Muon neutrino and antineutrino CC-0π cross-section measurements at T2K

Ciro Riccio on behalf of the T2K Collaboration

NuInt 18

Oct. 15th - 19th, 2018

Università degli Studi di Napoli Federico II

INFN Napoli

Overview

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- T2K experimental setup

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- Relevant (anti)neutrino interactions at T2K

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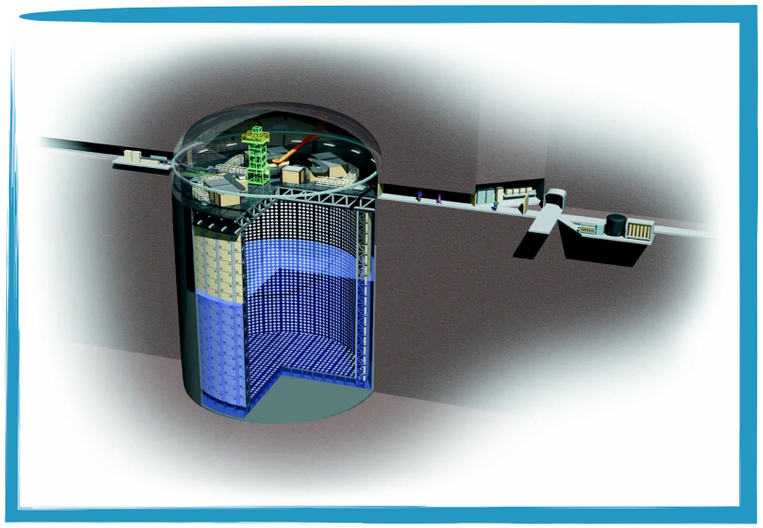
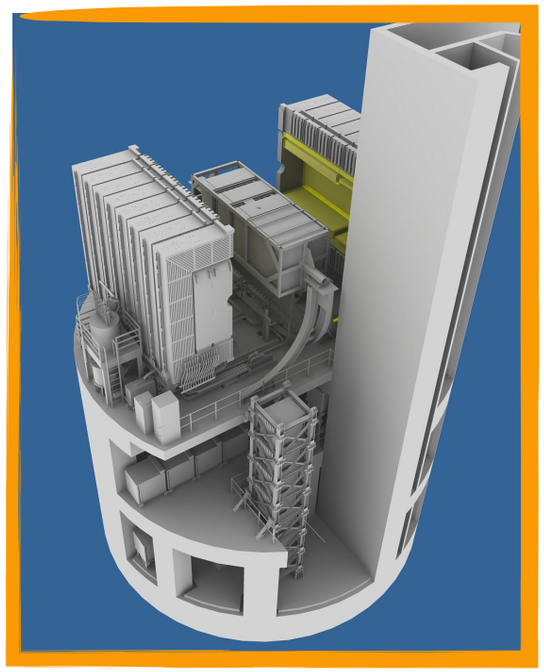
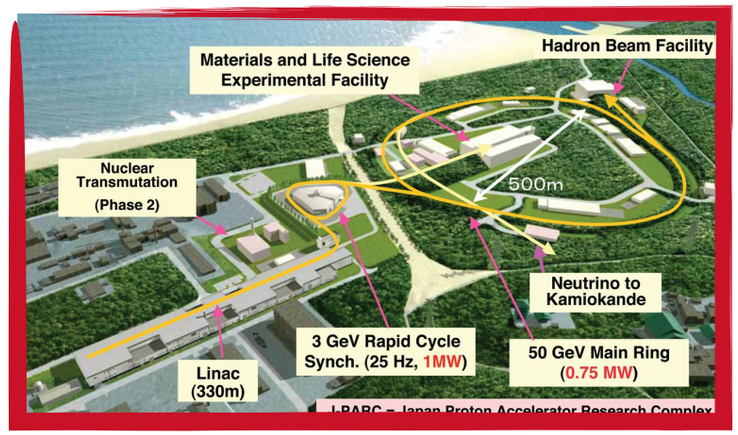
- Comparisons with generators and models
- Conclusions

The T2K experiment



Super-Kamiokande





Near Detectors

J-PARC

Mt. Noguchi-Goro
2,924 m

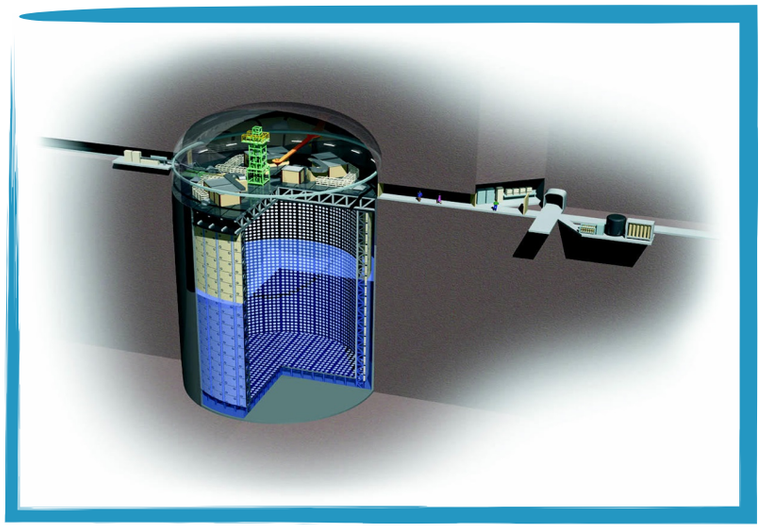
Mt. Ikeno-Yama
1,360 m

1,700 m below sea level

Neutrino Beam

295 km

The T2K experiment



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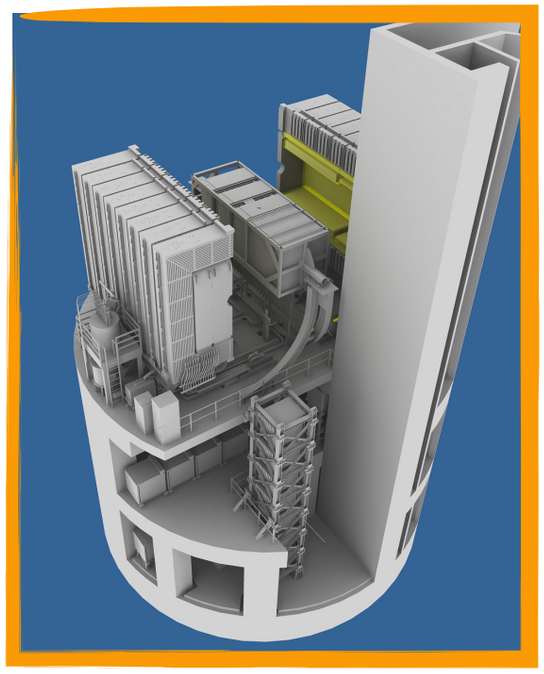

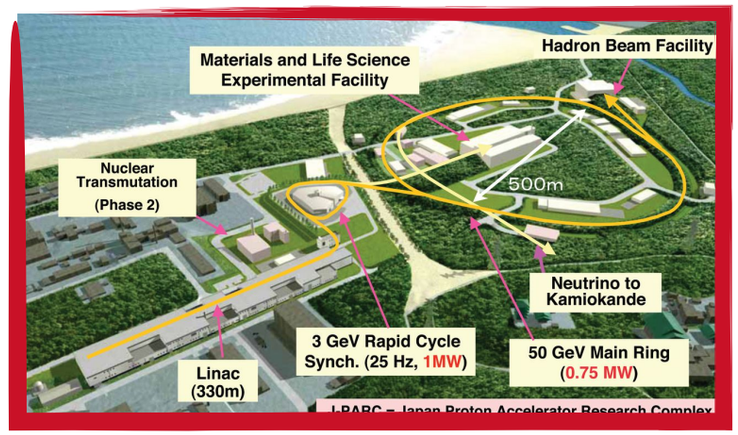

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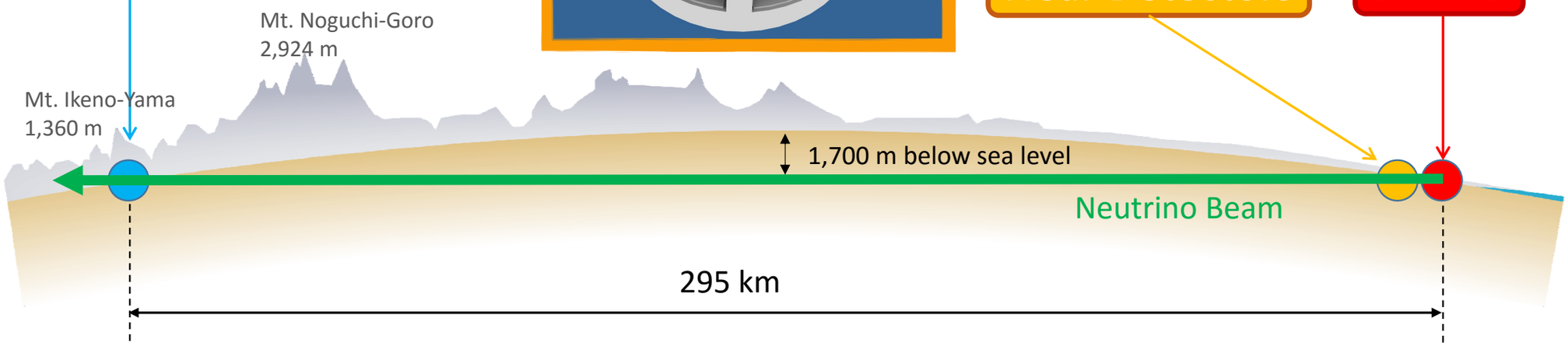
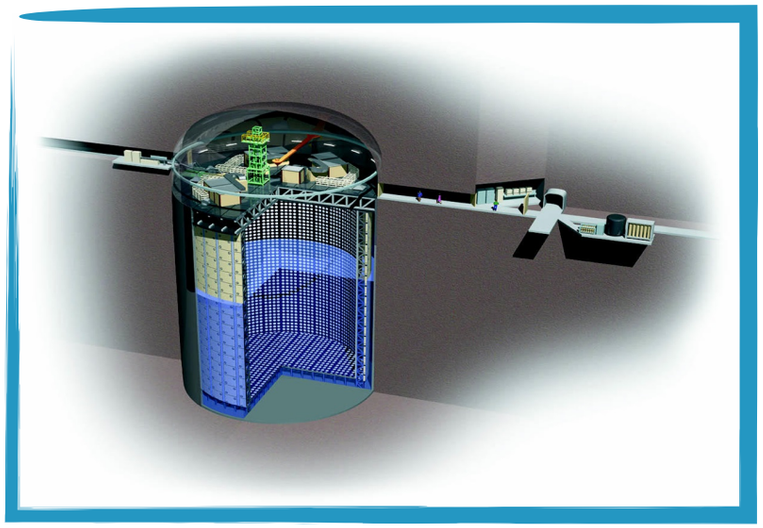


Physics goals:

The T2K experiment



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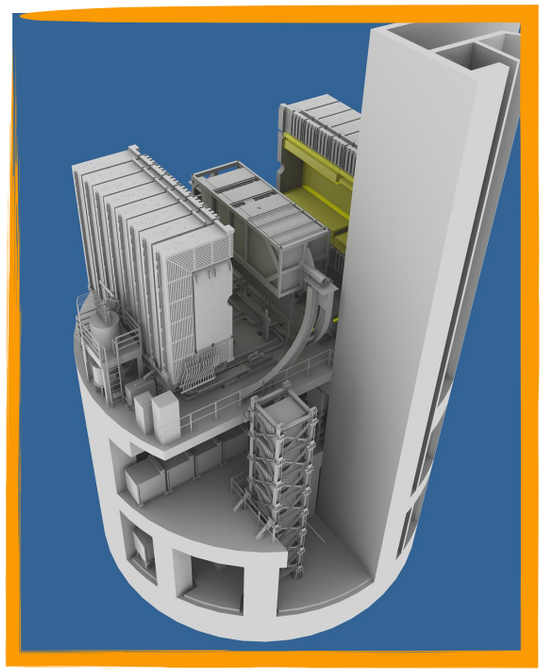

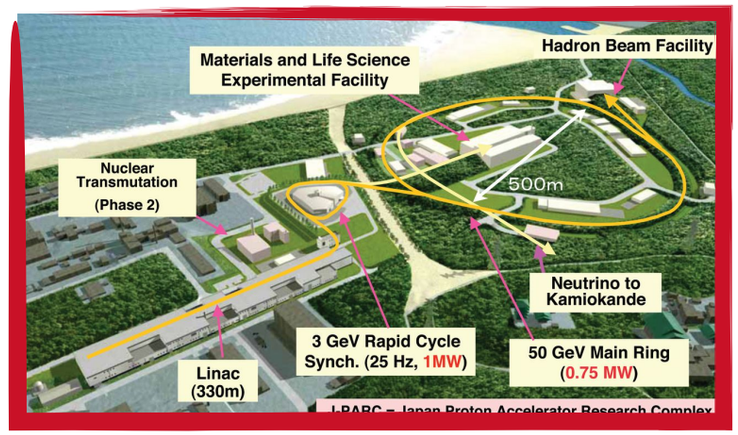

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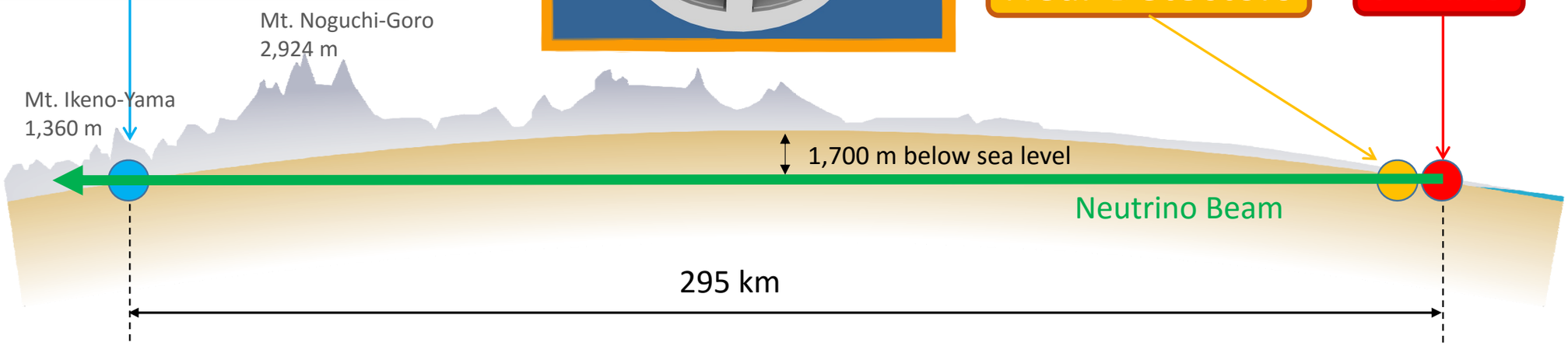

Physics goals:

- More precise measurement of θ_{23}, $|\Delta m_{32}^2|$

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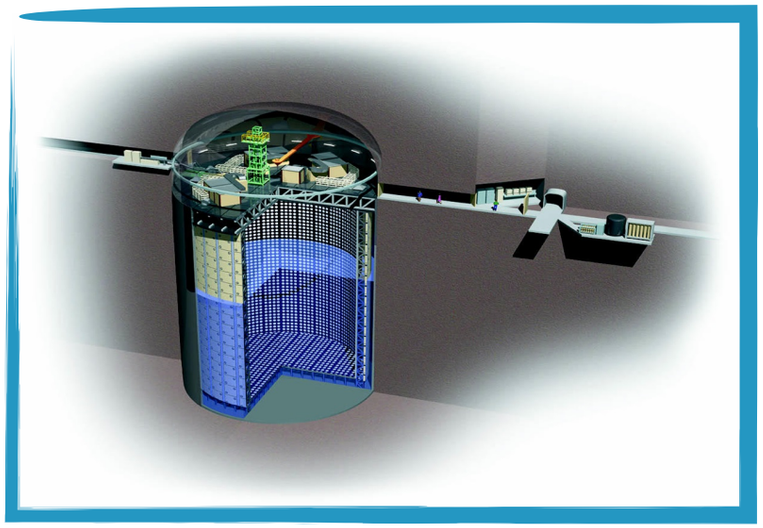

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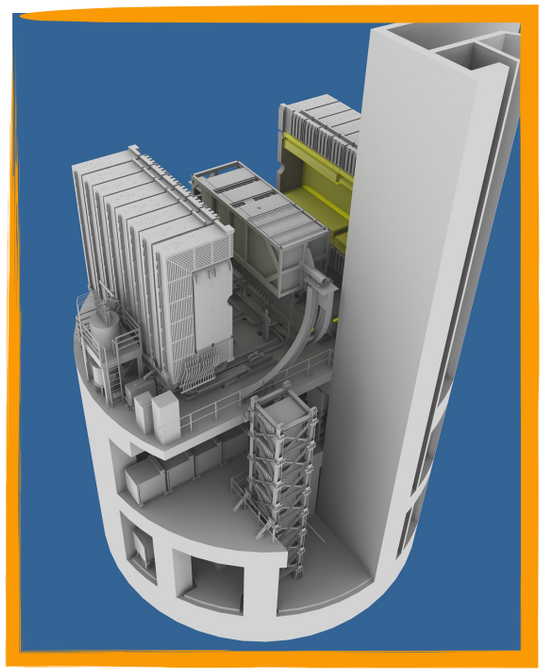

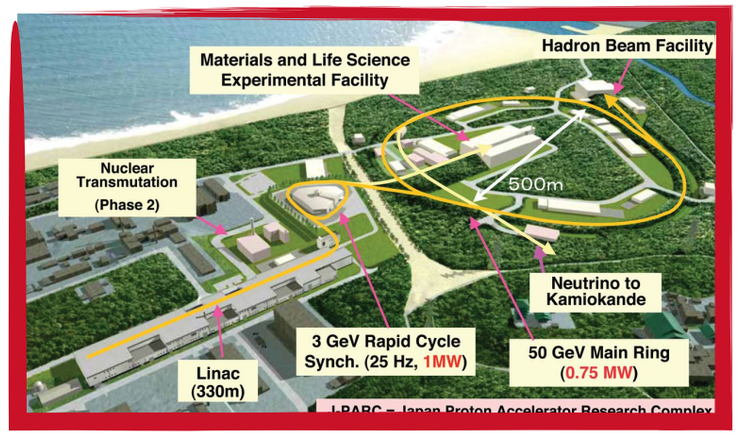

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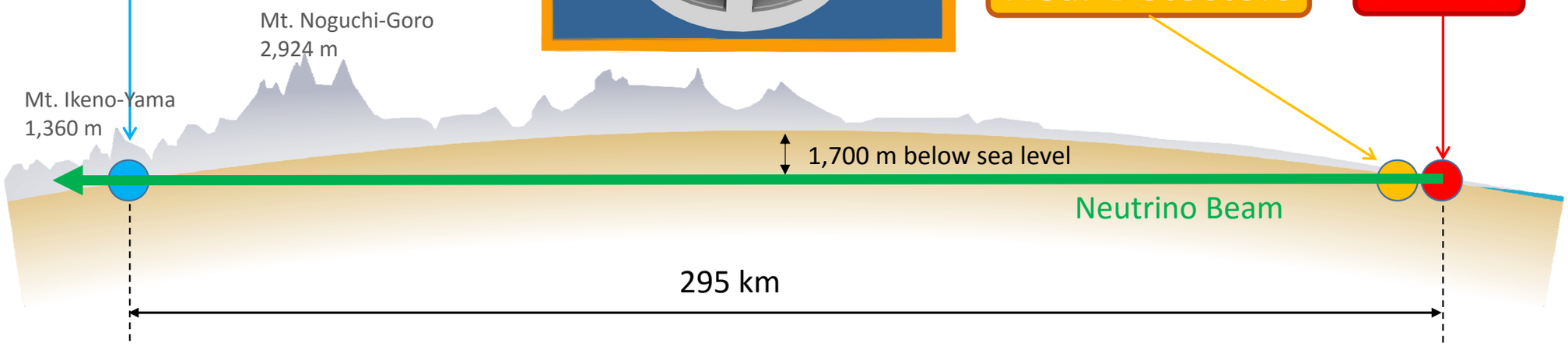

Physics goals:

- More precise measurement of θ_{23}, $|\Delta m_{32}^2|$
- Determine θ_{13} and δ_{CP}

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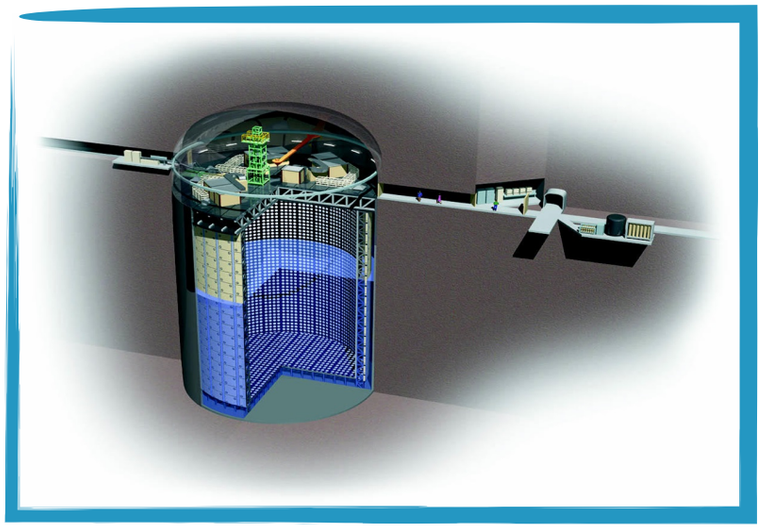

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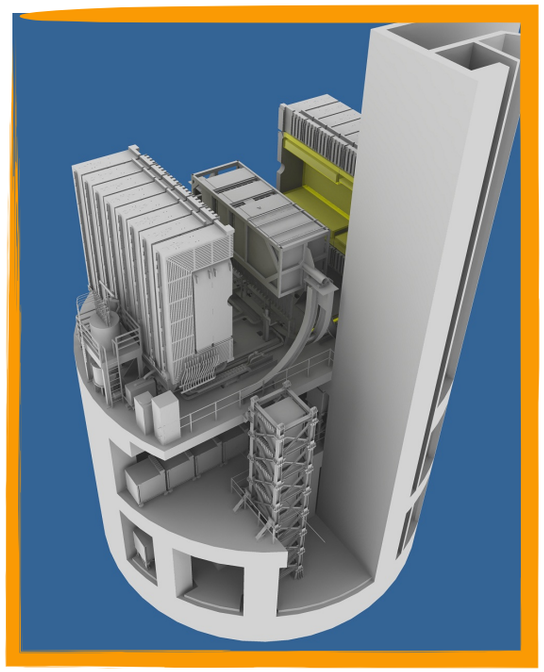

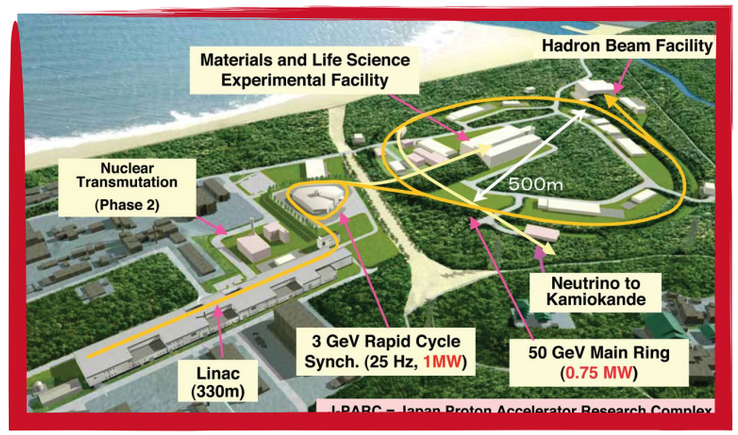

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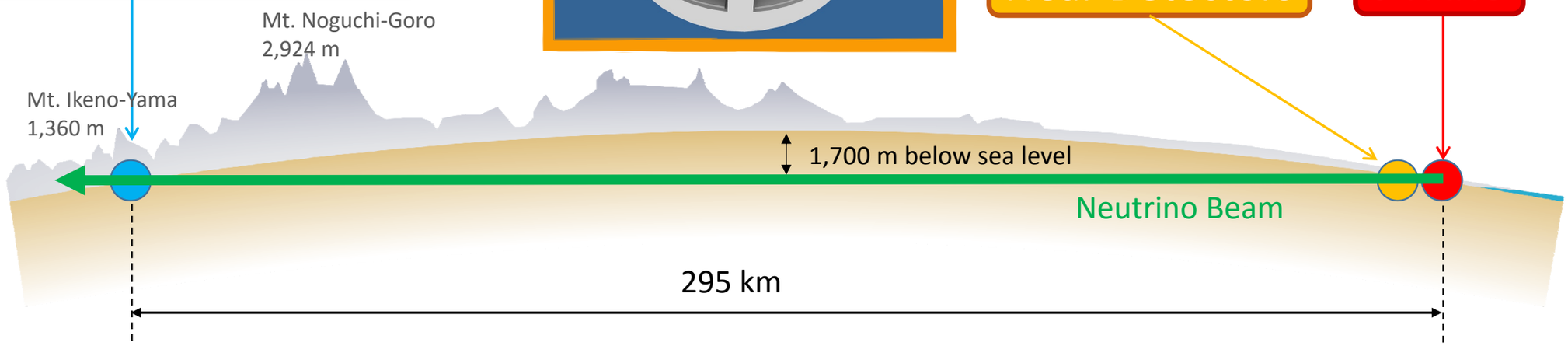

Physics goals:

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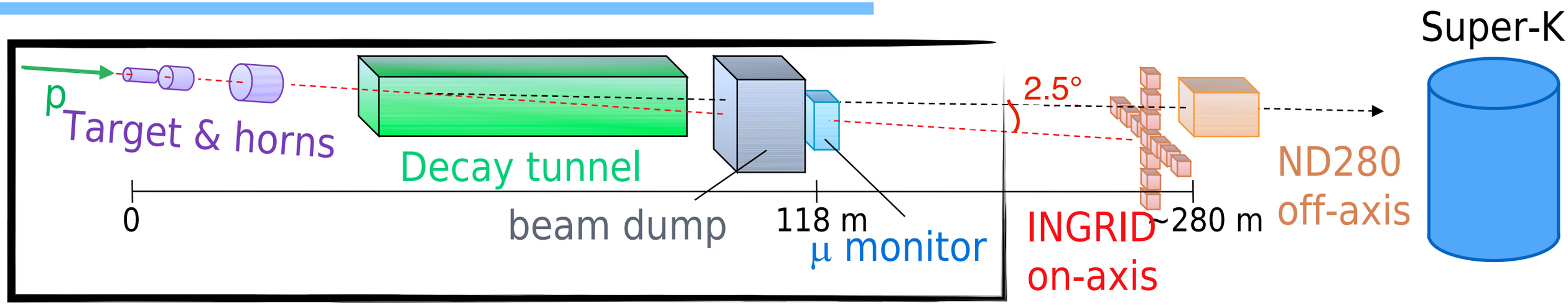
- **ν cross section measurements**

T2K Beam

See Tomislav Vladisavljevic's talk



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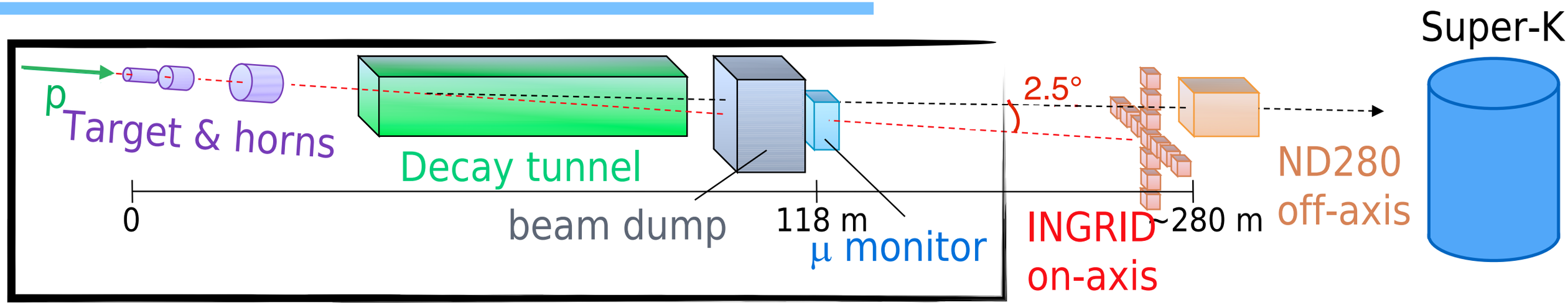

30 GeV proton beam from J-PARC Main Ring extracted onto a graphite target producing hadrons (mainly pions and kaons)

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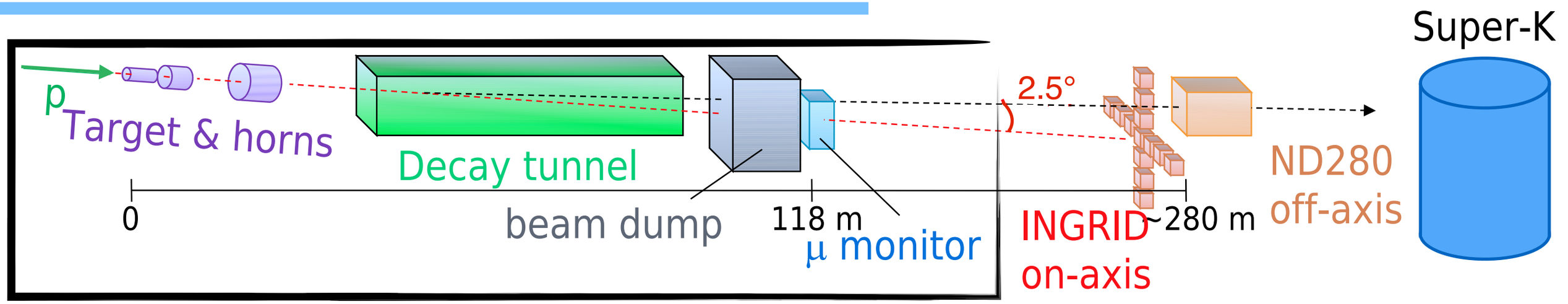
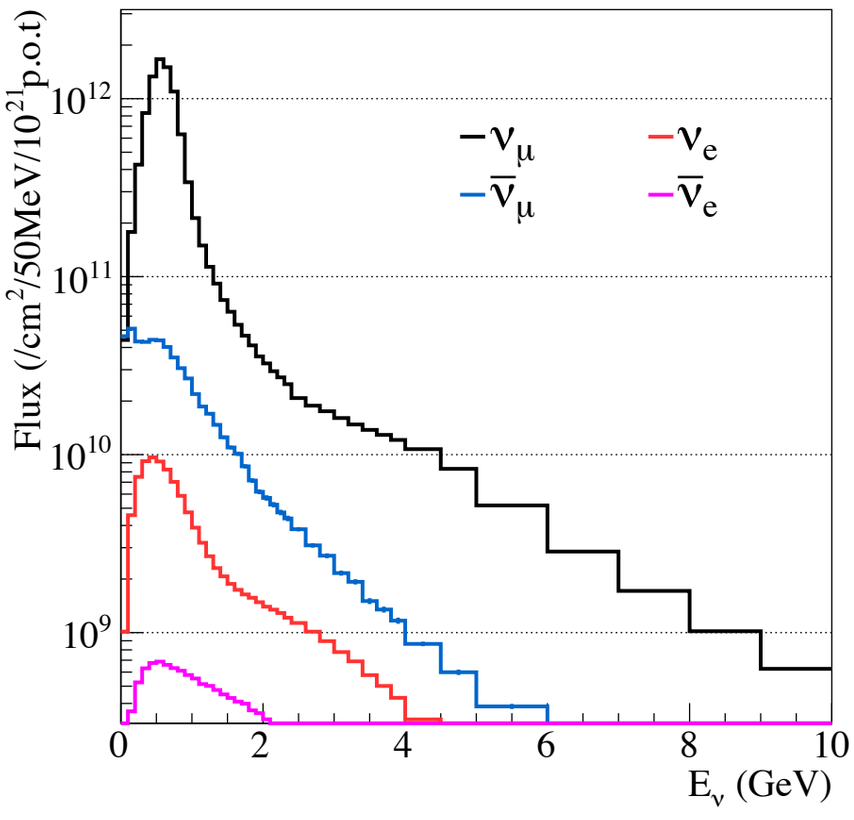


30 GeV proton beam from J-PARC Main Ring extracted onto a graphite target producing hadrons (mainly pions and kaons)

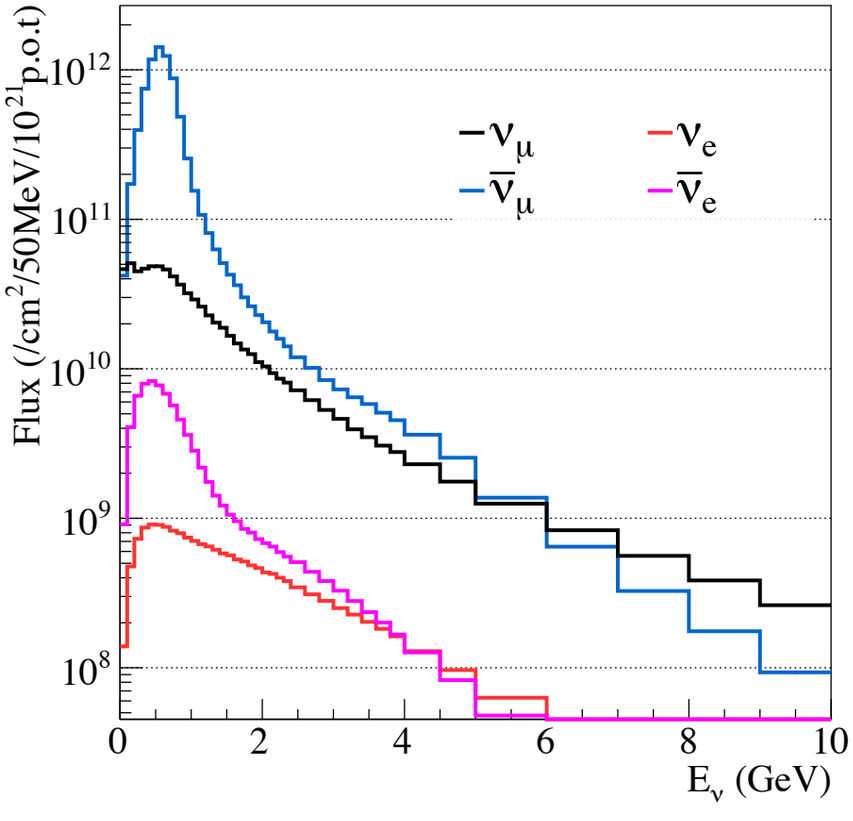
Hadrons are focused and selected in charge by 3 electromagnetic horns:

- $\nu\mu$ beam created by π^+
- $\bar{\nu}\mu$ beam by π^- decay

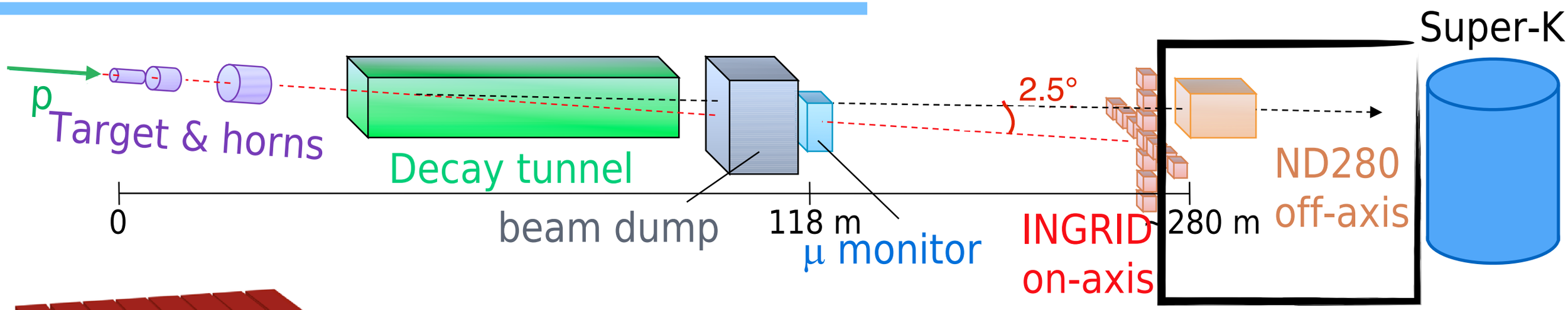
Neutrino Mode Flux at ND280

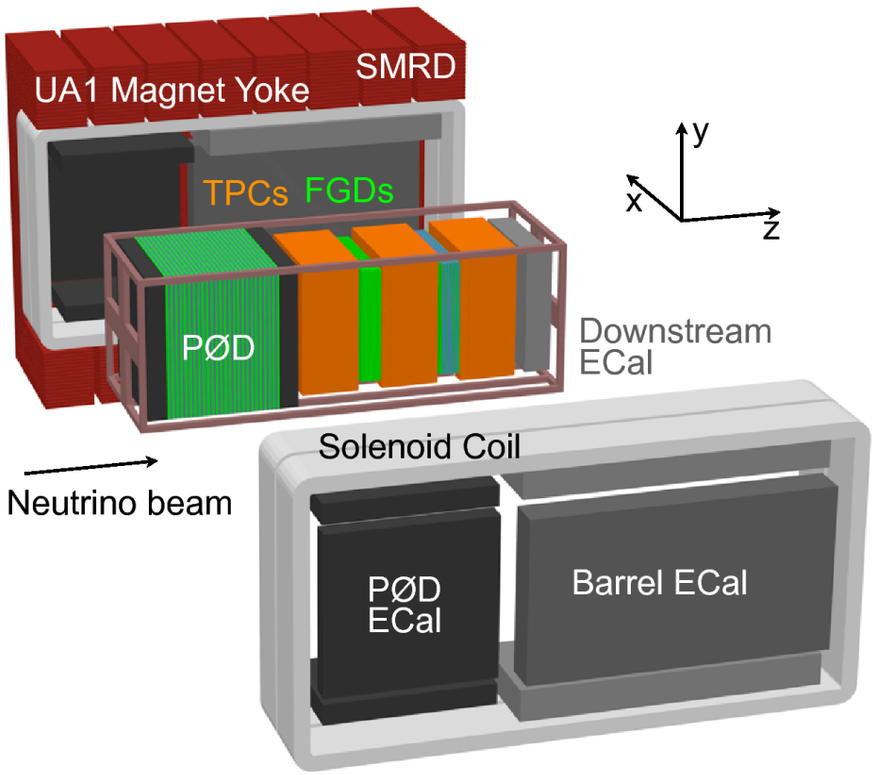


Antineutrino Mode Flux at ND280



The off-axis near detector (ND280)





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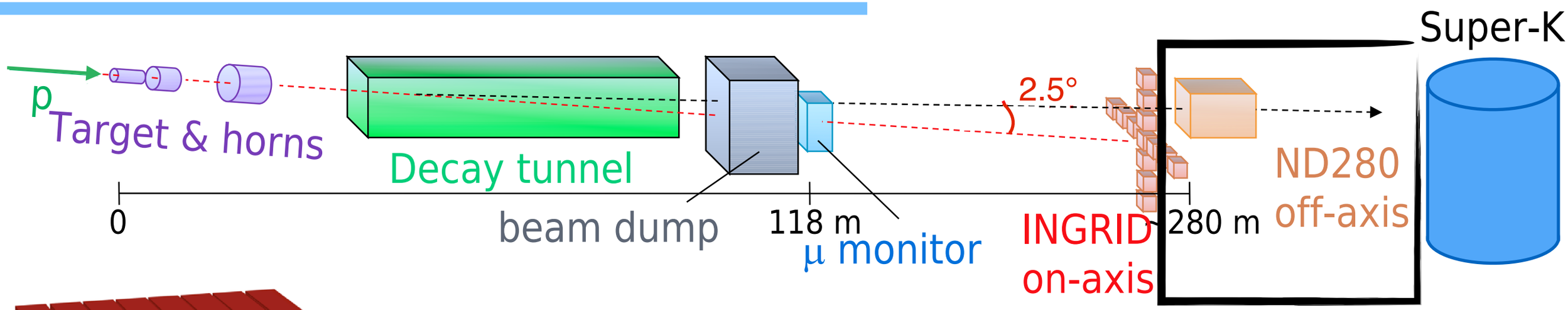

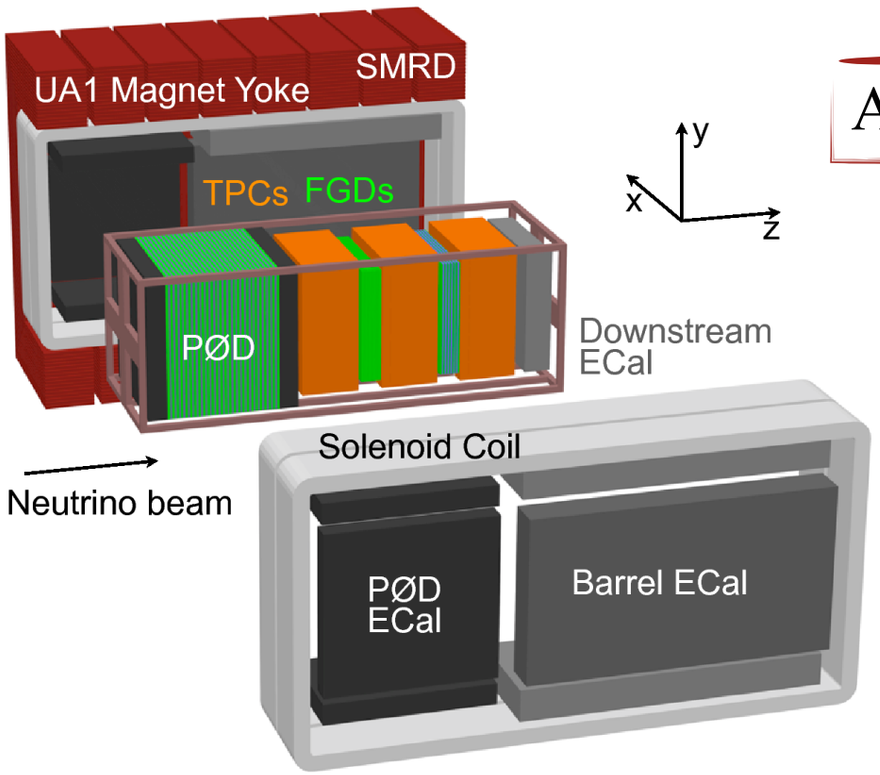

A large dipole magnet (UA1) produces 0.2 T.

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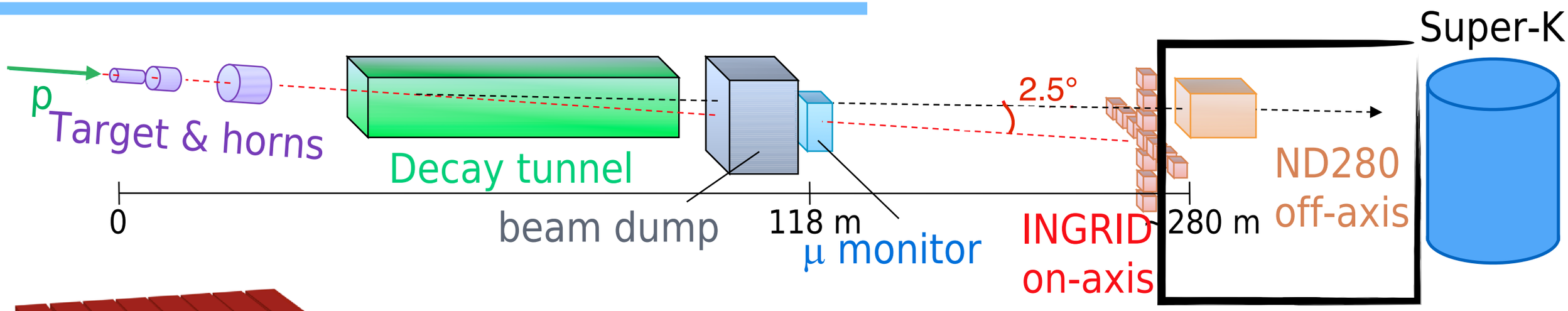

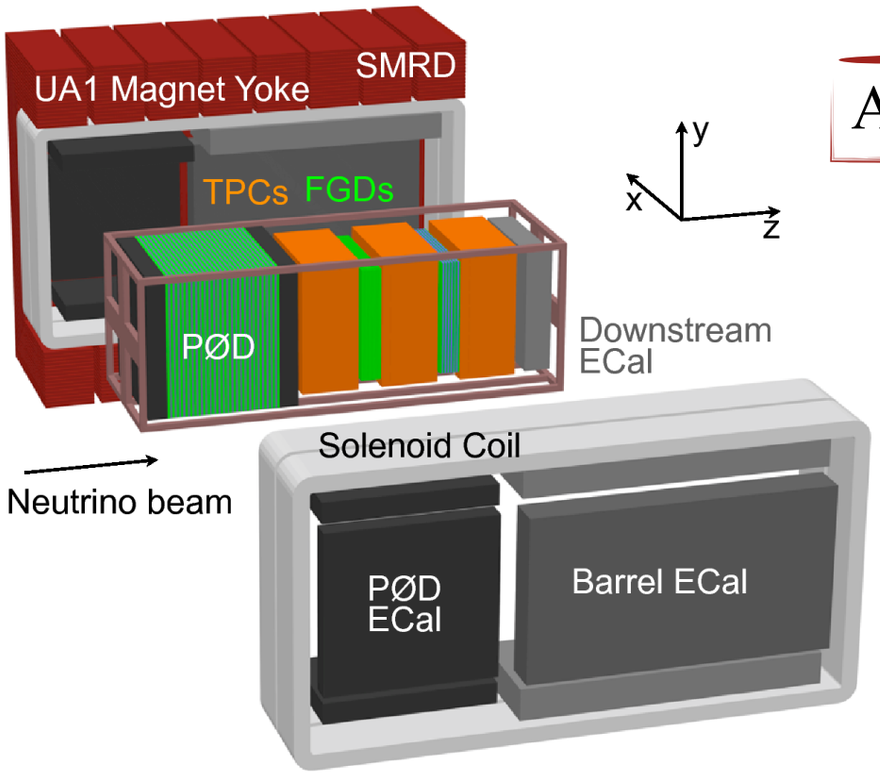

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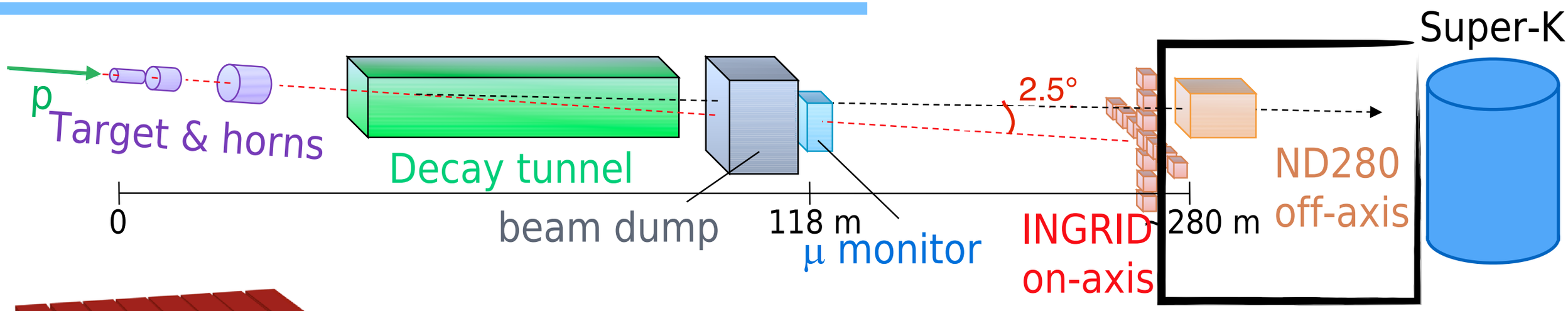

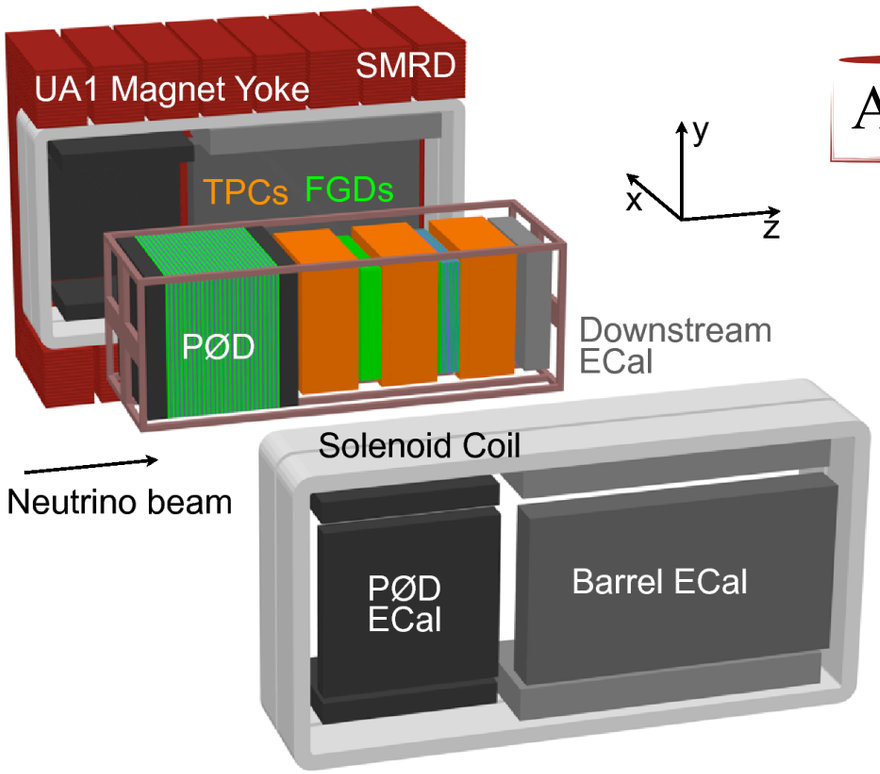

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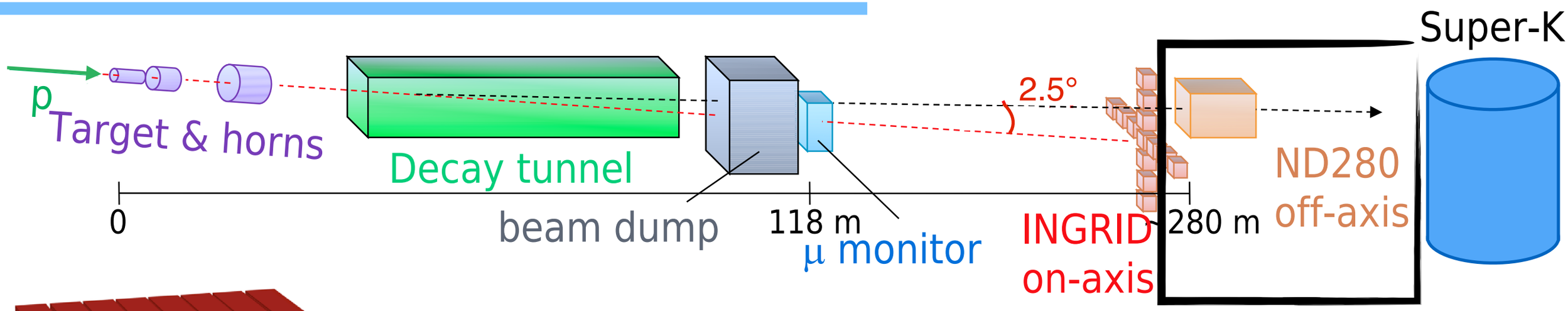

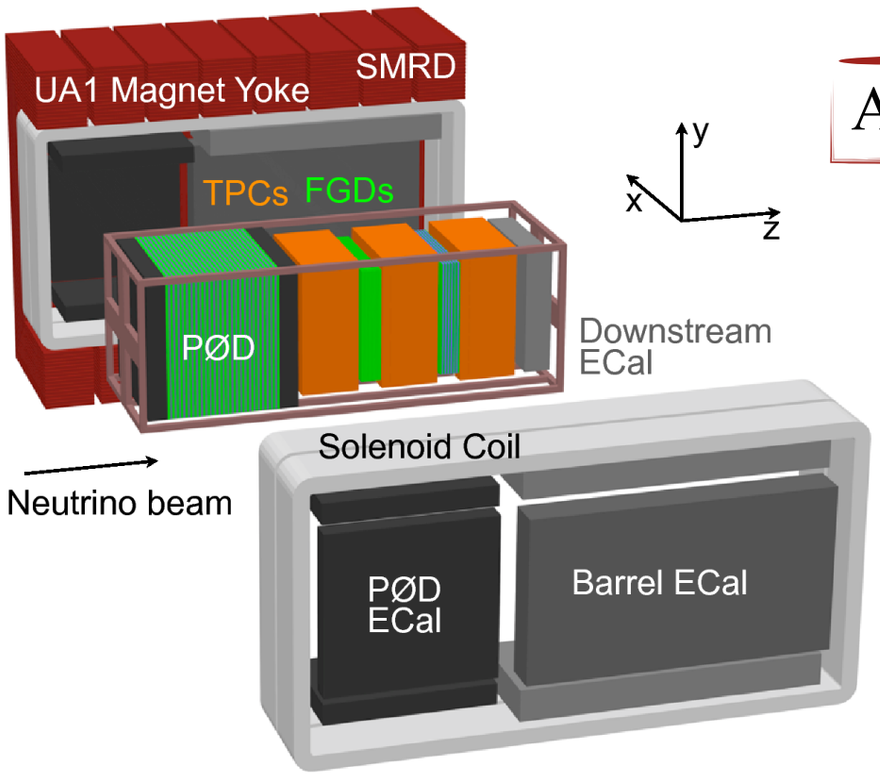

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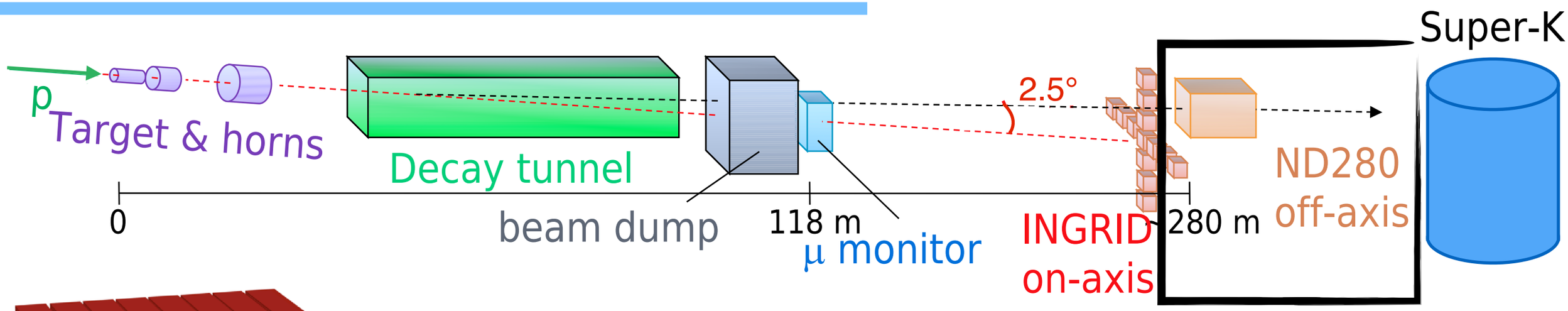

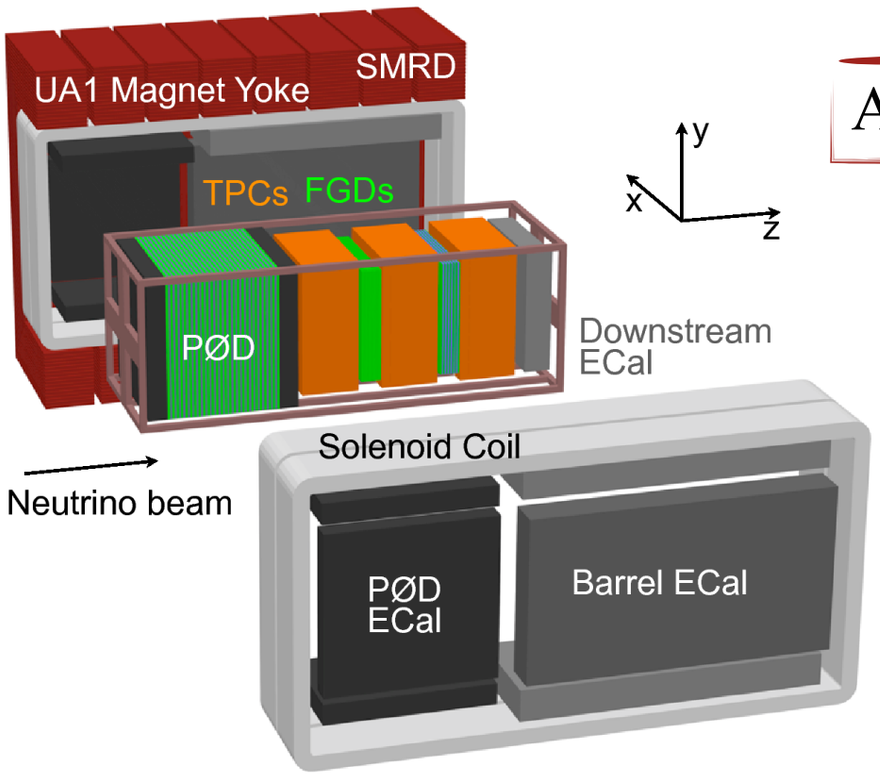

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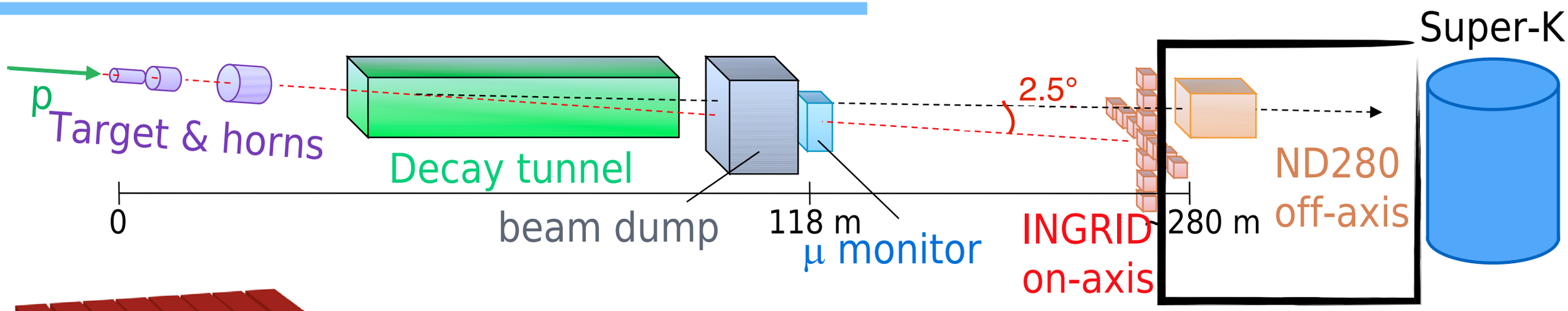

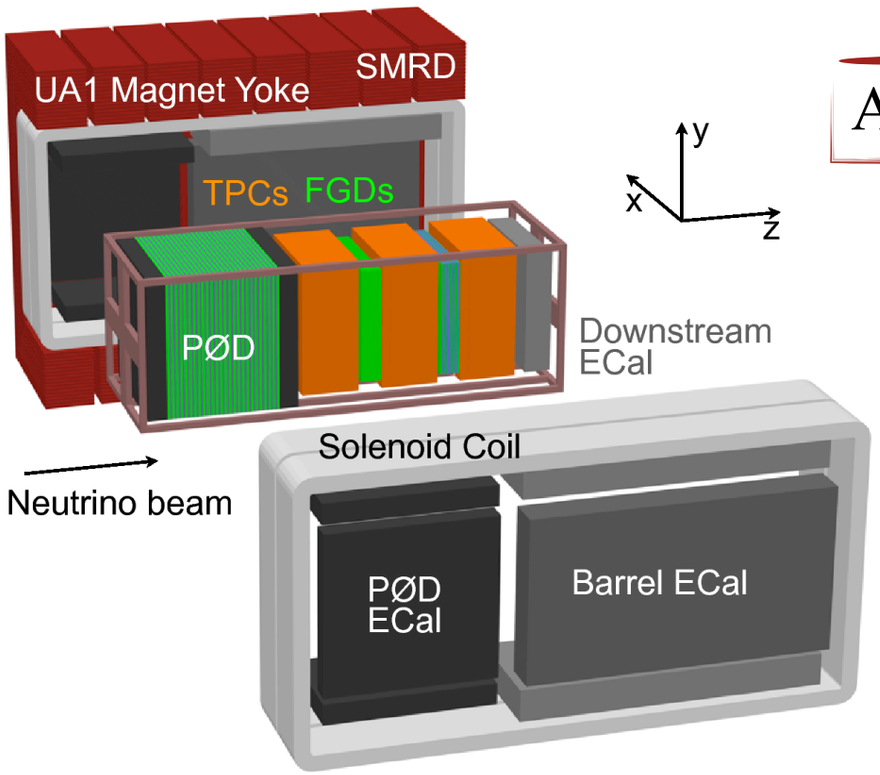

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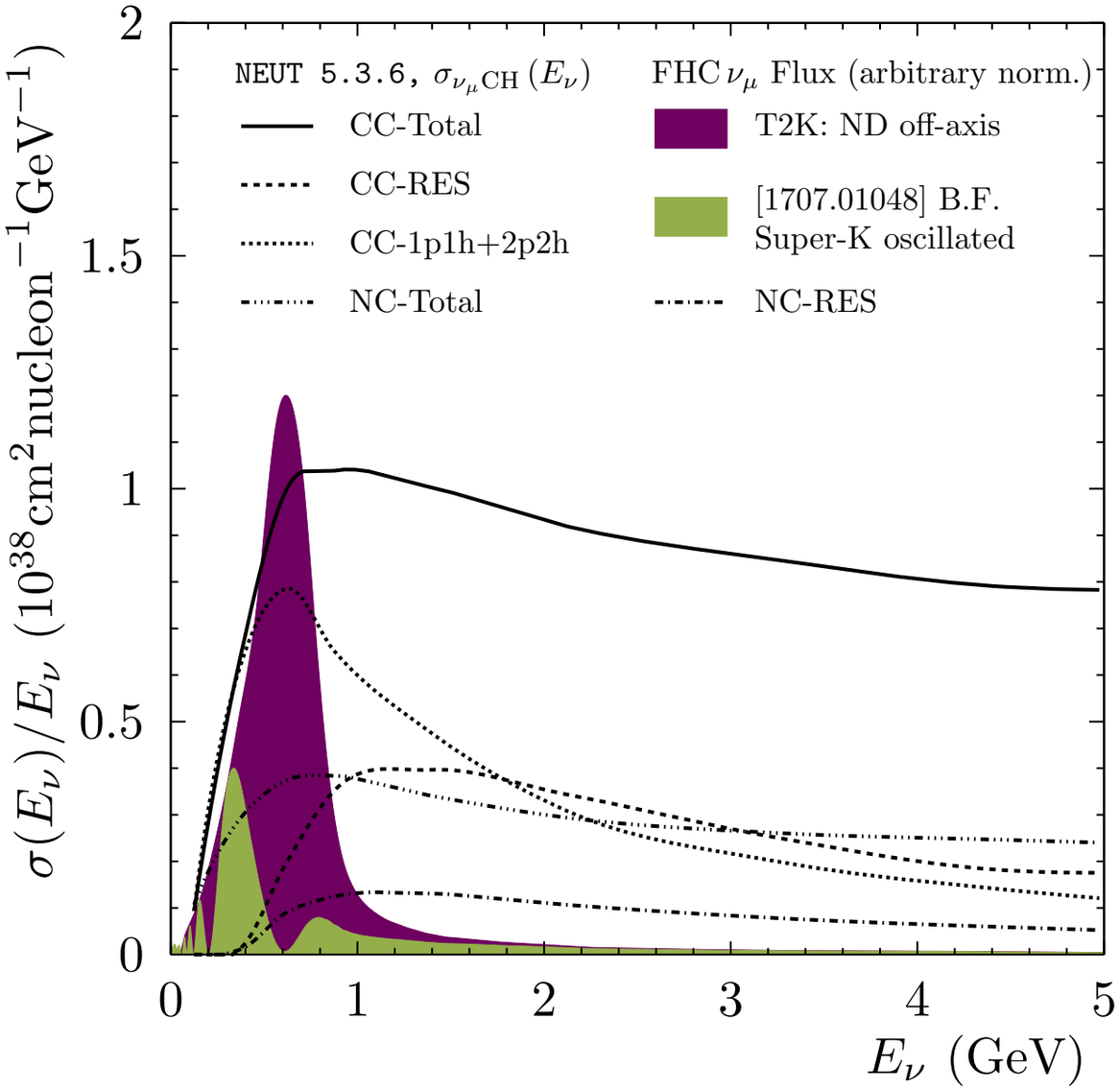
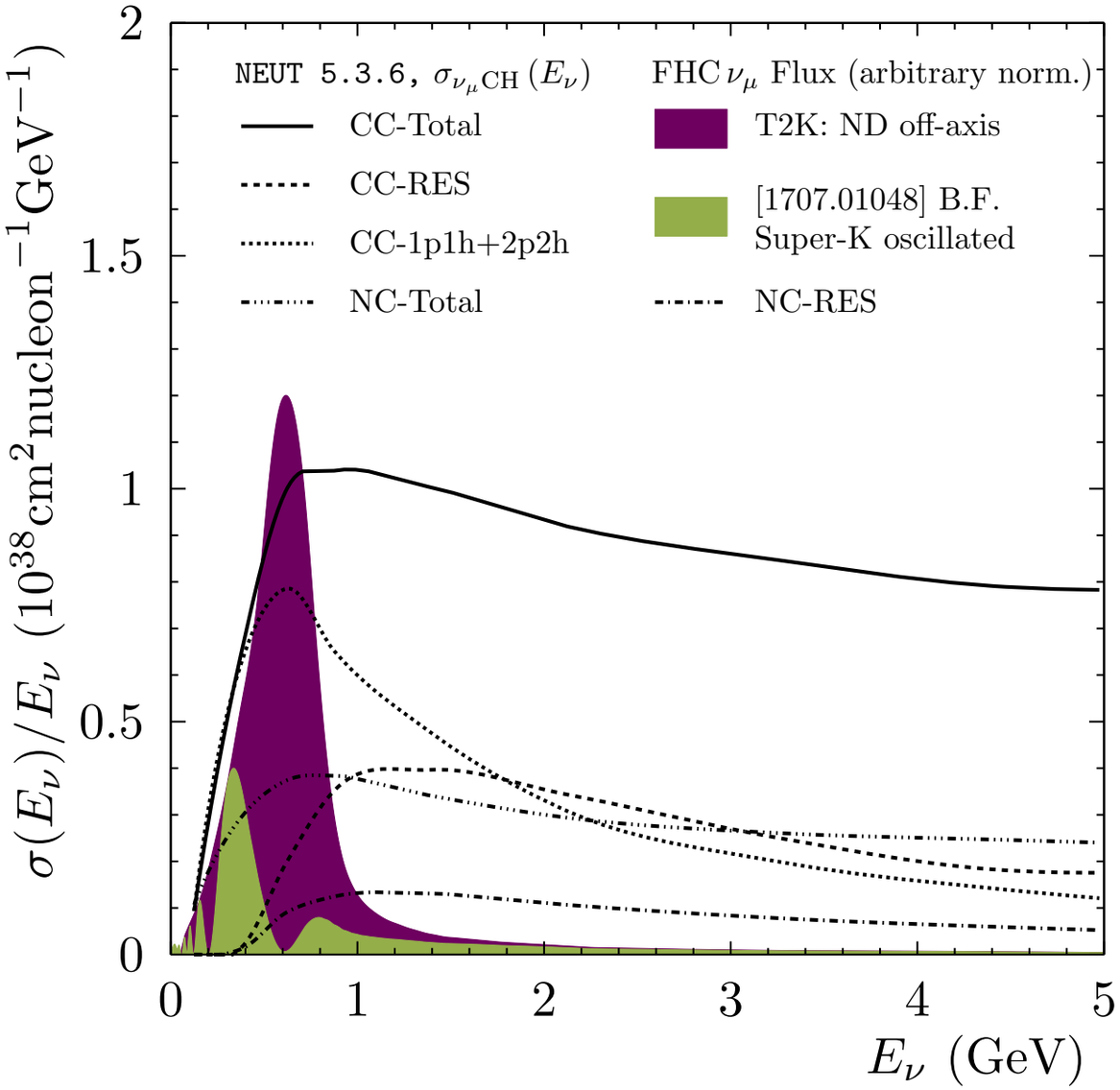
An electromagnetic calorimeter (ECal) is used to distinguish tracks from showers

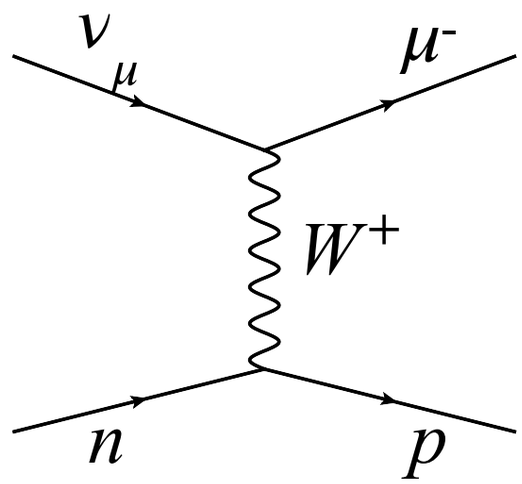
Relevant ν interactions at T2K



Relevant ν interactions at T2K

CCQE
(Charged-Current Quasi-Elastic)





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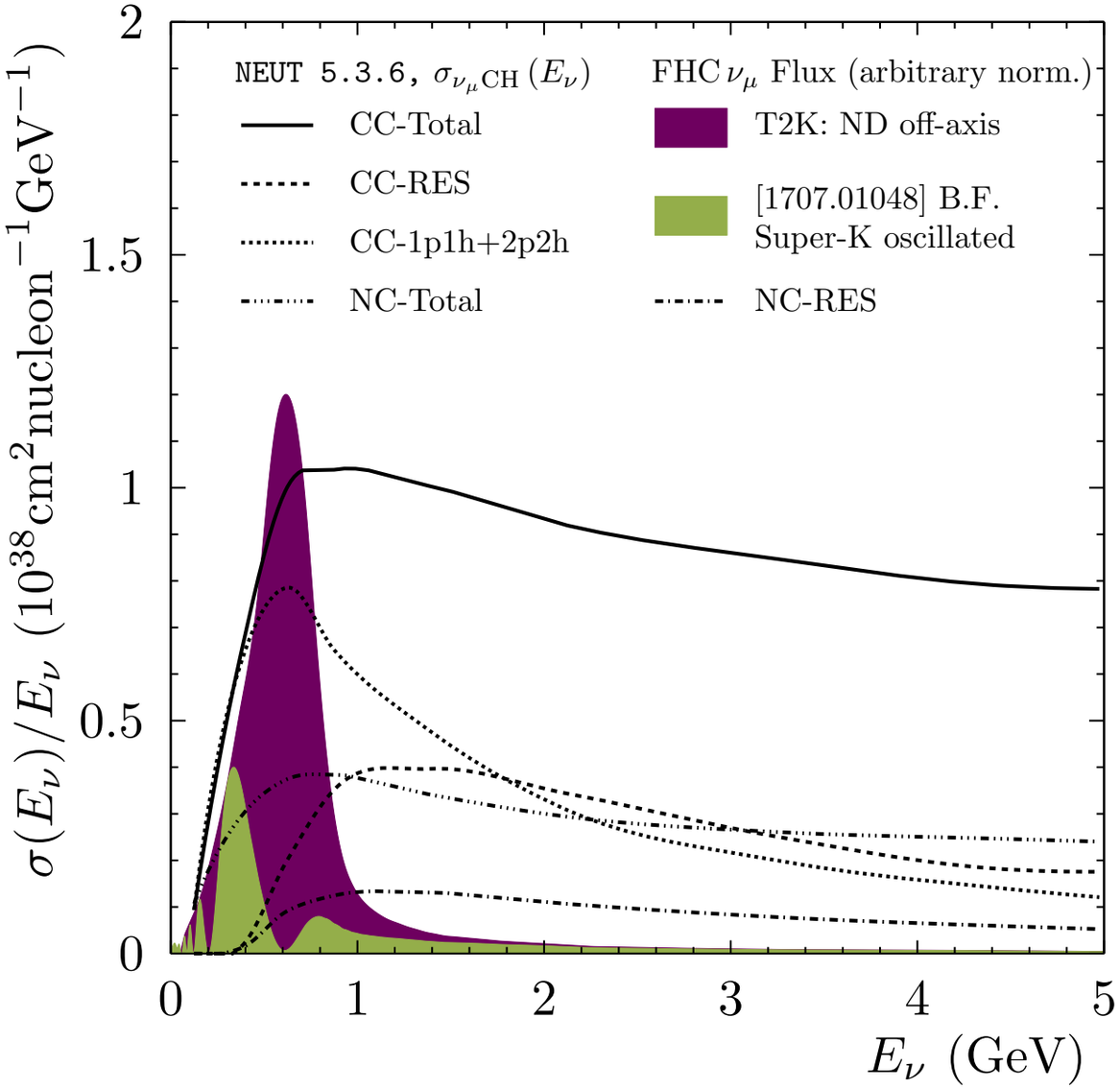

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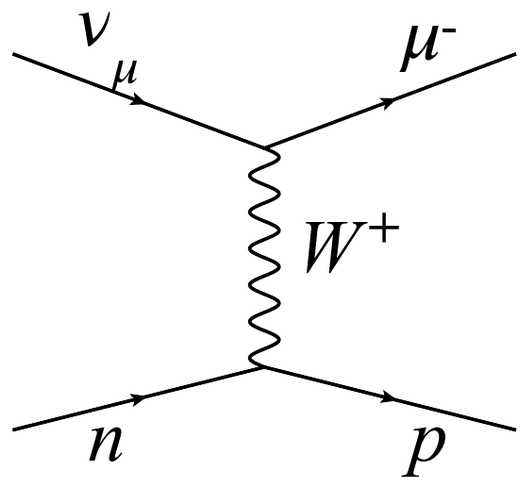
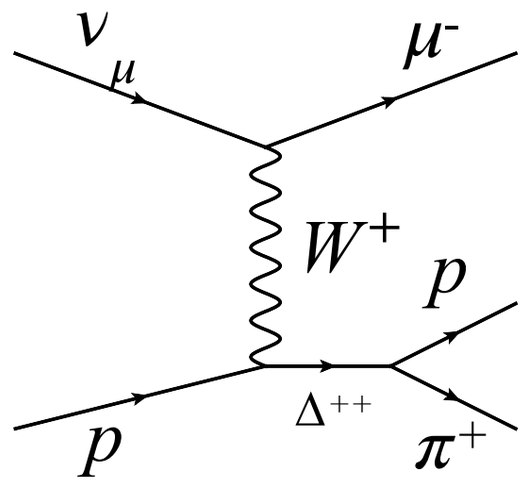


CCRES
(Charged-Current
Resonant pion production)



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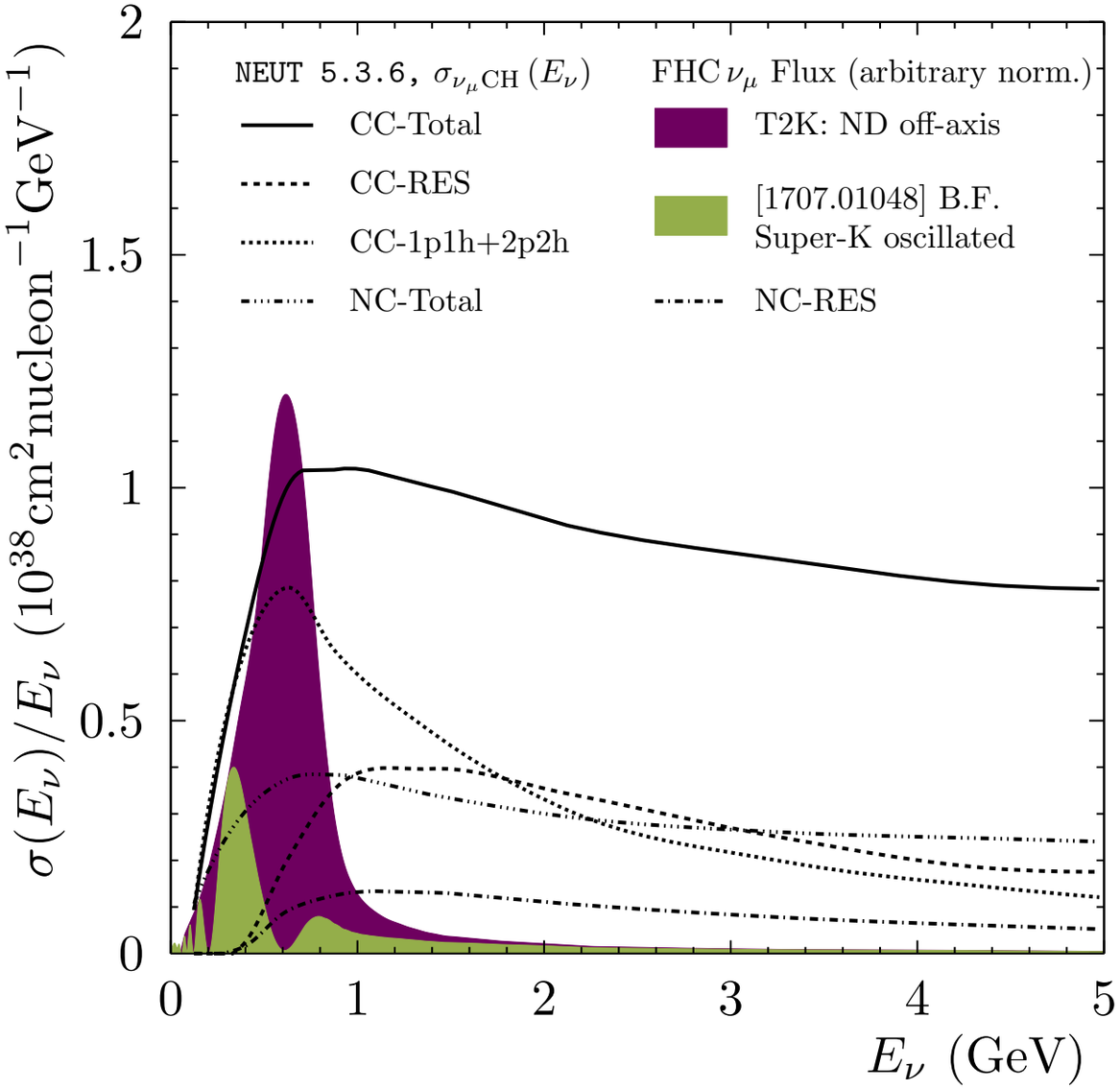

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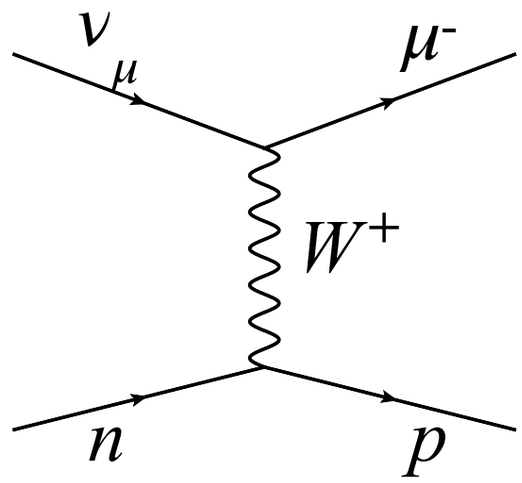

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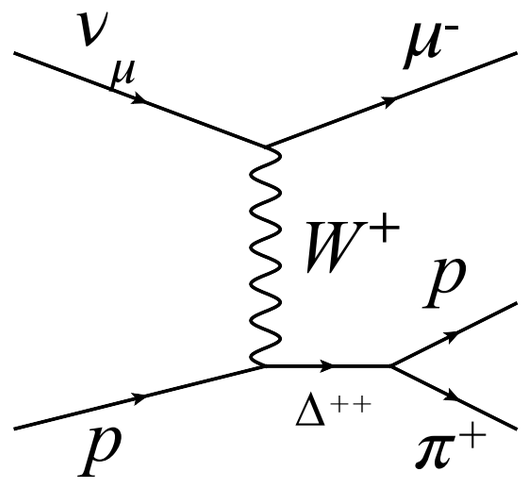
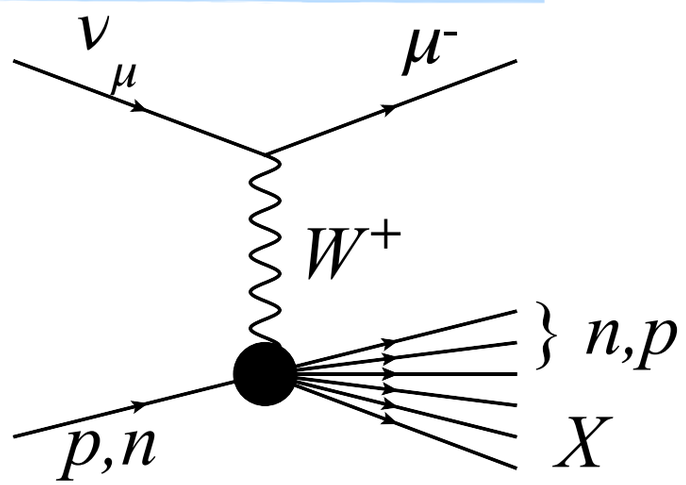
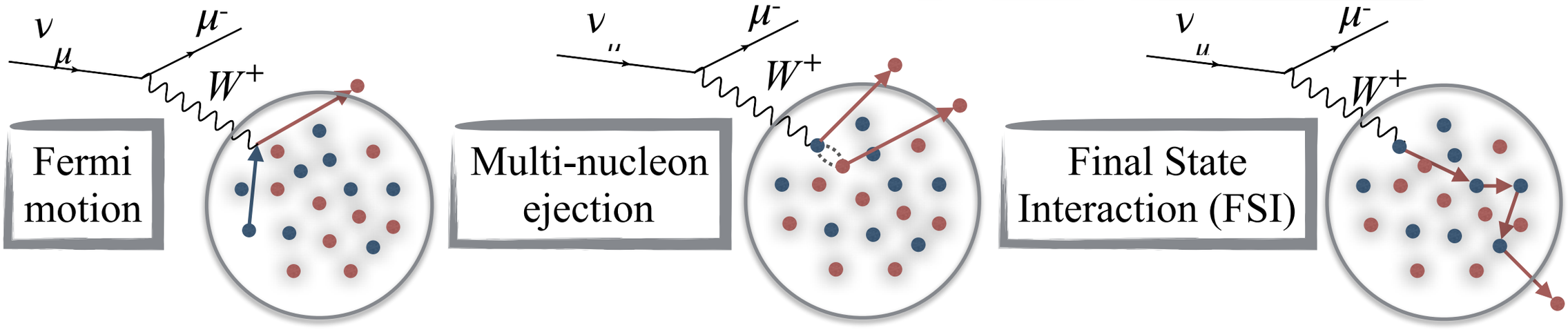


CCDIS
(Charged-Current Deep Inelastic Scattering)



Nuclear effects and detector acceptance

Nucleons bound in the nucleus ⇒ Nuclear effect!



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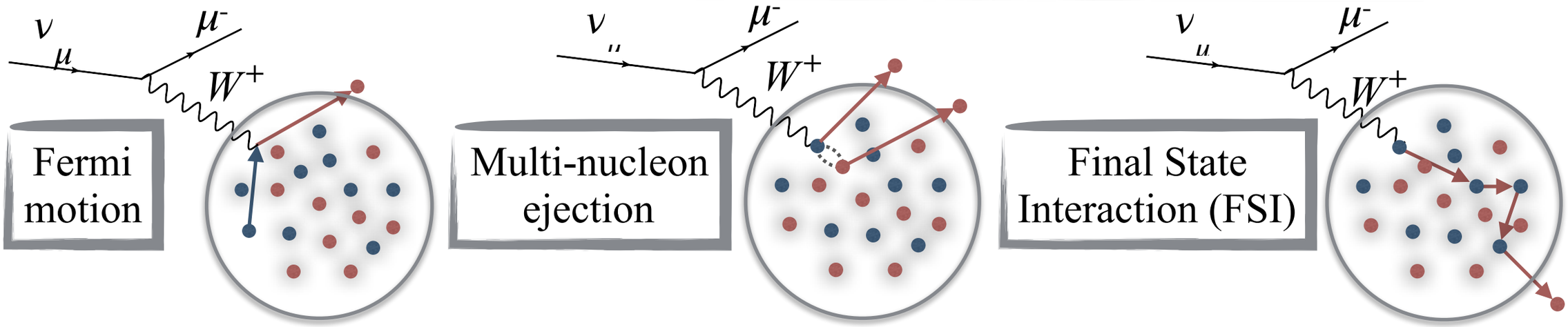

Limited detector acceptance

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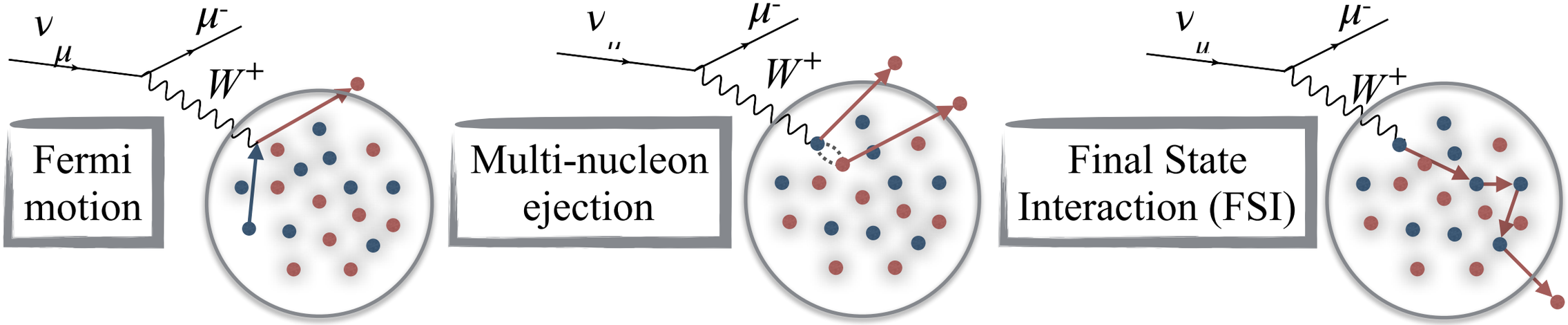
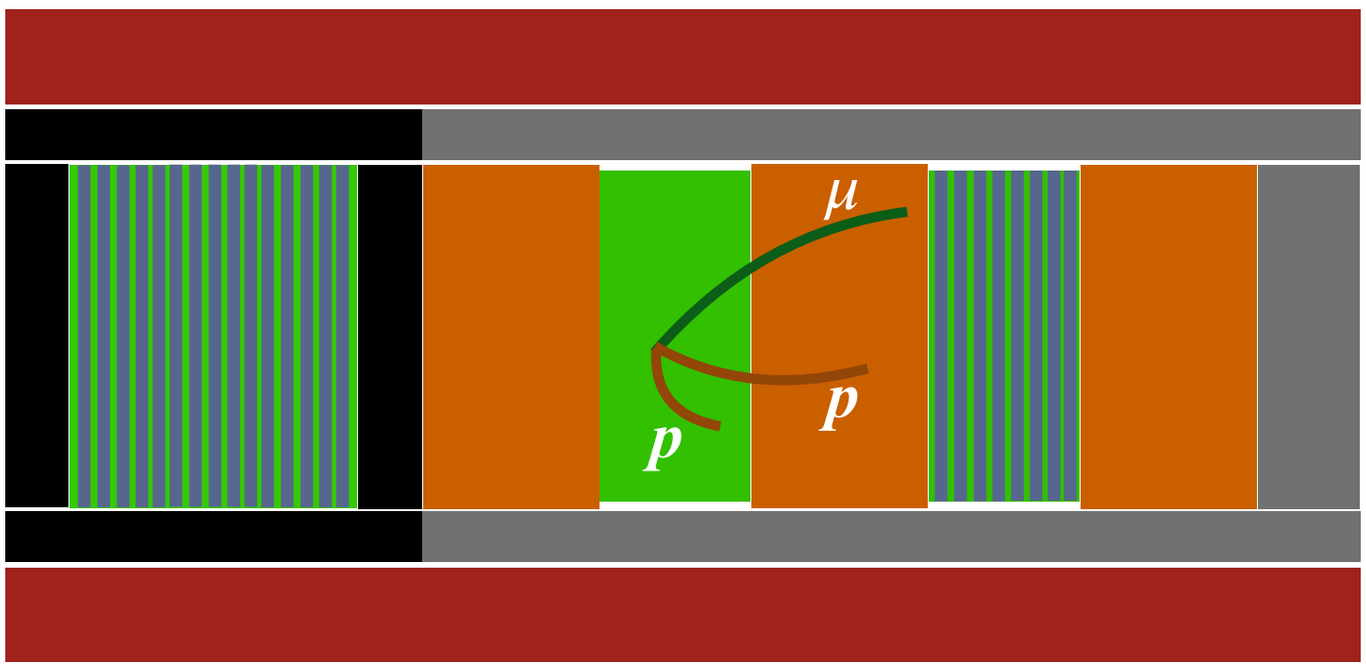
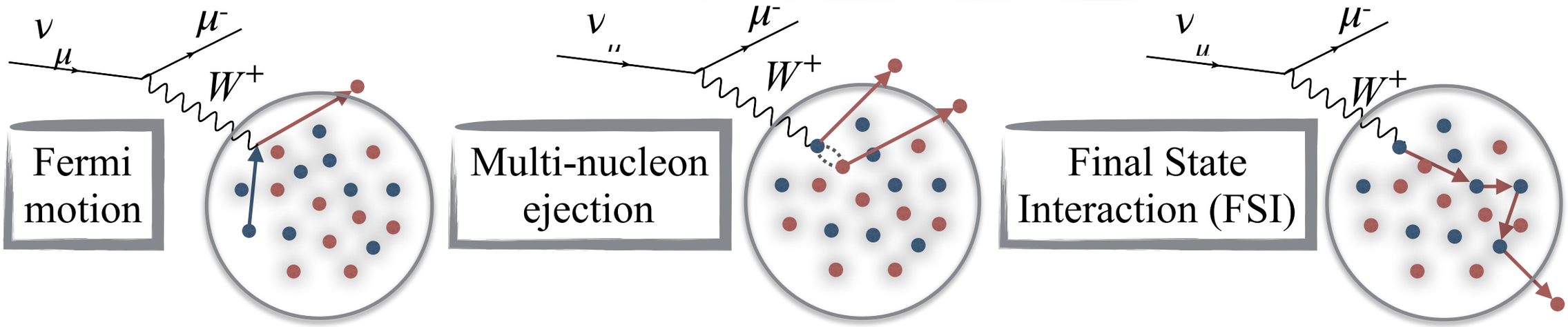


Limited detector acceptance



Nuclear effects and detector acceptance

Nucleons bound in the nucleus ⇒ Nuclear effect!



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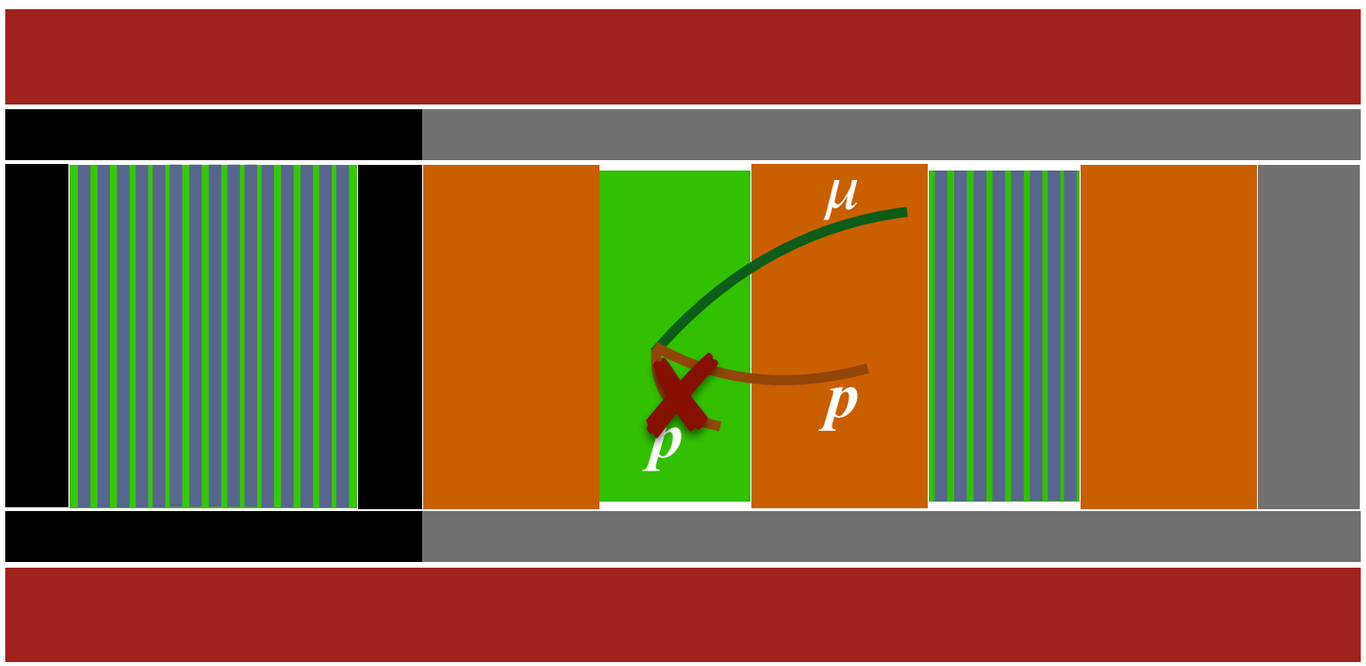

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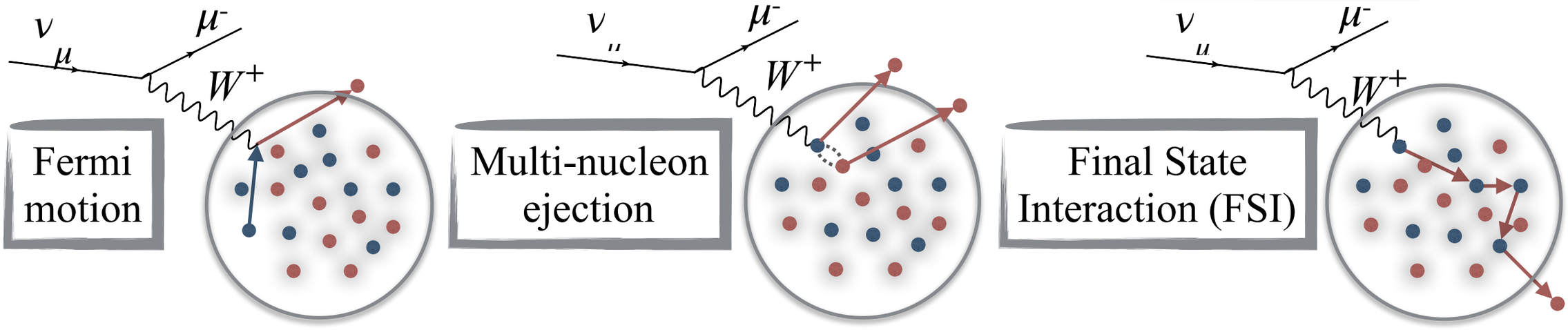

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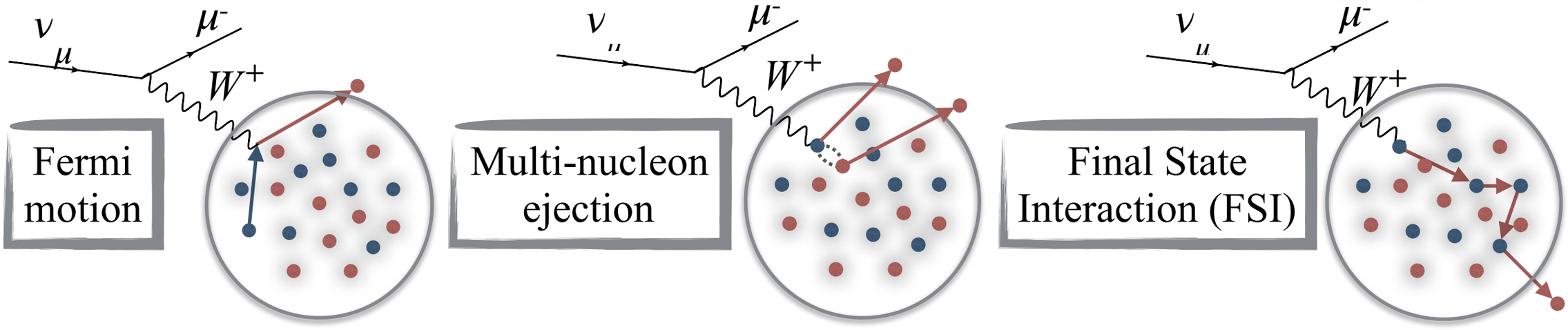

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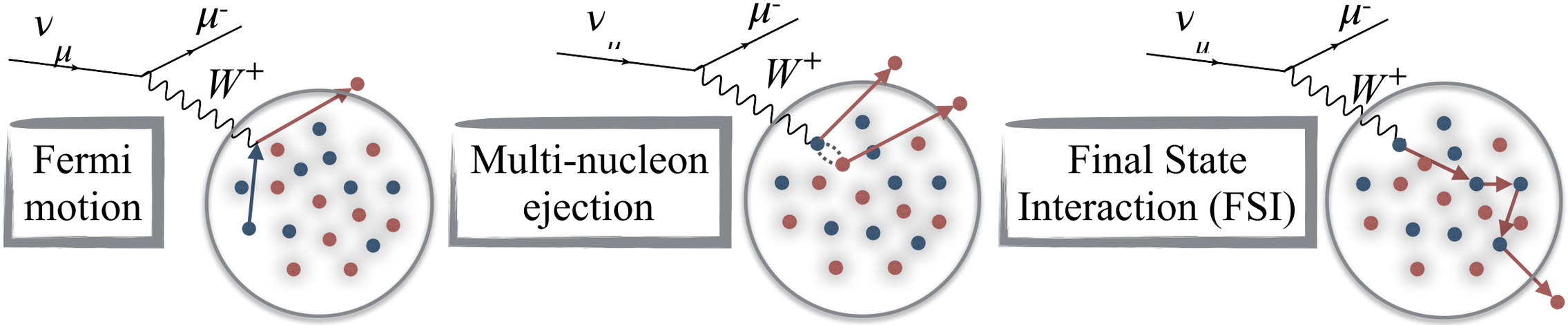
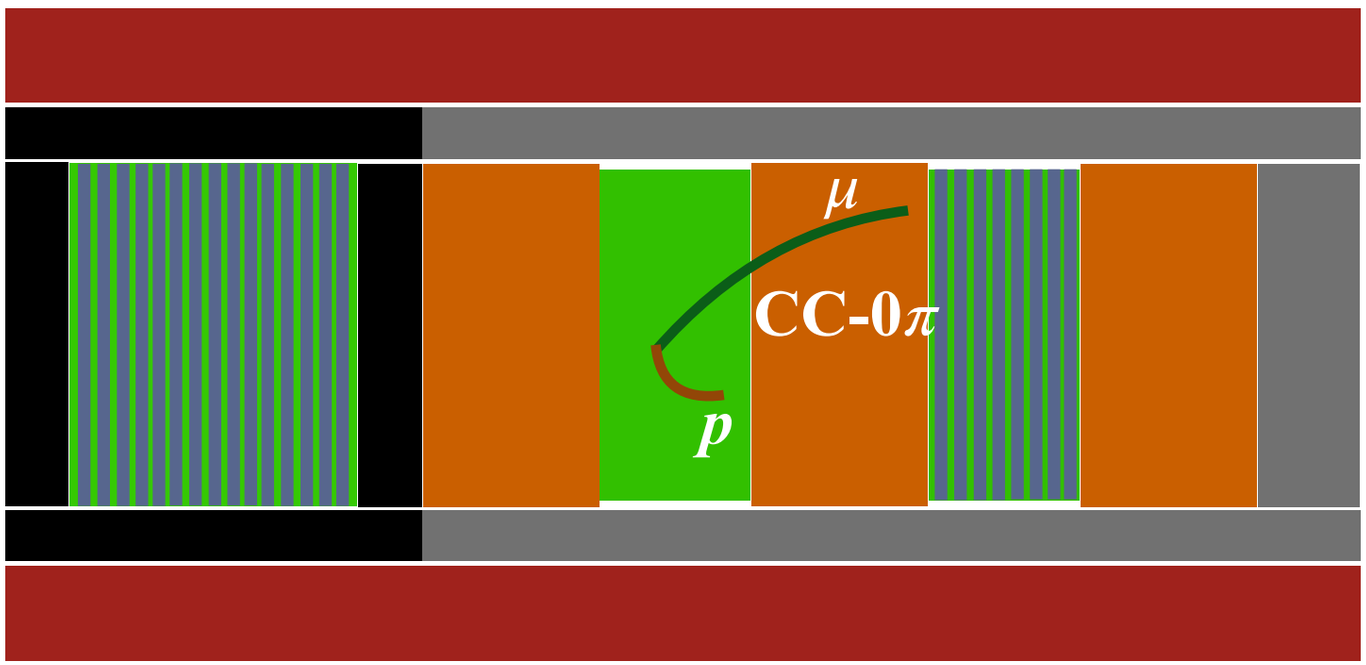
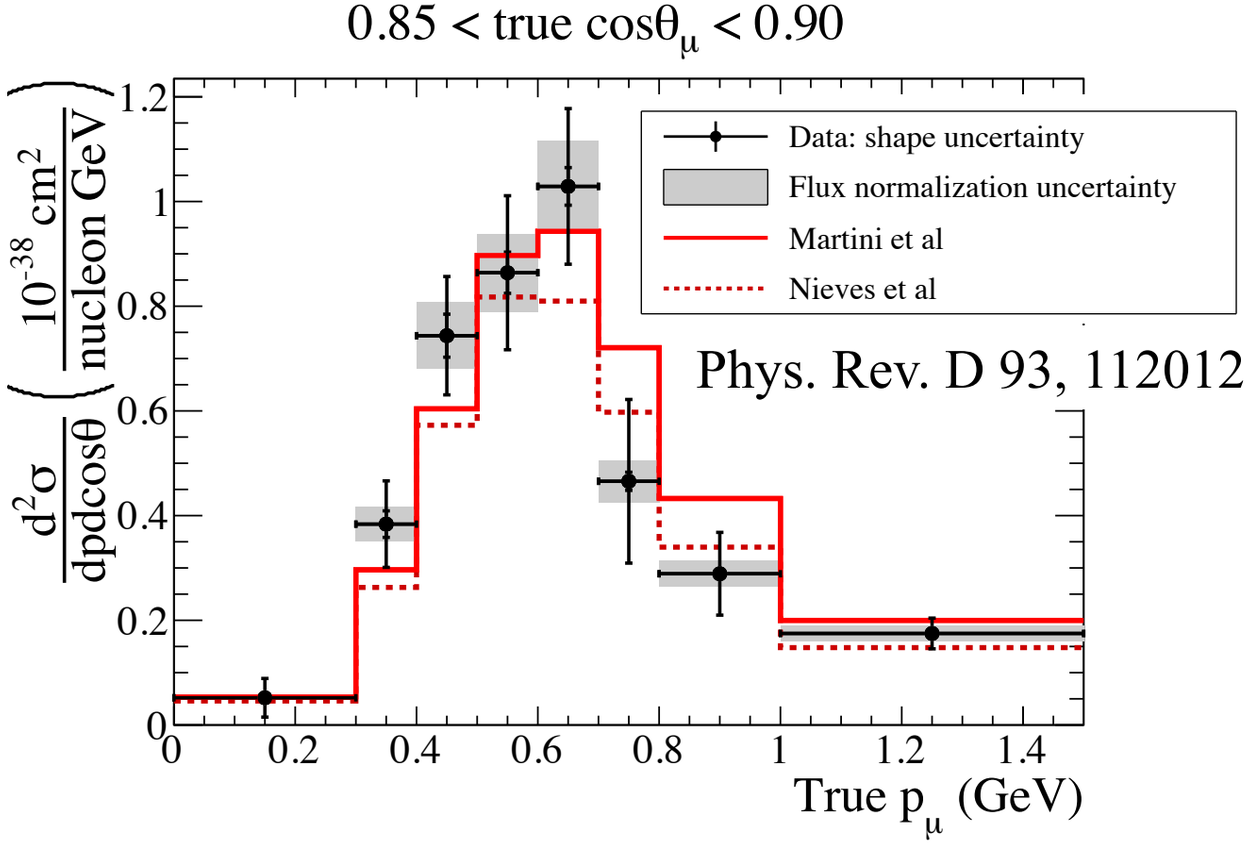


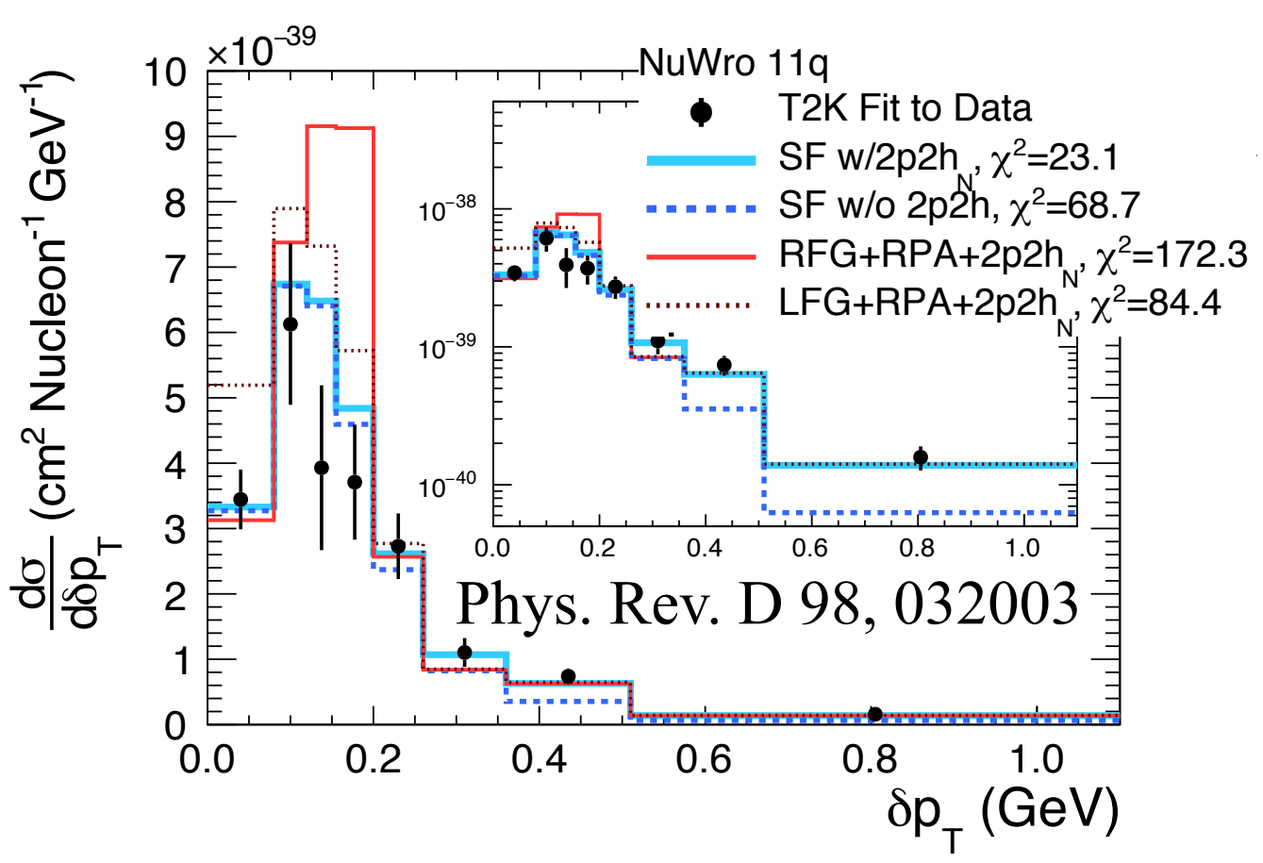
Increase acceptance and reduce the dependence from the cross-section modeling measuring interaction topologies



T2K cross section measurements

- Previous CC0-π cross sections extracted as function of muon and/or proton kinematics and using different targets (CH or H_2O)
- Such measurements start to show how relevant are nuclear effects in neutrino-nucleus scattering





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(Anti)neutrino and interactions differ by the sign of the V-A interference term. The relative weight of the different nuclear responses and the relative role of the multi-nucleon ejection are different

$$\frac{\partial^2\sigma}{\partial\Omega\,\partial\epsilon'} = \frac{G_F^2\,\cos^2\theta_c}{2\,\pi^2}k'\epsilon'\,\cos^2\frac{\theta}{2}\left[\frac{(q^2-\omega^2)^2}{q^4}\,G_E^2\,R_\tau + \frac{\omega^2}{q^2}\,G_A^2\,R_{\sigma\tau(L)} + \right.$$
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Neutrino-antineutrino cross section differences can shed light on the multi-nucleon ejection

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Martini and collaborators (Phys. Rev. C 91, 035501) compared their prediction with MiniBooNE neutrino-antineutrino sum and difference.

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At T2K we performed a combined analysis of ν_μ and $\overline{\nu}_\mu$

CC-0π cross sections on CH

Cross section analysis strategy

See Stephen Dolan's talk

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Perform an **extended binned likelihood fit** to the number of selected events as a function of the **muon momentum and scattering angle** simultaneously for muon neutrino and antineutrino.

$$\chi^2 = \chi^2_{\text{stat}} + \chi^2_{\text{syst}} = \sum_j^{\text{reco bins}} 2\left(N_j^{\nu_\mu} - N_j^{\nu_\mu\ \text{obs}} + N_j^{\nu_\mu\ \text{obs}} \ln \frac{N_j^{\nu_\mu\ \text{obs}}}{N_j^{\nu_\mu}}\right) \quad \nu \textbf{ sample}$$

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Combined analysis allows to reduce the systematics uncertainties: correlations between ν and $\bar{\nu}$

Extracted measurements

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- **Double differential CC-0π ν_μ and $\bar{\nu}_\mu$ flux integrated cross section**

$$\frac{\mathrm{d}\sigma_{\nu_\mu}}{\mathrm{d}p\mathrm{d}\cos\theta} = \frac{N^{\nu_\mu \mathrm{CC\text{-}0\pi}}}{\epsilon^{\nu_\mu}\Phi^{\nu_\mu}N^{\mathrm{FV}}_{\mathrm{nucleons}}\Delta p\Delta\cos\theta}$$

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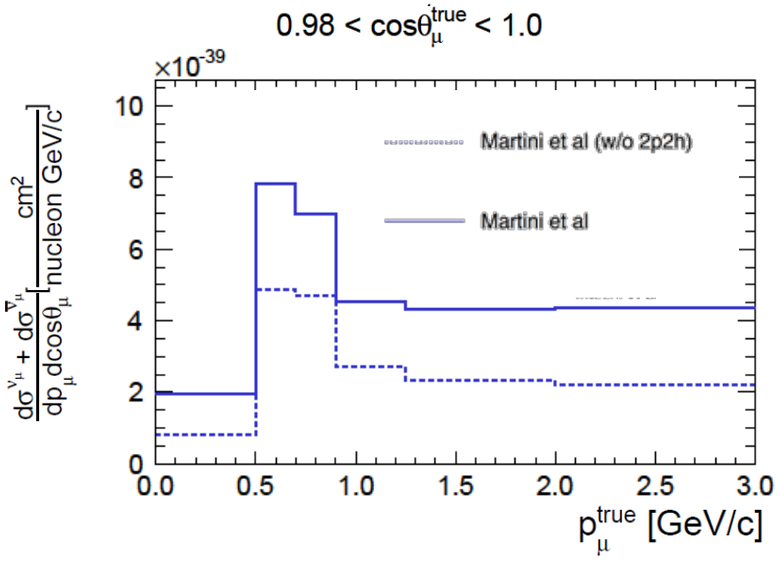
- **Sum and difference:**

$$\frac{\mathrm{d}\sigma_{\nu_\mu}}{\mathrm{d}p\mathrm{d}\cos\theta} \pm \frac{\mathrm{d}\sigma_{\bar{\nu}_\mu}}{\mathrm{d}p\mathrm{d}\cos\theta}$$



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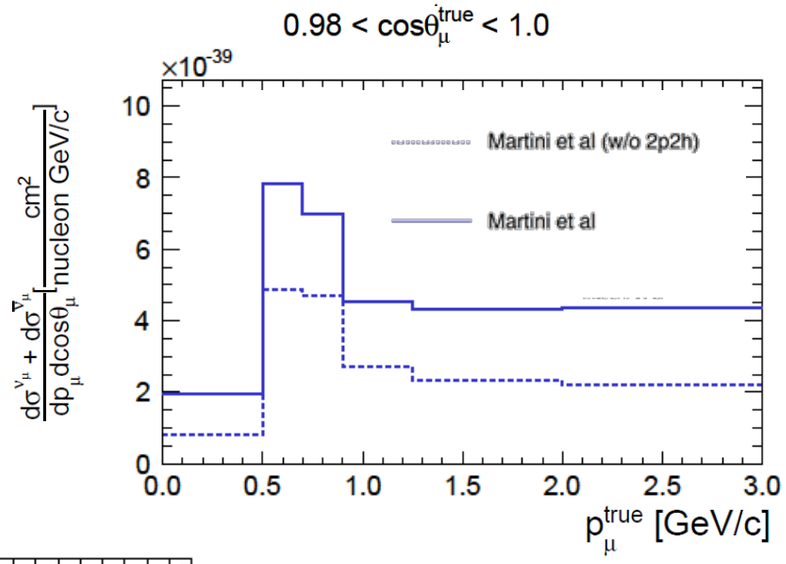
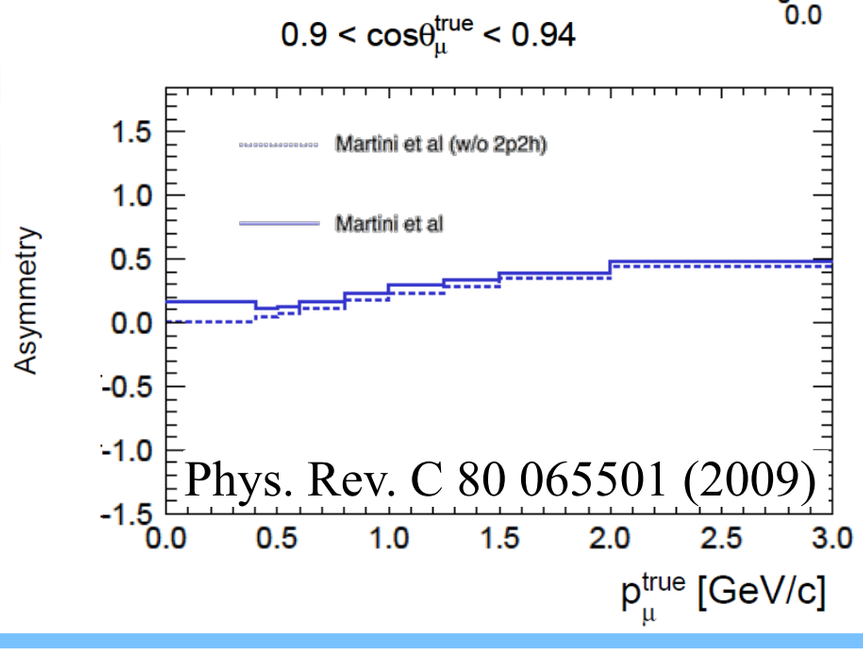
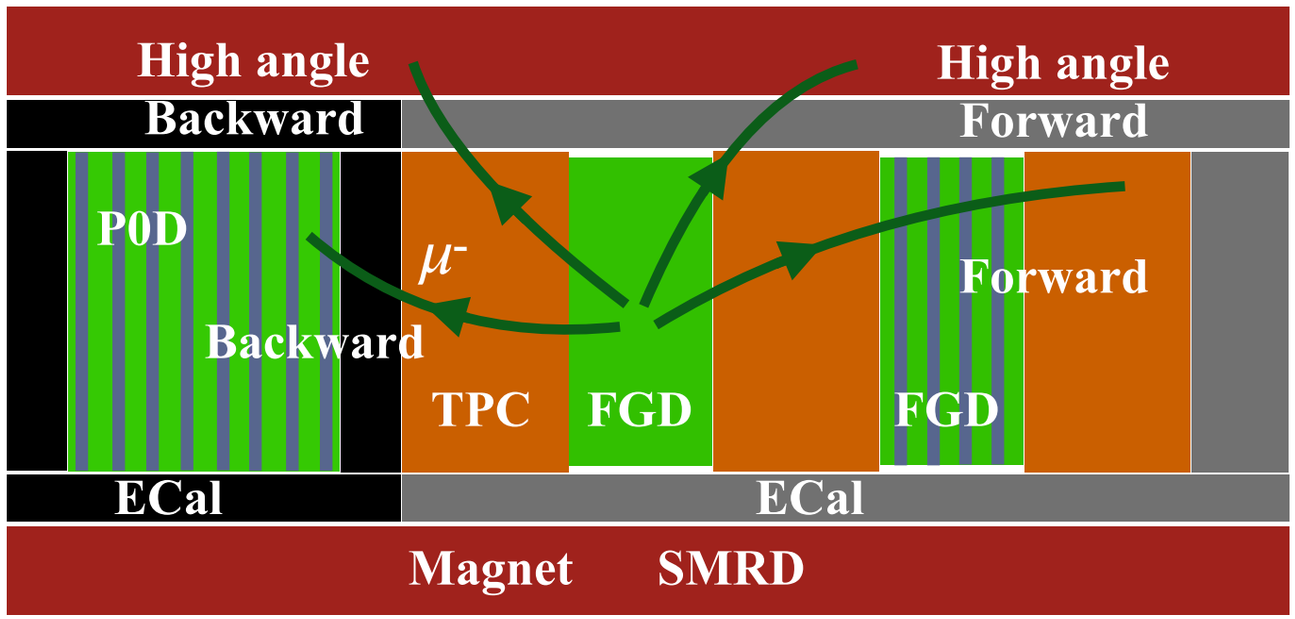


- **Asymmetry:**

$$\frac{\mathrm{d}\sigma_{\nu_\mu} - \mathrm{d}\sigma_{\bar{\nu}_\mu}}{\mathrm{d}\sigma_{\nu_\mu} + \mathrm{d}\sigma_{\bar{\nu}_\mu}}$$



ν_μ selection strategy



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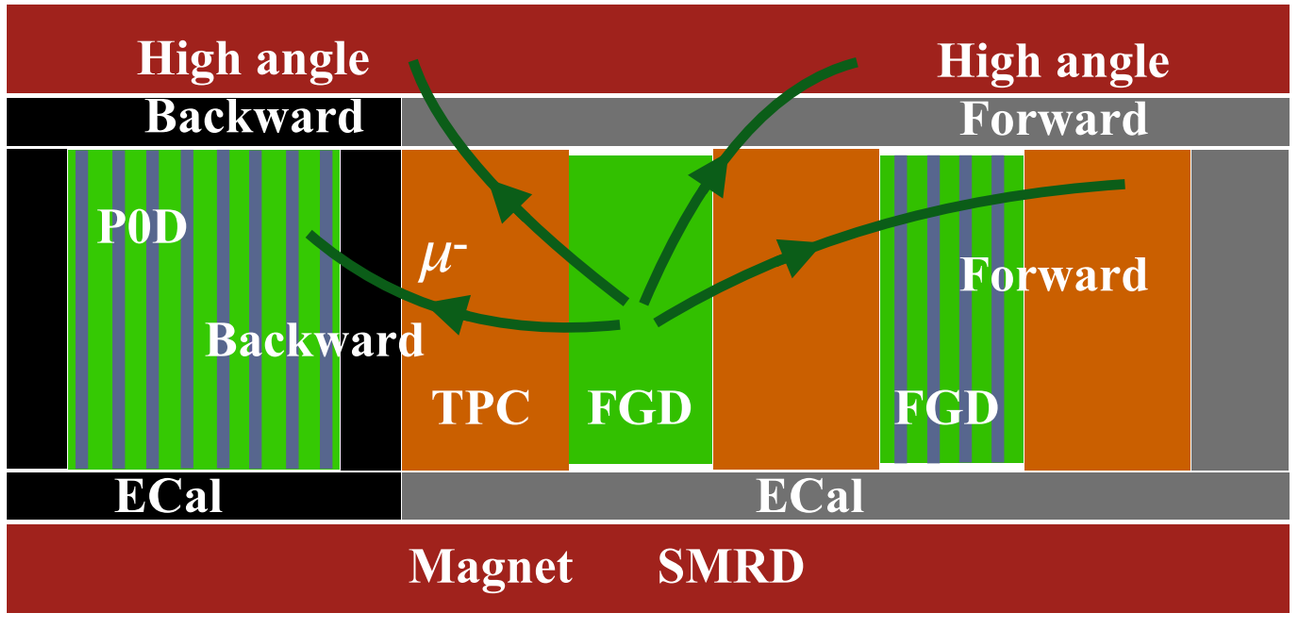
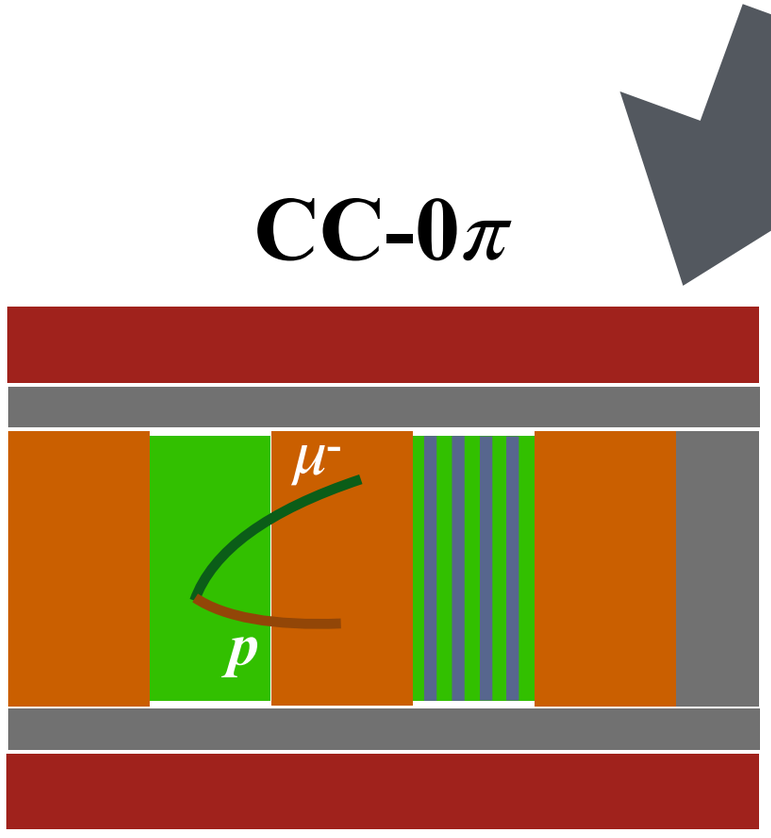


CC-0π



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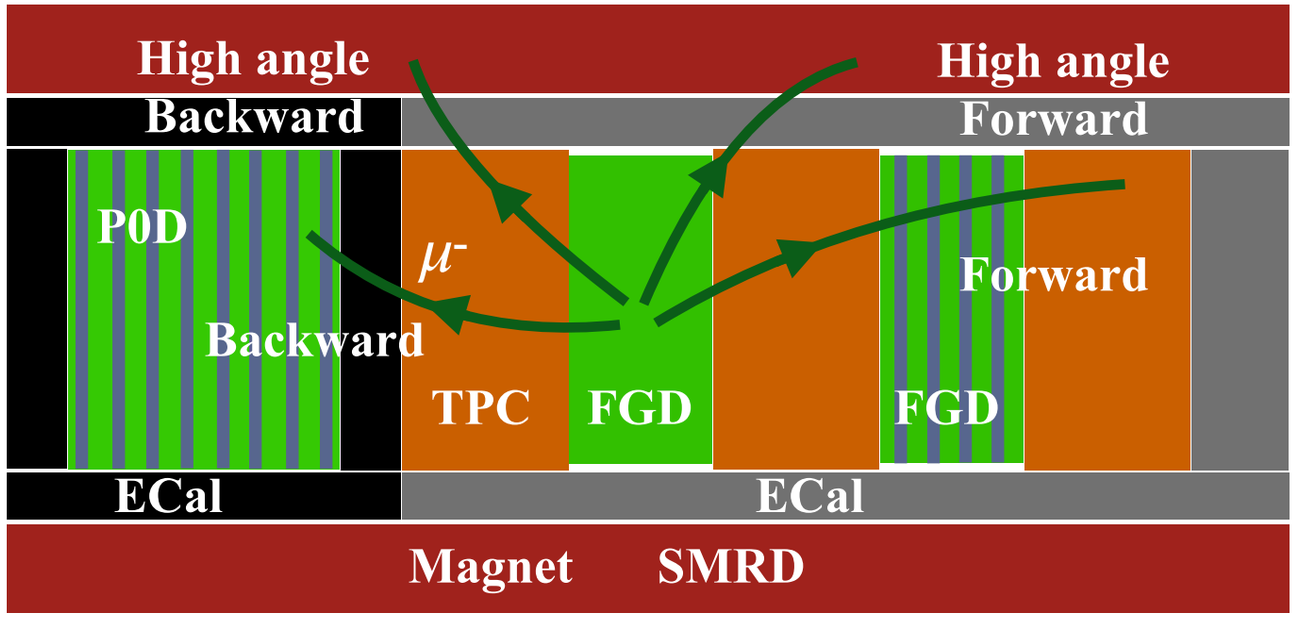

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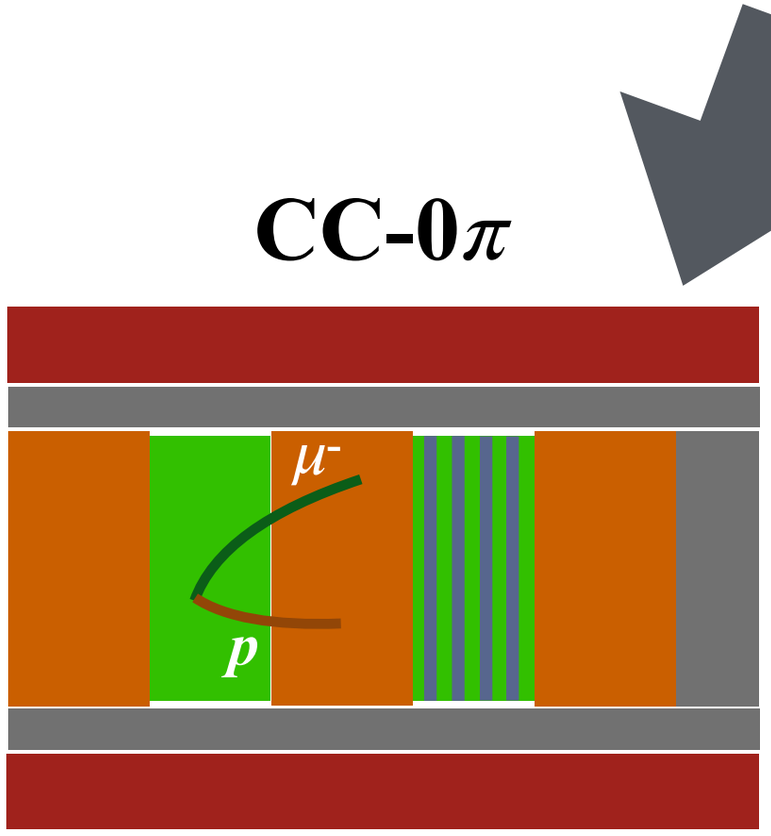
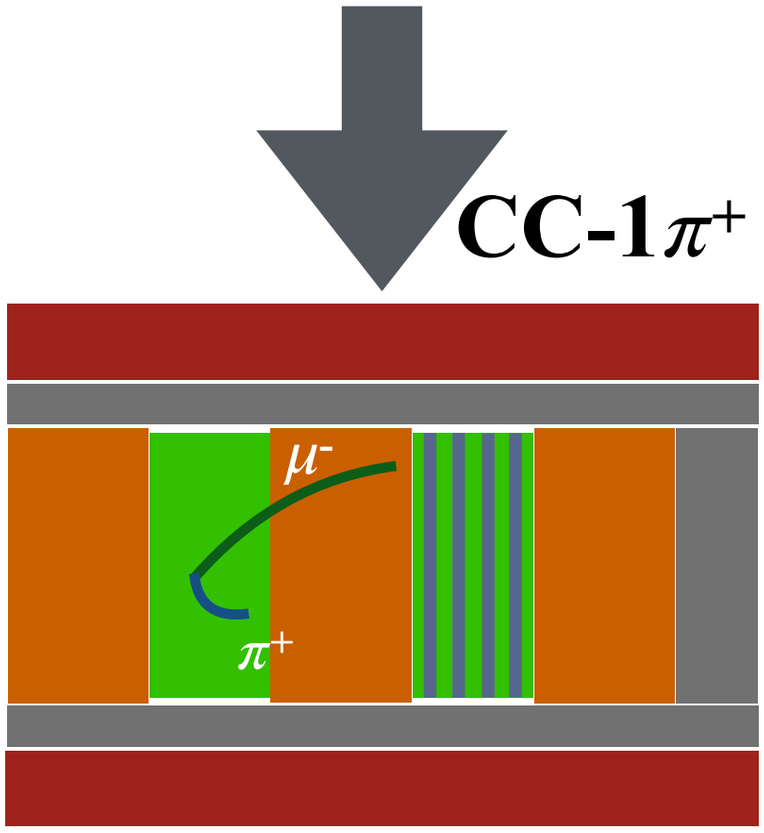
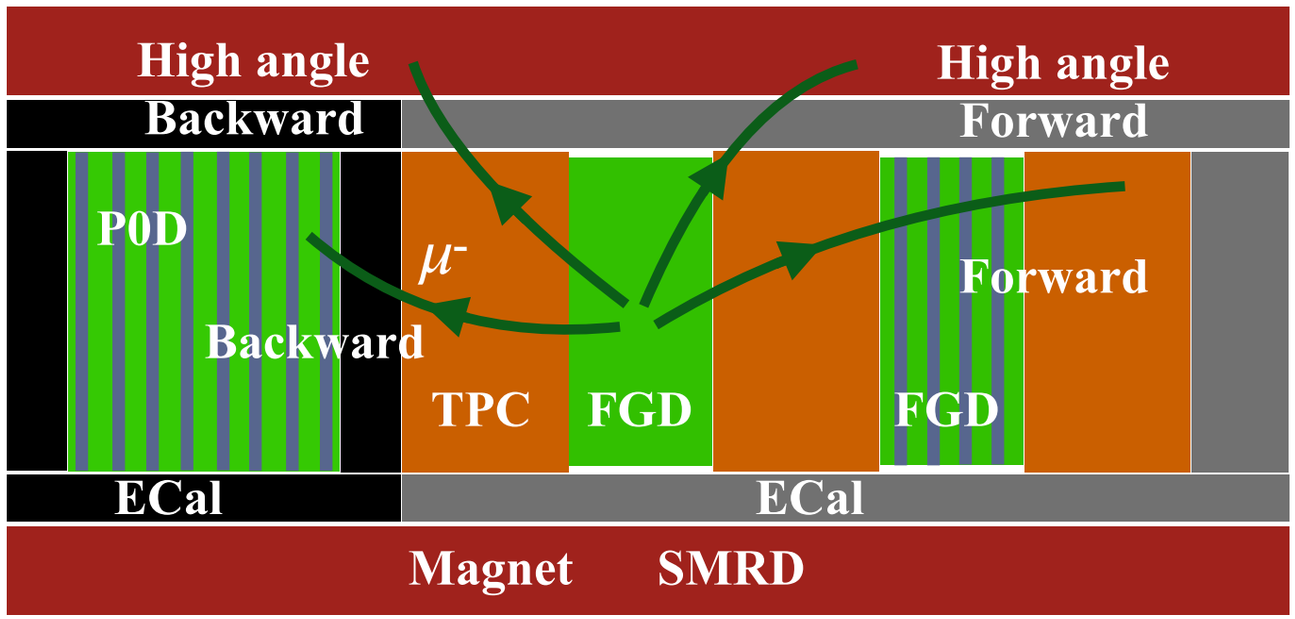


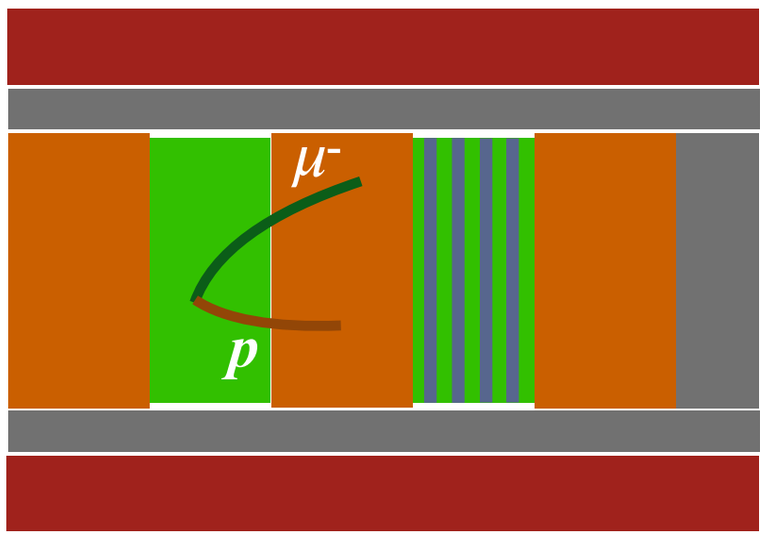
CC-1π^+



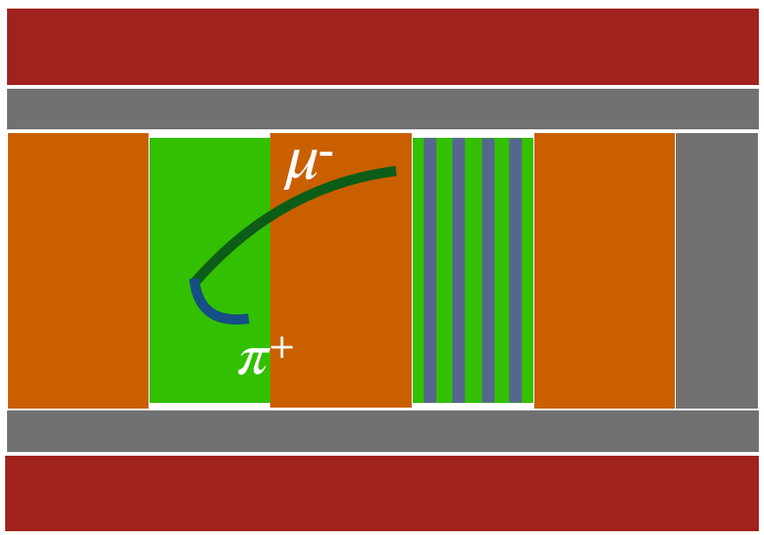
ν_μ selection strategy



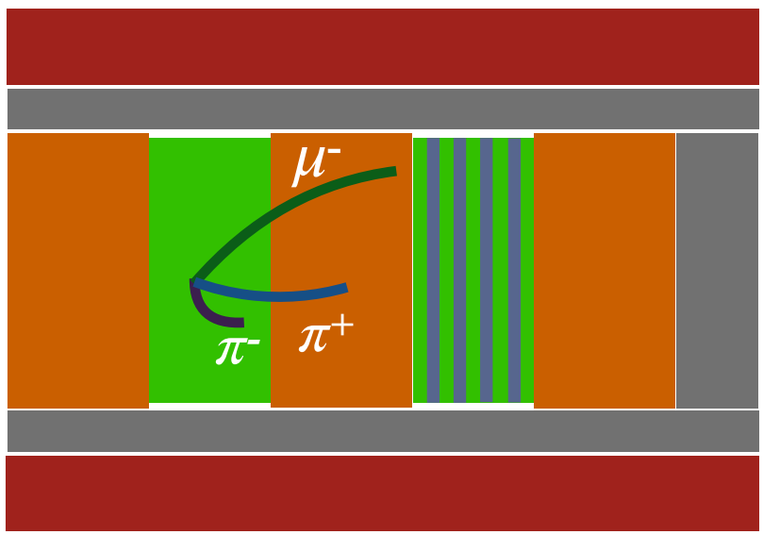
CC-0π



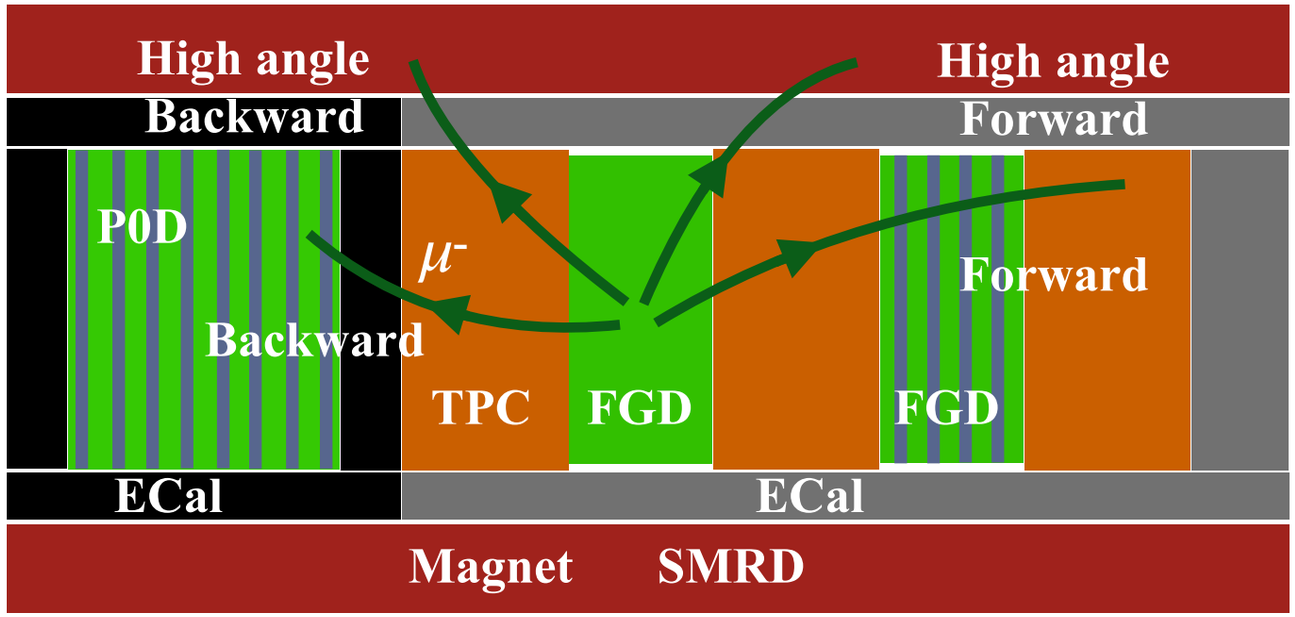
CC-1π^+



CC-Other



ν_μ selection strategy



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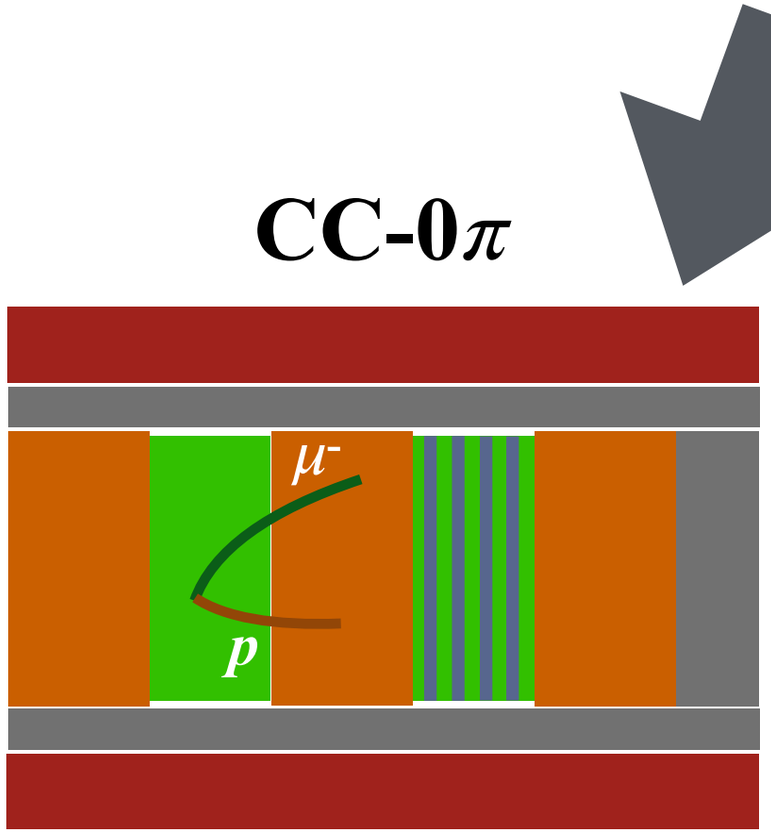

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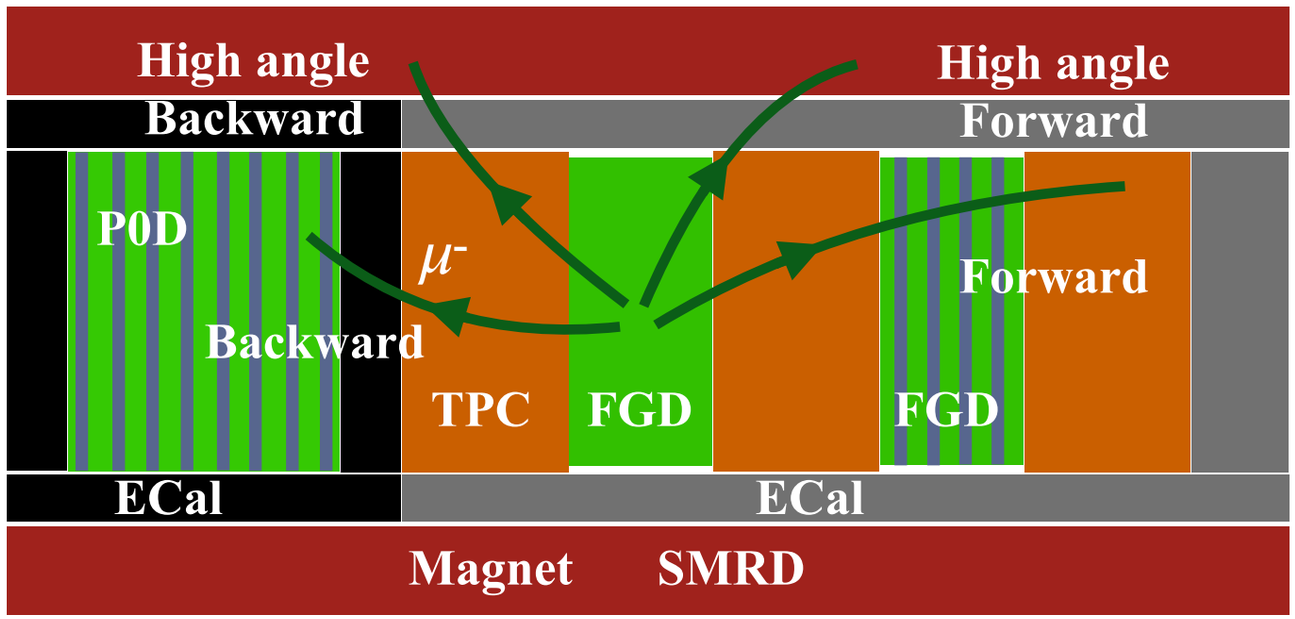
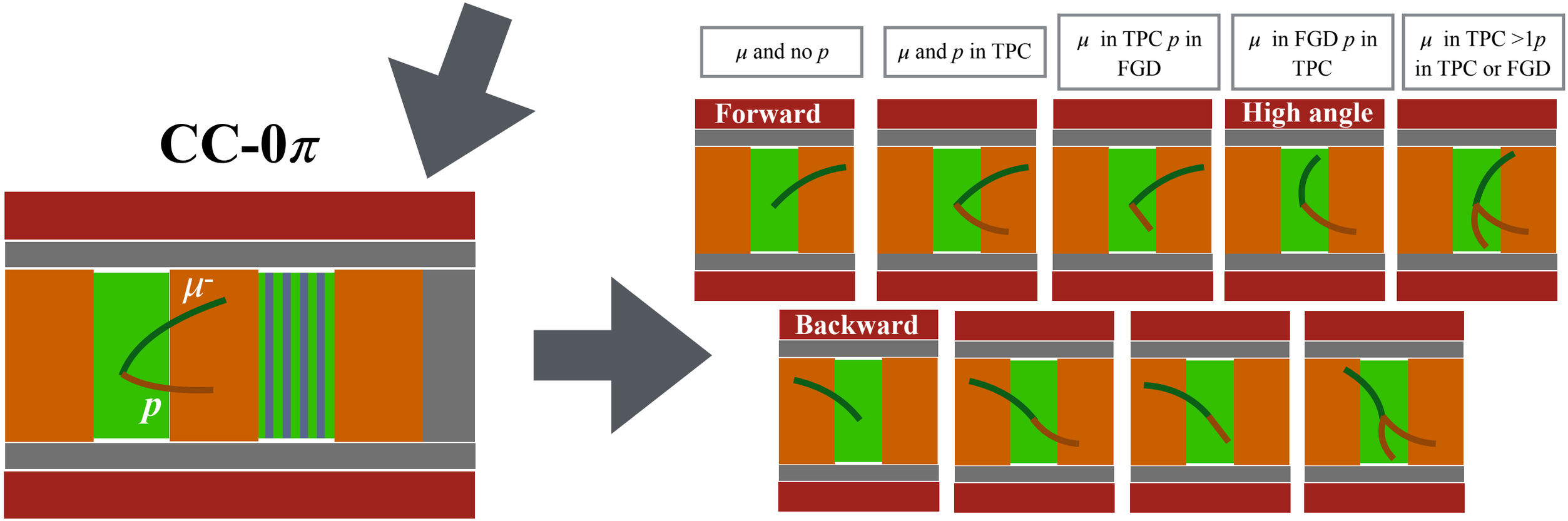
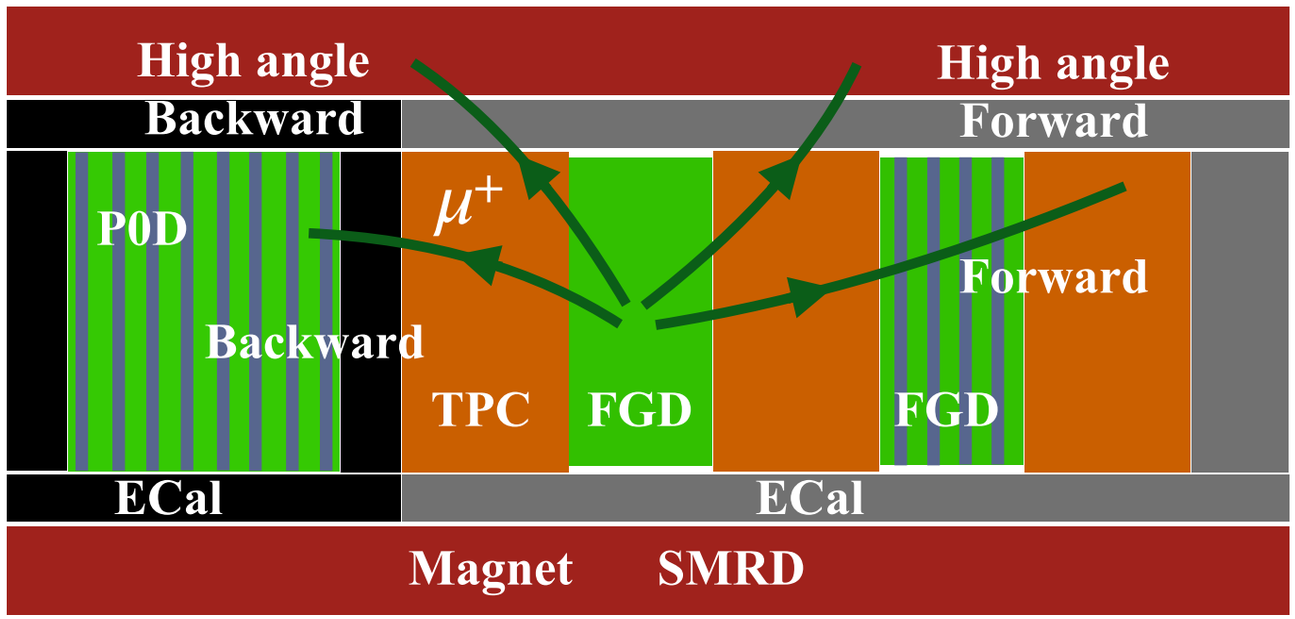
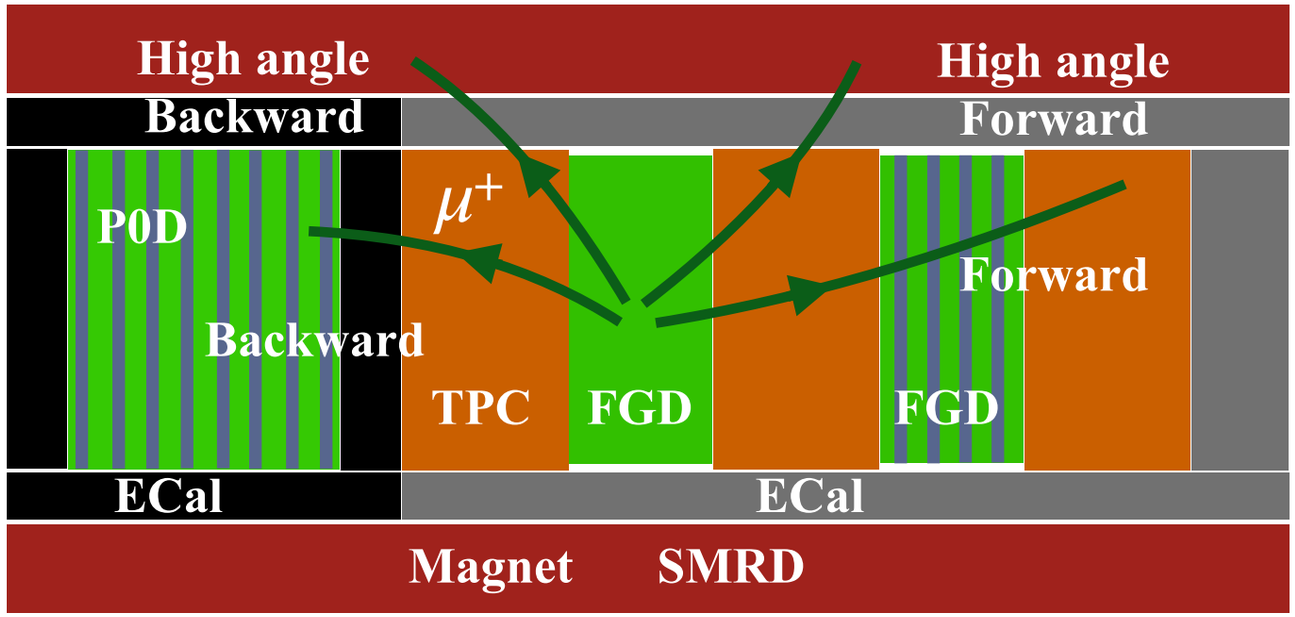




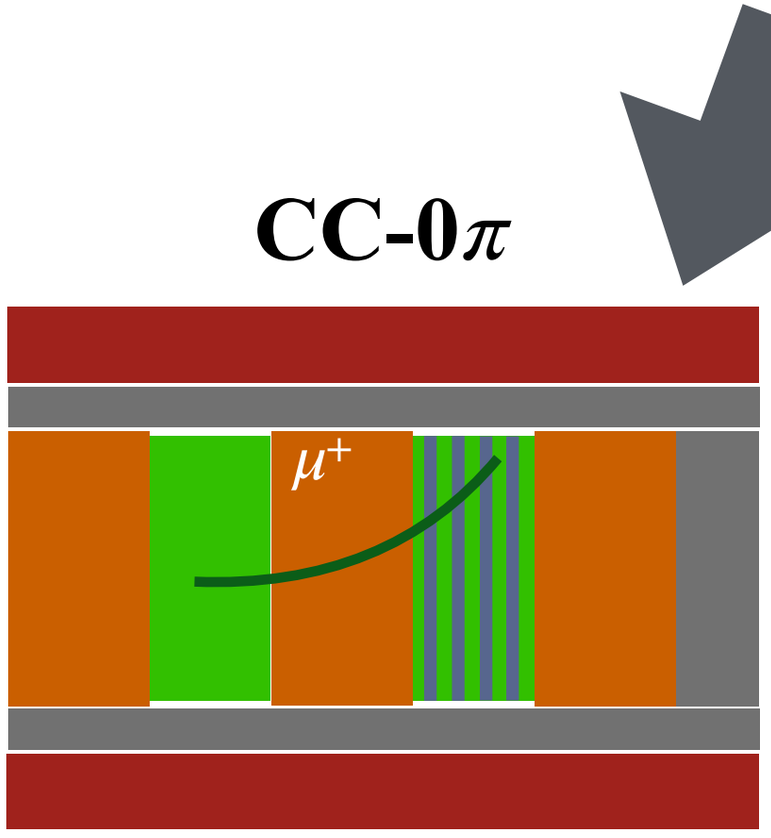
$\bar{\nu}_\mu$ selection strategy



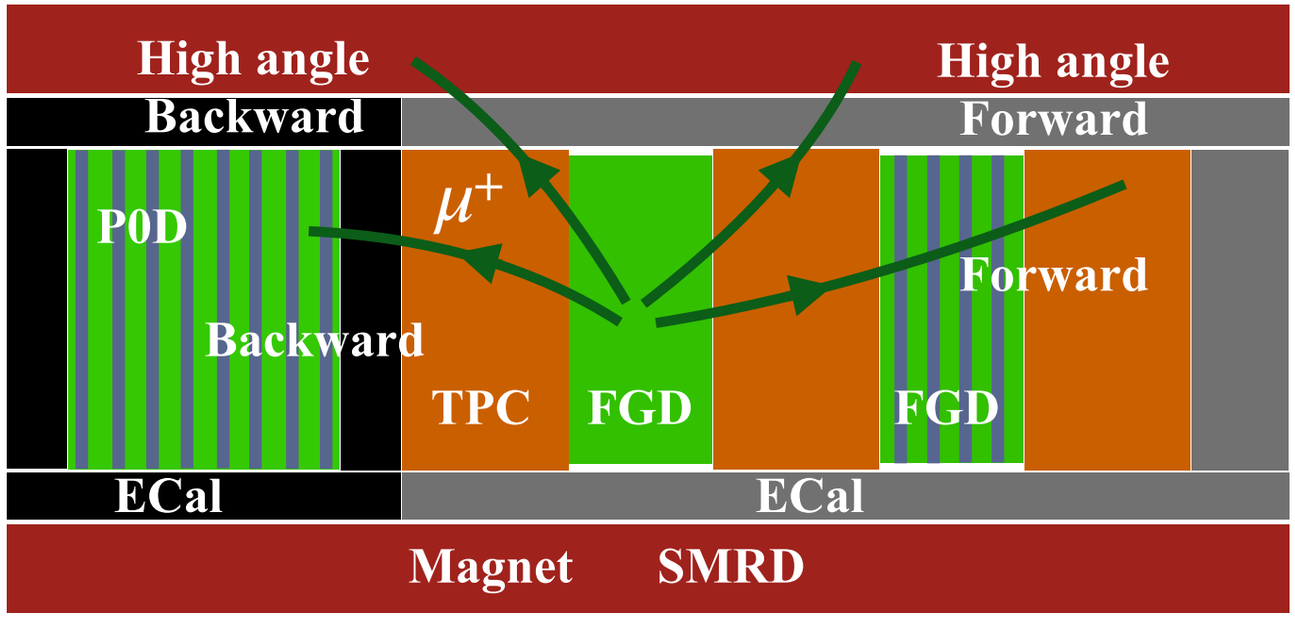
$\bar{\nu}_\mu$ selection strategy



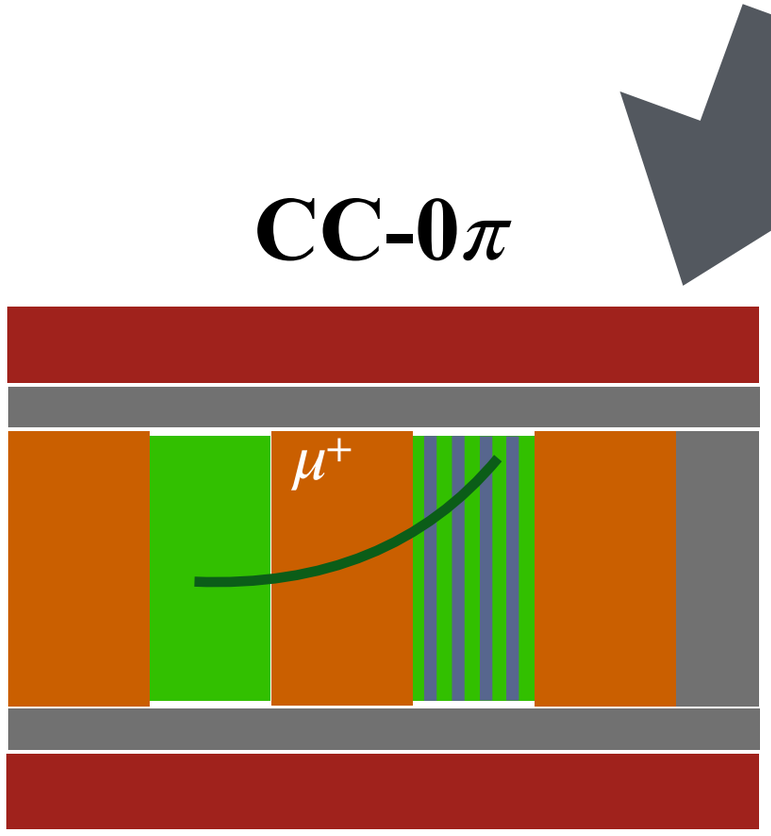
CC-0π



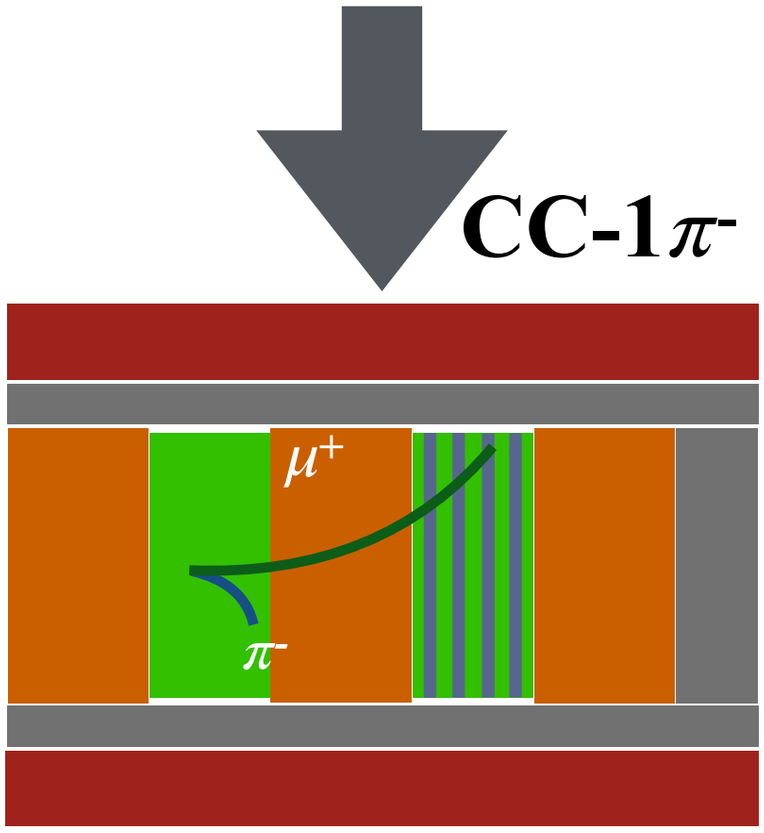
$\bar{\nu}_\mu$ selection strategy



CC-0π



CC-1π^-



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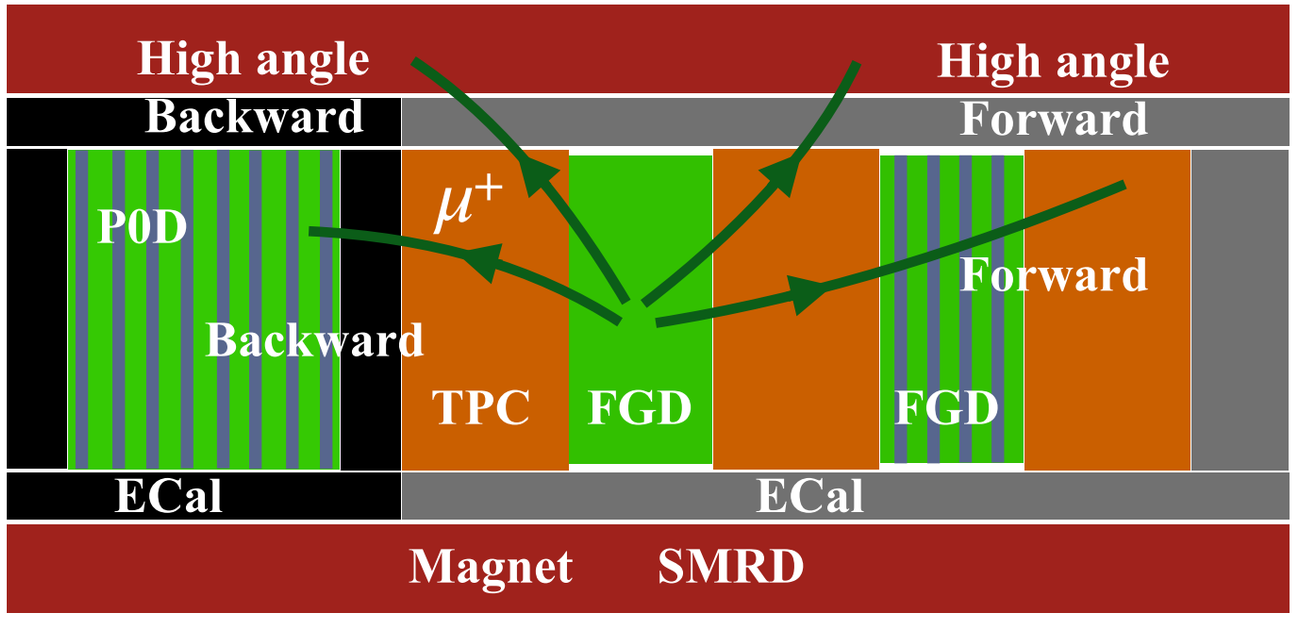
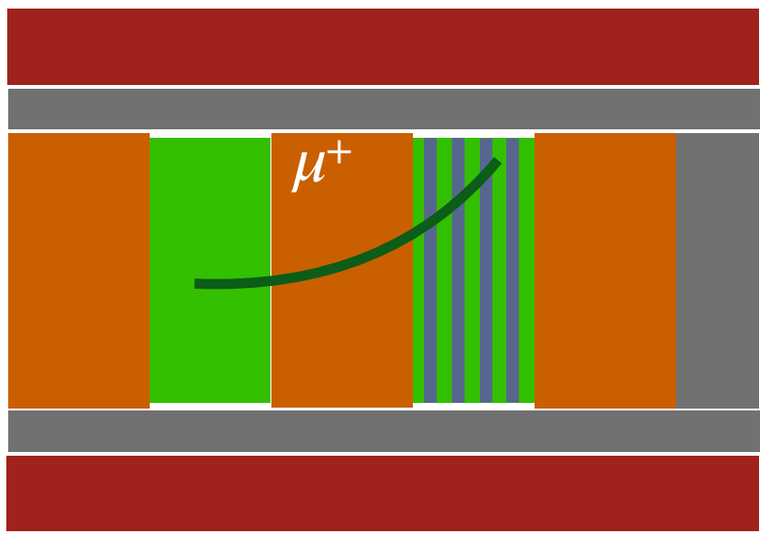
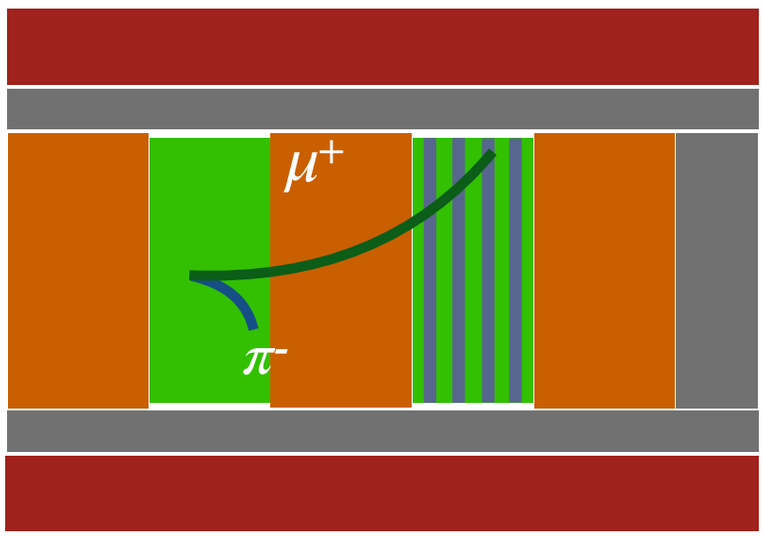


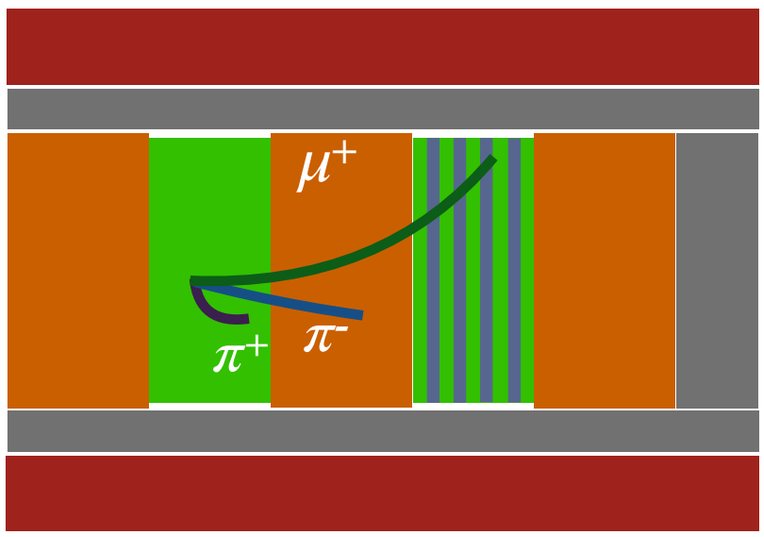
CC-0π



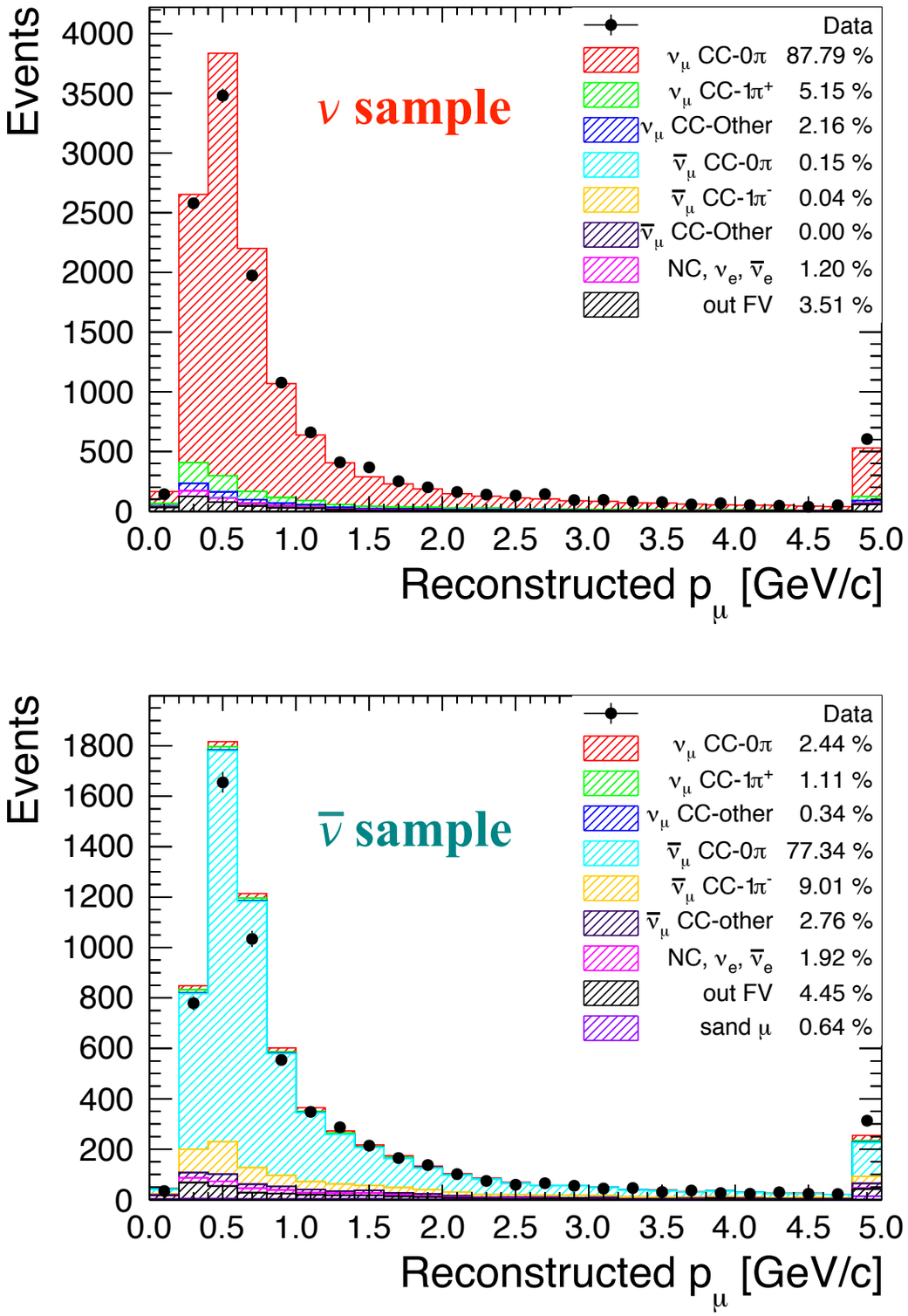
CC-1π^-

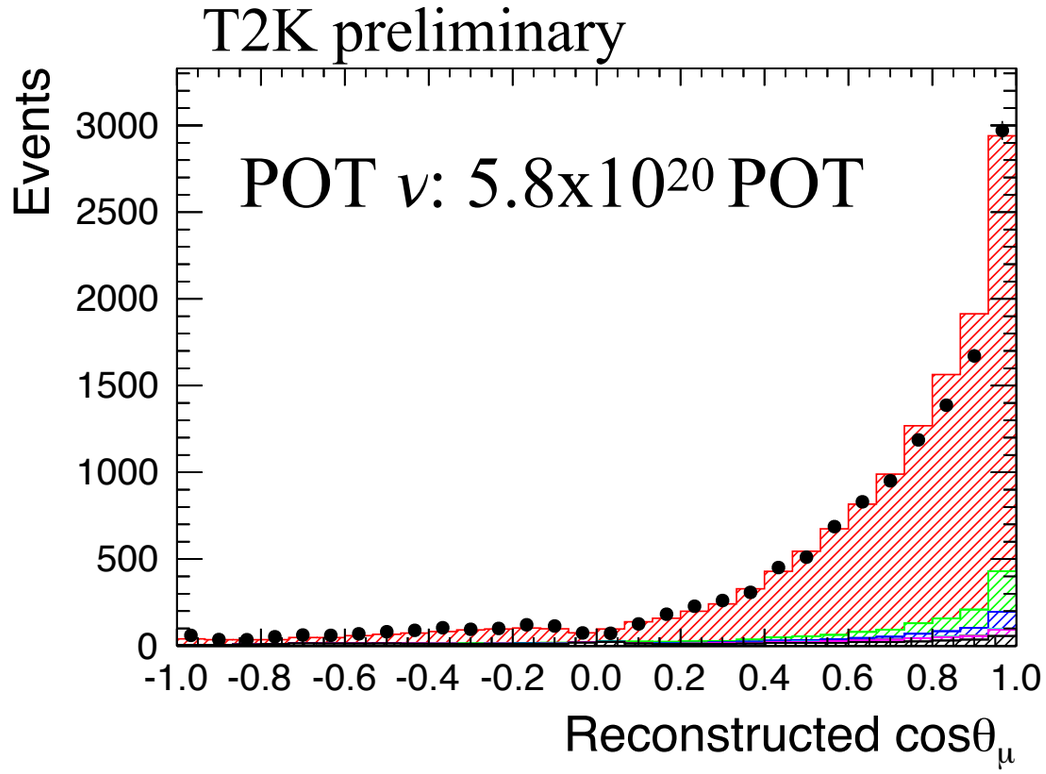


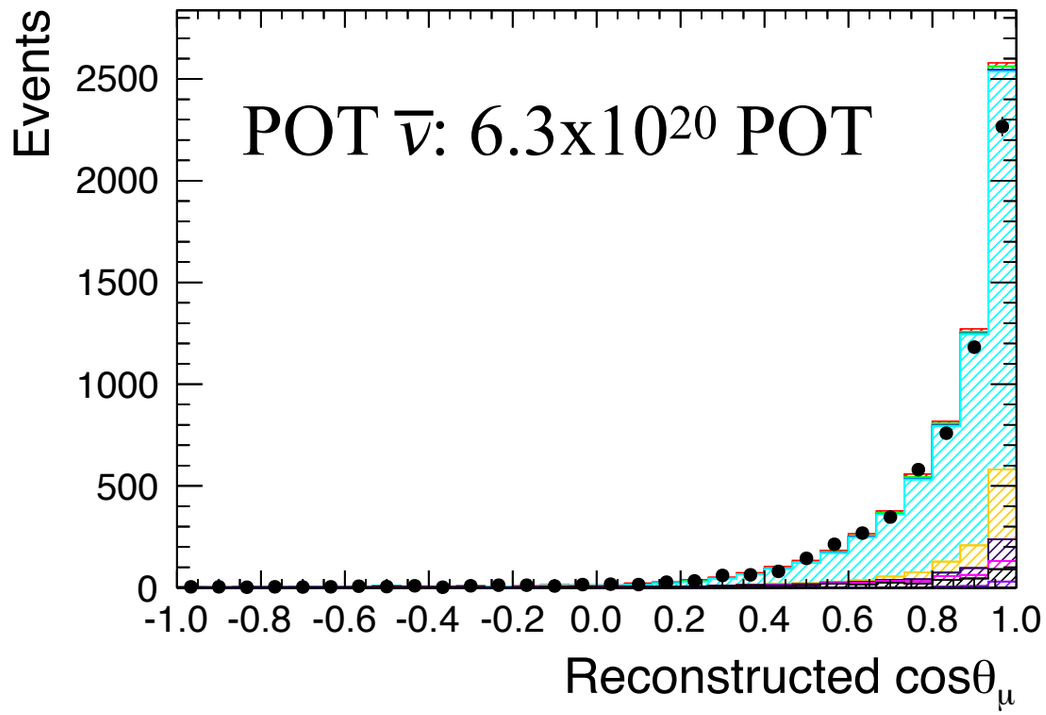
CC-Other



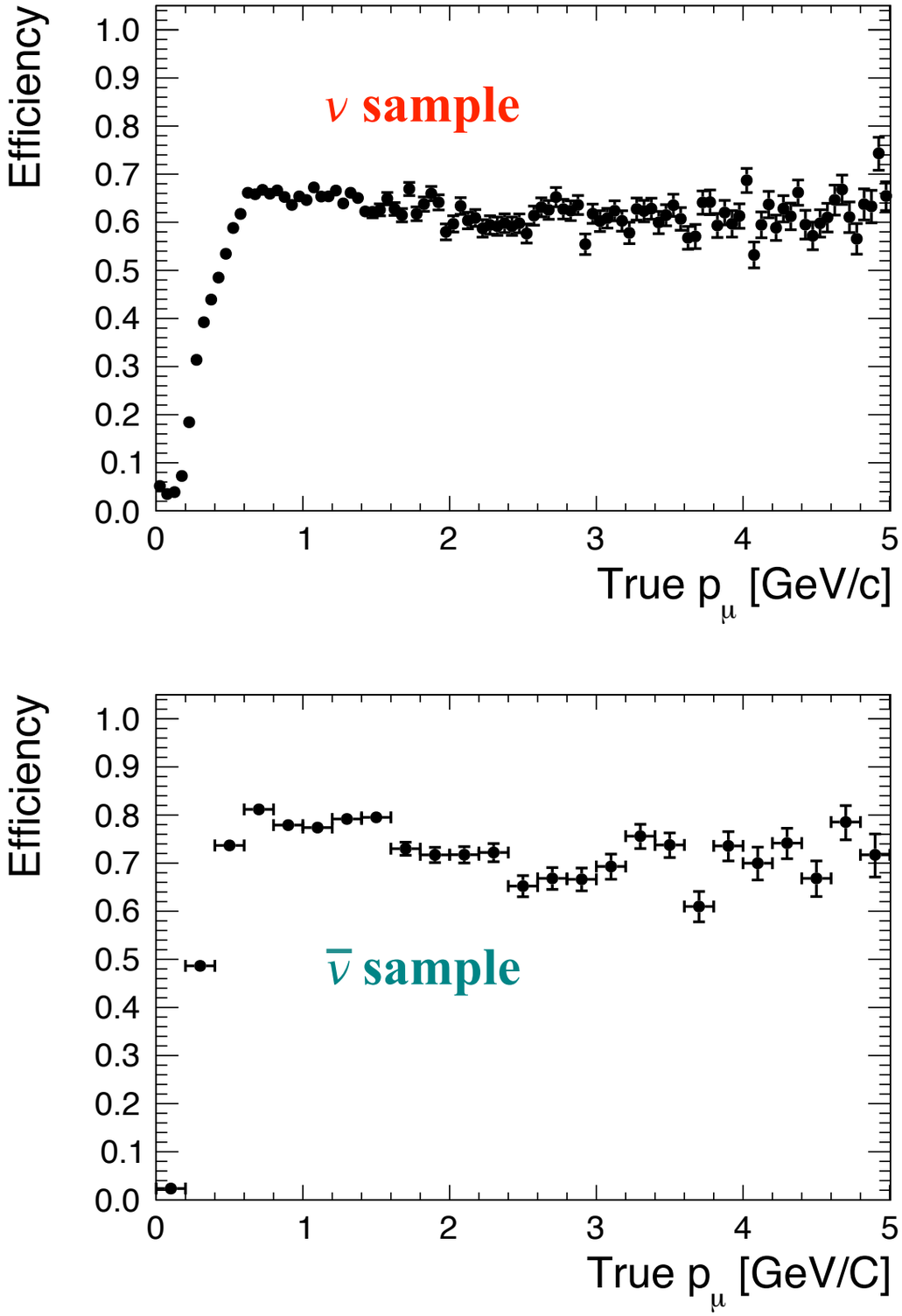
Signal distributions

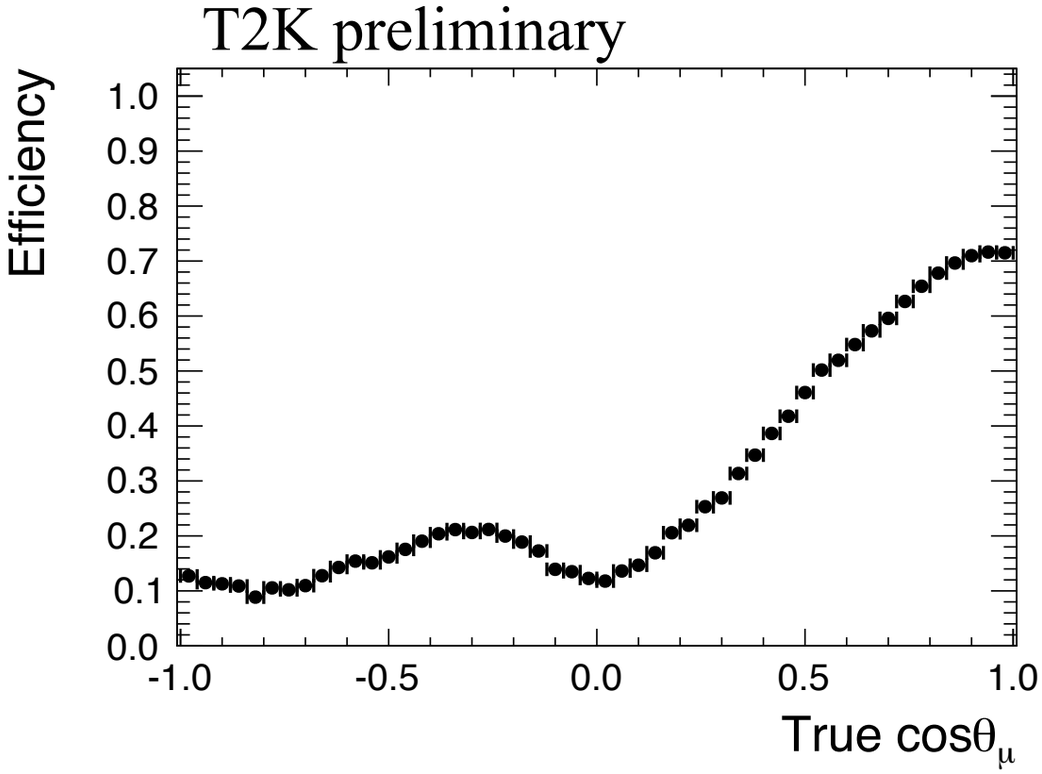


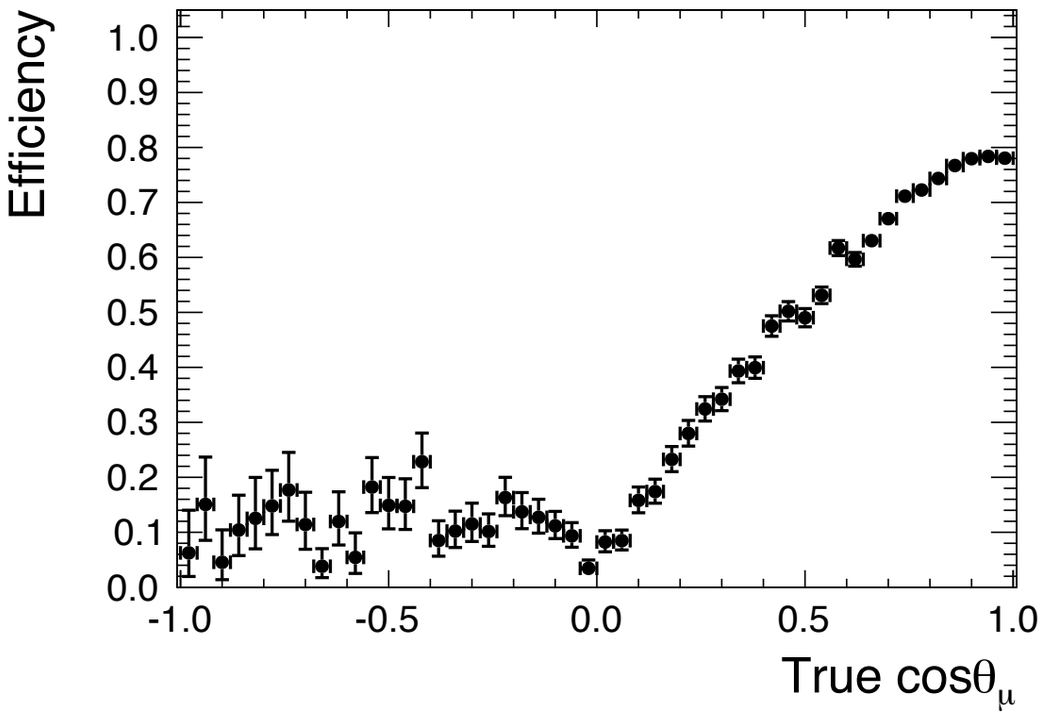




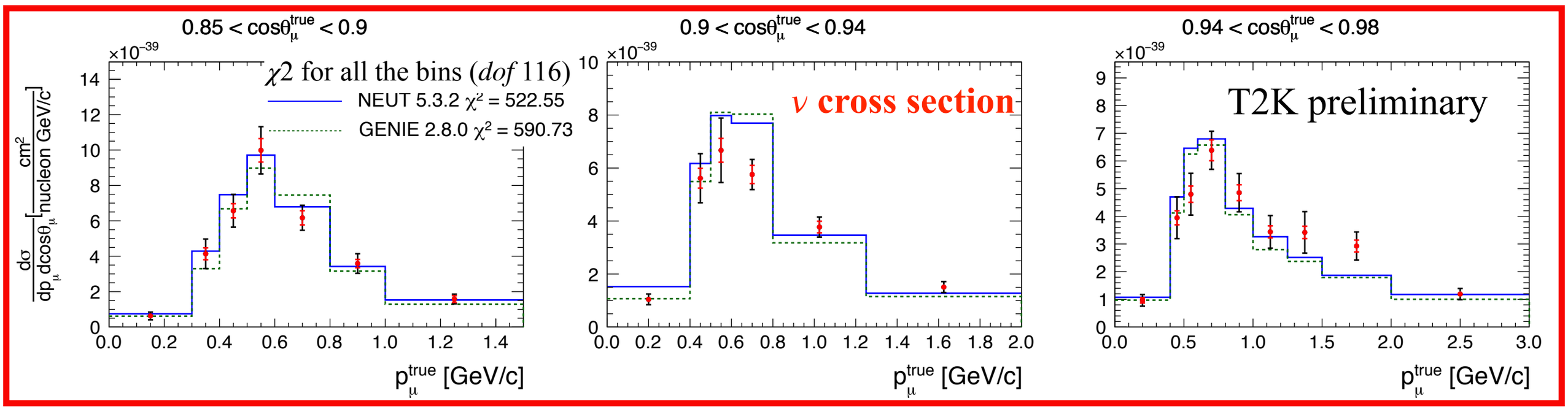
Signal efficiency

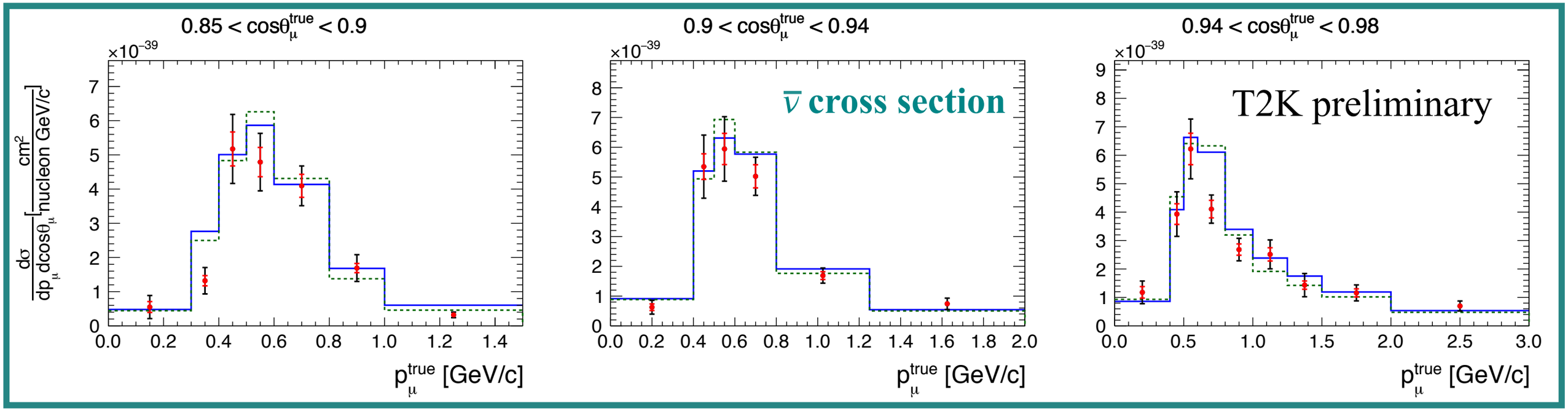






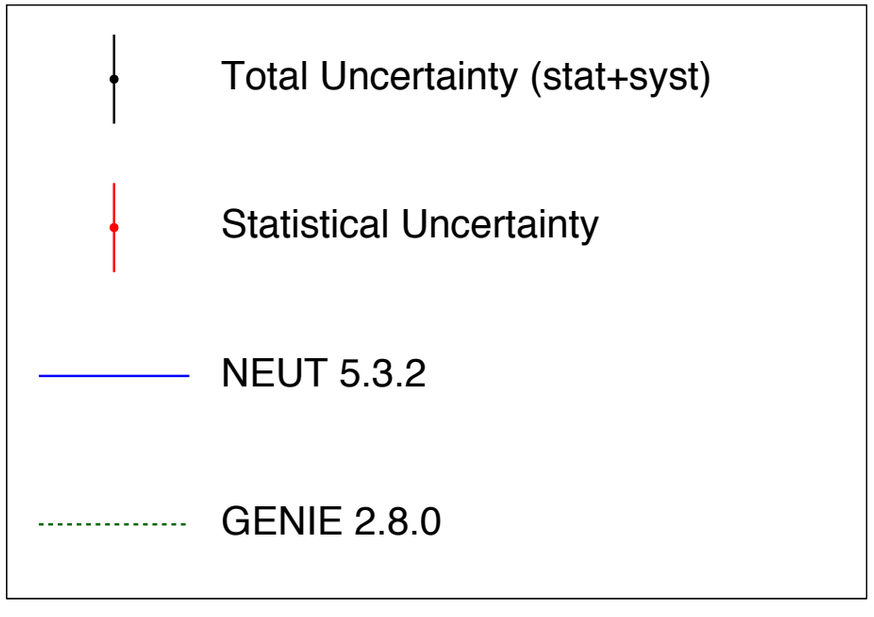
Data VS MC generators

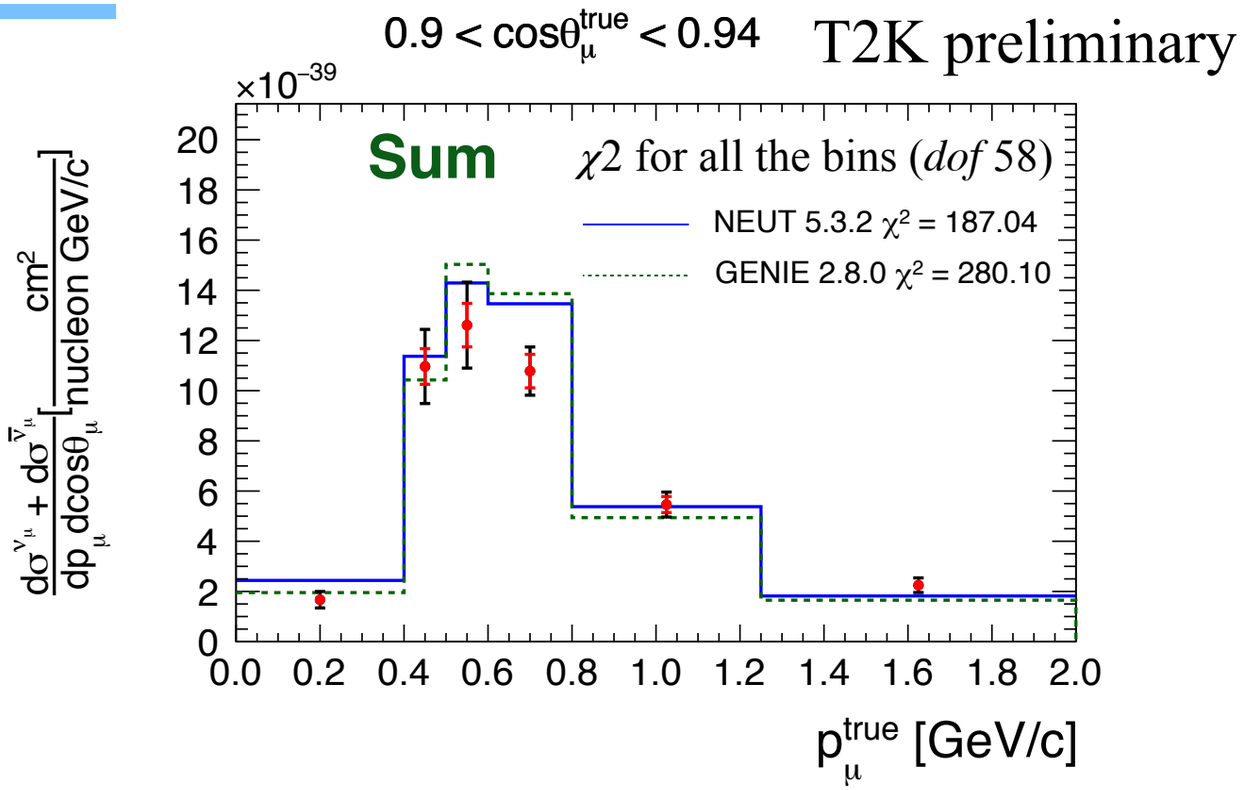


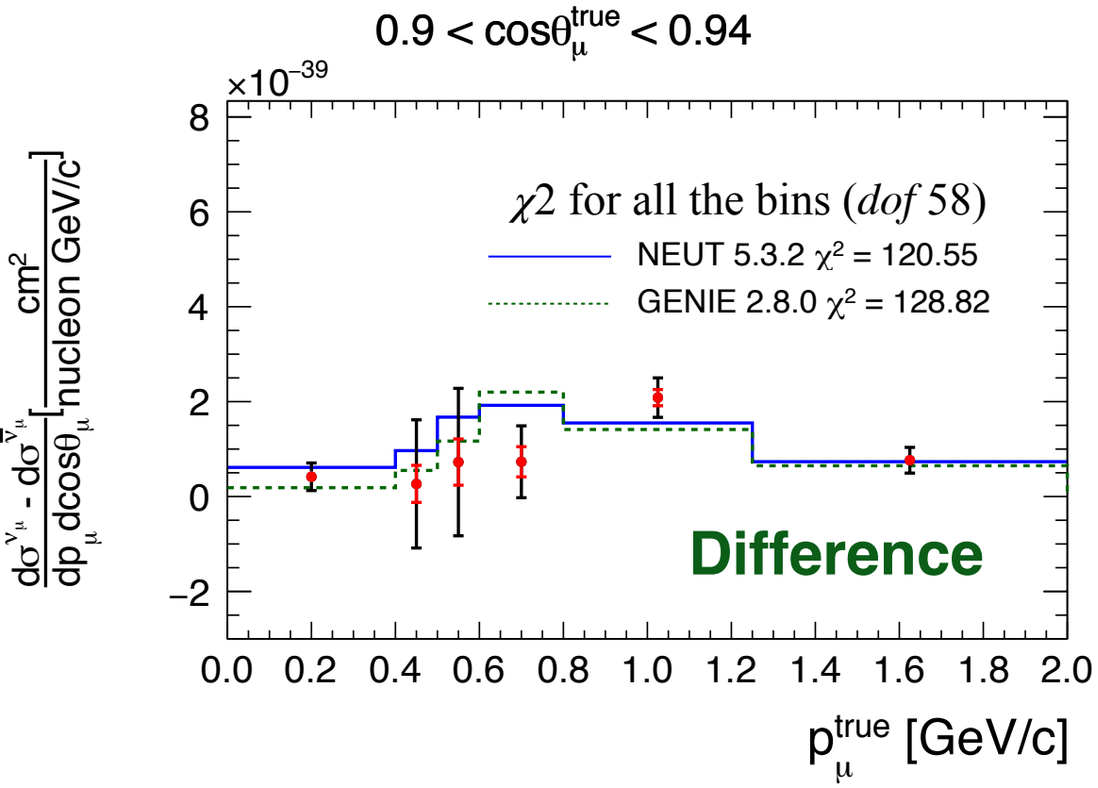


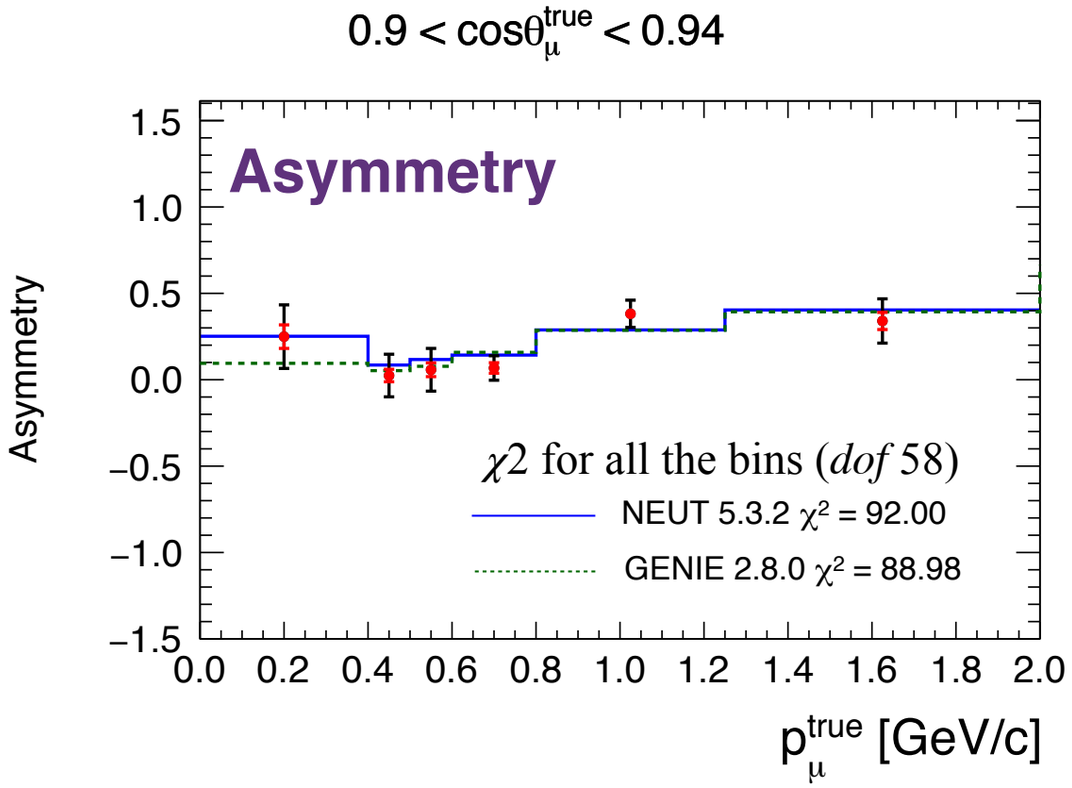
*Cross sections extracted for 58 bins both for neutrino and antineutrino

Data VS MC generators

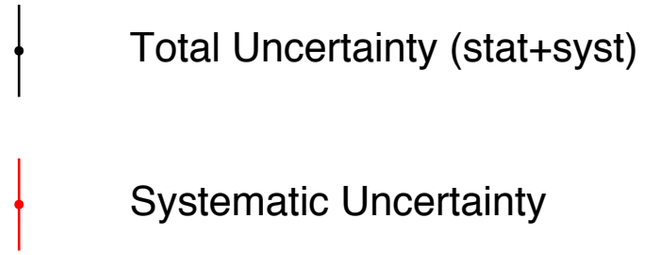


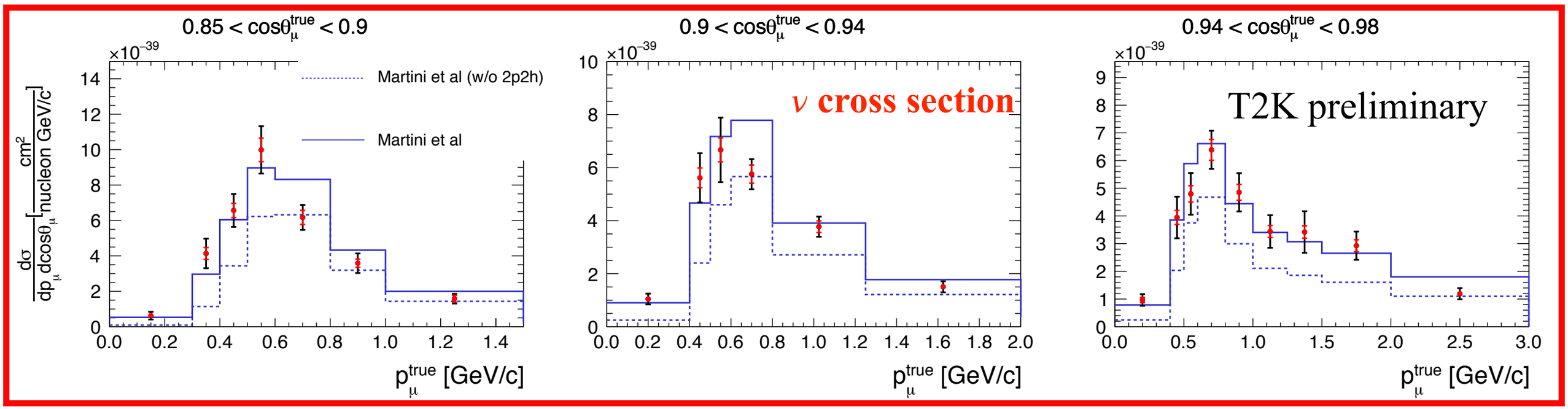


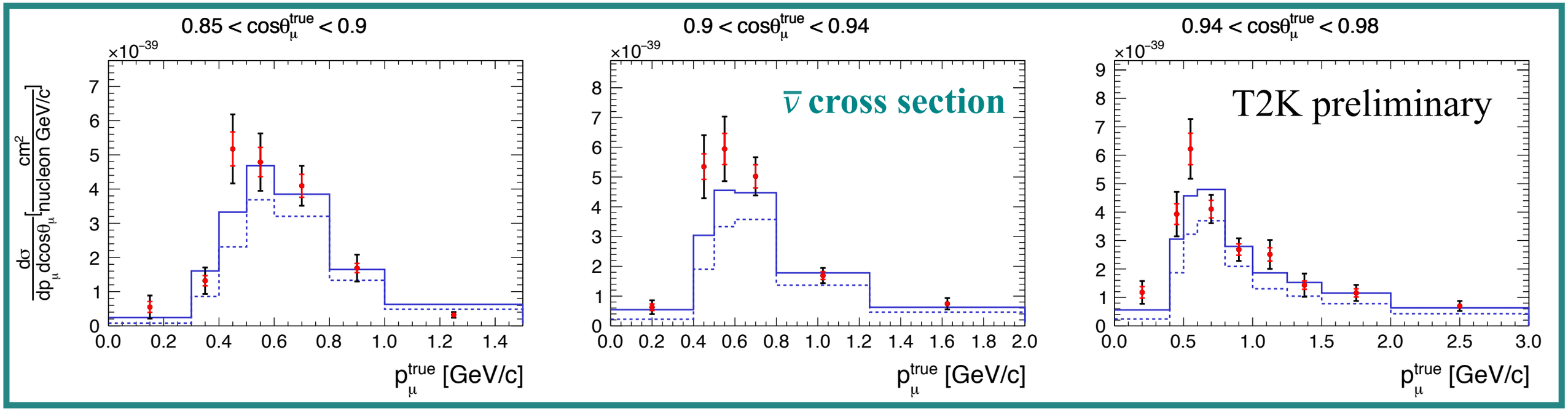




Data VS Martini et al.







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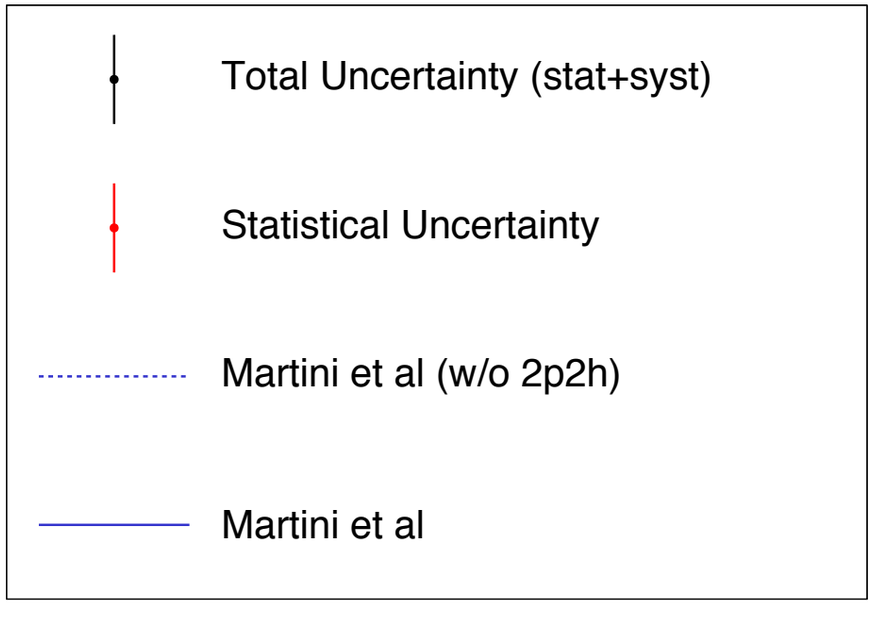

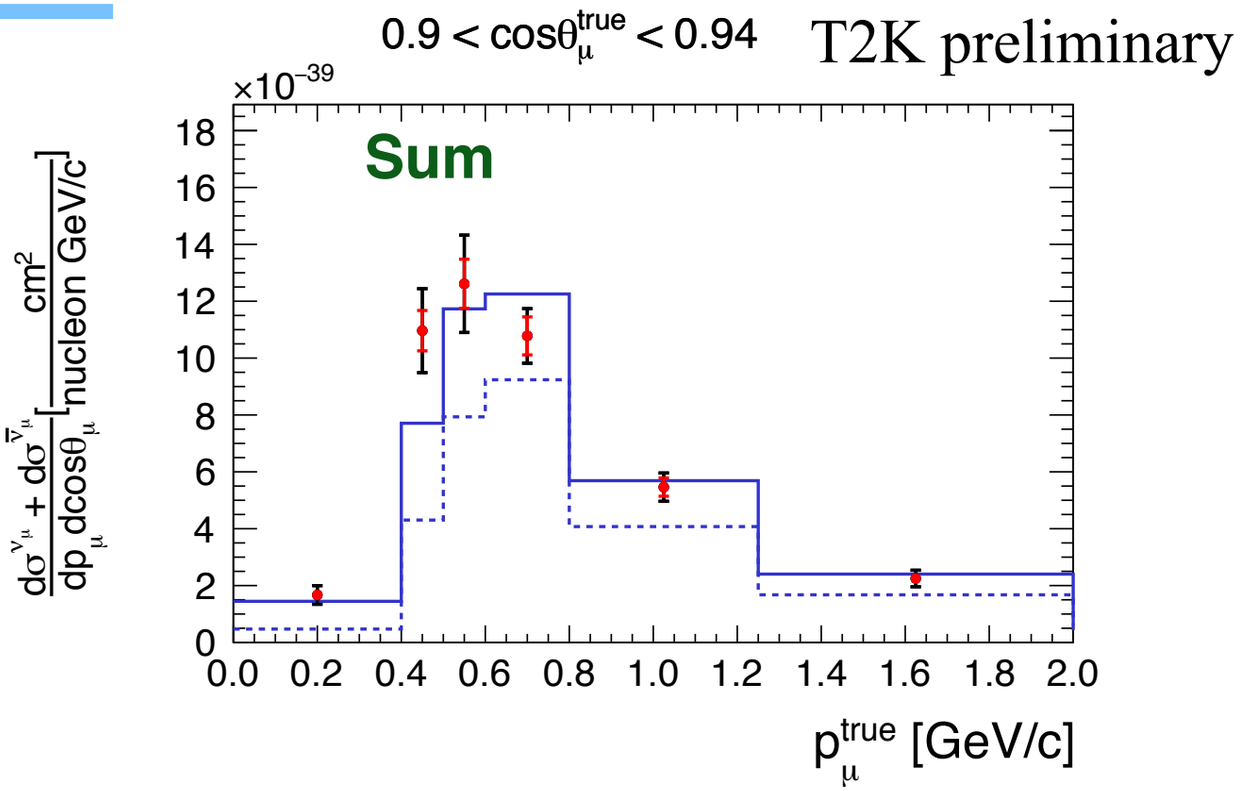

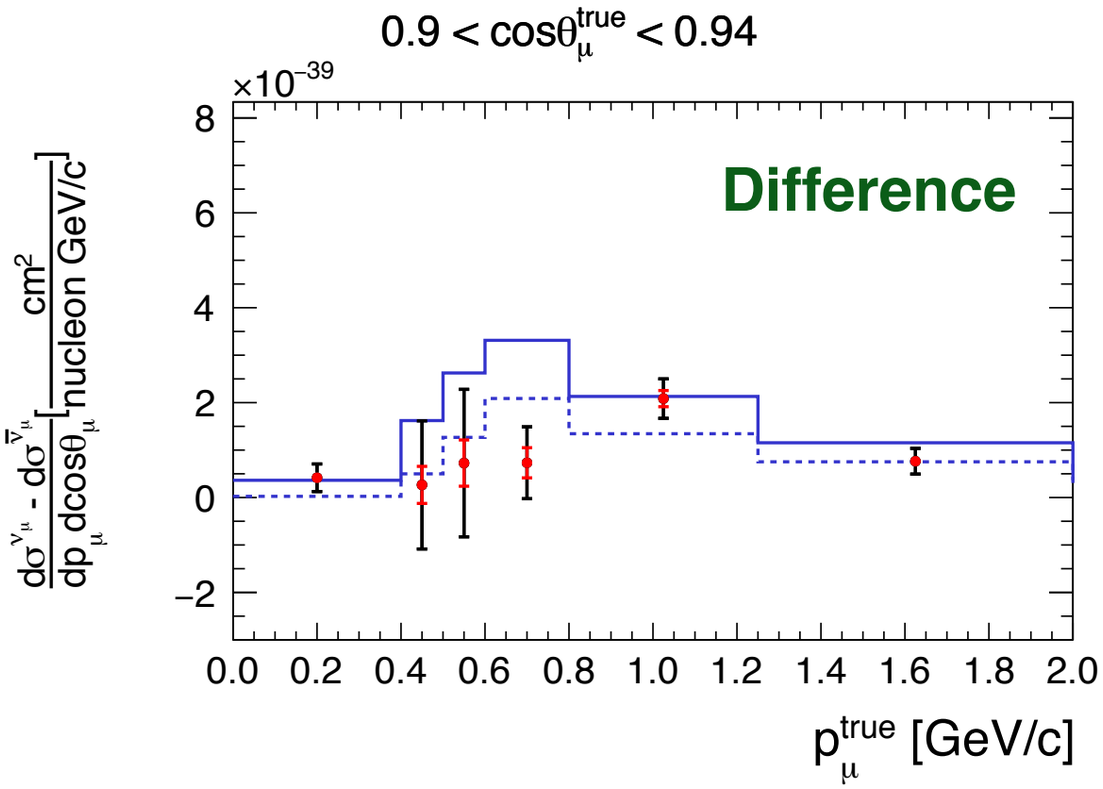

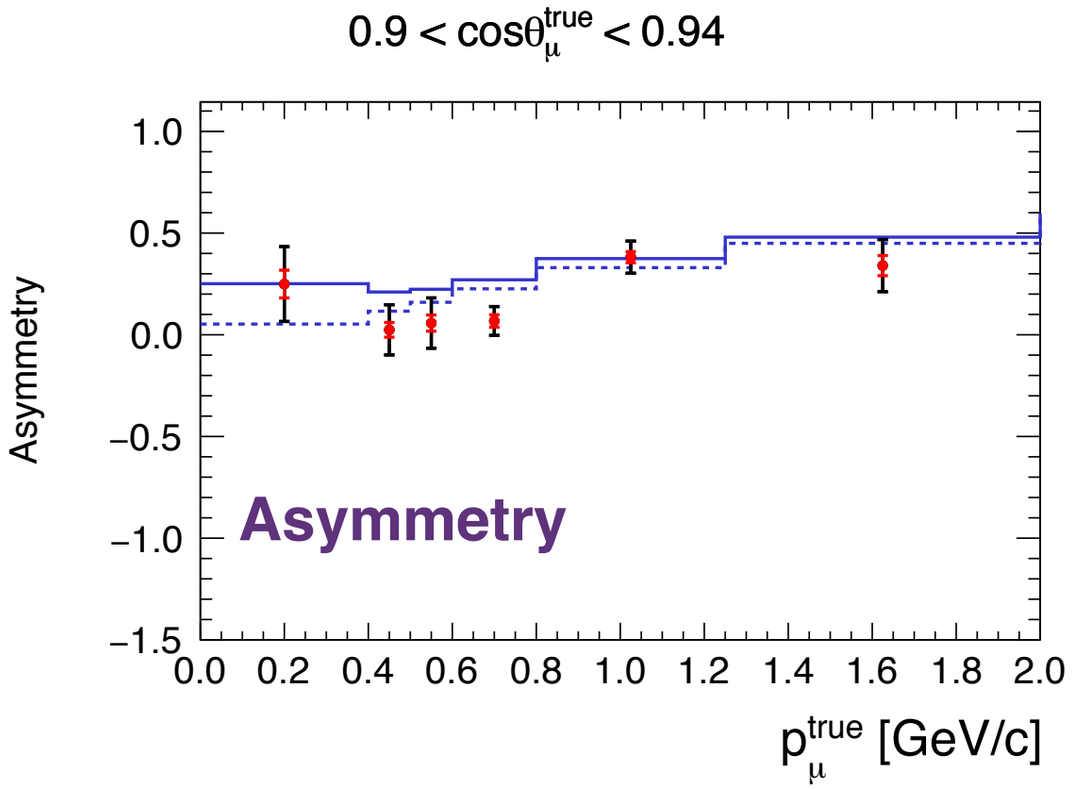

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- Nuclear effect are difficult to measure, but new and more accurate measurements will help
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- This result will be compared also with other generators and models in order to highlight the differences in the generators
- Stay tuned for more comparisons!

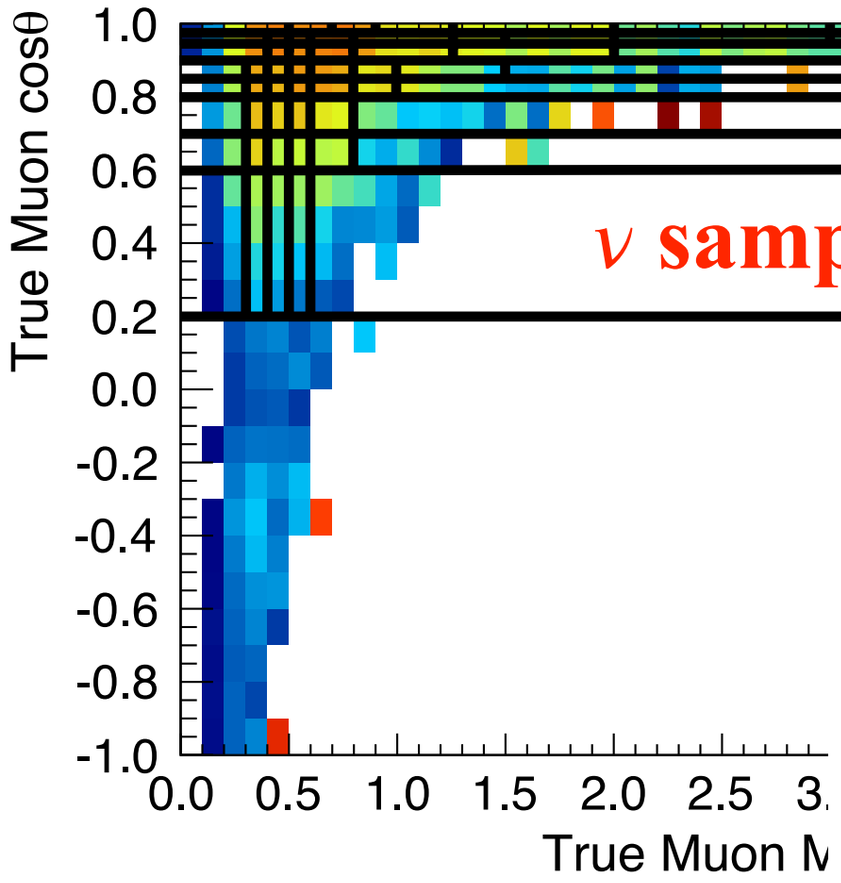
Thank you for your attention

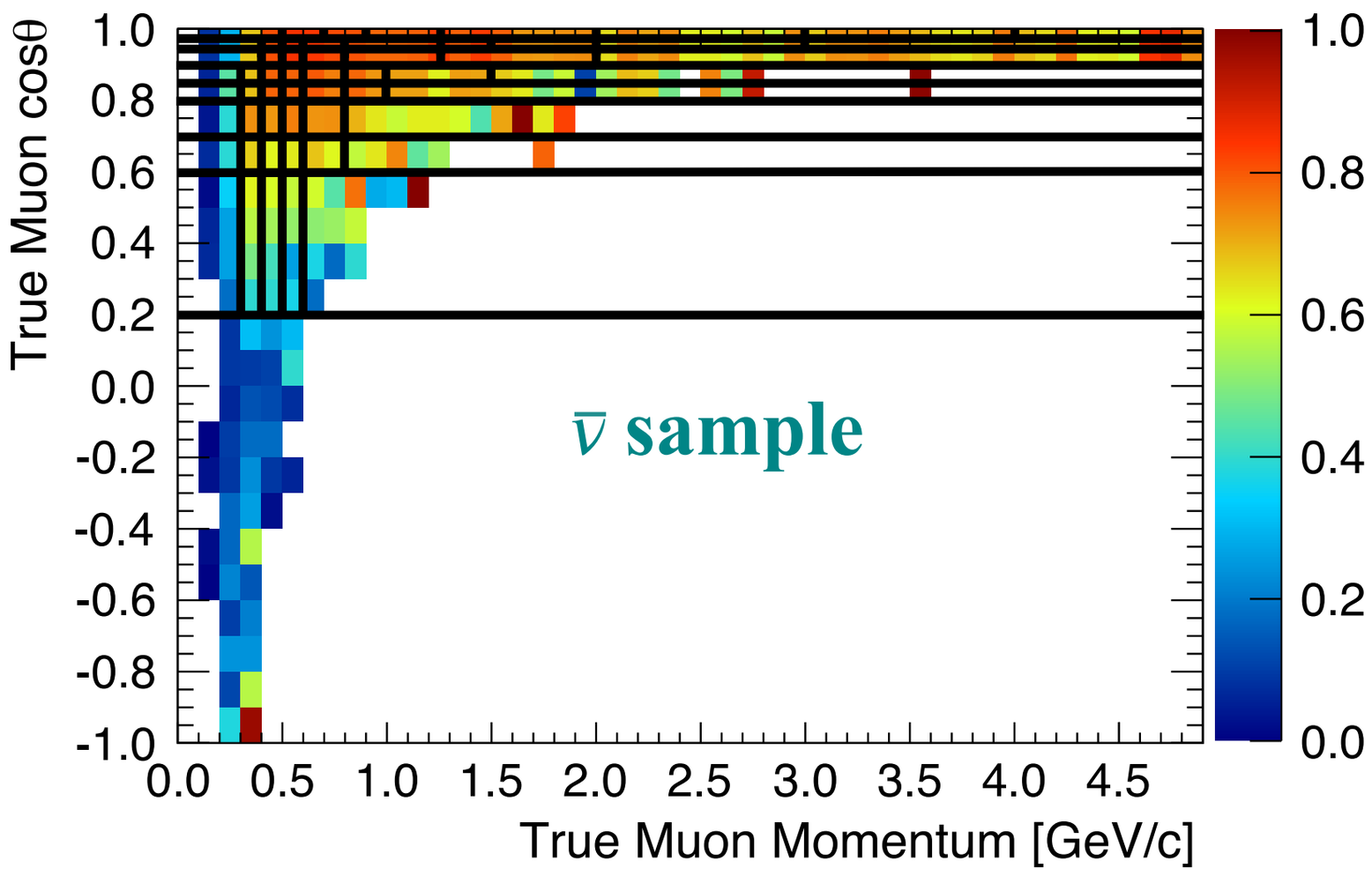
Backup

Event generators: details

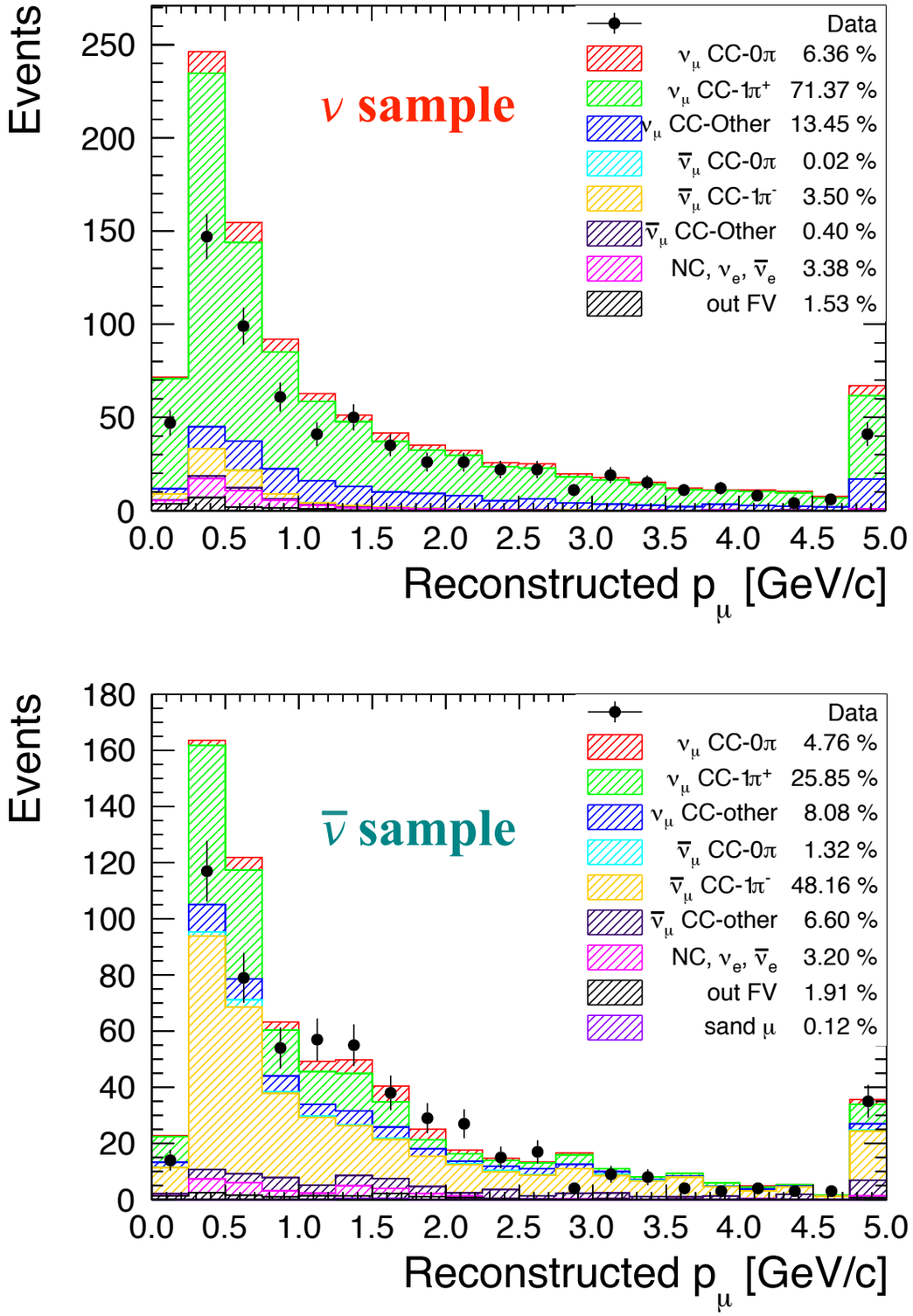
	NEUT 5.3.2	GENIE 2.8.0
CCQE	SF (Benhar et al., 2000) BBA05 (Bradford et al., 2005) M_A^{QE} = 1.21 GeV/c^2 p_F [^{12}C] = 217 MeV/c E_B [^{12}C] = 25 MeV	RFG (Bodek et al., 1981) BBA05 (Bradford et al., 2005) M_A^{QE} = 0.99 GeV/c^2 p_F [^{12}C] = 221 MeV/c E_B [^{12}C] = 25 MeV
2p2h	Nieves et al., 2011	-
CCRES	W<2 GeV Rein-Sehgal, 1981 FF (Graczyk et al., 2008)	W<1.7 GeV Rein-Sehgal, 1981 FF (Kuzmin et al., 2016)
CCDIS	W>1.3 GeV (w/o single π) GRV98 PDF (Glück et al. 1998) BY corr. at low Q2 (Bodek et al. 2003)	W>1.7 GeV (for W<1.7 GeV is tuned) GRV98 PDF (Glück et al. 1998) BY corr. at low Q2 (Bodek et al. 2005)
Hadronization	W < 2 GeV KNO scaling (Koba et al. 1972) W > 2 GeV PYTHIA/JETSET	W < 2.3 GeV AGKY (Koba et al. 1972) 2.3 GeV < W < 3 GeV AGKY (Koba et al. 1972) + PYTHIA/JETSET W > 3 GeV PYTHIA/JETSET
FSI	Intra-nuclear cascade	Intra-nuclear cascade (INTRANUKE hA)

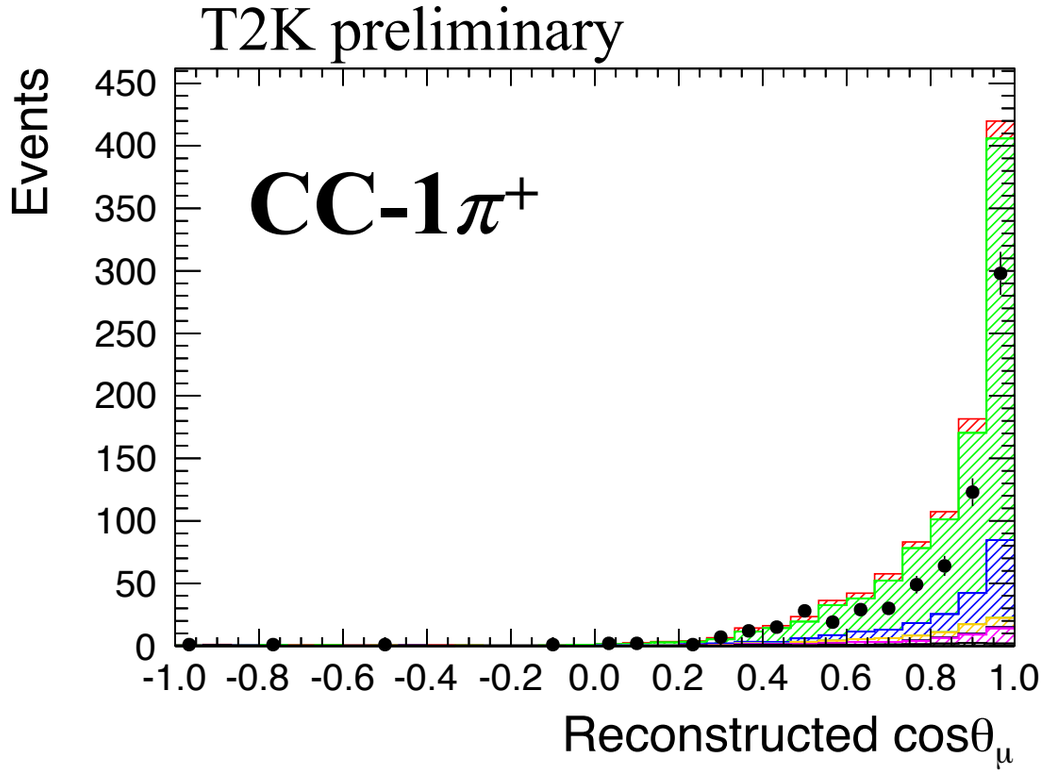
Signal region: 2D efficiency

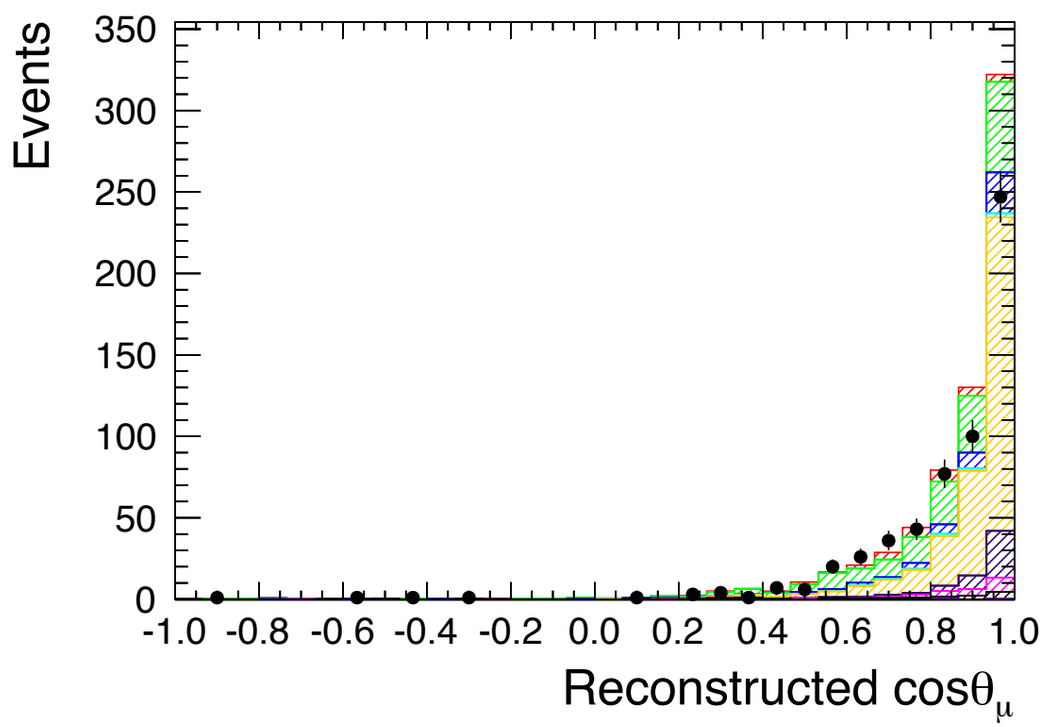




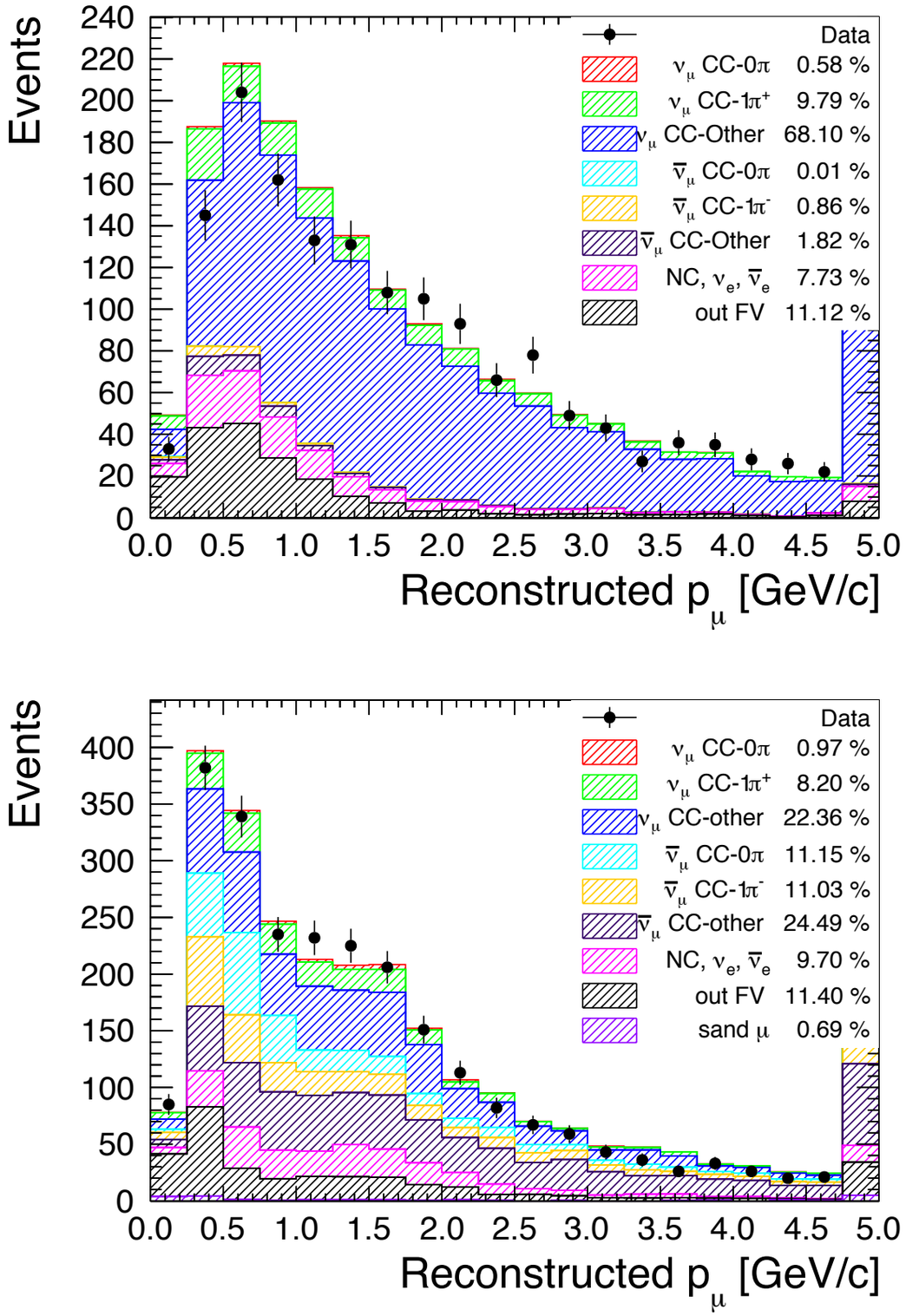
Control samples I

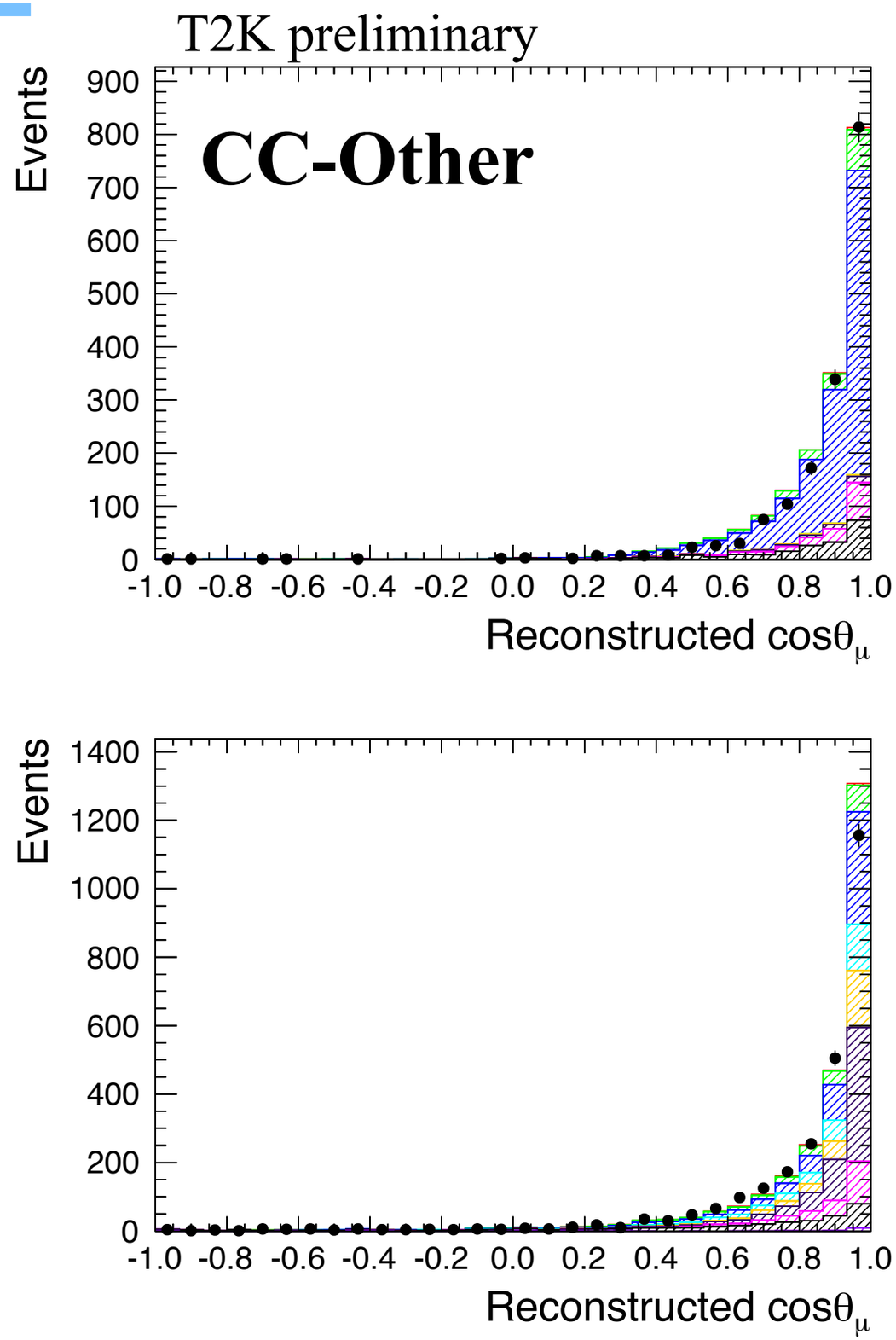




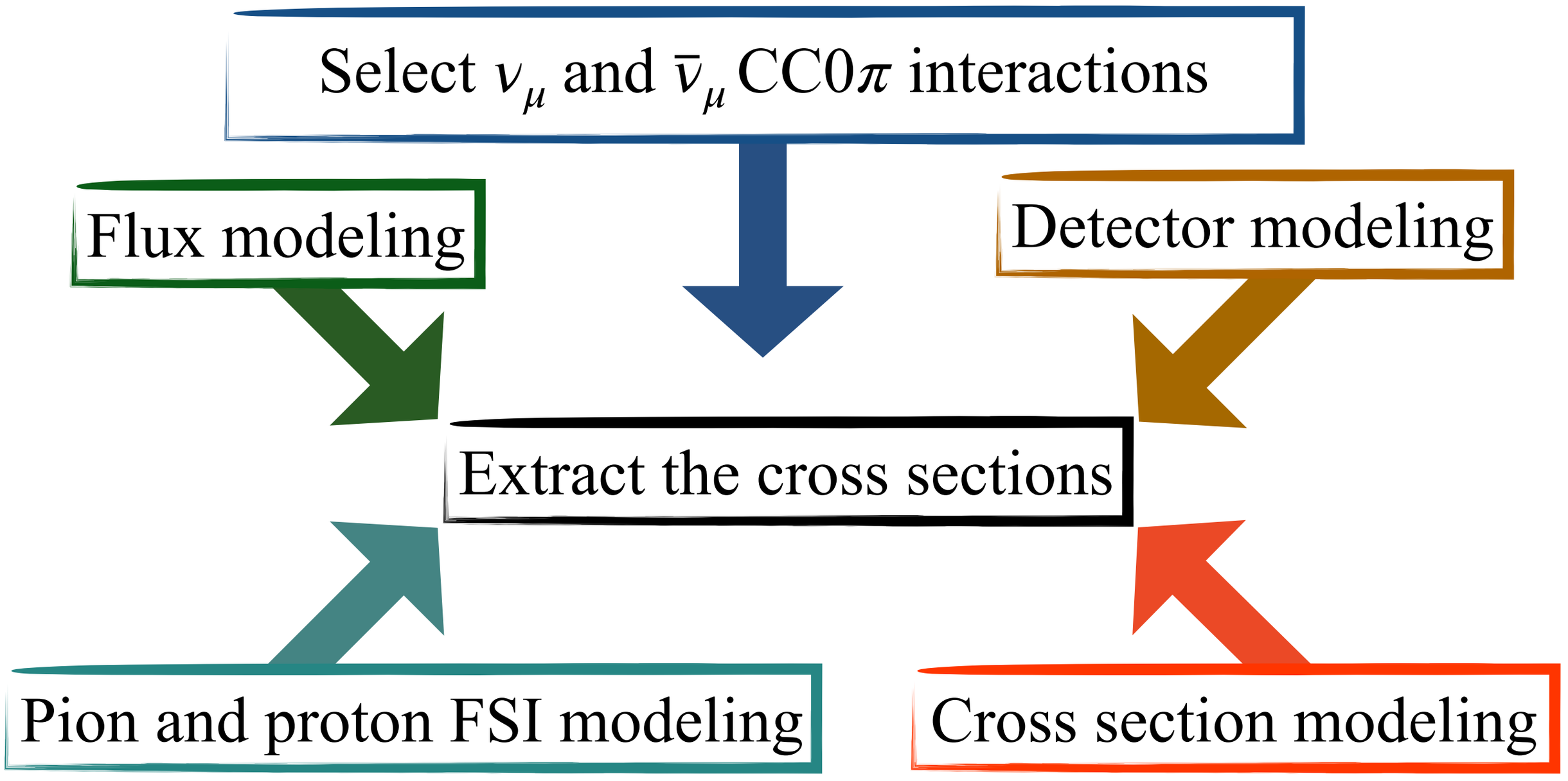


Control samples II





Analysis Strategy



Analysis Strategy

$$\chi^2 = \chi^2_{\text{stat}} + \chi^2_{\text{syst}} = \sum_{j}^{\text{reco bins}} 2\left(N_j^{\nu_\mu} - N_j^{\nu_\mu\ \text{obs}} + N_j^{\nu_\mu\ \text{obs}} \ln \frac{N_j^{\nu_\mu\ \text{obs}}}{N_j^{\nu_\mu}} \right) \quad \nu \text{ sample}$$

$$+ \sum_{j}^{\text{reco bins}} 2\left(N_j^{\bar{\nu}_\mu} - N_j^{\bar{\nu}_\mu\ \text{obs}} + N_j^{\bar{\nu}_\mu\ \text{obs}} \ln \frac{N_j^{\bar{\nu}_\mu\ \text{obs}}}{N_j^{\bar{\nu}_\mu}} \right) \quad \bar{\nu} \text{ sample}$$

$$+ \sum_{p} (\vec{p} - \vec{p}_{\text{prior}}) \left(V_{\text{cov}}^{\text{syst}}\right)^{-1} (\vec{p} - \vec{p}_{\text{prior}})$$

$$N_j = \sum_{i}^{\text{true bins}} [c_i^{\nu_\mu} \left(N_i^{\text{MC}\ \nu_\mu\ \text{CC-0}\pi} \prod_{s}^{\text{model}} w(s)_I^{\nu_\mu CC-0\pi} \right) +$$

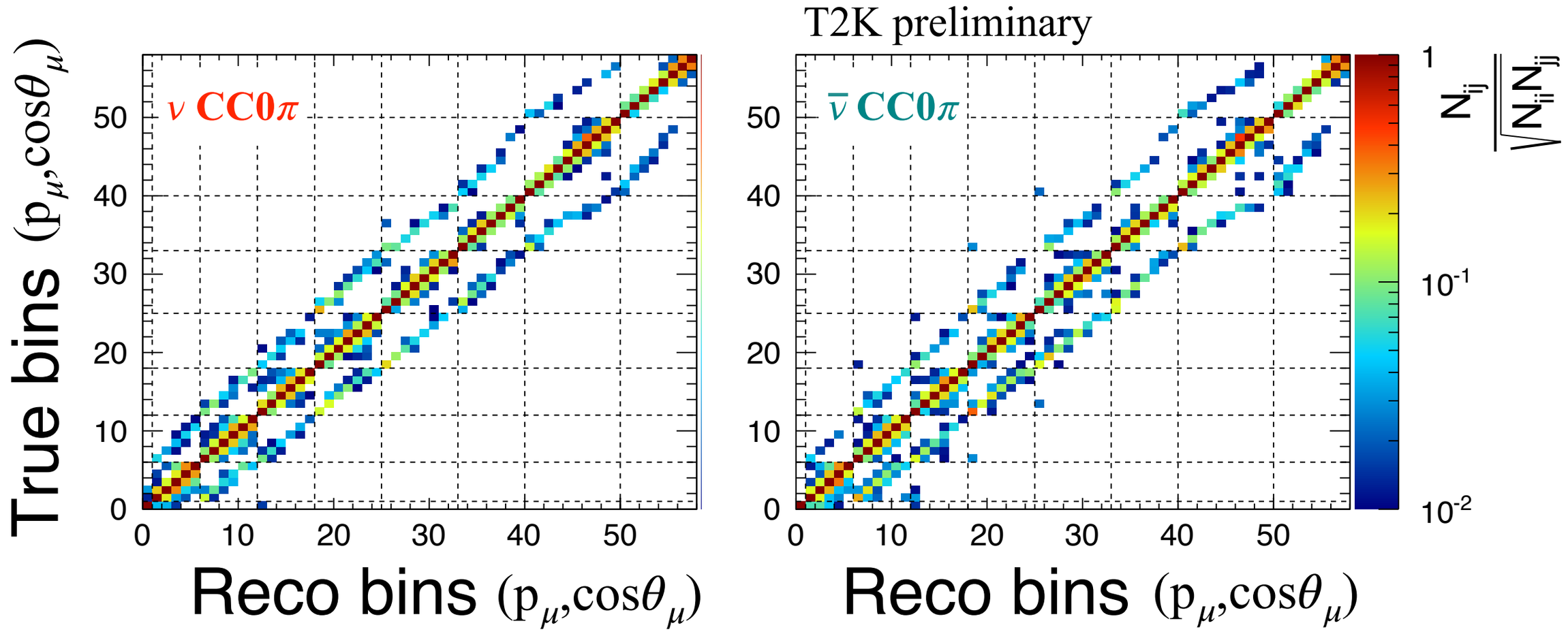
$$c_i^{\bar{\nu}_\mu} \left(N_i^{\text{MC}\ \bar{\nu}_\mu\ \text{CC-0}\pi} \prod_{s}^{\text{model}} w(s)_I^{\bar{\nu}_\mu CC-0\pi} \right) +$$

$$\sum_{k}^{\text{bkg reactions}} N_i^{\text{MC bkg } k} \prod_{b}^{\text{model}} w(b)_i^k] t_{ij}^{\text{det}} r_j \sum_{n}^{\text{E}_{\nu_\mu \text{ or } \bar{\nu}_\mu}} w_n^i f_n$$

Binning definition

The binning choice as been driven by the following requirements:

- Avoid big fluctuations in the statistical uncertainties
- The bin width must be always greater than the resolution of the variables under consideration.
- Have transfer matrix diagonal as much as possible



Analysis binning

Bin index	$\cos\theta_\mu$	p_μ [GeV/c]
0	-1, 0.2	0, 30
1	0.2, 0.6	0, 0.3
2	0.2, 0.6	0.3, 0.4
3	0.2, 0.6	0.4, 0.5
4	0.2, 0.6	0.5, 0.6
5	0.2, 0.6	0.6, 30
6	0.6, 0.7	0, 0.3
7	0.6, 0.7	0.3, 0.4
8	0.6, 0.7	0.4, 0.5
9	0.6, 0.7	0.5, 0.6
10	0.6, 0.7	0.6, 0.8
11	0.6, 0.7	0.8, 30
12	0.7, 0.8	0, 0.3
13	0.7, 0.8	0.3, 0.4
14	0.7, 0.8	0.4, 0.5
15	0.7, 0.8	0.5, 0.6
16	0.7, 0.8	0.6, 0.8
17	0.7, 0.8	0.8, 30
18	0.8, 0.85	0, 0.3
19	0.8, 0.85	0.3, 0.4
20	0.8, 0.85	0.4, 0.5
21	0.8, 0.85	0.5, 0.6
22	0.8, 0.85	0.6, 0.8
23	0.8, 0.85	0.8, 1.0
24	0.8, 0.85	1.0, 30
25	0.85, 0.9	0, 0.3
26	0.85, 0.9	0.3, 0.4
27	0.85, 0.9	0.4, 0.5
28	0.85, 0.9	0.5, 0.6

Bin index	$\cos\theta_\mu$	p_μ [GeV/c]
29	0.85, 0.9	0.6, 0.8
30	0.85, 0.9	0.8, 1.0
31	0.85, 0.9	1.0, 1.5
32	0.85, 0.9	1.5, 30
33	0.9, 0.94	0, 0.4
34	0.9, 0.94	0.4, 0.5
35	0.9, 0.94	0.5, 0.6
36	0.9, 0.94	0.6, 0.8
37	0.9, 0.94	0.8, 1.25
38	0.9, 0.94	1.25, 2.0
39	0.9, 0.94	2.0, 30
40	0.94, 0.98	0, 0.4
41	0.94, 0.98	0.4, 0.5
42	0.94, 0.98	0.5, 0.6
43	0.94, 0.98	0.6, 0.8
44	0.94, 0.98	0.8, 1.0
45	0.94, 0.98	1.0, 1.25
46	0.94, 0.98	1.25, 1.5
47	0.94, 0.98	1.5, 2.0
48	0.94, 0.98	2.0, 3.0
49	0.94, 0.98	3.0, 30
50	0.98, 1.0	0, 0.5
51	0.98, 1.0	0.5, 0.7
52	0.98, 1.0	0.7, 0.9
53	0.98, 1.0	0.9, 1.25
54	0.98, 1.0	1.25, 2.0
55	0.98, 1.0	2.0, 3.0
56	0.98, 1.0	3.0, 5.0
57	0.98, 1.0	5.0, 30

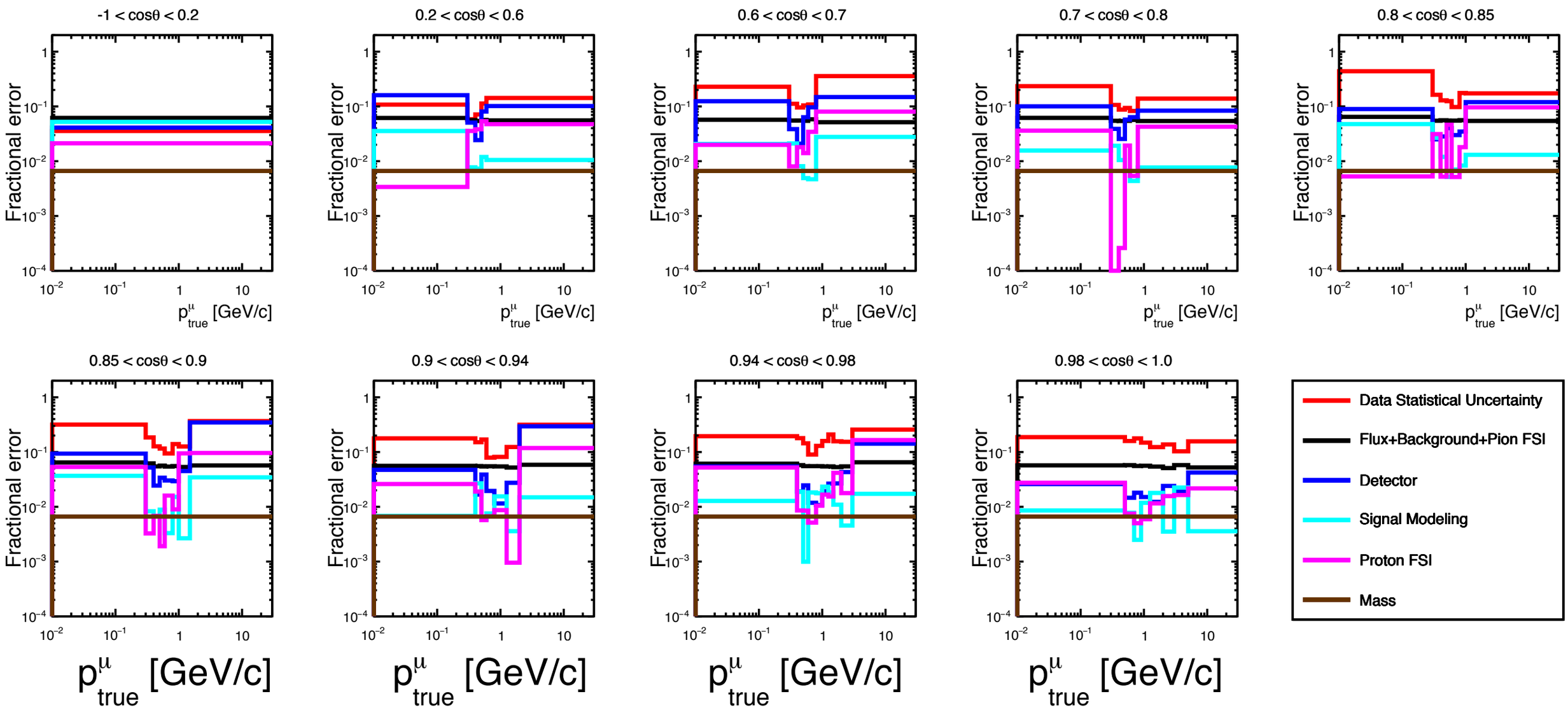
Uncertainties propagation and impact

Statistical uncertainty: vary the number of reconstructed events in each bin accordingly with a Poissonian obtaining a pseudo data sample that is fitted. Then the error is the RMS of the distribution of the results of the fit.

Systematics uncertainty: varying many times the parameters associated with systematic sources accordingly with their covariance matrices, it is possible to obtain a pseudo data sample that is fitted. Then the error is the RMS of the distribution of the results of the fit.

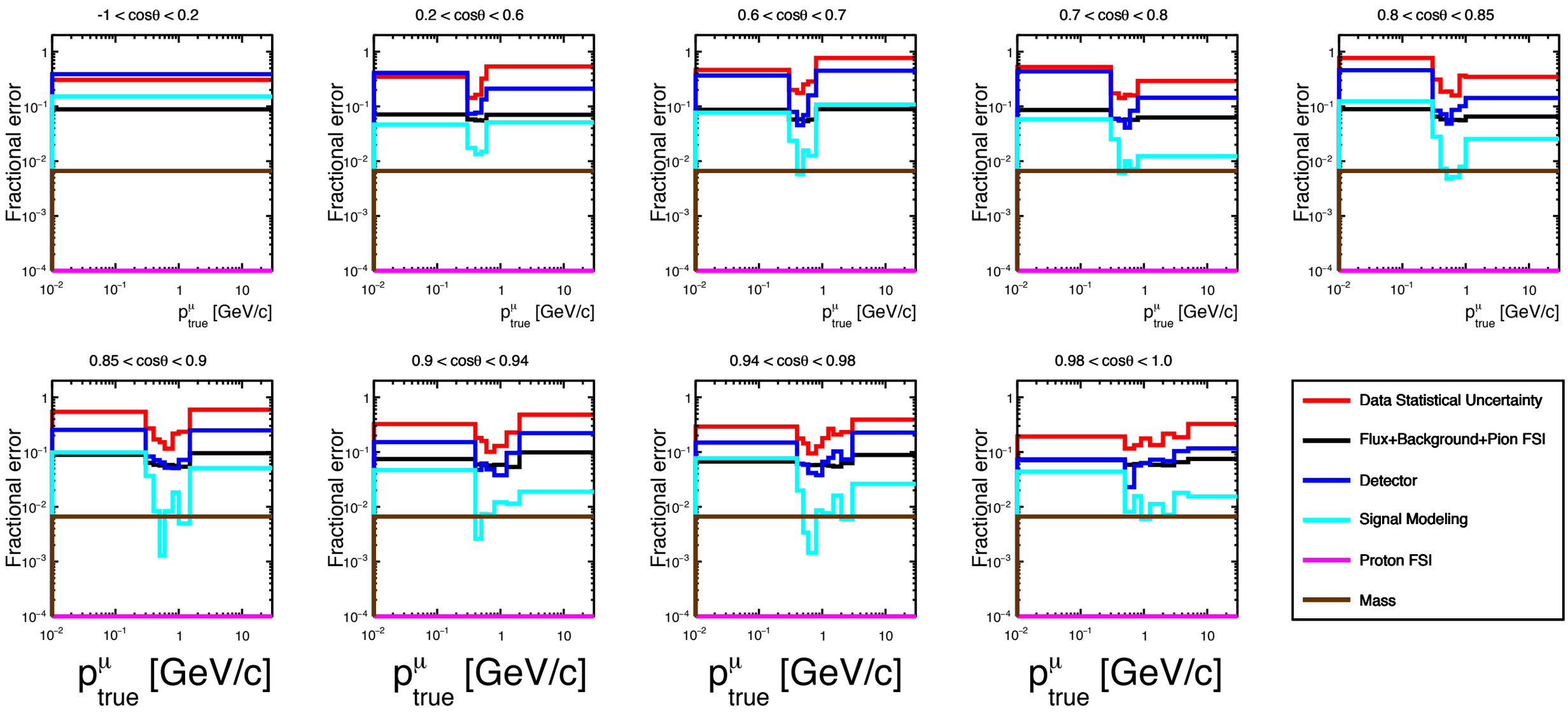
Fractional error ν_μ cross section

T2K preliminary



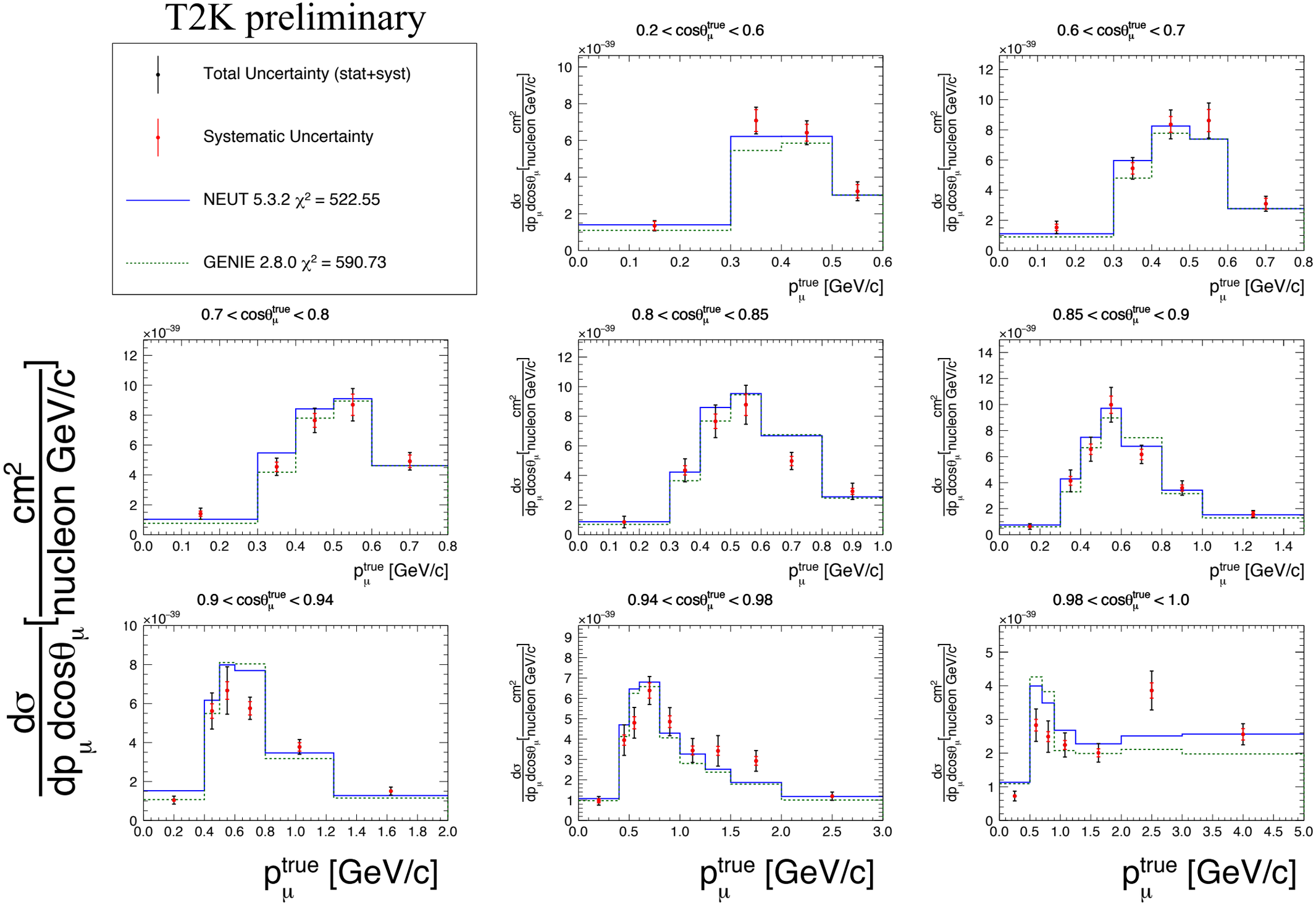
Fractional error $\bar{\nu}_\mu$ cross section

T2K preliminary



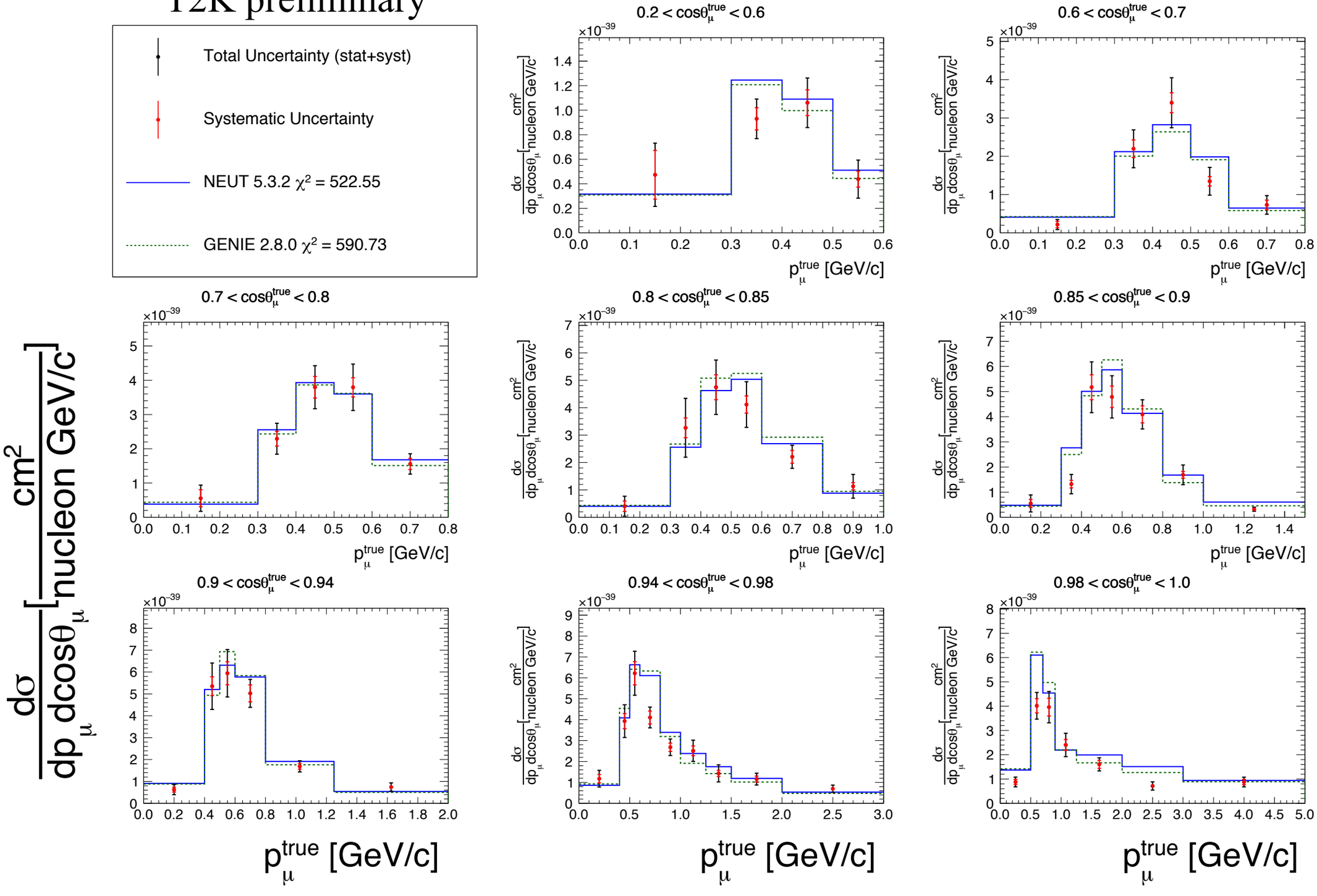
ν_μ cross section VS NEUT and GENIE

*Last bin in momentum does not shown



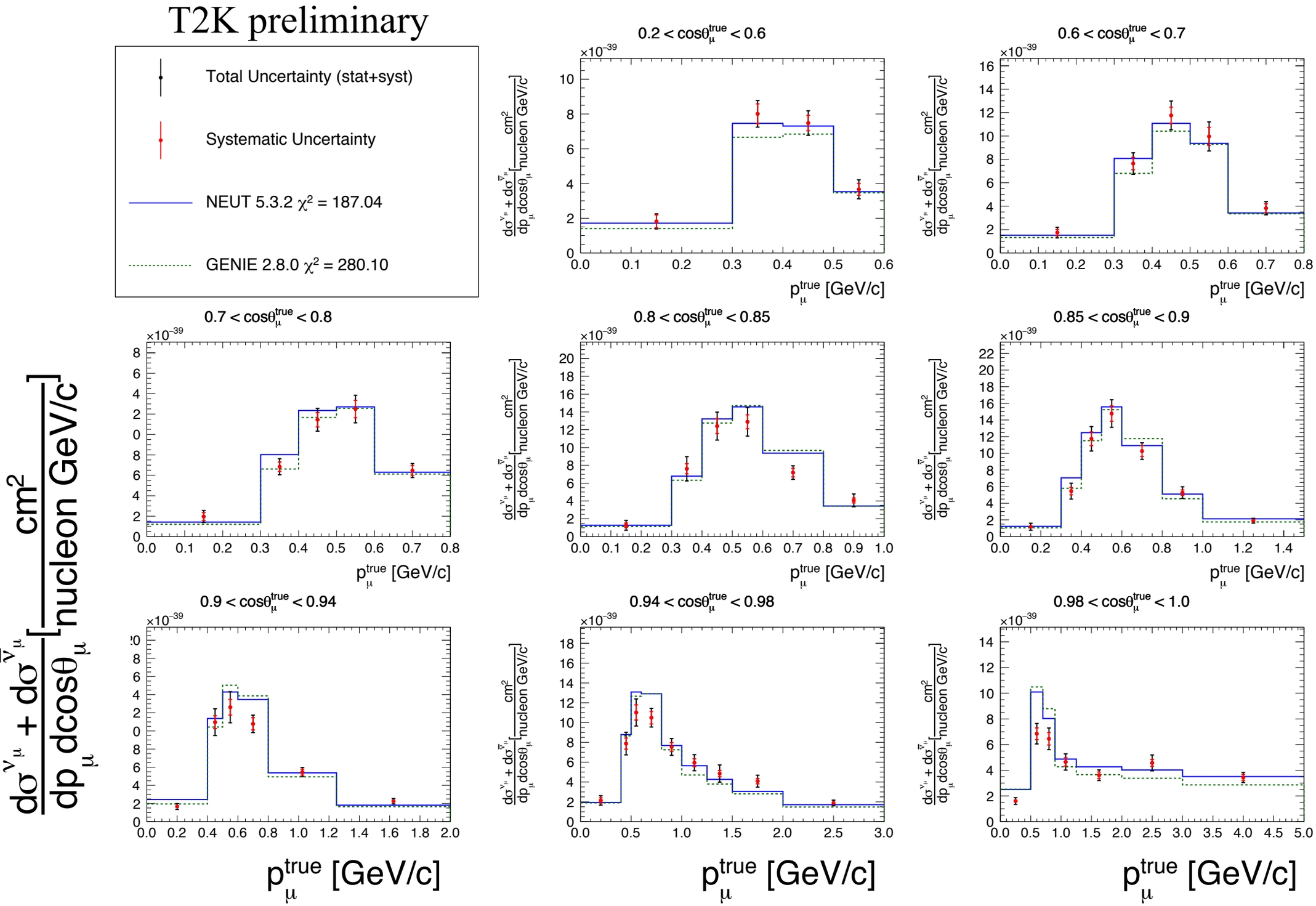
$\bar{\nu}_\mu$ cross section VS NEUT and GENIE

*Last bin in momentum does not shown



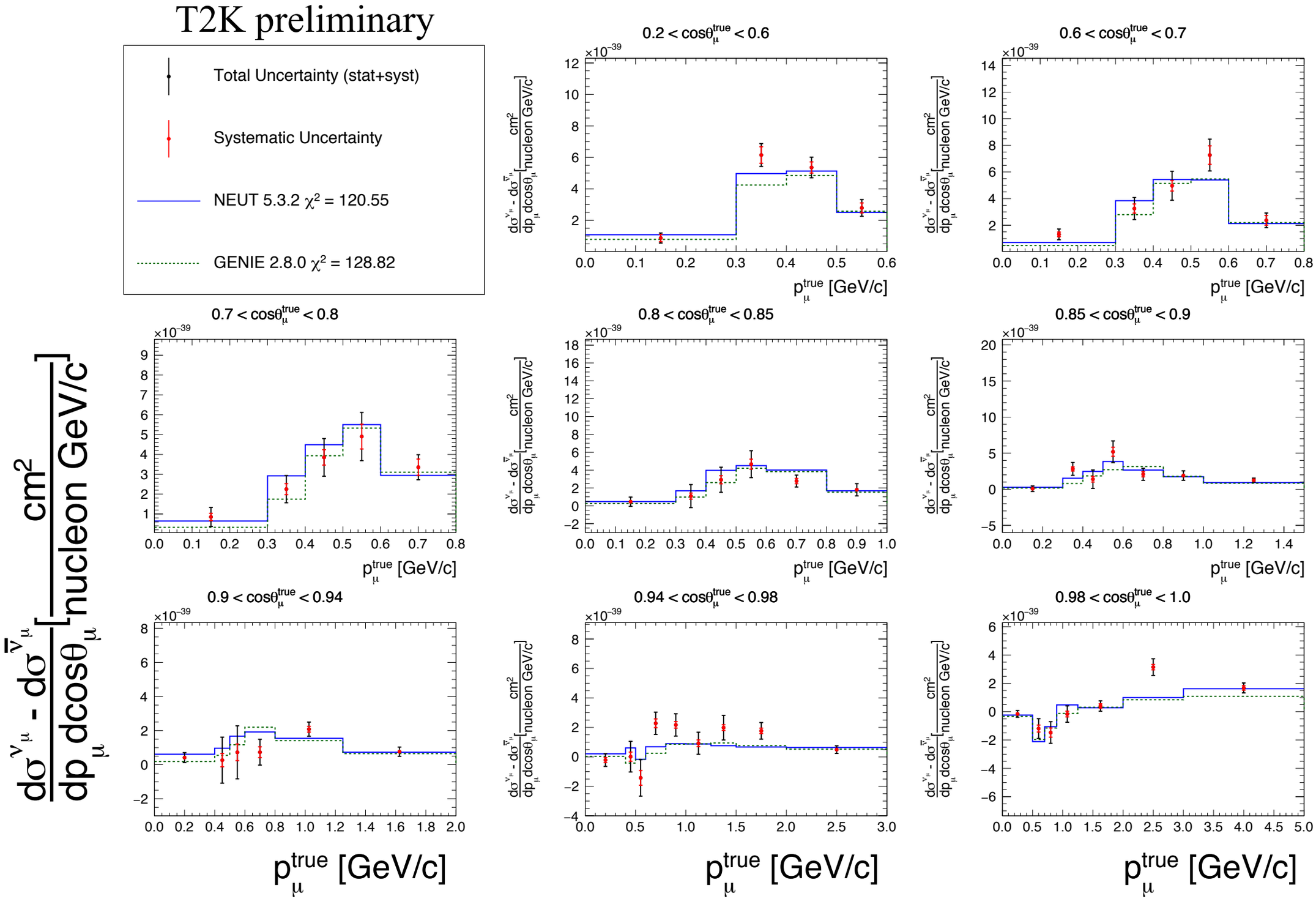
Sum VS NEUT and GENIE

*Last bin in momentum does not shown



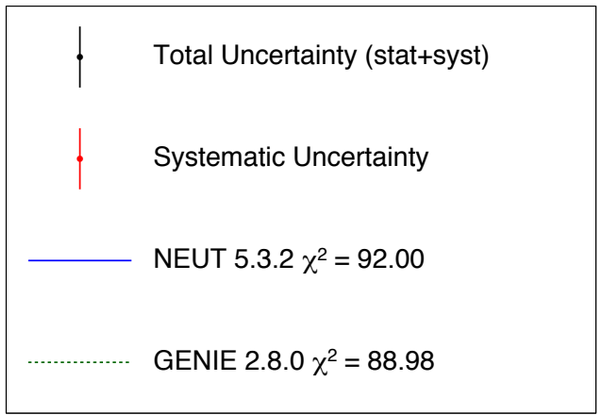
Difference VS NEUT and GENIE

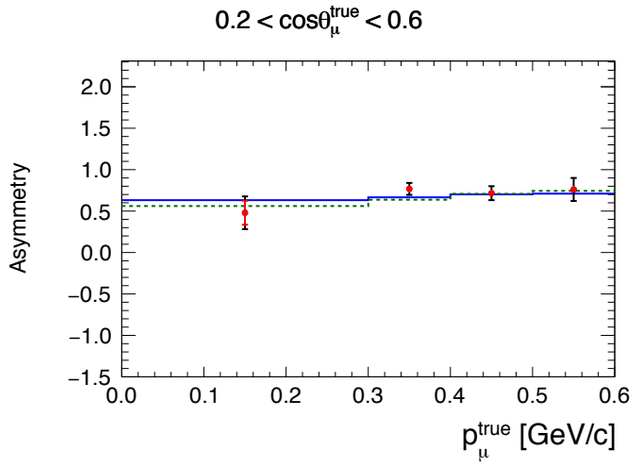
*Last bin in momentum does not shown

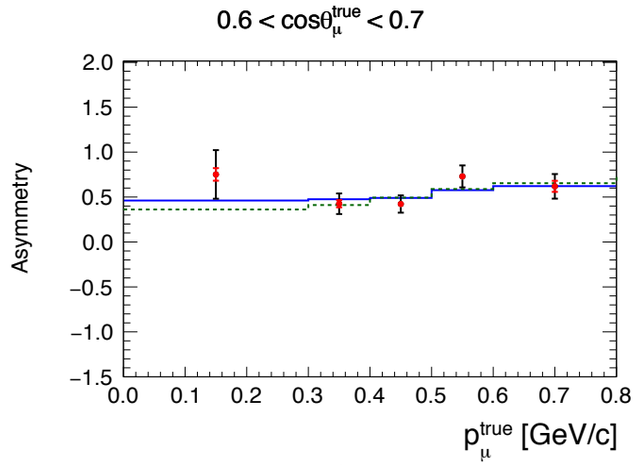


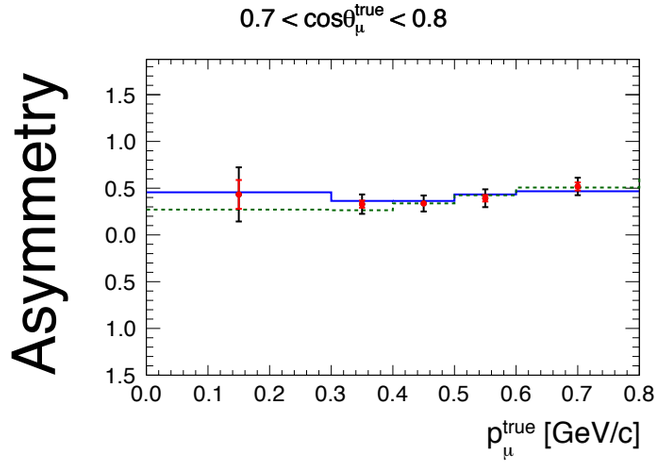
Asymmetry VS NEUT and GENIE

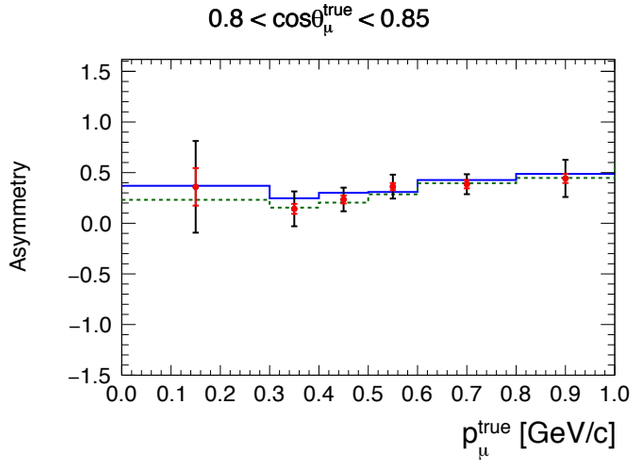
*Last bin in momentum does not shown

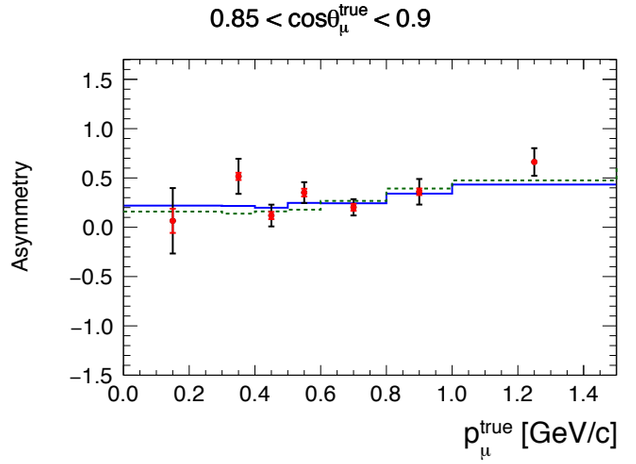


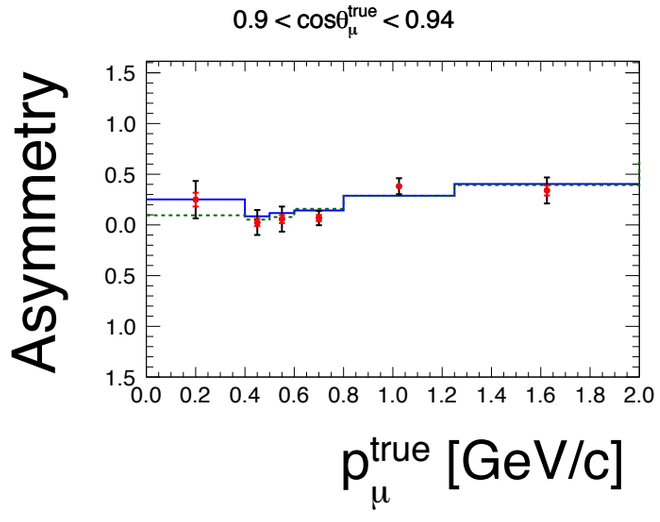


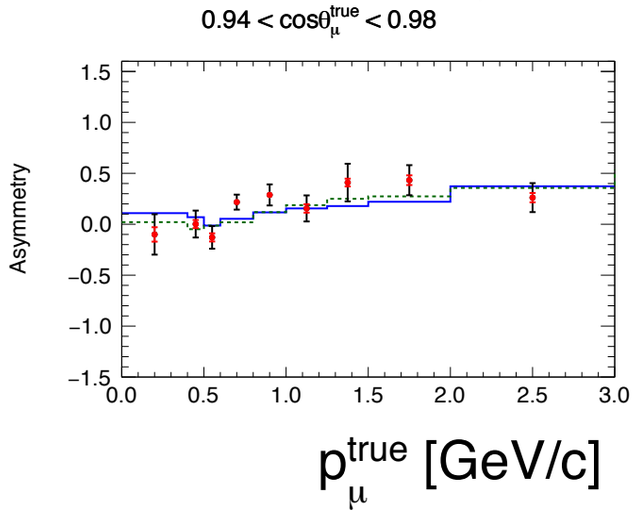


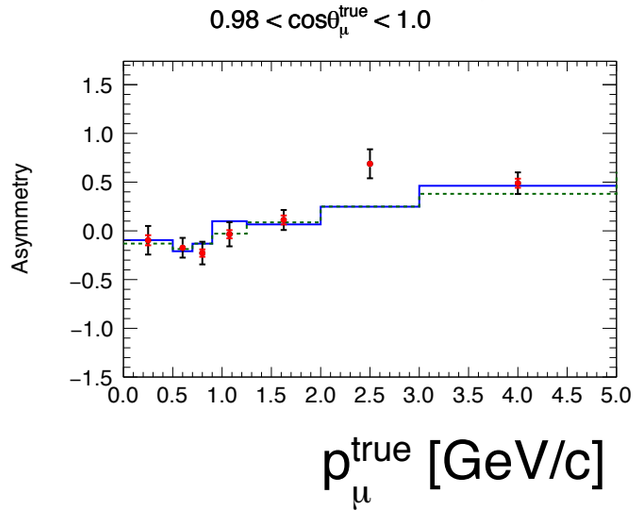






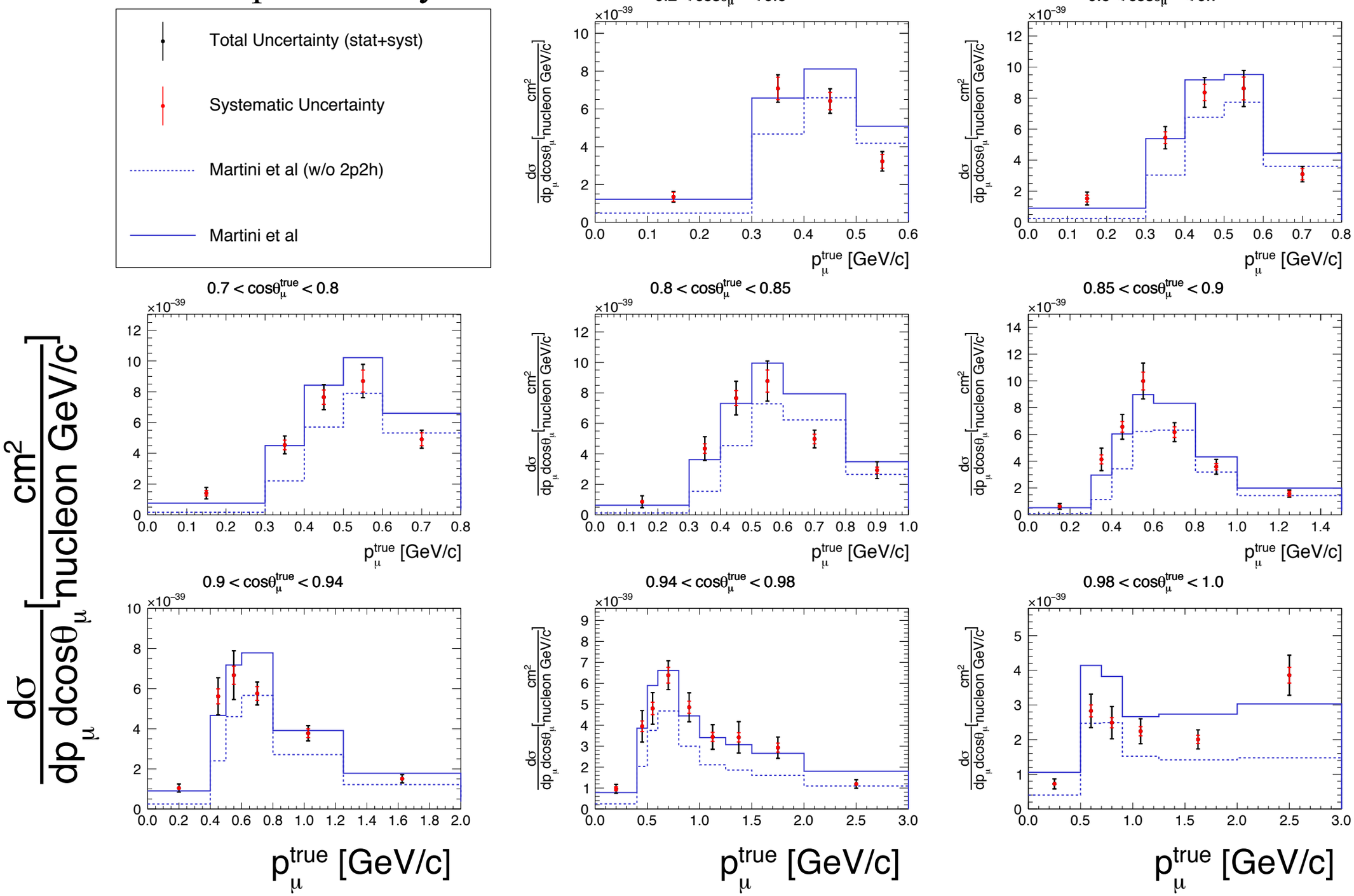






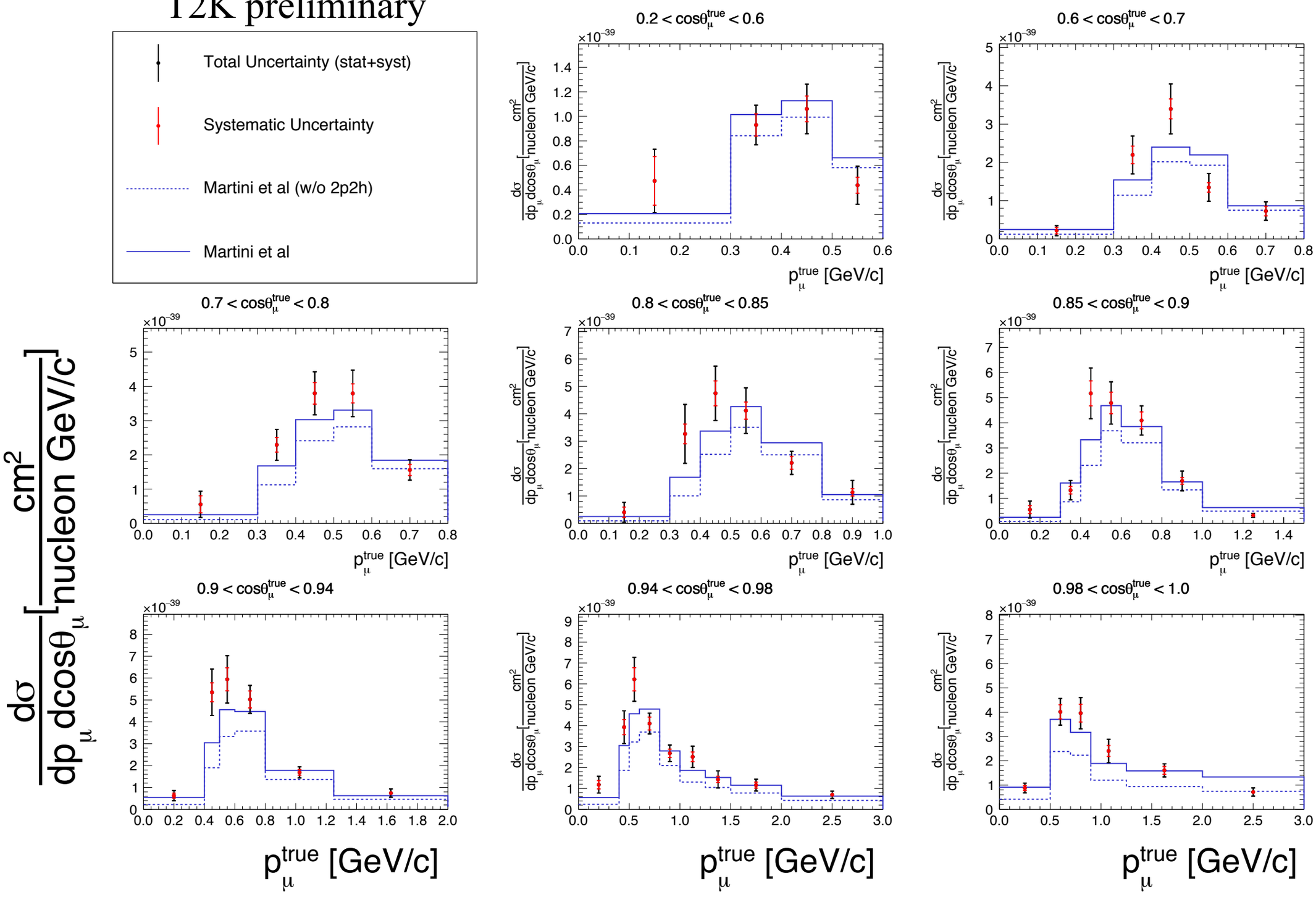
ν_μ cross section VS Martini et al.

*Last bin in momentum does not shown



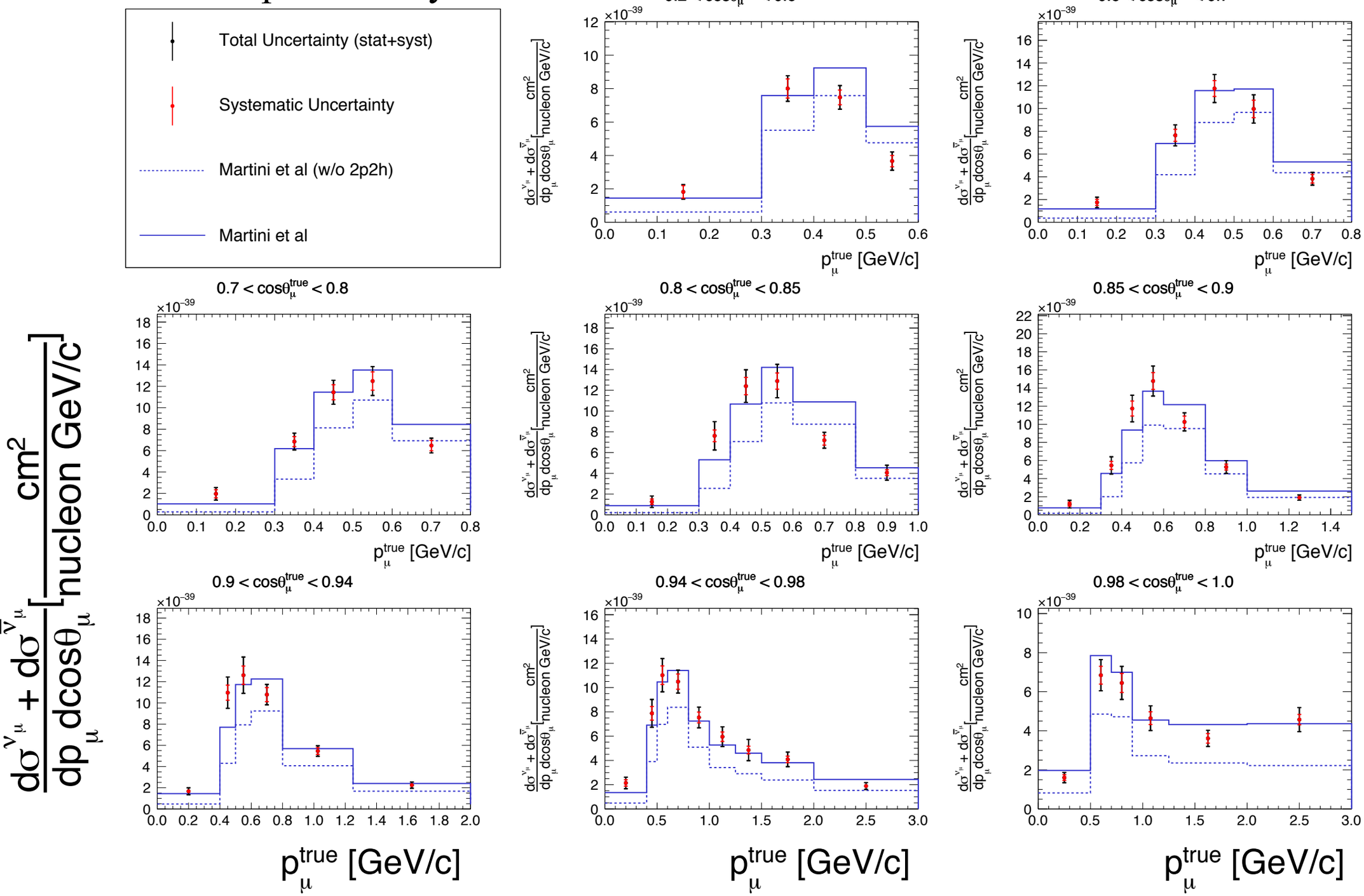
$\bar{\nu}_\mu$ cross section VS Martini et al.

*Last bin in momentum does not shown



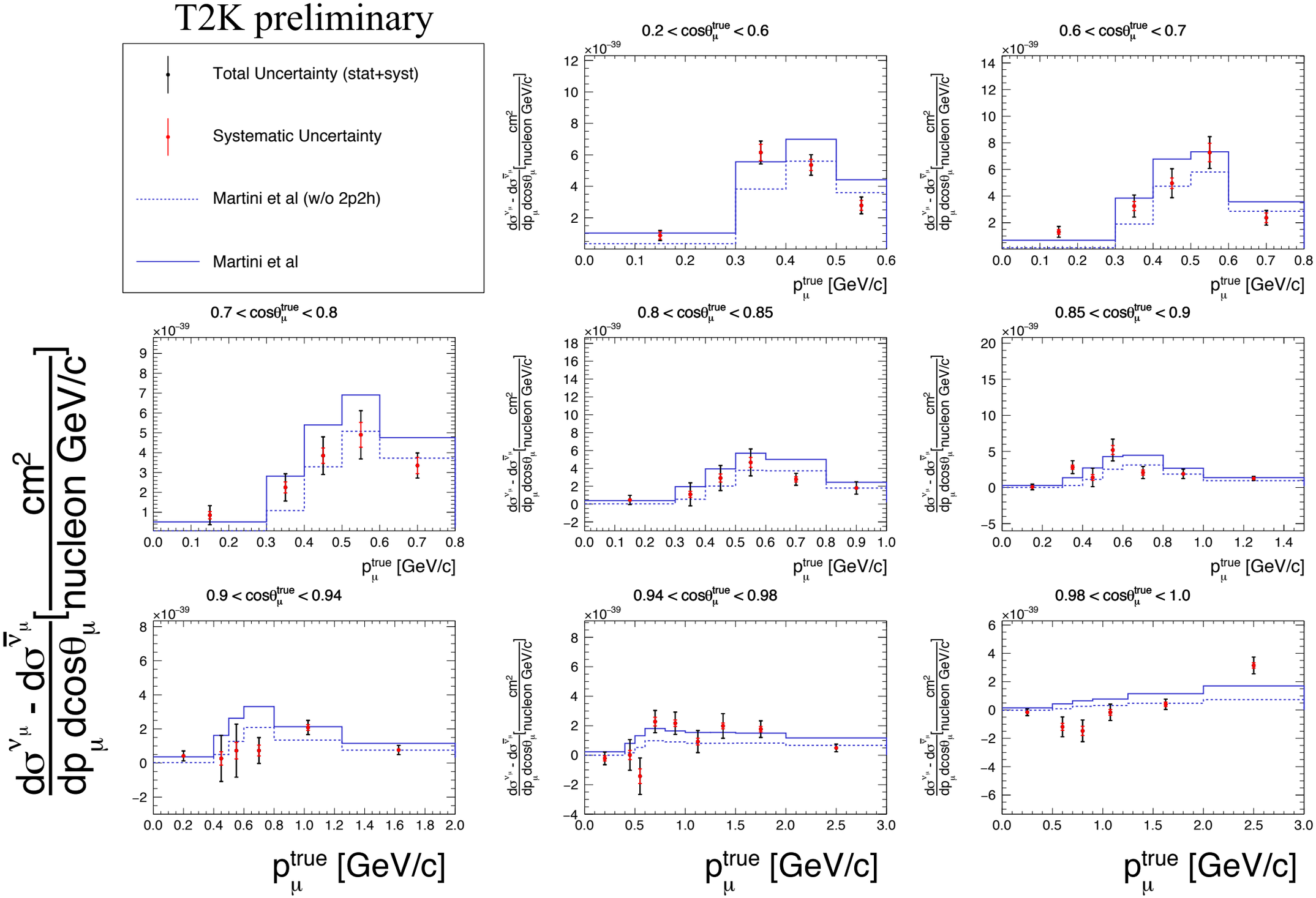
Sum VS Martini et al.

*Last bin in momentum does not shown



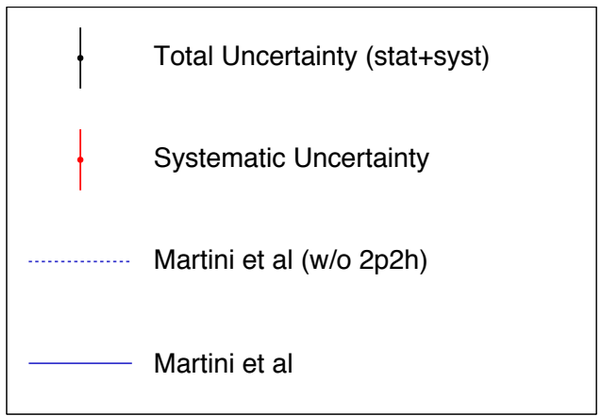
Difference VS Martini et al.

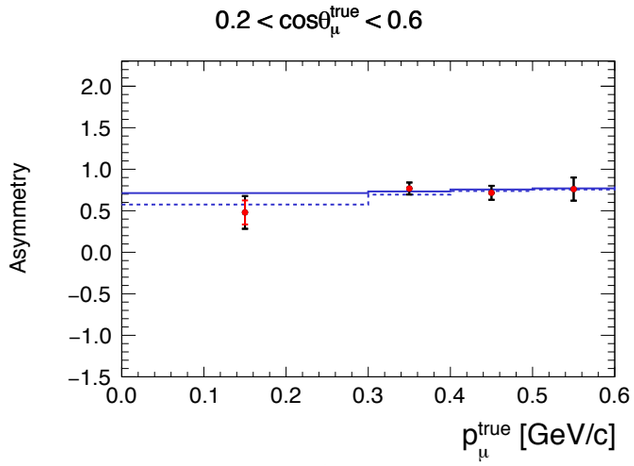
*Last bin in momentum does not shown

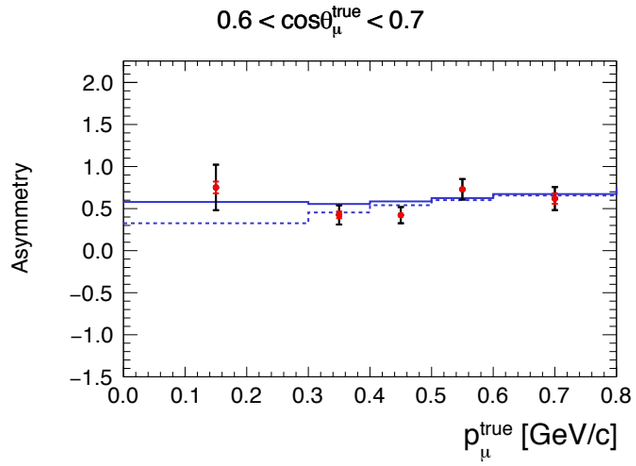


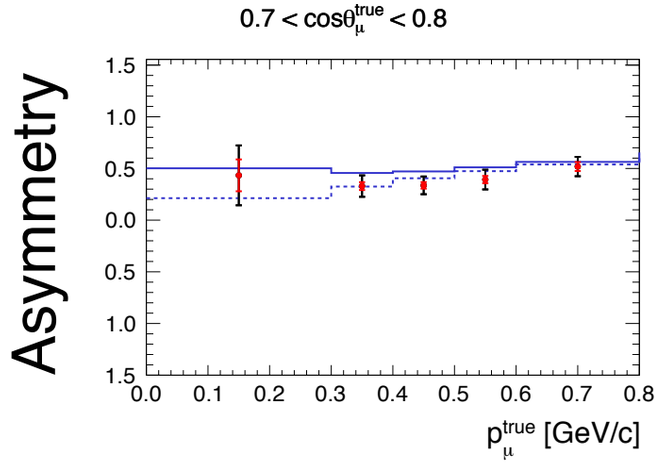
Asymmetry VS Martini et al.

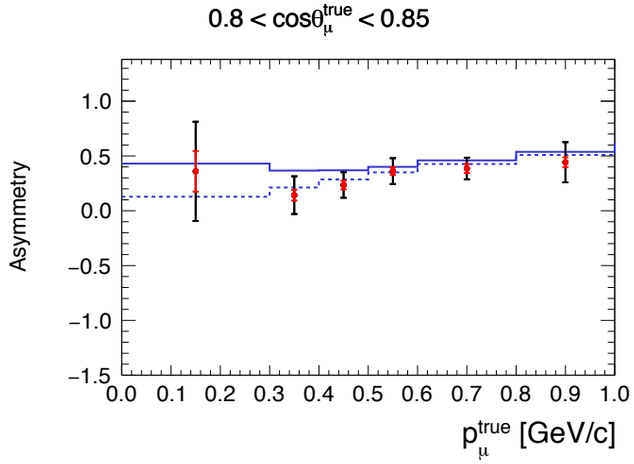
*Last bin in momentum does not shown

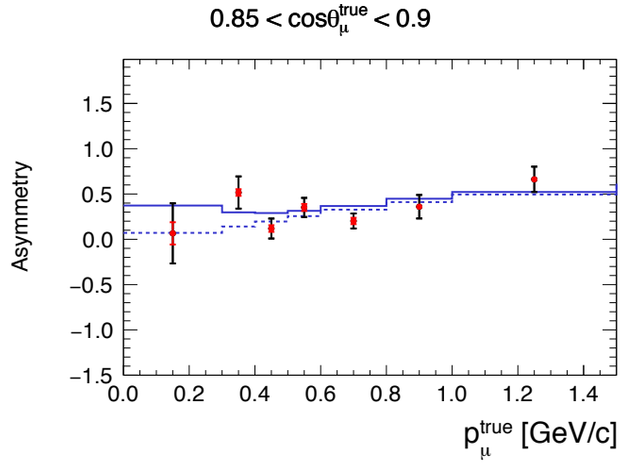


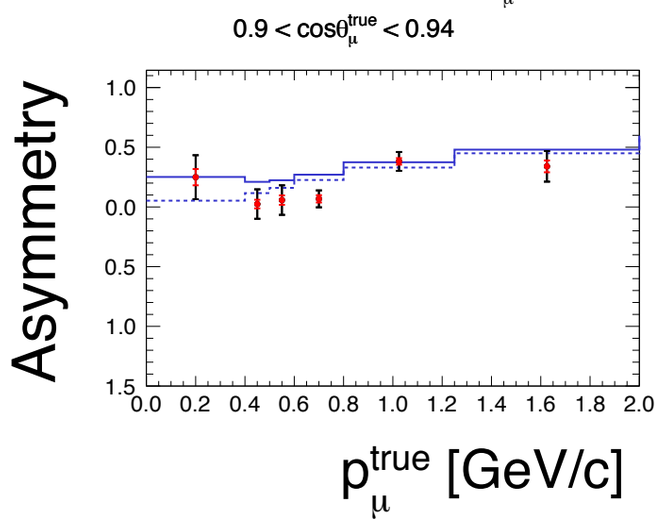


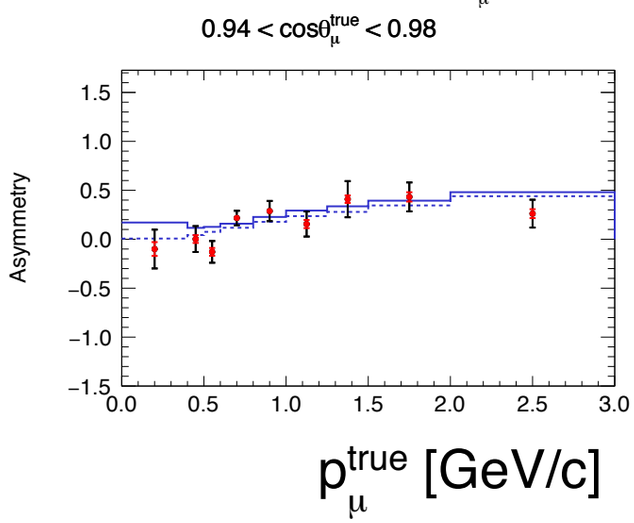


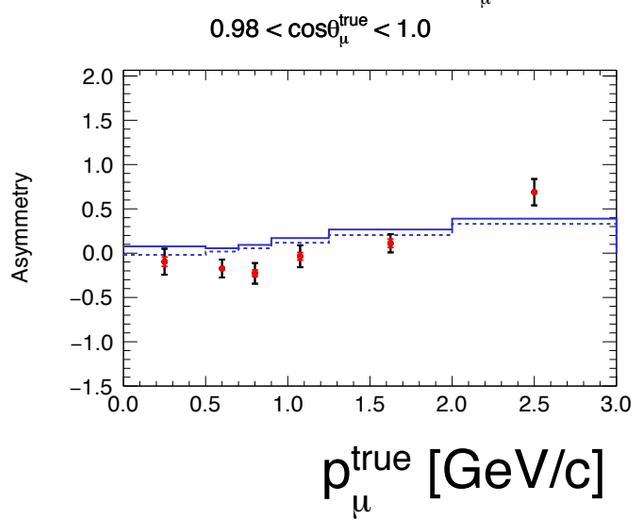






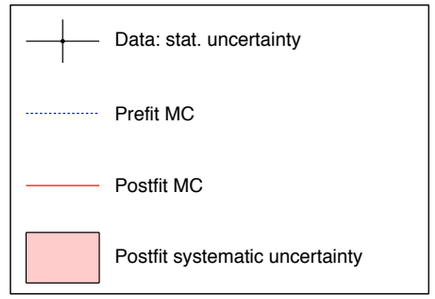


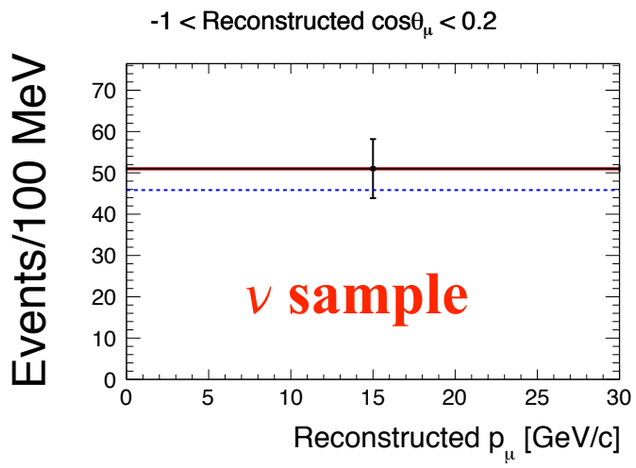


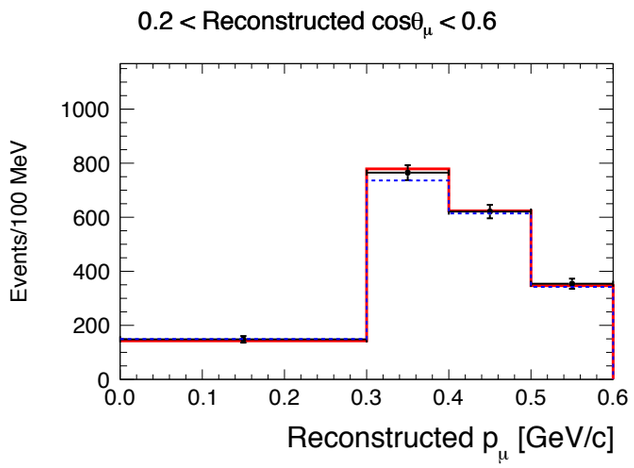


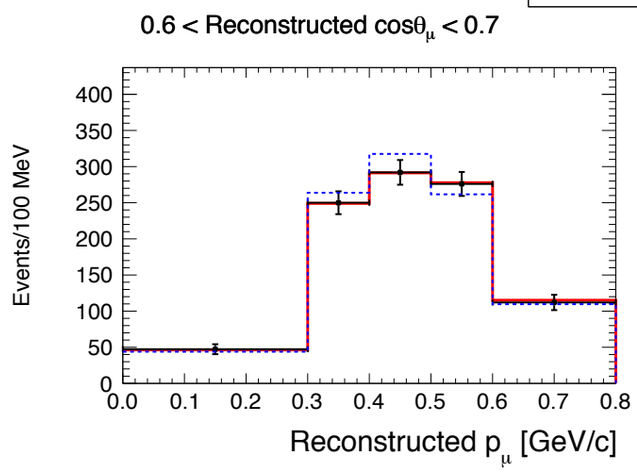
Post-fit signal distributions

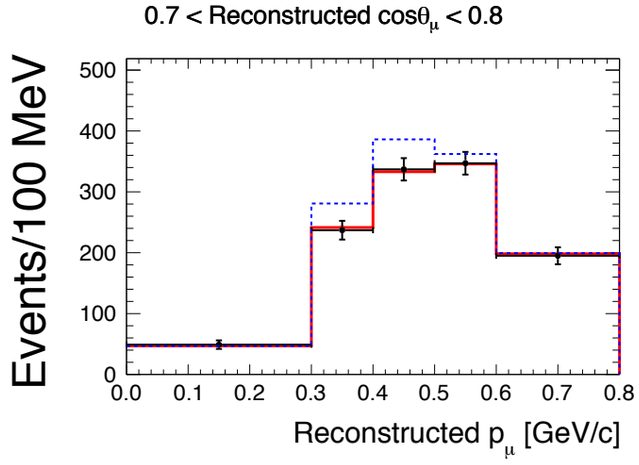
T2K preliminary

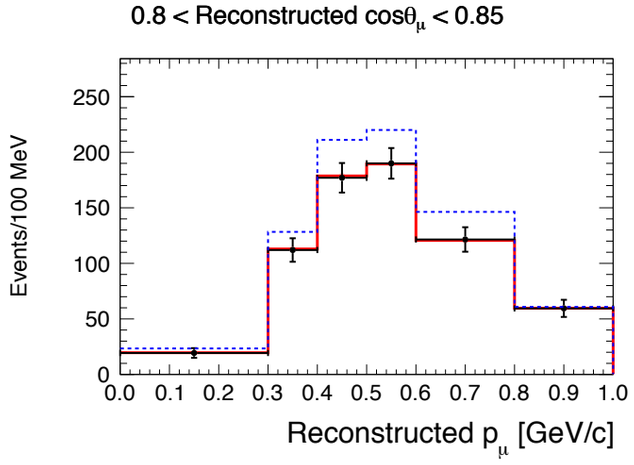


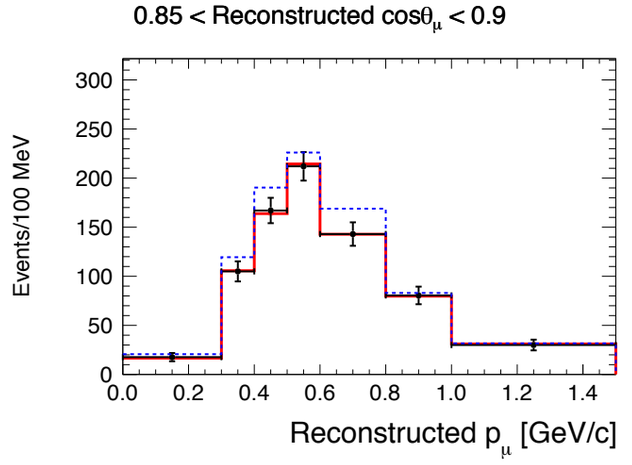


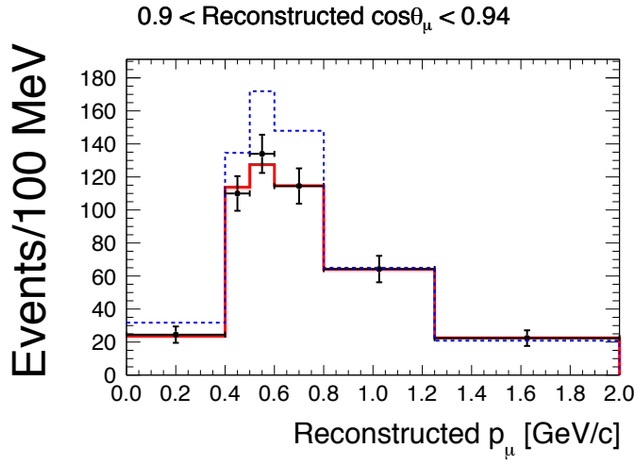


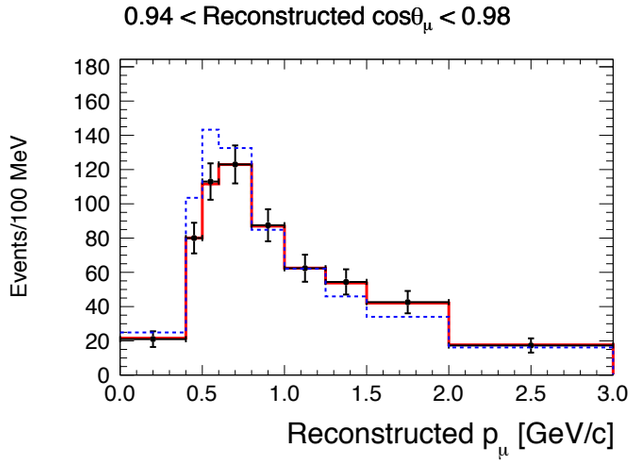


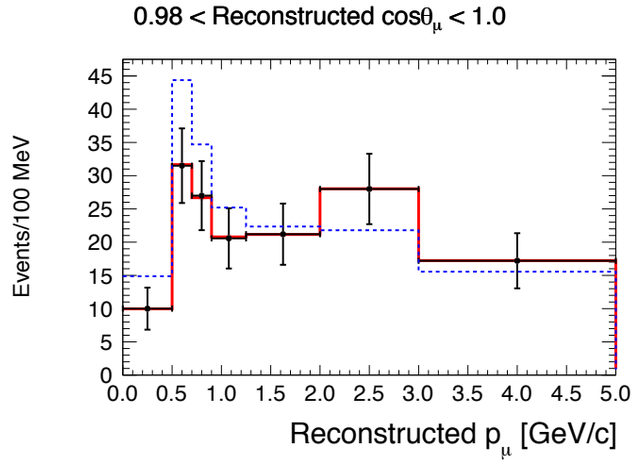






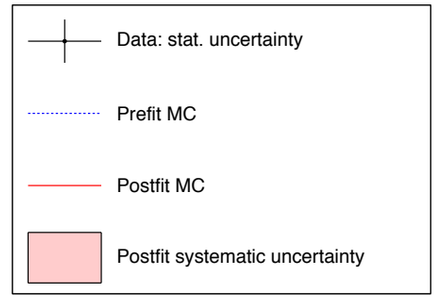


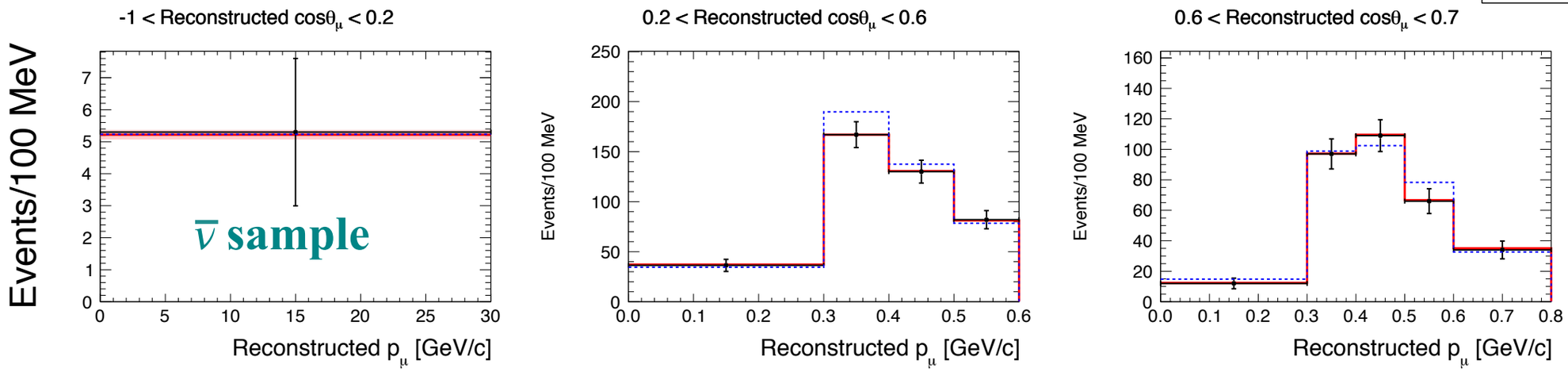


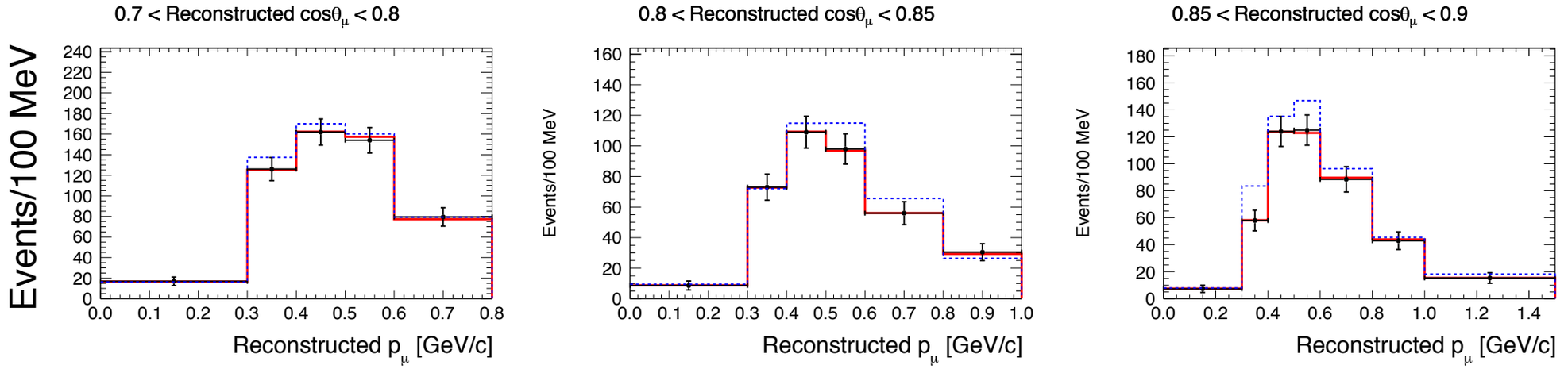


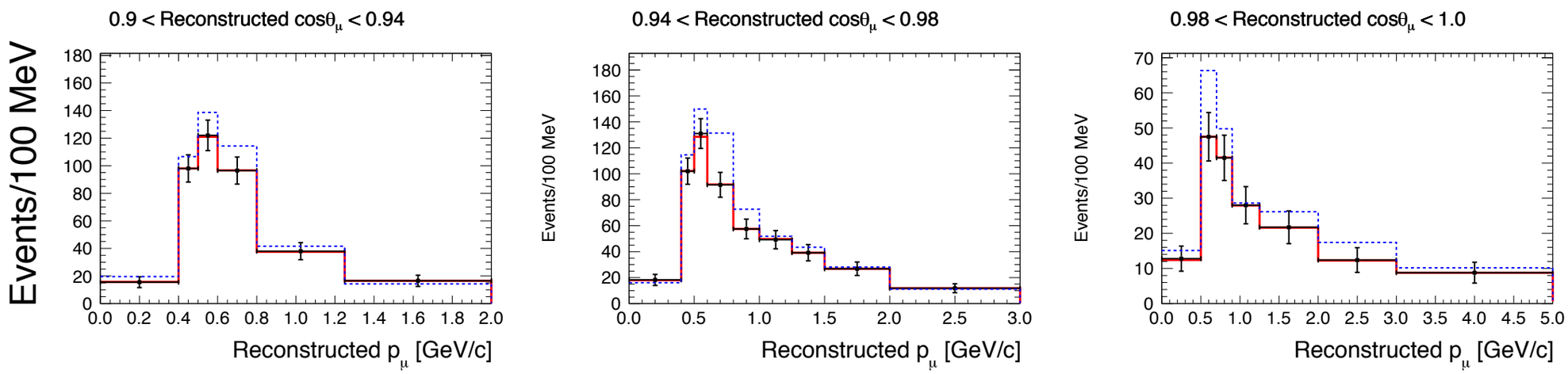
Post-fit signal distributions

T2K preliminary

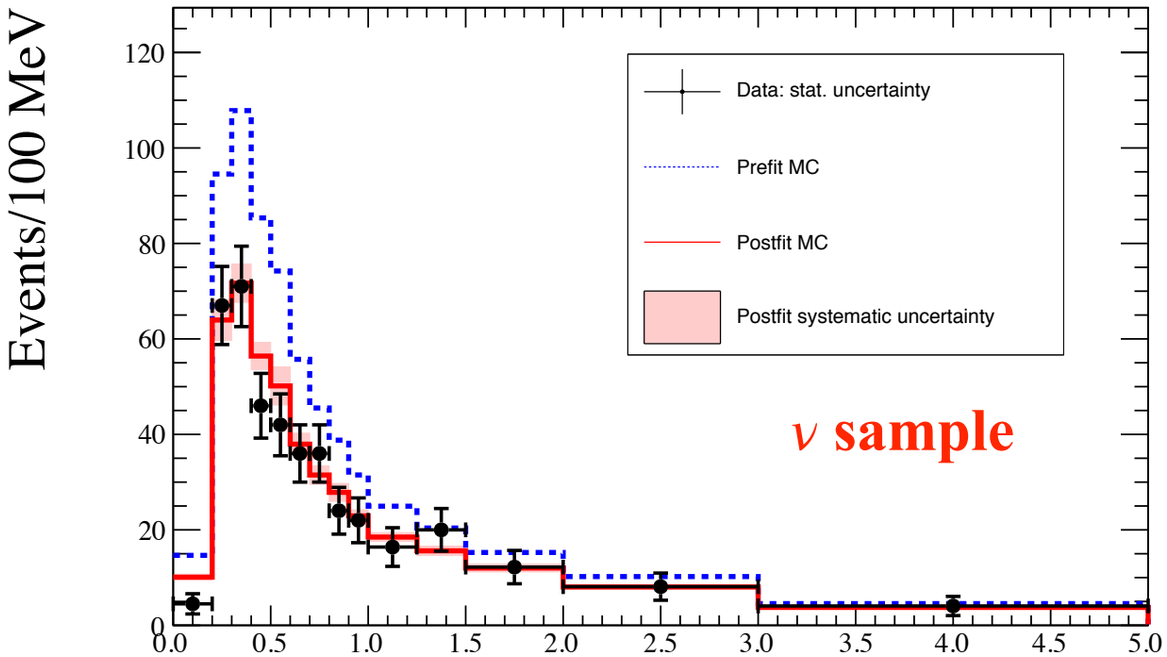


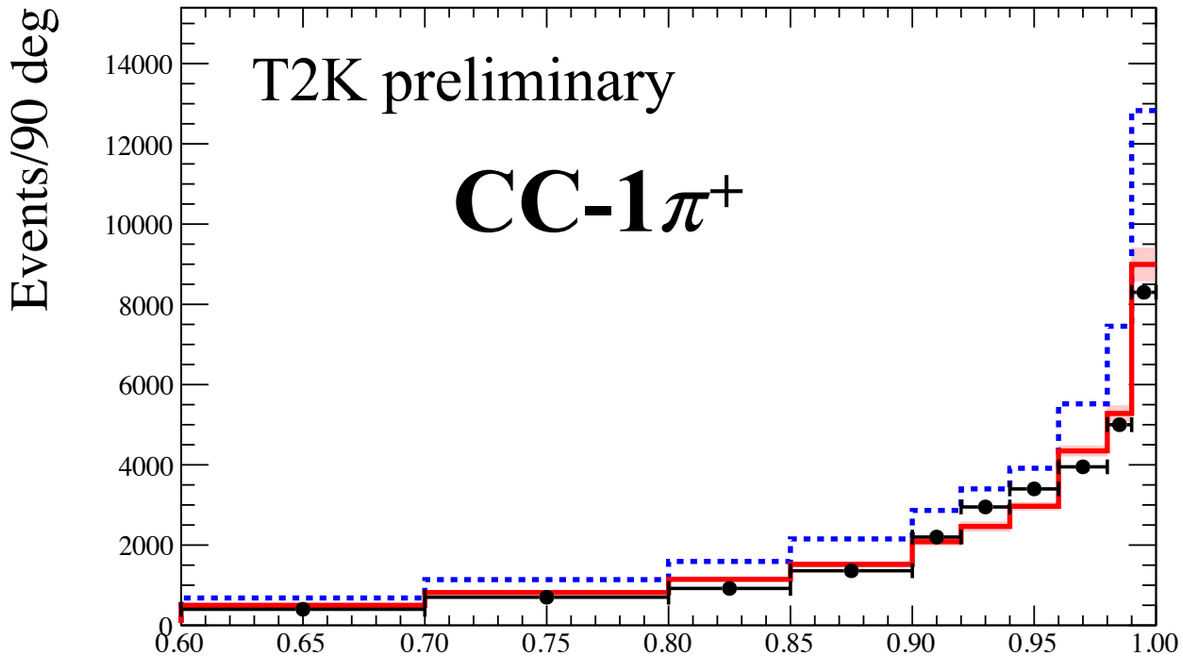


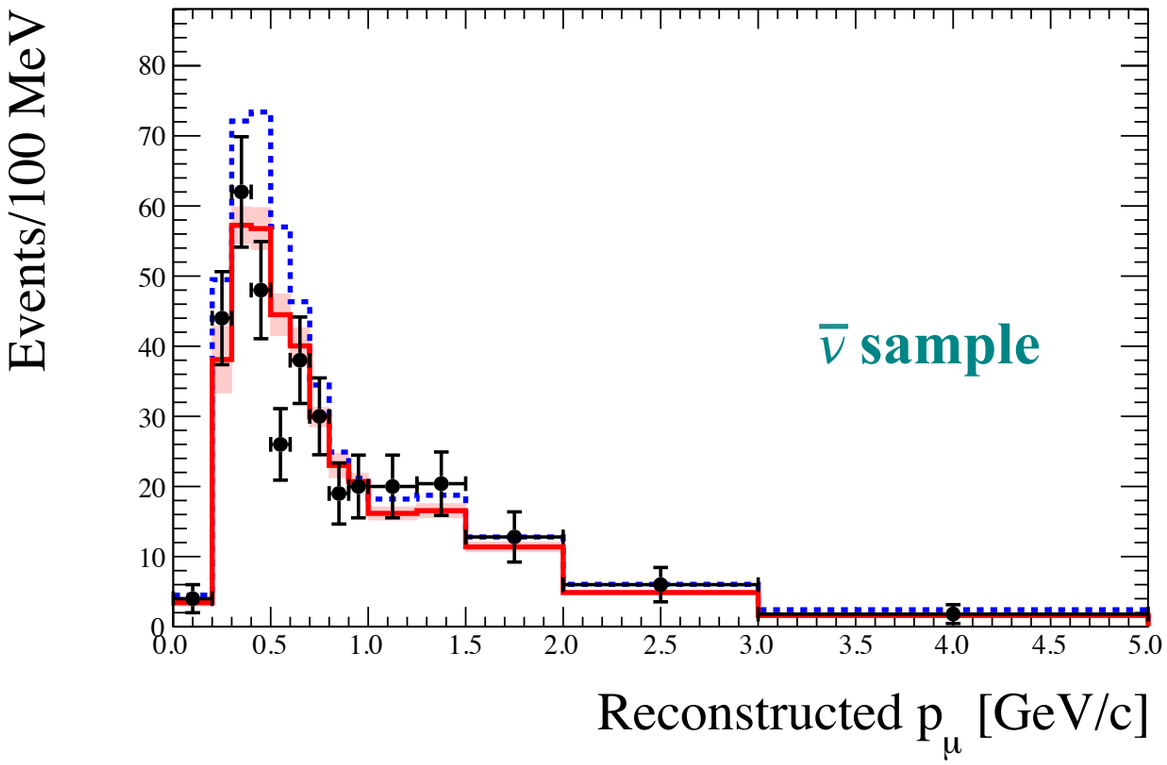


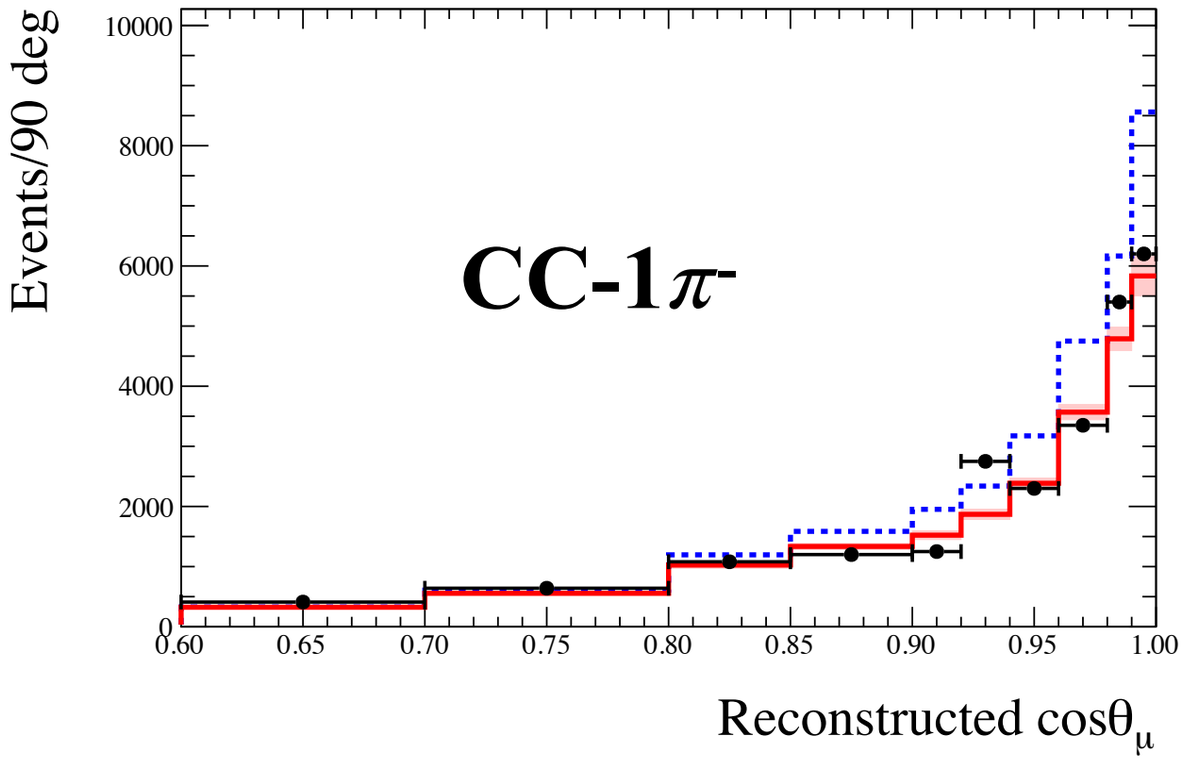


Control region I: CC-1$\pi^{\pm}$









Control region II: CC-Other