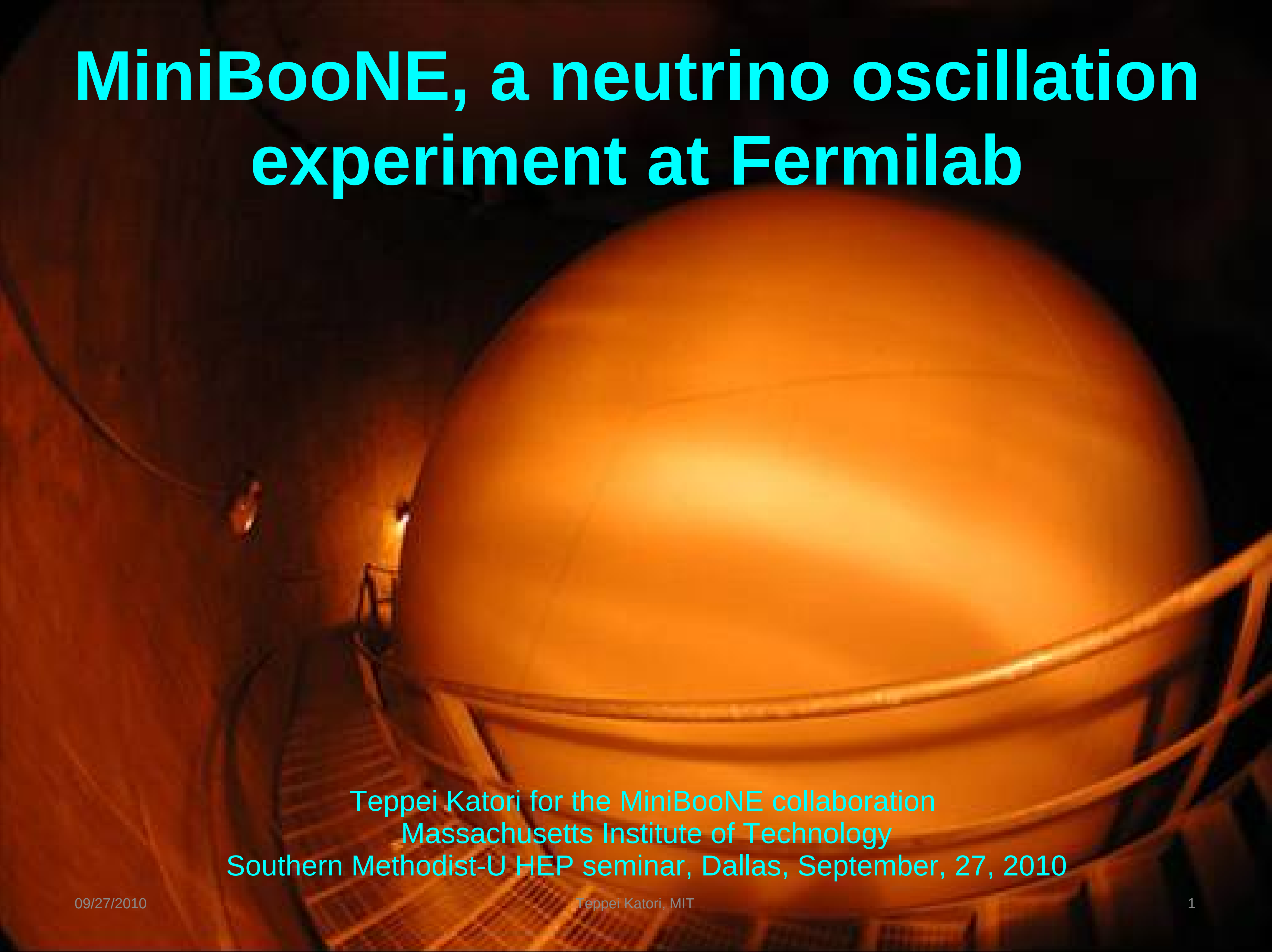

MiniBooNE, a neutrino oscillation experiment at Fermilab

Teppei Katori for the MiniBooNE collaboration
Massachusetts Institute of Technology
Southern Methodist-U HEP seminar, Dallas, September, 27, 2010

MiniBooNE, a neutrino oscillation experiment at Fermilab

Outline

1. Introduction
2. Neutrino beam
3. Events in the detector
4. Cross section model
5. Oscillation analysis
6. Neutrino oscillation result
7. New Low energy excess result
8. Anti-neutrino oscillation result
9. Neutrino disappearance result

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1. Neutrino oscillation

The neutrino weak eigenstate is described by neutrino Hamiltonian eigenstates, ν_1, ν_2, and ν_3 and their mixing matrix elements.

$$|\nu_e\rangle = \sum_{i=1}^{3} U_{ei} \, |\nu_i\rangle$$

The time evolution of neutrino weak eigenstate is written by Hamiltonian mixing matrix elements and eigenvalues of ν_1, ν_2, and ν_3.

$$|\nu_e(t)\rangle = \sum_{i=1}^{3} U_{ei} e^{-i\lambda_i t} \, |\nu_i\rangle$$

Then the transition probability from weak eigenstate ν_μ to ν_e is

$$P_{\mu\to e}(t) = \left|\langle \nu_e(t) \,|\, \nu_\mu \rangle\right|^2 = -4 \sum_{i>j} \left(U_{\mu i} U_{\mu j} U_{ei} U_{ej} \right) \sin^2\left(\frac{\Delta_{ij}}{2} t \right)$$

So far, model independent

1. Neutrino oscillation

From here, model dependent formalism.

In the vacuum, 2 neutrino state effective Hamiltonian has a form,

$$H_{eff} \rightarrow \begin{pmatrix} \frac{m_{ee}^2}{2E} & \frac{m_{e\mu}^2}{2E} \\ \frac{m_{e\mu}^2}{2E} & \frac{m_{\mu\mu}^2}{2E} \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \frac{m_1^2}{2E} & 0 \\ 0 & \frac{m_2^2}{2E} \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

Therefore, 2 massive neutrino oscillation model is

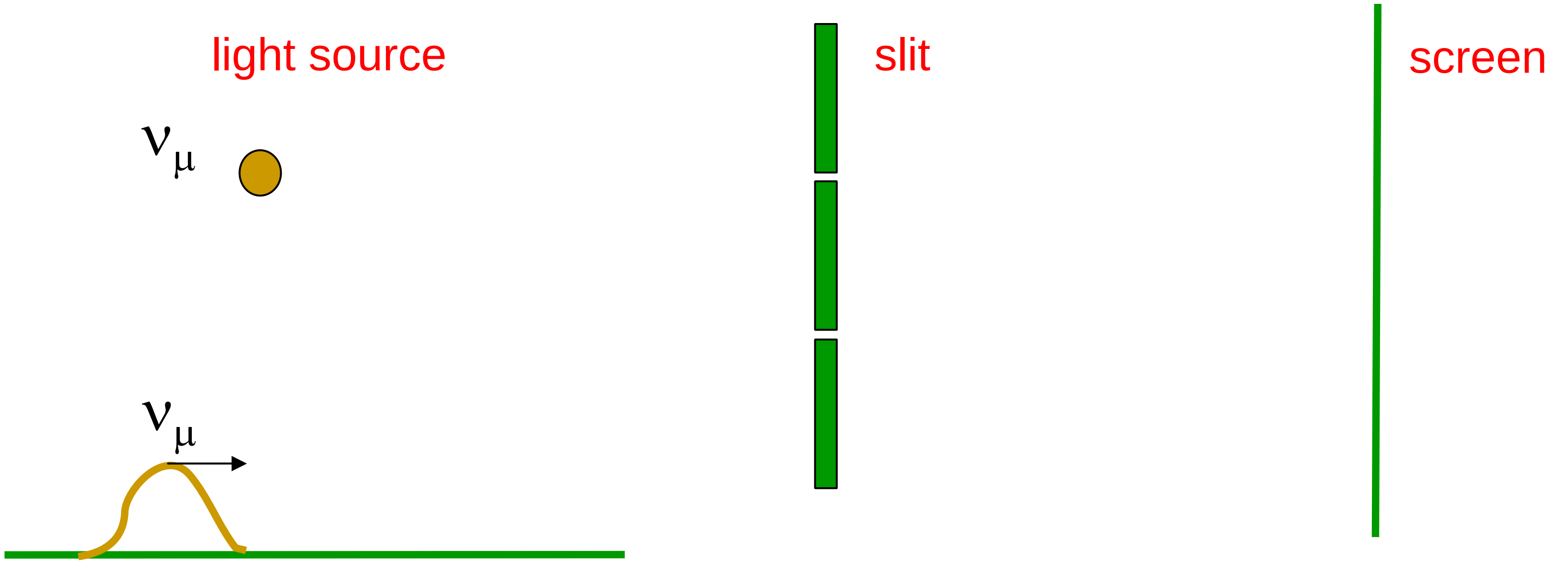
$$P_{\mu\rightarrow e}(t) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E} t\right)$$

Or, conventional form

$$P_{\mu\rightarrow e}(L/E) = \sin^2 2\theta \sin^2\left(1.27\,\Delta m^2(eV^2)\,\frac{L(m)}{E(MeV)}\right)$$

1. Neutrino oscillation

Neutrino oscillation is an interference experiment (cf. double slit experiment)



If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

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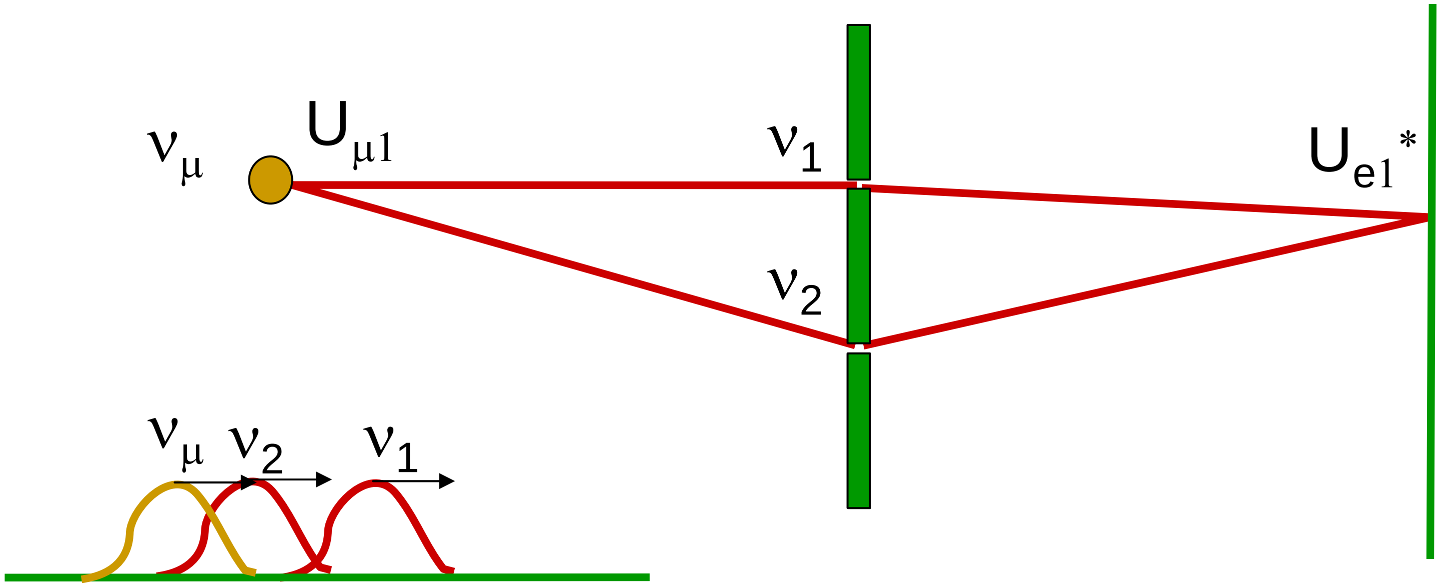

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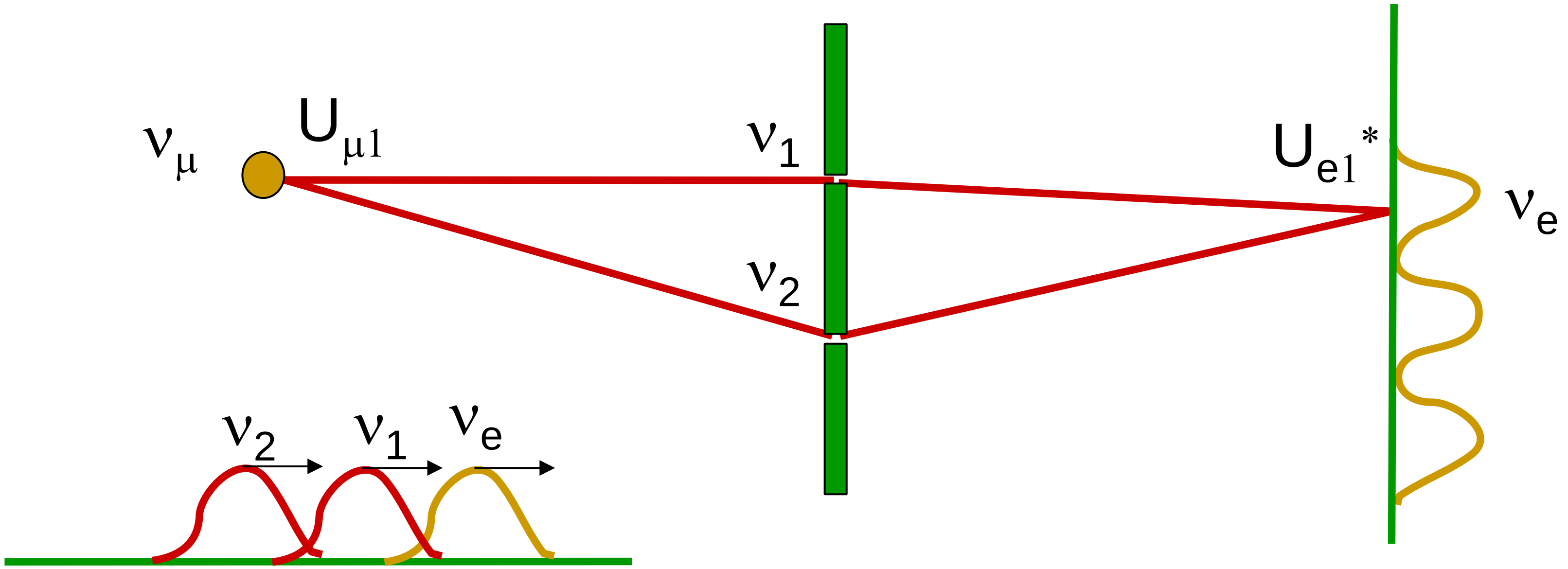

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LSND Collaboration,
PRD 64, 112007

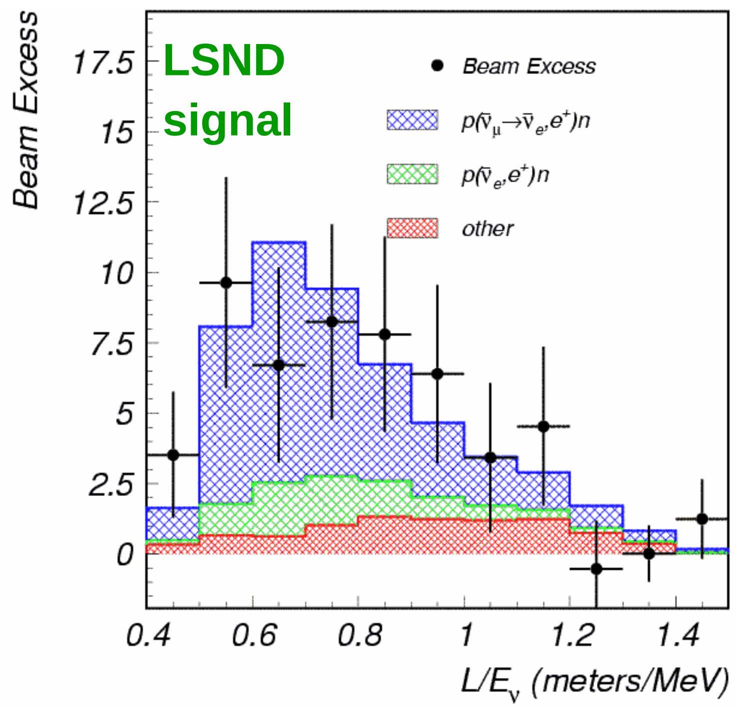
1. LSND experiment

LSND experiment at Los Alamos observed excess of anti-electron neutrino events in the anti-muon neutrino beam.

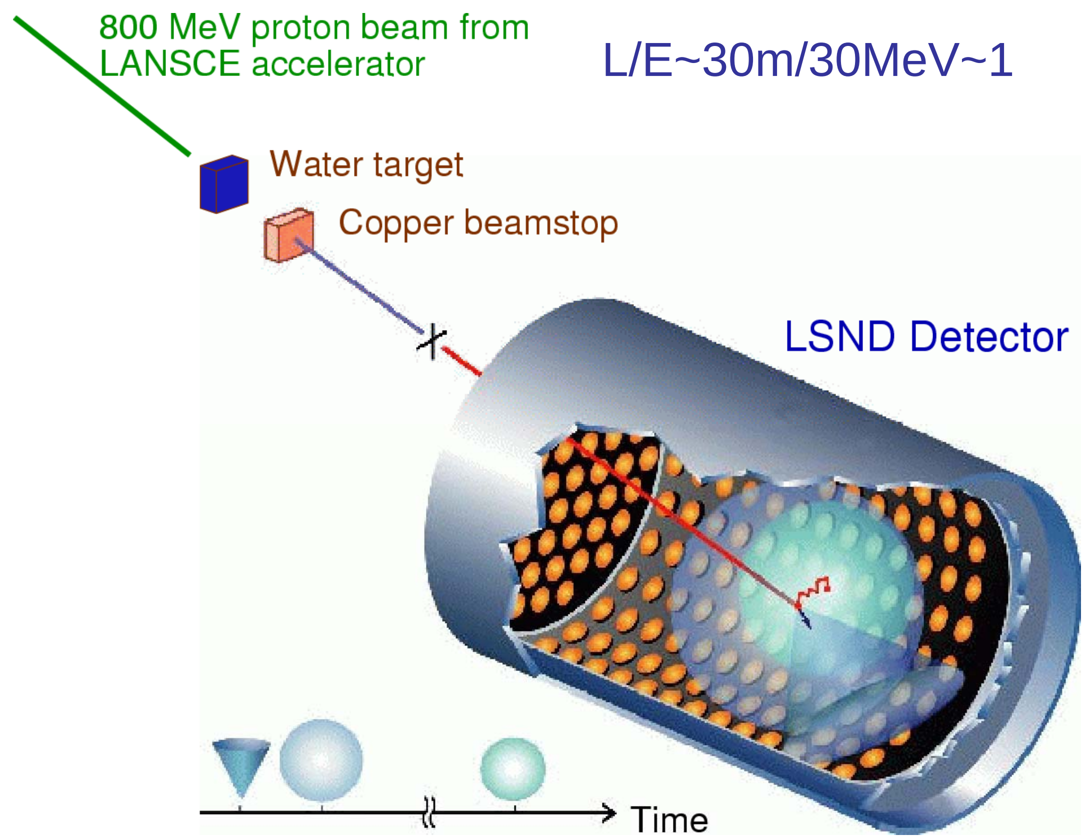
$$\bar{\nu}_\mu \xrightarrow{oscillation} \bar{\nu}_e + p \rightarrow e^+ + n$$

$$n + p \rightarrow d + \gamma$$

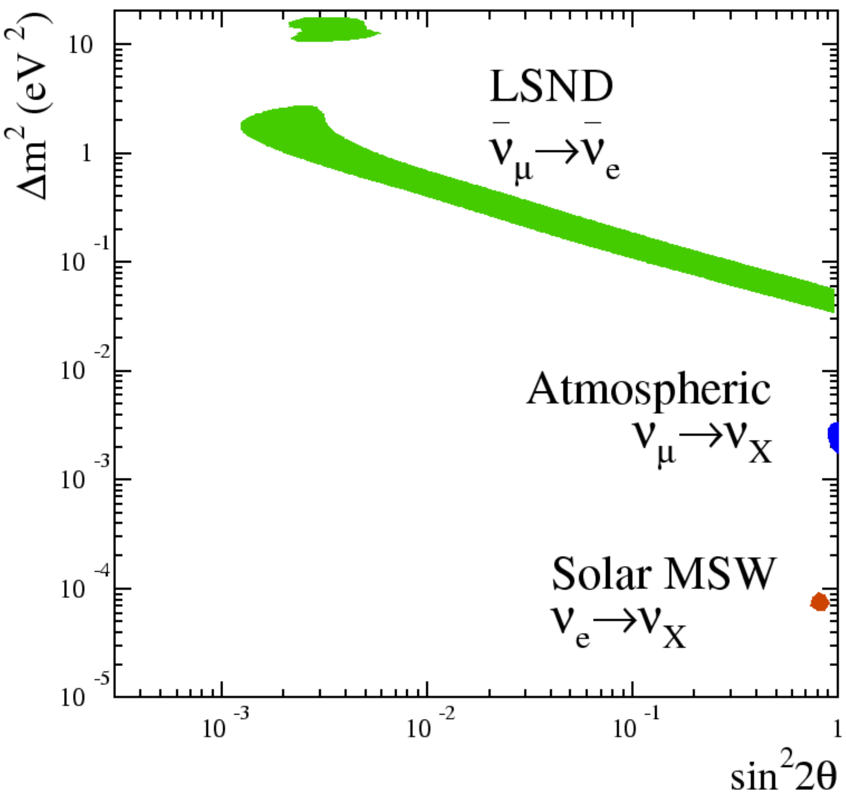
87.9 ± 22.4 ± 6.0 (3.8.σ)



L/E~30m/30MeV~1



1. LSND experiment

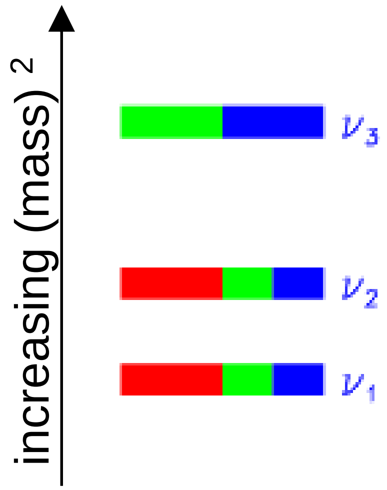


3 types of neutrino oscillations are found:

LSND neutrino oscillation: $\Delta m^2 \sim 1 eV^2$
Atmospheric neutrino oscillation: $\Delta m^2 \sim 10^{-3} eV^2$
Solar neutrino oscillation : $\Delta m^2 \sim 10^{-5} eV^2$

But we cannot have so many Δm^2!

$$\Delta m_{13}^2 \neq \Delta m_{12}^2 + \Delta m_{23}^2$$



We need to test LSND signal

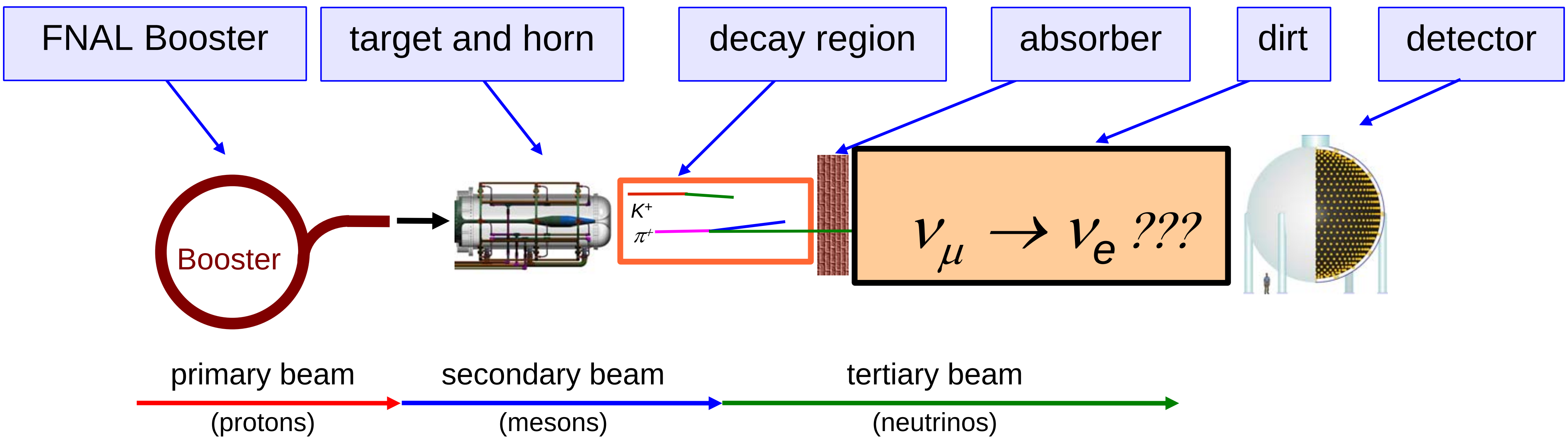
MiniBooNE experiment is designed to have same L/E~500m/500MeV~1 to test LSND $\Delta m^2 \sim 1 eV^2$

1. MiniBooNE experiment

Keep L/E same with LSND, while changing systematics, energy & event signature;

$P(\nu_\mu - \nu_e) = \sin^2 2\theta \, \sin^2(1.27 \Delta m^2 L/E)$

MiniBooNE is looking for the single isolated electron like events, which is the signature of ν_e events



MiniBooNE has;
- higher energy (~500 MeV) than LSND (~30 MeV)
- longer baseline (~500 m) than LSND (~30 m)

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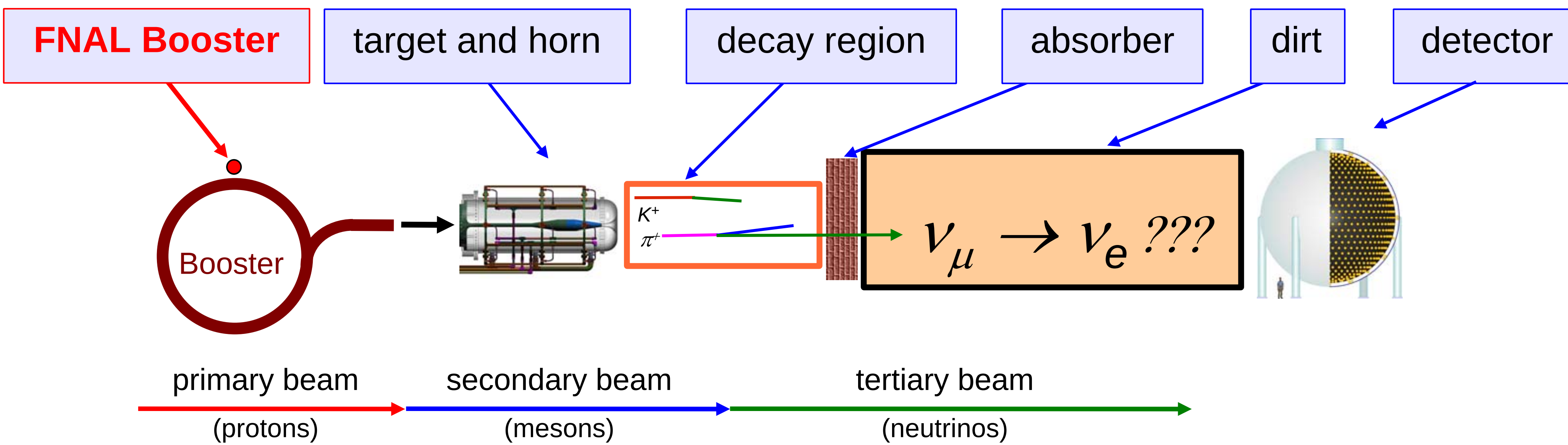
MiniBooNE collaboration, PRD79(2009)072002

2. Neutrino beam

MiniBooNE extracts beam from the 8 GeV Booster



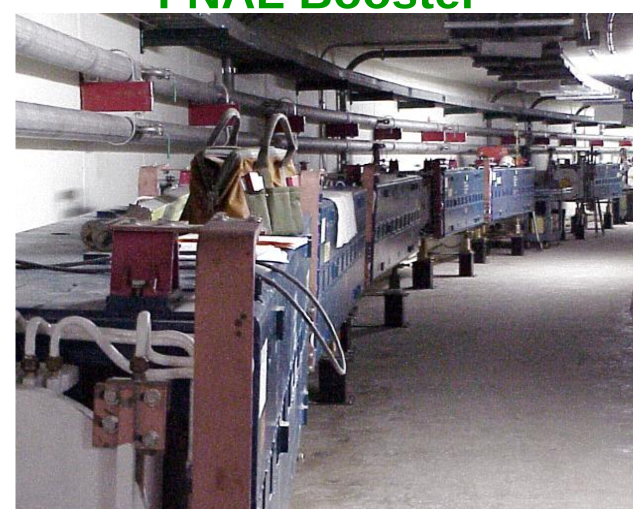
MiniBooNE collaboration,
PRD79(2009)072002

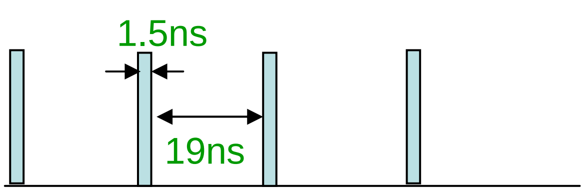
2. Neutrino beam

4×10^{12} protons per 1.6 μs pulse
delivered at up to 5 Hz.

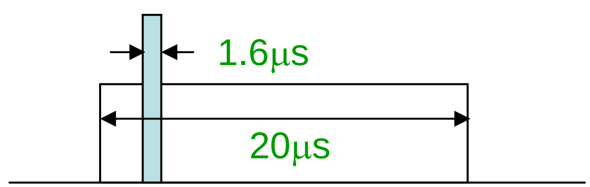
5.58×10^{20} POT (proton on target)

FNAL Booster





Beam micro structure

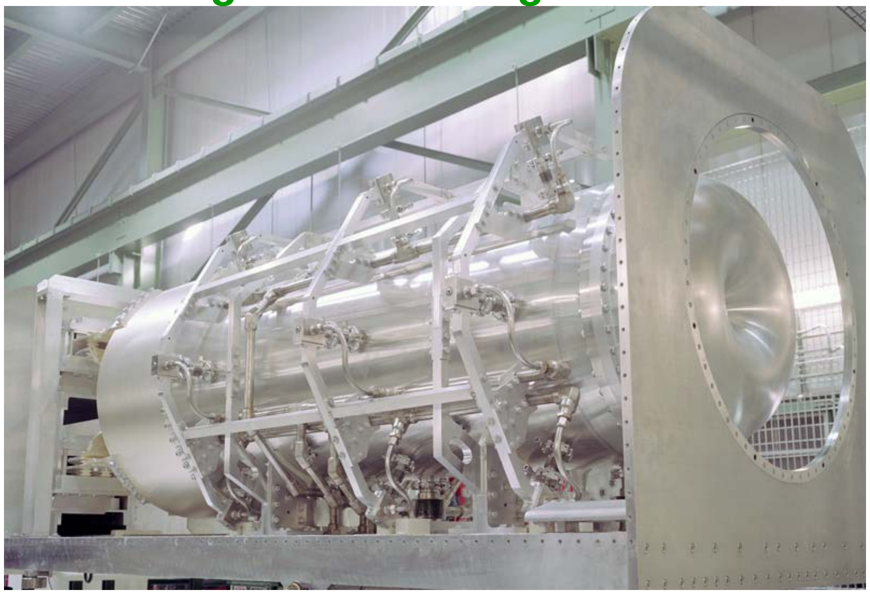


Beam macro structure

MiniBooNE collaboration,
PRD79(2009)072002

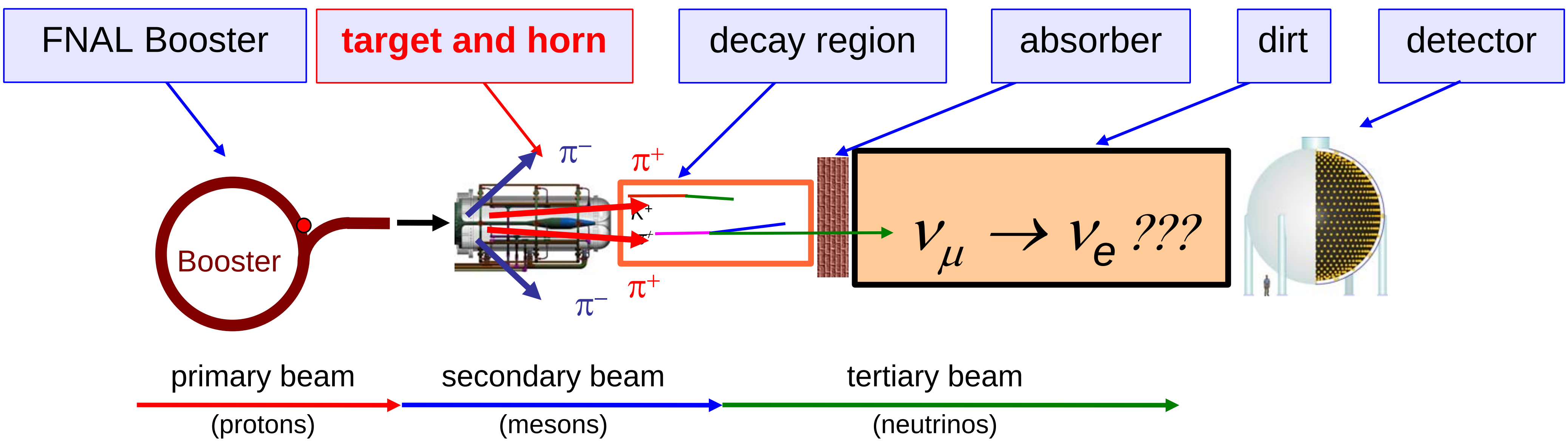
2. Neutrino beam

Magnetic focusing horn



8GeV protons are delivered to a 1.7 λ Be target

within a magnetic horn (2.5 kV, 174 kA) that increases the flux by × 6



MiniBooNE collaboration,
PRD79(2009)072002

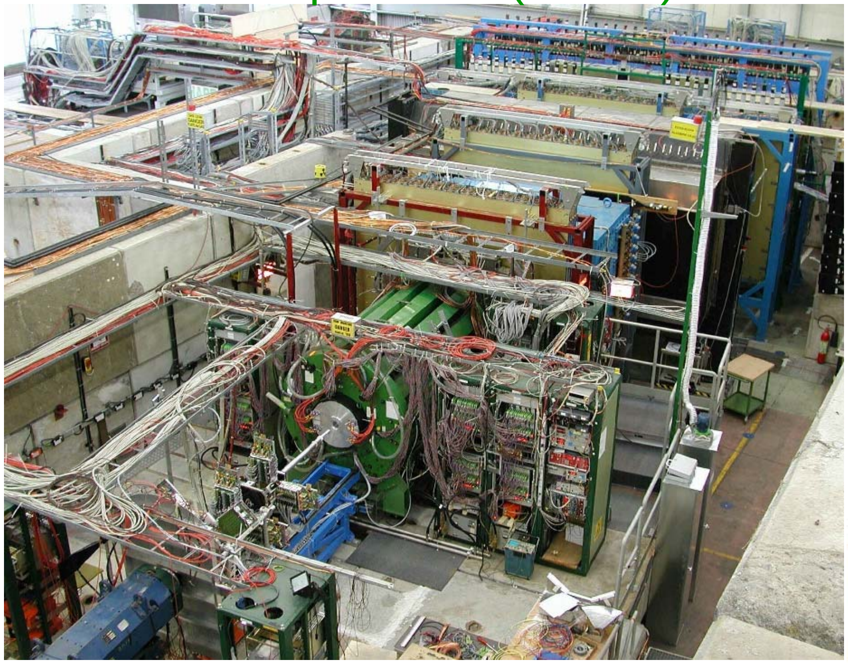
2. Neutrino beam

Modeling of meson production is based on the measurement done by HARP collaboration

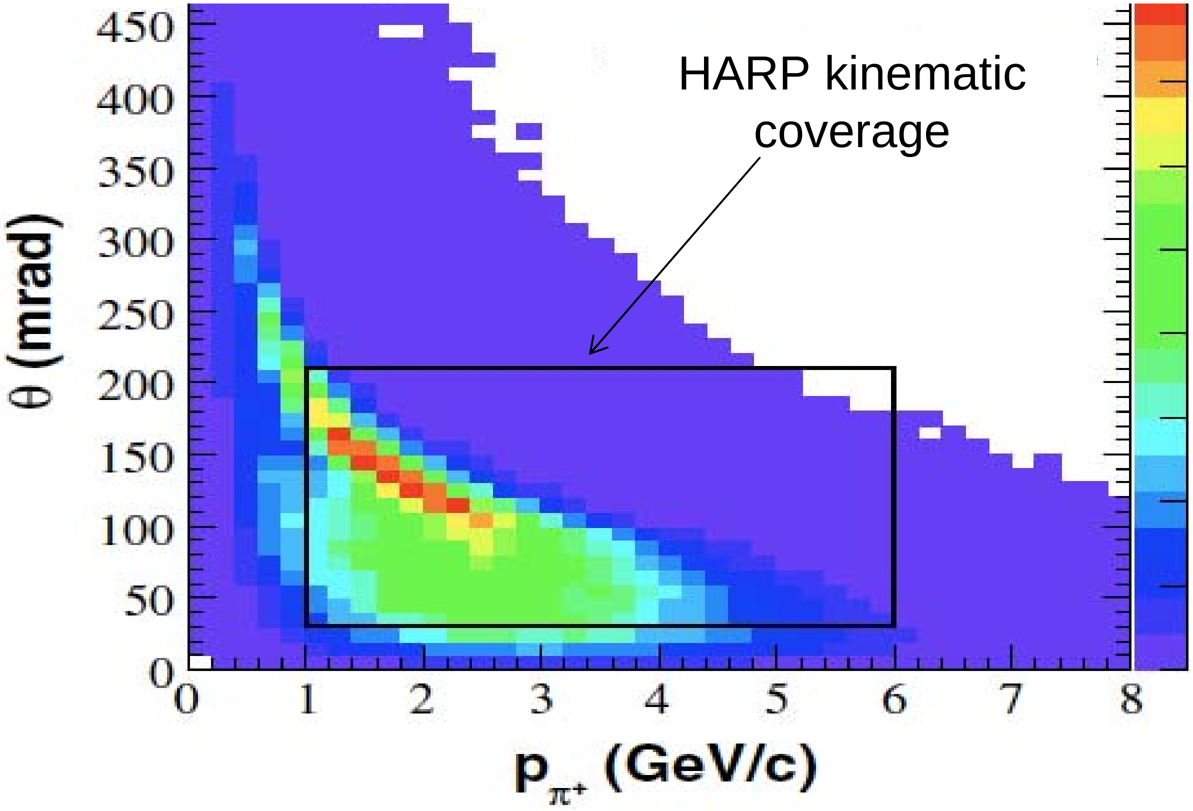
- Identical, but 5% λ Beryllium target
- 8.9 GeV/c proton beam momentum

HARP collaboration,
Eur.Phys.J.C52(2007)29

HARP experiment (CERN)



Booster neutrino beamline pion kinematic space



Majority of pions create neutrinos in MiniBooNE are directly measured by HARP (>80%)

MiniBooNE collaboration,
PRD79(2009)072002

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HARP collaboration,
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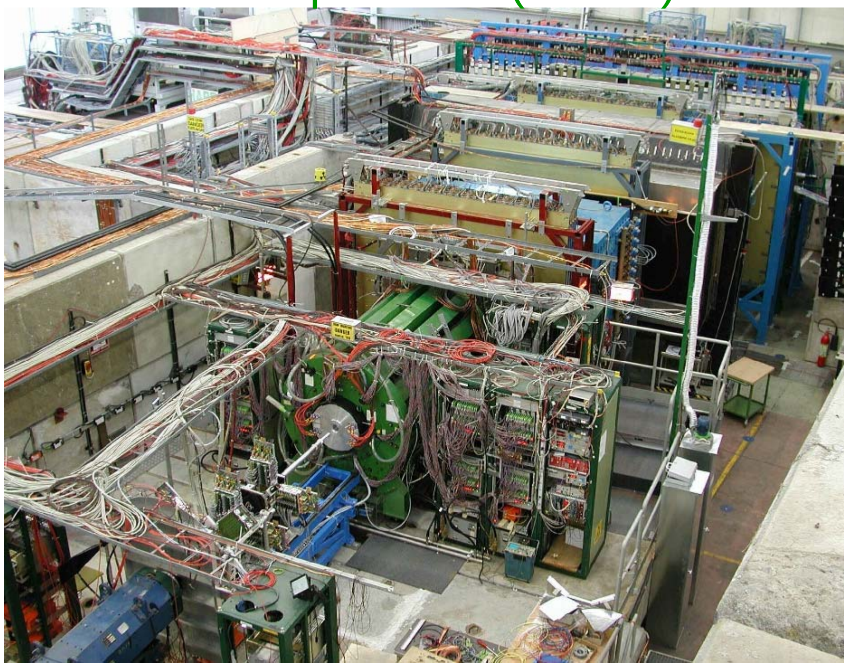
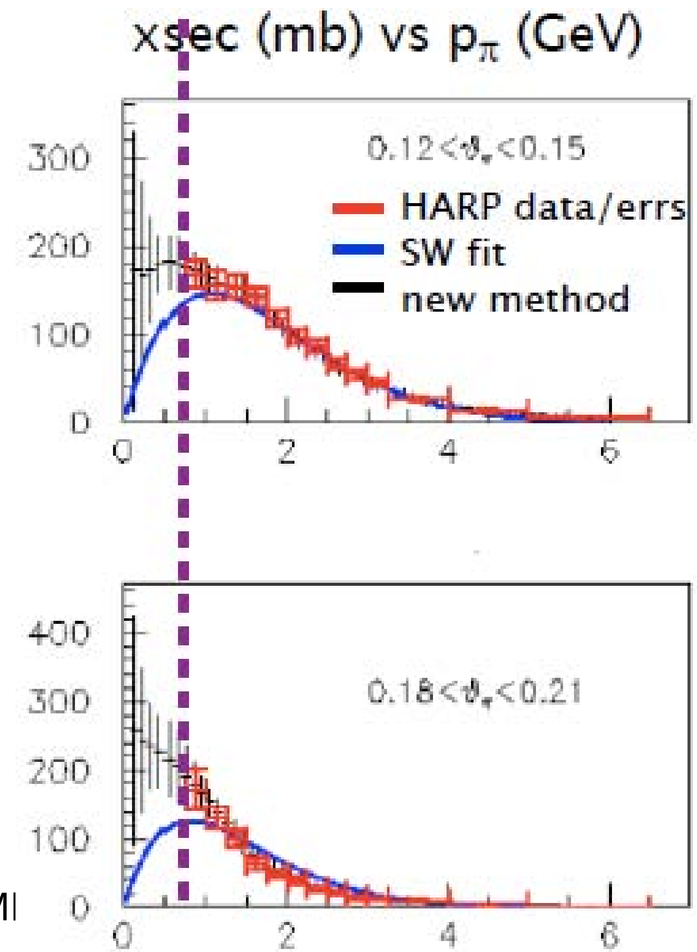
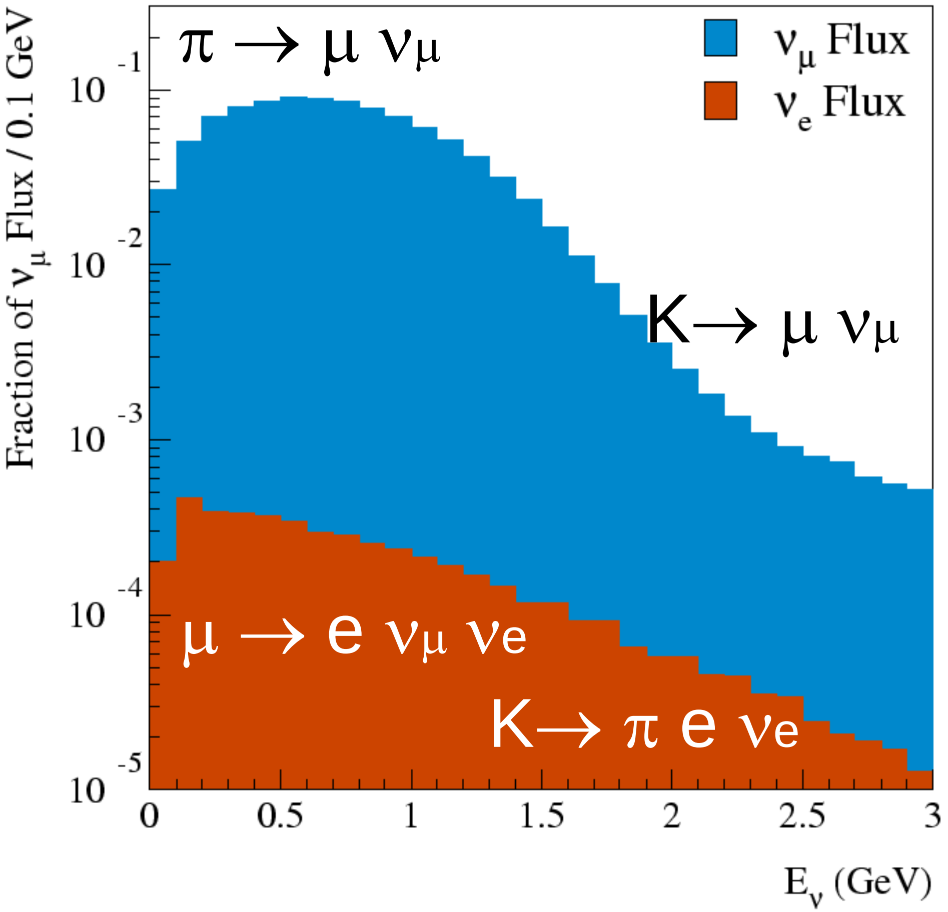




HARP data with 8.9 GeV/c proton beam momentum

The error on the HARP data (~7%) directly propagates.
The neutrino flux error is the dominant source of normalization error for an absolute cross section in MiniBooNE, however it doesn't affect oscillation analysis.

2. Neutrino beam



Neutrino Flux from GEANT4 Simulation

MiniBooNE is the ν_e appearance oscillation experiment

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

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

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

Antineutrino content: 6%

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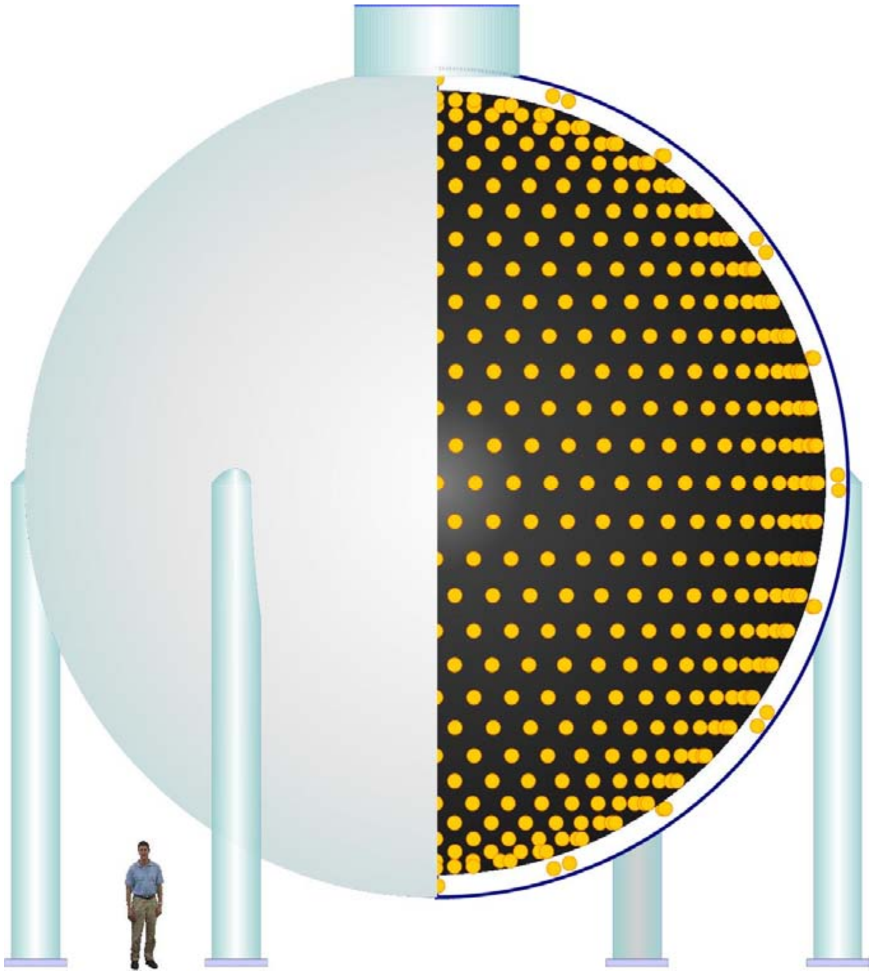
MiniBooNE collaboration,
NIM.A599(2009)28

3. Events in the Detector



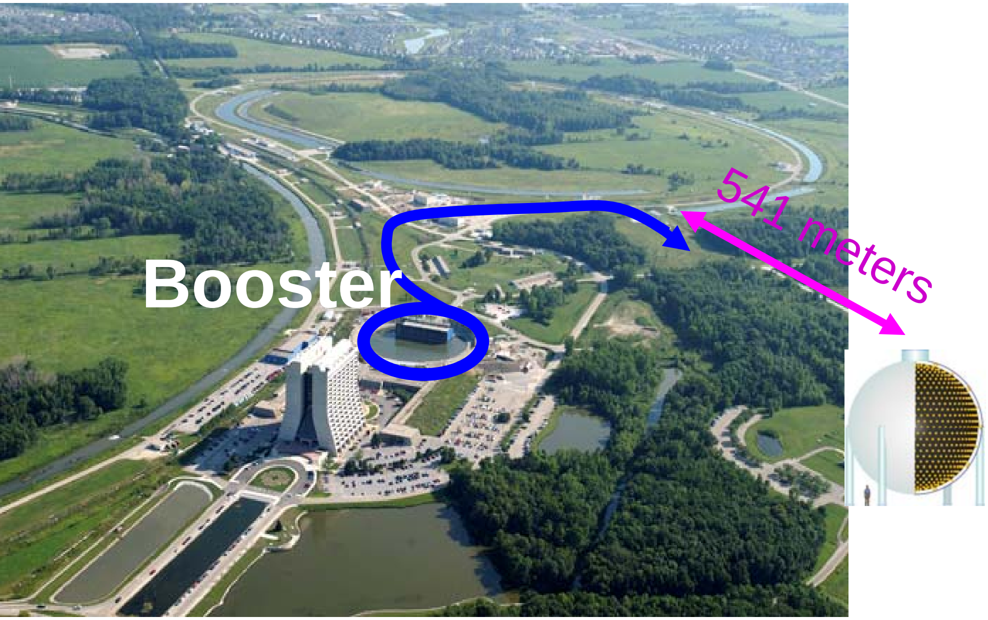
The MiniBooNE Detector

- 541 meters downstream of target
- 3 meter overburden
- 12 meter diameter sphere
  (10 meter "fiducial" volume)
- Filled with 800 t of pure mineral oil (CH_2)
  (Fiducial volume: 450 t)
- 1280 inner phototubes,
- 240 veto phototubes

Simulated with a GEANT3 Monte Carlo

MiniBooNE collaboration,
NIM.A599(2009)28

3. Events in the Detector



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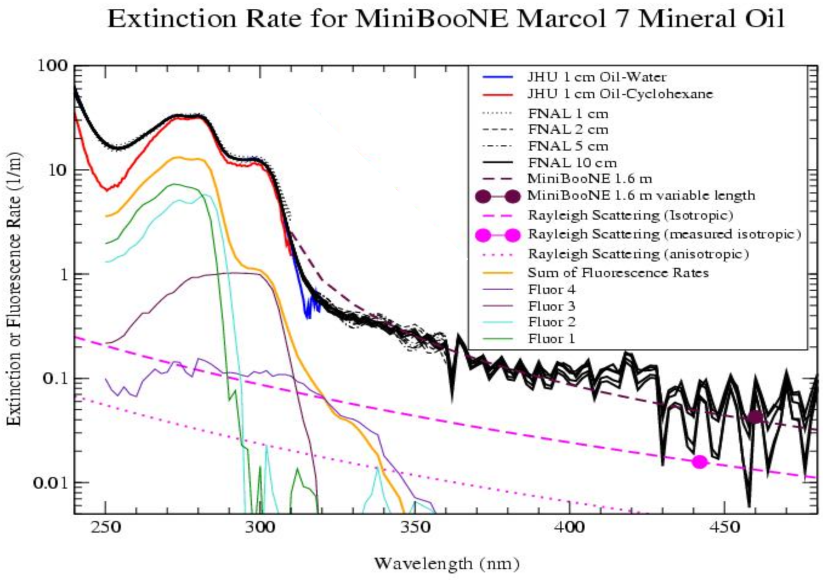
MiniBooNE collaboration,
NIM.A599(2009)28

3. Events in the Detector

Extinction rate of MiniBooNE oil



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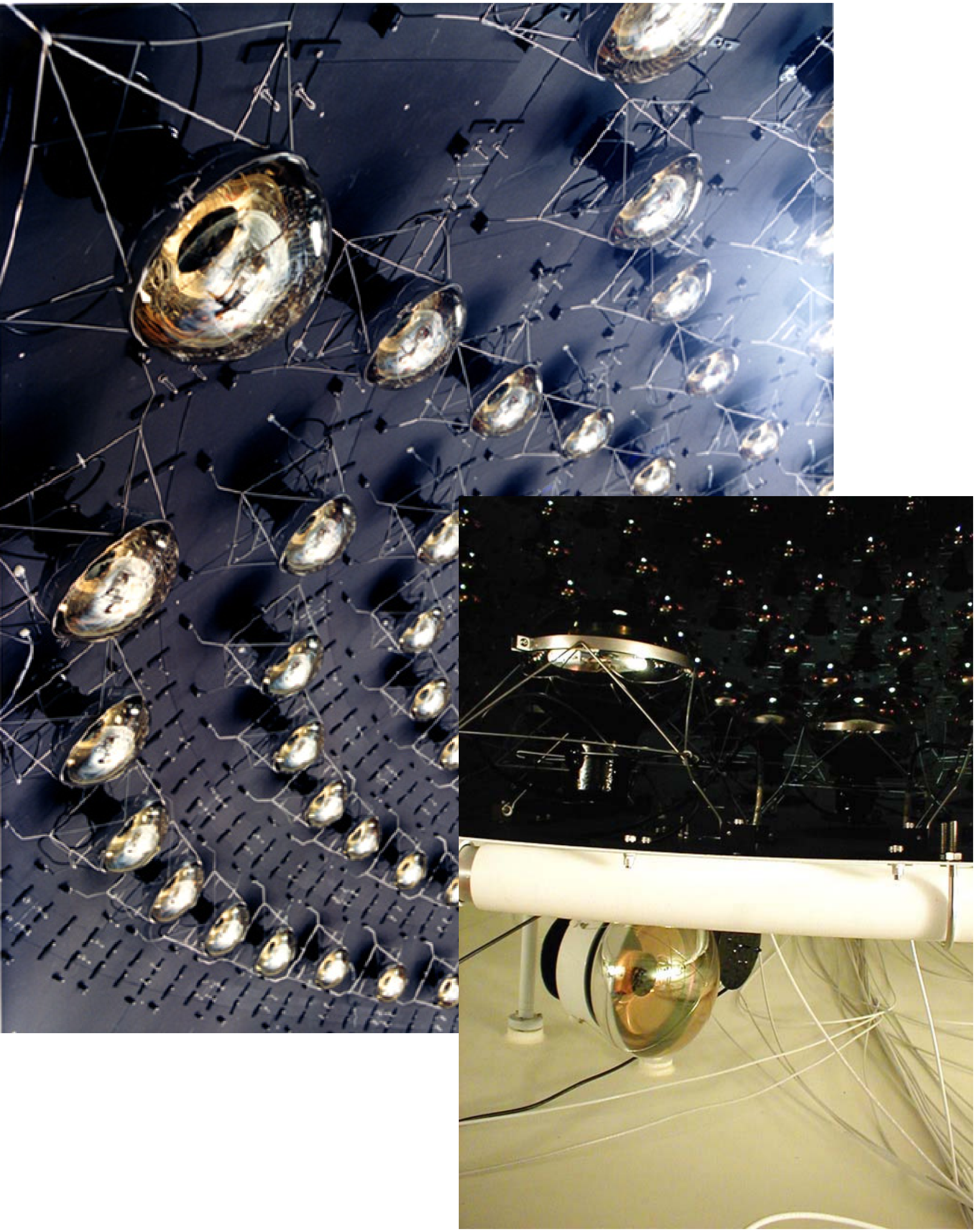

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MiniBooNE collaboration,
NIM.A599(2009)28

3. Events in the Detector

Times of hit-clusters (subevents)

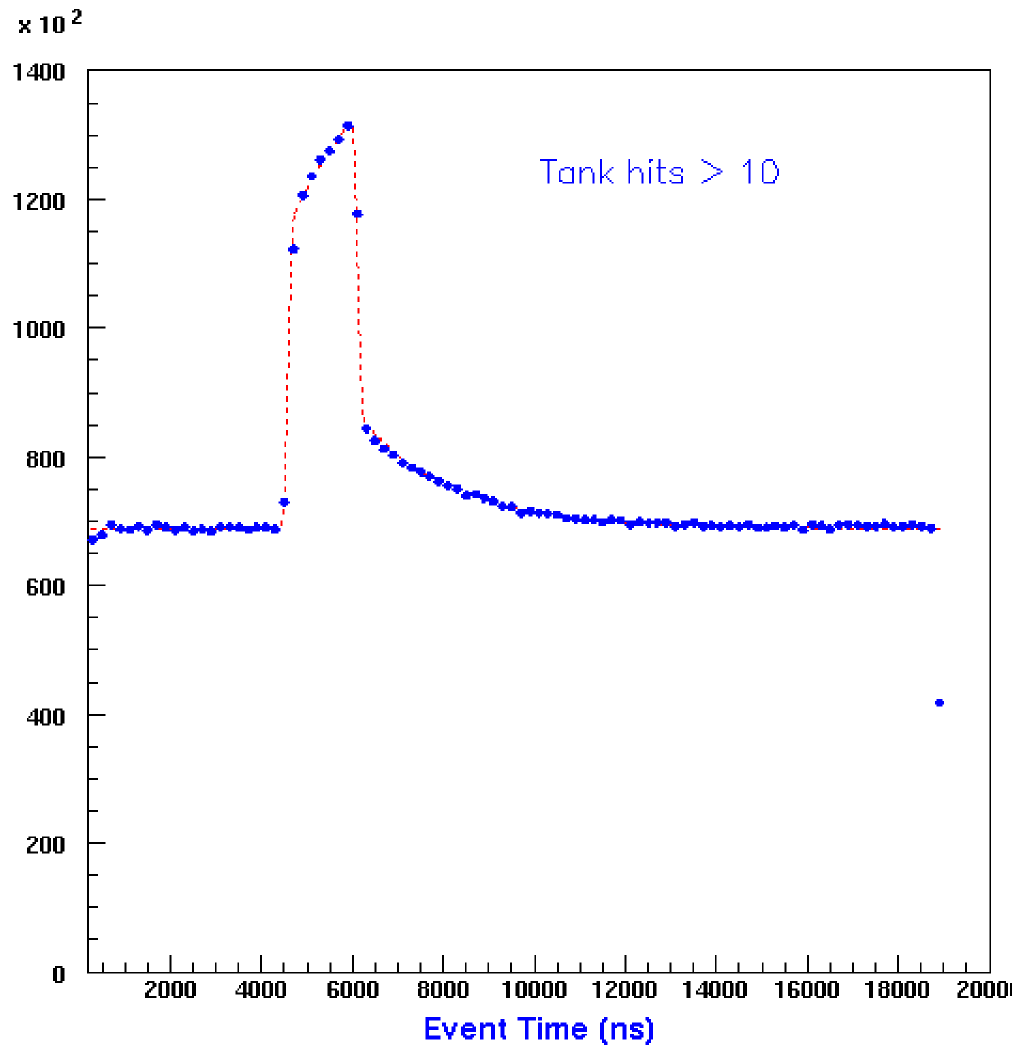
Beam spill (1.6μs) is clearly evident

- simple cuts eliminate cosmic backgrounds

Neutrino Candidate Cuts

- <6 veto PMT hits
  - Gets rid of muons
- >200 tank PMT hits
  - Gets rid of Michels
- Only neutrinos are left!

Beam and Cosmic BG



MiniBooNE collaboration,
NIM.A599(2009)28

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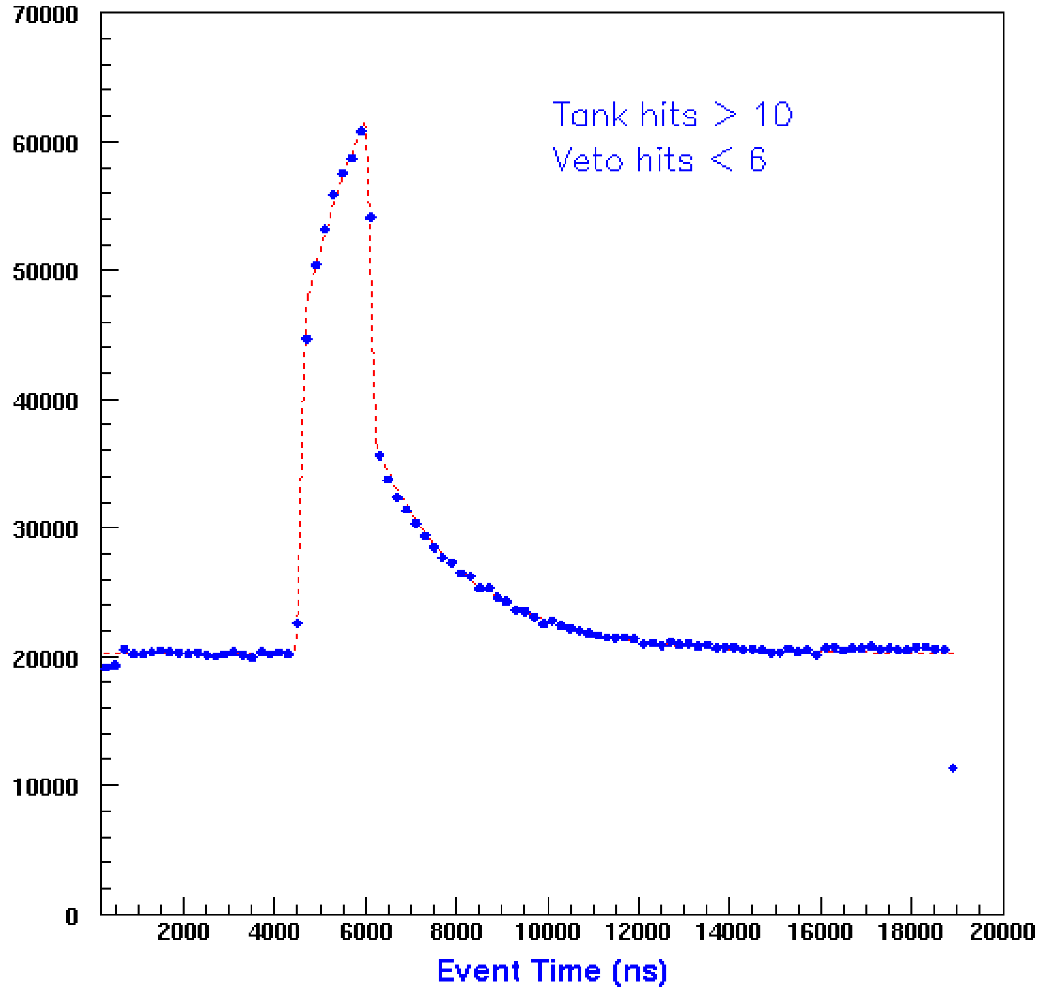

MiniBooNE collaboration,
NIM.A599(2009)28

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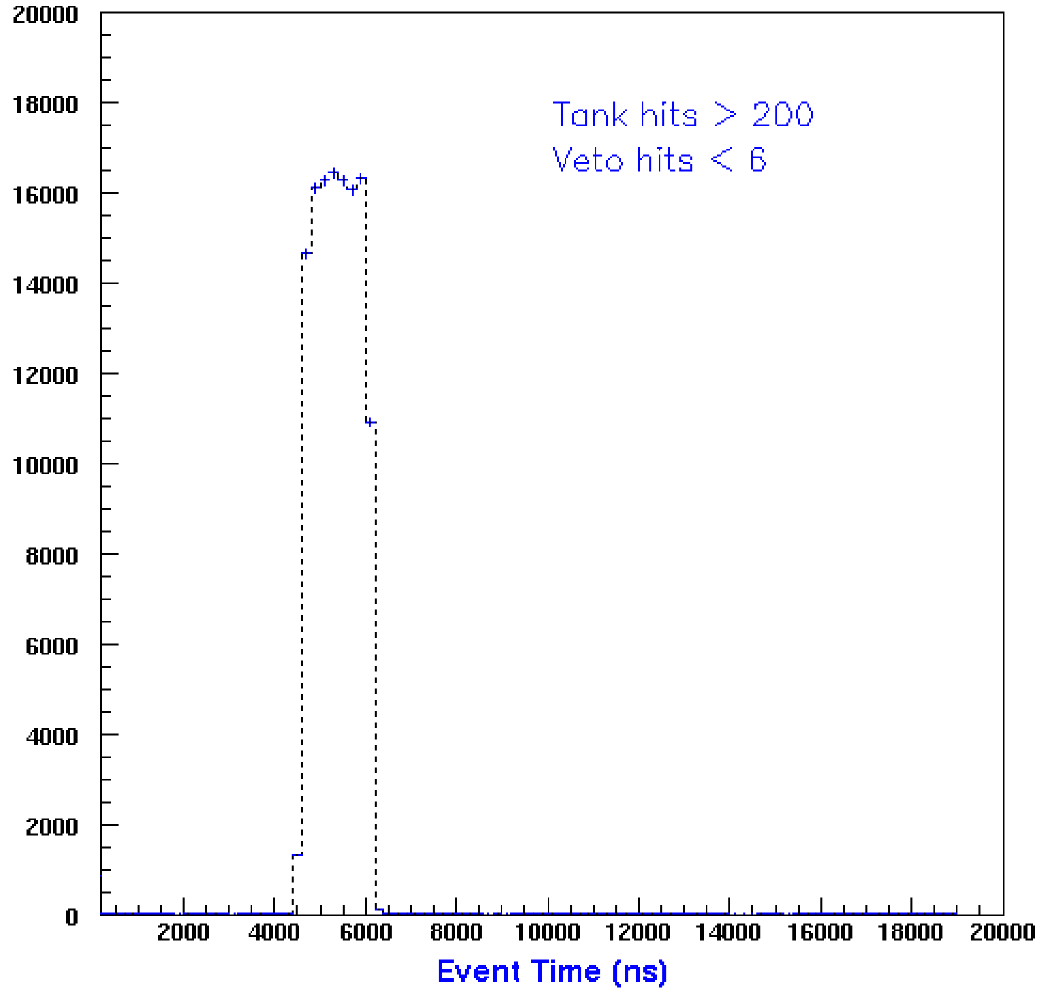
Beam Only



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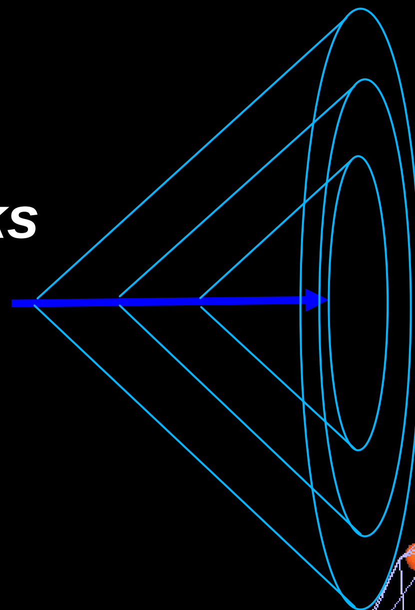
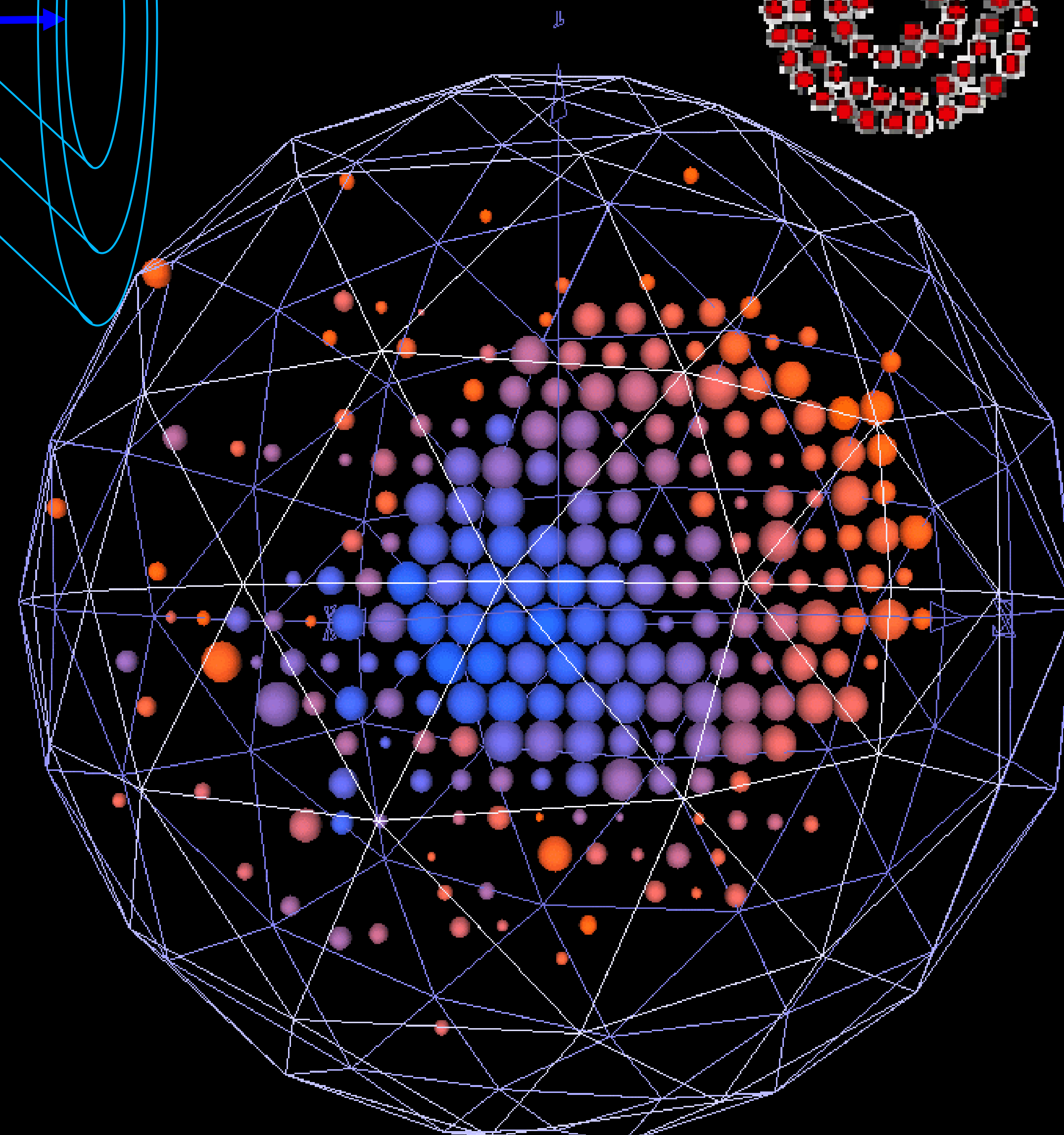
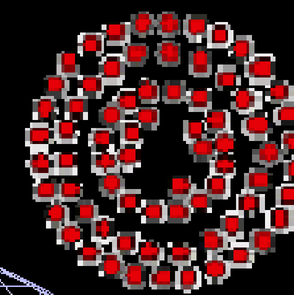
3. Events in the Detector

MiniBooNE collaboration, NIM.A599(2009)28

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







- Electrons
  - Scattered rings
    - Multiple scattering
    - Radiative processes
- Neutral Pions
  - Double rings
    - Decays to two photons

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MiniBooNE collaboration,
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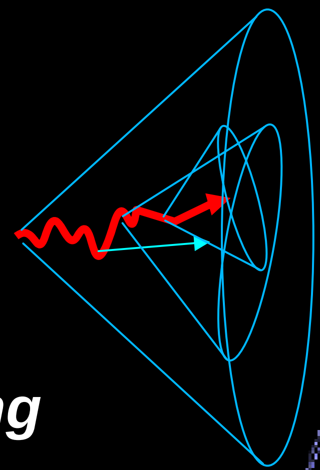

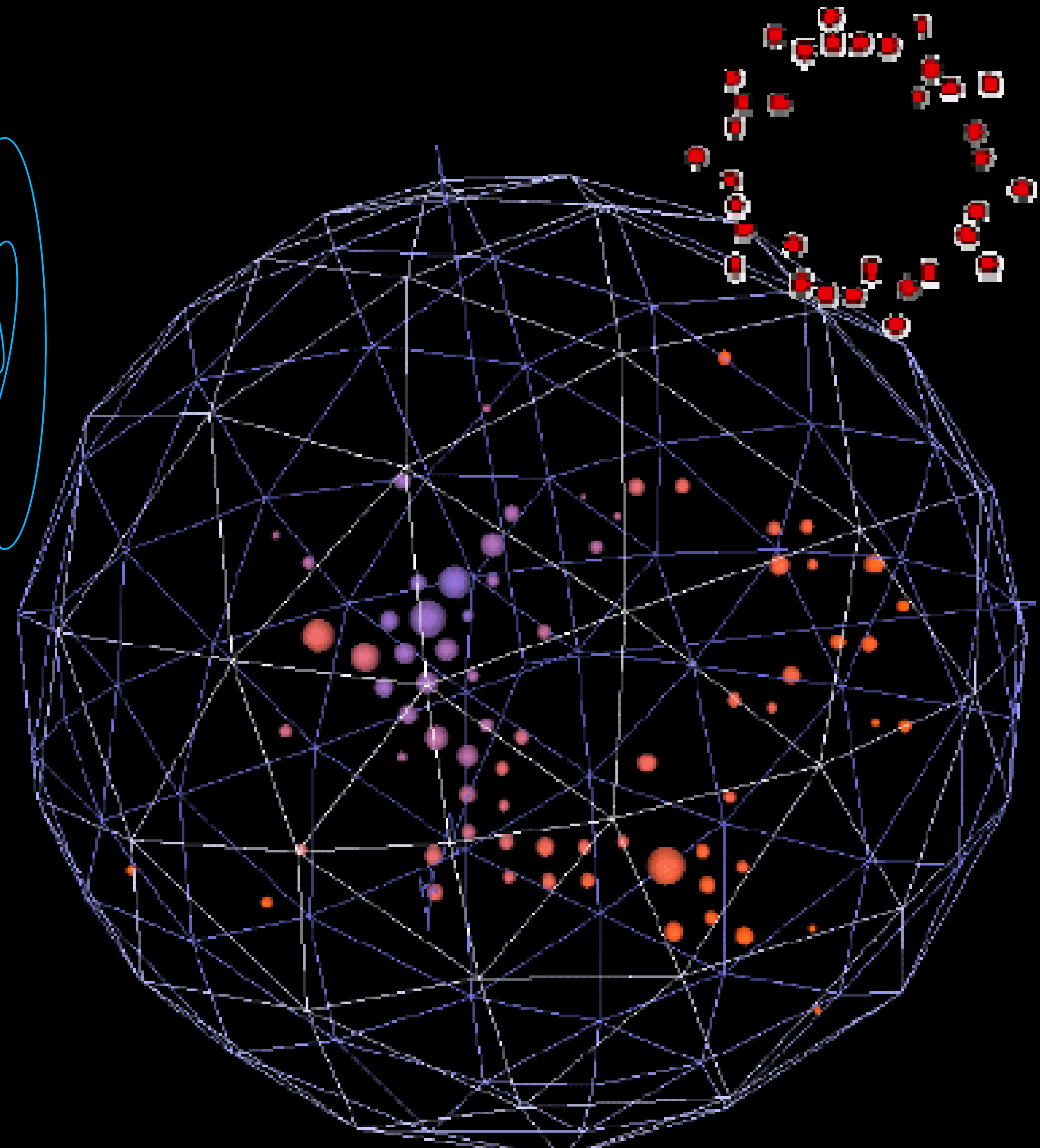

3. Events in the Detector

MiniBooNE collaboration, NIM.A599(2009)28

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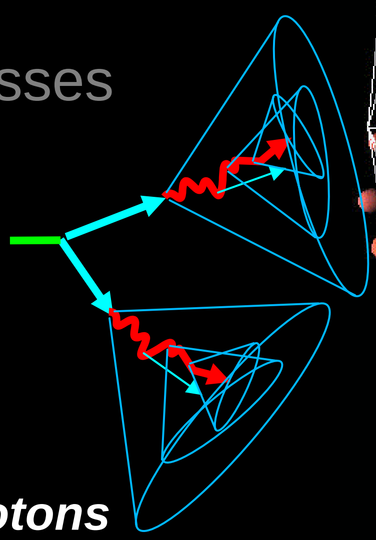

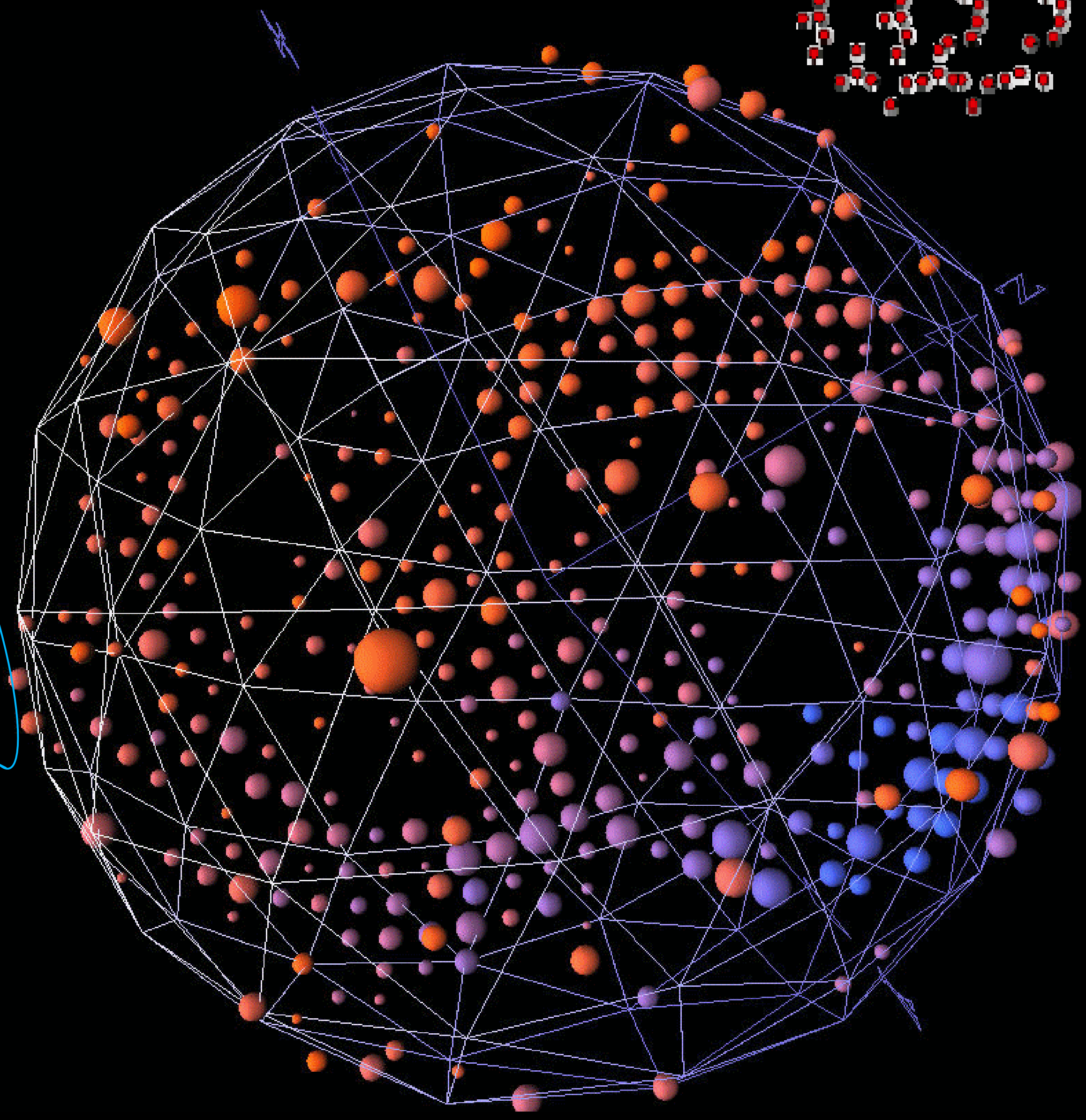

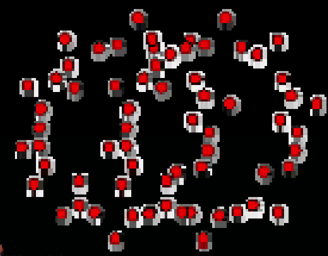

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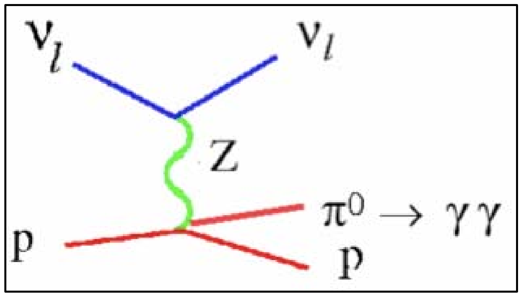
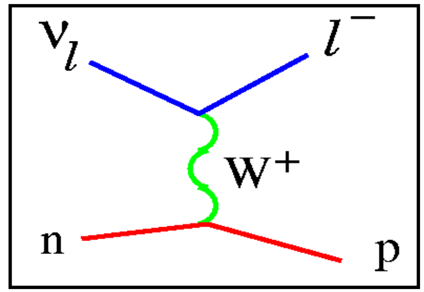
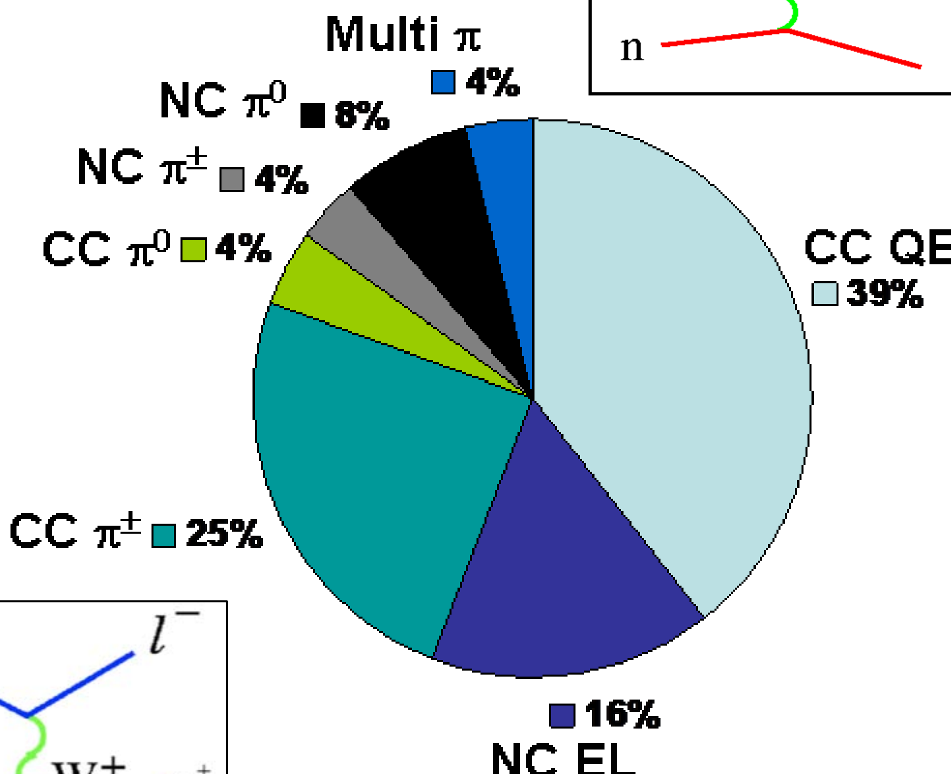
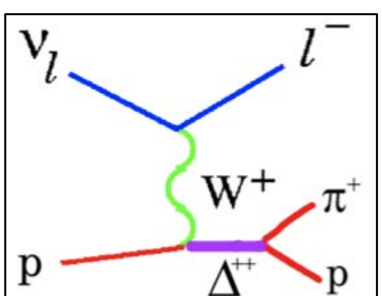
4. Cross section model



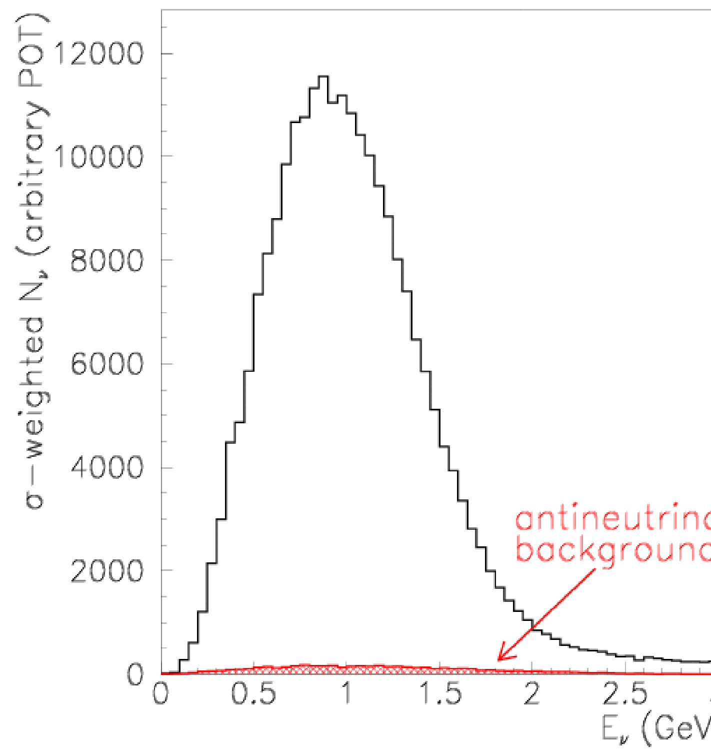






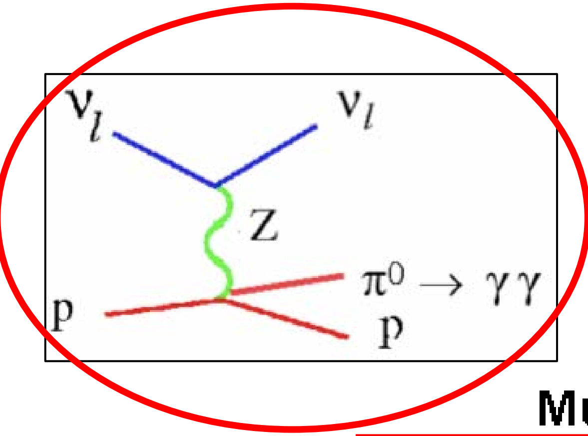
Predicted event rates before cuts (NUANCE Monte Carlo)

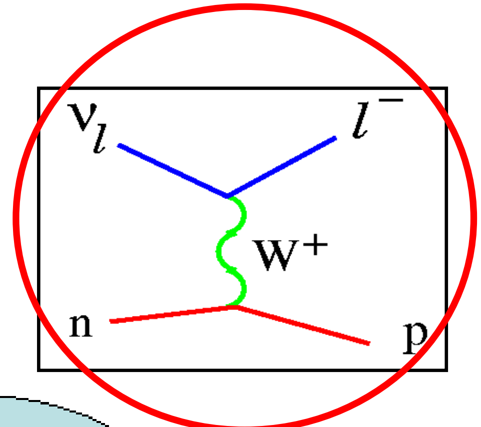
Casper, Nucl.Phys.Proc.Suppl.112(2002)161

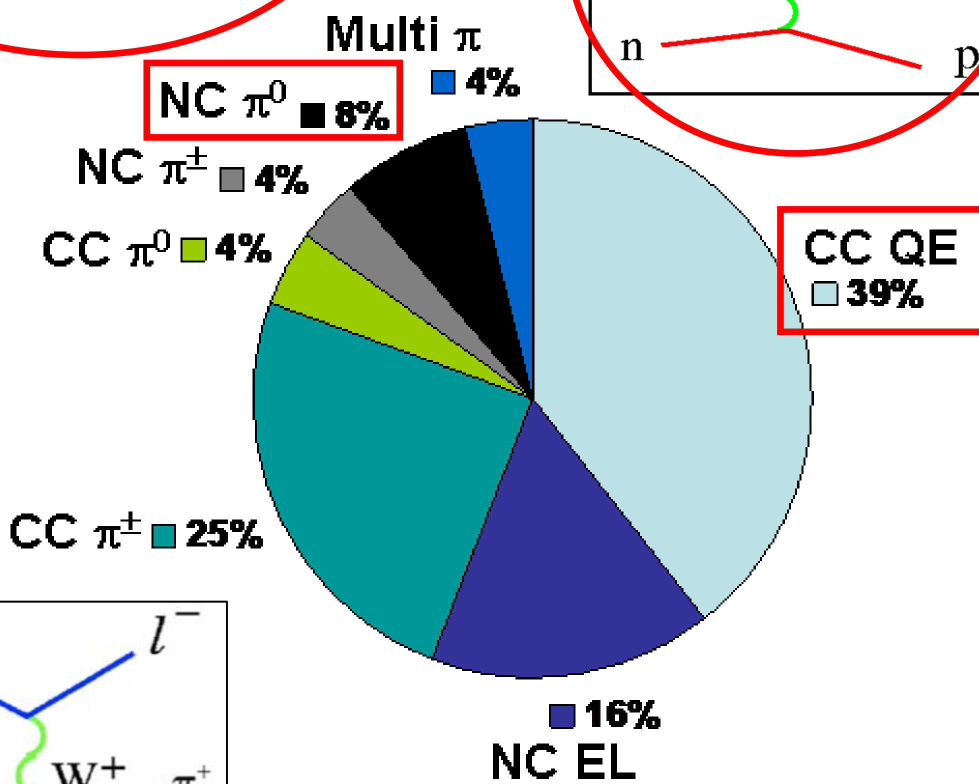


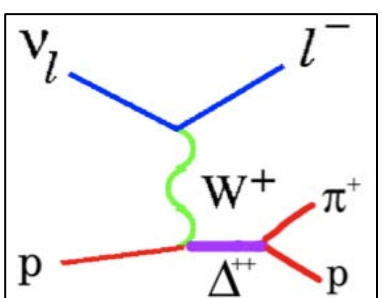
Event neutrino energy (GeV)

4. Cross section model



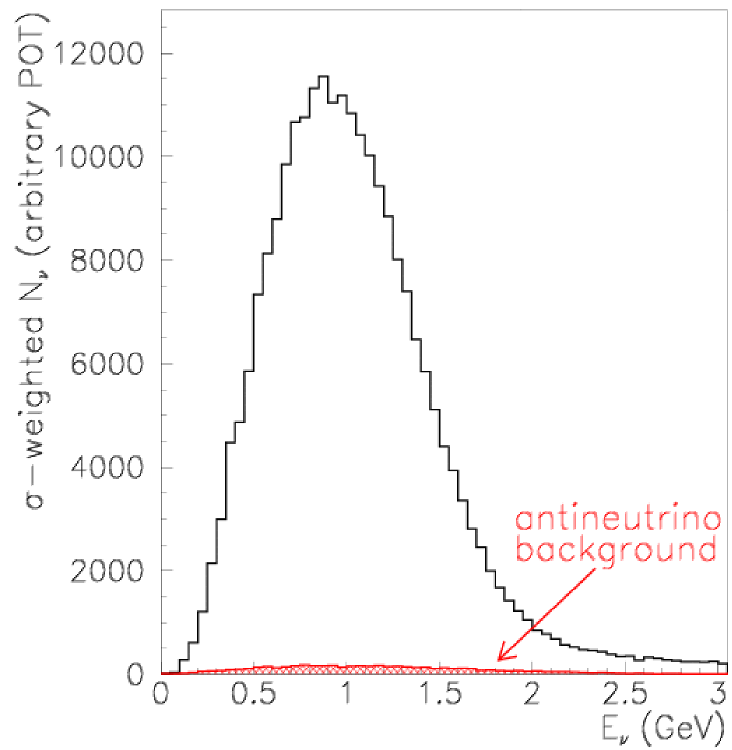






Predicted event rates before cuts (NUANCE Monte Carlo)

Casper, Nucl.Phys.Proc.Suppl.112(2002)161



Event neutrino energy (GeV)

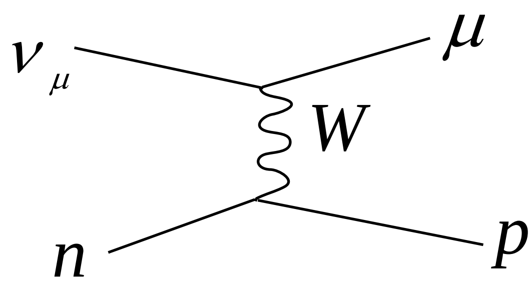
4. CCQE cross section model tuning

CCQE (Charged Current Quasi-Elastic)

ν_μ charged current quasi-elastic (ν_μ CCQE) interaction is the most abundant (~40%) and the fundamental interaction in MiniBooNE detector

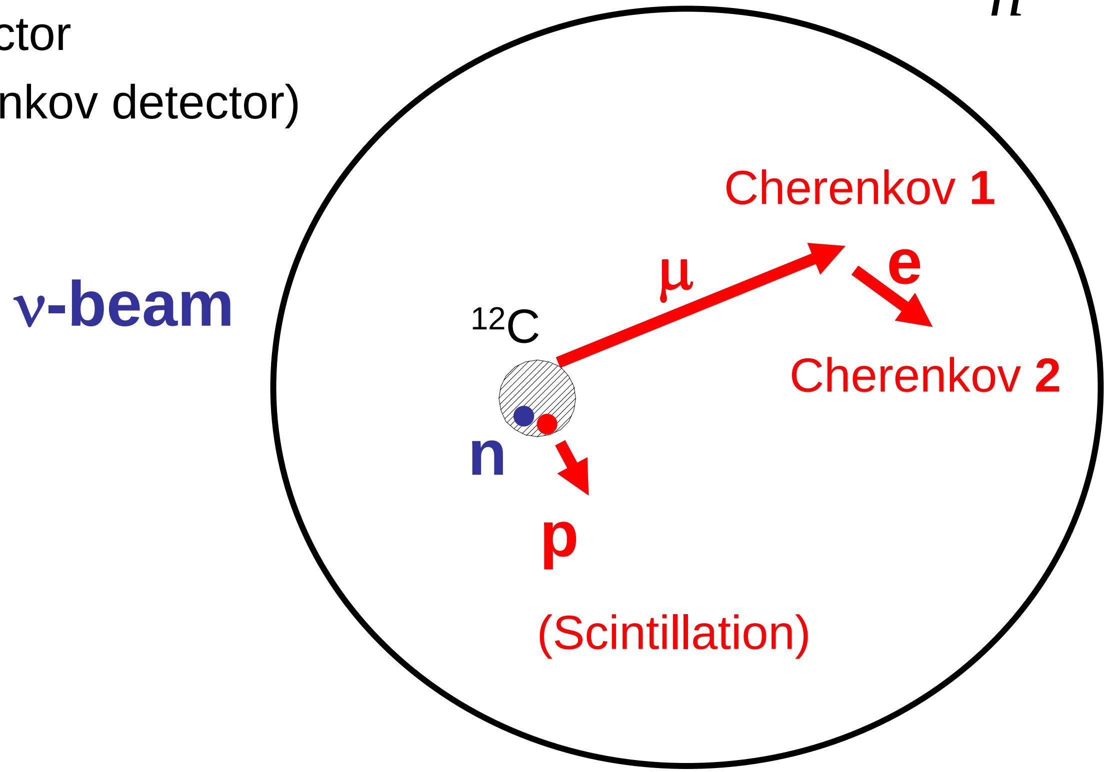
$$\nu_\mu + n \rightarrow p + \mu^-$$

$$(\nu_\mu + {}^{12}C \rightarrow X + \mu^-)$$



MiniBooNE detector

(spherical Cherenkov detector)



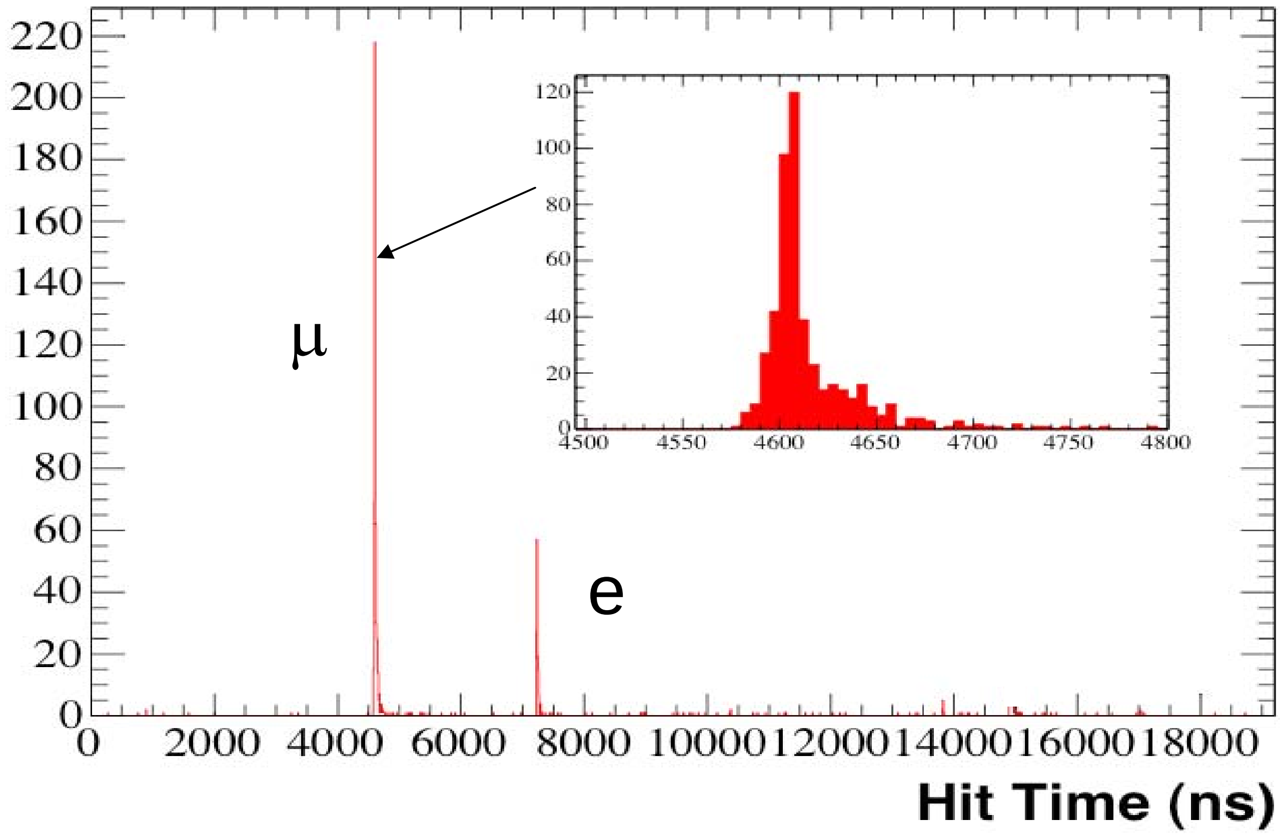
muon like Cherenkov light and subsequent decayed electron (Michel electron) like Cherenkov light are the signal of CCQE event

4. CCQE cross section model tuning

19.2 μs beam trigger window with the 1.6 μs spill
Multiple hits within a ~100 ns window form "subevents"

ν_μ CCQE interactions ($\nu+n \rightarrow \mu+p$) with characteristic two "subevent" structure from stopped $\mu \rightarrow \nu_\mu \nu_e e$

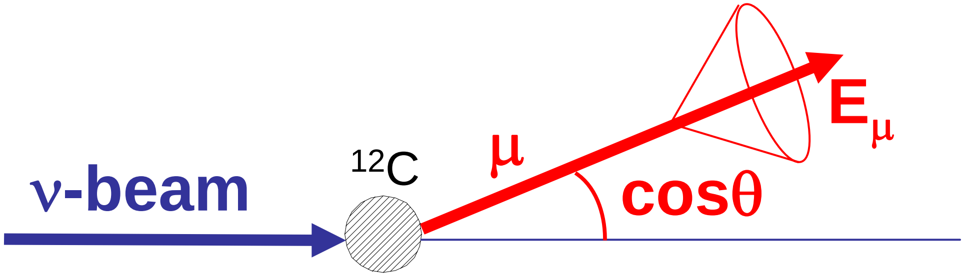
Number of tank hits for CCQE event



4. CCQE cross section model tuning

All kinematics are specified from 2 observables, muon energy E_μ and muon scattering angle θ_μ

Energy of the neutrino E_ν^{QE} and 4-momentum transfer Q_2^{QE} can be reconstructed by these 2 observables, under the assumption of CCQE interaction with bound neutron at rest ("QE assumption"). CCQE is the signal channel of ν_e candidate.



$$\nu_\mu + n \rightarrow p + \mu^-$$

$$(\nu_\mu + {}^{12}C \rightarrow X + \mu^-)$$

$$\nu_e + n \rightarrow p + e^-$$

$$(\nu_e + {}^{12}C \rightarrow X + e^-)$$

MiniBooNE collaboration
PRL100(2008)032301

4. CCQE cross section model tuning

The data-MC agreement in Q^2 (4-momentum transfer) is not good
We tuned nuclear parameters in Relativistic Fermi Gas model

Smith and Moniz,
Nucl.,Phys.,B43(1972)605

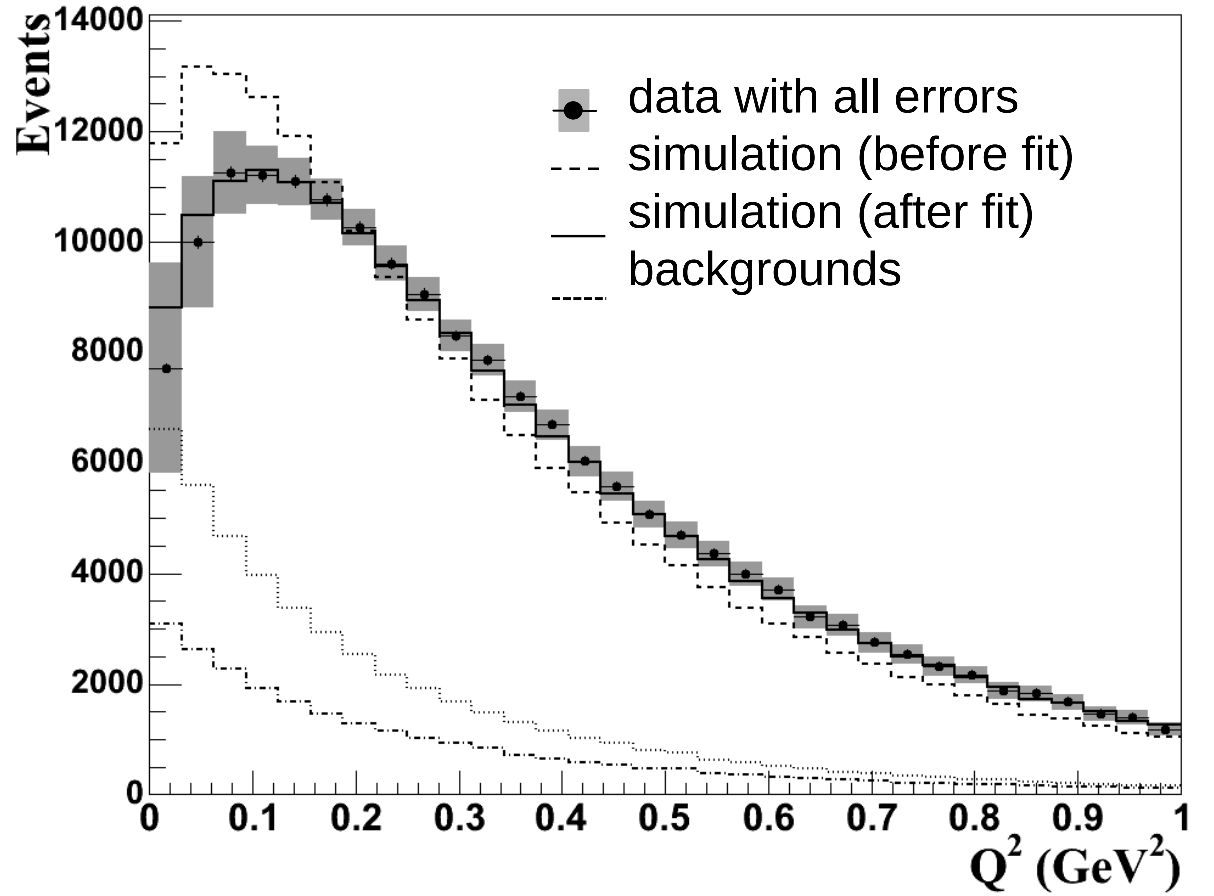
Q^2 fits to MB ν_μ CCQE data using the nuclear parameters:

M_A^{eff} - effective axial mass
κ - Pauli Blocking parameter

Relativistic Fermi Gas Model with tuned parameters describes ν_μ CCQE data well

This improved nuclear model is used in ν_e CCQE channel, too.

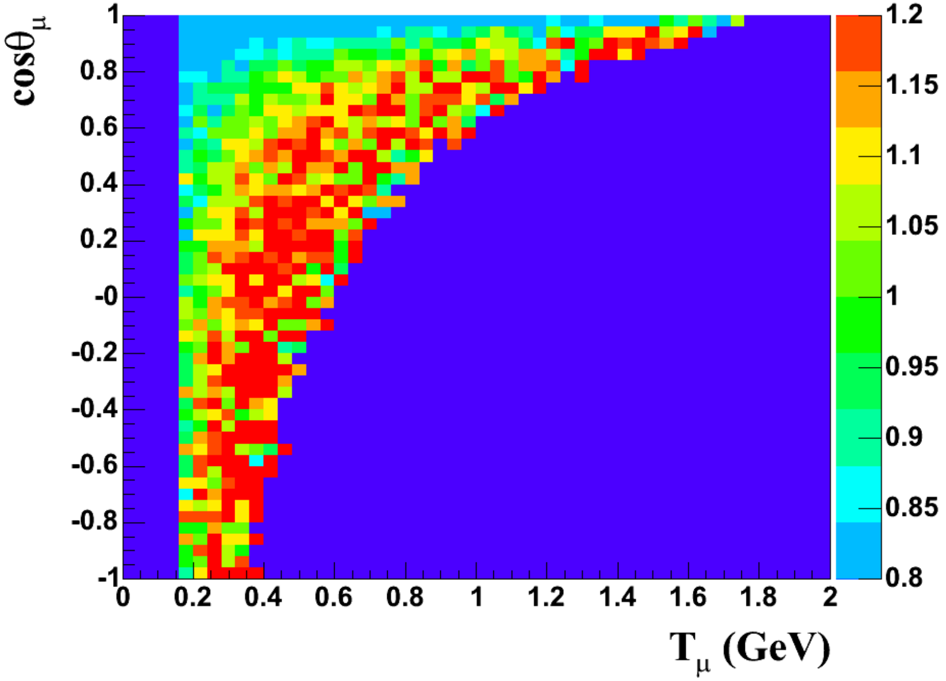
Q^2 distribution before and after fitting



4. CCQE cross section model tuning

Without knowing flux perfectly, we cannot modify cross section model

Data-MC ratio for T_μ-$\cos\theta_\mu$ plane, before tuning



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Data-MC mismatching follows Q^2 lines, not E_ν lines, therefore we can see the problem is not the flux prediction, but the cross section model

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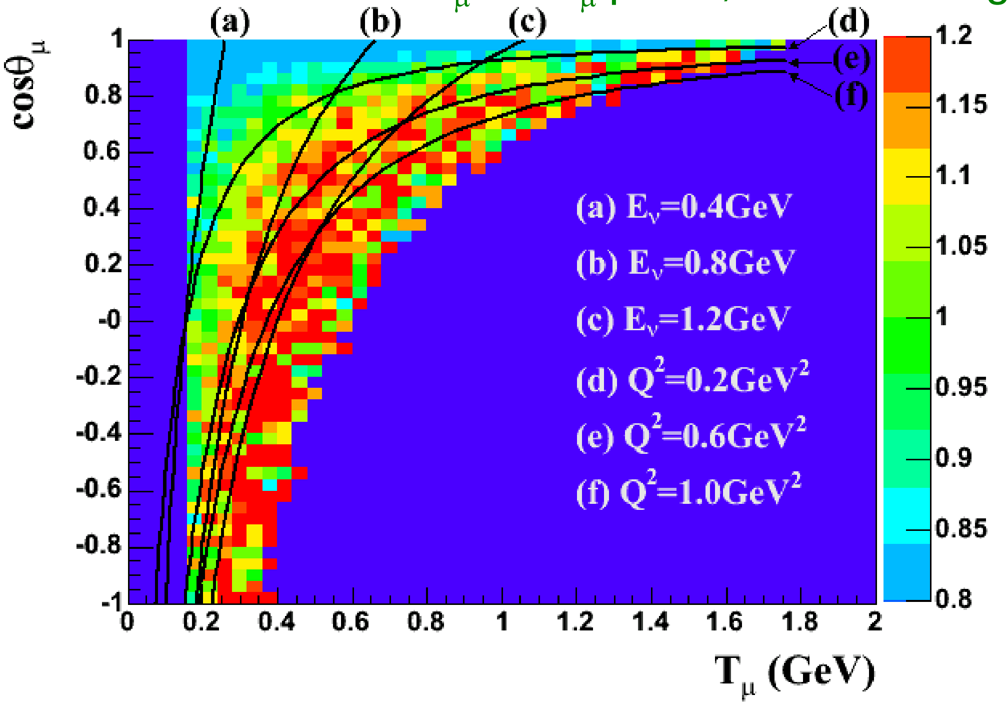

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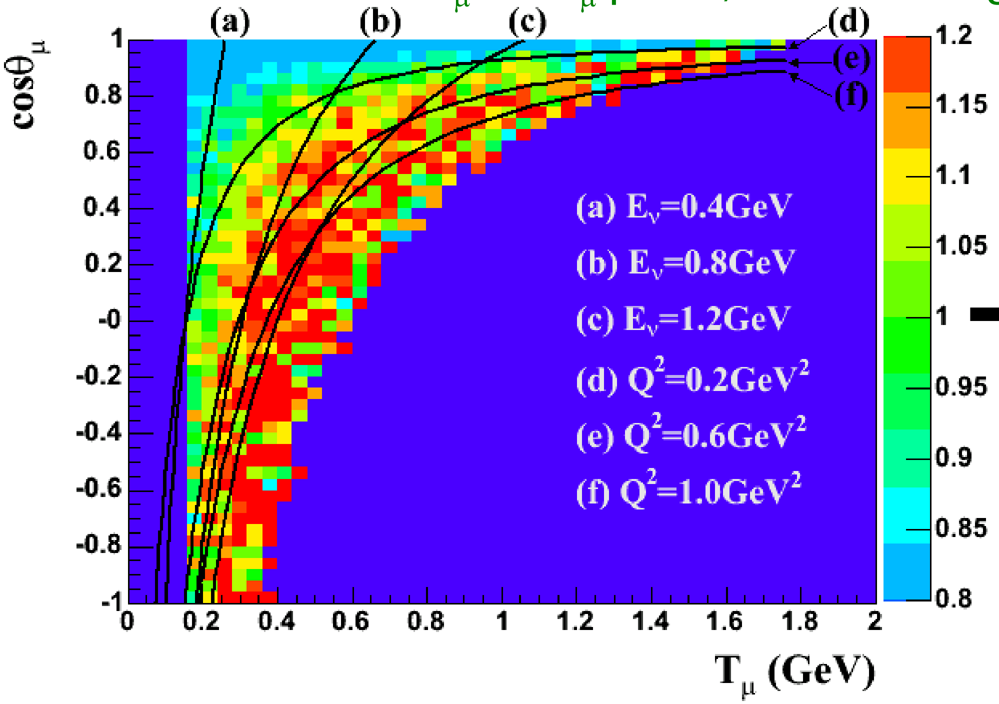
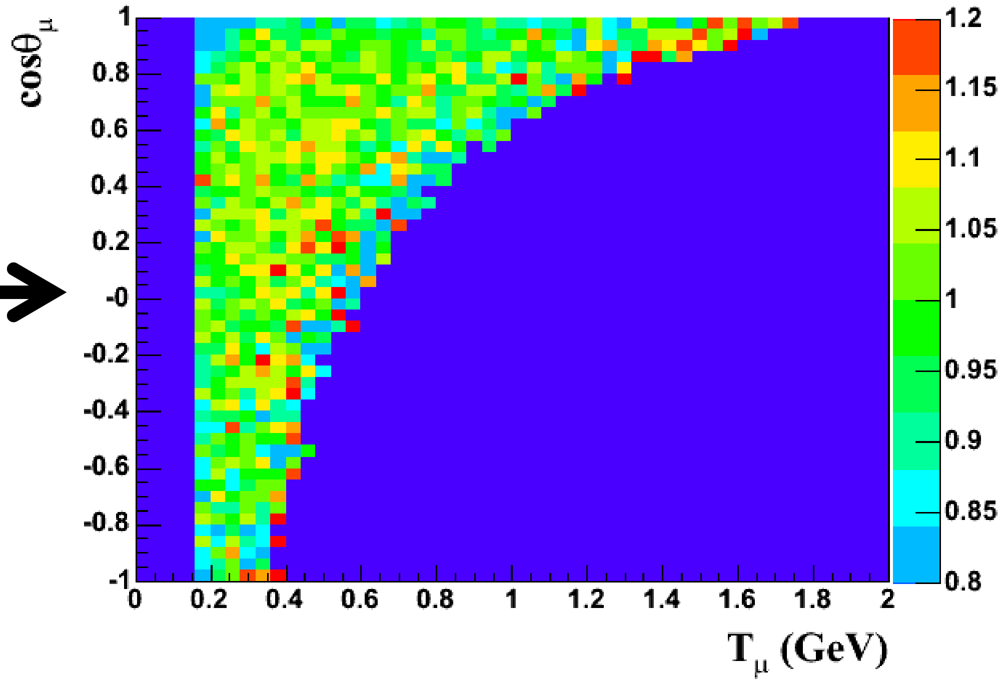


Data-MC ratio for T_μ-$\cos\theta_\mu$ plane,after tuning



4. NCπ^o rate tuning

NCπ^o (neutral current π^o production)

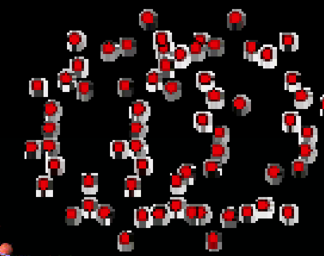
The signal of ν_e candidate is a single isolated electron

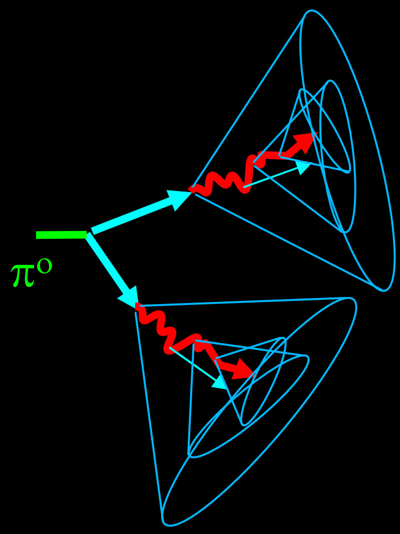
$$\nu_e + n \to p + e$$

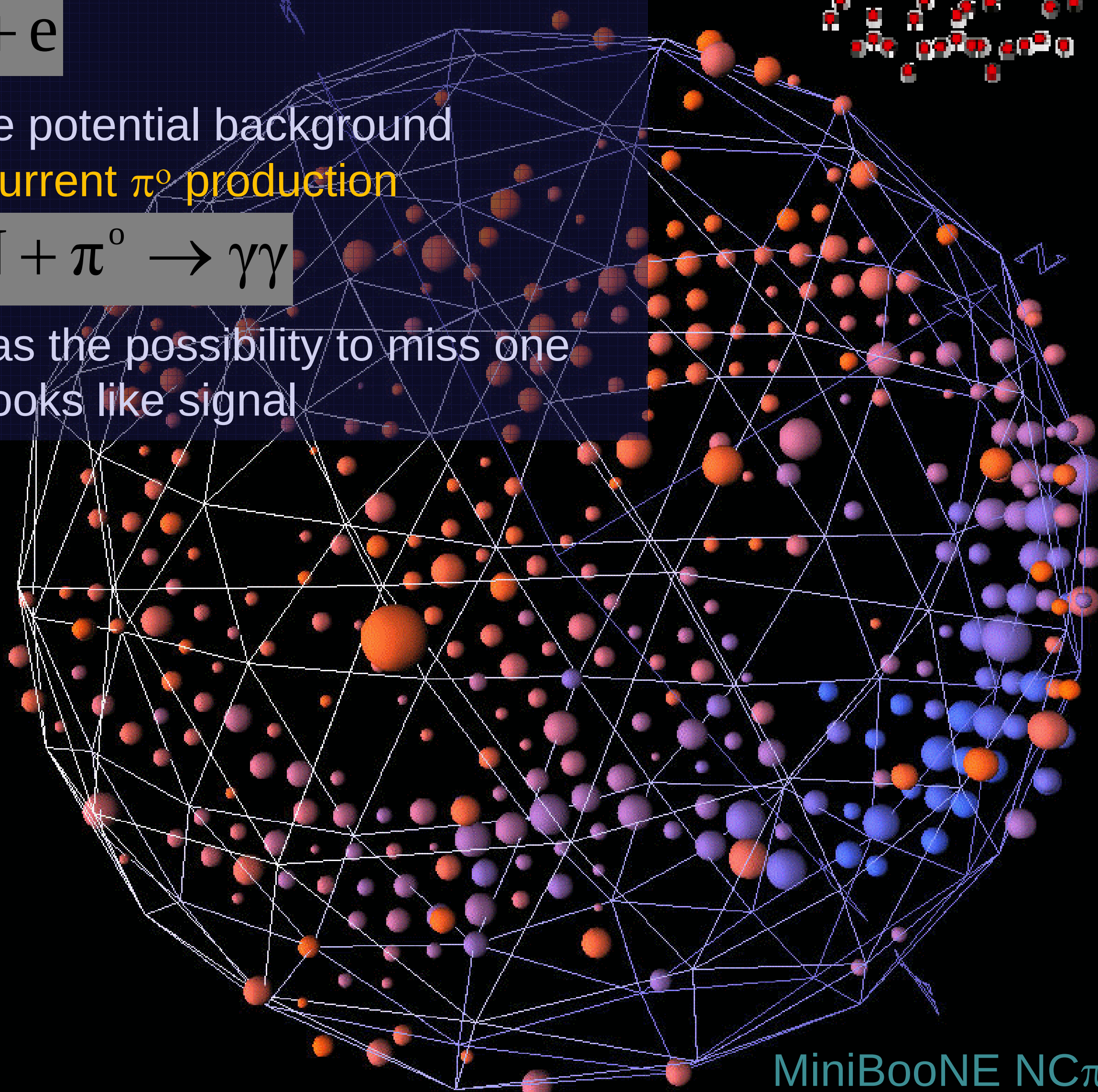
- single electromagnetic shower is the potential background
- the notable background is Neutral current π^o production

$$\nu_\mu + N \to \nu_\mu + N + \pi^o \to \gamma\gamma$$

Because of kinematics, one always has the possibility to miss one gamma ray, and hence this reaction looks like signal







MiniBooNE NCπ^o candidate

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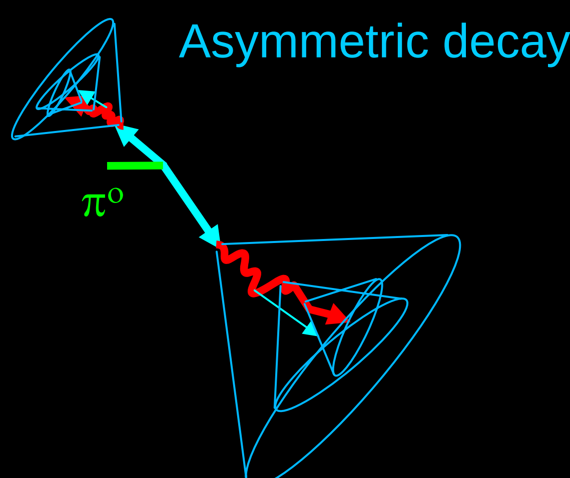
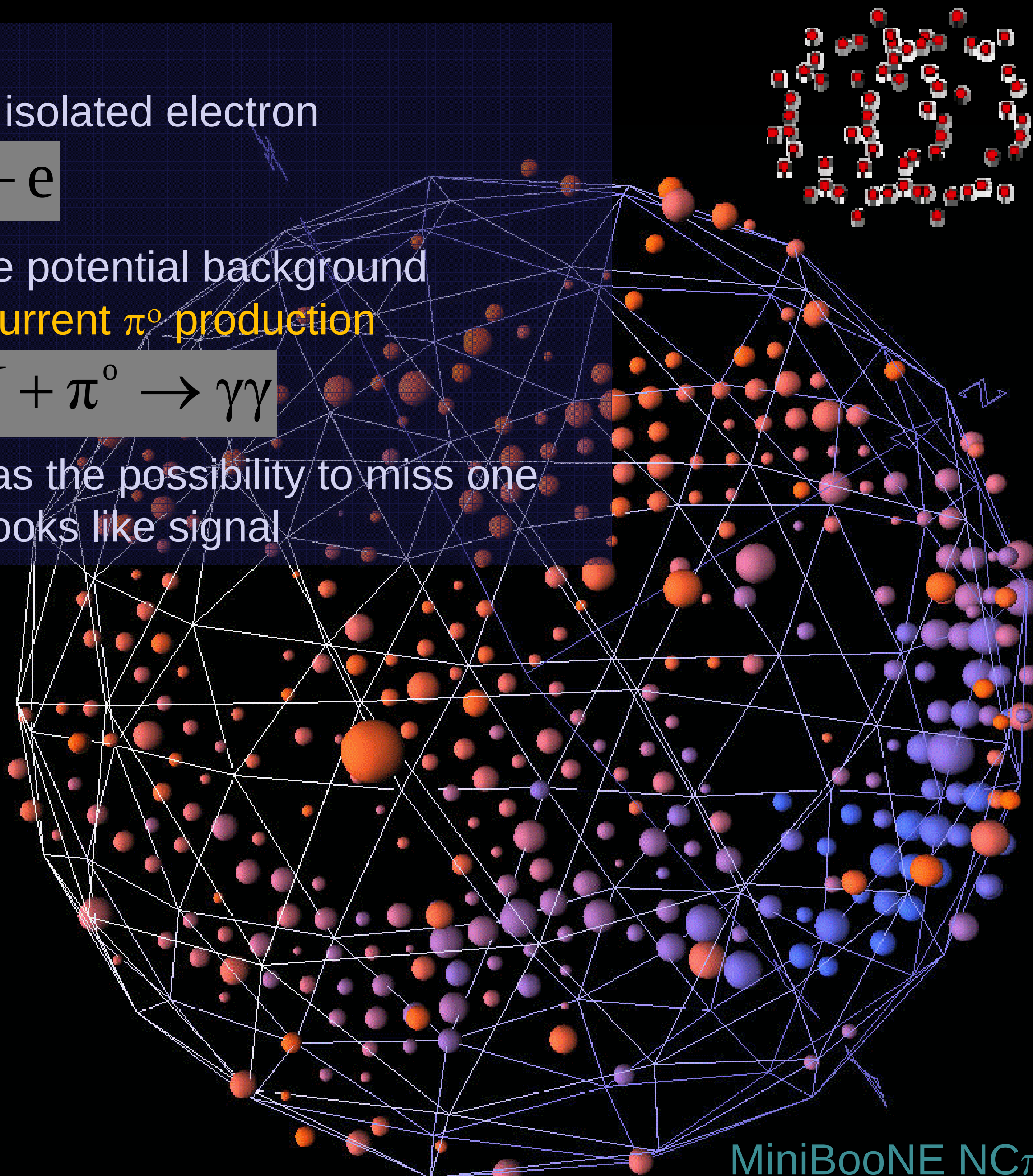
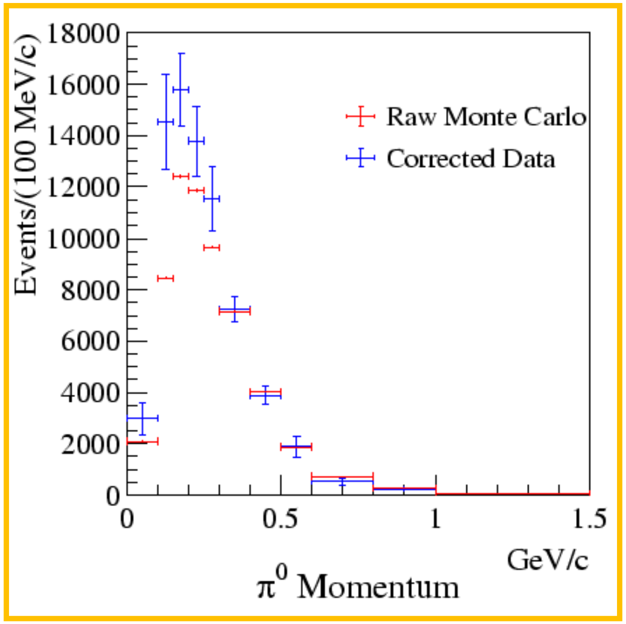




MiniBooNE NCπ^o candidate

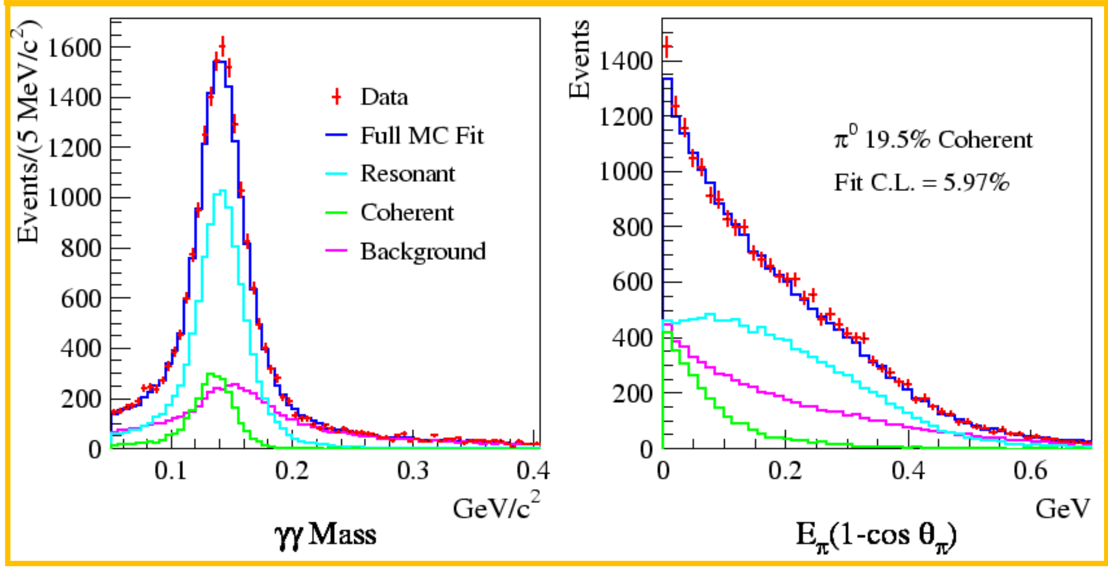
4. NCπº rate tuning

We tuned NCπº rate from our NCπº measurement. Since loss of gamma ray is pure kinematic effect, after tuning we have a precise prediction for intrinsic NCπº background for ν_e appearance search.



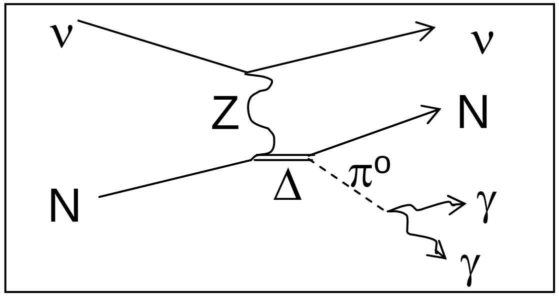
MiniBooNE collaboration
PLB664(2008)41

Data-Mc comparison of πº kinematics (after tuning)



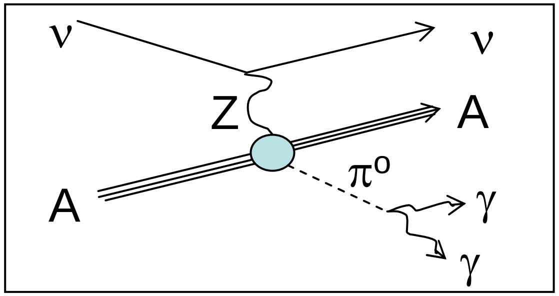
Resonance

$$\nu_\mu + N \rightarrow \nu_\mu + N + \pi^o$$



Coherent

$$\nu_\mu + A \rightarrow \nu_\mu + A + \pi^o$$



4. MiniBooNE cross section results

NuInt09, May18-22, 2009, Sitges, Spain
All talks proceedings are available on online (open access),
http://proceedings.aip.org/proceedings/confproceed/1189.jsp

NuInt09 MiniBooNE results
In NuInt09, MiniBooNE had 6 talks and 2 posters

1. charged current quasielastic (CCQE) cross section measurement
   by Teppei Katori, PRD81(2010)092005
2. neutral current elastic (NCE) cross section measurement
   by Denis Perevalov, arXiv:1007.4730
3. neutral current π^o production (NCπ^o) cross section measurement (ν and anti-ν)
   by Colin Anderson, PRD81(2010)013005
4. charged current single pion production (CCπ^+) cross section measurement
   by Mike Wilking, paper in preparation
5. charged current single π^o production (CCπ^o) cross section measurement
   by Bob Nelson, paper in preparation
6. improved CC1π^+ simulation in NUANCE generator
   by Jarek Novak
7. CCπ^+/CCQE cross section ratio measurement
   by Steve Linden, PRL103(2009)081801
8. anti-νCCQE measurement
   by Joe Grange, paper in preparation

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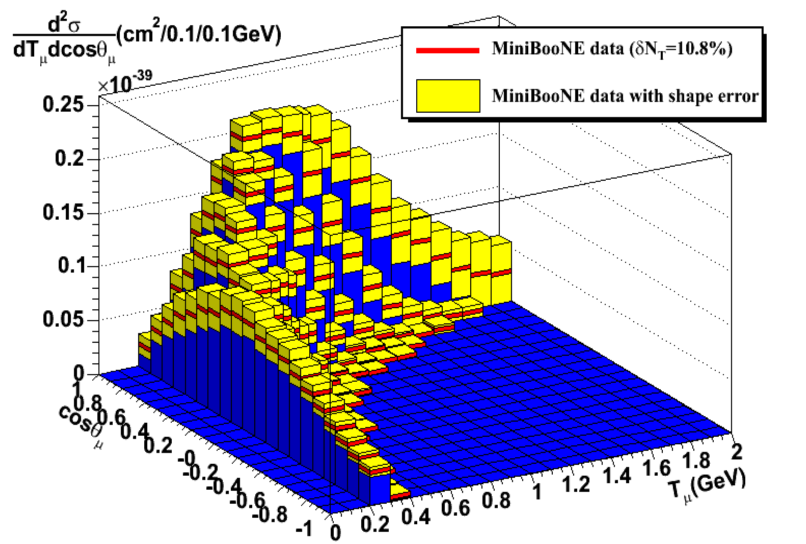
NuInt09 MiniBooNE results
In NuInt09, MiniBooNE had 6 talks and 2 posters

1. charged current quasielastic (CCQE) cross section measurement
   by Teppei Katori, PRD81(2010)092005

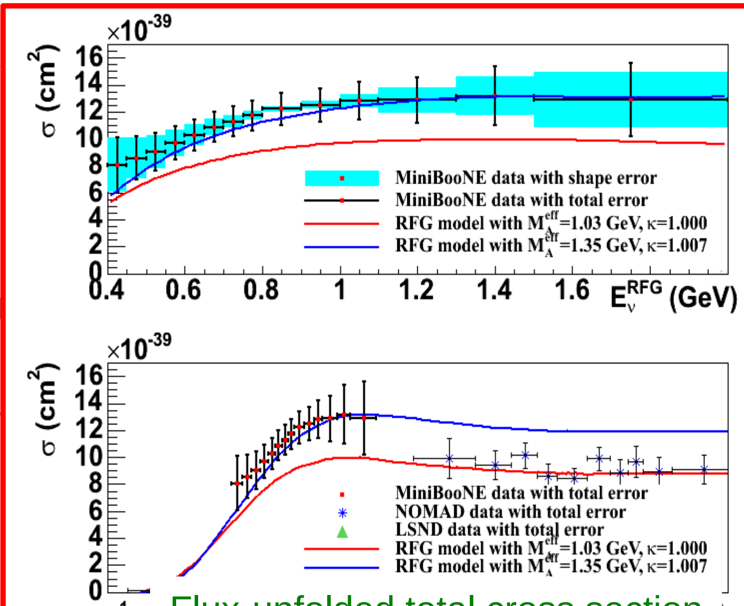
1. the first measurement of CCQE double differential cross section
2. measured Q^2 shape prefer high axial mass (M_A) under RFG model
3. ~30% higher absolute cross section from the recent NOMAD result

ent (ν and anti-ν)
Colin Anderson, PRD81(2010)013005

4 (CCπ
5 CCπ^o)
6 E gen
7 uremen
01
8



Flux-integrated double differential cross section



Flux-unfolded total cross section

1. Introduction

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3. Events in the detector

4. Cross section model

5. Oscillation analysis

6. Neutrino oscillation result

7. New Low energy excess result

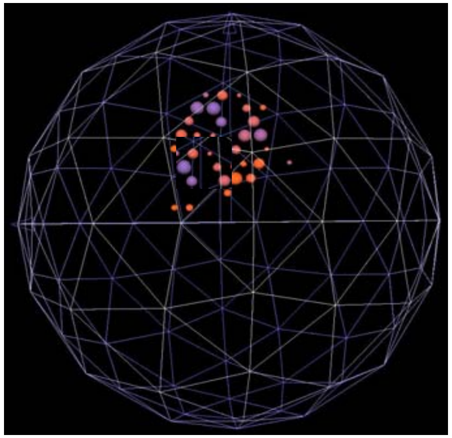
8. Anti-neutrino oscillation result

9. Neutrino disappearance result

5. Blind analysis

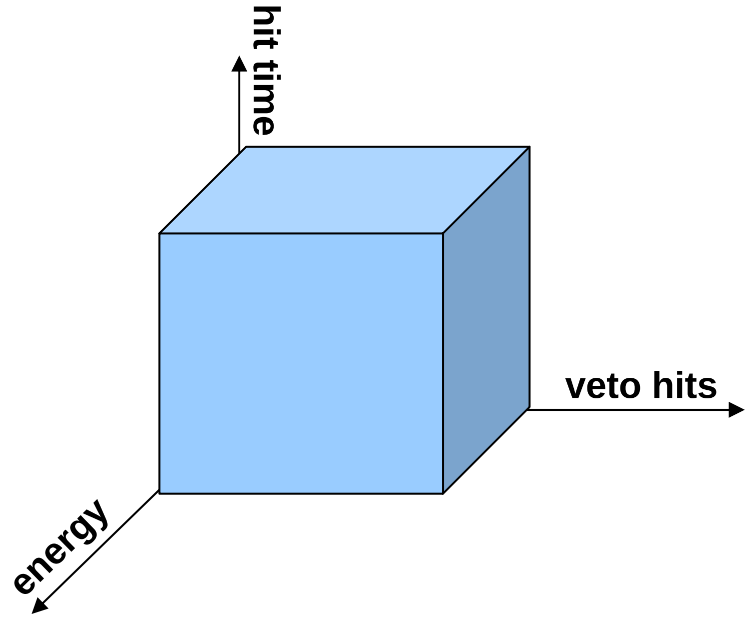
$$\nu_e + n \rightarrow p + e^-$$

$$(\nu_e + {}^{12}C \rightarrow X + e^-)$$



The MiniBooNE signal is small but relatively easy to isolate

The data is described in n-dimensional space;



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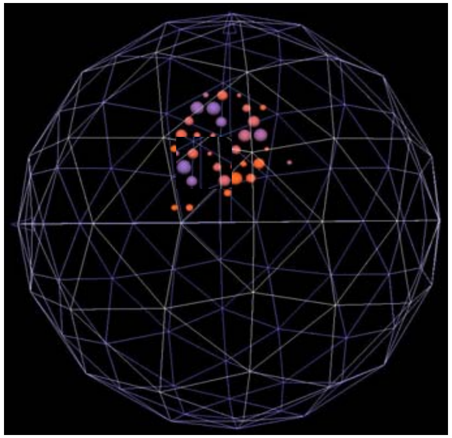

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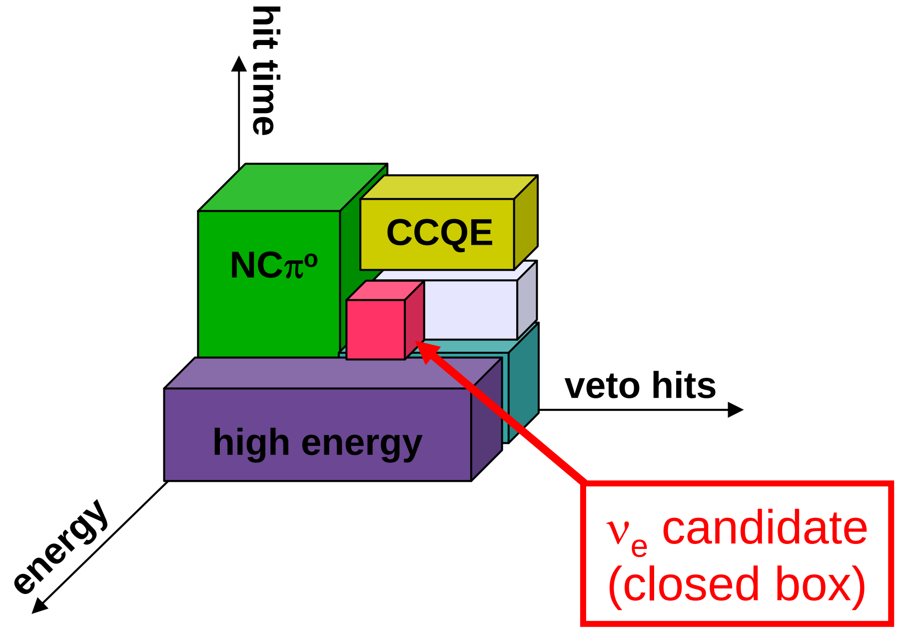
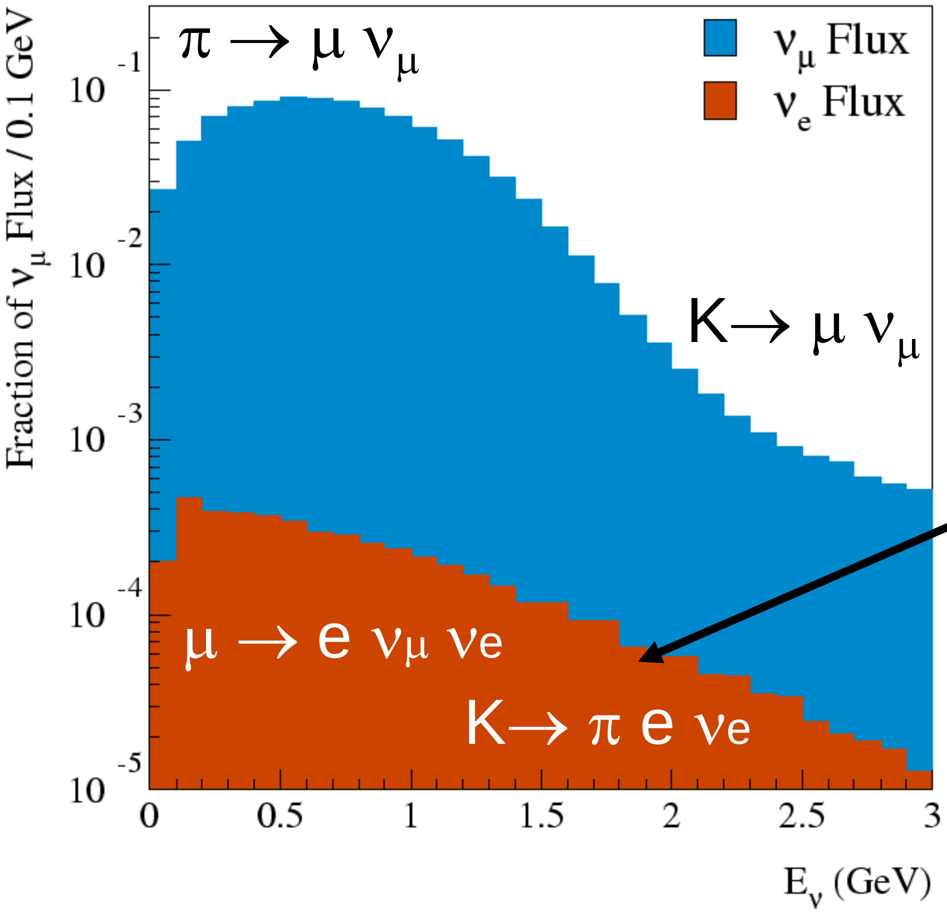


The data is classified into "box". For boxes to be "opened" to analysis they must be shown to have a signal < 1σ. In the end, 99% of the data were available (boxes need not to be exclusive set)

5. Blind analysis



"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%)

Since MiniBooNE is blind analysis experiment, we need to constraint intrinsic ν_e background without measuring directly

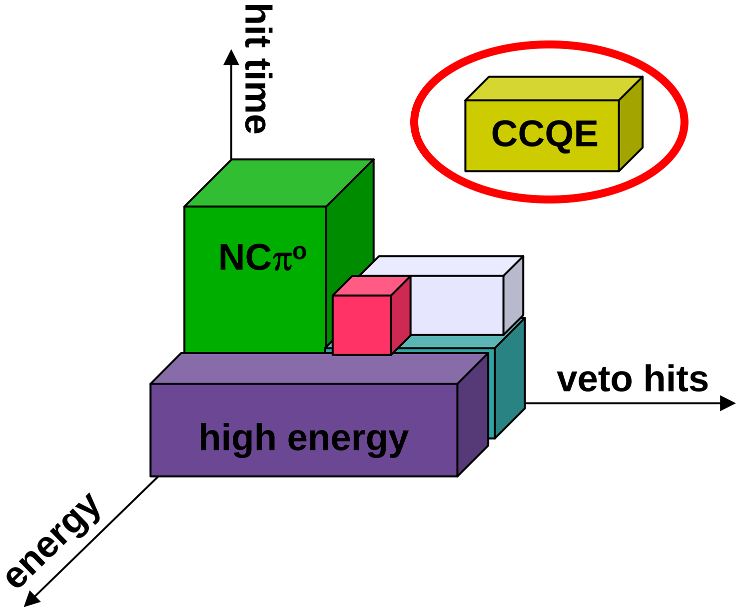
(1) μ decay ν_e background
(2) K decay ν_e background

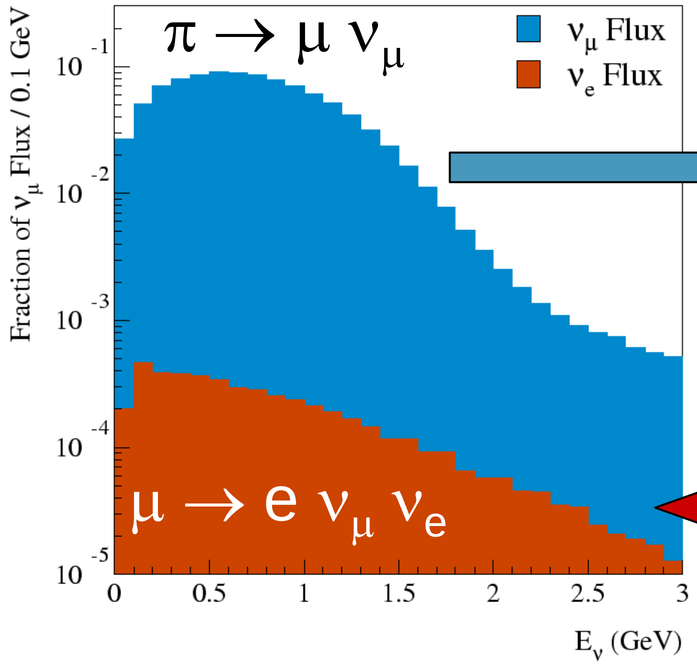
ν_e/ν_μ = 0.5%
Antineutrino content: 6%

5. Blind analysis

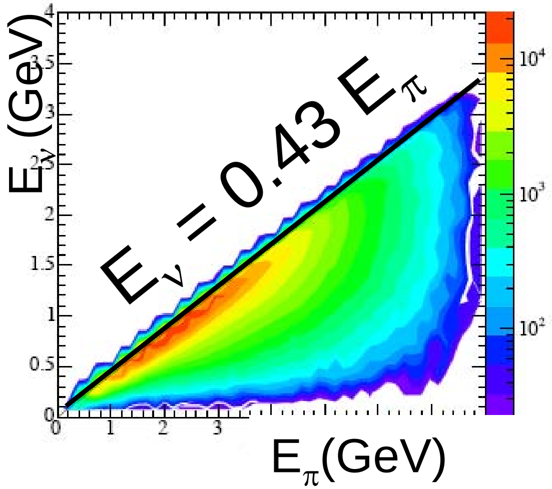
(1) measure ν_μ flux from ν_μCCQE event to constraint ν_e background from μ decay

ν_μCCQE is one of the open boxes.
Kinematics allows connection to π flux, hence intrinsic ν_e background from μ decay is constraint. In the really, simultaneous fit of ν_eCCQE and ν_μCCQE take care of this.





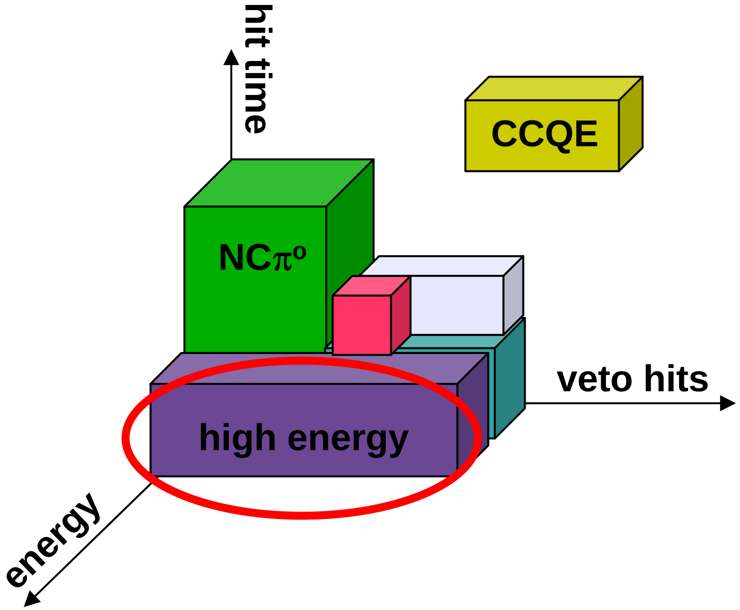
Eν-Eπ space

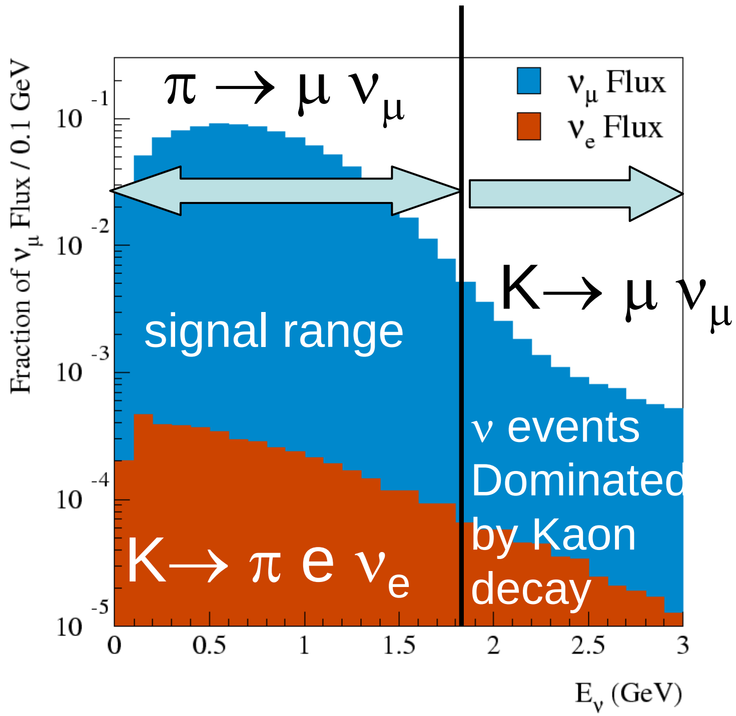


5. Blind analysis

(2) measure high energy ν_μ events to constraint ν_e background from K decay

At high energies, above “signal range” ν_μ and “ν_e -like” events are largely due to kaon decay





example of open boxes;
- ν_μCCQE
- high energy event
- $CC\pi^+$
- NC elastics
- NC π^o
- NC electron scattering
- Michel electron

etc....

5. MiniBooNE oscillation analysis structure

Start with a GEANT4 flux prediction for the ν spectrum from π and K produced at the target

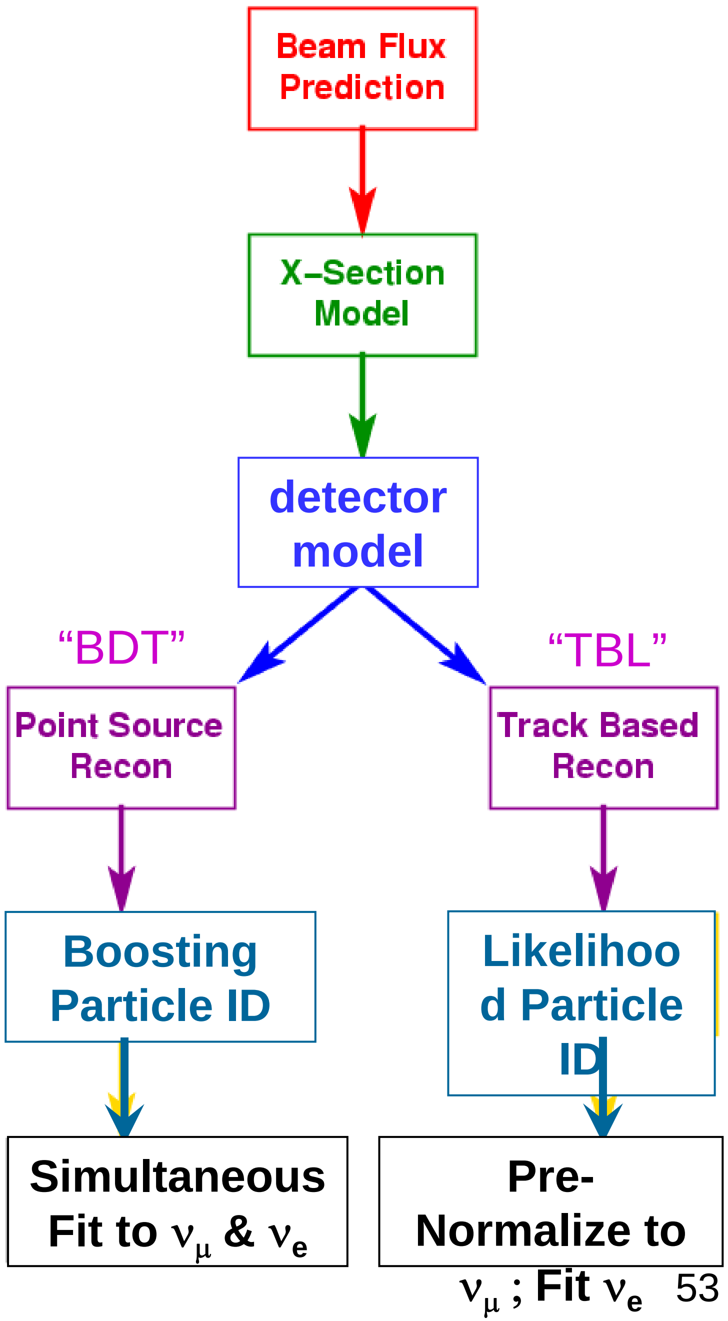
Predict ν interactions using NUANCE neutrino interaction generator

Pass final state particles to GEANT3 to model particle and light propagation in the tank

Starting with event reconstruction, independent analyses form: (1) Track Based Likelihood (TBL) and (2) Boosted Decision Tree (BDT)

Develop particle ID/cuts to separate signal from background

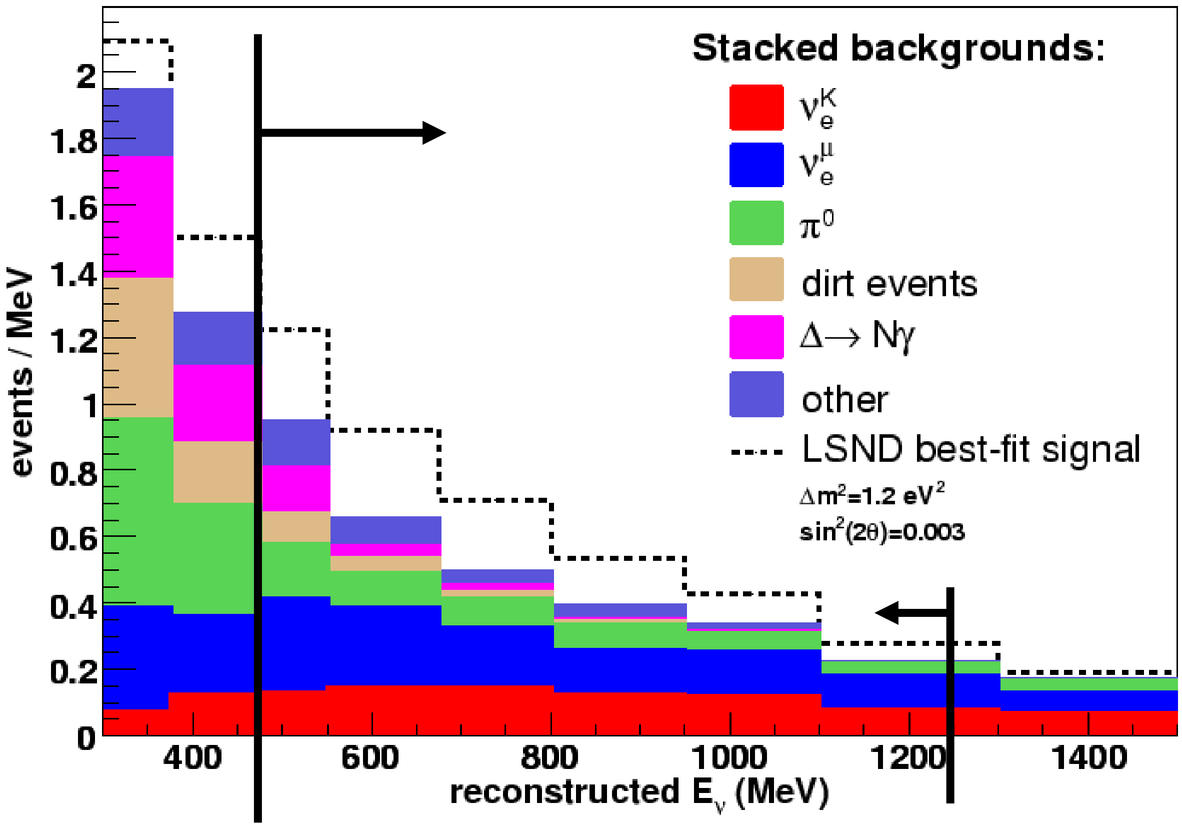
Fit reconstructed E_ν^{QE} spectrum for oscillations



5. Track-Based Likelihood (TBL) analysis

TBL analysis summary

- Oscillation analysis uses 475MeV<E<1250MeV



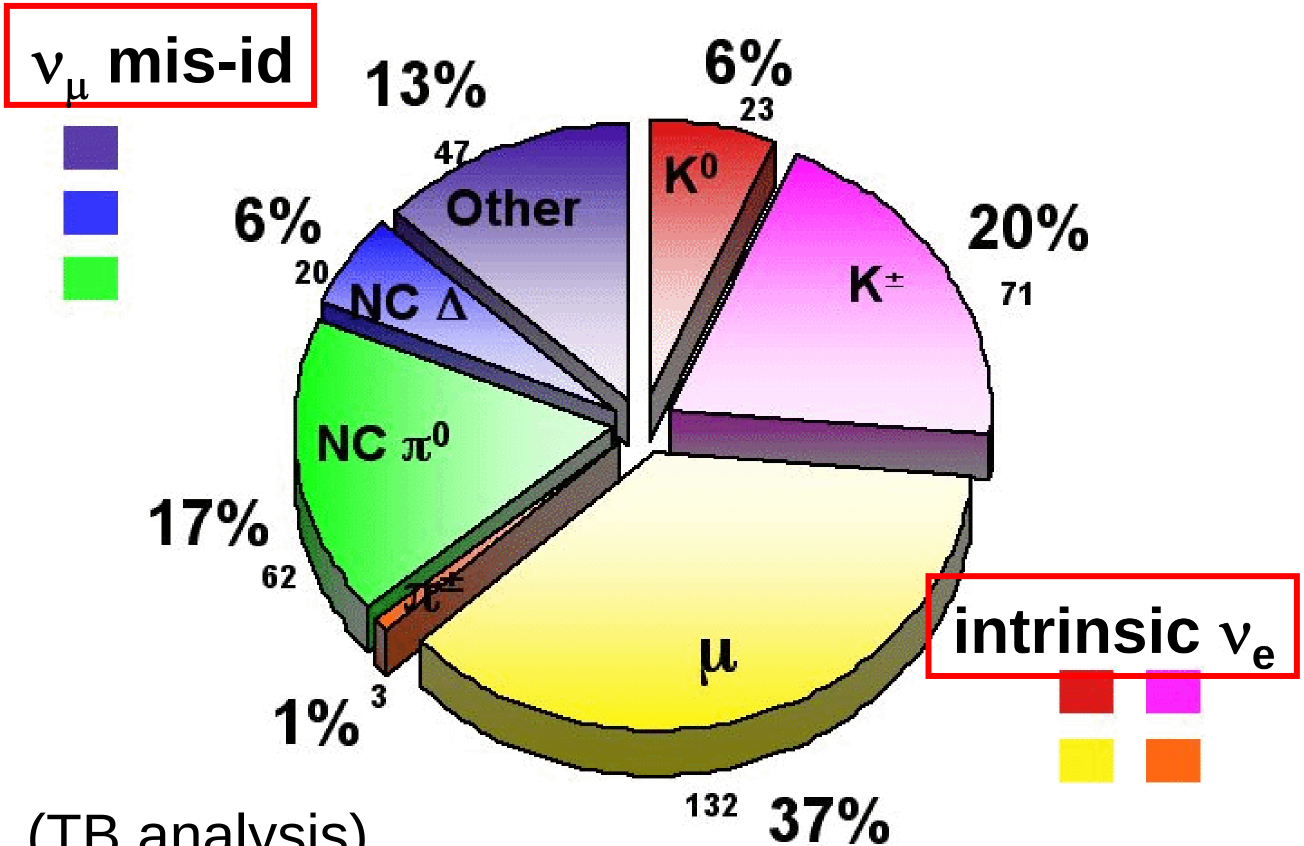
475 MeV – 1250 MeV

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

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

5. Track-Based Likelihood (TBL) analysis

We have two categories of backgrounds:



(TB analysis)

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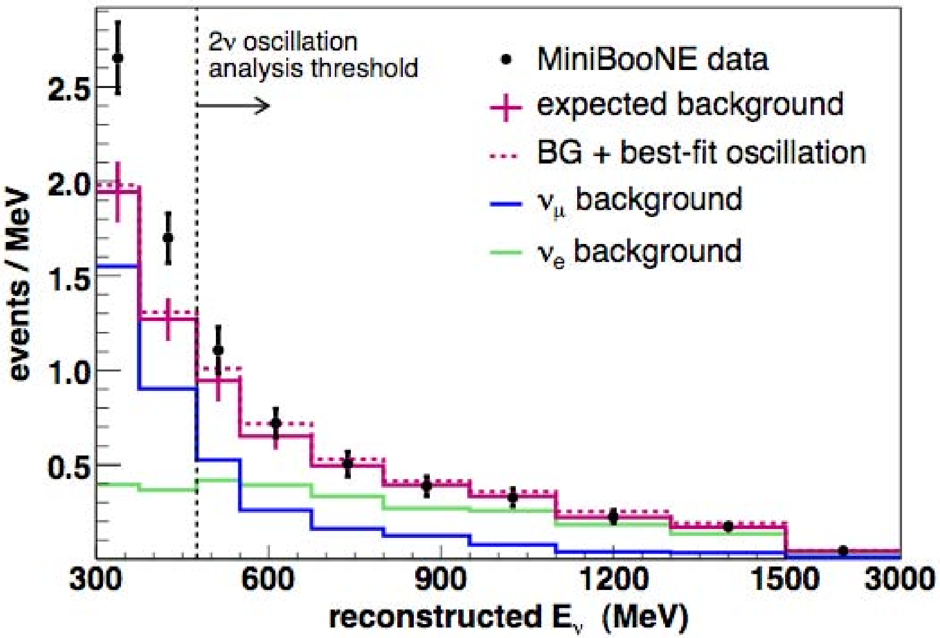
MiniBooNE collaboration,
PRL98(2007)231801

6. The MiniBooNE initial results



TBL analysis

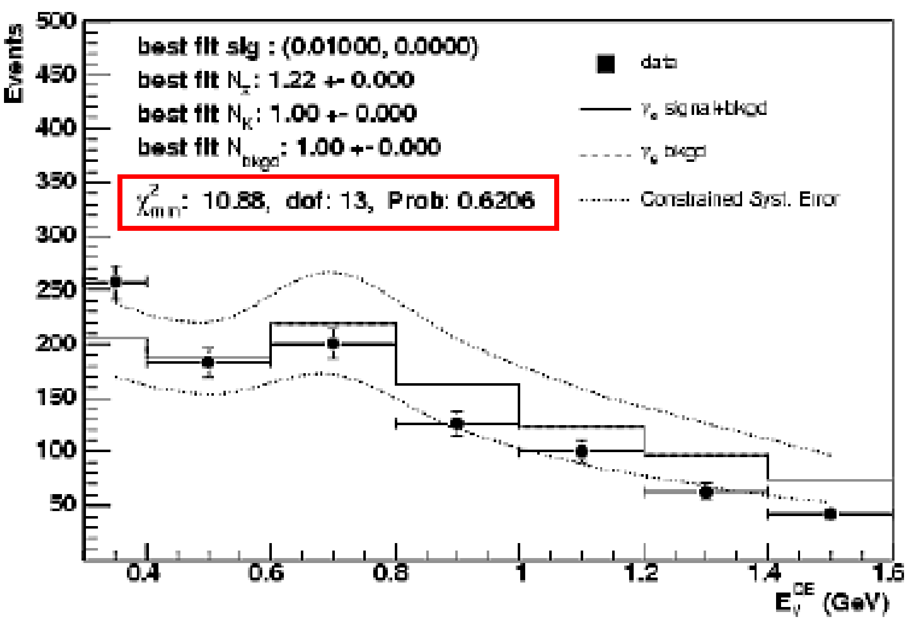
TBL show no sign of an excess in the analysis region (where the LSND signal is expected from 1 sterile neutrino interpretation)

Visible excess at low E

BDT analysis

BDT has a good fit and no sign of an excess, in fact the data is low relative to the prediction

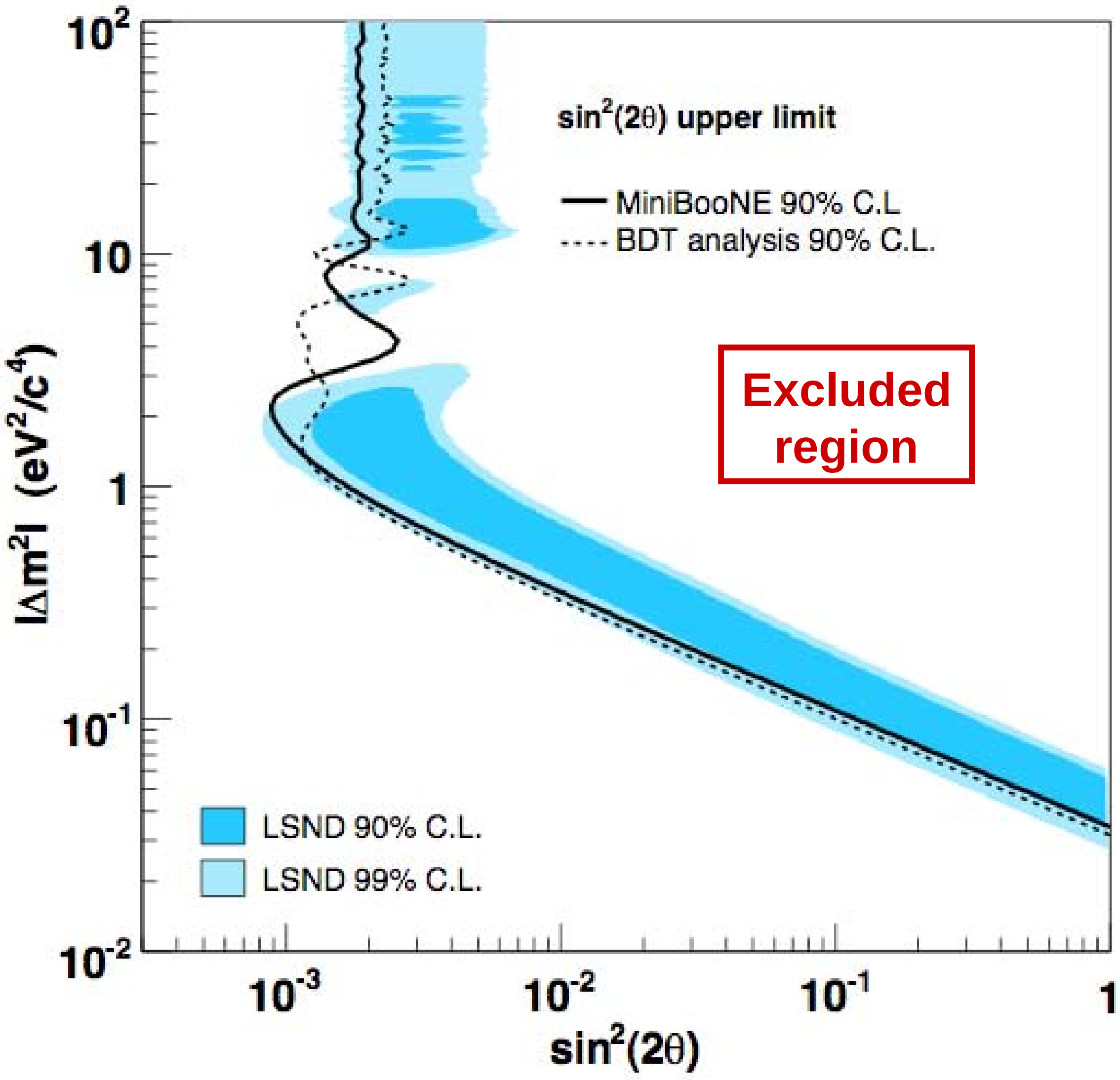
Also sees an excess at low E, but larger normalization error covers it



MiniBooNE collaboration,
PRL98(2007)231801

6. The MiniBooNE initial results

The observed reconstructed energy distribution
is inconsistent with a $\nu_\mu \to \nu_e$ appearance-only model



Energy-fit analysis:
solid: TBL
dashed: BDT

Independent analyses are in good agreement.

Within the energy range defined by this oscillation analysis, the event rate is consistent with background. 2 neutrino massive oscillation model is rejected as a explanation of LSND signal.

6. Excess at low energy region?

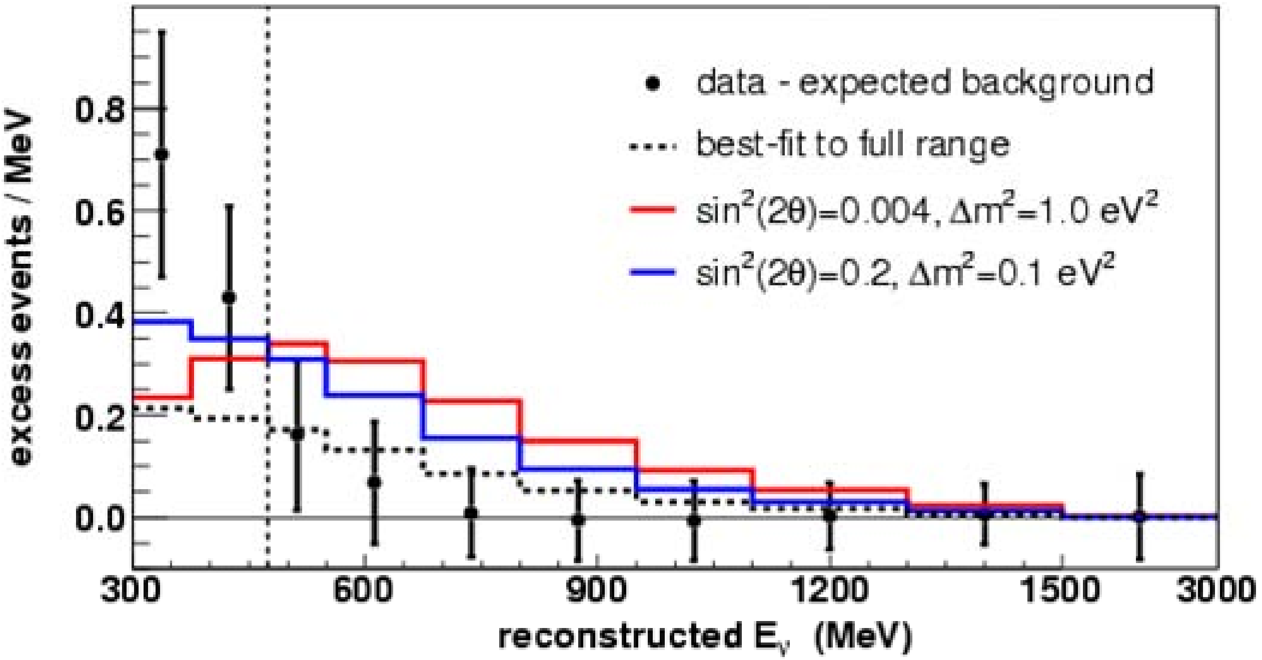
MiniBooNE collaboration,
PRL98(2007)231801

Our goals for this first analysis were:
- A generic search for a ν_e excess in our ν_μ beam,
- An analysis of the data within a $\nu_\mu \rightarrow \nu_e$ appearance-only context

Within the energy range defined by this oscillation analysis, the event rate is consistent with background.

However, there is statistically significant excess at low energy region.

The low energy excess is not consistent with any 2 neutrino massive oscillation models.



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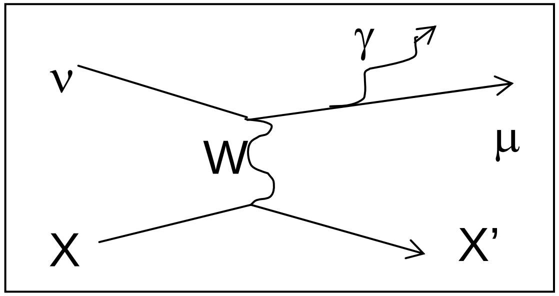
7. Excess at low energy region?

Commonplace idea Bodek, arXiv:0709.4004

Muon bremsstrahlung



✕

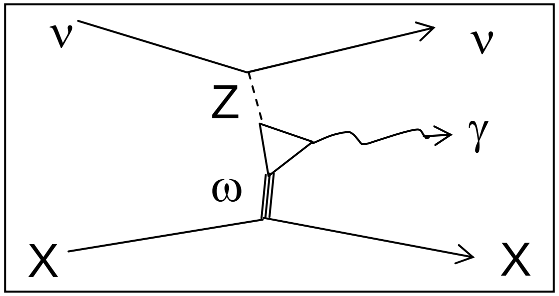
- We studied from our data, and rejected.

MiniBooNE collaboration, arXiv:0710.3897

Harvey, Hill, Hill, PRL99(2007)261601

Standard model, but new

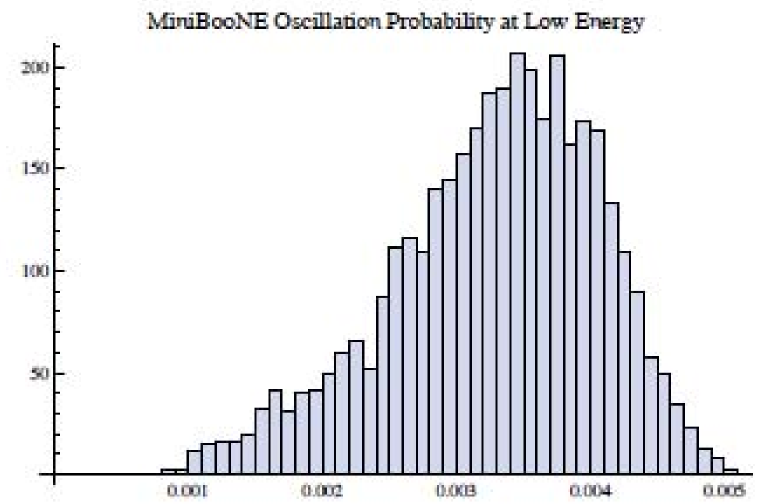
Anomaly mediated gamma emission



- Under study, need to know the coupling constant
- naïve approximation, same cross section for ν-N and $\bar{\nu}$-N

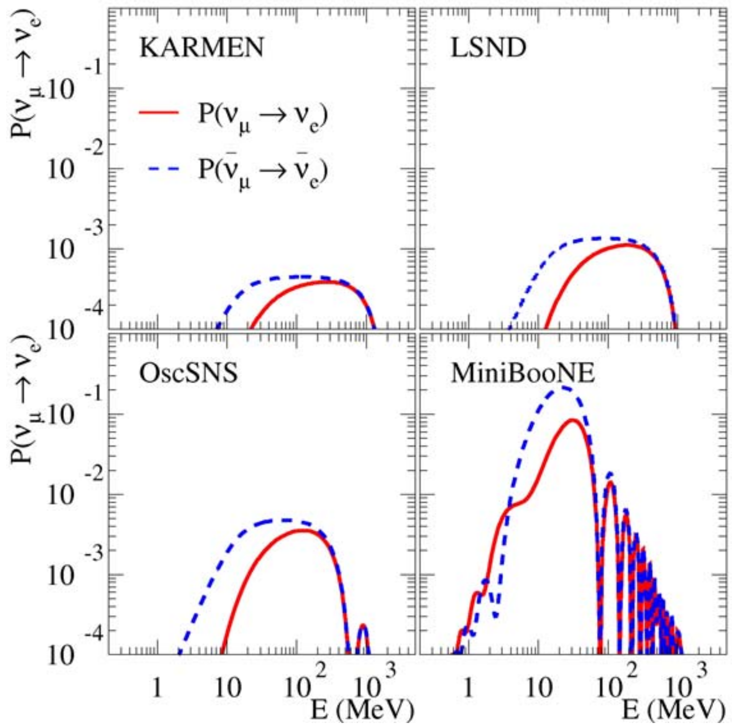
7. Excess at low energy region?

Nelson, Walsh,
PRD77(2008)033001



Beyond the Standard model (most popular)

New gauge boson production in the beamline
- can accommodate LSND and MiniBooNE
- solid prediction for anti-neutrinos.



Lorentz violating oscillation model
- can accommodate LSND and MiniBooNE
- predict low energy excess before MiniBooNE result.
- Under study

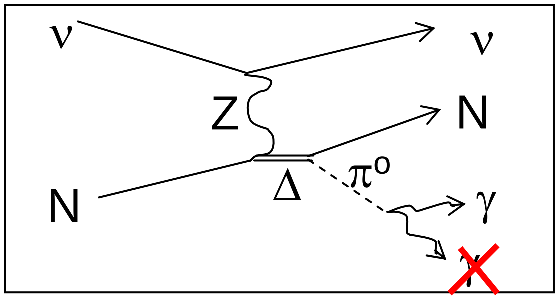
Kostelecky, TK, Tayloe,
PRD74(2006)105009

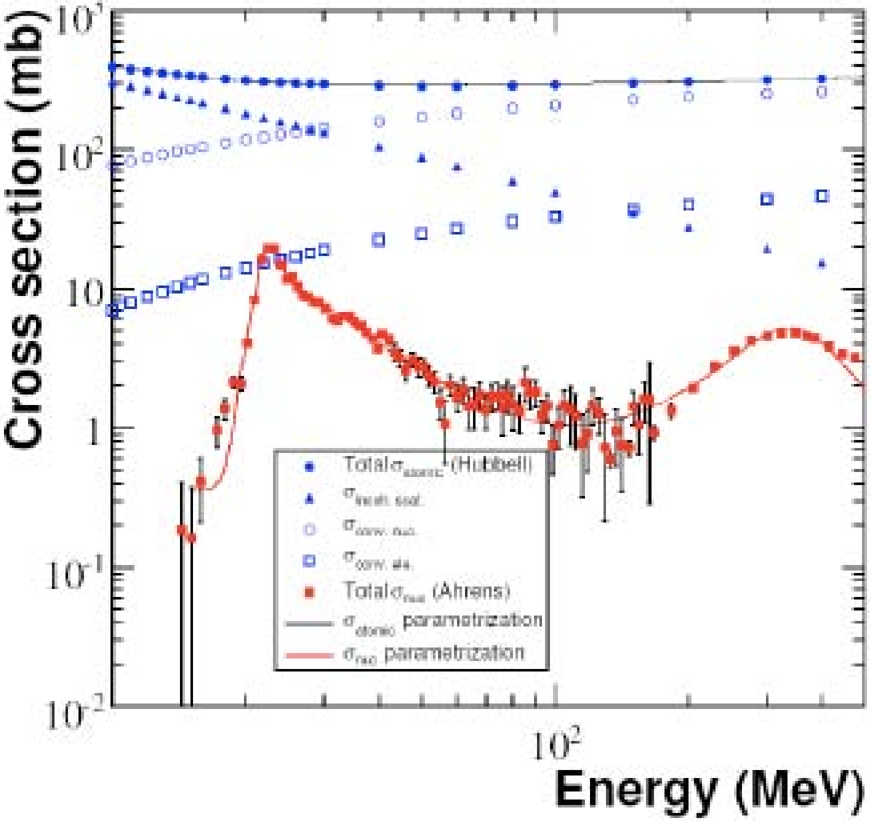
7. Oscillation analysis update

We re-visit all background source, to find any missing components

Photonuclear effect
Low energy gamma can excite nuclei, an additional source to remove one of gamma ray from NCπ^o

Photonuclear effect





Other missing processes, (π-C elastic scattering, radiative π^- capture, π induced Δ radiative decay) are negligible contribution to the background

7. Oscillation analysis update

We re-visit all background source, to find any missing components

New radiative gamma error

- single gamma emission process

- Delta resonance rate is constraint from data, so not hard to predict

- new analysis take account the re-excitation of Delta from struck pion, this increases the error from 9% to 12%.

7. Oscillation analysis update

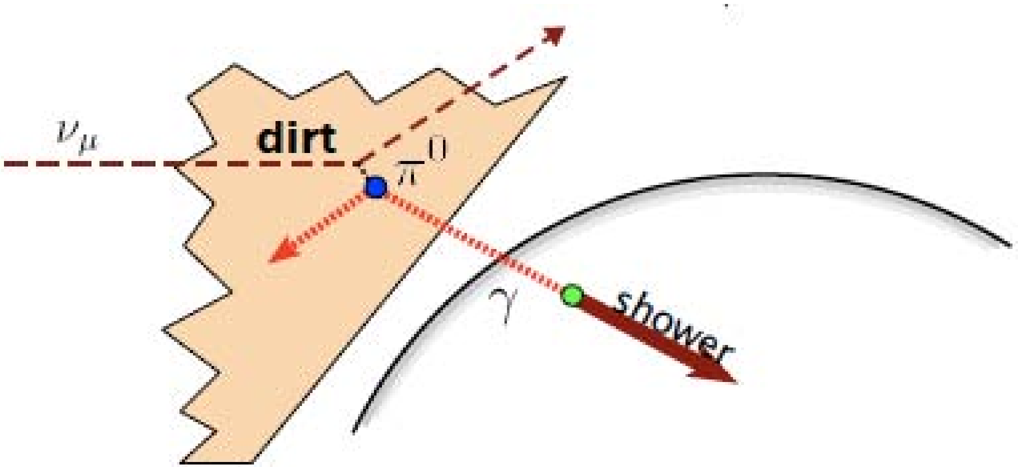
We re-visit all background source, to find any missing components

New flux prediction error
 - external measurement error directly propagates to MiniBooNE analysis, without relying on the fitting.

New low energy bin
 - analysis is extended down to 200MeV

New data set
 - additional 0.83E20 POT data.

New dirt background cut
 - remove 85% of dirt originated backgrounds (mostly π^o made outside of the detector)



MiniBooNE collaboration,
PRL102(2009)101802

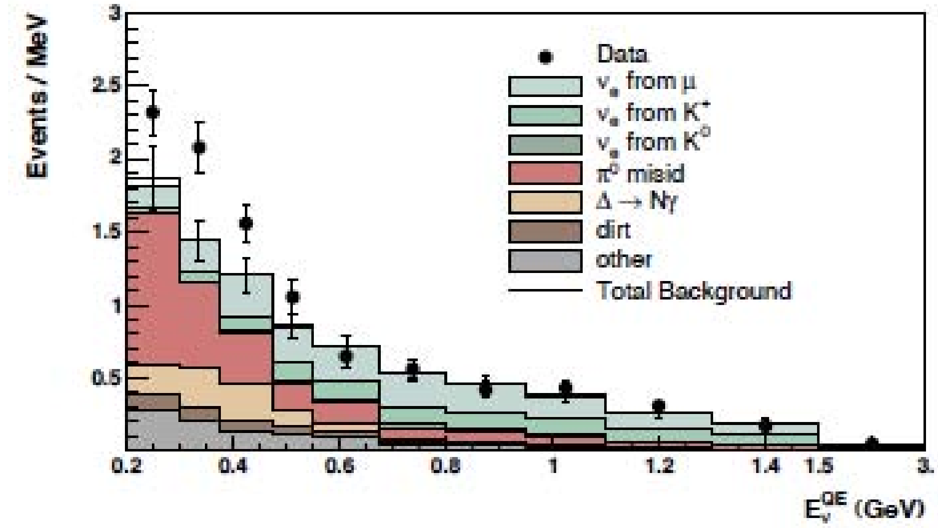
7. New oscillation analysis result

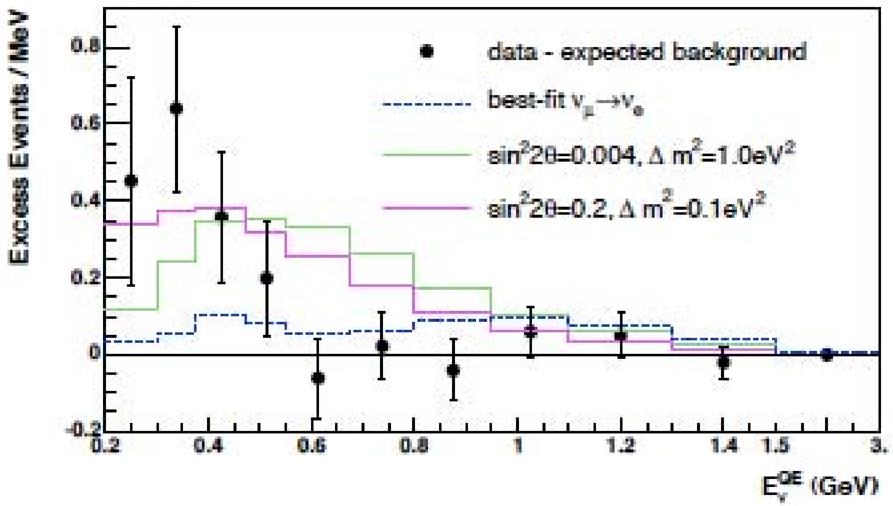
New ν_e appearance oscillation result

- low energy excess stays, the original excess in 300-475MeV becomes 3.4σ from 3.7σ after 1 year reanalysis.

- again, the shape is not described by any of two neutrino massive oscillation models

Now, we are ready to test exotic models, through antineutrino oscillation data





1. Introduction

2. Neutrino beam

3. Events in the detector

4. Cross section model

5. Oscillation analysis

6. Neutrino oscillation result

7. New Low energy excess result

8. Anti-neutrino oscillation result

9. Neutrino disappearance result

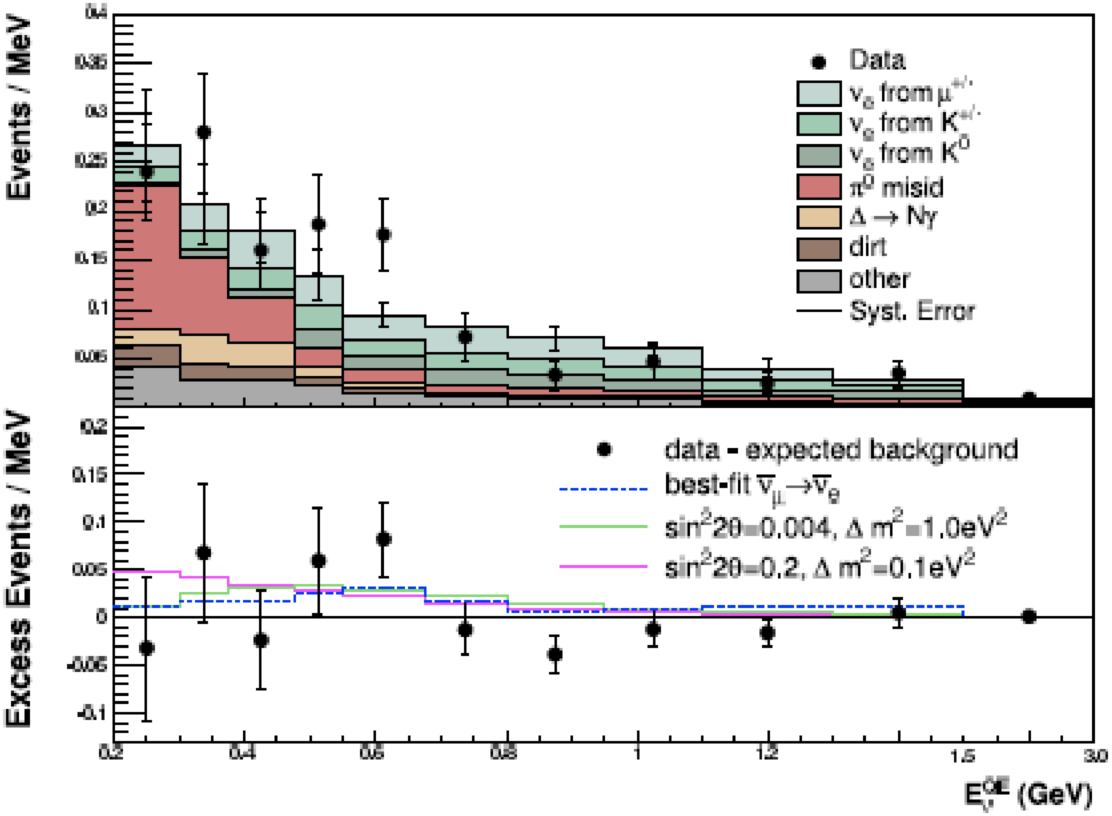
MiniBooNE collaboration,
PRL103(2009)111801

8. Antineutrino oscillation result

Many exotic models have some kind of predictions in antineutrino mode.

Analysis is quite parallel, because MiniBooNE doesn't distinguish e^- and e^+ or μ^- and μ^+ on event-by-event basis.

Bottom line, we don't see the low energy excess.



MiniBooNE collaboration,
PRL103(2009)111801

8. Antineutrino oscillation result

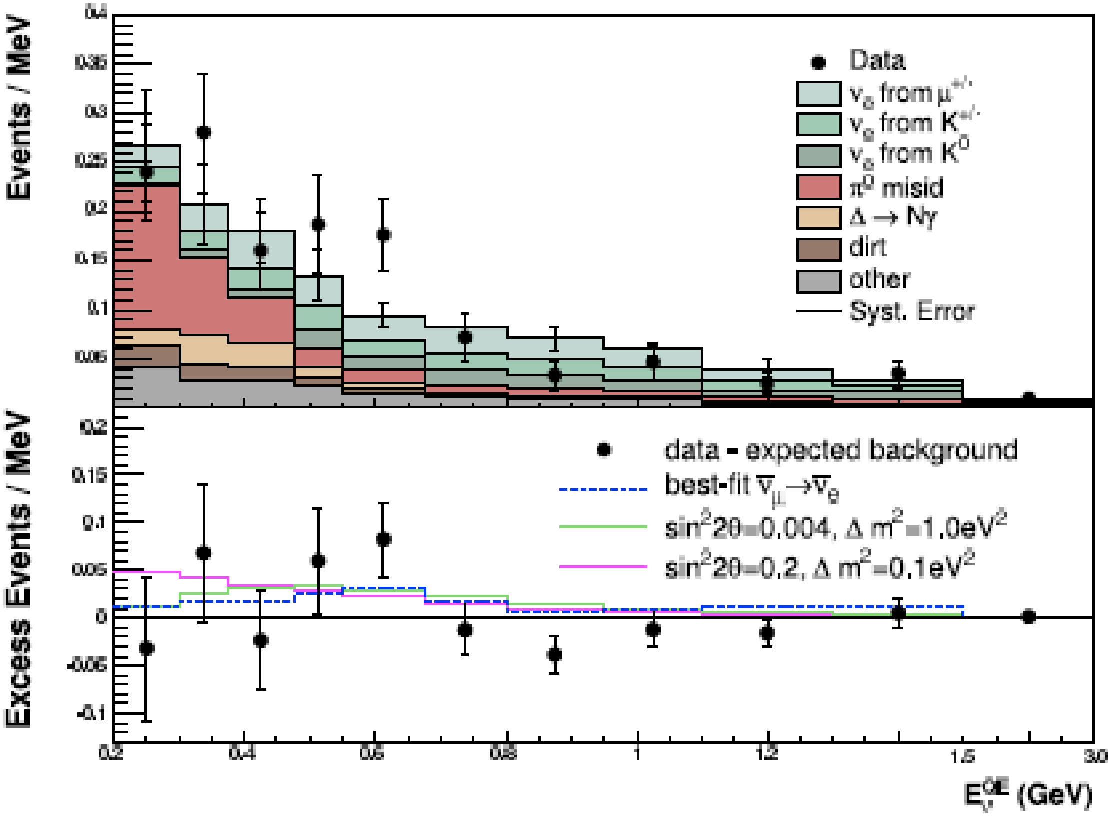
Implications

So many to say about models to explain low energy excess…

- The models based on same NC cross section for ν and anti-ν (e.g., anomaly gamma production) are disfavored.

-The models proportioned to POT (e.g., physics related to the neutral particles in the beamline) are disfavored.

- The models which predict all excess only in neutrino mode, but not antineutrino are favored, such as neutrino-only induced excess



MiniBooNE collaboration,
arXiv:1007.1150

8. New antineutrino oscillation result

- Antineutrino mode is the direct test of LSND signal
- Analysis is limited with statistics

New antineutrino oscillation result

	200-475 MeV	475-1250 MeV	200-3000 MeV
Data	119	120	277

- 70% more data
- low level checks have been done (beam stability, energy scale)
- new dirt event rate measurement (consistent with neutrino mode)
- new NCπ^o rate measurement (consistent with neutrino mode)
- ν fraction is measured in anti-ν beam

New antineutrino oscillation result
(presented at Neutrino 2010, Athens)

MiniBooNE collaboration,
arXiv:1007.1150

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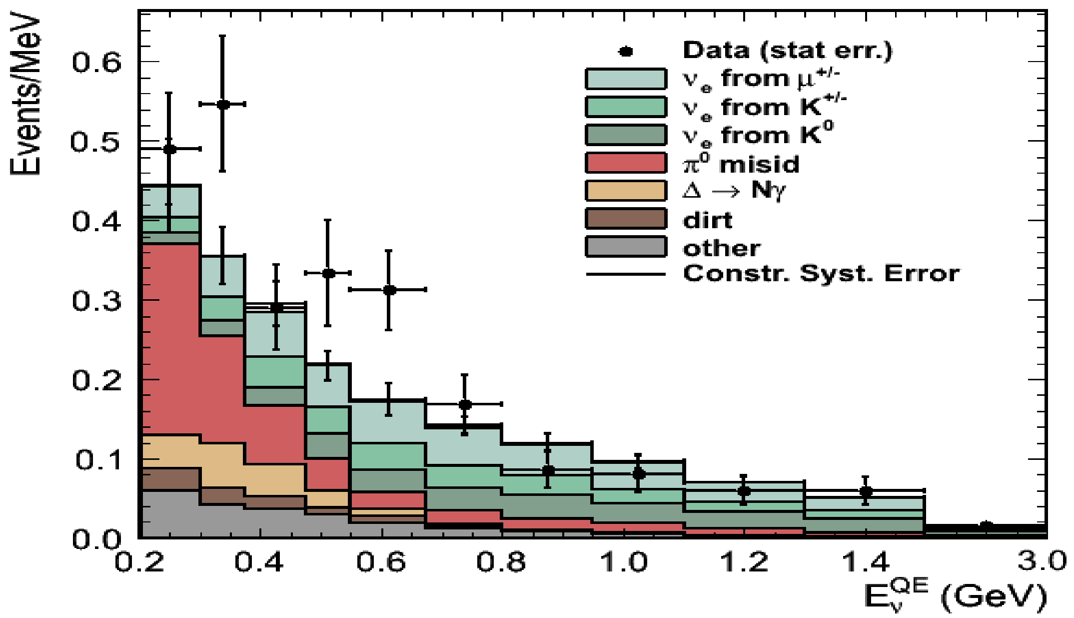
	200-475 MeV	475-1250 MeV	200-3000 MeV
Data	119	120	277
MC (stat+sys)	100.5 ± 14.3	99.1 ± 13.9	233.8 ± 22.5
Excess (stat+sys)	18.5 ± 14.3 (1.3σ)	20.9 ± 13.9 (1.5σ)	43.2 ± 22.5 (1.9σ)

MiniBooNE now see the excess in LSND-like Δm^2 region!



MiniBooNE collaboration, arXiv:1007.1150

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	before fit	
	χ^2/NDF	probability
475 < E_ν^{QE} < 1250 MeV	18.5/6	0.5%

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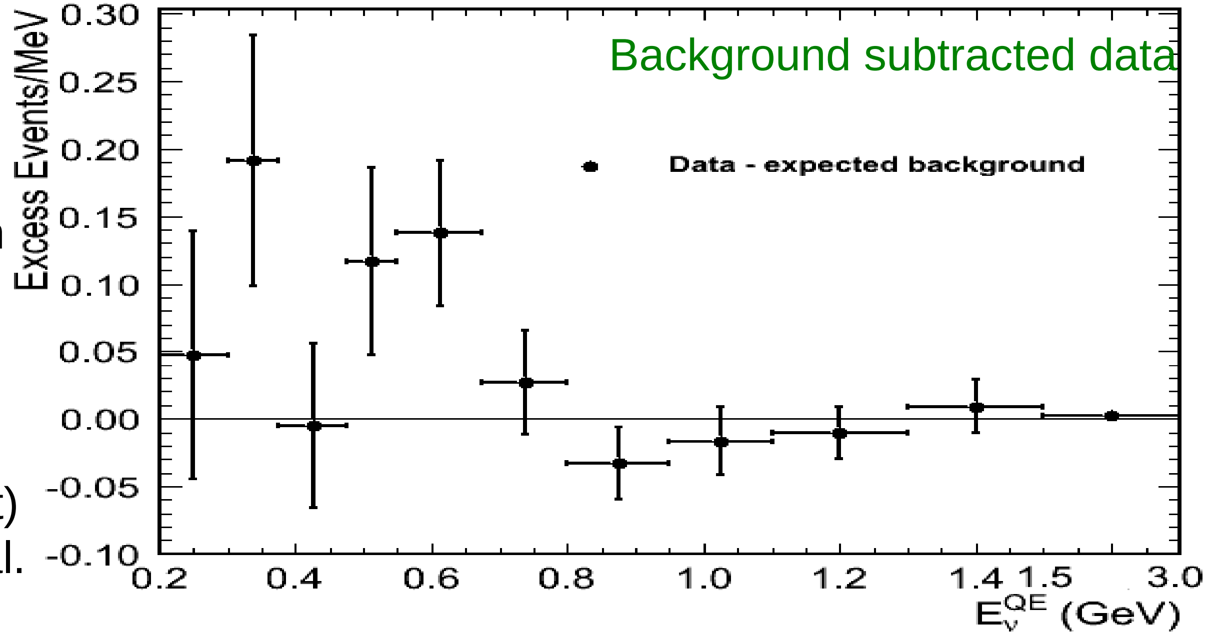
- flatness test (model independent test) shows statistically significance of signal.



MiniBooNE collaboration,
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8. New antineutrino oscillation result

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- Analysis is limited with statistics

	before fit		after fit	
	χ^2/NDF	probability	χ^2/NDF	probability
475 < E_ν^{QE} < 1250 MeV	18.5/6	0.5%	8.0/4	8.7%

New antineutrino oscillation result

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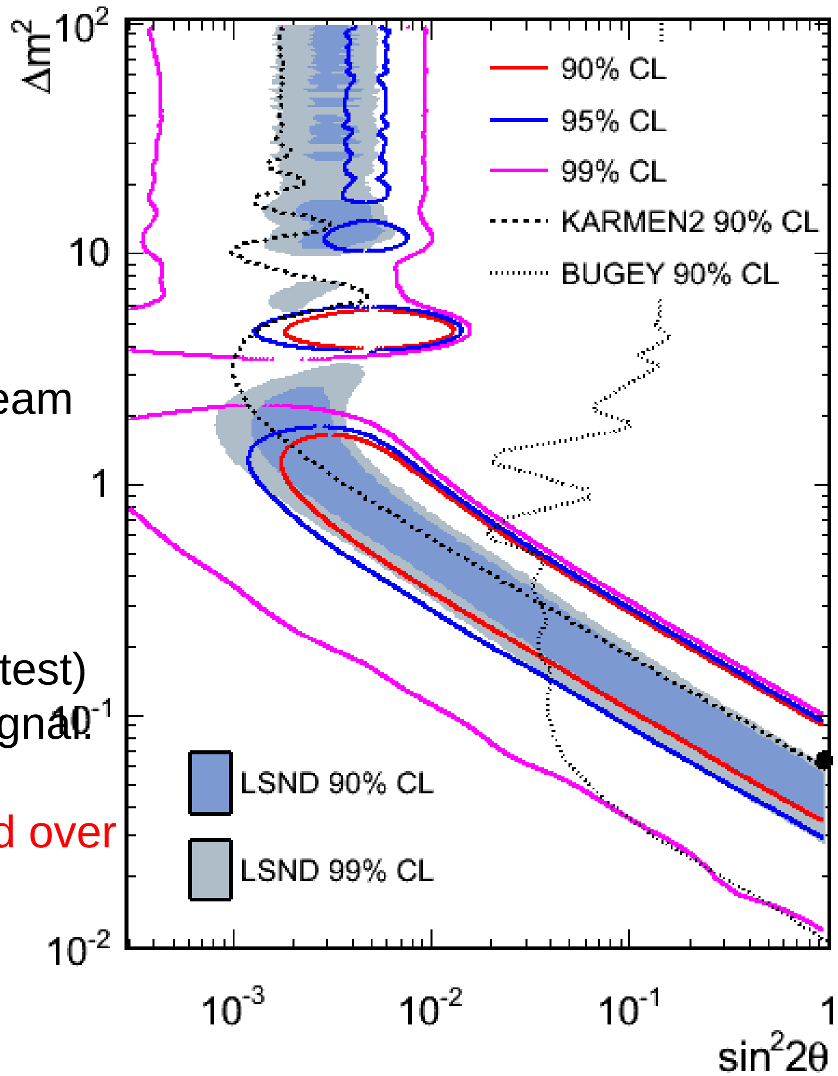
- ν fraction is measured in anti-ν beam

MiniBooNE now see the excess in LSND-like Δm^2 region!

- flatness test (model independent test) shows statistically significance of signal

2 massive neutrino model is favored over 99.4% than null hypothesis



E>475 MeV

Best ft point
$\Delta m^2 = 0.064 eV^2$
$\sin^2 2\theta = 0.96$

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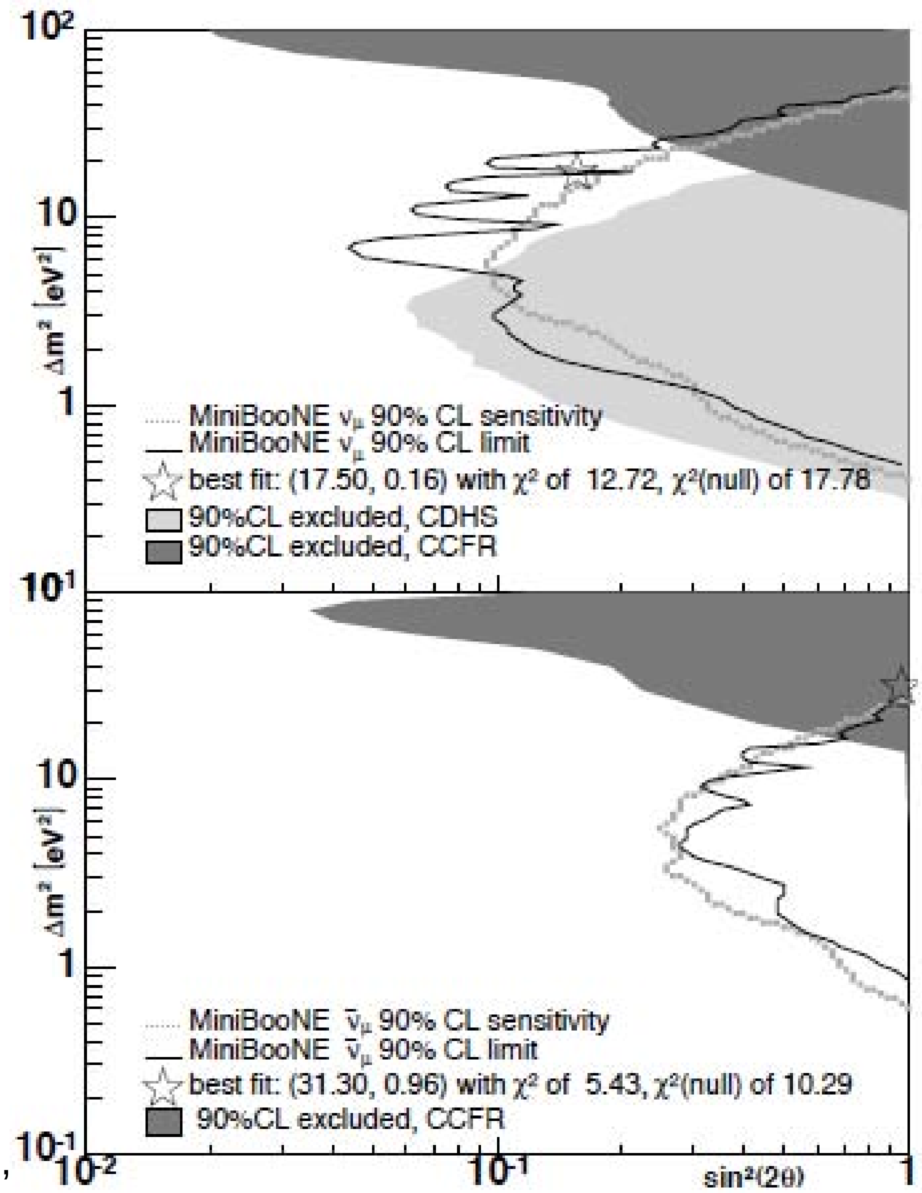
MiniBooNE collaboration,
PRL103(2009)061802

9. Neutrino disappearance oscillation result

ν_μ and anti-ν_μ disappearance oscillation

- test is done by shape-only fit for data and MC with massive neutrino oscillation model.

- MiniBooNE can test unexplored region by past experiments, especially there is no tests for antineutrino disappearance between $\Delta m^2=10eV^2$ and atmospheric Δm^2 .



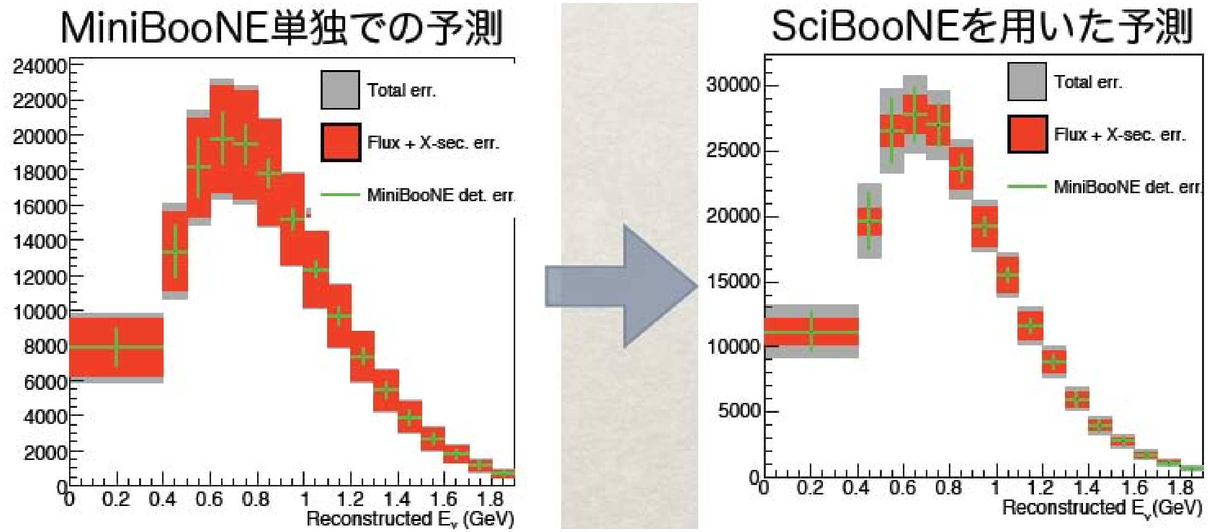
9. Neutrino disappearance oscillation result

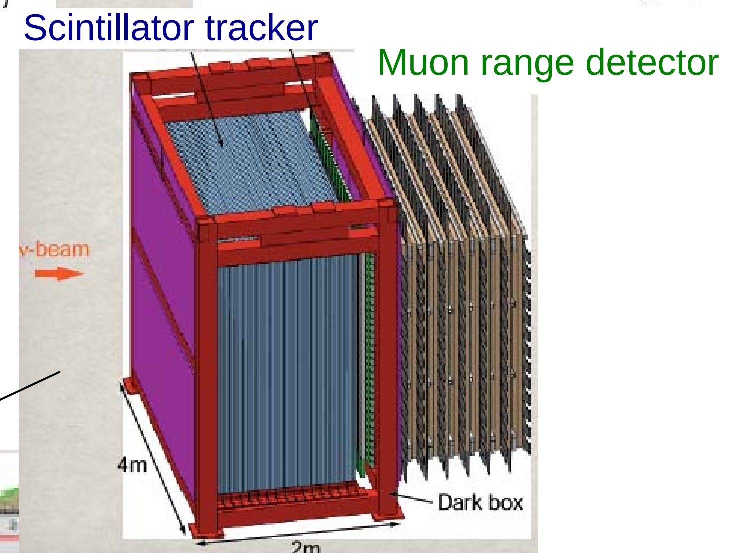
MiniBooNE-SciBooNE combined ν_μ disappearance oscillation analysis

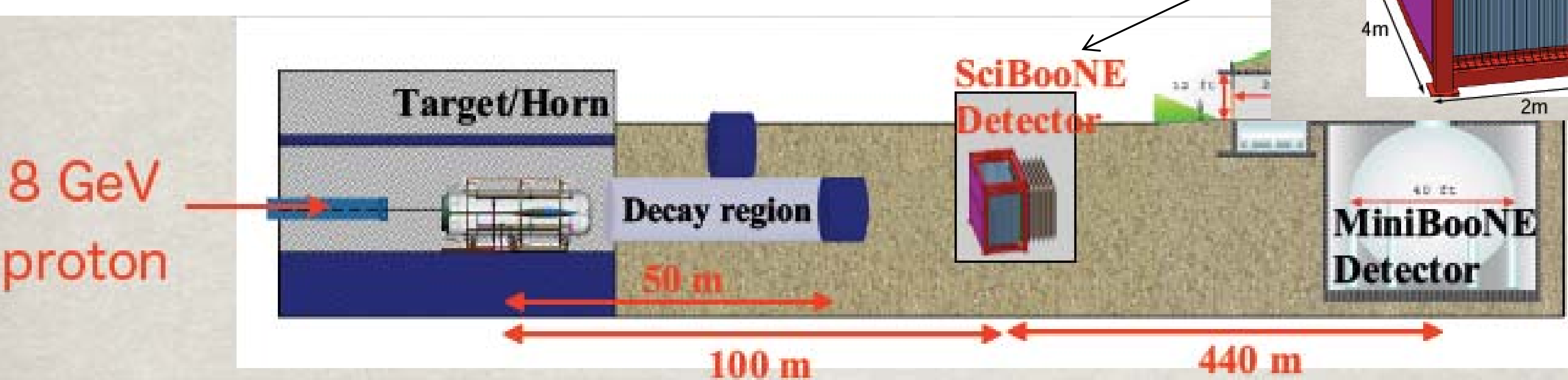
- combined analysis with SciBooNE can constrain Flux+Xsec error.

Flux-> same beam line

Xsec->same target (carbon)





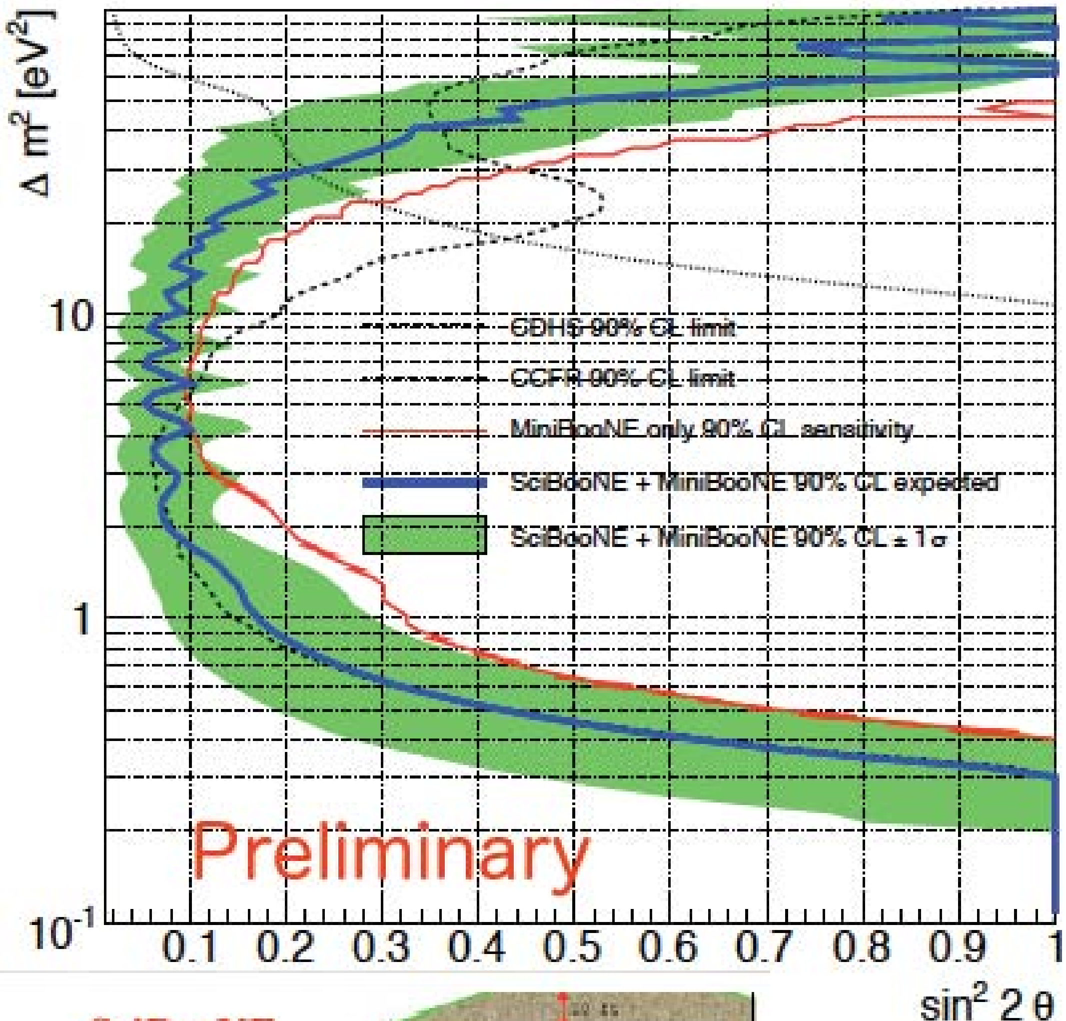


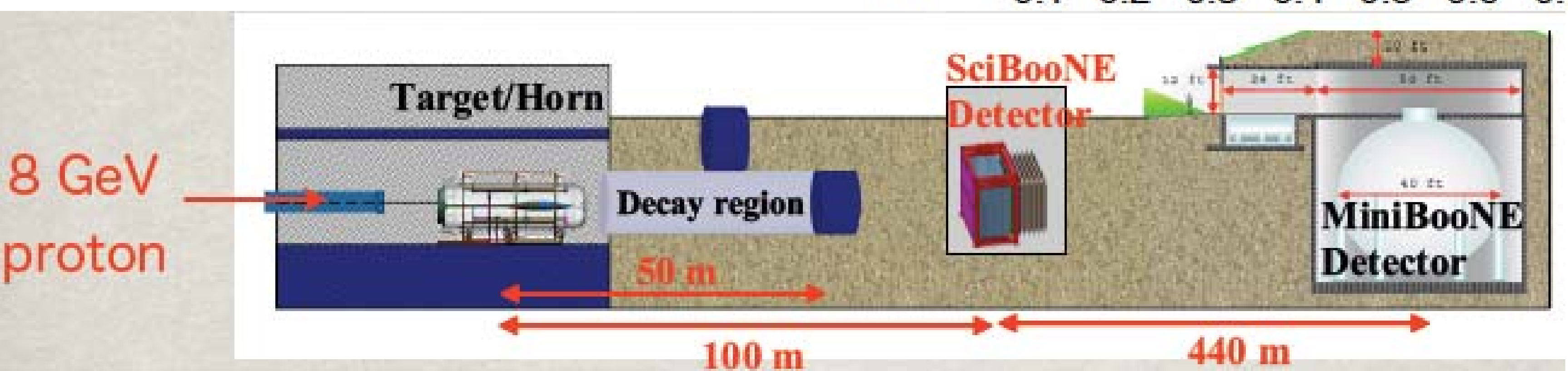
9. Neutrino disappearance oscillation result

MiniBooNE-SciBooNE combined ν_μ disappearance oscillation analysis

- combined analysis with SciBooNE can constrain Flux+Xsec error.
Flux-> same beam line
Xsec->same target (carbon)

- this significantly improves sensitivities, especially at low Δm^2. An analysis for anti-ν_μ is ongoing.



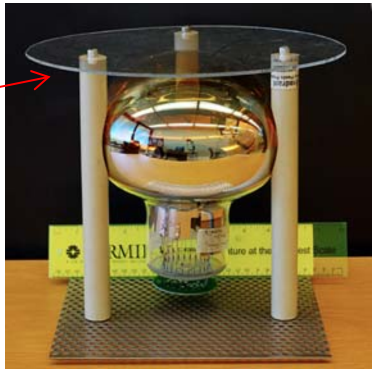


Future: MicroBooNE

scintillation from LiqAr

128nm

450nm

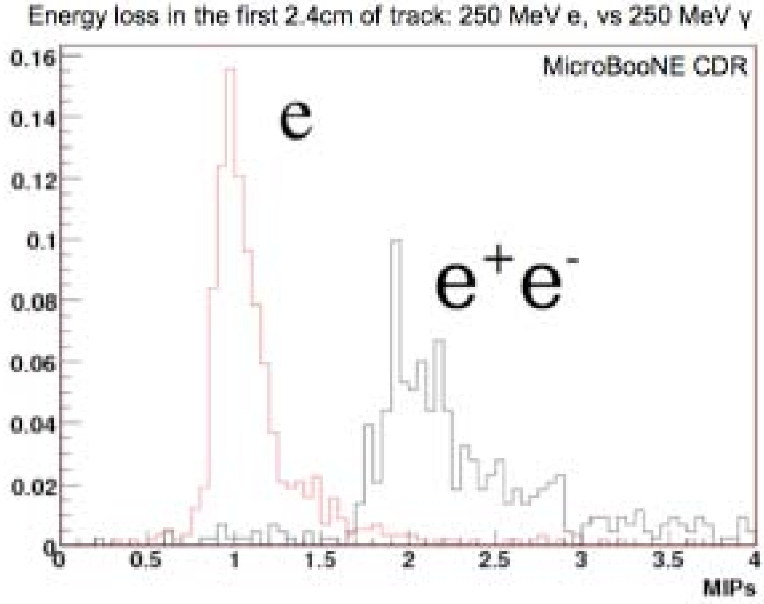


TPB (wave length shifter)
coated acrylic plate

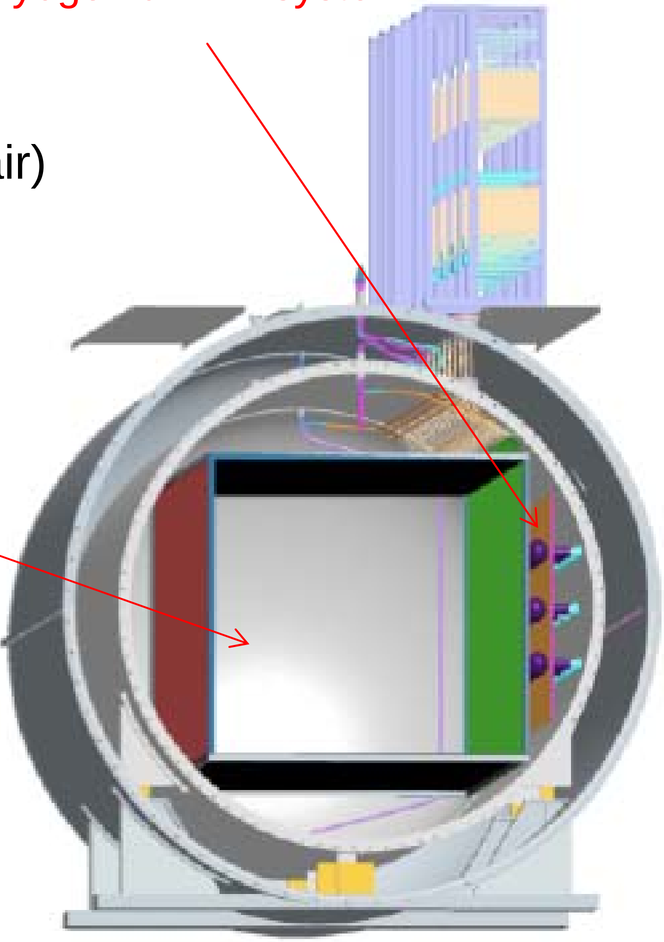
Cryogenic PMT system

Liquid Argon TPC experiment at Fermilab

- 70 ton fiducial volume LiqAr TPC
- R&D detector for future large LiqAr TPC for DUSEL
- 3D tracker (modern bubble chamber)
- data taking will start from 2013(?)
- dE/dx can separate single electron from gamma ray (e^+e^- pair)



liquid Argon TPC



Conclusions

MiniBooNE is a ν_e appearance oscillation experiment to test LSND signal

MiniBooNE successfully rejected two neutrino massive oscillation model as an explanation of LSND signal. However, MiniBooNE first result includes unexplained low energy event excess.

After 1 year re-visit for all background source, the low energy excess is now confirmed.

The initial data from antineutrino oscillation result doesn't show any low energy excess.

The new high statistics antineutrino oscillation show small excess at low energy region and the large excess at where LSND-like Δm^2 expect signal.

The MiniBooNE-SciBooNE combined ν_μ-disappearance analysis is ongoing.

BooNE collaboration

University of Alabama
Bucknell University
University of Cincinnati
University of Colorado
Columbia University
Embry Riddle Aeronautical University
Fermi National Accelerator Laboratory
Indiana University
University of Florida

Los Alamos National Laboratory
Louisiana State University
Massachusetts Institute of Technology
University of Michigan
Princeton University
Saint Mary's University of Minnesota
Virginia Polytechnic Institute
Yale University

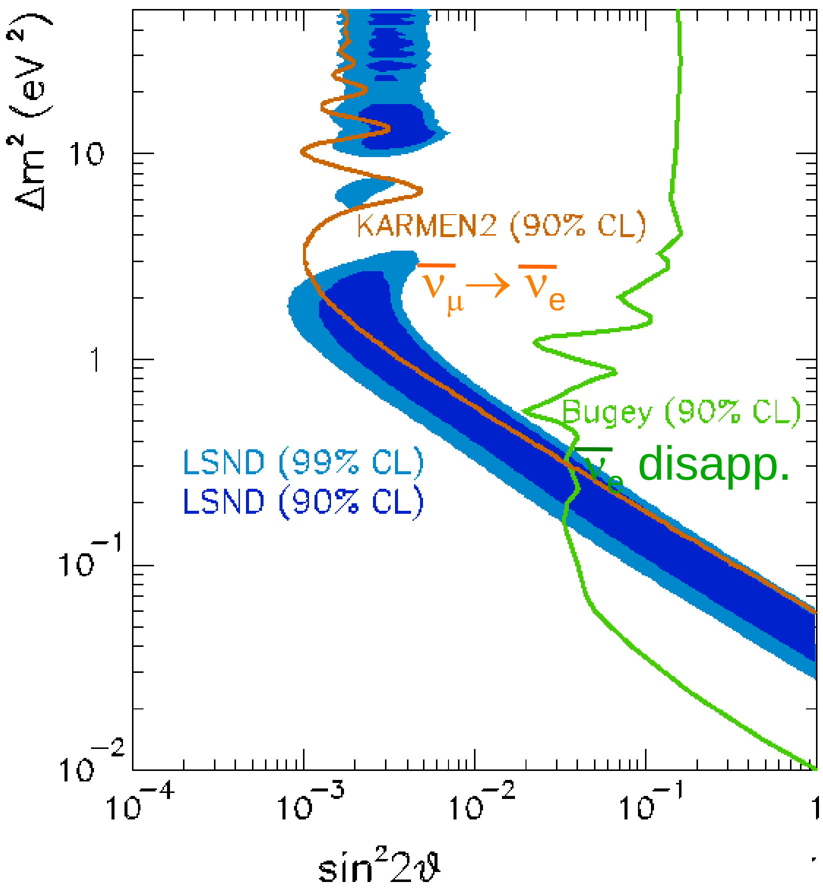
Thank you for your attention!

Buck up

2. LSND experiment

In terms of the oscillation probability,

$P(\bar{\nu}_\mu - \bar{\nu}_e) = 0.264 \pm 0.067 \pm 0.045$

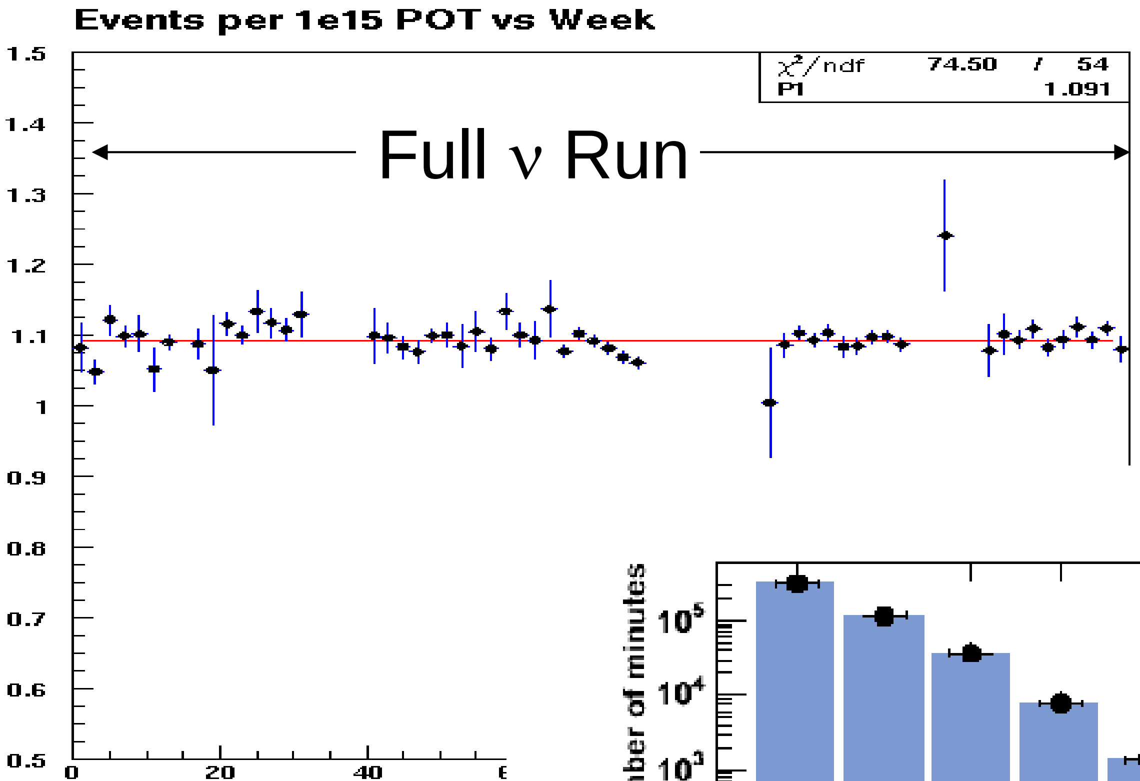


Under the 2 flavor massive neutrino oscillation model, one can map into Δm^2-$\sin^2 2\theta$ space (MS-diagram)

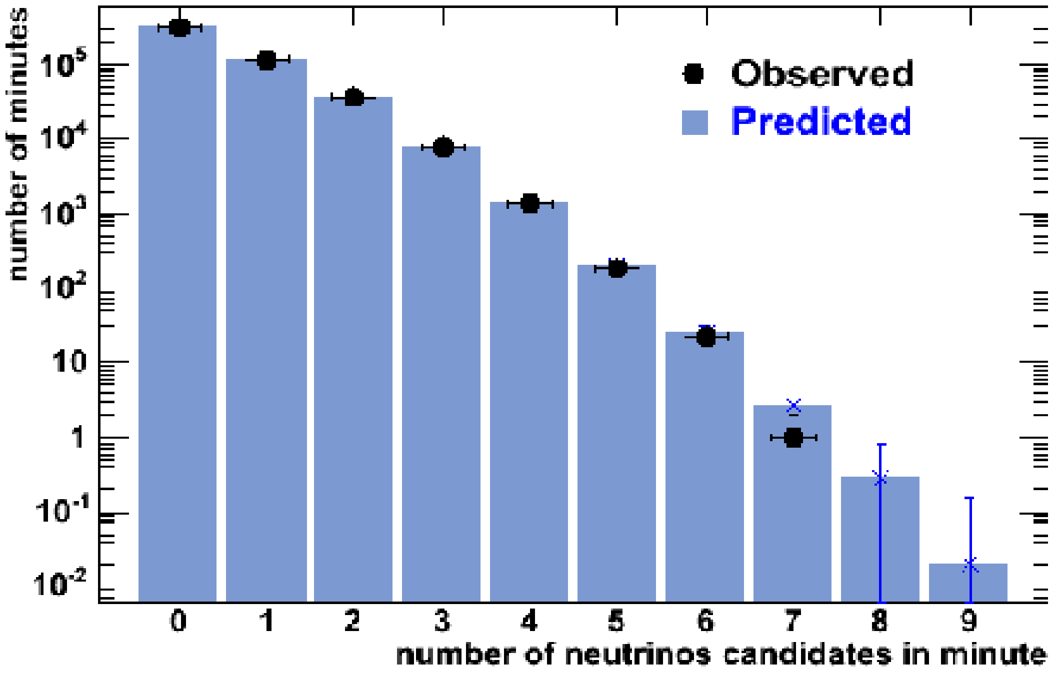
This model allows comparison to other experiments:

Karmen2
Bugey

3. Stability of running



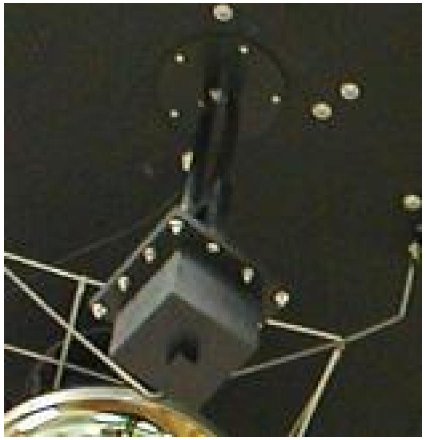
Observed and expected events per minute

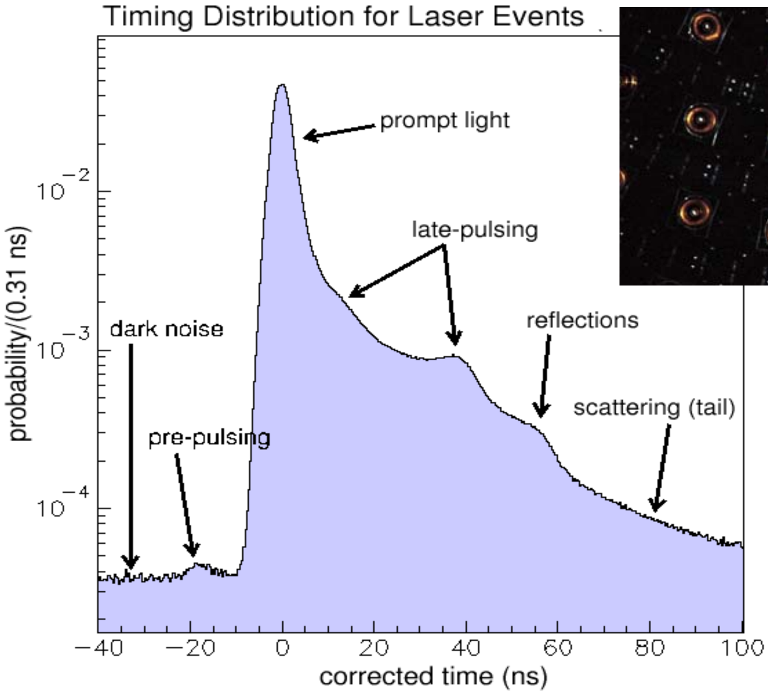


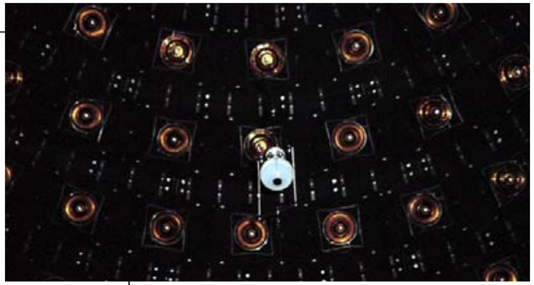
4. Calibration source

Laser flask system

Muon tracker and scintillation cube system







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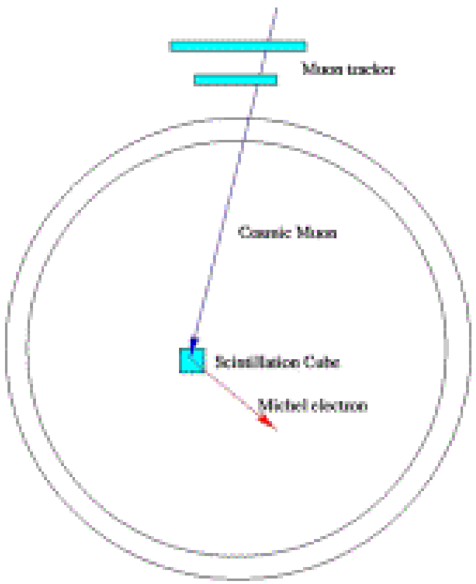
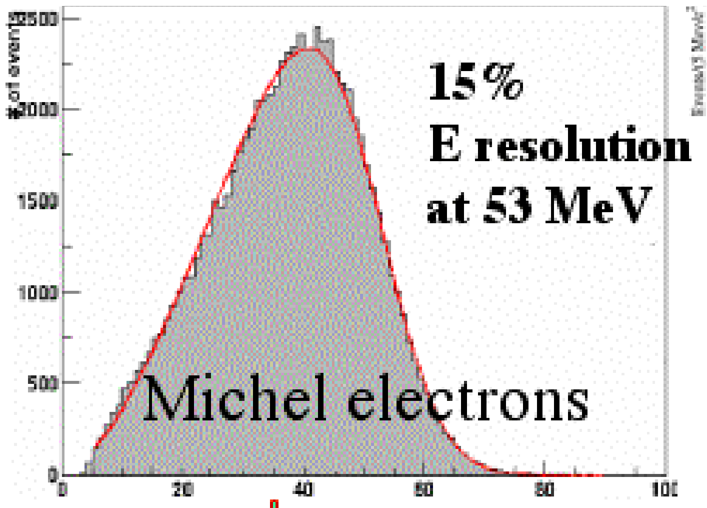
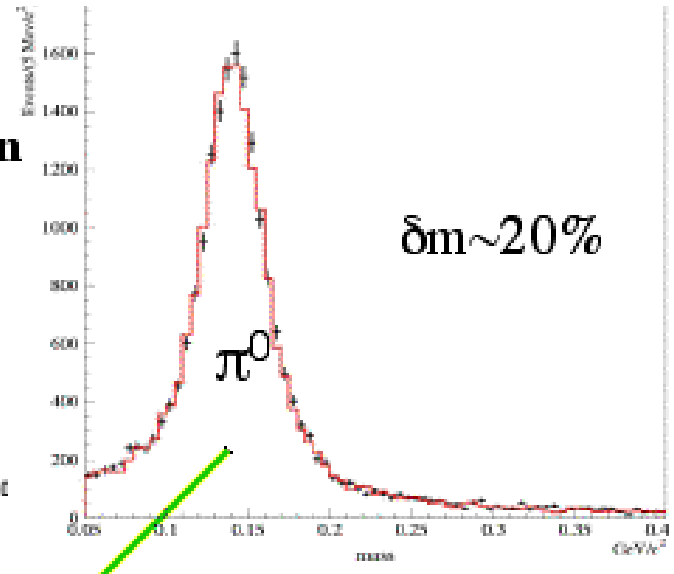
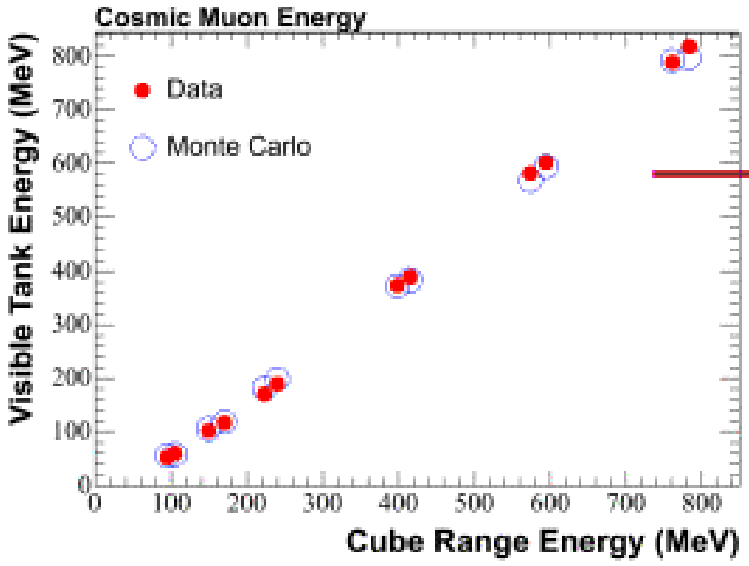
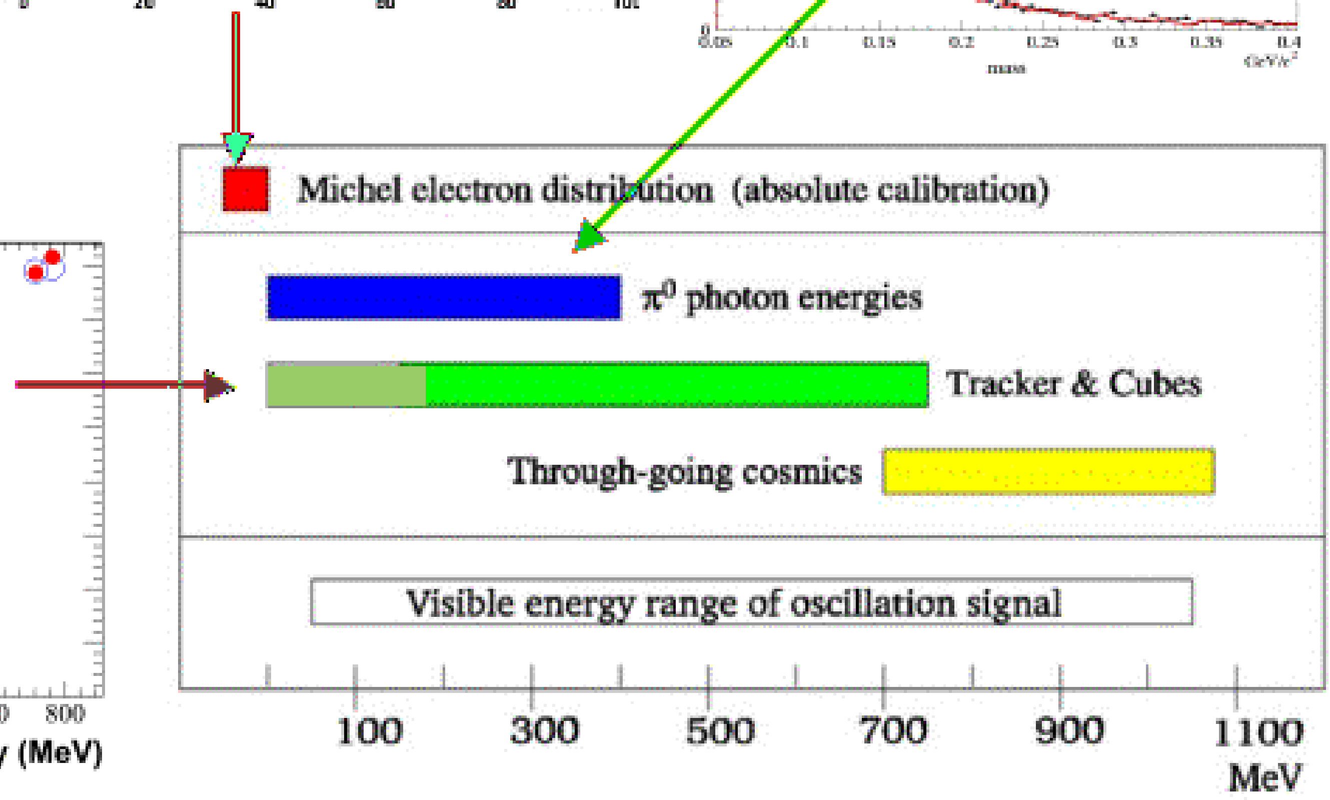
Tracker system











4. MiniBooNE cross section results

NuInt09, May18-22, 2009, Sitges, Spain
All talks proceedings are available on online (open access),
http://proceedings.aip.org/proceedings/confproceed/1189.jsp

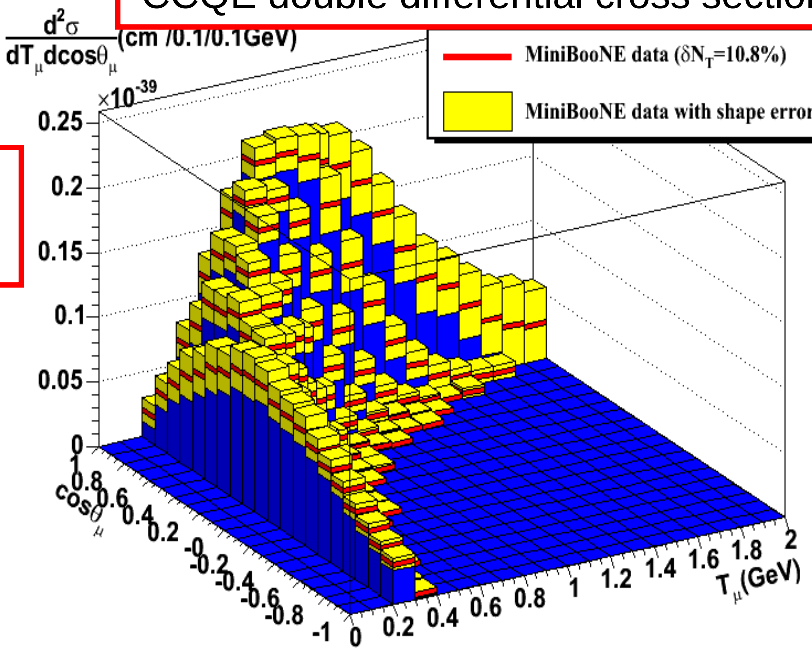
NuInt09 MiniBooNE results
In NuInt09, MiniBooNE had 6 talks and 2 posters

1. charged current quasielastic (CCQE) cross section measurement
   by Teppei Katori, PRD81(2010)092005
2. neutral current elastic (NCE) cross section measurement
   by Denis Perevalov, arXiv:1007.4730
3. neutral current π^o production ($NC\pi^o$) cross section m
   by Colin Anderson, PRD81(2010)013005

- first double differential cross section measurement
- observed large absolute cross section

5. charged current single π^o production ($CC\pi^o$) cross s
   by Bob Nelson, paper in preparation
6. improved $CC1\pi^+$ simulation in NUANCE generator
   by Jarek Novak
7. $CC\pi^+$/CCQE cross section ratio measurement
   by Steve Linden, PRL103(2009)081801
8. anti-νCCQE measurement
   by Joe Grange, paper in preparation

CCQE double differential cross section



by Denis Perevalov

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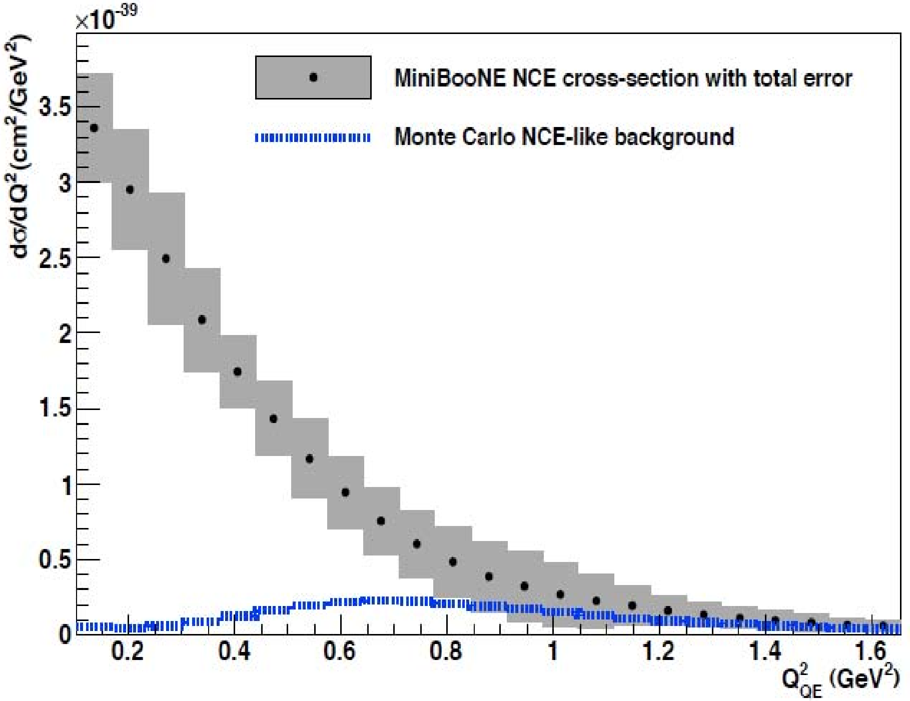
- highest statistics cross section measurement
- new Δs (strange quark spin) extraction method

Flux-averaged NCE p+n differential cross section



by Colin Anderson

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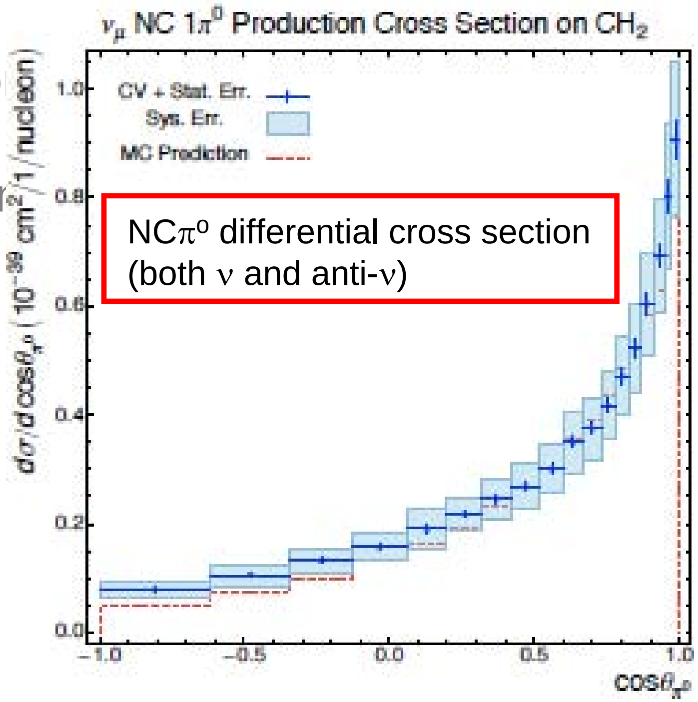

by Mike Wilking

4. MiniBooNE cross section results

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- first double differential cross section measurement
- observed large absolute cross section

4. charged current single pion production (CCπ^+) cross section measurement
   by Mike Wilking, paper in preparation
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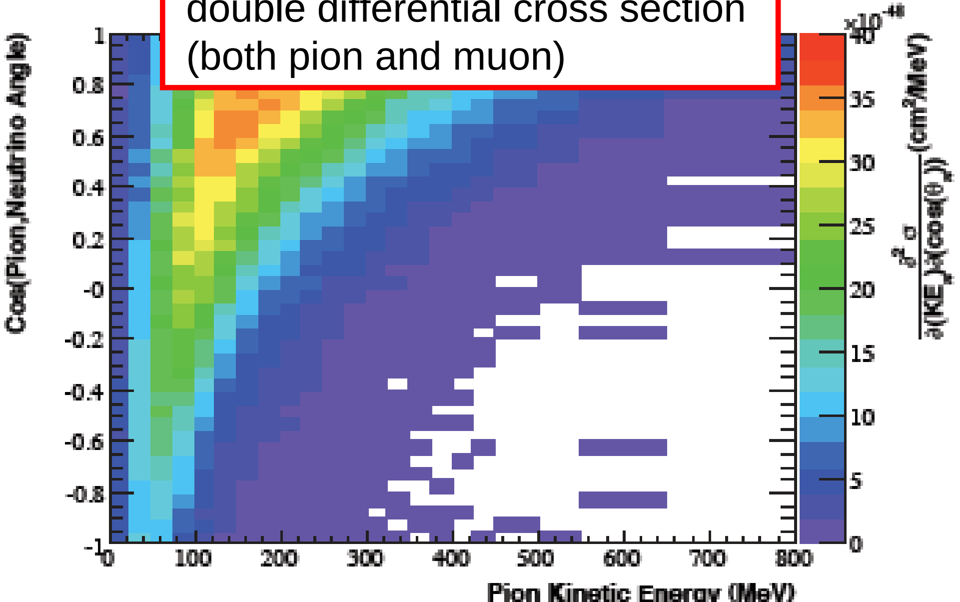
double differential cross section
(both pion and muon)



by Bob Nelson

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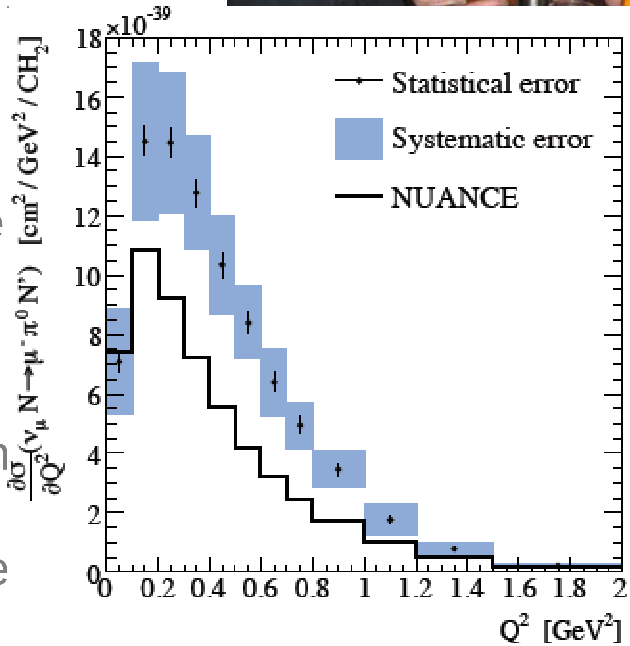

$CC\pi^o$ Q^2 differential cross section

by Jarek Novak

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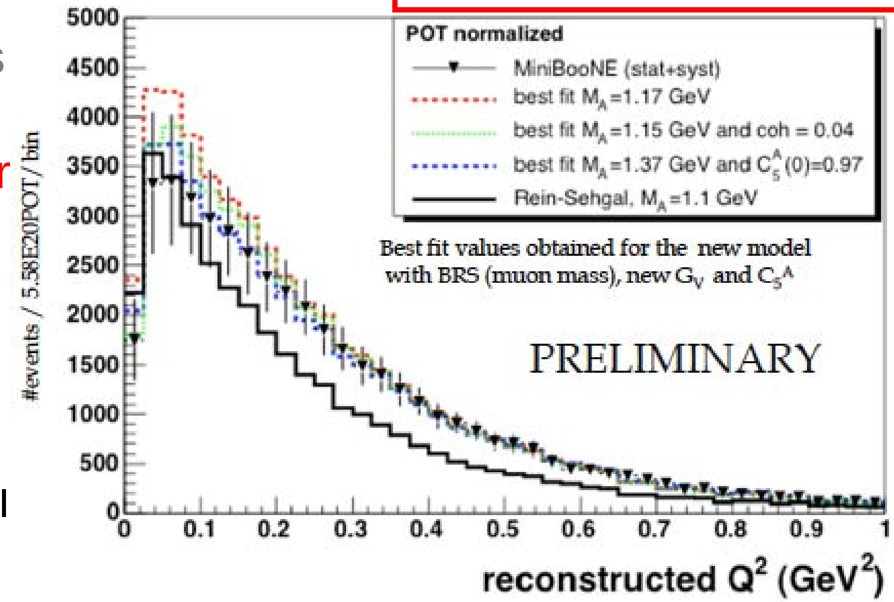
2. neutral current elastic (NCE) cross section measurement
   by Denis Perevalov, arXiv:1007.4730
3. ... measurement (ν and anti-ν)

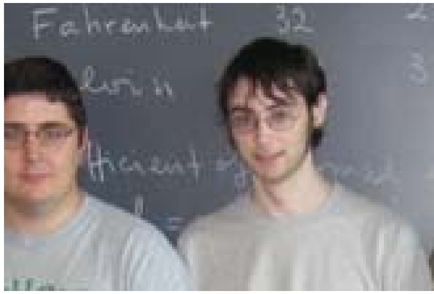
- state-of-art models are implemented, tested

4. charged current single pion production ($CC\pi^+$) cross section measur...
   by Mike Wilking, paper in preparation
5. charged current single π^o production ($CC\pi^o$) cross ...
   by Bob Nelson, paper in preparation
6. improved $CC1\pi^+$ simulation in NUANCE generator
   by Jarek Novak
7. $CC\pi^+$/CCQE cross section ratio measurement
   by Steve Linden, PRL103(2009)081801
8. anti-νCCQE measurement
   by Joe Grange, paper in preparation

$M_A^{1\pi}$ fit with Q^2 distribution for various nuclear models



by Steve Linden



4. MiniBooNE cross section results

NuInt09, May18-22, 2009, Sitges, Spain
All talks proceedings are available on online (open access),
http://proceedings.aip.org/proceedings/confproceed/1189.jsp

NuInt09 MiniBooNE results
In NuInt09, MiniBooNE had 6 talks and 2 posters

1. charged current quasielastic (CCQE) cross sectior
   by Teppei Katori, PRD81(2010)092005
2. neutral current elastic (NCE) cross section measur
   by Denis Perevalov, arXiv:1007.4730
3. neutral current π^o production (NCπ^o) cross section

- data is presented in theorist friendly style

4. charged current single pion production (CCπ^+) cros
   by Mike Wilking, paper in preparation
5. charged current single π^o production (CCπ^o) cross
   by Bob Nelson, paper in preparation
6. improved CC1π^+ simulation in NUANCE generator
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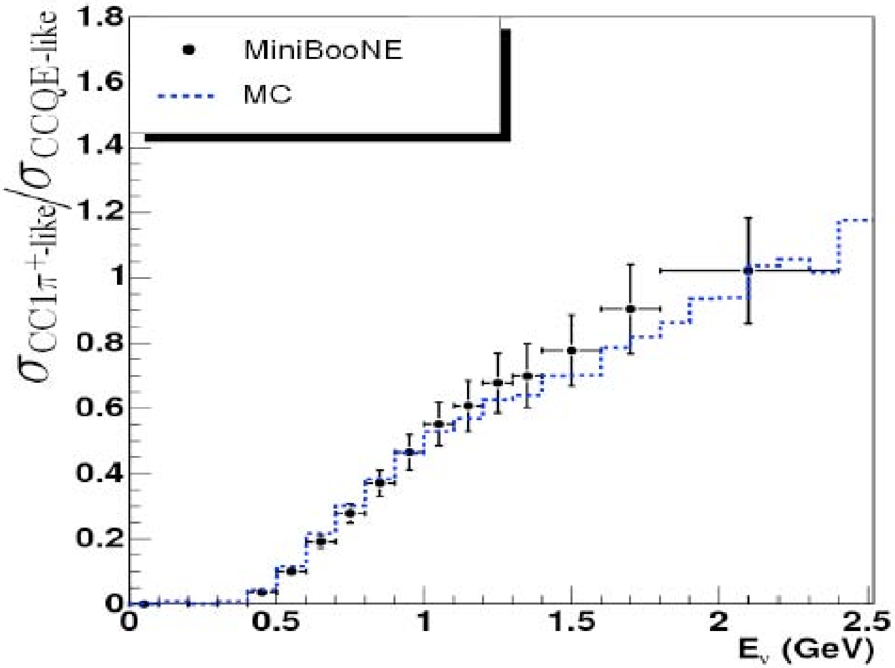

CCπ^+like/CCQElike cross section ratio

by Joe Grange

4. MiniBooNE cross section results

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- highest statistics in this channel
- support neutrino mode result
- new method to measure neutrino contamination

4. [illegible] secti
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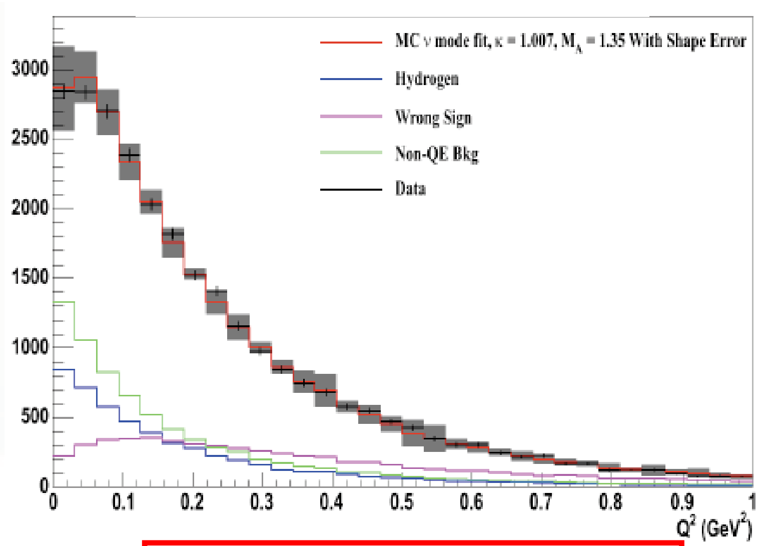
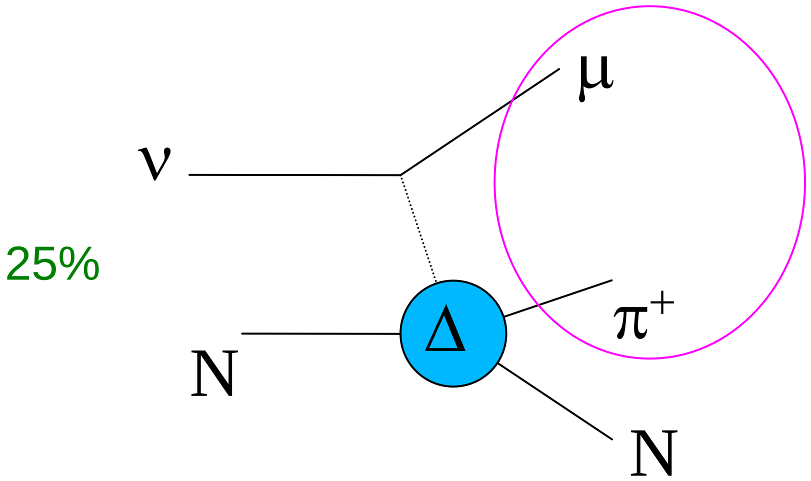
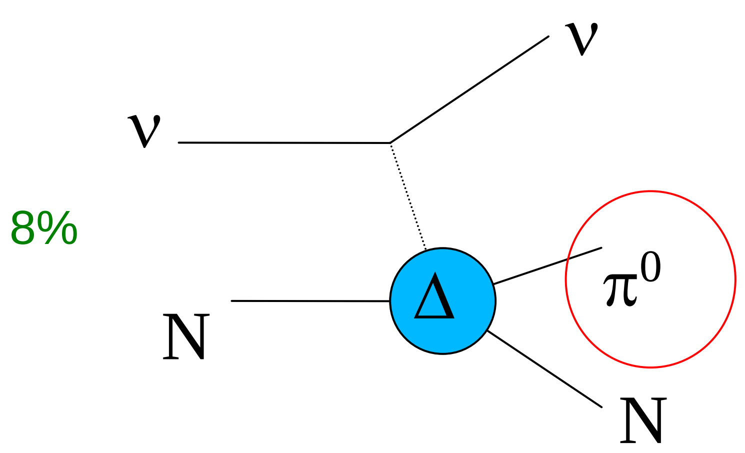


anti-νCCQE Q^2 distribution

5. Cross section model





(also decays to a single photon with 0.56% probability)

Events producing pions

$CC\pi^+$
Easy to tag due to 3 subevents. Not a substantial background to the oscillation analysis.

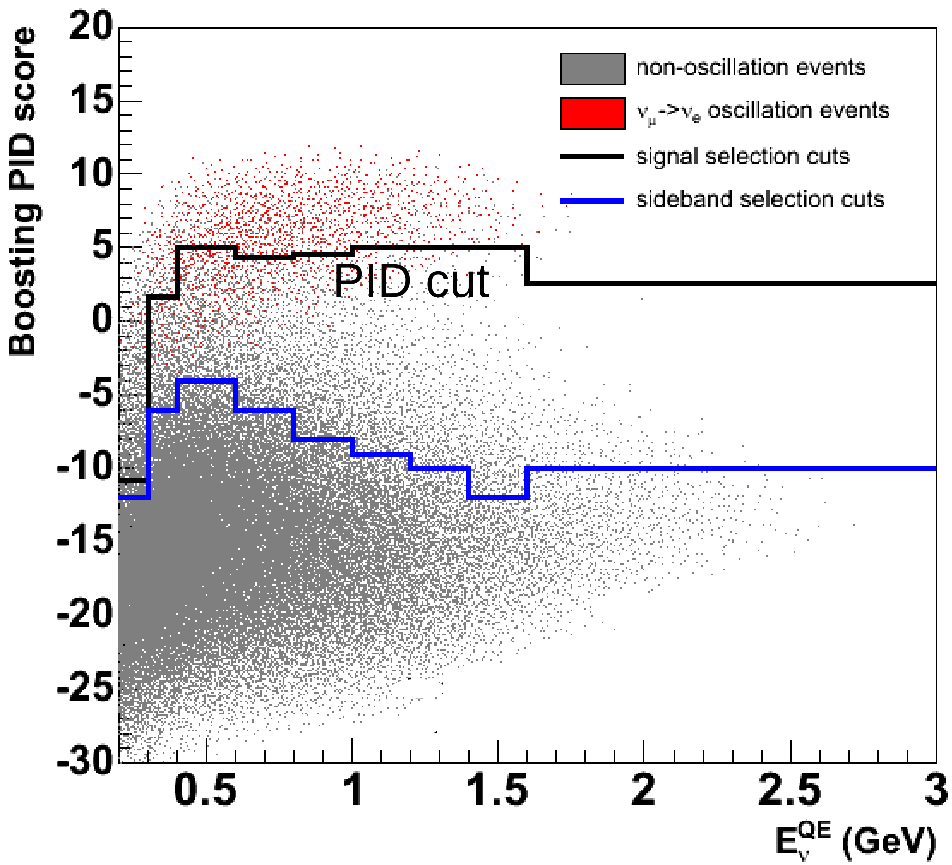
$NC\pi^0$
The π^0 decays to 2 photons, which can look “electron-like” mimicking the signal...

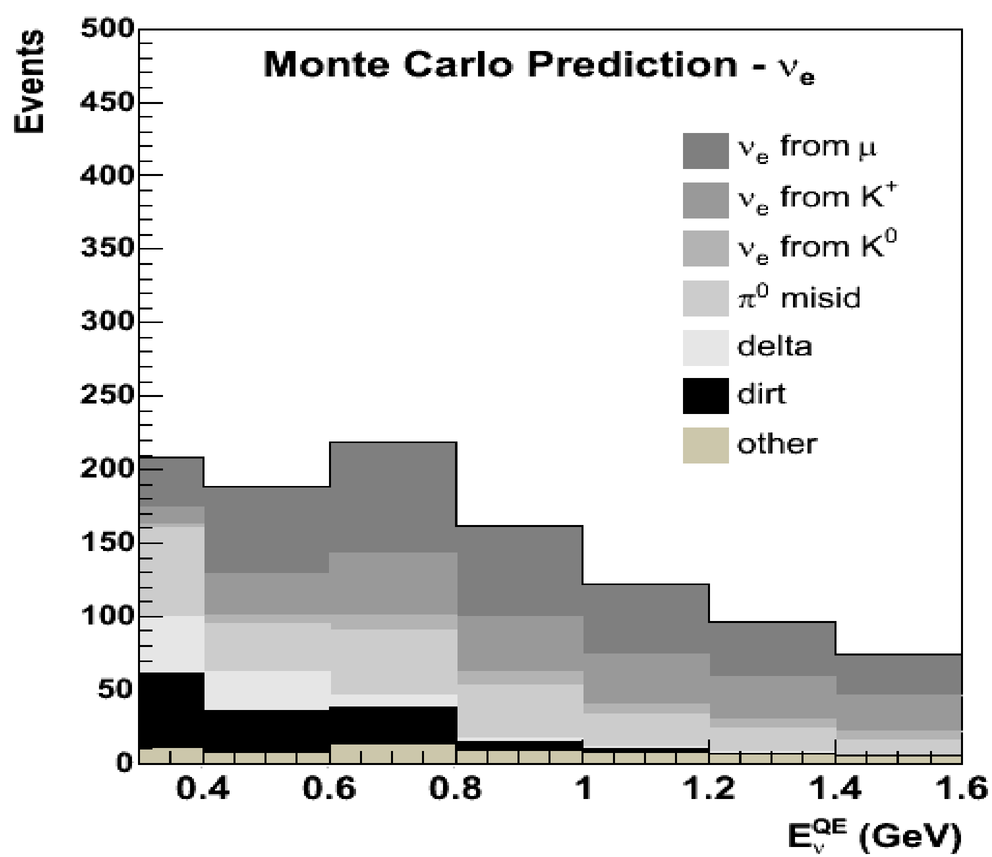
<1% of π^0 contribute to background.

5. Boosted Decision Tree (BDT) analysis

BDT analysis summary

- Oscillation analysis uses 300MeV<E<1600MeV
- PID cut is defined each E_ν^{QE} bin





5. Error analysis

Handling uncertainties in the analyses:

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

5. Error analysis

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and information on
the correlations
between bins

Input error matrix
keep the all correlation
of systematics

"multisim"
nonlinear error propagation

Output error matrix
keep the all correlation
of E_ν^{QE} bins

5. Multisim

Multi-simulation (Multisim) method
many fake experiments with different parameter set give the variation of correlated systematic errors for each independent error matrix

total error matrix is the sum of all independent error matrix

B.P.Roe,
Nucl.,Instrum.,Meth,A570(2007)157

Input error matrices

dependent

independent

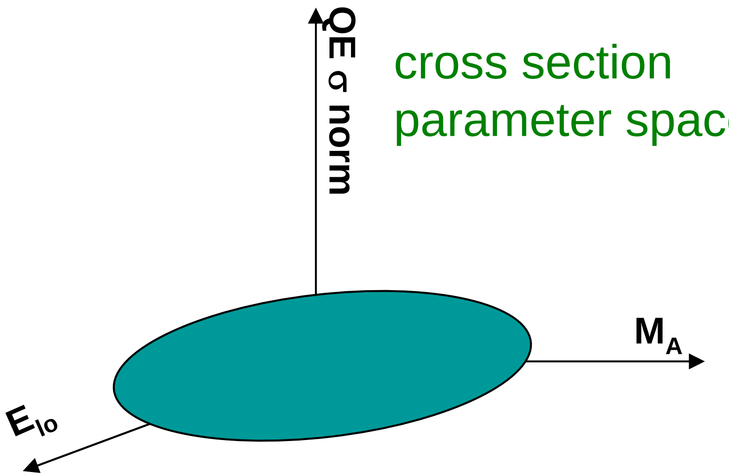
π^+ production	(8 parameters)
π^- production	(8 parameters)
K^+ production	(7 parameters)
K^0 production	(9 parameters)
beam model	(8 parameters)
cross section	(27 parameters)
π^0 yield	(9 parameters)
dirt model	(1 parameters)
detector model	(39 parameters)

5. Multisim

ex) cross section uncertainties

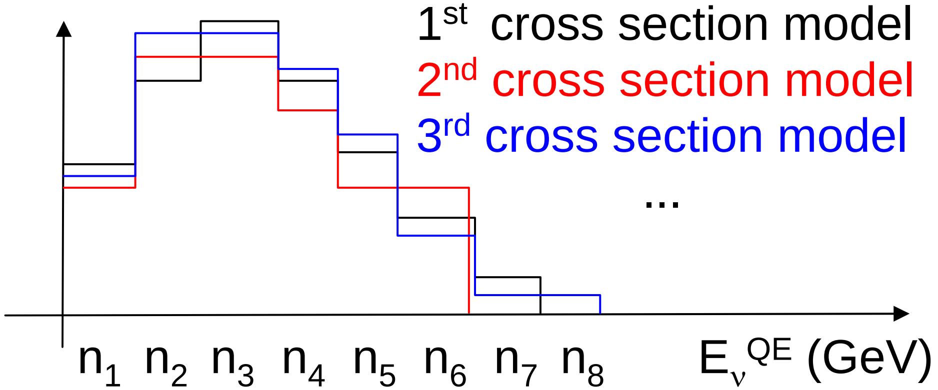
M_A^{QE}	6%	correlated
E_{lo}^{sf}	2%	
QE σ norm	10%	uncorrelated

cross section parameter space



Input cross section error matrix

cross section error for E_ν^{QE}



repeat this exercise many times to create smooth error matrix for E_ν^{QE}

5. Multisim

ex) cross section uncertainties

M_A^{QE}	6%	correlated
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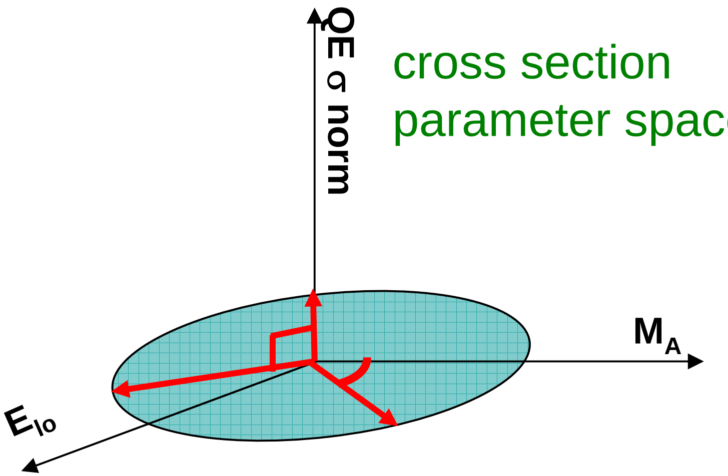
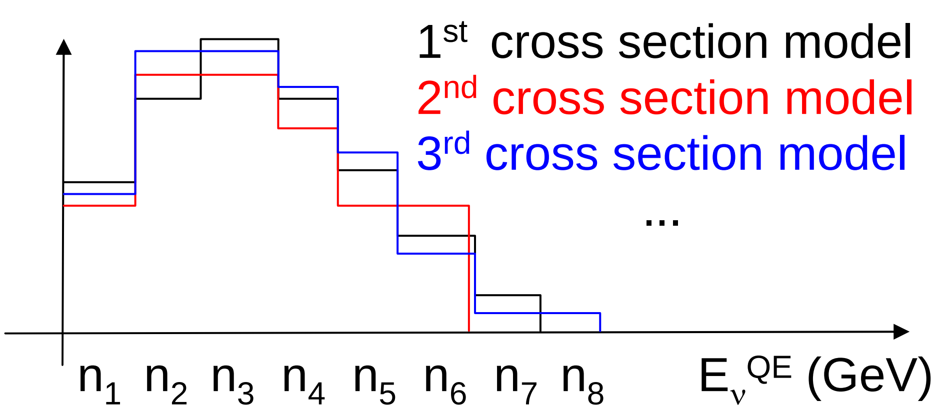


Input cross section error matrix

cross section error for E_ν^{QE}

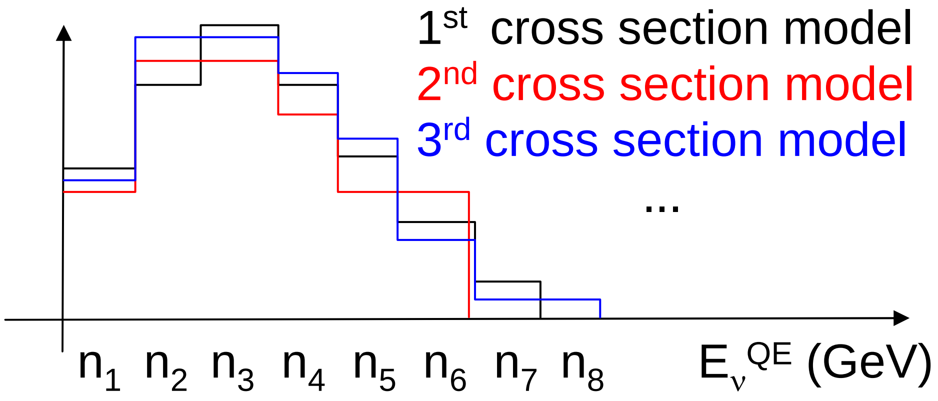


repeat this exercise many times to create smooth error matrix for E_ν^{QE}

5. Multisim

Output cross section error matrix for E_ν^{QE}

cross section error for E_ν^{QE}



Oscillation analysis use output error matrix for χ^2 fit;

$$\chi^2 = (\text{data} - \text{MC})^T (M_{output})^{-1} (\text{data} - \text{MC})$$

5. Multisim

ex) cross section uncertainties

M_A^{QE}	6%	determined from MiniBooNE ν_μ QE data
E_{lo}^{sf}	2%	
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	±25%	
$\Delta \to N\gamma$ 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%	

etc...

5. Multisim

Total output error matrix

$M_{total} =$ M(p^{+} production)
+ M(p^{-} production)
+ M(K^{+} production)
+ M(K^{0} production)
+ M(beamline model)
+ M(cross section model)
+ M(π^{0} yield)
+ M(dirt model)
+ M(detector model)
+ M(data stat)

Oscillation analysis χ^2 fit

$$\chi^2 = (\text{data} - \text{MC})^T (M_{total})^{-1} (\text{data} - \text{MC})$$

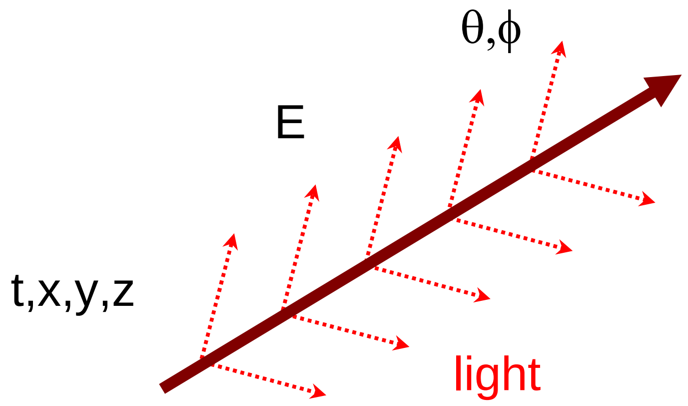
6. Track-Based Likelihood (TBL) analysis

This algorithm was found to have the better sensitivity to $\nu_\mu \rightarrow \nu_e$ appearance.
Therefore, before unblinding, this was the algorithm chosen for the "primary result"

Fit event with detailed, direct reconstruction of particle tracks,
and ratio of fit likelihoods to identify particle

Fit event under the different hypotheses;
- muon like
- electron like

Fit is characterized by 7 parameters

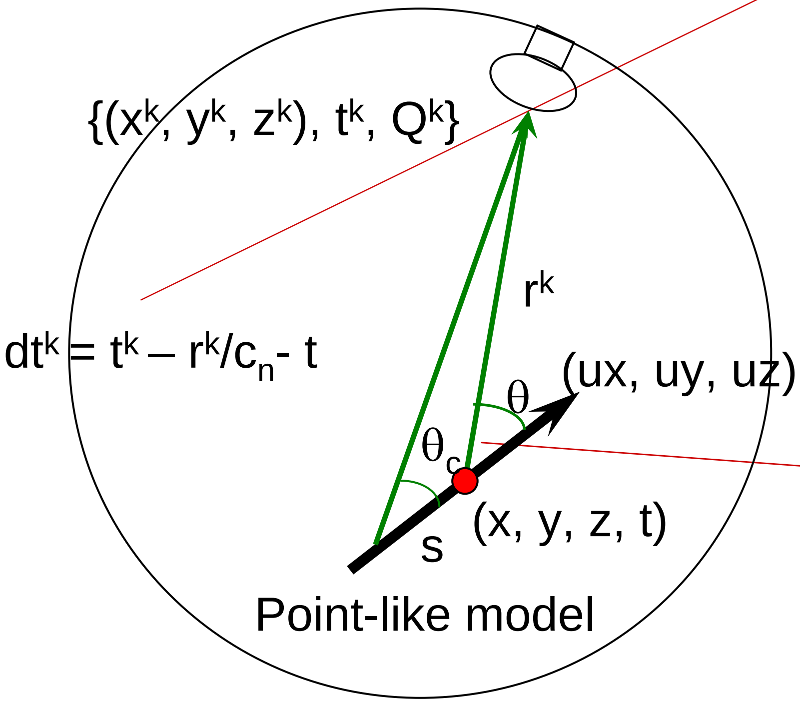


Fit knows
- scintillation, Cherenkov light fraction
- wave length dependent of light propagation
- scattering, reemission, reflection, etc
- PMT efficiencies

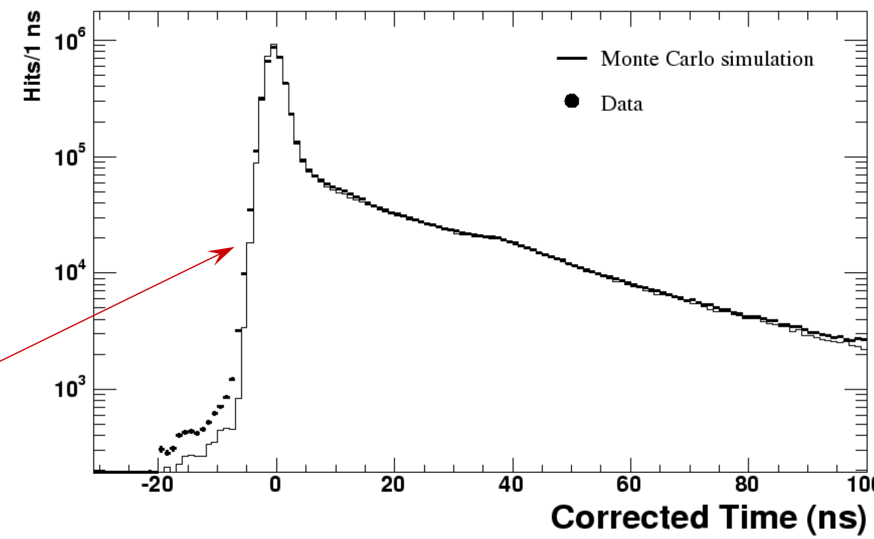
6. Boosted Decision Tree (BDT) analysis

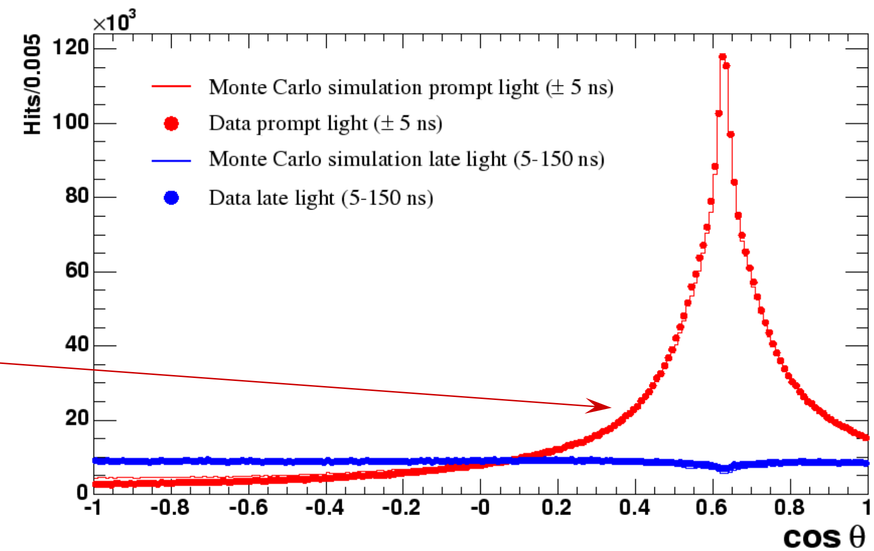
Events are reconstructed with point-like model

Construct a set of analysis variables (vertex, track length, time cluster, particle direction, event topology, energy, etc)



Muon decay electron spectrum

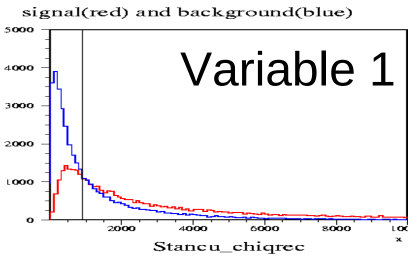




6. Boosted Decision Tree (BDT) analysis

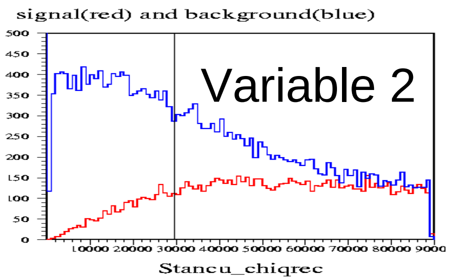
A Decision Tree
(sequential series of cuts based on MC study)

(N_{signal}/N_{bkgd})



bkgd-like

signal-like



9755/23695

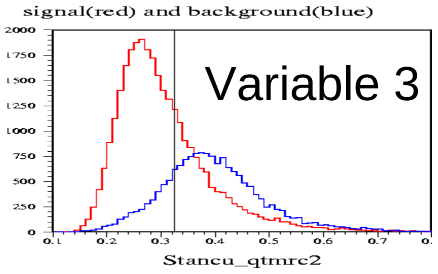
bkgd-like

sig-like

1906/11828

7849/11867

30,245/16,305



sig-like

bkgd-like

20455/3417

9790/12888

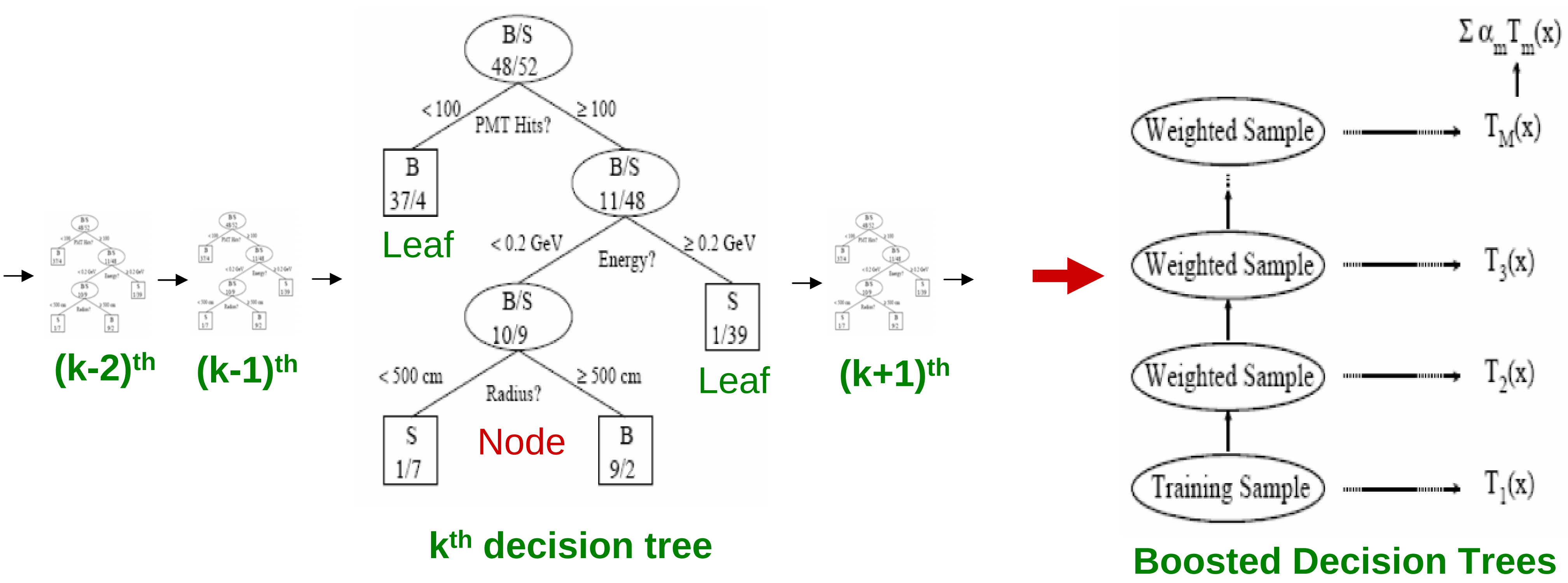
This tree is one of many possibilities...

etc.

6. Boosted Decision Tree (BDT) analysis

Boosted Decision Tree

- a kind of data learning method (e.g., neural network,...)
- training sample (MC simulation) is used to train the code
- combined many weak classifiers (~1000 weak trees) to make strong "committee"

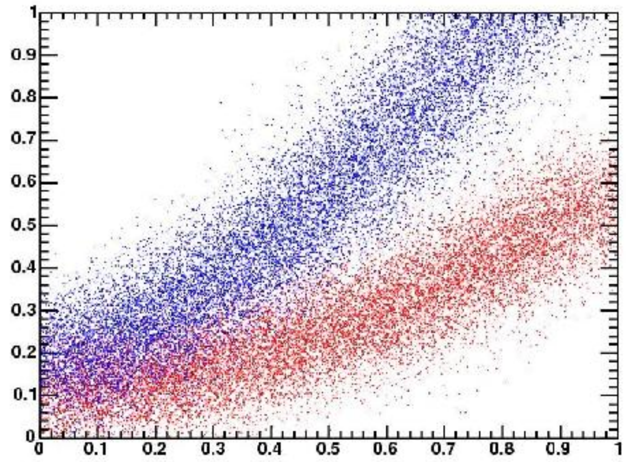


6. Boosted Decision Tree (BDT) analysis

Example of classification problem

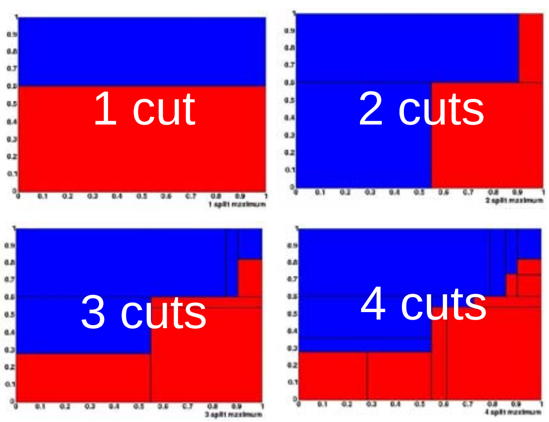
The goal of the classifier is to separate blue (signal) and red (background) populations.

Fake data sample

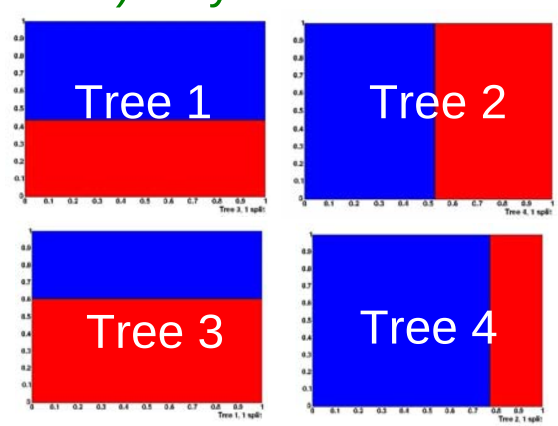


Two ways to use decision trees. 1) Multiple cuts on X and Y in a big tree, 2) Many weak trees (single-cut trees) combined

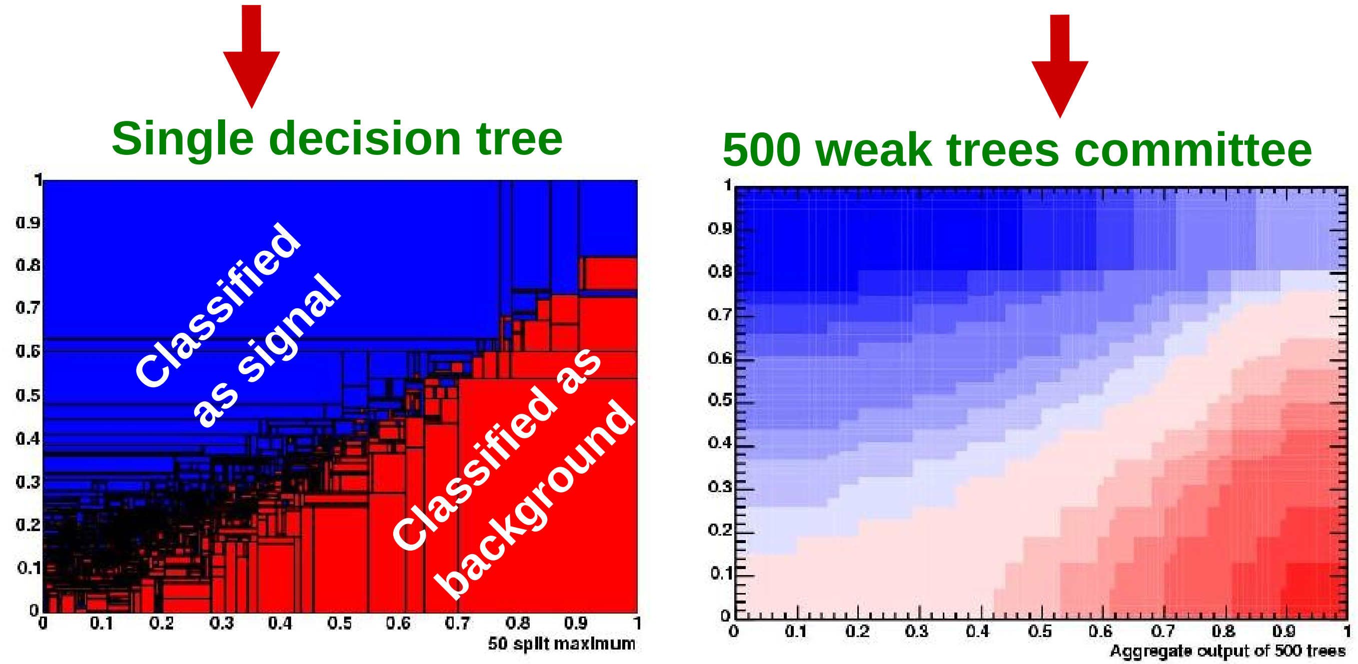
1) Development of a single decision tree



2) Many weak trees (single cut trees) only 4 trees shown

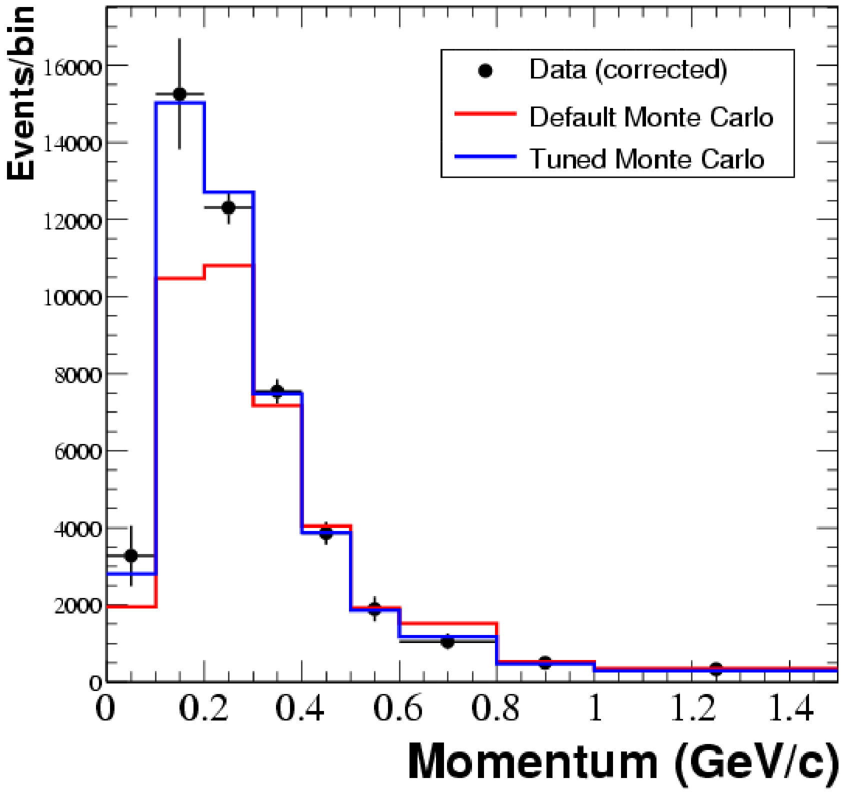


6. Boosted Decision Tree (BDT) analysis



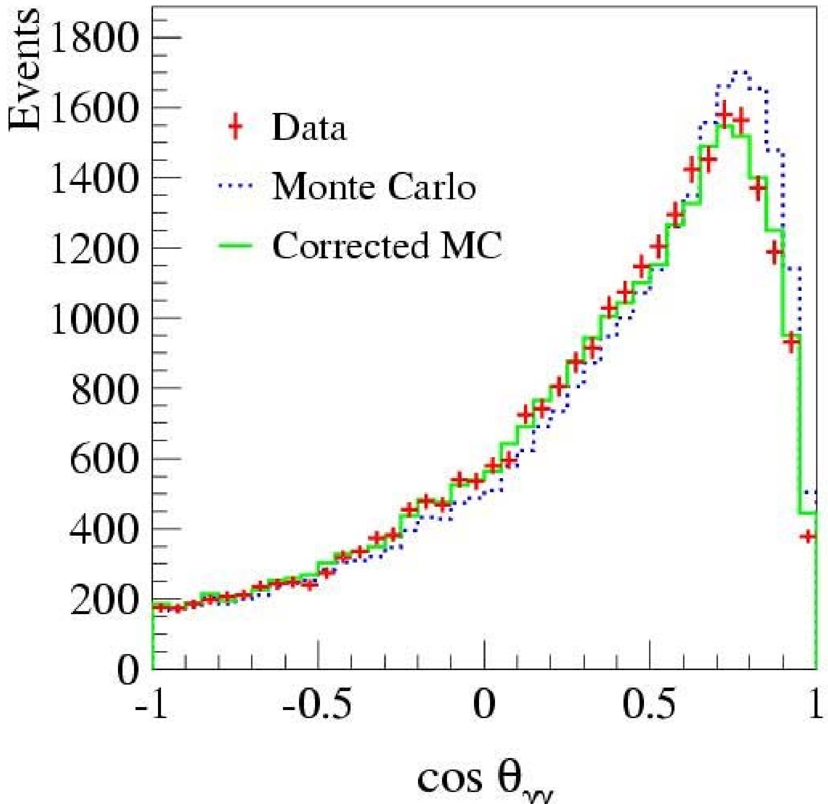
Boosting Algorithm has all the advantages of single decision trees, and less suceptibility to overtraining.

7. Error analysis



We constrain π^0 production using data from our detector

This reduces the error on predicted mis-identified π^0s



Reweighting improves agreement in other variables

Because this constrains the Δ resonance rate, it also constrains the rate of $\Delta \rightarrow N\gamma$

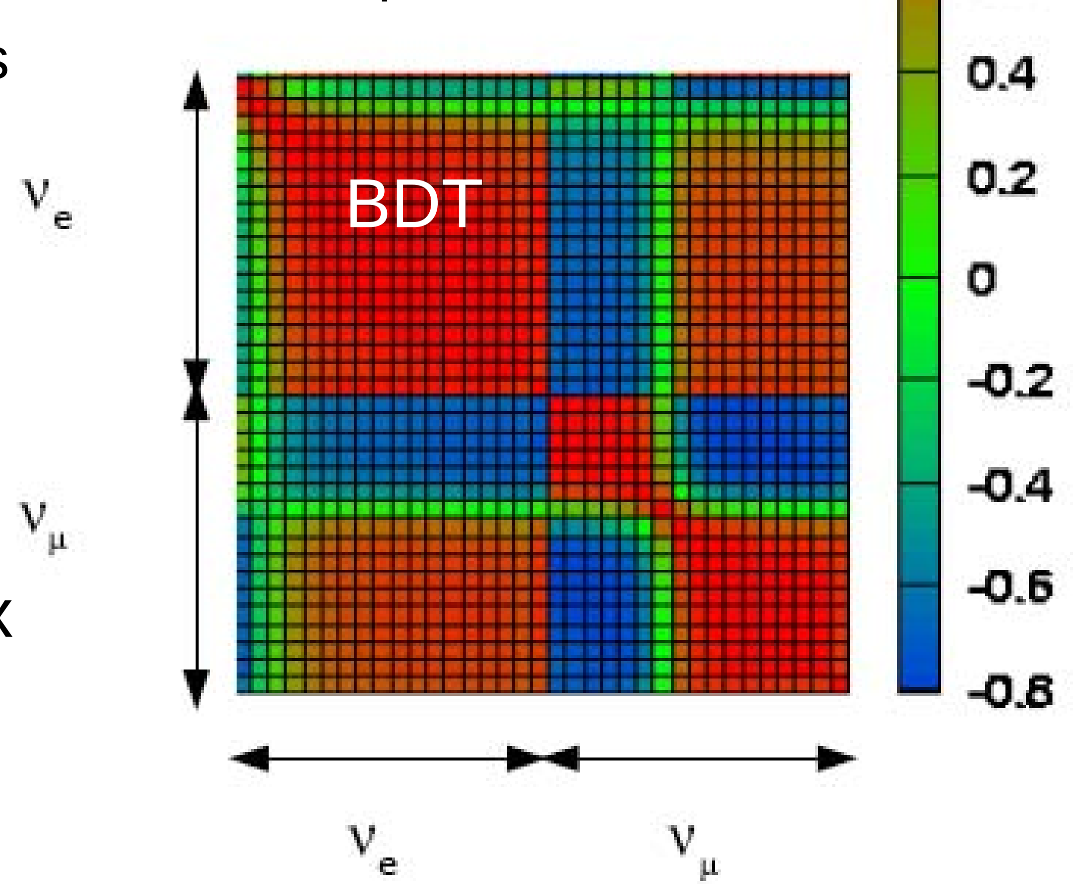
7. Multisim

Error Matrix Elements:

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

- 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

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



Total error matrix is sum from each source.

TB: ν_e-only total error matrix
BDT: ν_μ-ν_e total error matrix