MiniBooNE, a neutrino oscillation experiment at Fermilab

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

Teppei Katori for the MiniBooNE collaboration
Massachusetts Institute of Technology
New Trend in High Energy Physics, Alushta, Ukraine, Sep. 6, 2011

MiniBooNE, a neutrino oscillation experiment at Fermilab

If you stay this session until the end, you can get a free gorilka shot from Teppei! (at золотая ложка or whereever)

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1. Neutrino oscillation

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

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

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

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

Then the transition probability from weak eigenstate ν_μ to ν_e is,

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

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

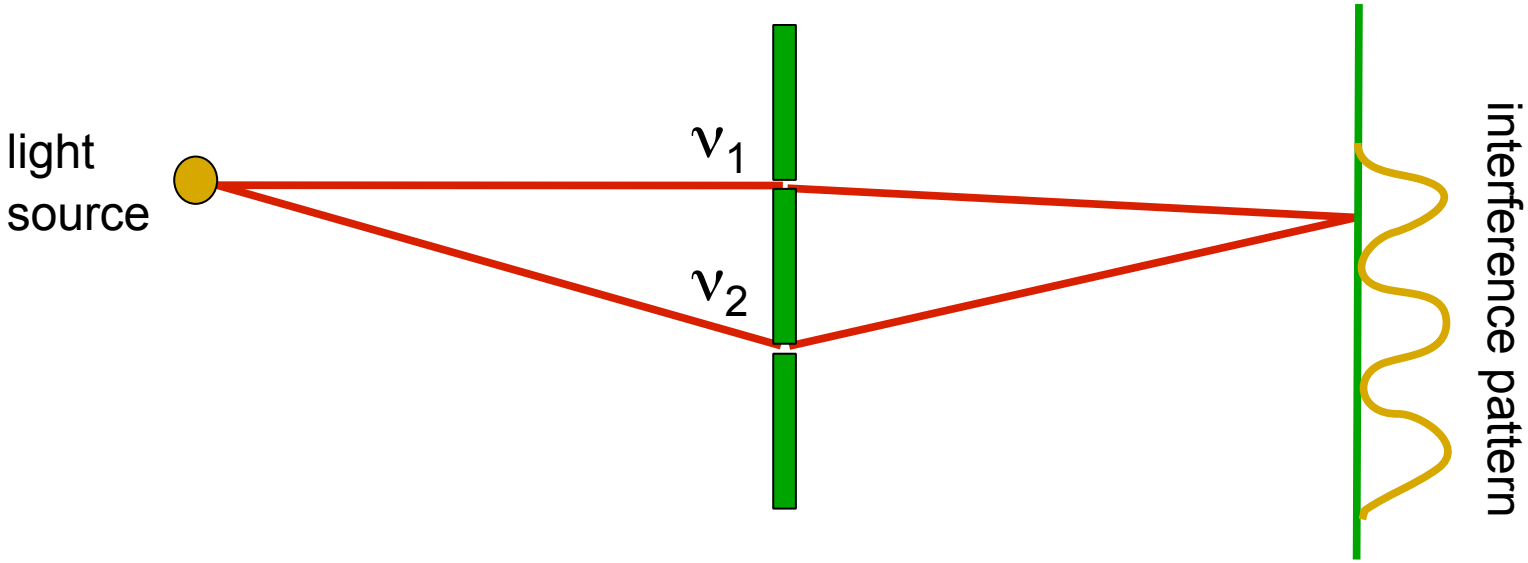
$$P_{\mu\rightarrow e}(t) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E} t\right)$$

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)



For double slit experiment, if path ν_1 and path ν_2 have different length, they have different phase rotations and it causes interference.

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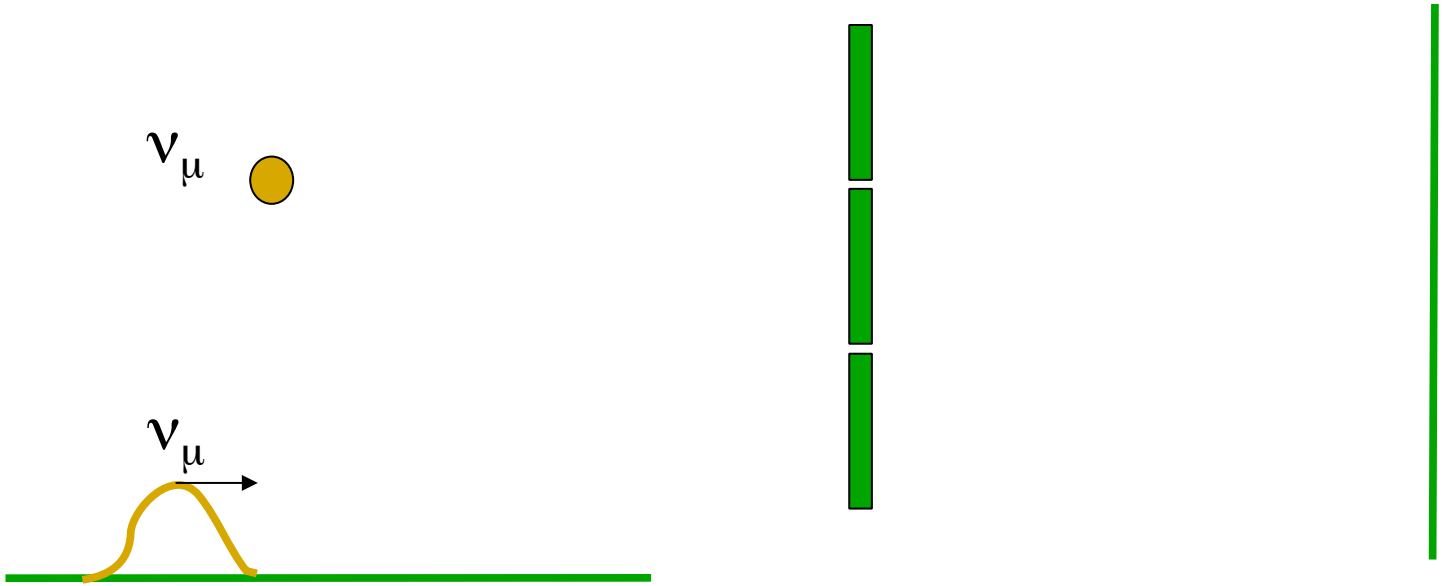

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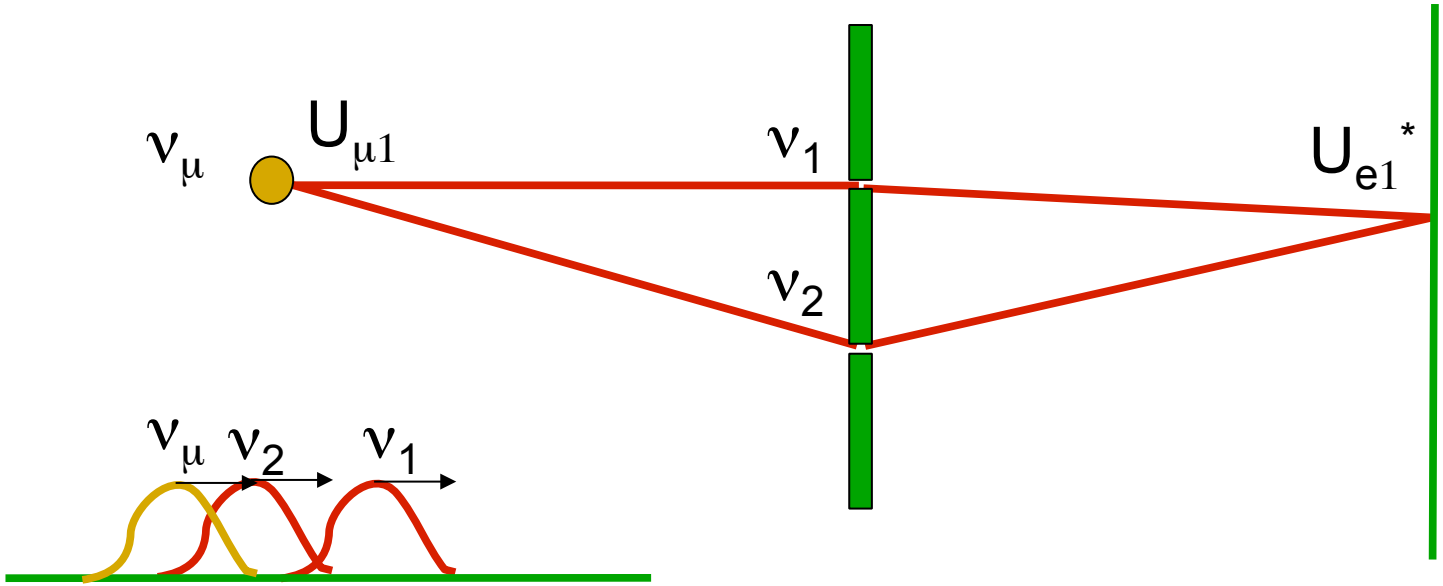

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For massive neutrinos, if ν_2 is heavier than ν_1, they have different group velocities hence different phase rotation, thus the superposition of those 2 wave packet no longer makes same state as before

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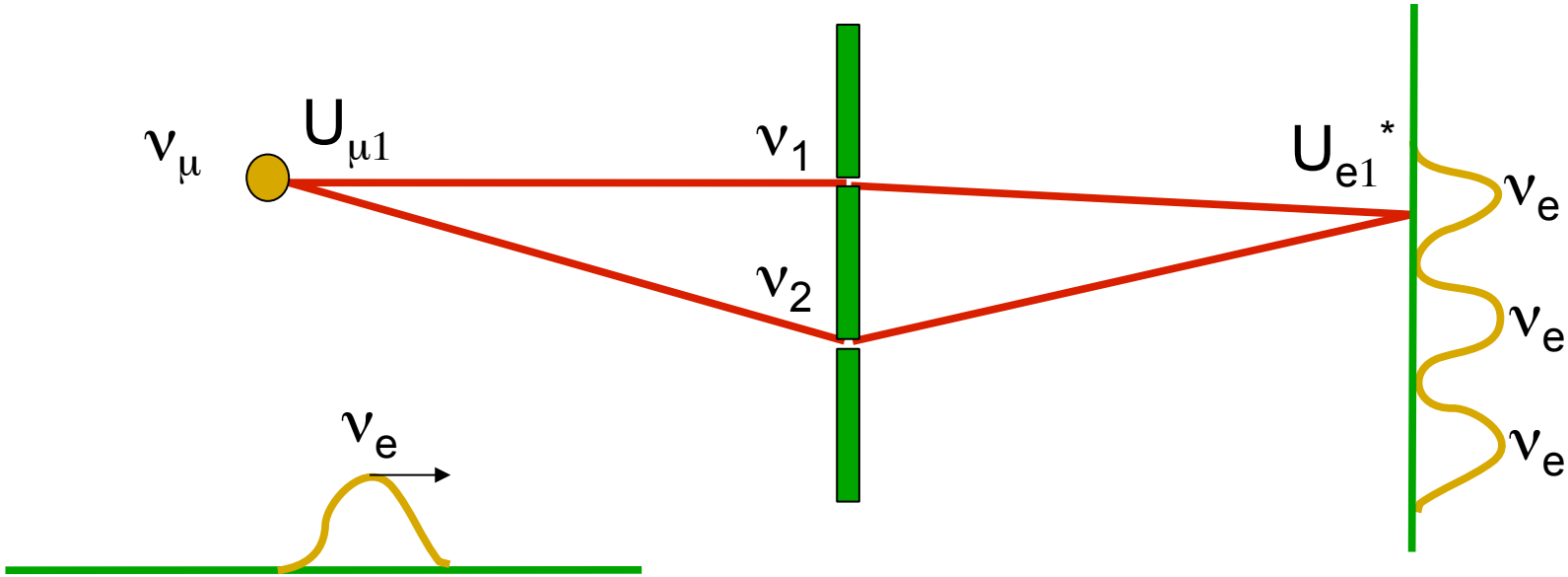

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LSND Collaboration,
PRD 64, 112007

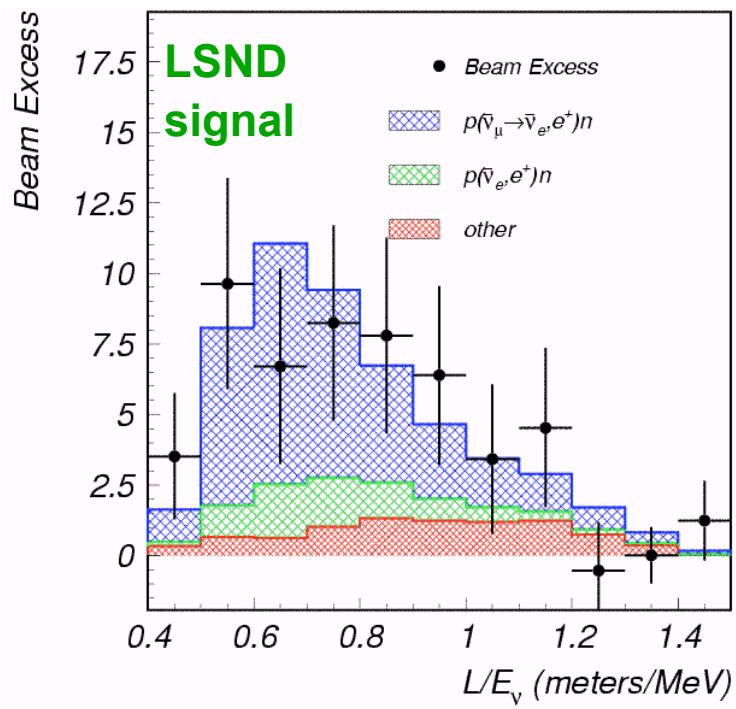
1. LSND experiment

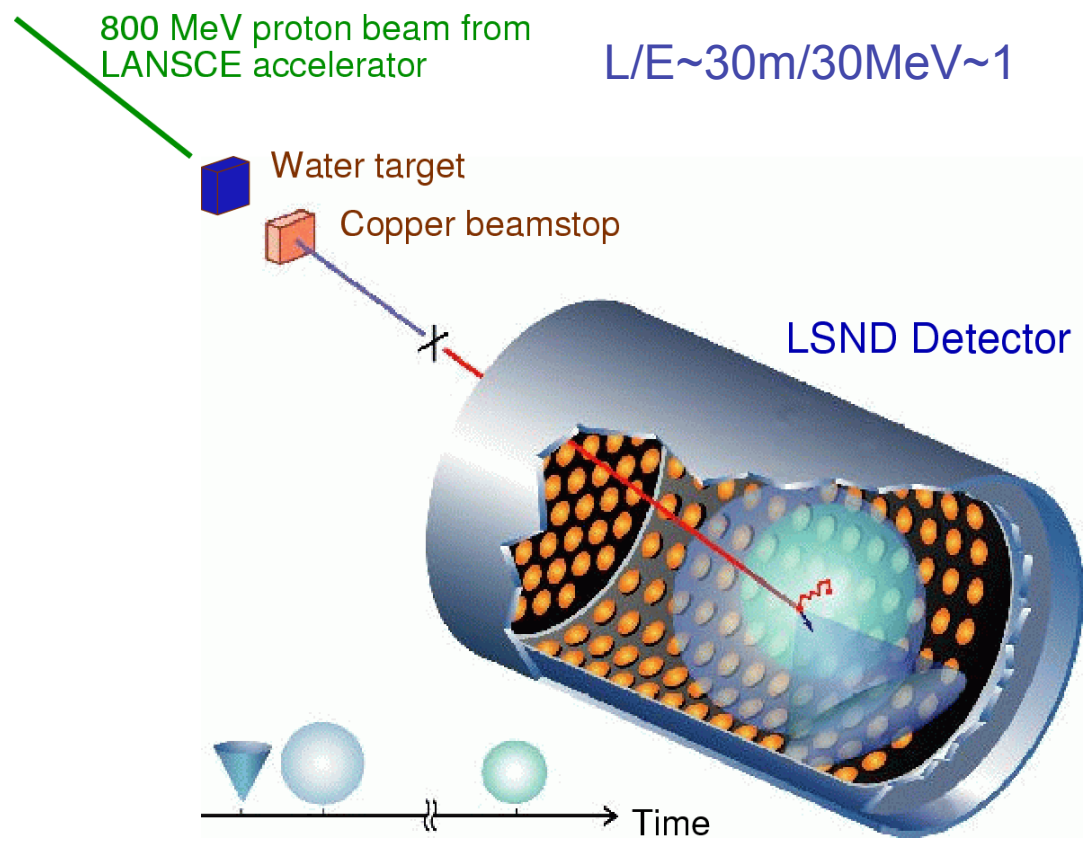
LSND experiment at Los Alamos observed excess of anti-electron neutrino events in the anti-muon neutrino beam.

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

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

87.9 ± 22.4 ± 6.0 (3.8.σ)





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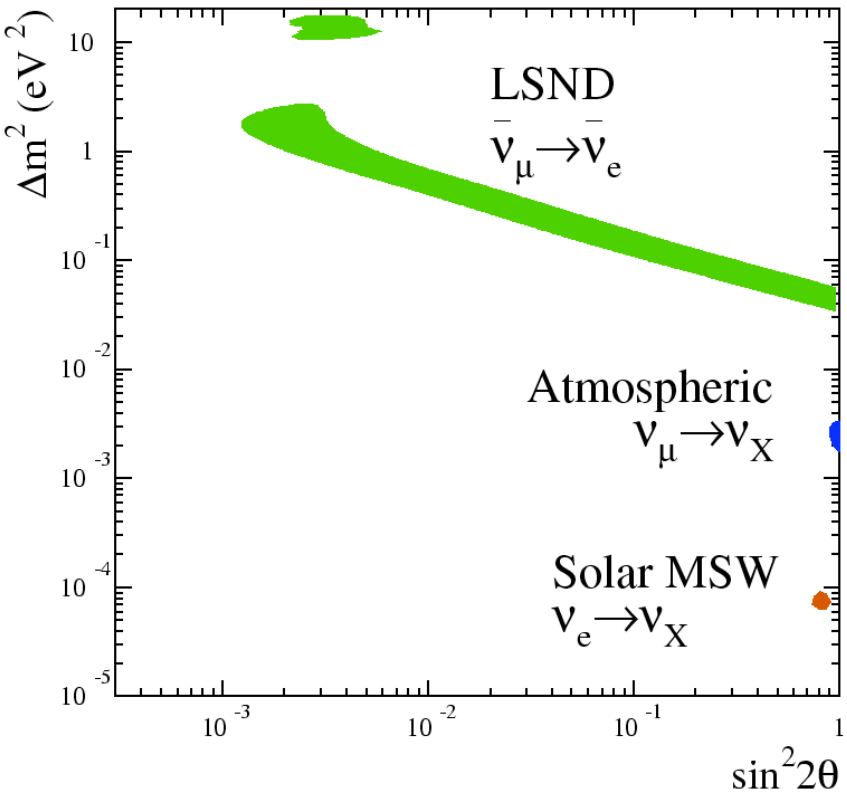
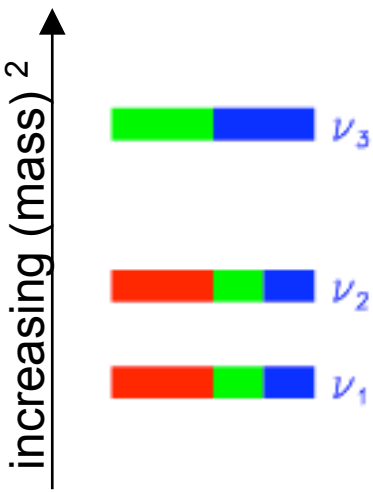


3 types of neutrino oscillations are found:

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

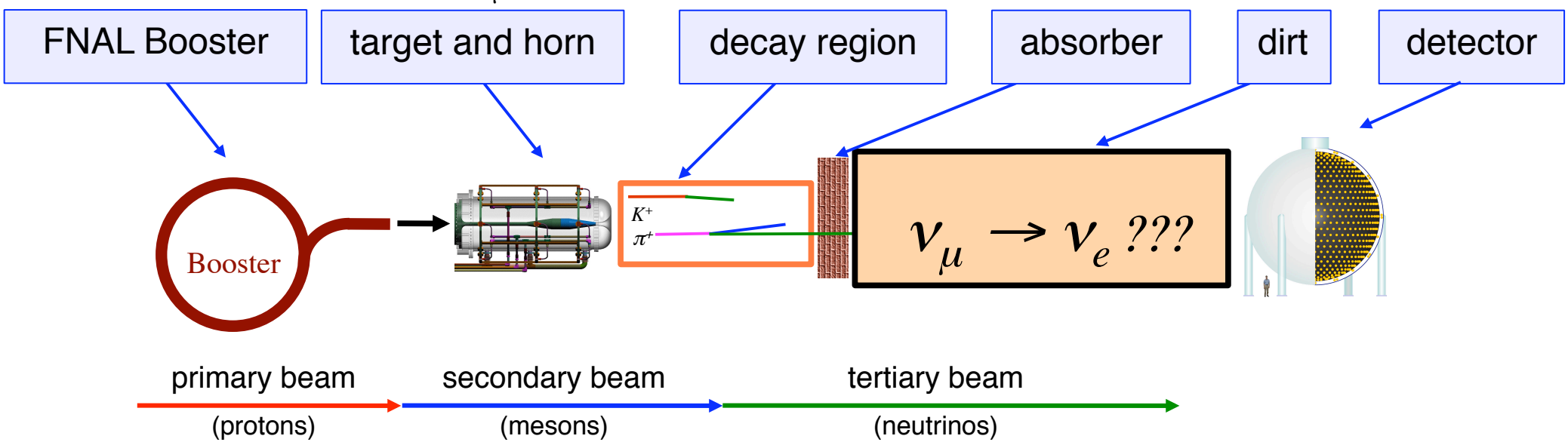
Keep L/E same with LSND, while changing systematics, energy & event signature;

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

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

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

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



MiniBooNE has;

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

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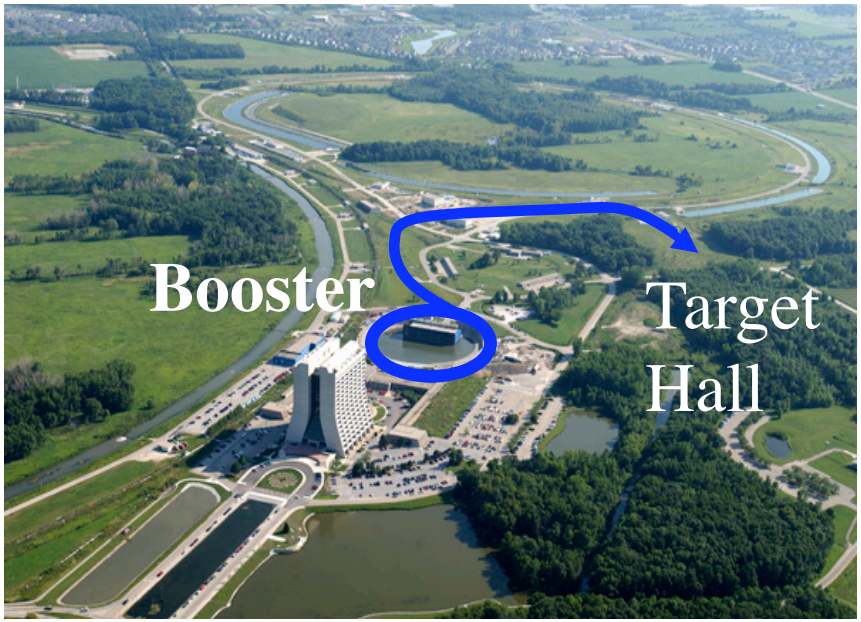
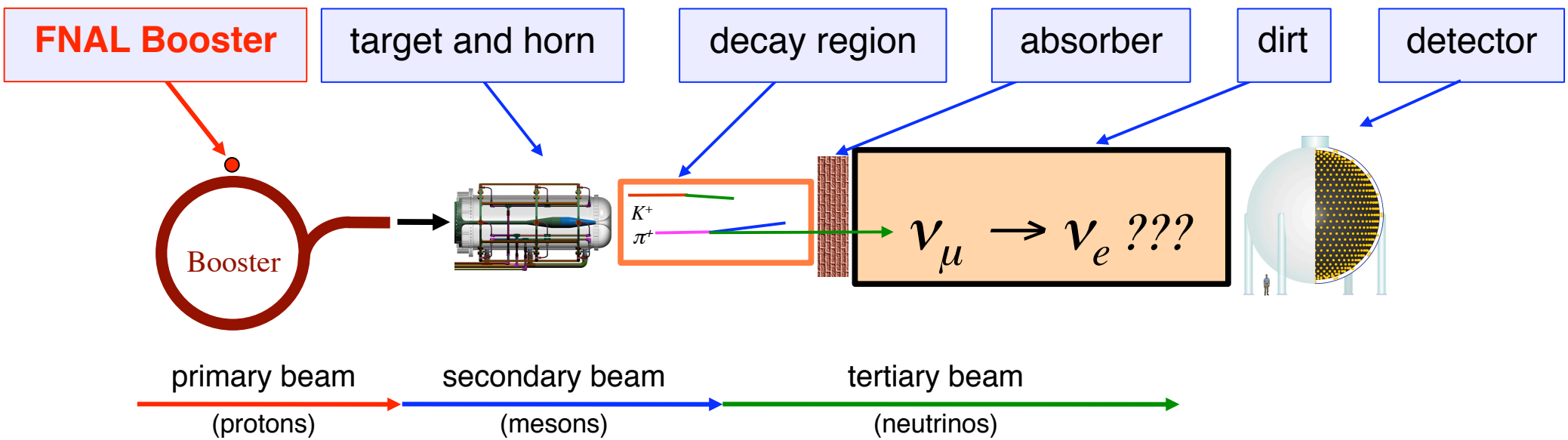
MiniBooNE collaboration, PRD79(2009)072002

2. Neutrino beam



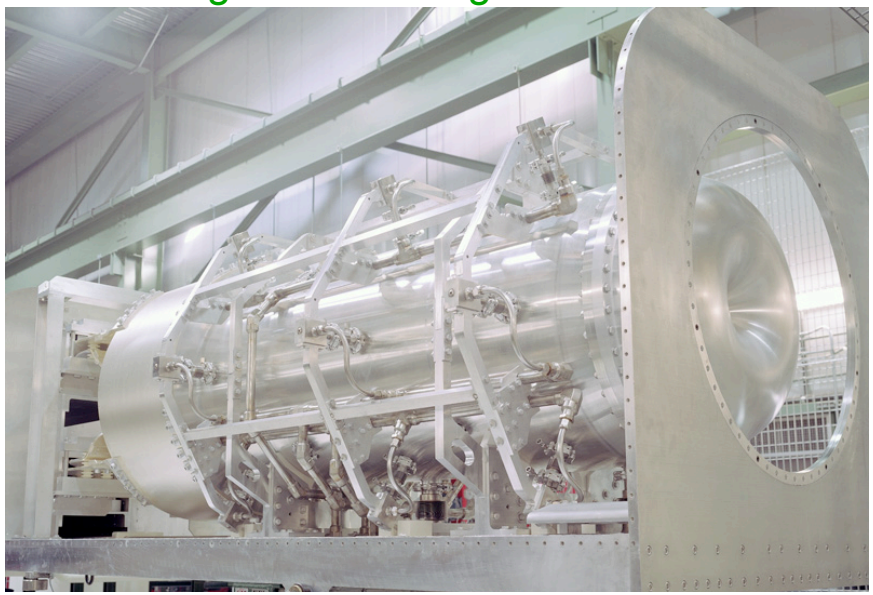
MiniBooNE extracts beam from the 8 GeV Booster



MiniBooNE collaboration, PRD79(2009)072002

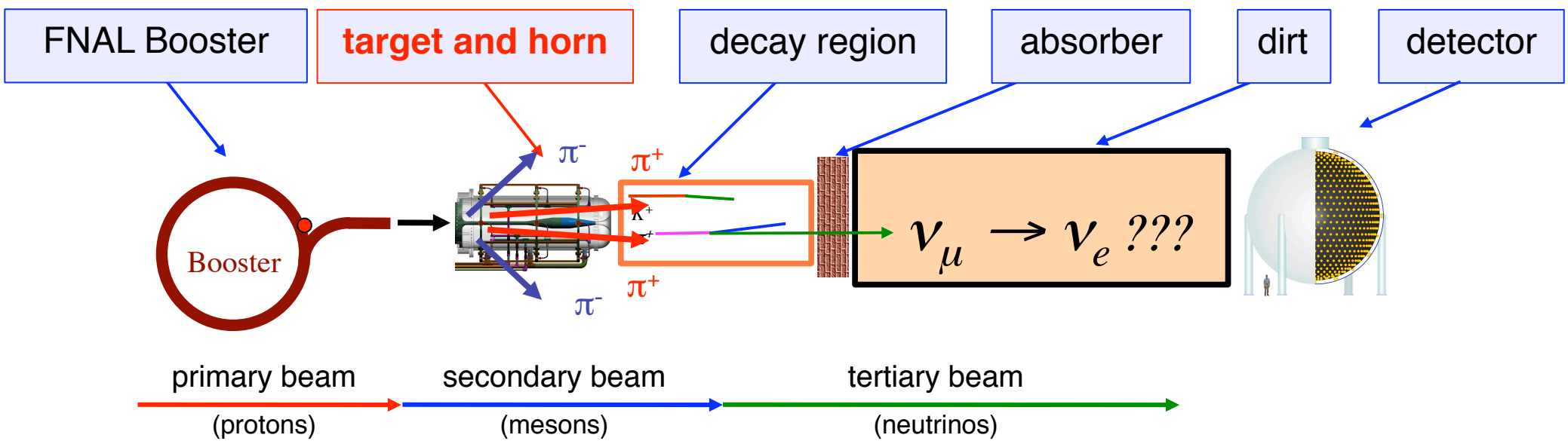
2. Neutrino beam

Magnetic focusing horn



8GeV protons are delivered to a 1.7 λ Be target

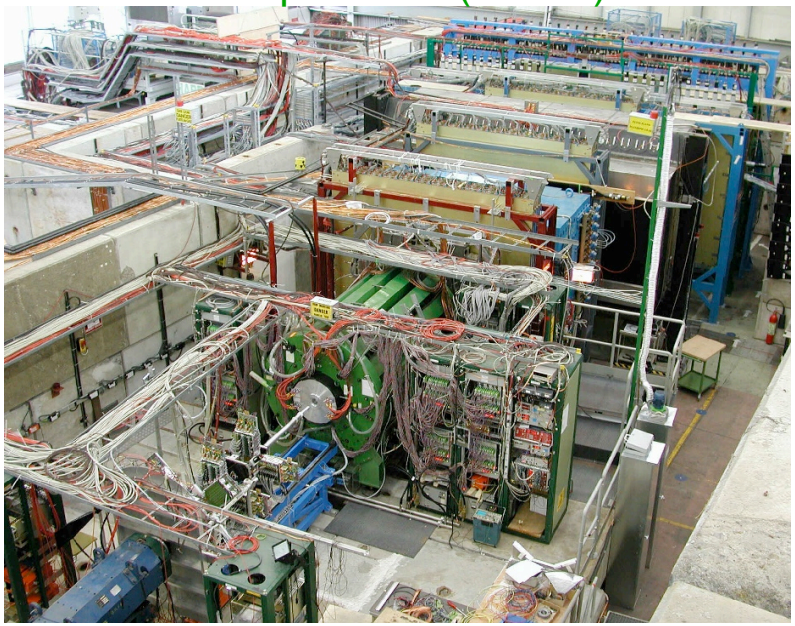
within a magnetic horn (2.5 kV, 174 kA) that increases the flux by × 6



MiniBooNE collaboration,
PRD79(2009)072002

2. Neutrino beam

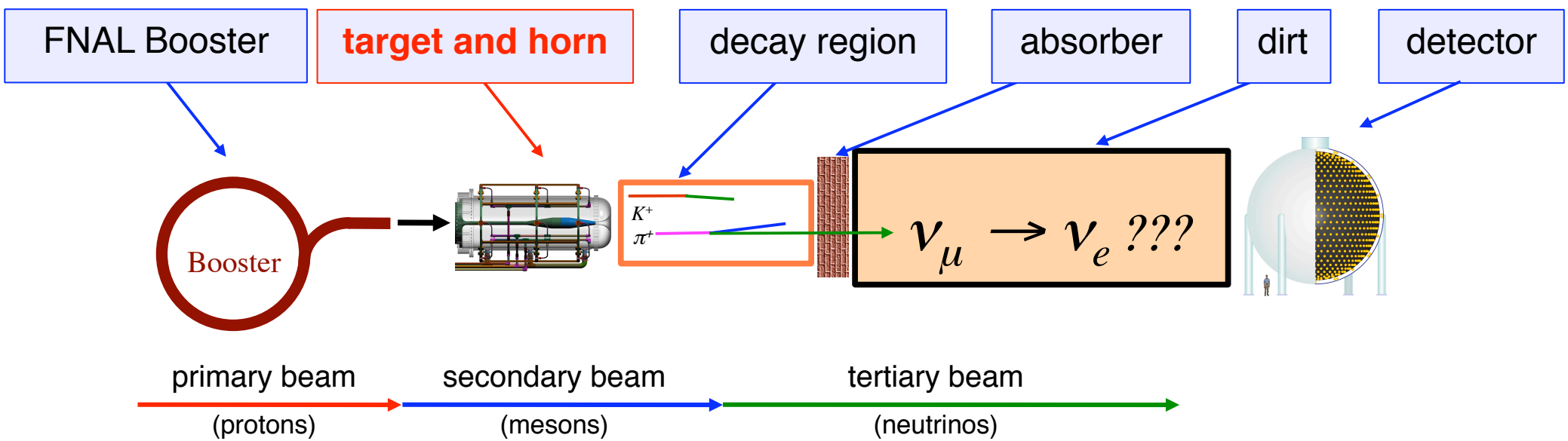
HARP experiment (CERN)



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, PRD79(2009)072002

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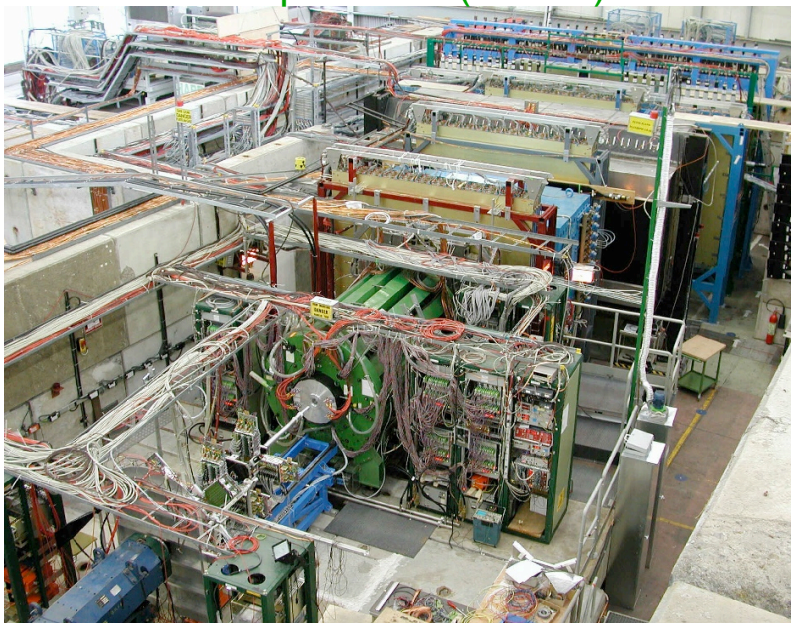

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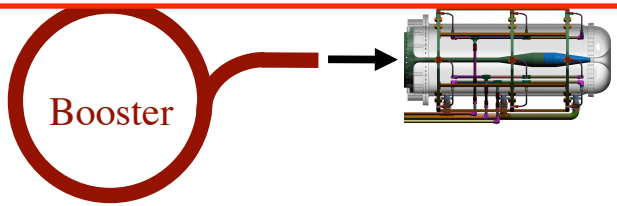
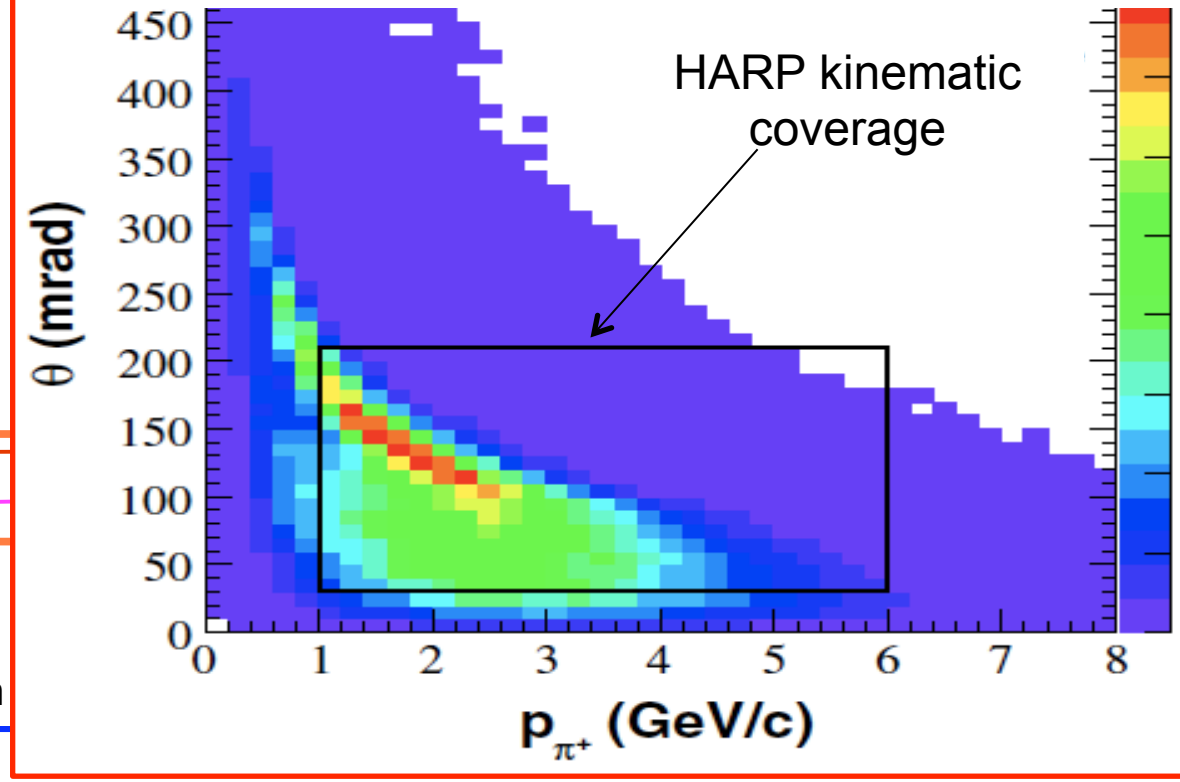
Majority of pions create neutrinos in MiniBooNE are directly measured by HARP (>80%)



primary beam (protons) → secondary beam (mesons)

Booster neutrino beamline pion kinematic space



MiniBooNE collaboration, PRD79(2009)072002

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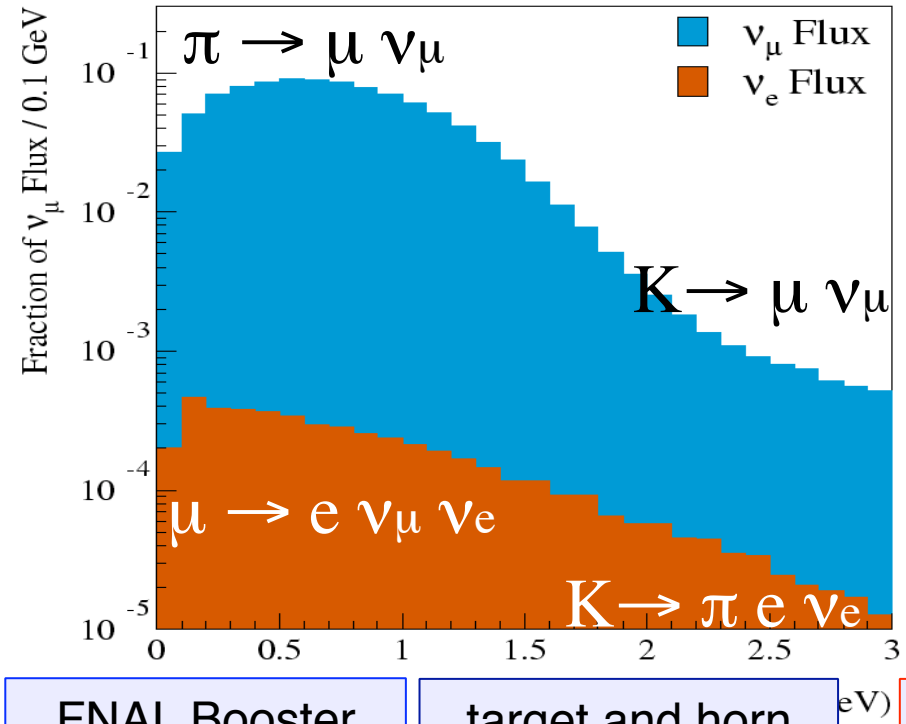
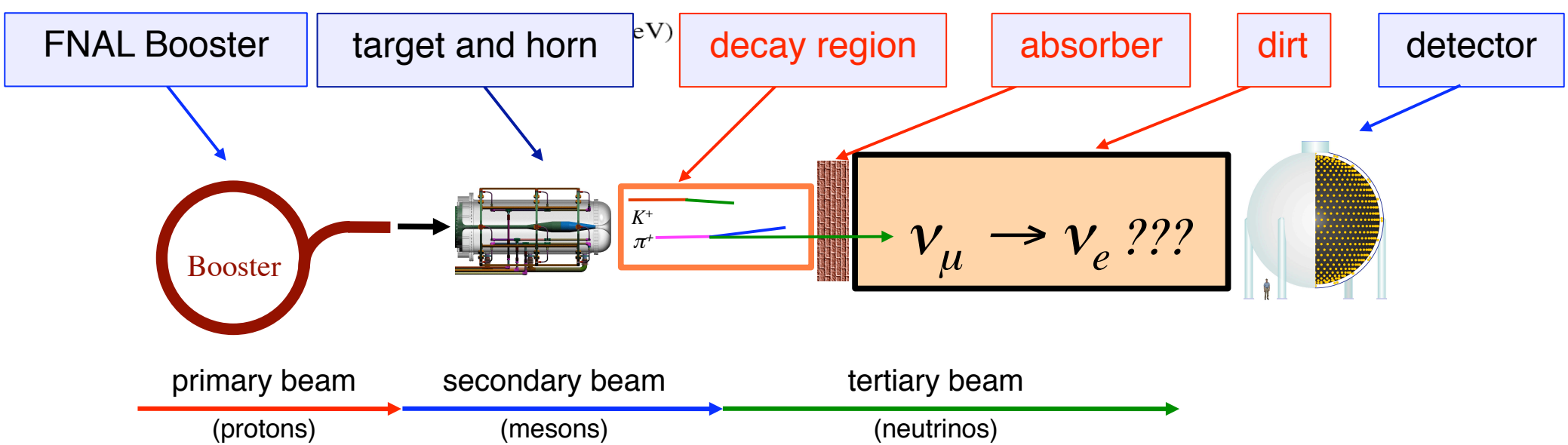


Neutrino flux from simulation by GEANT4

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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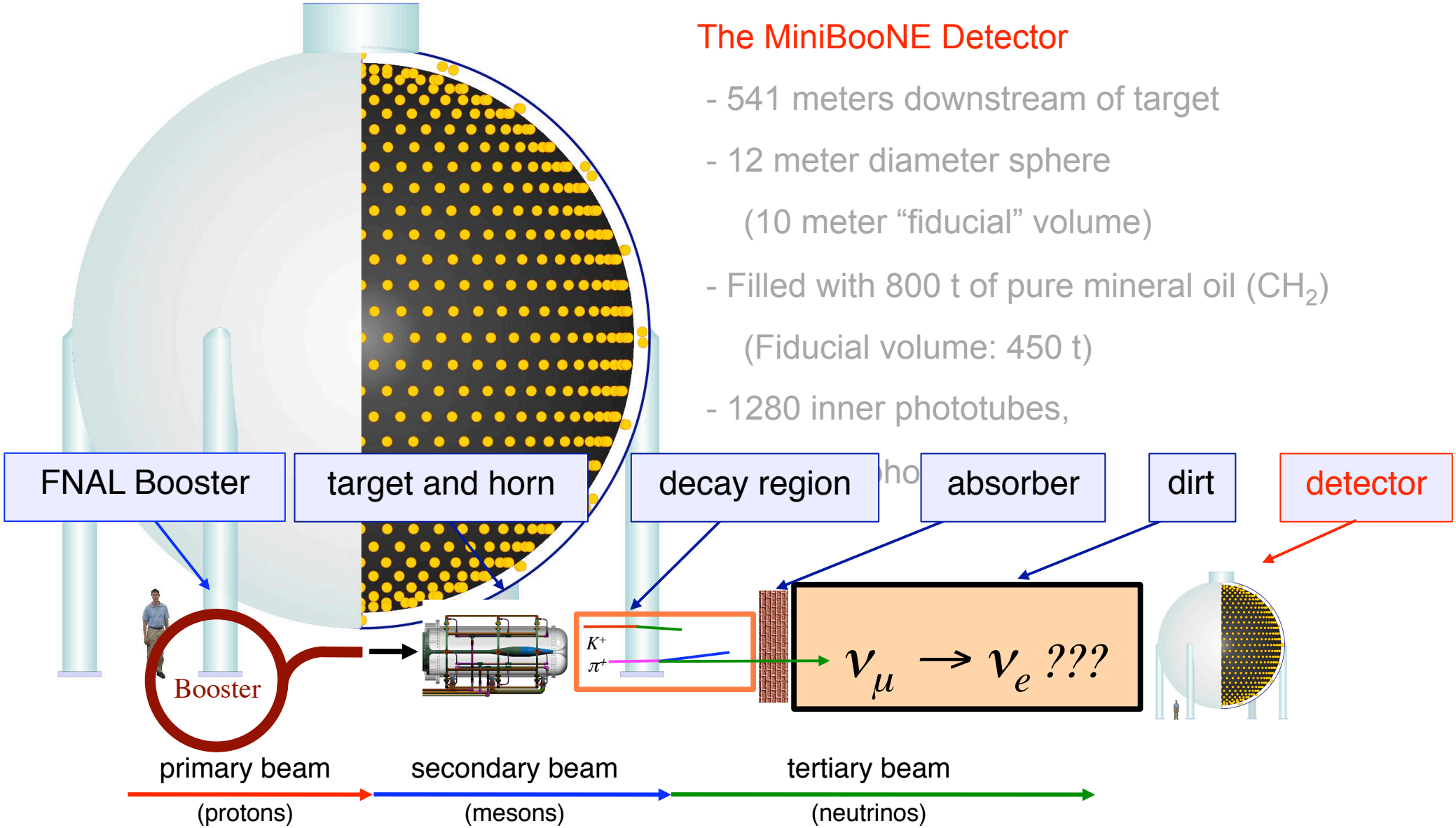
MiniBooNE collaboration,
NIM.A599(2009)28

3. Events in the Detector



The MiniBooNE Detector

- 541 meters downstream of target
- 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,

MiniBooNE collaboration,
NIM.A599(2009)28

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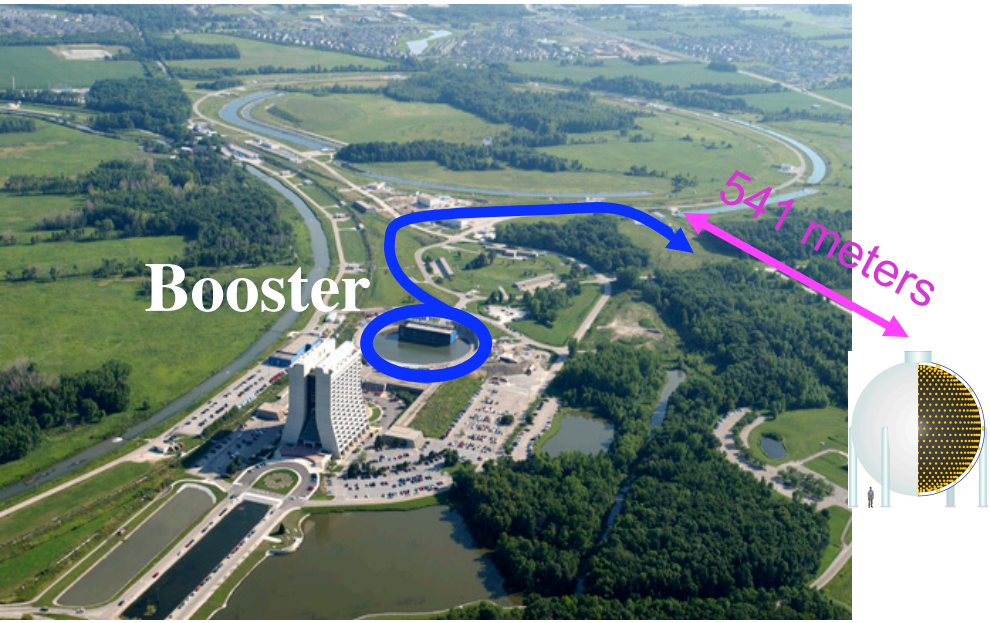

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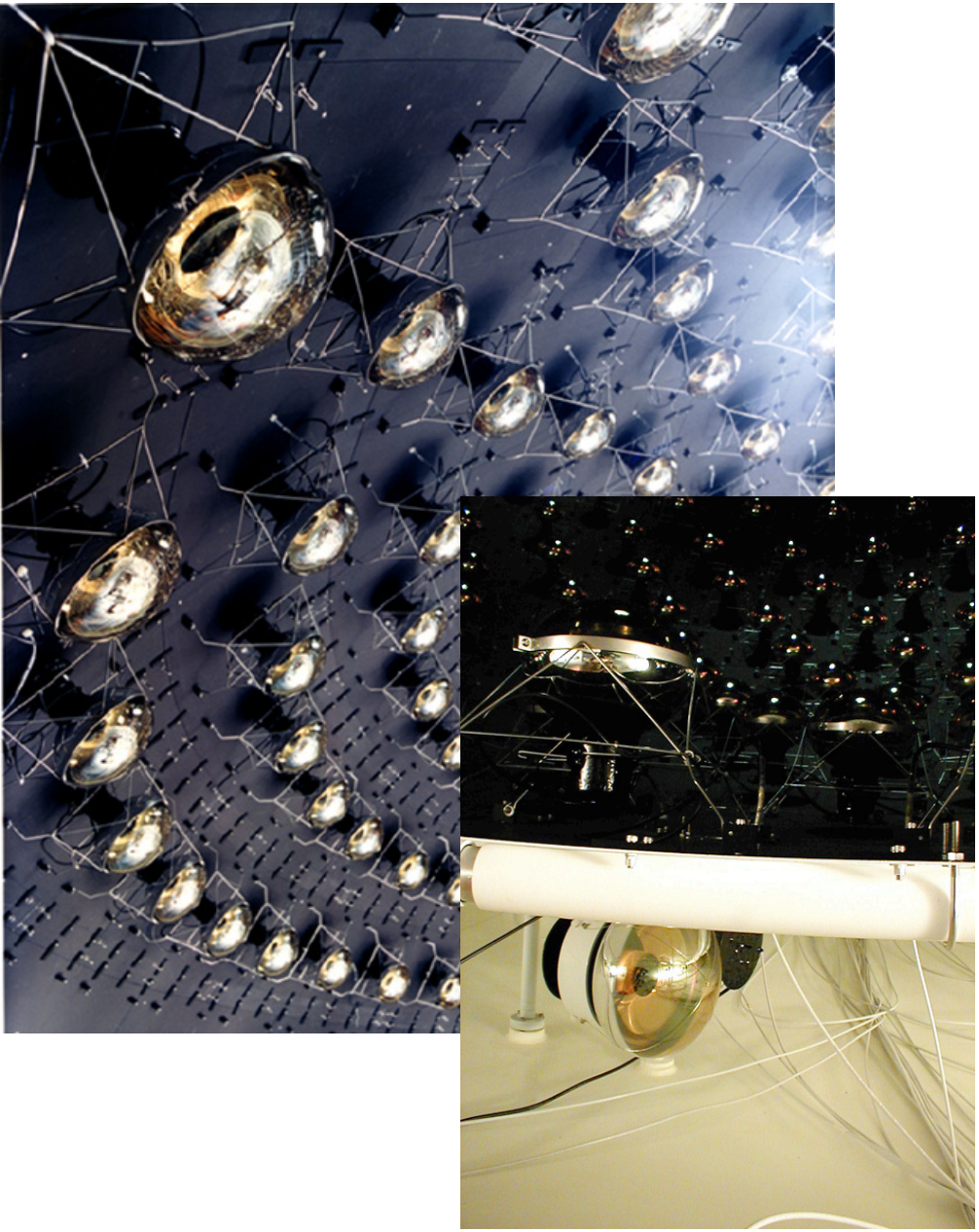

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3. Events in the Detector

Times of hit-clusters (subevents)

Beam spill (1.6μs) is clearly evident

simple cuts eliminate cosmic backgrounds

Neutrino Candidate Cuts

<6 veto PMT hits

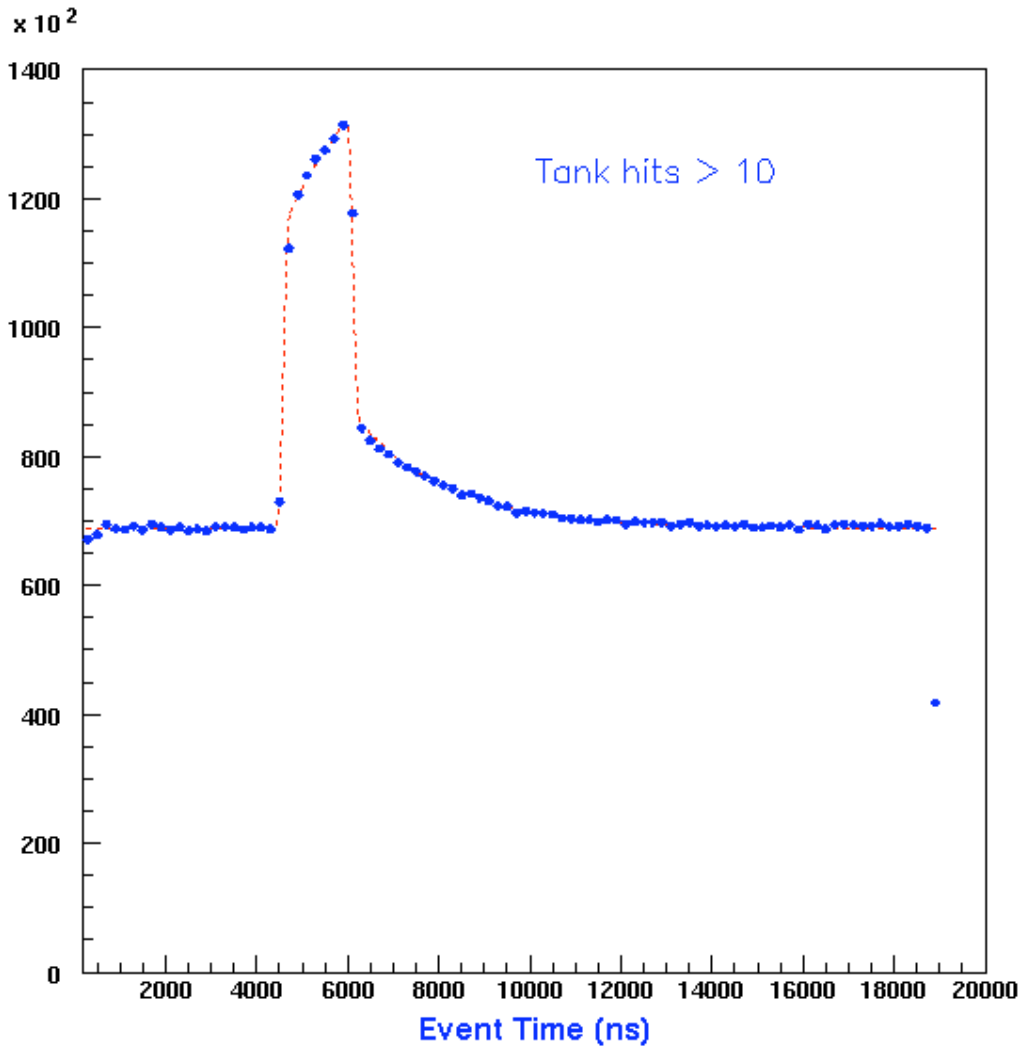
Gets rid of muons

>200 tank PMT hits

Gets rid of Michels

Only neutrinos are left!

Beam and Cosmic BG



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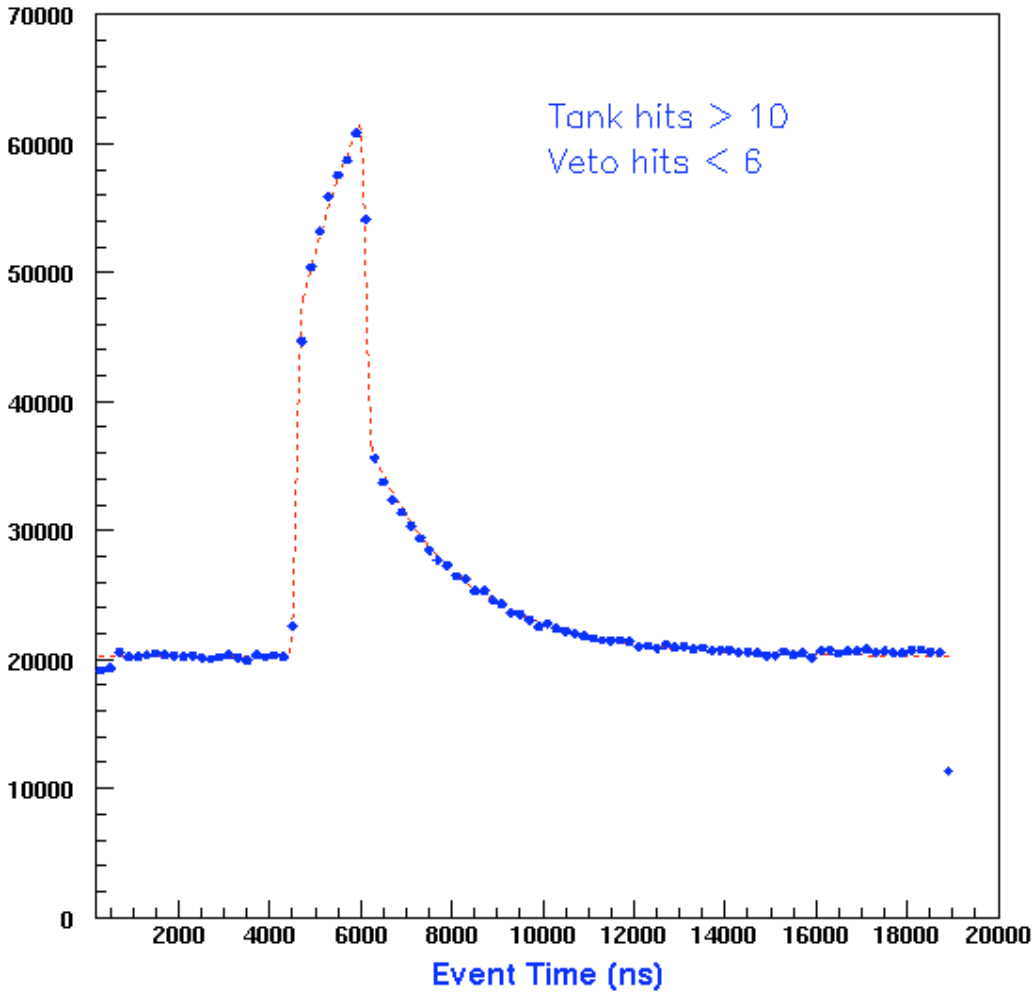

MiniBooNE collaboration, NIM.A599(2009)28

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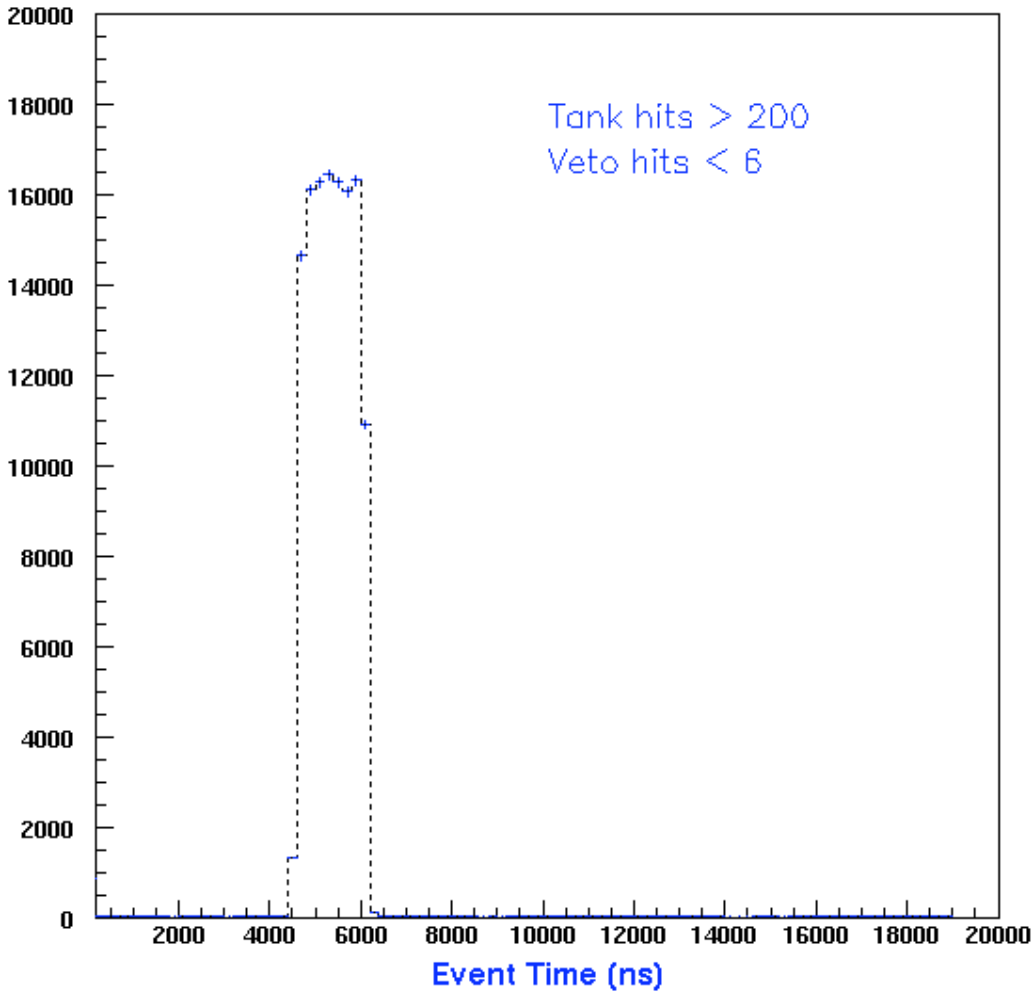
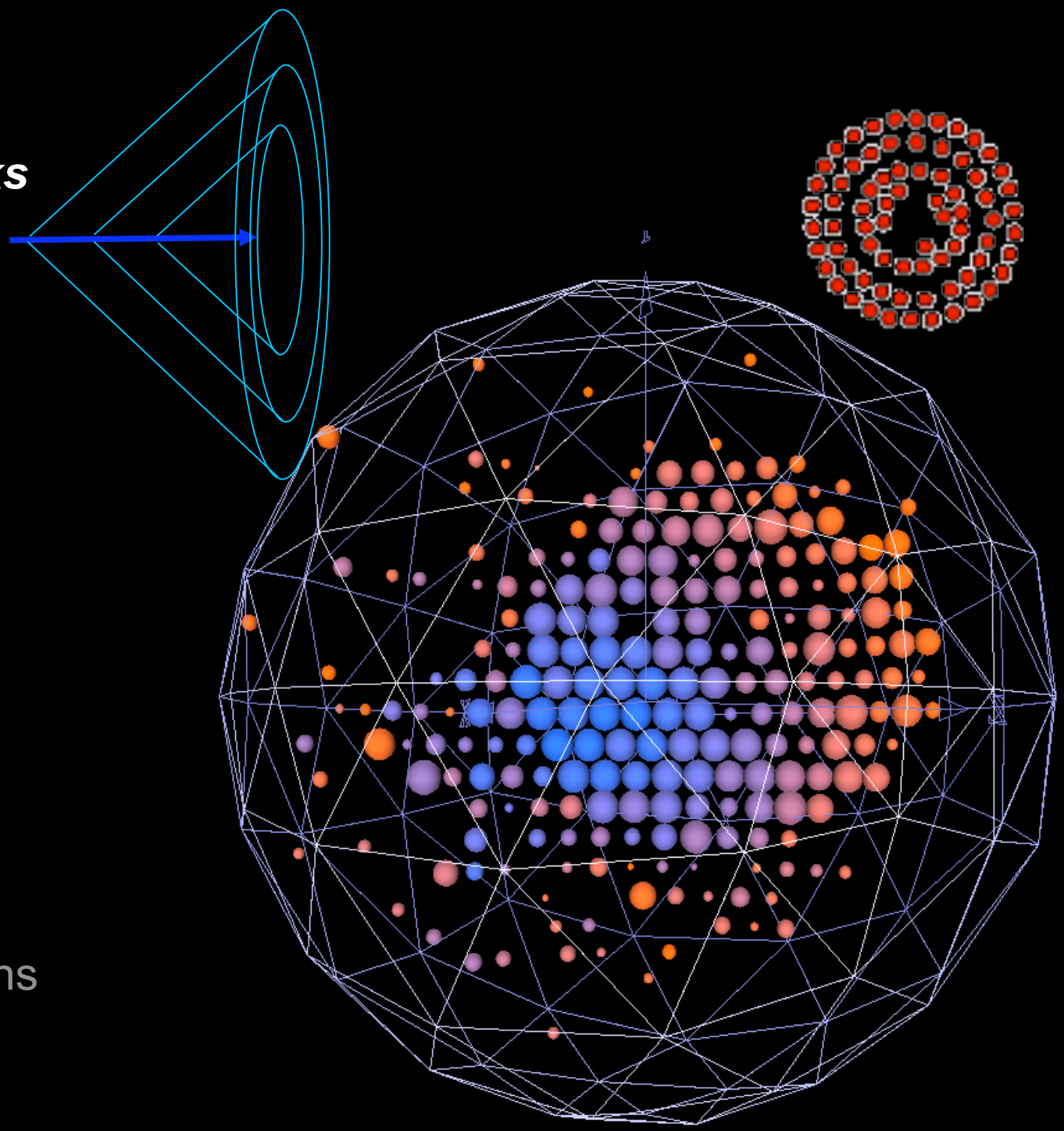
Beam Only



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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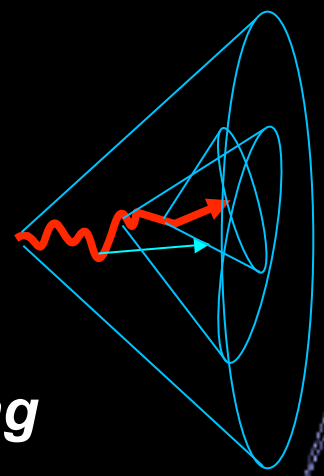

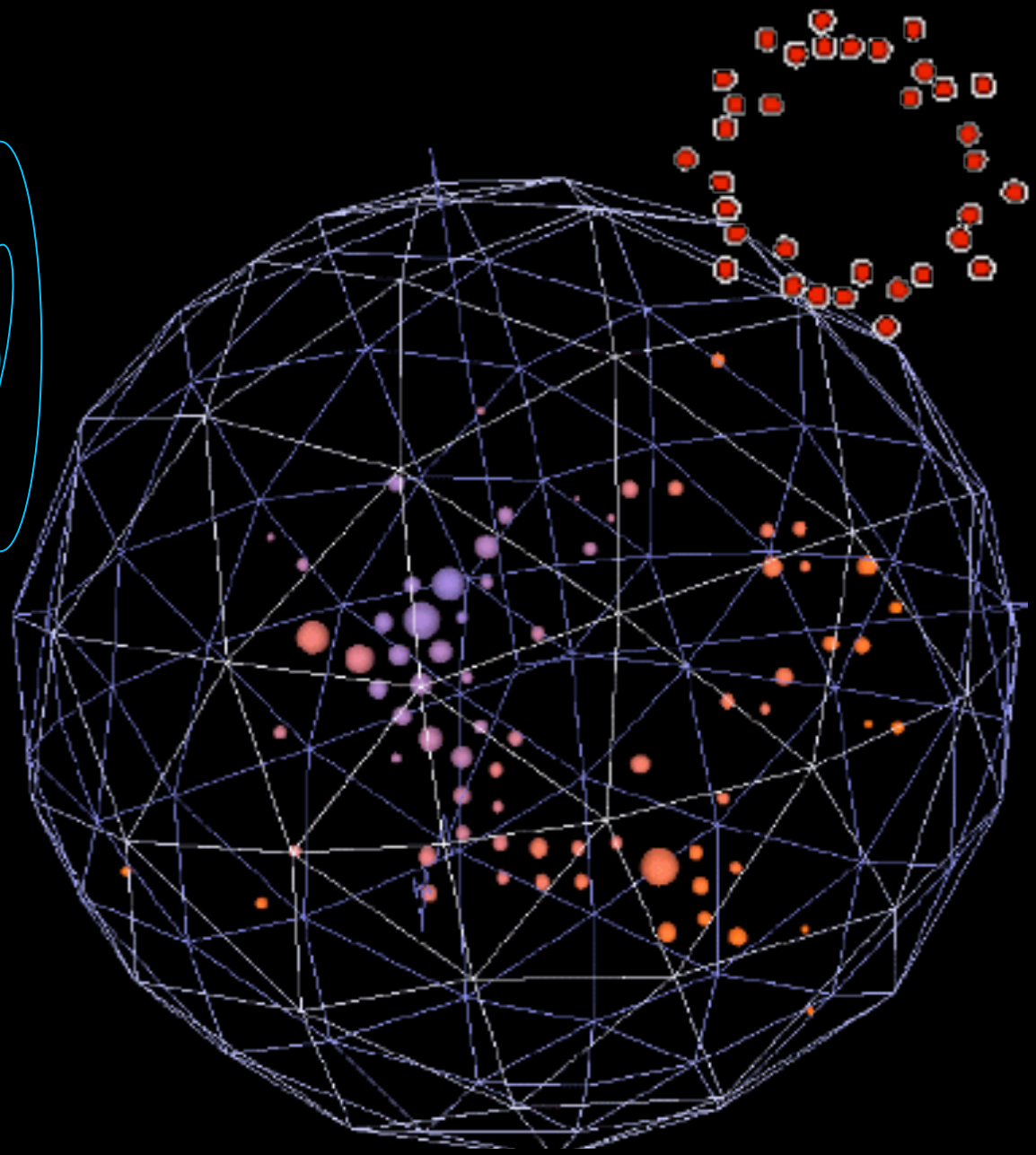

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MiniBooNE collaboration, NIM.A599(2009)28

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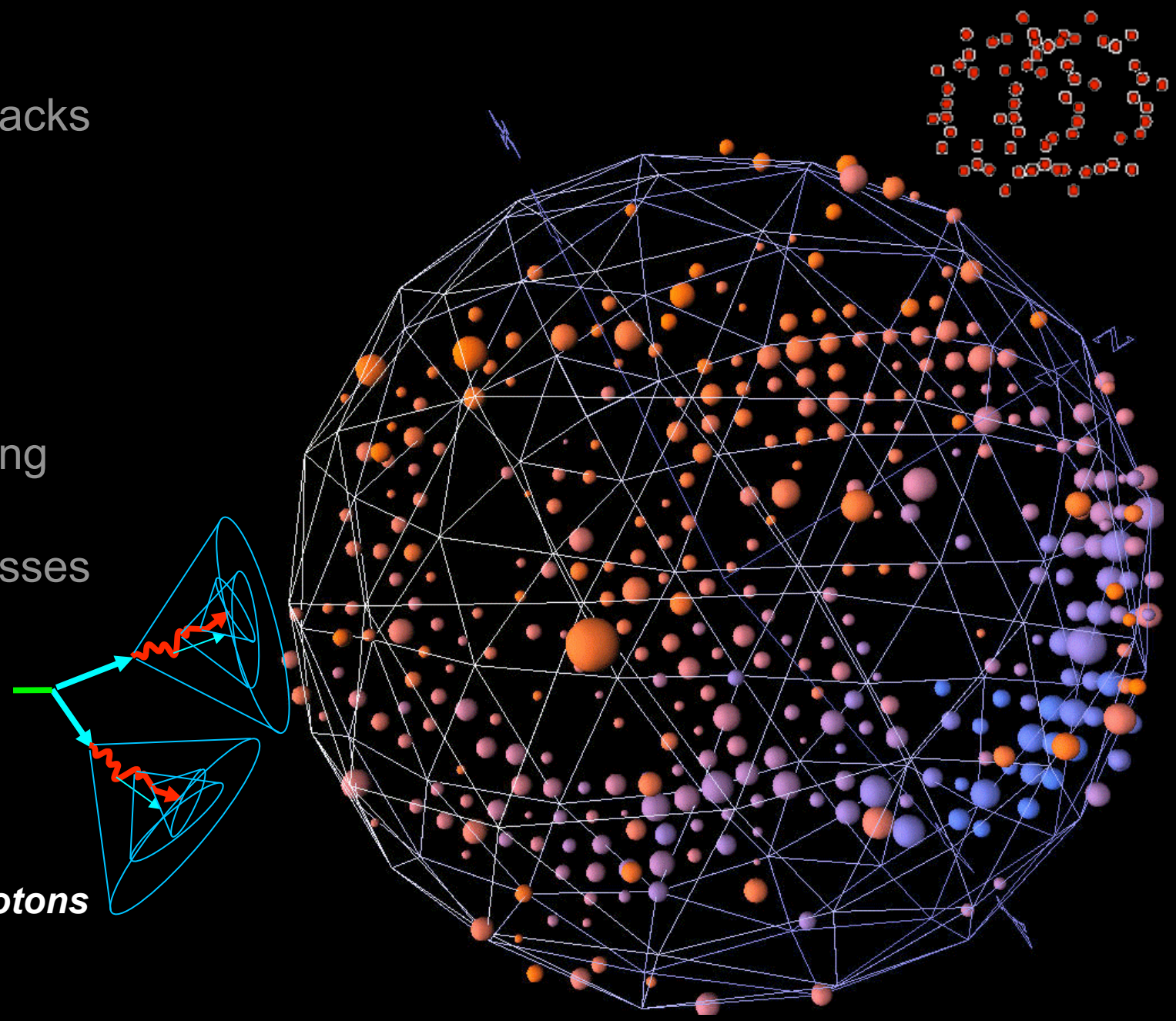

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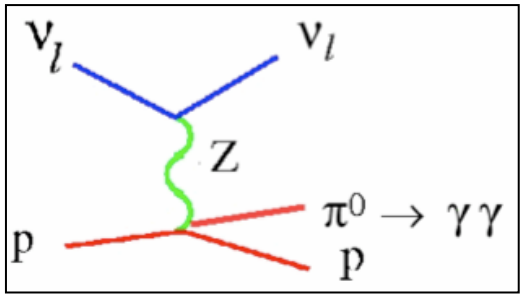
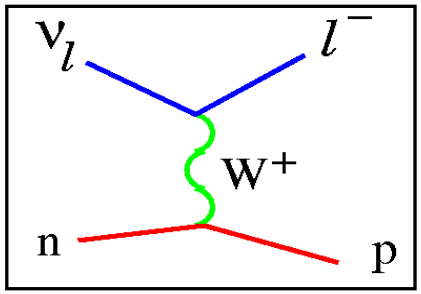
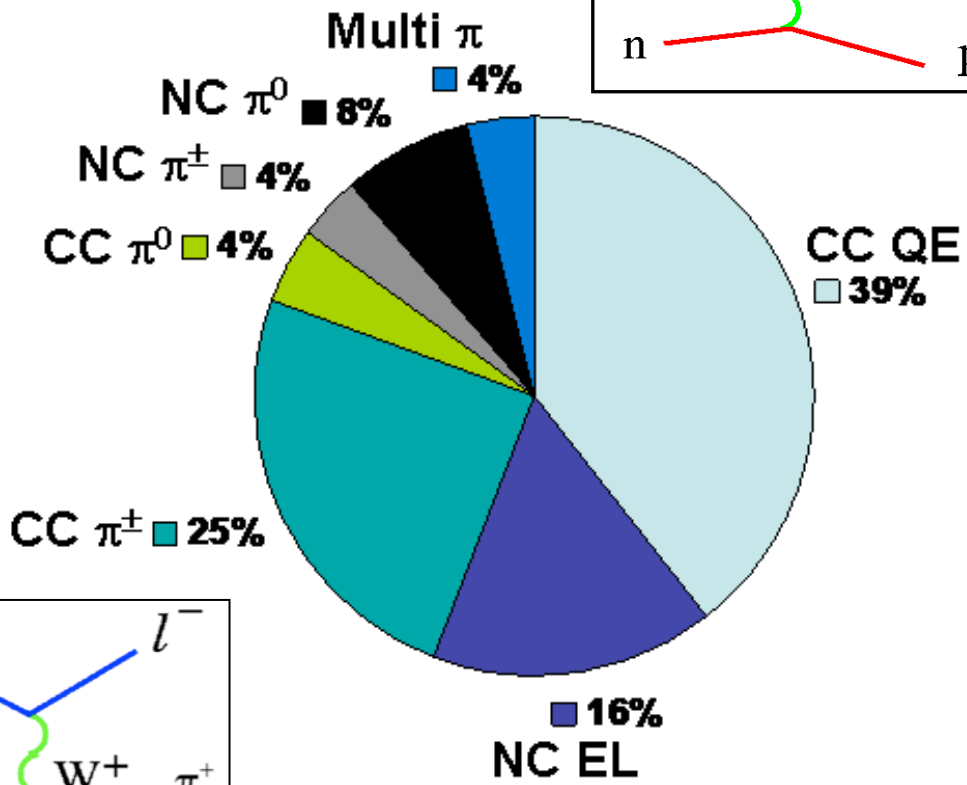
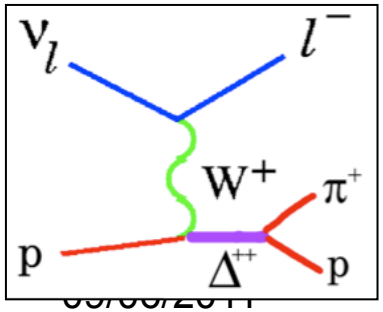


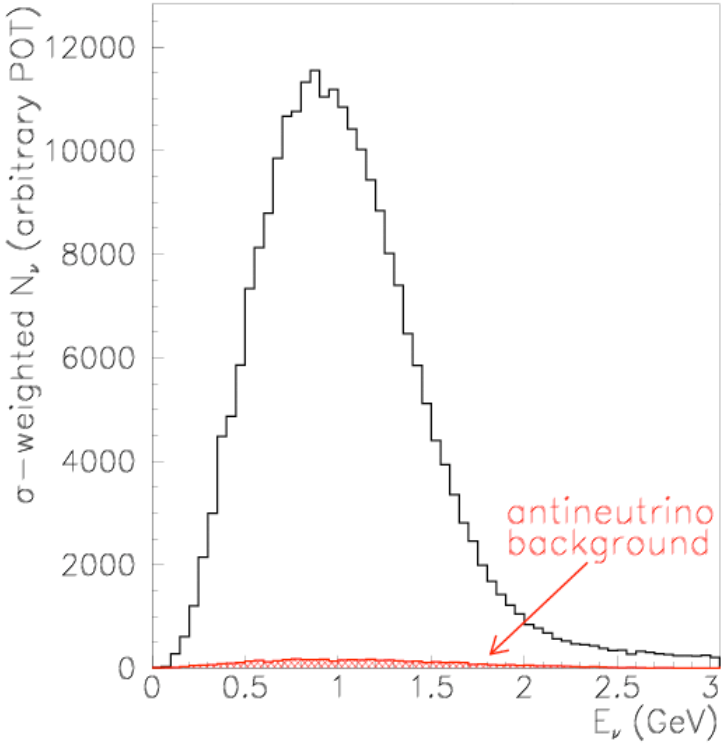






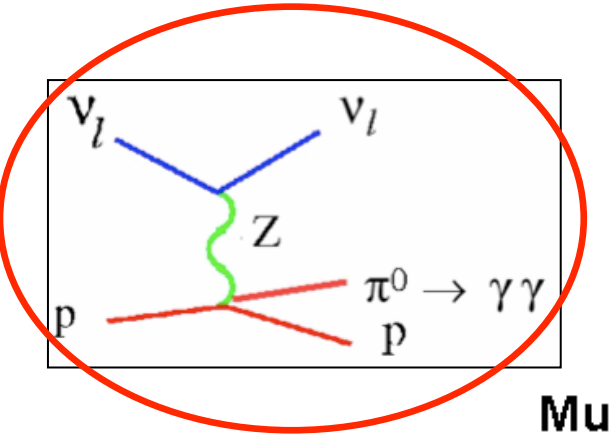
Predicted event rates before cuts (NUANCE Monte Carlo)

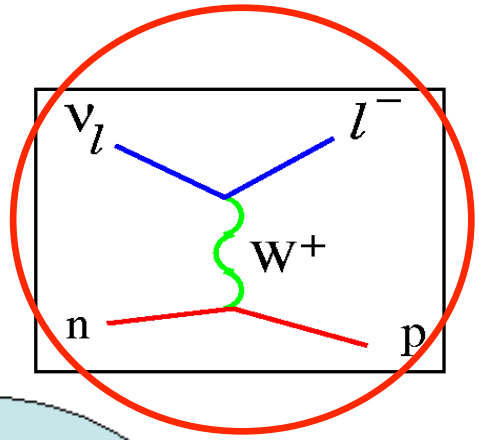
Casper, Nucl.Phys.Proc.Suppl.112(2002)161

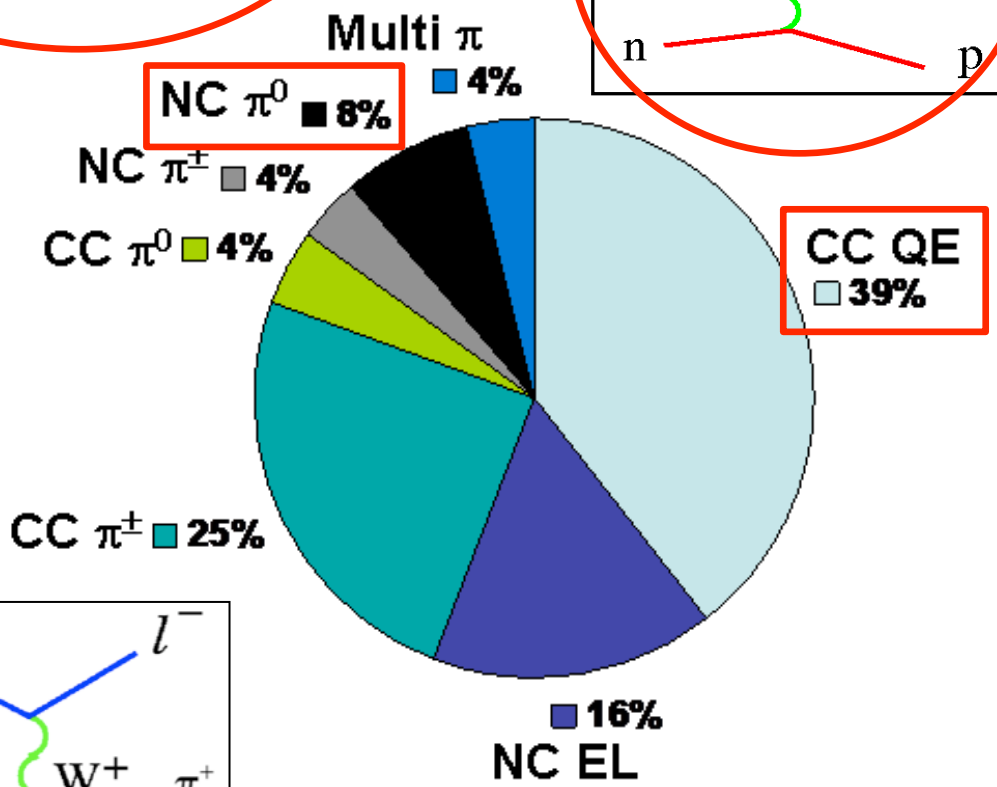


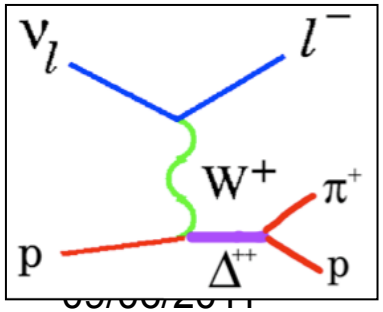
Event neutrino energy (GeV)

4. Cross section model



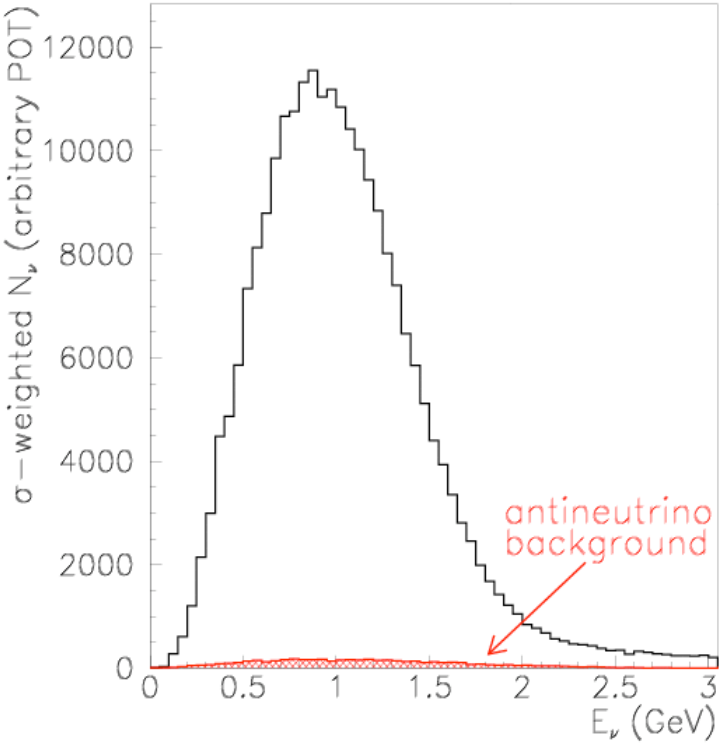






Predicted event rates before cuts (NUANCE Monte Carlo)

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



Event neutrino energy (GeV)

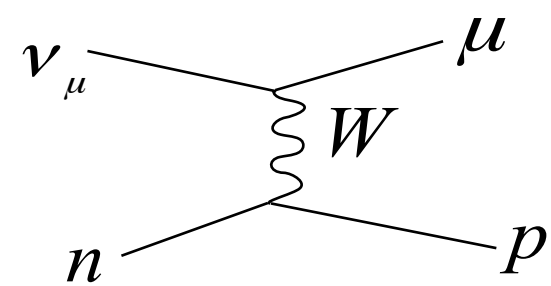
4. CCQE event measurement

CCQE (Charged Current Quasi-Elastic) event

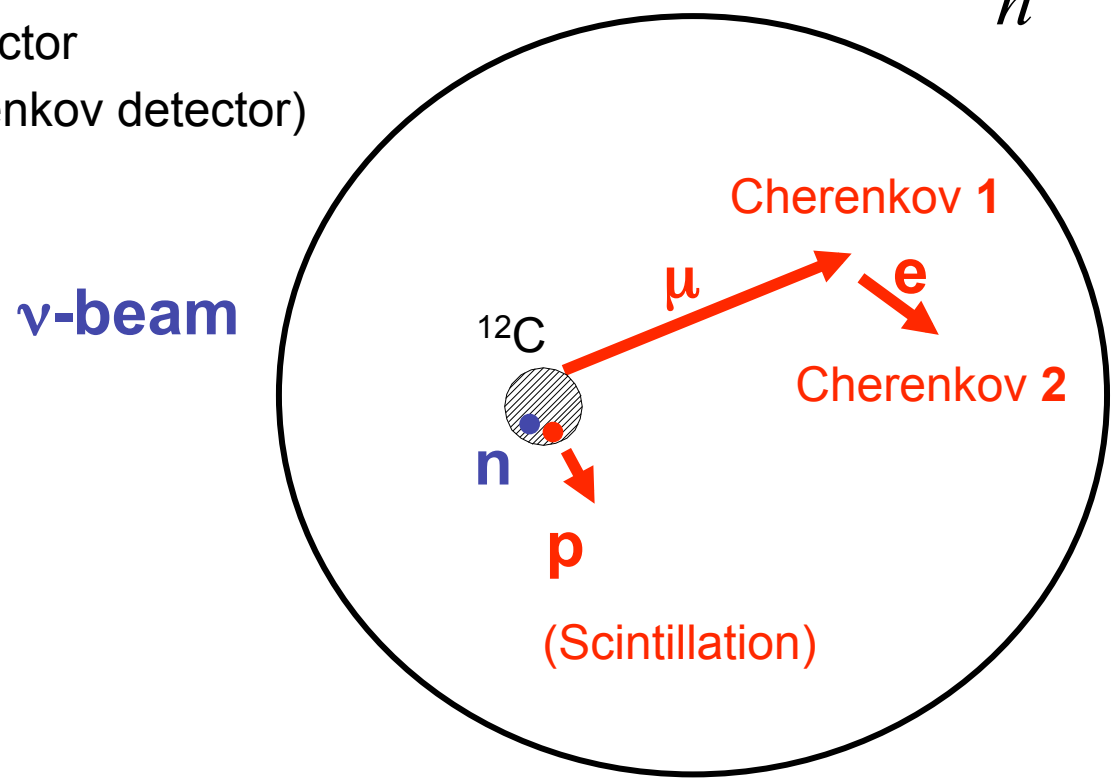
ν_μ charged current quasi-elastic (ν_μ CCQE) interaction is the most abundant (~40%) and the fundamental interaction in MiniBooNE detector

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

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



MiniBooNE detector
(spherical Cherenkov detector)



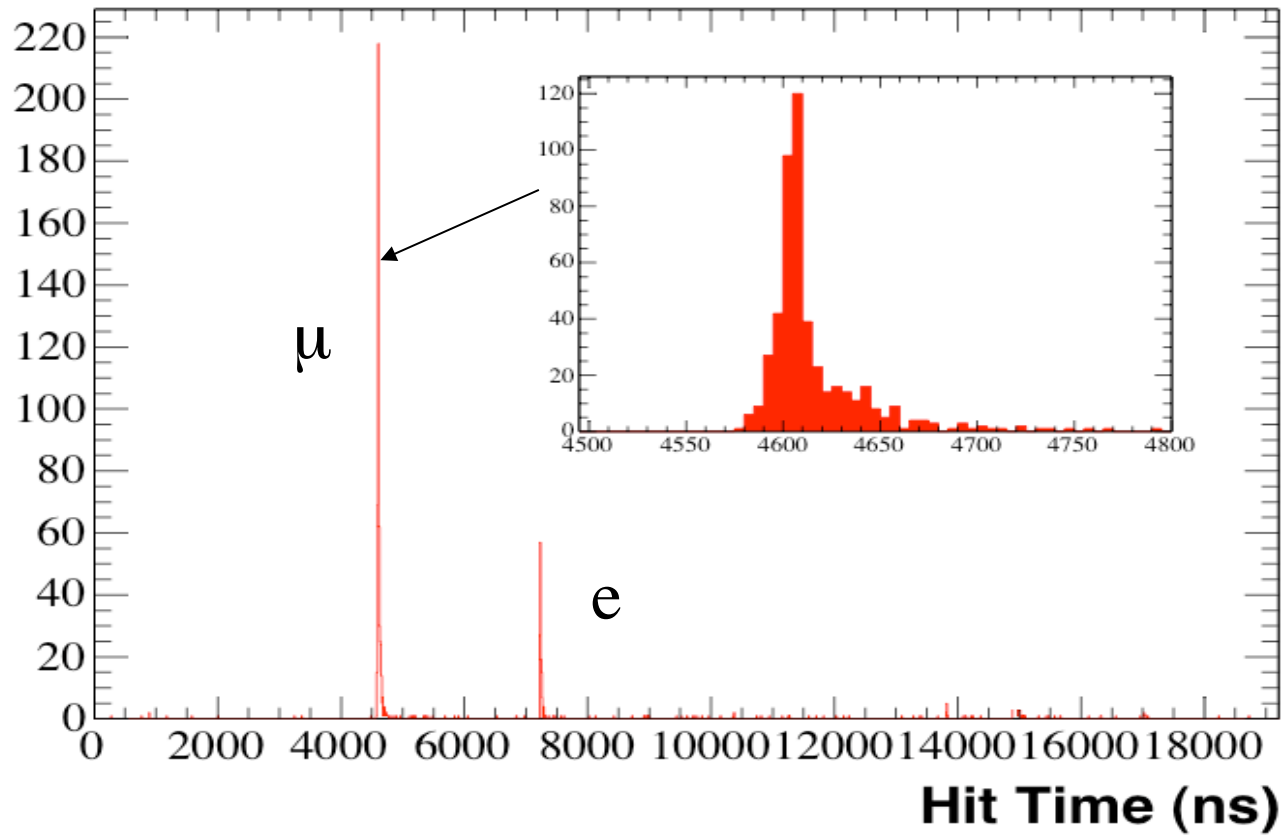
muon like Cherenkov light and subsequent decayed electron (Michel electron) like Cherenkov light are the signal of CCQE event

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 → 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.

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

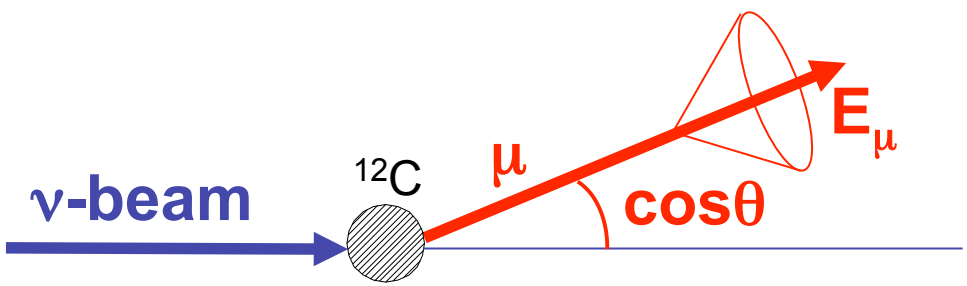
$$Q_{QE}^2 = -m_\mu^2 + 2E_\nu^{QE}(E_\mu - p_\mu \cos\theta_\mu)$$

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

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

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

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



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

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

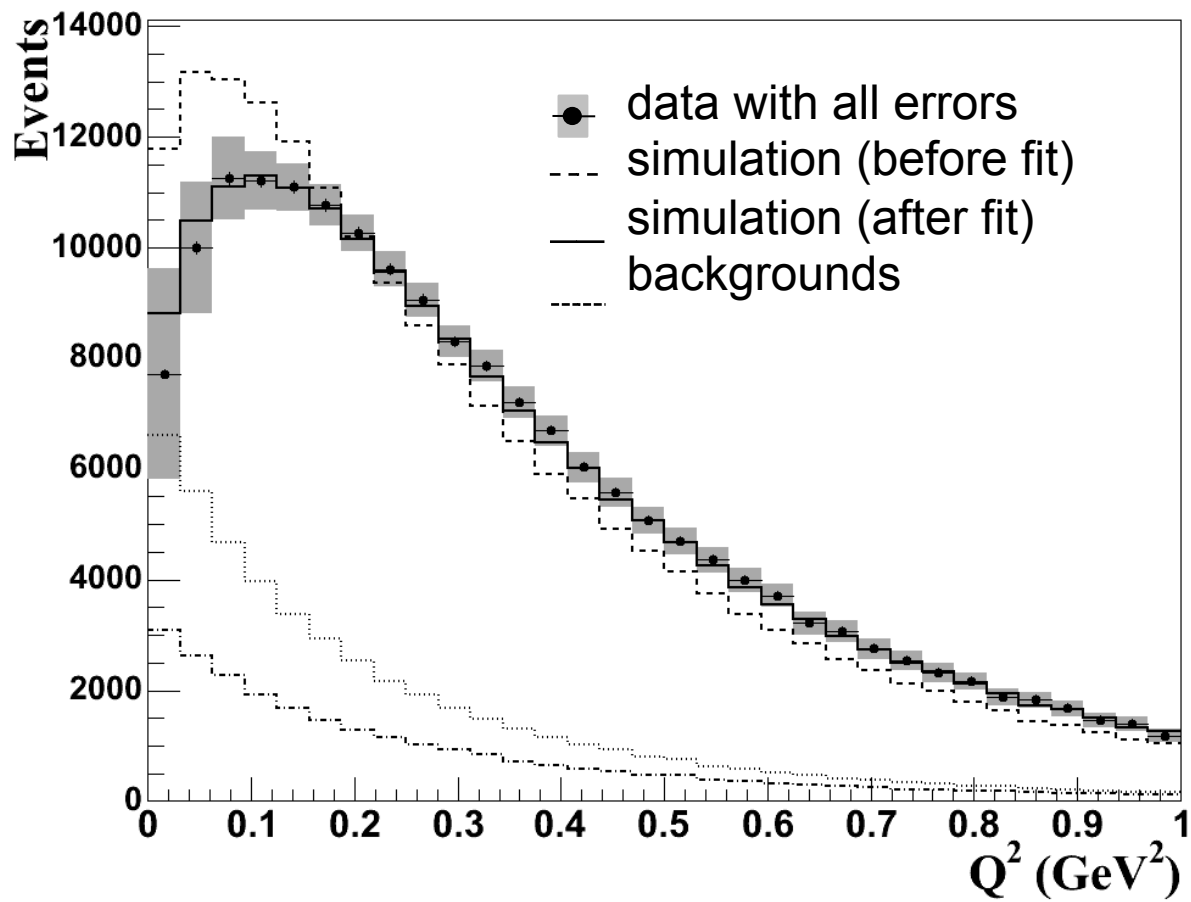
Q^2 fits to MB ν_μ CCQE data using the nuclear parameters:

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

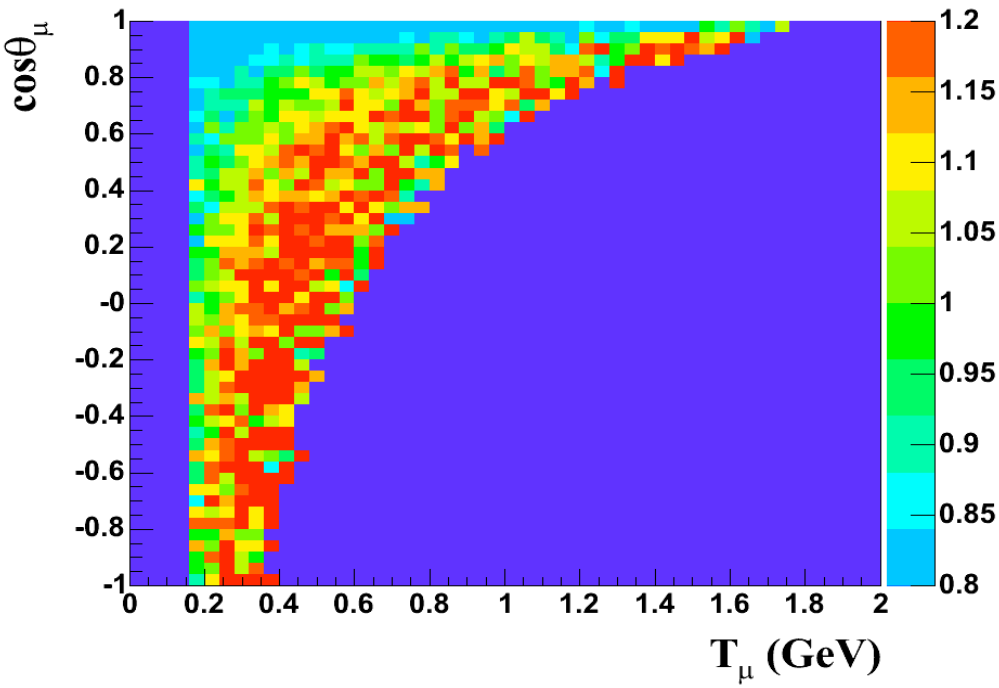


4. CCQE cross section model tuning

Without knowing flux perfectly, we cannot modify cross section model

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

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



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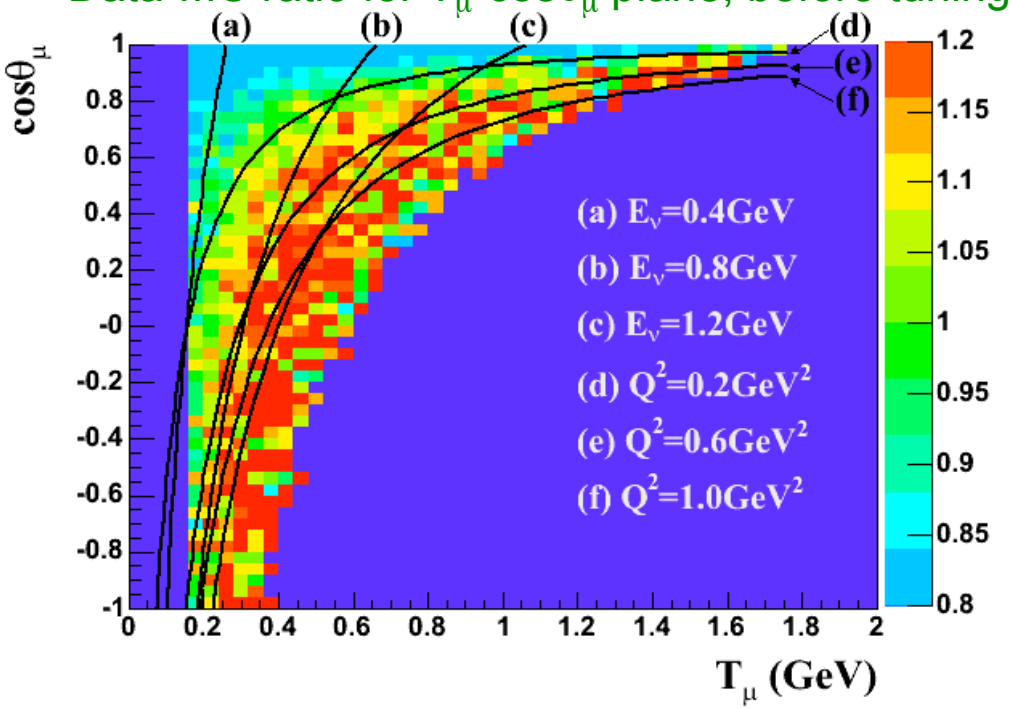
$$R(\text{interaction}[E_\nu, Q^2]) \propto \int (\text{flux}[E_\nu]) \times (\text{xs}[Q^2])$$

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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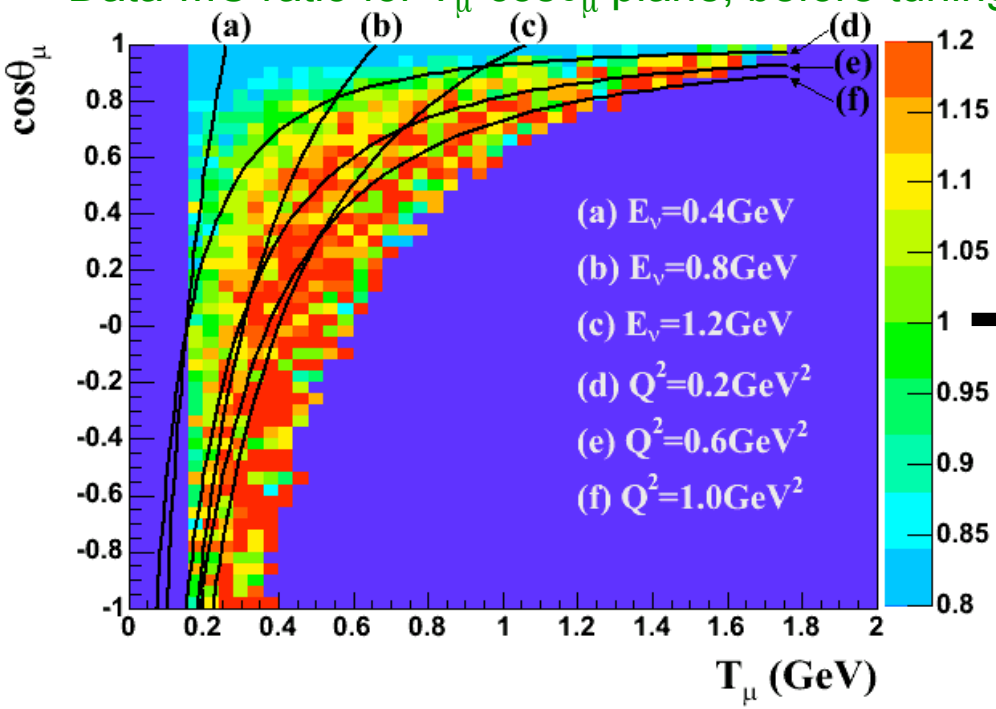
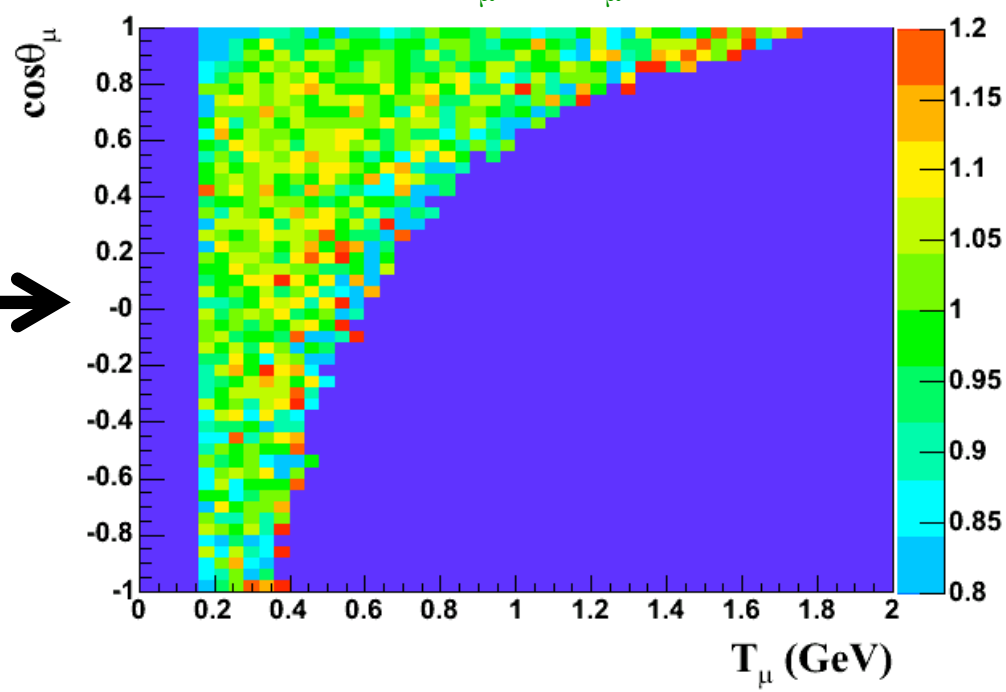


Data-MC ratio for T_μ-$\cos\theta_\mu$ plane,after tuning



4. NCπ^o rate tuning

NCπ^o (neutral current π^o production)

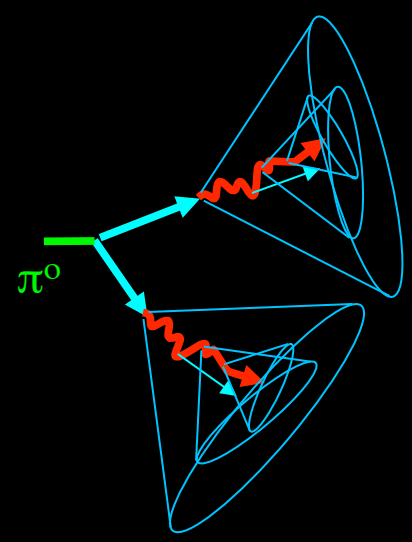
The signal of ν_e candidate is a single isolated electron

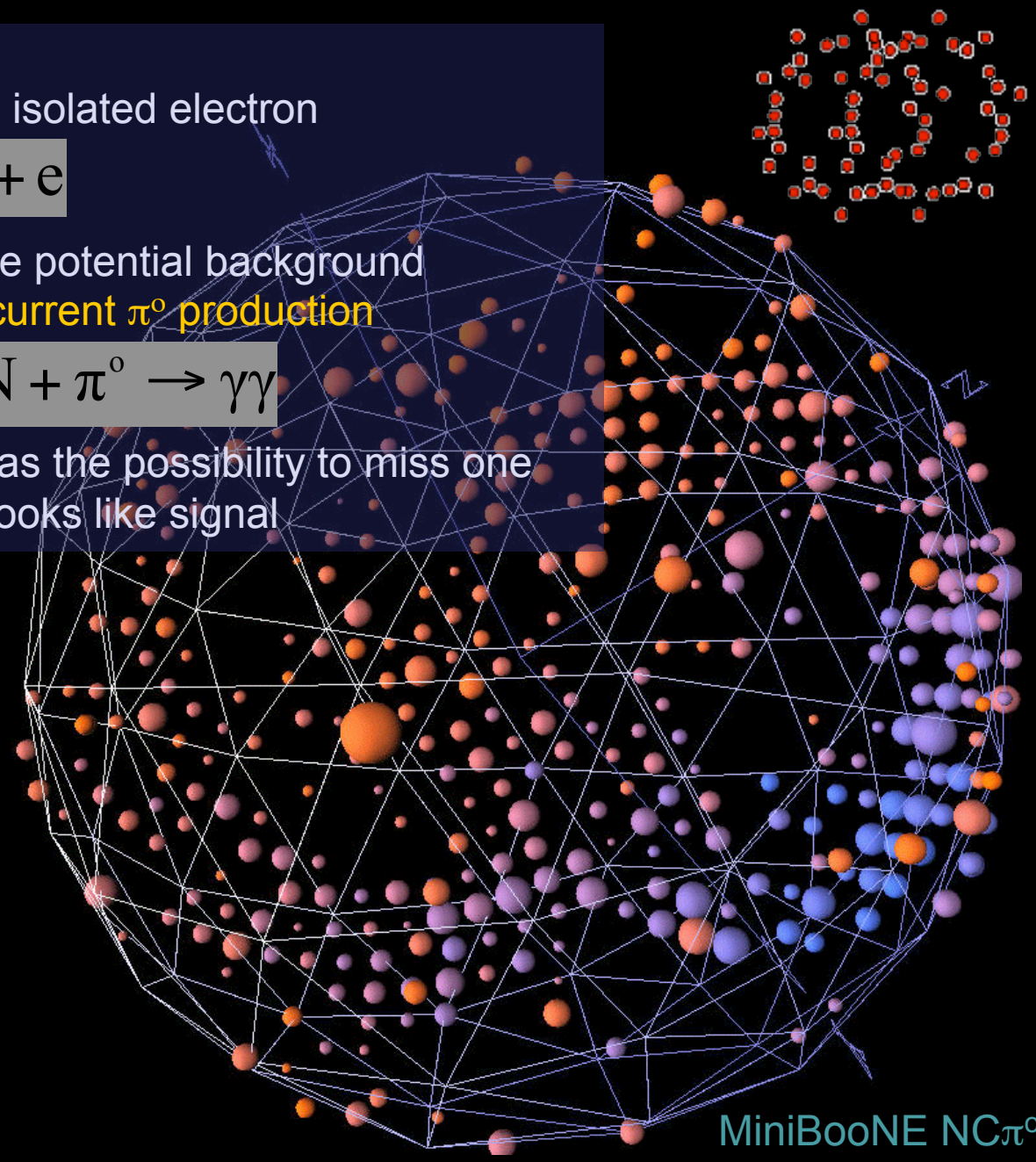
$$\nu_e + n \rightarrow p + e$$

- 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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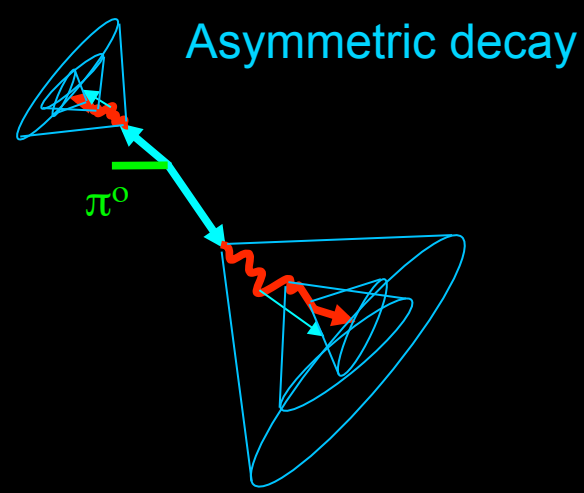

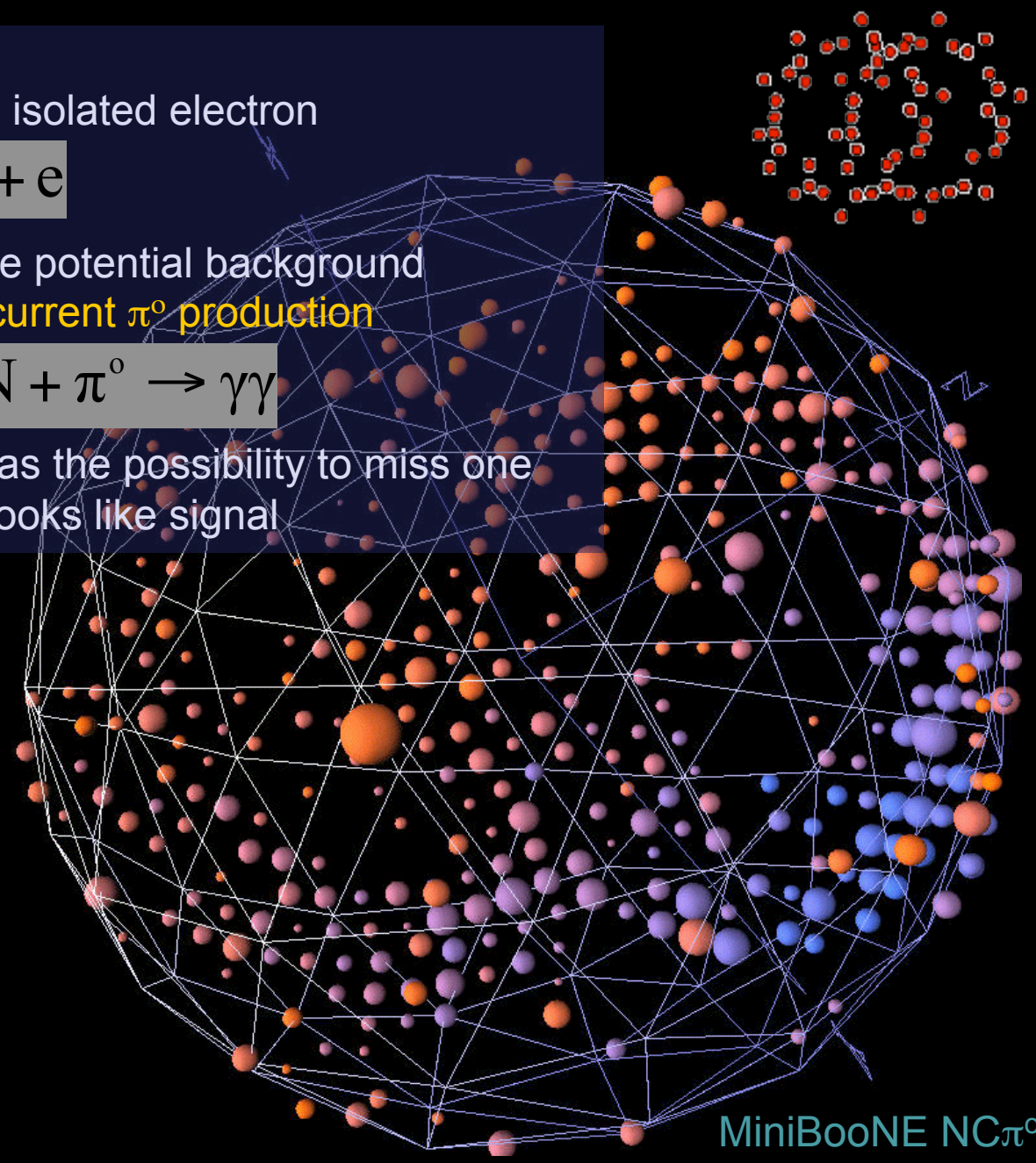

MiniBooNE NCπ^o candidate

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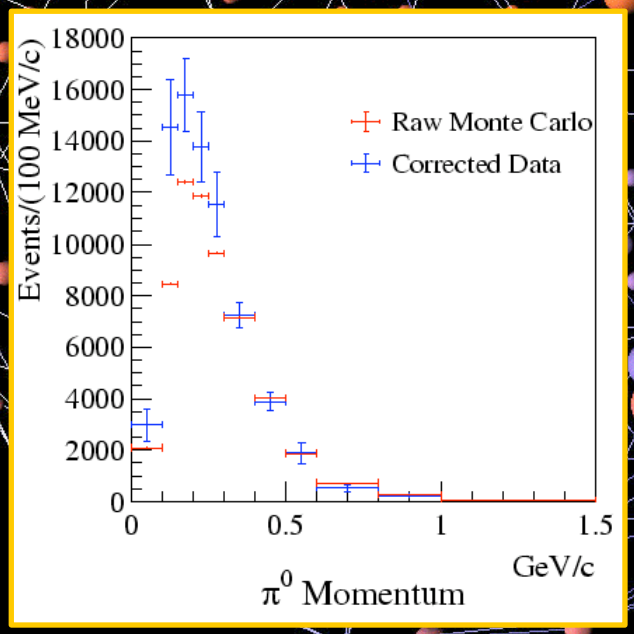
Because of kinematics, one always has the possibility to miss one gamma ray, and hence this reaction looks like signal

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.

MiniBooNE collaboration
PLB664(2008)41



MiniBooNE NCπ^o candidate

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, PRD83(2011)052007
5. charged current single π^o production (CCπ^o) cross section measurement
   by Bob Nelson, PRD83(2011)052009
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

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http://proceedings.aip.org/proceedings/confproceed/1189.jsp

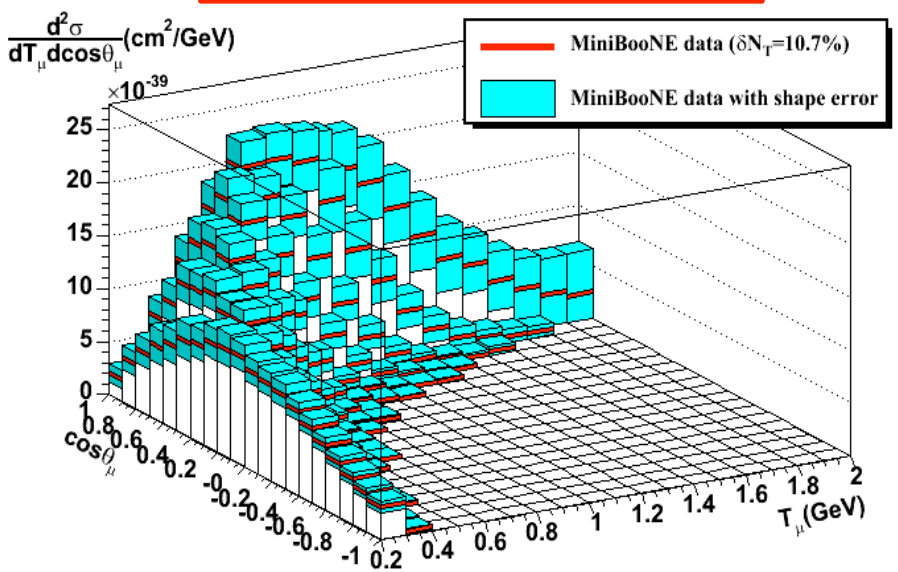
Main results are flux averaged differential cross section, they are function of measured variables (e.g., muon angle, pion energy, etc), not inferred variables (e.g., neutrino energy, momentum transfer)

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

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

3. neutral current π^o production (NCπ^o) cross section measurement (ν and anti-ν)
   by Colin Andersc
4. charge section measurement
   by Mik
5. charge ection measurement
   by Bob
6. CCπ^+/
   by Ste
7. anti-νC
   by Joe

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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   by Mike Wilking, PRD83(2011)052007
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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

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

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

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

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

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

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

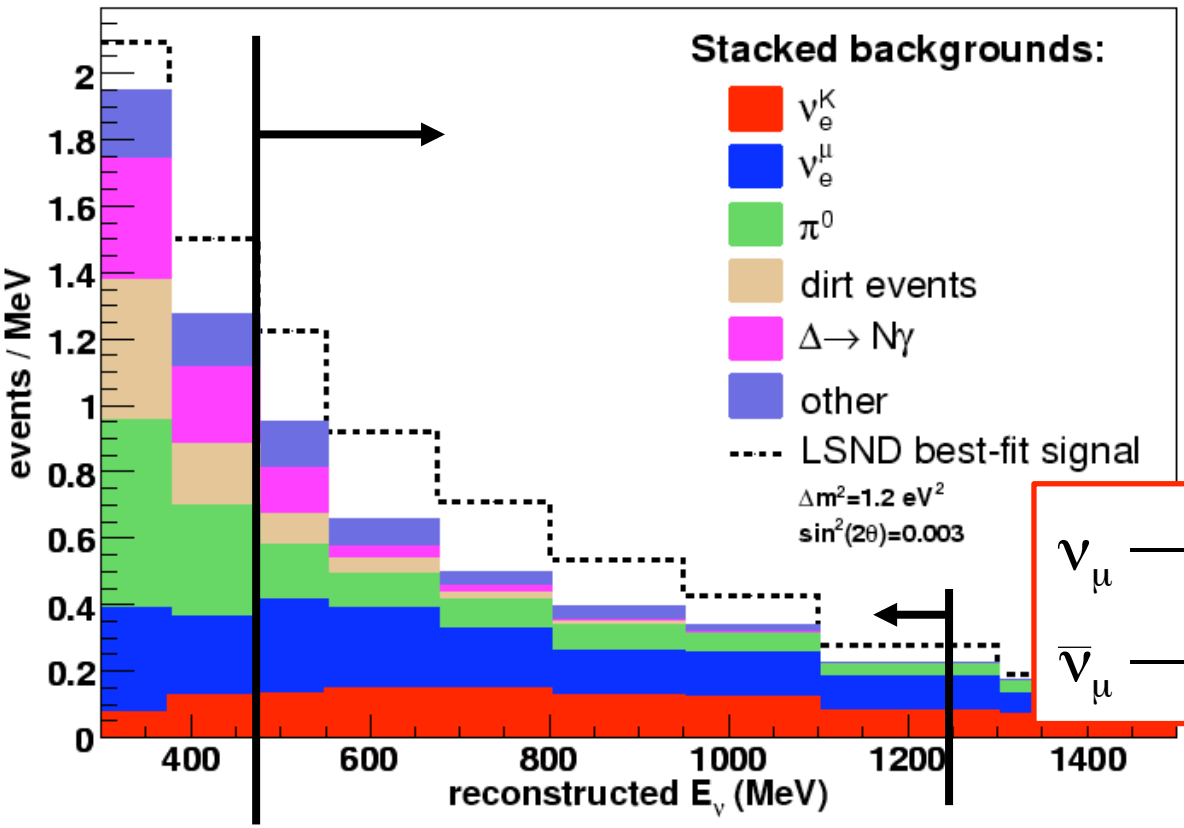
5. Oscillation analysis background summary

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



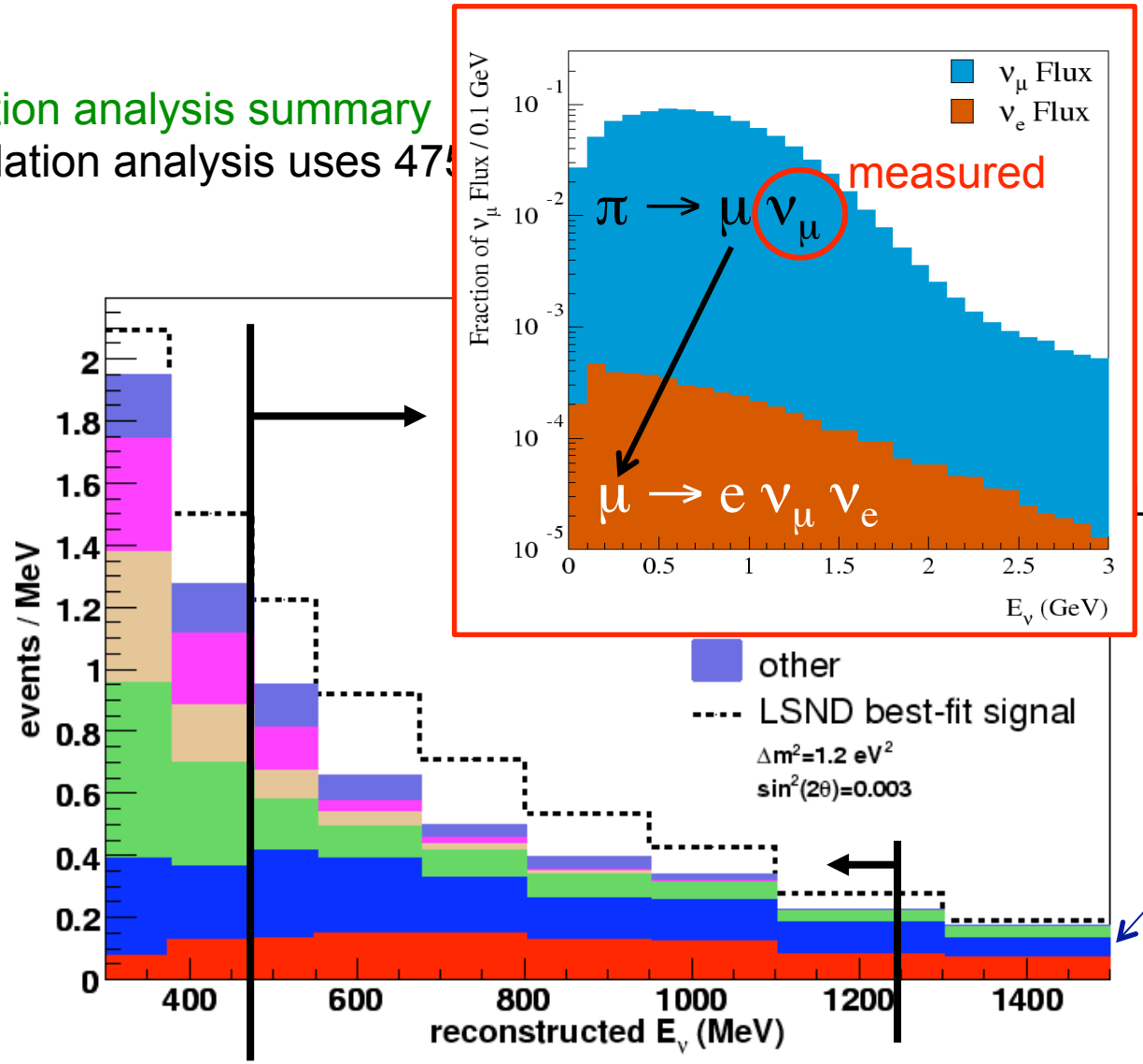
$$\nu_\mu \xrightarrow{\text{oscillation}} \nu_e + n \rightarrow p + \boxed{e^-}$$

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

5. Oscillation analysis background summary

Oscillation analysis summary

- Oscillation analysis uses 475



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ν_e from μ decay is constrained from ν_μCCQE measurement

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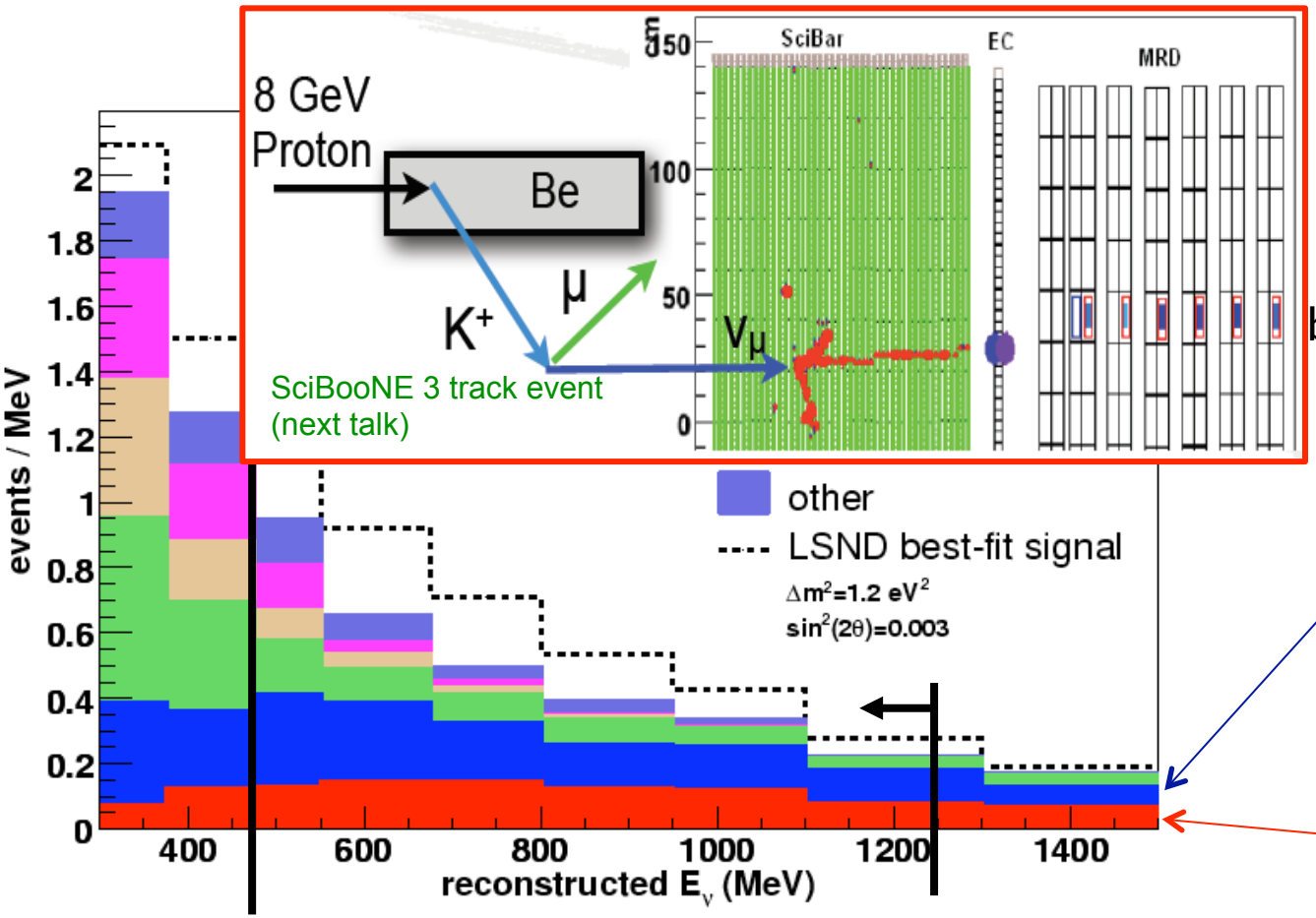

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ν_e from μ decay is constrained from ν_μCCQE measurement

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

5. Oscillation analysis background summary

Oscillation analysis summary

- Oscillation analysis uses 475MeV<E<1250MeV

Δ resonance rate is constrained from measured NCπ° rate

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total	358
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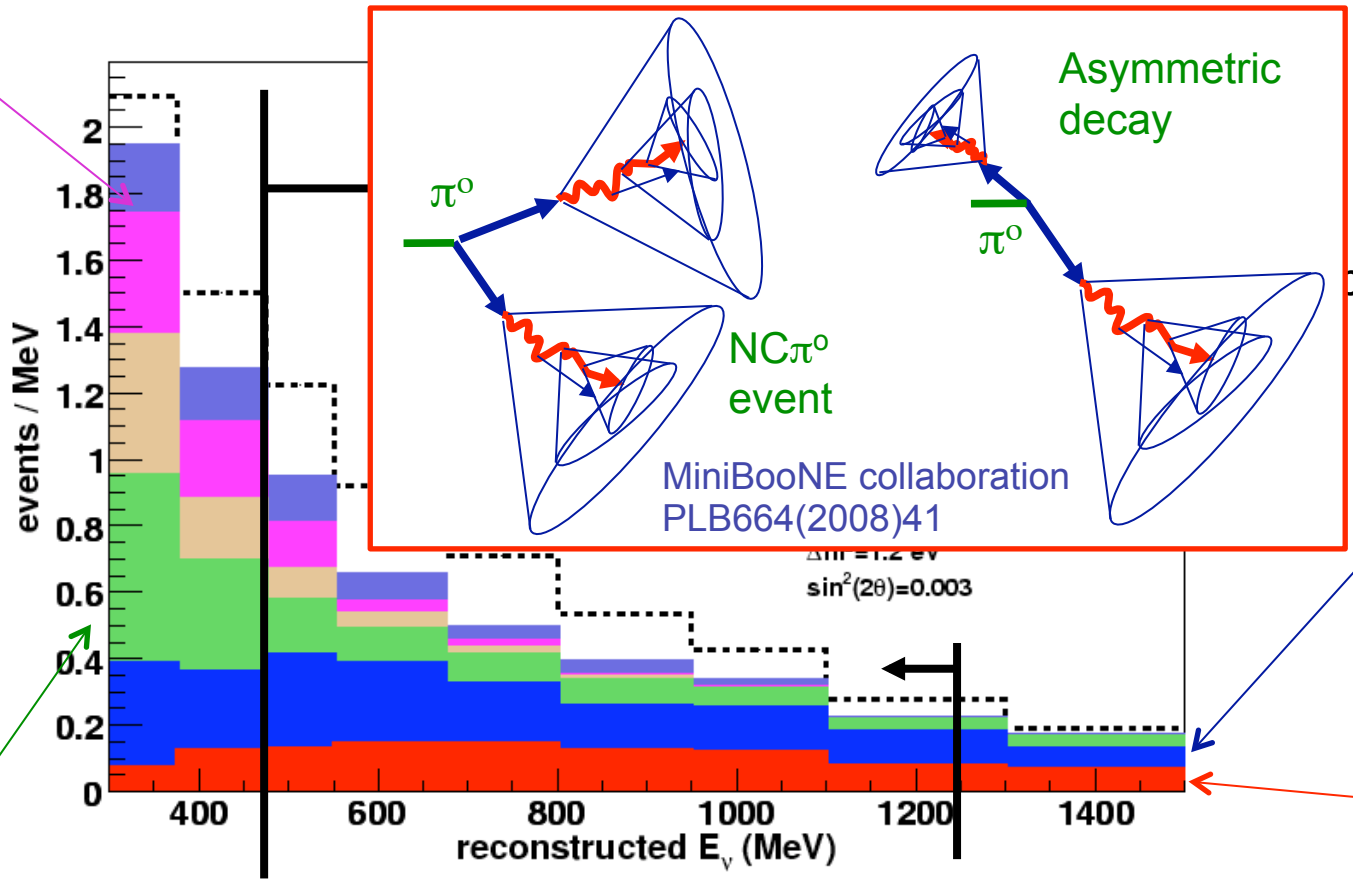


ν_e from μ decay is constrained from ν_μCCQE measurement

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

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

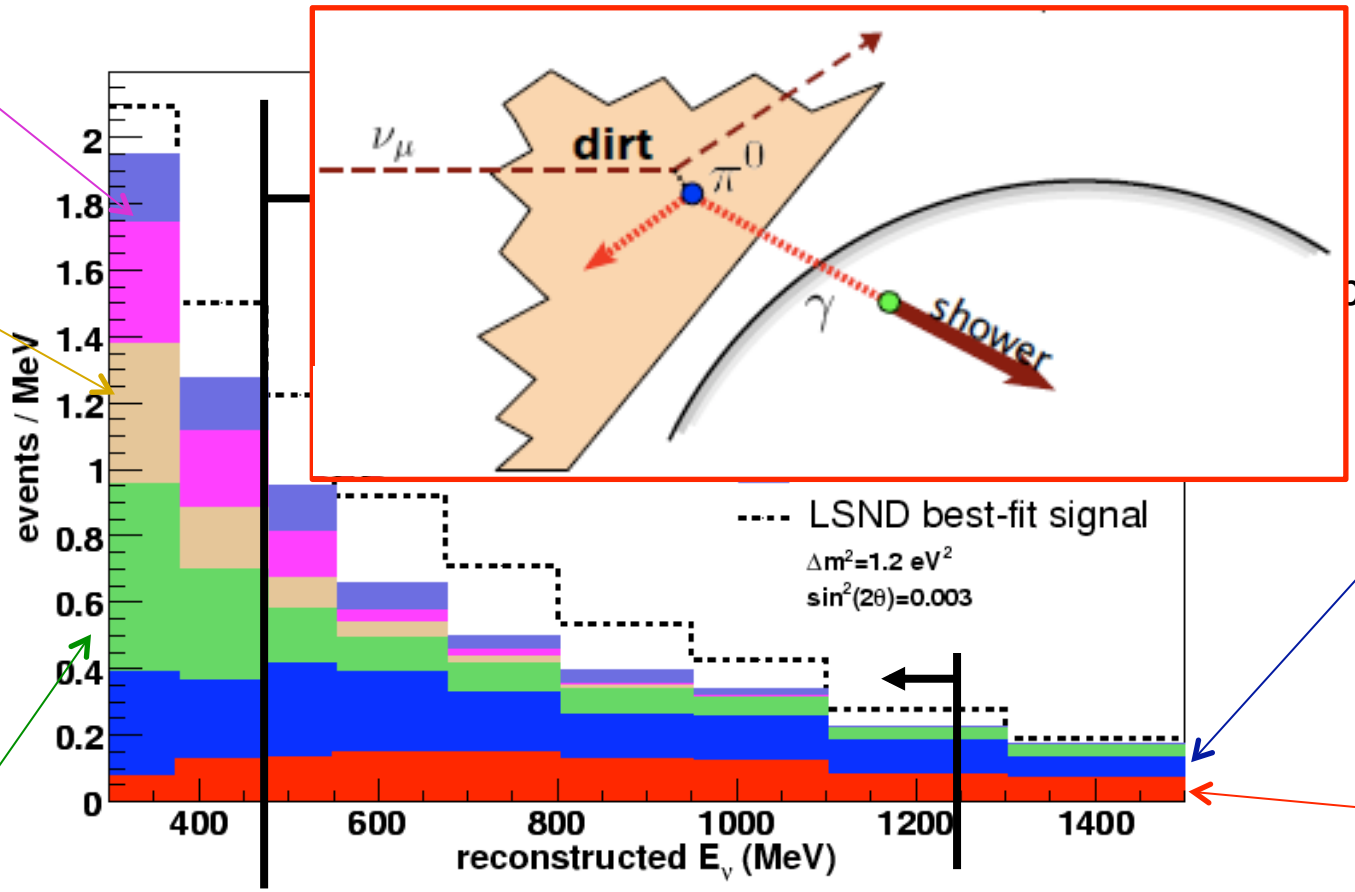
5. Oscillation analysis background summary

Oscillation analysis summary

- Oscillation analysis uses 475MeV<E<1250MeV

Δ resonance rate is constrained from measured NCπ° rate

dirt rate is measured from dirt data sample



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

ν_e from μ decay is constrained from ν_μCCQE measurement

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

Asymmetric π° decay is constrained from measured CCπ° rate (π°→γ)

5. Oscillation analysis background summary

475 MeV – 1250 MeV

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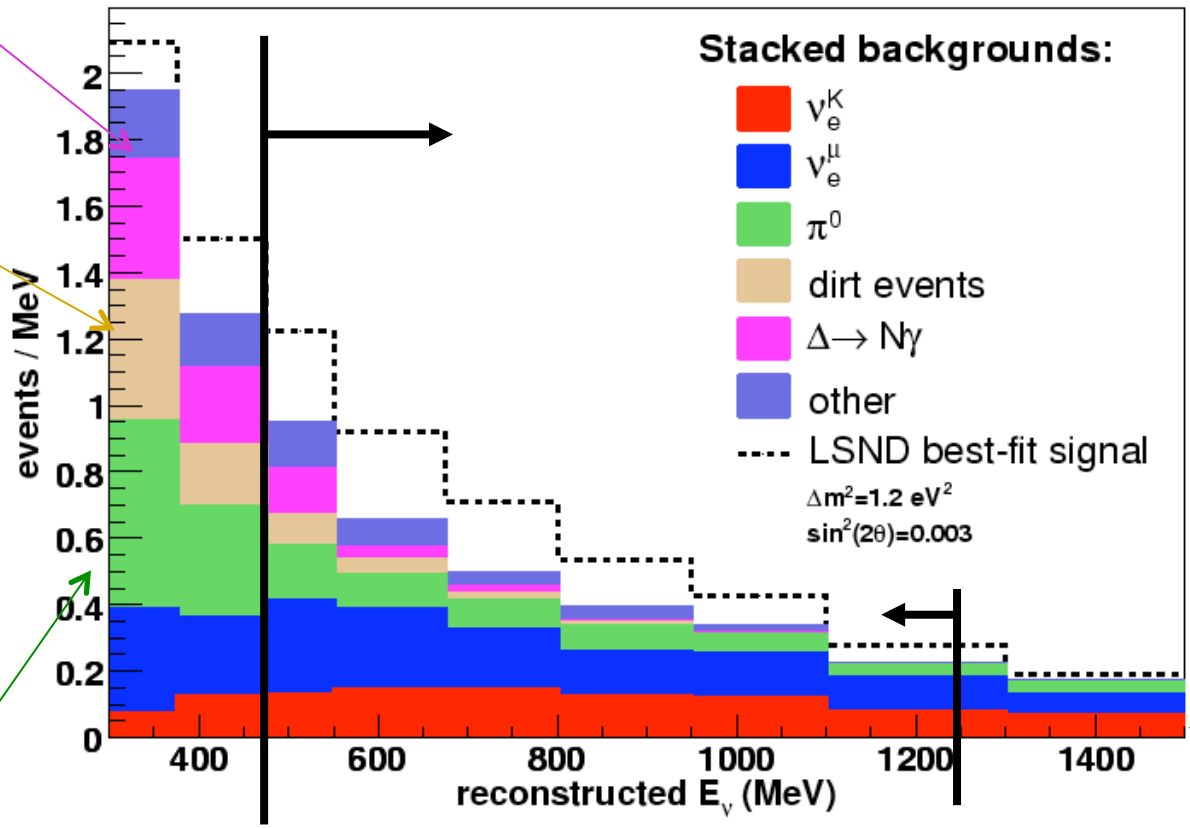
Oscillation analysis summary

- Oscillation analysis uses 475MeV<E<1250MeV

Δ resonance rate is constrained from measured NCπ^o rate

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 SciBooNE high energy ν_μ 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!

MiniBooNE collaboration, PRL102(2009)101802

5. Oscillation analysis result

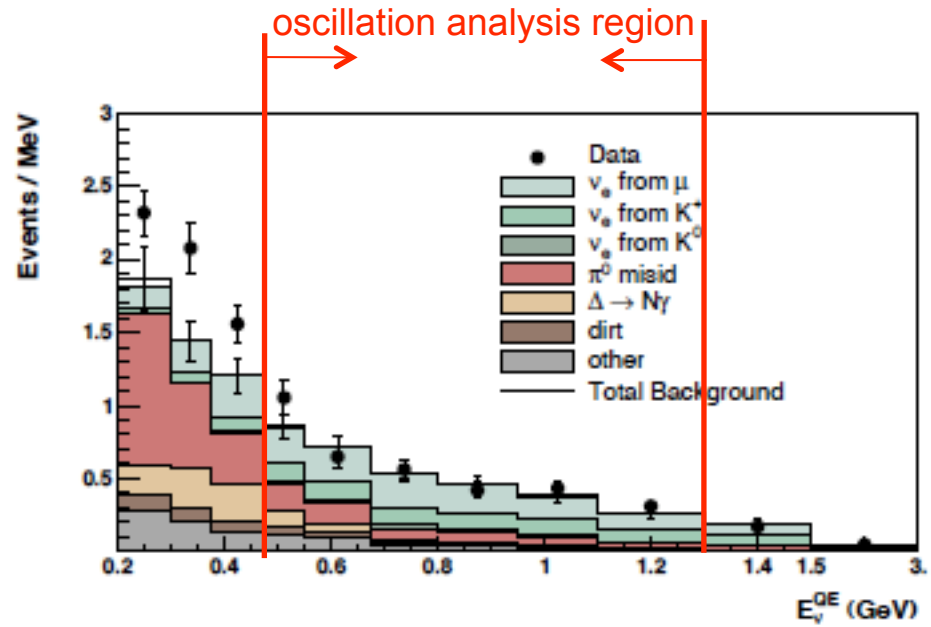
ν_e appearance oscillation result

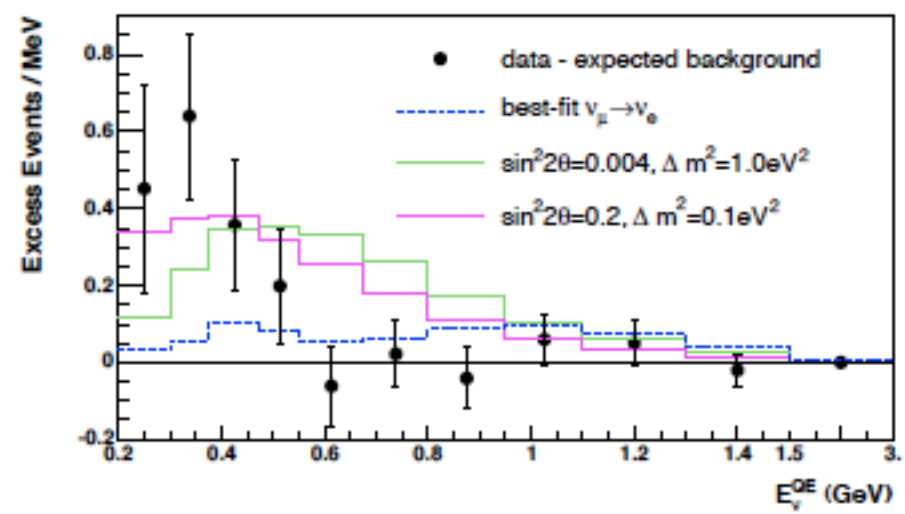
- The best fit result shows no sign of an excess in the analysis region (where the LSND signal is expected from 1 sterile neutrino interpretation). However, there is 3.4σ excess in low energy region (300-475MeV)

- many models are suggested to explain low energy excess...

- 3+2 with CP violation, Maltoni and Scwetz, PRD76(2007)093005
- New light gauge boson, Nelson Walsh, PRD77(2008)033001
- Heavy sterile neutrino decay, Gninenko, PRD83(2011)015015
- Extra dimension, Pas, Pakvasa, Weiler, PRD72(2005)095017
- Lorentz and CPT violation, Katori, Kostelecky, Tayloe, PRD(2006)105009

etc...





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5. Neutrino oscillation result

6. Anti-neutrino oscillation result

7. Outlook

6. Antineutrino oscillation result

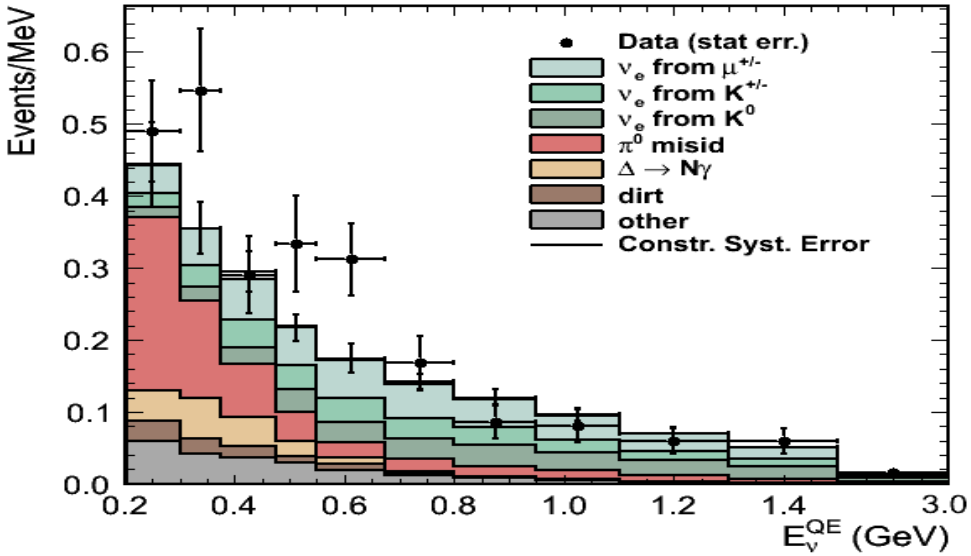
- Antineutrino mode is the direct test of LSND signal
- Analysis is limited with statistics

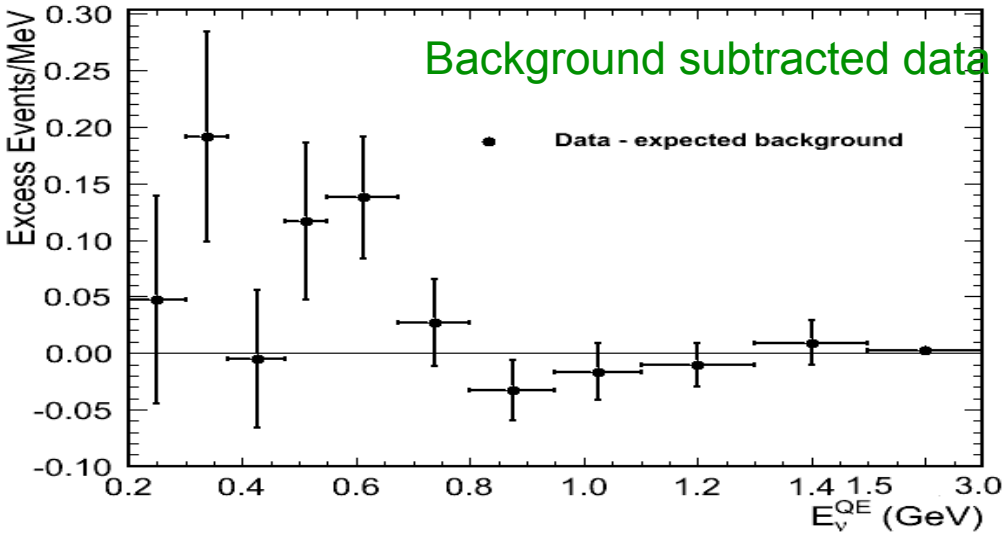
Neutrino 2010, Athens

MiniBooNE collaboration, PRL105(2010)181801

Antineutrino oscillation result

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





6. Antineutrino oscillation result

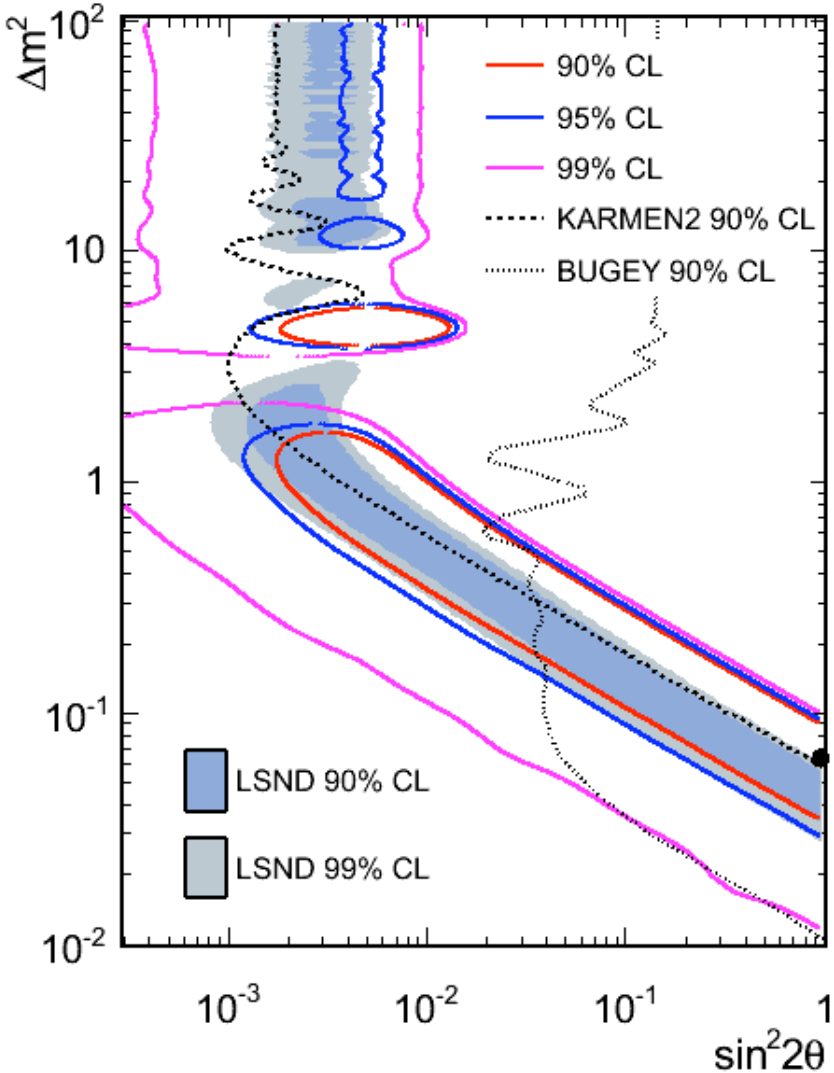
- Antineutrino mode is the direct test of LSND signal
- Analysis is limited with statistics

Neutrino 2010, Athens

MiniBooNE collaboration, PRL105(2010)181801

Antineutrino oscillation result

- 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
$\Delta m^2 = 0.064 eV^2$
$\sin^2 2\theta = 0.96$

6. New antineutrino oscillation result

PANIC 2011, Boston

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Antineutrino oscillation result

- MiniBooNE now see the excess in LSND-like Δm^2 region!
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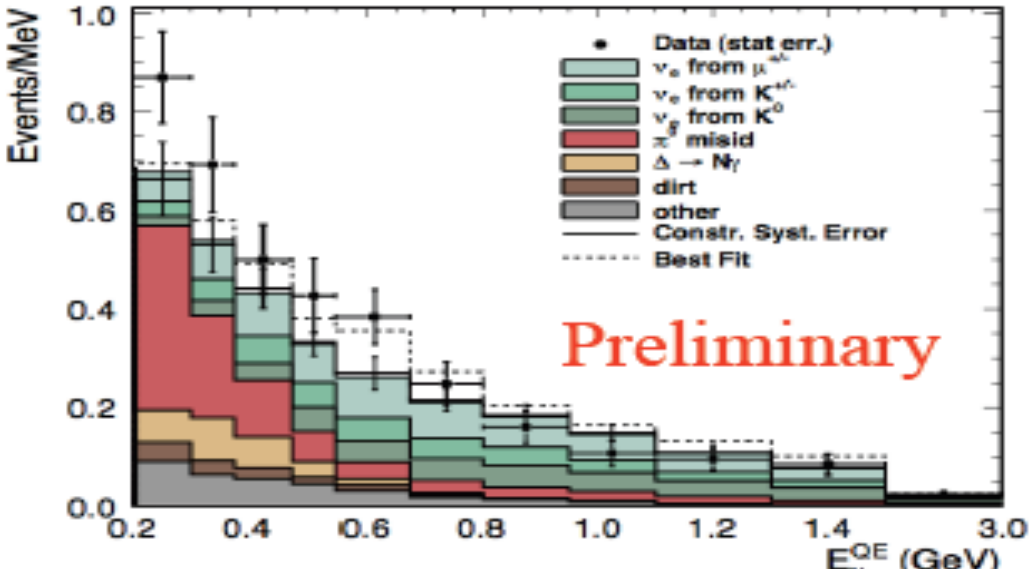
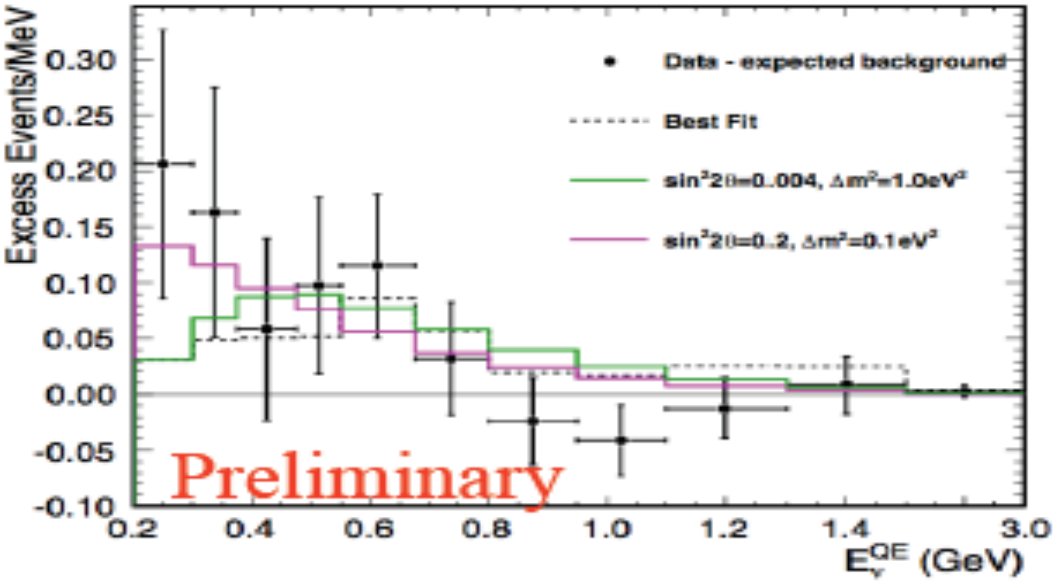
New antineutrino oscillation result

- After adding latest data set (50% more data), Overall excess (200-3000 MeV) changes,

43.2 ± 22.5 → 57.7 ± 28.5





6. New antineutrino oscillation result

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- Antineutrino mode is the direct test of LSND signal
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Antineutrino oscillation result

- MiniBooNE now see the excess in LSND-like Δm^2 region!
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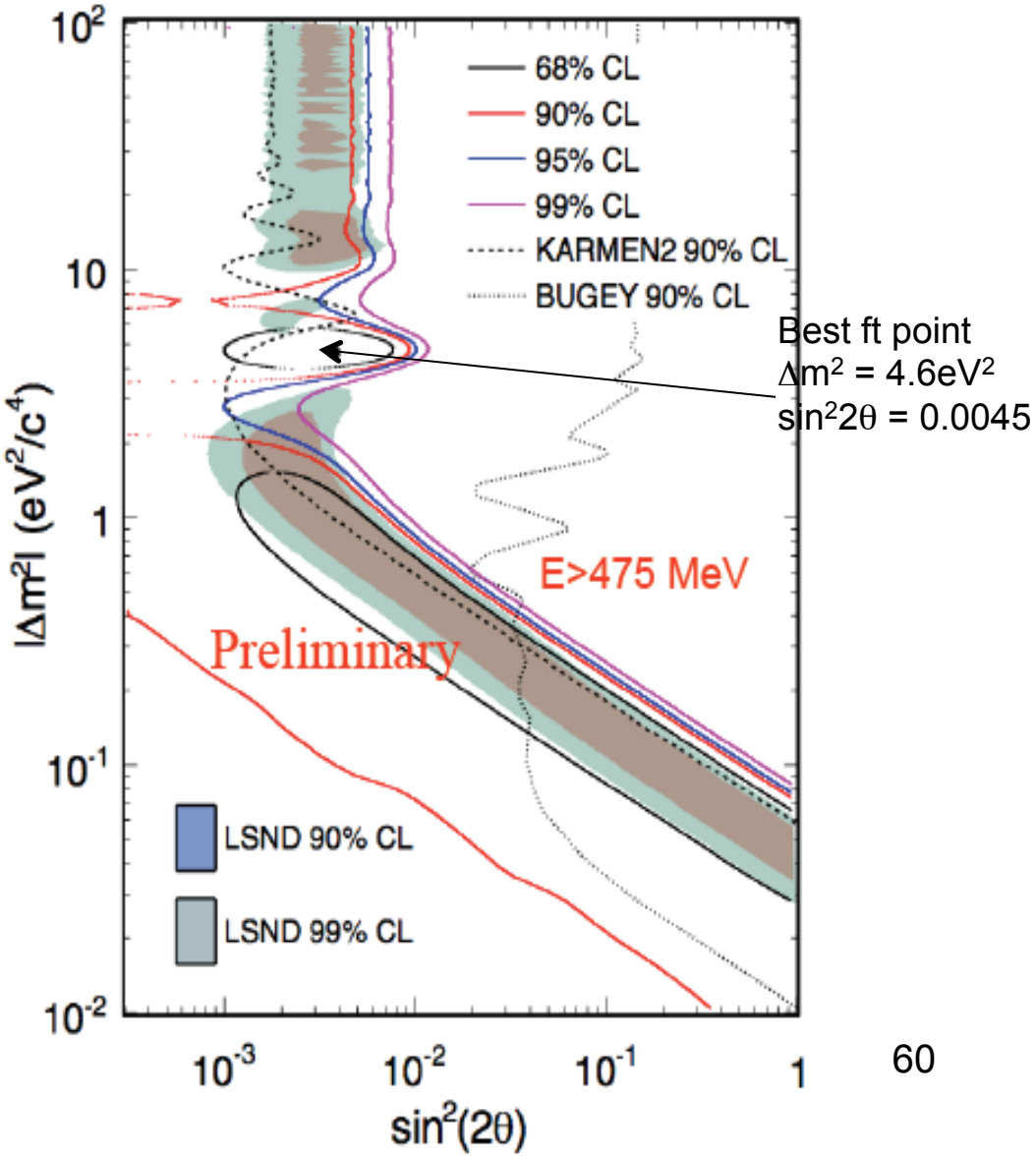
New antineutrino oscillation result

- After adding latest data set (50% more data), Overall excess (200-3000 MeV) changes,

$$43.2 \pm 22.5 \rightarrow 57.7 \pm 28.5$$

- However, significance of 2 neutrino massive model over null hypothesis decreases, E>475MeV, 2.75σ excess $\rightarrow$ 1.7σ excess, and now 2 massive neutrino model is favored over 91.4% than null hypothesis



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**

7. MiniBooNE oscillation results 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

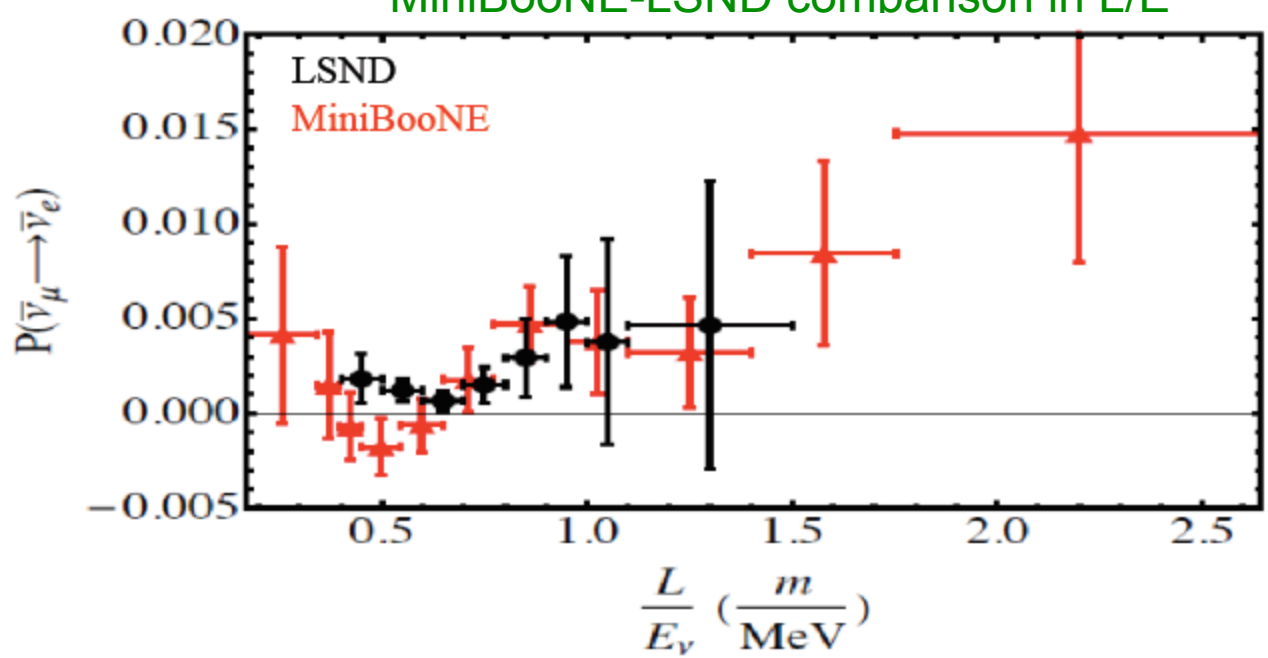
Antineutrino mode analysis
- excess is observed in low energy region
- LSND consistent excess is observed in the oscillation energy region

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

There is no convincing theoretical
model to solve all mysteries.

Is MiniBooNE wrong?

MiniBooNE-LSND comparison in L/E



7. History of neutrino oscillations

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, because CKM matrix element V_{cb}~0.04
-> Wrong, much larger

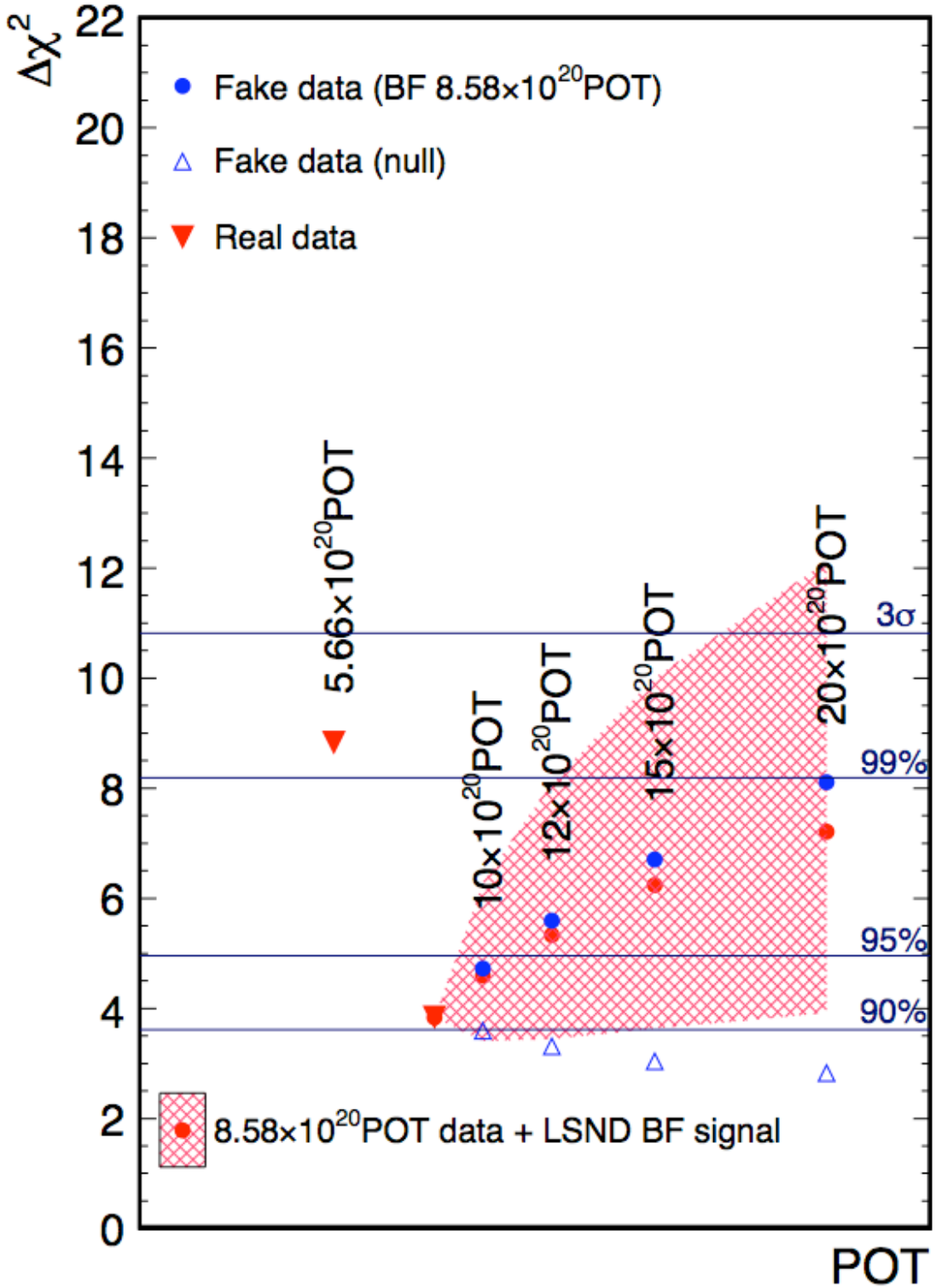
Neutrino physics keep surprising us, so does MiniBooNE!

7. Outlook

MiniBooNE will continue to take data until March 2012.

We can expect ~99% level signal at the end of run if the excess is the real signal, not a random fluctuation.

Further study of the low energy excess can be done by MicroBooNE (talk on Friday).



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

Дякую за вашу увагу!

Buck up