July 1st, 2008
NuFact08 @ Valencia

Experimental status of neutrino scattering physics and needed measurements

T. Nakaya (Kyoto University)

- Neutrino Scattering Physics
  - have **several puzzles**
  - addressed by Past, Current and Near-Future experiments
    - K2K, (NOMAD) , MiniBooNE, SciBooNE, MINOS, (OPERA), T2K ND280, MINERνA
- Needed Measurements
  - What shall we measure?
    - K2K , MiniBooNE, SciBooNE, MINOS, T2K, MINERνA
  - What necessary for neutrino oscillation experiment.
    - MiniBooNE, MINOS, **T2K**

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  - What necessary for neutrino oscillation experiment.
    - MiniBooNE, MINOS, **T2K**

1. Introduction (ν osci. experiment)

Intense beam

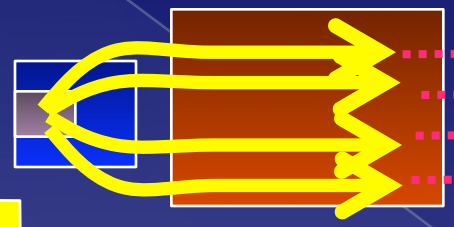
Gigantic detector

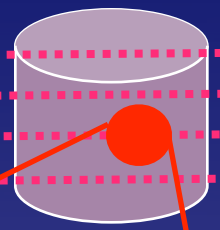
oscillation

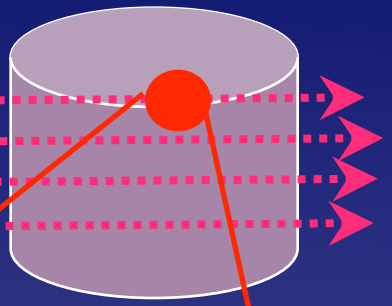
ν, ν, ν, ν

π, π, π, π, K

protons



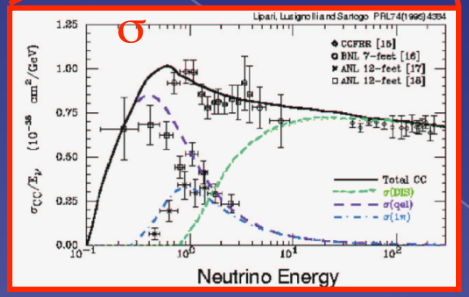


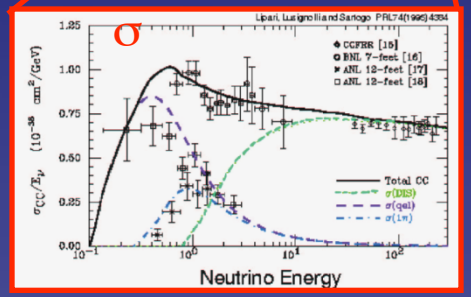


HARP

SHINE

$\Phi_\nu(E)$





$$\sigma(E)\cdot\Phi_\nu^{near}(E) \Leftrightarrow \sigma(E)\cdot\Phi_\nu^{far}(E)$$

MiniBooNE

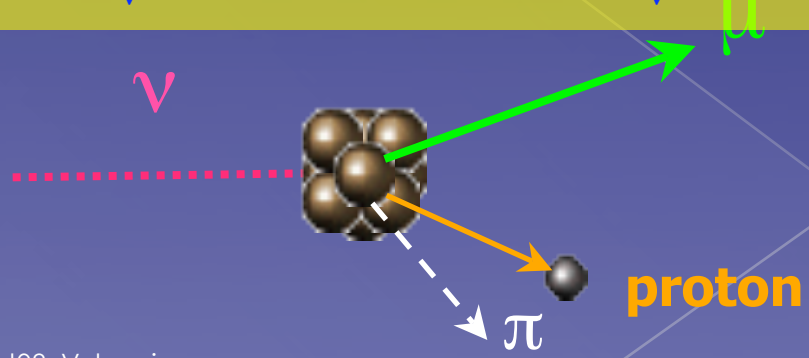
K2K

SciBooNE

MINERνA

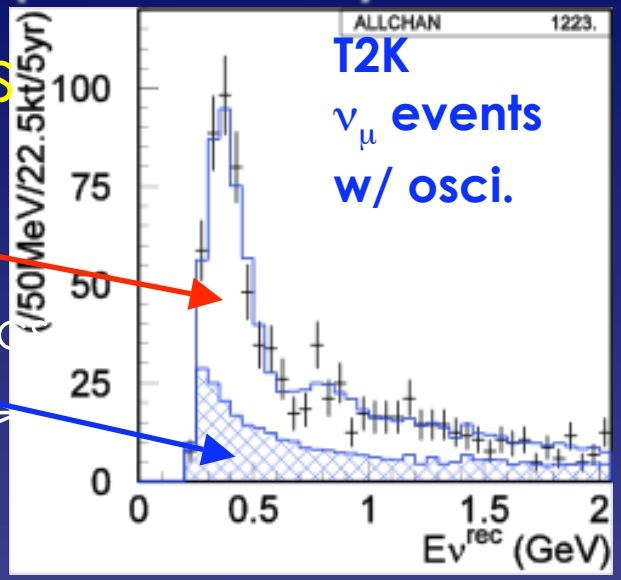
MINOS

T2K

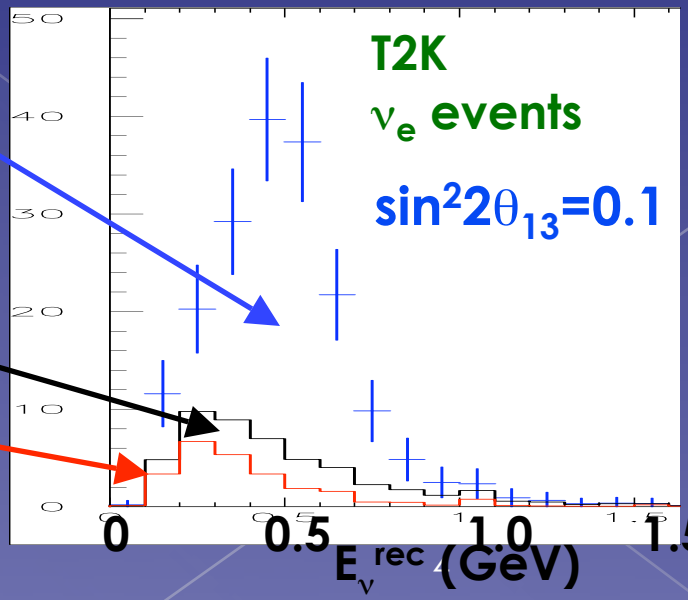


Impact of Neutrino Cross sections on oscillation measurements (T2K case)

- $\nu_\mu \rightarrow \nu_\mu$: precision measurements (θ_{23} and Δm_{23}^2)
  - Signal: CC-QE ($\nu + n \rightarrow \mu + p$)
    - Energy Reconstruction from μ kinematic
  - Background: Mainly CC-1$\pi^\pm$ ($\nu + N \rightarrow$ $+\pi + N'$)
    - Cross section with **the invisibility of π**



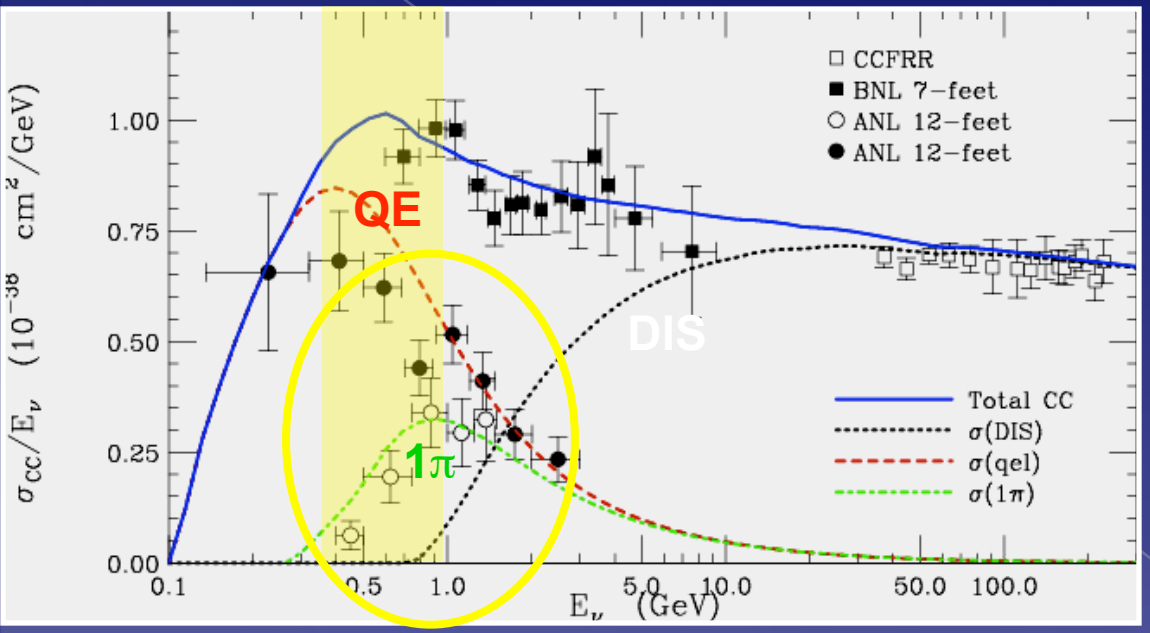
- $\nu_\mu \rightarrow \nu_e$: search for θ_{13}
  - Signal: CC-QE ($\nu + n \rightarrow e + p$)
  - Background
    - Beam ν_e
    - NCπ^0
      - Cross section as a function of the



Anti-ν for CP violation study

Unexplored Areas of Neutrino Physics

σ_ν in this E range of interest:



- **Data from old experiments** (1970~1980)
  - Low statistics
  - Systematic Uncertainties
- **Nuclear effects** (π/p/n absorption/scattering, shadowing, low Q^2 region)
  - Not well-modeled
- **New data** from K2K & MiniBooNE revealing surprises
- **More data at 1GeV with fine grained resolution will advance Neutrino Physics.**

MINOS, NuMI

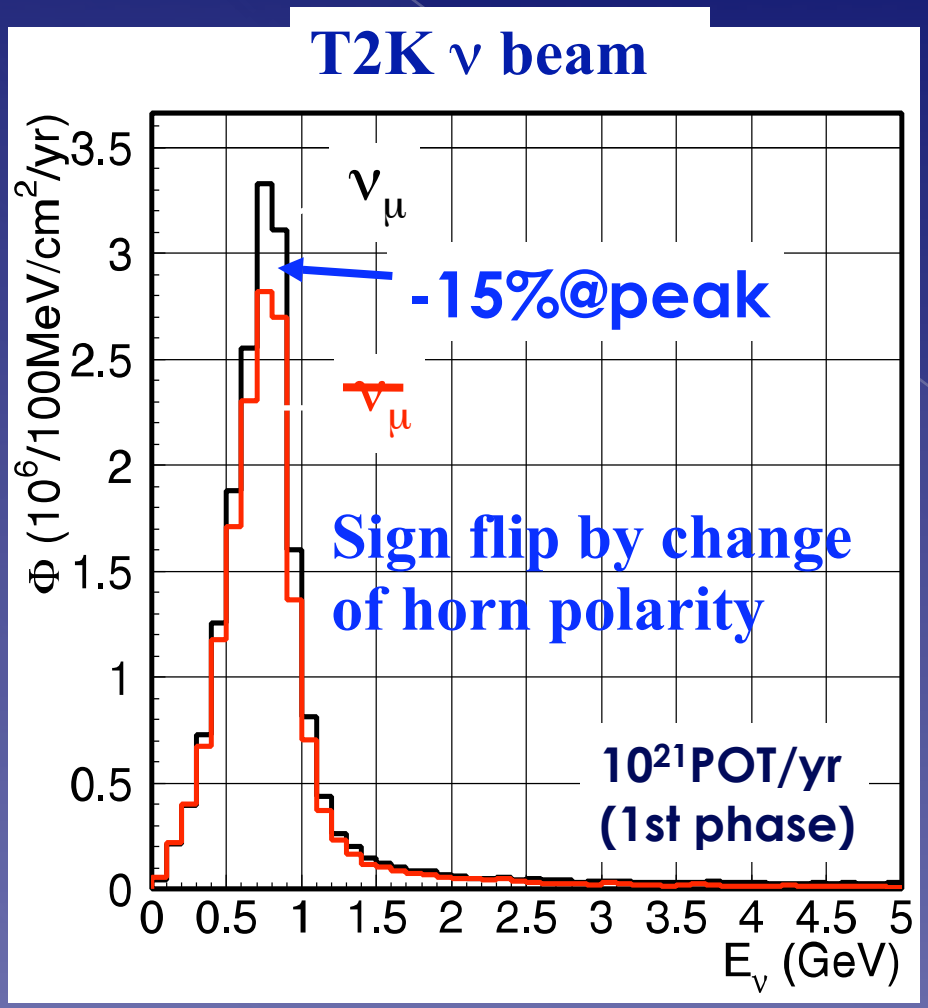
K2K, NOvA

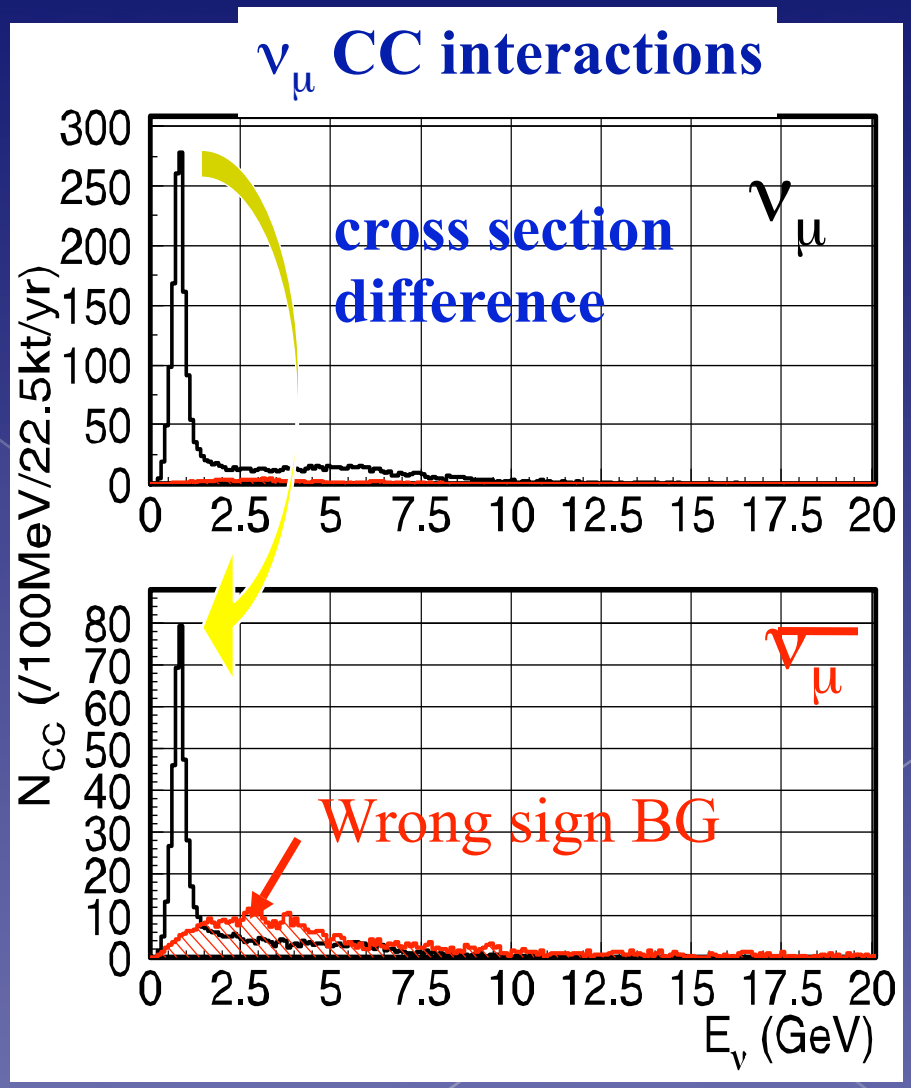
MiniBooNE, T2K, SciBooNE

Super-K atmospheric ν

Anti-ν cross section is in a poor situation.

CP violation search in T2K-II





ν_e appearance in T2K-II

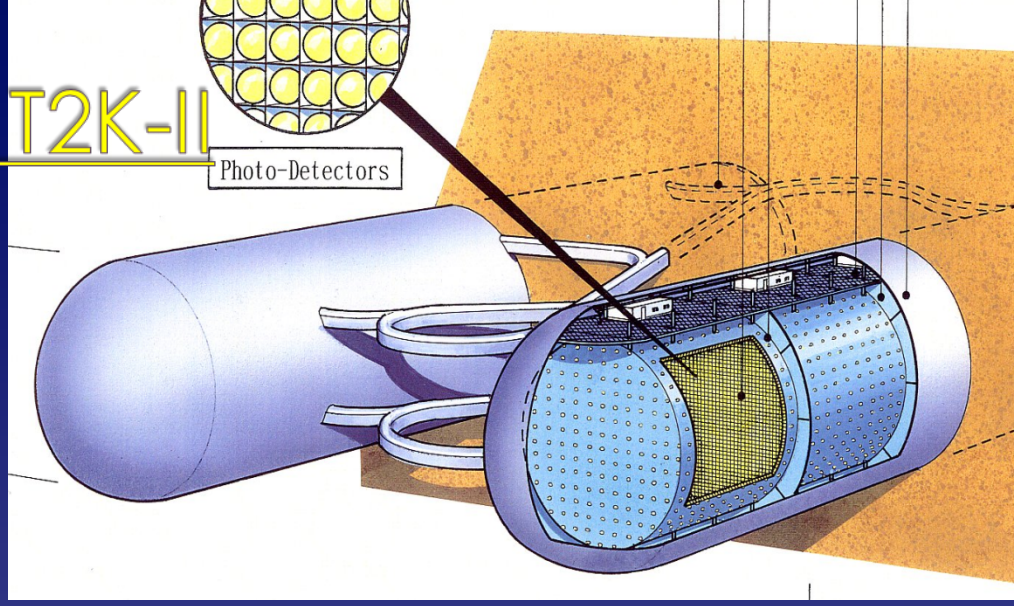
$\Delta m_{21}^2=6.9\times10^{-5}eV^2$

$\Delta m_{32}^2=2.8\times10^{-3}eV^2$

$\theta_{12}=0.594$

$\theta_{23}=\pi/4$

$\theta_{13}=0.05$ ($\sin^2 2\theta_{13}=0.01$)



ν_μ:2yr, $\bar{\nu}_\mu$:6.8yr

4MW (J-PARC upgrade)

0.54Mt (Hyper-K)

	signal		background				
	$\delta=0$	$\delta=\pi/2$	total	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
$\nu_\mu\rightarrow\nu_e$	536	229	913	370	66	450	26
$\bar{\nu}_\mu\rightarrow\bar{\nu}_e$	536	790	1782	399	657	297	430

Understanding of Neutrino Interactions with Nucleus is **IMPORTANT.**

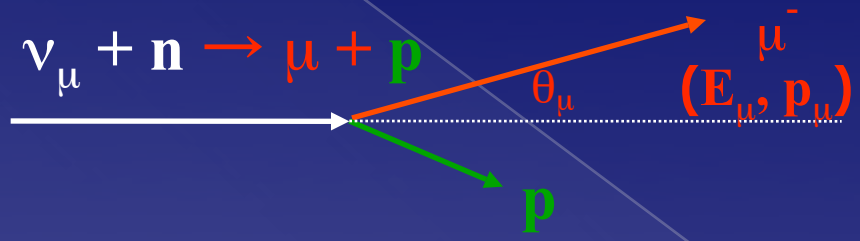
2. Puzzles

- Quasi-Elastic Scattering
  - M_A
  - Q^2 distribution (Muon angle in SciBooNE)
  - Low Q^2 region
- π production
  - Coherent π production (CC v.s. NC)
  - π^0 Momentum distribution
- Low energy e excess in MiniBooNE
- (maybe more)

2.1 QE (Quasi-Elastic) scattering

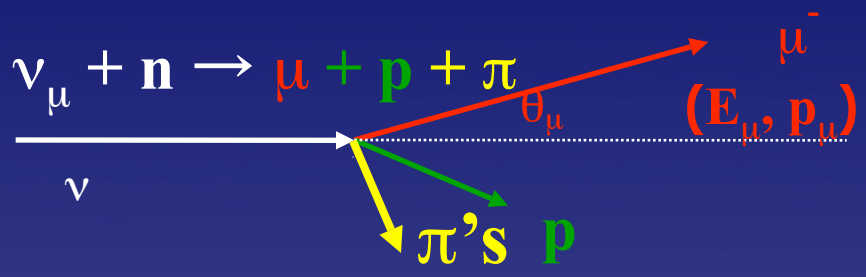
CC quasi elastic (QE)

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



CC inelastic

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

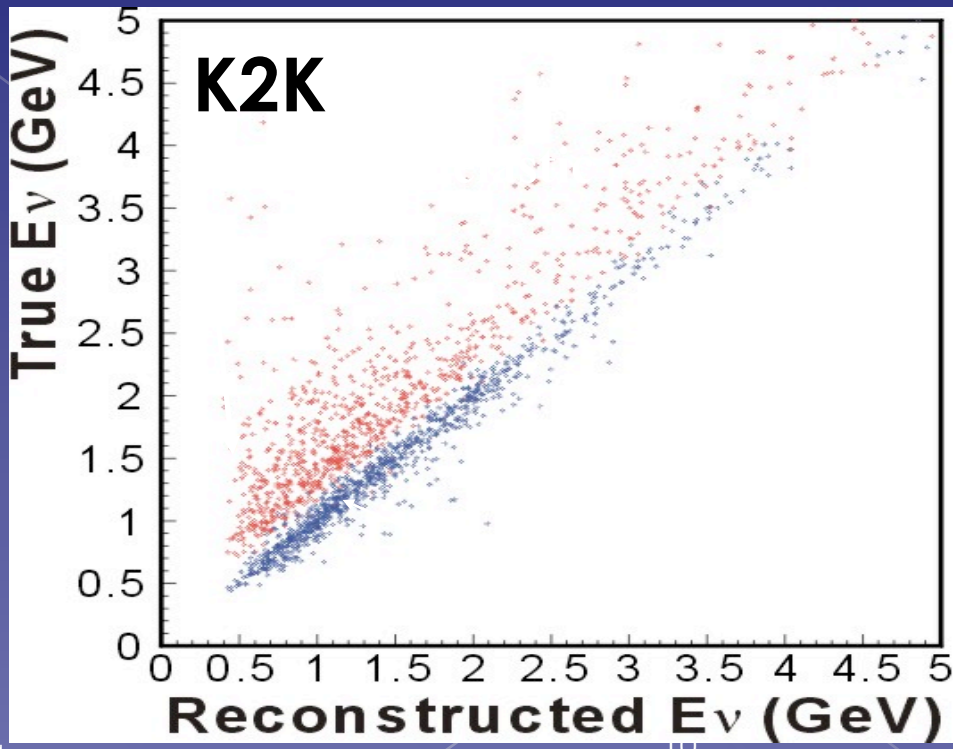


$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

Rate(Eν,Near) → <u>φ(Eν,Near)</u>

↑

σ(QE), σ(nonQE)



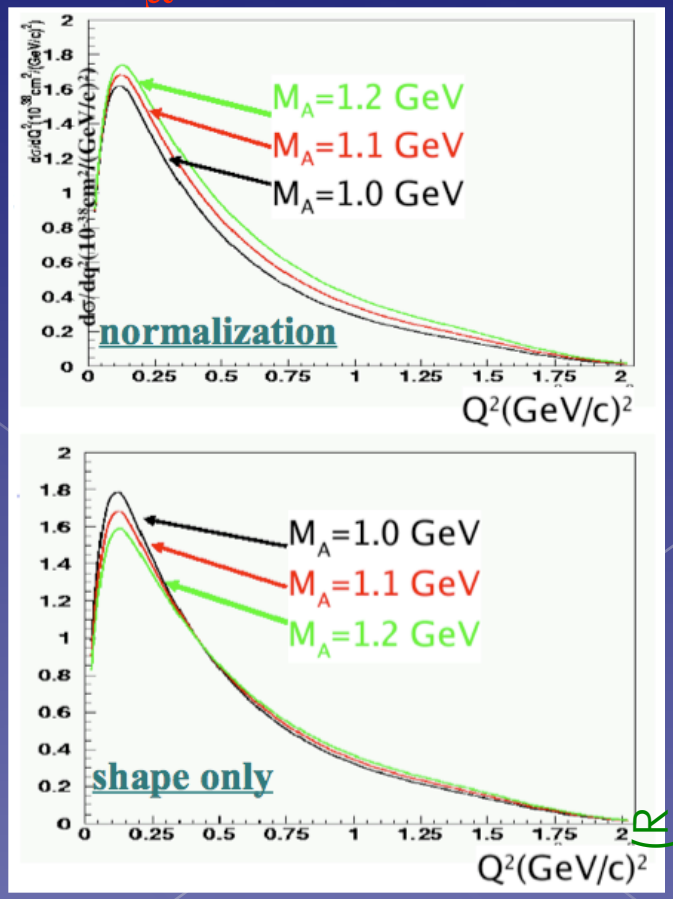
QE Scattering

- It is important to understand
  - Nuclear model
    - Assuming Fermi Gas model
  - Nuclear form factors (FF)
    - Vector FF is known from e^- scattering.
    - Axial Vector FF can be measured by neutrino scattering
    - Dipole form factor

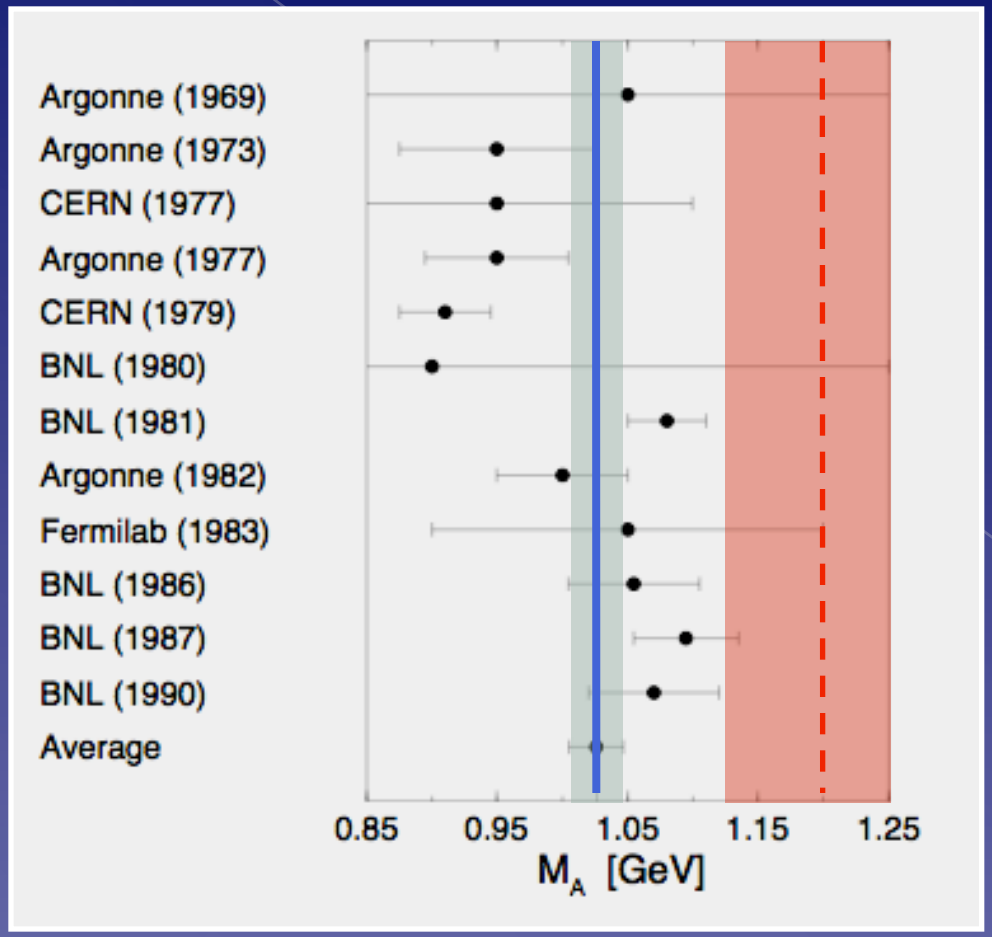
$$F_A(Q^2) = \frac{g_A}{\left(1 + Q^2/M_A^2\right)^2}$$

Single Parameter: **M_A (=1.03 GeV/c^2)** from the past measurements

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



Recent measurements of M_A

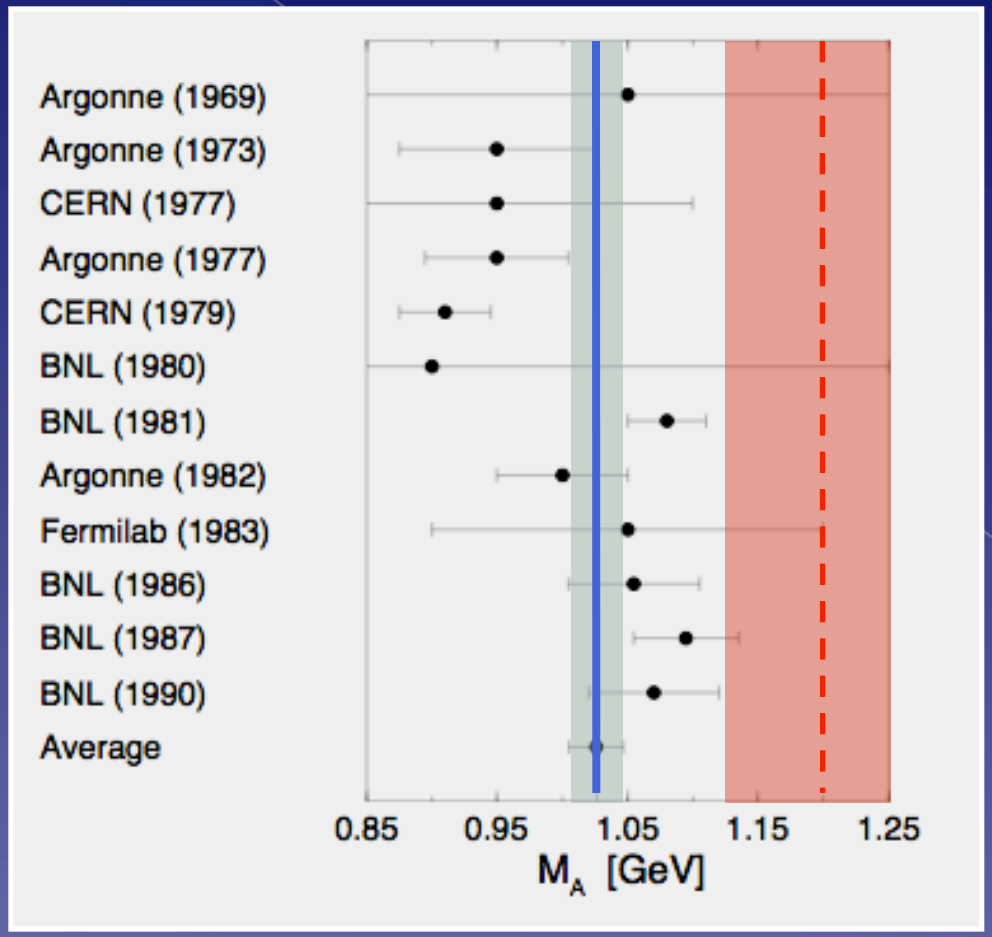


- **K2K SciFi** (^{16}O, Q^2>0.2)
  Phys. Rev. **D74**, 052002 (2006)
  M_A=1.20 ± 0.12 GeV
- **K2K SciBar** (^{12}C, Q^2>0.2)
  M_A=1.14 ± 0.11 GeV
- **MiniBooNE** (^{12}C, Q^2>0.25)
  Phys. Rev. Lett. **100**, 032301 (2008)
  M_A=1.25 ± 0.12 GeV

Systematic Difference?
Effective M_A in nucleus?

past world avg: M_A = 1.026 ± 0.021 GeV
J. Phys. **G28**, R1 (2002)

Recent measurements of M_A



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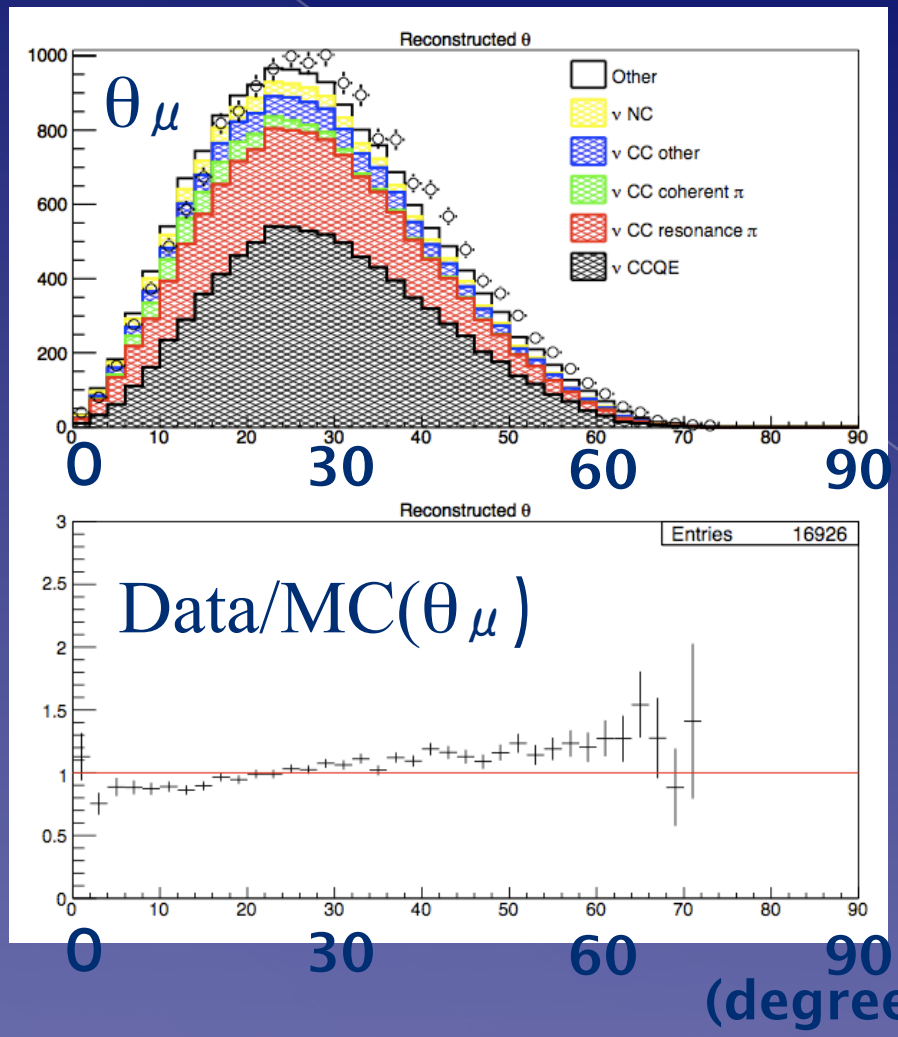
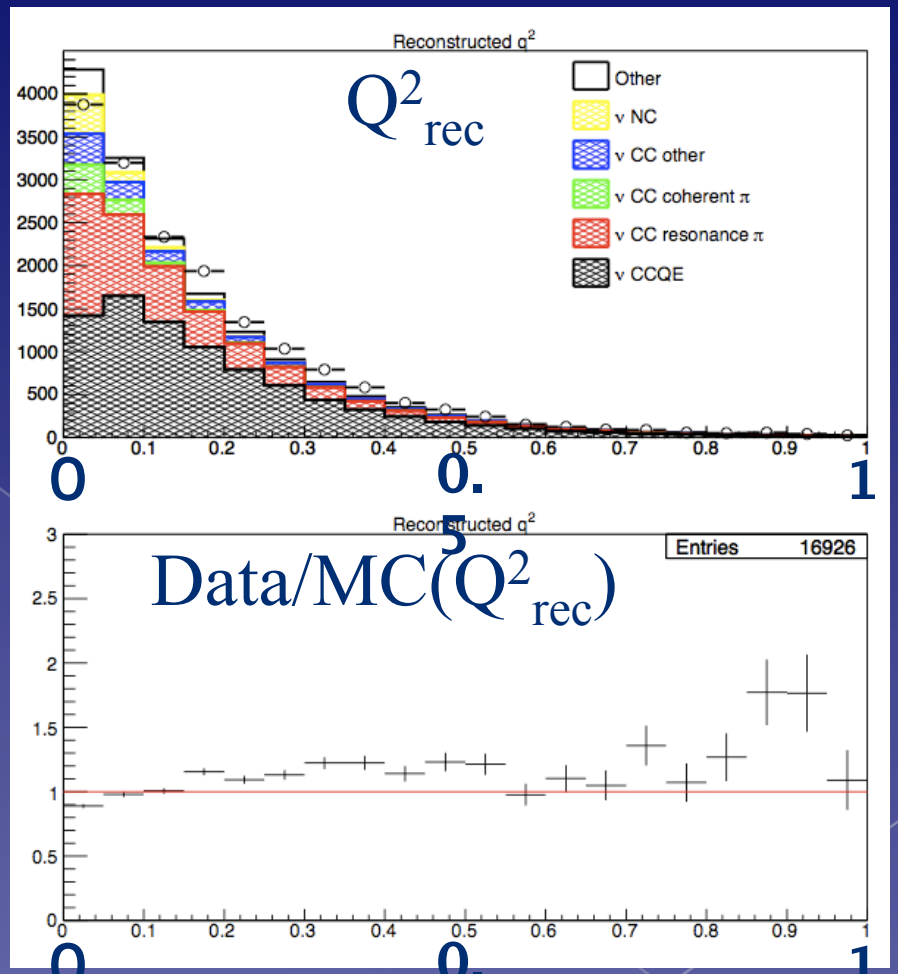
Puzzle1

θ_μ and Q^2 in SciBooNE

MRD Stopped sample (normalized by muon events)



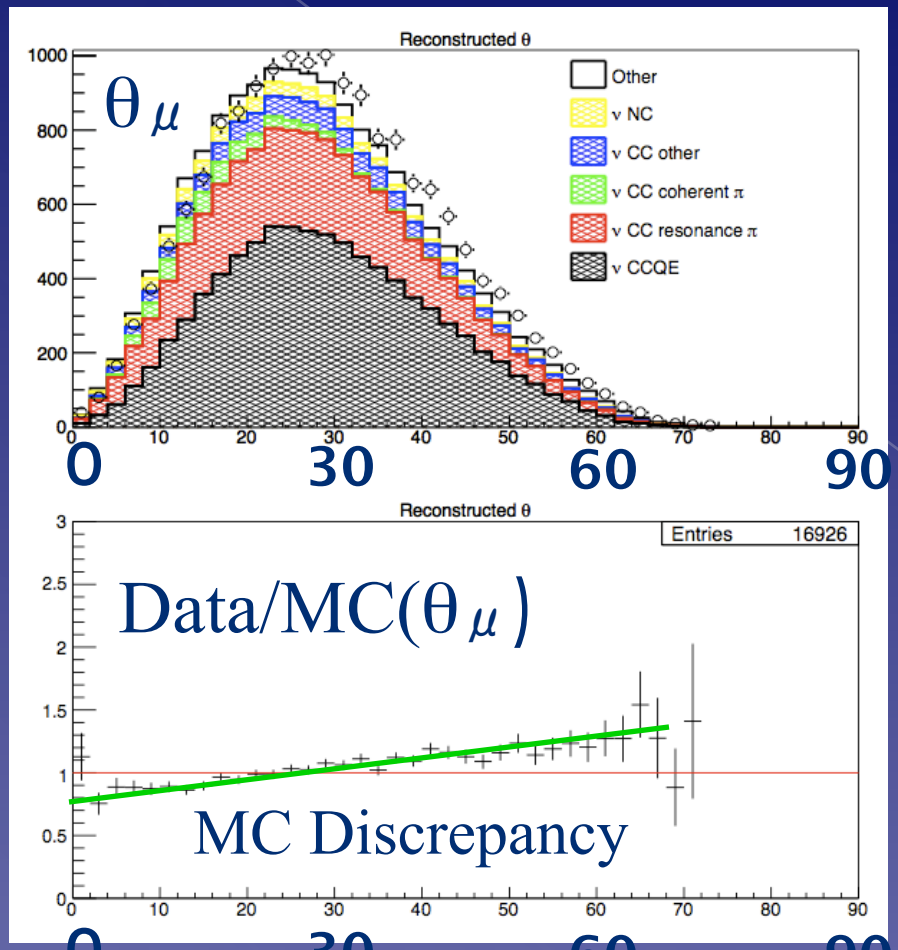


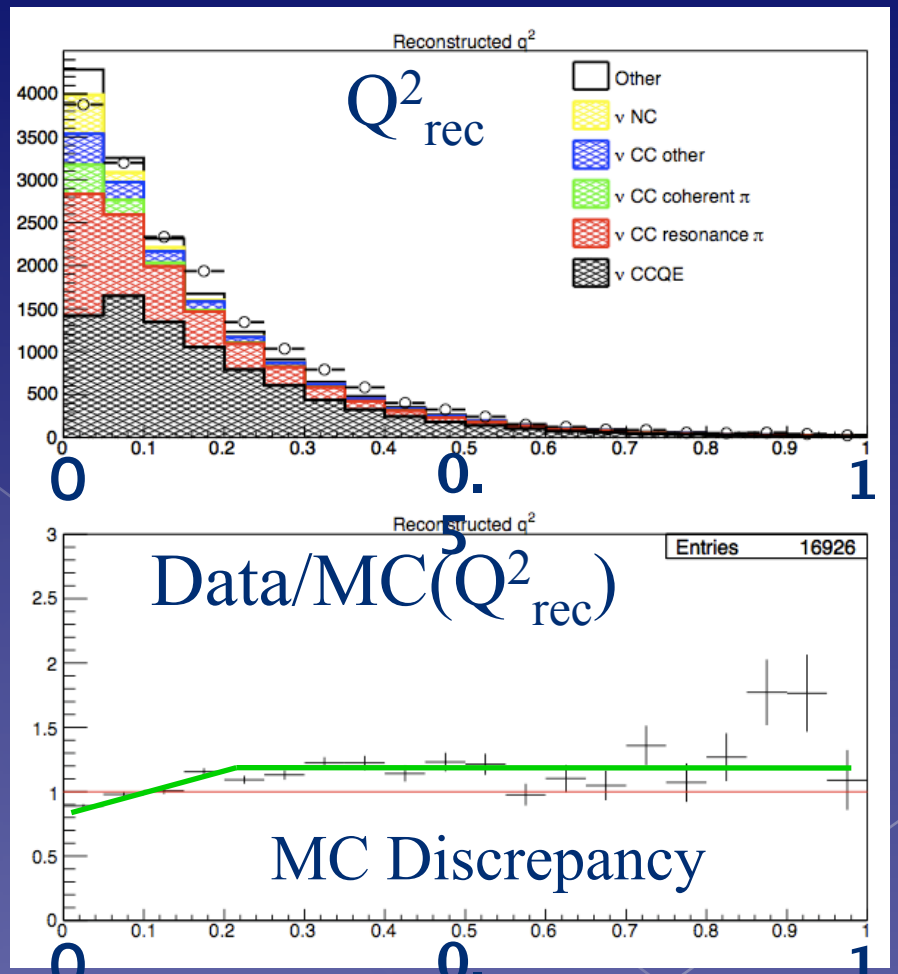
Talk by J. Alcaraz at WG2

M_A effect or other sources ?

θ_μ and Q^2 in SciBooNE

MRD Stopped sample (normalized by muon events)





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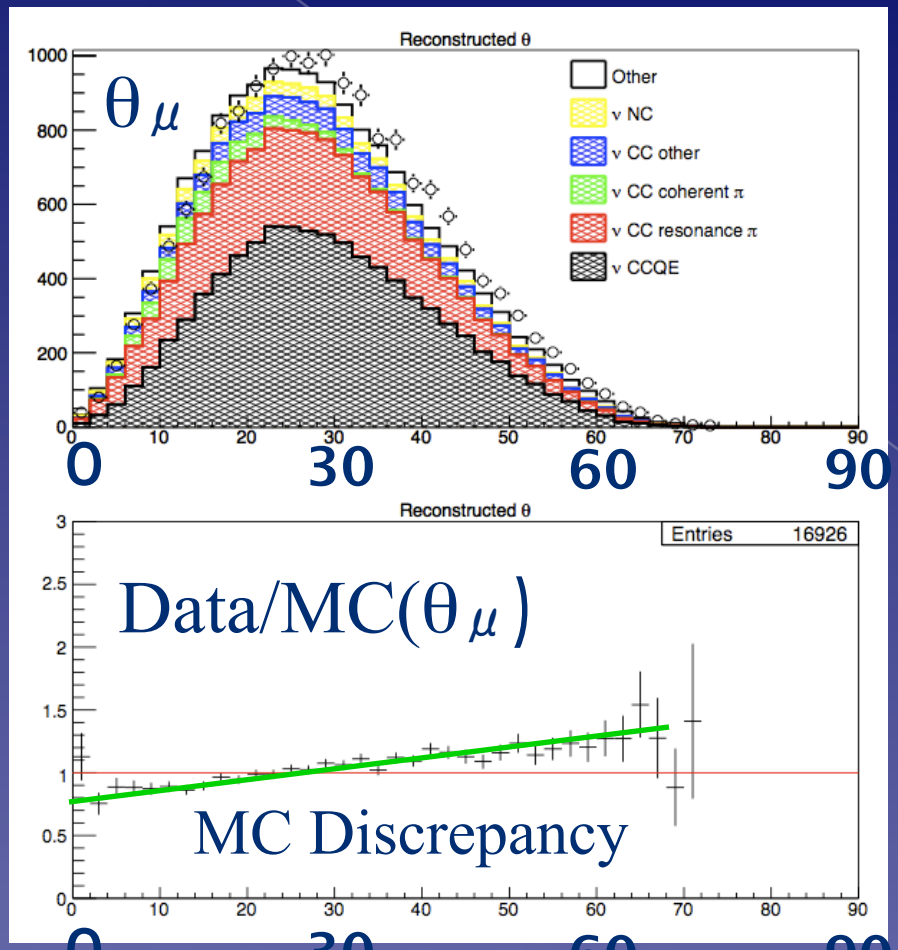
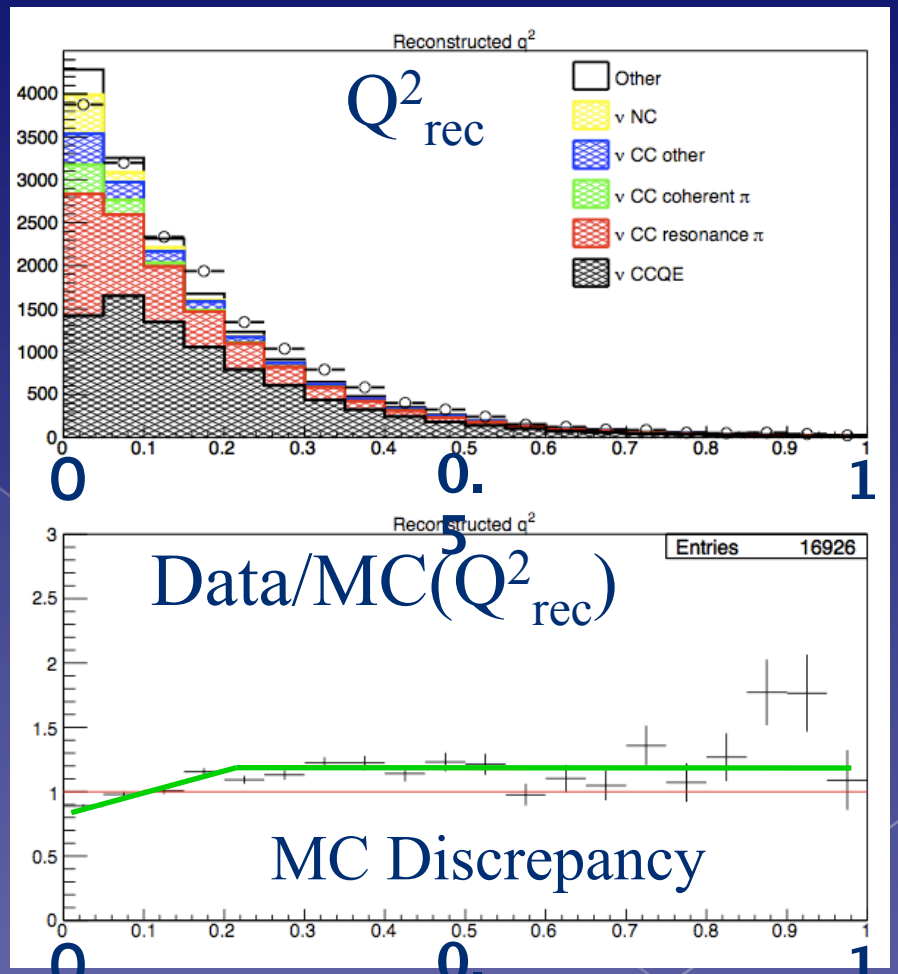


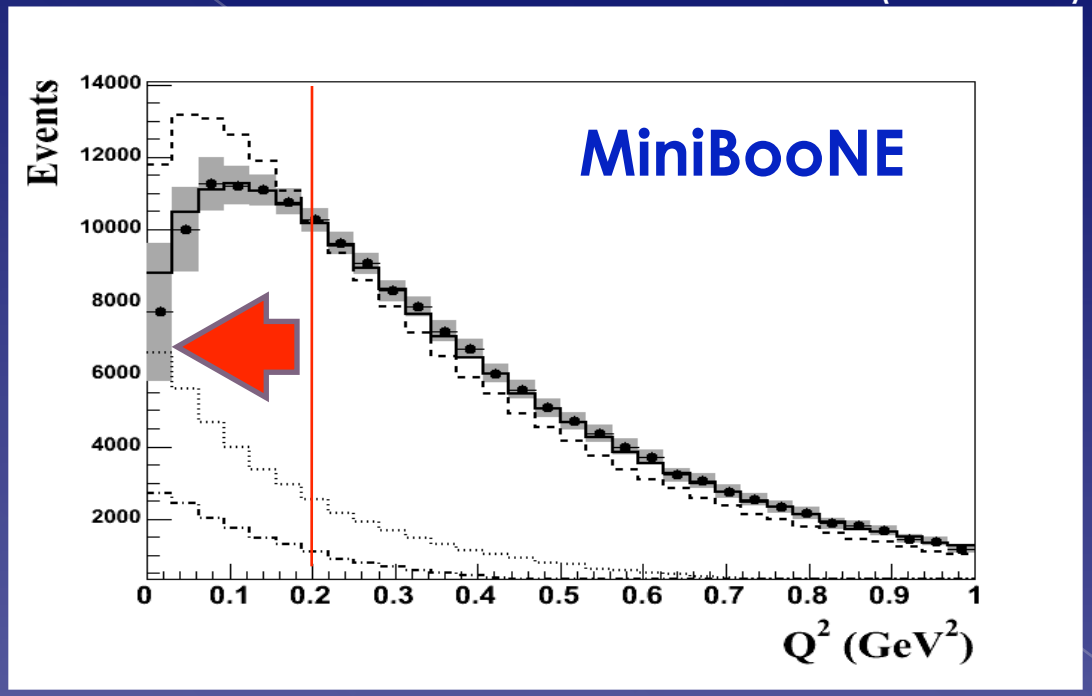


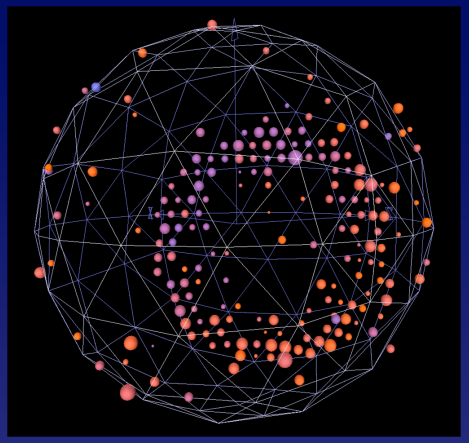
Talk by J. Alcaraz at WG2

Puzzle2 M_A effect or other sources ?

Low Q^2 region in QE

(T. Katori)





- fit to Q^2 distribution, $Q^2>0$, carbon
  - $M_A = 1.23 \pm 0.20$ GeV
  - $\kappa = 1.019 \pm 0.011$ (Pauli blocking par)

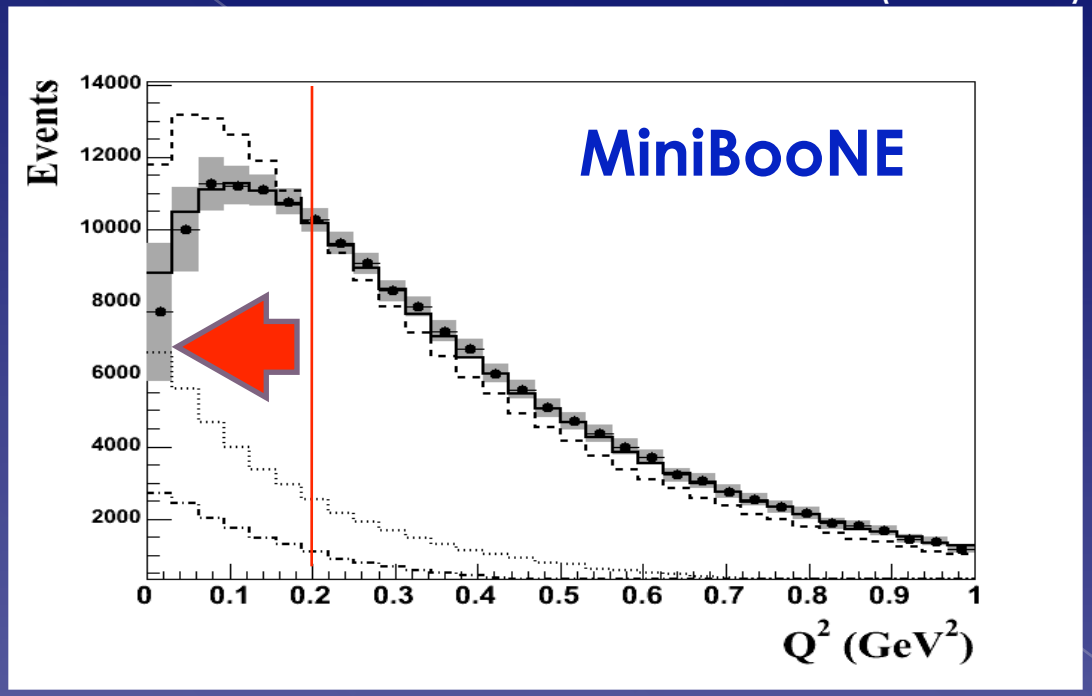
(PRL **100**, 032301 (2008))

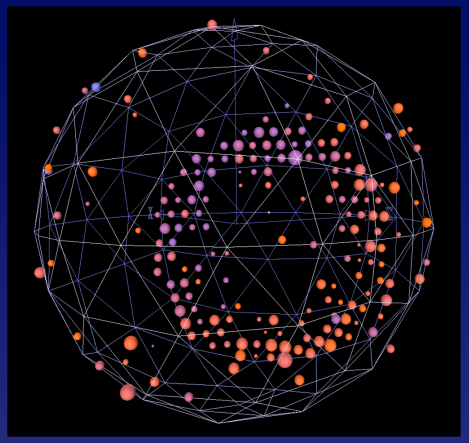
fixes high Q^2

fixes low Q^2

Low Q^2 region in QE

(T. Katori)





Puzzle3

- fit to Q^2 distribution, $Q^2>0$, carbon
  - $M_A = 1.23 \pm 0.20$ GeV → fixes high Q^2
  - $\kappa = 1.019 \pm 0.011$ (Pauli blocking par) → fixes low Q^2

(PRL **100**, 032301 (2008))

Discrepancy in the K2K result

MEASUREMENT OF NEUTRINO OSCILLATION BY THE . . . PHYSICAL REVIEW D **74,** 072003 (2006)

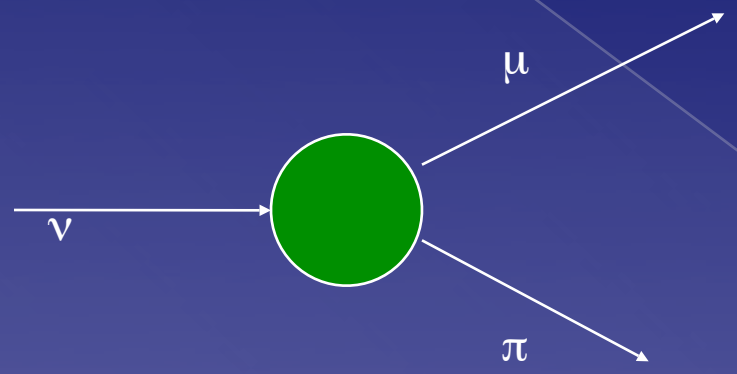
TABLE XIV. Results of the spectrum measurement. The best-fit value of each parameter is listed for the fits with all the detectors' data, with the 1KT data, with the SciFi data and with the SciBar data, respectively. The reduced χ^2 (χ^2_{total}/DOF) and the averaged χ^2 of each detector (χ^2/N_{bin}) are also shown.

Parameter	**Combined**	1KT only	SciFi only	SciBar only
f_1 (0.00–0.50 GeV)	**1.657 ± 0.437**	2.372 ± 0.383	≡ 1	≡ 1
f_2 (0.50–0.75 GeV)	**1.107 ± 0.075**	1.169 ± 0.072	0.882 ± 0.317	1.166 ± 0.251
f_3 (0.75–1.00 GeV)	**1.154 ± 0.061**	1.061 ± 0.065	1.157 ± 0.201	1.145 ± 0.134
f_4 (1.00–1.50 GeV)	**≡ 1**	≡ 1	≡ 1	≡ 1
f_5 (1.50–2.00 GeV)	**0.911 ± 0.044**	0.709 ± 0.151	0.980 ± 0.107	0.963 ± 0.070
f_6 (2.00–2.50 GeV)	**1.069 ± 0.059**	≡ 1	1.188 ± 0.096	0.985 ± 0.086
f_7 (2.50–3.00 GeV)	**1.152 ± 0.142**	≡ 1	1.062 ± 0.230	1.291 ± 0.283
f_8 (3.00– GeV)	**1.260 ± 0.184**	≡ 1	1.323 ± 0.203	1.606 ± 0.749
R_{nQE} **±0.2**	**0.964 ± 0.035**	0.589 ± 0.071	1.069 ± 0.060	1.194 ± 0.092

- RnQE ($\equiv\sigma_{\text{non-QE}}/\sigma_{\text{QE}}$)
  - 1KT measurement ⇒ **~0.6**
    - Low energy neutrinos
    - Extracted from the muon angular distributions.
  - SciBar measurement ⇒ **~1.2**
    - Medium-high energy neutrinos.
    - Extracted from both the number of tracks and the

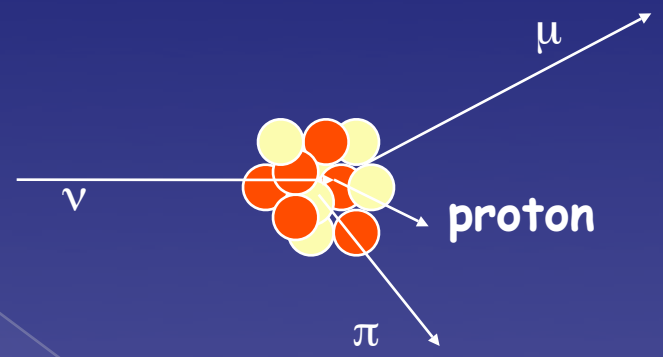
(CC)-ν π production at low energy (~1 GeV)

CC-coherent π (ν+A→μ+A+π)



CC-1π (ν+p→μ+p+π)

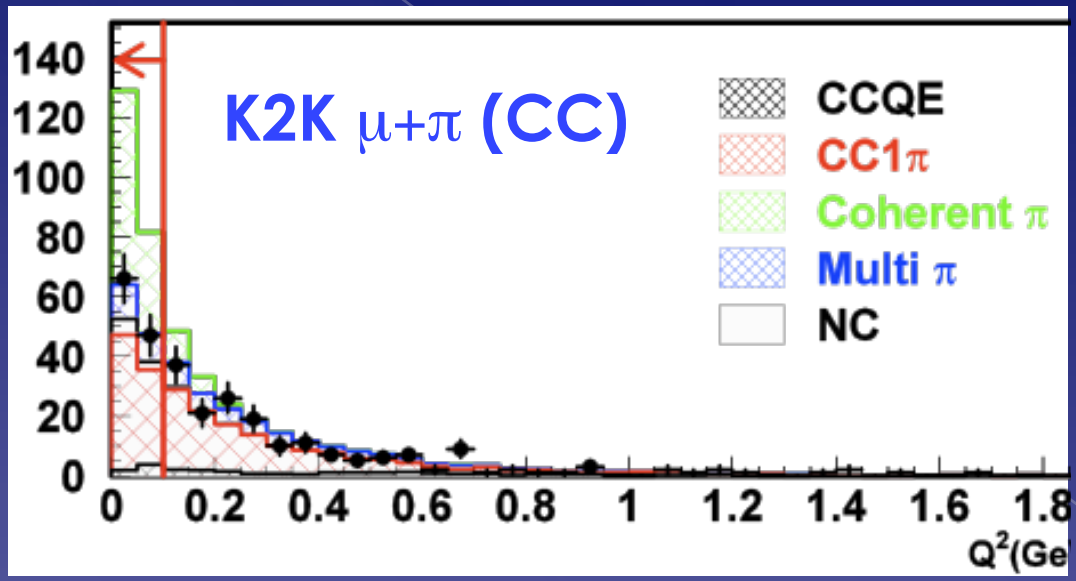
Mainly through Δ resonance.

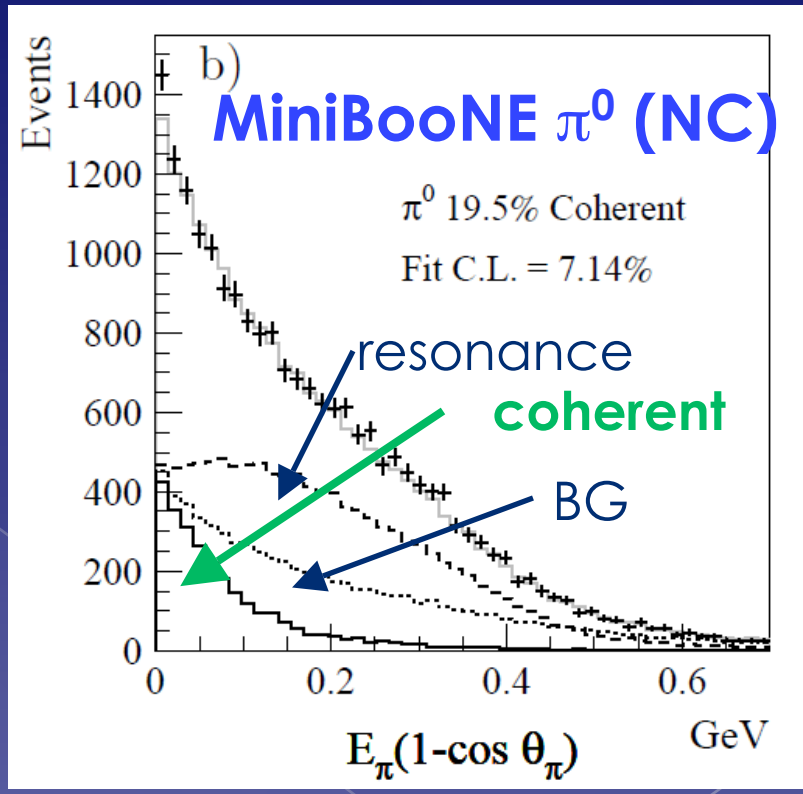


Coherent π signature

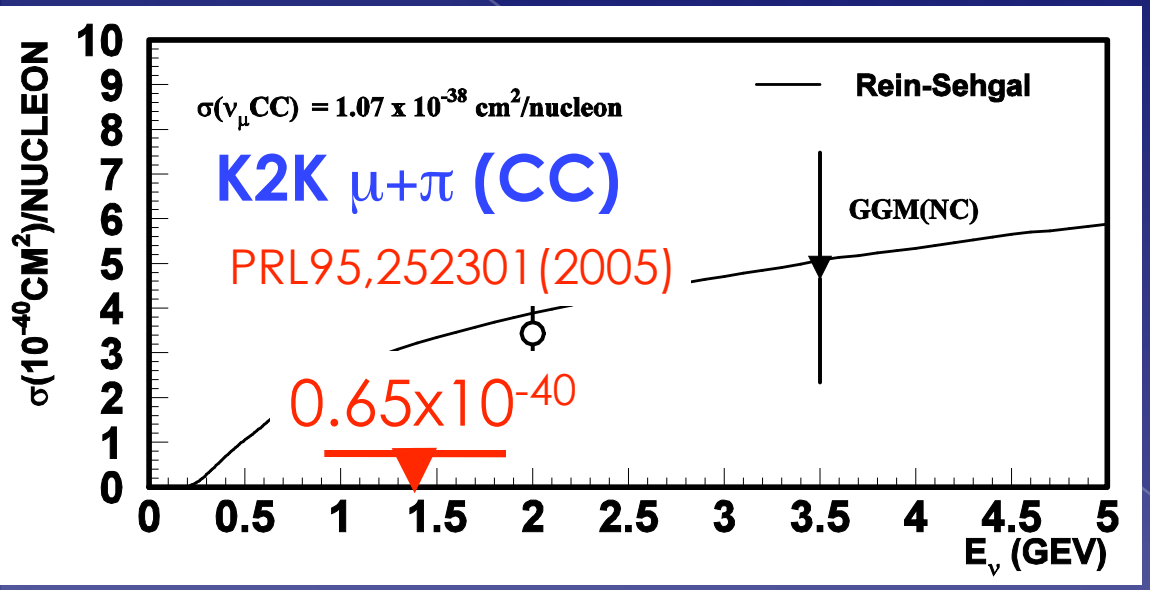
- One muon and one pion in the final state
- Low momentum transfer
- No vertex activity due to no proton

Coherent π production in CC and NC reaction

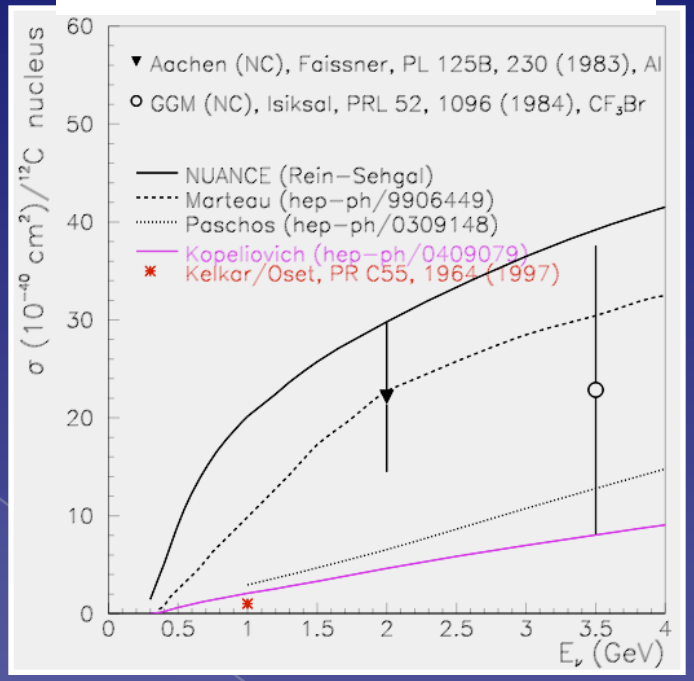




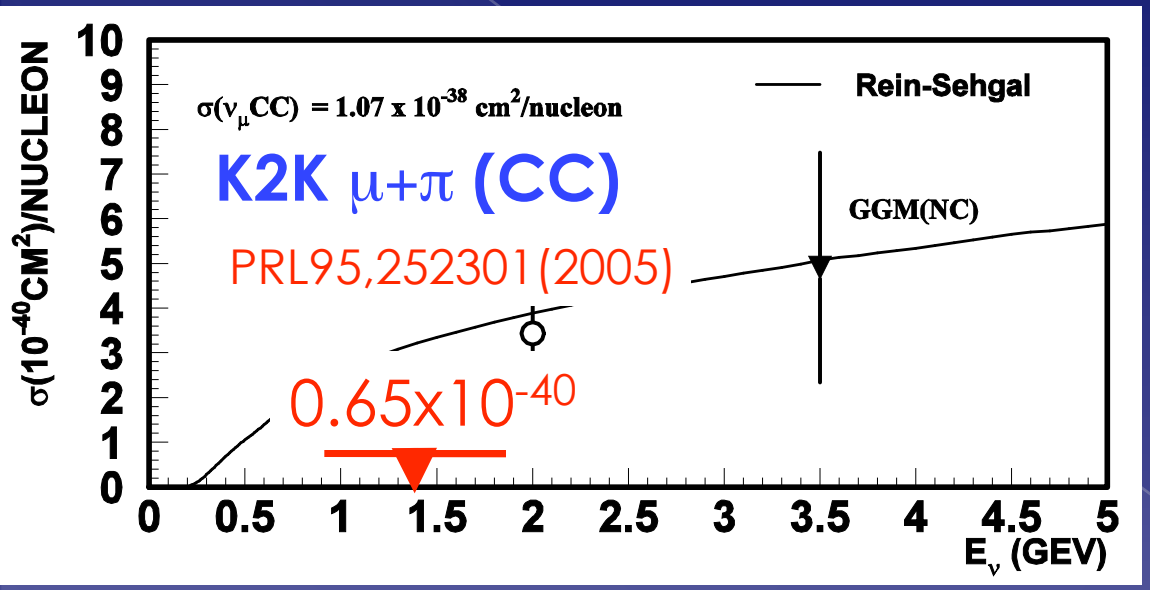
- CC-coherent π is **NOT** observed.
- NC-coherent π is observed.



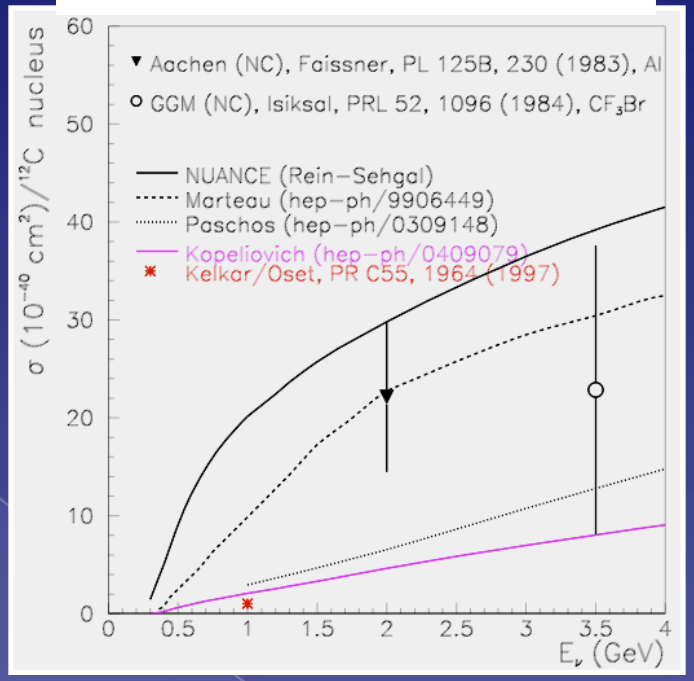
MiniBooNE π^0 (NC)



- Consistent?
  - New CC result will come from SciBooNE soon.



MiniBooNE π^0 (NC)



- Consistent? **Puzzle4**
  - New CC result will come from SciBooNE soon.

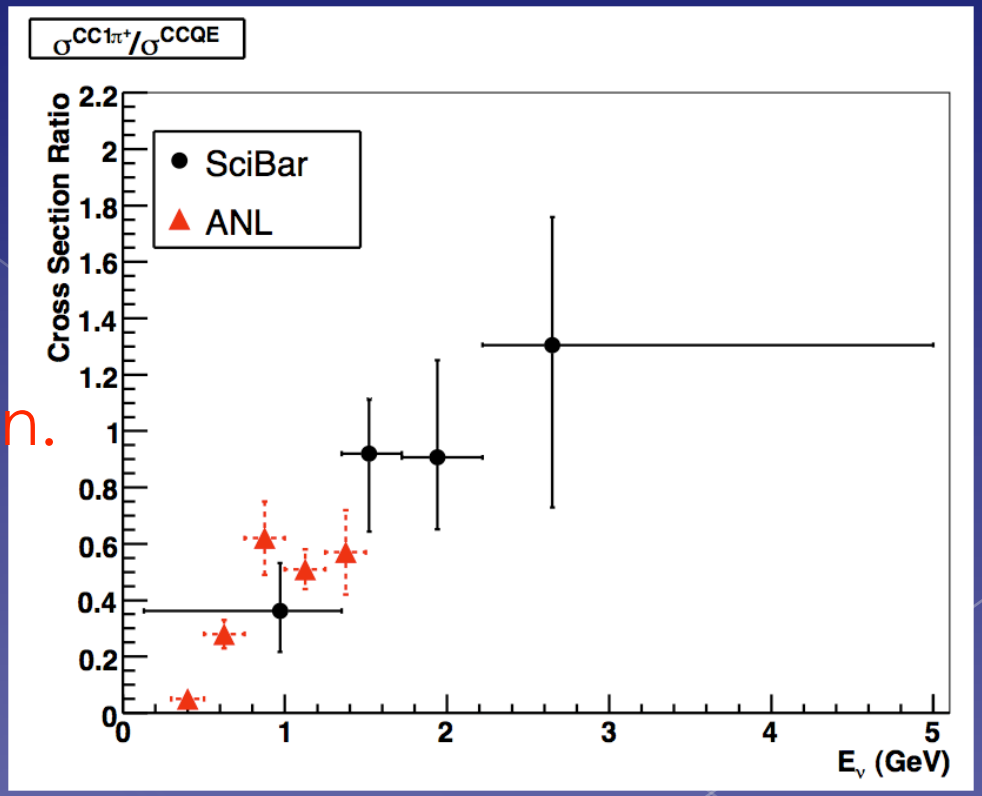
New K2K Result: CC π^+

accepted by PRD

$$\sigma_{CC\ \pi^+}/\sigma_{QE} = 0.734 \pm 0.086\ (\text{fit})^{+0.076}_{-0.103}\ (\text{nucl})^{+0.079}_{-}\ (\text{syst})$$

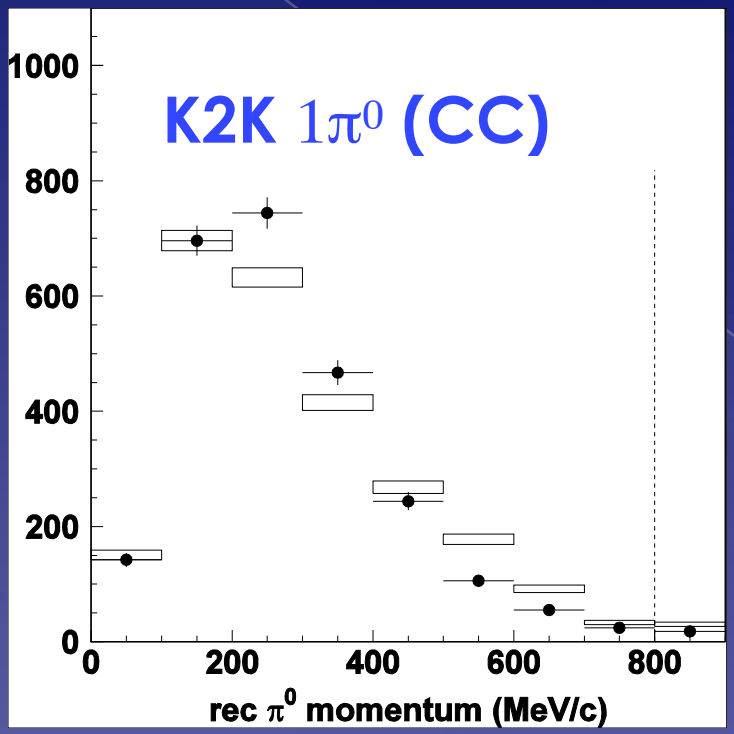
- consistent with ANL (1982, D_2)
- 20% measurement of σ ratio

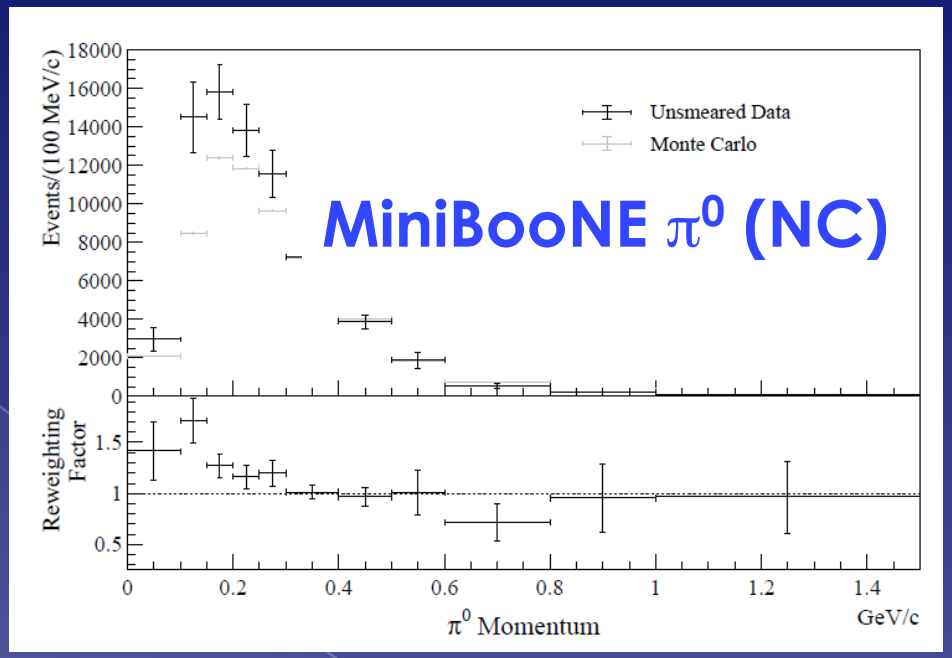
- T2K requests 5~10% precision.
  - Challenging?



Talk by L. Whitehead at WG2

π^0 momentum distribution



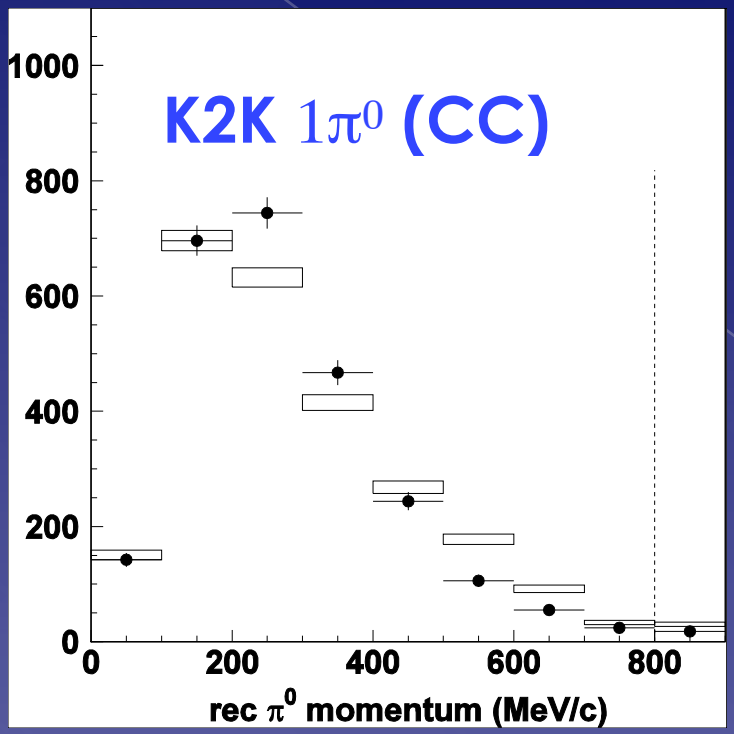


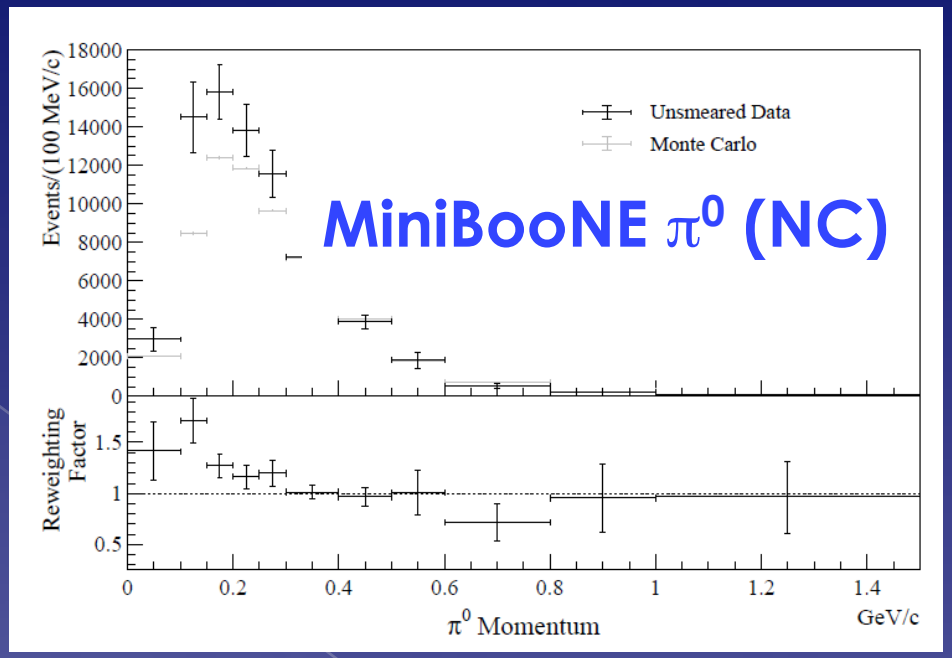
Talk by H. Tanaka at WG2

- More low momentum π^0?
  - Less high momentum π^0?
  - If so, it is a good news for ν osci. Experiments.

(K2K) : $\sigma_{NC1\pi^0}/\sigma_{CC\text{-}all}$=0.064±0.001 ±0.007 (MC: 0.065)

π^0 momentum distribution





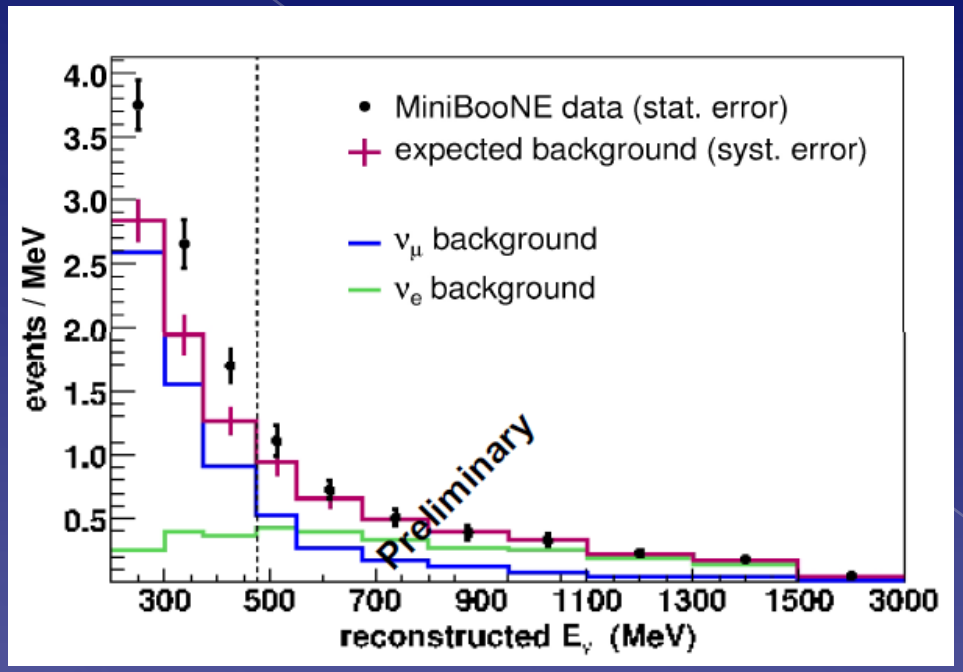
Talk by H. Tanaka at WG2

- More low momentum π^0?
  - Less high momentum π^0?
  - If so, it is a good news for ν osci. Experiments.

Puzzle5

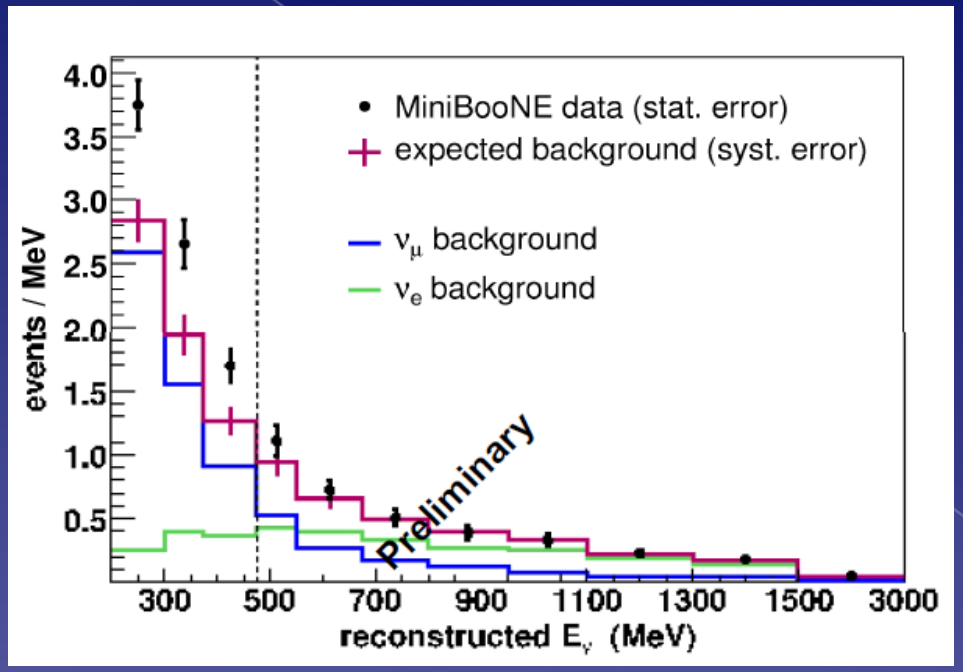
(K2K) : $\sigma_{NC1\pi^0}/\sigma_{CC\text{-}all}$=0.064±0.001 ±0.007 (MC: 0.065)

MiniBooNE low energy e excess



- Needless to say, it is important to understand the source of this effect.
  - However, the effect on T2K may be marginal.
    - T2K: sensitivity of $\sin^2 2\theta_{\mu e}$ ($=0.5\sin^2 2\theta_{13}$)~**0.004** ($0.35<E\nu<0.85$ GeV)
    - MiniBooNE: sensitivity of $\sin^2 2\theta$~**0.001** ($0.475<E\nu$ GeV)

MiniBooNE low energy e excess



Puzzle6

- Needless to say, it is important to understand the source of this effect.
  - However, the effect on T2K may be marginal.
    - T2K: sensitivity of $\sin^2 2\theta_{\mu e}$ ($=0.5\sin^2 2\theta_{13}$)~**0.004** ($0.35<E\nu<0.85$ GeV)
    - MiniBooNE: sensitivity of $\sin^2 2\theta$~**0.001** ($0.475<E\nu$ GeV)

New σ_ν Calculations (2006-2008)

Compiled by Sam Zeller (LANL)

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single π production

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- E. Hernandez *et al.*, arXiv:0802.1627 [hep-ph] (2008)
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- C. Praet *et al.*, arXiv:0710.0312 [nucl-th] (2007)
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DIS

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- A. Cooper-Sarkar *et al.*, JHEP **0801**, 075 (2008)
- S.A. Kulagin *et al.*, arXiv:0711.3956 [nucl-th] (2007)
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- S. Alekhin et al., AIP Conf. Proc. **967**, 215 (2007)
- W. Melnitchouk, AIP. Conf. Proc. **967**, 225 (2007)
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- S.A. Kulagin, R. Petti, hep-ph/0703033 (2007)
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- K.S. Kuzmin *et al.*, Phys. Atom. Nucl. **69**, 1857 (2006)
- T. Leitner et al., PRC **73**, 065502 (2006), PRC **74**, 065502 (2006),
- O. Benhar, D. Meloni, hep-ph/0610403 (2006)

3. ν Scattering Experiments

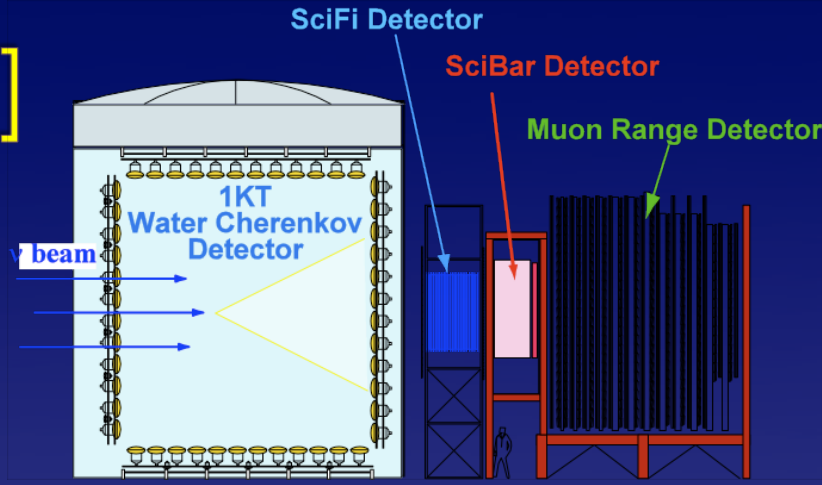
- K2K (1999-2004)
- MiniBooNE (2002-present)
- MINOS (2005-present)
- SciBooNE (2007-present)
- T2K (2009-)
- MINERνA (2009-)
  - (Results may come from NOMAD and OPERA)

Summary of ν scattering experiments

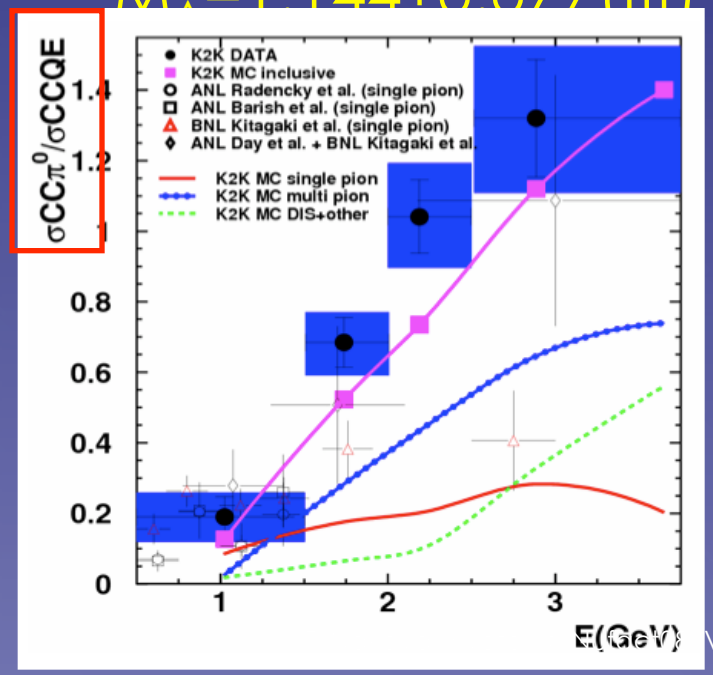
	<Eν> (GeV)	Detector	Fiducial Mass (ton)	Target	#ν events as reference
K2K	~1.3	Cherenkov , FGD	5~50	H_2O, CH, Fe	50k~100k
MiniBooNE	~0.7	Cherenkov	~440	CH_2	~500k
MINOS	2~30	Iron/Plastic sandwich	33	Fe	~5M
SciBooNE	~0.7	FGD	10	CH	~100k
T2K	~0.7	FGD	2~10	Fe, Pb, CH, H_2O	~500k
MINERνA	2~30	FGD	~3	Fe, Pb, C	~10M

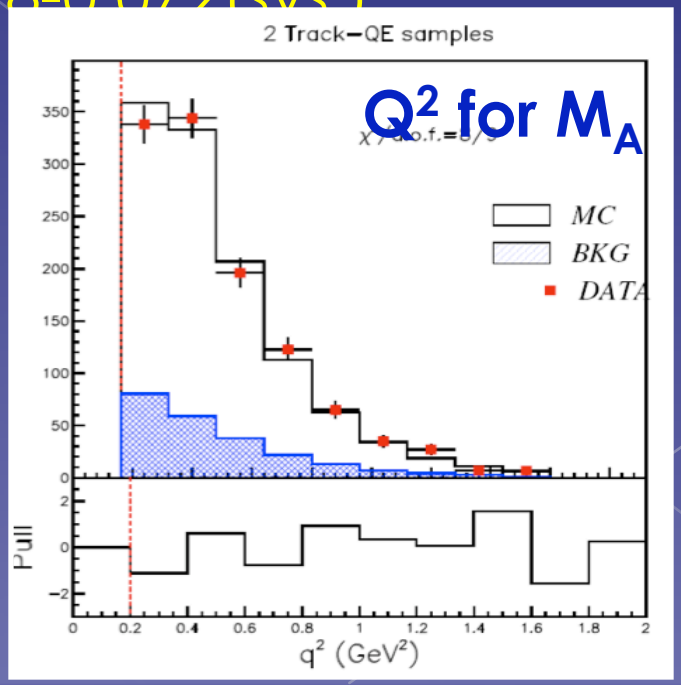
The above numbers are not official numbers from the experiments, but rough estimation by TN.

K2K [Near detectors]



- Final work for publication
  - $CC\pi^0$ production
    - $\sigma_{CC\pi0}/\sigma_{CC\text{-}QE}$=0.306±0.023(stat.)+0.023-0.021(sys.)
  - CC-QE M_A on Carbon.
    - M_A=1.144+0.077(fit)+0.078-0.072(sys.)



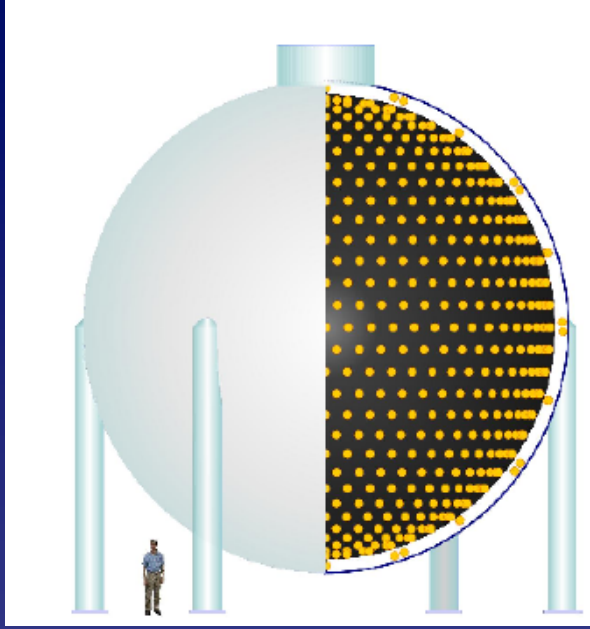


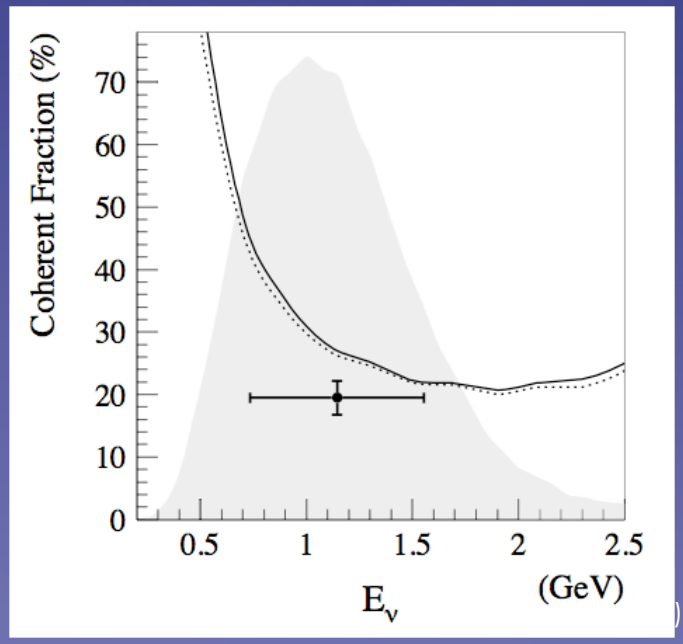
Published papers from K2K on ν scattering.

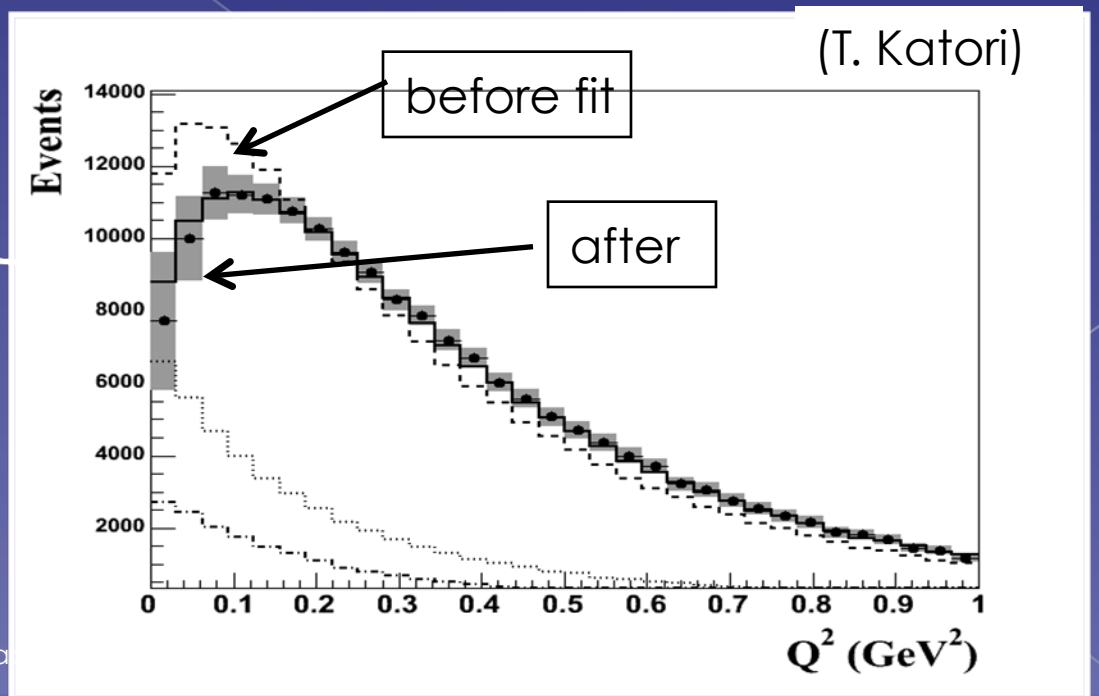
- NC-1π^0 production
  - Phys. Lett. B619 (2005) 255
- CC-coherent π search
  - Phy. Rev. Lett. 95, 252301 (2005)
- CC-QE M_A on Oxygen
  - Phy. Rev. D74, 052002 (2006)
- Study of CC-π^0 for proton decay $p \rightarrow e^+\pi^0$ search
  - Phy. Rev. D77, 032003 (2008)
- CC-π^+ production

MiniBooNE

- NC-coherent π^0 production
  - Fraction=(19.5±2.7)%
    - Phy. Lett. B .
    - MC prediction = 30%
- CC-QE M_A
  - M_A=1.23±0.20 GeV/c^2







Coming results from MiniBooNE

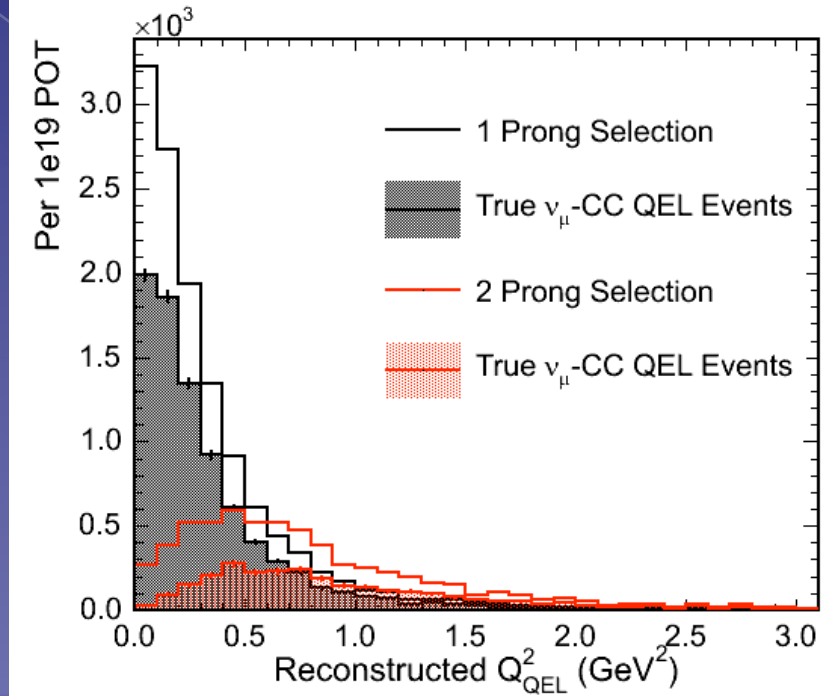
- CC π^+/QE ratio (S. Linden, J. Nowak)
- CC π^+ production (M. Wilking)
- CC π^0 production (R. Nelson)
- QE absolute differential σ (T. Katori)
- NC elastic scattering (D. Perevalov)

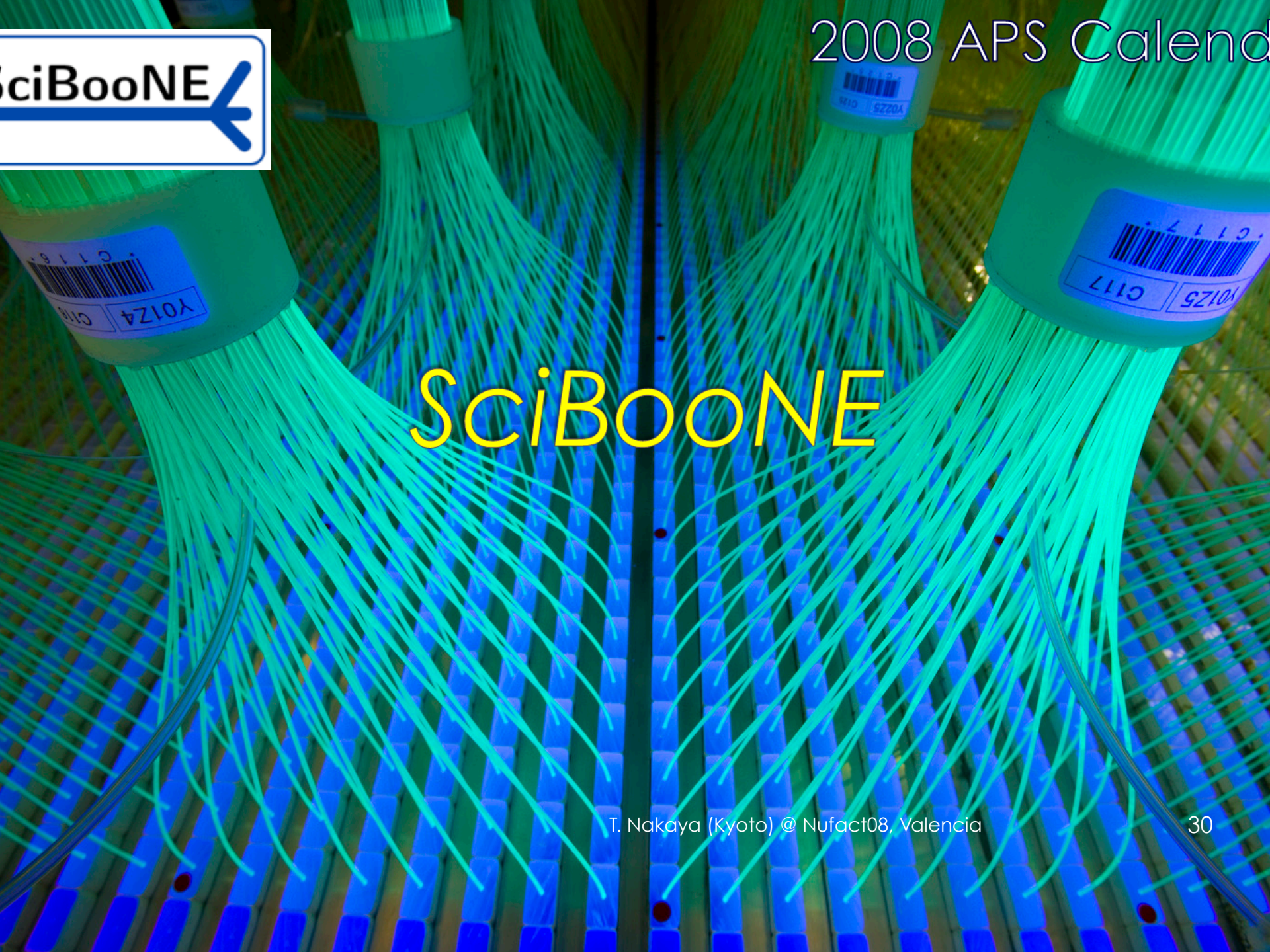
MINOS [Near Detector]

- CC-QE
  - M_A
- Inclusive ν_μ CC cross section
- Structure functions
- Di-muon
  - Strange quark content
- Coherent π production

	Fraction	Events/10^6
A) DIS:	24.2%	1.3
B) Low Q^2 DIS:	8.5%	0.5
C) RES ⇔ DIS:	32.4%	1.8
D) QEL + Δ:	34.8%	1.9

CC-QE selected events



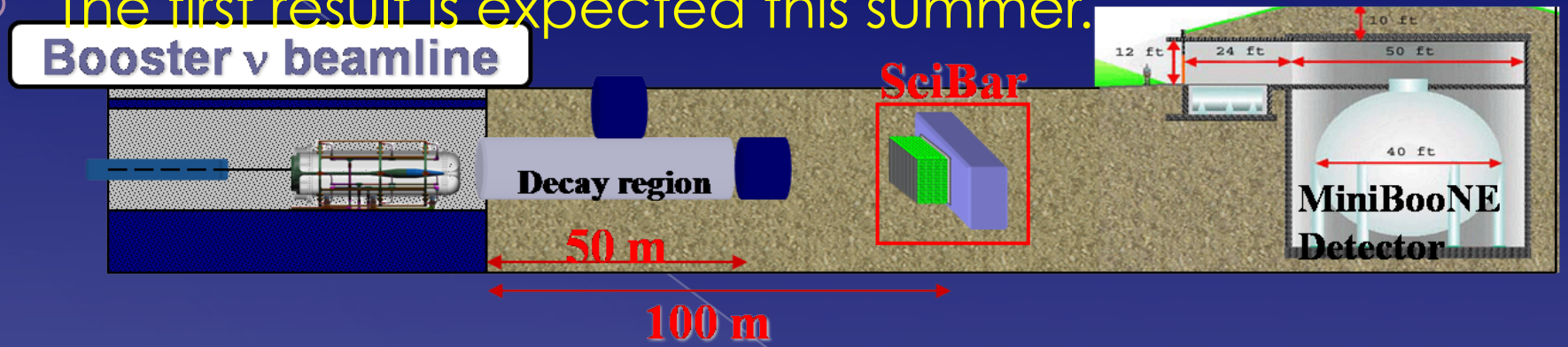

SciBooNE
2008 APS Calend
SciBooNE

SciBooNE

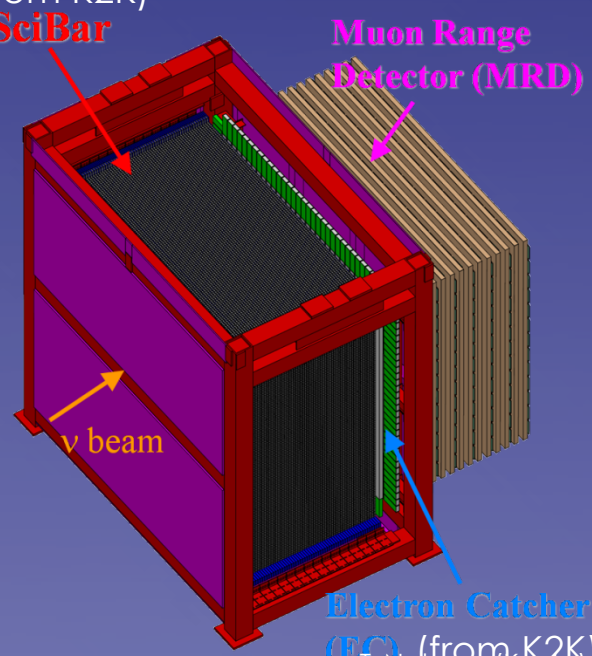
2005: proposed
2006: constructed
2007: Data taking started
2008: Achieved the targeted POT

FNAL E954

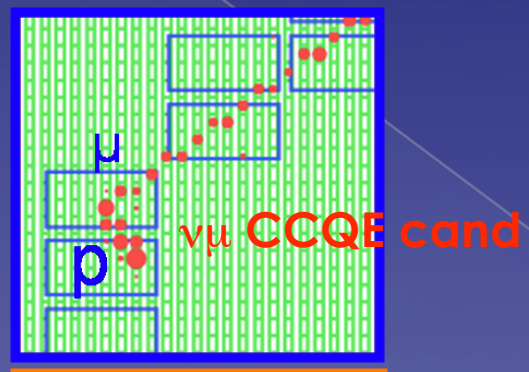
- $\nu_\mu, \bar{\nu}_\mu$ cross section at ~1GeV (for T2K)
- The first result is expected this summer.

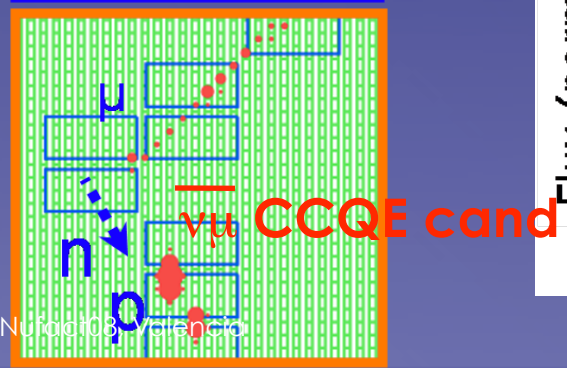


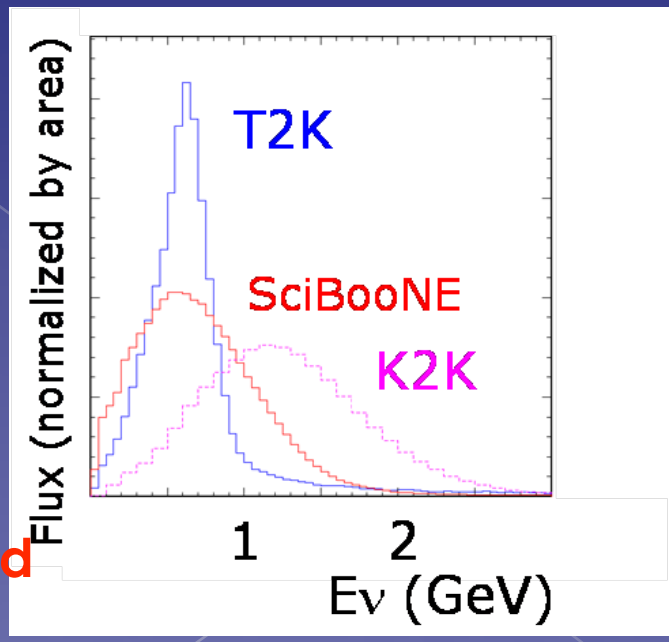
(from K2K)



(from K2K)

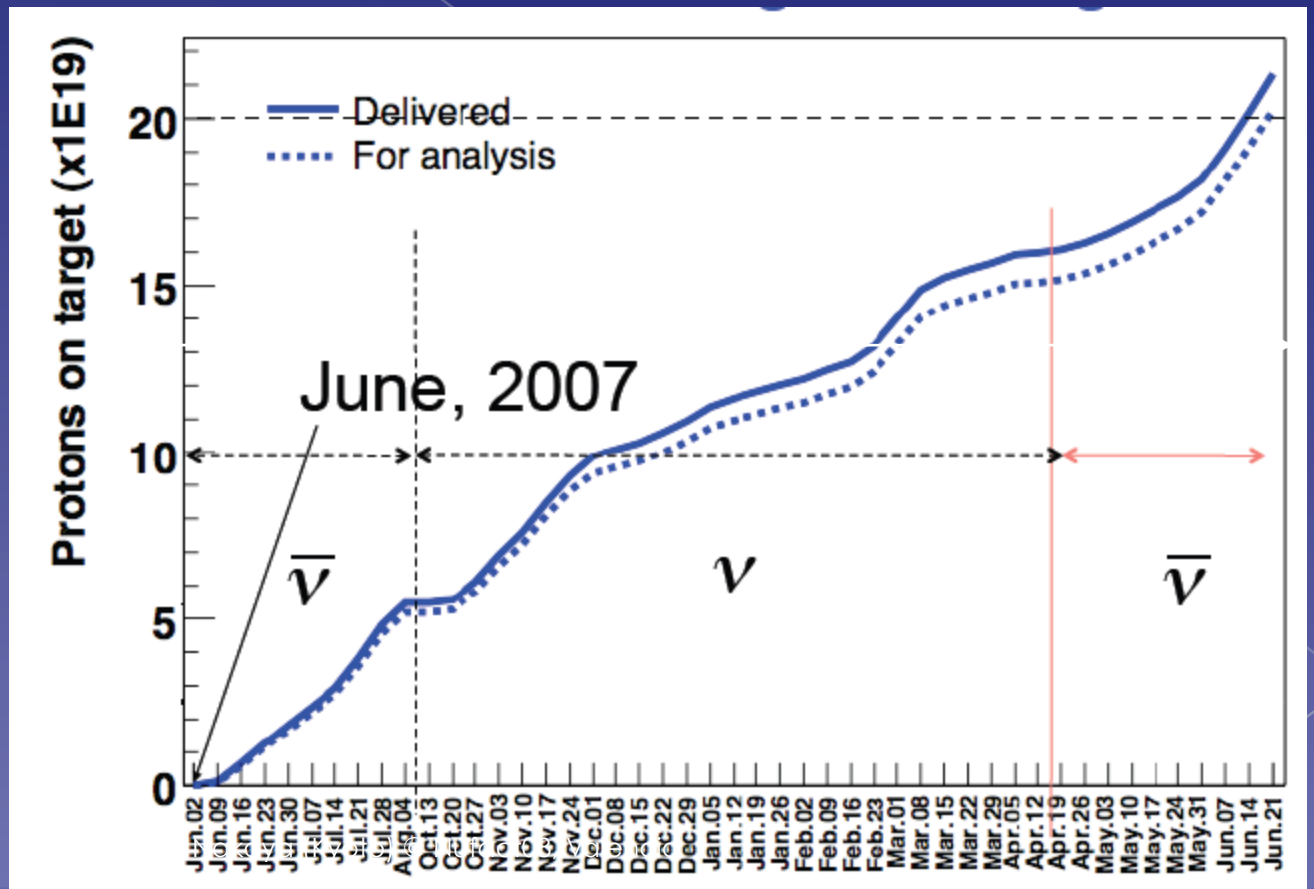






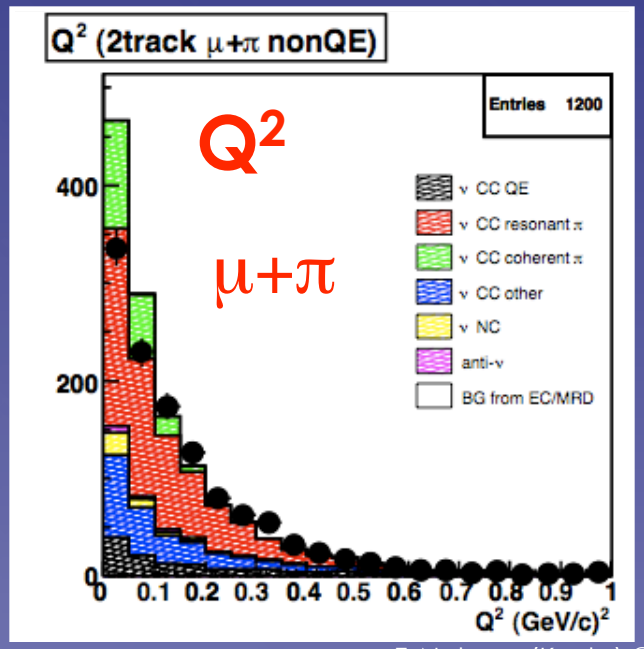
From June 2007 to August 2008

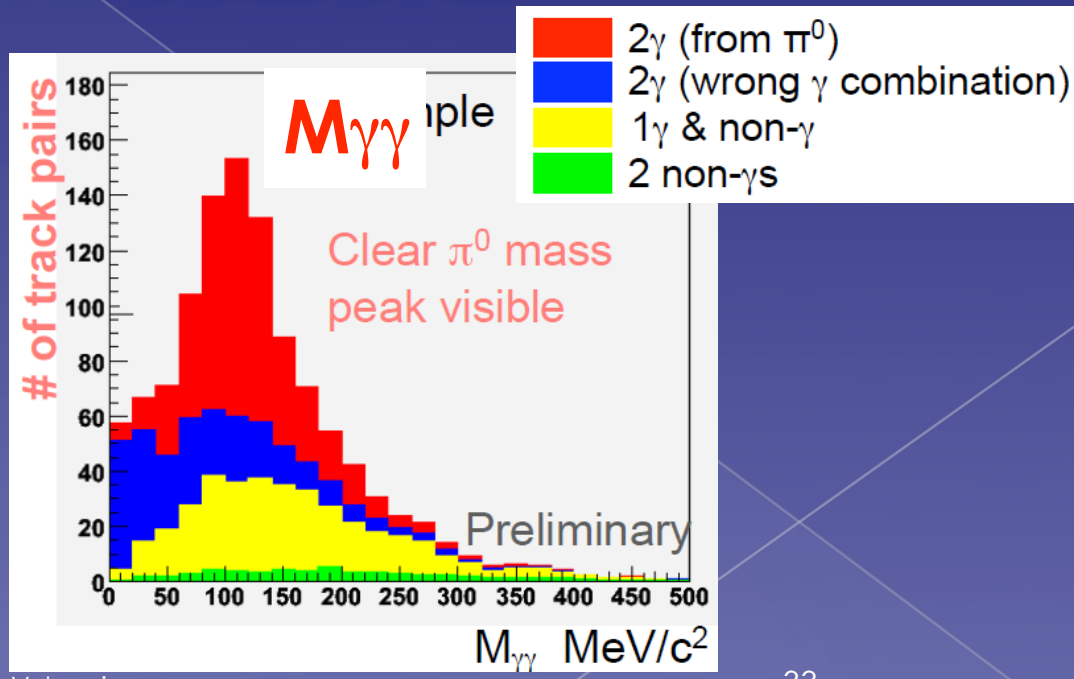
- Goal: 2E20 POT (Protons-On-Target)
- So far: 2. 12E20 (by June 28th, 2008)
  - ν: **9.9E19** (goal: 1E20) <- **completed**
  - $\bar{\nu}$: **1.13E19** (goal: 1E20) <- **achieved**



June 21

- CC-1π study
  - Coherent π and resonance productions
- NC-1π^0 study
  - π^0 mass is well reconstructed in SciBar
  - NC π^0 purity is 71%





SciBooNE physics topics

Both ν beam and anti-ν data

[ν result will come first, and later anti-ν result will follow]

- CC-QE study
- CC π^+ production
- CC π^0 production
- NC π^0 production
- NC elastic scattering
- + Short baseline ν_μ disappearance search with MiniBooNE

T2K

*(start in **April 2009**)*

&

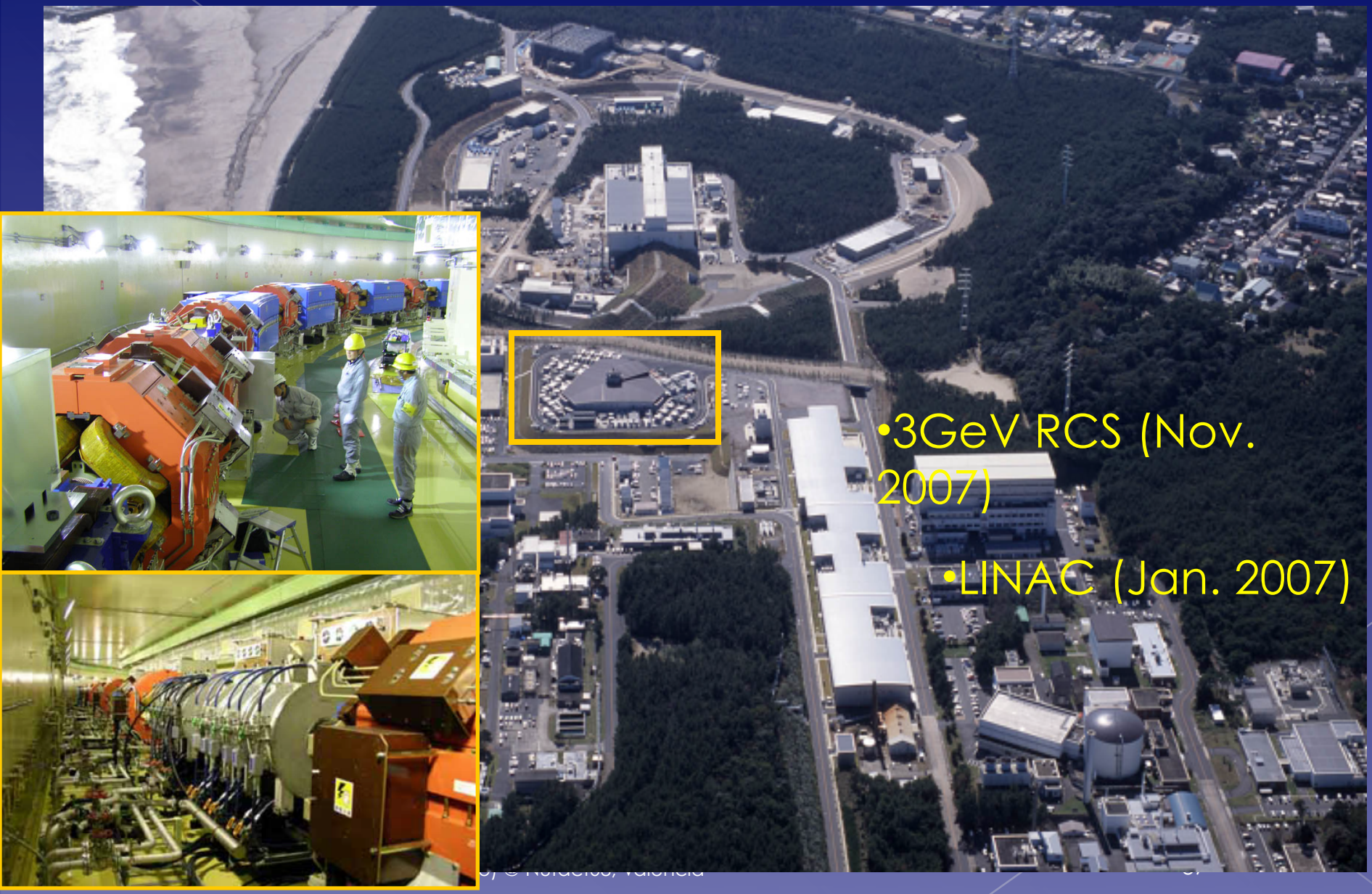
J-PARC

Accelerator commissioning on schedule

Accelerator commissioning on schedule

•LINAC (Jan. 2007)

Accelerator commissioning on schedule



Accelerator commissioning on schedule

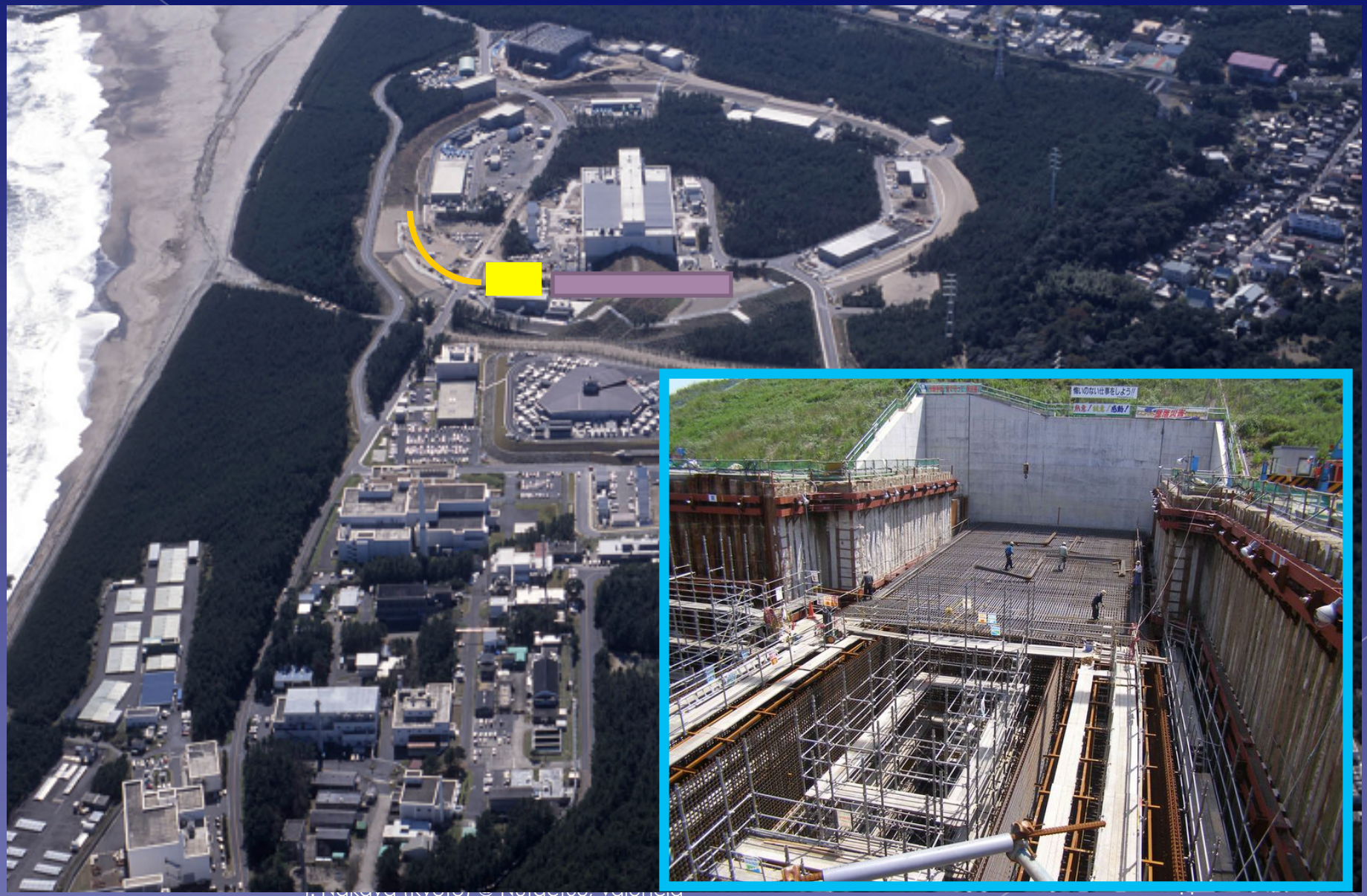
- MR (May. 2008)
  - Circulate the 3GeV proton beam.
- 3GeV RCS (Nov. 2007)
- LINAC (Jan. 2007)

ν beam construction status

ν beam construction status

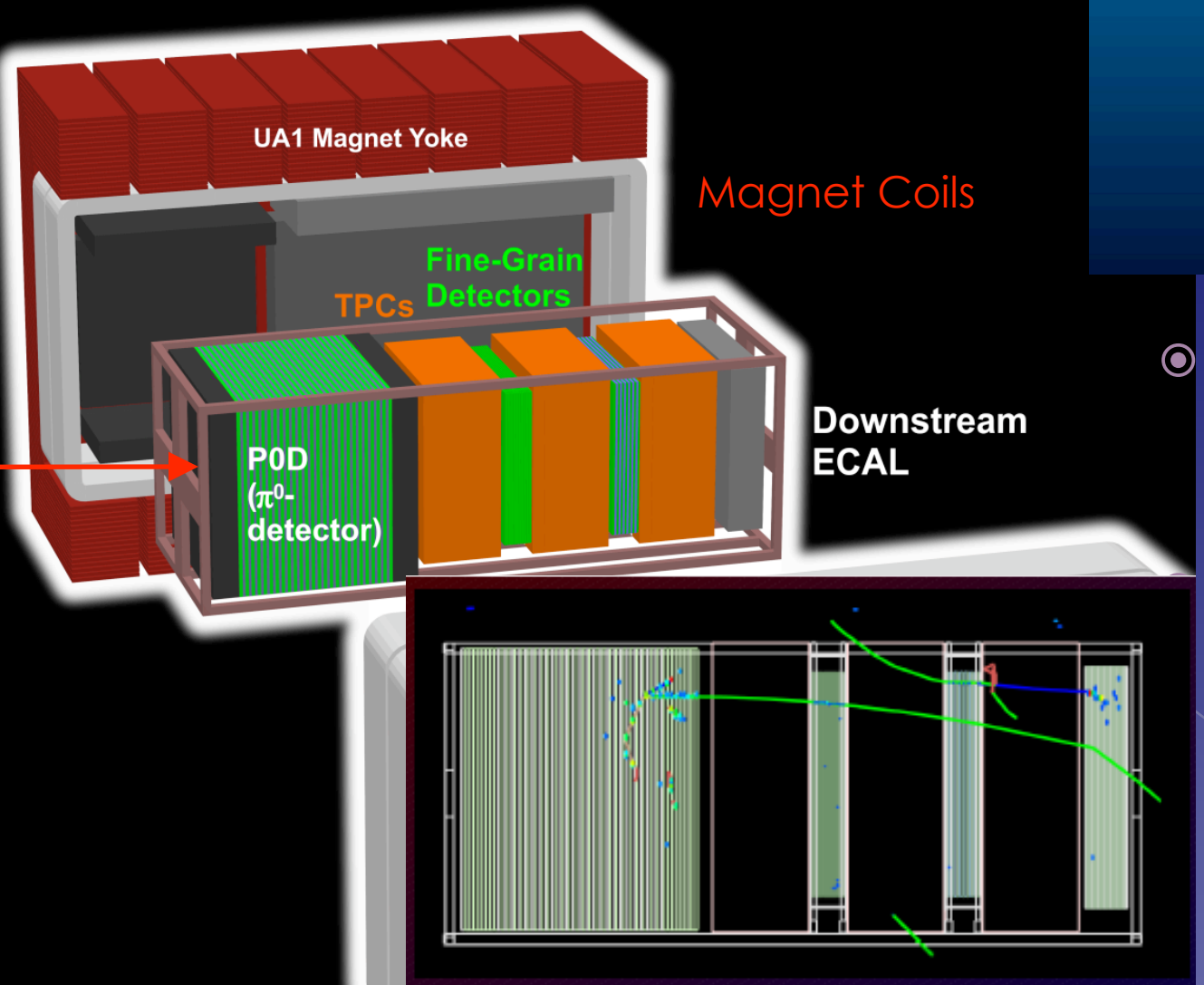
ν beam construction status

ν beam construction status

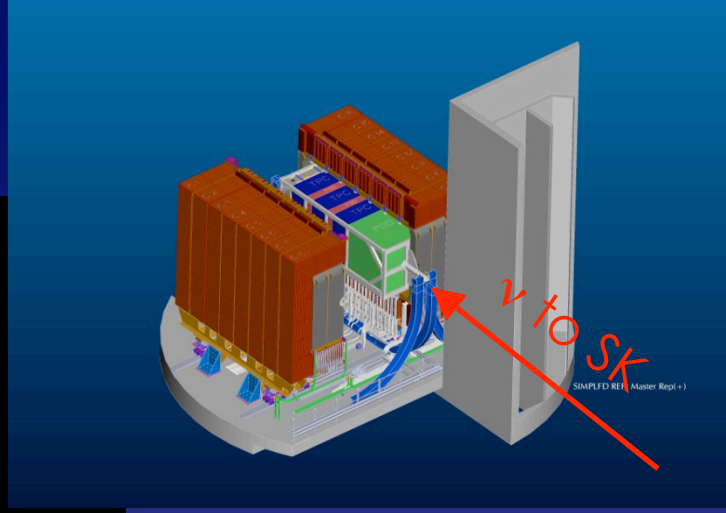


ν beam construction status

Off-Axis detector



A CC1π interaction in the P0D, with full-bunch background



- Detector volume:
  - $3.5 \times 3.5 \times 7.0 m^3$
- **P0D** π^0 detector
- **FGD+TPC:**
  - CC interactions
- **EM calorimeter**
- **Side Muon Range detector**

Neutrino Events (T2K-ND280-offaxis)

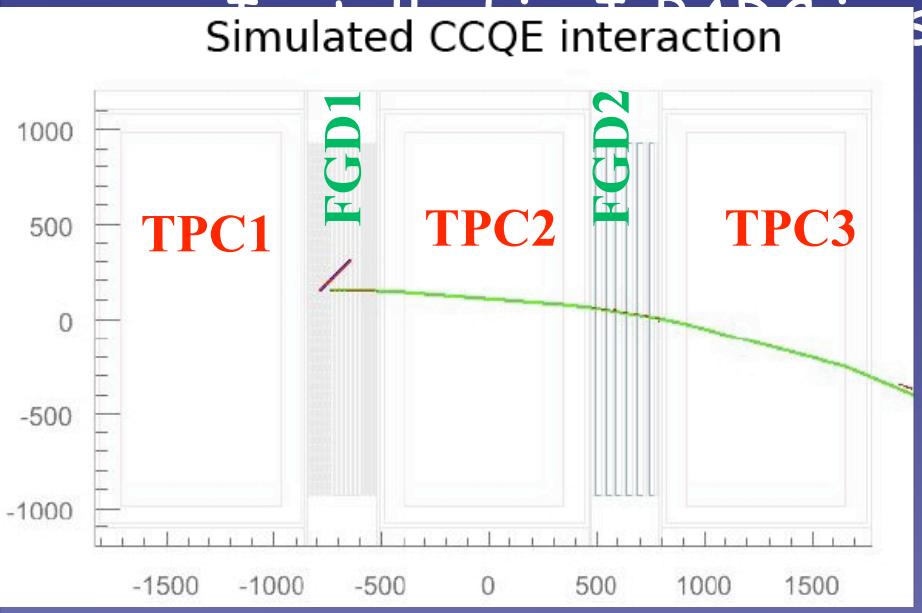
Interaction mode	Fraction	Events/year/ton
CC-QE	38%	65k
NC-Elastic	17%	30k
CC-1π^+	14%	23k
CC-1π^0	3%	5k
NC-1π^0	4%	7k
CC-coherent π^+	1%	2k
NC-coherent π^0	1%	1k
CC-multi-π+DIS	15%	25k
NC-multi-π+DIS	8%	8k

UA1/NOMAD magnet

- Shipped from CERN and installed in J-PARC
  - will operate at 0.2T
- With TPC
  - Measured charged particle momentum with LARGE acceptance.

Fine Grain Detectors (FGD)

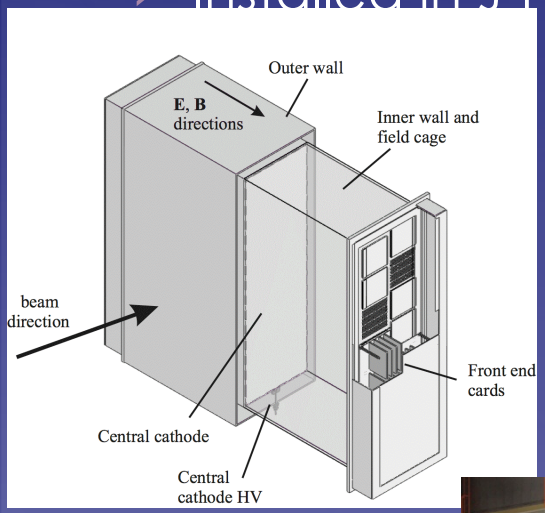
- Neutrino Target (Vertex) Detector
- $1\times1cm^2$ finely-segmented scintillator bar + WLS fiber + MPPC
- Under construction.
  - Beam test of full detector starting from July 2008.
  - Installed in T2K ND6 in summer 2009

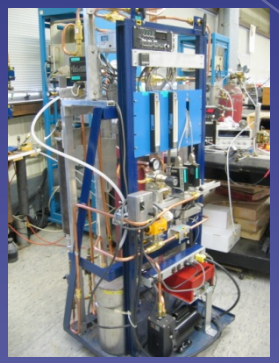


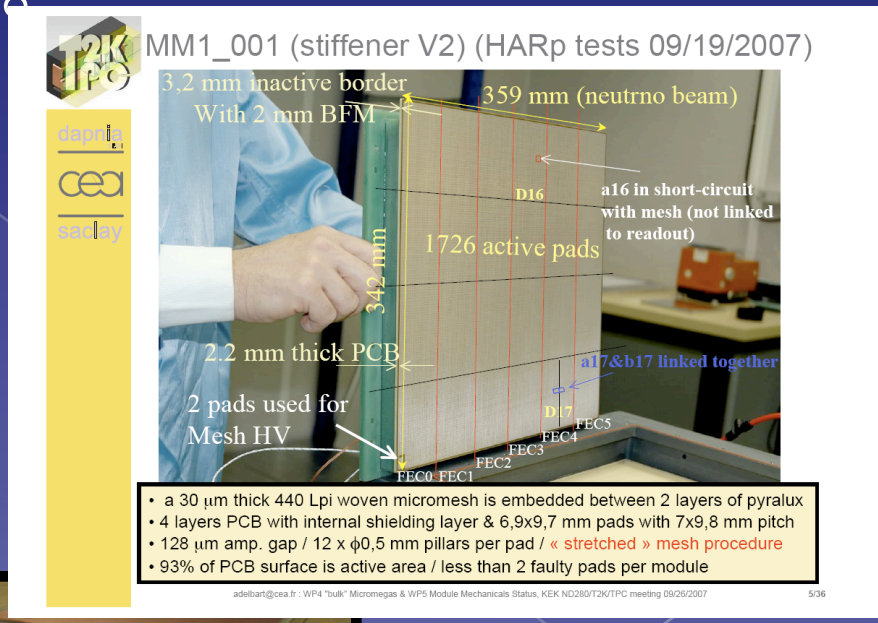
Tracker volume

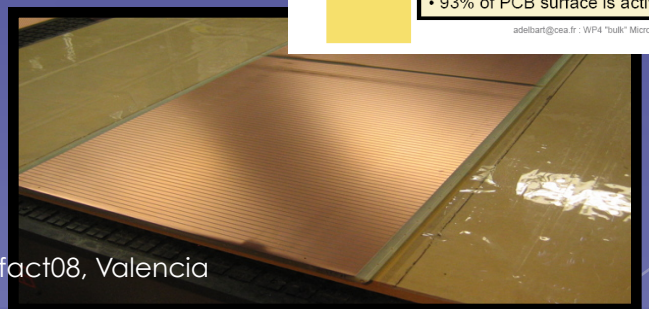
TPC (3 TPC modules)

- MicroMegas gas amplification (8×8mm2 pad sise)
- 10% momentum resolution (p<1GeV/c) with 10% dE/dx resolution
- Under construction.
  - Beam test of full detectors starting from July 2008.
  - Installed in J-PARC in summer 2009



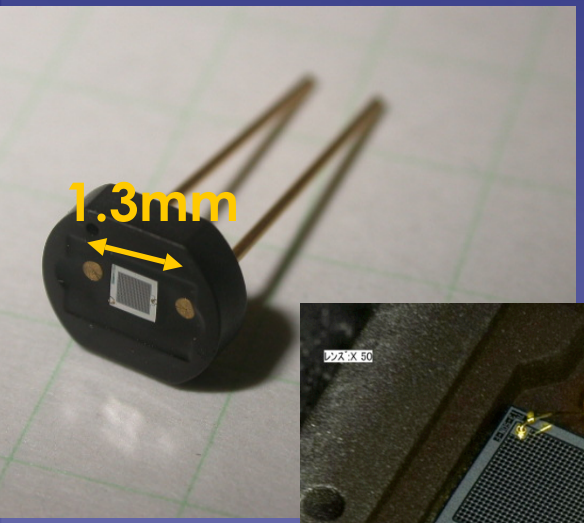


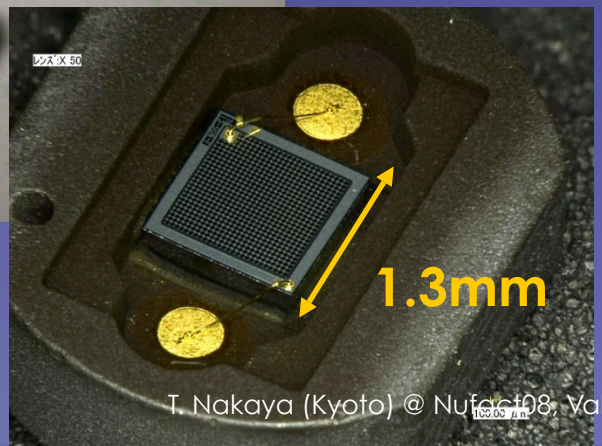


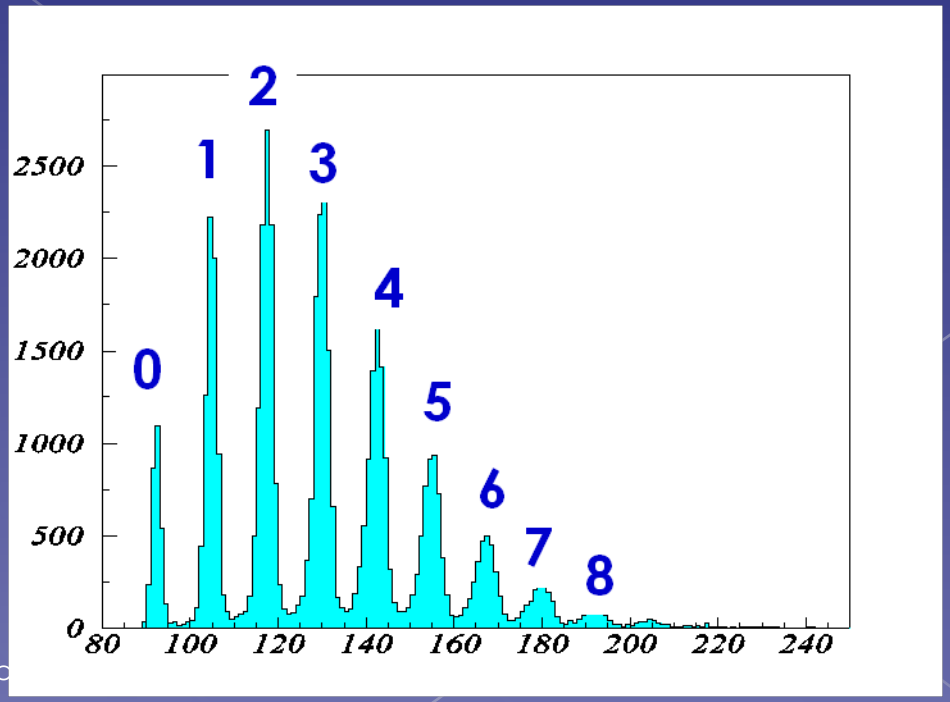


Hamamatsu MPPC

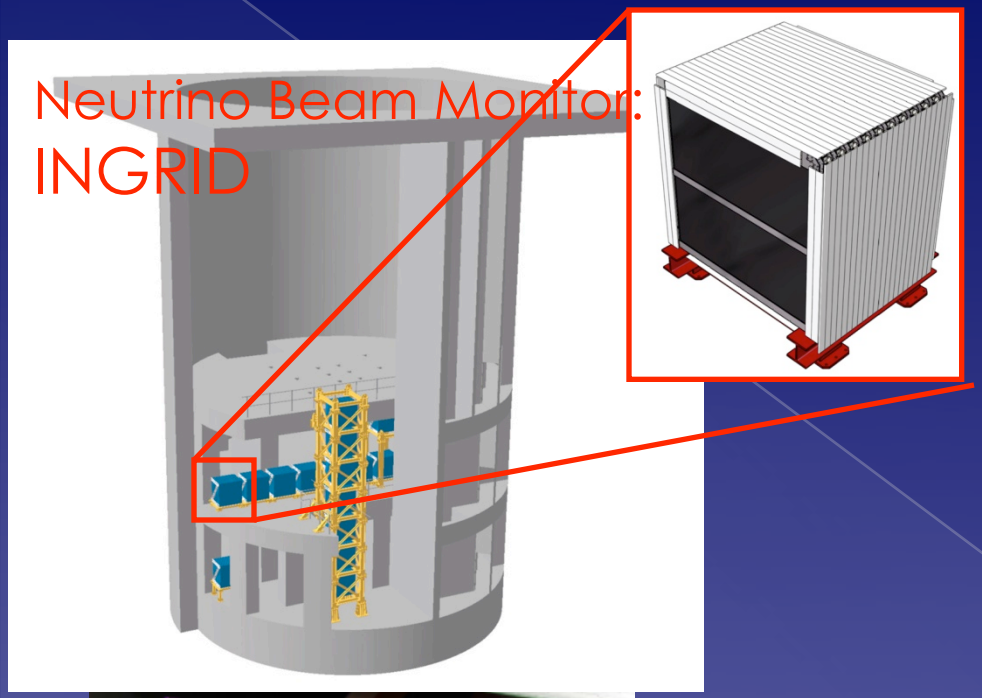
- **M**ulti-**P**ixel-**P**hoton-**C**ounter
  - Multi-pixel APD operating at the Geiger mode.
  - 667 pixels.
- Under production.
  - ~30,000 devices in our hand. (out of ~60,000.)
- Extensive mass-test is in process.

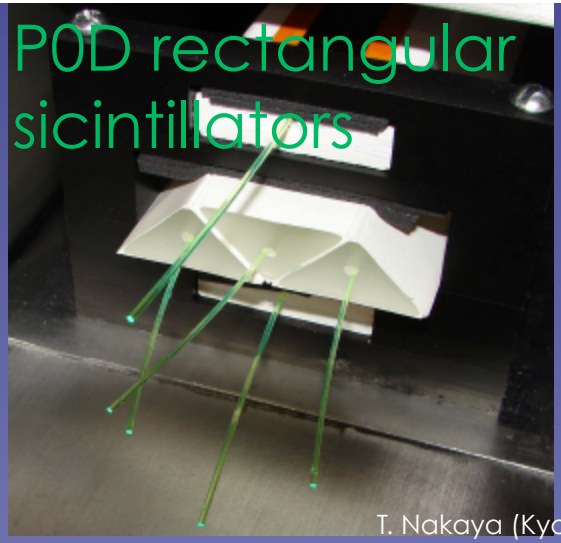






More T2K-ND280 detectors.





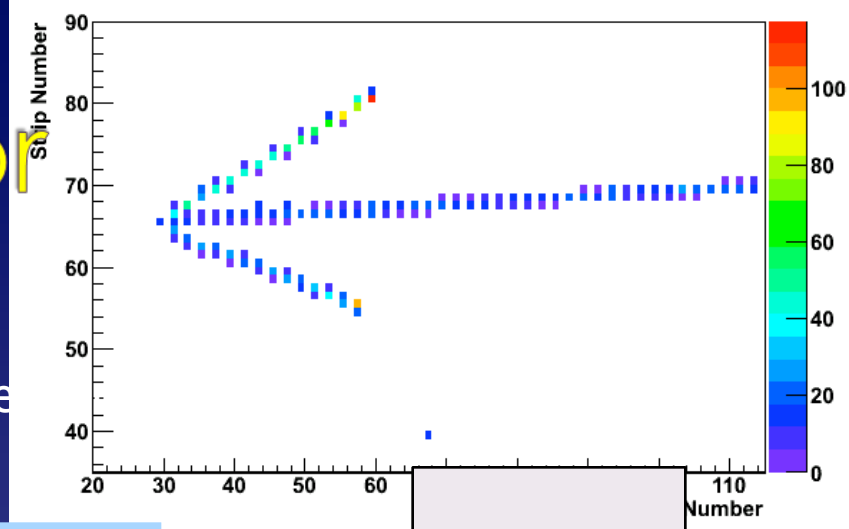
T2K is coming!

- T2K beam will start in April 2009.
  - Less than one year!
- T2K-ND280 will provide the high quality ν scattering data within a couple of years.

MINERvA

- MINERvA: precision ν scattering @ NuMI
- Finely segmented, fully active, scintillator tracking chamber, surrounded by ECAL, HCAL
  - Fully reconstruced exculsive final states
- Nuclear targets for A dependence
- Upstrea
m
 of MINOS (muon spectrometer)

MINERvA Detector



Fully Active Scintillator Target Re
8.3 tons (~3 tons fiducial)

Veto Wall

Liquid He 0.25ton

NuMI Beam

ECAL

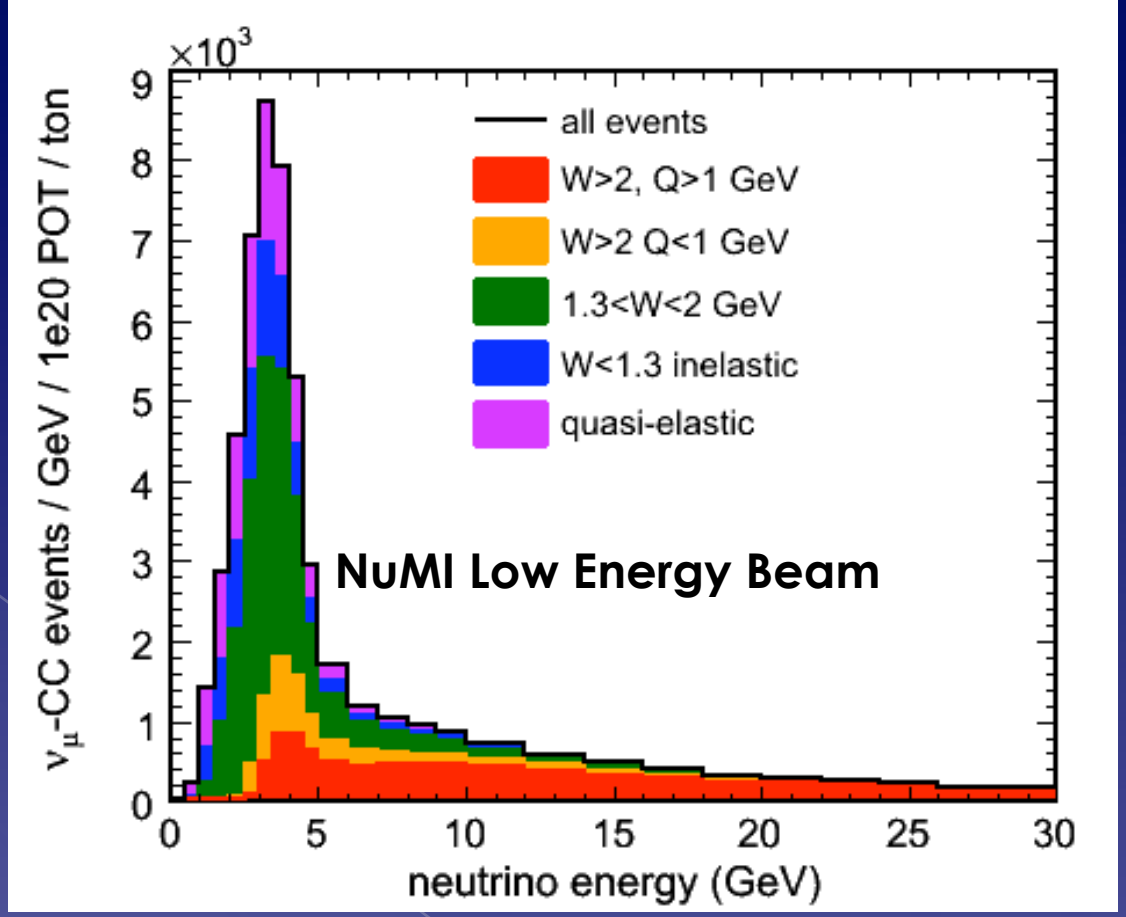
HCAL

MINOS near detector (muon spectrometer)

Nuclear Target Region with Pb, Fe, C
6.2 tons (including 40% Scintillator)

Event Yields

- With 4yr run
  4e20 POT LE beam
  12e20 POT ME beam
- Yield: ~14M
  (CC events)



Quasi-elastic	**0.8 M**
Resonance production	**1.7 M**
Resonance to DIS transition region	**2.1 M**
DIS Low Q^2 region and structure functions	**4.3 M**
Coherent Pion Production	**CC 89k, NC 44k**
charm / strange production	**230 k**

Nuclear Targets

He	0.6M
C	0.4M
Fe	2.0M
Pb	2.5M

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- Let's play and enjoy neutrinos!