

# Neutrino Nucleus Cross Sections for Oscillation Experiments

## outline

1. Timeline of the paper
2. Section structure
3. What we learned

Teppei Katori and Marco Martini  
NuSTEC meeting, Jan. 17, 2017

# 1. Paper timeline

2014 summer JPhysG contacted Marco to write a review paper on “neutrino-nucleus cross-sections for neutrino oscillation experiments”, Marco invited Teppei to join

2015 June 1st meeting (France+Belgium), make outline of the paper

2015 July Start to write the paper

2015 July The first draft of the paper (v2.1)

2015 August 2nd meeting (France), TRY to finalize the paper

2015 Autumn Unexpected delay (Marco changed contract, new house, car accident), etc

2016 February Getting pressure from JPhysG, resume to work

2016 April 3rd meeting (France), try to finish up the paper

2016 Summer Lots of work done..., many changes to take into accounts new publications

2016 September Marco had a baby, left few weeks

2016 October Teppei had a baby, left few weeks

2016 October Submit the paper to JPhysG/ArXiv

2017 now Working on referee comment corrections

# 1. Basic ideas of the paper

Since there are several neutrino cross section review papers, we try to define this paper to be different. The main focus is the discussions around “data-theory comparison”, and we skip discussions on physics where there is no data.

## Marco

- Use and update/modify text from past proceedings
- Summarize various conference presentation (such as “famous” 2p2h model comparison) and make a reference

## Teppei

- Use discussions from neutrino cross-section newsletter

## Main tools

- drop box to share documents
- a lot of Skype (~3-4/month last 3 years)

## 2. Section 1

### 1 Introduction

	Marco/Teppei
1.1 Neutrino oscillation physics . . . . .	Teppei
1.2 Accelerator-based neutrino experiments	Teppei
1.3 Neutrino fluxes . . . . .	Teppei

Introduction and abstract are mainly written by Marco

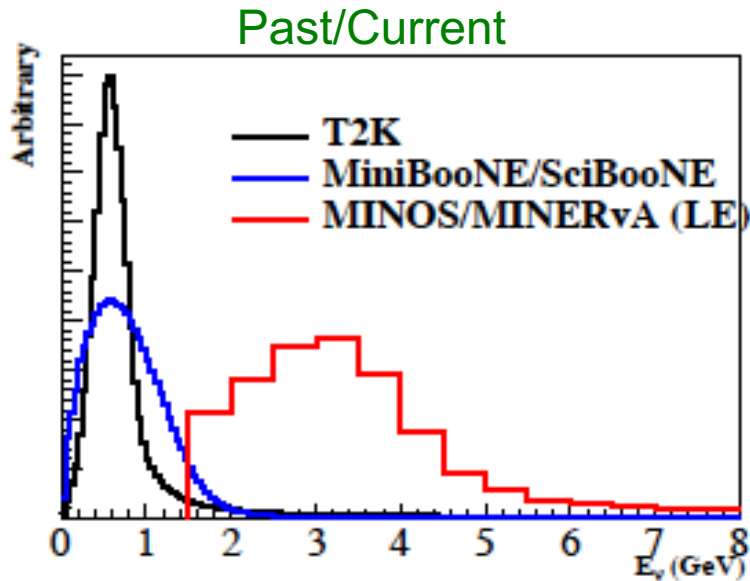
1.1 is based on lectures I gave on neutrino oscillations

1.2 is an updated copy of Luis/Hayato/Nieves paper experiment section (Sec. 2)

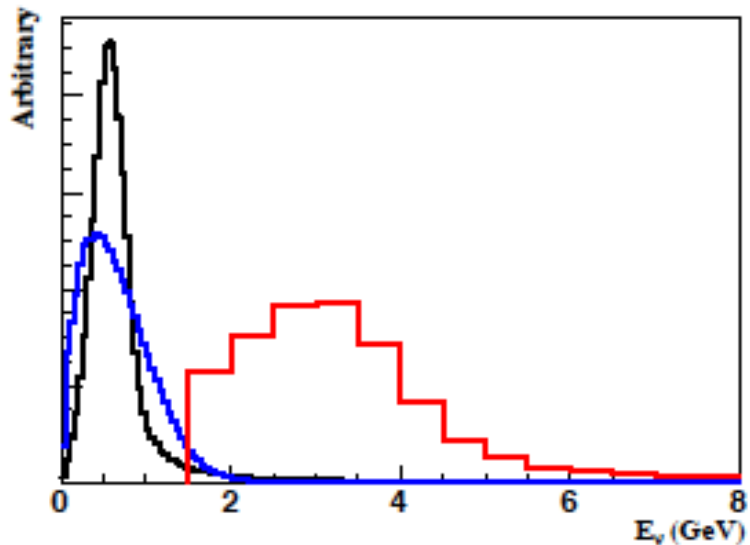
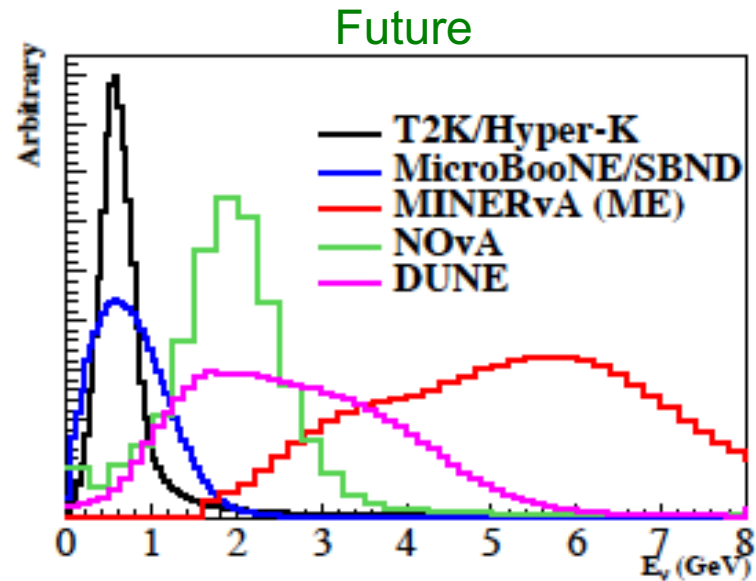
1.3 is new, I contacted all experiments to get preliminary flux (DUNE, MINERvA medium energy beam ,etc)

## 2. Section 1

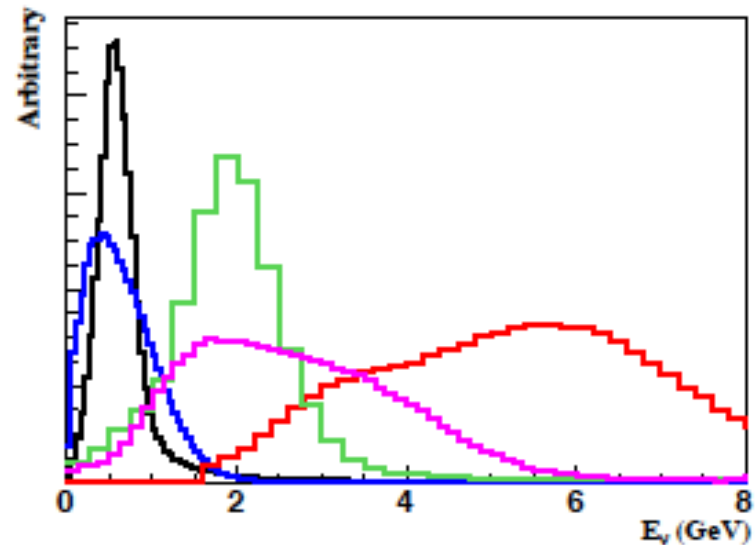
It seems importance beyond QE interaction (>1 GeV physics) is evident



$\nu_\mu$ -flux of  $\nu$ -mode



$\bar{\nu}_\mu$ -flux of  $\bar{\nu}$ -mode



## 2. Section 2

### 2 Neutrino cross section generalities

2.1	Theory . . . . .	Marco
2.2	Experiment . . . . .	Teppei
2.3	Matching Theory and Experiment . . . . .	Marco/Teppei

2.1 is by Marco

2.2 is loosely based on my proceedings and past papers

2.3 is based on our discussions from the first meeting. The section was revised by both and have inputs by both.

## 2. Section 2

$$\frac{d^2\sigma}{dT_l d\cos\theta} = \frac{1}{\int \Phi(E_\nu) dE_\nu} \int dE_\nu \left[ \frac{d^2\sigma}{d\omega d\cos\theta} \right]_{\omega=E_\nu-E_l} \Phi(E_\nu)$$

Theorists



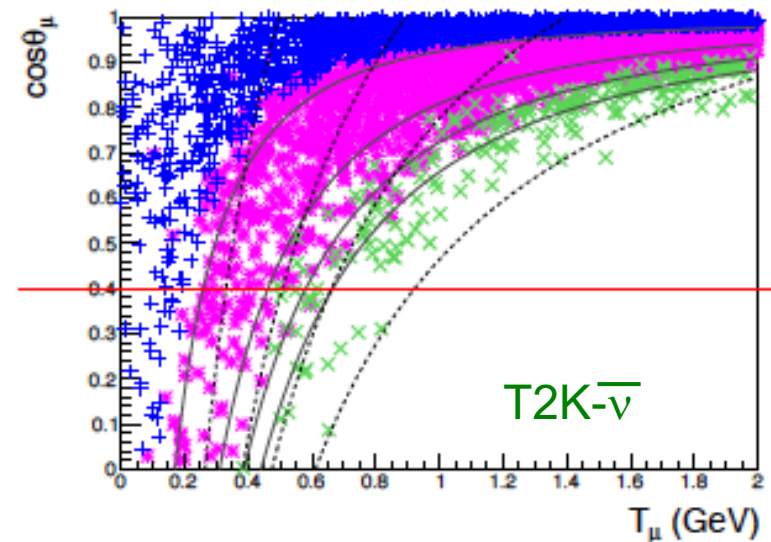
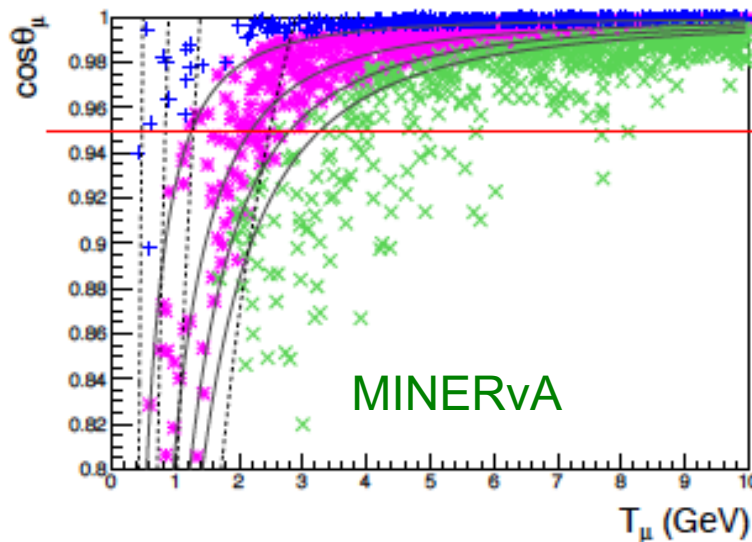
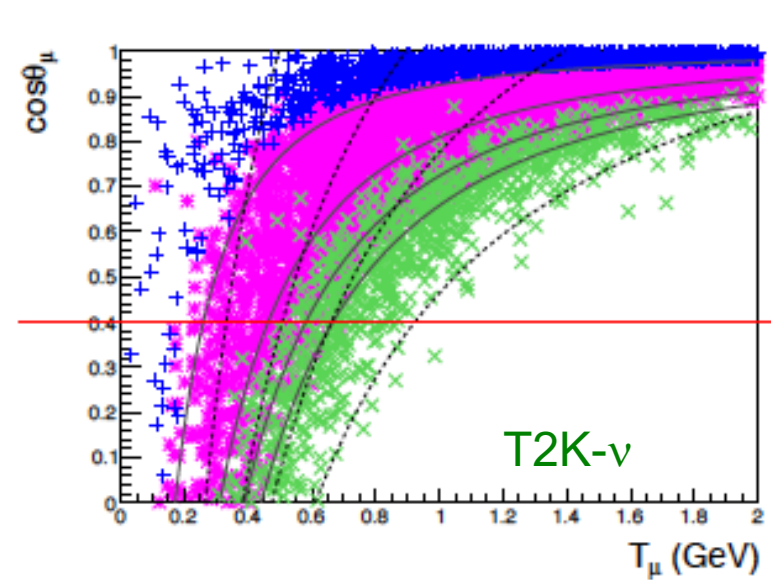
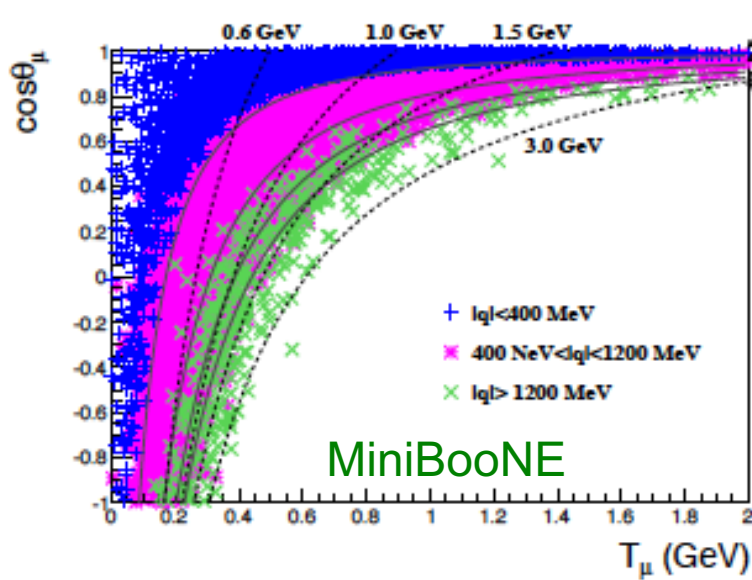
Experimentalists

$$\frac{d^2\sigma}{dT_l d\cos\theta} = \frac{\sum_j U_{ij}(d_j - b_j)}{\Phi \cdot T \cdot \epsilon_i \cdot (\Delta T_l, \Delta \cos\theta)_i}$$

Flux-integrated differential cross-section data are main tools for neutrino interaction physics community now. They allow theorists and experimentalists to talk

## 2. Section 2

Kinematics of these 3 experiments are not so different for CCQE





## 2. Section 3

### 3 Quasielastic

3.1	CCQE, CCQE-like, and CC0 $\pi$ . . . . .	Marco
3.2	np-nh excitations: theory vs experimental $d\sigma$	Marco
3.2.1	MiniBooNE . . . . .	Marco
3.2.2	T2K . . . . .	Marco
3.2.3	MINERvA . . . . .	Marco
3.3	Hadron information . . . . .	
3.3.1	one-track vs. two-track . . . . .	Teppei
3.3.2	MINERvA $\frac{d^2\sigma}{dE_{avail}d\bar{q}}$ . . . . .	Marco
3.3.3	ArgoNeuT . . . . .	Marco
3.3.4	Theoretical studies . . . . .	Marco

3.1 is based on Marco's past proceedings

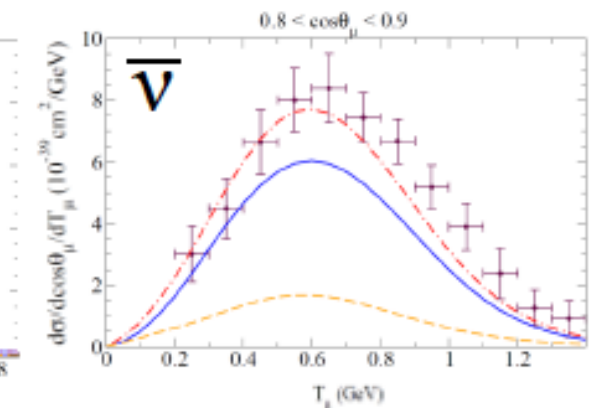
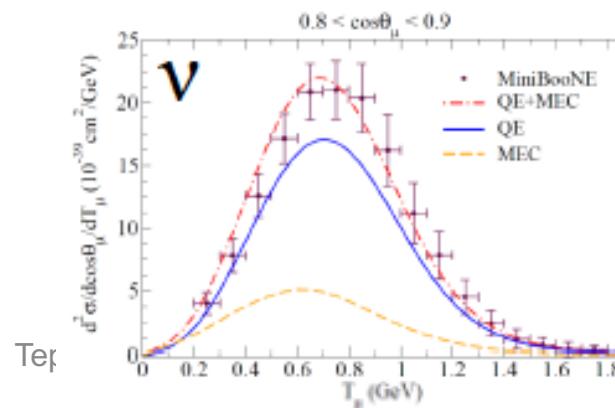
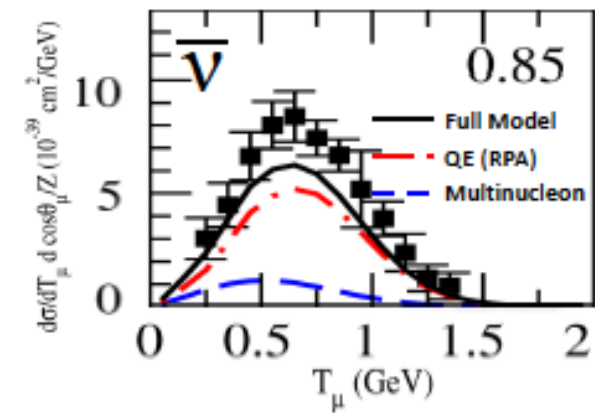
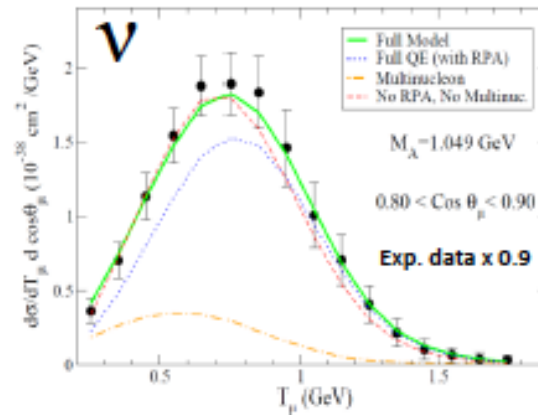
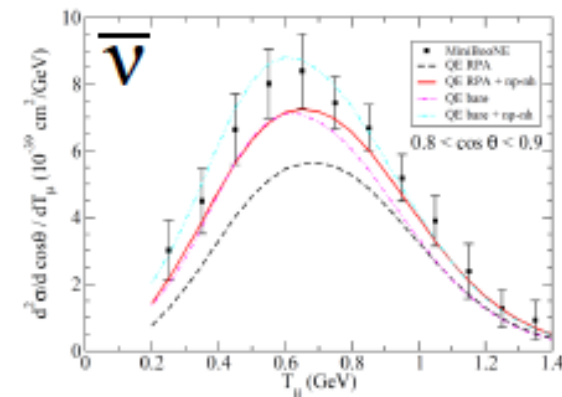
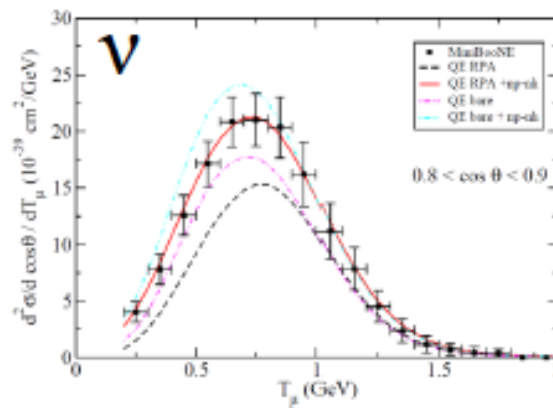
3.2 is a summary of Marco's past talks at various conferences about 2p2h Model comparison

3.3 is summary of recent papers, also based discussion in neutrino cross-section newsletter

## 2. Section 3

After adding axial MEC contribution, SuSA collaboration (Megias et al.) shows similar enhancement with other groups (Martini et al., Nieves et al., Meucci et al., Mosel et al., Bodek et al.).

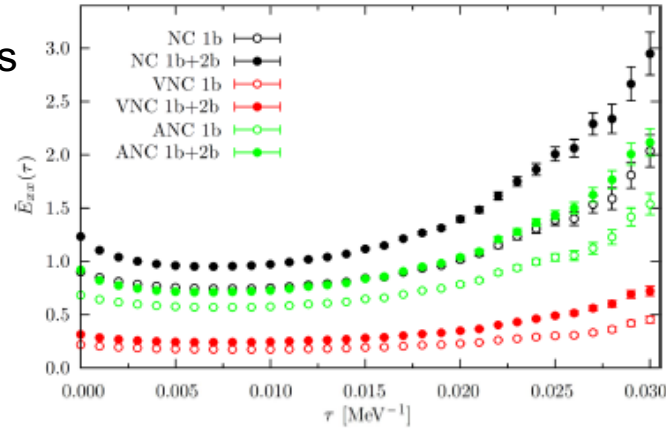
All groups agree **qualitatively** with MiniBooNE CCQE-like double differential data.



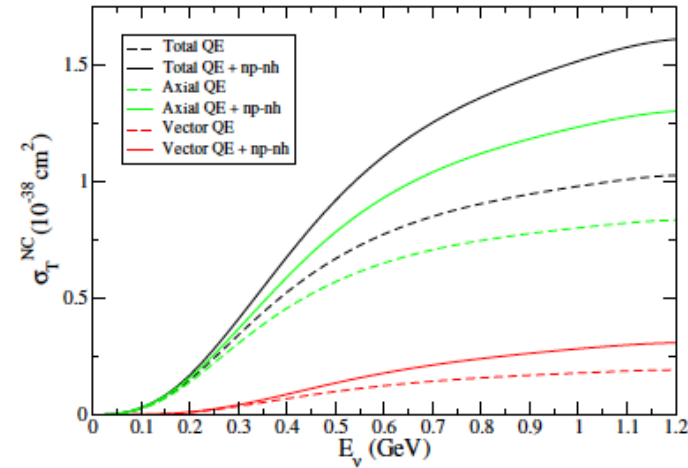
## 2. Section 3

Phenomenological models have strong support from ab initio calculations

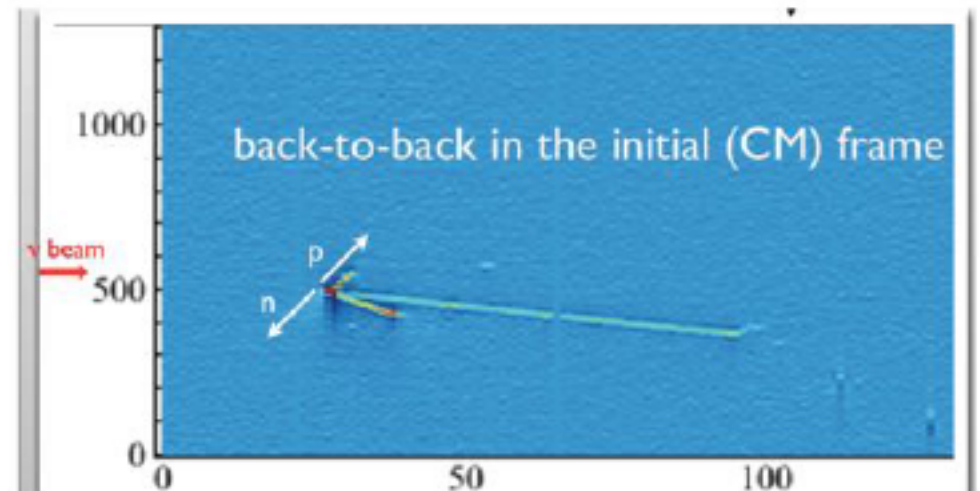
NC Euclidean transverse response



NCQE-like xs transverse contribution



The tests of models including nucleon kinematics are just started



## 2. Section 4

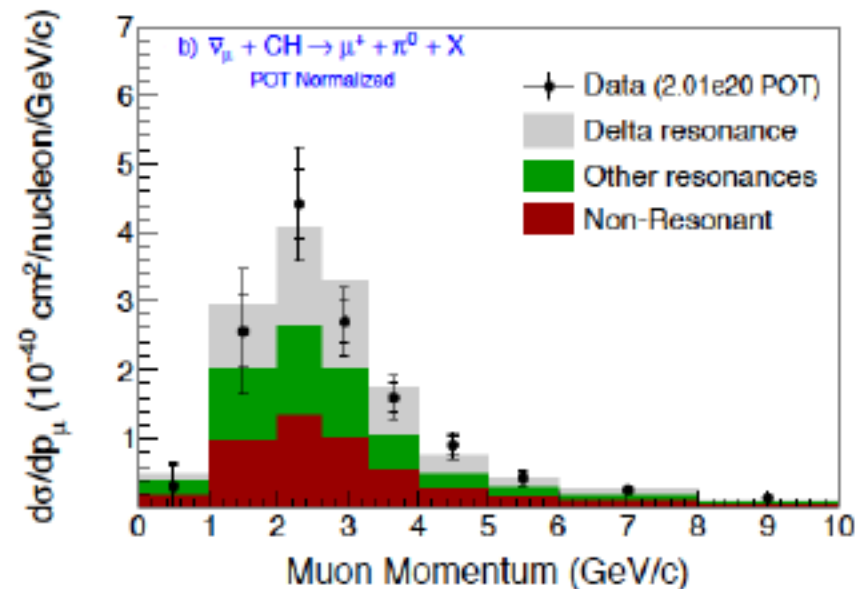
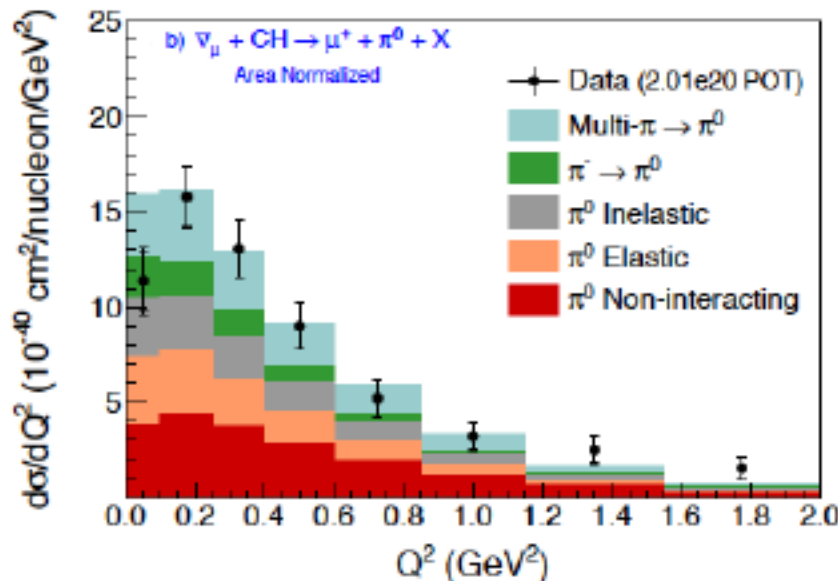
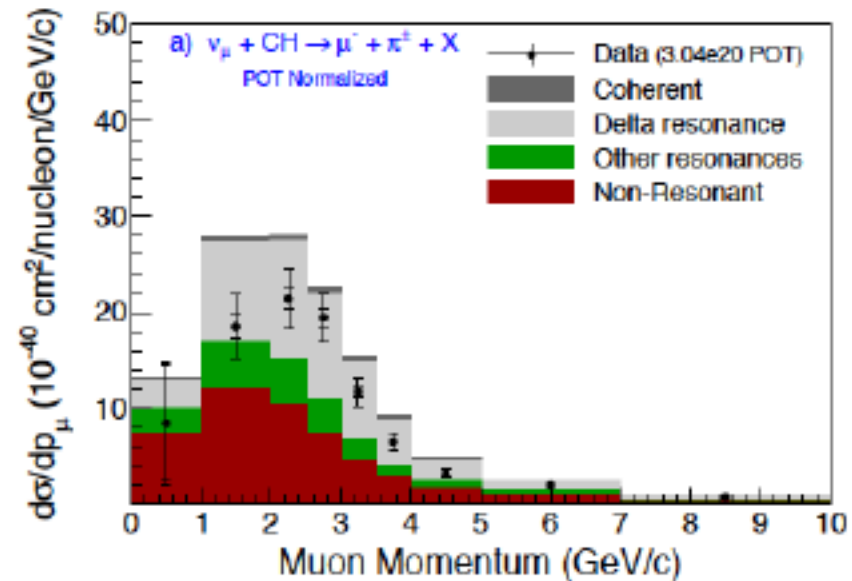
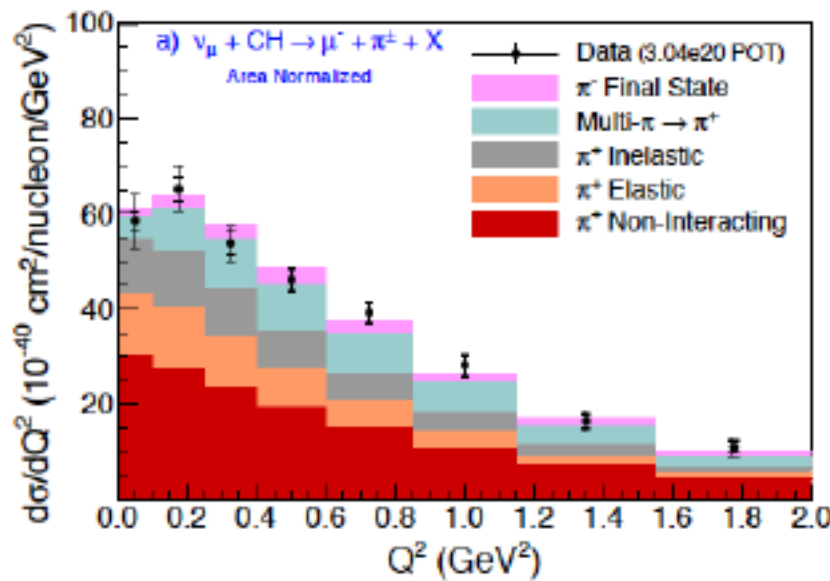
### 4 Pion production and inelastic channels Teppei

- 4.1 Charged current charged pion production
  - 4.1.1 Topology-based signal definition
  - 4.1.2 Directly observable variables . .
  - 4.1.3 Flux-integrated cross section . .
- 4.2 Charged current neutral pion production
- 4.3 MiniBooNE-MINERvA data comparison
  - 4.3.1 Normalization of theory . . . . .
  - 4.3.2 Normalization of data . . . . .
- 4.4 Neutral current neutral pion production
- 4.5 Toward the solution of the pion puzzle .
- 4.6 Kaon and strangeness production . . . . .
- 4.7 Coherent pion productions . . . . .

The main focus is “how to read hadron data” (Sec. 4.1) and “pion puzzle” (4.3, 4.5). There are so many new papers during writing this section (NuMI new flux, new MINERvA pion paper) and I needed to change text constantly...

## 2. Section 4

Do we understand MINERvA  $\nu_\mu$  CC1 $\pi^+$  and  $\bar{\nu}_\mu$  CC1 $\pi^0$  data differences?



## 2. Section 5, 6

### 5 Charged current inclusive cross sections

- 5.1  $\nu_\mu$  CC inclusive . . . . . Marco
- 5.2  $\nu_e$  cross sections . . . . .
- 5.3  $\nu_e$  vs  $\nu_\mu$  cross sections . . . . .

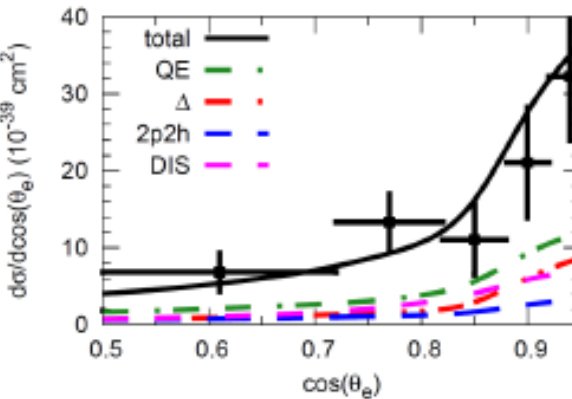
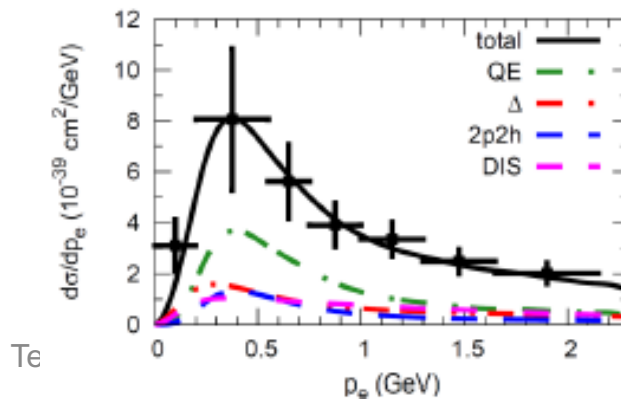
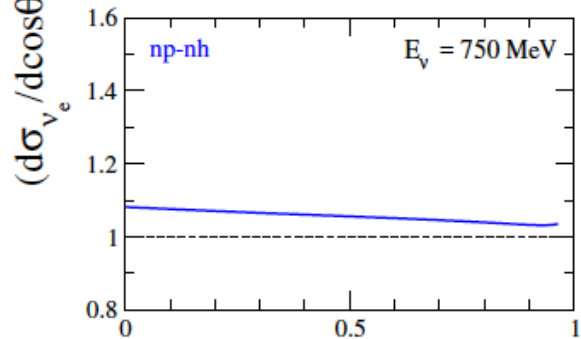
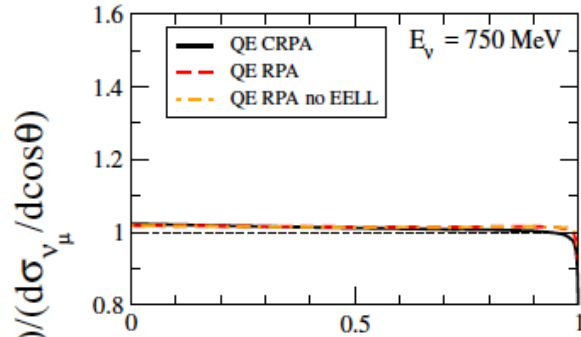
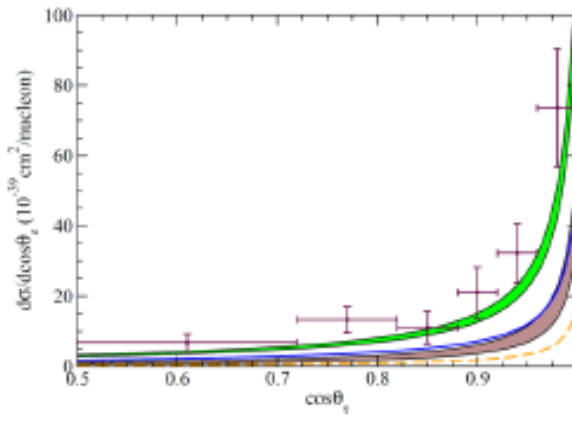
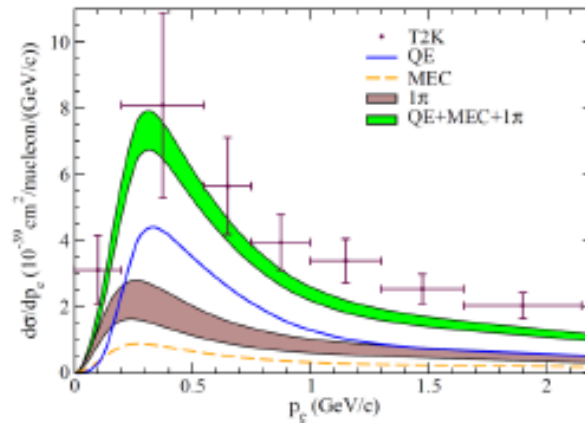
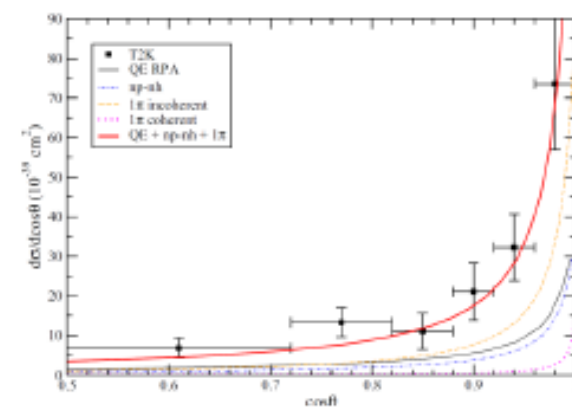
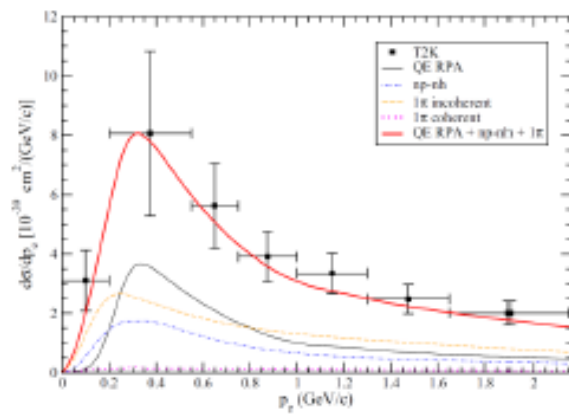
### 6 Neutrino energy reconstruction and neutrino oscillation analysis Marco

Marco did everything for chapter 6 and 7. There are new arguments/original plots here, too.

## 2. Section 5, 6

The first  $\nu_e$ CC differential cross section was published on 2014 by T2K, and already models agree very well!

$\nu_e/\nu_\mu$  ratio is understood well?  
 → first time modern interaction models contribute to reduce xs systematic errors



## 2. Section 7, 8

### 7 Future experiments

Teppei

- 7.1 Detectors . . . . .
  - 7.1.1 Liquid Argon Time Projection Chamber (LArTPC)
  - 7.1.2 Water Cherenkov detector . . . . .
- 7.2 Higher precision hadron information . . . . .
- 7.3 Highly controlled neutrino beam . . . . .
- 7.4 Near future neutrino experiments . . . . .

### 8 Conclusions

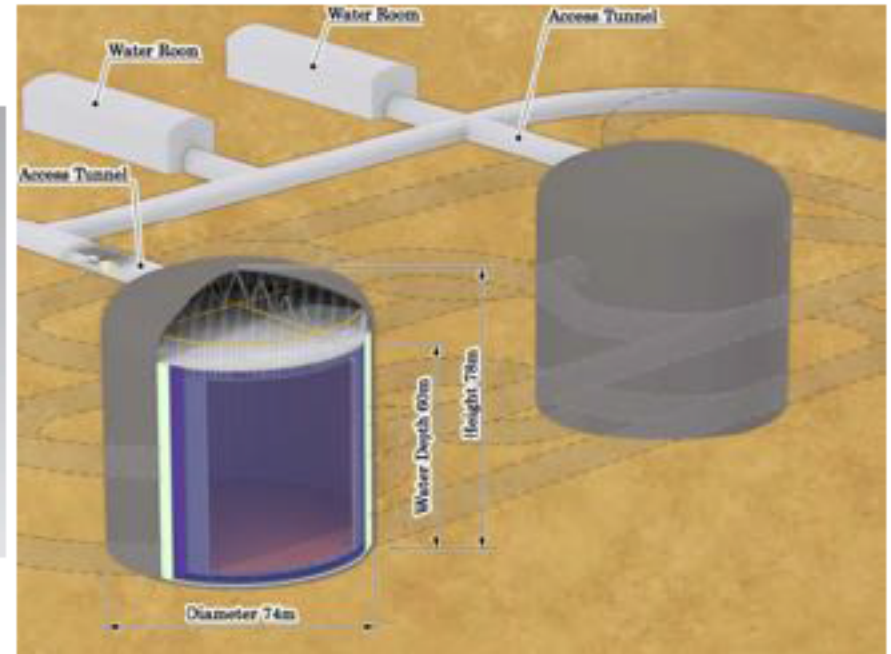
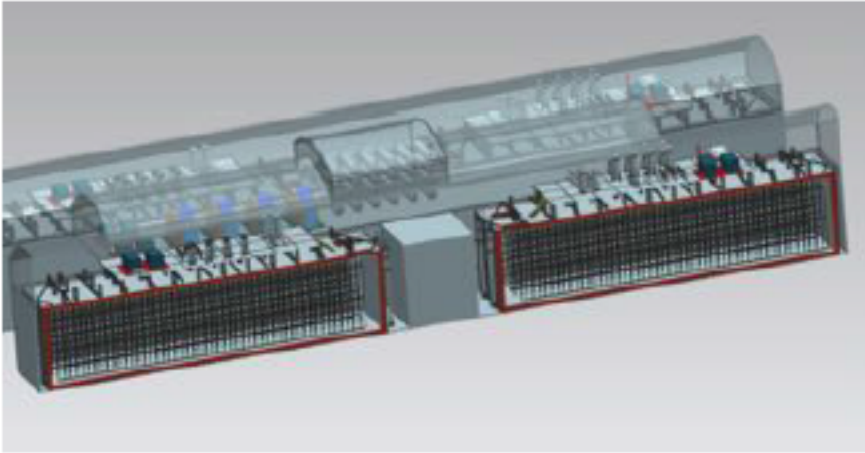
Teppei/Marco

I summarize all beam neutrino projects (analysis method, detector, beam) on the table. I try to be nice to both LArTPC and Water Cherenkov.

I also wrote most of conclusions.



## 2. Section 7, 8



DUNE (2025?)  
LArTPC detector  
argon target  
wideband 1-4 GeV  
(on-axis beam)

Hyper-Kamiokande (2026?)  
Water Cherenkov detector  
water target  
narrowband 0.6 GeV  
(off-axis beam)

## 3. What we learned

### We use our skills for different fields

- Marco: all theory sections
- Teppei: experiment/beam descriptions, event generation by GENIE/ROOT

### What we learned

- Culture and working habits of theorists and experimentalists
- Skill transfer on paper writings (reference, figure format, etc)
- It's manageable for 2 people, but not easy to expand more

### New ideas

- Section 2.3, Matching theory and experiment
- Section 3.3, Hadron information