Neutrino cross section measurements for long-baseline neutrino oscillation experiments

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SciBooNE vertex detector "SciBar"

1. Neutrino oscillation experiments

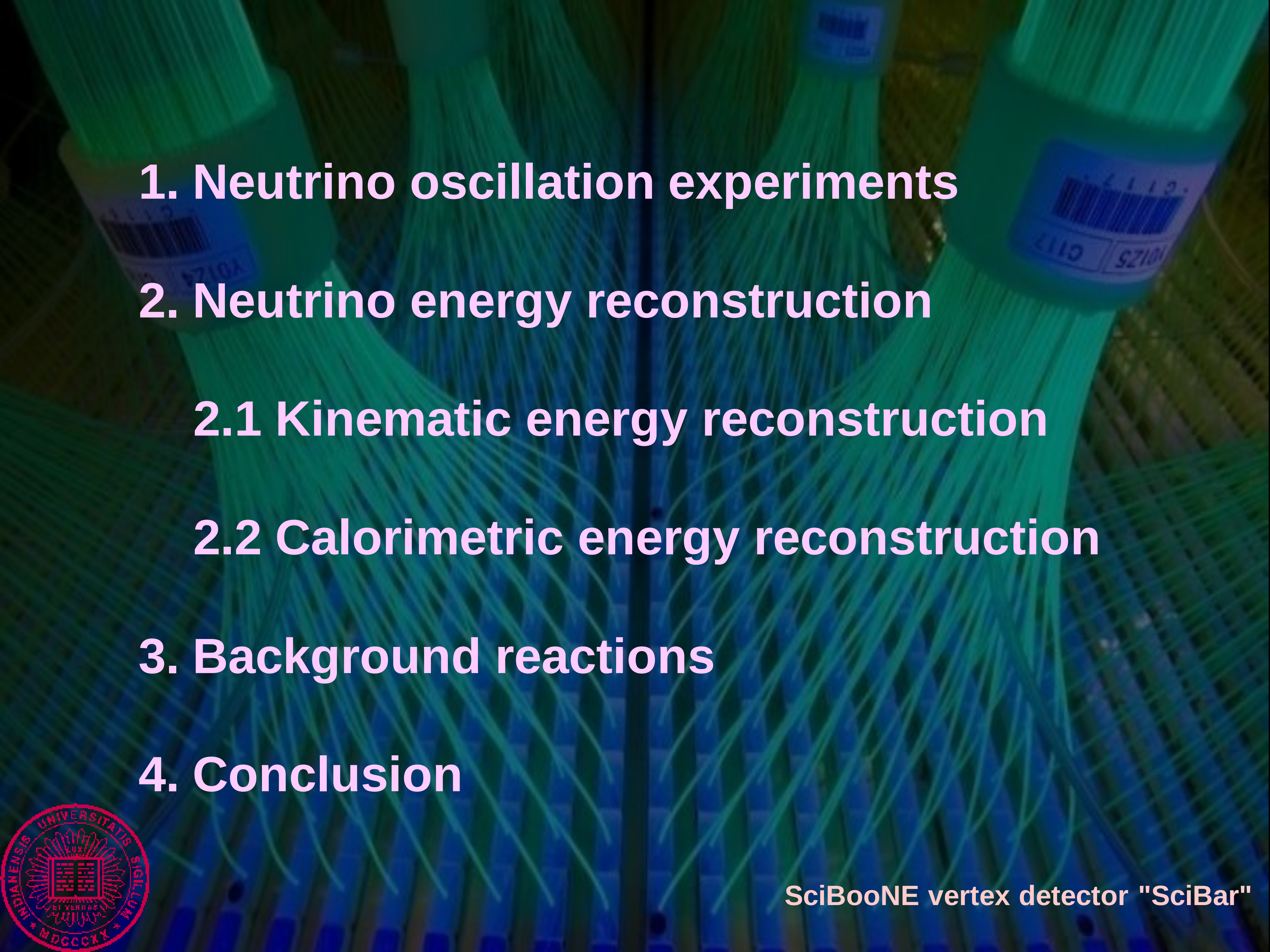
2. Neutrino energy reconstruction

    2.1 Kinematic energy reconstruction

    2.2 Calorimetric energy reconstruction

3. Background reactions

4. Conclusion



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1. Neutrino oscillation experiments

Long-baseline neutrino oscillation experiments

Observable is neutrino interaction rate

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

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

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

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

order of L ~ 100-1000km

order of E ~ 100-1000MeV

There are 2 next generation long-baseline neutrino oscillation experiments

1. T2K experiment

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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)

1. NOvA experiment

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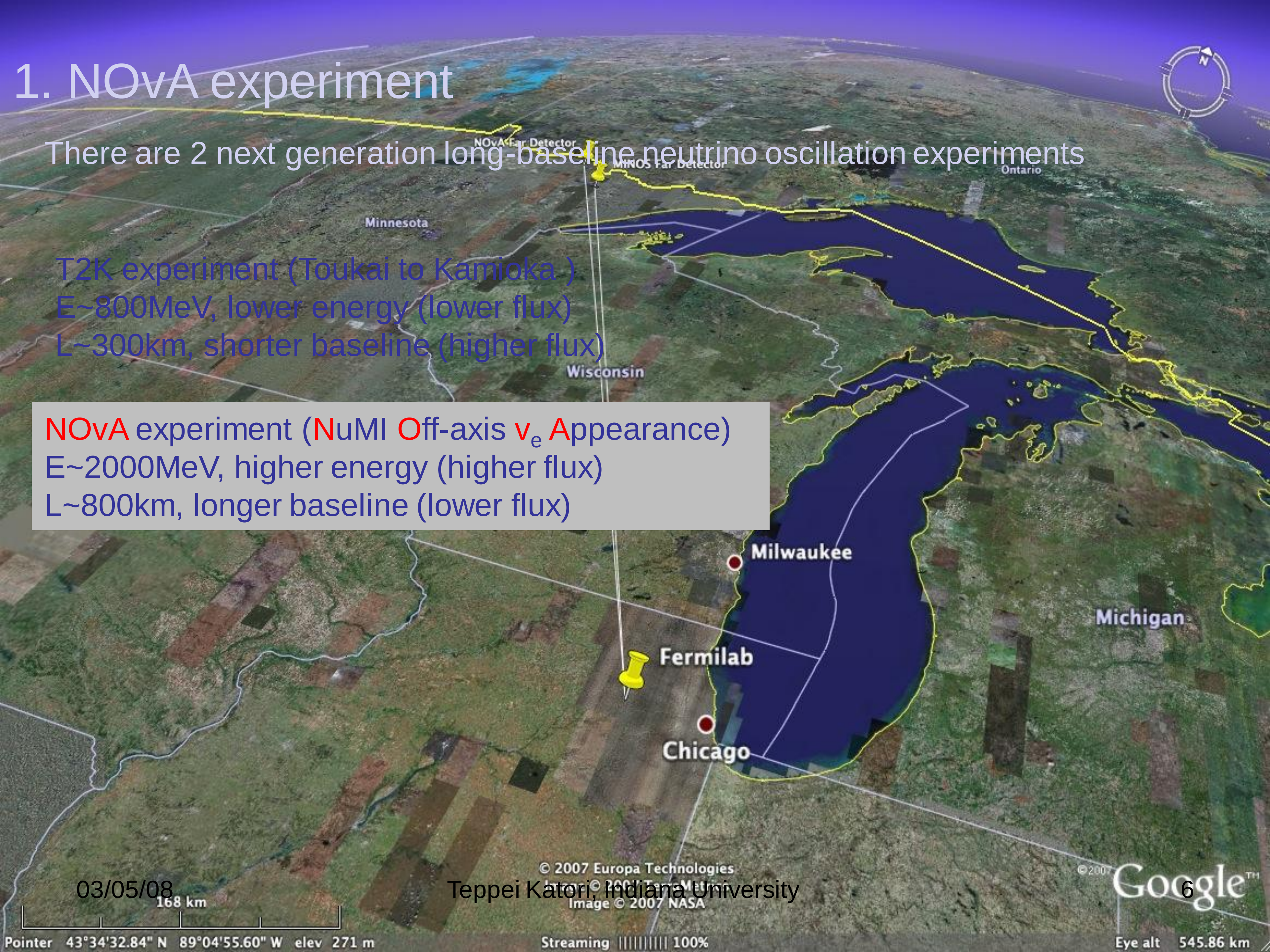
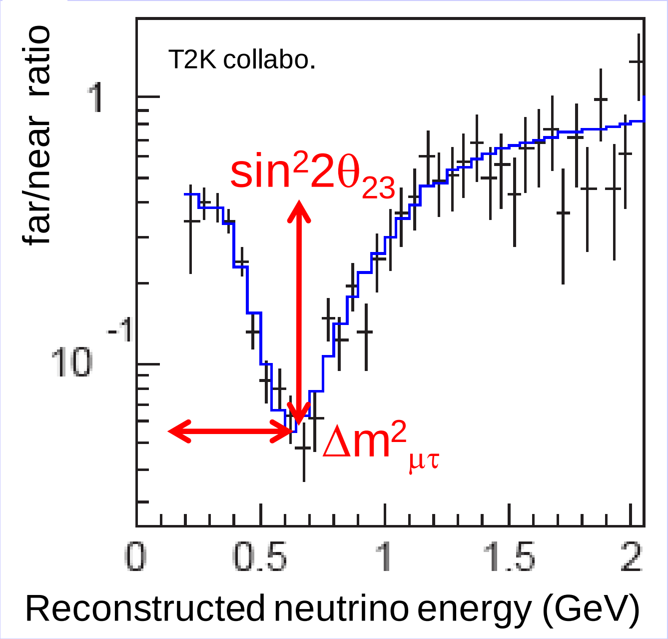


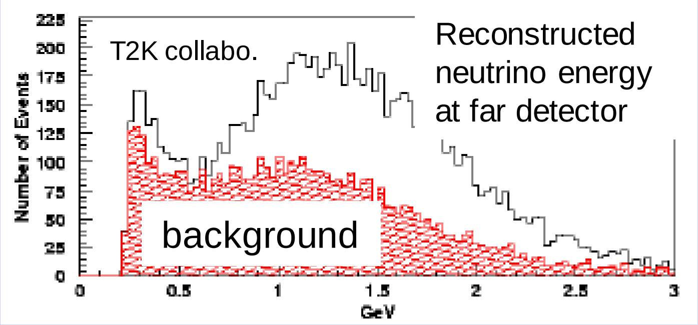
1. ν_μ disappearance measurement

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
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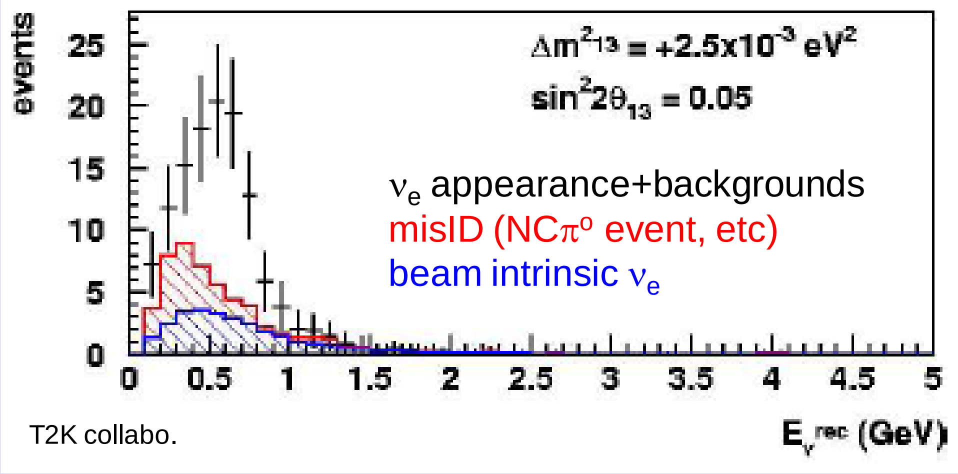
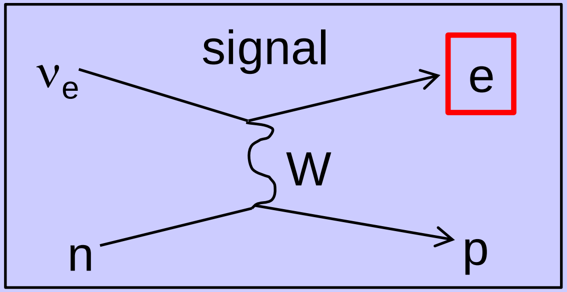
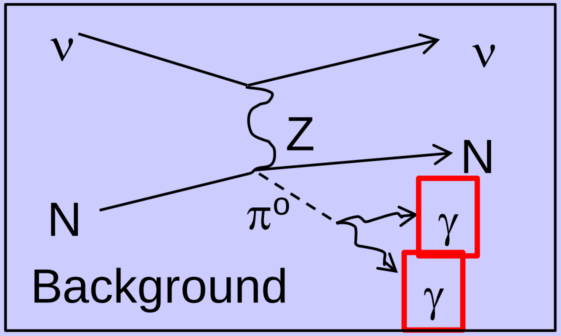
(2) ν_e appearance measurement (= $\sin^2 2\theta_{13}$)
- Careful rejection of background reactions





Background (misID) events, for example, NCπ^o events, are poorly understood

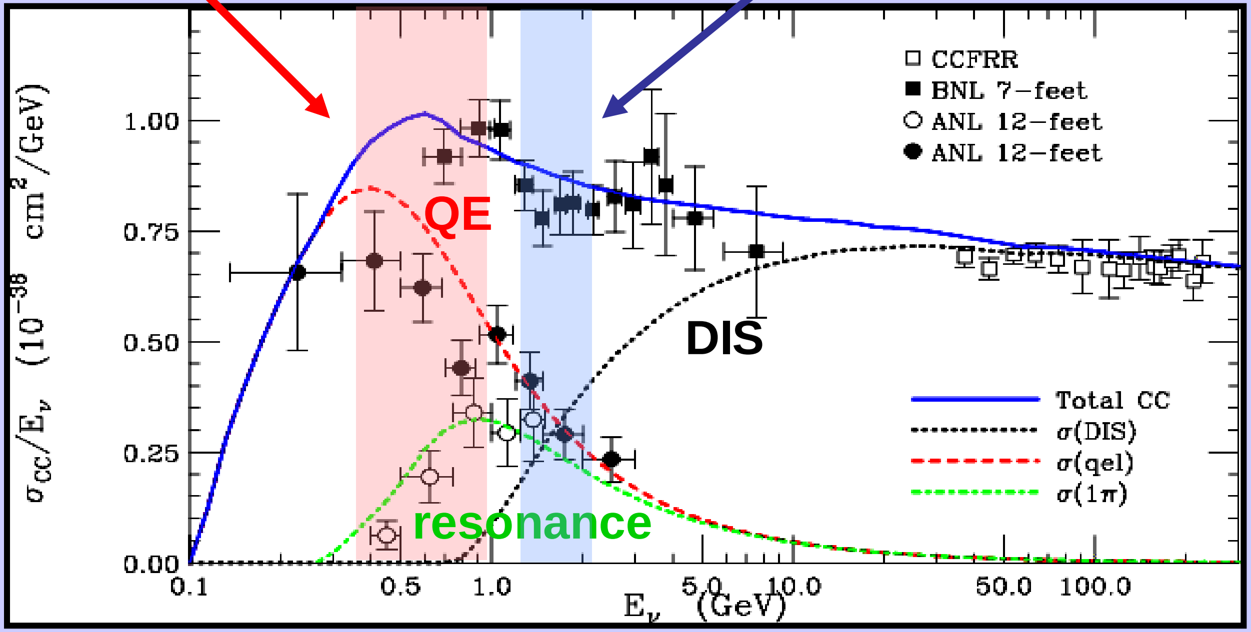


1. CC (Charged-Current) cross section

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



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A lot of future/current experiments!

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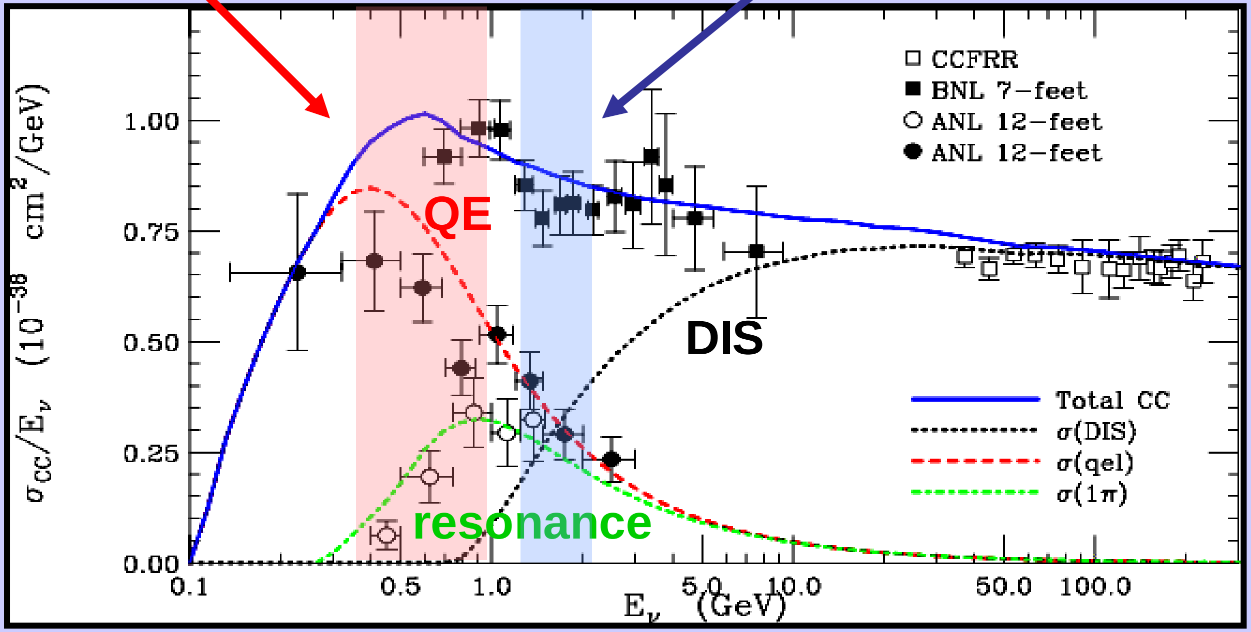

K2K, SciBooNE
MiniBooNE

MINOS,
MINERvA

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.

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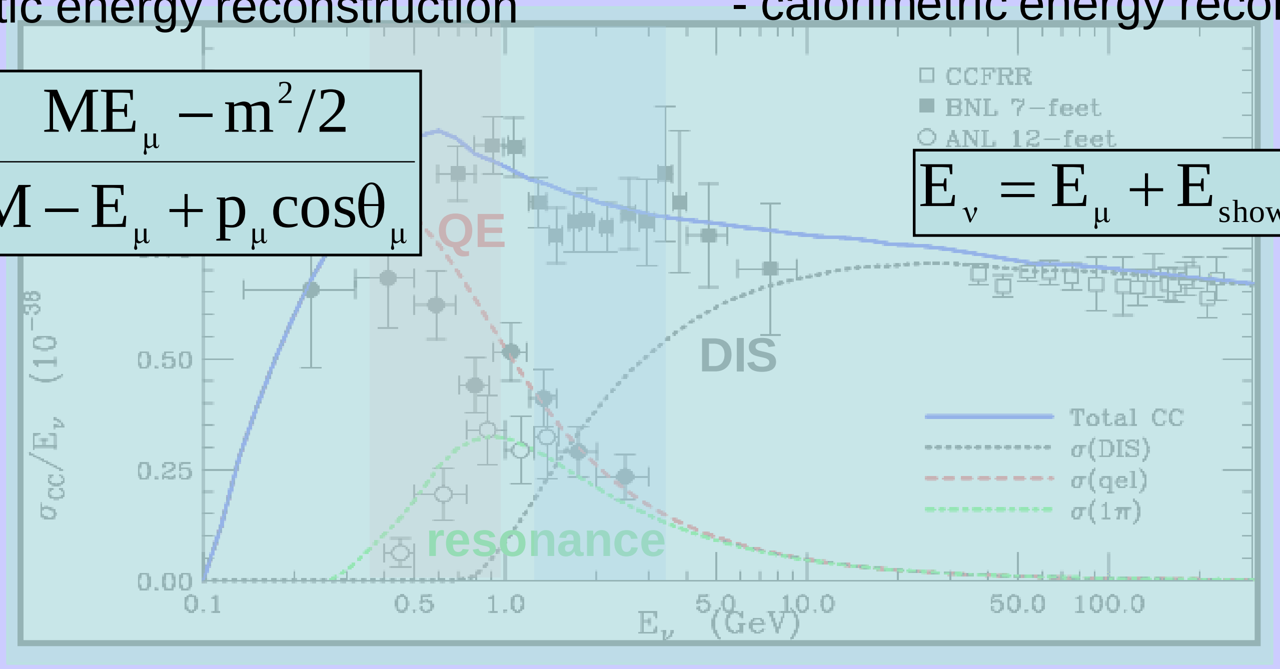
$$E_\nu = \frac{ME_\mu - m^2/2}{M - E_\mu + p_\mu \cos\theta_\mu}$$

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



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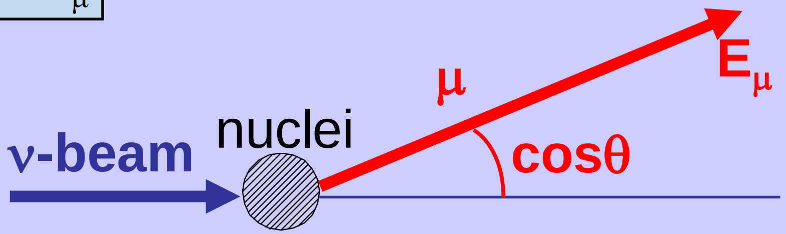
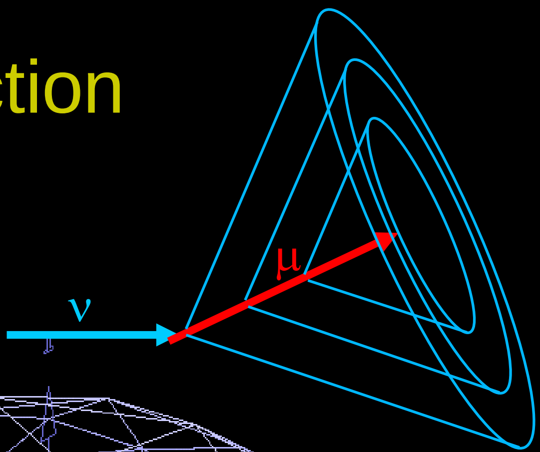


$$\nu_\mu + n \rightarrow p + \mu$$

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

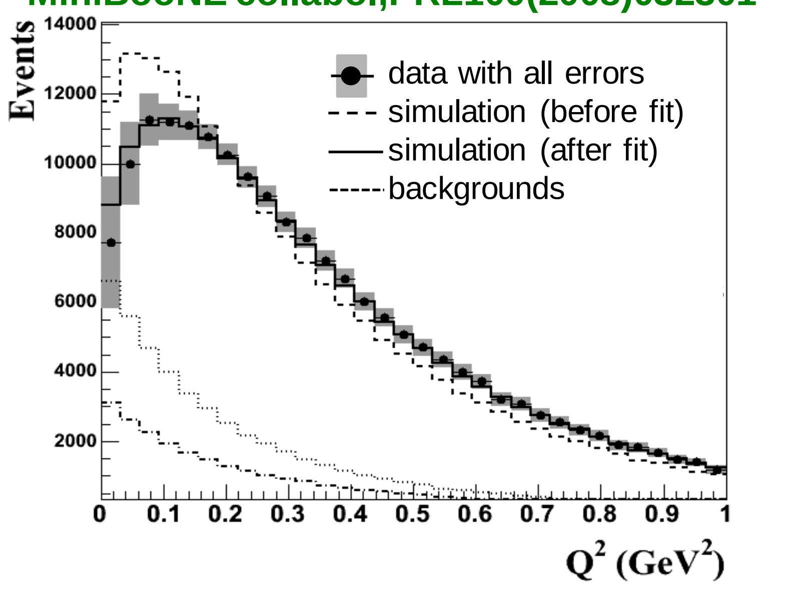
2. Kinematic neutrino energy reconstruction

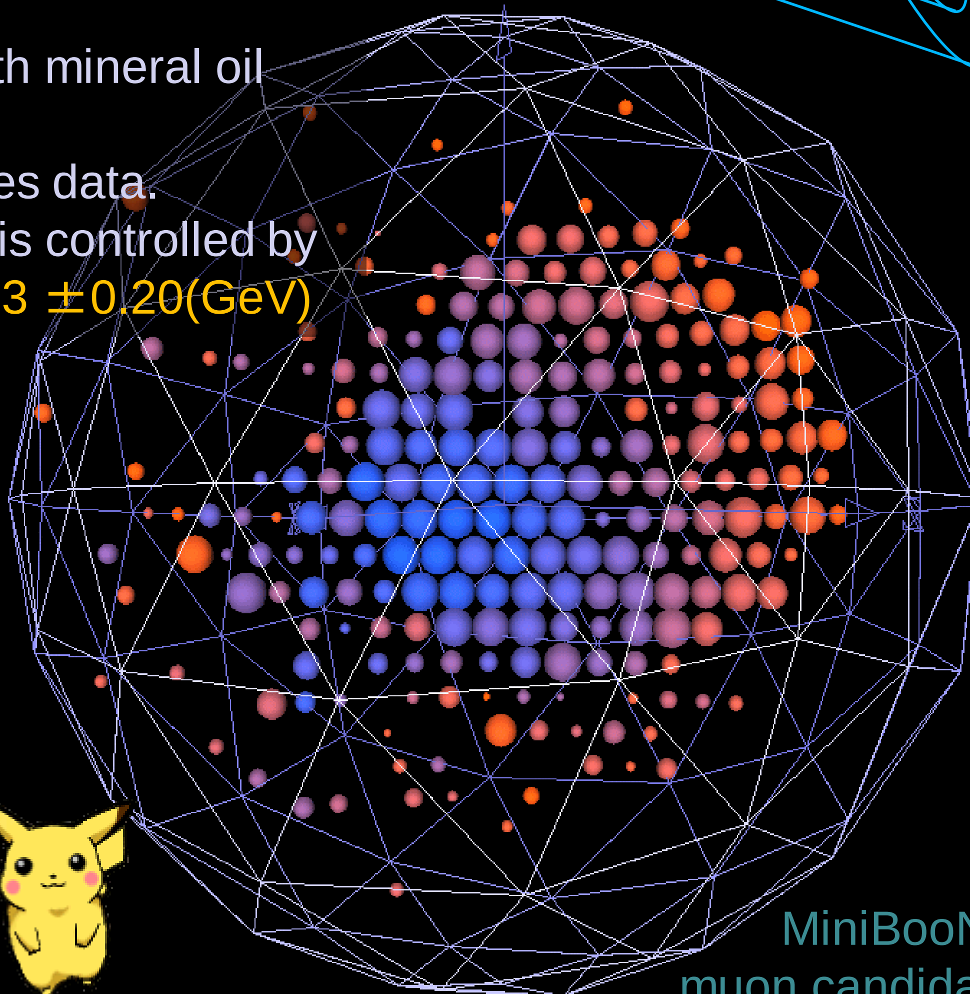


MiniBooNE (Mini-Booster Neutrino Experiment)
status: ongoing
- ~800MeV
- spherical Cerenkov detector, filled with mineral oil

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 ±0.20(GeV)

MiniBooNE collabo.,PRL100(2008)032301





MiniBooNE
muon candidate

2. Kinematic neutrino energy reconstruction

Neutrino-Nucleon cross section

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

$$A(Q^2) = \frac{Q^2}{M^2}\left\{\left(1+\frac{Q^2}{4M^2}\right)(G_A)^2 - \left(1-\frac{Q^2}{4M^2}\right)(F_1)^2 + \frac{Q^2}{4M^2}\left(1-\frac{Q^2}{4M^2}\right)(F_2)^2 + \frac{Q^2}{M^2}[F_1F_2]\right\}$$

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

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

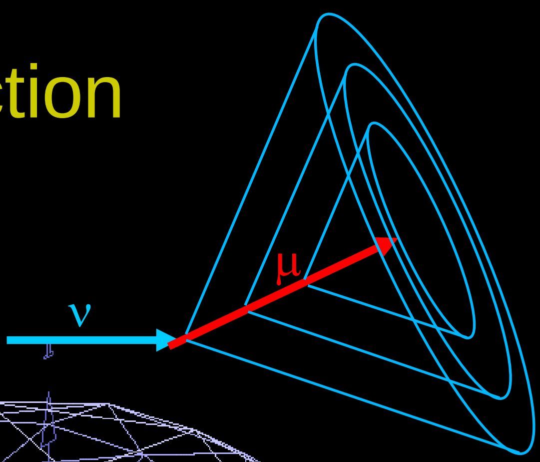
$$G_A(Q^2) = \frac{g_A}{\left(1+\frac{Q^2}{M_A^2}\right)^2}$$

axial vector form factor

axial coupling constant (=1.2671)

axial mass (=1.03GeV, default)

2. Kinematic neutrino energy reconstruction



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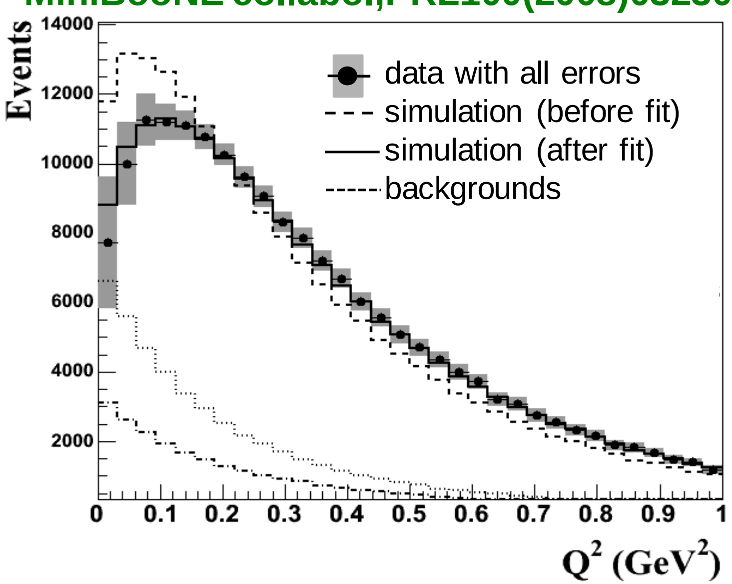
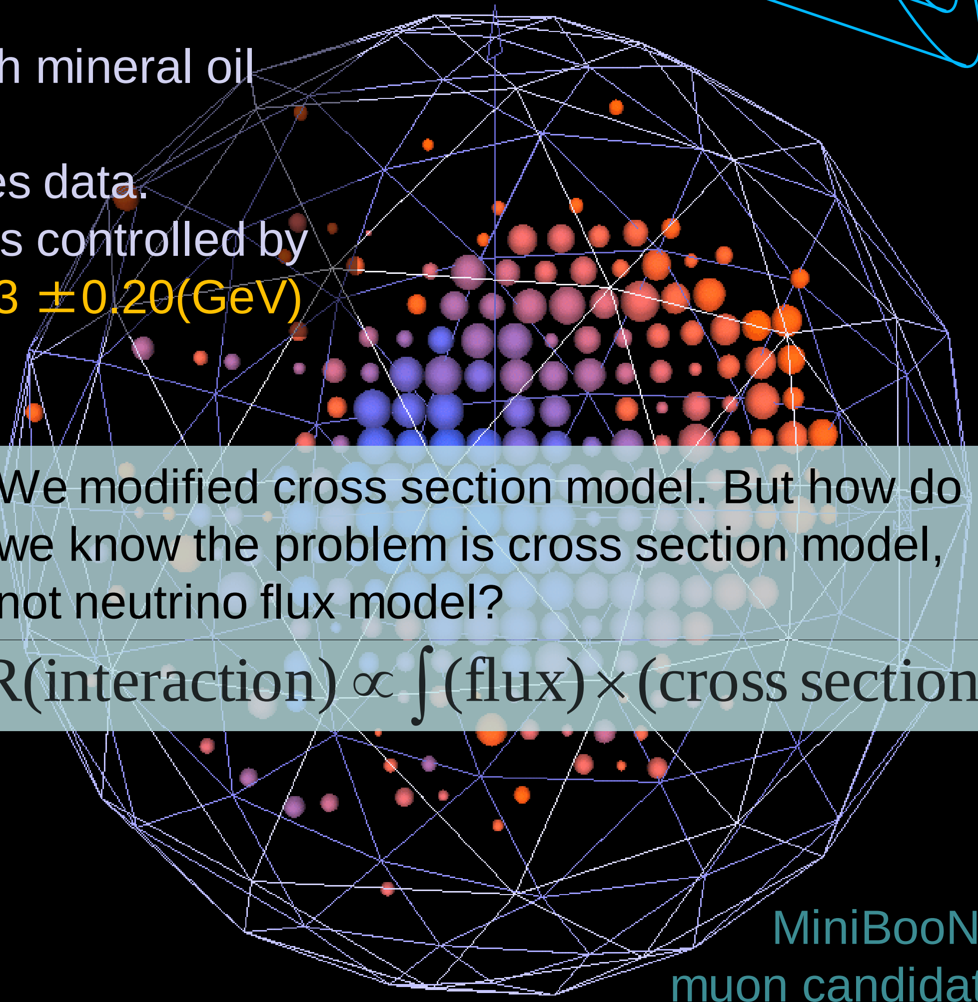


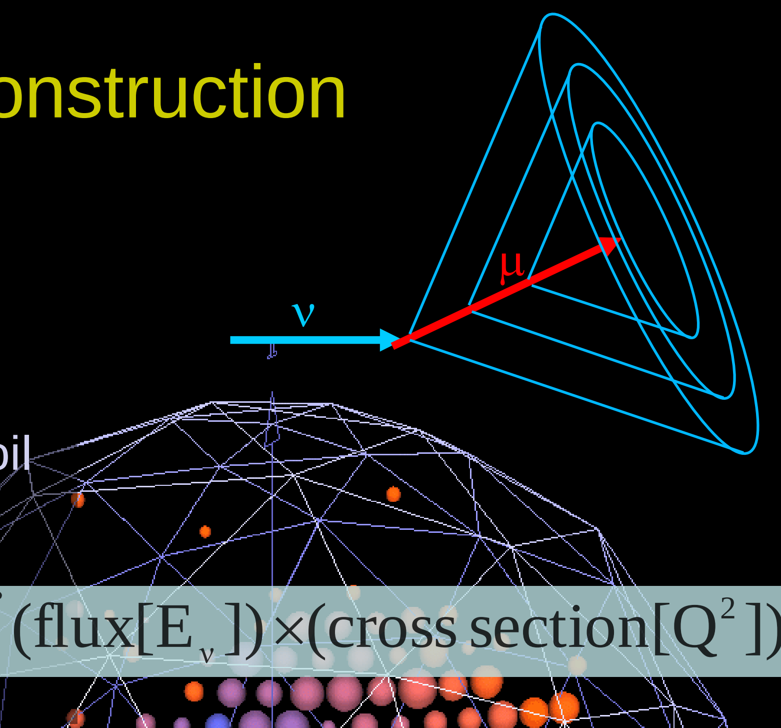
We modified cross section model. But how do we know the problem is cross section model, not neutrino flux model?

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



MiniBooNE muon candidate

2. Kinematic neutrino energy reconstruction



MiniBooNE (Mini-Booster Neutrino Experiment)
status: ongoing
- ~800MeV
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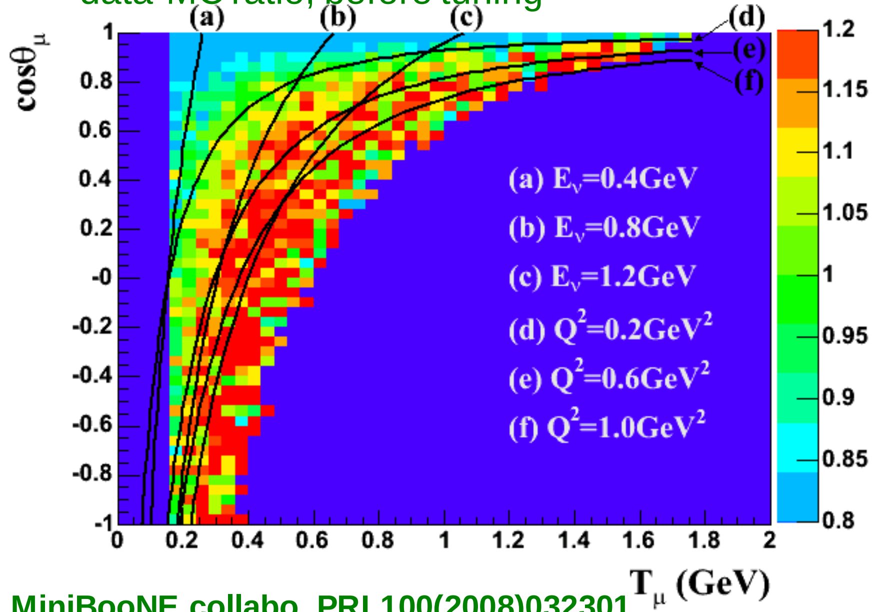
(a),(b),(c) : equal reconstructed Eν lines
(d),(e),(f) : equal reconstructed Q^2 lines
data-MC disagreement follows equal Q^2!

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

data-MC ratio, before tuning



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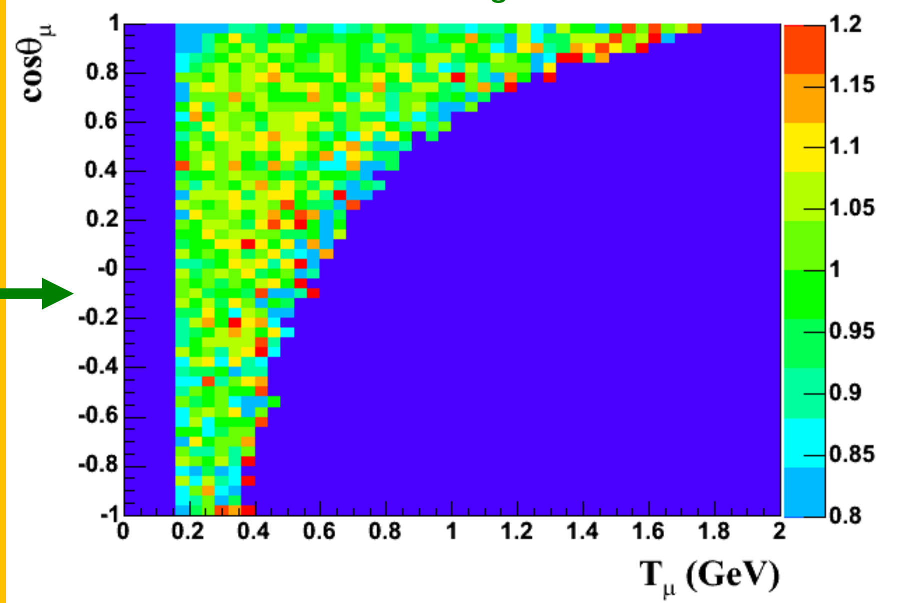


MiniBooNE collabo.,PRL100(2008)032301

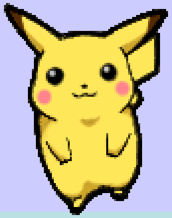
2. Kinematic neutrino energy reconstruction

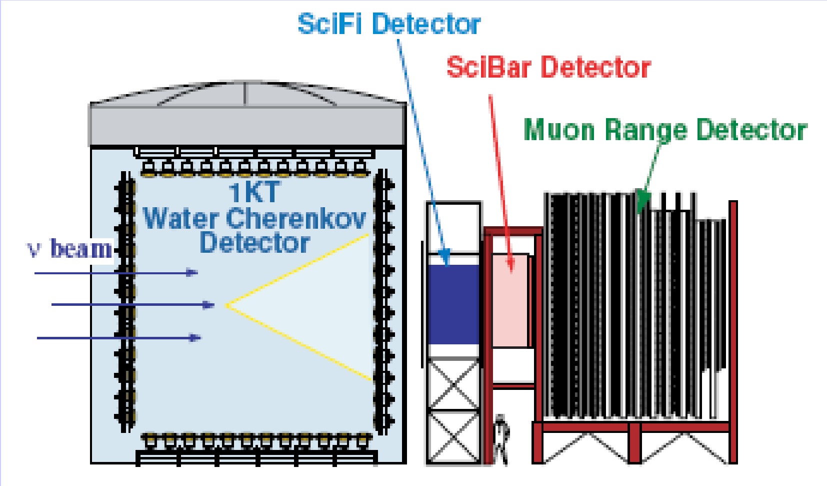
K2K (KEK to Kamioka experiment)
status: completed
- ~1.5GeV
- fine-grained scintillator

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

SciFi M_A=1.20 ±0.12 (GeV) K2K collabo.,PRD74(2006)052002

SciBar M_A=1.14 ±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 ±0.03 (GeV)

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

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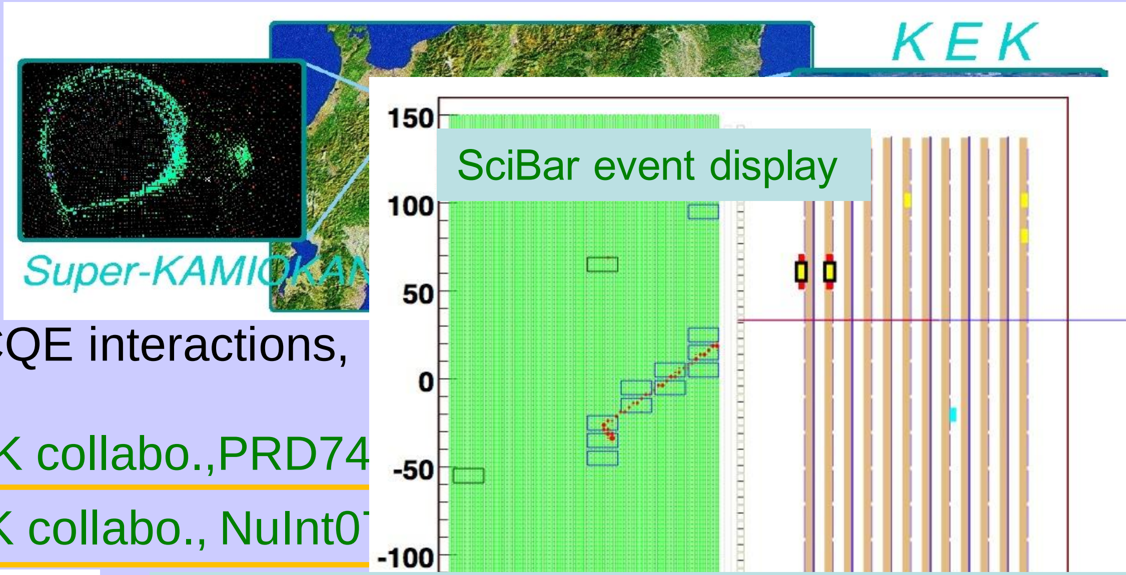

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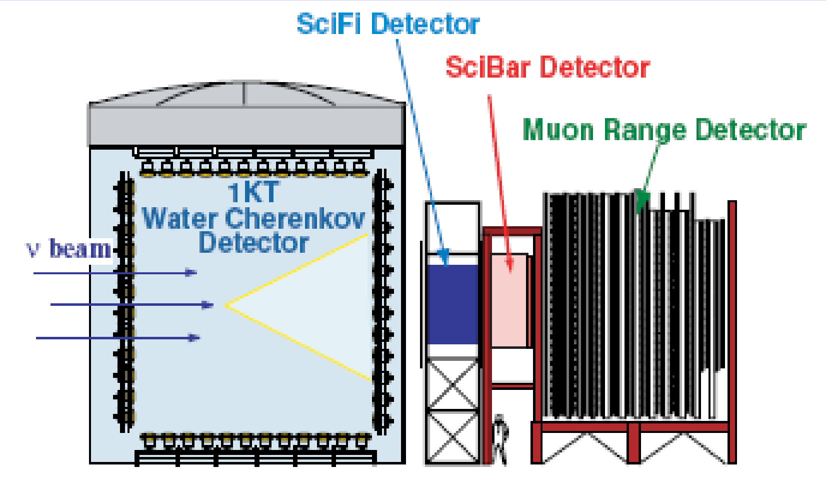
SciBar M_A=1.14 ±0.11 (GeV) K2K collabo., NuInt0



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2. Non-QE rejection for kinematic energy reconstruction

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- quasi-elastic (QE)
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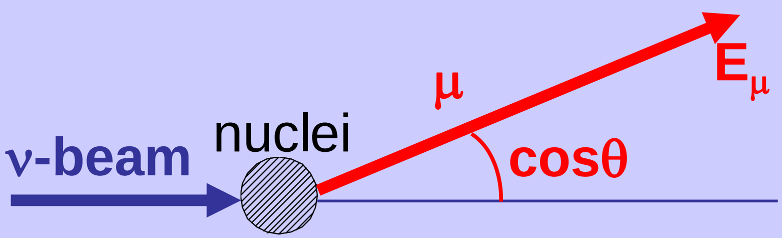

CCQE (charged-current quasi-elastic)
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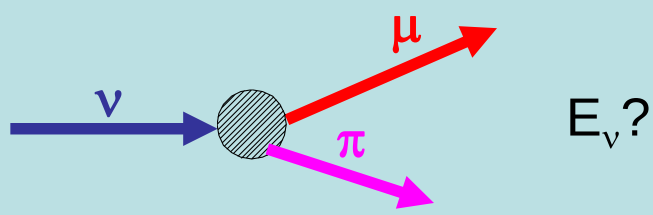
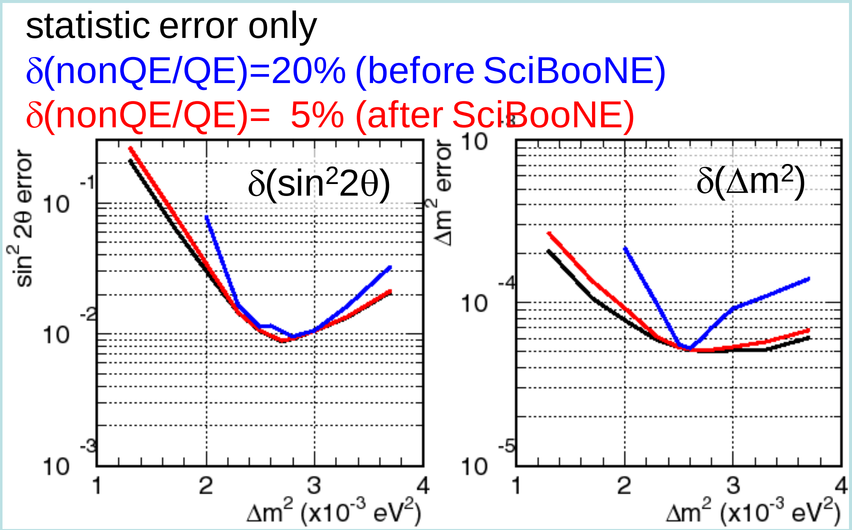
CC backgrounds (non-QE) spoils kinematic reconstruction.



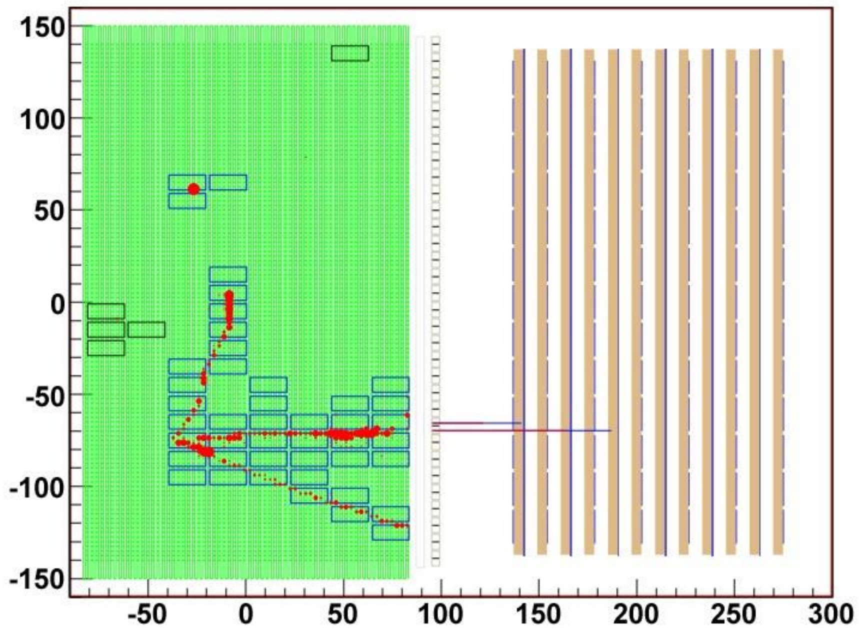


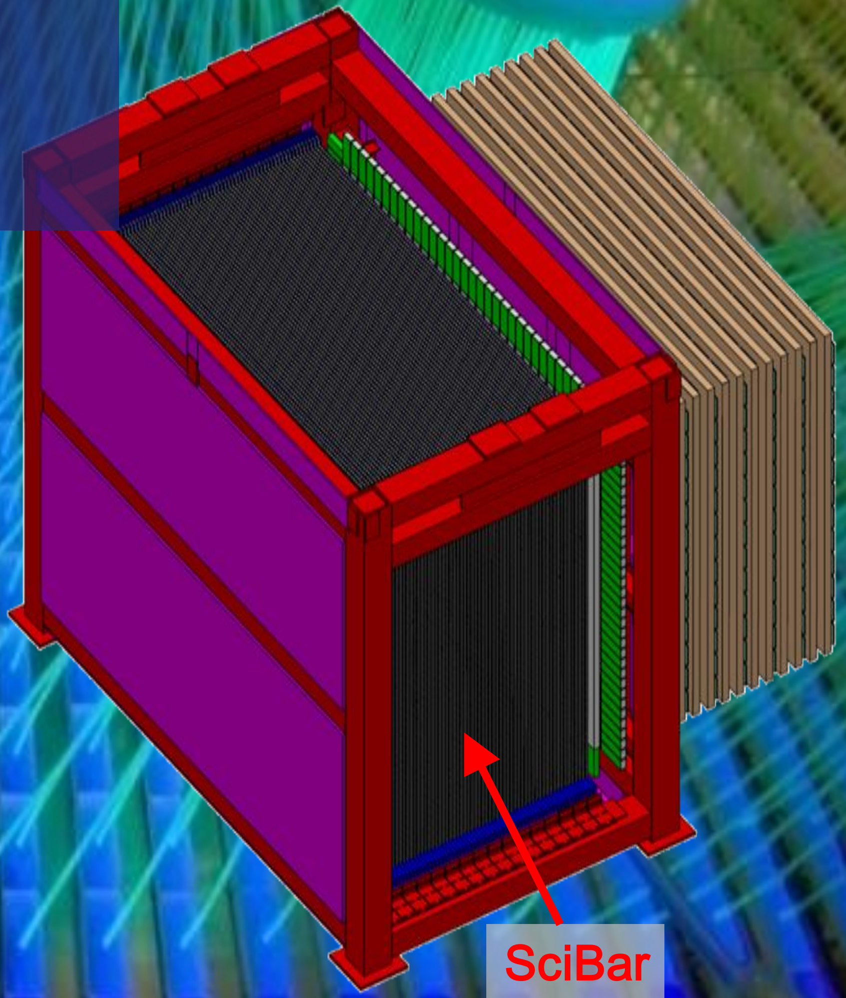
2. Non-QE rejection for kinematic energy reconstruction

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





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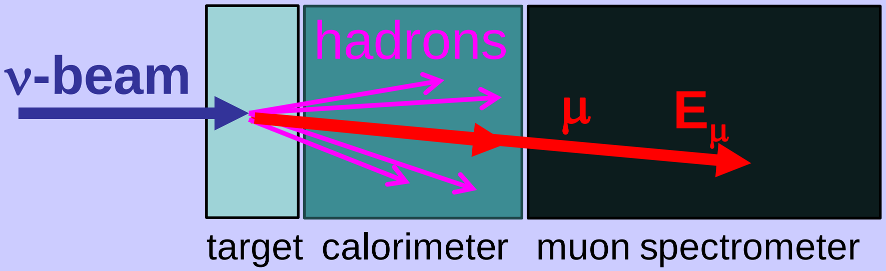
$$E_\nu = E_\mu + E_{showers}$$

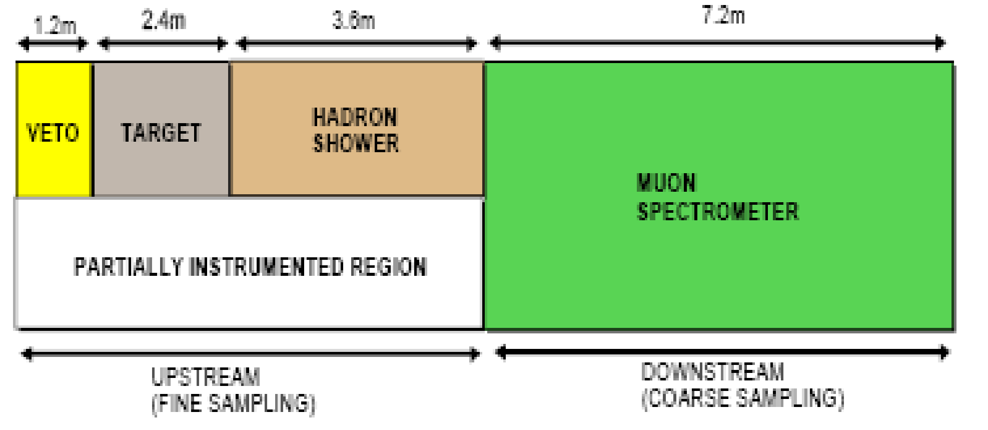


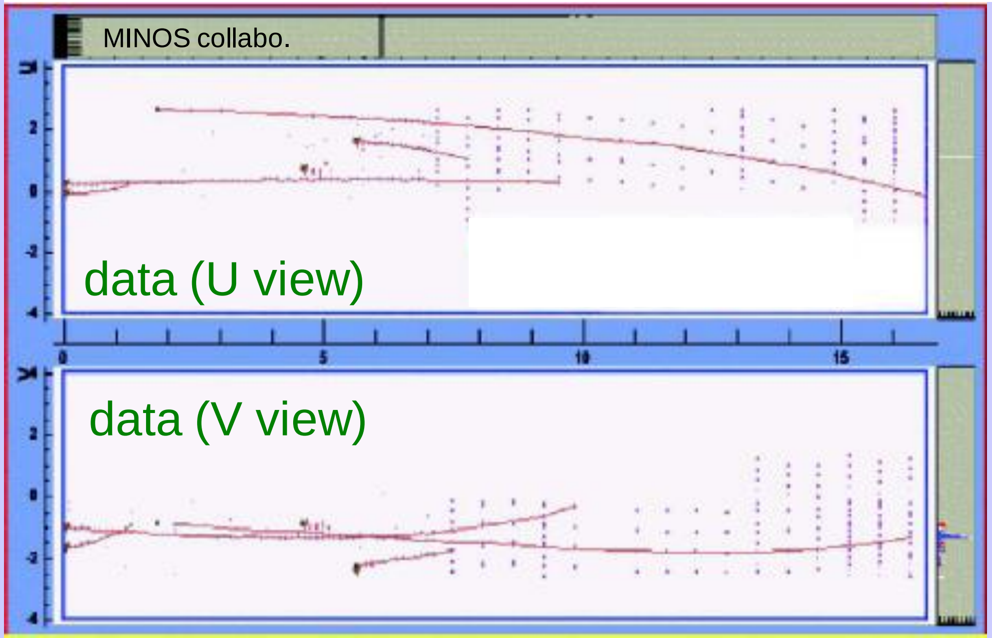
CC inclusive
- measure muon and total energy deposit

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

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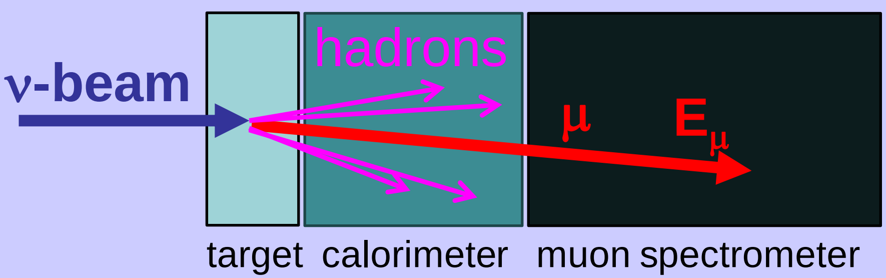
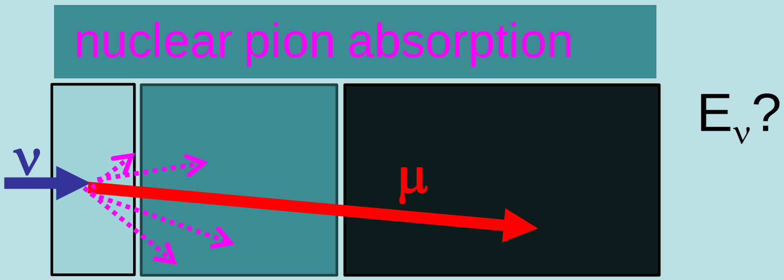
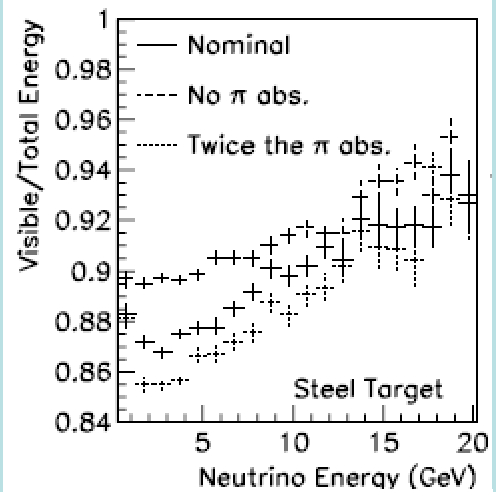


CC inclusive
- measure muon and total energy deposit

Missing energy (nuclear effect) spoils calorimetric energy reconstruction





MINERvA collabo.

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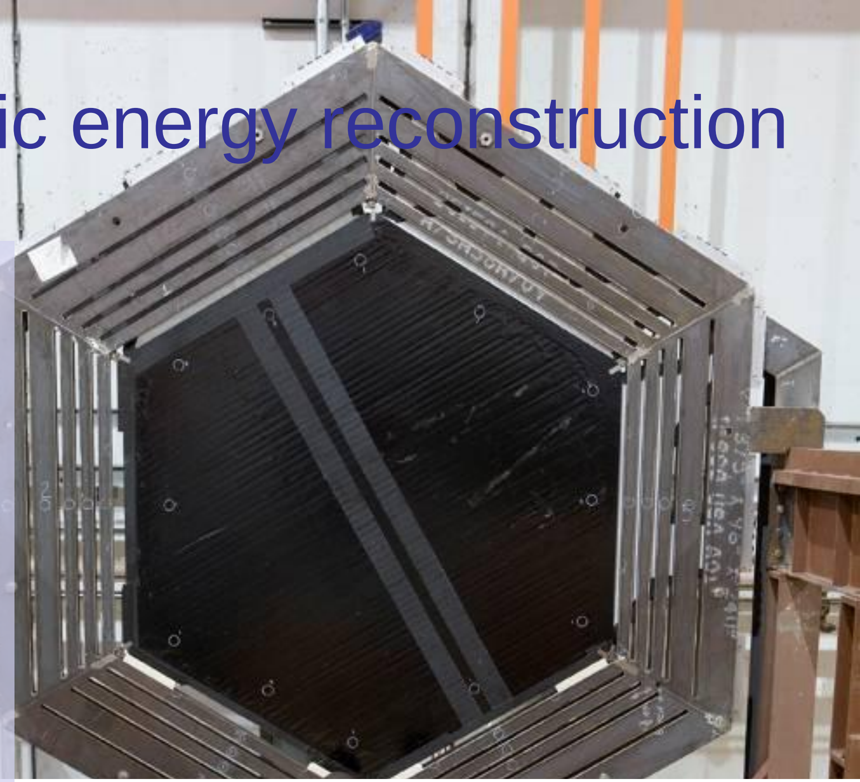
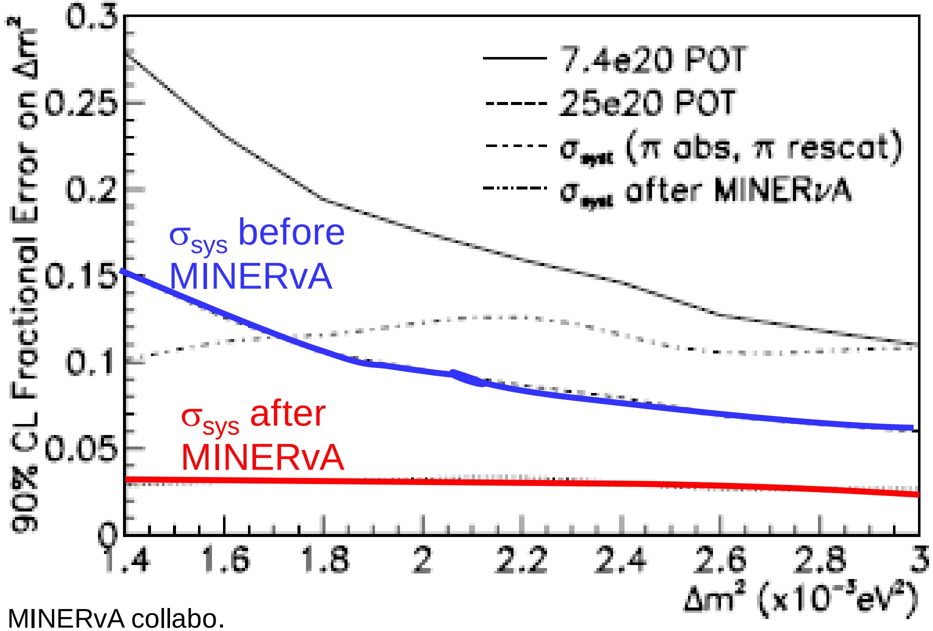


MINERvA (Main INjector ExpeRiment for ν-A)
status: approved, commissioning in 2009

- ~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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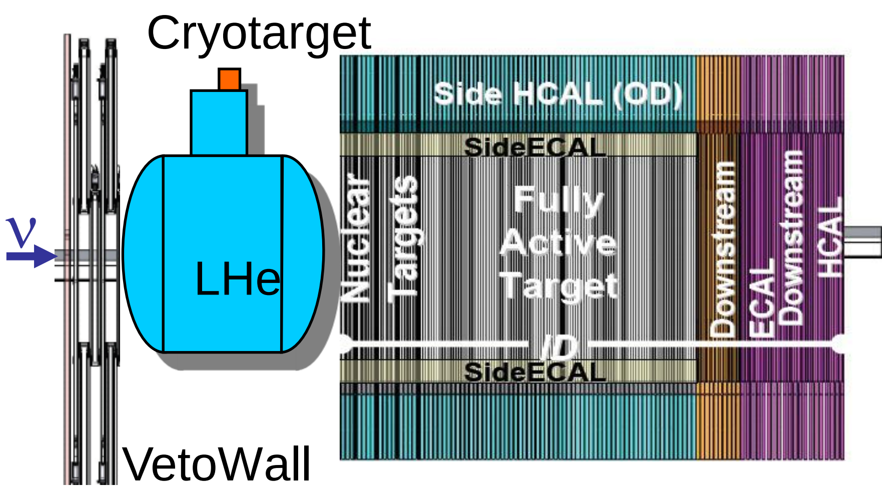

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ν_e appearance

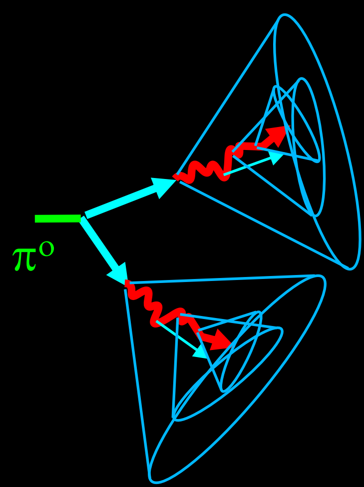
- signal of $\sin^2 2\theta_{13}$, goal of T2K and NOvA experiments
- ν_e candidate is a single isolated electron

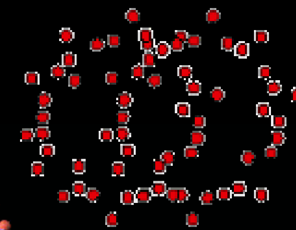
$$\nu_e + n \rightarrow p + e$$

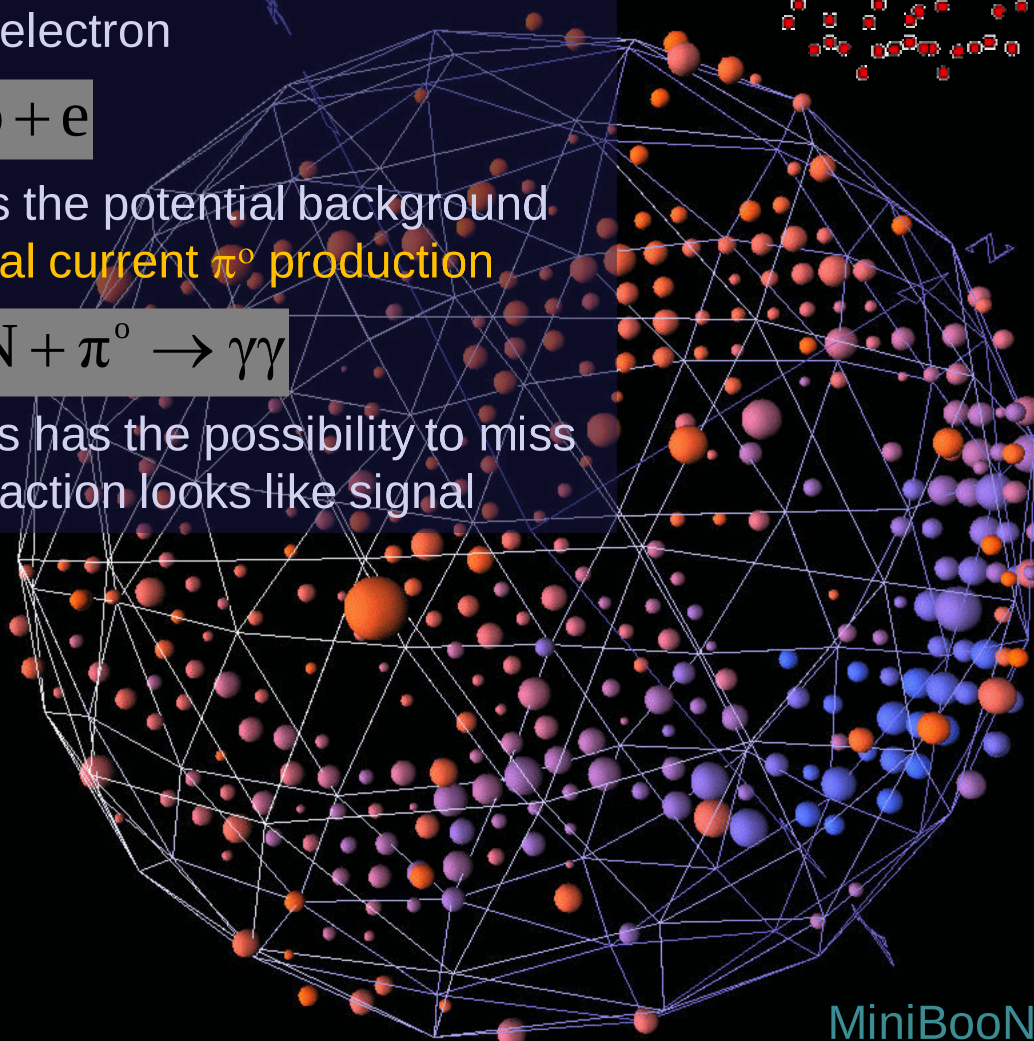
- single electromagnetic shower is the potential background
- the notable background is Neutral current π^o production

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

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







MiniBooNE
NCπ^o candidate

3. Background reactions

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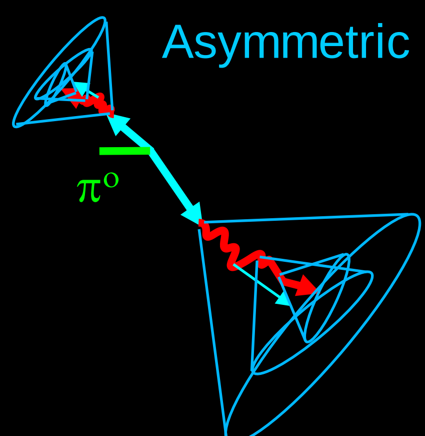
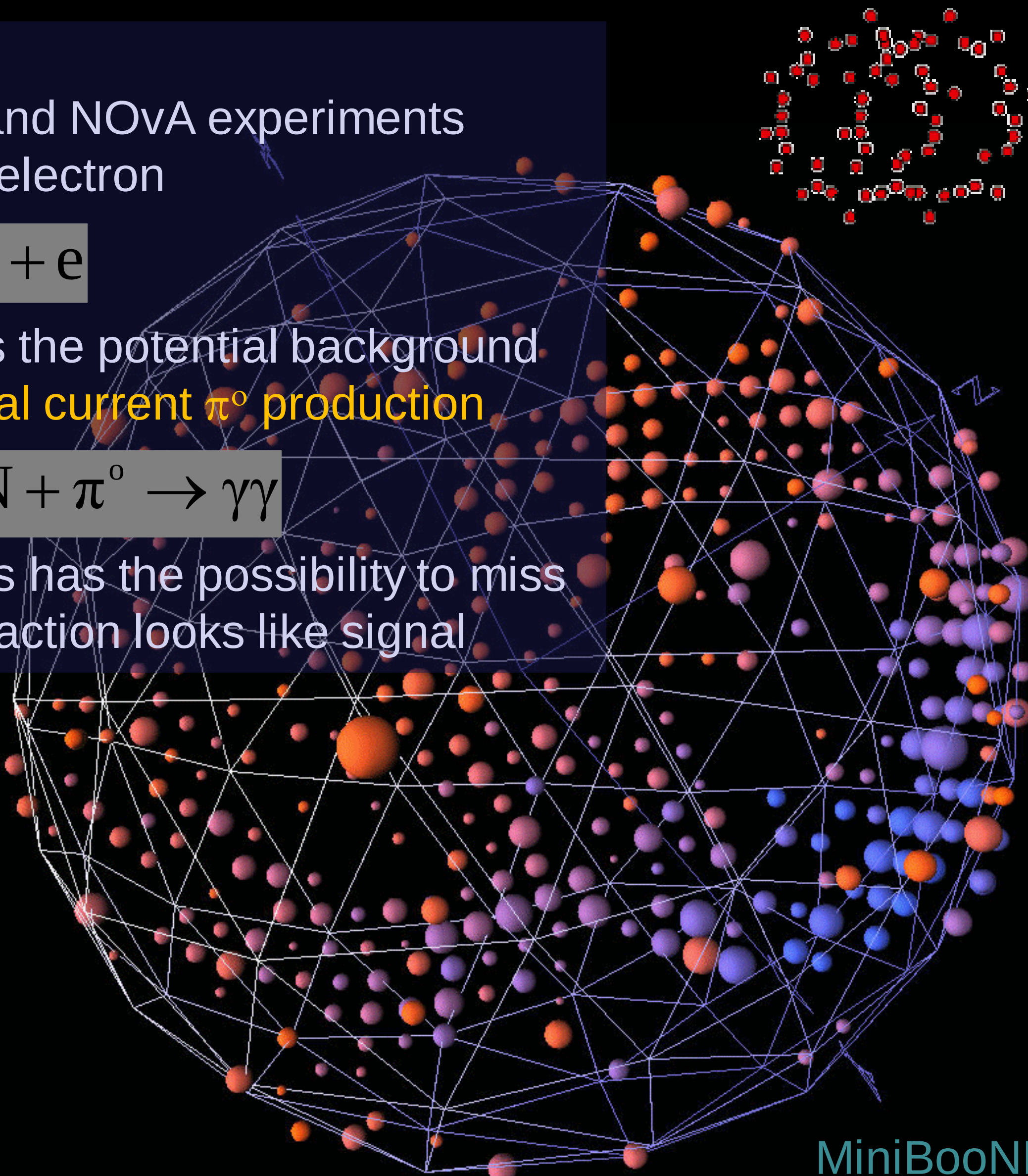


Asymmetric decay



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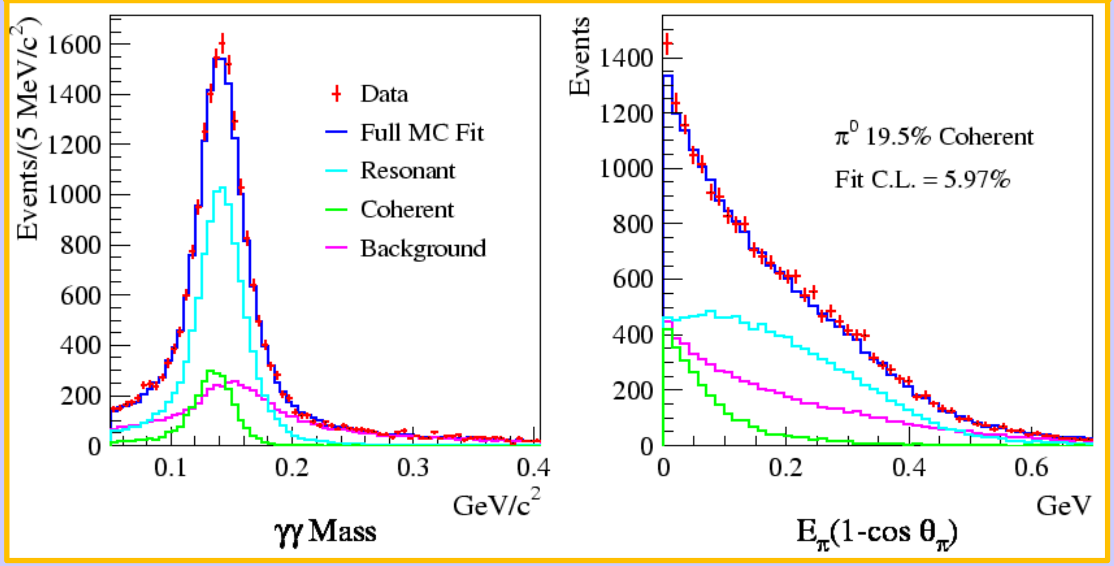
3. Background reactions

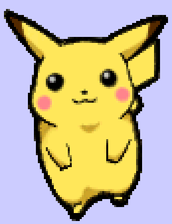
MiniBooNE

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

NCπ^o data fit well with resonance and coherent π^o production MC

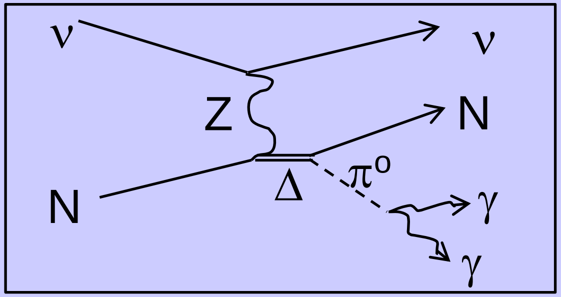
MiniBooNE collabo., NuInt07





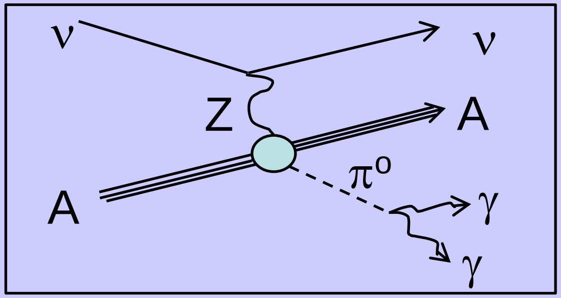
Resonance

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



Coherent

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



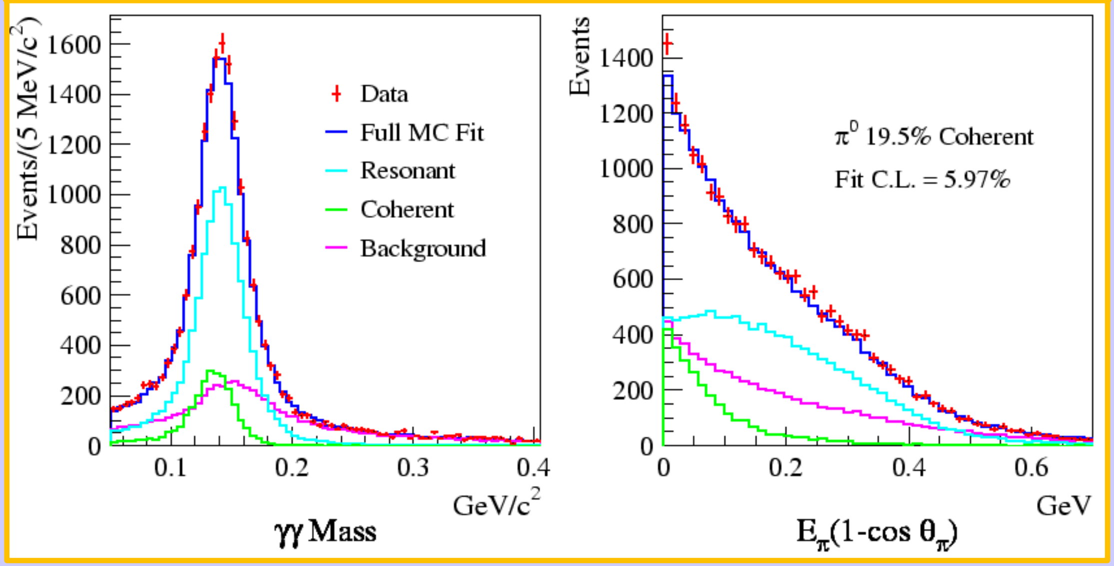
3. Background reactions

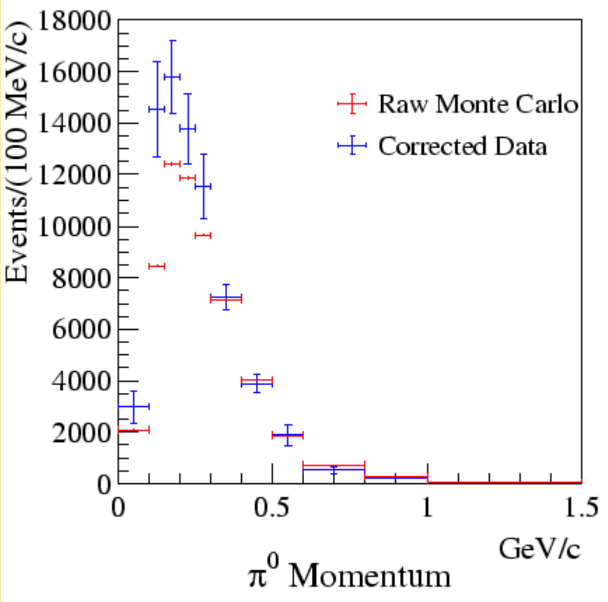
MiniBooNE

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

NCπ^o data fit well with resonance and coherent π^o production MC

MiniBooNE collabo., NuInt07





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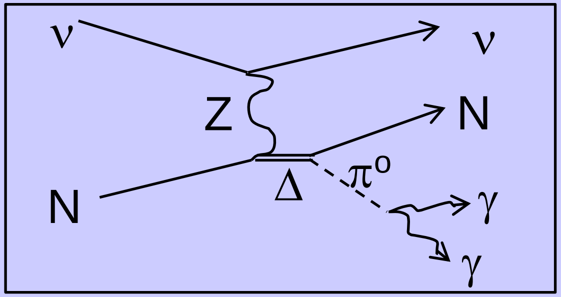

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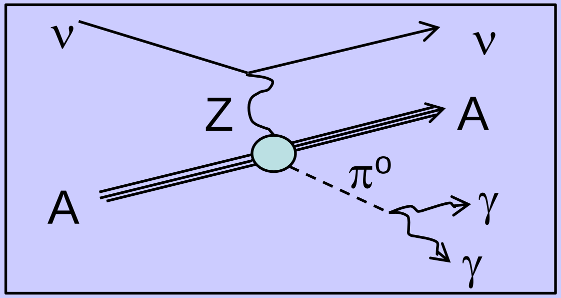

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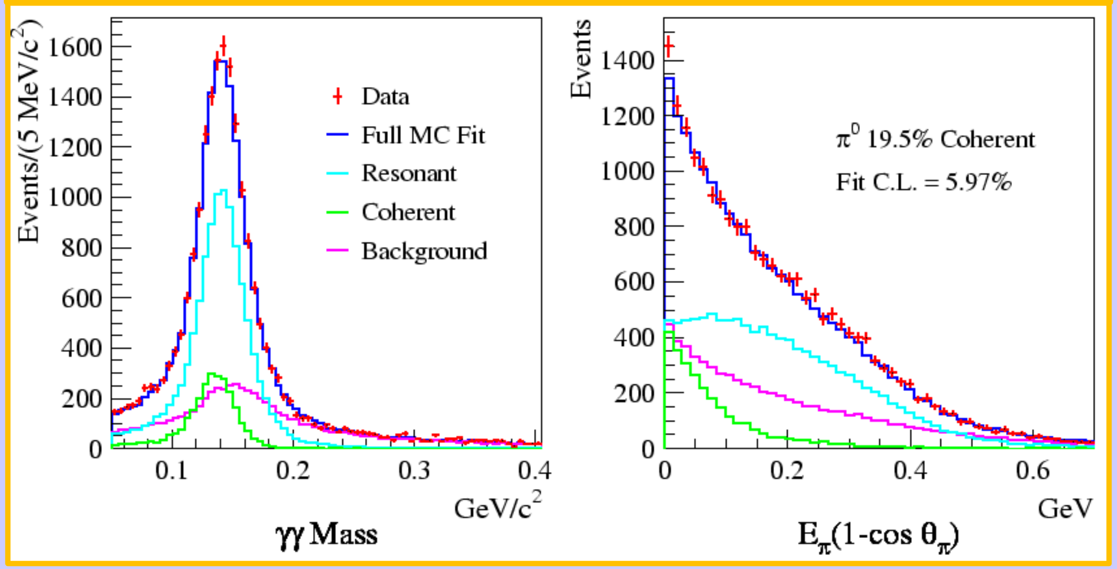
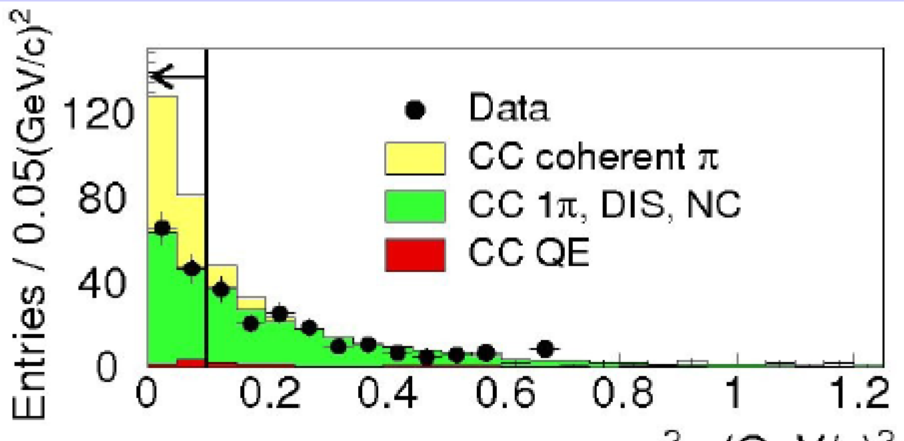


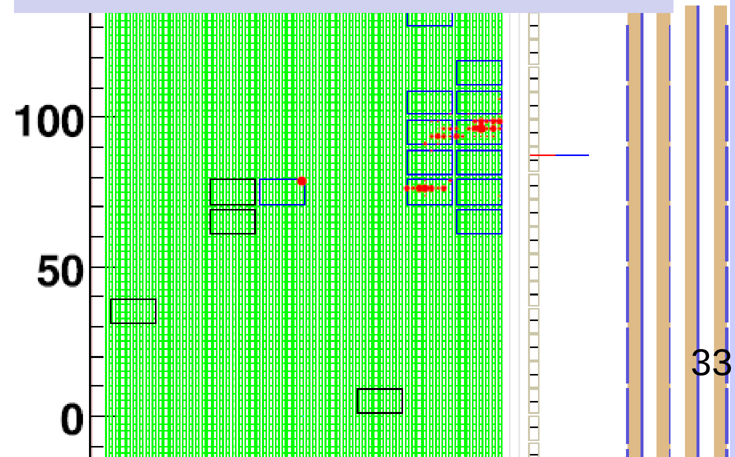
K2K
They suggest no CC coherent π^+ production.



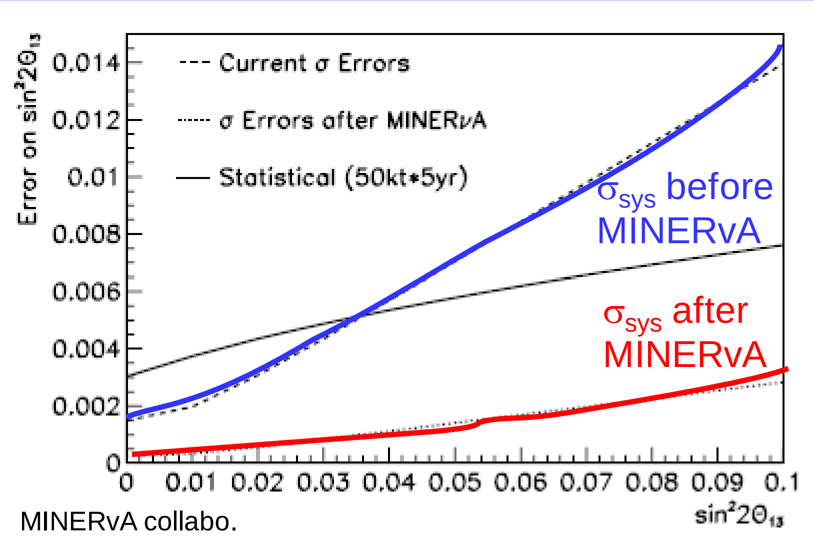
K2K collabo., PRL95(2005)252301

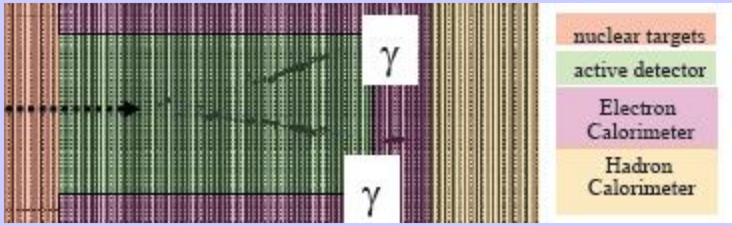
SciBooNE
Study for NCπ^o reaction is ongoing.

SciBooNE π^o candidate data



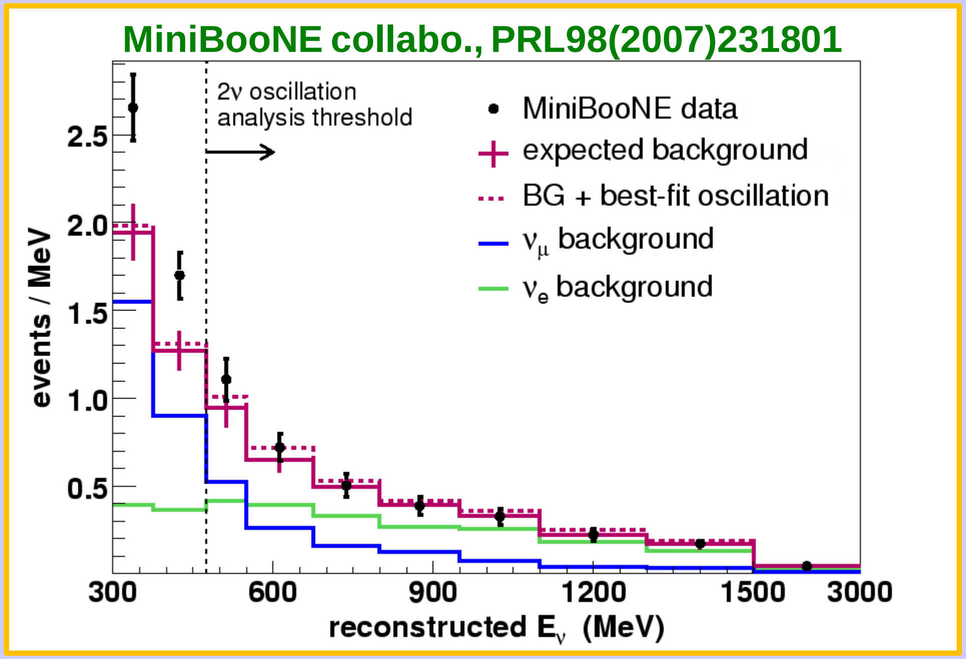
3. Background reactions





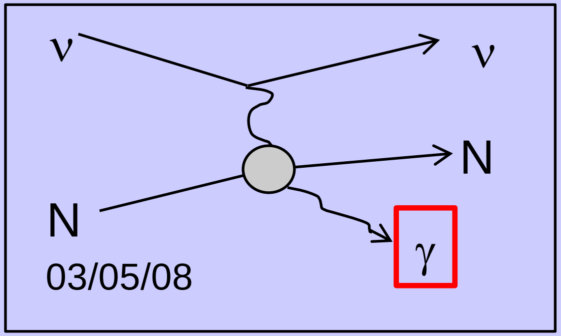
MINERvA

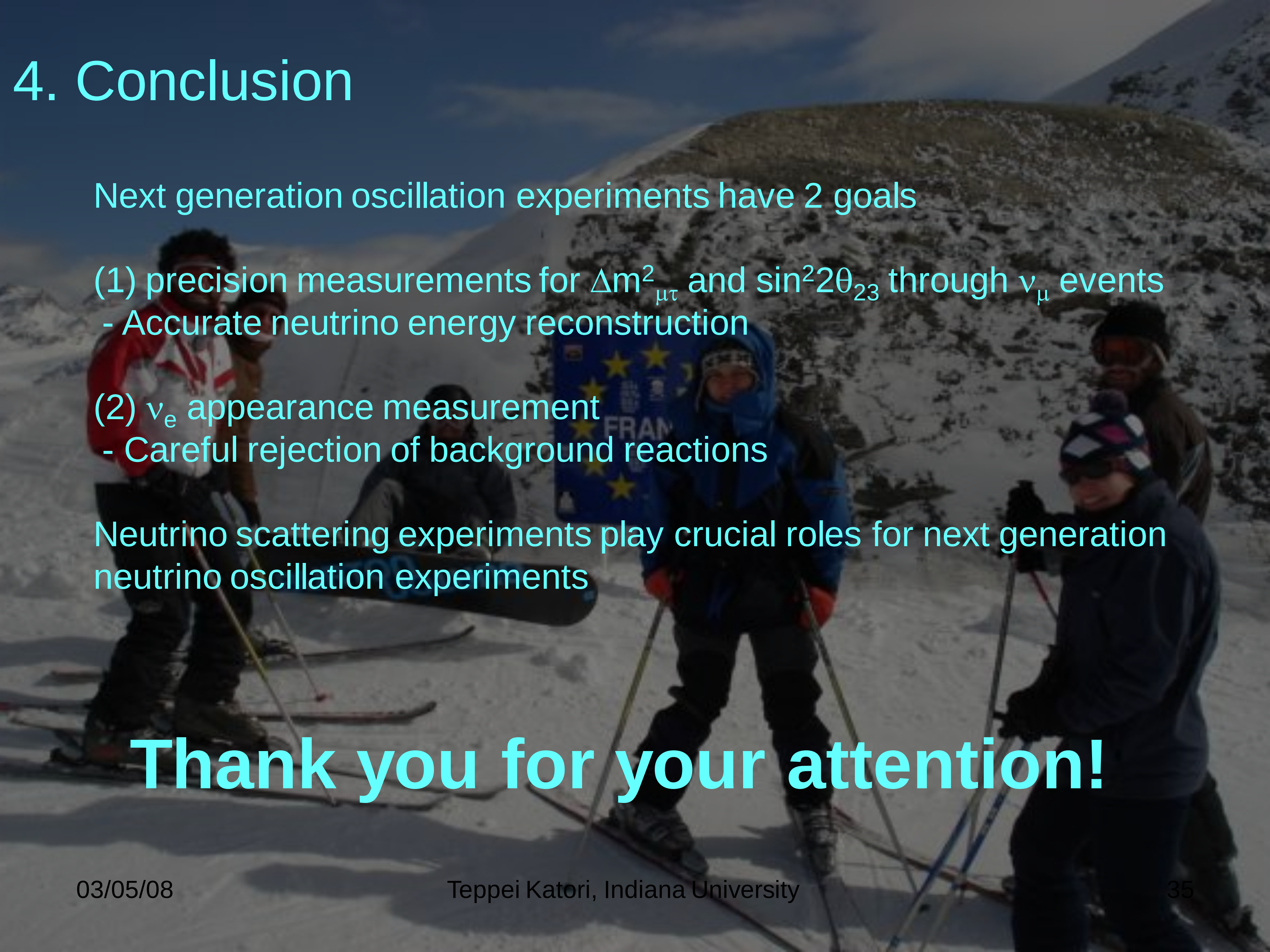
They can measure the high energy backgrounds which other experiments are not accessible



MiniBooNE

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





4. Conclusion

Next generation oscillation experiments have 2 goals

(1) precision measurements for $\Delta m^2_{\mu\tau}$ and $\sin^2 2\theta_{23}$ through ν_μ events
- Accurate neutrino energy reconstruction

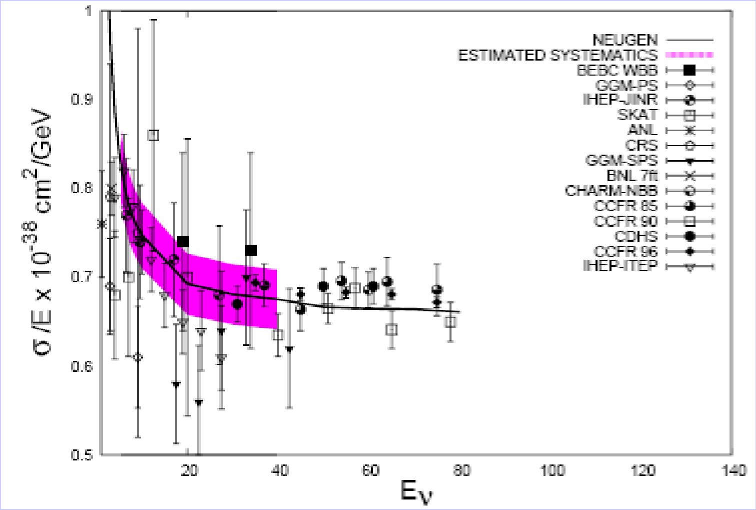
(2) ν_e appearance measurement
- Careful rejection of background reactions

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

Thank you for your attention!

10. Back up

4. Other physics

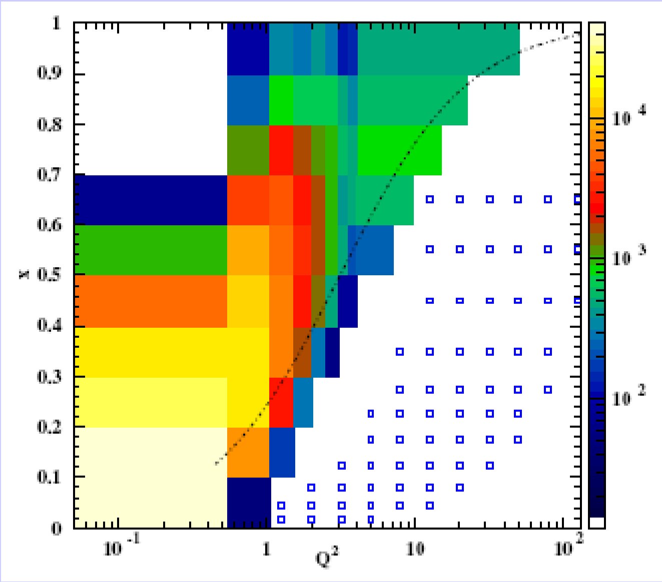


MINOS

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

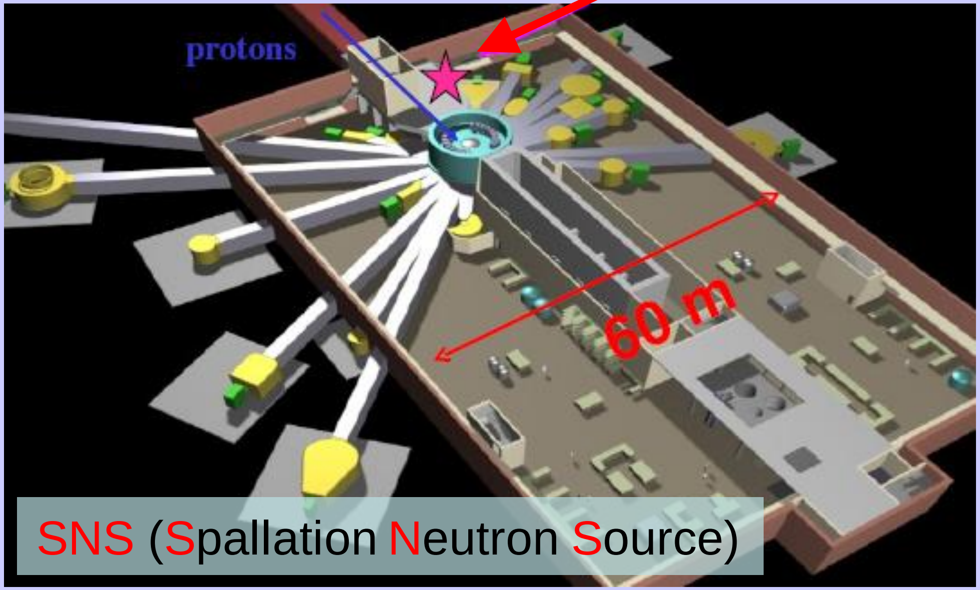
NC elastic scattering events have information of strange quark spin in nucleon

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

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

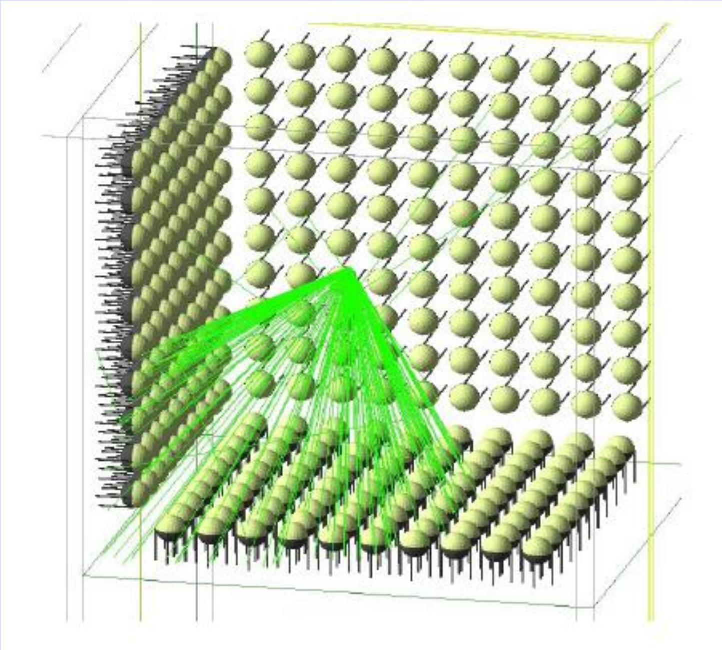
EMC(IDIS) $\Delta s \sim -0.1$
HERMES(SIDIS) $\Delta s \sim 0.03$

4. Astrophysics

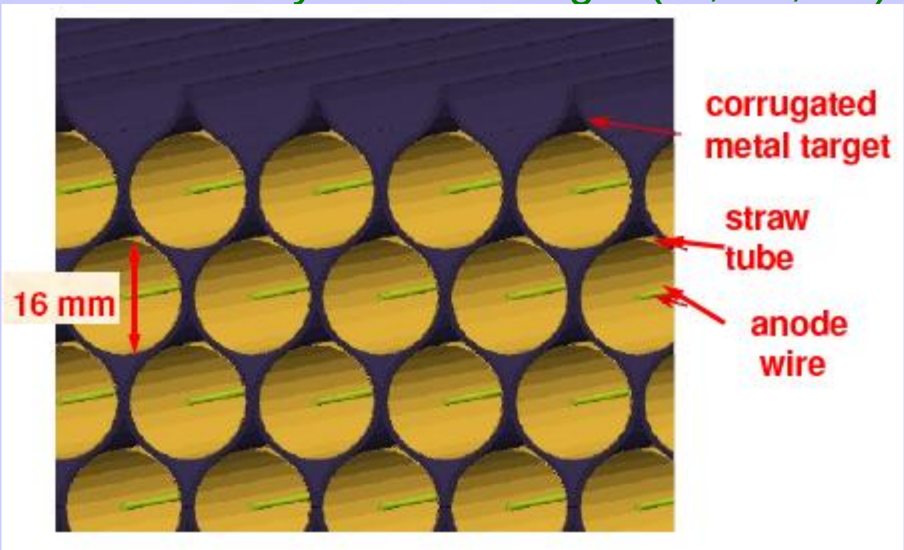


NuSNS (Neutrinos at the SNS)
Coherent scattering cross section with both light and heavy nuclei are the important input for supernova explosion simulation

NuSNS light element target (H, C, O)



NuSNS heavy element target (Al, Fe, Pb)



4. Short baseline oscillation experiment

SciBooNE/MiniBooNE combined oscillation experiment