MiniBooNE, a neutrino oscillation experiment at Fermilab

Teppei Katori for the MiniBooNE collaboration
Massachusetts Institute of Technology
U-Glasgow HEP seminar, Glasgow, Scotland, Mar. 21, 2011

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Outline

1. Introduction
2. Neutrino beam
3. Events in the detector
4. Cross section model
5. Neutrino oscillation result
6. Anti-neutrino oscillation result
7. Outlook

1. Introduction

2. Neutrino beam

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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 (no CP violation)

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

1. Neutrino oscillation

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

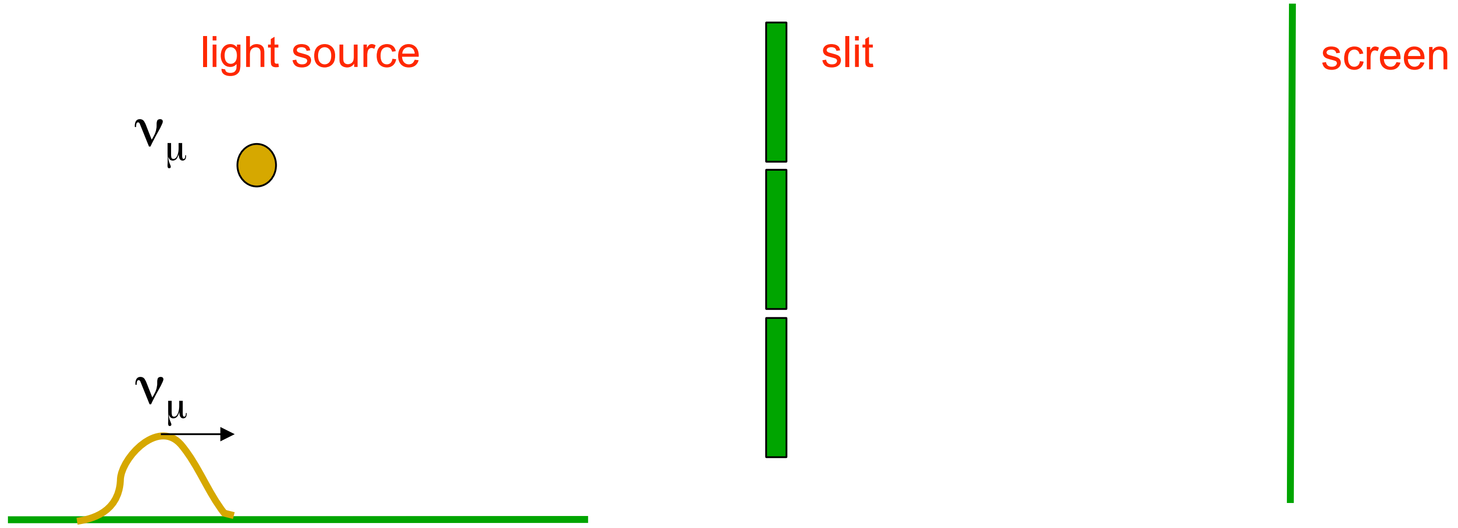
$$P_{\mu\rightarrow e}(t) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E} t\right)$$

Or, conventional form

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

1. Neutrino oscillation

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



If 2 light paths have different length, they have different phase rotation, and they make interference pattern on the screen.

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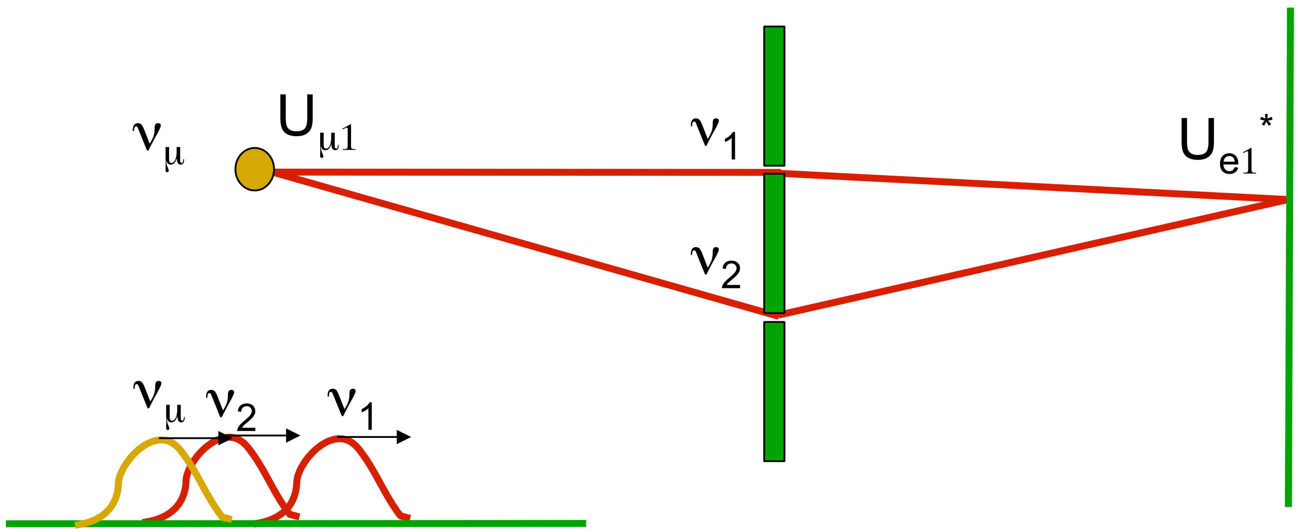

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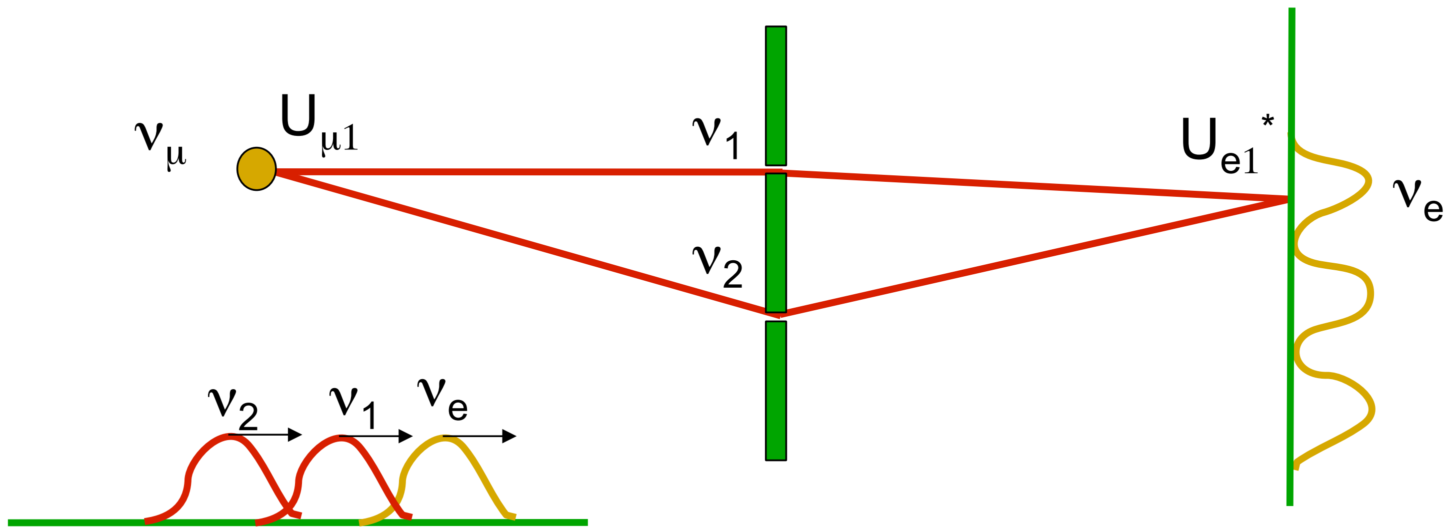

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LSND Collaboration,
PRD 64, 112007

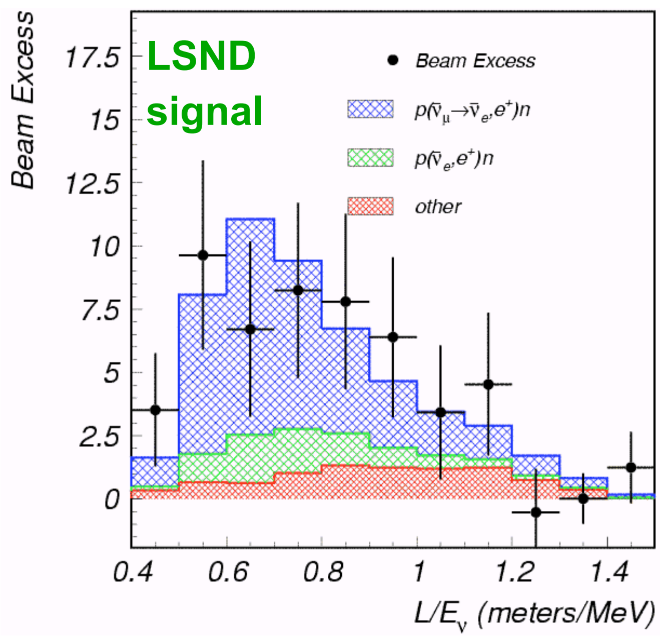
1. LSND experiment

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

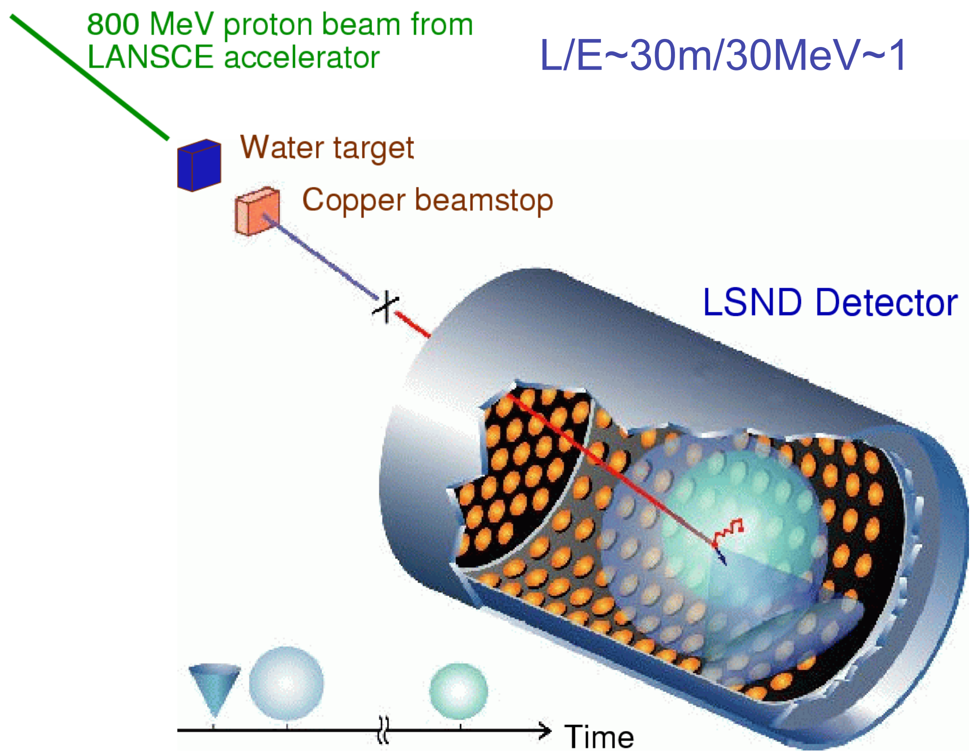
$$\bar{\nu}_{\mu} \xrightarrow{oscillation} \bar{\nu}_{e} + p \rightarrow e^{+} + n$$

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

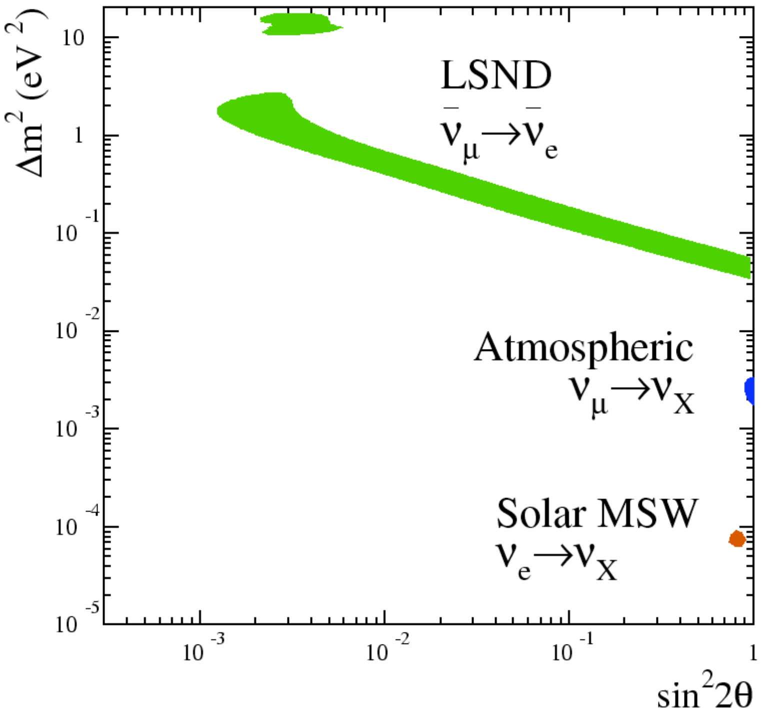
87.9 ± 22.4 ± 6.0 (3.8.σ)



L/E~30m/30MeV~1



1. LSND experiment

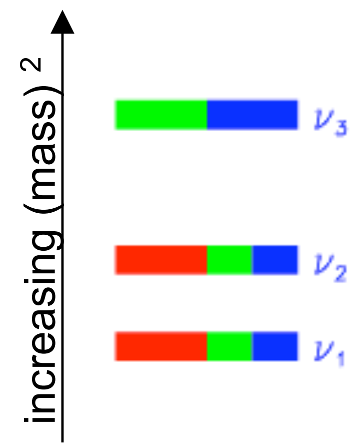


3 types of neutrino oscillations are found:

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

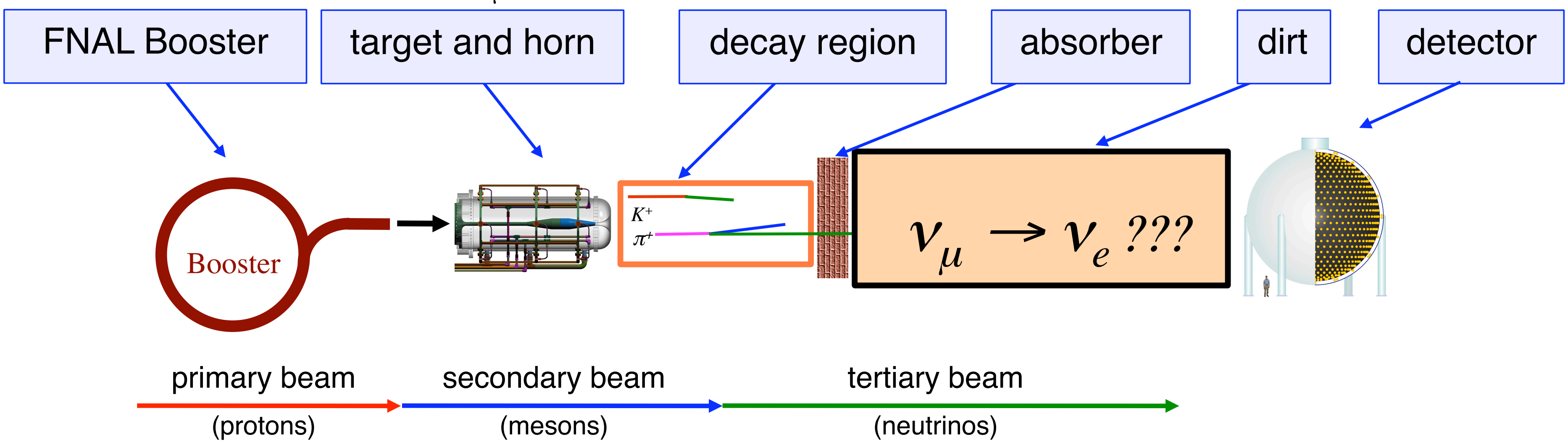
Keep L/E same with LSND, while changing systematics, energy & event signature;

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

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

$$\nu_\mu \xrightarrow{\text{oscillation}} \nu_e + n \rightarrow p + \boxed{e^-}$$

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



MiniBooNE has;

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

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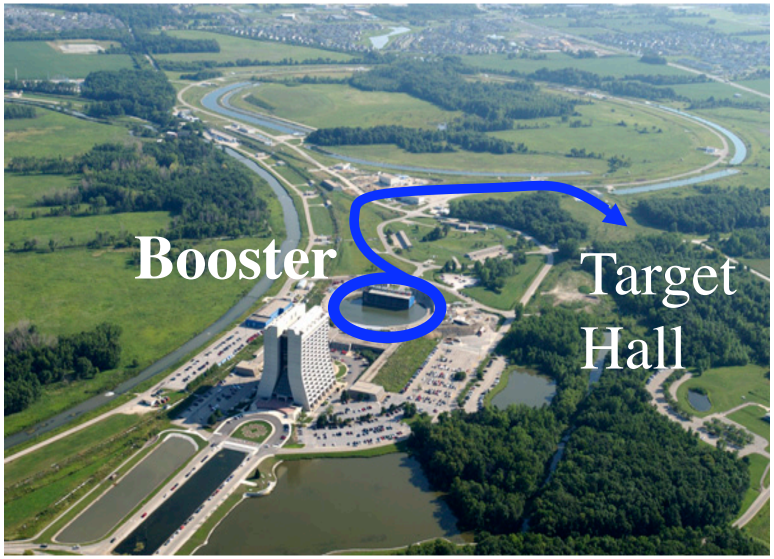
6. Anti-neutrino oscillation result

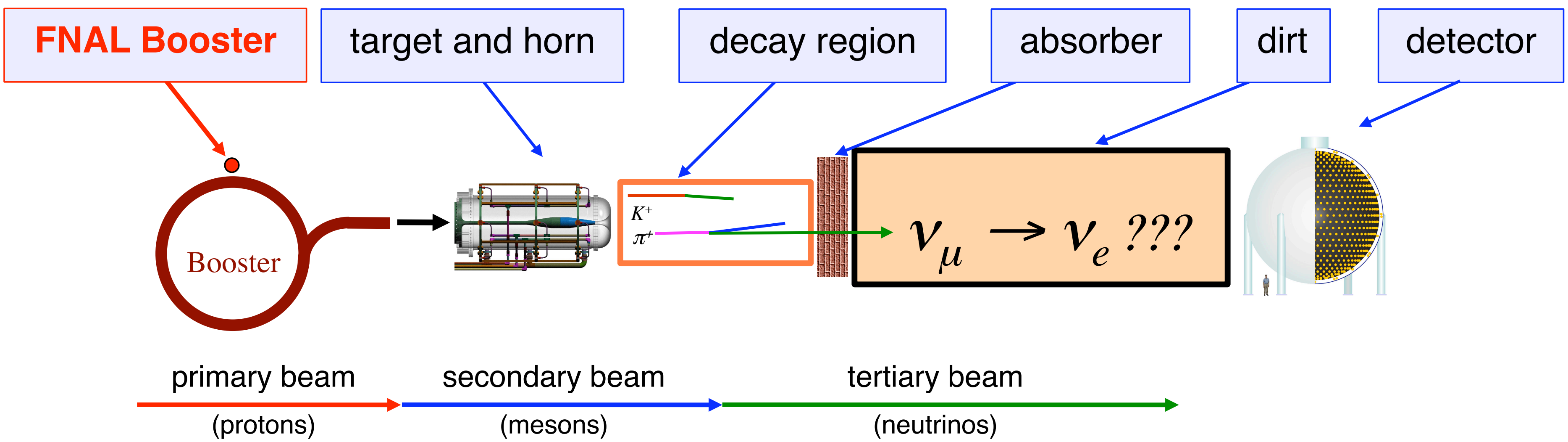
7. Outlook

MiniBooNE collaboration,
PRD79(2009)072002

2. Neutrino beam



MiniBooNE extracts beam from the 8 GeV Booster



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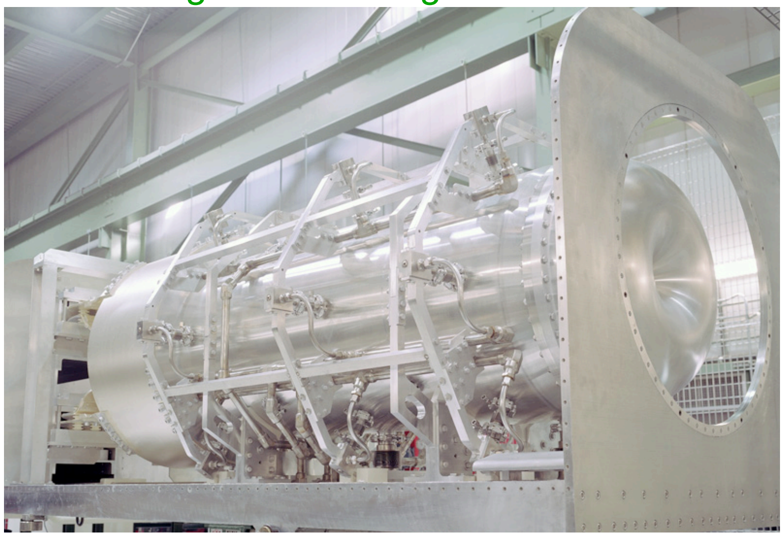
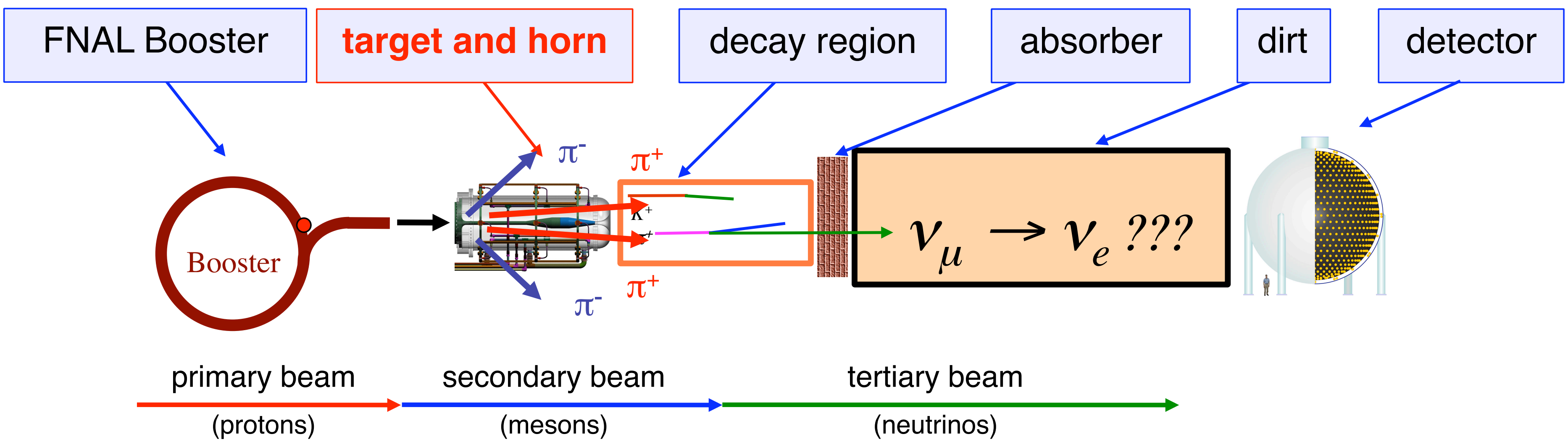
2. Neutrino beam

Magnetic focusing horn



8GeV protons are delivered to a 1.7 λ Be target

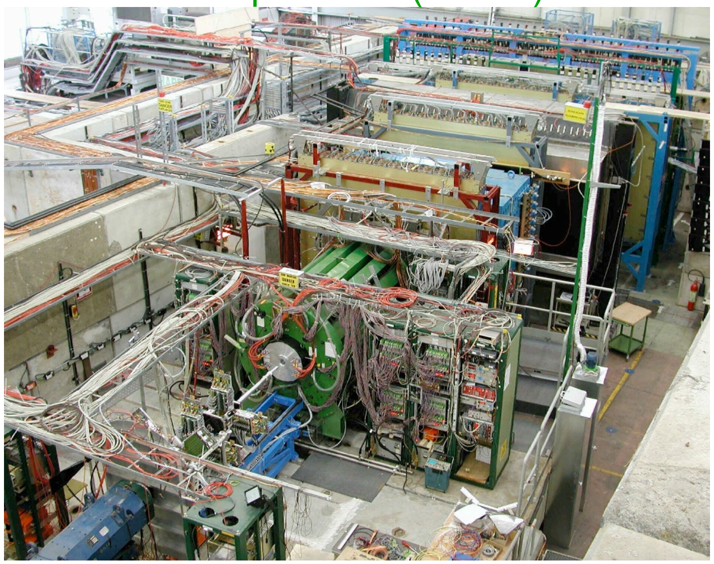
within a magnetic horn (2.5 kV, 174 kA) that increases the flux by $\times$ 6



MiniBooNE collaboration,
PRD79(2009)072002

2. Neutrino beam

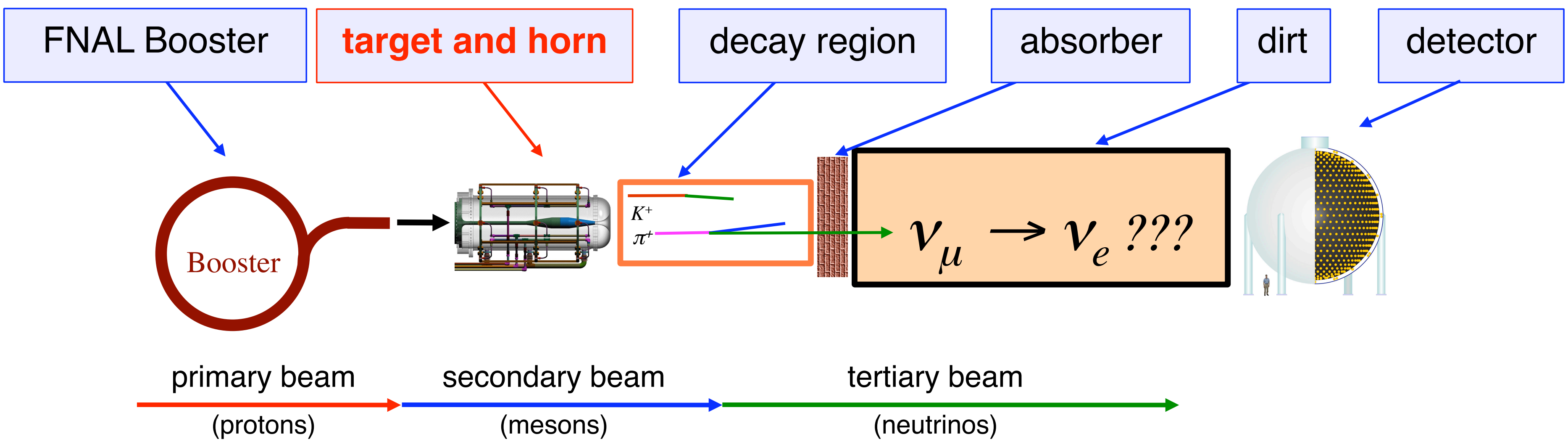
HARP experiment (CERN)



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

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

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



MiniBooNE collaboration,
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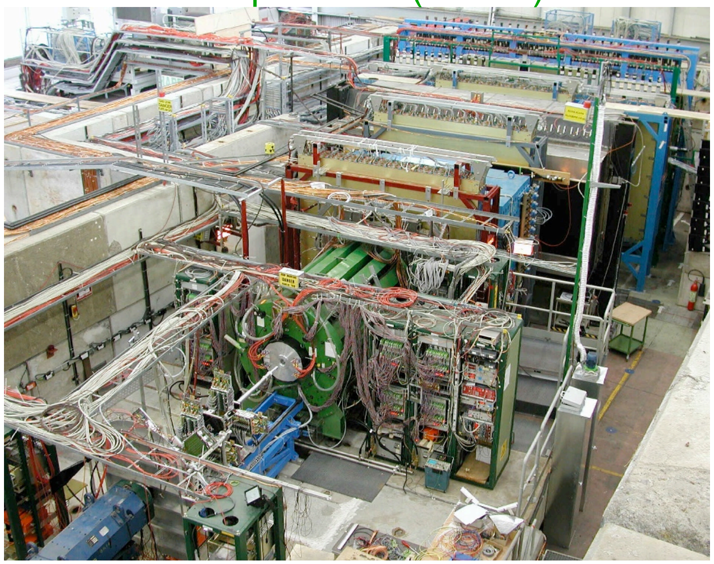

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HARP collaboration,
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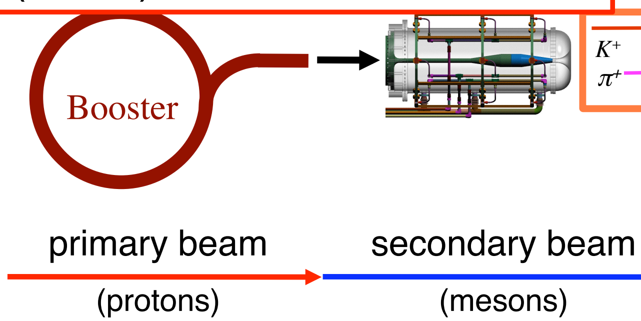
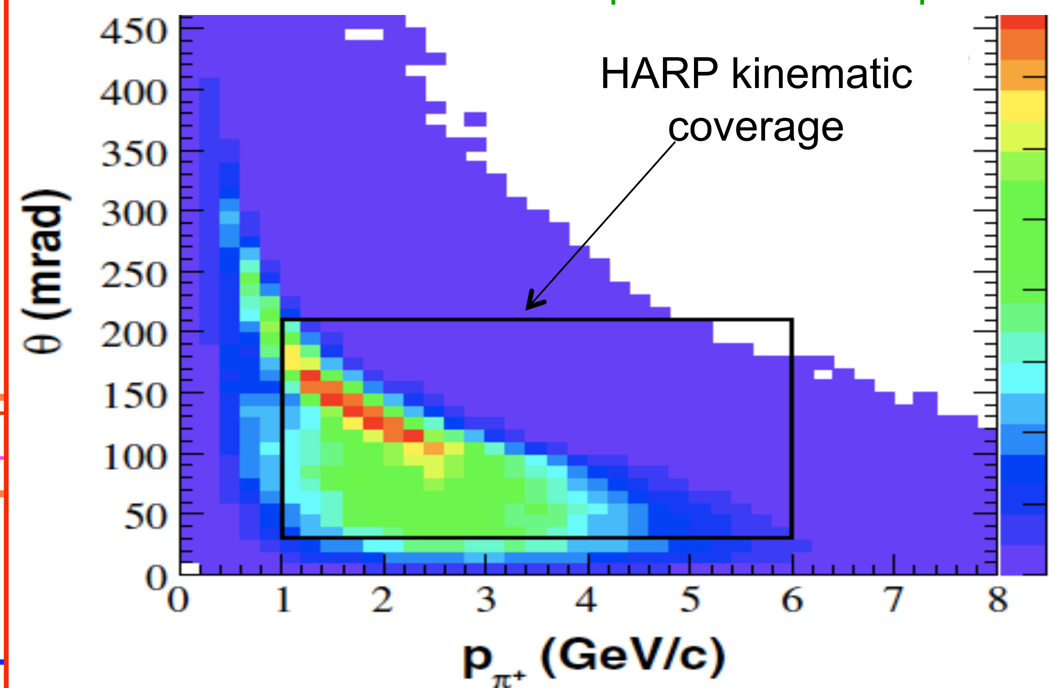
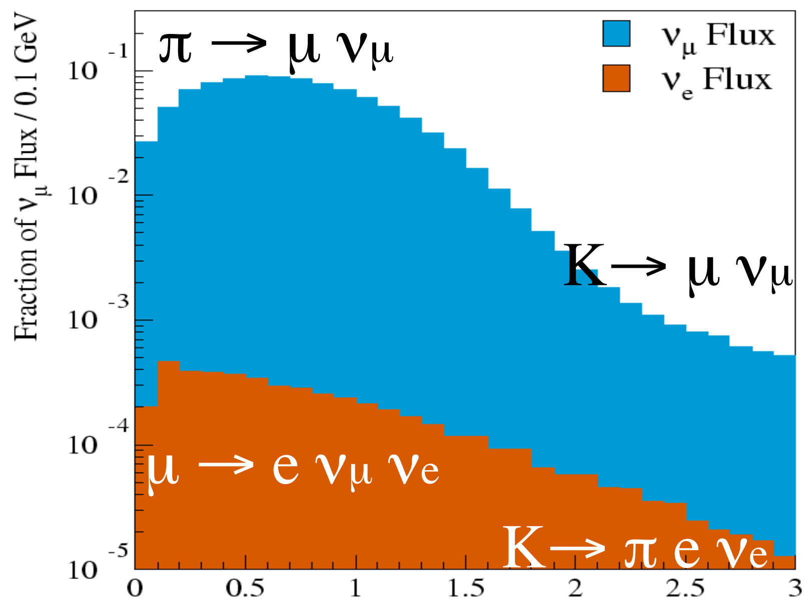
Majority of pions create neutrinos in MiniBooNE are directly measured by HARP (>80%)



Booster neutrino beamline pion kinematic space



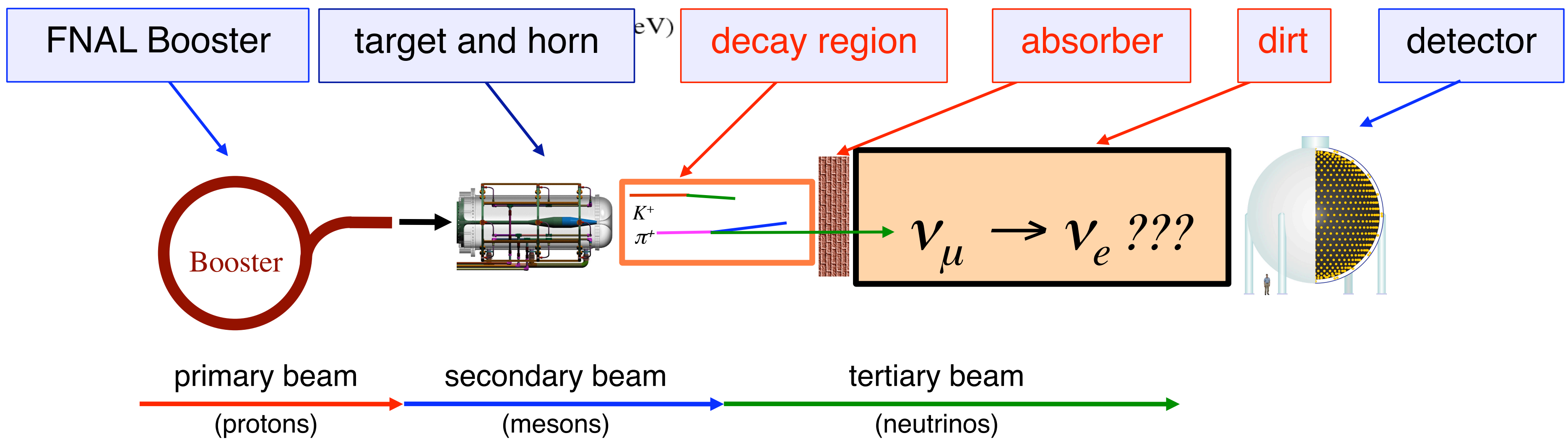
2. Neutrino beam



Neutrino flux from simulation by GEANT4

MiniBooNE is the ν_e (anti ν_e) appearance oscillation experiment, so we need to know the distribution of beam origin ν_e and anti ν_e (intrinsic ν_e)

	neutrino mode	antineutrino mode
intrinsic ν_e contamination	0.6%	0.6%
intrinsic ν_e from μ decay	49%	55%
intrinsic ν_e from K decay	47%	41%
others	4%	4%
wrong sign fraction	6%	16%



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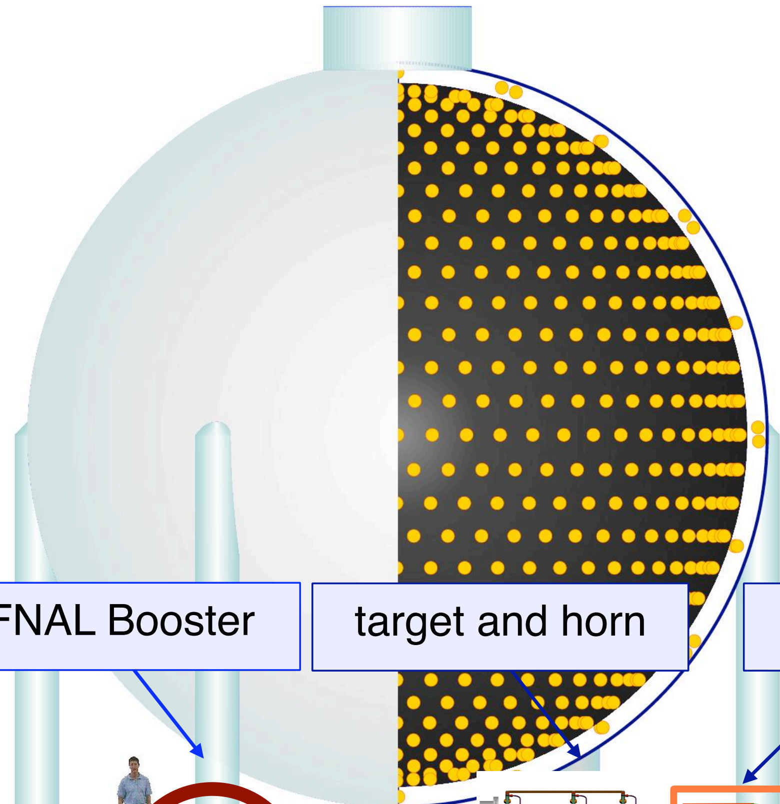
MiniBooNE collaboration,
NIM.A599(2009)28

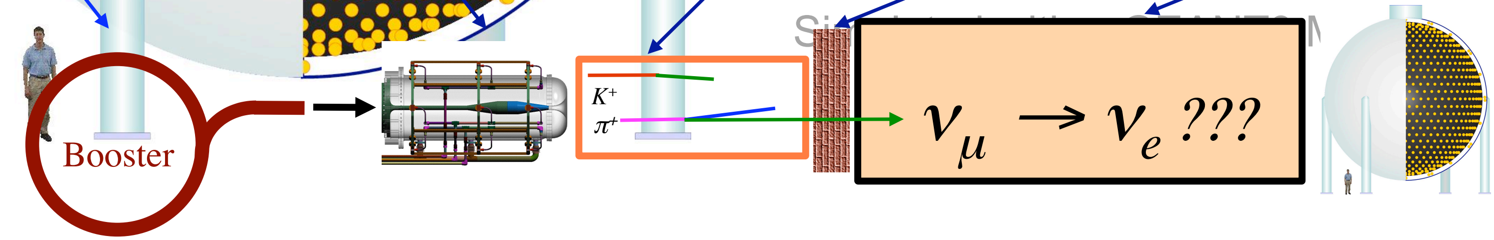
3. Events in the Detector



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)
- 240 veto phototubes

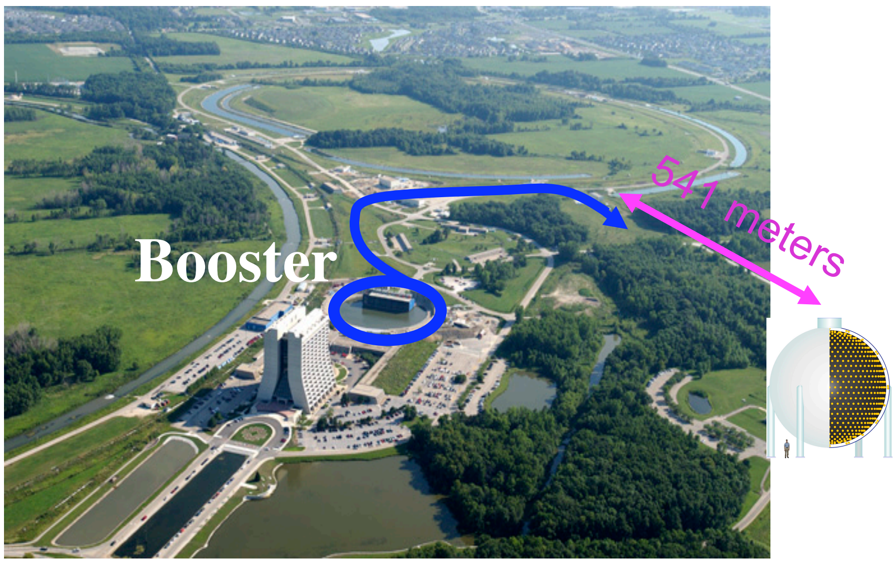
FNAL Booster | target and horn | decay region | absorber | dirt | detector



primary beam (protons) → secondary beam (mesons) → tertiary beam (neutrinos)

MiniBooNE collaboration,
NIM.A599(2009)28

3. Events in the Detector



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  Simulated with a GEANT3 Monte Carlo

MiniBooNE collaboration,
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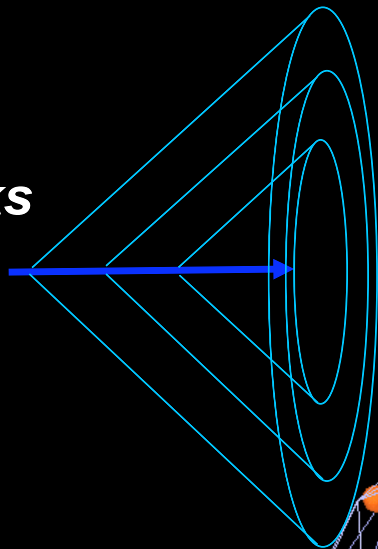
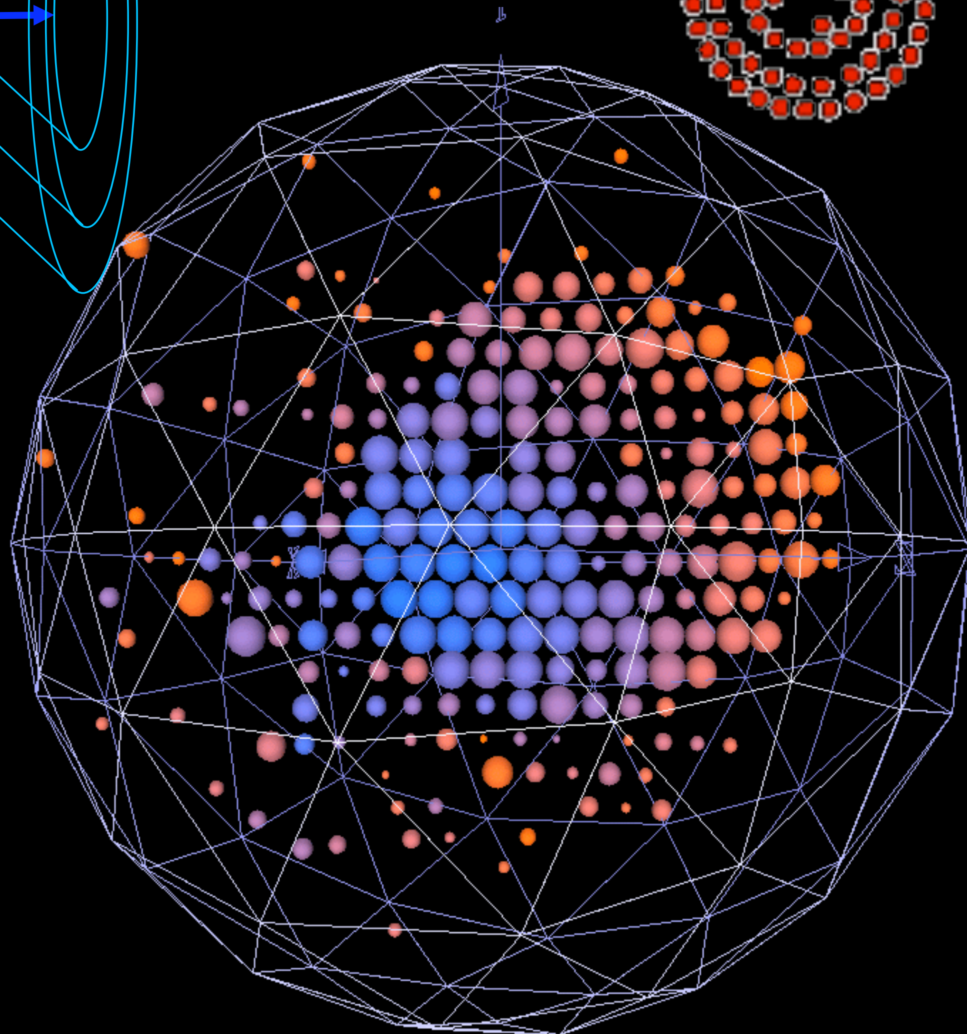
3. Events in the Detector

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, NIM.A599(2009)28

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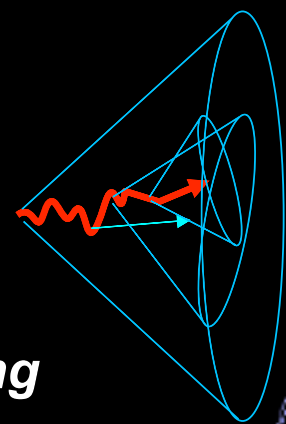

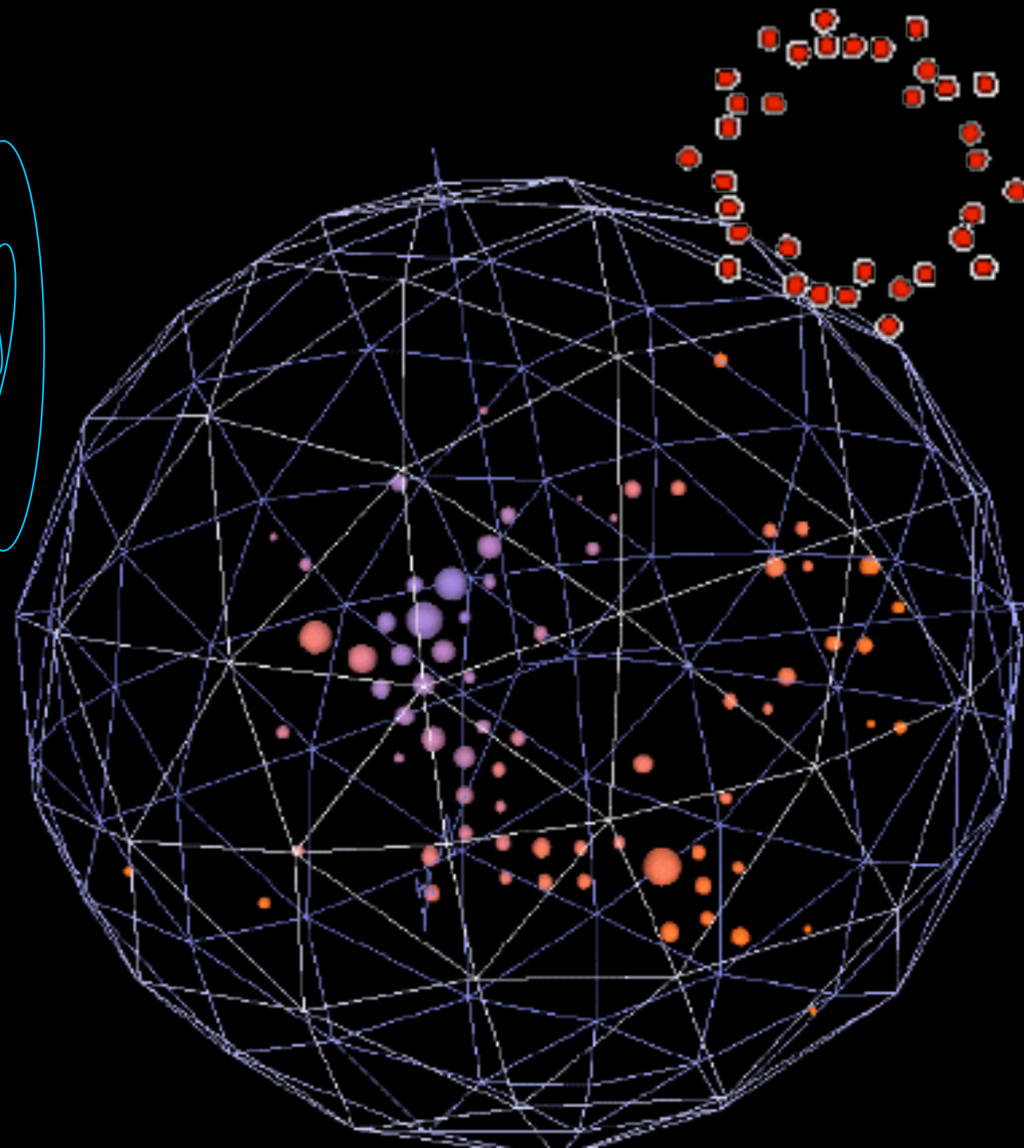

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MiniBooNE collaboration, NIM.A599(2009)28

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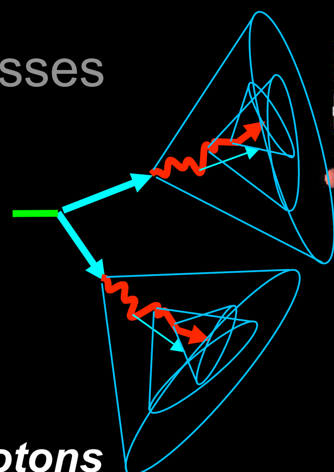
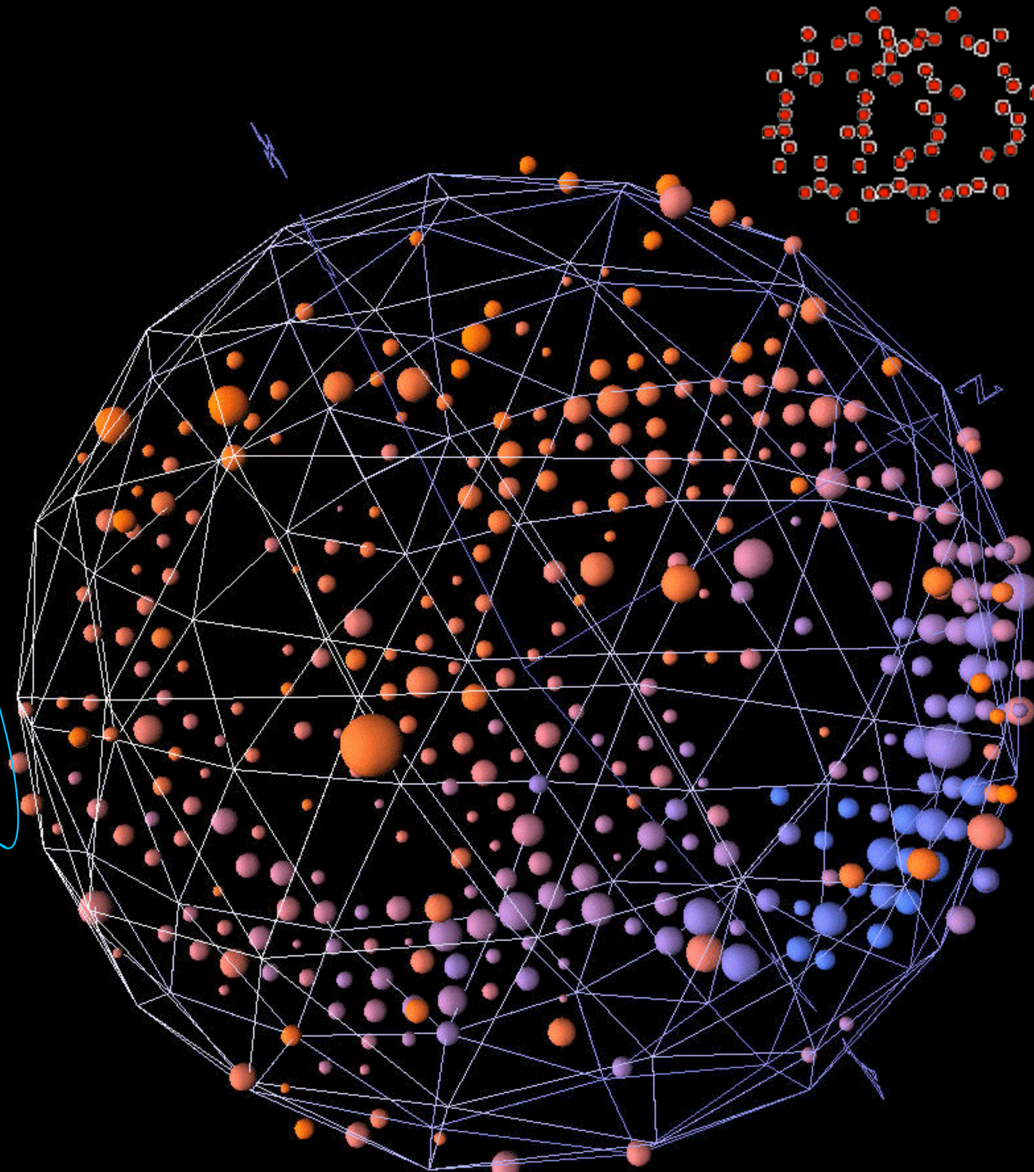
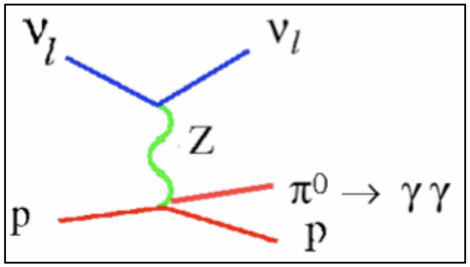
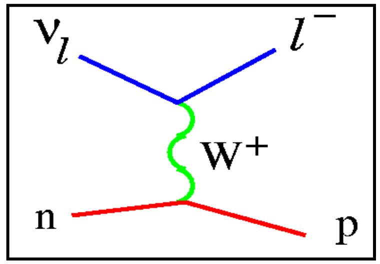
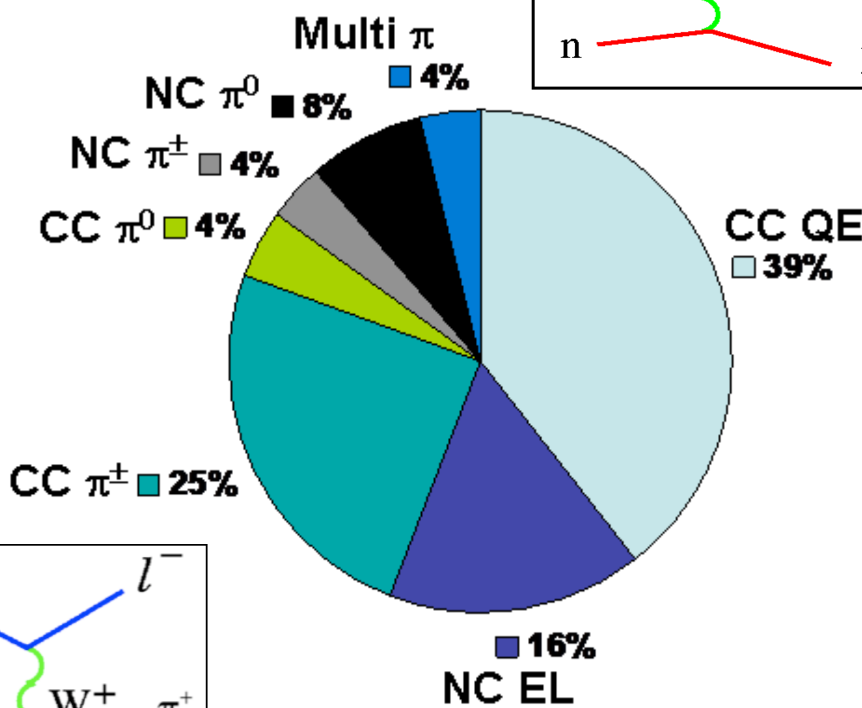


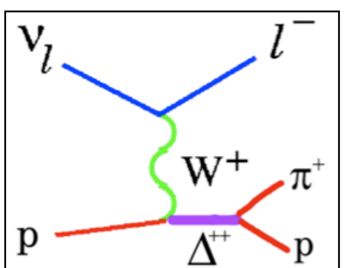


4. Cross section model



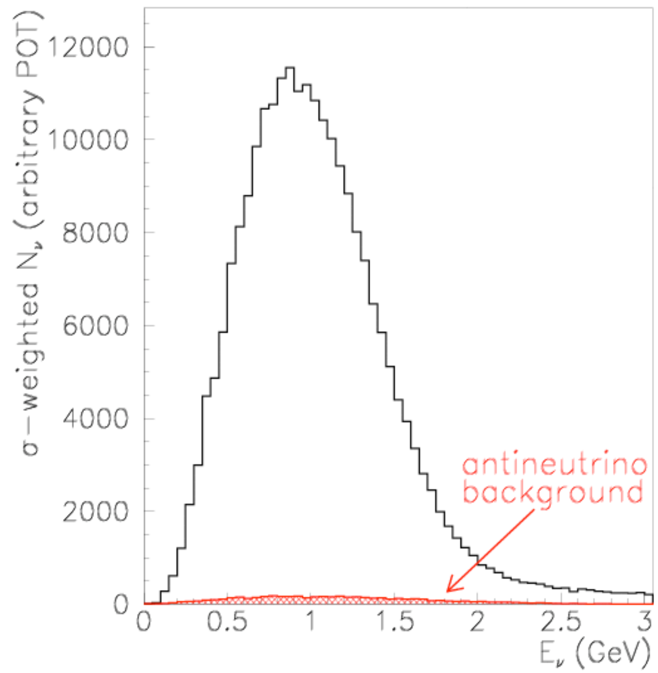






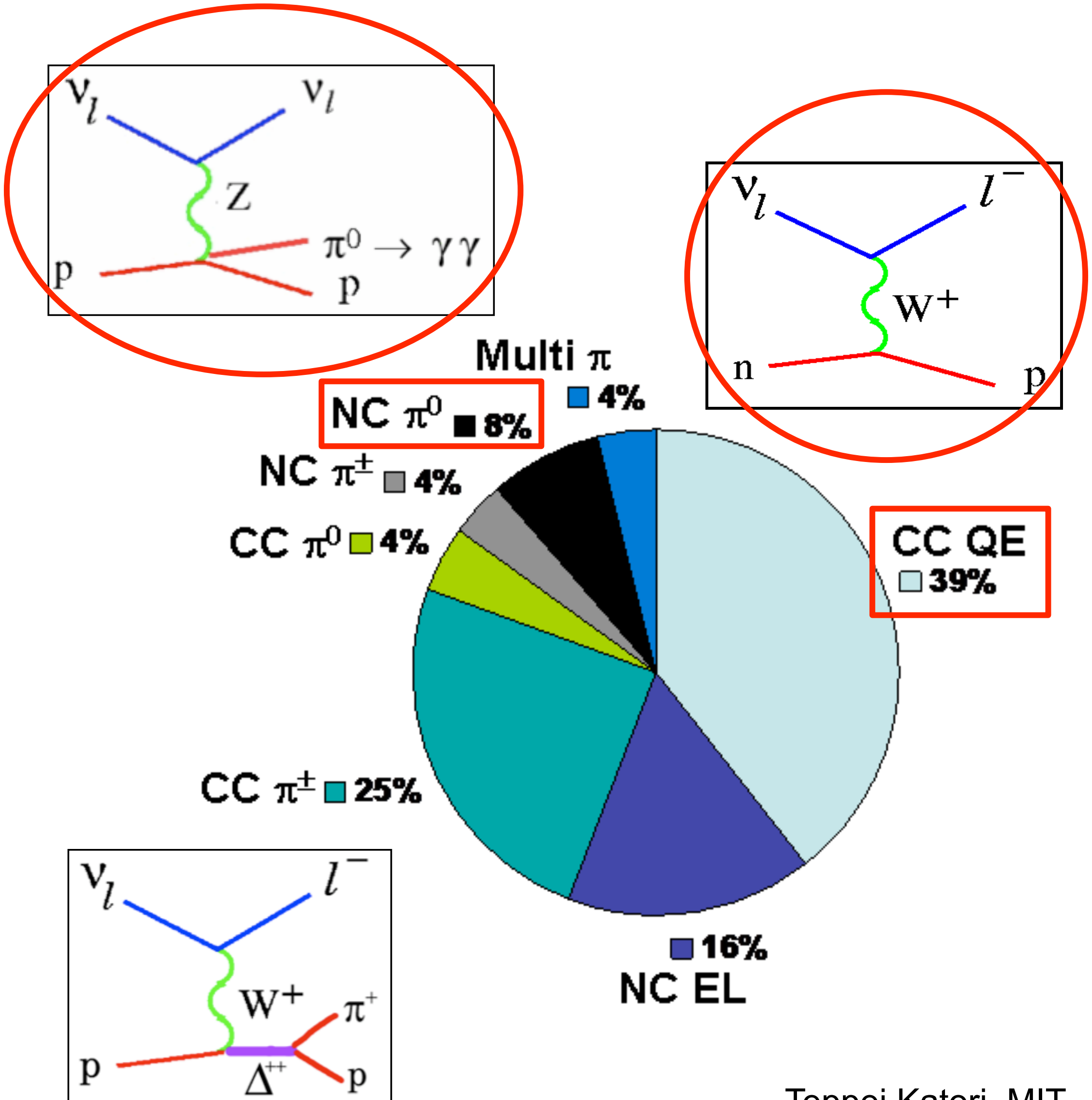
Predicted event rates before cuts
(NUANCE Monte Carlo)

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



Event neutrino energy (GeV)

4. Cross section model



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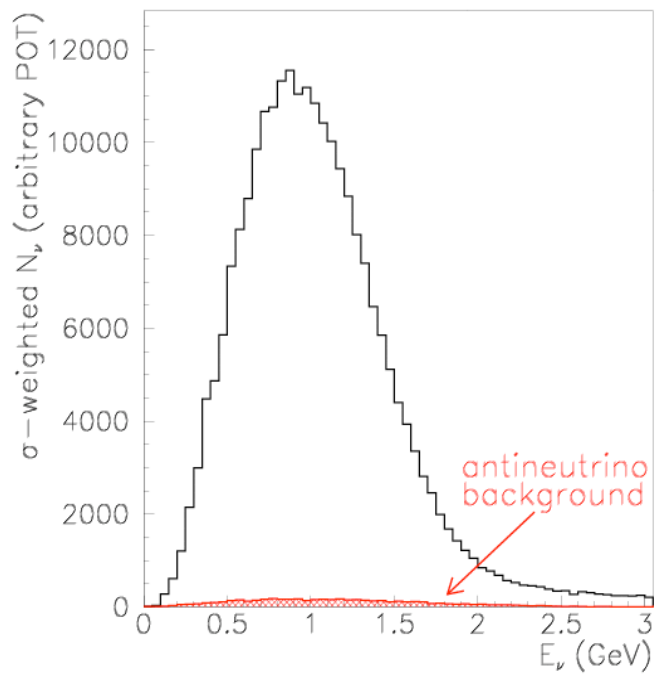


Event neutrino energy (GeV)

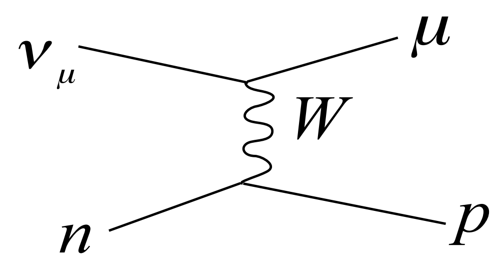
4. CCQE event measurement

CCQE (Charged Current Quasi-Elastic) event

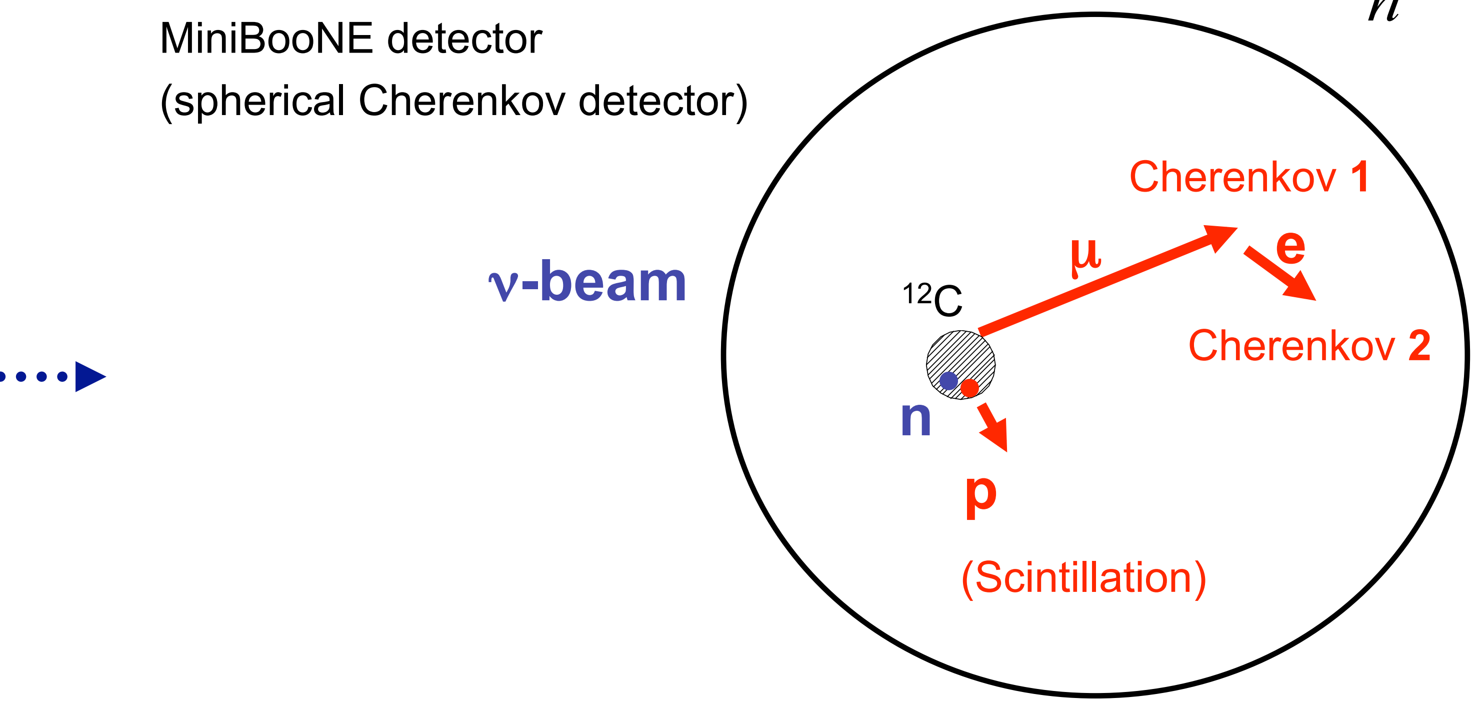
ν_μ charged current quasi-elastic (ν_μ CCQE) interaction is the most abundant (~40%) and the fundamental interaction in MiniBooNE detector

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

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



MiniBooNE detector
(spherical Cherenkov detector)



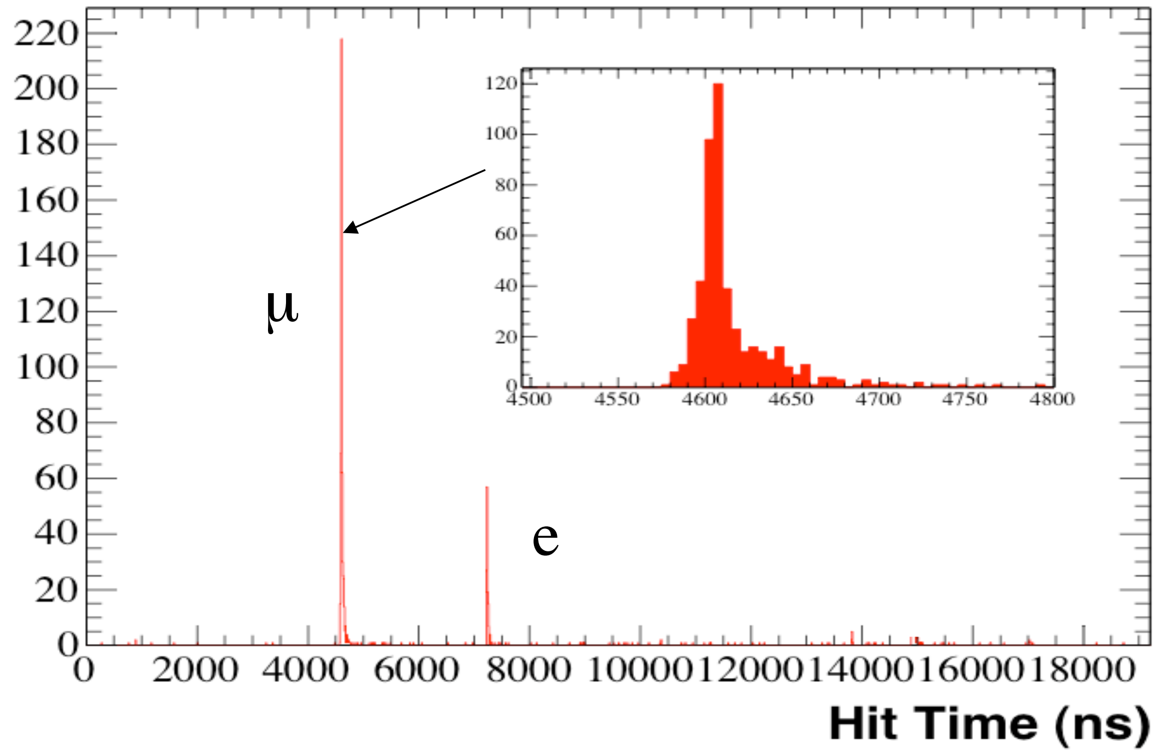
muon like Cherenkov light and subsequent decayed electron (Michel electron) like Cherenkov light are the signal of CCQE event

4. CCQE event measurement

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 (ν+n $\rightarrow$ μ+p) with characteristic two "subevent" structure from stopped $\mu \rightarrow \nu_\mu \nu_e e$

Number of tank hits for CCQE event



4. CCQE event measurement

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.

$$E_\nu^{QE} = \frac{2(M - E_B)E_\mu - (E_B^2 - 2ME_B + m_\mu^2 + \Delta M^2)}{2[(M - E_B) - E_\mu + p_\mu \cos\theta_\mu]}$$

$$Q_{QE}^2 = -m_\mu^2 + 2E_\nu^{QE}(E_\mu - p_\mu \cos\theta_\mu)$$

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

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

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

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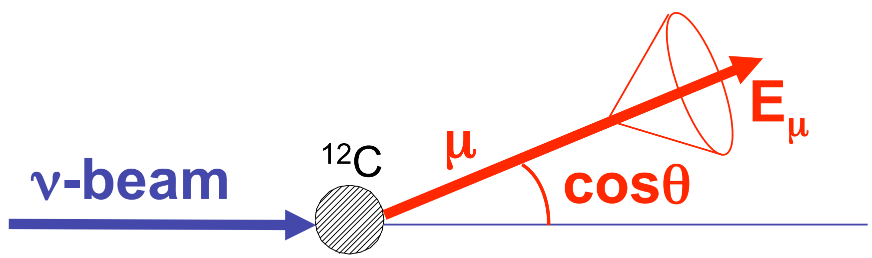


Smith and Moniz,
Nucl.,Phys.,B43(1972)605

4. Relativistic Fermi Gas (RFG) model

Relativistic Fermi Gas (RFG) Model

Carbon is described by the collection of incoherent Fermi gas particles. All details come from hadronic tensor.

$$(W_{\mu\nu})_{ab} = \int_{Elo}^{Ehi} f(\vec{k},\vec{q},w) T_{\mu\nu} dE : \text{hadronic tensor}$$

$$f(\vec{k},\vec{q},w) \ : \ \text{nucleon phase space density function}$$

$$T_{\mu\nu} = T_{\mu\nu}(F_1, F_2, F_A, F_P) \ : \ \text{nucleon tensor}$$

$$F_A(Q^2) = g_A/(1+Q^2/\boxed{M_A^2})^2 : \text{Axial form factor}$$

$$Ehi \ : \ \text{the highest energy state of nucleon} = \sqrt{(p_F^2 + M^2)}$$

$$Elo \ : \ \text{the lowest energy state of nucleon} = \boxed{\kappa}\left(\sqrt{(p_F^2 + M^2)} - \omega + E_B\right)$$

We tuned following 2 parameters using Q^2 distribution by least χ^2 fit;

M_A = effective axial mass

κ = Pauli blocking parameter

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

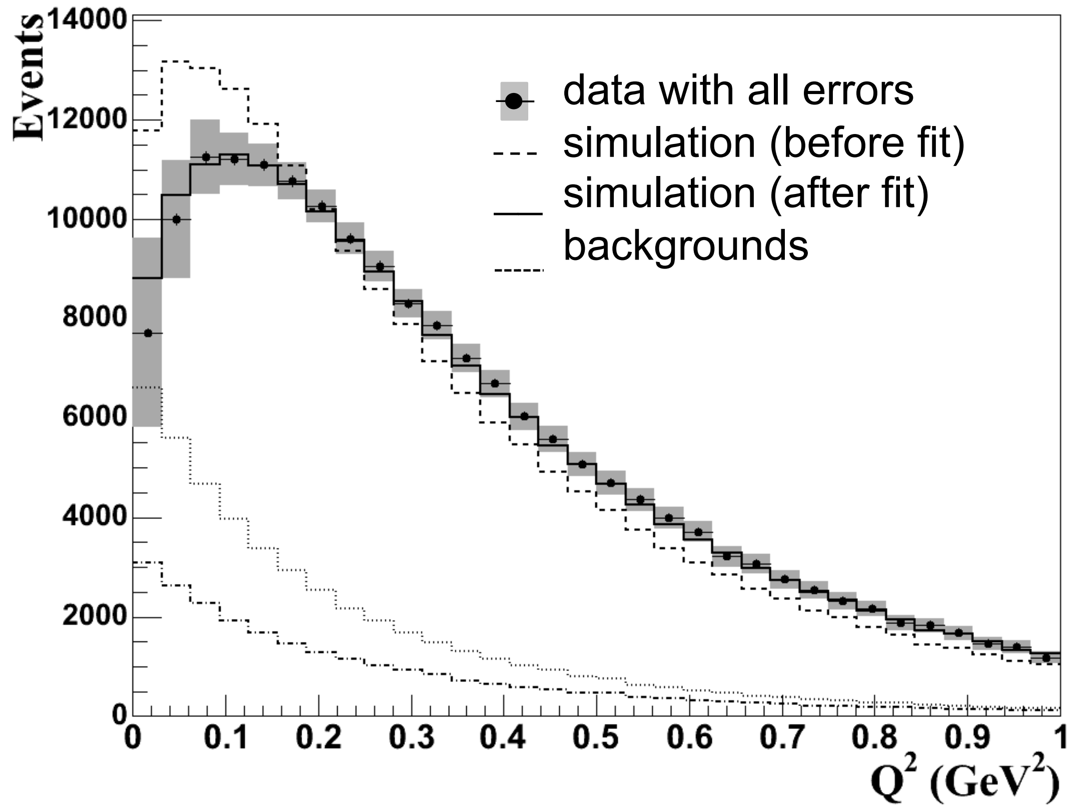
Q^2 fits to MB ν_μ CCQE data using the nuclear parameters:

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 model, too.

Q^2 distribution before and after fitting

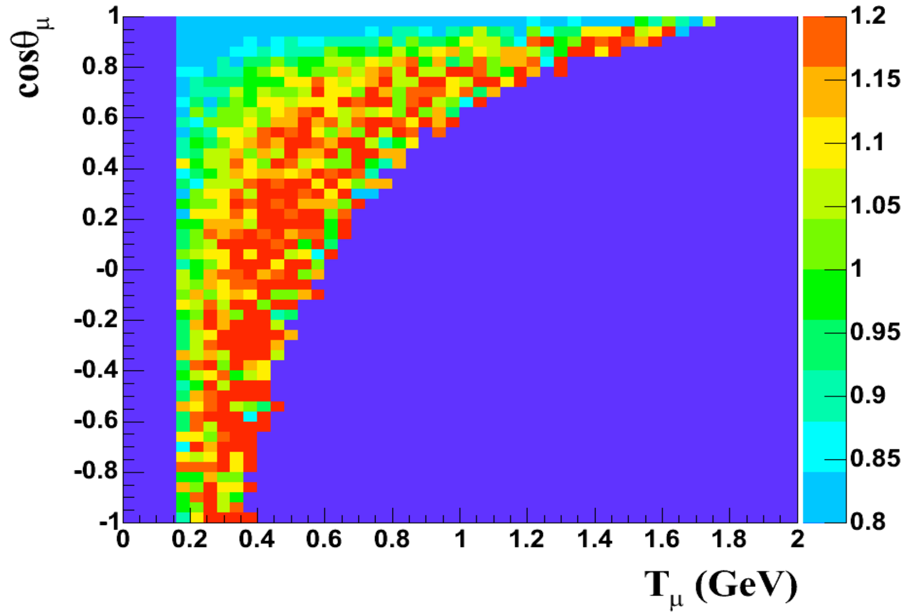


4. CCQE cross section model tuning

Without knowing flux perfectly, we cannot modify cross section model

$$R(\mathrm{interaction}) \propto \int (\mathrm{flux}) \times (\mathrm{xs})$$

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



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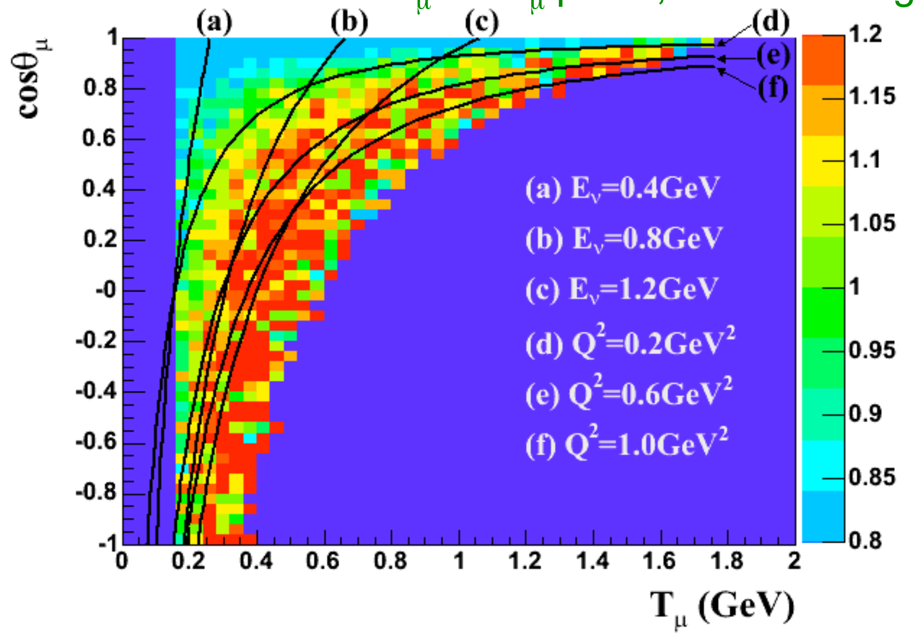
$$R(\mathrm{interaction}[E_\nu, Q^2]) \propto \int (\mathrm{flux}[E_\nu]) \times (\mathrm{xs}[Q^2])$$

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

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



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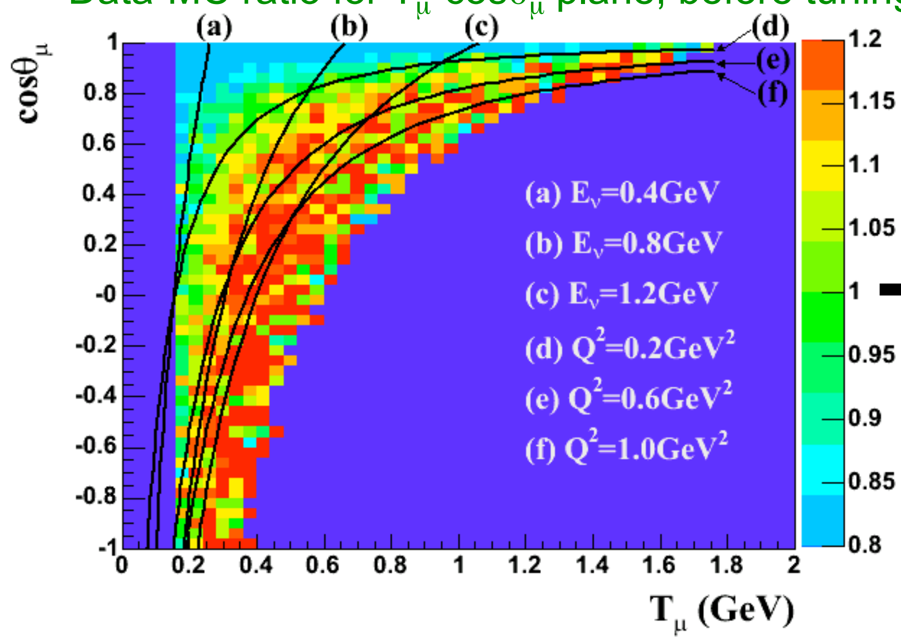
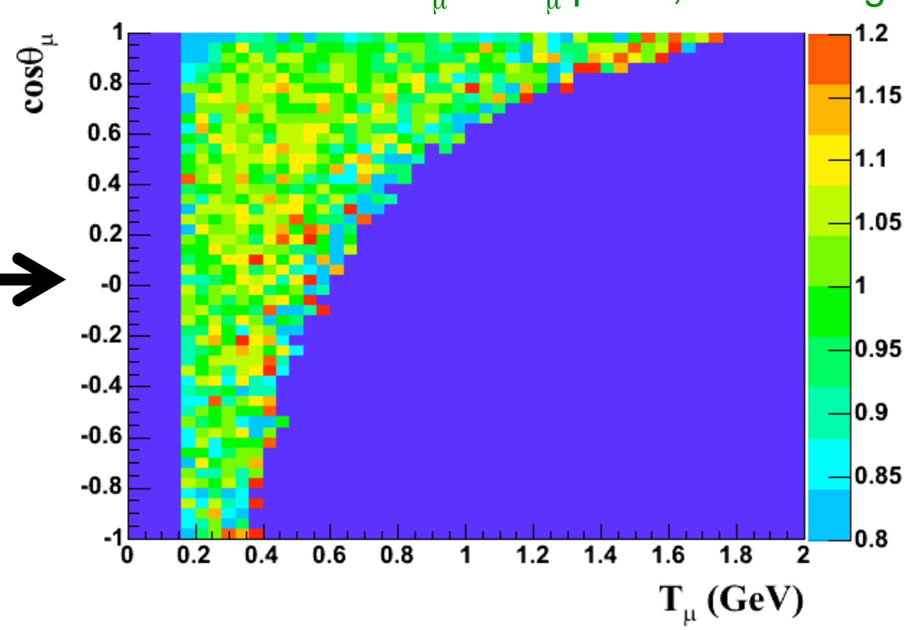


Data-MC ratio for T_μ-$\cos\theta_\mu$ plane,after tuning



4. NCπ^o rate tuning

NCπ^o (neutral current π^o production)

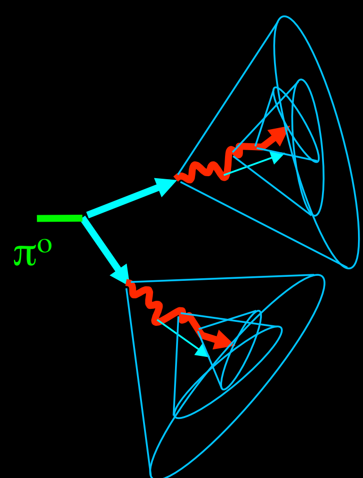
The signal of ν_e candidate is a single isolated electron

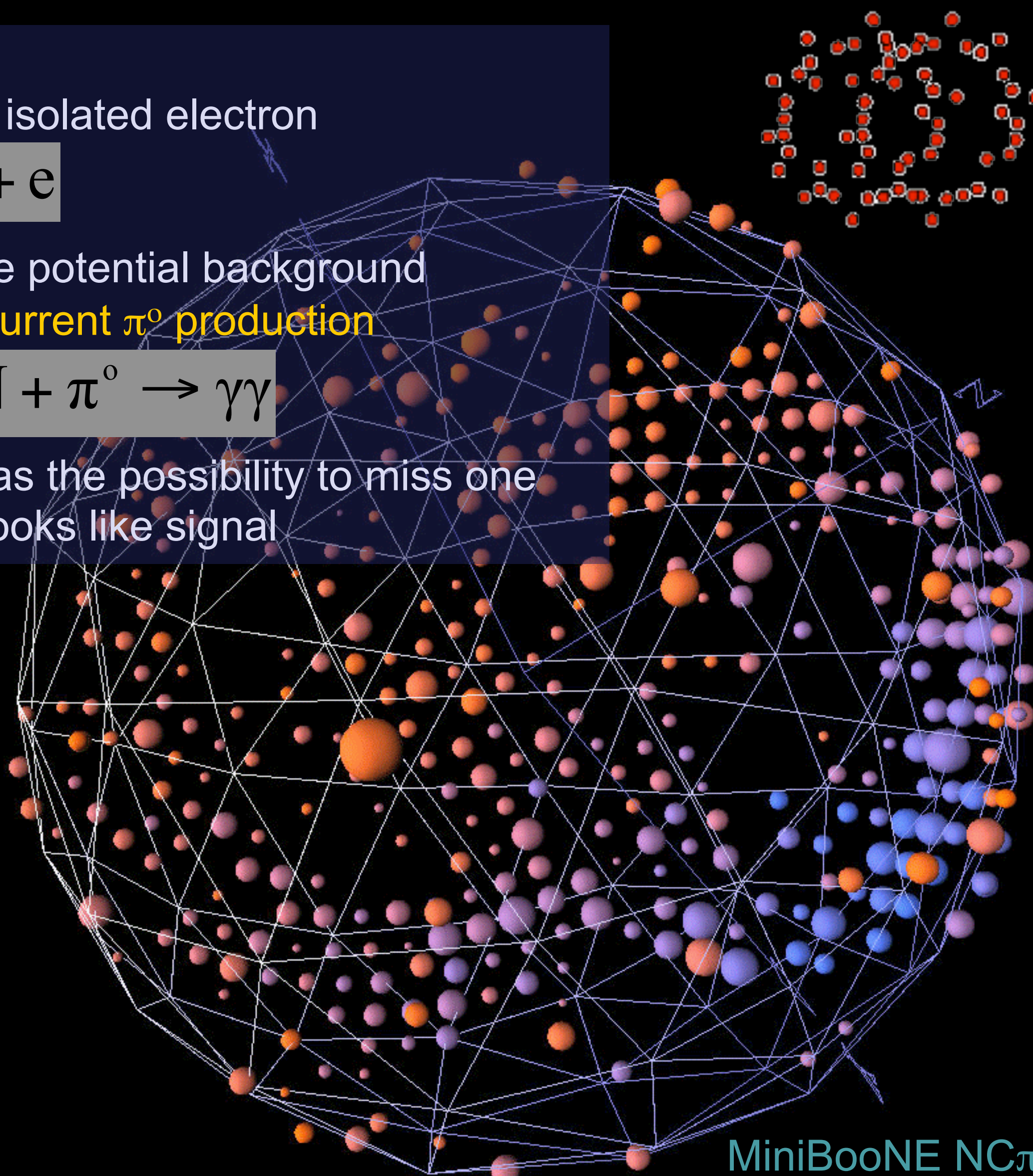
$$\nu_e + n \rightarrow p + e$$

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

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- the notable background is Neutral current π^o production

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

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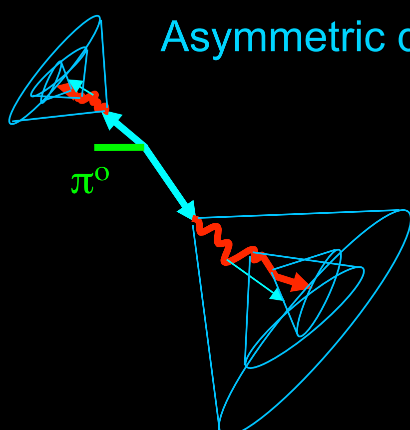
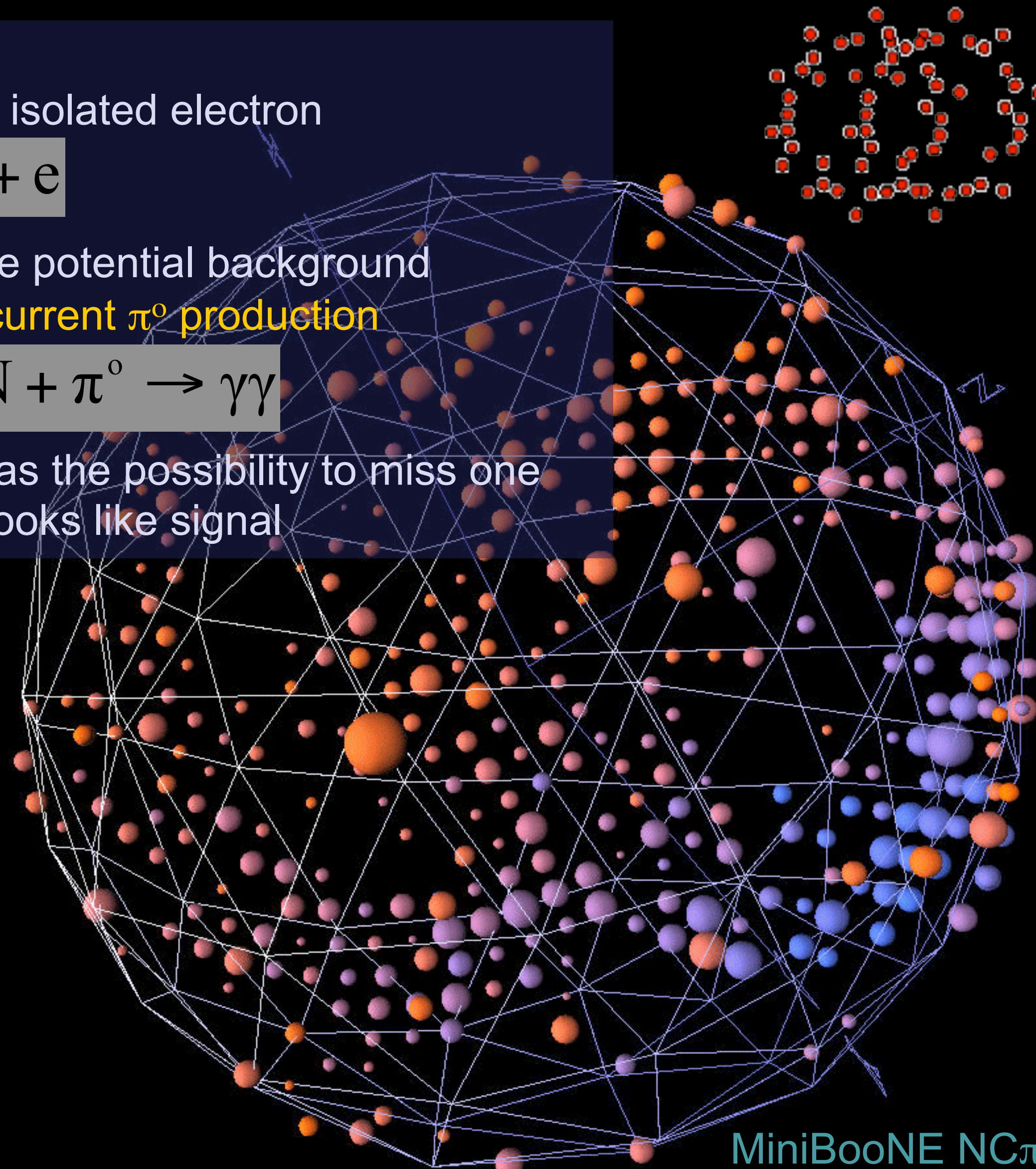
Asymmetric decay



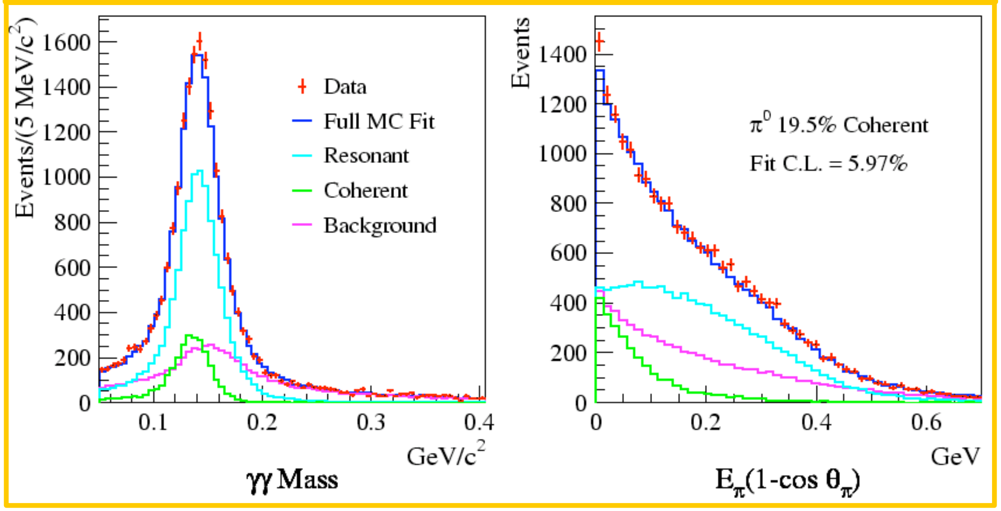


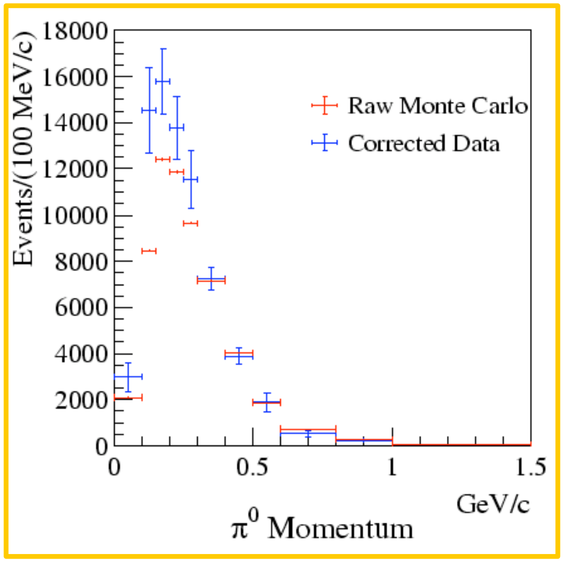
MiniBooNE NCπ^o candidate

4. NCπ^o rate tuning

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

Data-Mc comparison of π^o kinematics (after tuning)





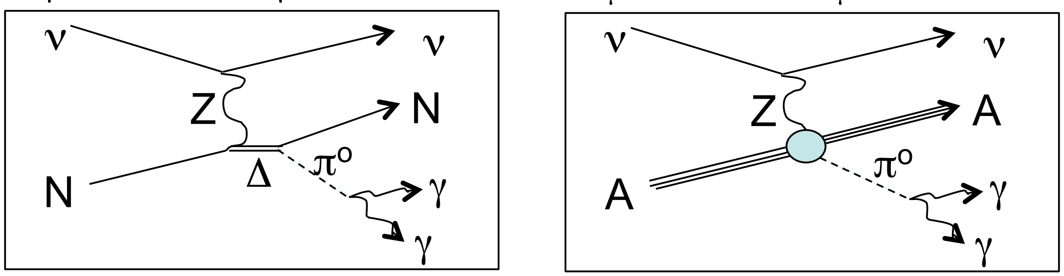
MiniBooNE collaboration
PLB664(2008)41

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

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, PRD82(2010)092005
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, arXiv:1011.3572
5. charged current single π^o production (CCπ^o) cross section measurement
   by Bob Nelson, arXiv:1010.3264
6. CCπ^+/CCQE cross section ratio measurement
   by Steve Linden, PRL103(2009)081801
7. anti-νCCQE measurement
   by Joe Grange, aiXiv:1102:1964

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

Main results are flux averaged differential cross section, they are function of measured variables (e.g., muon angle, pion energy, etc), not inferred variables (e.g., neutrino energy, momentum transfer)

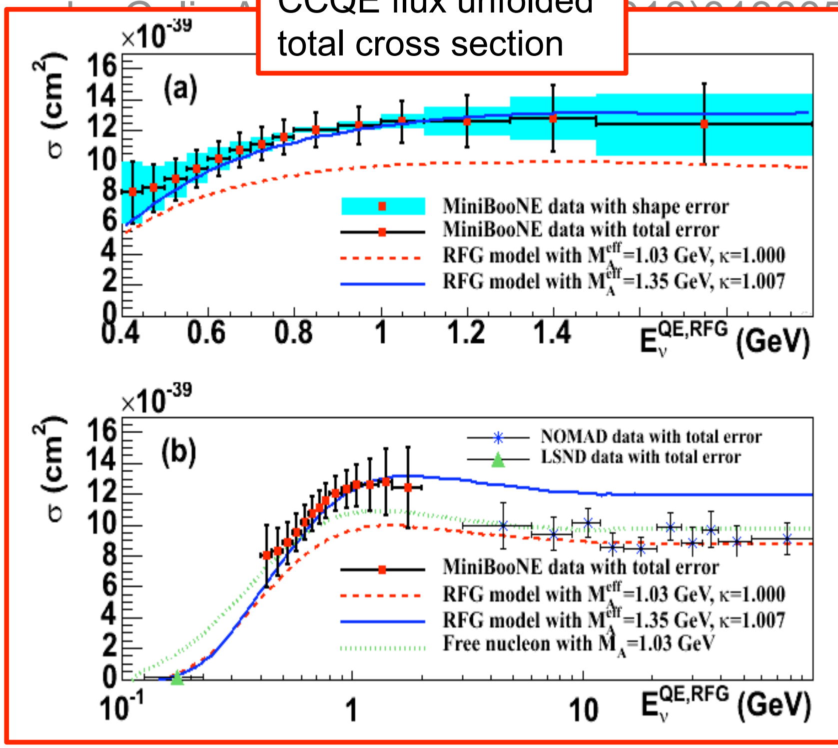
$$\nu_\mu + n \rightarrow p + \mu^-$$

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

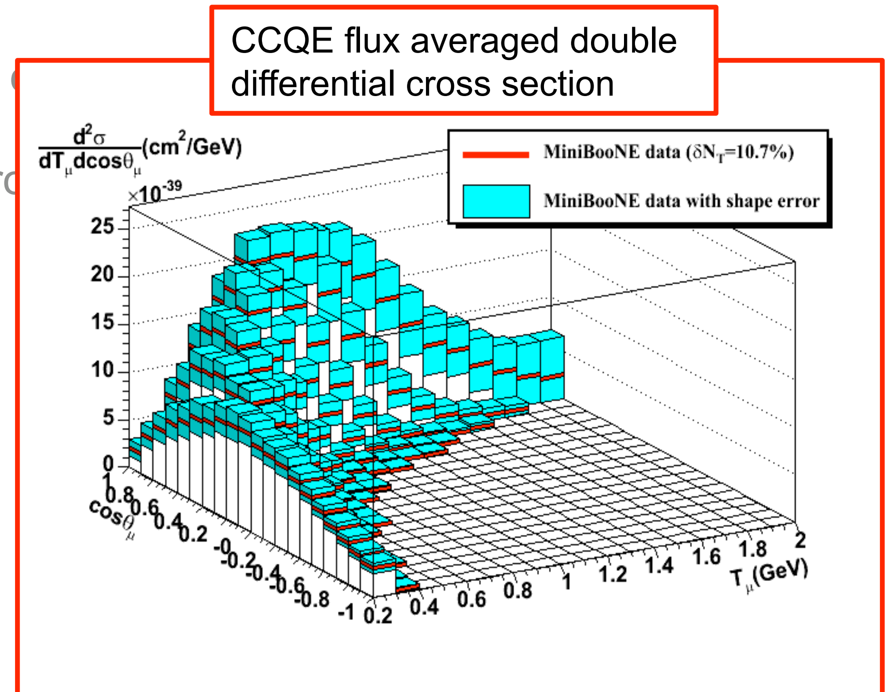
by Denis Perevalov, PRD82(2010)092005

3. neutral current π⁰ production (NCπ⁰) cross section measurement (ν and anti-ν)

CCQE flux unfolded total cross section



CCQE flux averaged double differential cross section



4. MiniBooNE cross section results

NuInt11, Mar. 07-11, 2011, Dehradun, India

In NuInt11, MiniBooNE presented 2 new anti-neutrino measurement results.

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, PRD82(2010)092005
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6. CCπ^+/CCQE cross section ratio measurement
   by Steve Linden, PRL103(2009)081801
7. anti-νCCQE measurement
   by Joe Grange, aiXiv:1102:1964
8. new anti-νCCQE measurement
   by Joe Grange
9. anti-ν NCE measurement
   by Ranjan Dharmapalan

$$\bar{\nu}_\mu + p \rightarrow n + \mu^+$$

$$\left(\begin{array}{c} \bar{\nu}_\mu + {}^{12}C \rightarrow X + \mu^+ \\ \bar{\nu}_\mu + {}^{1}H \rightarrow n + \mu^+ \end{array} \right)$$

$$\bar{\nu}_\mu + p \rightarrow \bar{\nu}_\mu + p$$

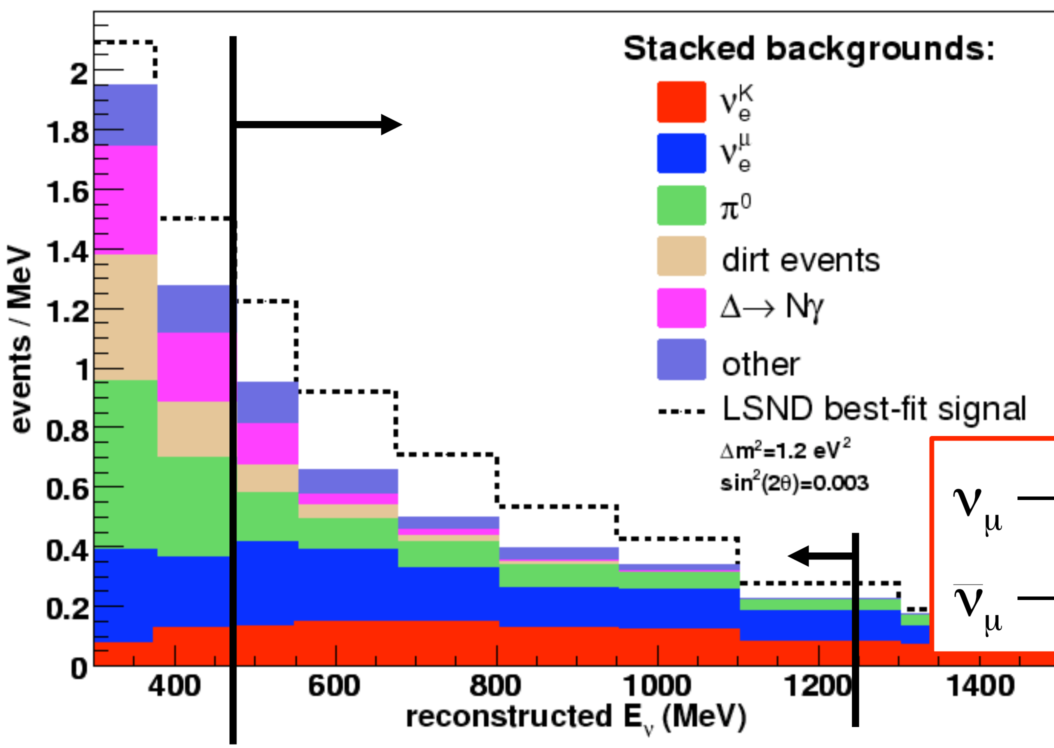
$$\bar{\nu}_\mu + n \rightarrow \bar{\nu}_\mu + n$$

Anti-neutrino interaction measurement is the best place to test neutrino interaction models developed in neutrino mode.

5. Oscillation analysis background summary

Oscillation analysis summary

- Oscillation analysis uses 475MeV<E<1250MeV



475 MeV – 1250 MeV

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

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

$$\nu_\mu \xrightarrow{\text{oscillation}} \nu_e + n \rightarrow p + \boxed{e^-}$$

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

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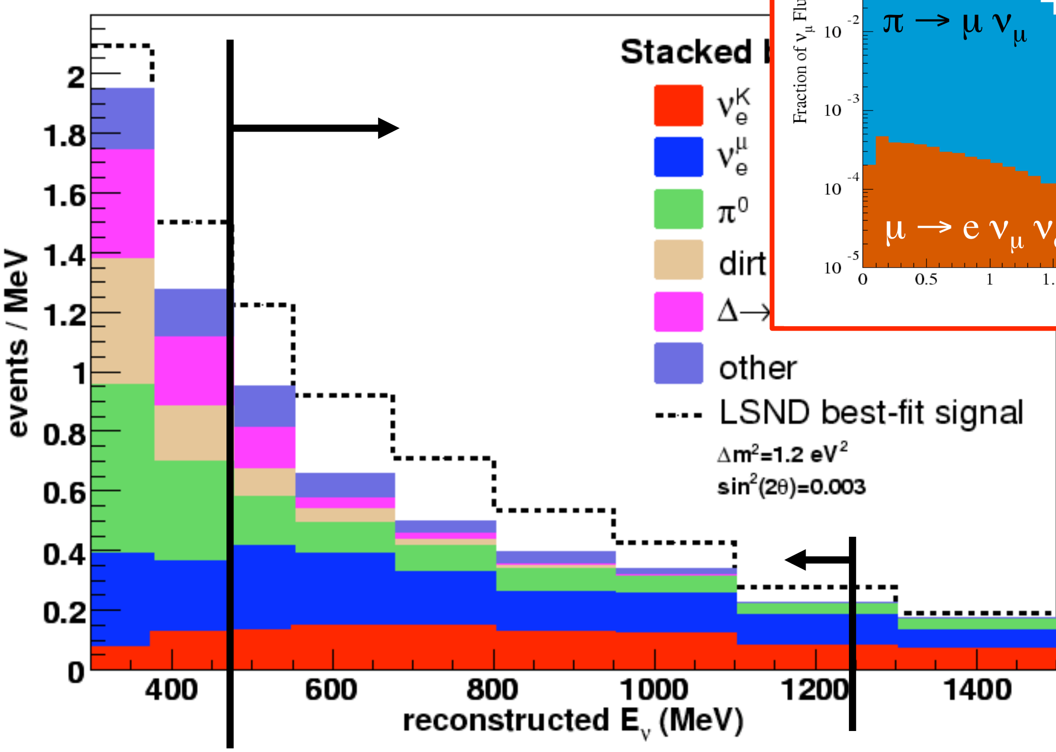

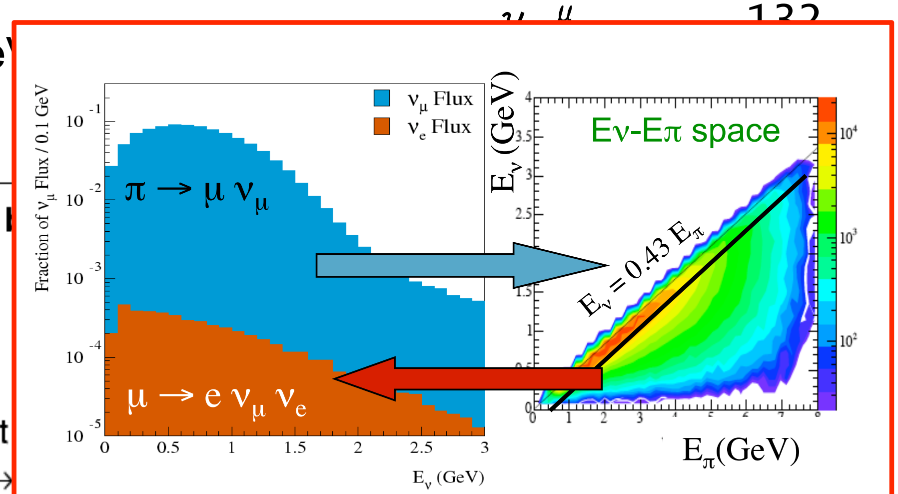

ν_e from μ decay is constrained from ν_μCCQE measurement

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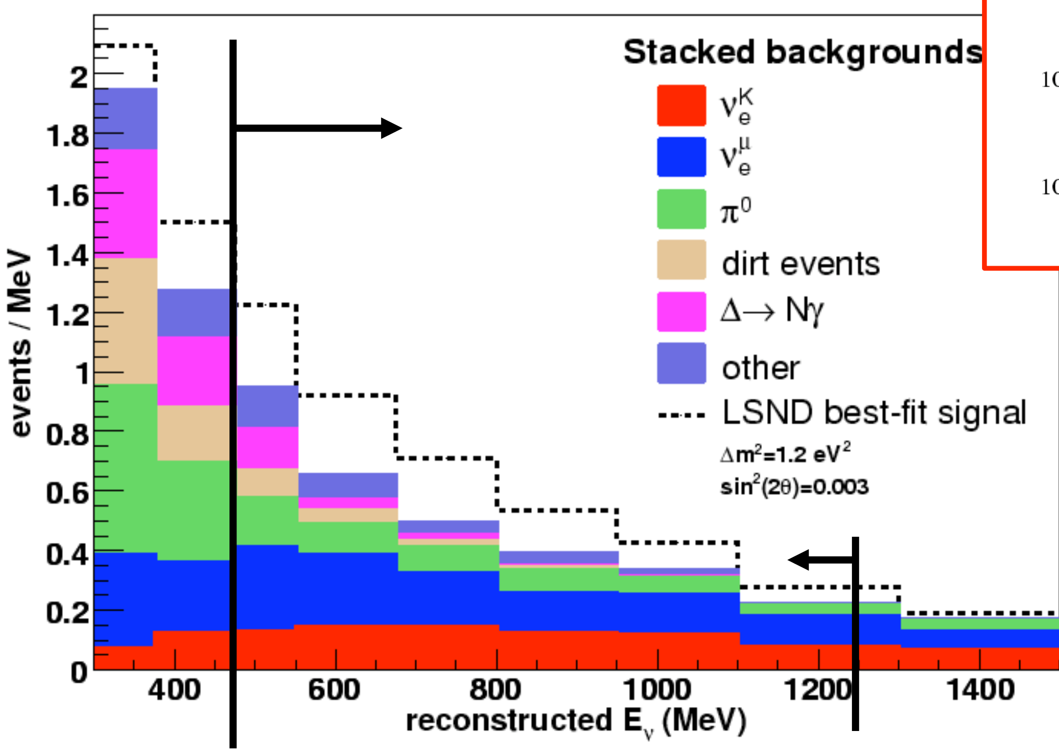
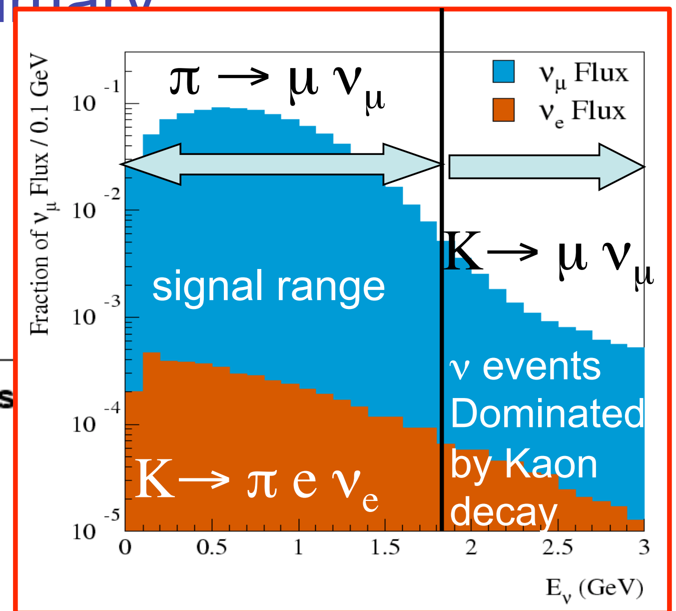




ν_e from μ decay is constrained from ν_μCCQE measurement

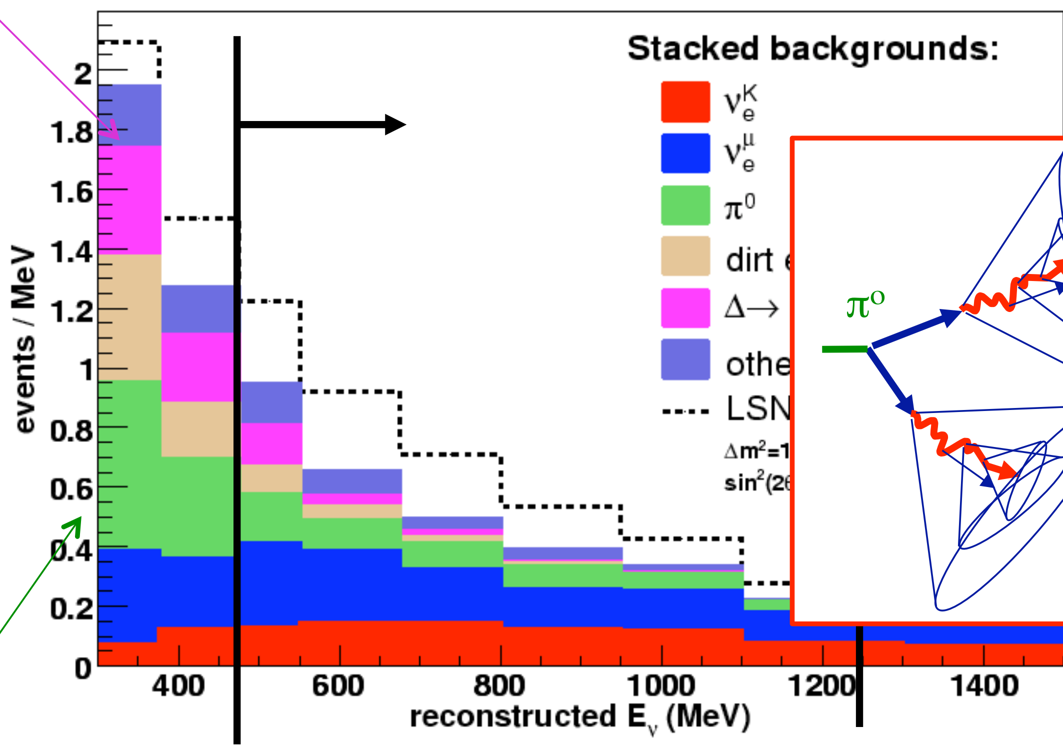
ν_e from K decay is constrained from high energy ν_e event measurement

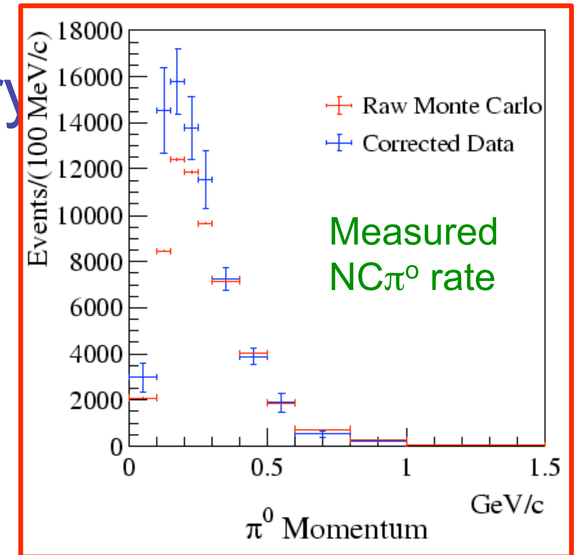
5. Oscillation analysis background summary

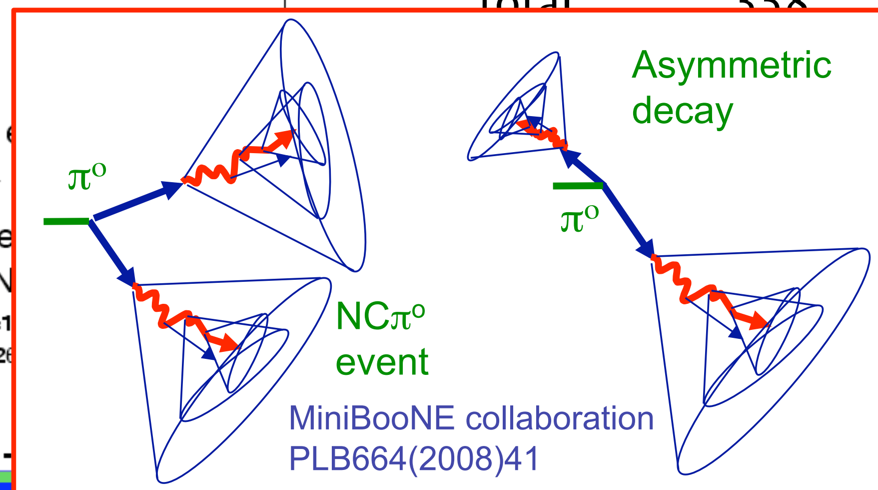
Oscillation analysis summary

- Oscillation analysis uses 475MeV<E<1250MeV

Δ resonance rate is constrained from measured CCπ^o rate







ν_e from K decay is constrained from high energy ν_e event measurement

Asymmetric π^o decay is constrained from measured CCπ^o rate ($\pi^o \rightarrow \gamma$)

5. Oscillation analysis background summary

475 MeV – 1250 MeV

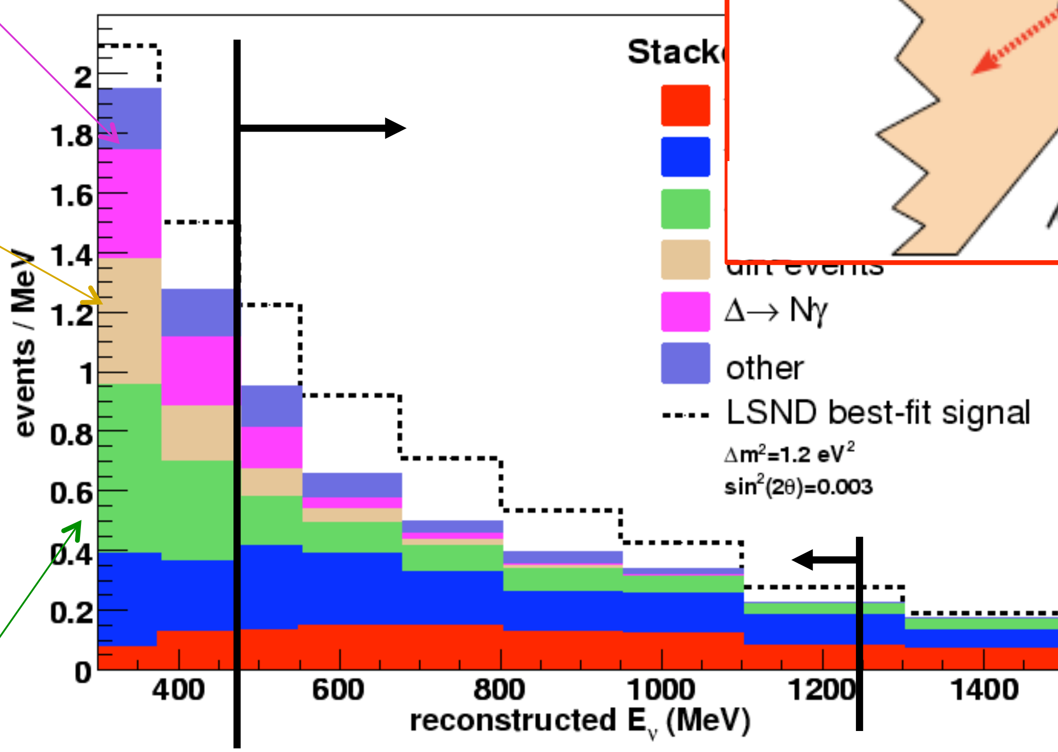
ν_e^K 94

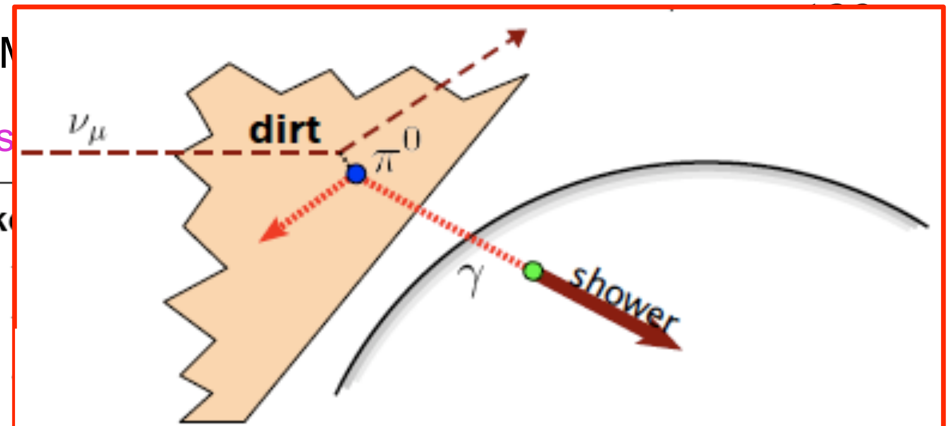
Oscillation analysis summary

- Oscillation analysis uses 475MeV<E<1250M

Δ resonance rate is constrained from meas

dirt rate is measured from dirt data sample





ν_e from μ decay is constrained from ν_μCCQE measurement

ν_e from K decay is constrained from high energy ν_e event measurement

Asymmetric π^o decay is constrained from measured CCπ^o rate ($\pi^o \rightarrow \gamma$)

5. Oscillation analysis background summary

Oscillation analysis summary

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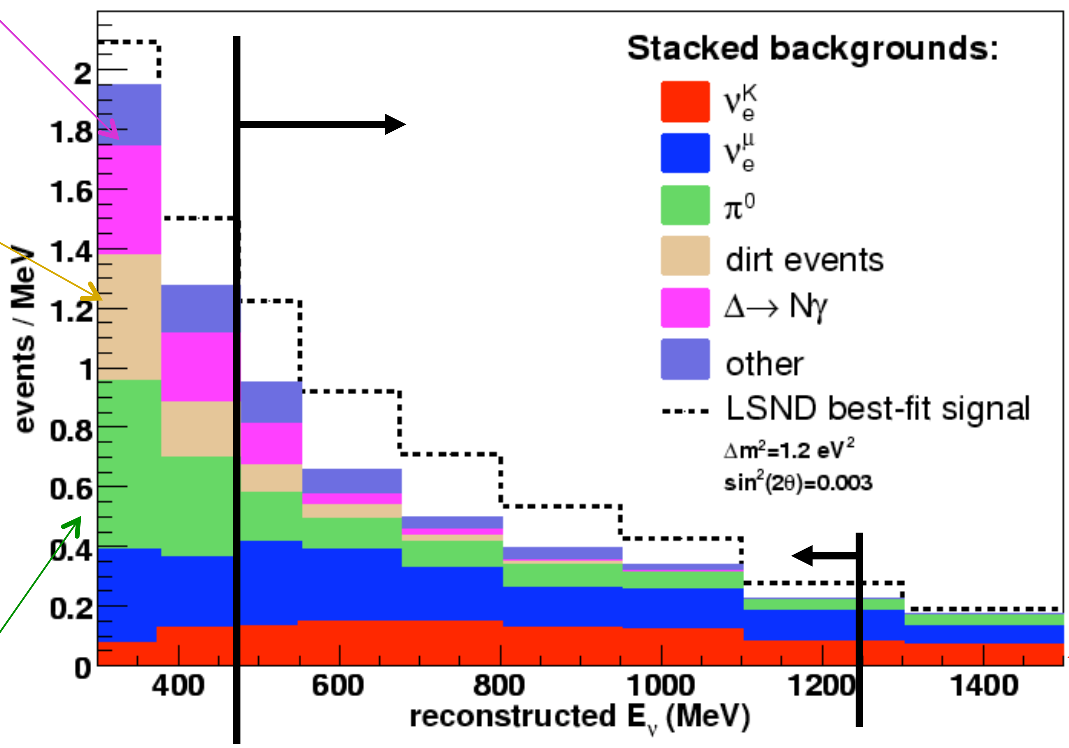


ν_e from μ decay is constrained from ν_μCCQE measurement

ν_e from K decay is constrained from high energy ν_e event measurement

Asymmetric π^o decay is constrained from measured CCπ^o rate ($\pi^o \rightarrow \gamma$)

All backgrounds are measured in other data sample and their errors are constrained!

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

5. Error analysis - Multisim

Input error matrix
keep all correlation
of systematics

"multisim"
nonlinear error propagation $\longrightarrow$

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

Multi-simulation (Multisim) method

many fake experiments (~1000) with different parameter set give the variation of correlated systematic errors for each independent error matrix

The total error matrix is the sum of all independent error matrix

The total error matrix is used for oscillation fit to extract the best fit Δm^2 and $\sin^2 2\theta$.

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)

MiniBooNE collaboration,
PRL102(2009)101802

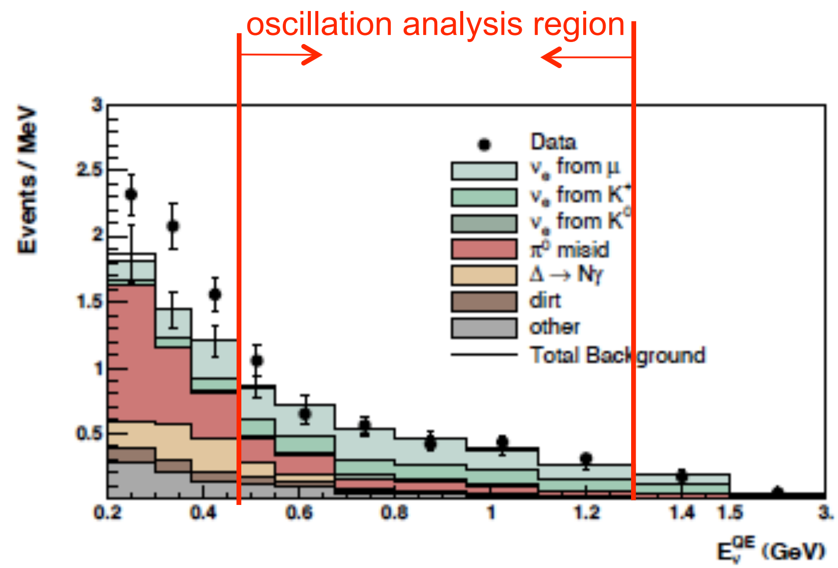
5. Oscillation analysis result

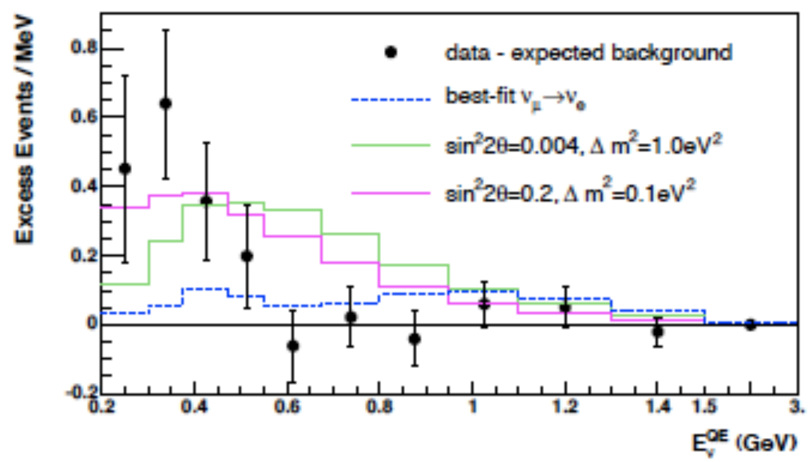
ν_e appearance oscillation result

- The best fit result shows no sign of an excess in the analysis region (where the LSND signal is expected from 1 sterile neutrino interpretation). However, there is 3.4σ excess in low energy region (300-475MeV)

- The shape of low energy excess is not described by any of two neutrino massive oscillation models

- many models are suggested to explain low energy excess, and can test those exotic models through antineutrino oscillation data





1. Introduction
2. Neutrino beam
3. Events in the detector
4. Cross section model
5. Neutrino oscillation result
6. **Anti-neutrino oscillation result**
7. Outlook

MiniBooNE collaboration,
PRL103(2009)111801

6. Antineutrino oscillation result

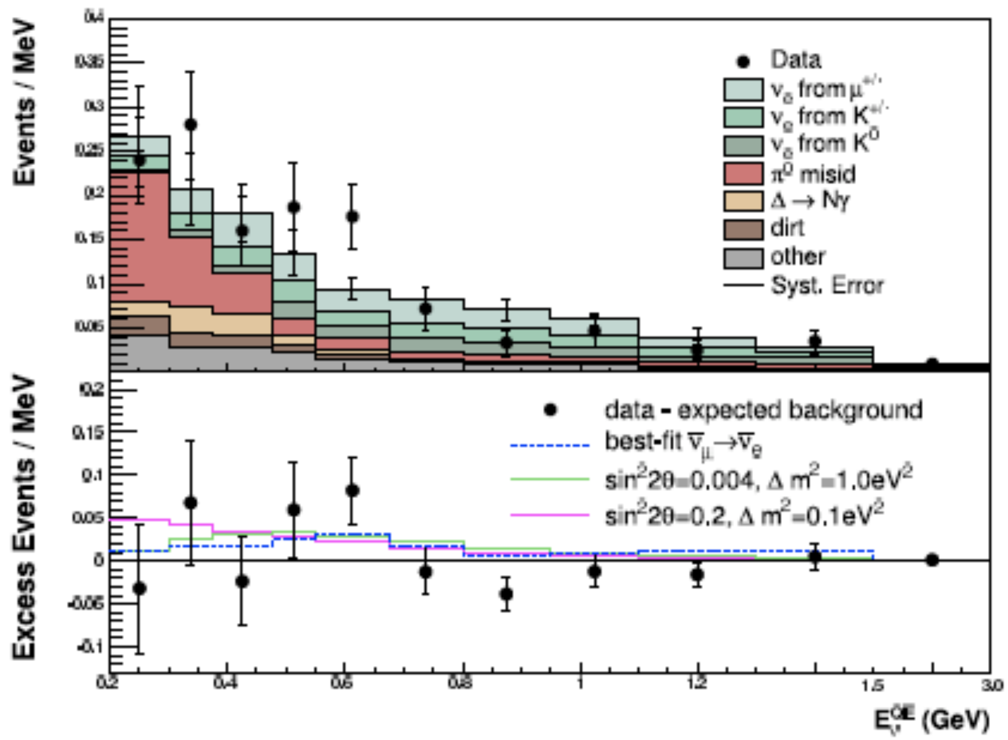
Many exotic models have some kind of predictions in antineutrino mode.

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

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

$$\bar{\nu}_e + p \rightarrow n + e^+$$

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



MiniBooNE collaboration,
PRL103(2009)111801

6. Antineutrino oscillation result

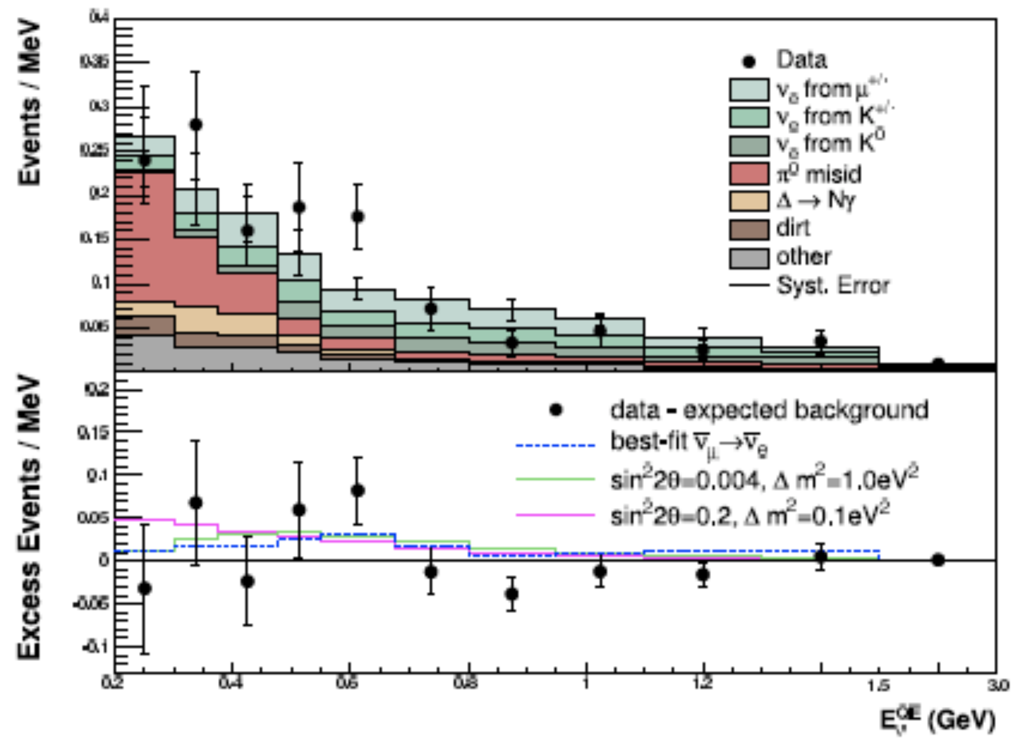
Implications

There are many theoretical models to explain low energy excess.

- The models based on same NC cross section for ν and anti-ν are disfavored.

-The models proportioned to POT are disfavored.

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



Hi theorists! new models are welcome!

MiniBooNE collaboration,
PRL105(2010)181801

6. 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
anti ν_e candidate	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, PRL105(2010)181801

6. New antineutrino oscillation result

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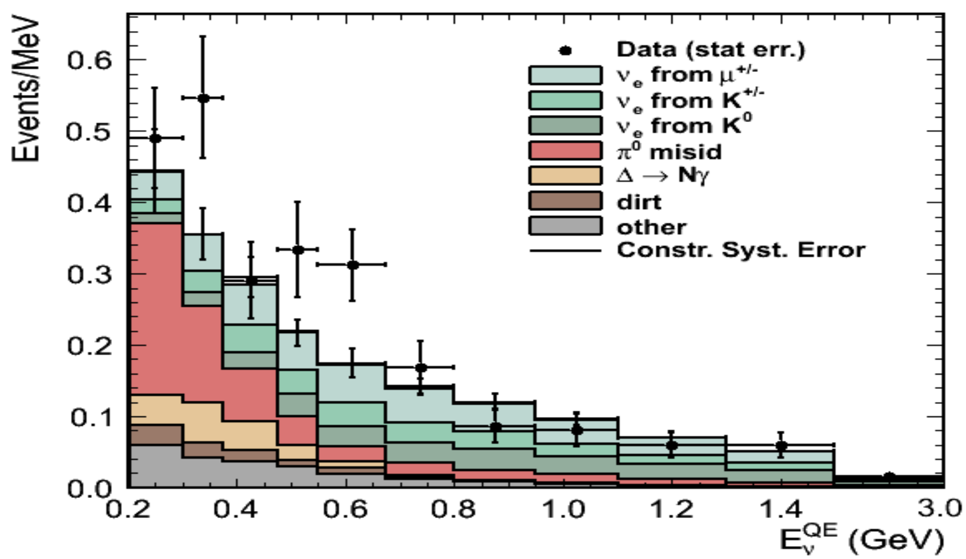
MiniBooNE now see the excess in LSND-like Δm^2 region!

	200-475 MeV	475-1250 MeV	200-3000 MeV
anti ν_e candidate	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 collaboration, PRL105(2010)181801

6. New antineutrino oscillation result

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

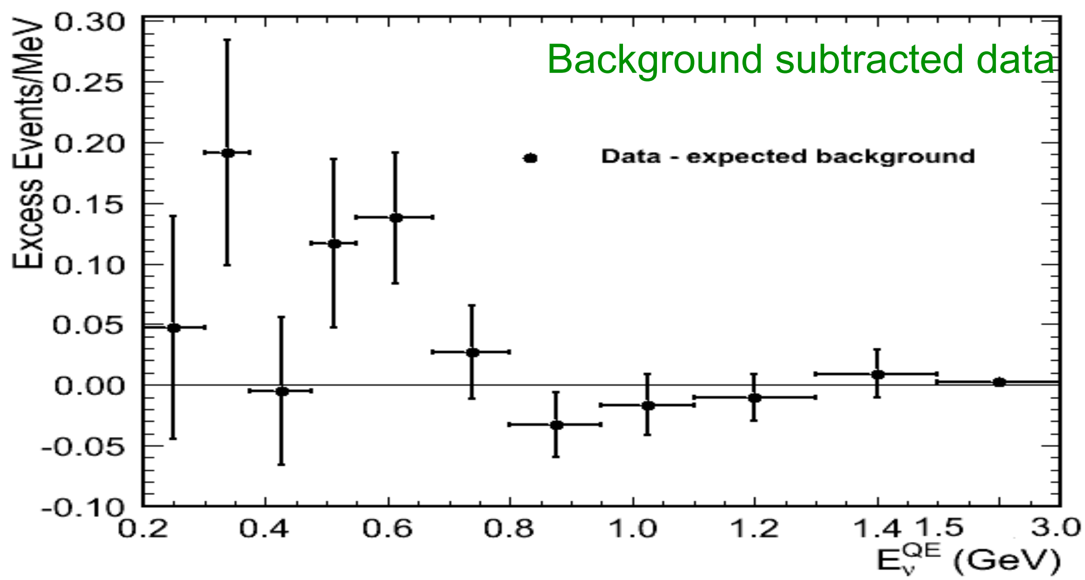
New antineutrino oscillation result

	before fit	
	χ^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)
- 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.



MiniBooNE collaboration, PRL105(2010)181801

6. New antineutrino oscillation result

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New antineutrino oscillation result

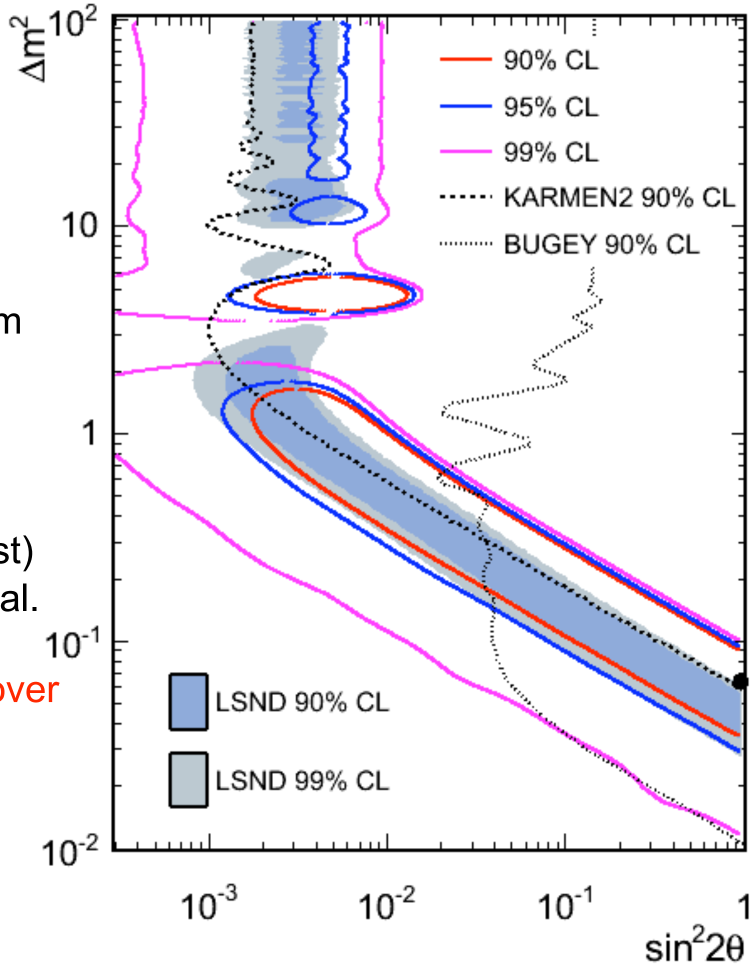
	before fit		after fit	
	χ^2/NDF	probability	χ^2/NDF	probability
$475 < E_\nu^{QE} < 1250$ MeV	18.5/6	0.5%	8.0/4	8.7%

- 70% more data
- low level checks have been done (beam stability, energy scale)
- new dirt event rate measurement (consistent with neutrino mode)
- new NCπ^o rate measurement (consistent with neutrino mode)
- 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
$\Delta m^2 = 0.064 eV^2$
$\sin^2 2\theta = 0.96$

7. MiniBooNE oscillation result summary

Neutrino mode analysis

- no excess is observed in the energy region where excess is expected from LSND
- significant excess is observed in low energy region

Antineutrino mode analysis

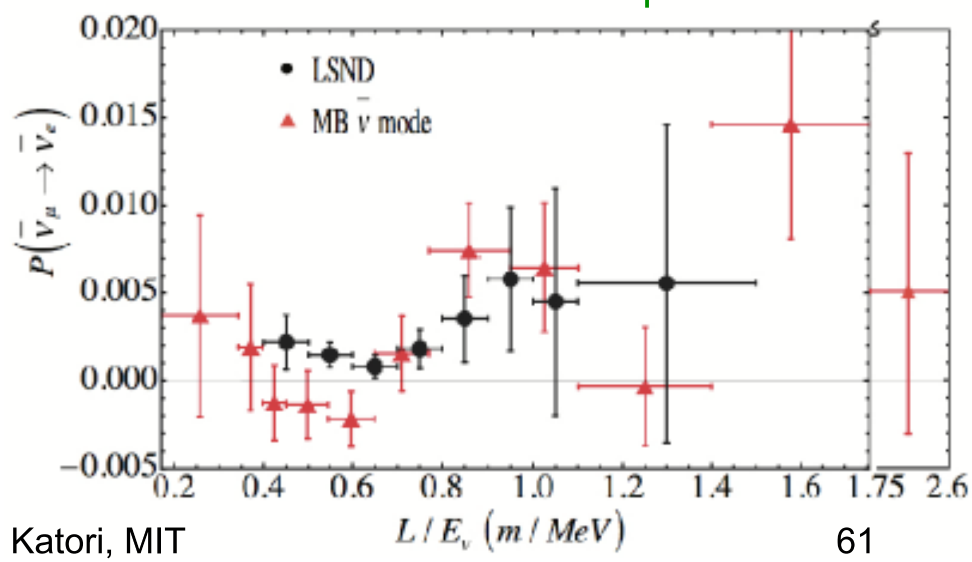
- small excess is observed in low energy region
- LSND consistent excess is observed in the oscillation energy region

These results are not main interest of Neutrino community (this is not θ_{13} nor leptonic CP violation nor Majorana mass measurement).

There is no convincing theoretical model to solve all mysteries.

Is MiniBooNE wrong?

MiniBooNE-LSND comparison in L/E



MiniBooNE collaboration,
PRD81(2010)092005

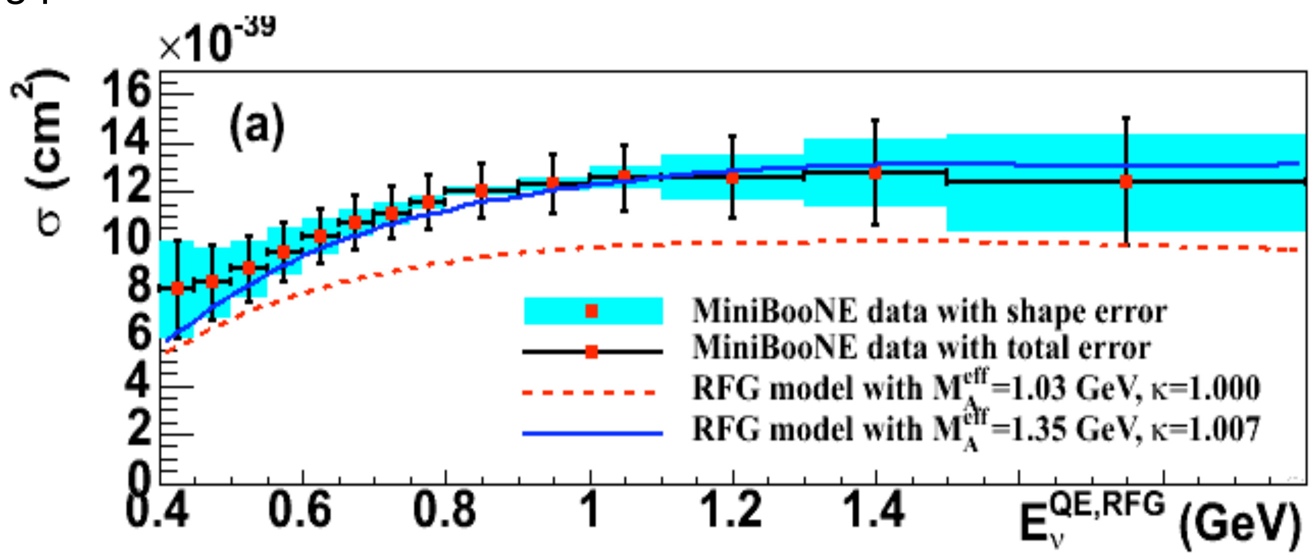
7. MiniBooNE CCQE absolute cross section

CCQE total cross section from MiniBooNE

MiniBooNE observed 30% higher neutrino cross section from RFG model with world averaged nuclear parameter from all past precise bubble chamber experiments.

When we first published this, we got so many criticism. Even a theorist claimed "MiniBooNE overestimate cross section!"

…but there is a turning point…



Martini et al

7. MiniBooNE CCQE absolute cross section

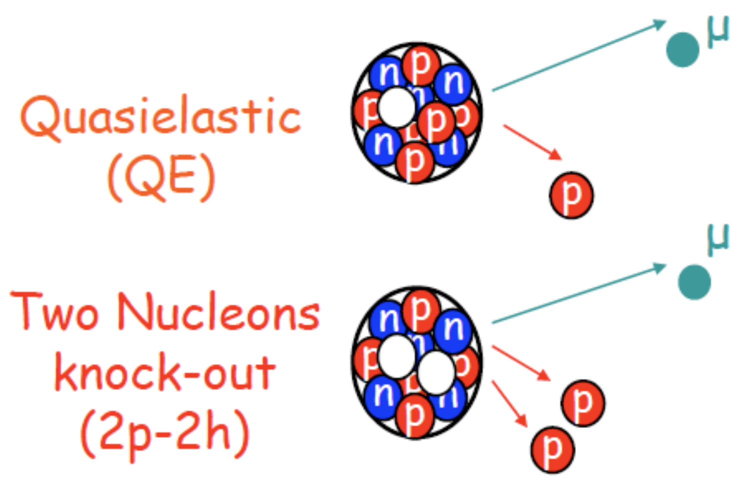
CCQE total cross section from MiniBooNE and RPA model

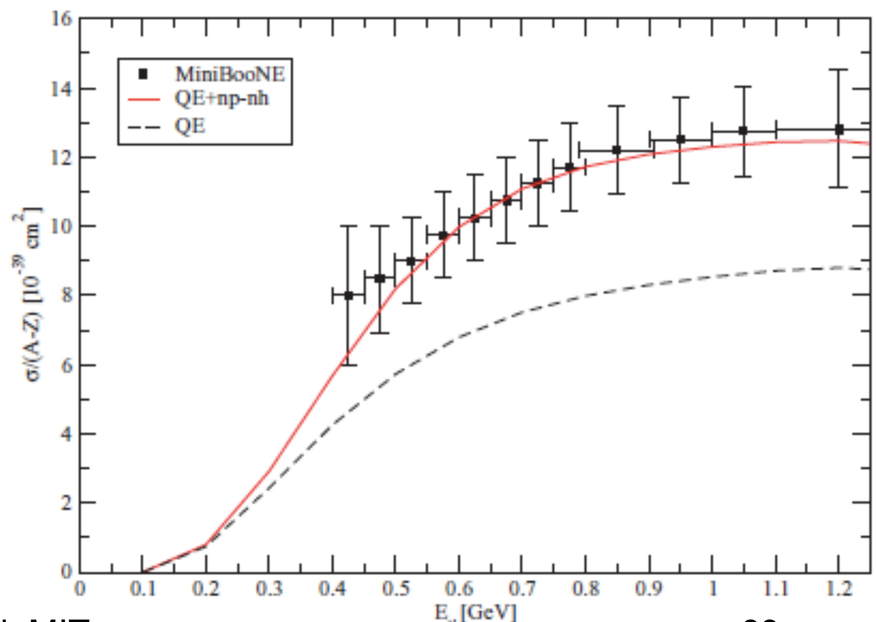
Martini et al.,
PRC80(2009)065501

Martini et al published their new RPA calculation result. They took into account the detail of nucleon emission channel (np-nh effect) and they explained MiniBooNE data.

Suddenly, many theorists start to appreciate this discovery by MiniBooNE.

So why all past experiments couldn't find this?





Martini et al

7. MiniBooNE CCQE absolute cross section

CCQE total cross section from MiniBooNE and RPA model

Martini et al., PRC80(2009)065501

Martini et al published their new RPA calculation result. They took into account the detail of nucleon emission channel (np-nh effect) and they explained MiniBooNE data.

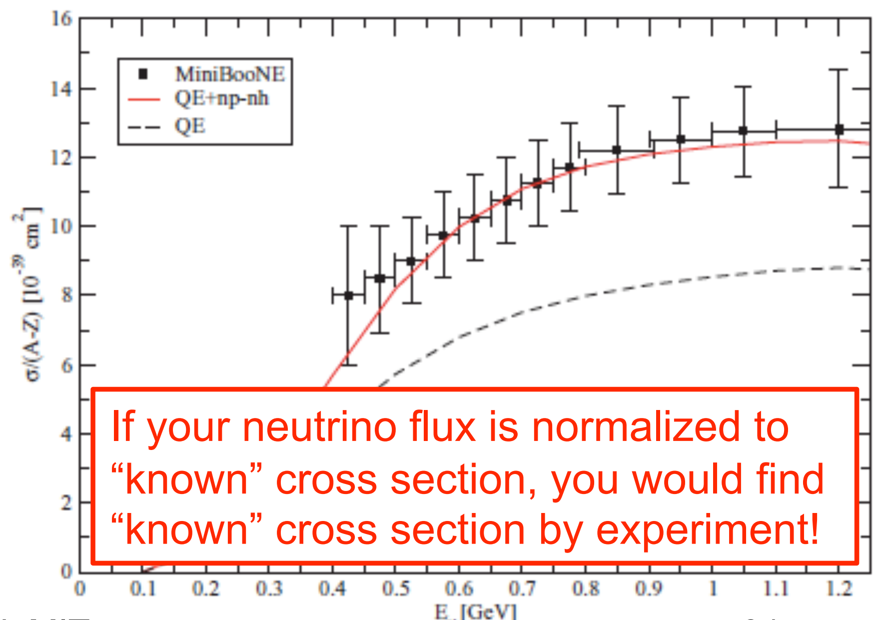
Suddenly, many theorists start to appreciate this discovery by MiniBooNE.

So why all past experiments couldn't find this?

There is a tendency for people to measure and discover what is predicted

Phys. Rev. DXX, (19XX)

The distribution of events in neutrino energy for the 3C $\nu d \to \mu^- p p_s$ events is shown in Fig. 4 together with the quasielastic cross section $\sigma(\nu n \to \mu^- p)$ calculated using the standard $V-A$ theory with $M_A = 1.05 \pm 0.05$ GeV and $M_V = 0.84$ GeV. The absolute cross sections for the CC interactions have been measured using the quasielastic events and its known cross section.[4]



7. MiniBooNE CCQE absolute cross section

We shouldn't do this kind of mistake.

Many of MiniBooNE result are unexpected, and unexplained. But that cannot be a reason to be wrong. Remember, how much our naïve assumptions were correct for what we call now standard neutrino model.

(Neutrino 2006, Murayama)
Solar neutrino oscillation solution is SMA, because it's pretty
-> Wrong, LMA is the right solution

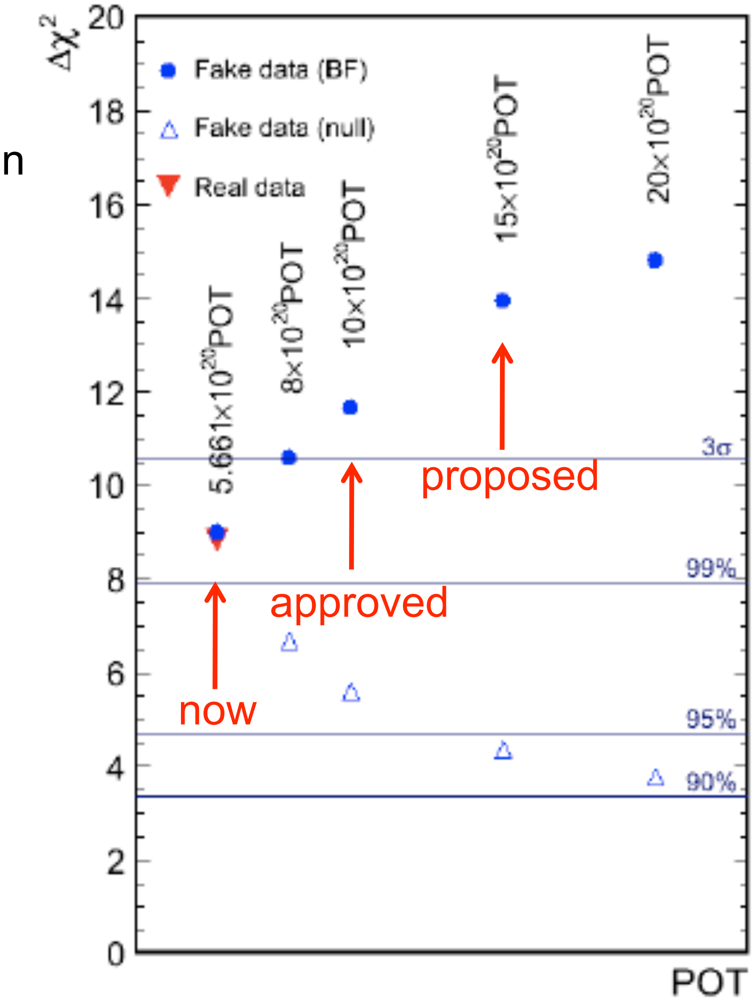
Natural scale of neutrino mass is ~10-100eV^2 because it's cosmologically interesting
-> Wrong, much smaller

Atmospheric mixing should be small like CKM matrix element V_{cb}~0.04, cannot be large
-> Wrong, much larger

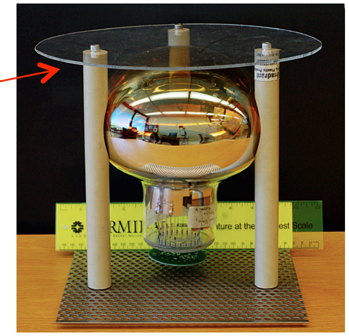
Neutrino physics keep surprising us, so does MiniBooNE!

7. MiniBooNE future plan

We continue to take data until March 2012 (approved), then we will double the statistics and expect 3σ excess in antineutrino mode. We are putting a proposal for 15E20 extension.



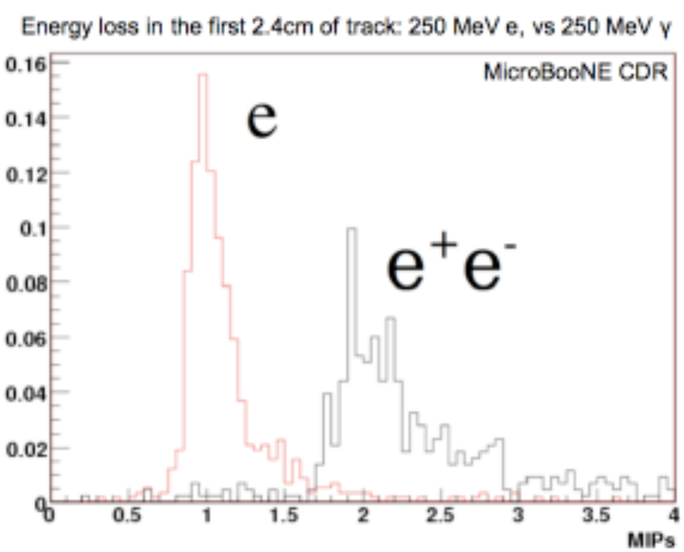
7. MicroBooNE

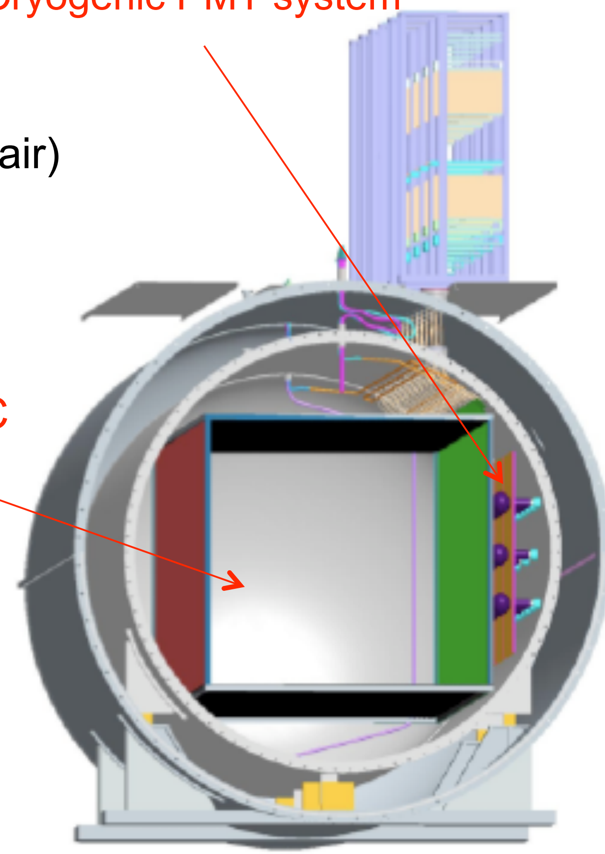


Cryogenic PMT system

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)





MiniBooNE 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

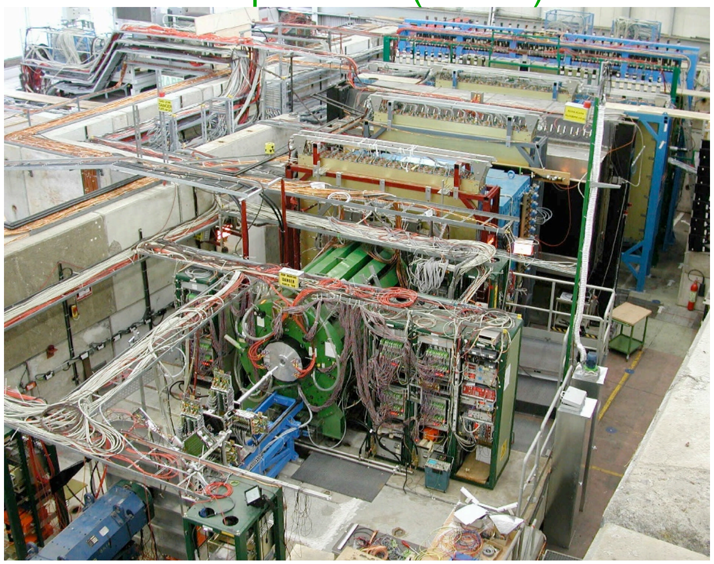
Thank you for your attention!

Buck up

MiniBooNE collaboration,
PRD79(2009)072002

2. Neutrino beam

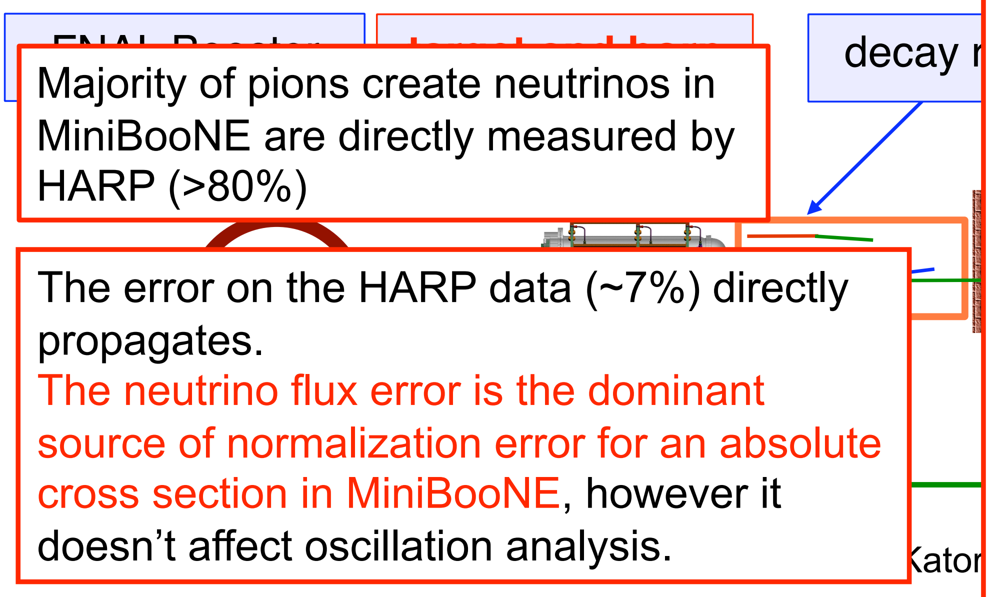
HARP experiment (CERN)



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

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

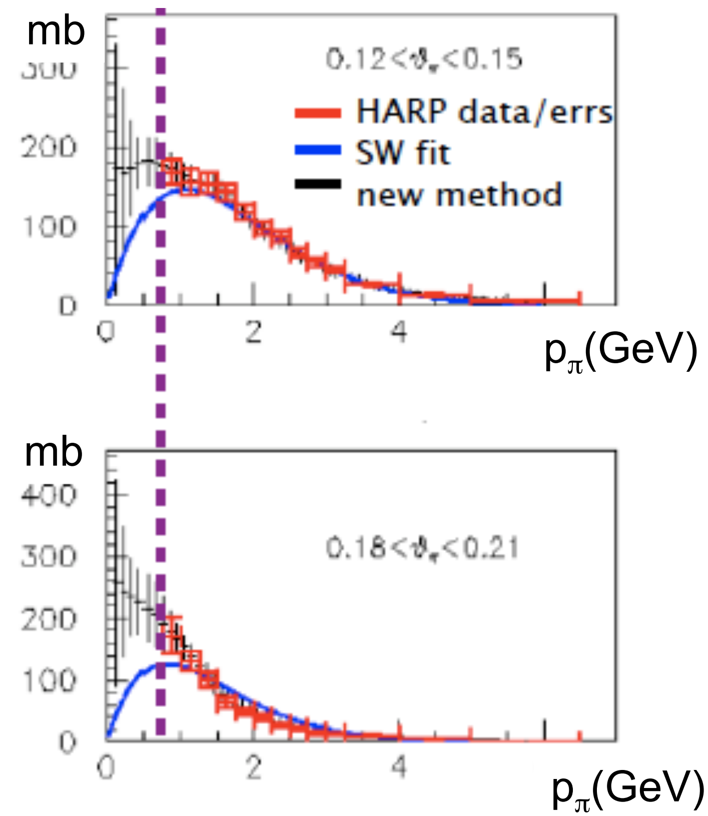
- Identical, but 5% λ Beryllium target
- 8.9 GeV/c proton beam momentum



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

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.

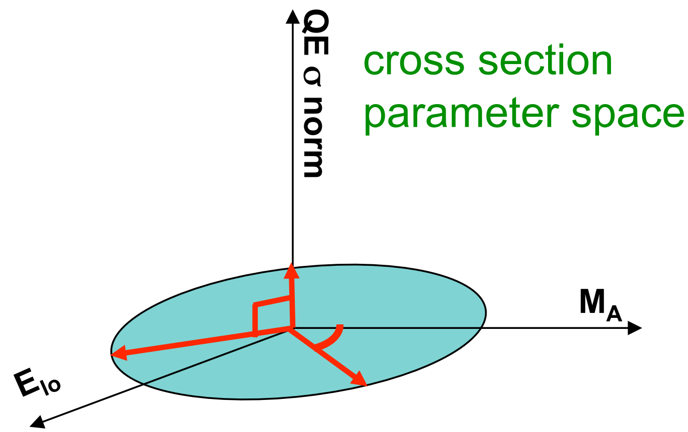
HARP data with 8.9 GeV/c proton beam momentum



5. Multisim

ex) cross section uncertainties

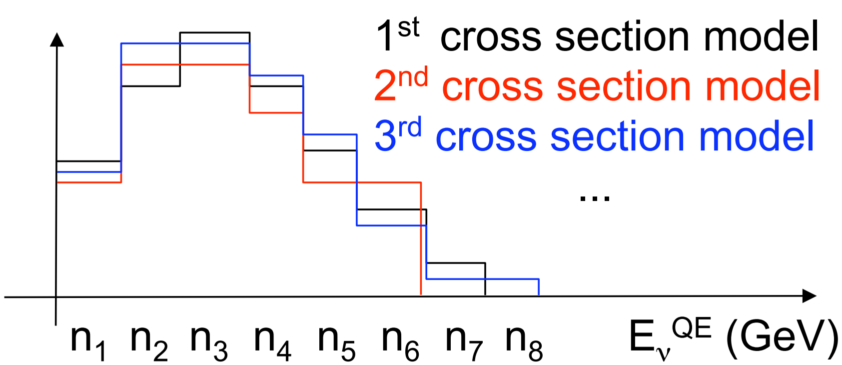
M_A^{QE}	6%	correlated
E_{lo}^{sf}	2%	
QE σ norm	10%	uncorrelated



Input cross section error matrix

$$M_{input}(xs) = \begin{pmatrix} var(M_A) & cov(M_A, E_{lo}) & 0 \\ cov(M_A, E_{lo}) & var(E_{lo}) & 0 \\ 0 & 0 & var(\sigma - norm) \end{pmatrix}$$

cross section error for E_ν^{QE}



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

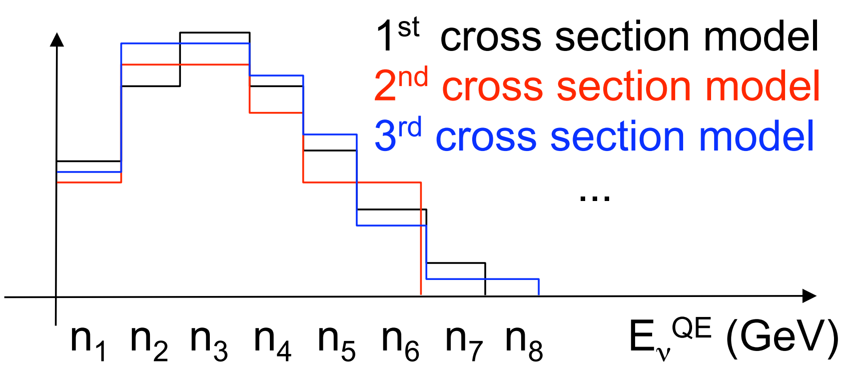
5. Multisim

Output cross section error matrix for E_ν^{QE}

$$\left[M_{output}(xs)\right]_{ij} \approx \frac{1}{S}\sum_{k}^{S}\left(N_i^k(xs)-N_i^{MC}\right)\left(N_j^k(xs)-N_j^{MC}\right)$$

$$M_{output}(xs)=\begin{pmatrix} var(n_1) & cov(n_1,n_2) & cov(n_1,n_3) & \cdots \\ cov(n_1,n_2) & var(n_2) & cov(n_2,n_3) & \cdots \\ cov(n_1,n_3) & cov(n_2,n_3) & var(n_3) & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

cross section error for E_ν^{QE}



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

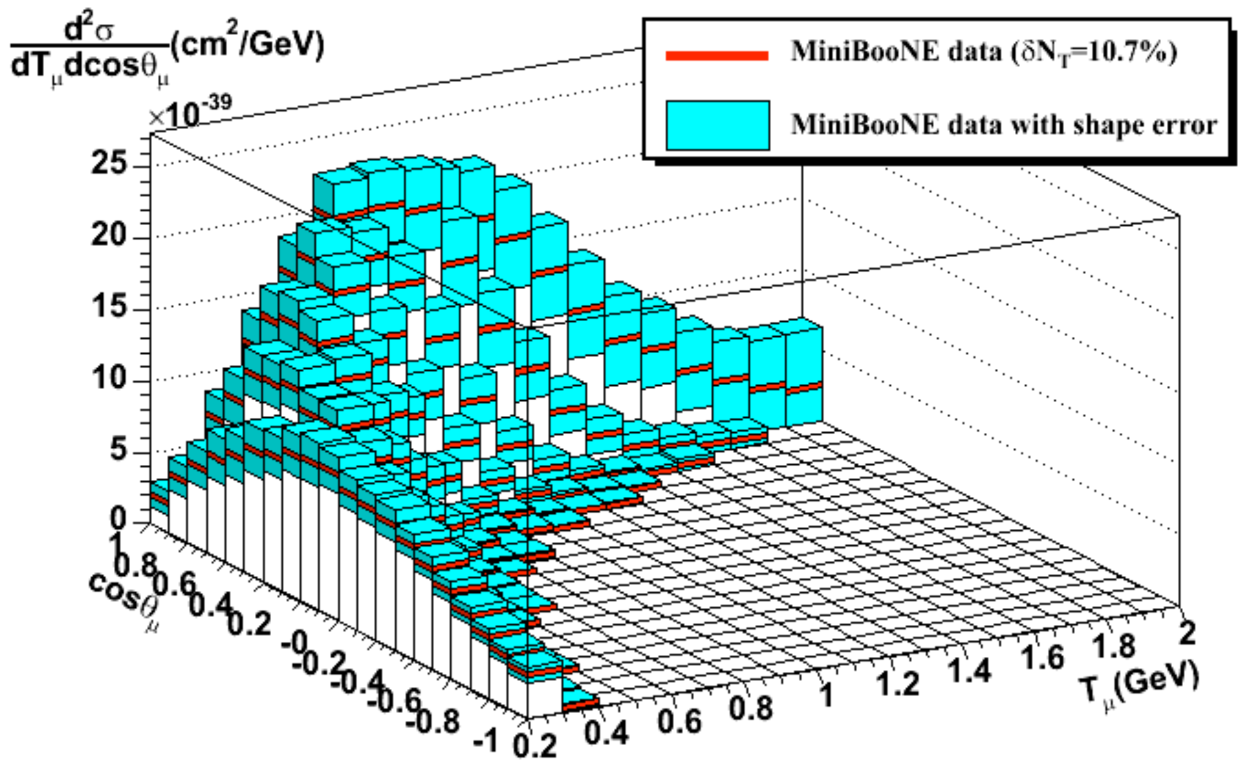
$$\chi^2 = (\text{data - MC})^T (M_{output})^{-1} (\text{data - MC})$$

6. CCQE double differential cross section

Flux-integrated double differential cross section (T_μ-$\cos\theta$)

This is the most complete information about neutrino cross section based on muon kinematic measurement.

The error shown here is shape error, a total normalization error (δN_T=10.7%) is separated.



6. Paradigm shift in neutrino cross section!?

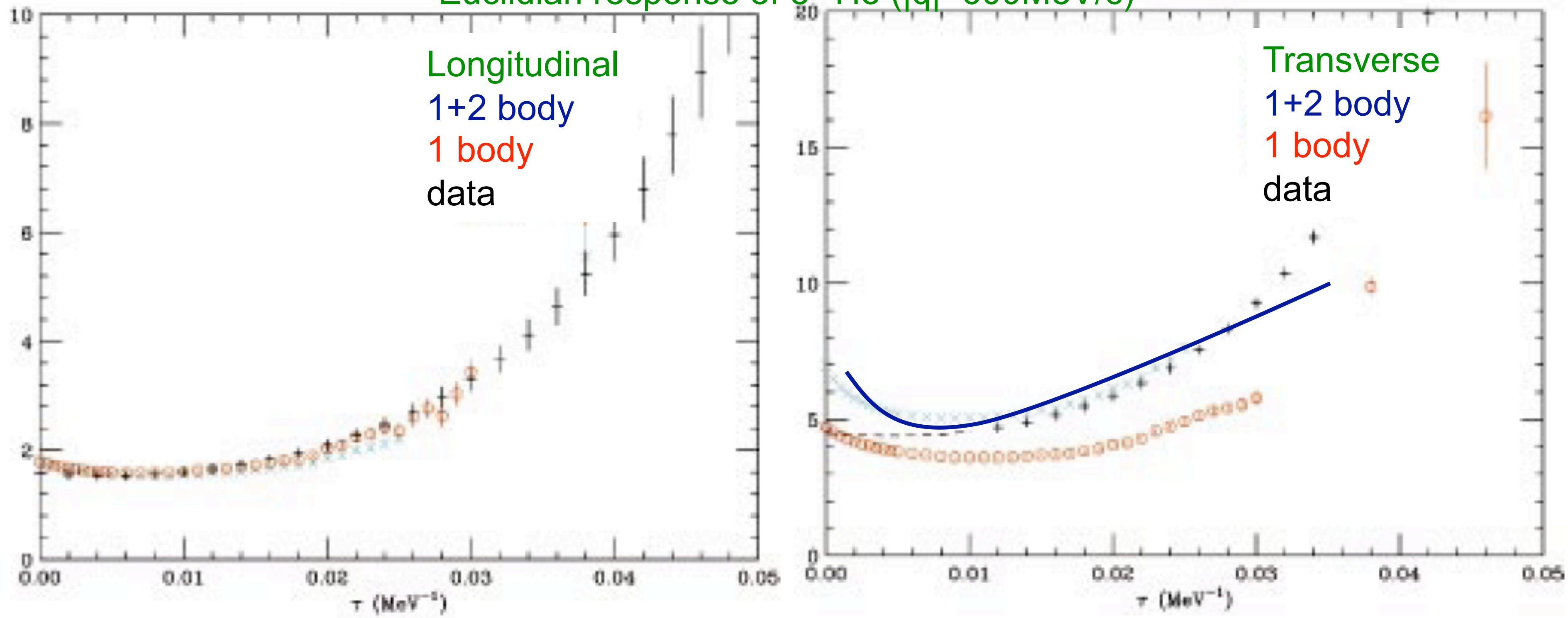
Theoretical approaches for the large cross section and harder Q^2 spectrum

RPA formalism
SRC+MEC

Martini et al.,PRC80(2009)065501
Carlson et al.,PRC65(2002)024002

Transverse response is enhanced by presence of short range correlation (SRC) and 2-body current (meson exchange current, MEC).

Euclidian response of e-^{4}He (|q|=600MeV/c)



Jon Link, Nov. 18, 2005
Fermilab Wine & Cheese seminar

PHYSICAL REVIEW D VOLUME 23, NUMBER 11 1 JUNE 1981

Quasielastic neutrino scattering: A measurement of the weak nucleon axial-vector form factor

N. J. Baker, A. M. Cnops,* P. L. Connolly, S. A. Kahn, H. G. Kirk, M. J. Murtagh, R. B. Palmer, N. P. Samios, and M. Tanaka
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 February 1981)

Brookhaven AGS

7ft D_2 Bubble Chamber

The quasielastic reaction $\nu_\mu n \to \mu^- p$ was studied in an experiment using the BNL 7-foot deuterium bubble chamber exposed to the wide-band neutrino beam with an average energy of 1.6 GeV. A total of 1138 quasielastic events in the momentum-transfer range $Q^2 = 0.06 - 3.00\ (\mathrm{GeV}/c)^2$ were selected by kinematic fitting and particle identification and were used to extract the axial-vector form factor $F_A(Q^2)$ from the Q^2 distribution. In the framework of the conventional $V-A$ theory, we find that the dipole parametrization is favored over the monopole. The value of the axial-vector mass M_A in the dipole parametrization is 1.07 ± 0.06 GeV, which is in good agreement with both recent neutrino and electroproduction experiments. In addition, the standard assumptions of conserved vector current and no second-class currents are checked.

We have used a maximum likelihood method to extract M_A from the shape of the Q^2 distribution for each observed neutrino energy. This likelihood function $\mathfrak{L}^I$ is independent of the shape of the neutrino spectrum . . .

They didn't even try to determine their ν flux from pion production and beam dynamics.

Phys. Rev. D **25**, 617 (1982)

The distribution of events in neutrino energy for the 3C $\nu d \to \mu^- p p_s$ events is shown in Fig. 4 together with the quasielastic cross section $\sigma(\nu n \to \mu^- p)$ calculated using the standard $V-A$ theory with $M_A = 1.05 \pm 0.05$ GeV and $M_V = 0.84$ GeV. The absolute cross sections for the CC interactions have been measured using the quasielastic events and its known cross section.[4]

In subsequent cross section analyses the theoretical ("known") quas-ielastic cross section and observed quasi-elastic events were used to determine the flux.

Jon Link, Nov. 18, 2005
Fermilab Wine & Cheese seminar

VOLUME 49, NUMBER 2 PHYSICAL REVIEW LETTERS 12 JULY 1982

Fermilab
15ft D_2 Bubble Chamber

Neutrino Flux and Total Charged-Current Cross Sections in High-Energy Neutrino-Deuterium Interactions

T. Kitagaki, S. Tanaka, H. Yuta, K. Abe, K. Hasegawa, A. Yamaguchi, K. Tamai, T. Hayashino, Y. Ohtani, and H. Hayano
Tohoku University, Sendai 980, Japan

To obtain the total cross section from the number of events, the neutrino flux has to be measured on an absolute scale. In this analysis, we determine the neutrino flux using 362 quasielastic events identified in our data[10] and the cross section for reaction (2) derived from the $V-A$ theory.

Again, they use QE events and theoretical cross section to calculate the ν.

When they try to get the flux from meson (π and K) production and decay kinematics they fail miserably for E_ν<30 GeV.

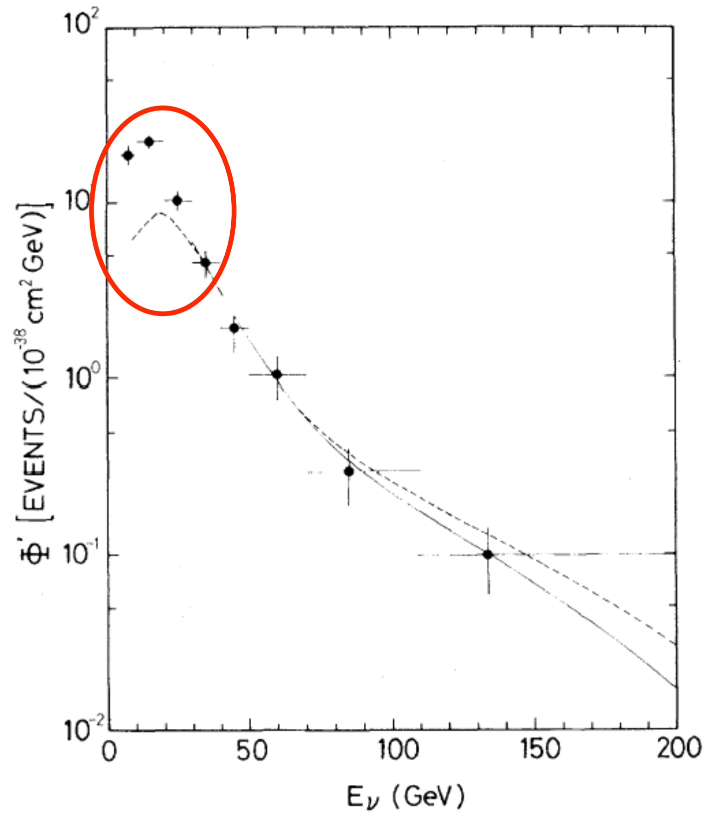


FIG. 2. Neutrino flux distribution obtained from the quasielastic events and the predicted cross section with M_A = 1.05 GeV. The solid curve is obtained from the best fit to the flux data for E_ν > 30 GeV. The dashed curve is taken from the Monte Carlo simulation of the flux.

Jon Link, Nov. 18, 2005
Fermilab Wine & Cheese seminar

PHYSICAL REVIEW D VOLUME 34, NUMBER 1 1 JULY 1986

Determination of the neutrino fluxes in the Brookhaven wide-band beams

L. A. Ahrens, S. H. Aronson, P. L. Connolly,* B. G. Gibbard, M. J. Murtagh, S. J. Murtagh,† S. Terada, and D. H. White
Physics Department, Brookhaven National Laboratory, Upton, New York 11973

Brookhaven AGS

Liquid Scintillator

The beam calculations described here were based on the Grote, Hagedorn, and Ranft (GHR) (Ref. 11) parametrization; that of Sanford and Wang was used for comparison. An estimate was made of pion production by reinteracting protons guided by the shape of the observed ν_μ spectrum and the observed angular distribution of muons from quasielastic events. The procedure is described[12] in the Appendix.

The Procedure

- Pion production cross sections in some low momentum bins are scaled up by 18 to 79%.
- The K^+ to π^+ ratio is increased by 25%.
- Overall neutrino (anti-neutrino) flux is increased by 10% (30%).

All driven by the neutrino events observed in the detector!

Jon Link, Nov. 18, 2005
Fermilab Wine & Cheese seminar

PHYSICAL REVIEW D VOLUME 16, NUMBER 11 1 DECEMBER 1977

Argonne ZGS
12ft D_2 Bubble Chamber

Study of neutrino interactions in hydrogen and deuterium: Description of the experiment and study of the reaction $\nu + d \rightarrow \mu^- + p + p_s$†

S. J. Barish,* J. Campbell,‡ G. Charlton,§ Y. Cho, M. Derrick, R. Engelmann,‖ L. G. Hyman, D. Jankowski, A. Mann,¶ B. Musgrave, P. Schreiner, P. F. Schultz, R. Singer, M. Szczekowski,** T. Wangler, and H. Yuta††
Argonne National Laboratory, Argonne, Illinois 60439

Flux derived from pion production data. Were able to test assumptions about the form of the cross section using absolute rate and shape information.

TABLE IV. Results of axial-form-factor fits.

Likelihood function	M_A^{Dipole} (GeV)	M_A^{Monopole} (GeV)	M_A^{Tripole} (GeV)
Rate	$0.75^{+0.13}_{-0.11}$	$0.45^{+0.11}_{-0.07}$	$0.96^{+0.17}_{-0.14}$
Shape	1.010 ±0.09	0.56 ± 0.08	1.32 ± 0.11
Rate and shape	0.95 ±0.09	0.52 ± 0.08	1.25 ± 0.11
Flux independent	0.95 ±0.09	0.53 ± 0.08	1.25 ± 0.11

- Pion production measured in ZGS beams were used in this analysis
- A very careful job was done to normalize the beam.
- Yet they have a 25% inconsistency between the axial mass they measure considering only rate information verses considering only spectral information.

Interpretation: Their normalization is wrong.

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

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

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

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

2. neutral current elastic (NCE) cross section measurement
   by Denis Perevalov, PRD82(2010)092005
3. neutral current π^o production (NCπ^o) cross section measurement (ν and anti-ν)

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

by Mike Wilking, arXiv:1011.3572

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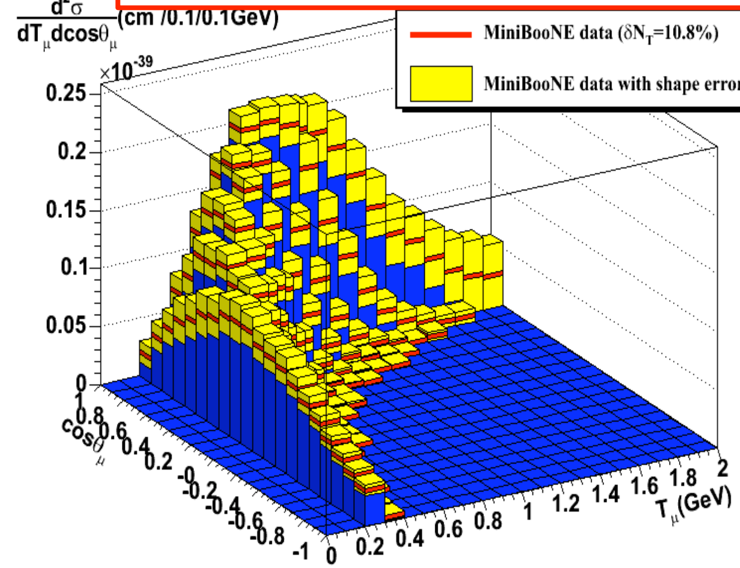
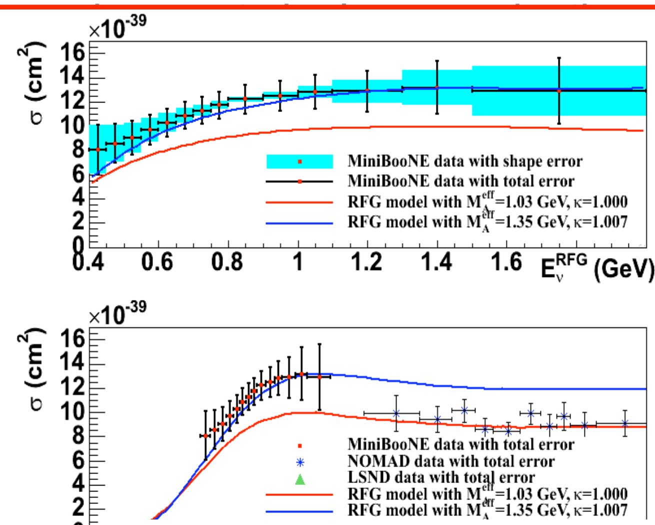
CCQE double differential cross section





Flux-unfolded total cross section

by Denis Perevalov

4. MiniBooNE cross section results

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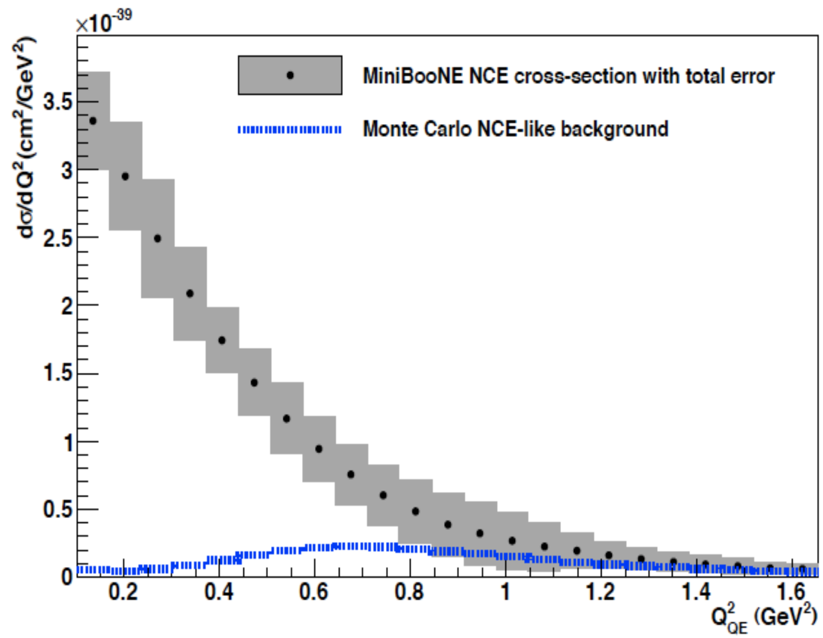
   by Colin Anderson, PRD81(2010)013005
4. charged current single pion production (CCπ^+) cross section measurement
   by Mike Wilking, arXiv:1011.3572
6. CCπ^+/CCQE cross section ratio measurement
   by Steve Linden, PRL103(2009)081801
7. anti-νCCQE measurement
   by Joe Grange, aiXiv:1102:1964

$$\nu_\mu + p \rightarrow \nu_\mu + p$$

$$\nu_\mu + n \rightarrow \nu_\mu + n$$

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

Flux-averaged NCE p+n differential cross section



by Colin Anderson

4. MiniBooNE cross section results

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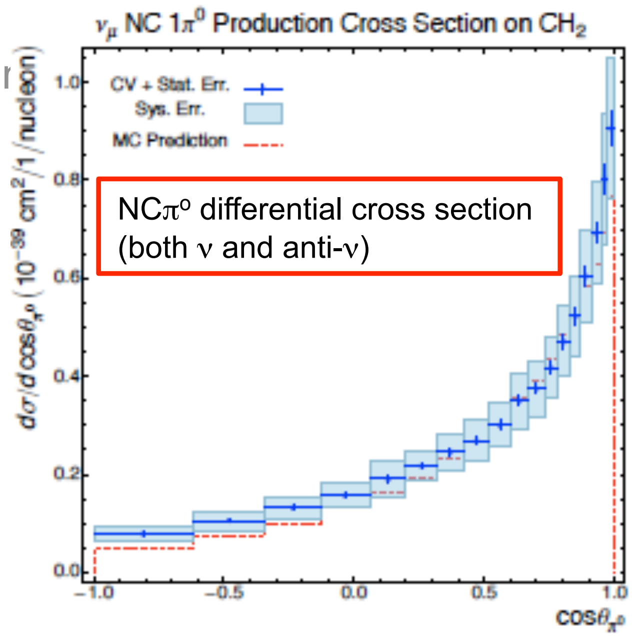
6.
   by Steve Linden, PRL103(2009)081801
7. anti-νCCQE measurement
   by Joe Grange, aiXiv:1102:1964

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

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



by Mike Wilking

4. MiniBooNE cross section results

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   by Colin Anderson, PRD81(2010)013005
4. charged current single pion production (CCπ^+) cross section measurement
   by Mike Wilking, arXiv:1011.3572

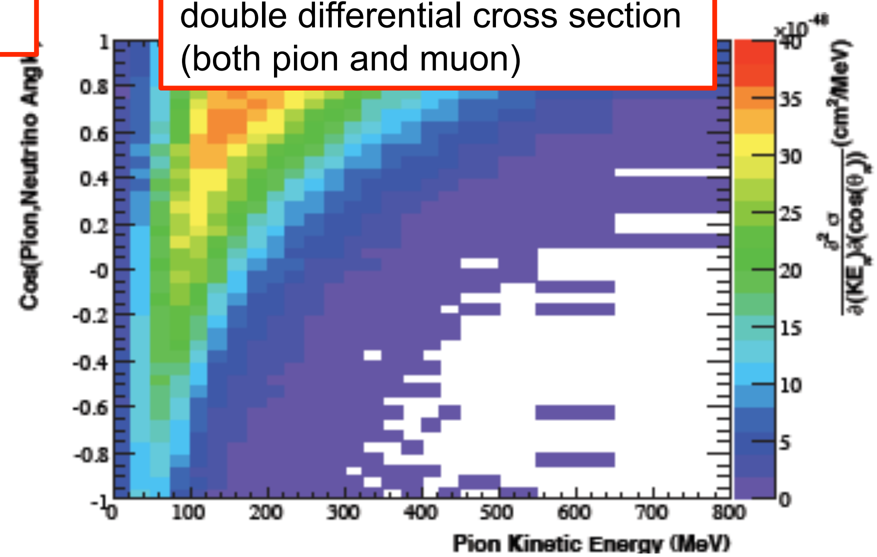
$$\nu_\mu + p(n) \rightarrow \mu + \Delta^{+(+)} \rightarrow \mu + p(n) + \pi^+$$
$$\nu_\mu + A \rightarrow \mu + A + \pi^+$$

s section measurement

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

6. CCπ^+/CCQE cross section ratio measurement
   by Steve Linden, PRL103(2009)081801
7. anti-νCCQE measurement
   by Joe Grange, aiXiv:1102:1964

double differential cross section
(both pion and muon)



4. MiniBooNE cross section results

by Bob Nelson

NuInt09, May18-22, 2009, Sitges, Spain
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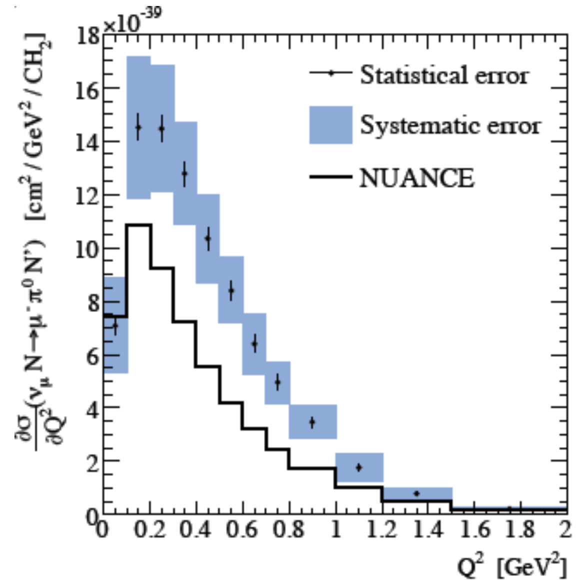
5. charged current single π^o production (CCπ^o) cross section measurement
   by Bob Nelson, arXiv:1010.3264
6.
7.
   by Joe Grange, aiXiv:1102:1964

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

$$\nu_\mu + n \rightarrow \mu + \Delta^+ \rightarrow \mu + p + \pi^o$$

CCπ^o Q^2 differential cross section



by Steve Linden

4. MiniBooNE cross section results

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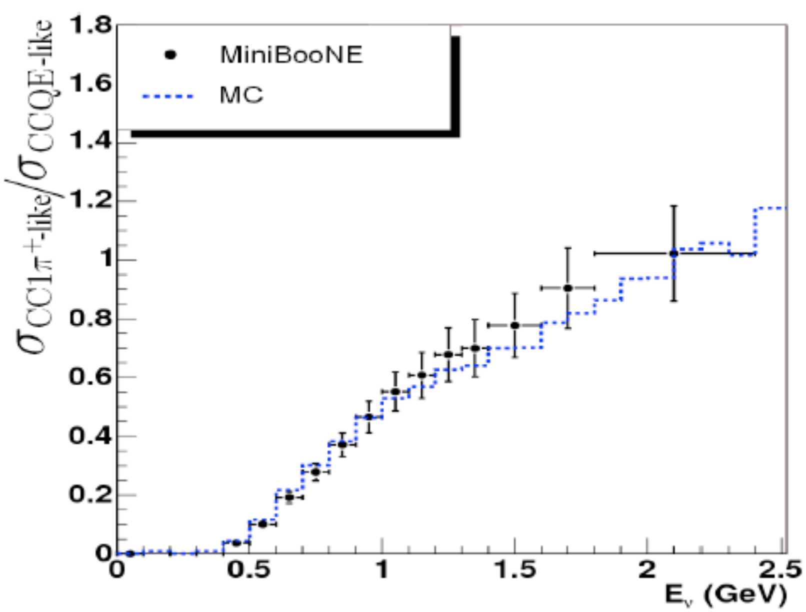
7. a
   by Joe Grange, arXiv:1102.1964

- data is presented in theorist friendly style



CCπ^+like/CCQElike cross section ratio

4. MiniBooNE cross section results

by Joe Grange

NuInt09, May18-22, 2009, Sitges, Spain
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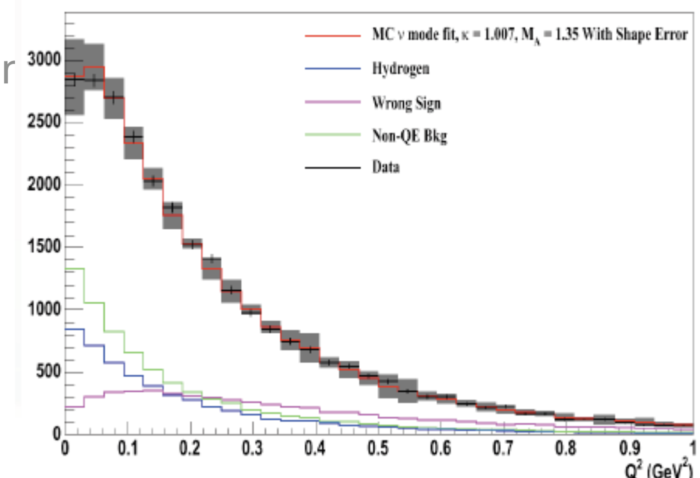
$$\bar{\nu}_\mu + p \rightarrow n + \mu^+$$

$$\left(\begin{array}{c} \bar{\nu}_\mu + {}^{12}C \rightarrow X + \mu^+ \\ \bar{\nu}_\mu + {}^{1}H \rightarrow n + \mu^+ \end{array} \right)$$

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



anti-νCCQE Q^2 distribution

by Joe Grange

4. MiniBooNE cross section results

NuInt11, Mar. 07-11, 2011, Dehradun, India

In NuInt11, MiniBooNE presented 2 anti-neutrino measurement results.

$$\bar{\nu}_\mu + p \rightarrow n + \mu^+$$

$$\begin{pmatrix} \bar{\nu}_\mu + {}^{12}C \rightarrow X + \mu^+ \\ \bar{\nu}_\mu + {}^{1}H \rightarrow n + \mu^+ \end{pmatrix}$$

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, PRD82(2010)092005
3. neutral current π^o production (NCπ^o) cross section measurement (ν
   by Colin Anderson, PRD81(2010)013005
4. charged current single pion production (CCπ^+) cross section measurement
   by Mike Wilking, arXiv:1011.3572
5. charged current single π^o production (CCπ^o) cross section measurement
   by Bob Nelson, arXiv:1010.3264
6.
7.

- background subtracted absolute rate
- key to understand nuclear effect
- key to understand role of axial form factor

8. new anti-νCCQE measurement
   by Joe Grange
9. anti-ν NCE measurement
   by Ranjan Dharmapalan

by Ranjan Dharmapalan

4. MiniBooNE cross section results

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$$\bar{\nu}_\mu + n \rightarrow \bar{\nu}_\mu + n$$

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, PRD82(2010)092005
3. neutral current π^o production ($NC\pi^o$) cross section measurement (ν and anti-ν)
   by Colin Anderson, PRD81(2010)013005
4. charged current single pion production ($CC\pi^+$) cross section measurement
   by Mike Wilking, arXiv:1011.3572
5. charged current single π^o production ($CC\pi^o$) cross section measurement
   by Bob Nelson, arXiv:1010.3264
6. $CC\pi^+$/CCQE cross section ratio measurement
   by Steve Linden, PRL103(2009)081801
7. anti-νCCQE measurement

- last channel to measure in non-resonance CC/NC interaction
- understanding of role of strange quark in nucleon static limit

9. anti-ν NCE measurement
   by Ranjan Dharmapalan