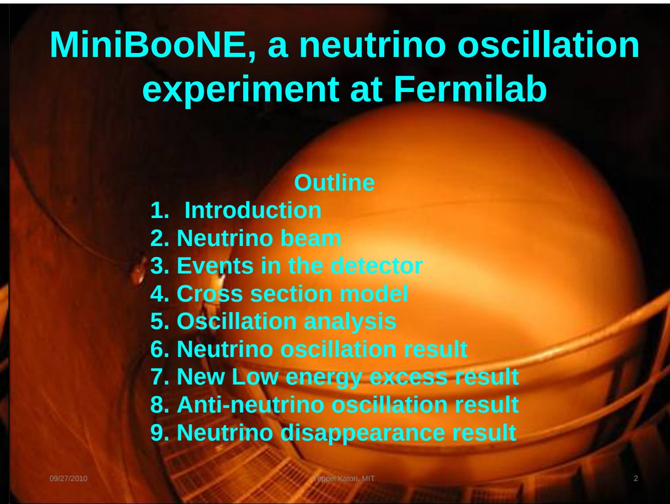
# MiniBooNE, a neutrino oscillation experiment at Fermilab

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



## 1. Neutrino oscillation

The neutrino weak eigenstate is described by neutrino Hamiltonian eigenstates, $\nu_1$, $\nu_2$, and $\nu_3$ 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 $\nu_1$, $\nu_2$, and $\nu_3$.

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

Then the transition probability from weak eigenstate $\nu_\mu$ to $\nu_e$ 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,

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

Therefore, 2 massive neutrino oscillation model is

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

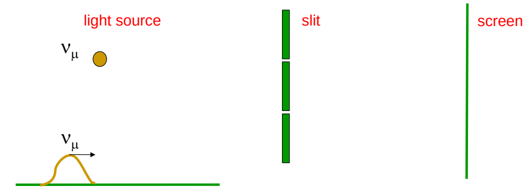
Or, conventional form

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



## 1. Neutrino oscillation

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

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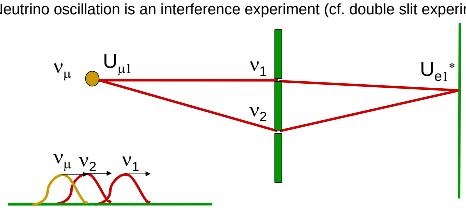

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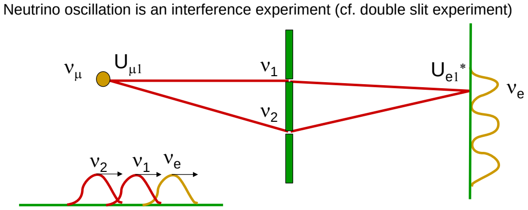

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LSND Collaboration, PRD 64, 112007

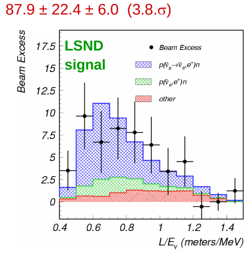
## 1. LSND experiment

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

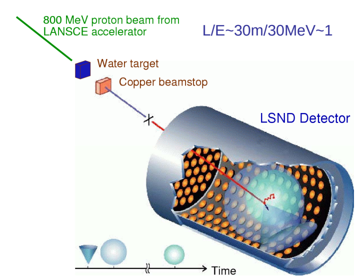
$$\bar{\nu}_\mu \xrightarrow{oscillation} \bar{\nu}_e + p \to e^+ + n$$

$$n + p \to d + \gamma$$

87.9 ± 22.4 ± 6.0 (3.8.σ)




L/E~30m/30MeV~1



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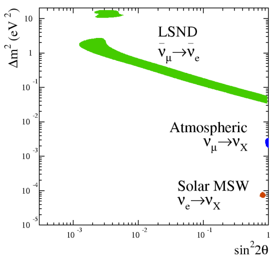
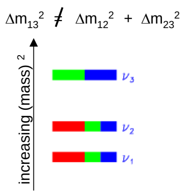



3 types of neutrino oscillations are found:

LSND neutrino oscillation: $\Delta m^2 \sim 1eV^2$
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 $\Delta m^2$!




We need to test LSND signal

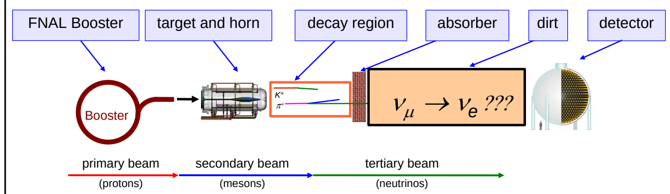
MiniBooNE experiment is designed to have same L/E~500m/500MeV~1 to test LSND $\Delta m^2 \sim 1eV^2$



## 1. MiniBooNE experiment

Keep L/E same with LSND, while changing systematics, energy & event signature;
$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$

MiniBooNE is looking for the single isolated electron like events, which is the signature of $\nu_e$ events




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



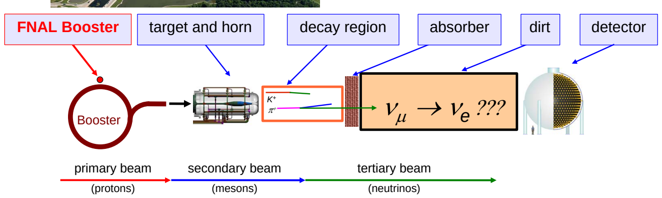




MiniBooNE collaboration, PRD79(2009)072002

## 2. Neutrino beam


MiniBooNE extracts beam from the 8 GeV Booster



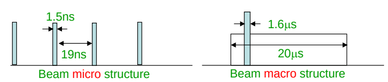



MiniBooNE collaboration, PRD79(2009)072002

## 2. Neutrino beam


$4 \times 10^{12}$ protons per 1.6 $\mu$s pulse delivered at up to 5 Hz.

$5.58 \times 10^{20}$ POT (proton on target)



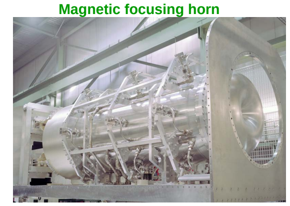

FNAL Booster



MiniBooNE collaboration, PRD79(2009)072002

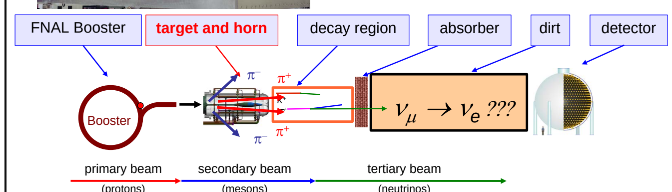
## 2. Neutrino beam

Magnetic focusing horn



8GeV protons are delivered to a 1.7 $\lambda$ Be target

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

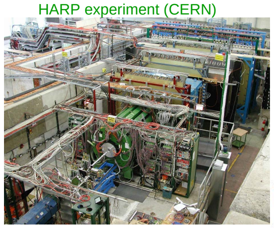





MiniBooNE collaboration, PRD79(2009)072002

## 2. Neutrino beam

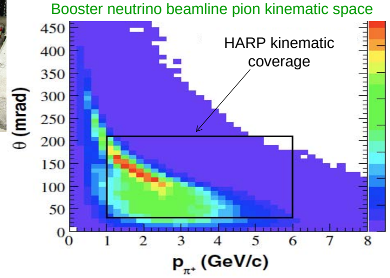
HARP experiment (CERN)



Modeling of meson production is based on the measurement done by HARP collaboration
- Identical, but 5% $\lambda$ Beryllium target
- 8.9 GeV/c proton beam momentum

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

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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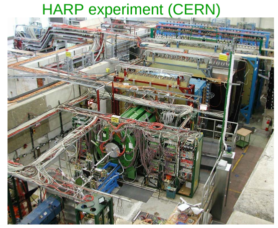
HARP experiment (CERN)



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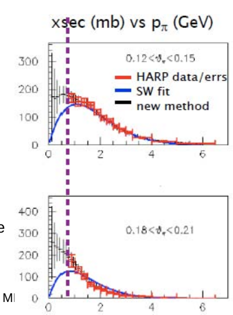
HARP collaboration, Eur.Phys.J.C52(2007)29




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.



MiniBooNE collaboration, PRD79(2009)072002

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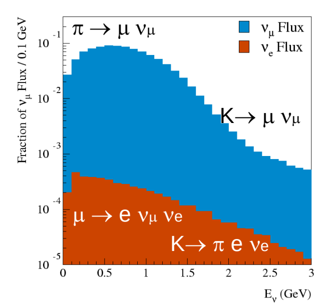


Neutrino Flux from GEANT4 Simulation

MiniBooNE is the $\nu_e$ appearance oscillation experiment

"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%)

$\nu_e/\nu_\mu = 0.5\%$
Antineutrino content: 6%

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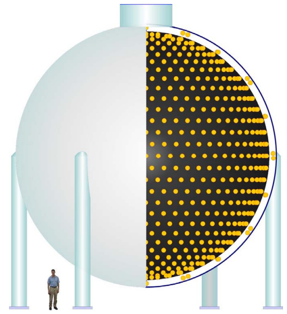
MiniBooNE collaboration, NIM.A599(2009)28

## 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



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MiniBooNE collaboration, NIM.A599(2009)28

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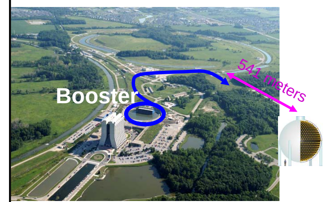


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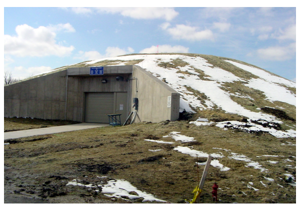

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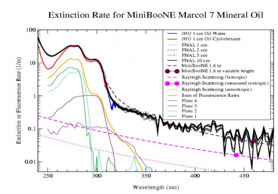
MiniBooNE collaboration, NIM.A599(2009)28

## 3. Events in the Detector

Extinction rate of MiniBooNE oil

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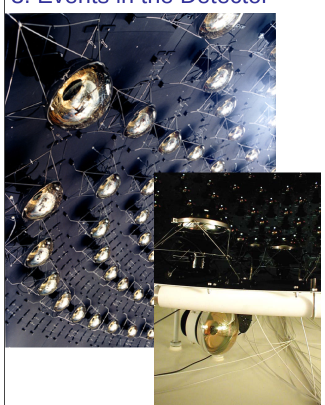

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MiniBooNE collaboration, NIM.A599(2009)28

## 3. Events in the Detector

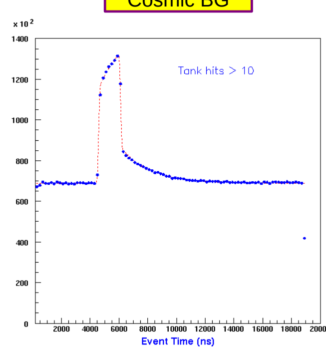
Times of hit-clusters (subevents)
Beam spill (1.6μs) is clearly evident
simple cuts eliminate cosmic backgrounds

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



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MiniBooNE collaboration, NIM.A599(2009)28

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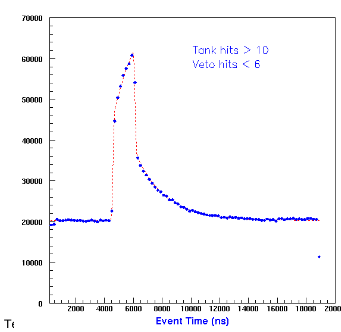

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MiniBooNE collaboration, NIM.A599(2009)28

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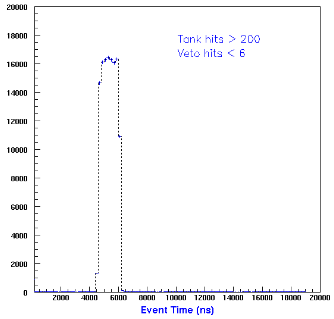
Beam Only



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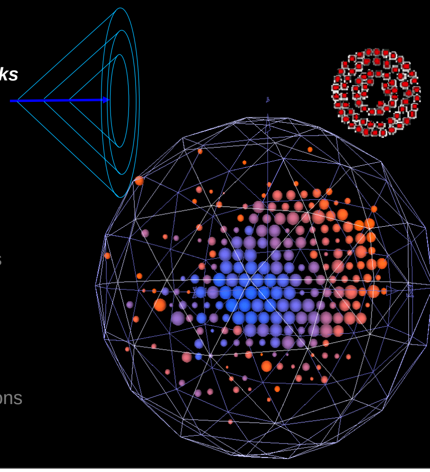
## 3. Events in the Detector

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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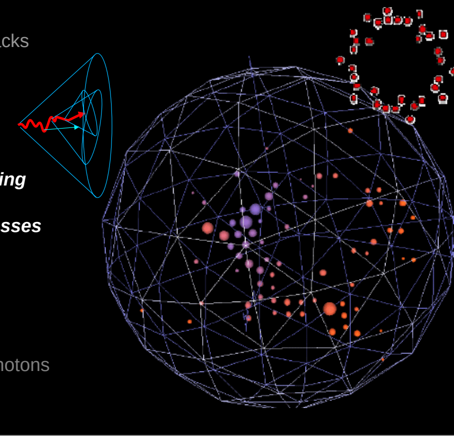

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MiniBooNE collaboration, NIM.A599(2009)28

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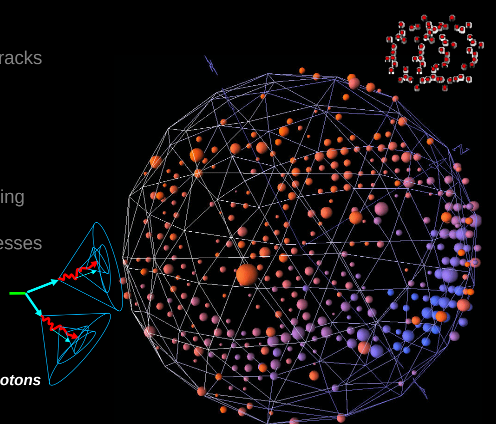

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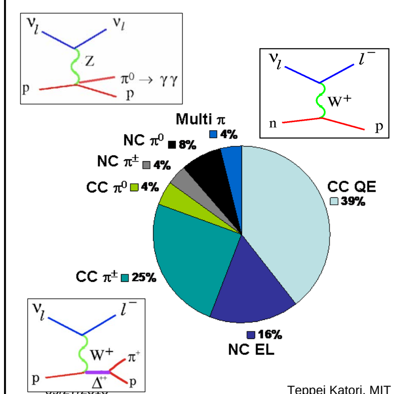
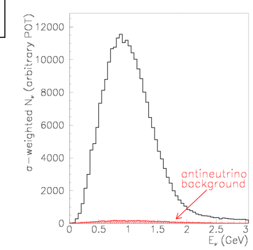
## 4. Cross section model

Predicted event rates before cuts
(NUANCE Monte Carlo)
Casper, Nucl.Phys.Proc.Suppl.112(2002)161




Event neutrino energy (GeV)



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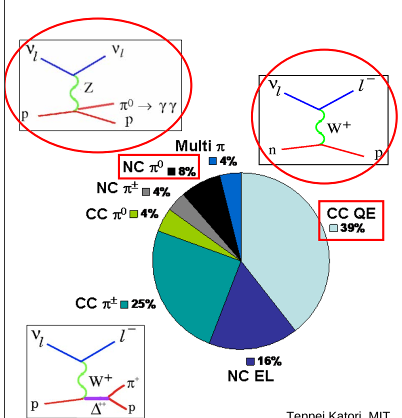
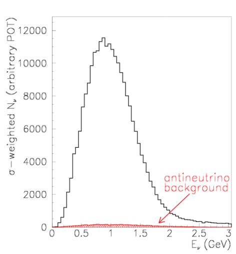
Casper, Nucl.Phys.Proc.Suppl.112(2002)161




Event neutrino energy (GeV)



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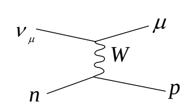
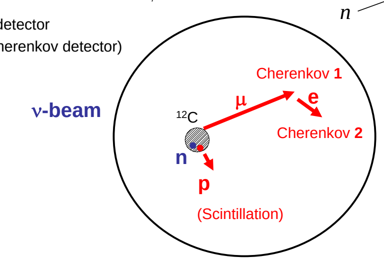
## 4. CCQE cross section model tuning

CCQE (Charged Current Quasi-Elastic)
$\nu_\mu$ charged current quasi-elastic ($\nu_\mu$ CCQE) interaction is the most abundant (~40%) and the fundamental interaction in MiniBooNE detector

$$\nu_\mu + n \to p + \mu^-$$
$$(\nu_\mu + {}^{12}C \to X + \mu^-)$$



MiniBooNE detector
(spherical Cherenkov detector)




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



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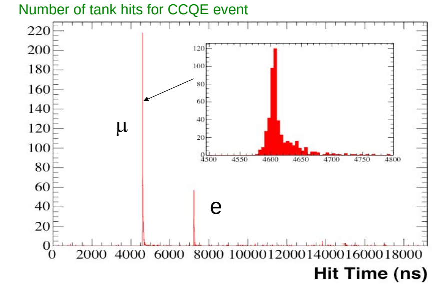
## 4. CCQE cross section model tuning

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

$\nu_\mu$ CCQE interactions ($\nu$+n → μ+p) with characteristic two "subevent" structure from stopped $\mu \to \nu_\mu \bar{\nu}_e e$

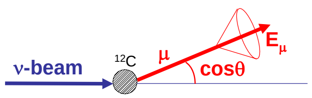
Number of tank hits for CCQE event



## 4. CCQE cross section model tuning

All kinematics are specified from 2 observables, muon energy $E_\mu$ and muon scattering angle $\theta_\mu$

Energy of the neutrino $E_\nu^{QE}$ 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 $\nu_e$ 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

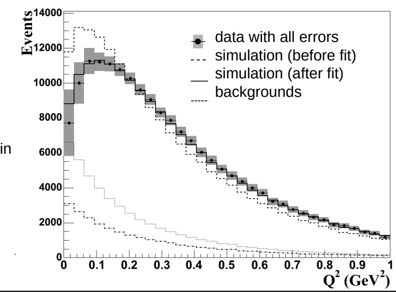
$Q^2$ fits to MB $\nu_\mu$ CCQE data using the nuclear parameters:

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

Relativistic Fermi Gas Model with tuned parameters describes $\nu_\mu$ CCQE data well

This improved nuclear model is used in $\nu_e$ CCQE channel, too.

$Q^2$ distribution before and after fitting

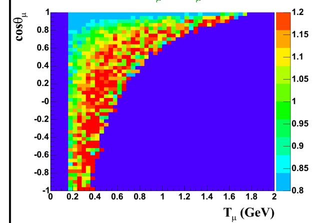





## 4. CCQE cross section model tuning

Without knowing flux perfectly, we cannot modify cross section model

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



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

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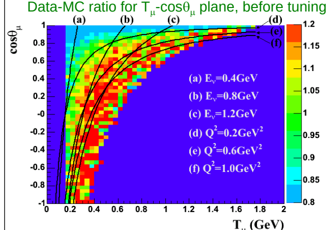




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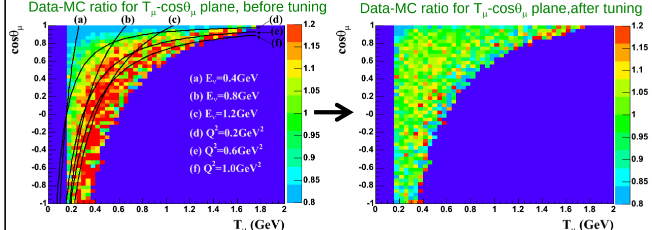
Data-MC ratio for $T_\mu$-$\cos\theta_\mu$ plane,after tuning






## 4. NCπº rate tuning

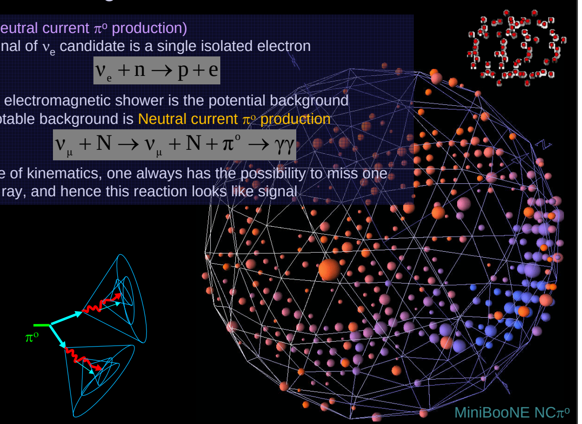
NCπº (neutral current πº production)
The signal of $\nu_e$ candidate is a single isolated electron

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

- single electromagnetic shower is the potential background
- the notable background is Neutral current πº production

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

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




MiniBooNE NCπº candidate

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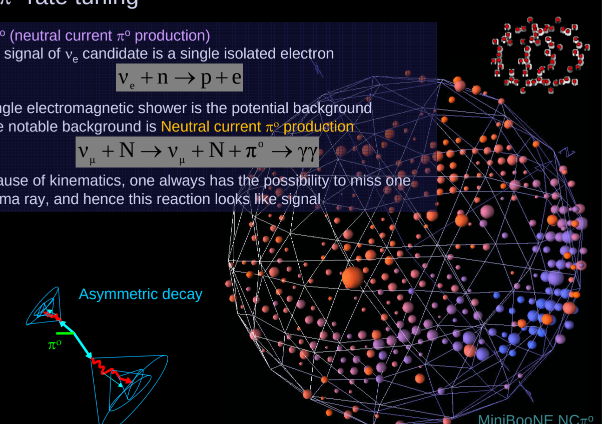
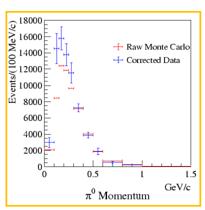


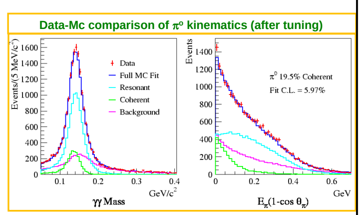

MiniBooNE NCπº candidate

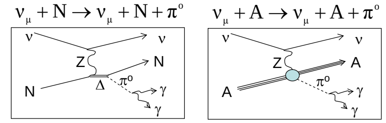
## 4. NCπº rate tuning

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 $\nu_e$ appearance search.




MiniBooNE collaboration
PLB664(2008)41




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



## 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 πº production (NCπº) 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 πº production (CCπº) 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

## 4. MiniBooNE cross section results

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NuInt09 MiniBooNE results
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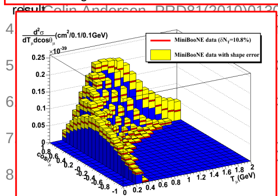
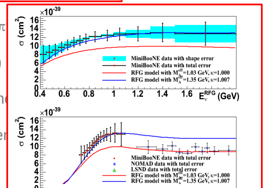
1. charged current quasielastic (CCQE) cross section measurement
by Teppei Katori, PRD81(2010)092005

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


Flux-integrated double differential cross section


Flux-unfolded total cross section



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

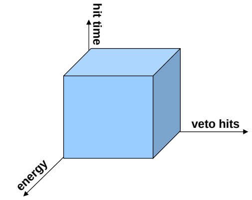


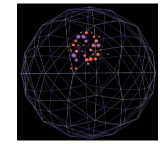
## 5. Blind analysis

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

The MiniBooNE signal is small but relatively easy to isolate

The data is described in n-dimensional space;





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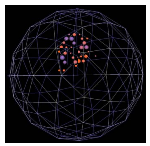
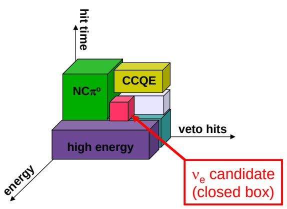
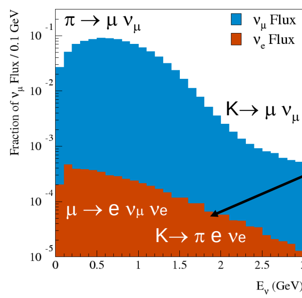





The data is classified into "box". For boxes to be "opened" to analysis they must be shown to have a signal < 1σ. In the end, 99% of the data were available (boxes need not to be exclusive set)



## 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 $\nu_e$ background without measuring directly

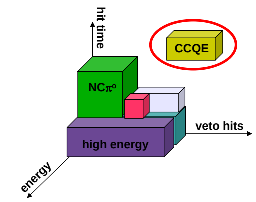
(1) μ decay $\nu_e$ background
(2) K decay $\nu_e$ background

$\nu_e/\nu_\mu = 0.5\%$
Antineutrino content: 6%

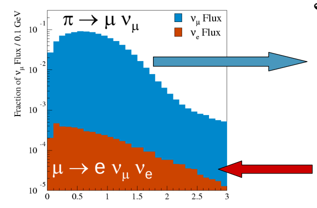


## 5. Blind analysis

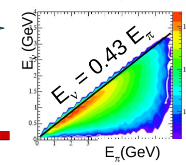
(1) measure $\nu_\mu$ flux from $\nu_\mu$CCQE event to constraint $\nu_e$ background from μ decay




$\nu_\mu$CCQE is one of the open boxes.
Kinematics allows connection to π flux, hence intrinsic $\nu_e$ background from μ decay is constraint. In the really, simultaneous fit of $\nu_e$CCQE and $\nu_\mu$CCQE take care of this.




Eν-Eπ space

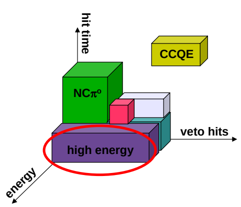


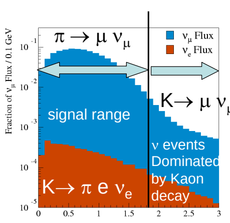



## 5. Blind analysis

(2) measure high energy $\nu_\mu$ events to constraint $\nu_e$ background from K decay

At high energies, above "signal range" $\nu_\mu$ and "$\nu_e$ -like" events are largely due to kaon decay




example of open boxes;
- $\nu_\mu$CCQE
- high energy event
- $CC\pi^+$
- NC elastics
- NC $\pi^0$
- 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

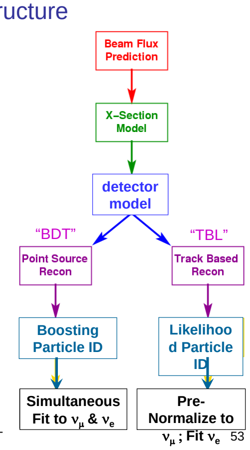
Predict ν interactions using NUANCE neutrino interaction generator

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

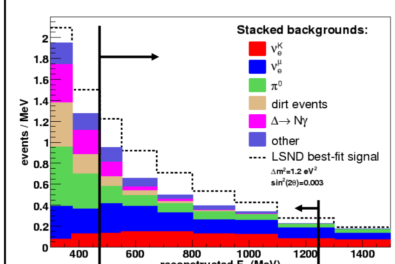
Fit reconstructed $E_\nu^{QE}$ spectrum for oscillations






## 5. Track-Based Likelihood (TBL) analysis

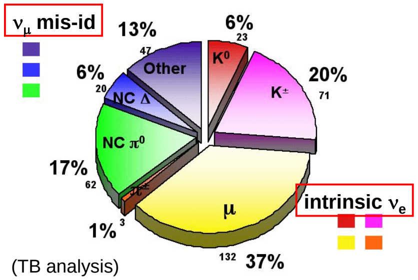
TBL analysis summary
- Oscillation analysis uses 475MeV<E<1250MeV




| 475 MeV – 1250 MeV | |
|---|---|
| $\nu_e^K$ | 94 |
| $\nu_e^\mu$ | 132 |
| $\pi^0$ | 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)

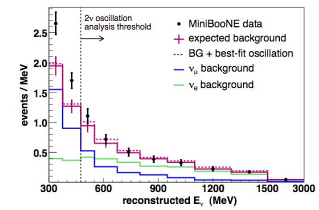






MiniBooNE collaboration, PRL98(2007)231801

## 6. The MiniBooNE initial results

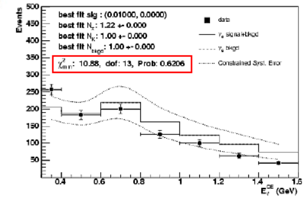



TBL analysis
TBL show no sign of an excess in the analysis region (where the LSND signal is expected from 1 sterile neutrino interpretation)

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

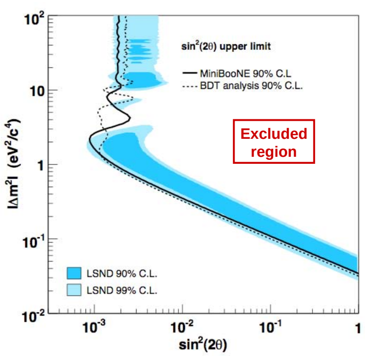




MiniBooNE collaboration, PRL98(2007)231801

## 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.



MiniBooNE collaboration, PRL98(2007)231801

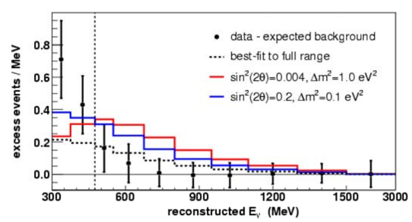
## 6. Excess at low energy region?

Our goals for this first analysis were:
- A generic search for a $\nu_e$ excess in our $\nu_\mu$ beam,
- An analysis of the data within a $\nu_\mu \to \nu_e$ 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.







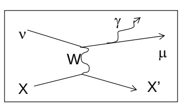



## 7. Excess at low energy region?

Commonplace idea Bodek, arXiv:0709.4004
Muon bremsstrahlung

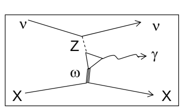
✗

- 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



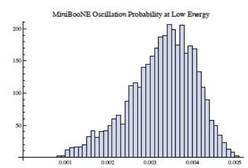


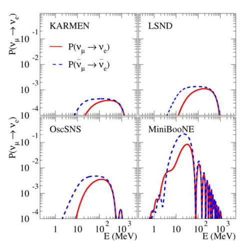

## 7. Excess at low energy region?

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

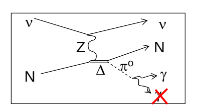


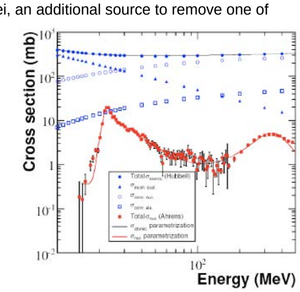
## 7. Oscillation analysis update

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 NC$\pi^o$

Photonuclear effect




Other missing processes, (π-C elastic scattering, radiative $\pi^-$ 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

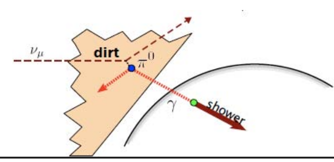
We re-visit all background source, to find any missing components

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 $\pi^o$ made outside of the detector)






MiniBooNE collaboration, PRL102(2009)101802

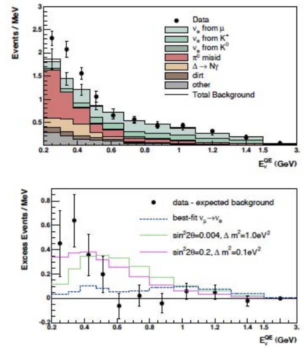
## 7. New oscillation analysis result

New $\nu_e$ appearance oscillation result

- low energy excess stays, the original excess in 300-475MeV becomes 3.4$\sigma$ from 3.7$\sigma$ 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









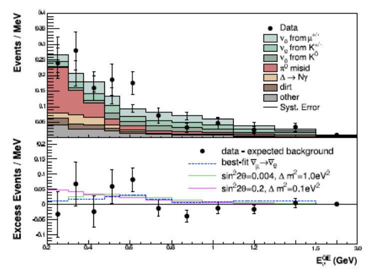

MiniBooNE collaboration, PRL103(2009)111801

## 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 $\mu^-$ and $\mu^+$ on event-by-event basis.

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






MiniBooNE collaboration, PRL103(2009)111801

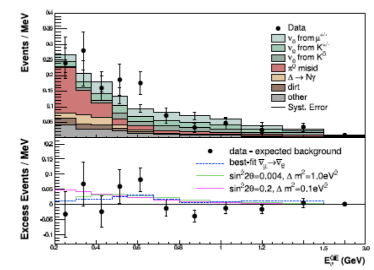
## 8. Antineutrino oscillation result

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

- The models based on same NC cross section for $\nu$ and anti-$\nu$ (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

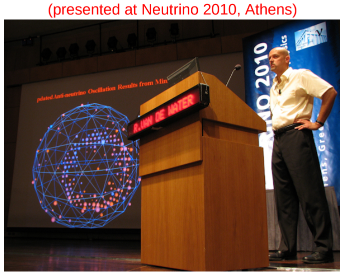
- Antineutrino mode is the direct test of LSND signal
- Analysis is limited with statistics

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 NC$\pi^o$ rate measurement (consistent with neutrino mode)
- $\nu$ fraction is measured in anti-$\nu$ beam

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





MiniBooNE collaboration, arXiv:1007.1150

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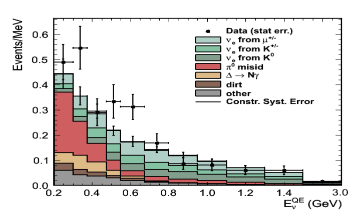
New antineutrino oscillation result

| | 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) |

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

MiniBooNE now see the excess in LSND-like $\Delta m^2$ region!






MiniBooNE collaboration, arXiv:1007.1150

## 8. New antineutrino oscillation result

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

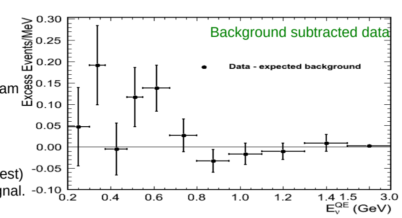
New antineutrino oscillation result

| | before fit | |
|---|---|---|
| | $\chi^2$/NDF | probability |
| 475 < $E_\nu^{QE}$ < 1250 MeV | 18.5/6 | 0.5% |

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

MiniBooNE now see the excess in LSND-like $\Delta m^2$ region!

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



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

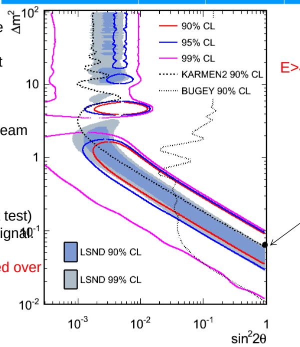
| | before fit | | after fit | |
|---|---|---|---|---|
| | $\chi^2$/NDF | probability | $\chi^2$/NDF | probability |
| 475 < $E_\nu^{QE}$ < 1250 MeV | 18.5/6 | 0.5% | 8.0/4 | 8.7% |

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

MiniBooNE now see the excess in LSND-like $\Delta m^2$ 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
$\Delta m^2$ = 0.064eV$^2$
$\sin^2 2\theta$ = 0.96







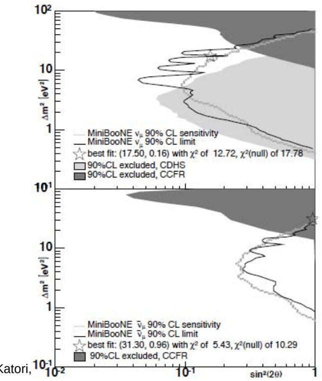
MiniBooNE collaboration, PRL103(2009)061802

## 9. Neutrino disappearance oscillation result

$\nu_\mu$ and anti-$\nu_\mu$ 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 $\Delta m^2$ .

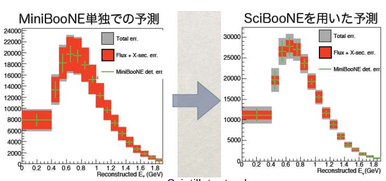


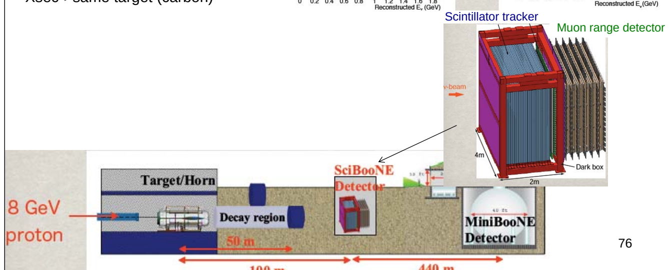



## 9. Neutrino disappearance oscillation result

MiniBooNE-SciBooNE combined $\nu_\mu$ disappearance oscillation analysis

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



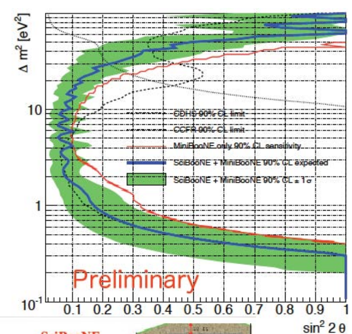


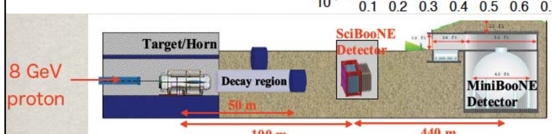

## 9. Neutrino disappearance oscillation result

MiniBooNE-SciBooNE combined $\nu_\mu$ disappearance oscillation analysis

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

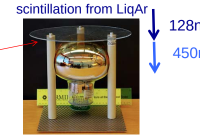
- this significantly improves sensitivities, especially at low $\Delta m^2$. An analysis for anti-$\nu_\mu$ is ongoing.



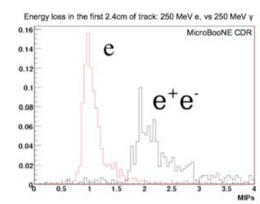



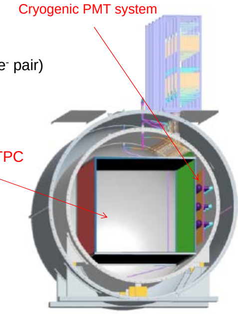



## Future: MicroBooNE




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)






## Conclusions

MiniBooNE is a $\nu_e$ 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 $\Delta m^2$ expect signal.

The MiniBooNE-SciBooNE combined $\nu_\mu$ 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

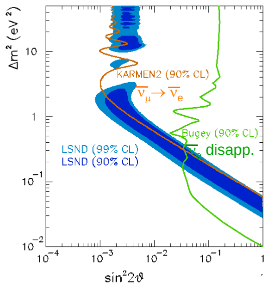
Los Alamos National Laboratory
Louisiana State University
Massachusetts Institute of Technology
University of Michigan
Princeton University
Saint Mary's University of Minnesota
Virginia Polytechnic Institute
Yale University

Thank you for your attention!

# Buck up

# 2. LSND experiment

In terms of the oscillation probability,
$P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e) = 0.264 \pm 0.067 \pm 0.045$

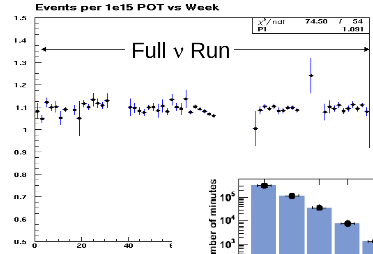



Under the 2 flavor massive neutrino oscillation model, one can map into $\Delta m^2$-$\sin^2 2\theta$ space (MS-diagram)

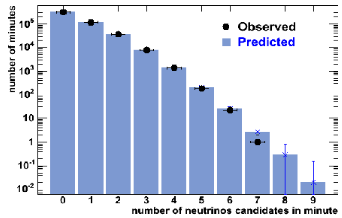
This model allows comparison to other experiments:
Karmen2
Bugey



# 3. Stability of running




Observed and expected events per minute

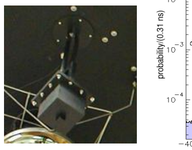


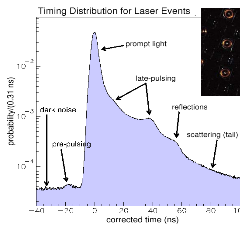


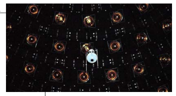

# 4. Calibration source

Laser flask system

Muon tracker and scintillation cube system



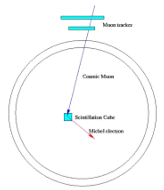


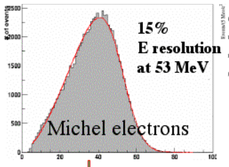



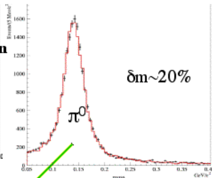


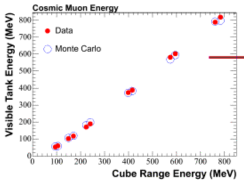
# 4. Calibration source

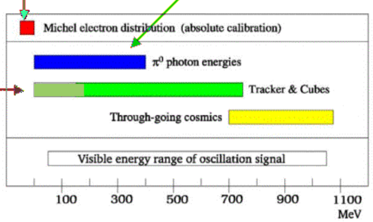
Tracker system






# 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
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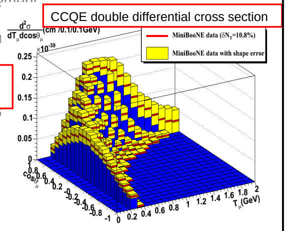
by Denis Perevalov, arXiv:1007.4730
3. neutral current $\pi^0$ production (NC$\pi^0$) cross section m...
by Colin Anderson, PRD81(2010)013005
- first double differential cross section measurement
- observed large absolute cross section
5. charged current single $\pi^0$ production (CC$\pi^0$) cross s...
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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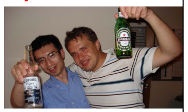

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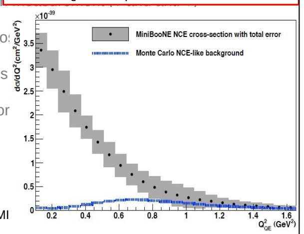
Flux-averaged NCE p+n differential cross section






by Colin Anderson

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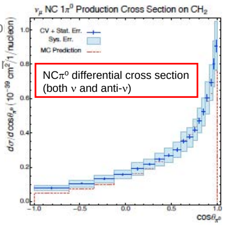




by Mike Wilking

# 4. MiniBooNE cross section results

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by Jarek Novak
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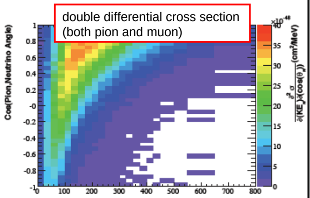
by Steve Linden, PRL103(2009)081801
8. anti-νCCQE measurement
by Joe Grange, paper in preparation

double differential cross section (both pion and muon)






by Bob Nelson

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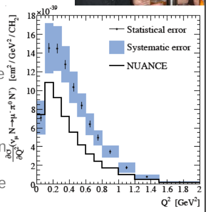
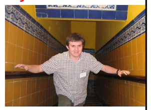
CC$\pi^0$ $Q^2$ differential cross section



by Jarek Novak

## 4. MiniBooNE cross section results



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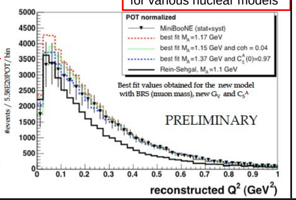
8. anti-$\nu$CCQE measurement by Joe Grange, paper in preparation

- state-of-art models are implemented, tested

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






by Steve Linden

## 4. MiniBooNE cross section results

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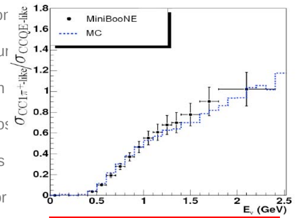
- data is presented in theorist friendly style

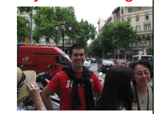



CC$\pi^+$like/CCQElike cross section ratio



by Joe Grange

## 4. MiniBooNE cross section results



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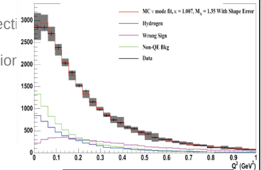
8. anti-$\nu$CCQE measurement by Joe Grange, paper in preparation

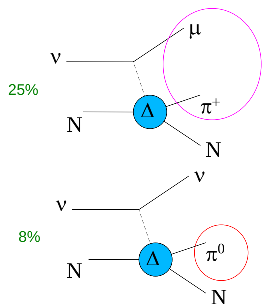
- highest statistics in this channel
- support neutrino mode result
- new method to measure neutrino contamination



anti-$\nu$CCQE $Q^2$ distribution



## 5. Cross section model




Events producing pions

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

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

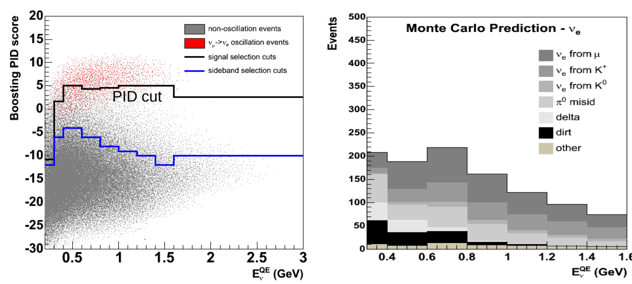
<1% of $\pi^0$ contribute to background.

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



## 5. Boosted Decision Tree (BDT) analysis

BDT analysis summary
- Oscillation analysis uses 300MeV<E<1600MeV
- PID cut is defined each $E_\nu^{QE}$ 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 $E_\nu^{QE}$ and information on the correlations between bins



## 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 $E_\nu^{QE}$ 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 $E_\nu^{QE}$ 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

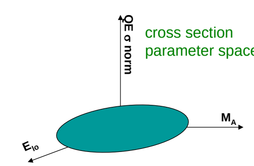
| | |
|---|---|
| $\pi^+$ production | (8 parameters) |
| $\pi^-$ production | (8 parameters) |
| $K^+$ production | (7 parameters) |
| $K^0$ production | (9 parameters) |
| beam model | (8 parameters) |
| cross section | (27 parameters) |
| $\pi^0$ yield | (9 parameters) |
| dirt model | (1 parameters)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



## 5. Multisim

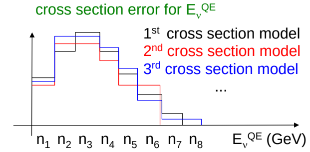
ex) cross section uncertainties

| | | |
|---|---|---|
| $M_A^{QE}$ | 6% | correlated |
| $E_{lo}^{sf}$ | 2% | |
| QE $\sigma$ norm | 10% | uncorrelated |




Input cross section error matrix

cross section error for $E_\nu^{QE}$

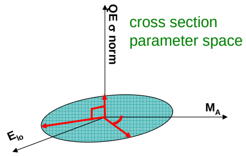



repeat this exercise many times to create smooth error matrix for $E_\nu^{QE}$

## 5. Multisim

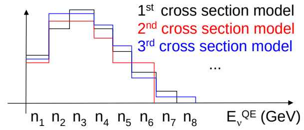
ex) cross section uncertainties

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




Input cross section error matrix

cross section error for $E_\nu^{QE}$



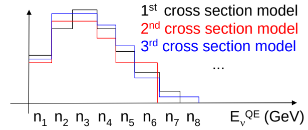

repeat this exercise many times to create smooth error matrix for $E_\nu^{QE}$



## 5. Multisim

Output cross section error matrix for $E_\nu^{QE}$

cross section error for $E_\nu^{QE}$




Oscillation analysis use output error matrix for $\chi^2$ fit;

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



## 5. Multisim

ex) cross section uncertainties

| | | |
|---|---|---|
| $M_A^{QE}$ | 6% | determined from MiniBooNE $\nu_\mu$ QE data |
| $E_{lo}^{sf}$ | 2% | |
| QE σ norm | 10% | |
| QE σ shape | function of $E_\nu$ | |
| $\nu_e/\nu_\mu$ QE σ | function of $E_\nu$ | |
| NC $\pi^0$ rate | function of $\pi^0$ mom | determined from MiniBooNE $\nu_\mu$ NC $\pi^0$ data |
| $M_A^{coh}$, coh σ | ±25% | |
| $\Delta \to N\gamma$ rate | function of $\gamma$ 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($\pi^0$ yield)
+ M(dirt model)
+ M(detector model)
+ M(data stat)

Oscillation analysis $\chi^2$ fit

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



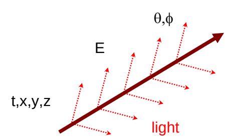
## 6. Track-Based Likelihood (TBL) analysis

This algorithm was found to have the better sensitivity to $\nu_\mu \to \nu_e$ 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



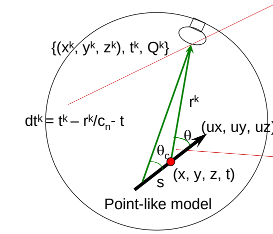

Fit knows
- scintillation, Cherenkov light fraction
- wave length dependent of light propagation
- scattering, reemission, reflection, etc
- PMT efficiencies



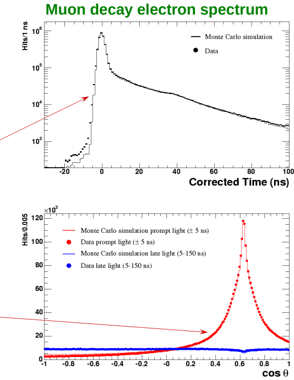
## 6. Boosted Decision Tree (BDT) analysis

Events are reconstructed with point-like model

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

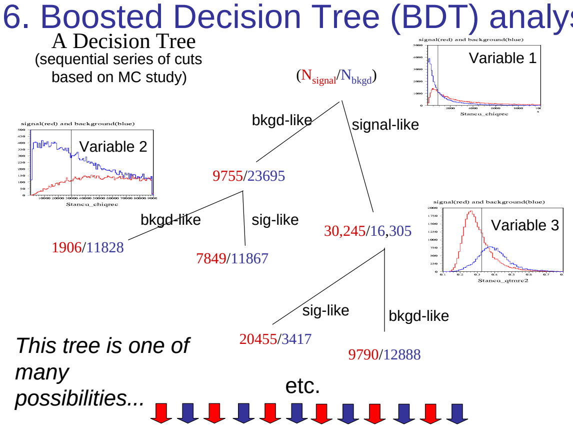



**Muon decay electron spectrum**






## 6. Boosted Decision Tree (BDT) analysis

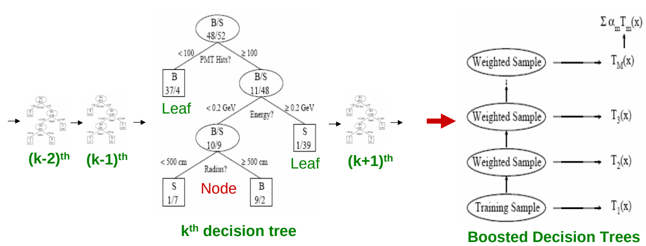





## 6. Boosted Decision Tree (BDT) analysis

### 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"



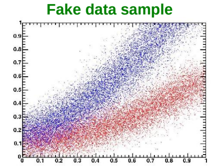



## 6. Boosted Decision Tree (BDT) analysis

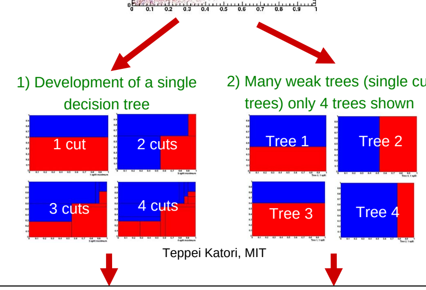
### Example of classification problem

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

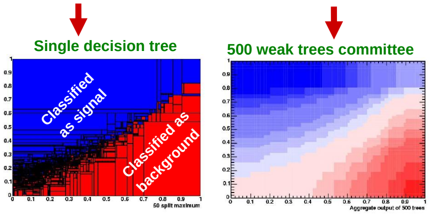
**Fake data sample**



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



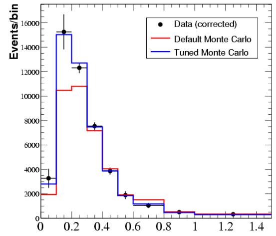
# 6. Boosted Decision Tree (BDT) analysis




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

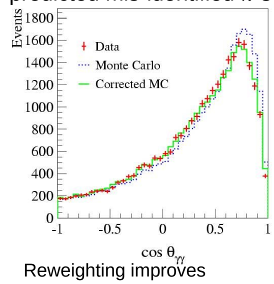


# 7. Error analysis




We constrain $\pi^0$ production using data from our detector

This reduces the error on predicted mis-identified $\pi^0$s




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

Reweighting improves agreement in other variables



# 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
- $\alpha$ represents a given multisim
- M is the total number of multisims
- i,j are $E_\nu^{QE}$ bins

Total error matrix is sum from each source.

TB: $\nu_e$-only total error matrix

BDT: $\nu_\mu$-$\nu_e$ total error matrix

Correlations between $E_\nu^{QE}$ bins from the optical model: