

Neutrino cross section measurements for long-baseline neutrino oscillation experiments

Teppei Katori
Indiana University
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La Thuile, Italia, Mar., 05, 08



SciBooNE vertex detector "SciBar"

1. Neutrino oscillation experiments

2. Neutrino energy reconstruction

2.1 Kinematic energy reconstruction

2.2 Calorimetric energy reconstruction

3. Background reactions

4. Conclusion



1. Neutrino oscillation experiments

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1. Neutrino oscillation experiments

Long-baseline neutrino oscillation experiments

Observable is neutrino interaction rate

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

Neutrino oscillation is a function of neutrino energy and neutrino flight distance

$$R(\text{oscillation}) \propto \sin^2 \left(1.27 \Delta m^2 (\text{eV}^2) \frac{L(\text{m})}{E(\text{MeV})} \right)$$

If we want to measure $\Delta m_{\mu\tau}^2 \sim 10^{-3}$, then L/E should be tuned around $\sim 10^3$

order of $L \sim 100\text{-}1000\text{km}$

order of $E \sim 100\text{-}1000\text{MeV}$

There are 2 next generation long-baseline neutrino oscillation experiments

1. T2K experiment

There are 2 next generation long-baseline neutrino oscillation experiments

T2K experiment (Toukai to Kamioka)
E~800MeV, lower energy (lower flux)
L~300km, shorter baseline (higher flux)

NOvA experiment (NuMI Off-axis ν_e Appearance)
E~2000MeV, higher energy (higher flux)
L~800km, longer baseline (lower flux)

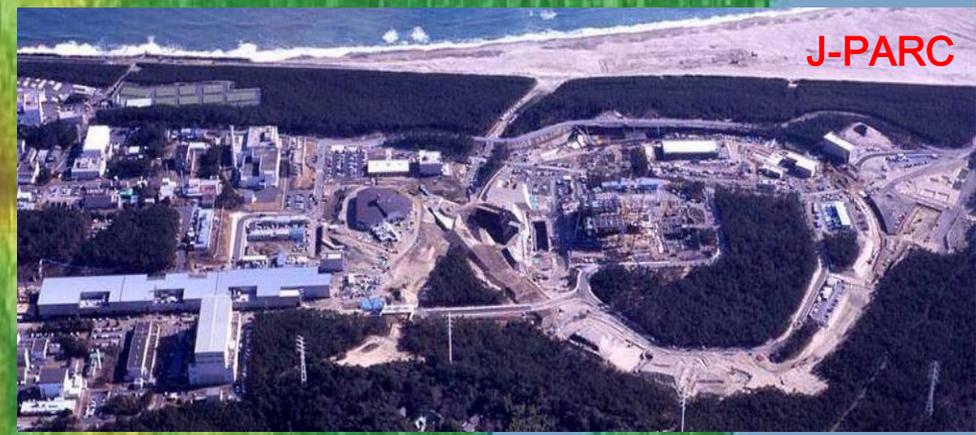
295 km

東海村

神岡



Super-K



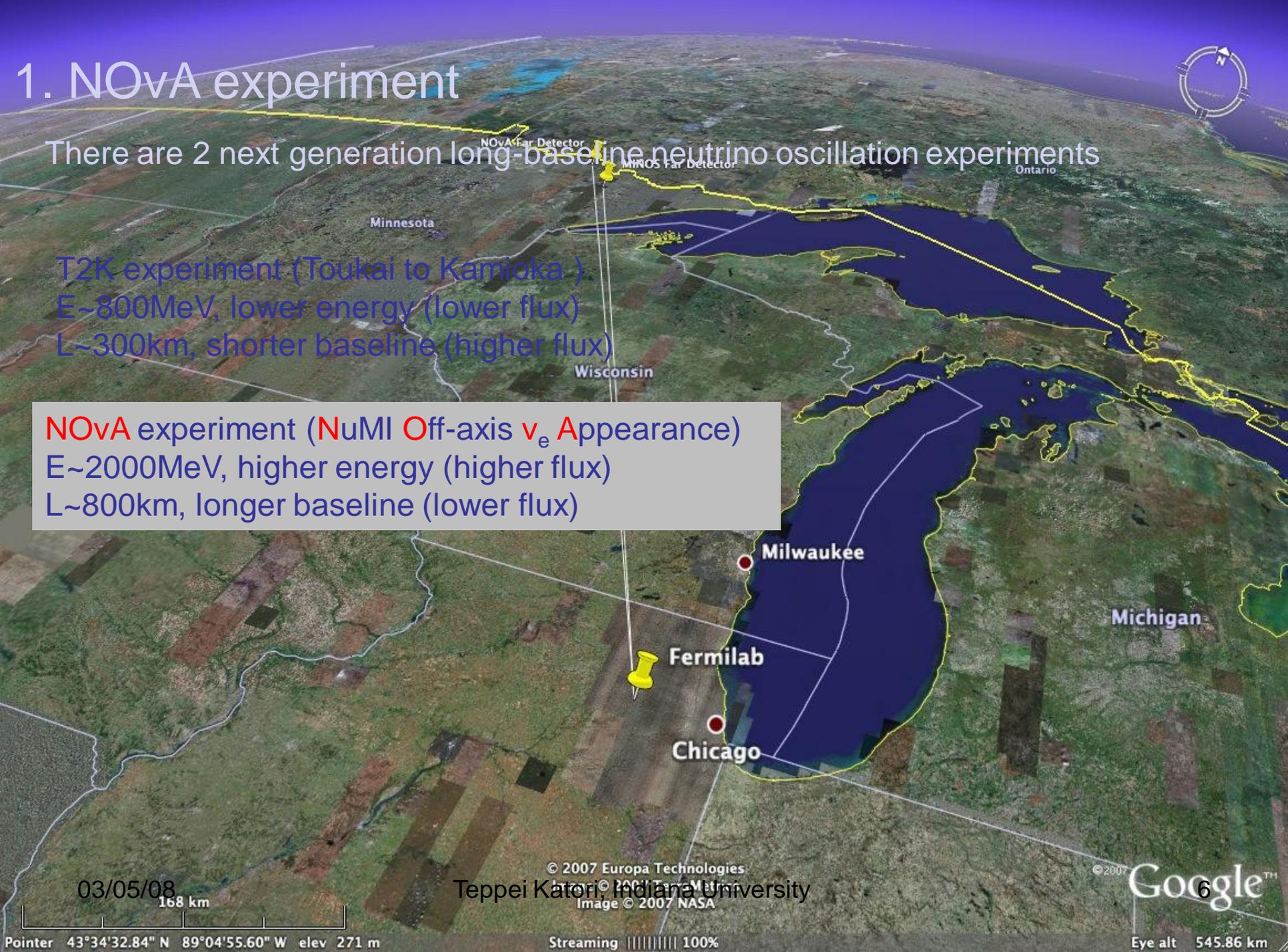
J-PARC

1. NOvA experiment

There are 2 next generation long-baseline neutrino oscillation experiments

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E~800MeV, lower energy (lower flux)
L~300km, shorter baseline (higher flux)

NOvA experiment (NuMI Off-axis ν_e Appearance)
E~2000MeV, higher energy (higher flux)
L~800km, longer baseline (lower flux)



03/05/08

168 km

Pointer 43°34'32.84" N 89°04'55.60" W elev 271 m

© 2007 Europa Technologies
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Teppei Katori, Indiana University

Streaming 100%

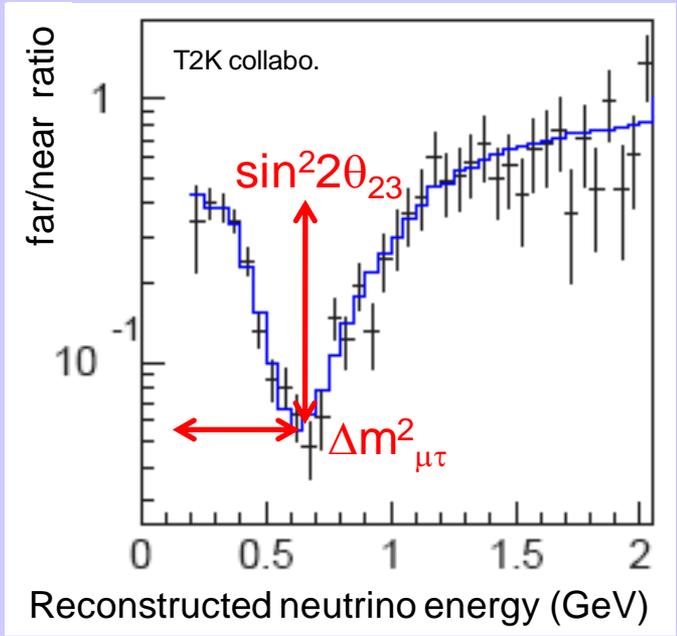
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Eye alt 545.86 km

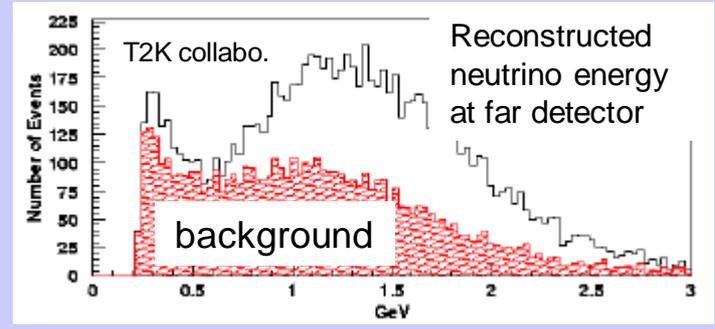
1. ν_μ disappearance measurement

2 goals for T2K and NOvA experiments

- (1) precision measurement for $\Delta m^2_{\mu\tau}$ and $\sin^2 2\theta_{23}$ through ν_μ events
 - Accurate neutrino energy reconstruction
- (2) ν_e appearance measurement
 - Careful rejection of background reactions



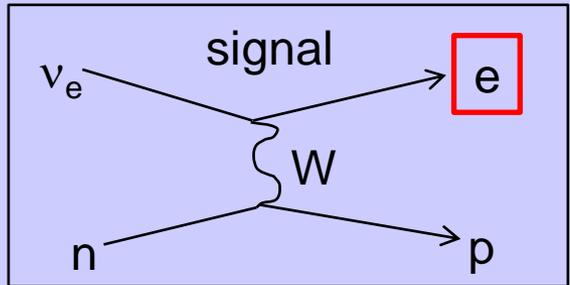
mis-reconstruction of neutrino energy spoils ν_μ disappearance signals



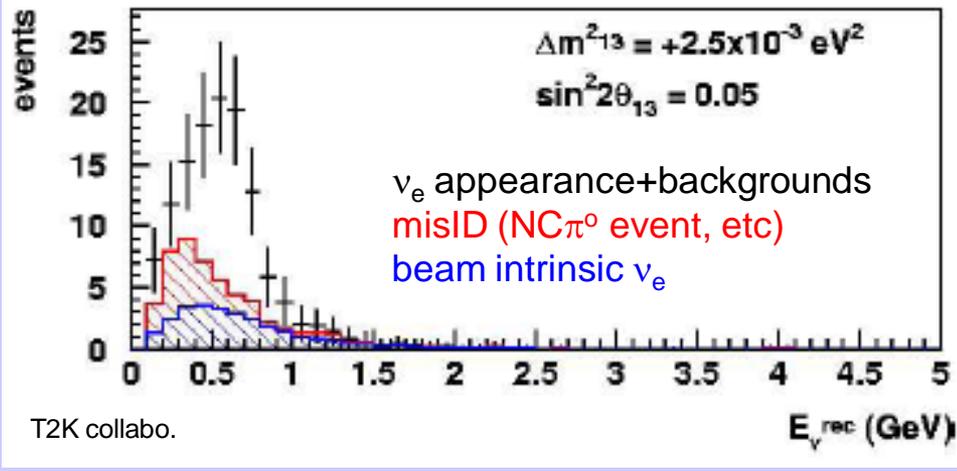
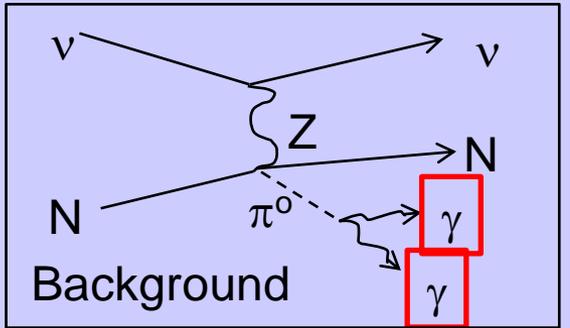
1. ν_e appearance measurement

2 goals for T2K and NOvA experiments

- (1) precision measurement for $\Delta m^2_{\mu\tau}$ and $\sin^2 2\theta_{23}$ through ν_μ events
 - Accurate neutrino energy reconstruction
- (2) ν_e appearance measurement (= $\sin^2 2\theta_{13}$)
 - Careful rejection of background reactions



Background (misID) events, for example, $NC\pi^0$ events, are poorly understood

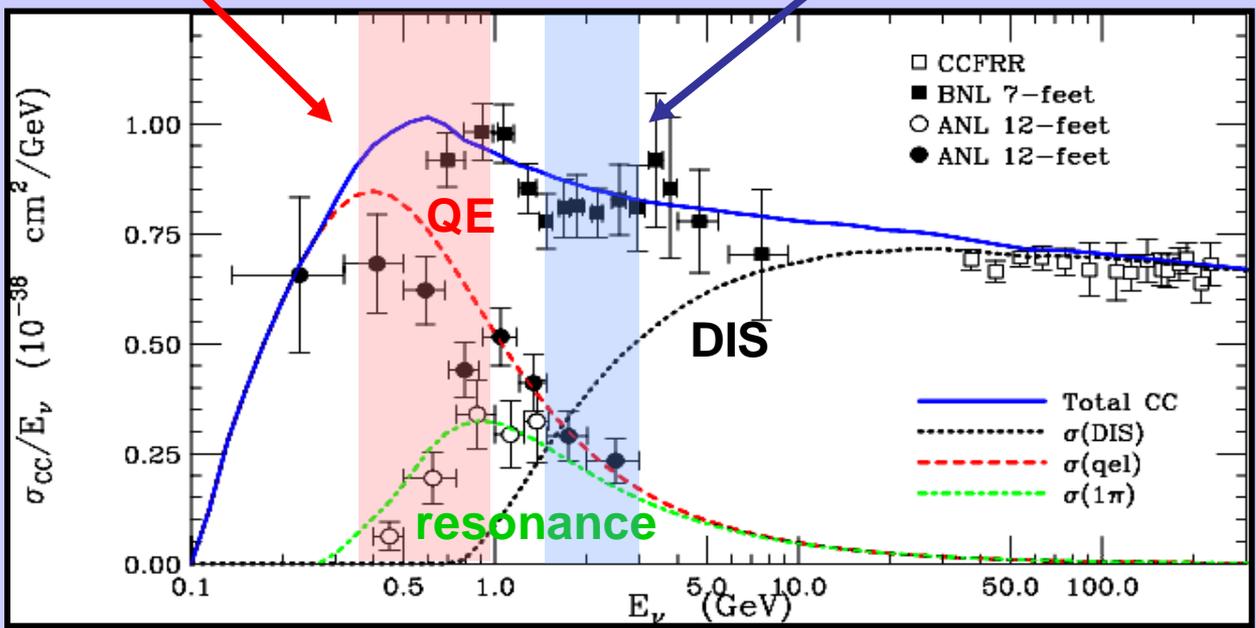


1. CC (Charged-Current) cross section

CC reaction is essential for neutrino experiments.
There are many reactions in this narrow energy region!

T2K (E~800MeV)
- quasi-elastic (QE)

NOvA (E~2000MeV)
- QE, resonance, DIS

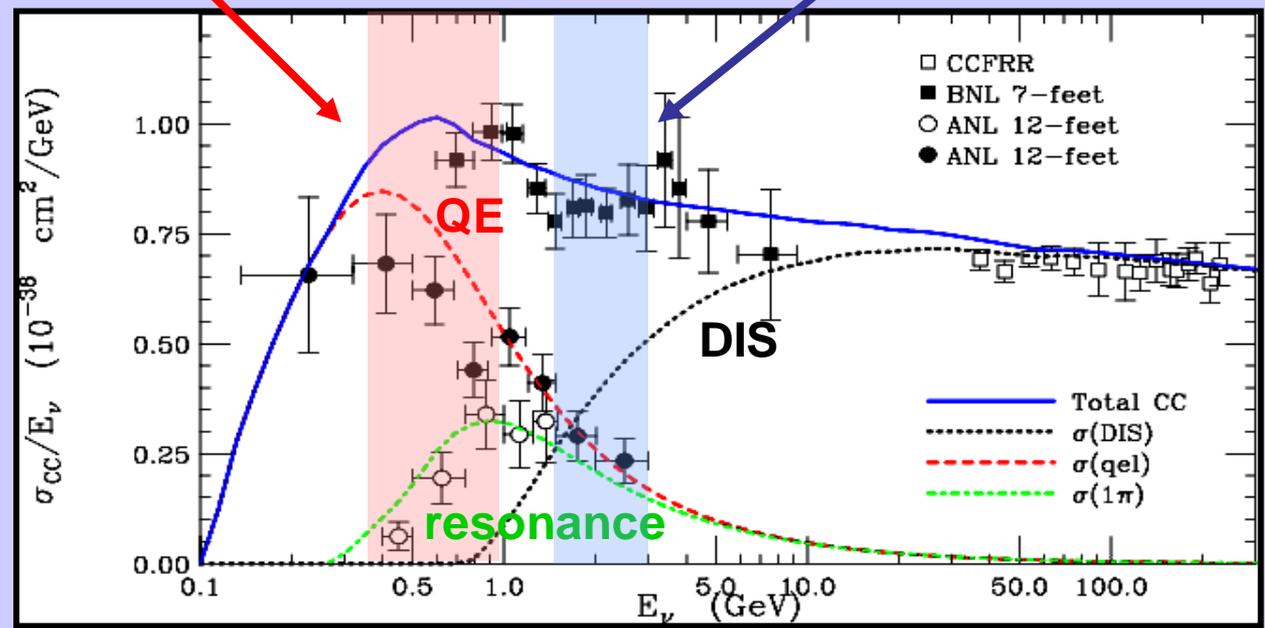


1. CC (Charged-Current) cross section

CC reaction is essential for neutrino experiments.
 There are many reactions in this narrow energy region!
A lot of future/current experiments!

T2K (E~800MeV)
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1. Neutrino oscillation experiments

2. Neutrino energy reconstruction

2.1 Kinematic energy reconstruction

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2. Neutrino energy reconstruction

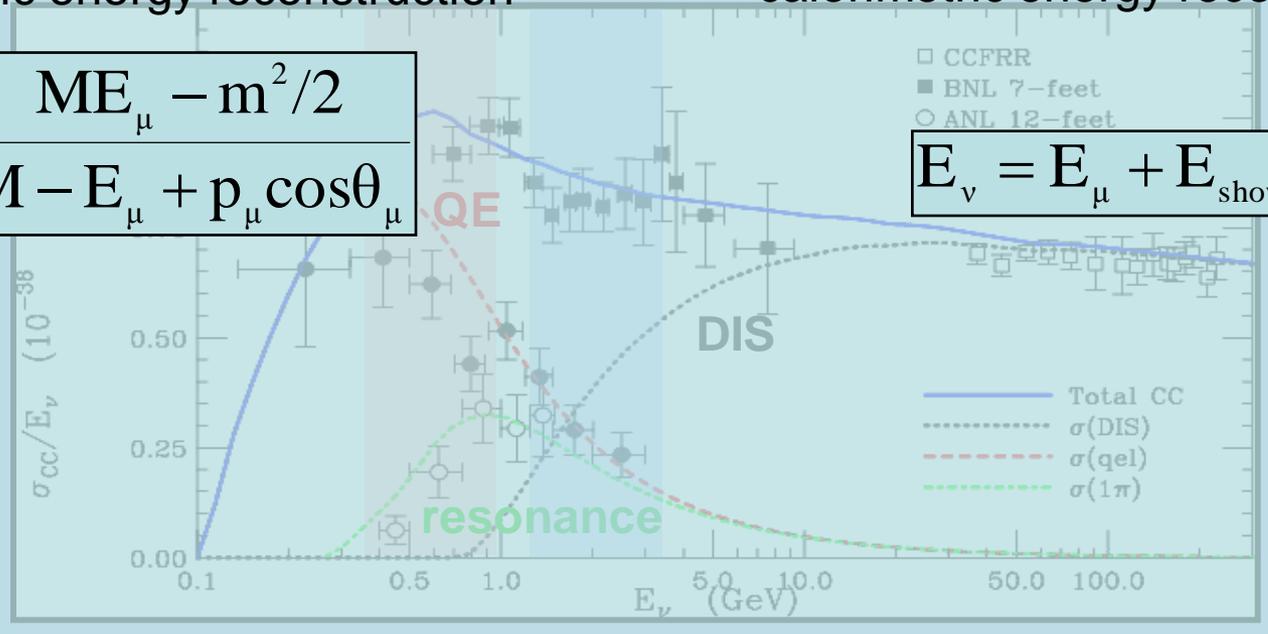
To understand neutrino oscillation, reconstruction of neutrino energy is essential. These 2 energy scales require 2 different schemes for energy reconstruction.

- T2K (E~800MeV)
- quasi-elastic (QE)
 - kinematic energy reconstruction

- NOvA (E~2000MeV)
- QE, resonance, DIS
 - calorimetric energy reconstruction

$$E_\nu = \frac{ME_\mu - m^2/2}{M - E_\mu + p_\mu \cos\theta_\mu}$$

$$E_\nu = E_\mu + E_{\text{showers}}$$



1. Neutrino oscillation experiments

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2. Kinematic neutrino energy reconstruction

To understand neutrino oscillation, reconstruction of neutrino energy is essential. These 2 energy scales require 2 different schemes for energy reconstruction.

T2K ($E \sim 800 \text{ MeV}$)

- quasi-elastic (QE)

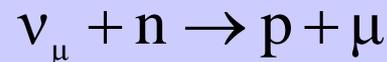
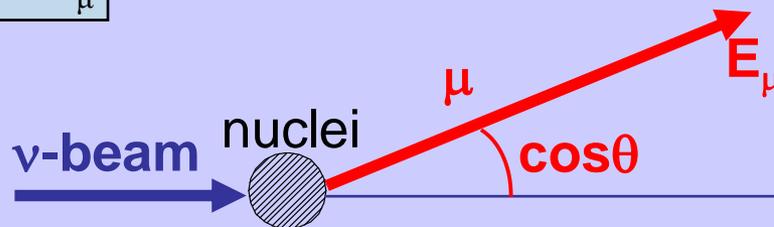
- **kinematic energy reconstruction**

NOvA ($E \sim 2000 \text{ MeV}$)

- QE, resonance, DIS

- calorimetric energy reconstruction

$$E_\nu = \frac{ME_\mu - m^2/2}{M - E_\mu + p_\mu \cos\theta_\mu}$$



CCQE (charged-current quasi-elastic)

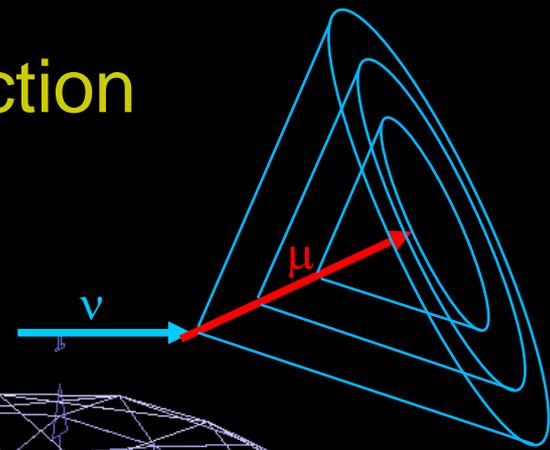
- measure muon angle and energy

2. Kinematic neutrino energy reconstruction

MiniBooNE (Mini-Booster Neutrino Experiment)

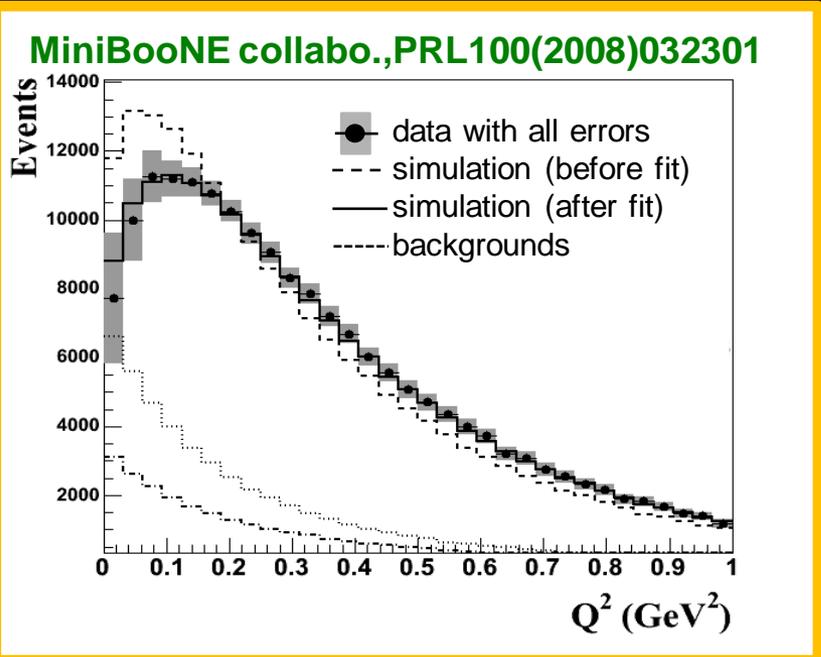
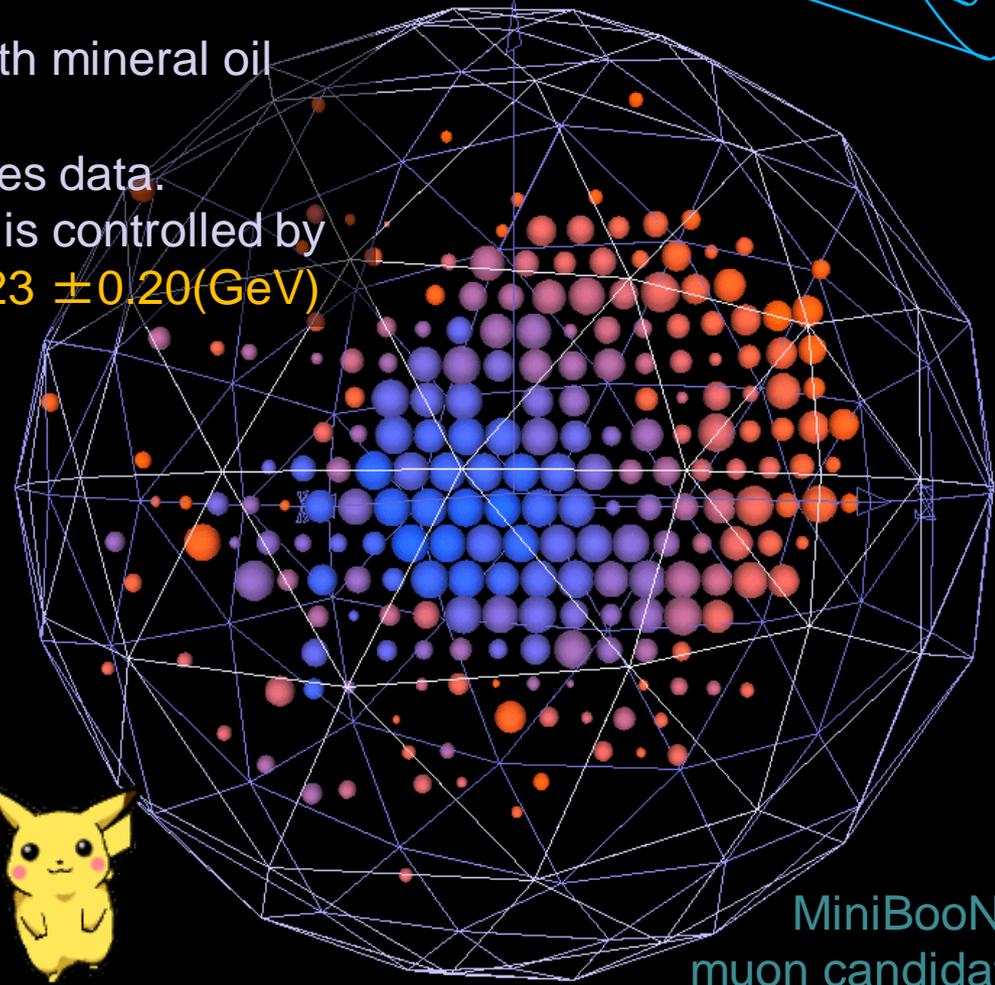
status: ongoing

- ~800MeV
- spherical Cerenkov detector, filled with mineral oil



We showed our tuned MC well describes data.

Q^2 dependence of axial vector current is controlled by axial mass, MiniBooNE obtains $M_A=1.23 \pm 0.20(\text{GeV})$



MiniBooNE
muon candidate

2. Kinematic neutrino energy reconstruction

Neutrino-Nucleon cross section

$$\frac{d\sigma}{dQ^2} = \frac{M^2 G_F^2}{8\pi v} \left[A(Q^2) \pm B(Q^2) \frac{(s-u)}{M^2} + C(Q^2) \frac{(s-u)^2}{M^4} \right]$$

$$A(Q^2) = \frac{Q^2}{M^2} \left\{ \left(1 + \frac{Q^2}{4M^2} \right) (G_A)^2 - \left(1 - \frac{Q^2}{4M^2} \right) (F_1)^2 + \frac{Q^2}{4M^2} \left(1 - \frac{Q^2}{4M^2} \right) (F_2)^2 + \frac{Q^2}{M^2} [F_1 F_2] \right\}$$

$$B(Q^2) = \frac{Q^2}{M^2} [G_A (F_1 + F_2)]$$

$$C(Q^2) = \frac{1}{4} \left\{ (G_A)^2 + (F_1)^2 + \frac{Q^2}{4M^2} (F_2)^2 \right\}$$

$$G_A(Q^2) = \frac{g_A}{\left(1 + \frac{Q^2}{M_A^2} \right)^2}$$

axial coupling constant (=1.2671)

axial vector form factor

axial mass (=1.03 GeV, default)

2. Kinematic neutrino energy reconstruction

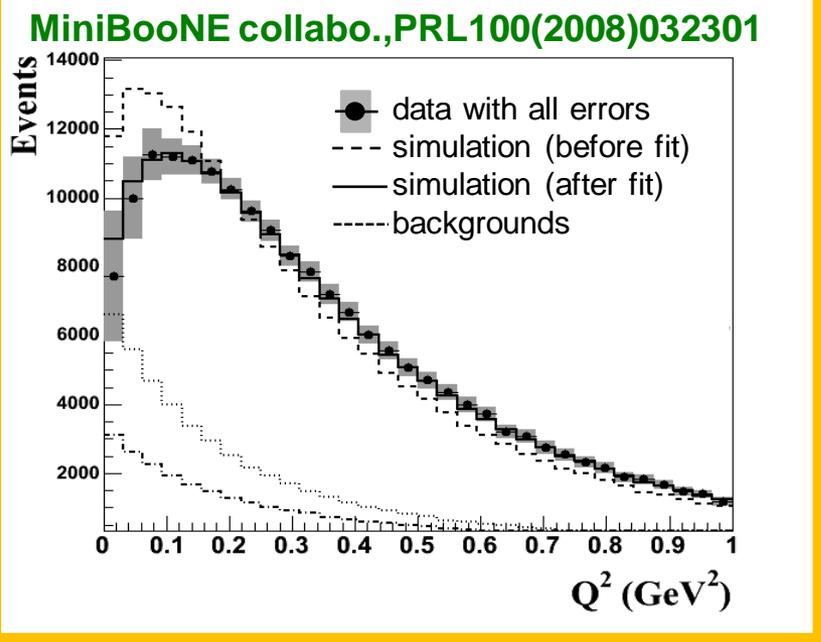
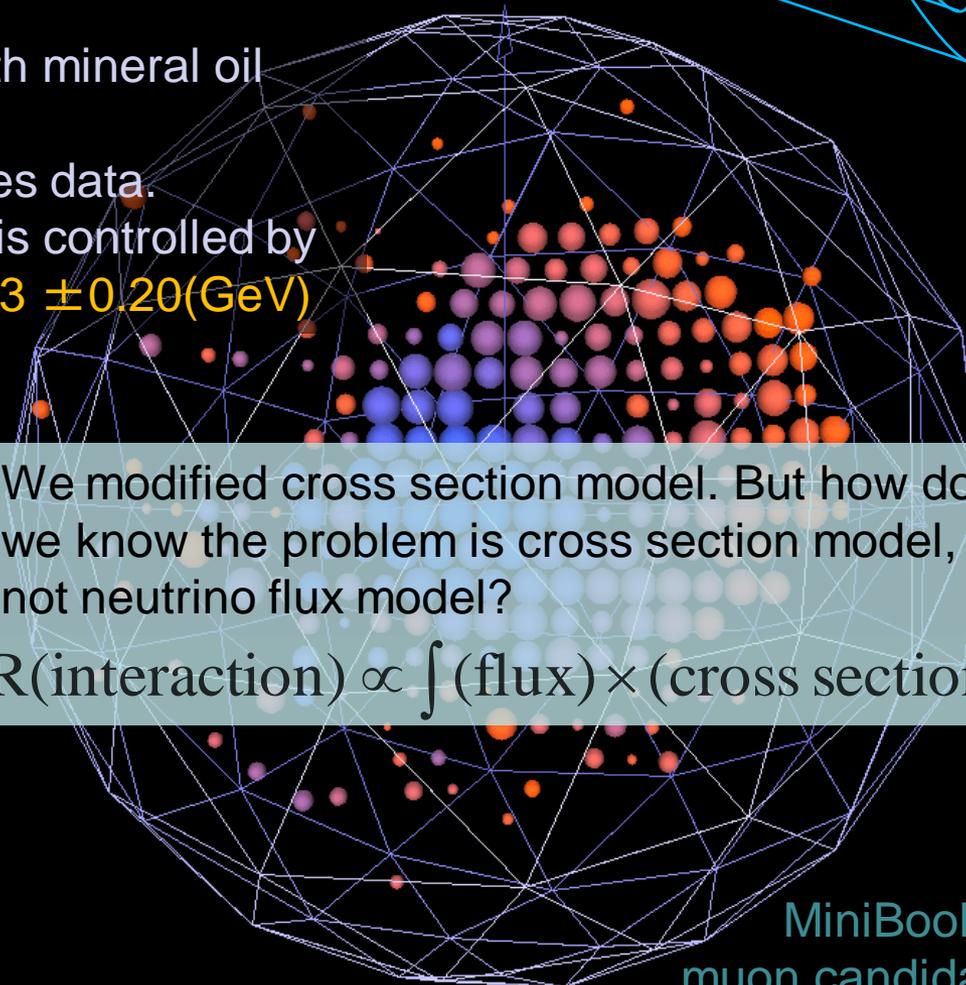
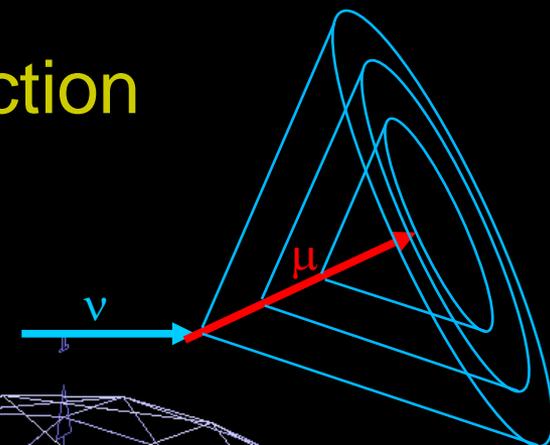
MiniBooNE (Mini-Booster Neutrino Experiment)

status: ongoing

- ~800MeV
- spherical Cerenkov detector, filled with mineral oil

We showed our tuned MC well describes data.

Q^2 dependence of axial vector current is controlled by axial mass, MiniBooNE obtains $M_A = 1.23 \pm 0.20 (\text{GeV})$



We modified cross section model. But how do we know the problem is cross section model, not neutrino flux model?

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

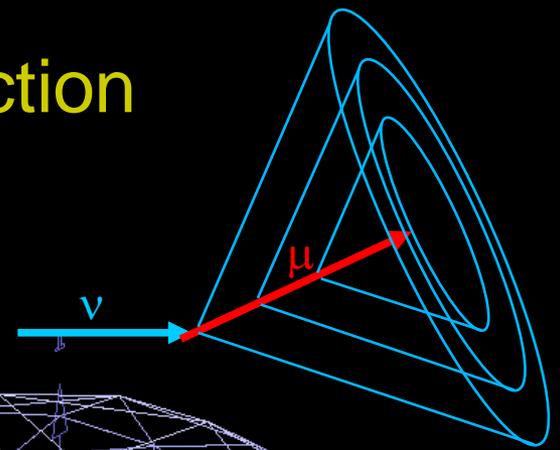
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muon candidate

2. Kinematic neutrino energy reconstruction

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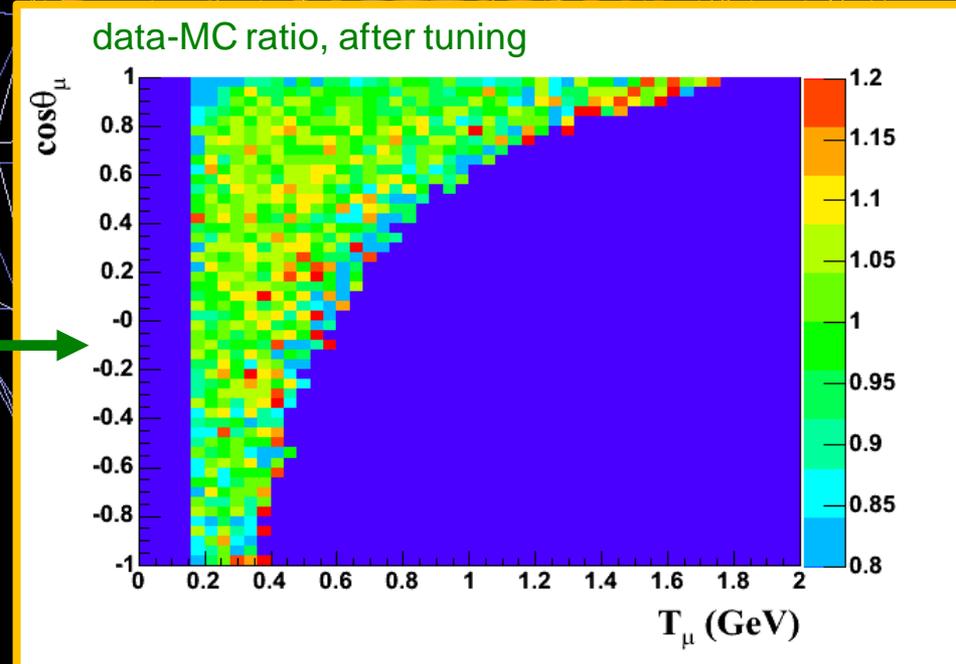
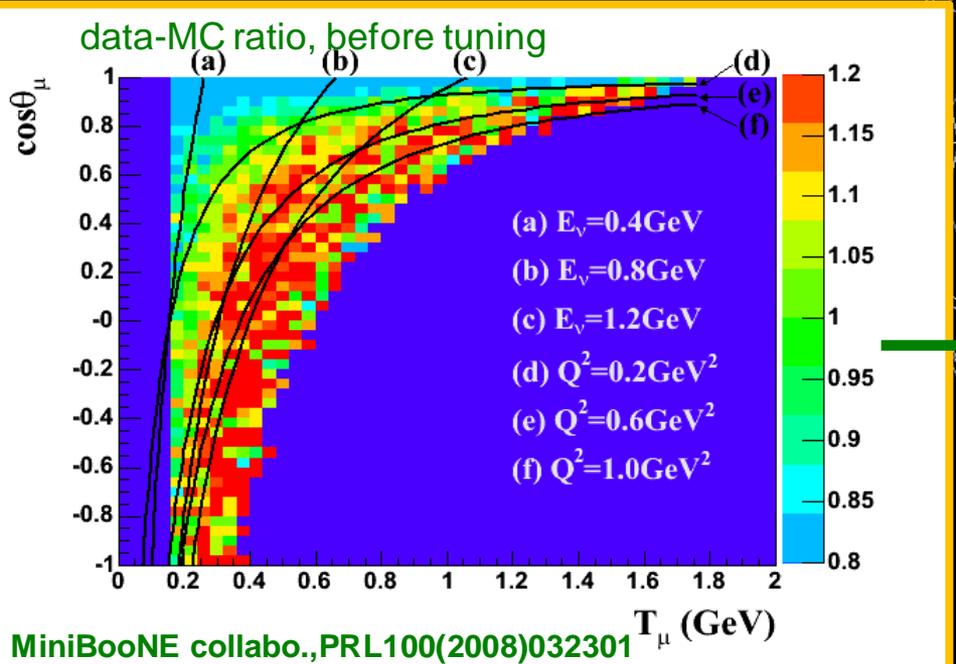
status: ongoing

- ~800MeV
- spherical Cerenkov detector, filled with mineral oil



(a),(b),(c) : equal reconstructed E_ν lines
 (d),(e),(f) : equal reconstructed Q^2 lines
data-MC disagreement follows equal Q^2 !

$$R \propto \int (\text{flux}[E_\nu]) \times (\text{cross section}[Q^2])$$



2. Kinematic neutrino energy reconstruction

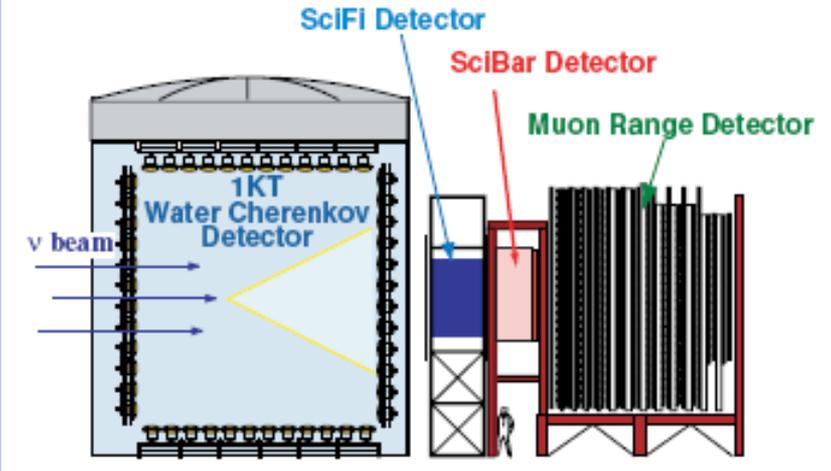
K2K (KEK to Kamioka experiment)
 status: completed
 - ~1.5GeV
 - fine-grained scintillator



Both SciFi and SciBar measure CCQE interactions,
 and measured axial mass,

SciFi $M_A = 1.20 \pm 0.12$ (GeV) K2K collabo., PRD74(2006)052002

SciBar $M_A = 1.14 \pm 0.11$ (GeV) K2K collabo., NuInt07

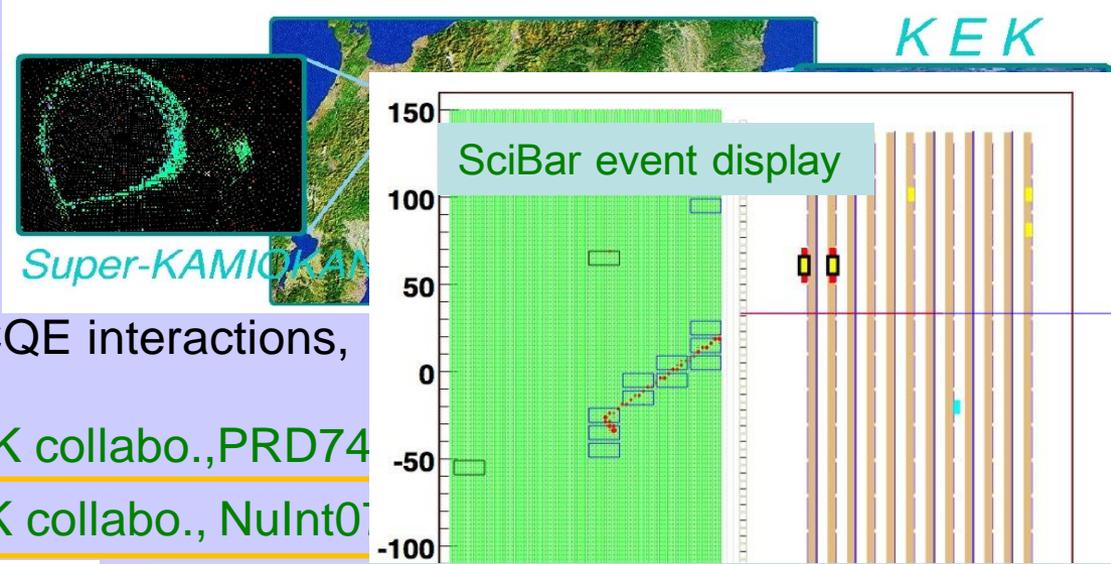


Modern experiments, such as MiniBooNE and K2K agree well for M_A , but many sigmas off from world average
 average (2001) $M_A = 1.03 \pm 0.03$ (GeV)

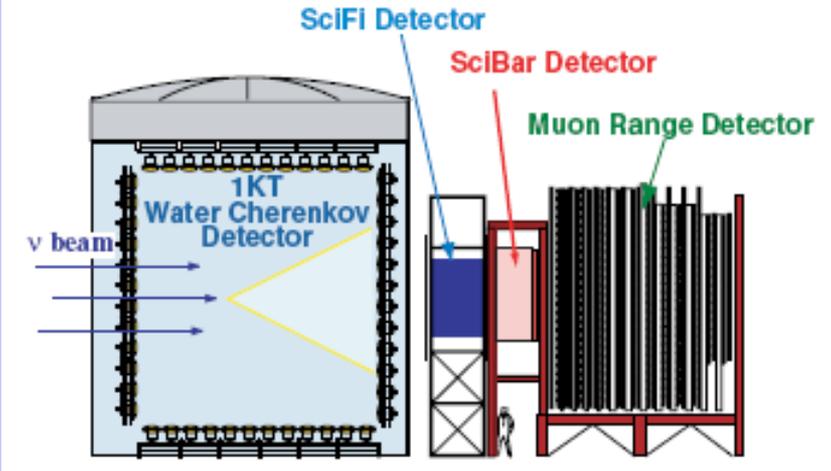
~15% increase of M_A increase ~10% neutrino rate!
 (nuclear effect?)

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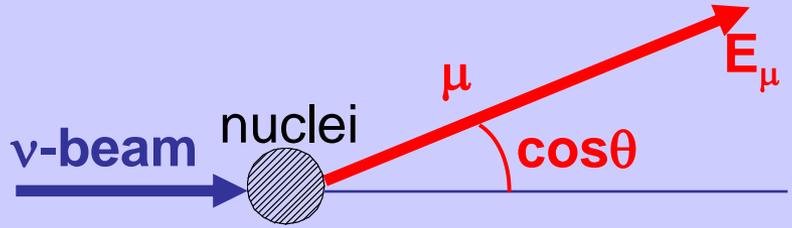
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2. Non-QE rejection for kinematic energy reconstruction

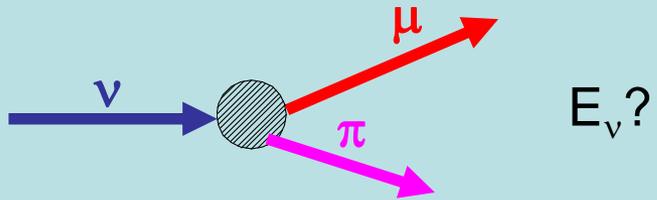
T2K ($E \sim 800 \text{ MeV}$)
 - quasi-elastic (QE)
 - **kinematic energy reconstruction**

$$E_\nu = \frac{ME_\mu - m^2/2}{M - E_\mu + p_\mu \cos\theta_\mu}$$

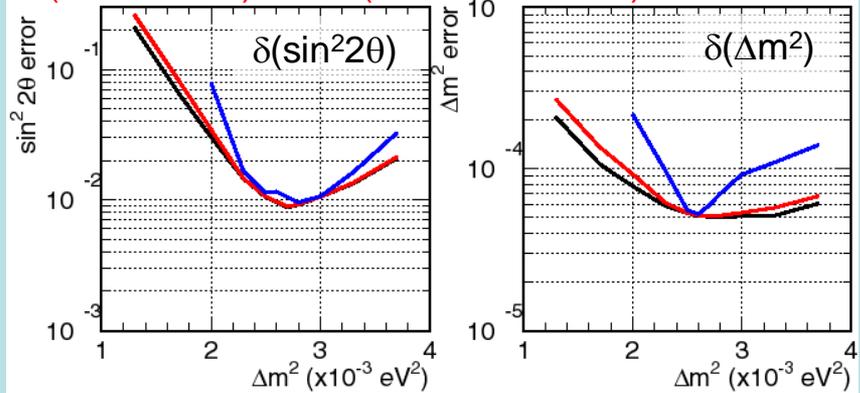


CCQE (charged-current quasi-elastic)
 - measure muon angle and energy

CC backgrounds (non-QE) spoils kinematic reconstruction.



statistic error only
 $\delta(\text{nonQE}/\text{QE}) = 20\%$ (before SciBooNE)
 $\delta(\text{nonQE}/\text{QE}) = 5\%$ (after SciBooNE)



2. Non-QE rejection for kinematic energy reconstruction

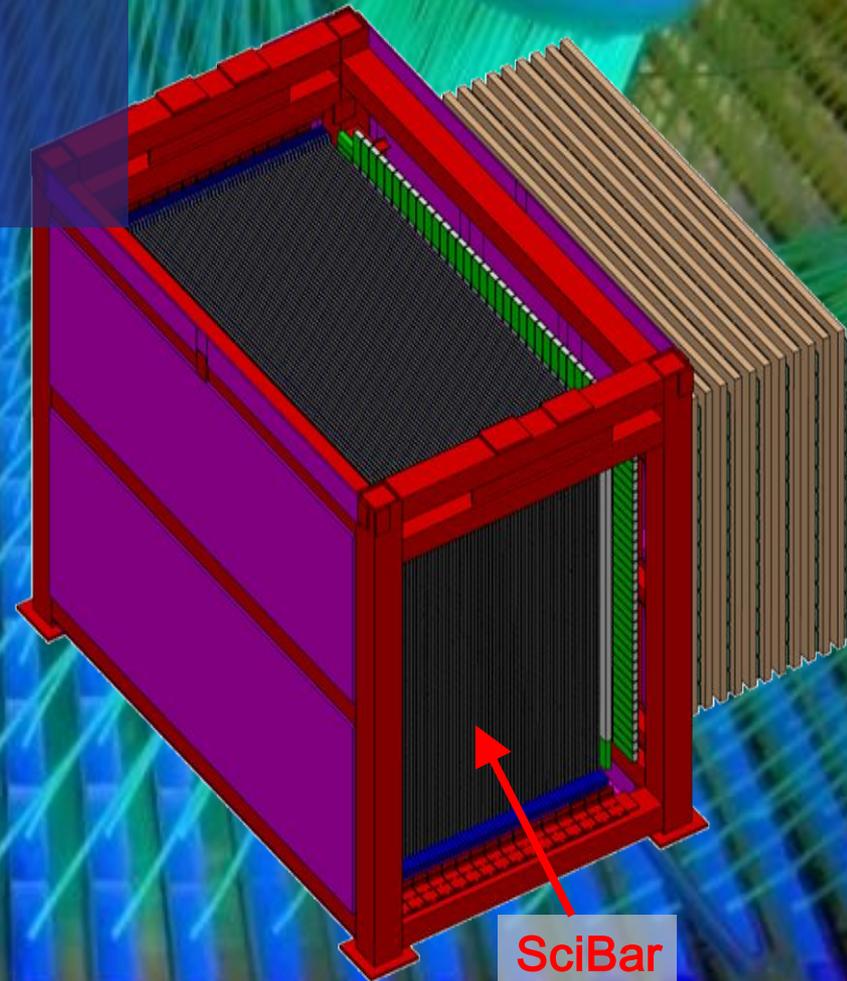
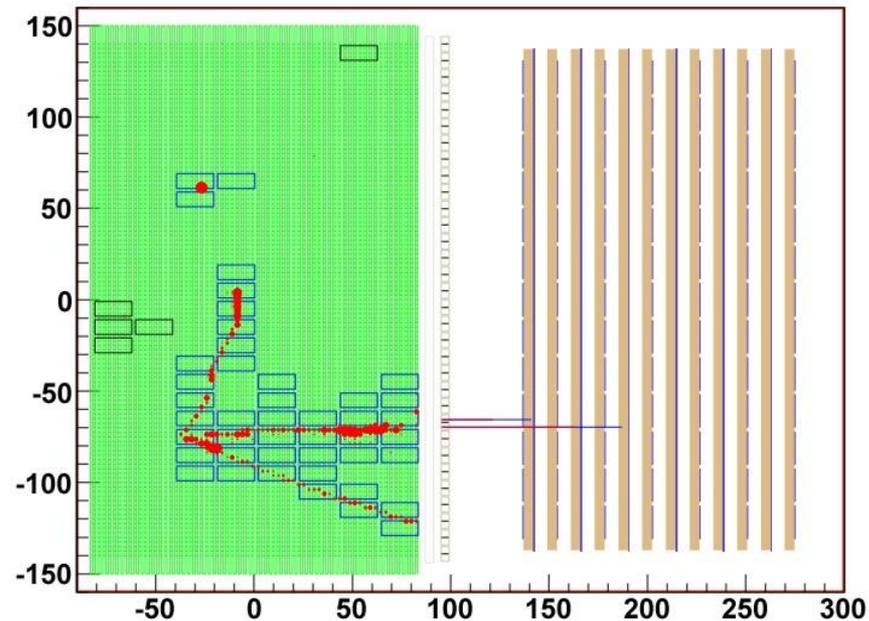
SciBooNE (SciBar Booster Neutrino Experiment)

status: ongoing

- ~800MeV
- fine-grained scintillator
- detector is recycled from K2K experiment

Goal is to measure nonQE/QE ~5% accuracy

SciBooNE data



1. Neutrino oscillation experiments

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2.1 Kinematic energy reconstruction

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3. Background reactions

4. Conclusion

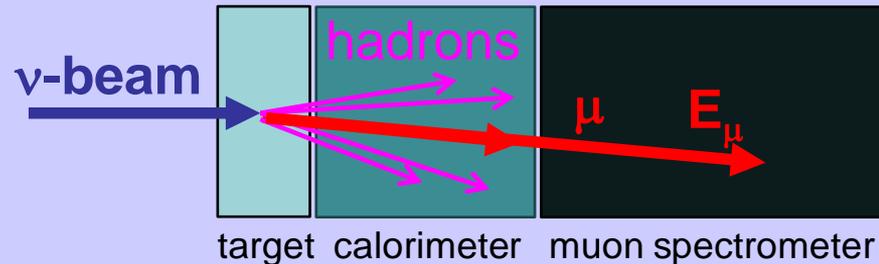
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To understand neutrino oscillation, reconstruction of neutrino energy is essential. These 2 energy scales require 2 different schemes for energy reconstruction.

T2K ($E \sim 800 \text{ MeV}$)
- quasi-elastic (QE)
- kinematic energy reconstruction

NOvA ($E \sim 2000 \text{ MeV}$)
- QE, resonance, DIS
- **calorimetric energy reconstruction**

$$E_{\nu} = E_{\mu} + E_{\text{showers}}$$



CC inclusive

- measure muon and total energy deposit

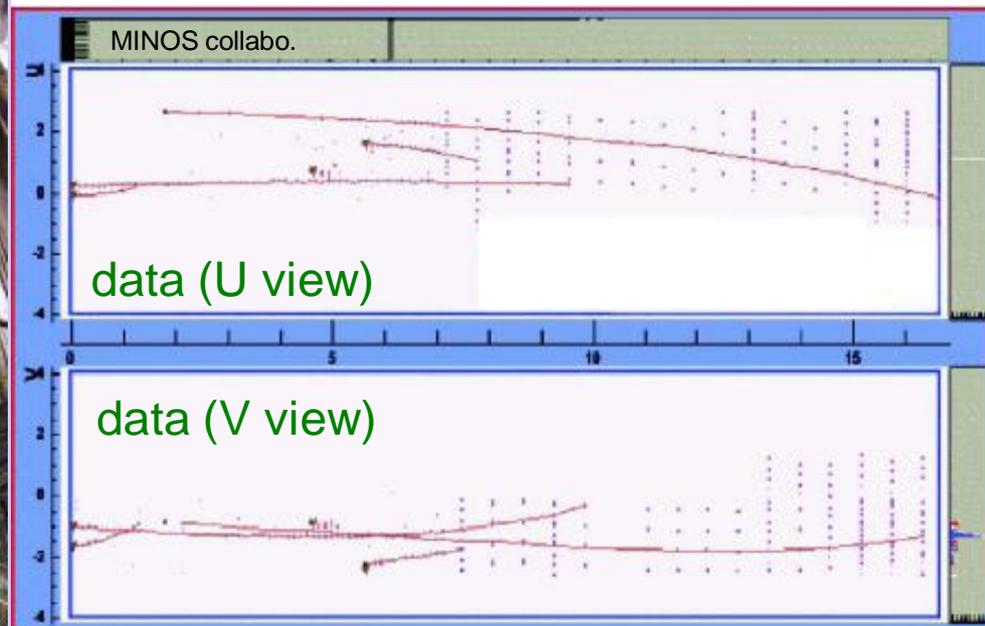
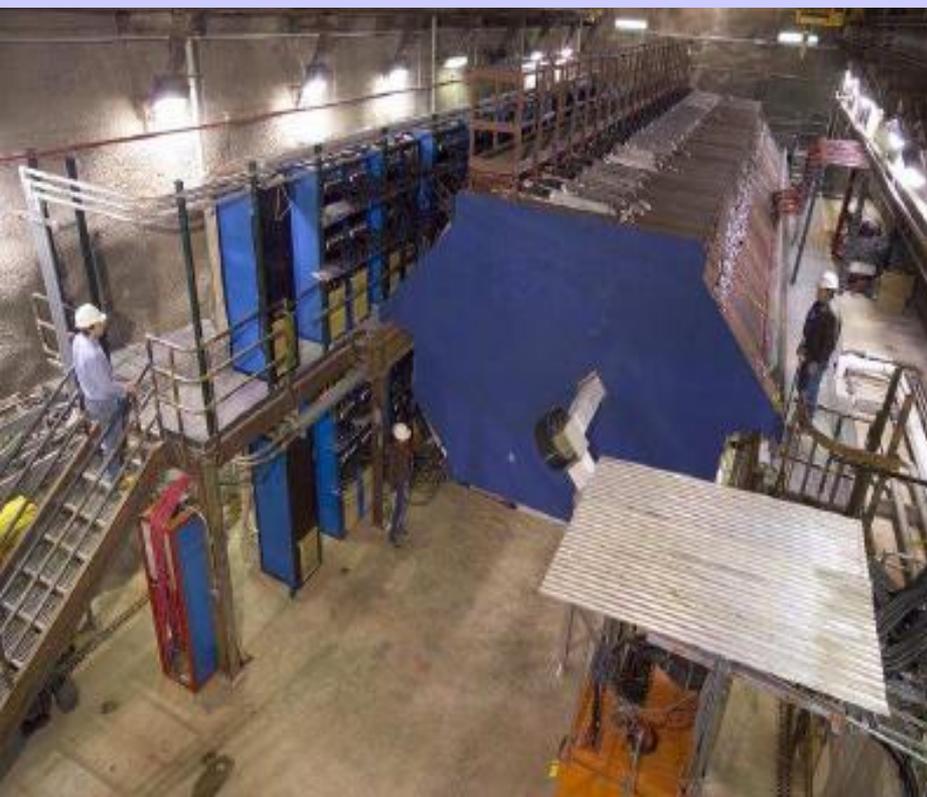
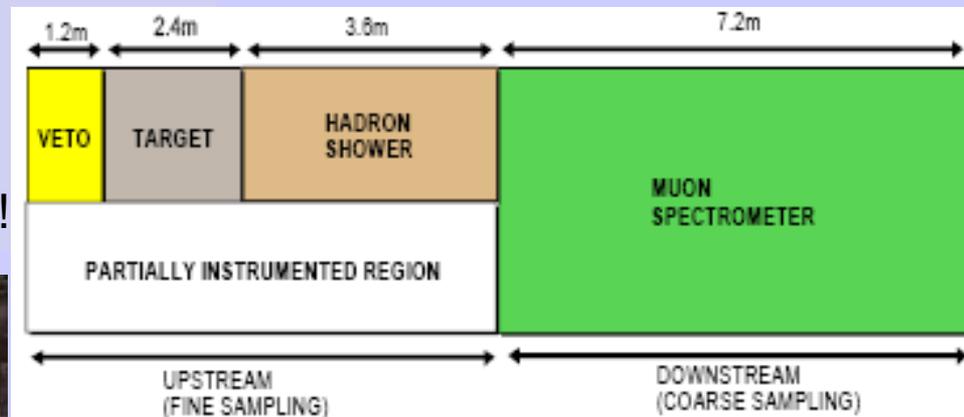
2. Calorimetric neutrino energy reconstruction

MINOS (Main Injector Neutrino Oscillation Search)

status: ongoing

- ~1-20GeV
- steel and scintillator
- magnetized for muon sign separation

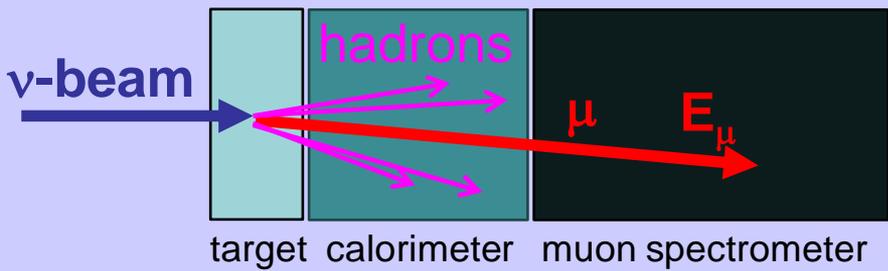
K2K/MiniBooNE CCQE will be tested here!



2. Nuclear effects for calorimetric energy reconstruction

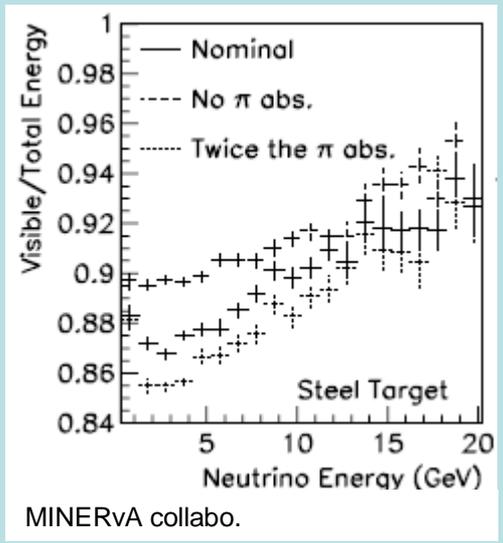
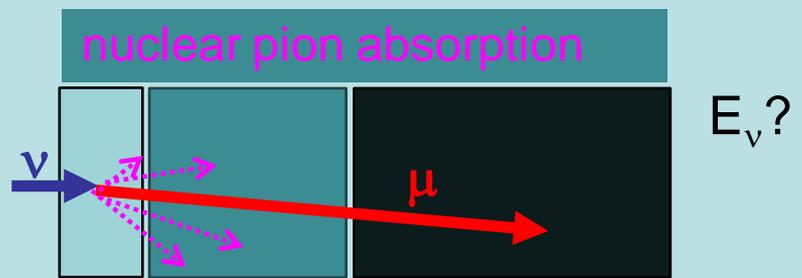
NOvA ($E \sim 2000 \text{ MeV}$)
 - QE, resonance, DIS
 - calorimetric energy reconstruction

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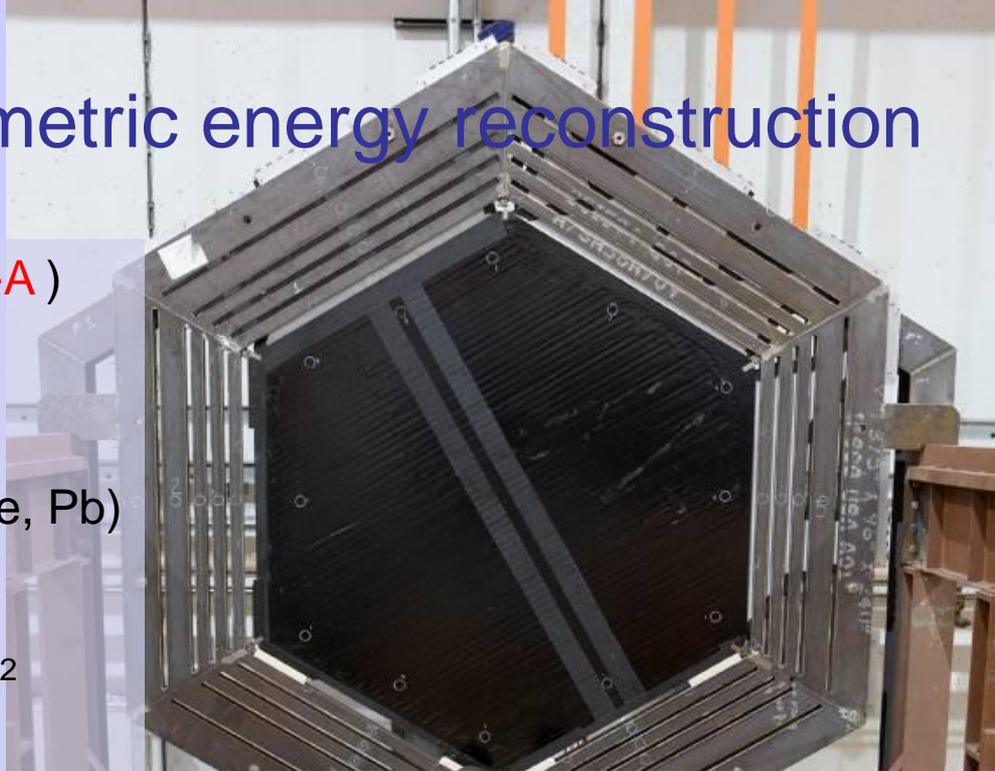
CC inclusive
 - measure muon and total energy deposit

Missing energy (nuclear effect) spoils calorimetric energy reconstruction

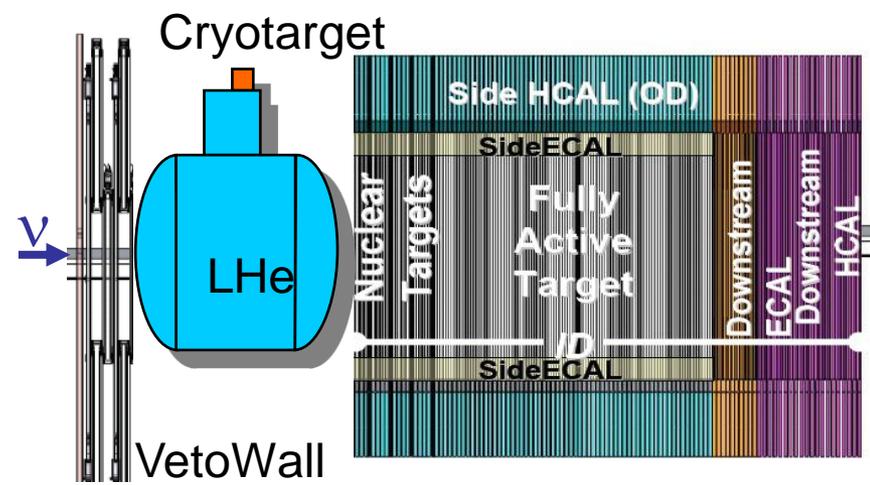
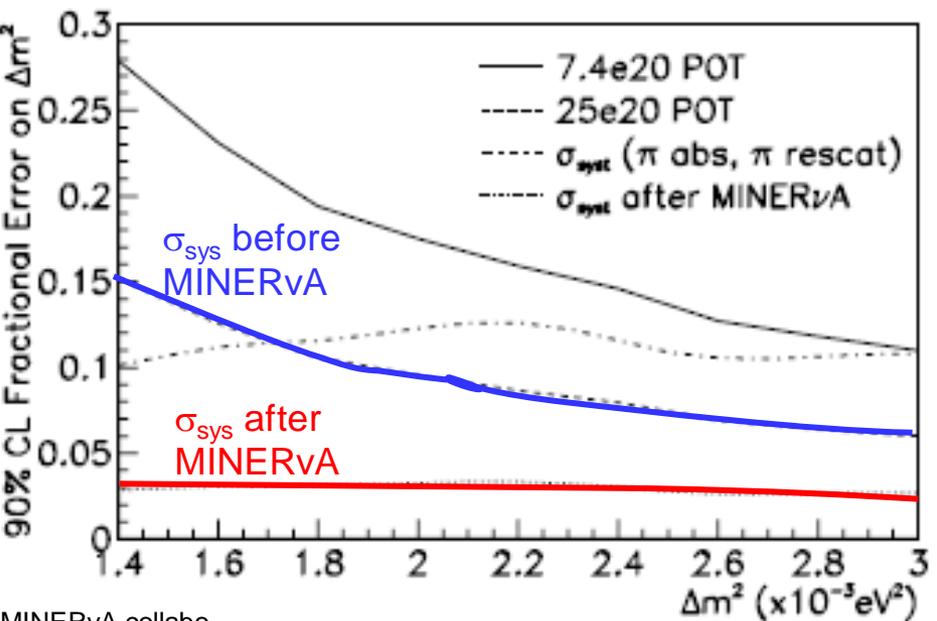


2. Nuclear effects for calorimetric energy reconstruction

MINERvA (Main INjector ExpeRiment for ν -A)
 status: approved, commissioning in 2009
 - ~1-20GeV
 - fine grained scintillator and calorimeter
 - can change the nuclear targets (He, C, Fe, Pb)



Their R&D shows studies of nuclear effects significantly reduce systematic error for Δm^2 extraction



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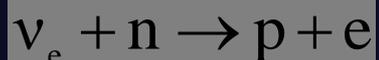
3. Background reactions

4. Conclusion

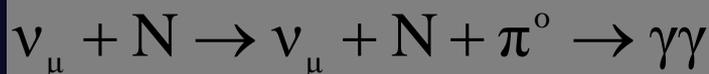
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ν_e appearance

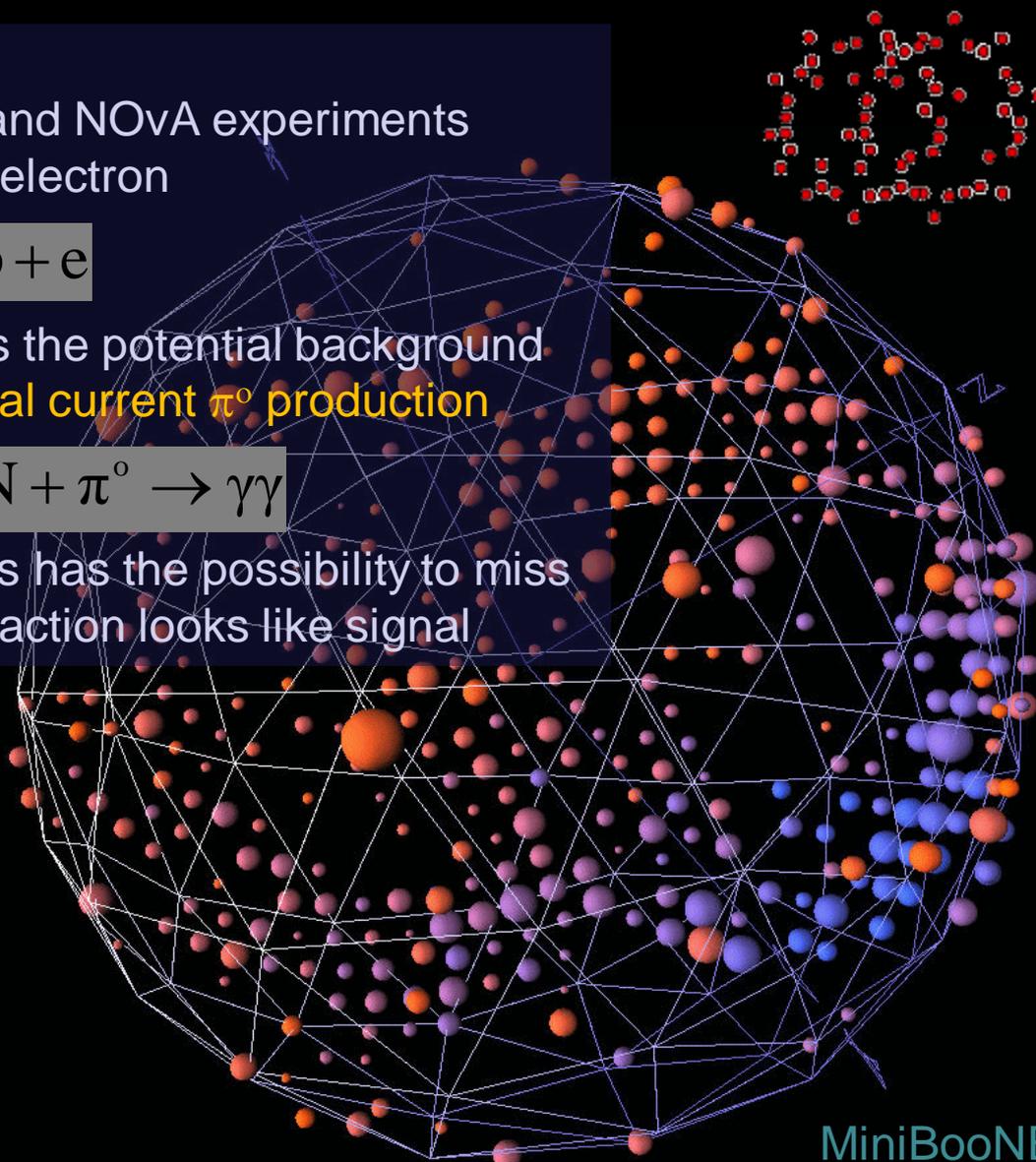
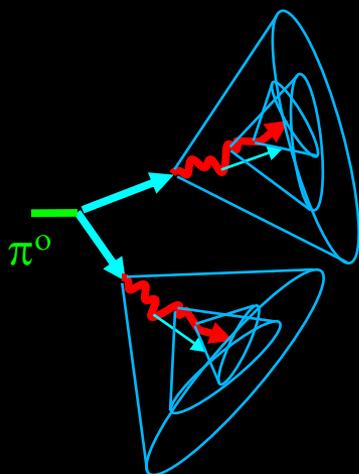
- signal of $\sin^2 2\theta_{13}$, goal of T2K and NOvA experiments
- ν_e candidate is a single isolated electron



- single electromagnetic shower is the potential background
- the notable background is **Neutral current π^0 production**



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

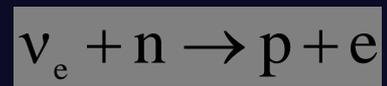


MiniBooNE
NC π^0 candidate

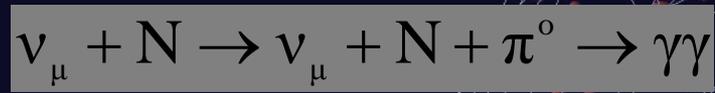
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ν_e appearance

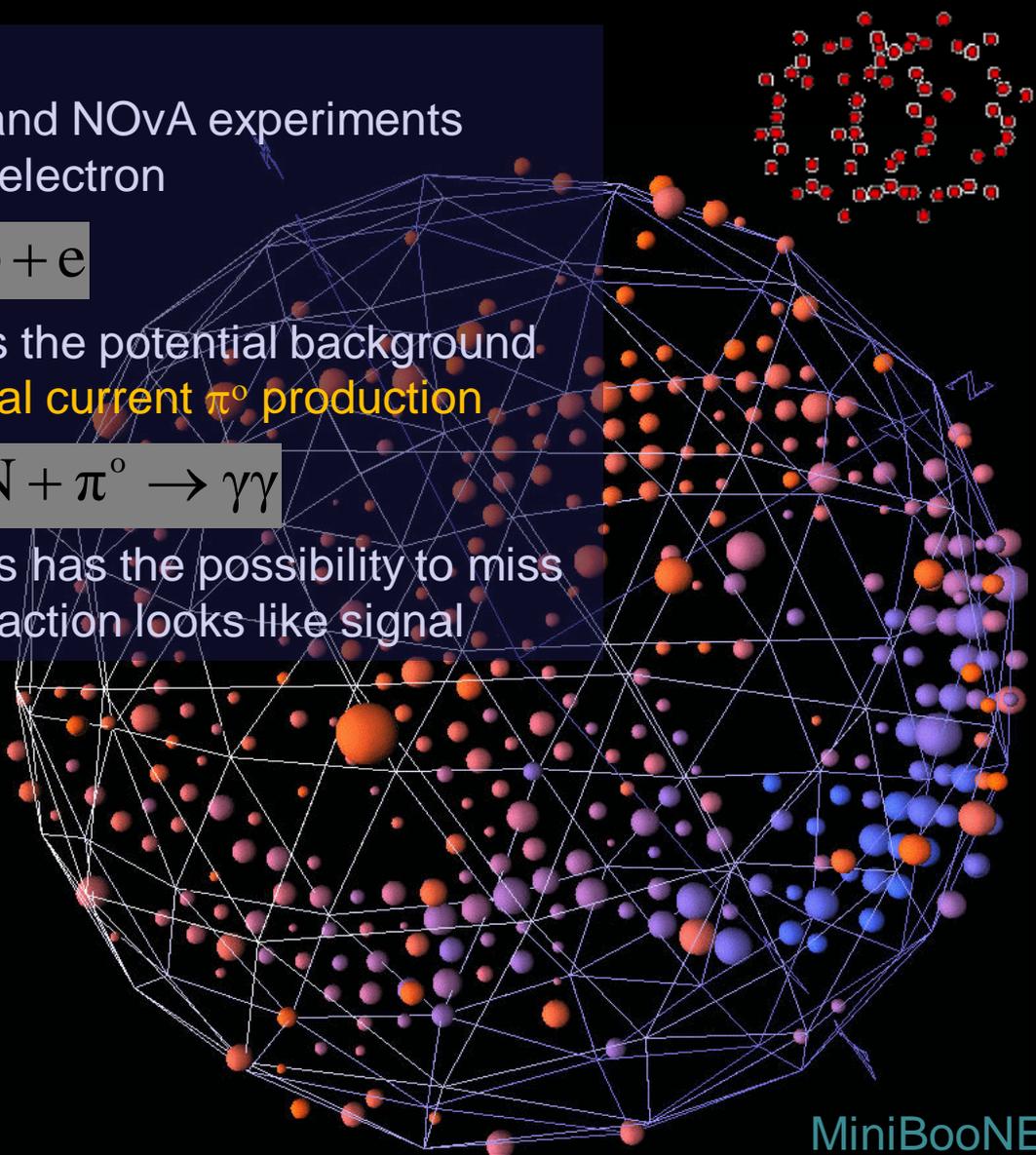
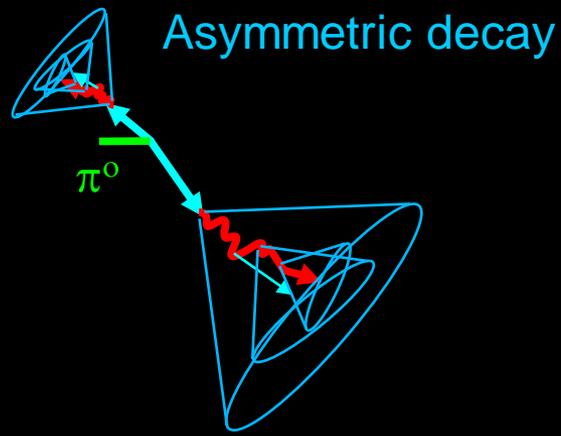
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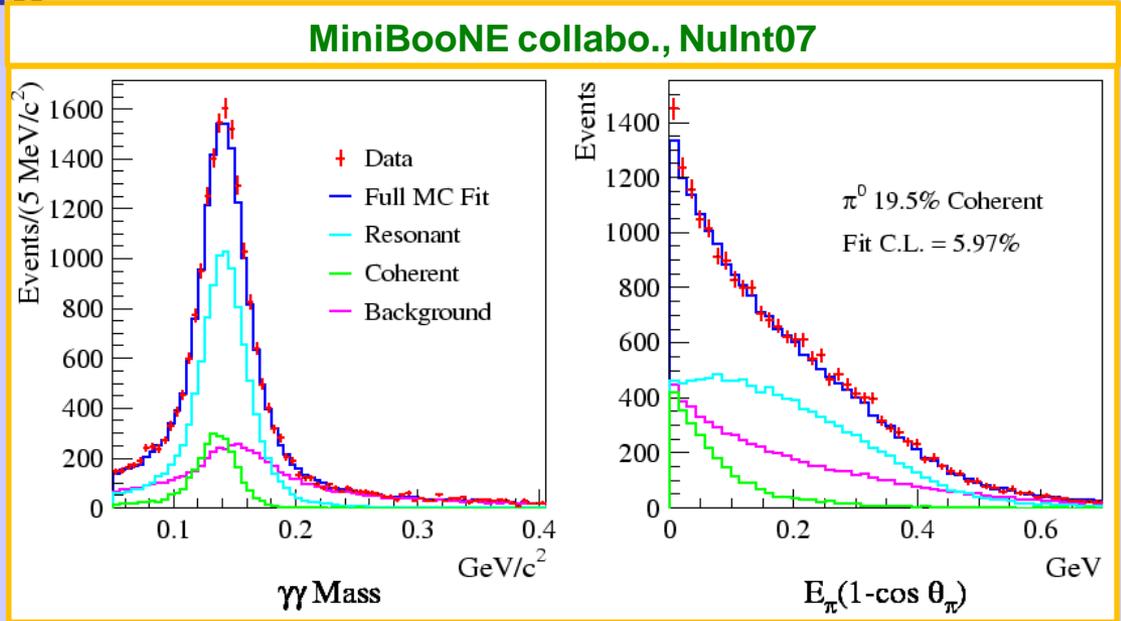
MiniBooNE
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3. Background reactions

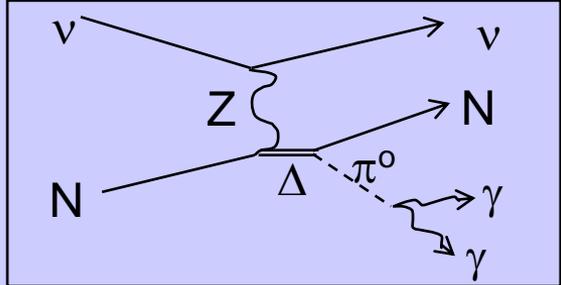
MiniBooNE

We tuned MC to describe π^0 distribution correctly for ν_e appearance search.

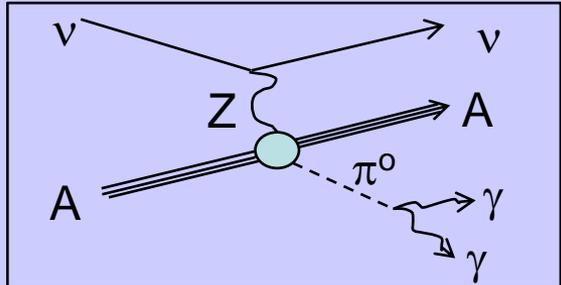
NC π^0 data fit well with resonance and coherent π^0 production MC



Resonance



Coherent

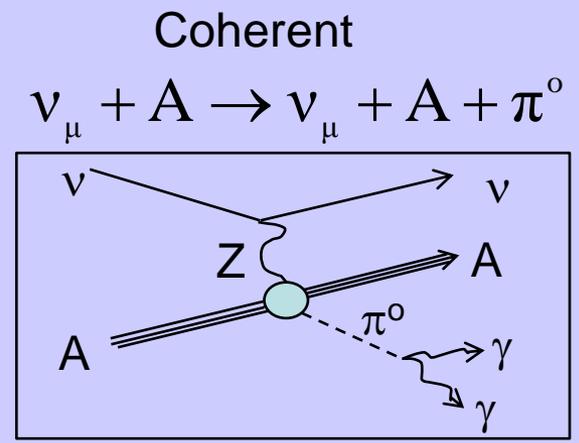
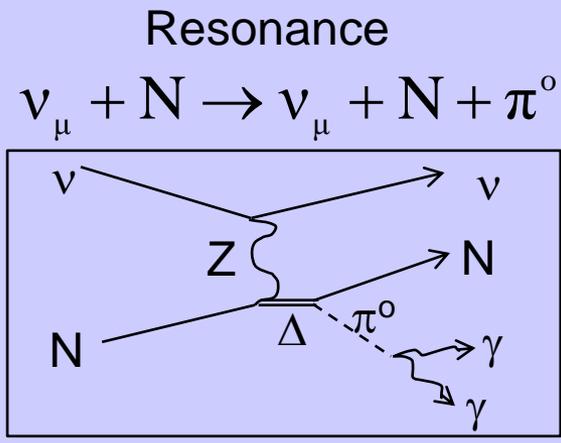
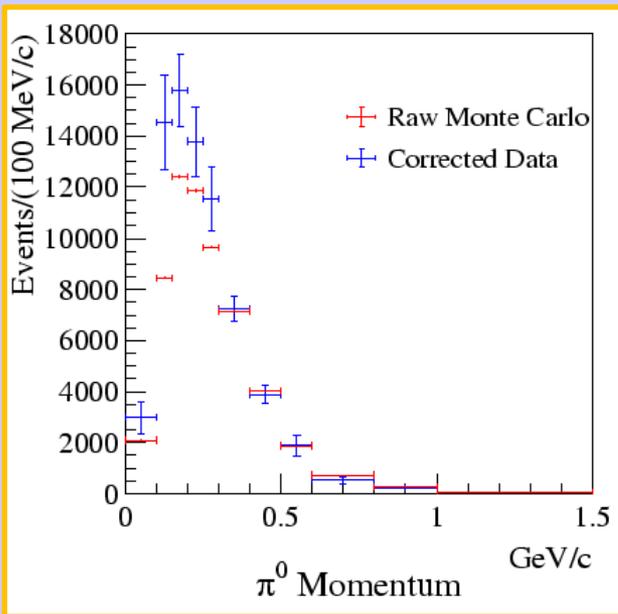
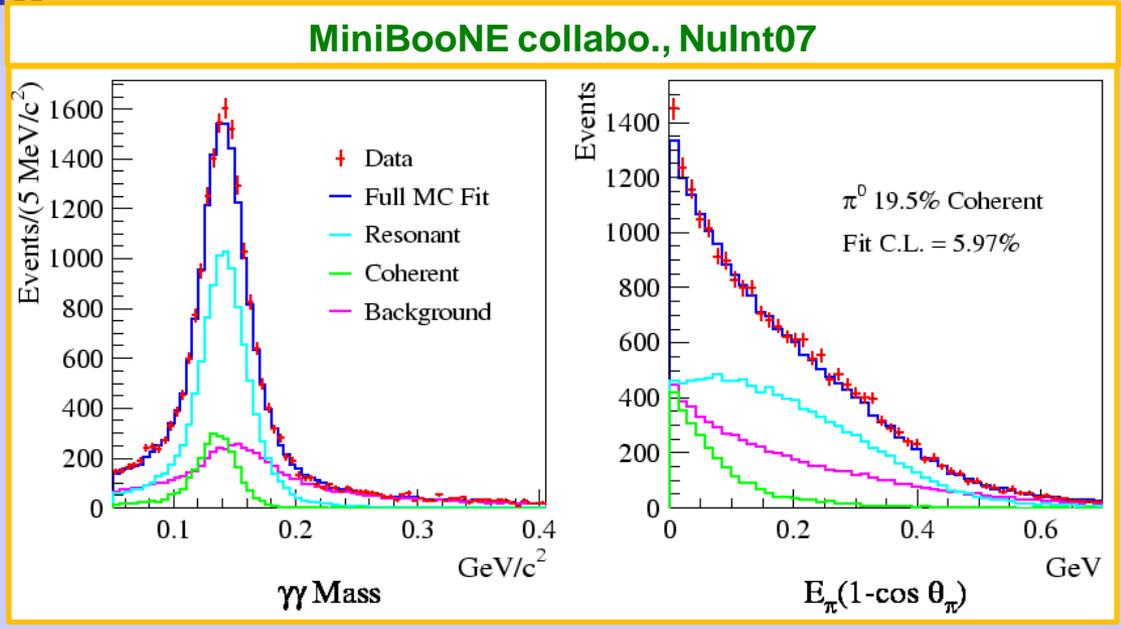


3. Background reactions

MiniBooNE

We tuned MC to describe π^0 distribution correctly for ν_e appearance search.

NC π^0 data fit well with resonance and coherent π^0 production MC



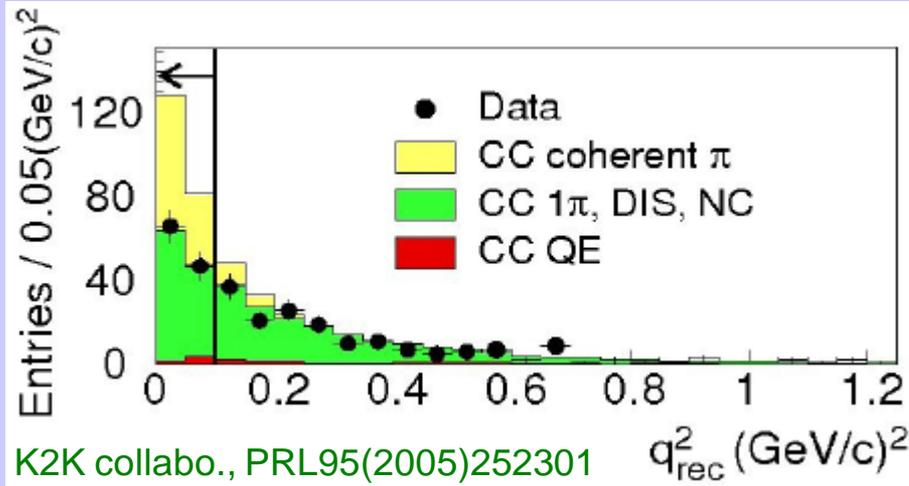
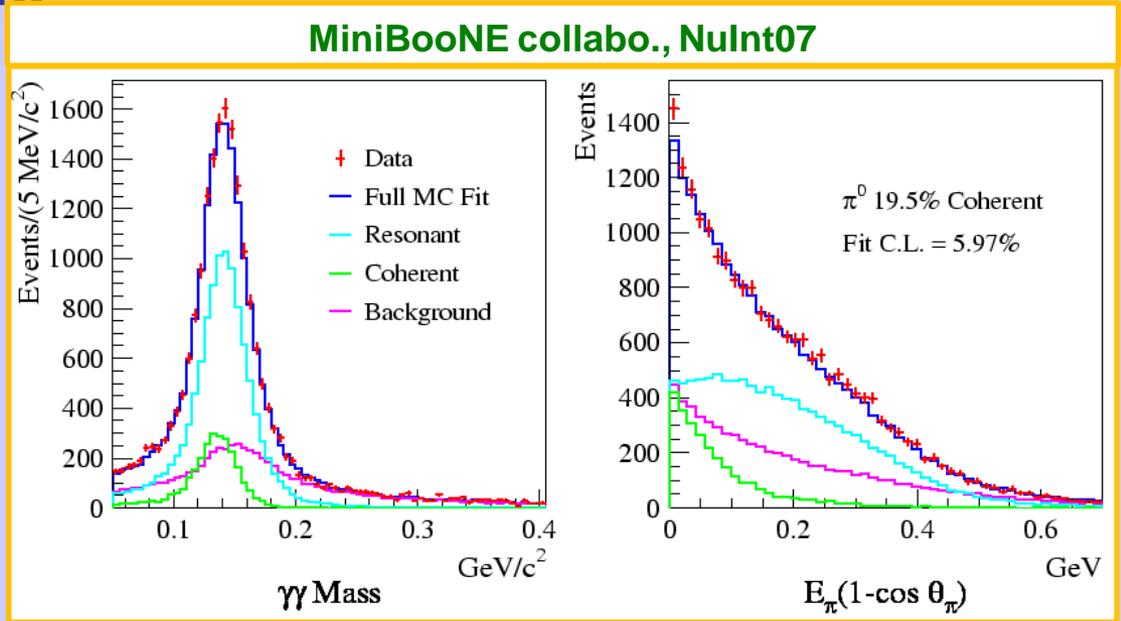
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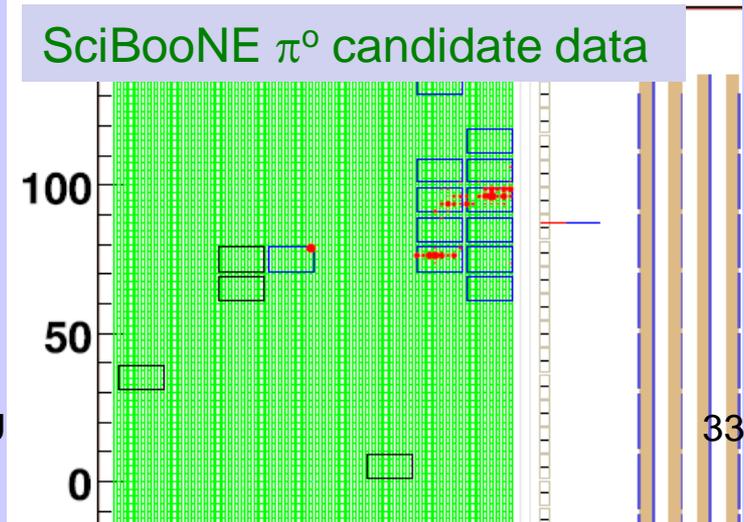
K2K

They suggest no CC coherent π^+ production.

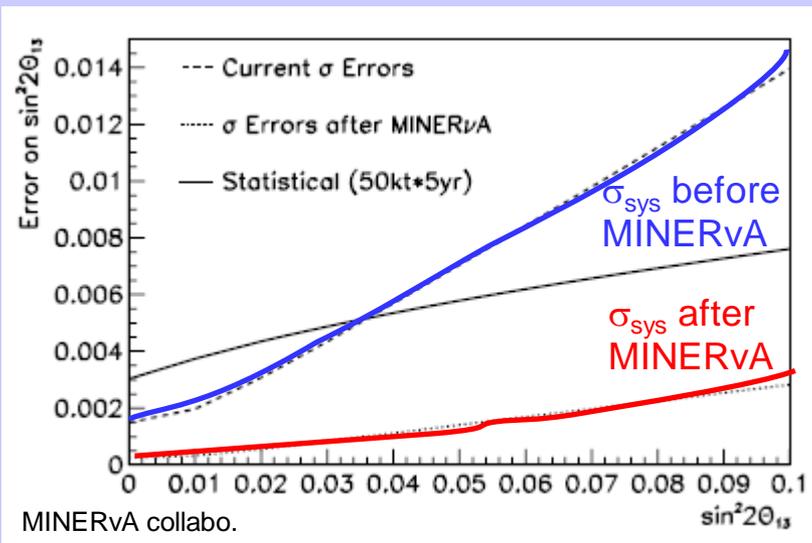


SciBooNE

Study for NC π^0 reaction is ongoing.

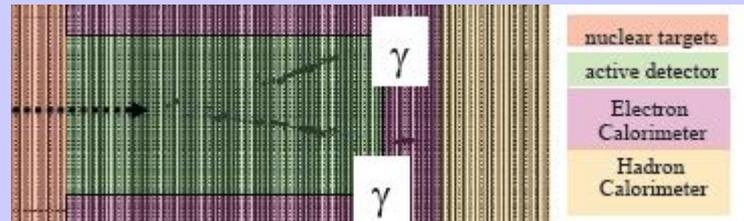
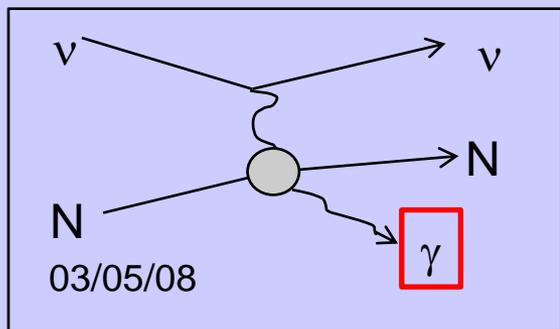


3. Background reactions



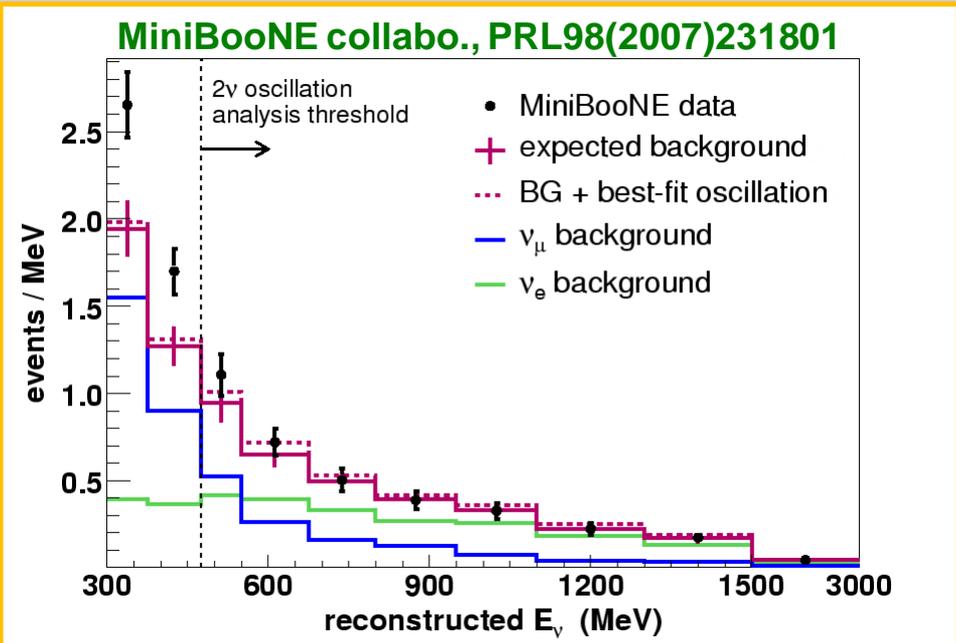
MiniBooNE

If unexpected low energy excess is cross section systematics, it might be a potential background for T2K and NOvA



MINERvA

They can measure the high energy backgrounds which other experiments are not accessible



4. Conclusion

Next generation oscillation experiments have 2 goals

- (1) precision measurements for $\Delta m_{\mu\tau}^2$ and $\sin^2 2\theta_{23}$ through ν_{μ} events
 - Accurate neutrino energy reconstruction
- (2) ν_e appearance measurement
 - Careful rejection of background reactions

Neutrino scattering experiments play crucial roles for next generation neutrino oscillation experiments

Thank you for your attention!

10. Back up

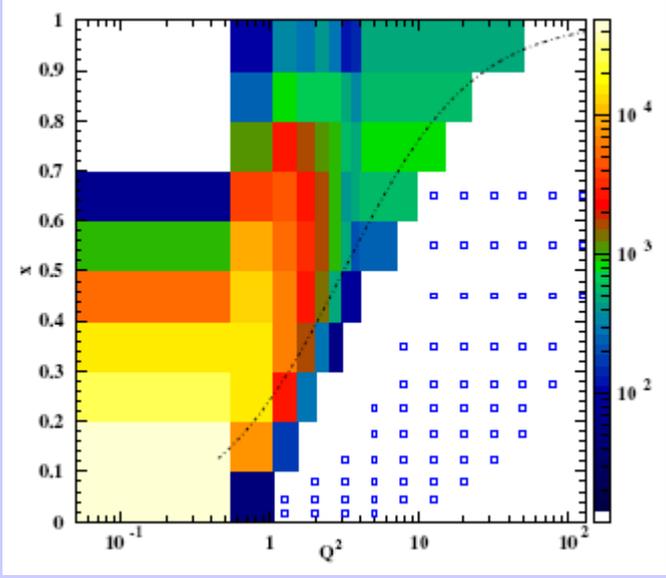
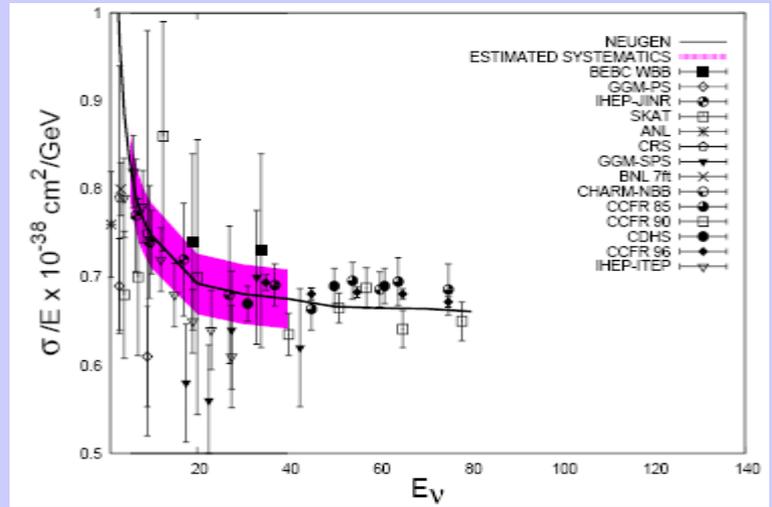
4. Other physics

MINOS

Total cross section measurement, normalized to world average at high energy

MINERvA

High statistics data on Q^2 - x_{Bj} space will shed the light on resonance-DIS transition region



SciBooNE

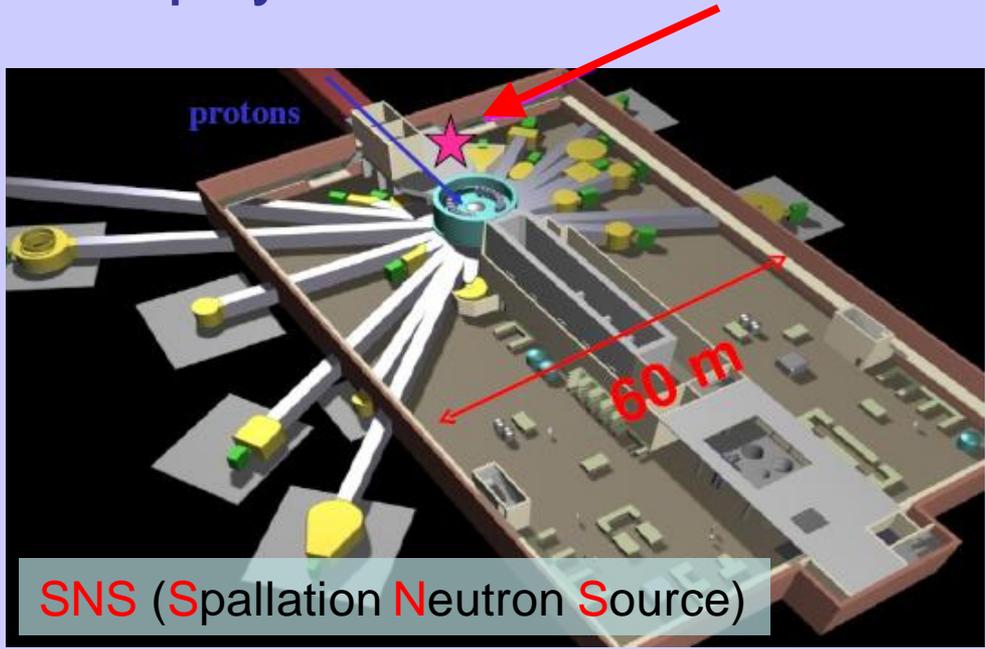
NC elastic scattering events have information of strange quark spin in nucleon

$$G_A^s(Q^2 = 0) = \Delta s = \int_0^1 \Delta s(x) dx$$

BNL-E734(neutrino)
 $\Delta s \sim -0.2$

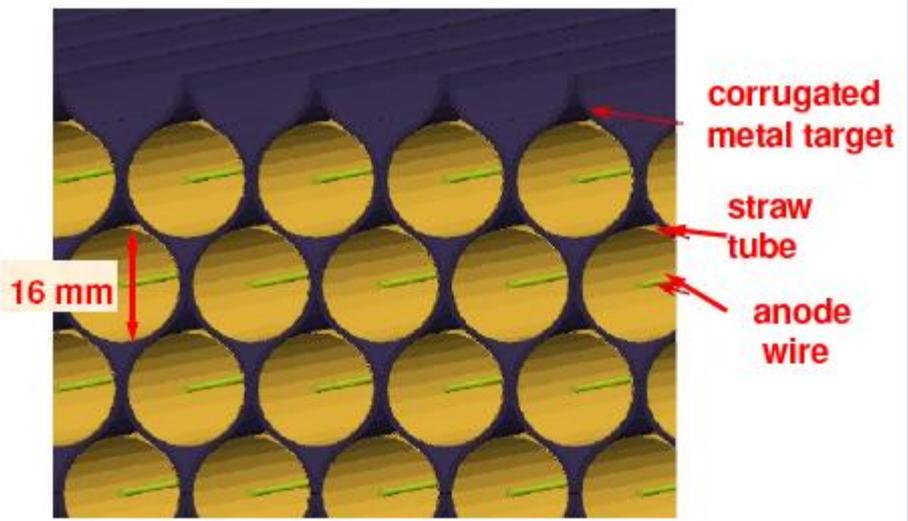
EMC(IDIS) $\Delta s \sim -0.1$
 HERMES(SIDIS) $\Delta s \sim 0.03$

4. Astrophysics

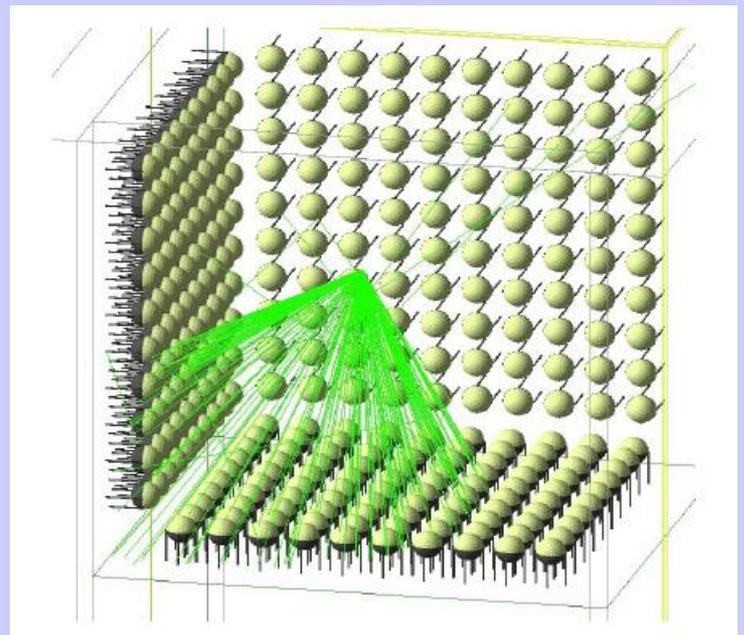


NuSNS (Neutrinos at the SNS)
Coherent scattering cross section with both light and heavy nuclei are the important input for supernova explosion simulation

NuSNS heavy element target (Al, Fe, Pb)

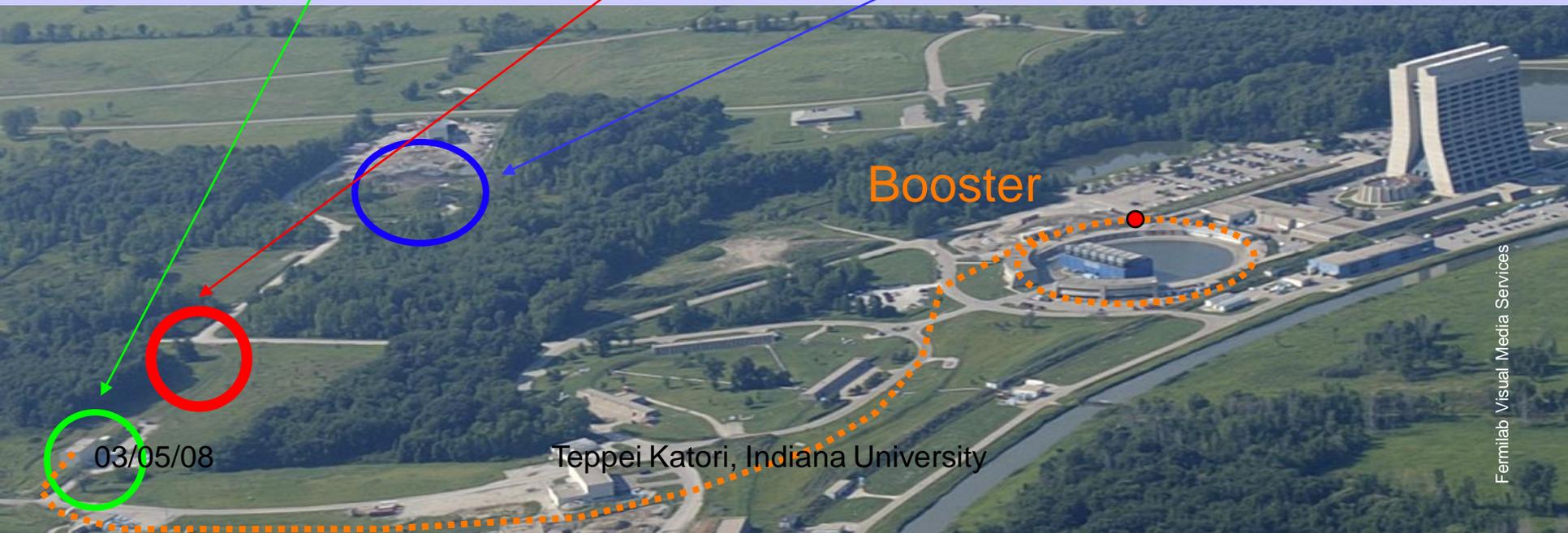
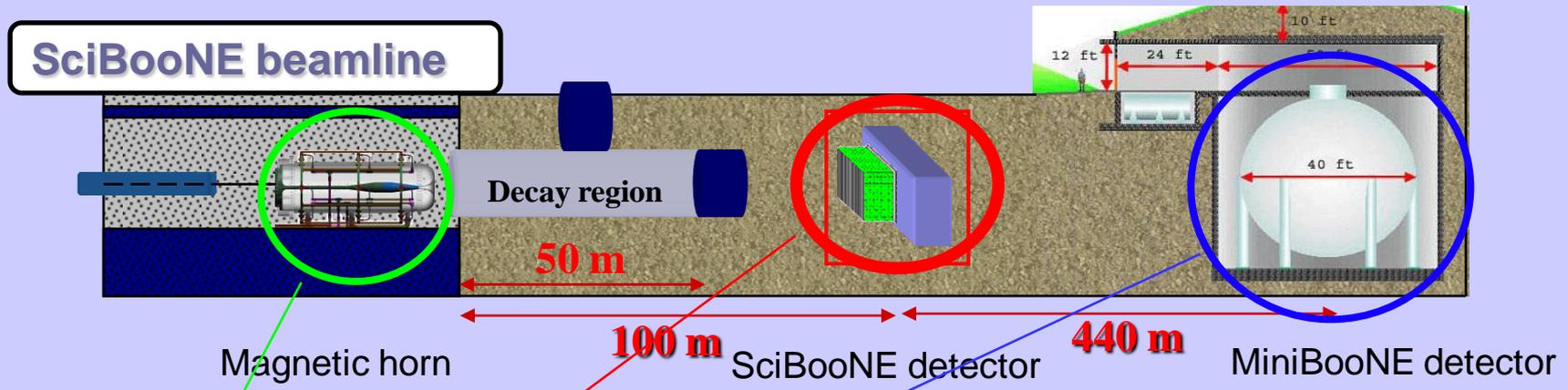


NuSNS light element target (H, C, O)



4. Short baseline oscillation experiment

SciBooNE/MiniBooNE combined oscillation experiment



1. CC (Charged-Current) cross section

CC reaction is essential for neutrino experiments.
There are many reactions in this narrow energy region!

