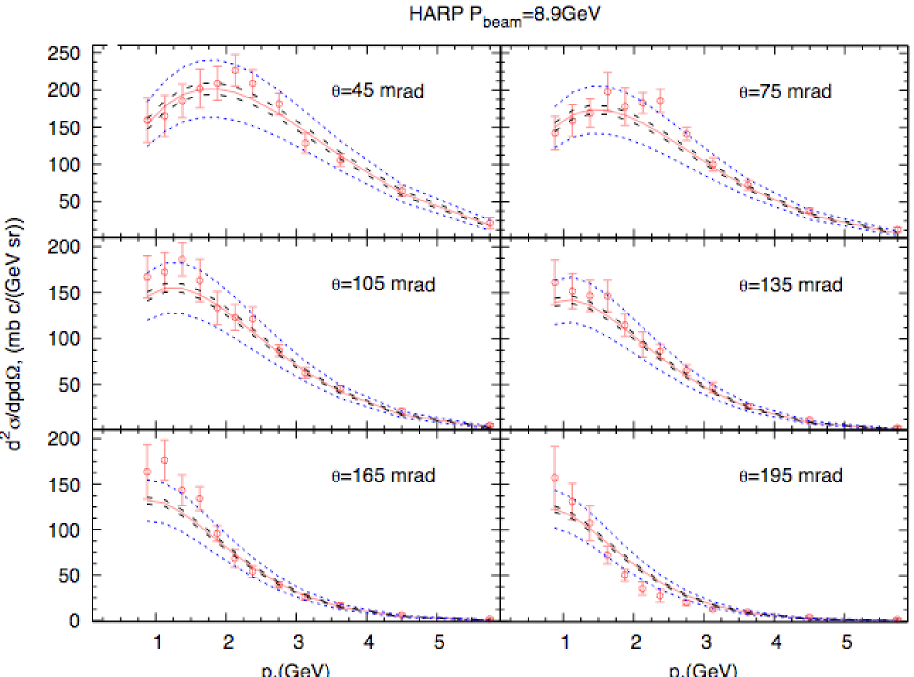
- The MiniBooNE signal is small but relatively easy to isolate
- As data comes in it is classified into 'boxes'
- For boxes to be opened to analysis they must be shown to have a signal $< 1\sigma$
- In the end, 99% of the data were available prior to unblinding...necessary to understand errors

Flux Prediction



Meson production at the target

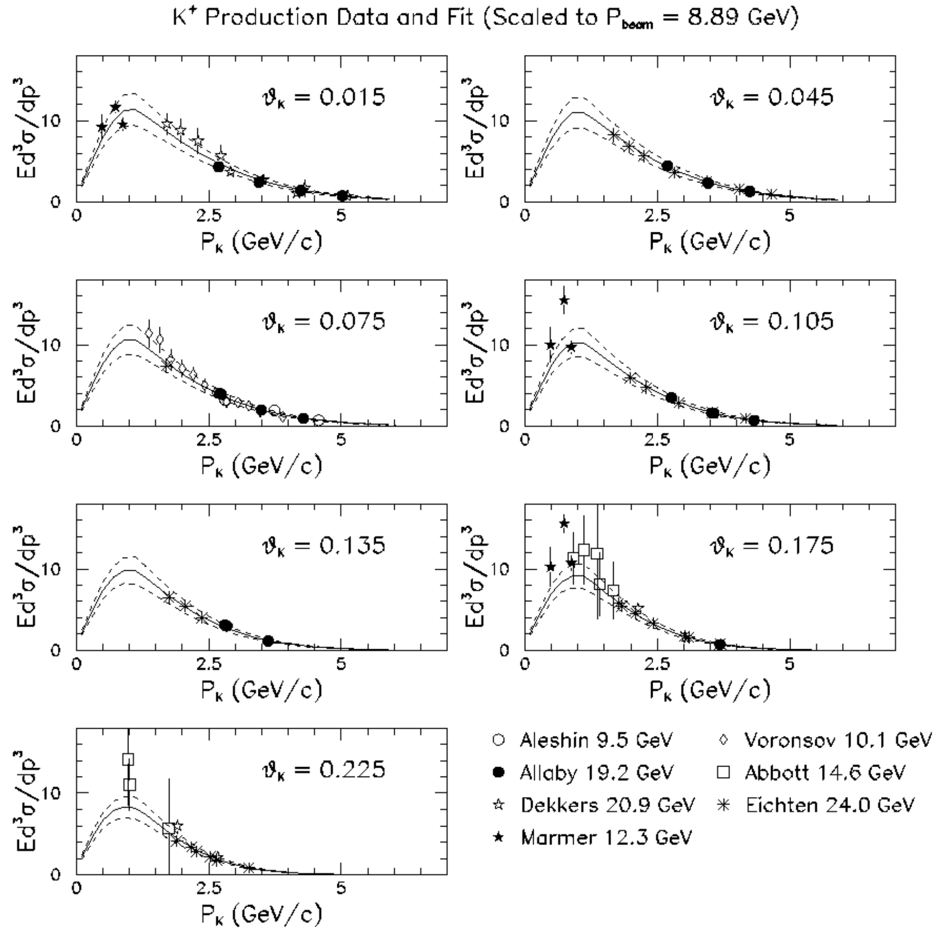
Pions:



HARP collaboration, hep-ex/0702024

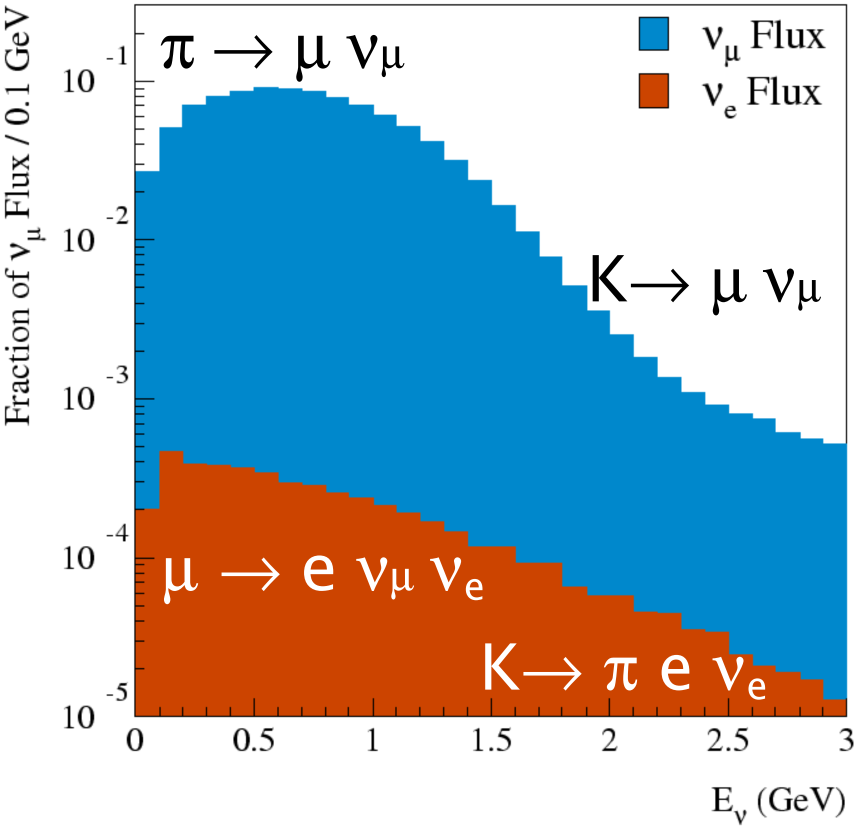
- MiniBooNE members joined the HARP collaboration
  - 8 GeV proton beam
  - 5% λ Beryllium target
- Data were fit to Sanford-Wang parameterization

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



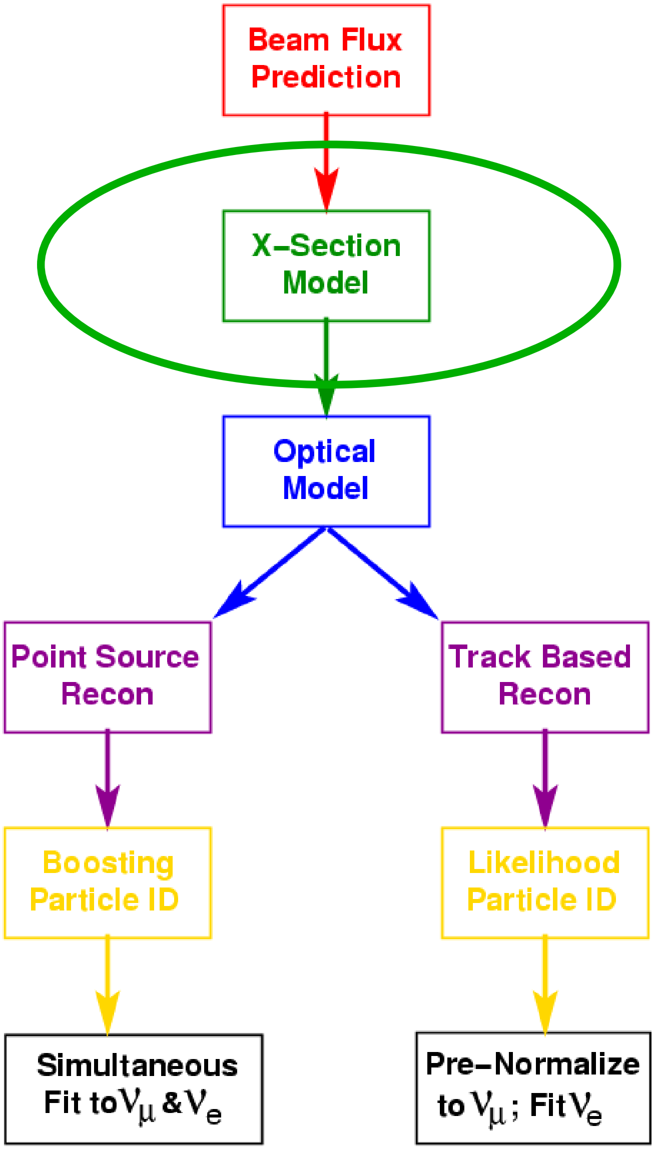
$\nu_e / \nu_\mu = 0.5\%$

"Intrinsic" $\nu_e + \bar{\nu}_e$ sources:

$\mu^+ \rightarrow e^+\ \bar{\nu}_\mu\, \nu_e$	(52%)
$K^+ \rightarrow \pi^0\, e^+\ \nu_e$	(29%)
$K^0 \rightarrow \pi\, e\, \nu_e$	(14%)
Other	(5%)

Antineutrino content: 6%

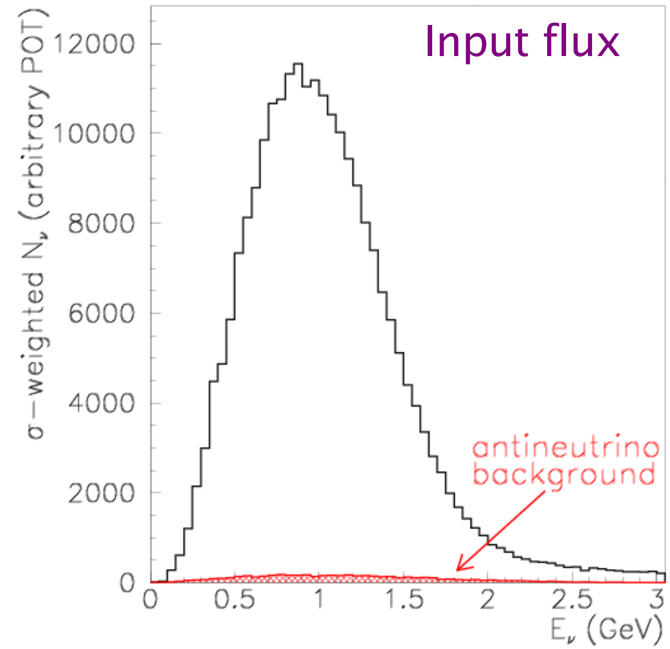
X–Section Model

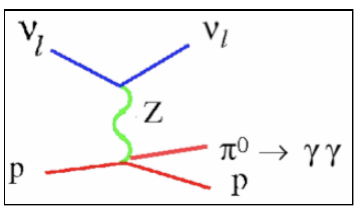


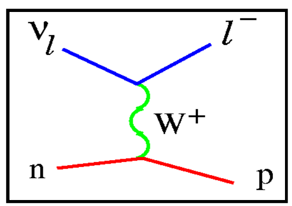
Nuance Monte Carlo

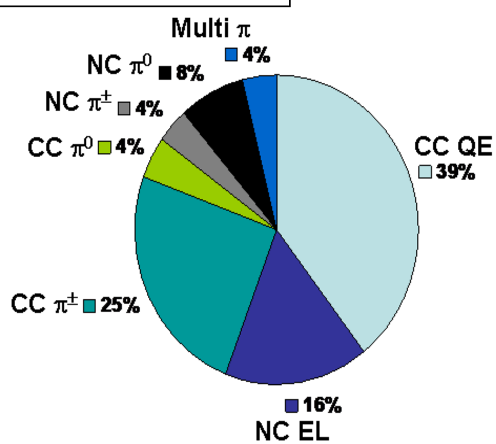
D. Casper, NPS, 112 (2002) 161

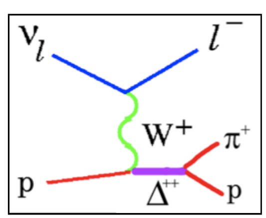
- Comprehensive generator, covers entire E_ν range
- Predicts relative rate of specific ν interactions from input flux
- Expected interaction rates in MiniBooNE (before cuts) shown below
- Based on world data, ν_μ CC shown below right
- Also tuned on internal data

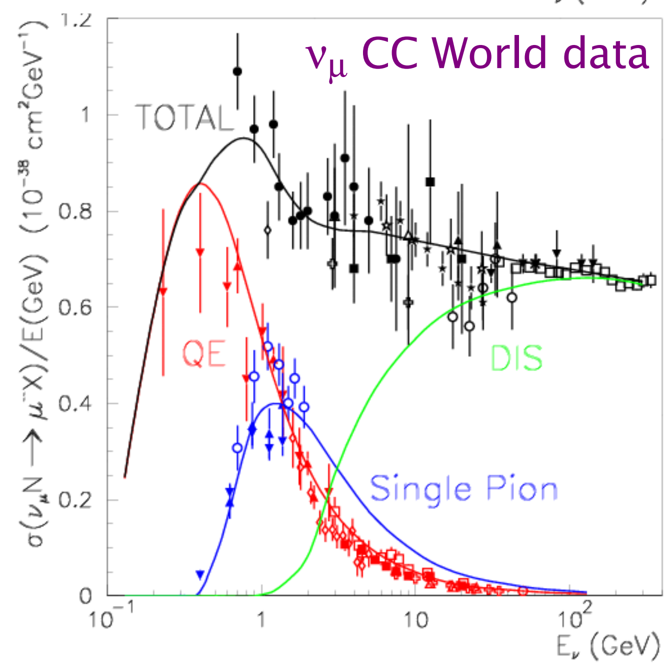








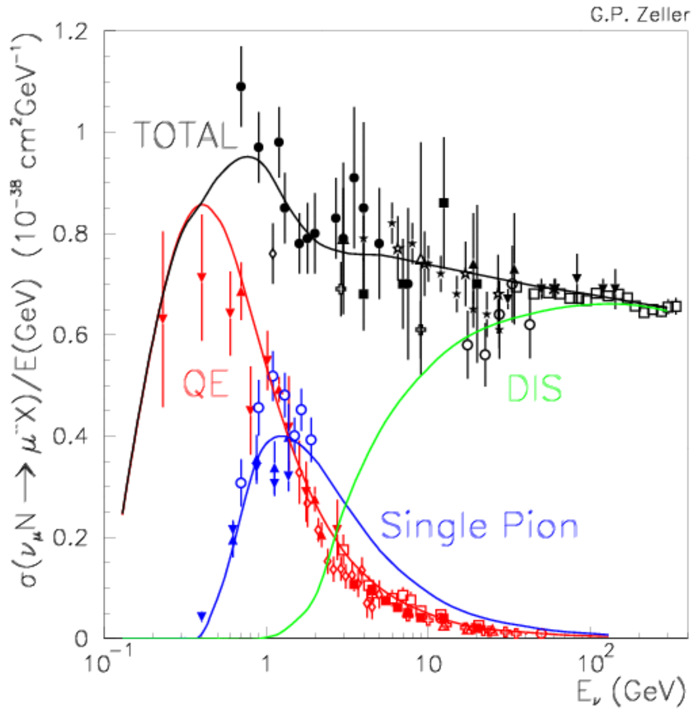


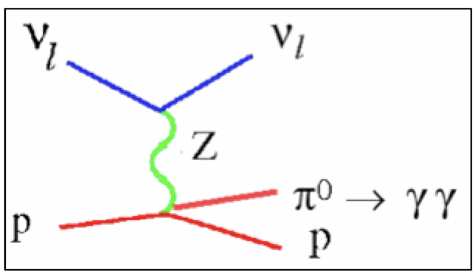


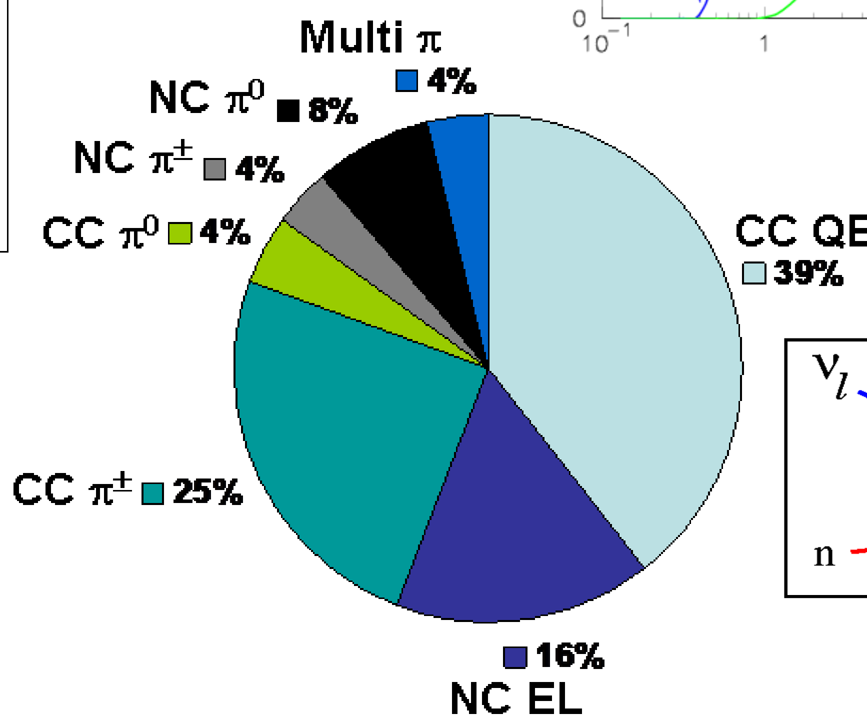
Nuance Monte Carlo

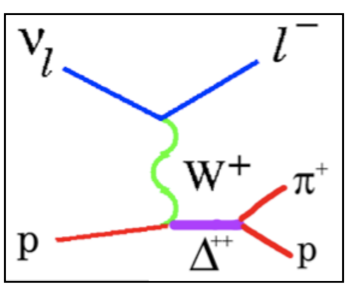
D. Casper, NPS, 112 (2002) 161

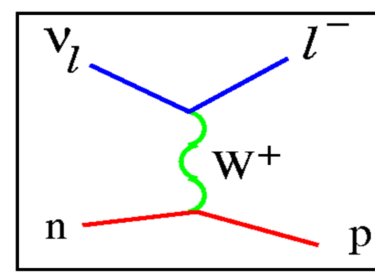
- Used to predict rate of specific ν interactions
- World data for various channels shown at right
- Tuned on external and internal data
- Expected interaction rate in MiniBooNE (before cuts) shown below



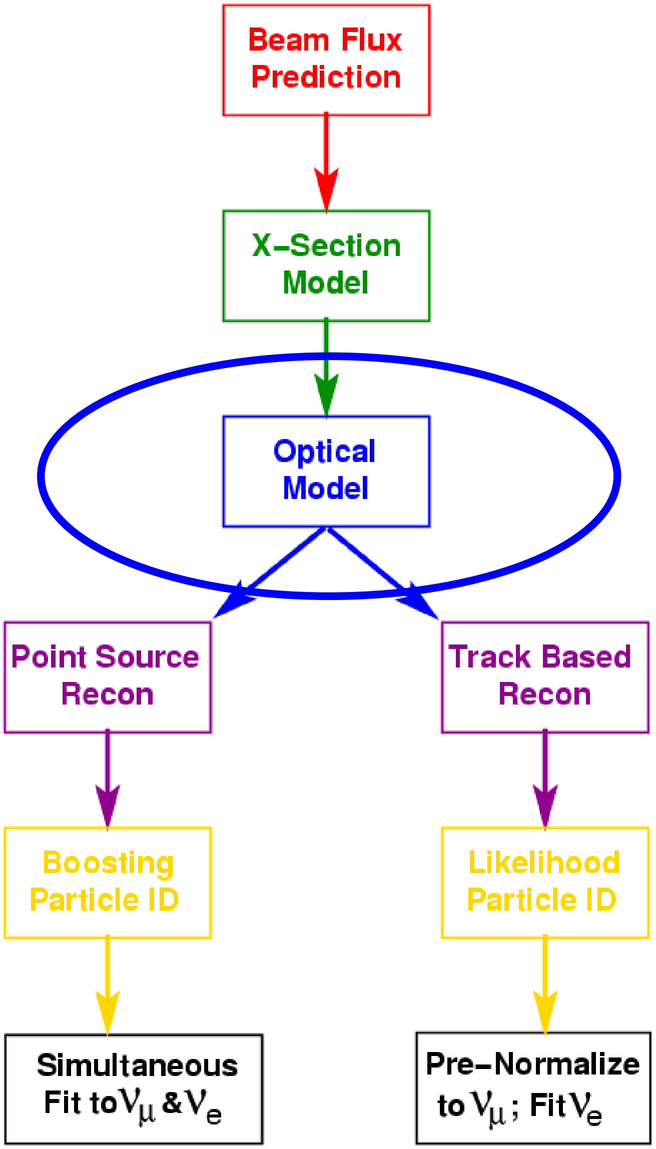




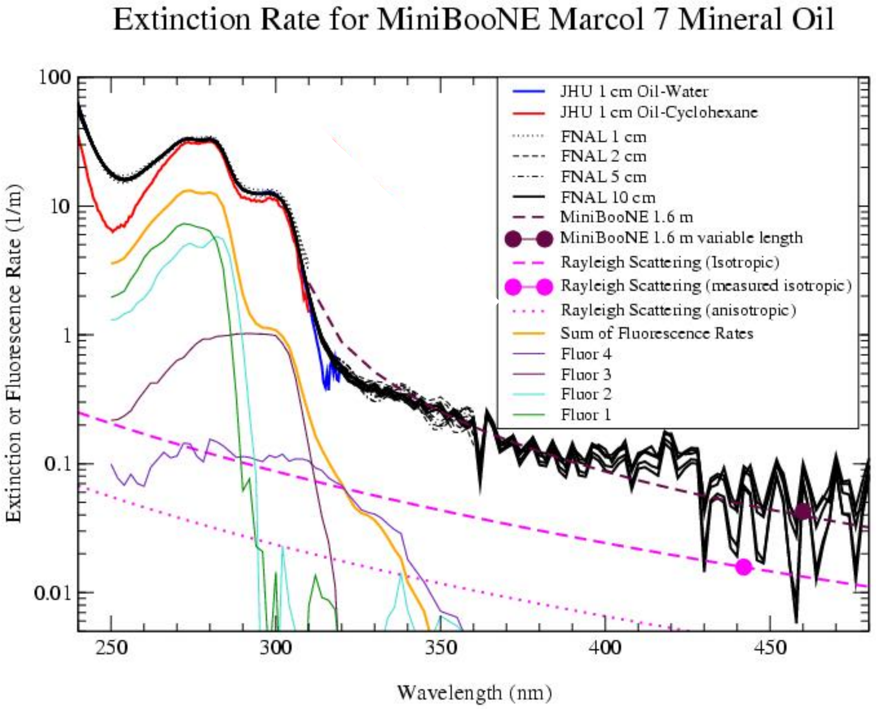


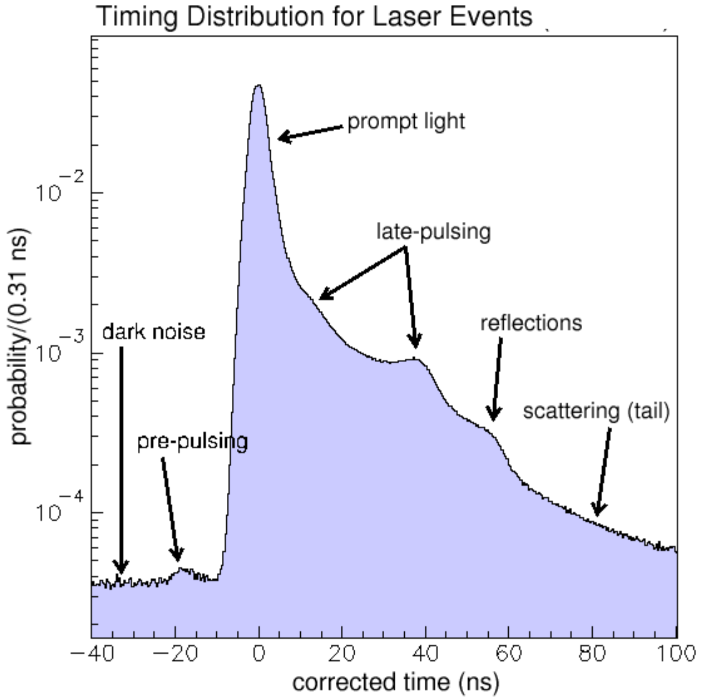


Optical Model



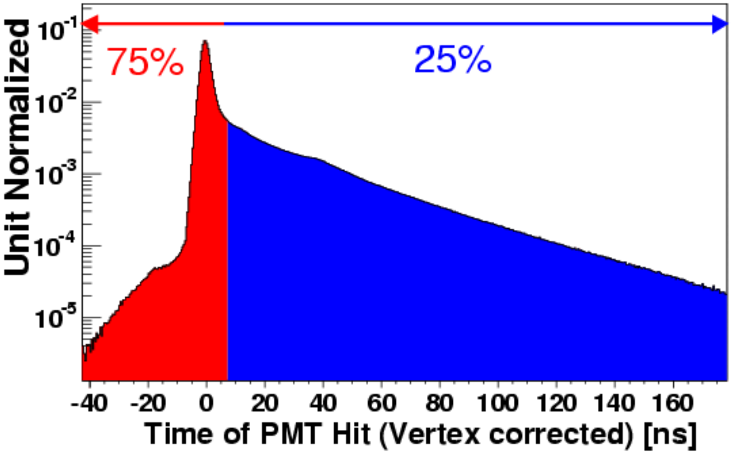
Light propagation in the detector



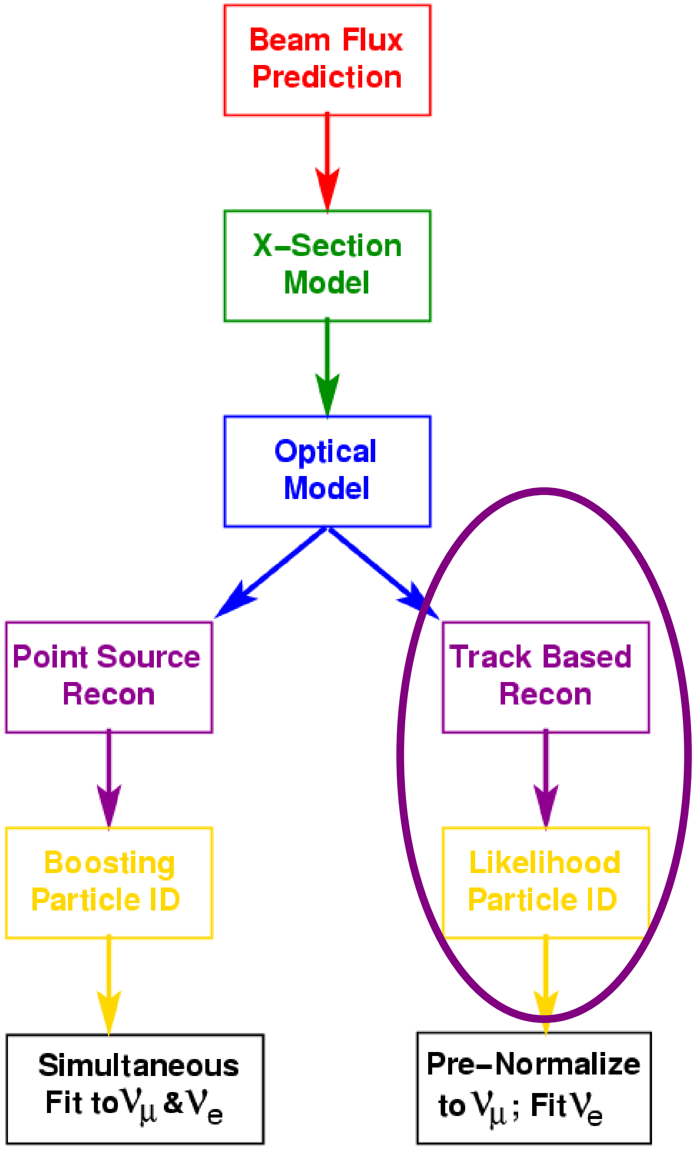


- Optical model is very complex
  - Cerenkov, scintillation, fluorescence
  - PMT Q/t response
  - Scattering, reflection, prepulses
- Overall, about 40 parameters

Michel electron t distribution

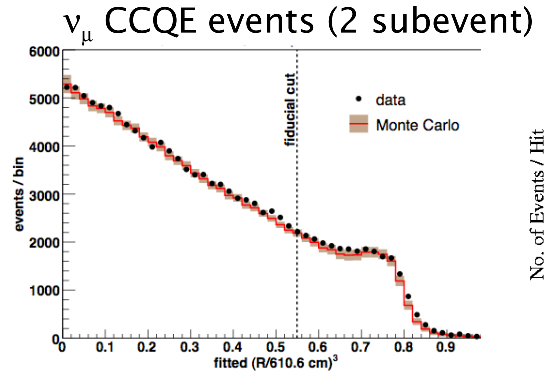


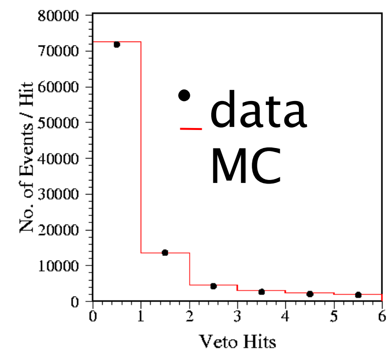
Track–Based Likelihood (TBL) Reconstruction and Particle ID

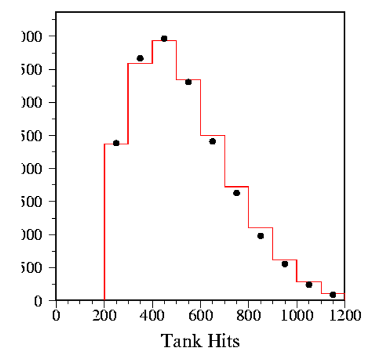


TBL Analysis: Separating e from μ

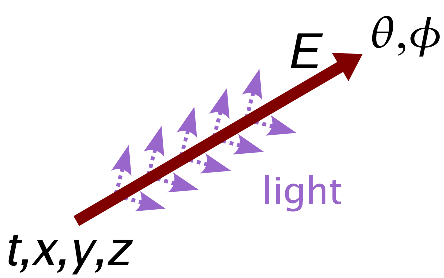
- Analysis pre-cuts
  - Only 1 subevent
  - Veto hits < 6
  - Tank hits > 200
  - Radius < 500 cm

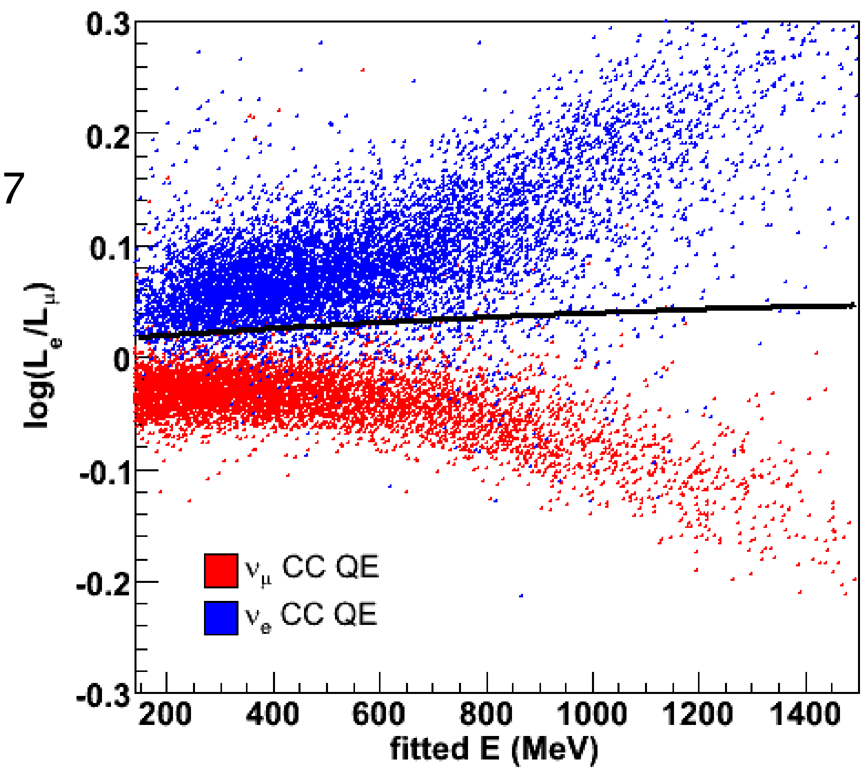






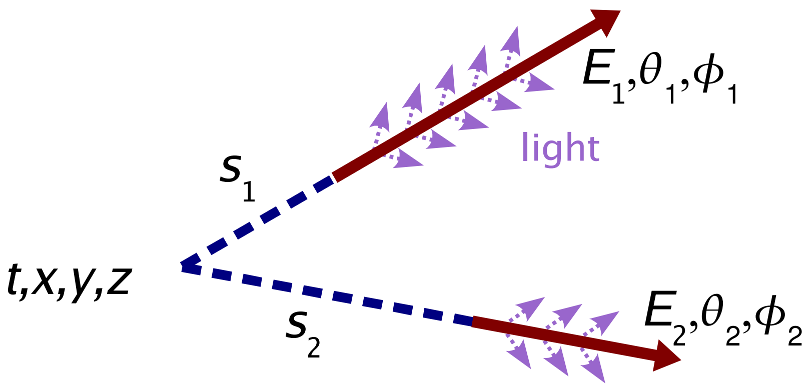
- Event is a collection of PMT-level info (q,t,x)
- Form sophisticated Q and T pdfs, and fit for 7 track parameters under 2 hypotheses
  - The track is due to an electron
  - The track is coming from a muon

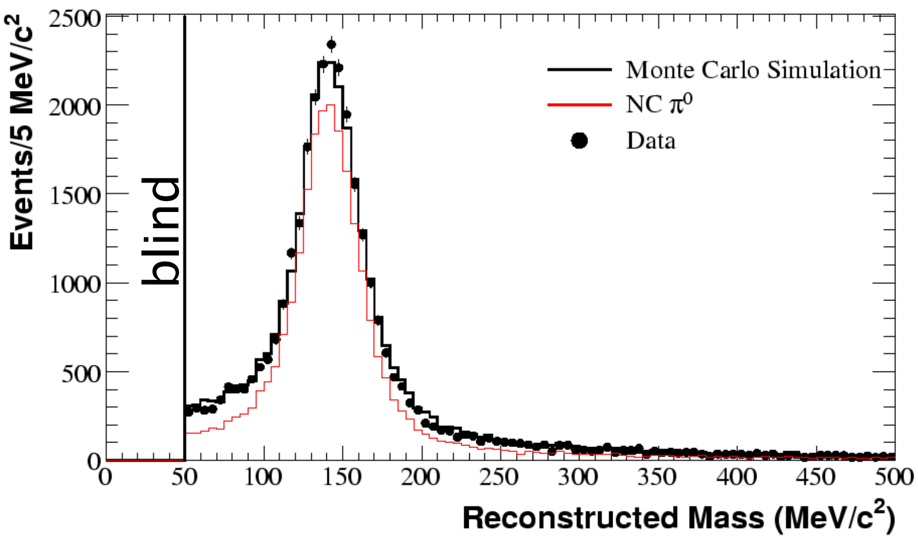


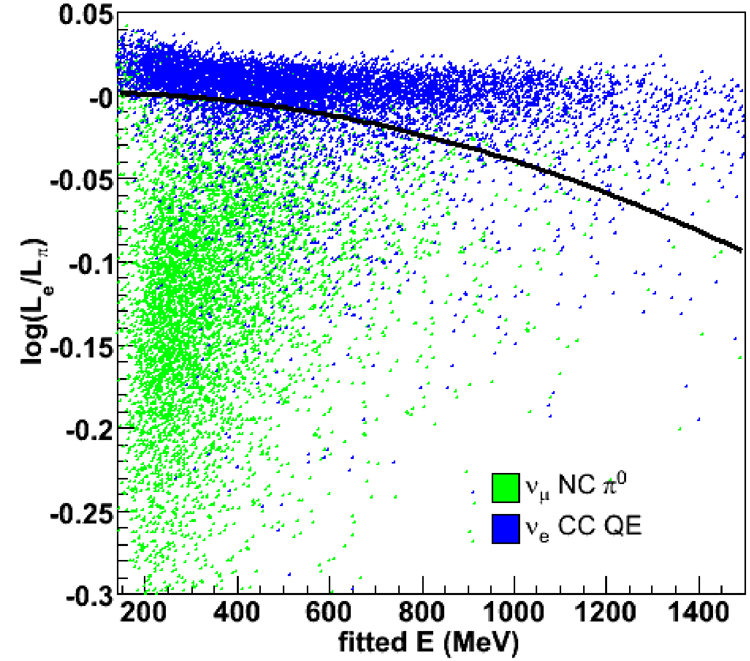


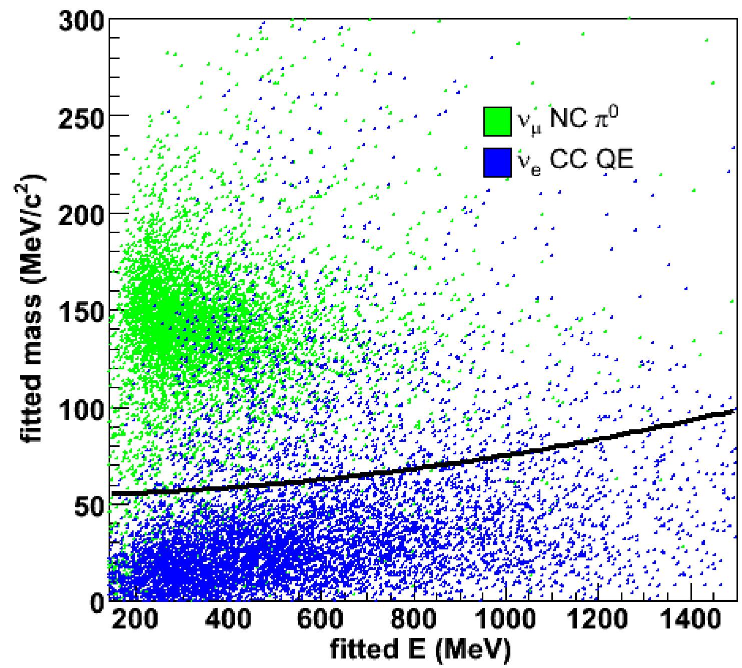
Separating e from π^0

- Extend fit to include two e-like tracks
- Very tenacious fit...5 minutes per event
- Nearly 500k CPU hours used

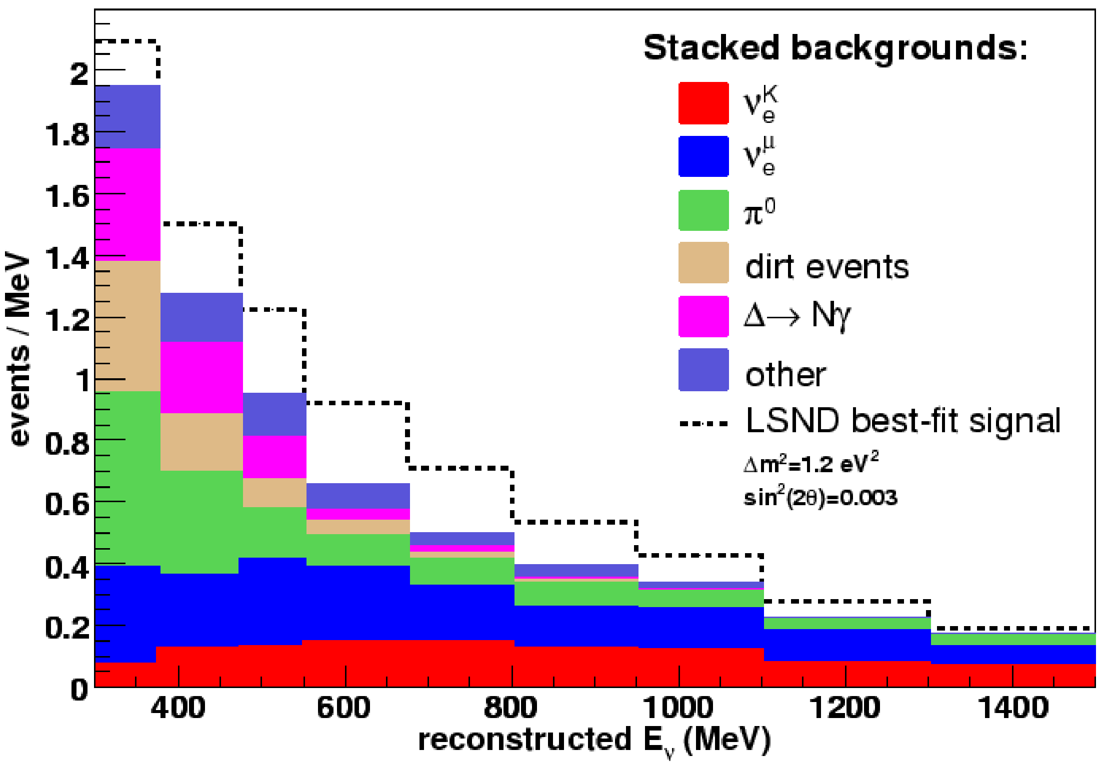








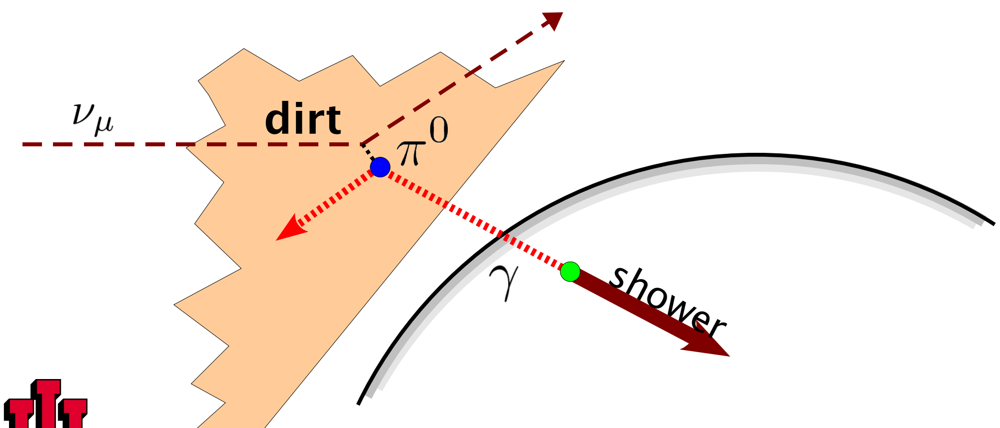
TBL Analysis: Expected event totals

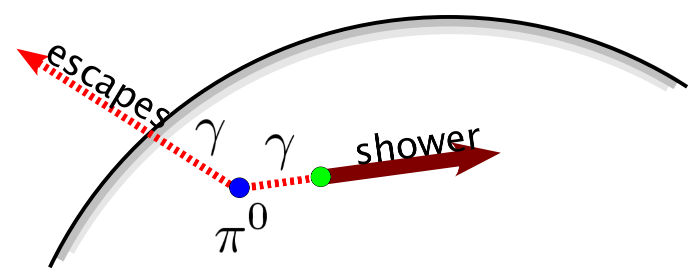


475 MeV – 1250 MeV

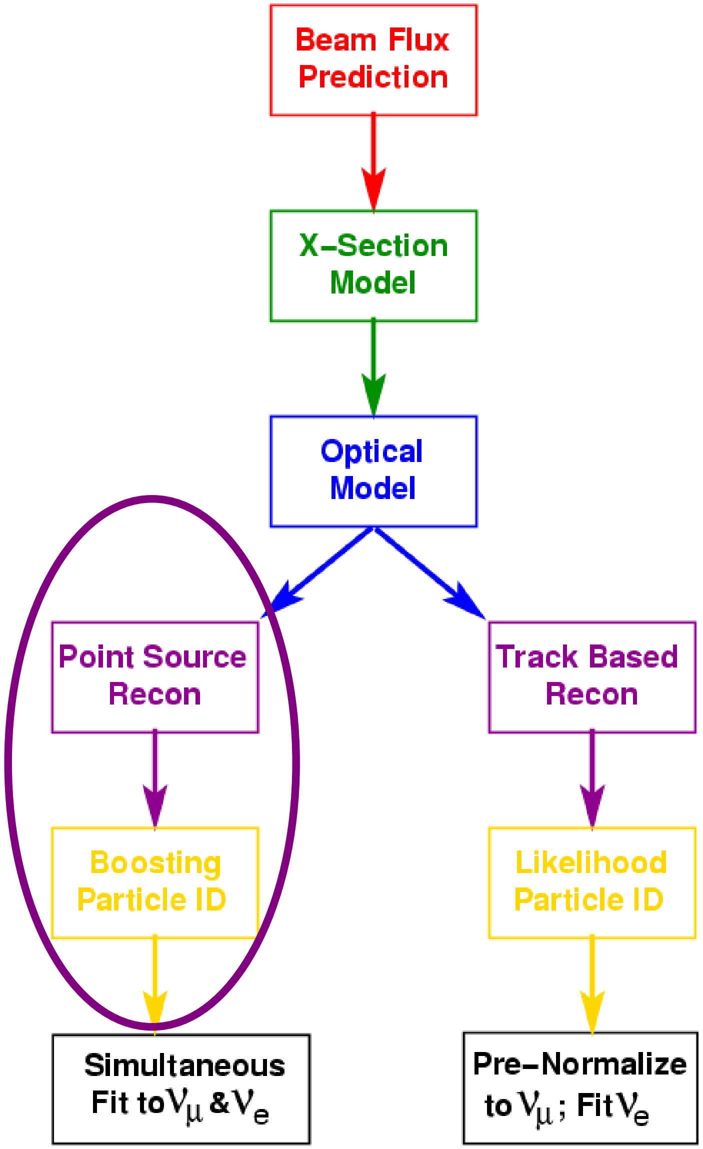
ν_e^K	94
ν_e^μ	132
π^0	62
dirt	17
$\Delta \rightarrow N\gamma$	20
other	33
total	358

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





Boosted Decision Tree (BDT) Reconstruction and Particle ID



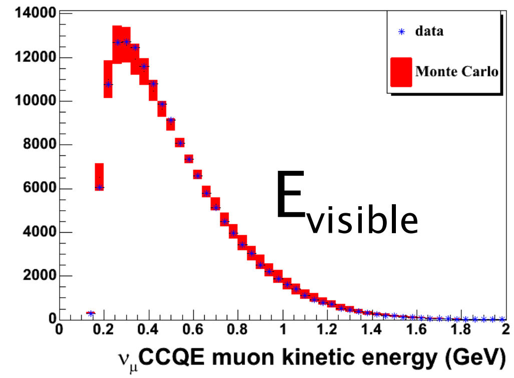
BDT Reconstruction

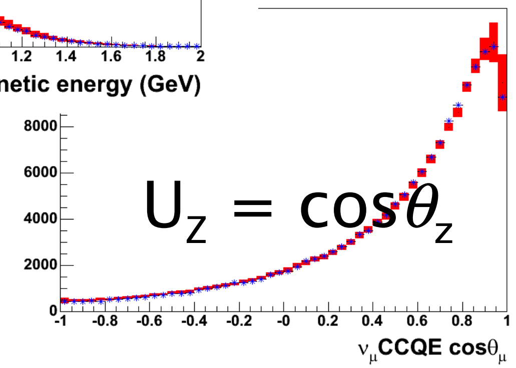
- Same pre-cuts as TBL (taking R from different reconstruction)
- Different reconstruction:
  - Treats particles more like point sources, *i.e.* not as careful about dE/dx
  - Not as tenacious about getting out of local minima, particularly with pion fit
  - Reconstruction runs nearly 10 times faster
- To make up for the simple fit, the BDT analysis relies on a form of machine learning, the boosted decision tree. Byron P. Roe, *et al.*, NIM A543 (2005) 577.
- Boosting Input Variables:
  - Low-level (# tank hits, early light fraction, etc.)
  - High-level (Q2, U_z, fit likelihoods, etc.)
  - Topology (charge in anuli, isotropic light, etc.)
- A total of 172 variables were used
- All 172 were checked for agreement within errors in 5 important 'boxes' (ν_μ CCQE, NC π^0, NC-elastic, Michel decay e, 10% closed)
- Boosting Output: Single 'score', + is signal-like

BDT Resolution:
vertex: 24 cm
direction: 3.8°
energy 14%

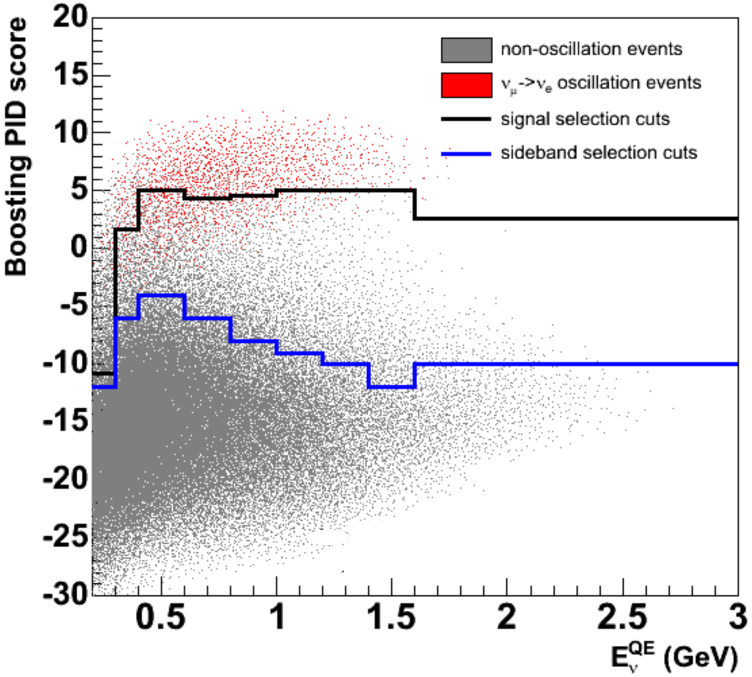
TBL Resolution:
vertex: 22 cm
direction: 2.8°
energy 11%

ν_μ CCQE Examples



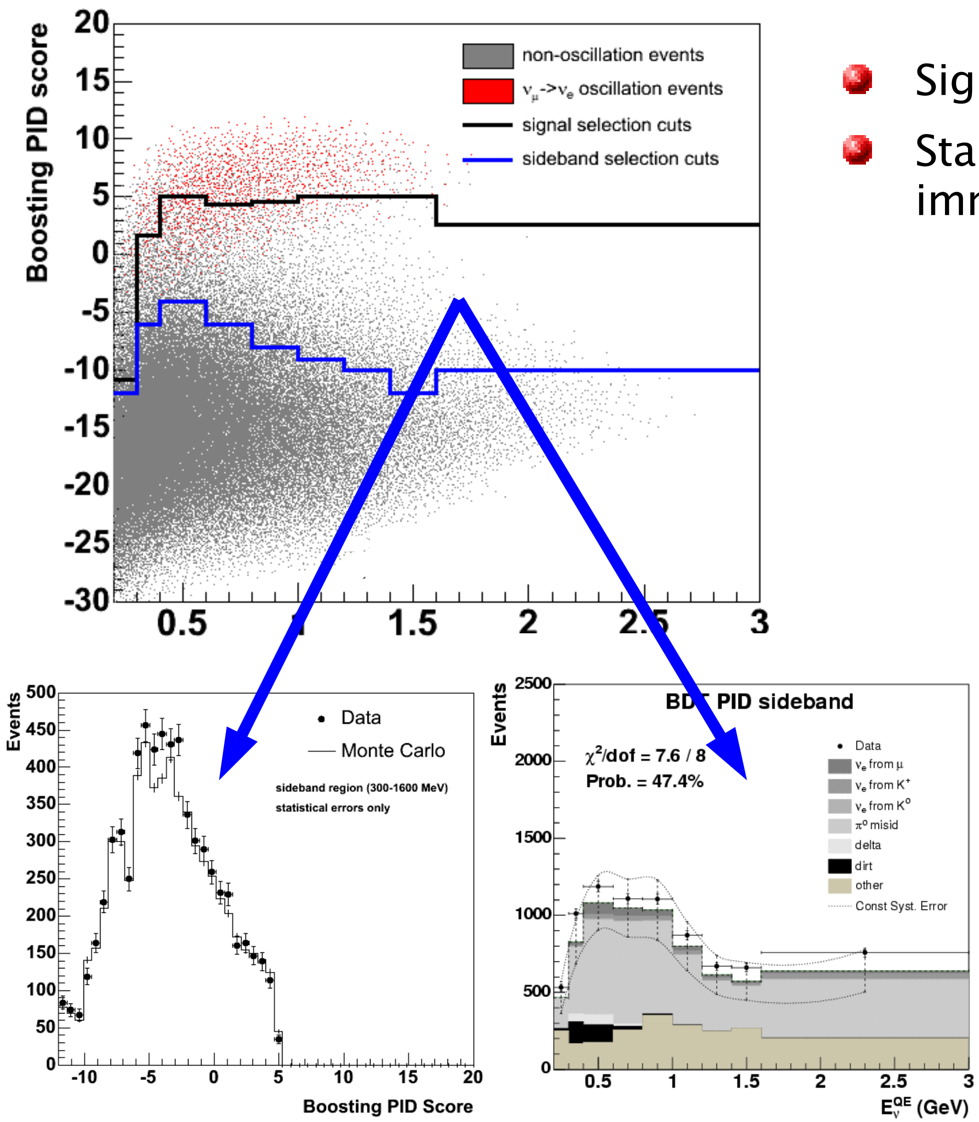


BDT Analysis: Signal/background regions



- Signal prediction (red) versus all bkgs (gray)

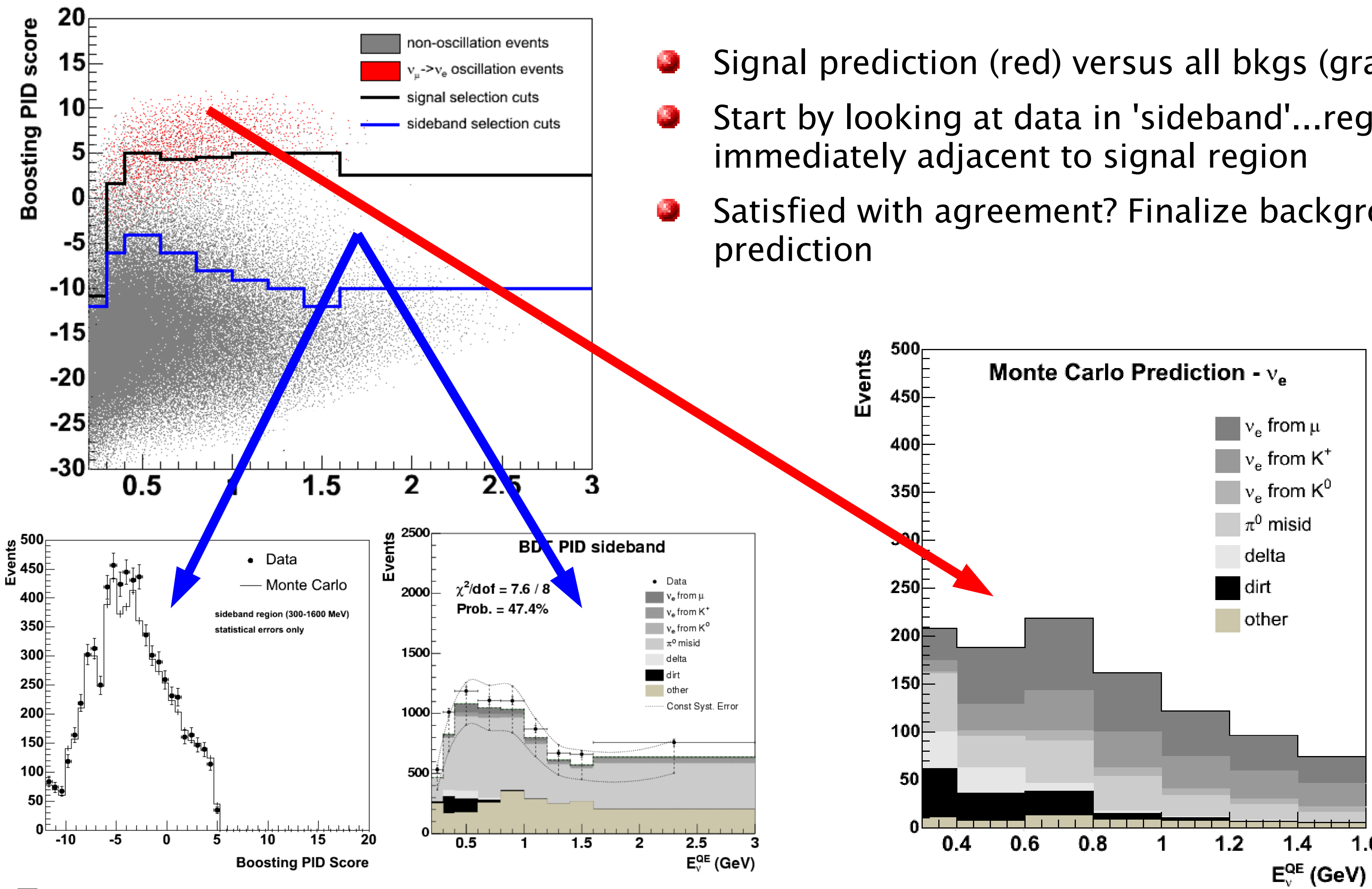
BDT Analysis: Signal/background regions



- Signal prediction (red) versus all bkgs (gray)
- Start by looking at data in 'sideband'...region immediately adjacent to signal region

BDT Analysis: Signal/background regions

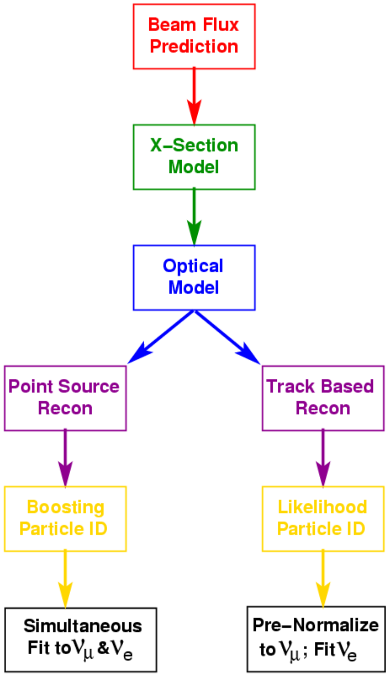
- Signal prediction (red) versus all bkgs (gray)
- Start by looking at data in 'sideband'...region immediately adjacent to signal region
- Satisfied with agreement? Finalize background prediction



Systematic Error Analysis and Results

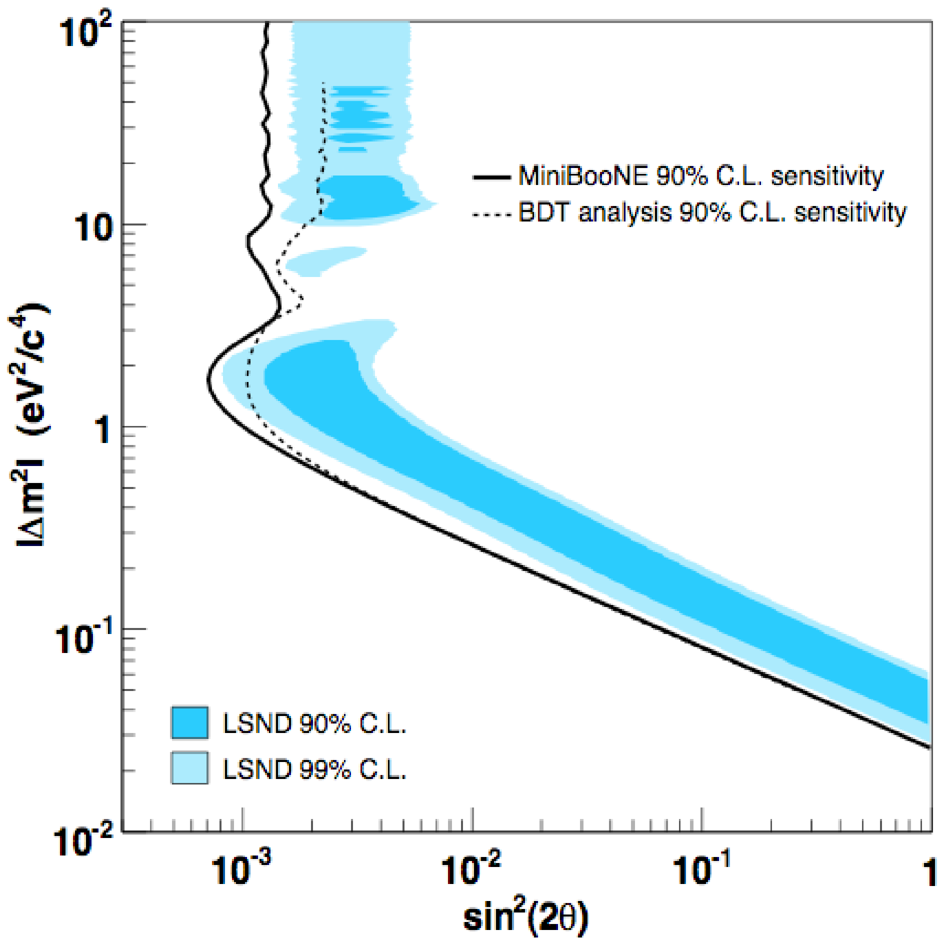
Final error budget (diagonals only...greatly simplified)

Source of uncertainty on ν_e background	TBL/BDT error in %	Constrained by MB data	Reduced by tying ν_e to ν_μ
Flux from π^+/μ^+ decay	6.2 / 4.3	√	√
Flux from K^+ decay	3.3 / 1.0	√	√
Flux from K^0 decay	1.5 / 0.4	√	√
Target/beam models	2.8 / 1.3	√	
ν–cross section	12.3 / 10.5	√	√
NC π^0 yield	1.8 / 1.5	√	
Dirt interactions	0.8 / 3.4	√	
Optical model	6.1 / 10.5	√	√
DAQ electronics model	7.5 / 10.8	√	



- Every checkmark in this table could easily consume a 30 minute talk
  - All error sources had some *in situ* constraint
  - Some reduced by combined fit to ν_μ and ν_e
- Errors arise from common uncertainties in flux, xsec, and optical model
- Reconstruction and PID unique
  - BDT had higher signal–to–background
  - TBL more impervious to systematics
  - About 50% event overlap

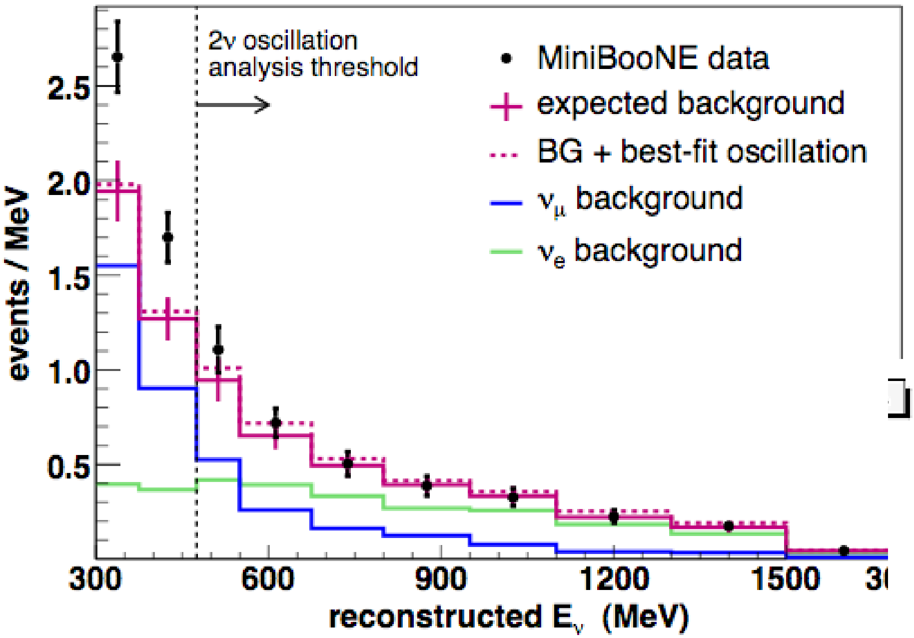
BDT/TBL sensitivity comparison



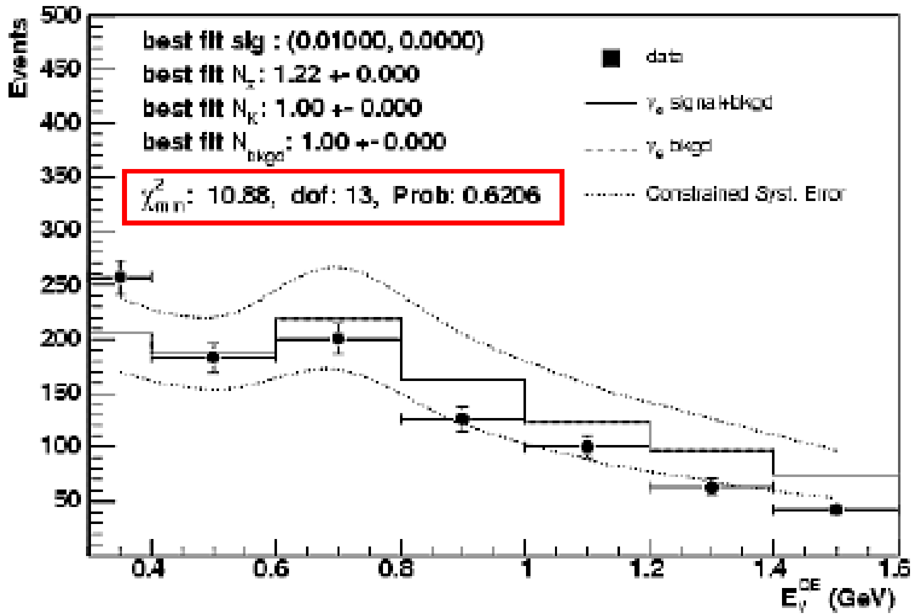
- Sensitivity is determined from simulation only (no data yet!)
- Decided before unblinding that the analysis with higher sensitivity would be the final analysis
- TBL (solid) is better at high Δm^2
- 90% CL defined by $\Delta\chi^2 = 1.64$

After many man-years and CPU-hours...

Finally we see the data in the signal region...



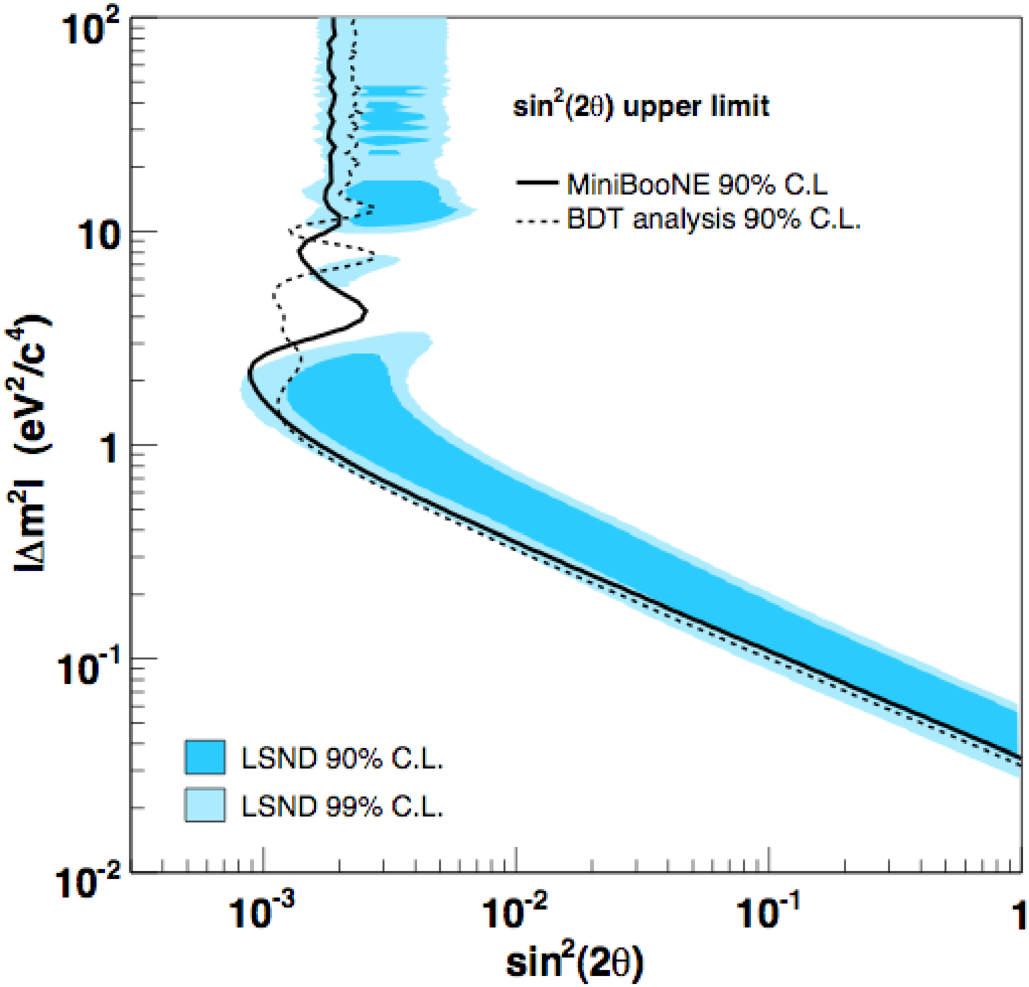
- TBL shows no sign of an excess in the analysis region (where the LSND signal is expected for the 2ν mixing hypothesis)
- Visible excess at low E



- BDT has a good fit and no sign of an excess, in fact the data is low relative to the prediction
- Also sees an excess at low E, but larger normalization error complicates interpretation

Neither analysis shows an evidence for $\nu_\mu \rightarrow \nu_e$ appearance in the analysis region

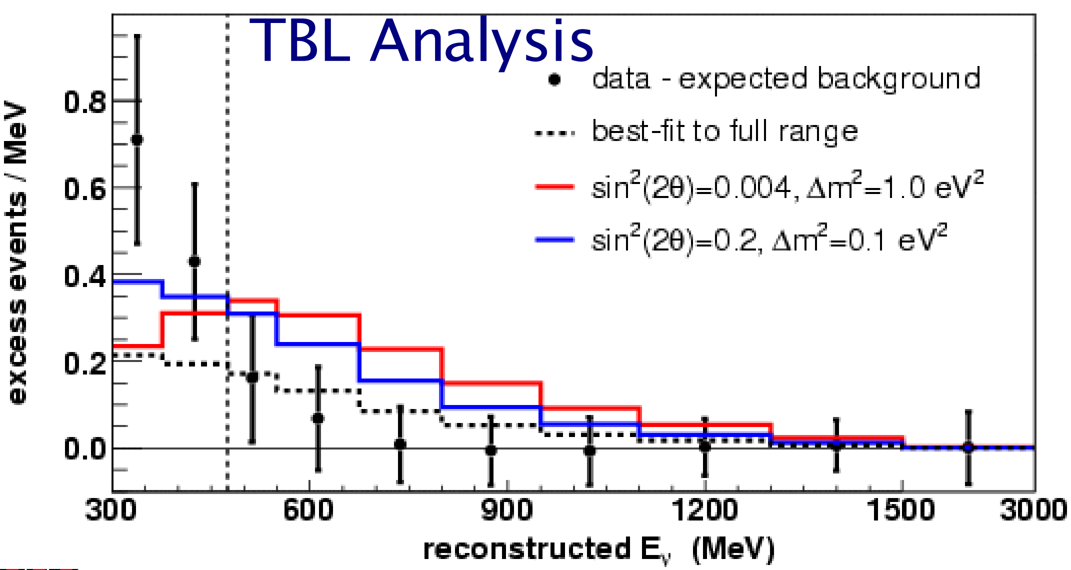
Fit results mapped into $\sin^2(2\theta)$ Δm^2 plane



- Energy–fit analysis:
  - solid: TBL
  - dashed: BDT
- Independent analyses in good agreement
- Looks similar to sensitivity because of the lack of a signal
- Had there been a signal, these curves would have curled around and closed into contours
- Possible outs for LSND?
  - CP violation, ν not the same as anti–ν?
  - LSND signal is not due to physics that scales as L/E?
  - Is the excess at low E in MB telling us something?

Future work for MiniBooNE

- Papers in support of this analysis
  - NC π^0 background measurement
  - ν_μ CCQE analysis
- Continued improvements of the ν oscillation analysis
  - Combined BDT and TBL
  - More work on reducing systematics
- Re-examine low E backgrounds and significance of low E excess



- Lots of work on cross-sections
- MB has more ν_μ interactions than prior experiments in an energy range useful to future ν expts.
- Event counts before cuts:

ν channel	events
all channels	810k
CC quasielastic	340k
NC elastic	150k
CC π^+	180k
CC π^0	30k
NC π^0	48k
NC $\pi^{+/-}$	27k
CC/NC DIS, multi-π	35k

6×10^{20} POT
ν mode

$\bar{\nu}$ channel	events
all channels	54k
CC quasielastic	24k
NC elastic	10k
CC π^-	8.9k
CC π^0	1.7k
NC π^0	4.9k
NC $\pi^{+/-}$	1.8k
CC/NC DIS, multi-π	1.9k

2×10^{20} POT
$\bar{\nu}$ mode

- Currently running in anti-ν mode for anti-ν cross sections

Backup Slides

Update on the low E excess...

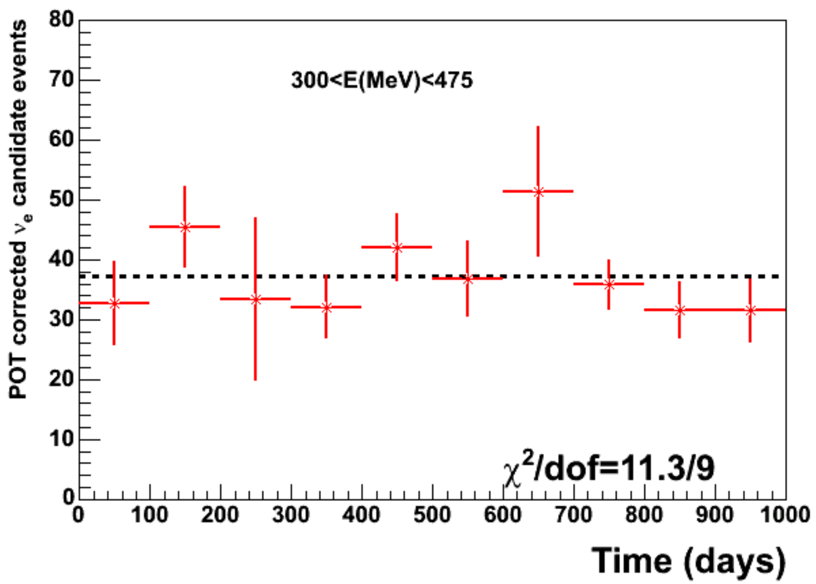
No Detector anomalies found

– Example: rate of electron candidate events is constant (within errors) over course of run

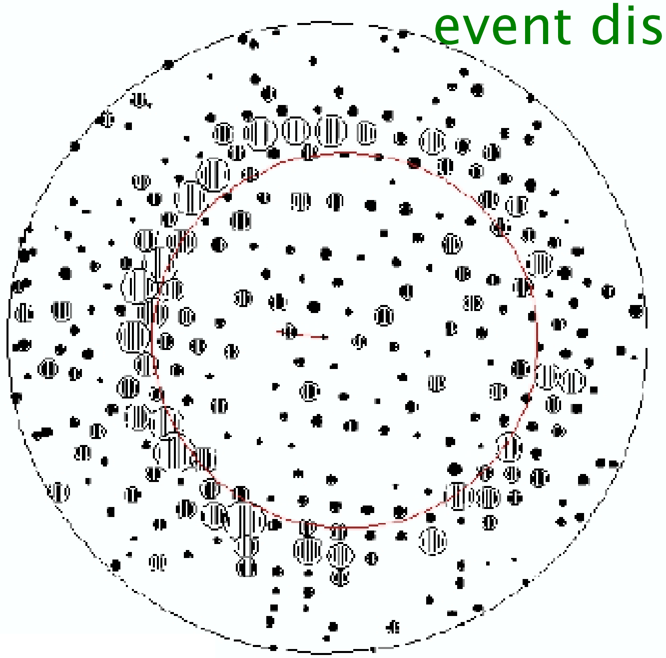
No Reconstruction problems found

– All low-E electron candidate events have been examined via event displays, consistent with 1-ring events

event/POT vs day, 300<Enu<475 MeV



example signal-candidate event display

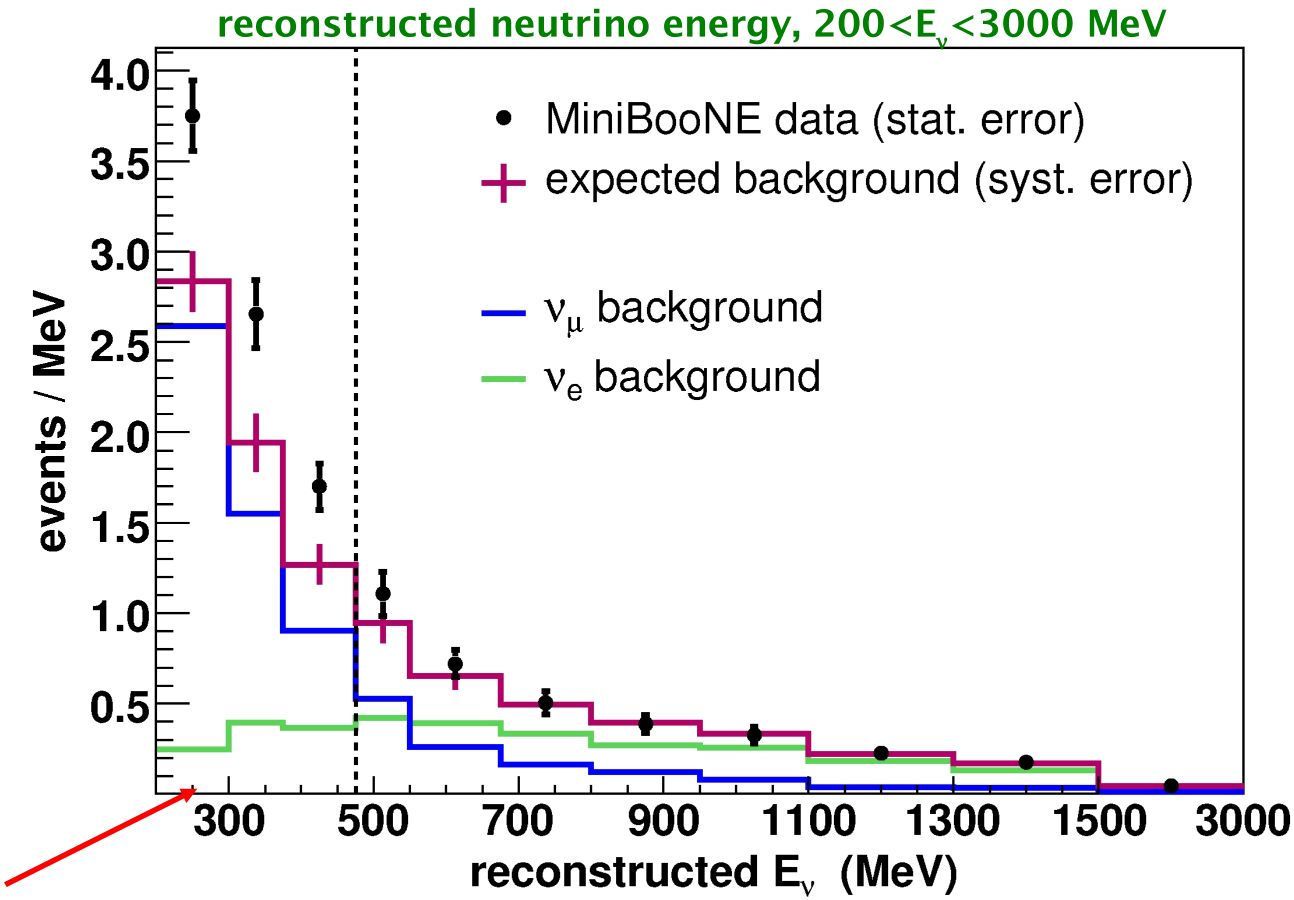


Signal candidate events are consistent with single-ring neutrino interactions

– But could be either electrons or photons

Update on the low E excess...

Excess persists below 300 MeV but background is also rising



New low energy bin

Update on the low E excess…

E_ν^{QE} [MeV]	200-300	300-475	475-1250	
total background	284±25	274±21	358±35	(syst. error)
ν_e intrinsic	26	67	229	
ν_μ induced	258	207	129	
NC π^0	115	76	62	
NC $\Delta \rightarrow N\gamma$	20	51	20	
Dirt	99	50	17	
other	24	30	30	
Data	375±19	369±19	380±19	(stat. error)
Data-MC	91±31	95±28	22±40	(stat+syst)

200-300 MeV:

- NC π^0 largest
- Dirt background significant
- NC $\Delta \rightarrow N\gamma$ falling off
- Intrinsic ν_e negligible

300-475 MeV:

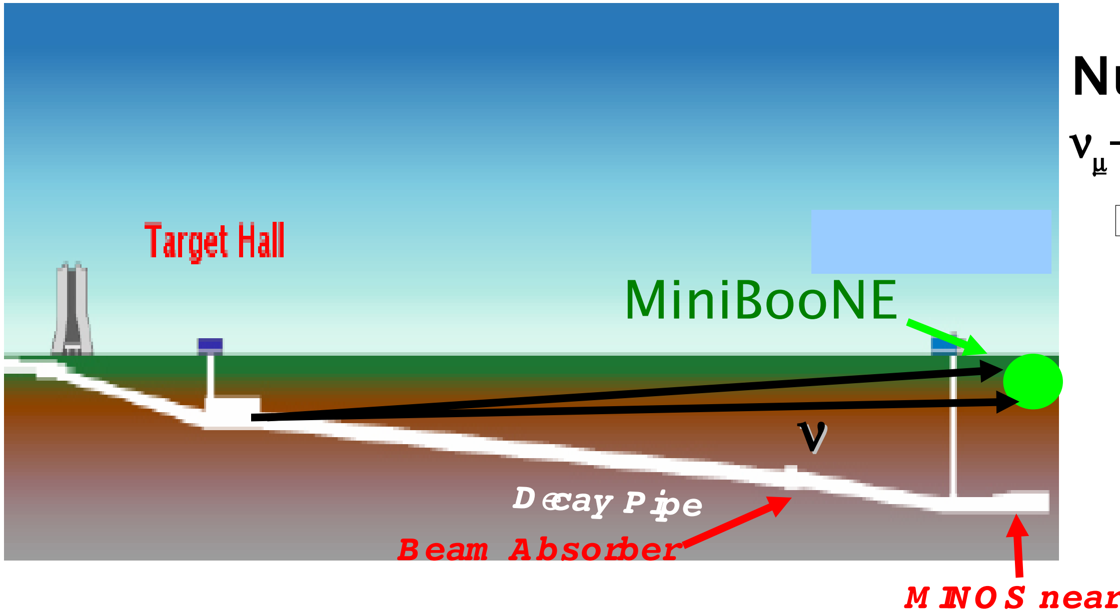
- Three main:
  - NC π^0
  - Dirt bkgnd
  - NC $\Delta \rightarrow N\gamma$
- Intrinsic ν_e small

475-1250 MeV:

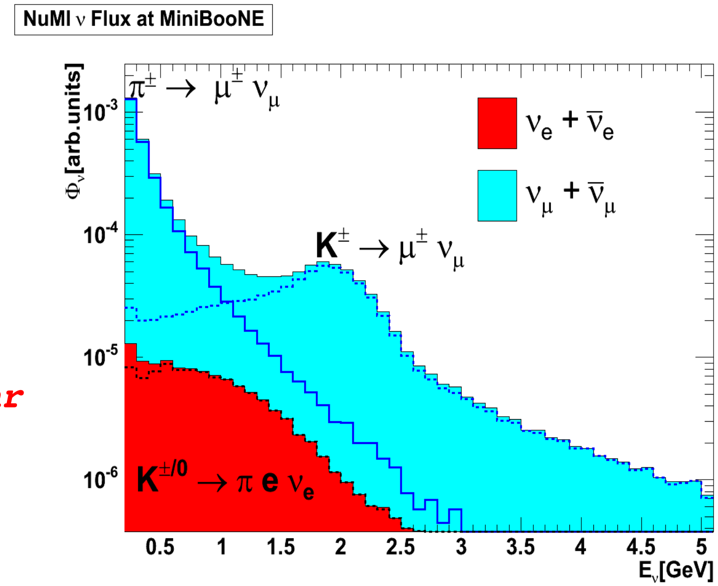
- Intrinsic ν_e largest
- NC π^0 significant
- Others small

★ Systematics/backgrounds at low E still under study…

NuMI neutrinos in the MB detector...

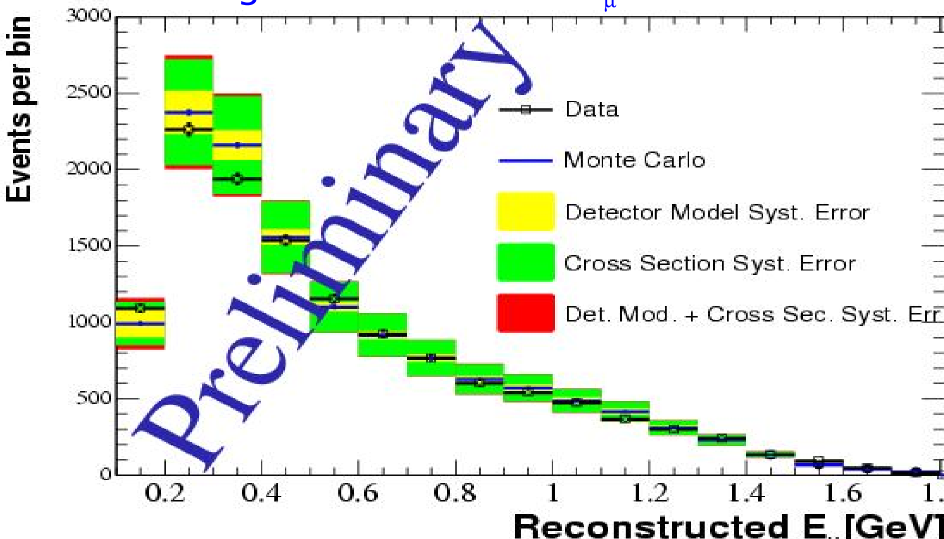


NuMI event composition:
ν_μ–81%, ν_e–5%, $\bar{\nu}_\mu$–13%, $\bar{\nu}_e$–1%

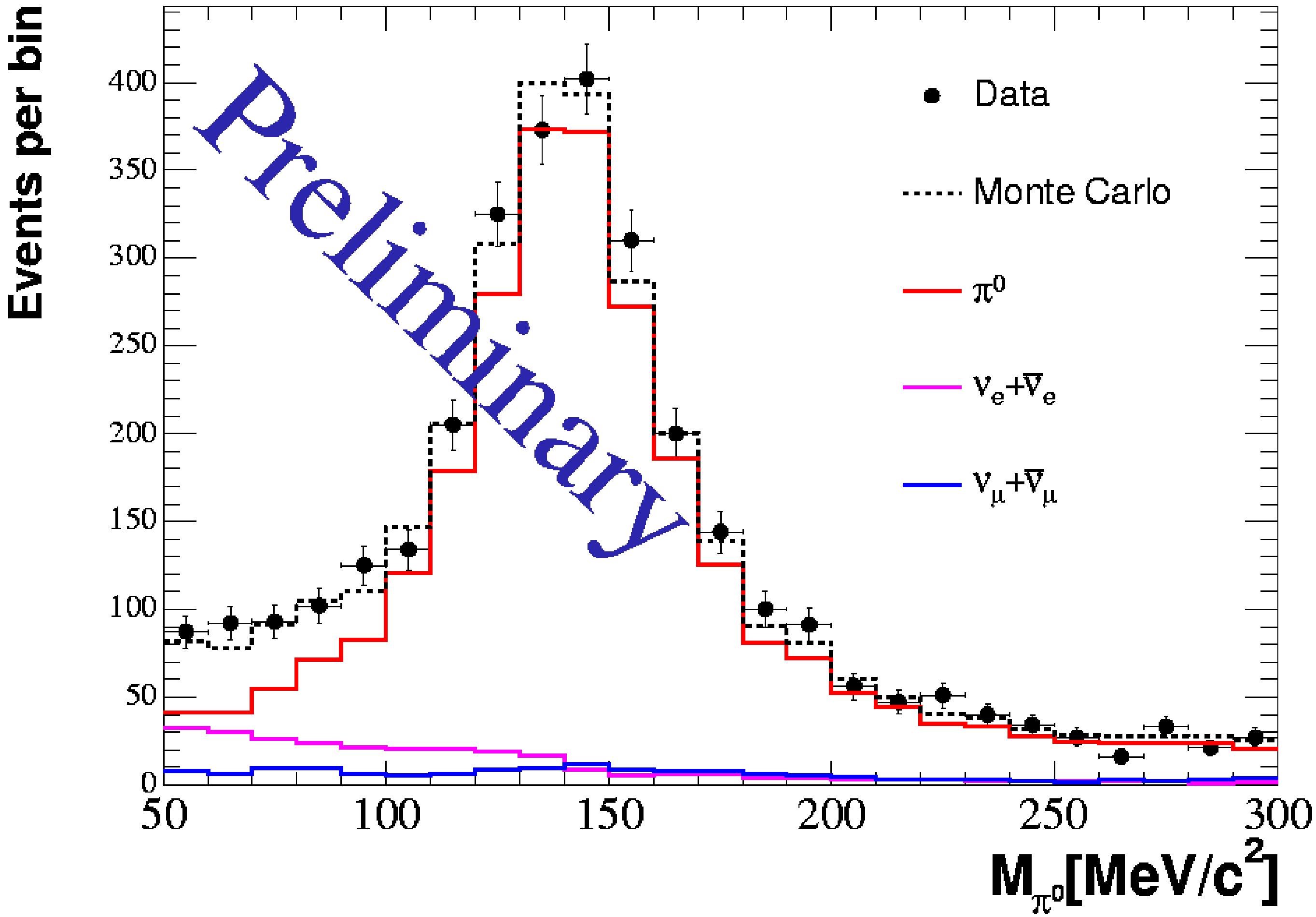


The beam at MiniBooNE from NuMI is significantly enhanced in ν_e from K decay because of the off-axis position.

Data vs MC Agreement for NuMI ν_μ events in MiniBooNE

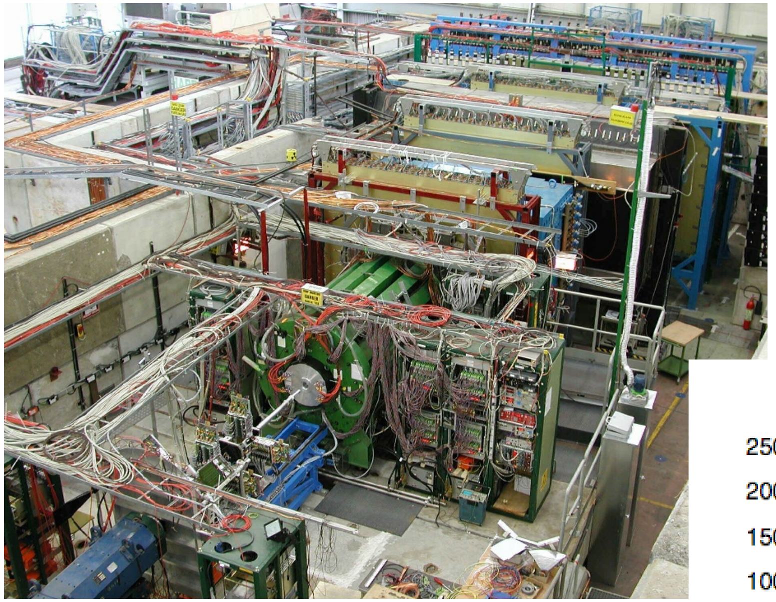


Analysis of π^0 events from NuMI beam

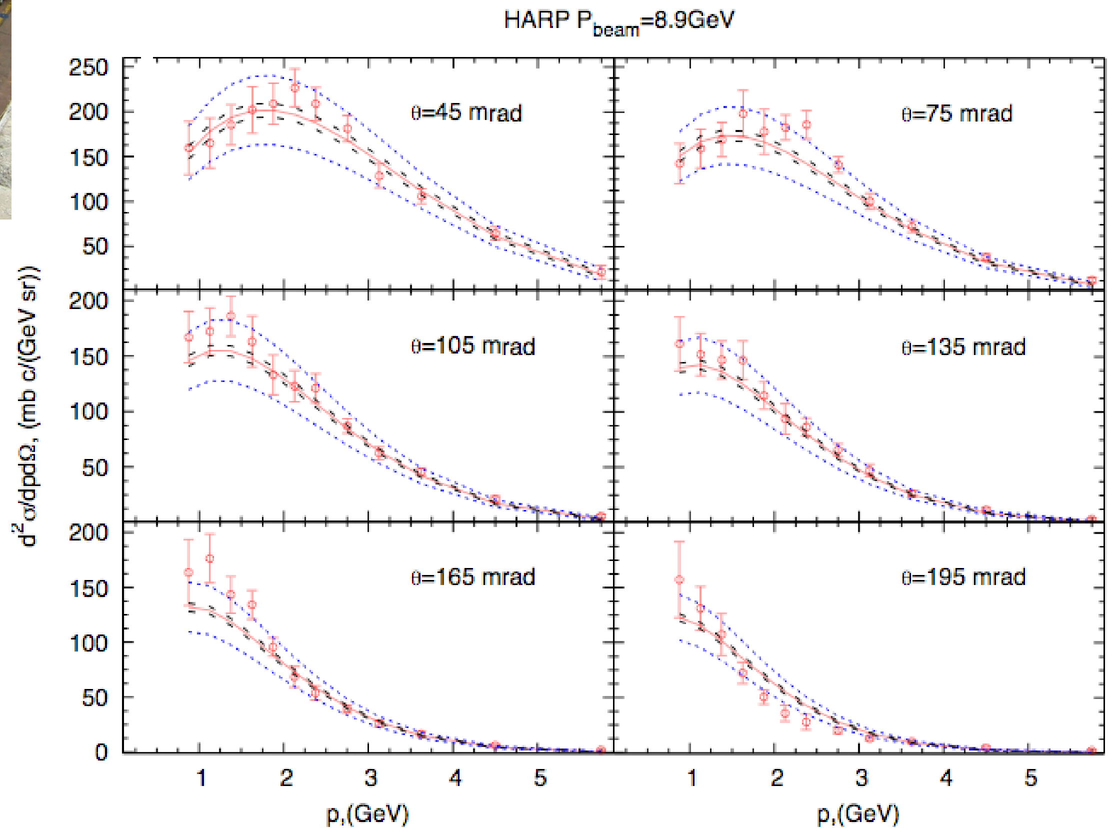


- Good data/MC agreement for π^0 events
- Ready to finalize background predictions/systematics
- Final step: Look for ν_e oscillation or excess

Modeling pion production



- HARP (CERN)
  - 5% λ Beryllium target
  - 8.9 GeV proton beam momentum



Data are fit to a Sanford-Wang parameterization.

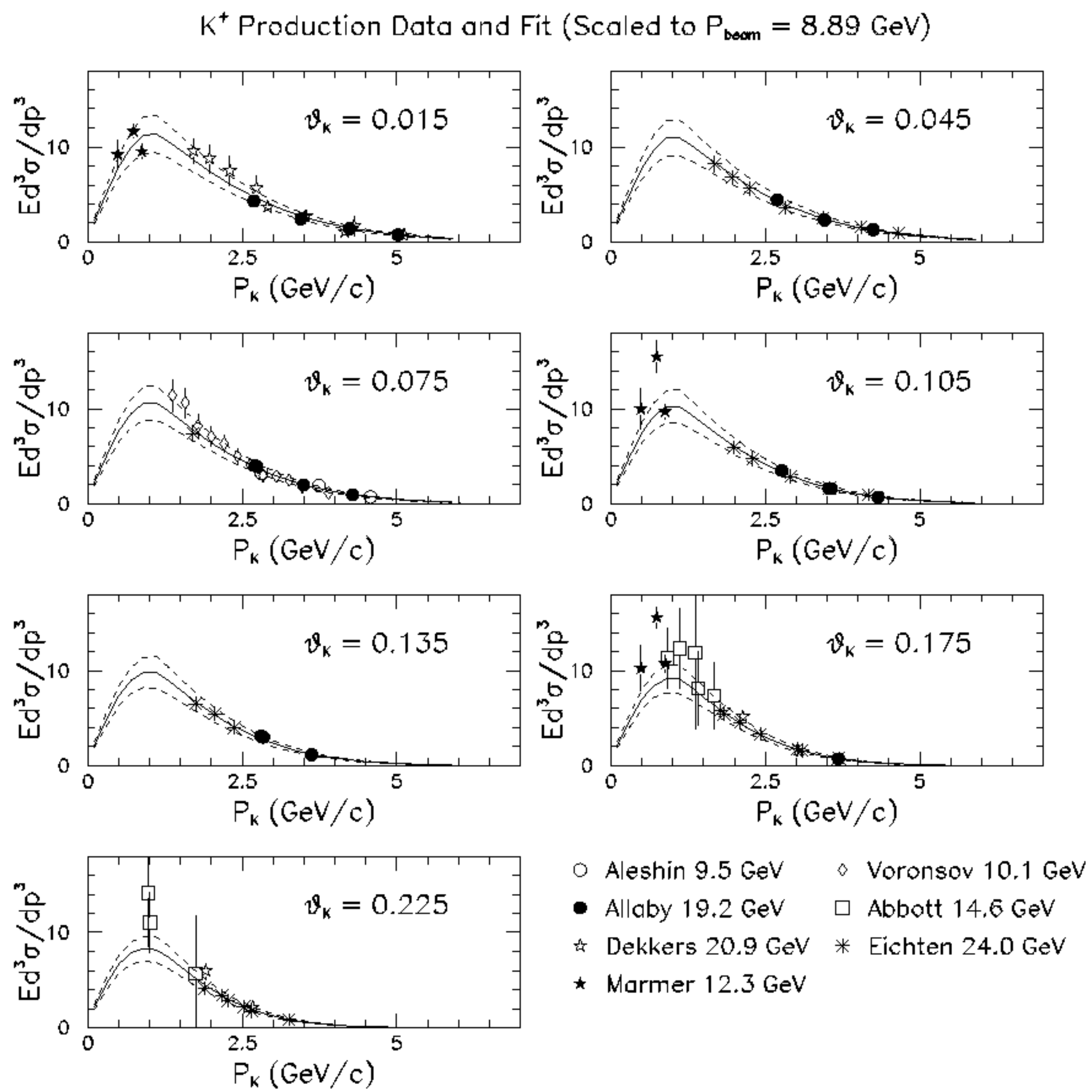
HARP collaboration, hep-ex/0702024

Modeling kaon production

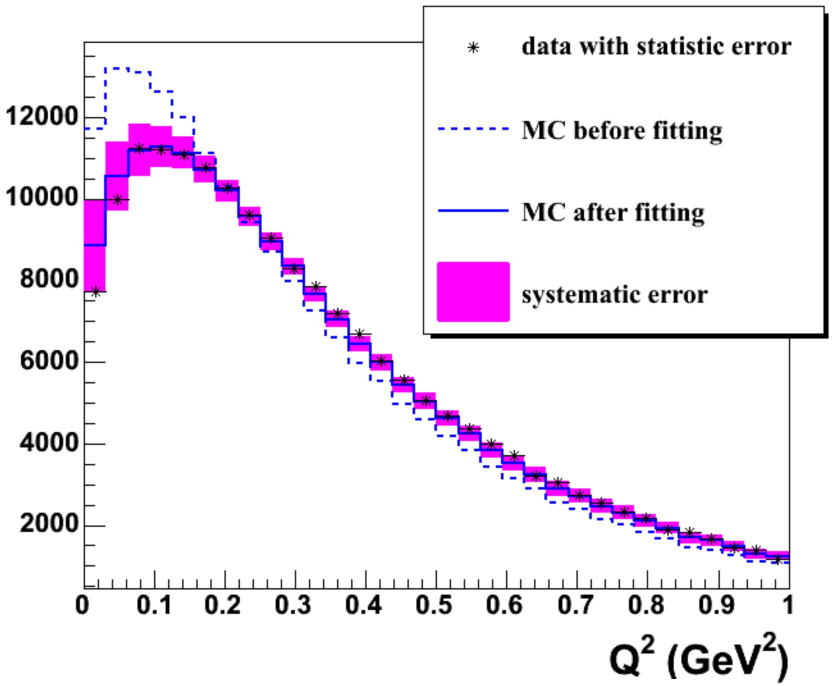
K^+ Data from 10 – 24 GeV.
uses a Feynman scaling parameterization.

data -- points
dash --total error
(fit ⊕ parameterization)

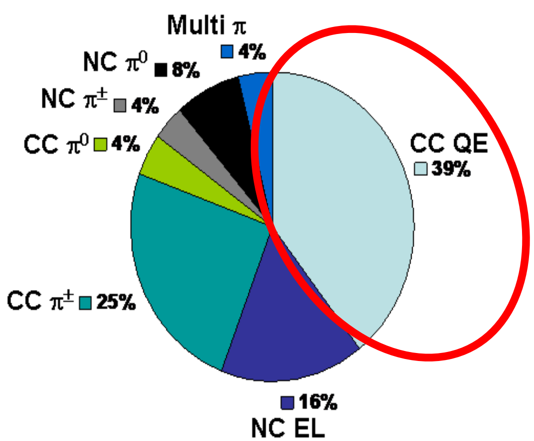
K^0 data are also parameterized.

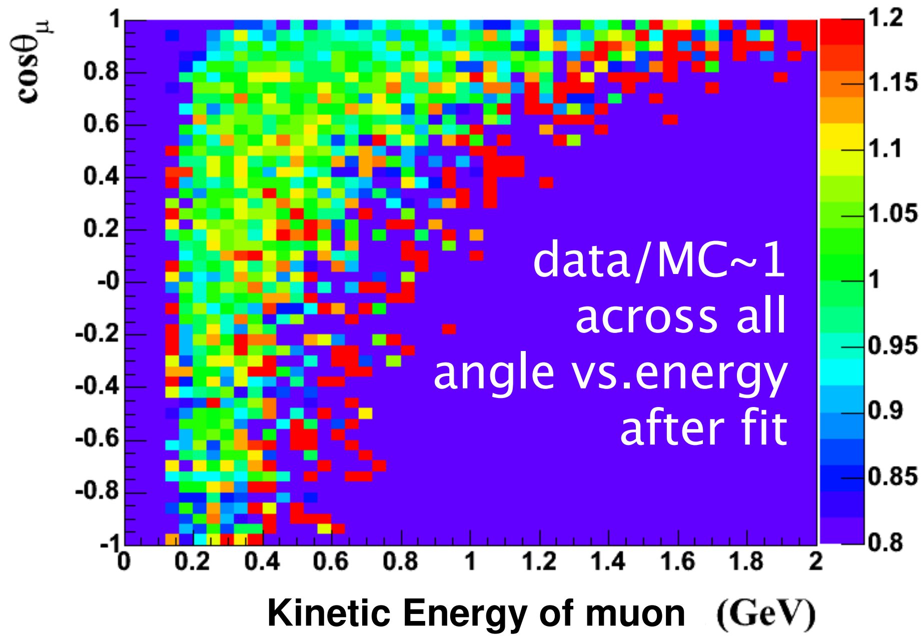


Tuning Nuance on internal ν_μ CCQE data



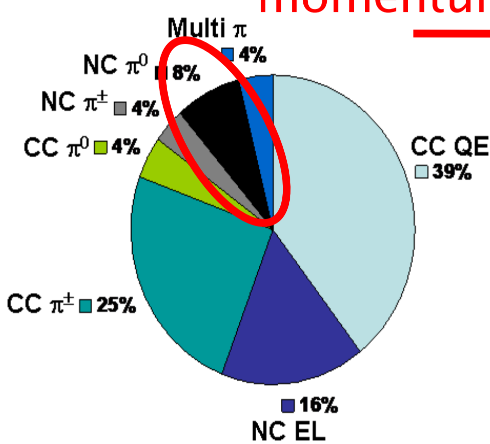
- From Q^2 fits to MB ν_μ CCQE data:
  - M_A^{eff} -- effective axial mass
  - E_{lo}^{SF} -- Pauli Blocking parameter
- From electron scattering data:
  - E_b -- binding energy
  - p_f -- Fermi momentum
- Model describes CCQE ν_μ data well



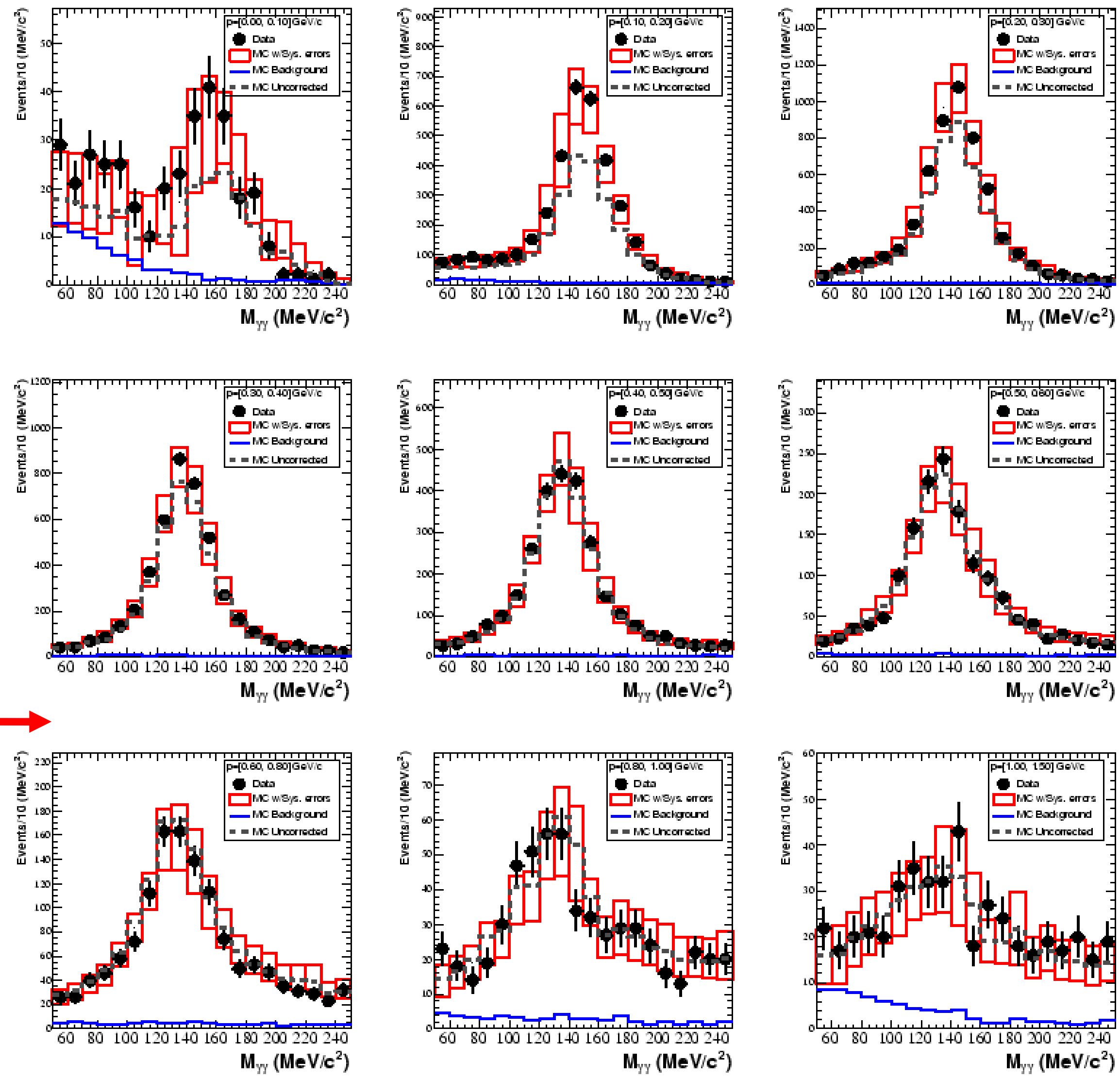


Tuning Nuance on internal NC π^0 data

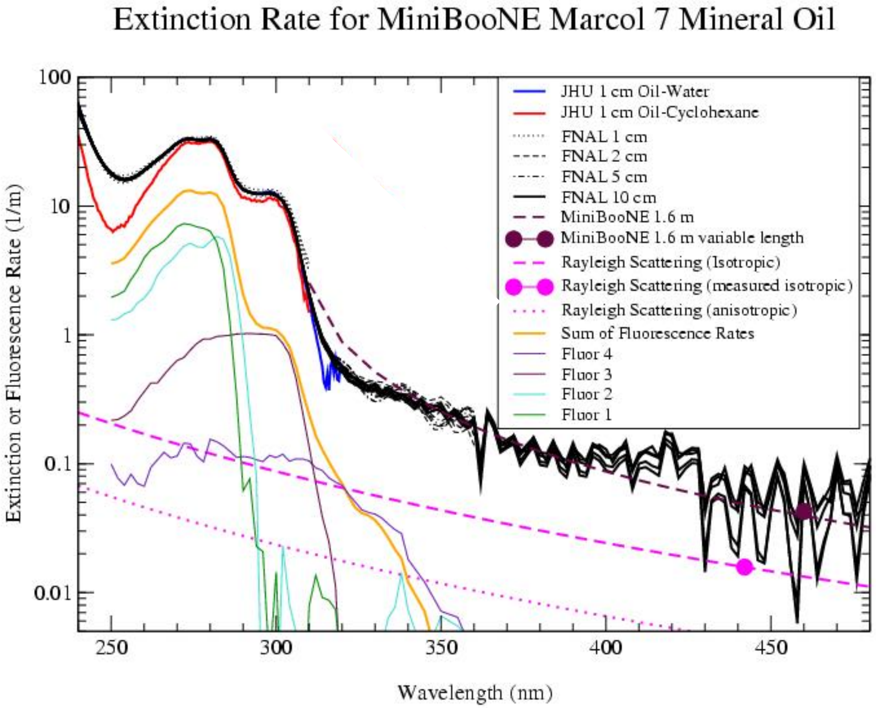
- 90%+ pure π^0 sample (mainly $\Delta \rightarrow N\pi^0$)
- Measure rate as function of momentum
- Default MC underpredicts rate at low momentum
- analysis reaches 1.5 GeV
- $\Delta \rightarrow N\gamma$ also constrained (though to a lesser extent)

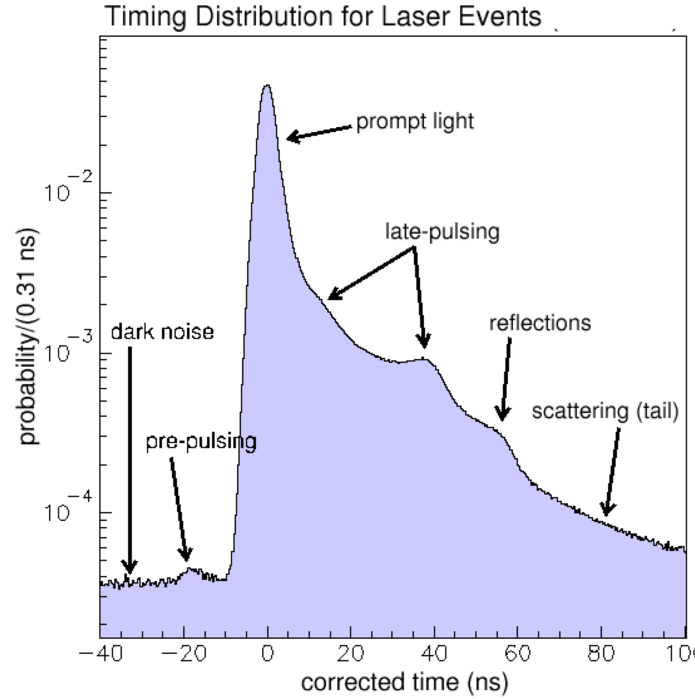


Invariant mass distributions in momentum bins

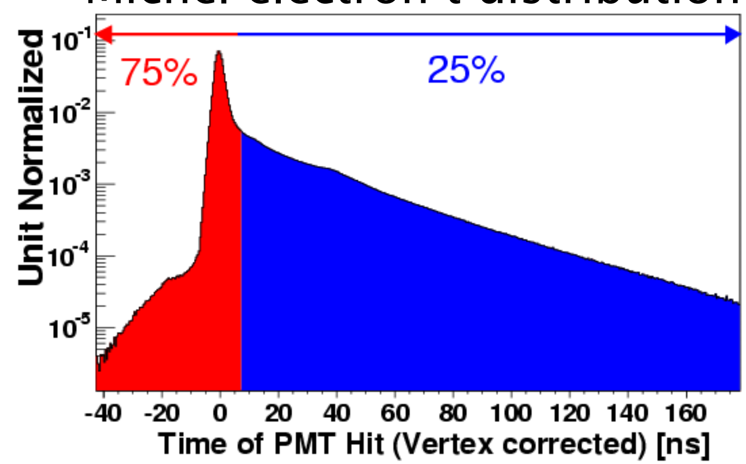


Light propagation in the detector





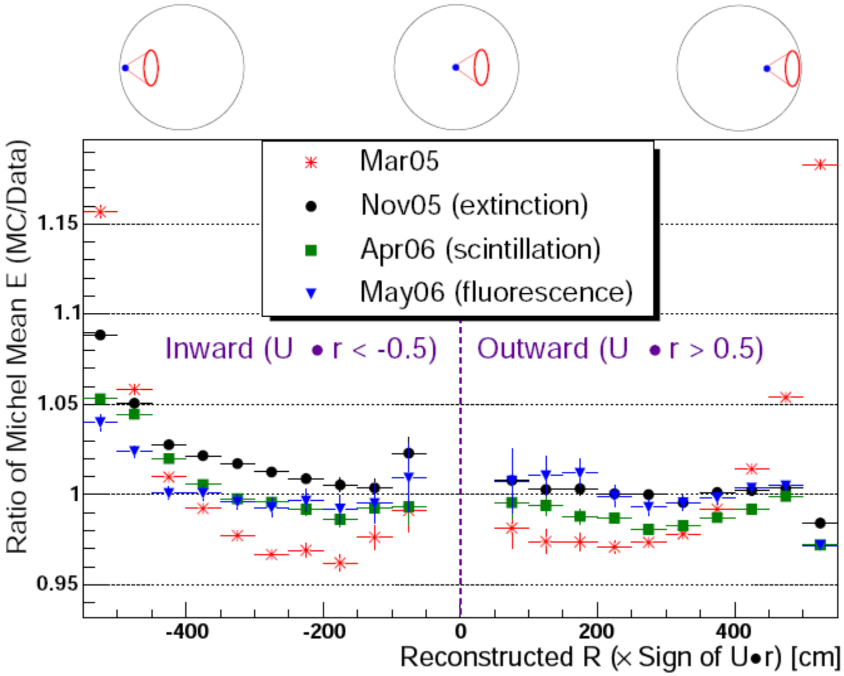
Michel electron t distribution



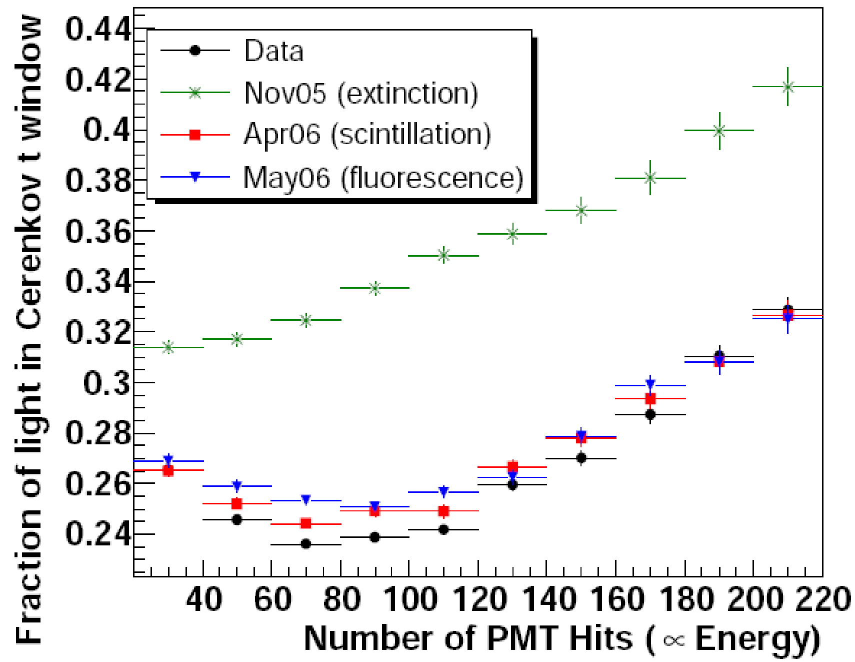
- Optical model is very complex
  - Cerenkov, scintillation, fluorescence
  - PMT Q/t response
  - Scattering, reflection, prepulses
- Overall, about 40 non-trivial parameters

Tuning the optical model

Using Michel electrons…

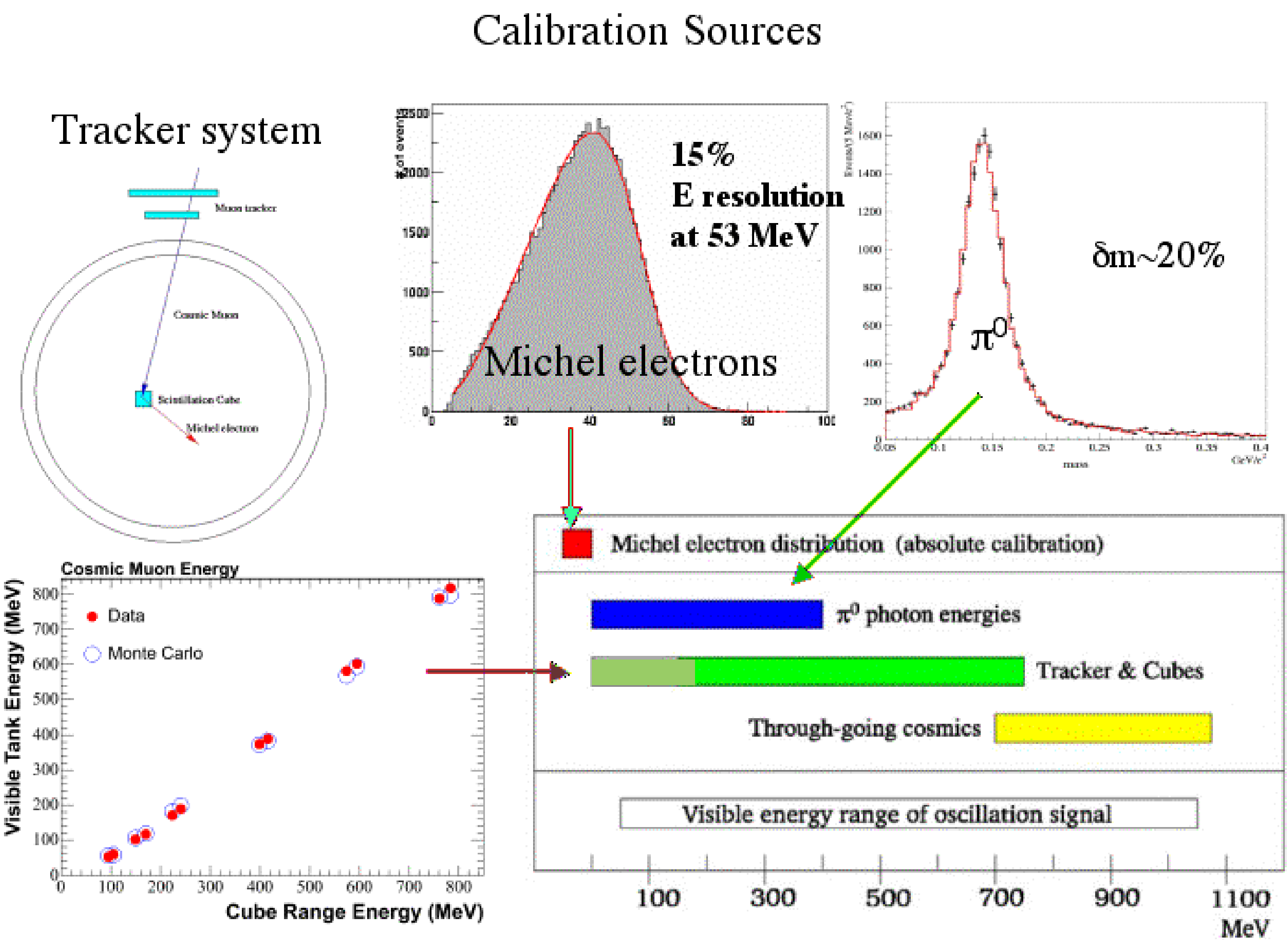


Using NC elastic ν interactions…

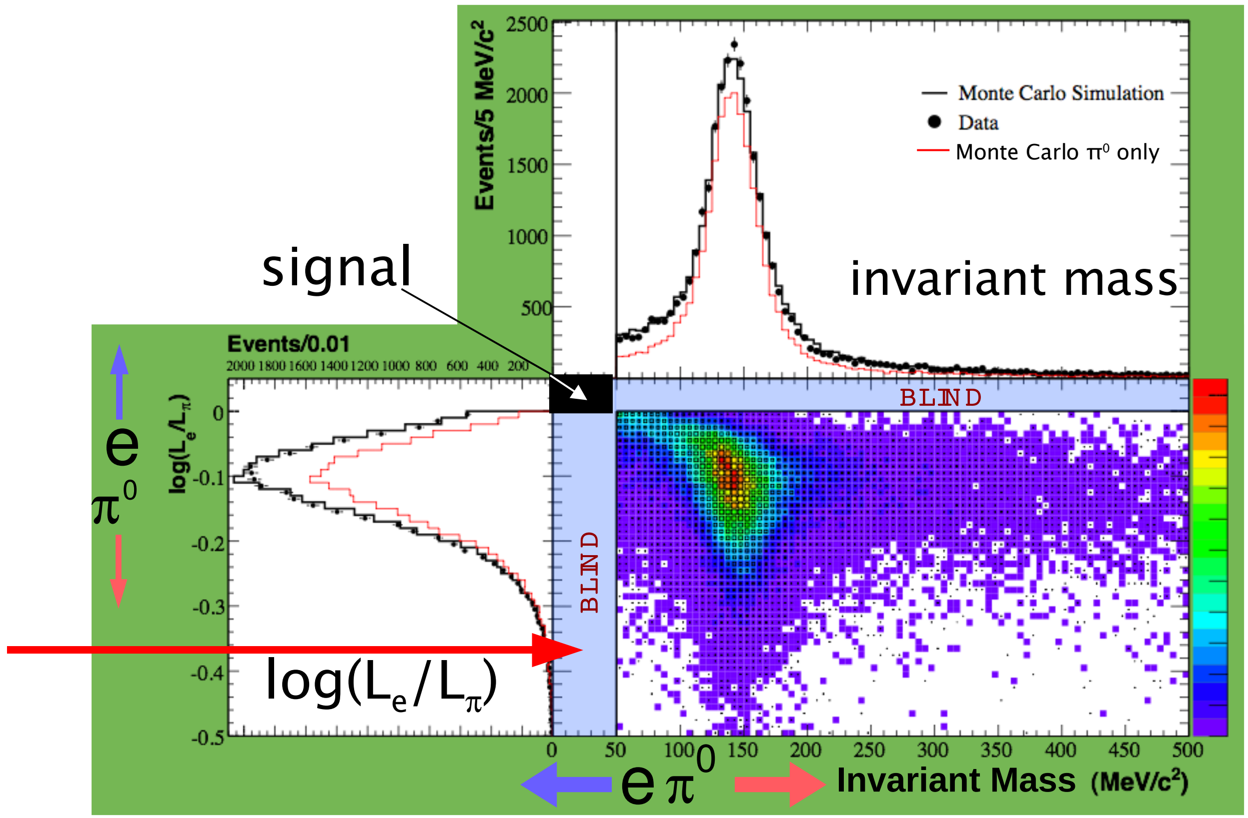


- Initial optical model defined through many benchtop measurements
- Subsequently tuned with *in situ* sources, examples
  - Left: Michel e populate entire tank, useful for tuning extinction
  - Right: NC elastic n interactions below Cerenkov threshold useful for distinguishing scintillation from fluorescence

Calibration sources span various energies

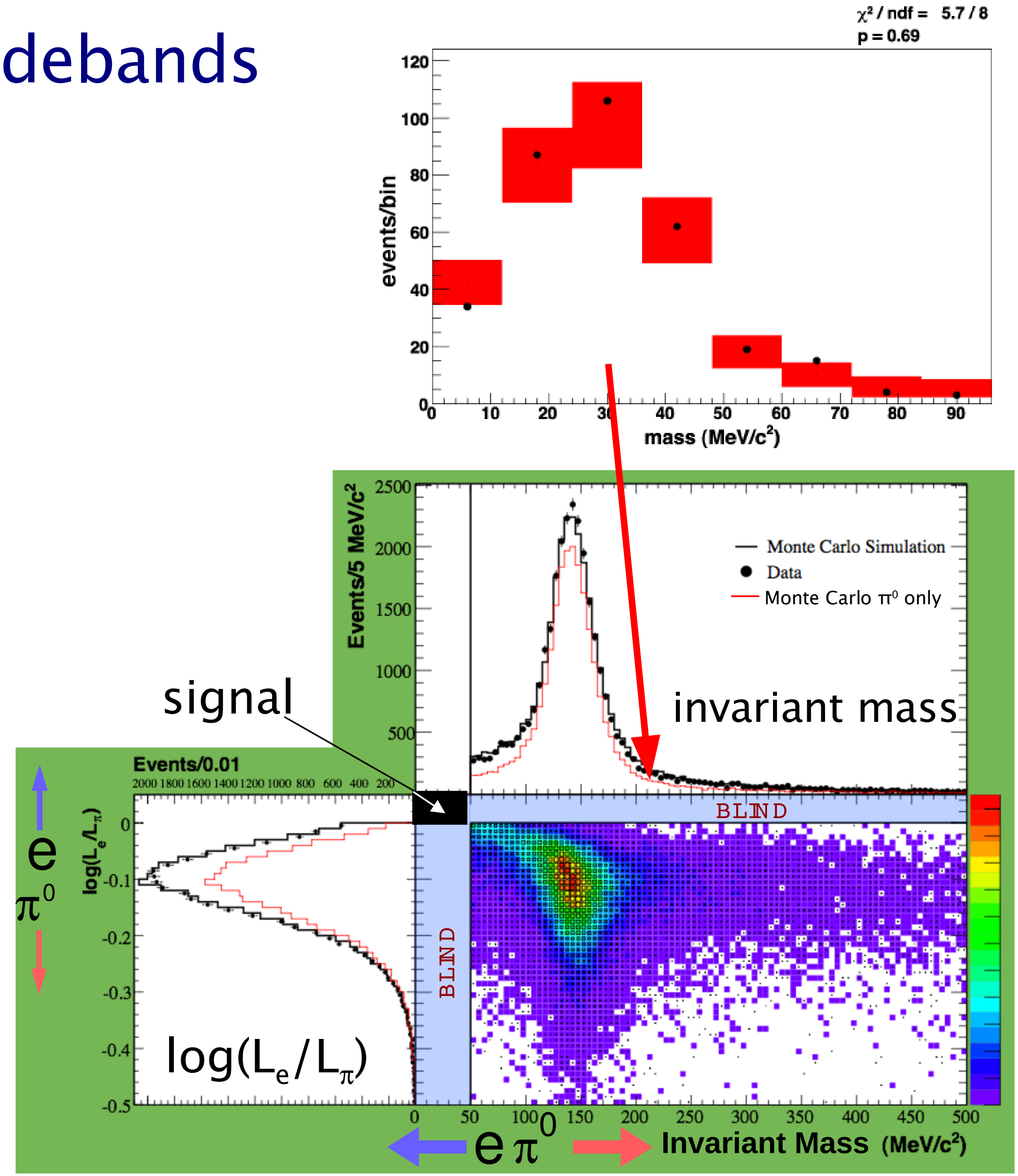


Checking signal sidebands



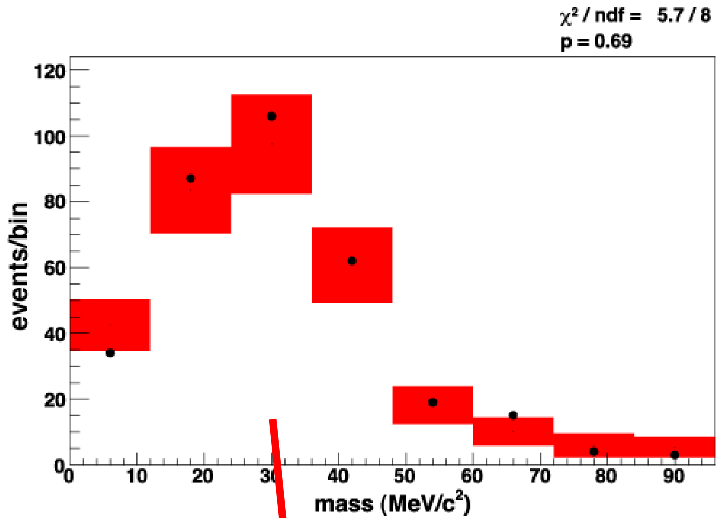
Checking signal sidebands

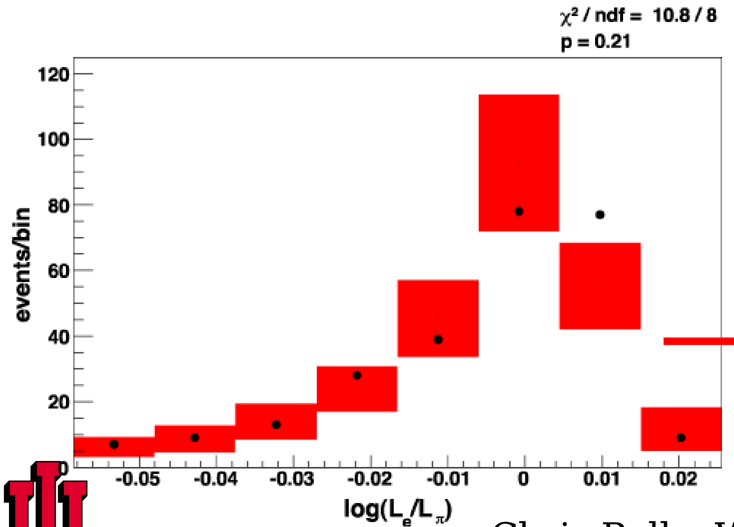
- Region at low $\log(L_e/L_\pi)$

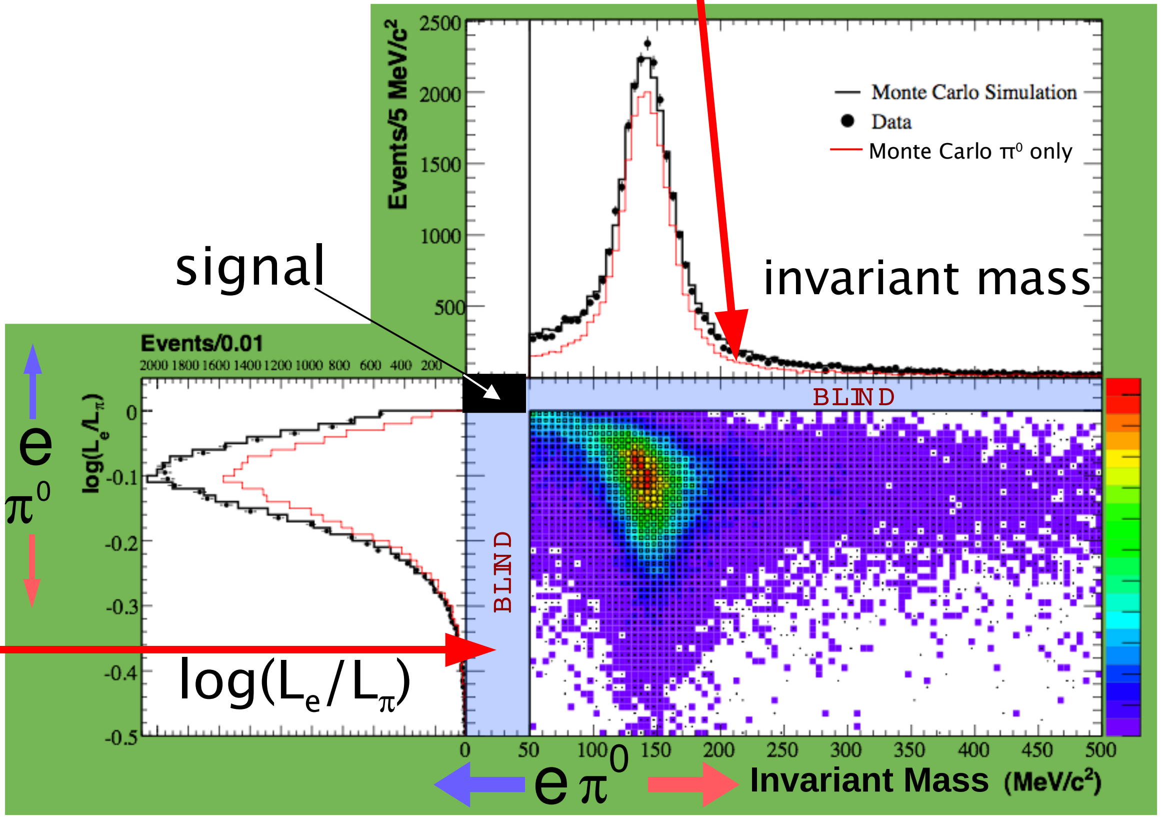


Checking signal sidebands

- Region at low $\log(L_e/L_\pi)$
- Region at low invariant mass

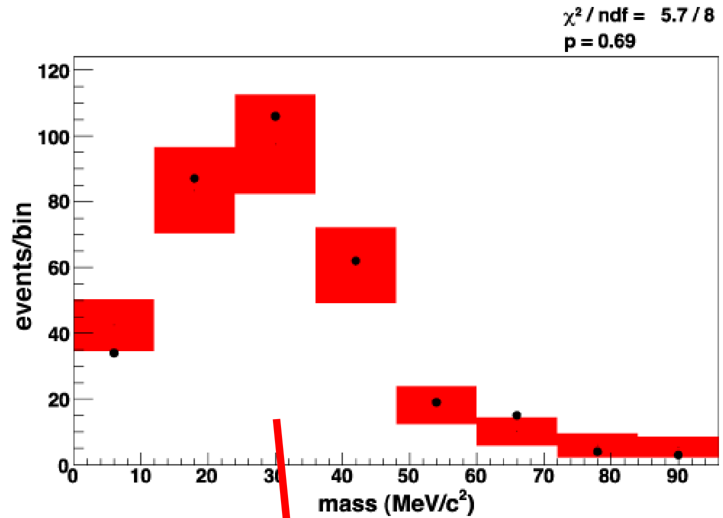


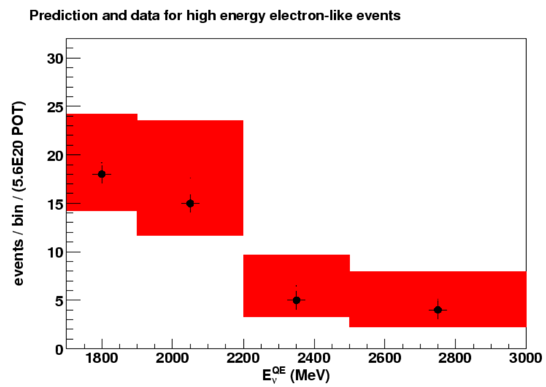


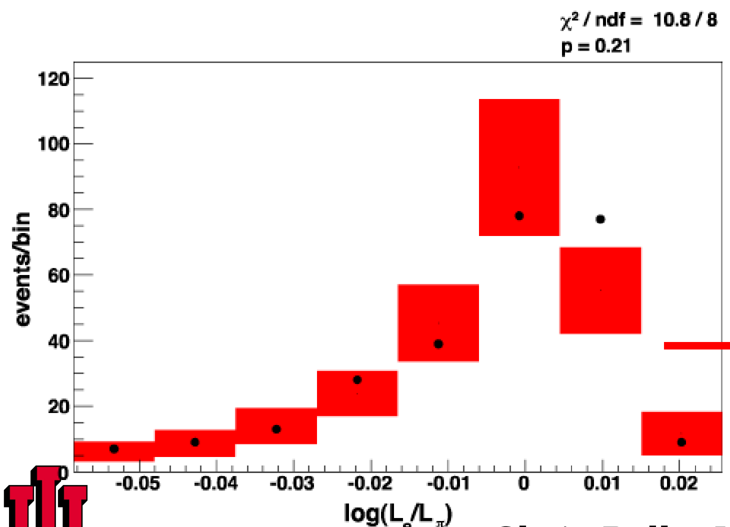


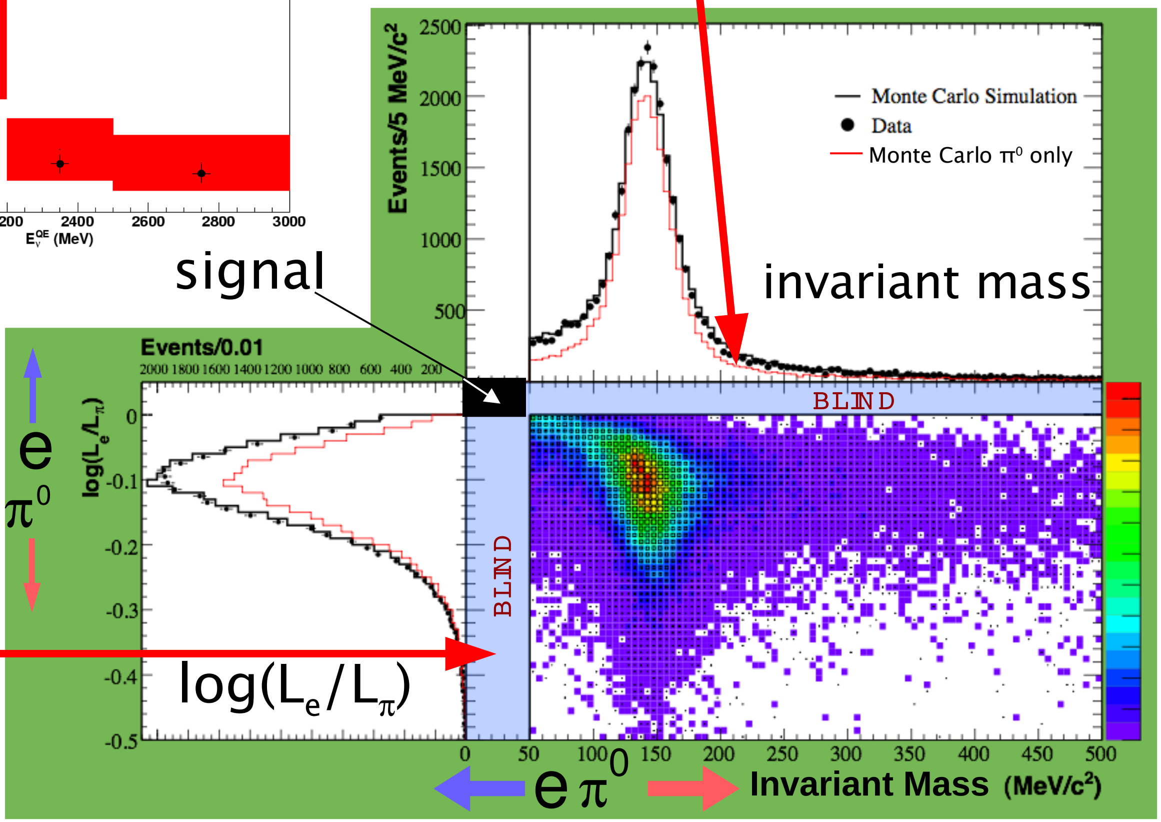
Checking signal sidebands

- Region at low $\log(L_e/L_\pi)$
- Region at low invariant mass
- Region in signal, but at high E_ν



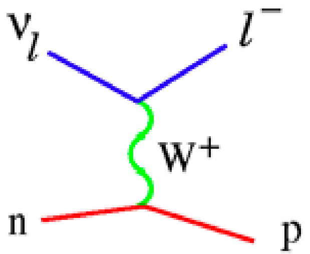




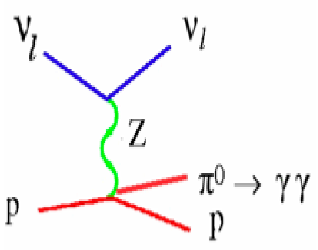


MB cross-section analyses from NuInt07...

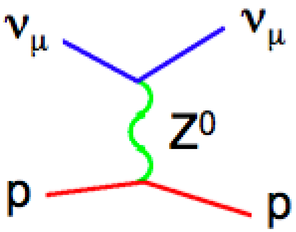
- ν_μ CCQE



- NC π^0

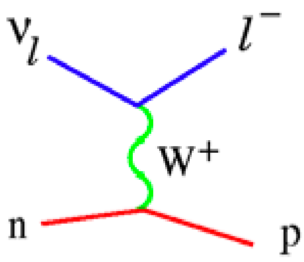


- NC elastic

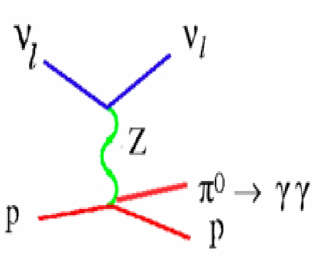


MB cross-section analyses from NuInt07...

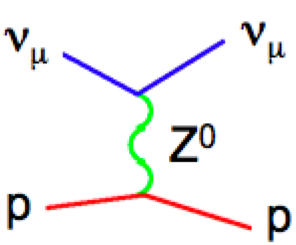
- ν_μ CCQE



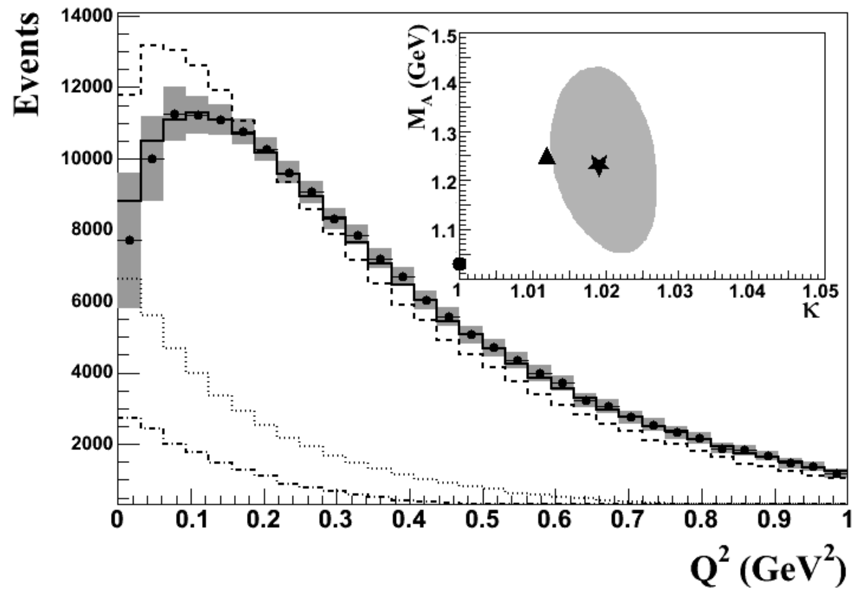
- NC π^0



- NC elastic



ν_μ CCQE Q^2 distribution (hep-ex/0706.0926)

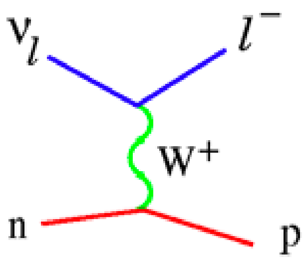


- 198,000 events allows for detailed 1 and 2d kinematic views
- Agreement between data (points) and MC (solid) after fitting for modified Fermi gas parameters
- 'Golden channel' for normalizing flux X xsec in oscillation analysis

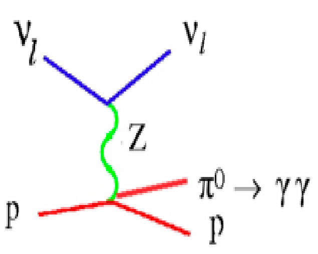
T. Katori, NuInt07

MB cross-section analyses from NuInt07...

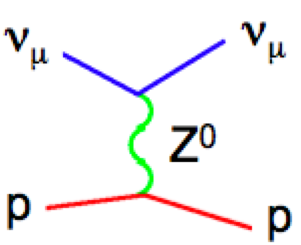
- ν_μ CCQE



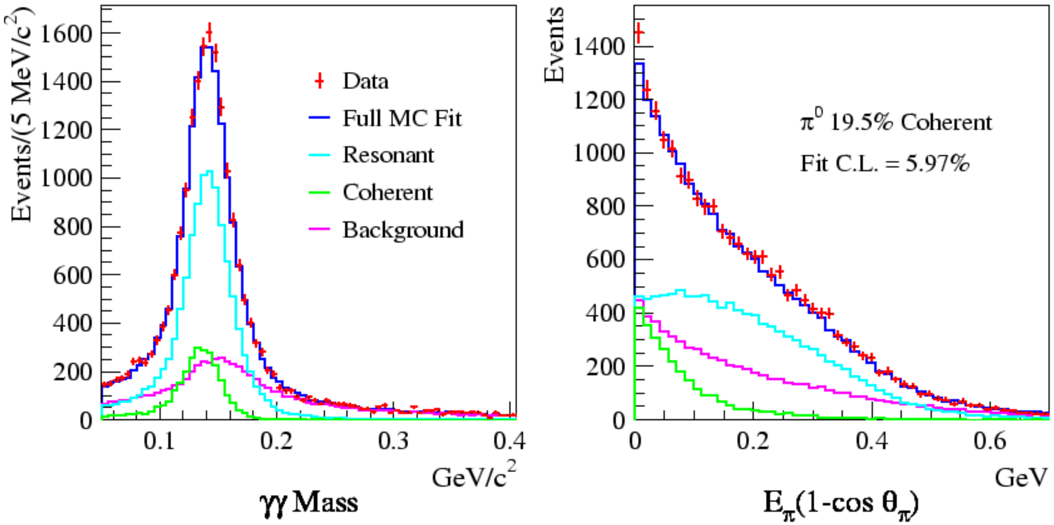
- NC π^0



- NC elastic



NC π^0 fits to resonant/coherent fractions

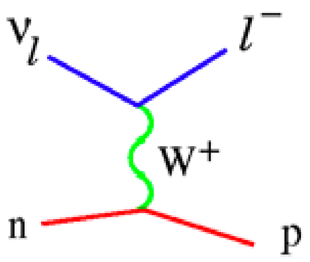


- 28,600 events, largest sample to date
- For MB flux and Nuance model we find that (19.5±1.1)% of exclusive NC π^0 production is coherent
- Very important background for oscillation analysis

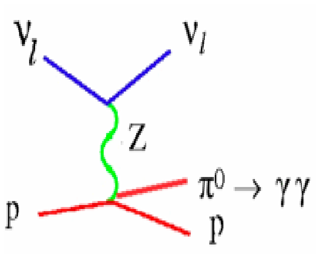
J. Link, NuInt07

MB cross-section analyses from NuInt07...

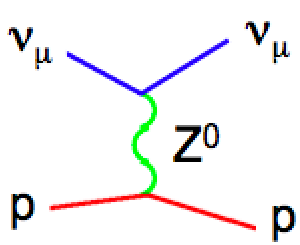
- ν_μ CCQE



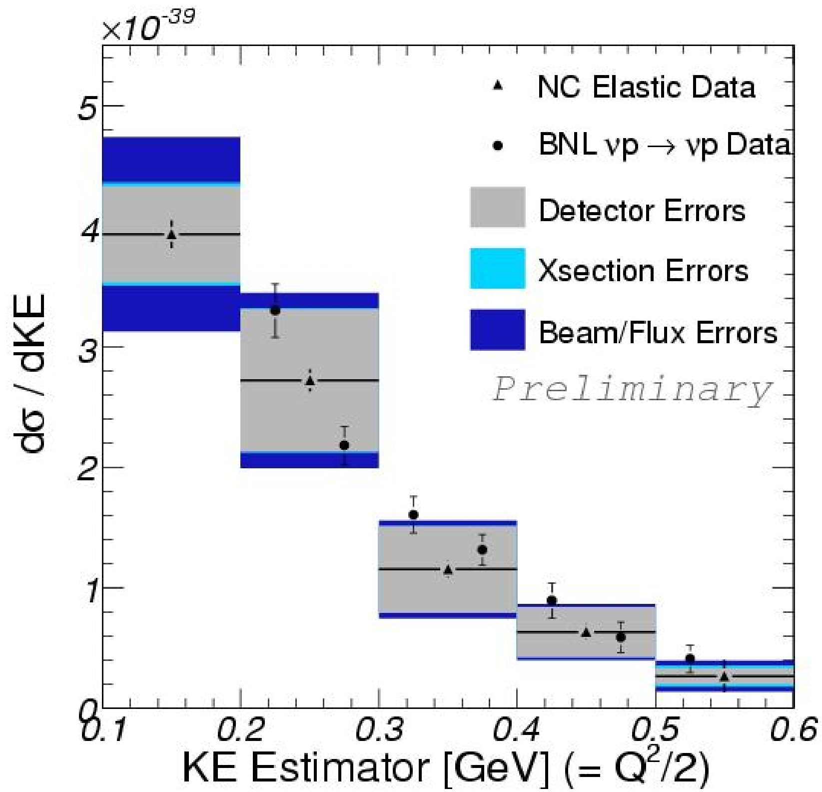
- NC π^0



- NC elastic



NC elastic absolute cross section

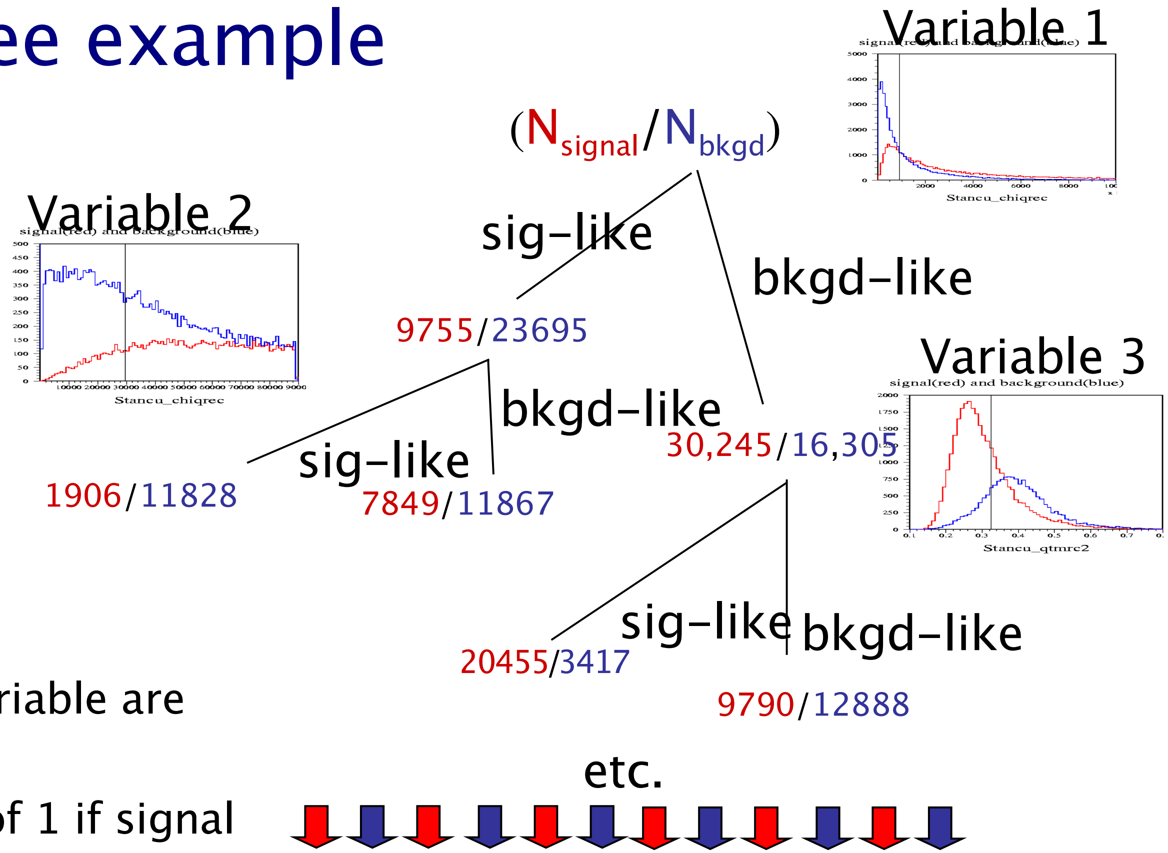


- Data shown is 10% of total sample
- Comparison to BNL E734
- First differential cross section from MB

D. Cox, NuInt07

Decision tree example

(sequential series of cuts based on MC study)



This tree is one of many possibilities...

- Optimal cuts on each variable are determined
- An event gets a weight of 1 if signal -1 if background
- Hard to identify backgrounds are iteratively given more weight
- Many trees built
- PID 'score' established from ensemble

Handling uncertainties in the analysis

What we begin with...

For a given source of uncertainty,

Errors on a wide range of parameters in the underlying model

... what we need

For a given source of uncertainty,

Errors in bins of E_ν^{QE} and information on the correlations between bins

Incorporating the ν_μ constraint into the errors

Two Approaches

TBL: Reweight MC prediction to match measured ν_μ result (accounting for systematic error correlations)

BDT: include the correlations of ν_μ to ν_e in the error matrix:

$$\chi^2 = \left(\Delta_i^{\nu_e} \quad \Delta_i^{\nu_\mu} \right) \begin{pmatrix} M_{ij}^{e,e} & M_{ij}^{e,\mu} \\ M_{ij}^{\mu,e} & M_{ij}^{\mu,\mu} \end{pmatrix}^{-1} \begin{pmatrix} \Delta_j^{\nu_e} \\ \Delta_j^{\nu_\mu} \end{pmatrix}$$

where $\Delta_i^{\nu_e} = \mathrm{Data}_i^{\nu_e} - \mathrm{Pred}_i^{\nu_e}(\Delta m^2, \sin^2 2\theta)$ and $\Delta_i^{\nu_\mu} = \mathrm{Data}_i^{\nu_\mu} - \mathrm{Pred}_i^{\nu_\mu}$

Systematic (and statistical) errors are included in $(M_{ij})^{-1}$,

where i, j are bins of E_ν^{QE}

Example: Underlying X-section parameter errors

(Many are common to ν_μ and ν_e and cancel in the fit)

M_A^{QE}, e_{lo}^{sf}	6%, 2% (stat + bkg only)	determined from MiniBooNE ν_μ QE data
QE σ norm	10%	
QE σ shape	function of E_ν	
ν_e/ν_μ QE σ	function of E_ν	

NC π^0 rate	function of π^0 mom	determined from MiniBooNE ν_μ NC π^0 data
M_A^{coh}, coh σ	$\pm$25%	
$\Delta \rightarrow N\gamma$ rate	function of γ mom + 7% BF	

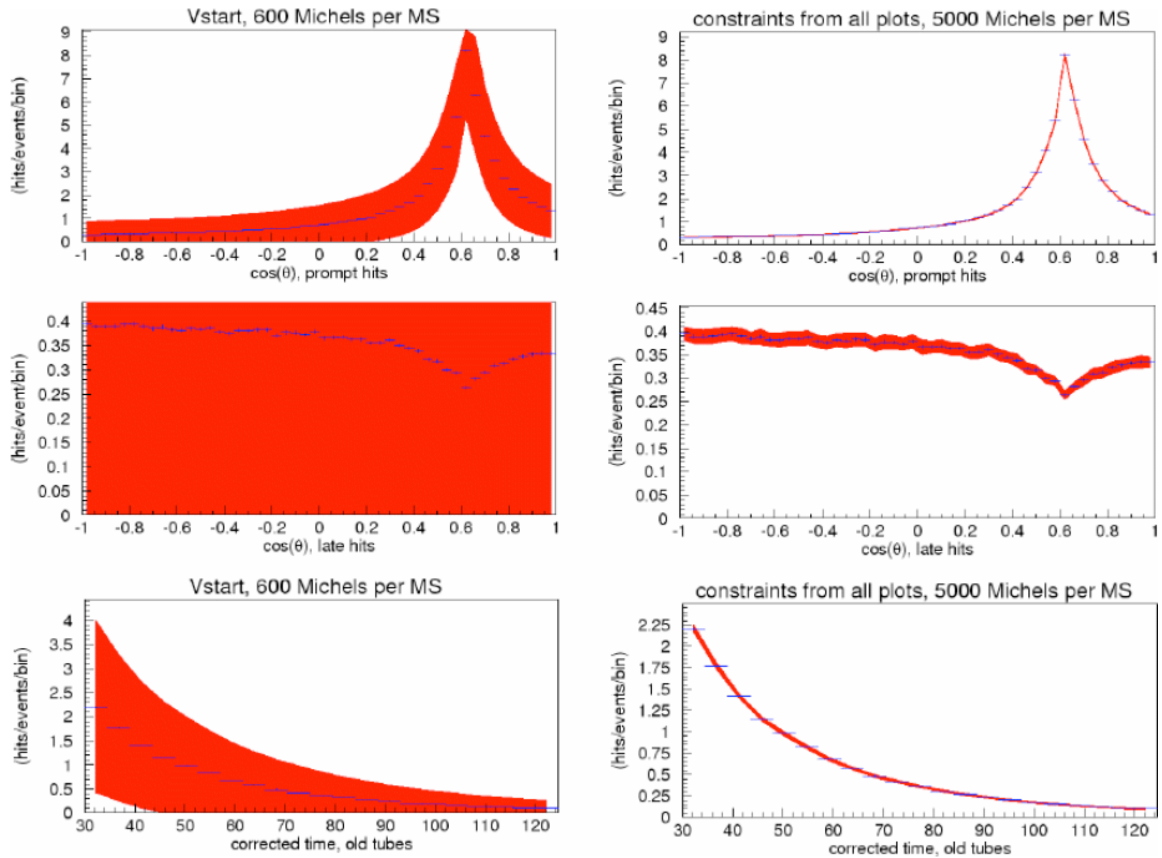
E_B, p_F	9 MeV, 30 MeV	determined from other experiments
Δs	10%	
$M_A^{1\pi}$	25%	
$M_A^{N\pi}$	40%	
DIS σ	25%	

Extracting the OM systematic error

- 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

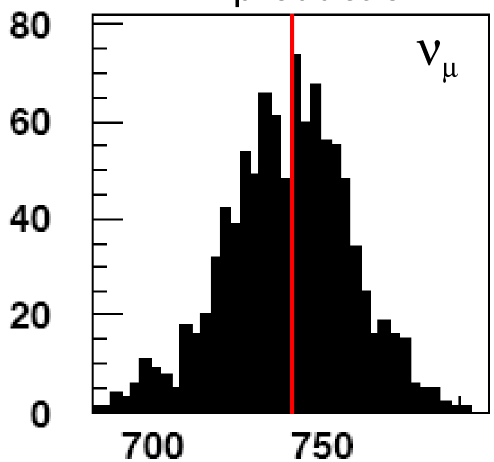
(near) ending uncertainties

"Multisim" approach to assessing systematics

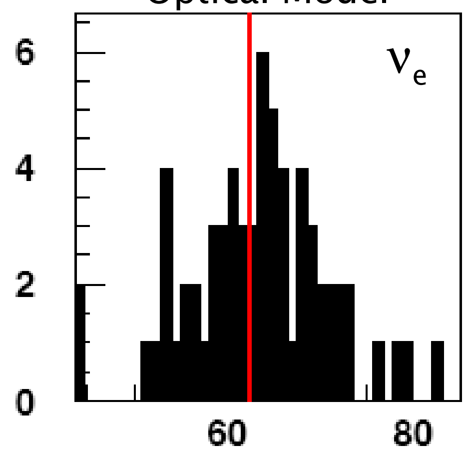
- A multisim is defined as a random draw from the underlying parameter that is considered allowed
- Allowed means the draw does not violate internal or external constraints
- Draws are taken from covariance matrices that dictate how parameters are allowed to change in combination, imagine Cerenkov and scintillation as independent sources of light but requiring the Michel energy to be conserved
- For flux and X-section multisims can be done via reweighting, optical model requires running hit level simulation

1000 multisims for K^+ production

number of multisims



70 multisims Optical Model



red line: standard MC

Number of events passing cuts in bin $500<E_\nu^{QE}<600$ MeV

Optical model error matrix

$$E_{ij} = \frac{1}{M}\sum_{a=1}^{M}\left(N_i^{a} - N_i^{CV}\right)\left(N_j^{MC} - N_j^{CV}\right)^{MC}$$

- N is number of events passing cuts
- MC is standard monte carlo
- α represents a given multisim
- M is the total number of multisims
- i,j are E_ν^{QE} bins

Total error matrix is calculated from the sum of 9 independent sources

TB: ν_e–only total error matrix

BDT: ν_μ–ν_e total error matrix

Correlations between E_ν^{QE} bins from the optical model: