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Oxford Physics

CC-Inclusive Cross Section measured with the T2K Near Detector

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For the T2K Collaboration

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  - Producing Neutrinos
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- Selecting Events
- Cross Section Extraction
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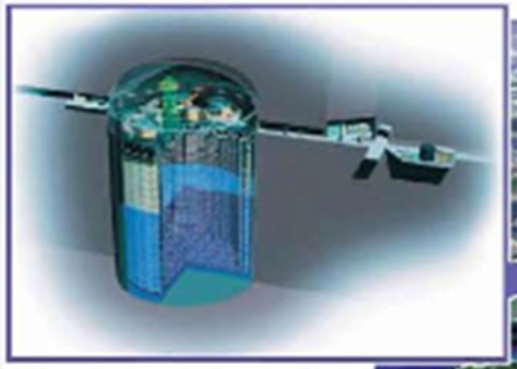
The T2K Experiment

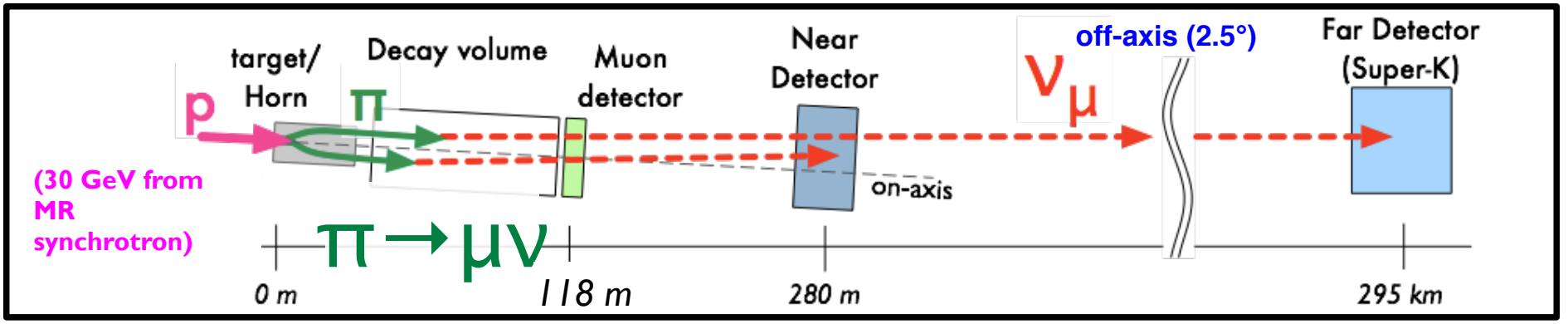


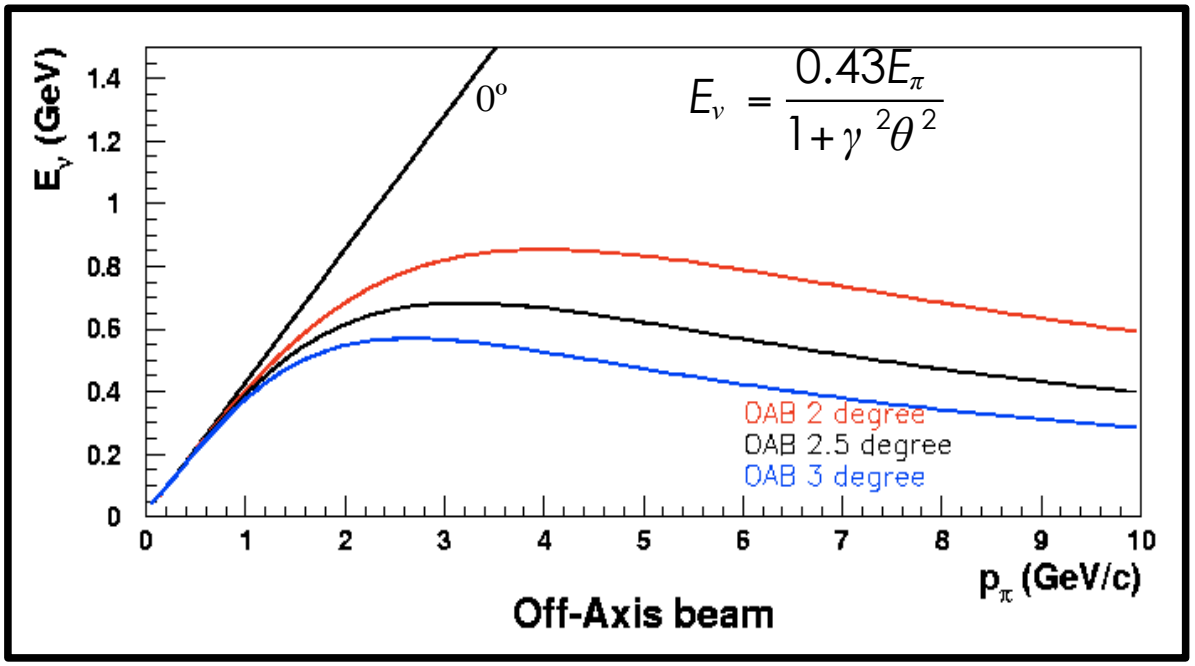
Super-Kamiokande
(ICRR, Univ. Tokyo)

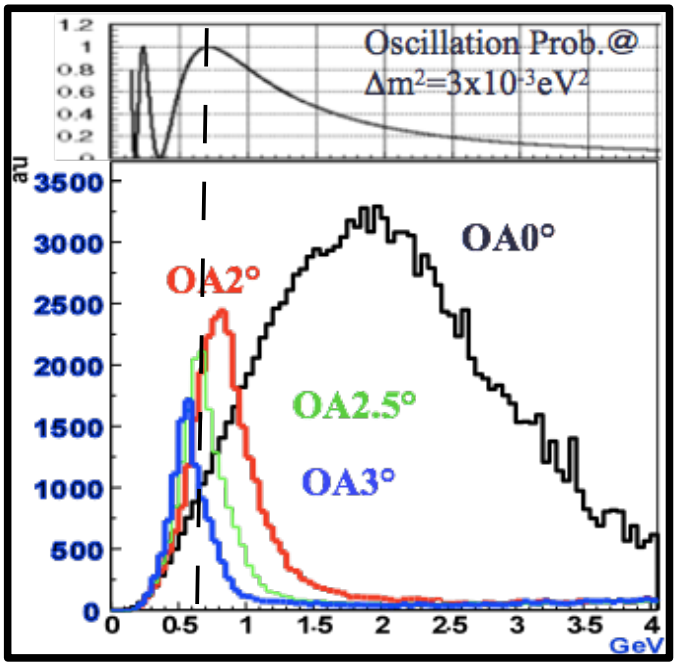
J-PARC Main Ring
(KEK-JAEA, Tokai)

- Neutrino Beam from j-parc
  - Beam power 50 – 190 kW
- Detector 280m from target
  - Run 1&2 analysed (2010/11)
  - 1.43×10^{20} p.o.t. (this analysis) / 3.01×10^{20} p.o.t. (now)
  - 5% of expected total

Producing Neutrinos

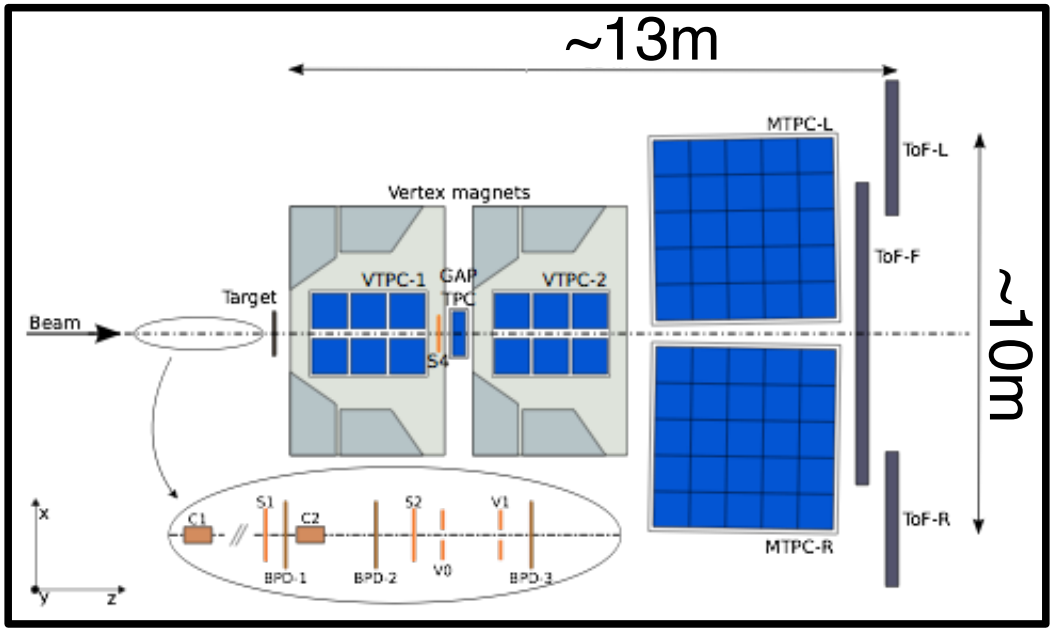






NA61/SHINE

- hadron(π , K) yield
  - 30 GeV p + C
- High-acceptance
  - ToFs and spectrometers
- 2cm thin target (4% λ_I)
- π^+ analysis:
  - dE/dx only analysis low momenta (Phys.Rev.C84.2011.034604)
  - dE/dx+ToF analysis high momenta (Phys.Rev.C85.2011.035210)

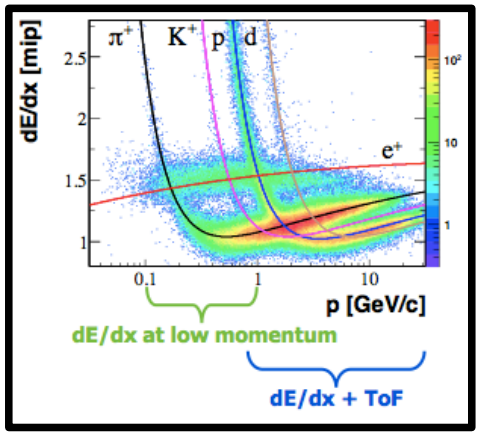


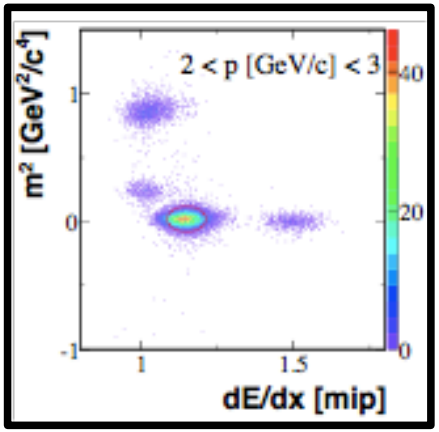
$$\sigma(p)/p^2 \approx 2\times10^{-3},\ 7\times10^{-3},\ 3\times10^{-2}(\mathrm{GeV/c})^{-1}$$

$$\text{for } p > 5,\ p = 2,\ p = 1\ \mathrm{GeV/c}$$

$$\sigma(\mathrm{dE/dx})/\langle \mathrm{dE/dx}\rangle \approx 0.04$$

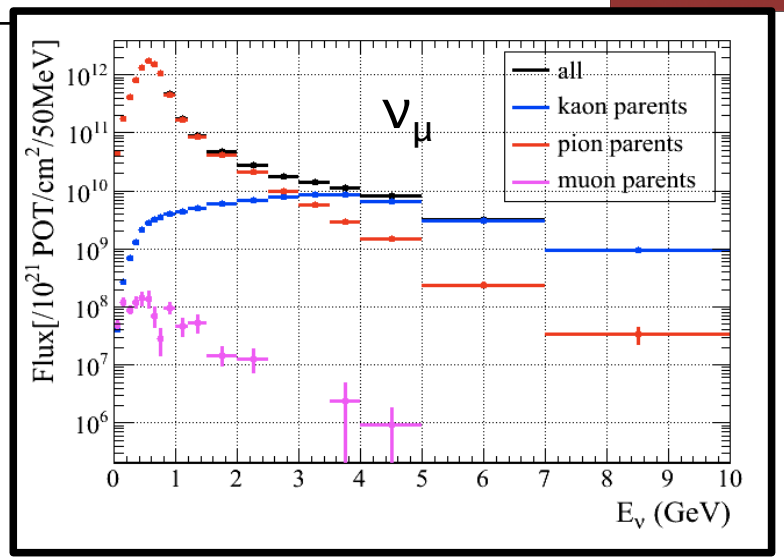
$$\sigma(\text{TOF-F}) \approx 115\ \mathrm{ps}$$

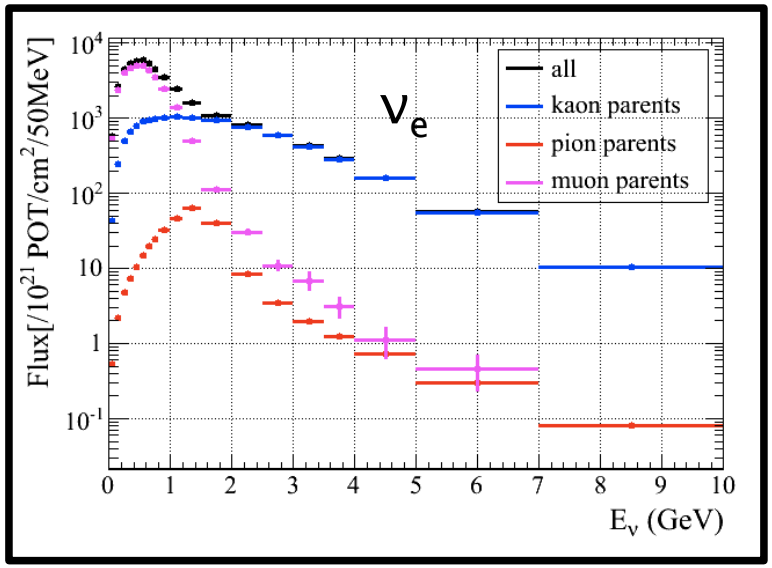


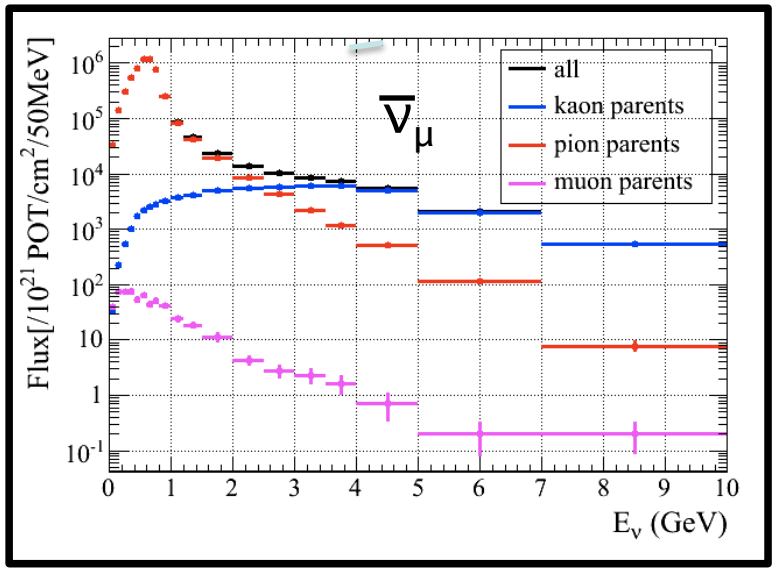


Predicted Flux

- ν_μ fluxes in analysis region dominated by pion decays
  - Kaons important in tail
- ν_e flux in analysis region dominated by muons
  - From decay chain
  - Primary pions modelled with NA61 data

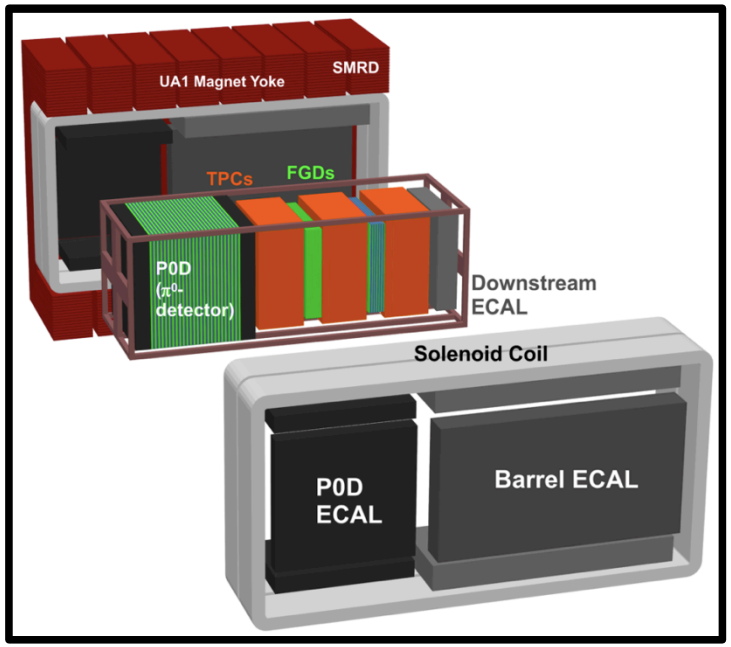


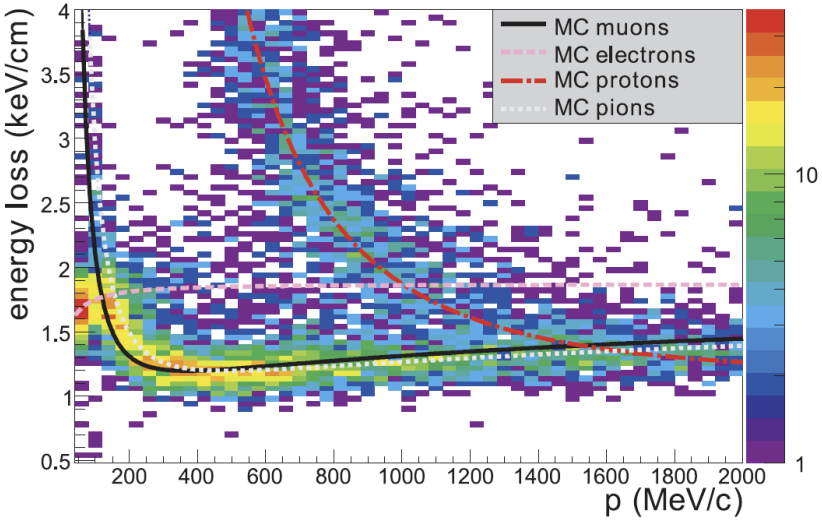


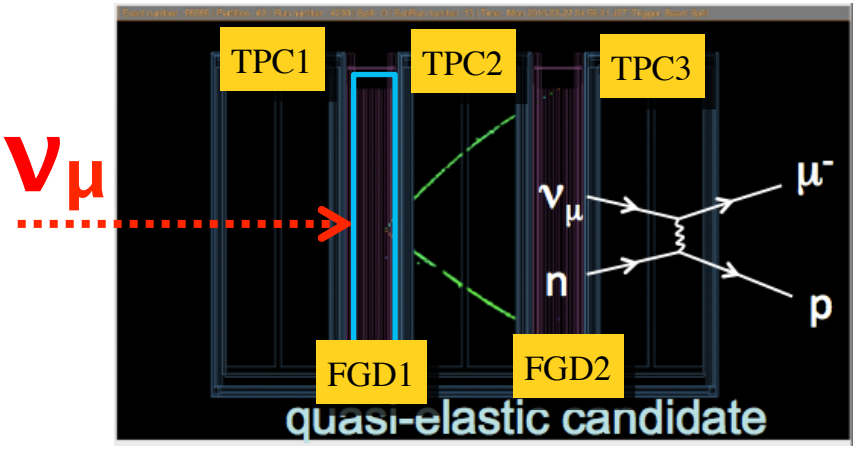


ND280 detector

- 0.2 T magnet (recycled from UA1)
- Plastic scintillator detectors:
  - Fine Grained Detector (FGD)
    - 1.6 ton fiducial mass for analysis
  - π^0 detector (P0D)
  - ECals and SMRD
- Time projection chambers (TPC)
  - <10% dE/dx resolution
  - 10% momentum res. at 1GeV/c
- Analysis use ν_μ-CC event rate in FGD1

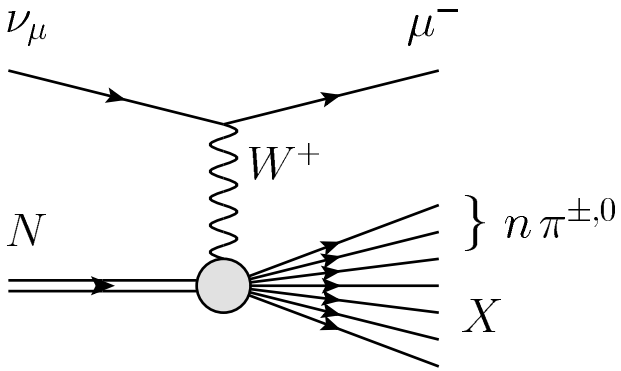




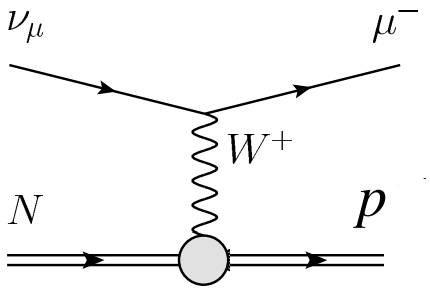


FV

CC Interaction

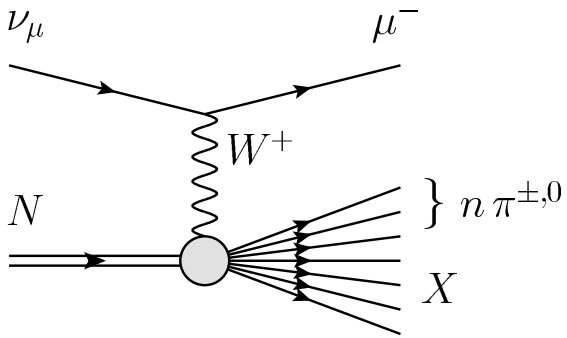


CC-Quasi Elastic (CCQE)



CC-nonQE (CCnQE)

= all CC that is not QE

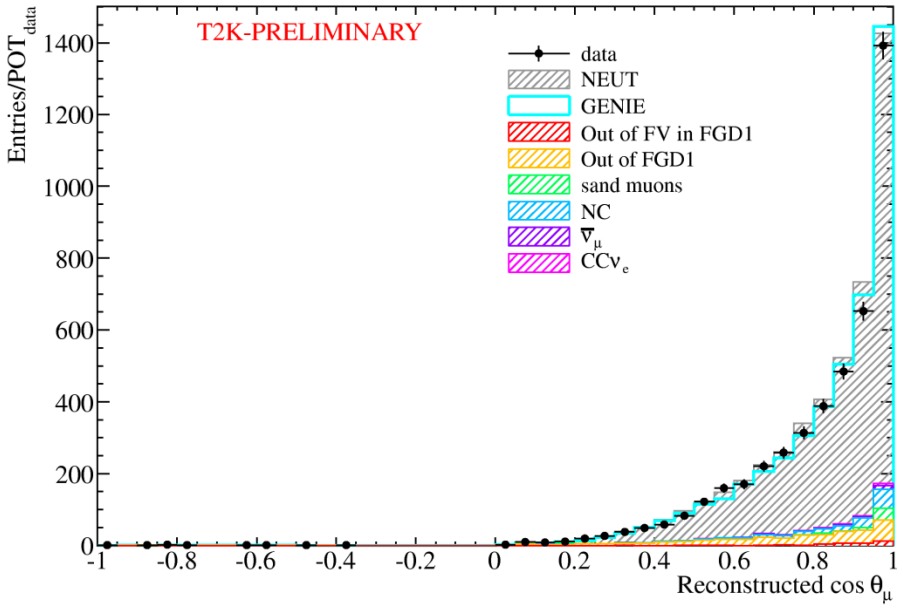


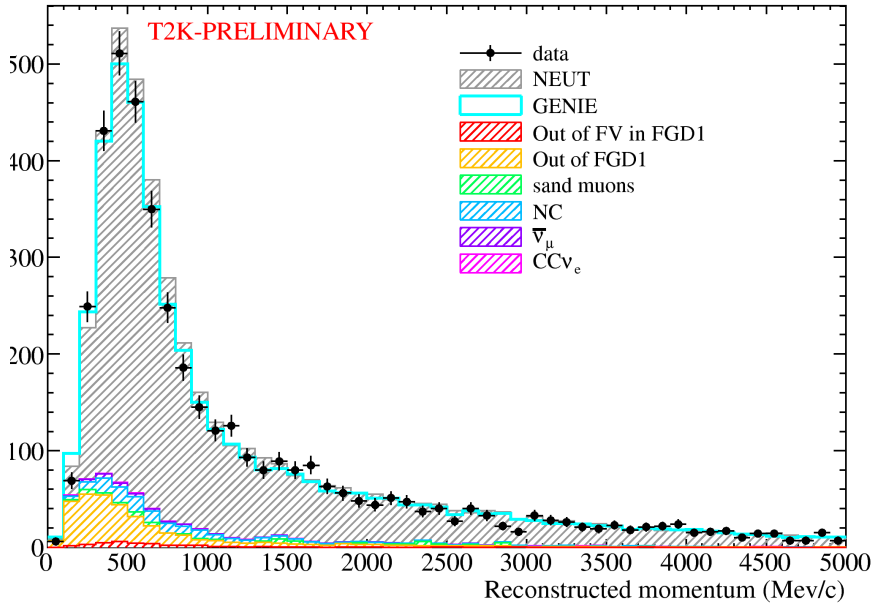
CC Event Selection

- Good data quality
- At least one negative track in TPC
- Track starts in fiducial volume of FGD
- dE/dx compatible with muon
- No significant activity upstream of FV

Efficiency = 50%

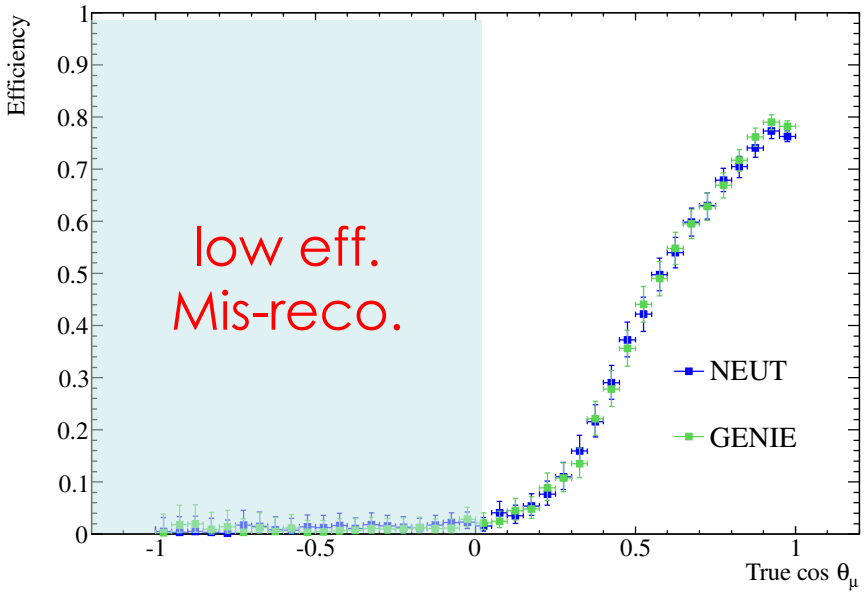
Purity = 88%

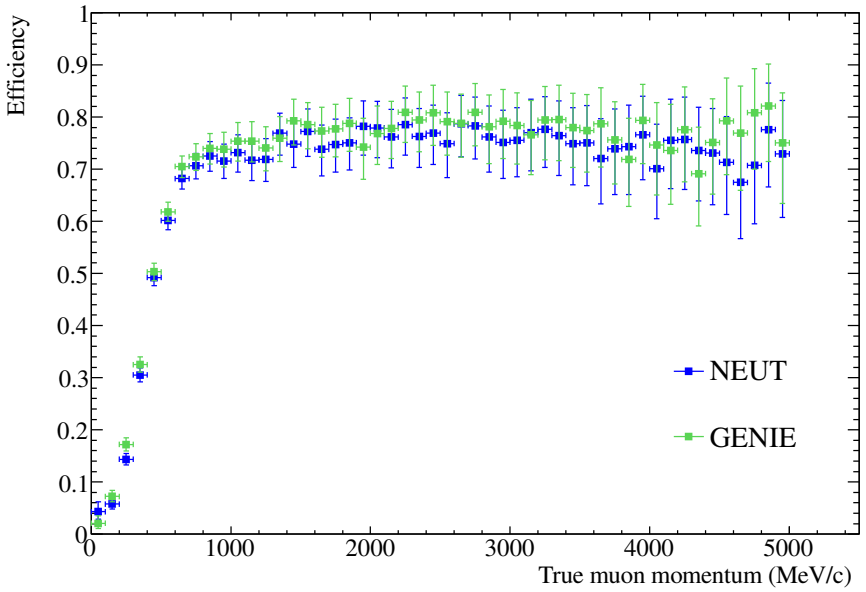




Selection Efficiency

- Simple selection
- Little reconstruction efficiency for backward or high angle tracks
- Largely independent of signal composition





Cross Section Formalism

- Flux averaged differential Cross Section

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

# of interactions in true bin

# of target nucleons

flux

- Complications
  - True energy and momentum are unknown
  - Background in sample
- Solution
  - Subtract background
  - "unfold" limited resolution in momentum and angle

Bayesian Unfolding

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

# of interactions in true bin

# of target nucleons

flux

G. D'Agostini
arXiv:1010.0632

2D binning: (k,l) $\Leftrightarrow$ $(p_k, \cos\theta_l)$

1D binning: k $\Leftrightarrow$ $(p, \cos\theta)_k$

Method

Unfolding

$$N_k^{\text{int}} \approx \hat{N}_k = \frac{U_{kj}}{\epsilon_k}(N_j^{sel} - B_j)$$

unfolding matrix

efficiency

# of sel. events

background in rec. bin

unfolding based on Bayes' theorem

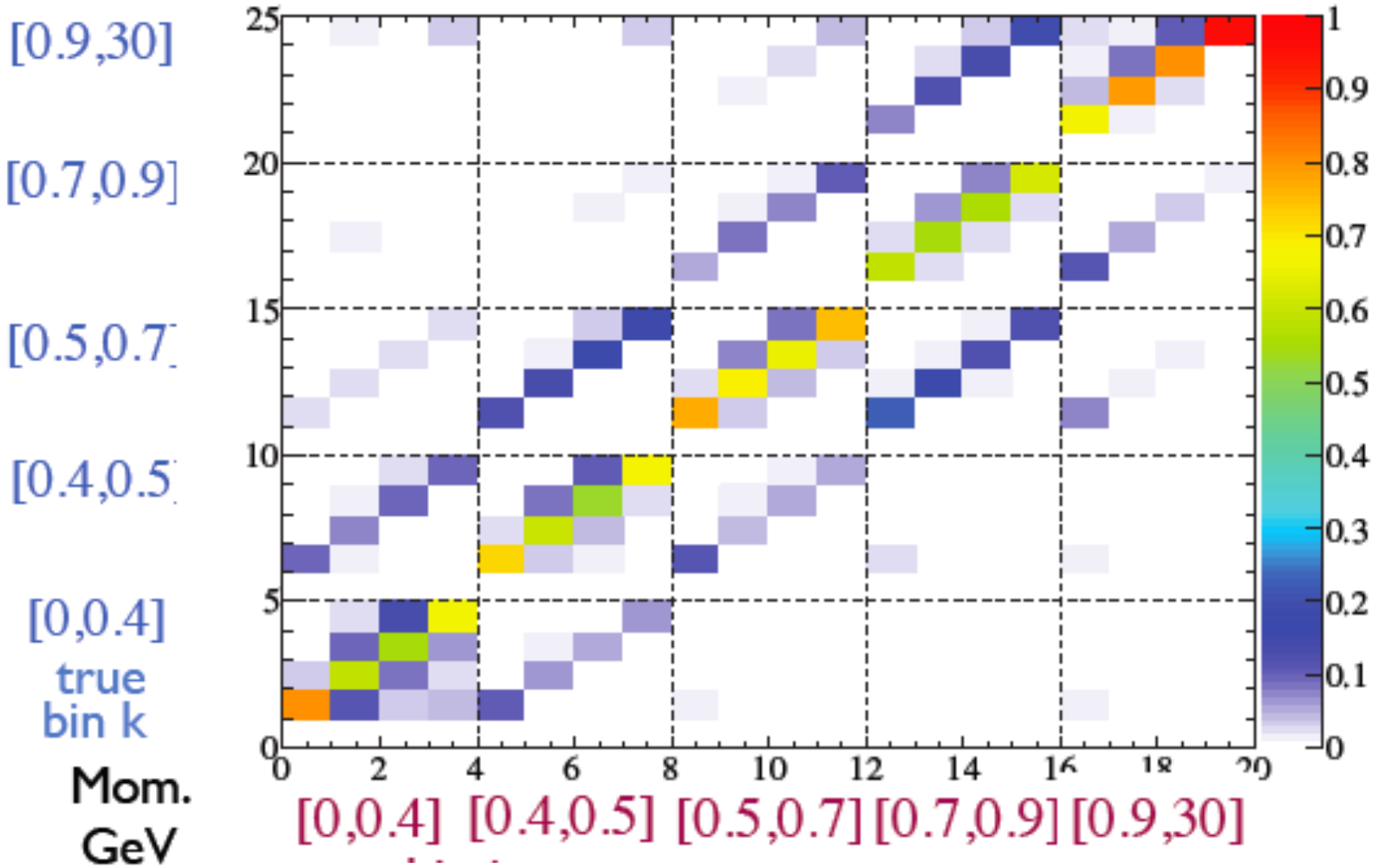
$$U_{kj} = P(k|j) = \frac{P(j|k)P(k)}{\sum_\alpha P(j|\alpha)}$$

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

reco. (j index)

true (k index)

Migration Matrix

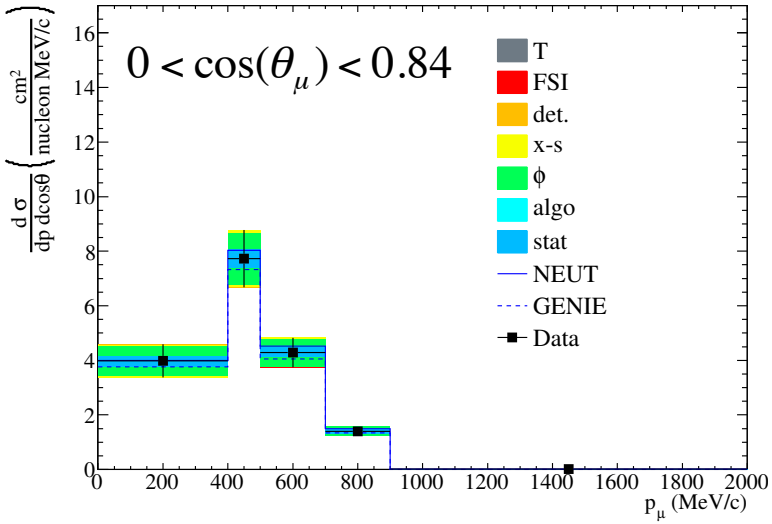


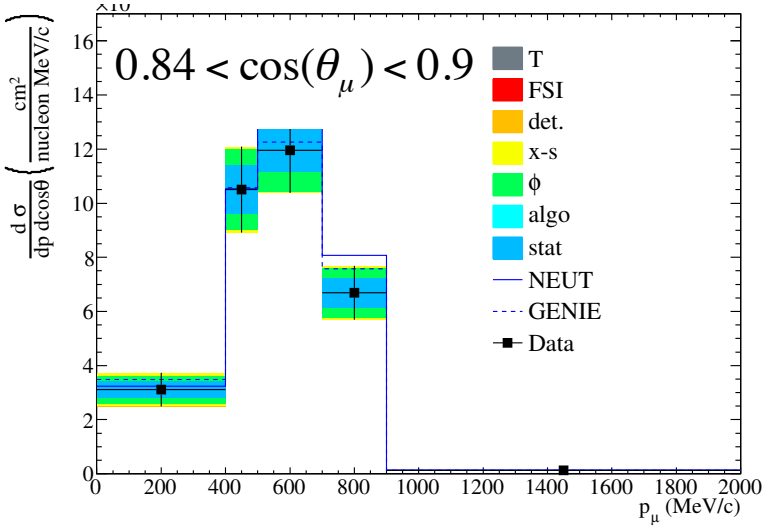
Systematic Uncertainties

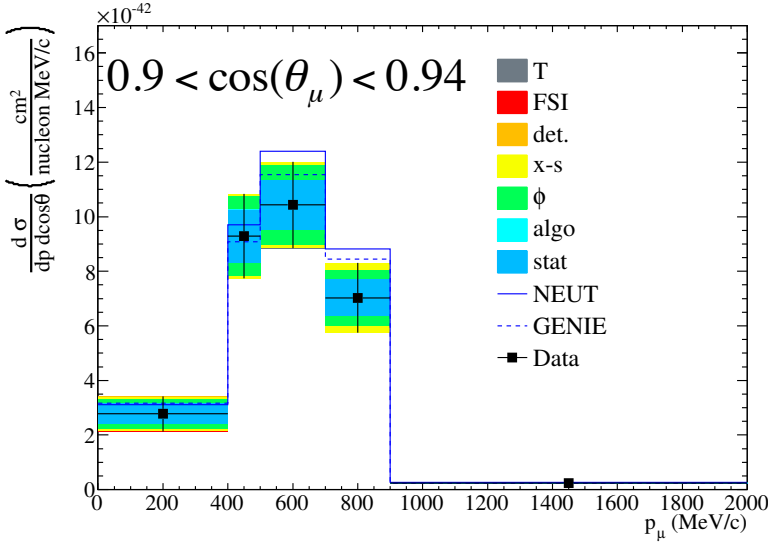
P_μ (GeV/c)	$\cos\theta_\mu$	algo. (%)	ϕ (%)	x-s (%)	det. (%)	FSI (%)	syst (%)	stat (%)	tot (%)
[0.0, 0.4]	[−1, 0]	0.53	11.40	17.99	2.13	0.46	21.43	2.04	21.53
	[0, 0.84]	0.62	12.79	5.52	3.65	1.21	14.49	4.95	15.31
	[0.84, 0.90]	0.26	13.13	10.76	2.73	1.41	17.28	9.52	19.72
	[0.90, 0.94]	1.21	14.05	10.73	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

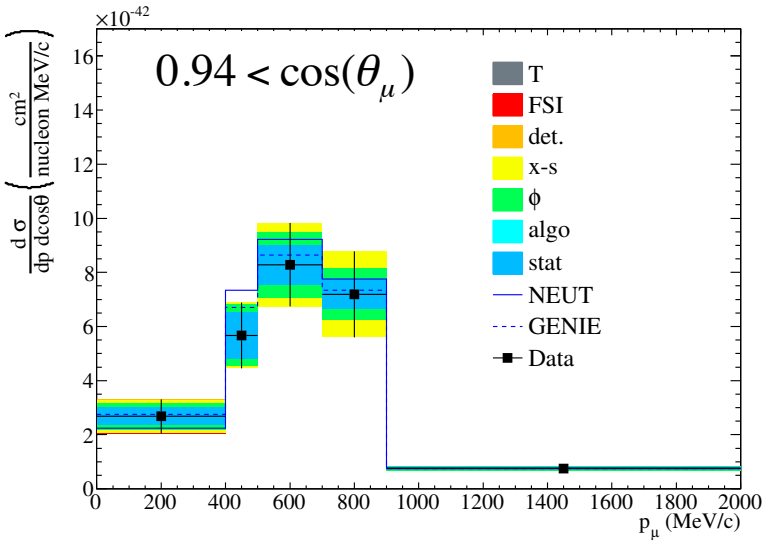
Differential Cross Section

*T: Target, **FSI**: Final State Interaction **det.**: detector, **x-s**: cross-section, **algo**: unfolding algorithm*

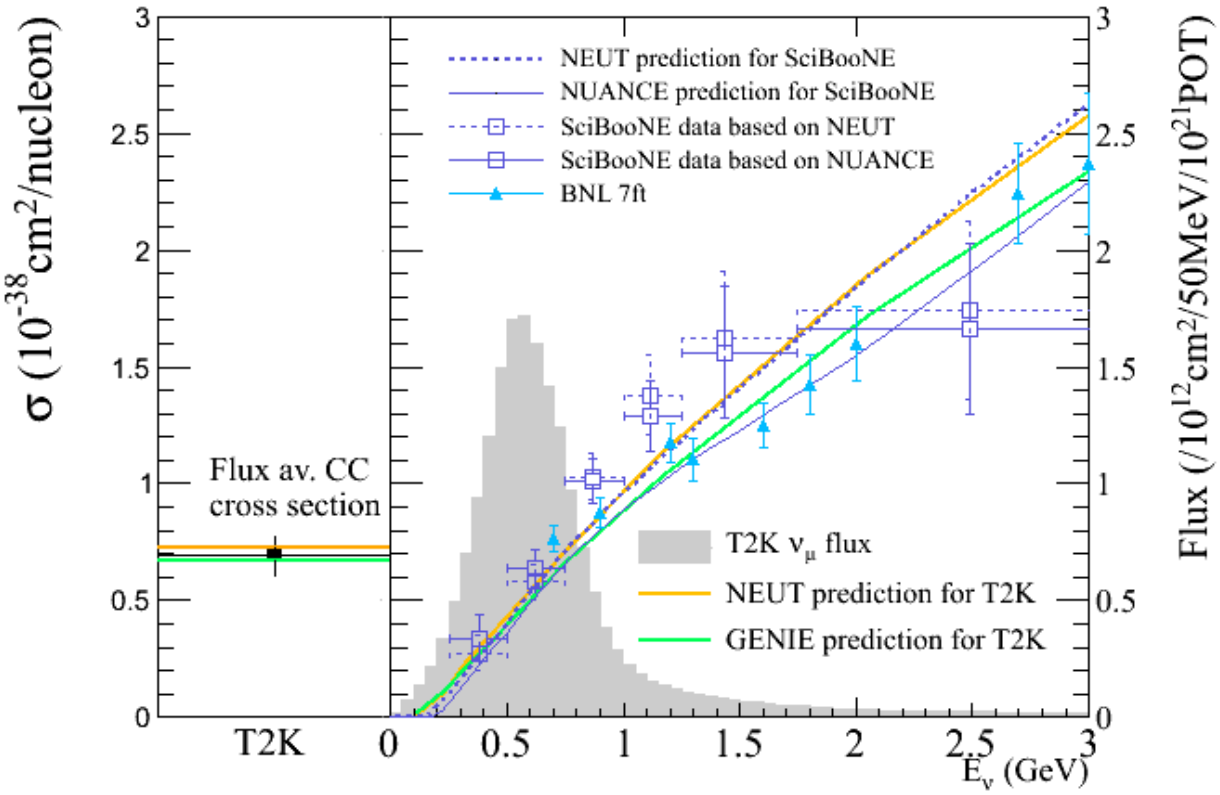








Total Cross Section



data

$$\langle\sigma_{\mathrm{CC}}\rangle_\phi = (6.93 \pm 0.13(stat) \pm 0.85(syst)) \times 10^{-39} \frac{\mathrm{cm}^2}{\mathrm{nucleons}}$$

predicted from generators

$$\langle\sigma_{\mathrm{CC}}^{\mathrm{NEUT}}\rangle_\phi = 7.26 \times 10^{-39} \frac{\mathrm{cm}^2}{\mathrm{nucleons}}$$

$$\langle\sigma_{\mathrm{CC}}^{\mathrm{GENIE}}\rangle_\phi = 6.68 \times 10^{-39} \frac{\mathrm{cm}^2}{\mathrm{nucleons}}$$

Summary & Conclusion

- T2K has presented its first cross section measurement
  - CC Inclusive

$$\langle \sigma_{\mathrm{CC}} \rangle_{\phi} = (6.93 \pm 0.13(stat) \pm 0.85(syst)) \times 10^{-39} \frac{\mathrm{cm}^2}{\mathrm{nucleons}}$$

  - Systematically limited

- Significant improvements are possible
  - Reduced flux systematics
  - Increased acceptance
  - Larger data set
  - Exclusive channels & model studies
  - Using water target

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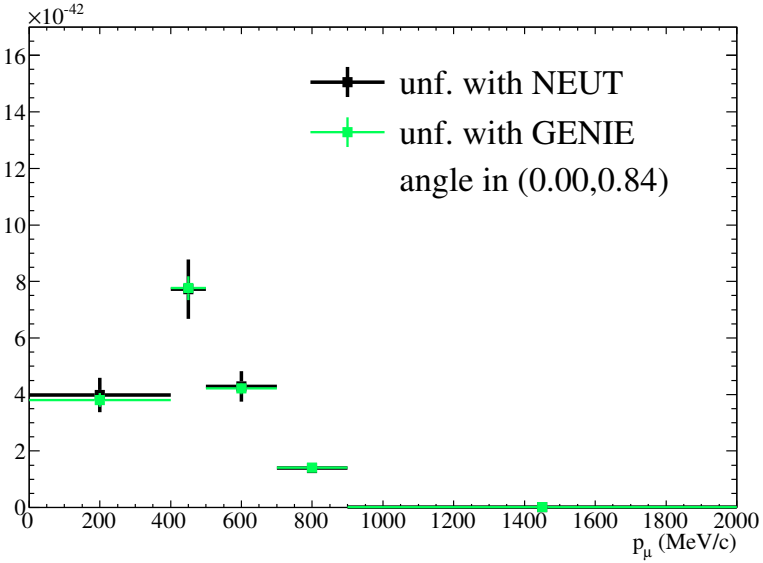
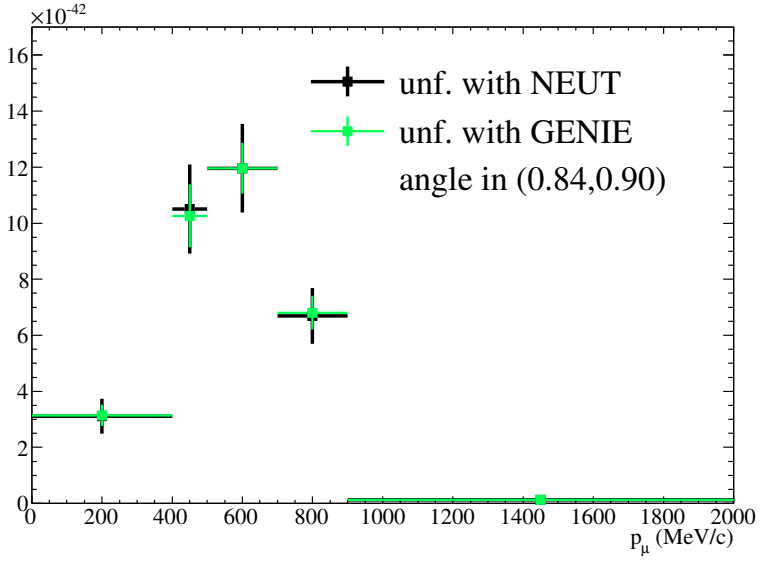
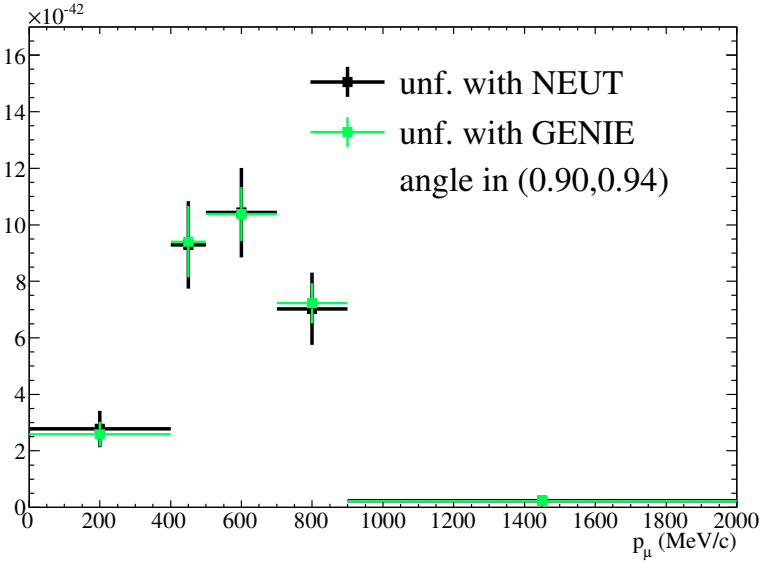
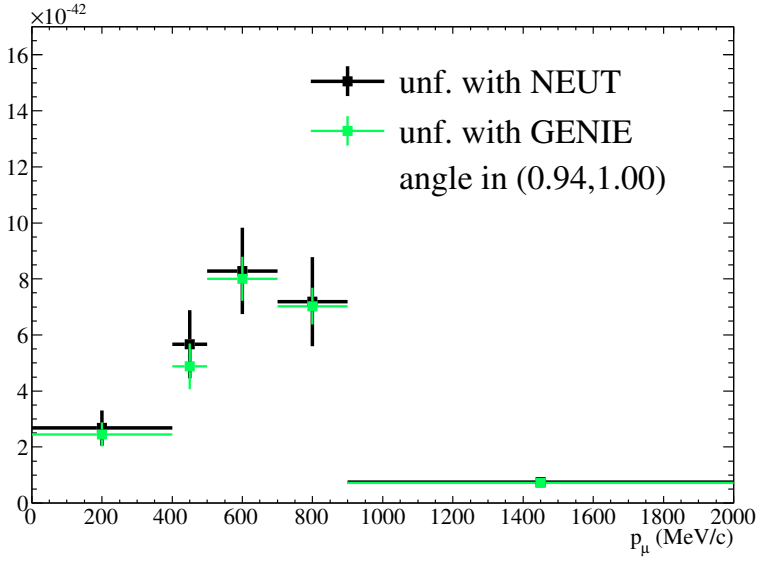
Backup

Generator Dependence









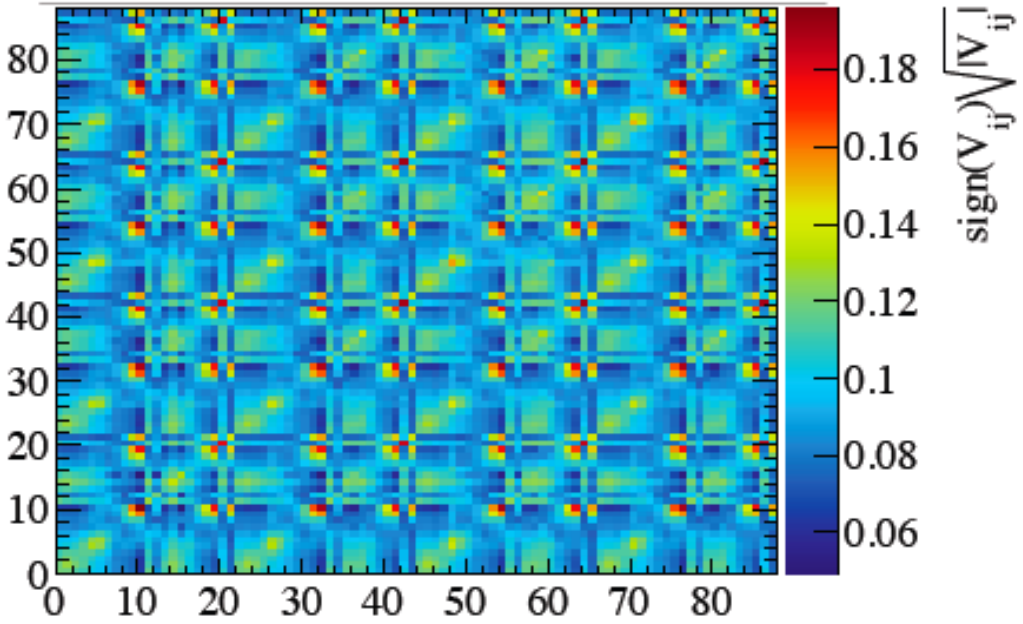
Flux Systematics

sources	Max. Error (%)	Min. Error (%)	Norm. Error (%)
Kaon	16.7	0.4	0.8
Pion	6.1	0.6	5.0
Proton beam	5.1	0.2	1.1
Off-axis angle	5.4	0.1	1.6
Horn ang. align.	1.0	0.2	0.5
Horn field assym.	6.7	0.01	0.3
Cross-sec. production	7.8	4.5	6.4
Horn abs. current	1.9	0.4	0.9
Target align.	2.6	0.05	0.2
Sec. nucl. production	8.5	2.9	6.9
Total	19.6	8.9	10.9

bin 0-10 : ND280 ν_μ
bin 11-12: ND280 anti-ν_μ
bin 13-19: ND280 ν_e
bin 20-21: ND280 anti-ν_e

bin 22-32: SK ν_μ
bin 33-34: SK anti-ν_μ
bin 35-41: SK ν_e
bin 42-43: SK anti-ν_e

Flux error matrix



Cross Section Systematics

P_μ (GeV/c)	$\cos\theta_\mu$	M_A^{QE} (%)	M_A^{RES} (%)	$n\pi^{shp}$ (%)	SF (%)	P_f (%)	ΔW (%)	pdd (%)	$1\pi^{shp}$ (%)	total (%)
[0.0, 0.4]	[−1, 0]	13.44	1.04	3.22	8.68	2.99	3.03	0.29	3.92	17.35
	[0, 0.84]	1.53	0.77	2.06	0.63	0.71	0.85	0.62	2.38	3.85
	[0.84, 0.90]	6.69	1.10	0.93	2.43	0.34	0.97	3.44	4.51	9.27
	[0.90, 0.94]	5.00	1.35	2.83	1.03	1.48	0.63	0.88	4.04	7.45
	[0.94, 1]	2.56	1.20	2.41	3.70	2.14	0.29	1.42	4.56	7.41
[0.4, 0.5]	[−1, 0]	33.69	0.60	4.06	18.75	6.17	0.52	0.68	1.37	39.30
	[0, 0.84]	3.33	0.47	1.57	3.29	0.84	0.13	0.60	0.37	5.09
	[0.84, 0.90]	3.48	0.63	0.65	0.81	0.57	0.61	0.45	0.75	3.88
	[0.90, 0.94]	1.78	0.45	2.51	2.38	3.94	0.96	0.83	0.24	5.70
	[0.94, 1]	1.91	1.16	3.80	1.55	1.83	0.51	0.27	0.28	5.06
[0.5, 0.7]	[−1, 0]	38.70	2.18	2.48	10.33	5.91	0.84	1.84	0.88	40.69
	[0, 0.84]	2.74	0.39	0.97	1.59	0.56	0.77	0.09	0.04	3.47
	[0.84, 0.90]	1.18	0.54	1.33	0.49	0.23	0.64	0.19	0.47	2.10
	[0.90, 0.94]	1.07	0.53	1.00	5.71	0.19	0.16	0.12	0.41	5.94
	[0.94, 1]	1.27	0.62	2.84	9.20	1.68	0.79	0.97	0.53	9.97
[0.7, 0.9]	[−1, 0]	159.27	2.04	0.19	15.91	4.68	3.42	3.99	0.70	160.23
	[0, 0.84]	1.69	0.06	0.15	0.35	0.37	0.68	0.58	0.47	2.04
	[0.84, 0.90]	1.34	0.90	1.12	4.28	0.77	0.81	0.30	0.26	4.86
	[0.90, 0.94]	1.59	0.81	0.97	10.44	0.63	1.36	0.08	0.41	10.74
	[0.94, 1]	1.40	0.90	2.06	16.61	1.86	1.10	0.32	0.84	16.99
[0.9, 30.0]	[−1, 0]	-	-	-	-	-	-	-	-	-
	[0, 0.84]	2.58	0.91	0.68	1.56	0.09	0.31	0.28	0.35	3.27
	[0.84, 0.90]	1.45	0.27	0.17	0.82	0.24	0.08	0.06	0.45	1.77
	[0.90, 0.94]	0.91	0.05	0.20	0.60	0.39	0.36	0.11	0.02	1.24
	[0.94, 1]	1.13	0.13	0.34	1.36	0.33	0.12	0.11	0.33	1.88

Detector Systematics

P_μ (GeV/c)	$\cos\theta_\mu$	Pscale (%)	Qconf (%)	sandmu (%)	Pdist (%)	OOFV (%)	PiAbs (%)	fgdTpcEff (%)	fgdM (%)	total (%)
[0.0, 0.4]	[−1, 0]	0.31	0.59	0.27	0.37	1.88	0.63	0.81	2.29	
	[0, 0.84]	1.56	0.31	0.12	0.90	3.39	0.57	0.64	3.95	
	[0.84, 0.90]	1.17	0.23	0.12	0.75	2.30	0.38	0.45	2.76	
	[0.90, 0.94]	1.33	0.29	0.68	0.87	4.29	0.46	0.54	4.68	
	[0.94, 1]	1.42	0.32	0.42	0.97	4.14	0.43	0.49	4.56	
[0.4, 0.5]	[−1, 0]	0.70	0.57	0.35	0.59	2.27	0.63	0.80	2.74	
	[0, 0.84]	0.18	0.22	0.03	0.67	1.04	0.39	0.48	1.41	
	[0.84, 0.90]	0.45	0.12	0.04	0.46	0.56	0.20	0.23	0.91	
	[0.90, 0.94]	0.56	0.11	0.14	0.61	0.90	0.21	0.24	1.28	
	[0.94, 1]	0.89	0.22	0.13	0.94	1.99	0.37	0.42	2.45	
[0.5, 0.7]	[−1, 0]	0.11	0.56	0.43	0.59	1.28	0.57	0.77	1.85	
	[0, 0.84]	0.33	0.19	0.03	0.49	0.67	0.33	0.40	1.05	
	[0.84, 0.90]	0.06	0.10	0.03	0.28	0.55	0.20	0.22	0.70	
	[0.90, 0.94]	0.08	0.10	0.15	0.40	0.53	0.19	0.23	0.76	
	[0.94, 1]	0.22	0.12	0.19	0.43	0.71	0.23	0.27	0.96	
[0.7, 0.9]	[−1, 0]	0.28	0.53	0.20	1.02	0.91	0.34	0.56	1.64	
	[0, 0.84]	0.55	0.18	0.08	0.63	0.65	0.28	0.37	1.18	
	[0.84, 0.90]	0.17	0.12	0.02	0.71	0.36	0.24	0.26	0.89	
	[0.90, 0.94]	0.09	0.12	0.05	0.77	0.30	0.22	0.22	0.90	
	[0.94, 1]	0.10	0.10	0.03	0.51	0.36	0.18	0.19	0.70	
[0.9, 30.0]	[−1, 0]	-	-	-	-	-	-	-	-	
	[0, 0.84]	0.58	0.26	0.07	0.58	0.82	0.24	0.37	1.27	
	[0.84, 0.90]	0.30	0.19	0.10	0.43	0.41	0.19	0.28	0.78	
	[0.90, 0.94]	0.16	0.22	0.05	0.41	0.31	0.17	0.24	0.66	
	[0.94, 1]	0.07	0.39	0.12	0.25	0.27	0.19	0.26	0.64	