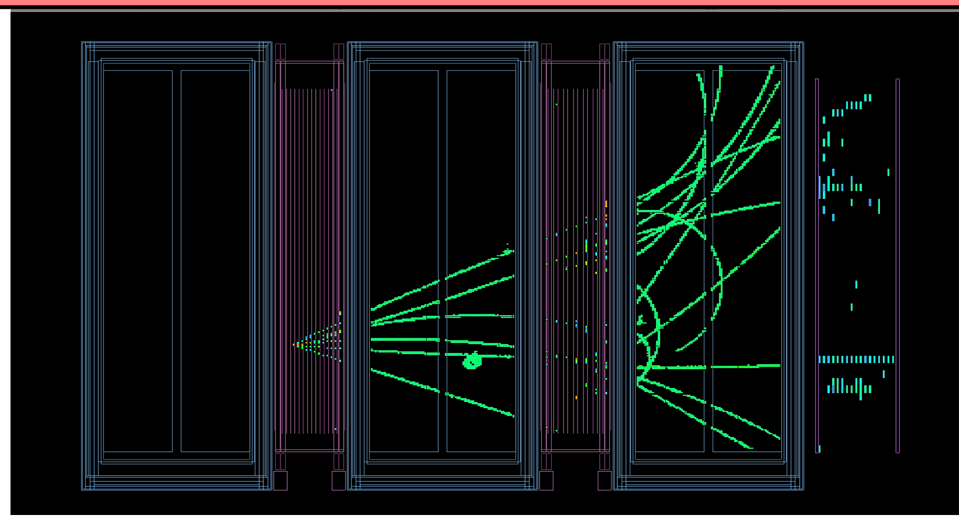
T2K Off-Axis Cross Section Measurements



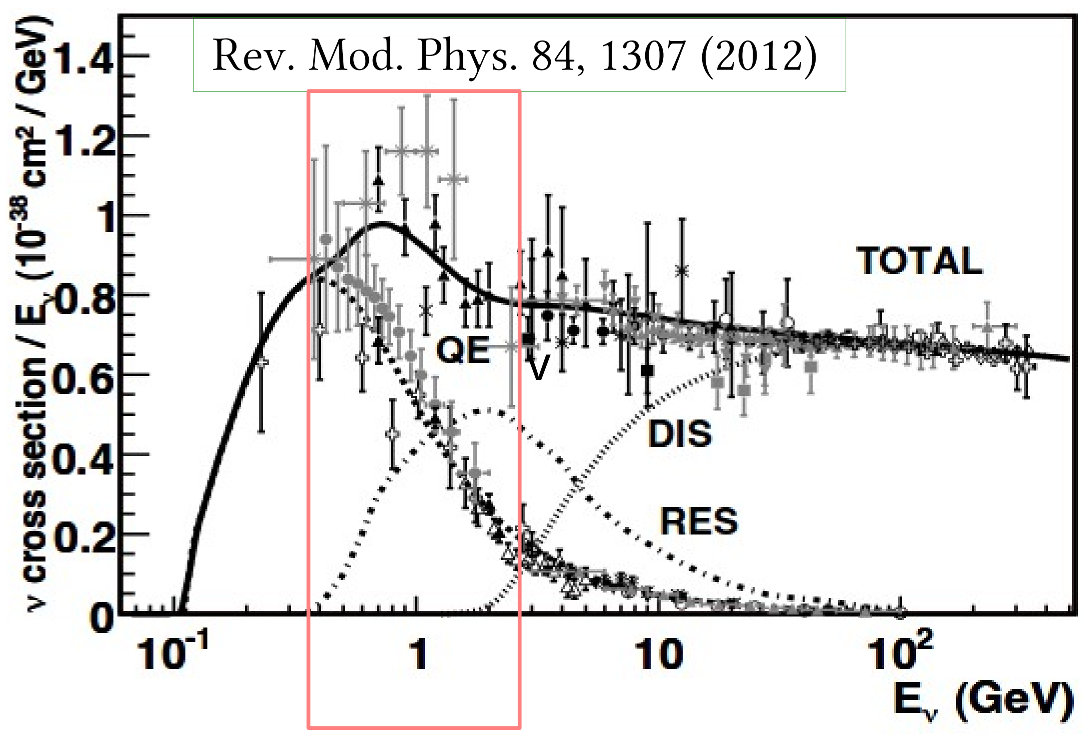
Raquel Castillo (IFAE)

On behalf of the T2K Collaboration

NuFact 2014, Glasgow (Scotland)

Motivation

- Understanding how neutrinos interact with matter is critical to reduce the systematic uncertainties in oscillation experiments.
- Published data from other experiments show discrepancies with the most common theoretical models.



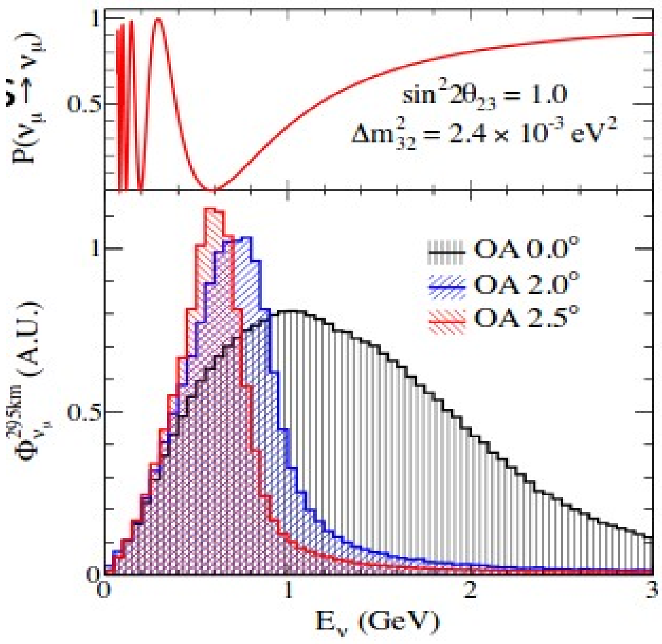
T2K E_{ν} peak ~0.6 GeV

Data collected in the near detector of the T2K experiment provide a coverage of the critical low to intermediate energy region

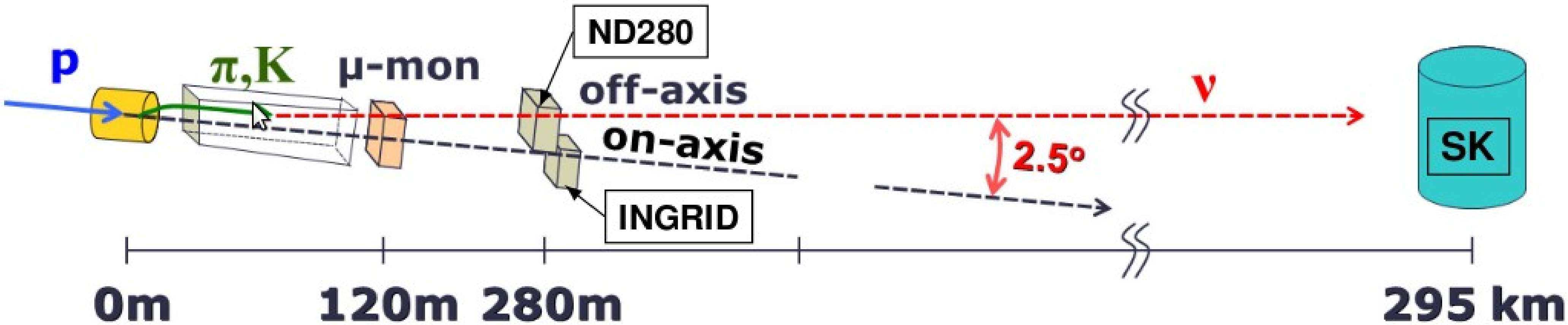
The T2K Experiment

T2K (Tokai-to-Kamioka) is a long baseline neutrino accelerator based experiment in Japan.
Main goal is to measure neutrino oscillation parameters:

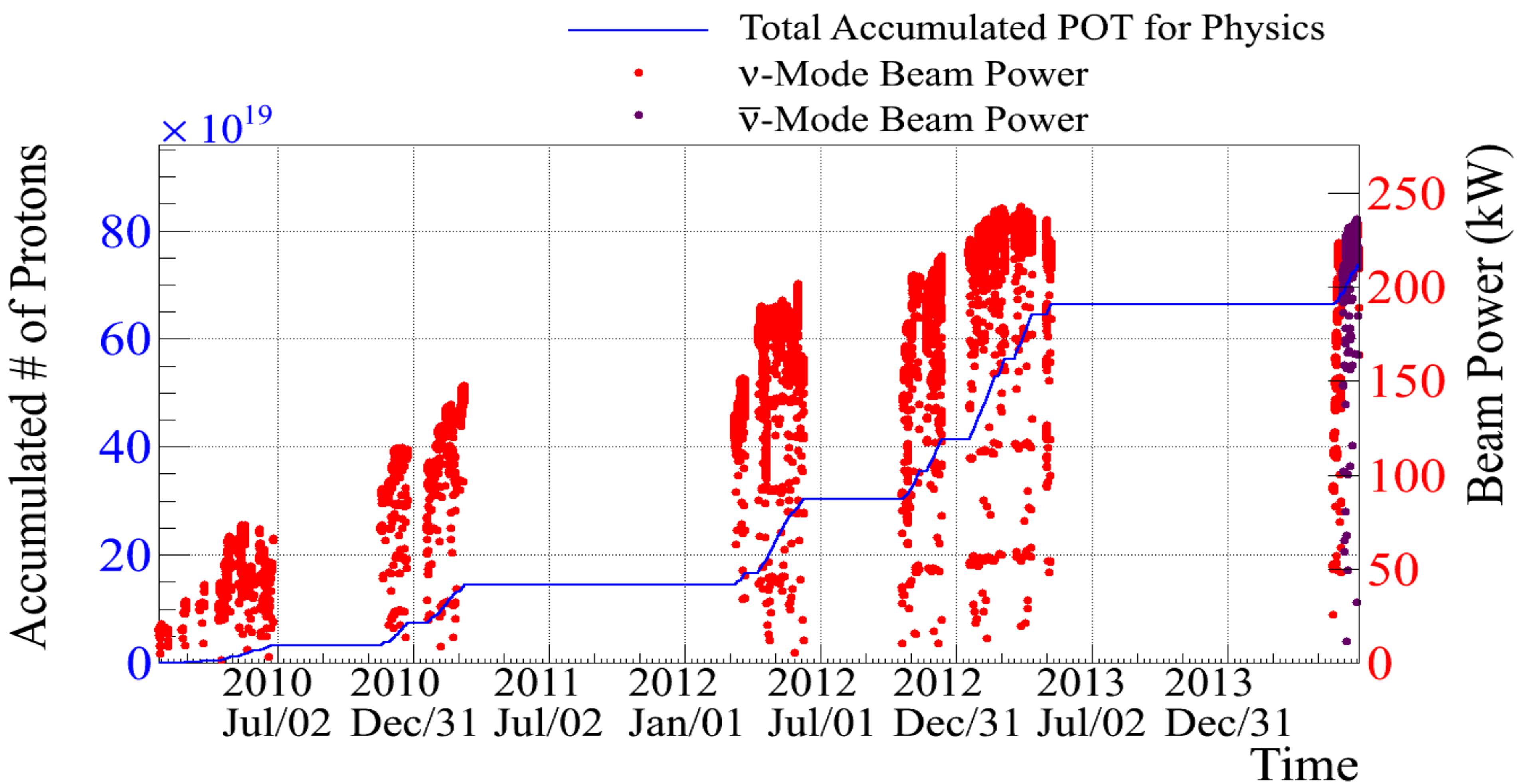
- ν_e appearance $\longrightarrow \sin^2(2\theta_{13})$
- ν_μ disappearance $\longrightarrow \sin^2(2\theta_{23})$ and $|\Delta m^2_{32}|$
- Look for CP violation



See talk by Christophe Bronner on Tuesday 26th



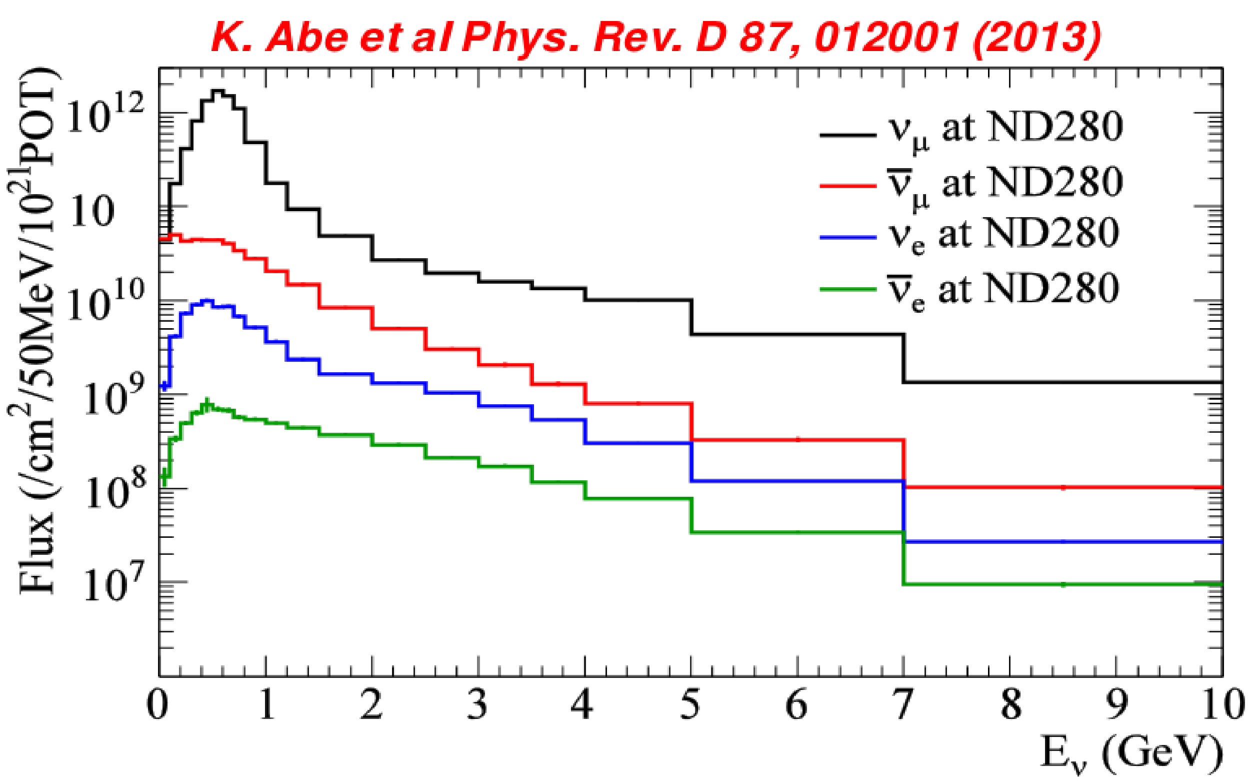
Collected Data in T2K



- Beam power reached 235 KW ($1.2\cdot10^{14}$ protons/pulse)
- Data for analysis: $7.39\cdot10^{20}$ protons on target (PoT), 8% of final design goal.
  - ν-Mode: $6.88\cdot10^{20}$ PoT
  - $\bar{\nu}$-Mode: $0.51\cdot10^{20}$ PoT
- Run 5 started in May 2014

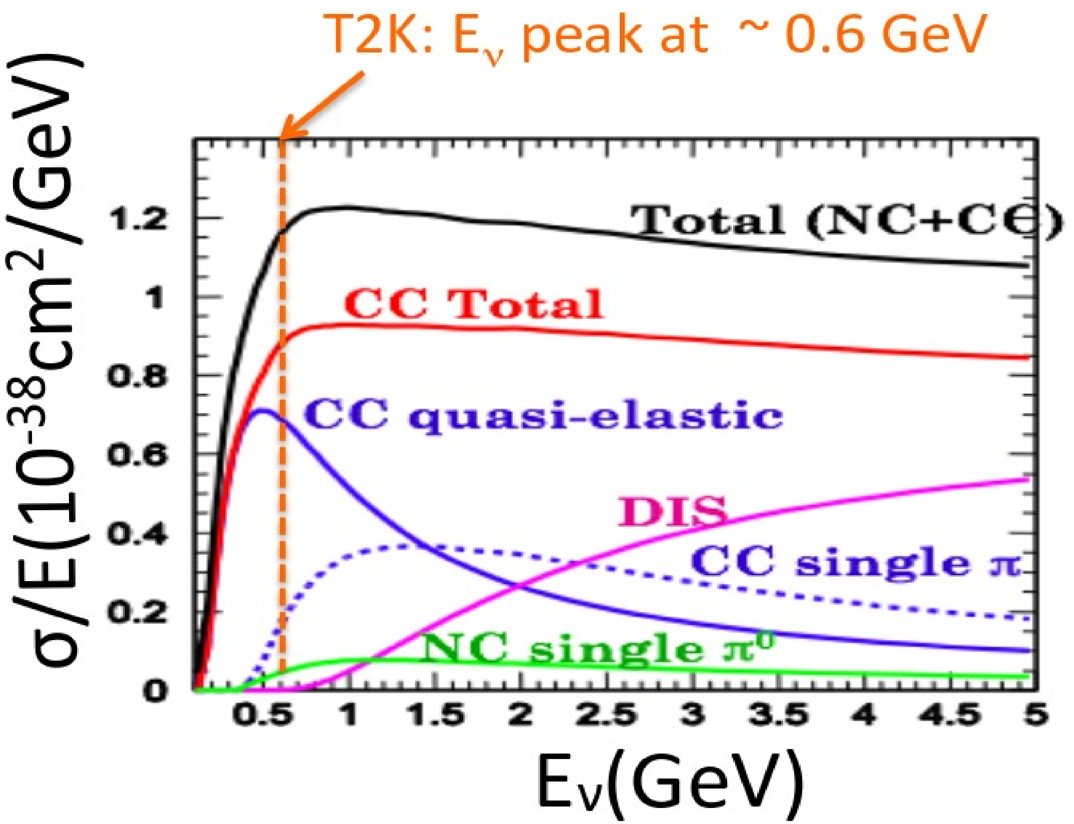
Flux Prediction for ND280

- Narrow band of a pure (92.5%) ν_μ beam @2.5° off-axis angle.
- Flux prediction based on NA61/SHINE hadron production cross section measurements.
- Proton beam monitoring.



ν_μ Interactions in T2K

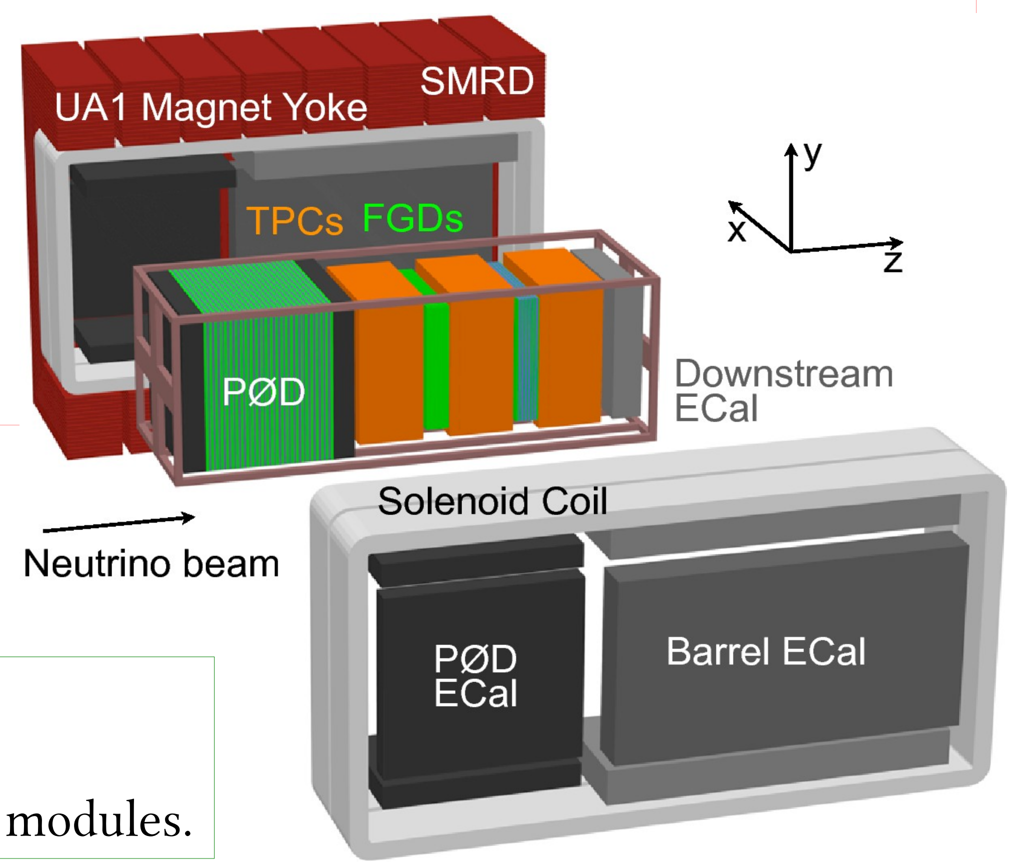
- CC (Charged Current) QE (quasi elastic)
  - $\nu_\mu + n \longrightarrow \mu^- + p$
- CC Resonance single π (CC1π⁺)
  - $\nu_\mu + n(p) \longrightarrow \mu^- + \pi^+ + n(p)$
- CC-DIS (Deep Inelastic Scattering)
  - $\nu_\mu + N \longrightarrow \mu- + m\pi^{+/-/0} + N'$
- CC Coherent π
  - $\nu_\mu + A \longrightarrow \mu- + \pi^+ + A$
- NC (Neutral Current)
  - NCE (Neutral Current Elastic), NCπ^0,...



And nuclear effects:
- Pion absorption
- Multinucleon effects
- ...

Off-Axis Near Detector ND280

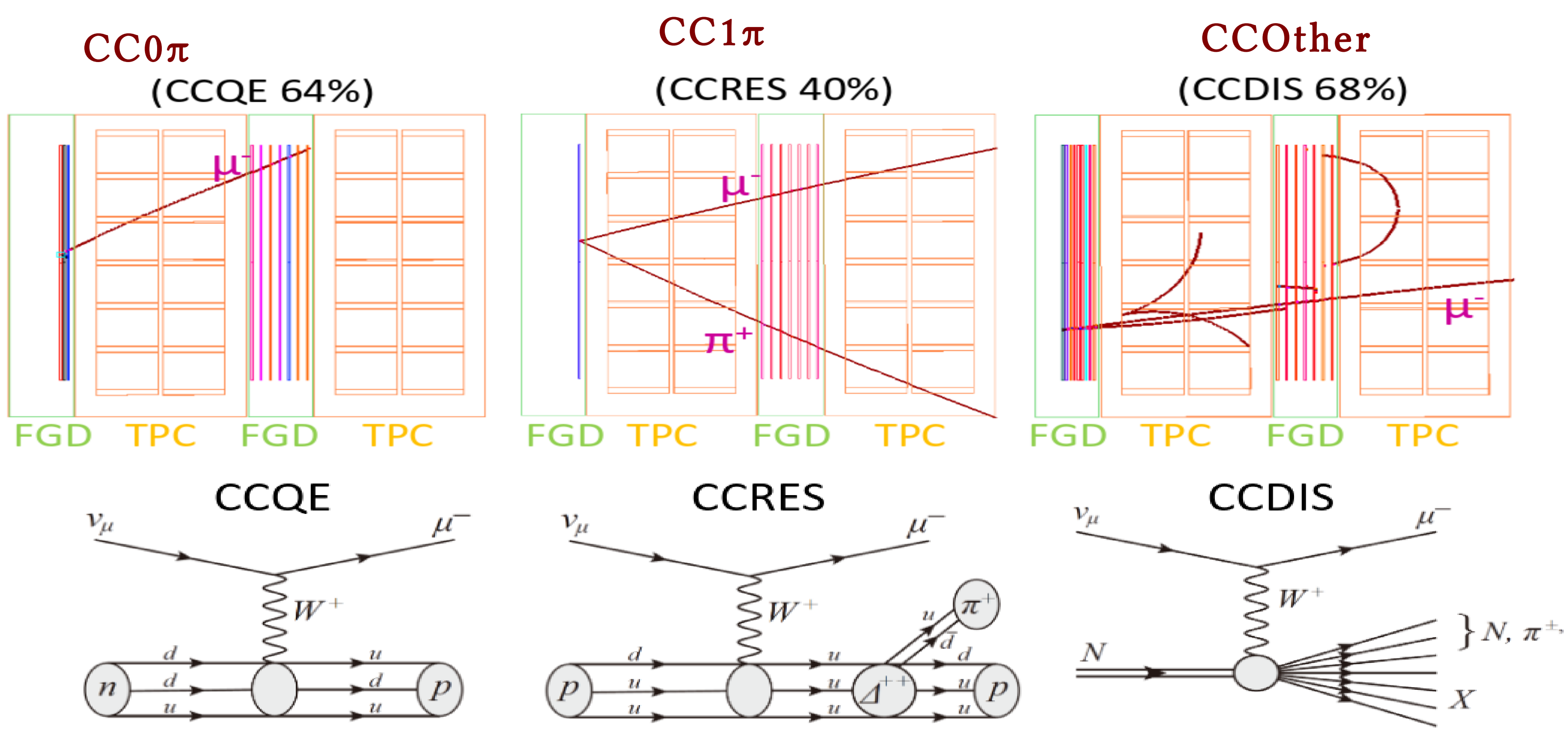
- **0.2T Magnetic field**
- **Tracker Region**:
  - **3 TPC** → Gas Argon time projection chambers using MicroMegas detectors. Provides an accurate PID using dE/dx information and a high momentum resolution.
  - **2 FGD*** → Fine grained detectors. Active targets made of layers of scintillator bars. Vertex information.
- **P0D**: dedicated π^0 detector.
- Electromagnetic Calorimeter: **ECal**.
- Side muon range detector: **SMRD**



*2FGDs:
First FGD is fully scintillator (CH).
Second FGD is divided into scintillator and water modules.

Topologies at ND280

- ND280 is used to constrain uncertainties at Super-K for flux and cross section parameters, jointly with external data.
- A topological description is used for the event categorization based upon the number of particles leaving the nucleus.
- Three exclusive samples are defined according the number of pions on the final state.



ND280 Cross Section Measurements

- Cross Section results on Carbon*
  - ν_μ CC Inclusive (Tracker)
  - ν_e CC Inclusive (Tracker)
  - ν_μ CCQE (Tracker)
  - ν_μ CC1π^+ (Tracker)

- Cross Section results per nucleon
  - ν_μ NCE (P0D)

- Prospects for Cross section measurements in ND280

* Scintillator (CH)

ν_μ Differential CC Inclusive on CH

Phys. Rev. D 87, 092003 (2013)

Differential cross section definition:

$$\left\langle\frac{\partial^2\sigma}{\partial p_\mu \partial\cos\theta_\mu}\right\rangle_{kl} = \frac{N^{\text{int}}_{kl}}{T\phi\Delta p_{\mu,k}\Delta\cos\theta_{\mu,l}}$$

N^{int}_{kl}: # of interactions in true bin

T: # of target nucleons

ϕ: flux

2D binning: (k,l)

Same methodology used in all current ND280 differential cross section measurements

1D binning: k

Method

Unfolding

$$N^{\text{int}}_k \approx \widehat{N}_k = \frac{U_{kj}}{\epsilon_k}\left(N^{sel}_j - B_j\right)$$

U_{kj}: un-smearing matrix

ϵ_k: efficiency

N^{sel}_j: # of sel. events

B_j: background in rec. bin

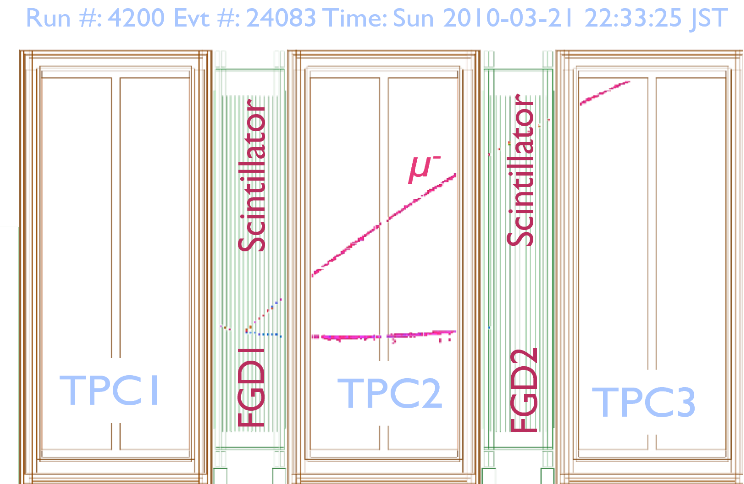
unfolding based on Bayes' theorem

reco

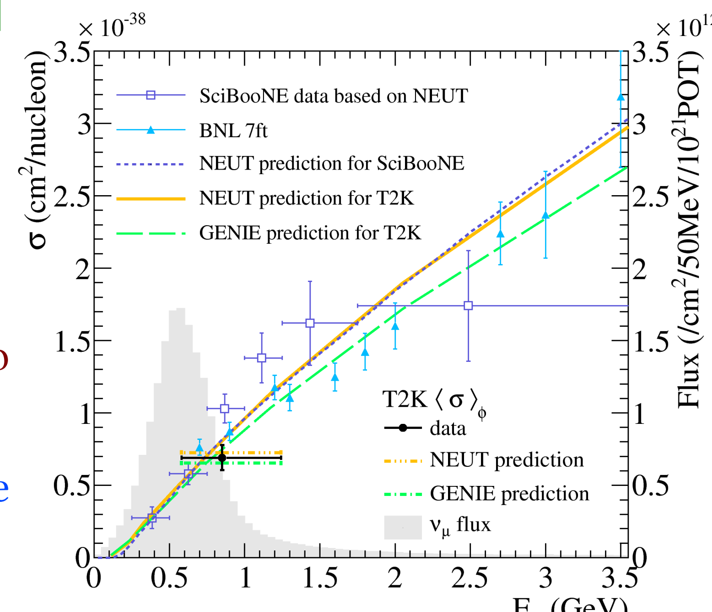
true

$$U_{kj} = P(k|j) = \frac{P(j|k)P(k)}{\sum_\alpha P(j|\alpha)}$$

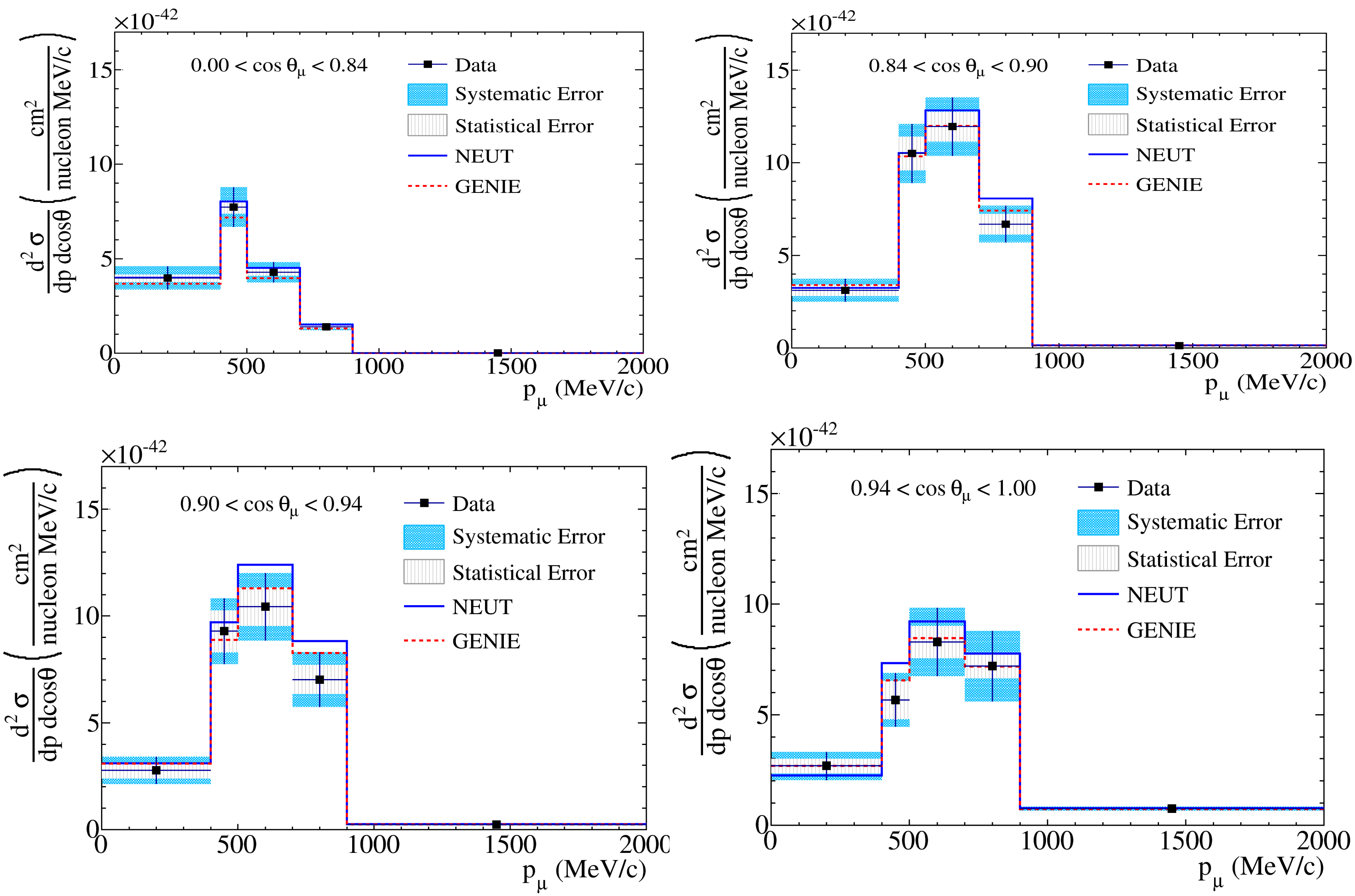
U_{kj} = probability to have an interaction in bin k, when having reconstructed the event in bin j



Data: 1.08×10^{20} PoT



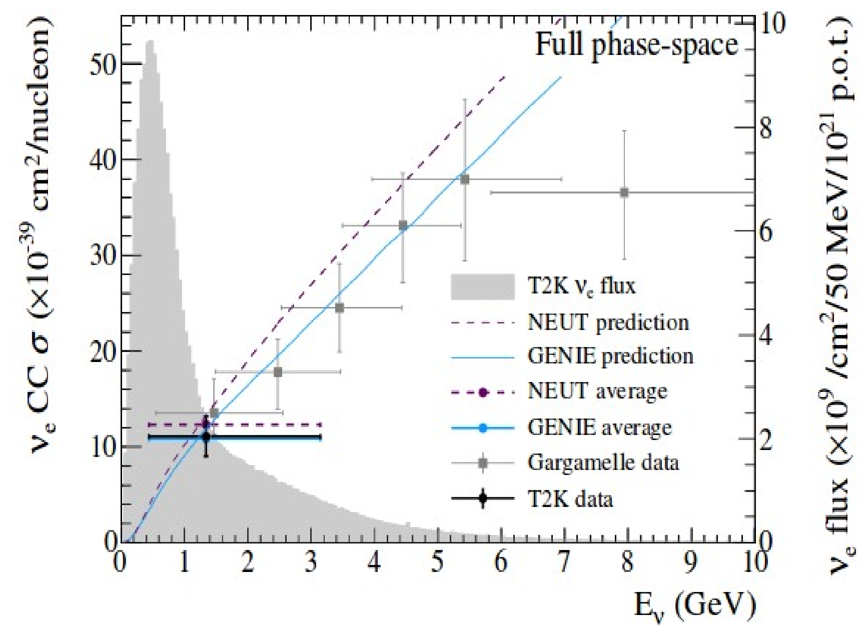
ν_μ Differential CC Inclusive on CH



Data in good agreement with NEUT and GENIE predictions

ν_e Differential CC Inclusive on CH

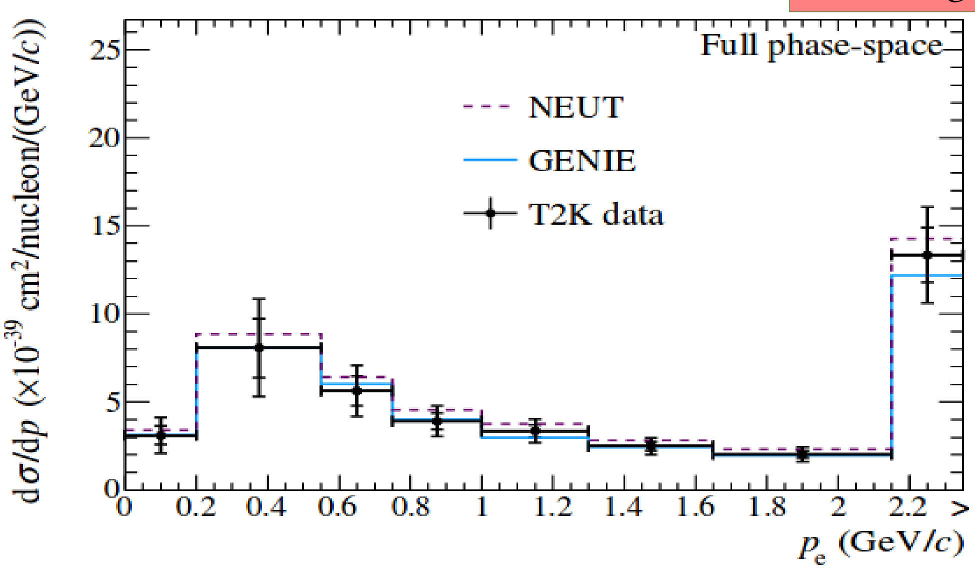
- Understanding ν_μ vs ν_e is crucial for sensitivities studies.
- Using Bayesian unfolding method.
- First ν_e cross section result at the GeV scale since Gargamelle in 1978.
- Result given differentially in:
  - Electron momentum
  - Electron Angle
  - Q^2 assuming CCQE interaction.
- Total flux averaged cross section.

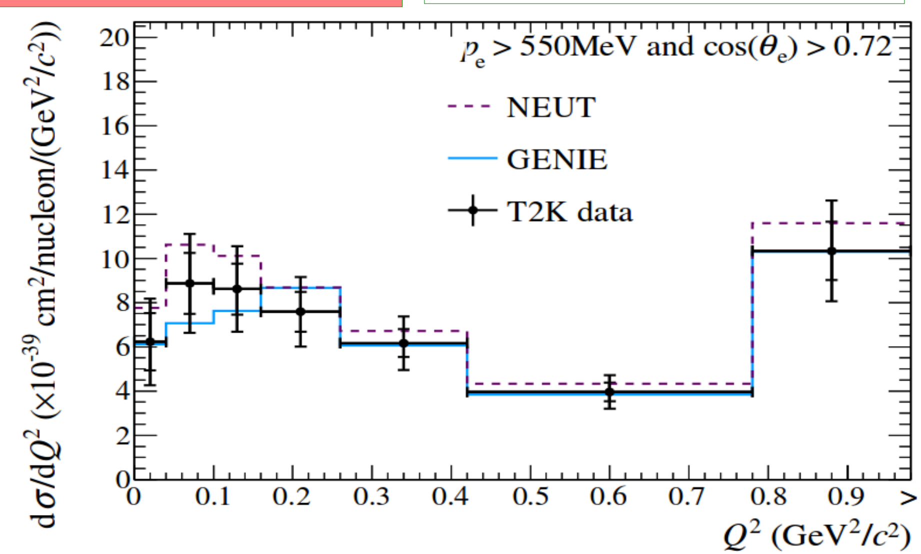


arXiv:1407.7389

Good agreement with NEUT prediction

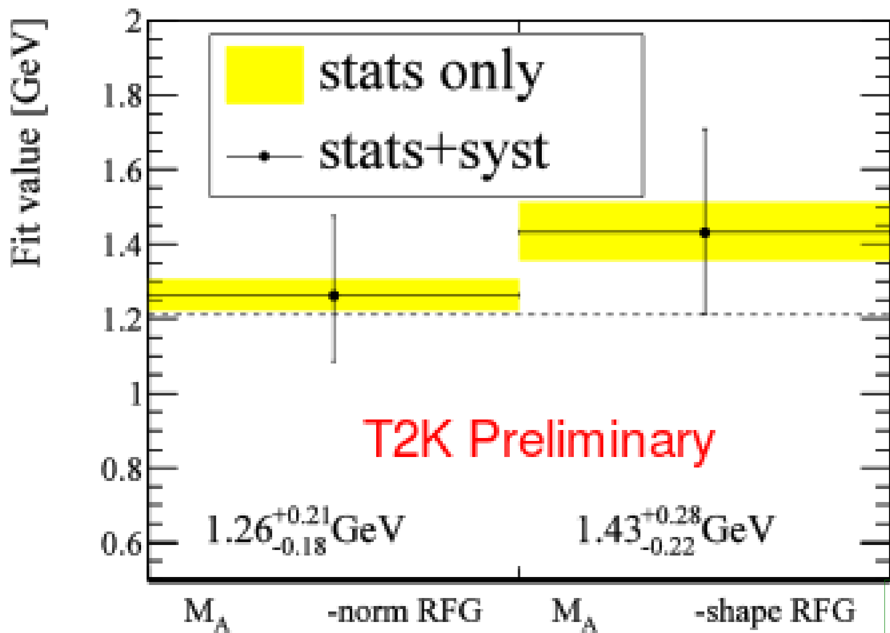
Data:5.9 x 10^{20} PoT

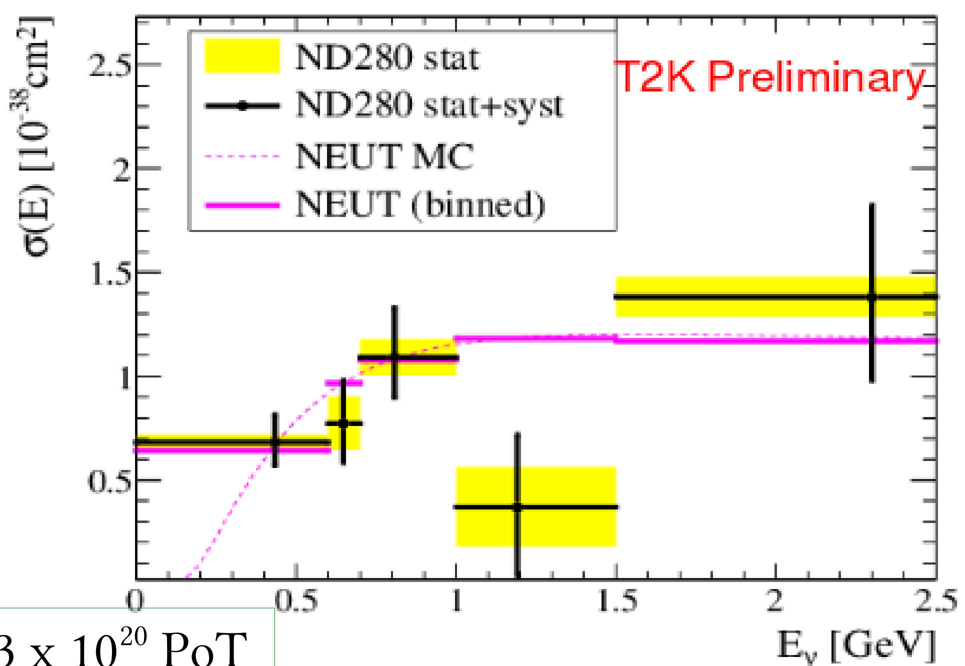




ν_μ CCQE on CH

- Fit done in bins of p_μ, θ_μ, then projected into E_ν
- Events with only 1 μ-like track and no pions at the final state are used to fit the MC (NEUT)
- Fitted effective M_A^{QE} value is consistent with previous low energy measurements, MiniBooNE & K2K.





Data:2.63 x 10^{20} PoT

New T2K analysis ongoing:

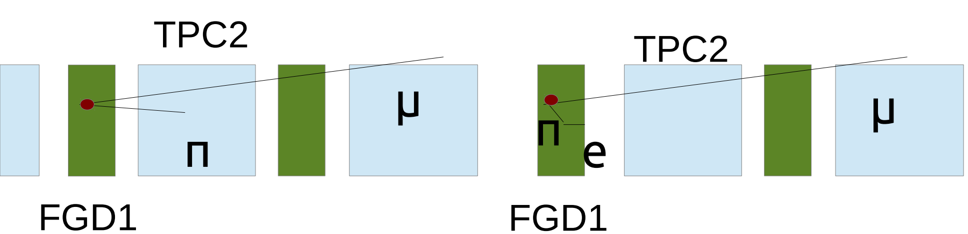
- ✓ CCQE double differential with improved event reconstruction.
- ✓ 2p2h effect included in next NEUT MC release.
- ✓ Dedicated 2p2h analysis ongoing.

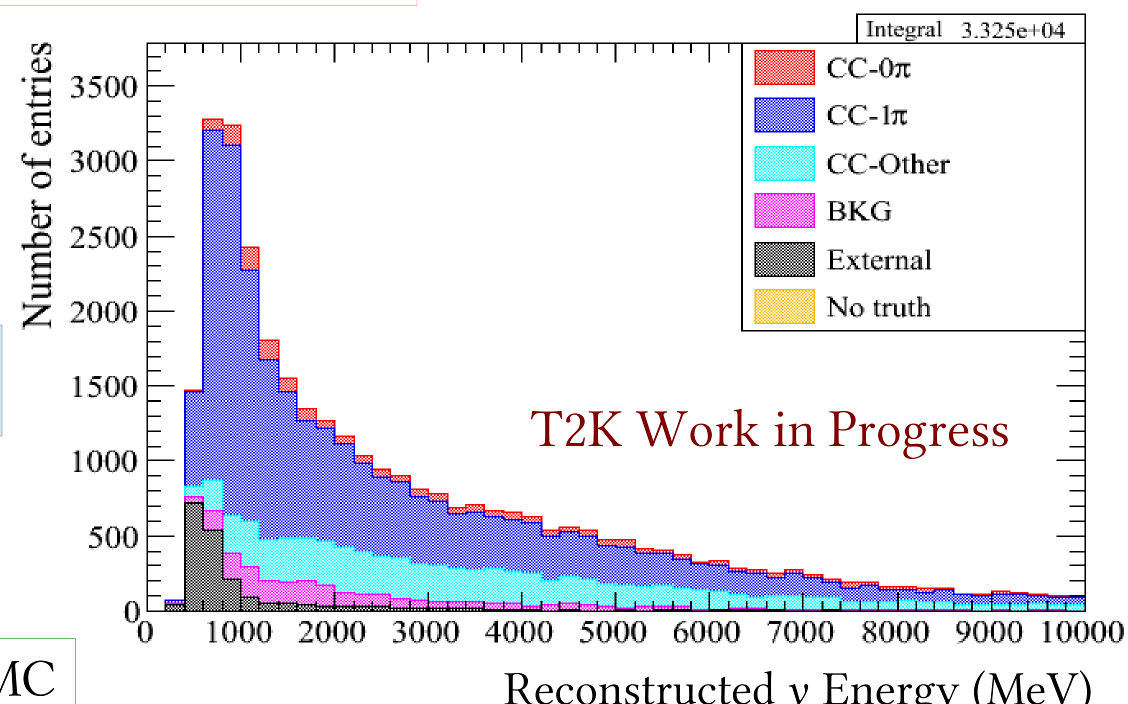
See Callum Wilkinson talk

ν_μ Differential CC1π^+ on CH

- Event selection: 1 μ-like and 1 π^+-like in final state.
- No kinematical cuts applied.
- Cross section result with respect to several variables:
  - E_ν, single differentials Q^2, $|Q_3|$, invariant mass, double differential (Q^2, Q_3)
  - Double differential (P_μ, θ_μ)
  - Single differentials P_π, θ_π
  - respect more angular distributions…

- ✓ Control samples to fit the background
- ✓ Finalizing systematic calculation
- ✓ Result will be ready soon.

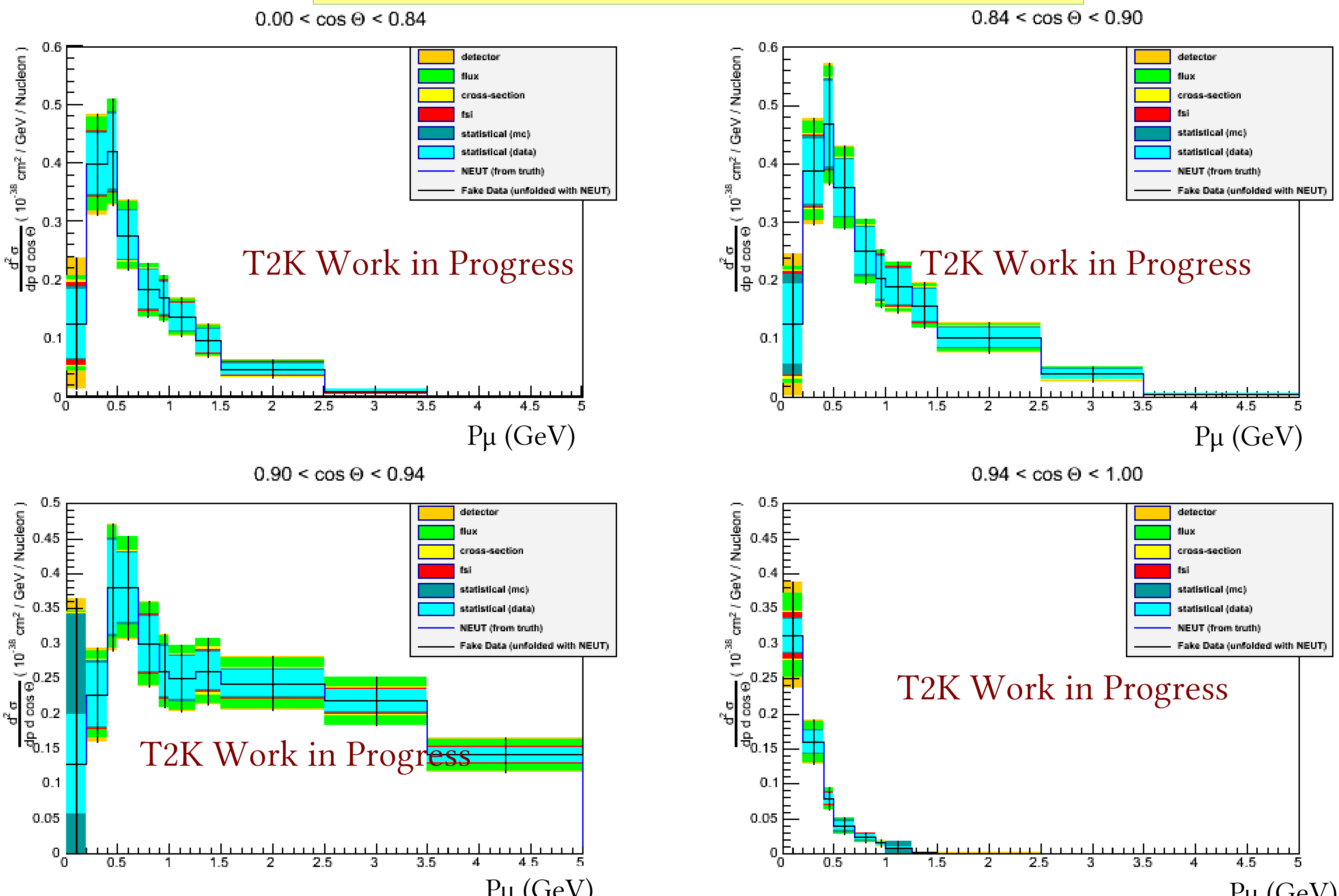




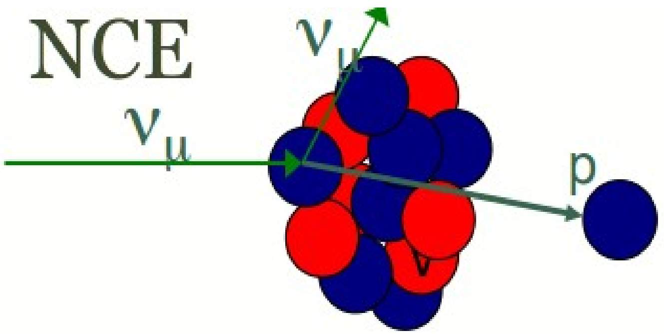
Only MC

ν_μ Differential CC1π^+ on CH

Using MC as fake data before final results with real data



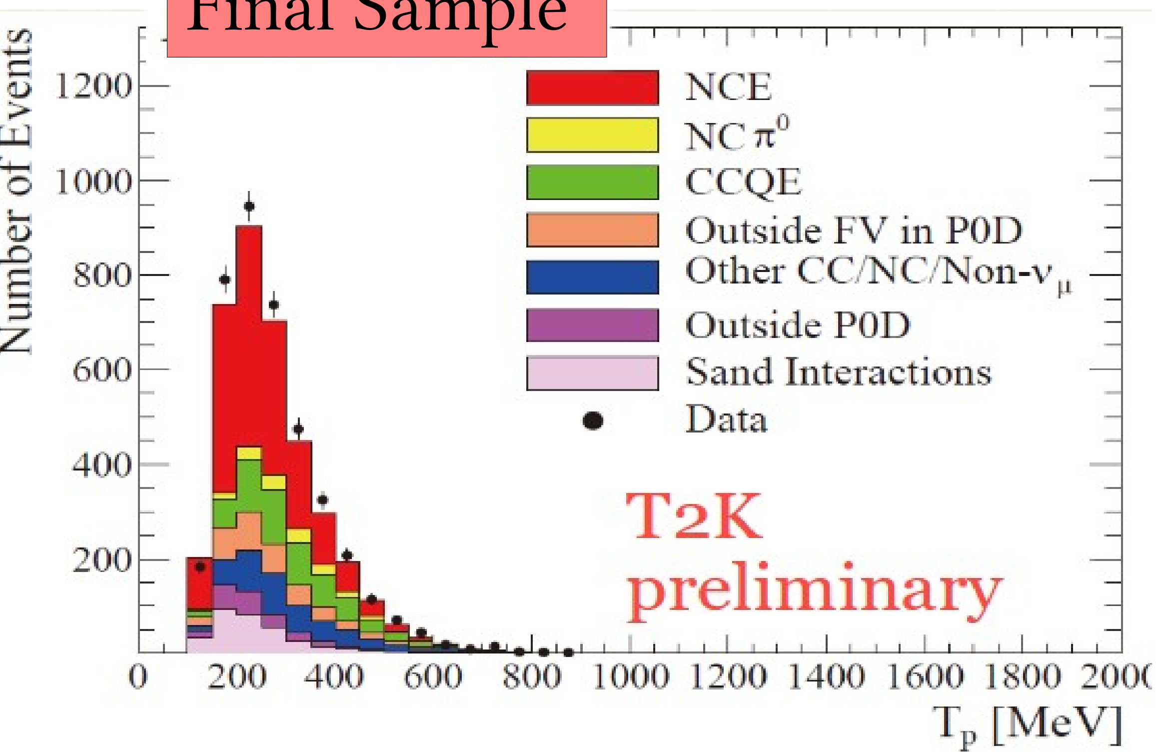
ν_μ NC Elastic per nucleon



- Selecting proton-like with dE/dx in P0D
- Only one track in the final state
- Consistent with NEUT and GENIE models

$$\langle\sigma\rangle_{flux} = 2.24\times10^{-39} \pm 0.07(stat.)\,^{+0.53}_{-0.63}(syst.)\,\frac{cm^2}{nucleon}$$

Final Sample



$$NEUT\,\langle\sigma\rangle_{flux} = 2.02\times10^{-39}\,\frac{cm^2}{nucleon}$$

$$GENIE\,\langle\sigma\rangle_{flux} = 1.78\times10^{-39}\,\frac{cm^2}{nucleon}$$

Data: 9.92×10^{19} PoT

Prospects for Cross Section Measurement in ND280

More analysis ongoing in ND280:

- Differential $CC1\pi^+$ with explicit presence of a proton on carbon.
- CC Coherent pion production on carbon.
- $CC1\pi^+$ on water (P0D) $\longrightarrow$ single energy bin.
- Improving the CCQE result on carbon $\longrightarrow$ double differential measurement with more statistics and improved event reconstruction.
- Searches of 2p-2h events on carbon.
- Differential $CC1\pi^+$ on water, using the FGD2 water modules.
- Differential CC Inclusive on water, using the FGD2 water modules.
- <u>Anti-Neutrino cross section on carbon*.</u>
- <u>Anti-Neutrino cross section on water*.</u>

See Linda Cremonesi poster

*With $\bar{\nu}$-Mode

Summary

- Cross section measurements are not only important for neutrino interaction understanding by itself but it is also crucial for oscillation analysis.

- The intermediate energy range became the most controversial scenario since several distinct neutrino scattering mechanism contribute to the full picture. The products of these neutrino interactions includes a huge variety of final states.

- T2K covers the intermediate energy range and the near detector, ND280, can measure neutrino cross sections in carbon and water targets.

- CC Inclusive measurements for ν_μ and ν_e on carbon have appearer in PRD and referee journal respectively, the ν_e result being the first one since Gargamelle. ν_μ CCQE measurement on carbon and ν_μ NC Elastic on the P0D have also been showed.

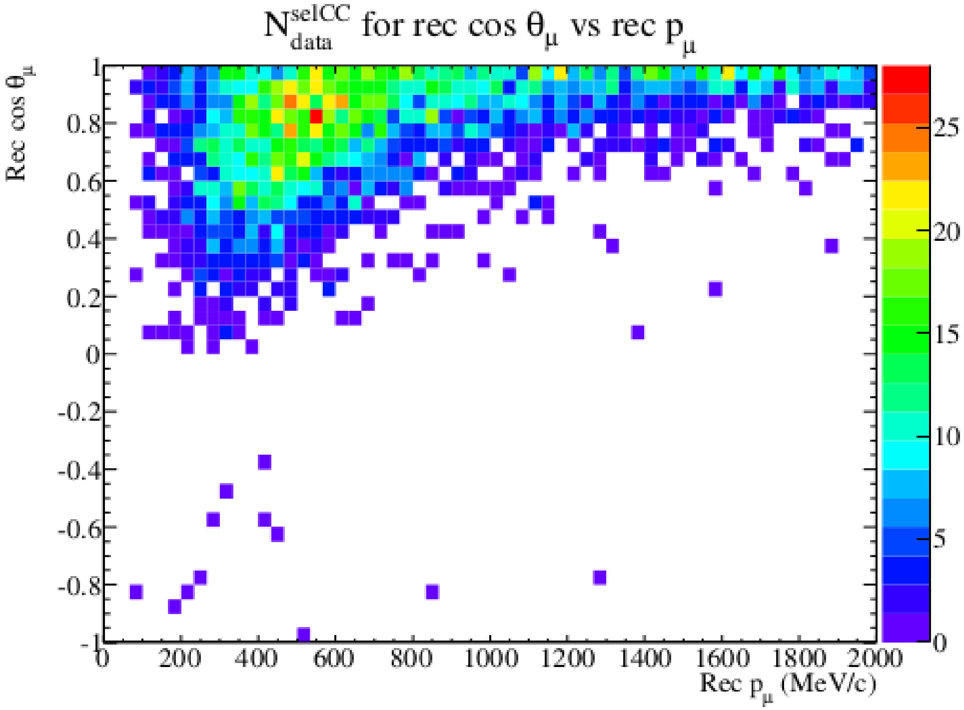
- First look into the next result on ν_μ CC1π^+ measurement on carbon. Result will be provided in single and double differential over several interesting variables.

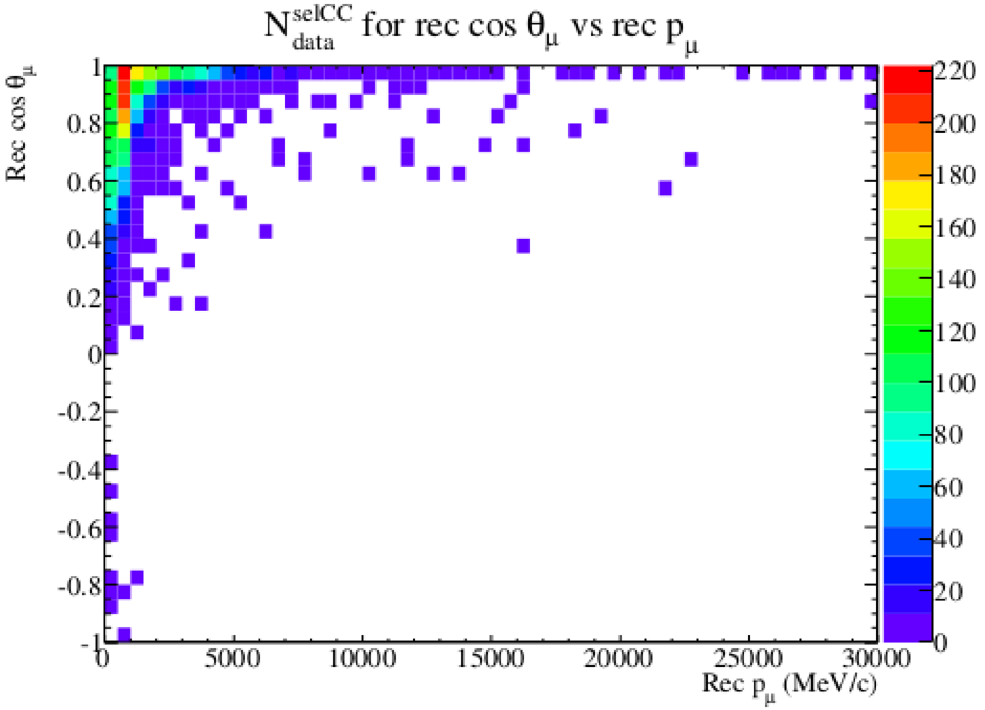
- Additional measurements are ongoing in ND280, on carbon and water. Starting preparation of anti-ν cross section.

Thanks!!

Backup

ν_μ Differential CC Inclusive on CH



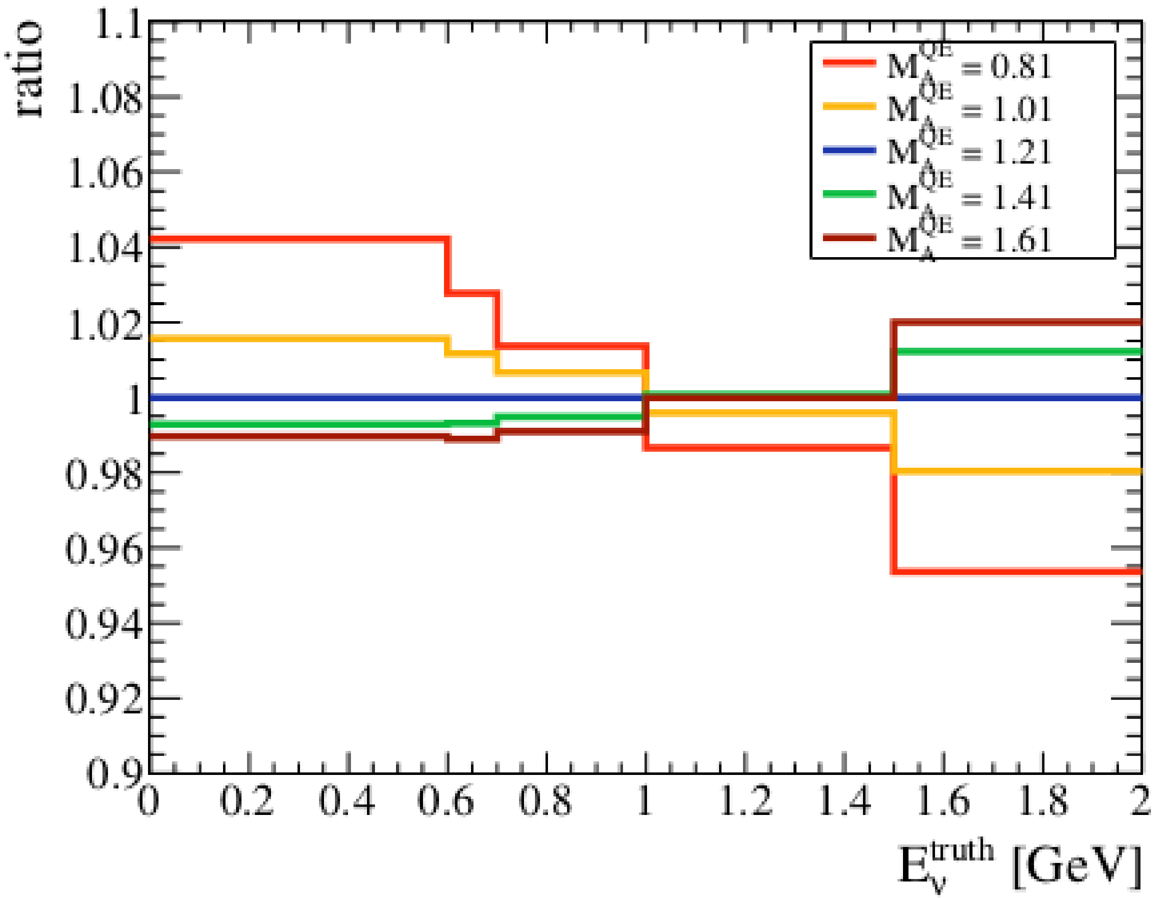


ν_μ Differential CC Inclusive on CH

P_μ (GeV/c)	$\cos\theta_\mu$	algo. (%)	ϕ (%)	x-s (%)	det. (%)	FSI (%)	syst (%)	stat (%)	tot (%)
[0.0, 0.4]	[−1, 0]	0.53	11.40	17.99	2.13	0.46	21.43	2.04	21.53
	[0, 0.84]	0.62	12.79	5.52	3.65	1.21	14.49	4.95	15.31
	[0.84, 0.90]	0.26	13.13	10.76	2.73	1.41	17.28	9.52	19.72
	[0.90, 0.94]	1.21	14.05	10.73	5.02	3.55	18.78	12.26	22.42
	[0.94, 1]	0.22	14.03	12.94	4.94	2.97	19.96	14.72	24.80
[0.4, 0.5]	[−1, 0]	1.32	11.98	39.47	2.72	0.87	41.38	3.19	41.50
	[0, 0.84]	0.17	11.39	5.69	1.30	0.34	12.83	4.20	13.50
	[0.84, 0.90]	0.01	11.36	4.99	1.01	0.42	12.48	8.61	15.16
	[0.90, 0.94]	0.82	11.66	5.38	1.28	0.51	12.97	10.08	16.43
	[0.94, 1]	0.55	13.11	7.19	2.27	0.92	15.19	11.74	19.19
[0.5, 0.7]	[−1, 0]	0.63	12.60	46.13	1.86	0.42	47.87	8.48	48.62
	[0, 0.84]	0.33	11.13	3.79	1.09	0.37	11.84	3.78	12.43
	[0.84, 0.90]	0.41	10.85	3.44	0.82	0.30	11.45	6.18	13.02
	[0.90, 0.94]	0.48	11.01	5.73	0.81	0.35	12.48	7.28	14.45
	[0.94, 1]	0.52	11.64	11.45	1.09	0.28	16.39	7.91	18.20
[0.7, 0.9]	[−1, 0]	3.63	13.53	148.34	1.97	0.57	149.02	32.74	152.57
	[0, 0.84]	0.59	11.38	3.17	1.10	0.41	11.91	5.07	12.95
	[0.84, 0.90]	0.56	10.92	5.88	0.83	0.20	12.47	6.84	14.22
	[0.90, 0.94]	0.31	10.72	11.13	1.05	0.46	15.52	7.68	17.32
	[0.94, 1]	0.19	11.00	17.59	0.93	0.39	20.79	6.97	21.93
[0.9, 30.0]	[−1, 0]	-	-	-	-	-	-	-	-
	[0, 0.84]	0.20	11.88	5.61	1.37	0.63	13.26	5.44	14.33
	[0.84, 0.90]	0.03	11.34	2.49	0.87	0.25	11.68	5.85	13.06
	[0.90, 0.94]	0.18	11.13	2.27	0.71	0.36	11.42	5.18	12.54
	[0.94, 1]	0.20	10.93	2.31	0.75	0.26	11.24	2.93	11.61

ν_μ CCQE on CH

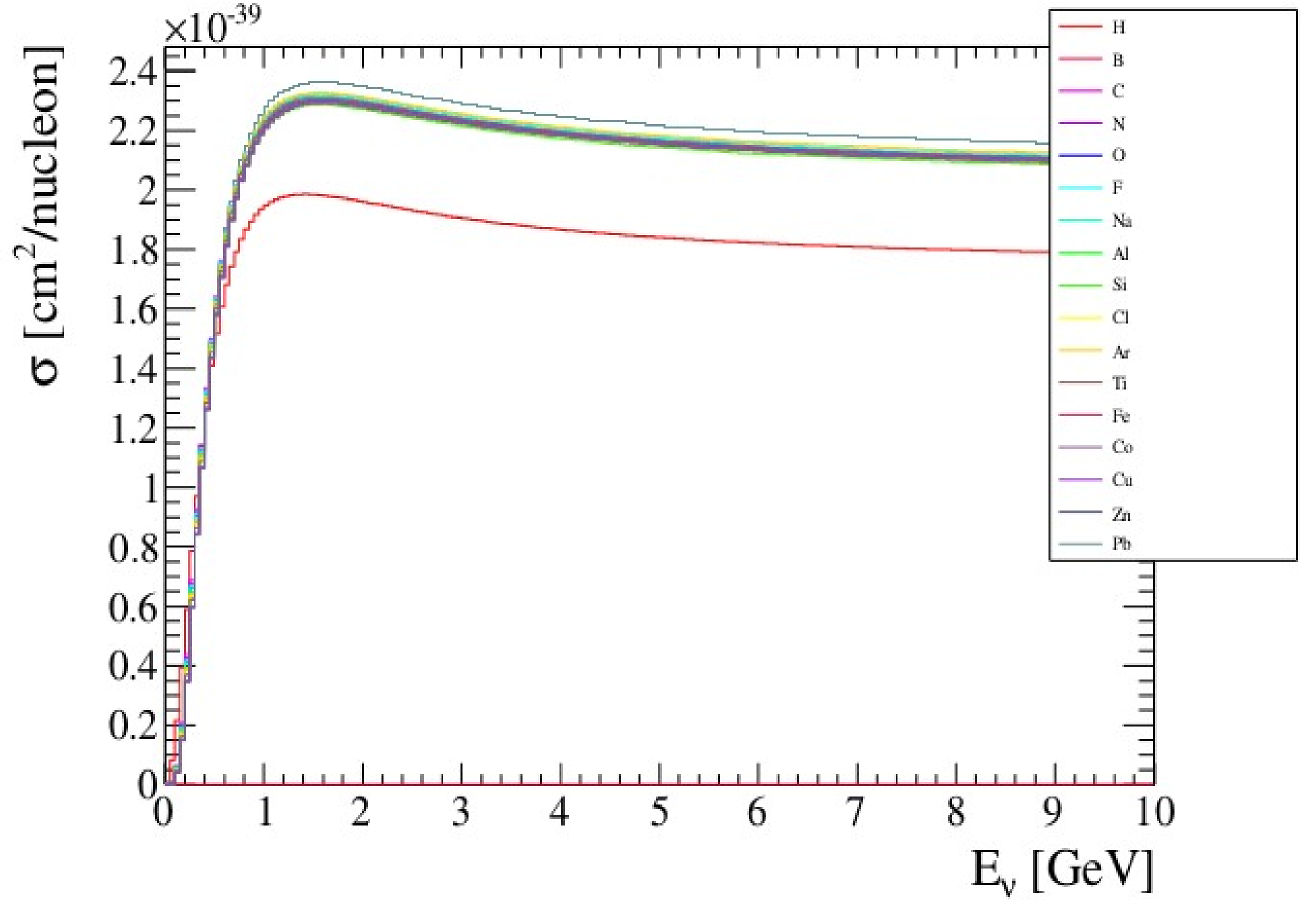
$$w_{\text{shape}}(M_A^{\text{QE}}{}_{\text{modified}}) = w_{\text{norm}}(M_A^{\text{QE}}{}_{\text{modified}}) \frac{\sigma(M_A^{\text{QE}}{}_{\text{nominal}})}{\sigma(M_A^{\text{QE}}{}_{\text{modified}})}$$



Event Type	Events	Fraction (%)
CCQE	4496.62	72.0
CC1π	1007.32	16.1
CC multi-π	203.45	3.3
CC DIS	151.32	2.4
CC coherent	111.79	1.8
NC1π	59.45	1.0
NC other	65.43	1.0
No Truth	98.33	1.6
other	50.04	0.8
total MC	6243.75	100.0

ν_μ NC Elastic per nucleon

$$< \sigma >_{flux} = \frac{N_{sel.} - B_{mc}}{\frac{\int \Phi(E_\nu) \mathrm{d}E_\nu}{1 \times 10^{21} P.O.T.} \times \mathrm{p.o.t.}_{exposure} \times N_{Targets} \times \epsilon_{mc}}$$



ν_μ Differential CC1π^+ on CH

- $d\sigma/dp_\mu$, $d\sigma/dp_\mu \mathrm{Cos}\theta_\mu$
- $d\sigma/dp_\pi$, $d\sigma/d\theta_\pi$
- $d\sigma/dE_\nu$ (reconstructed neutrino energy formula)
- $d\sigma/dQ^2$
- $d\sigma/d|Q_3|$, $d\sigma/d|Q_3|dQ^2$
- $d\sigma/d\theta_{\mu\pi}$
- $d\sigma/d\theta_{|Q3|\pi}$
- $d\sigma/d\theta_{planar}$ — $|\bar{v} \times \bar{l}|$ vs $\bar{\pi}$
- $d\sigma/d\phi_{planar}$ — $\bar{v} \times |\bar{v} \times \bar{l}|$ vs $\bar{\pi}$
- $d\sigma/dW$ (W → invariant mass)

$$E_\nu = \frac{m_\mu^2 + m_\pi^2 - 2m_N(E_\mu + E_\pi) + 2p_\mu \cdot p_\pi}{2\left(E_\mu + E_\pi - |\mathbf{p}_\mu|\cos\theta_{\nu,\mu} - |\mathbf{p}_\pi|\cos\theta_{\nu,\pi} - m_N\right)}$$