T2K acceptance maps

Clarence Wret

Ed Atkin
(T2K-SK)

Imperial College London

University of Rochester

e.atkin17@imperial.ac.uk
c.wret@rochester.edu

NOvA-T2K Workshop, FNAL
26 Feb 2019

Overview

- Compare selections and efficiencies at T2K and NOvA
- What sort of events are selected, and why?
- Complimentary features of the detectors?
- Effect of systematics may be different from detector geometries and selections

- Future: put through generated events, apply detector acceptance, apply tune, what happens to event spectra?
  - Can do first studies on parameter correlations

Acceptance definition

- Want to pass through raw generateor events → signal definition and variables in truth
- What is the probability of:
  - Event with true selection *x* to be reconstructed as true selection *y* in ND280 or SK
  - Or not reconstructed at all!
- Run over events, bin up (`True Selection == x && Reco Selection == y`), and `True Selection == x`
- Get the ratio → Acceptance of `True Selection == x`
- Identical selections, reconstruction and MC events that enter official T2K analyses
- True selections (e.g. 1μ0π) do not cut on proton or kaon multiplicities: only counts leptons and pions (charged and neutral)

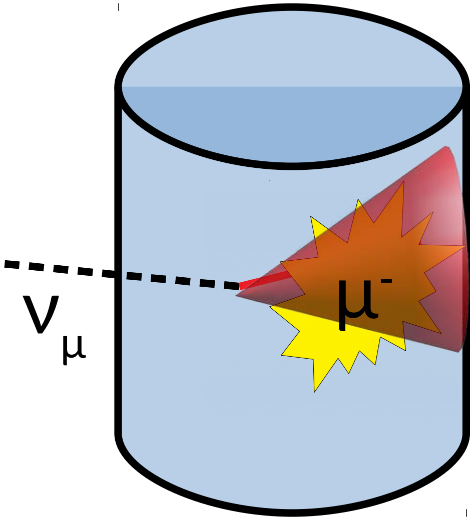
Acceptance/efficiency maps

- Kinematic variables

$p_{lep}, \cos\theta_{lep} \quad p_\pi, \cos\theta_\pi \quad p_\pi, \cos\theta_{\mu,\pi} \quad q_0, q_3 \quad q_0, W_{Obs} \quad E_\nu, y$

- Use the acceptance map of the variable you want to plot
  - e.g. don't use $p_\pi \cos\theta_\pi$ map to predict $p_\mu \cos\theta_\mu$
- No weights are applied
  - e.g. POT, cross-section, oscillation probabilities
- Have maps for all true topologies being reconstructed as any topology: only showing a few here
- Happy to release full plots, root files, and/or `TTree`

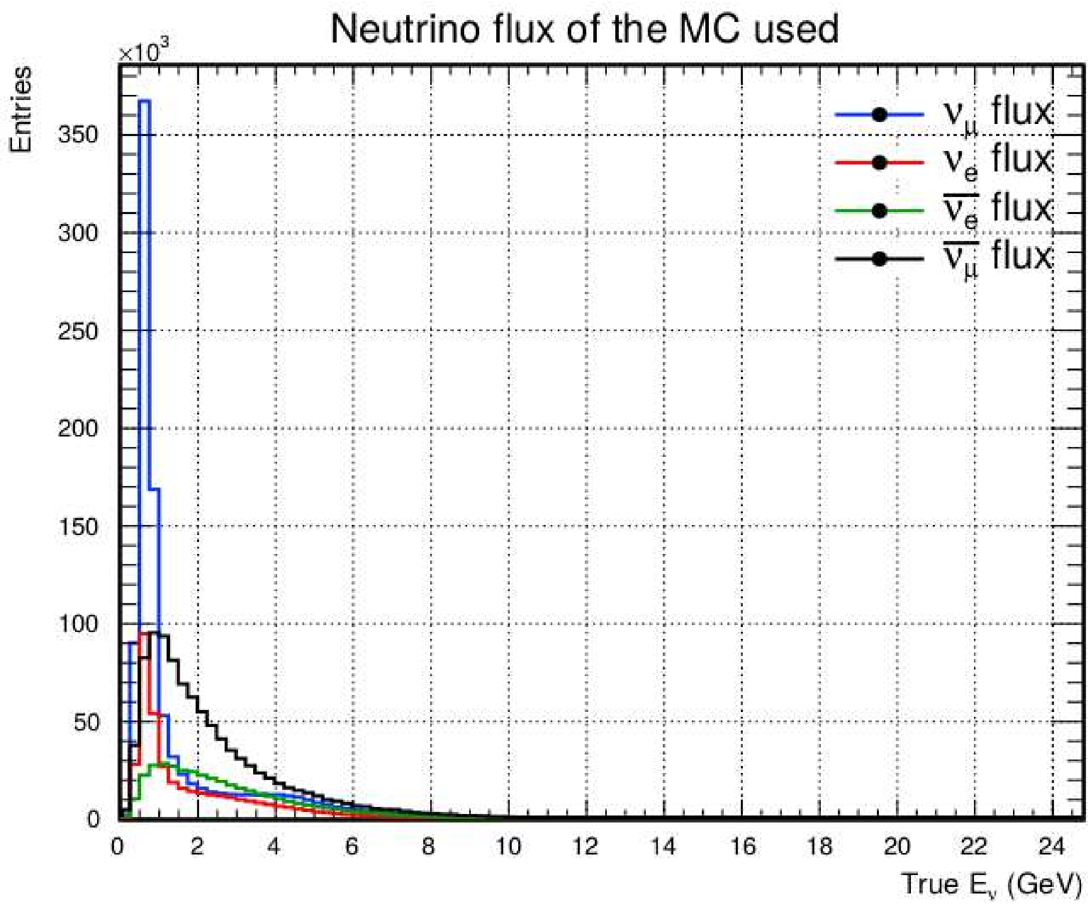
SK selections



- Cylindrical Water Cherenkov detector
- 1Rμ, 1Re, 1Re1d.e. (only in FHC): 5 selections. **Showing only FHC**
  - Analysis proceeds using lepton variables and decay electron
- Containment, ring-counting, likelihood cuts (details in backup)
- 1Rμ: reconstructed p_μ > 200 MeV; 1Re: E_{rec}<1.25 GeV
- For acceptance maps "signal" in 1Re1de is defined as 1e, 1π^+

SK flux

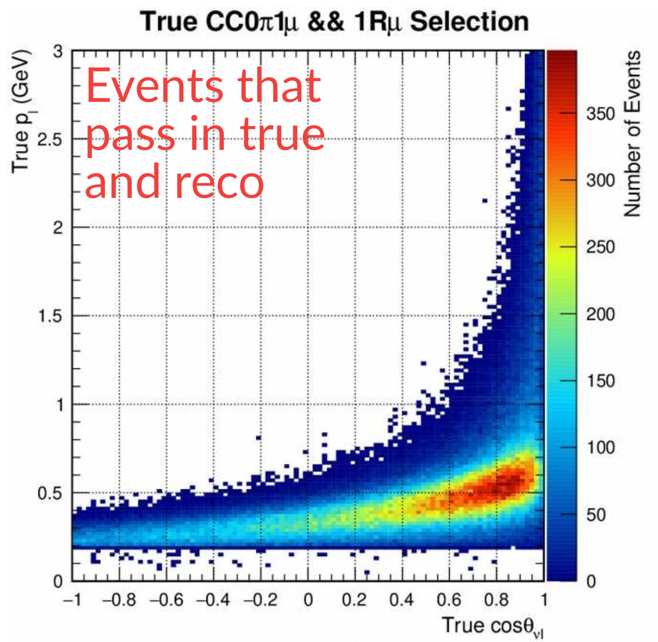
- These studies do not use oscillated or flux weighted events at SK
  - Acceptance is slightly different with oscillations

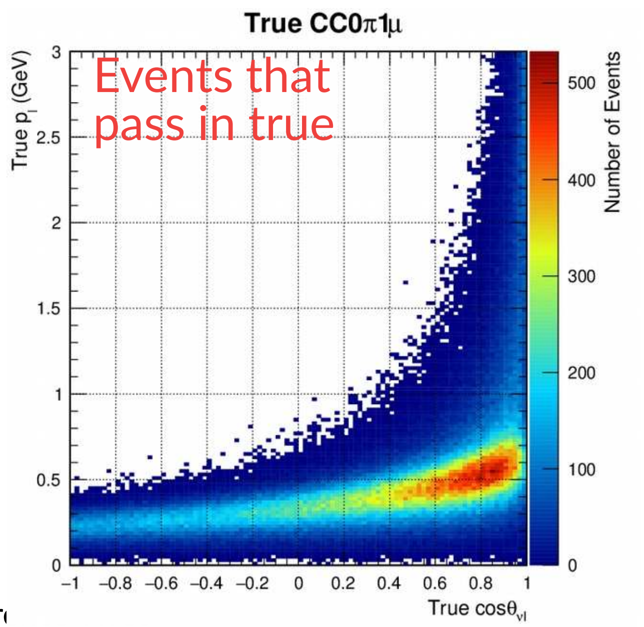


- May want to discuss and revisit this

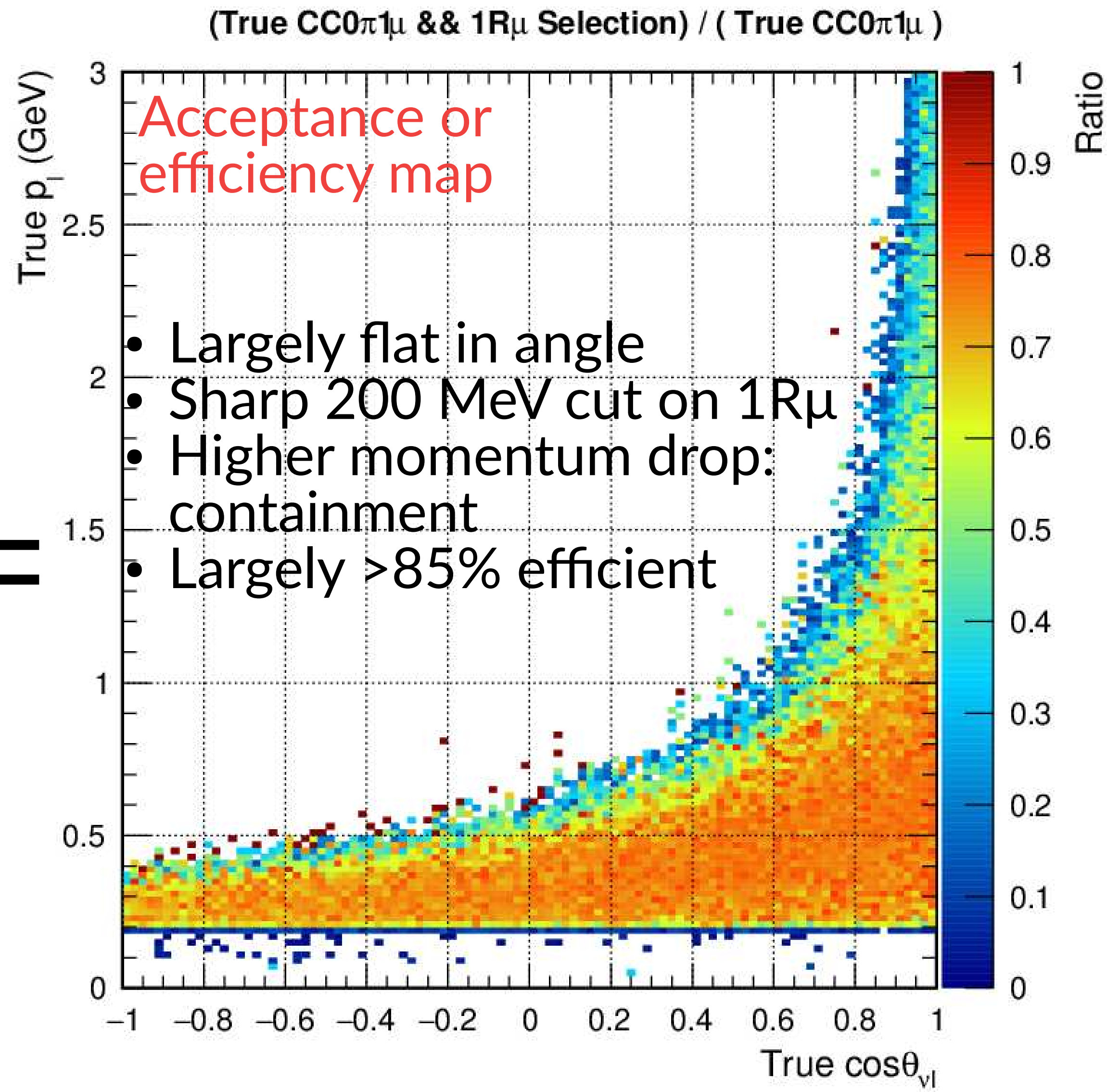
SK 1Rμ

- Event has true 1μ0π selection, and reco SK 1Rμ selection





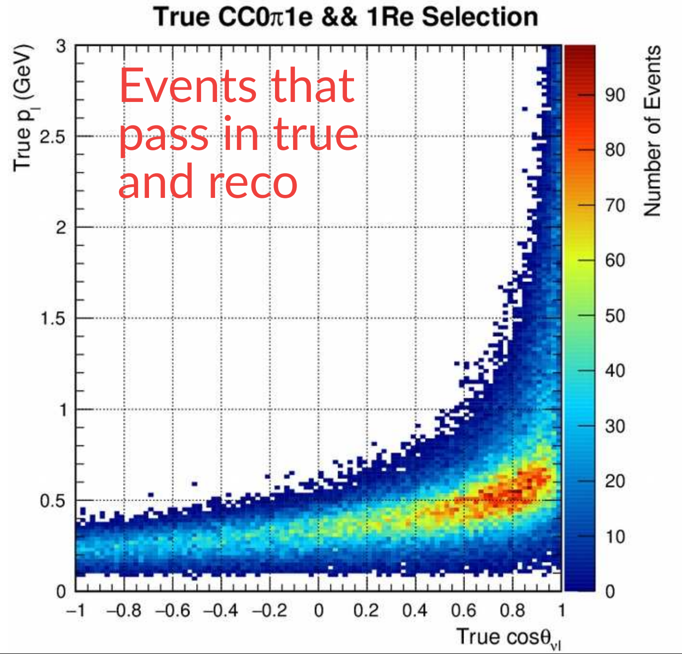
=

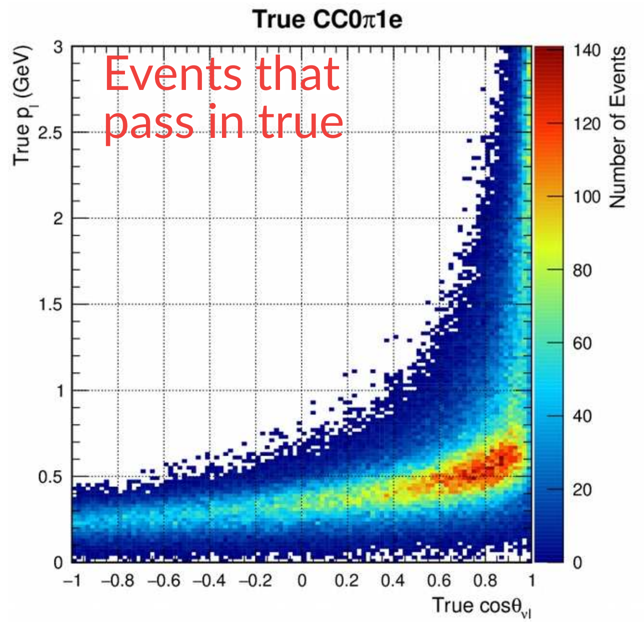


- Largely flat in angle
- Sharp 200 MeV cut on 1Rμ
- Higher momentum drop: containment
- Largely >85% efficient

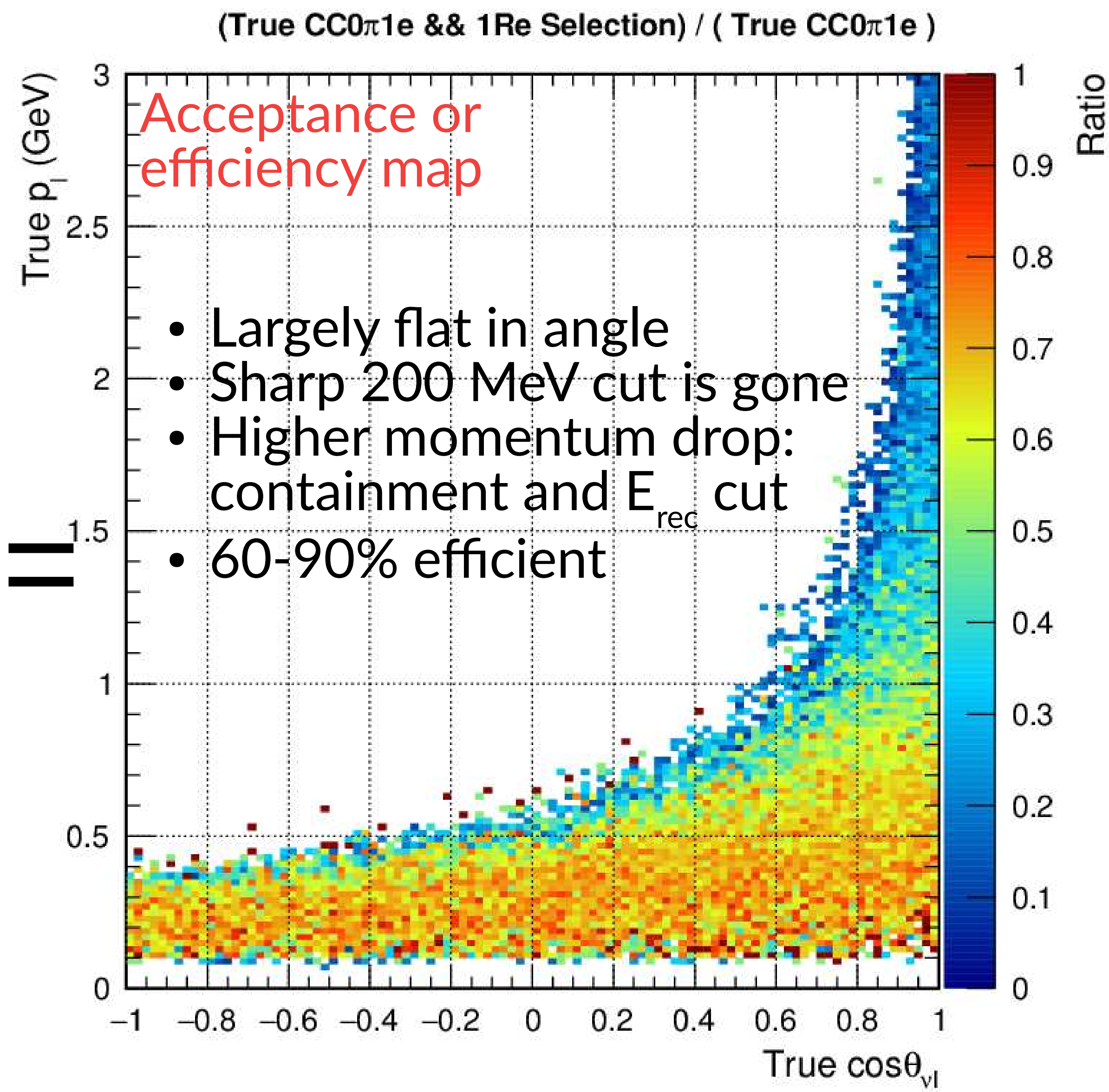
SK 1Re

- Event has <u>true 1e0π selection</u>, and <u>reco SK 1Re selection</u>



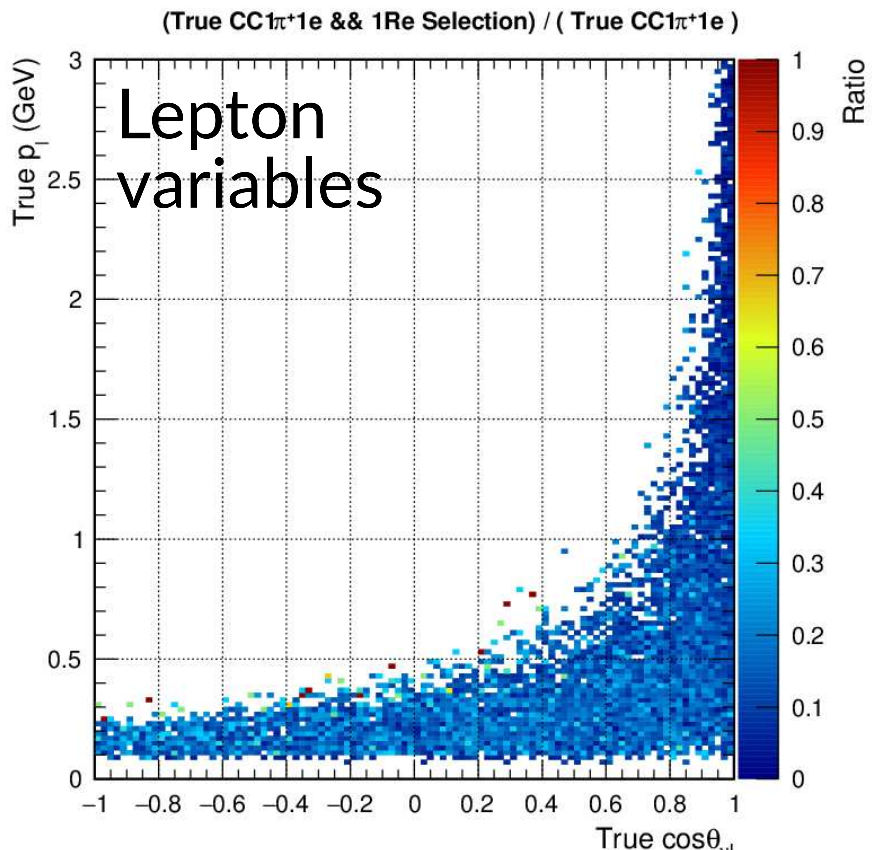


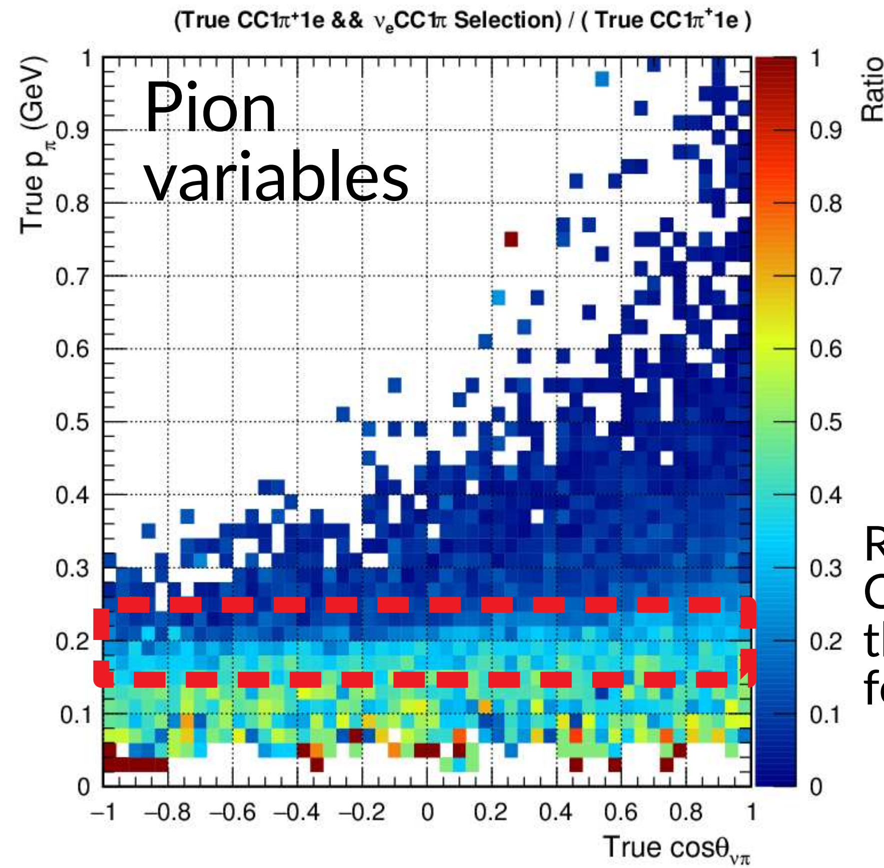
=



SK 1Re1de

- Event has true $1e1\pi^+$ selection, and reco SK 1Re1de selection
- Lepton variables not very informative
- Best acceptance at lower pion mometum
  - True selection is $1e1\pi^+$; 1Re1de is $1e1\pi^+$ with π^+ below Cherenkov threshold → selects low momentum pions but not high since high momentum pion produces 2R

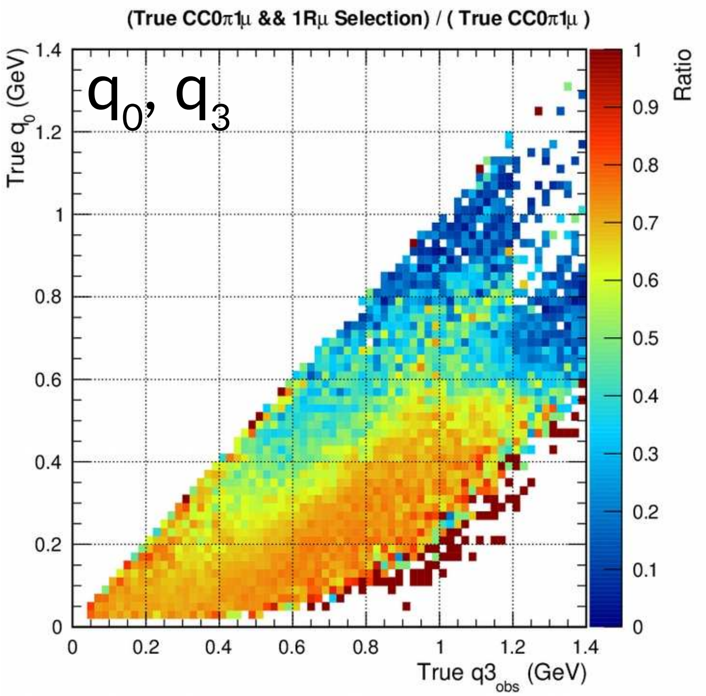


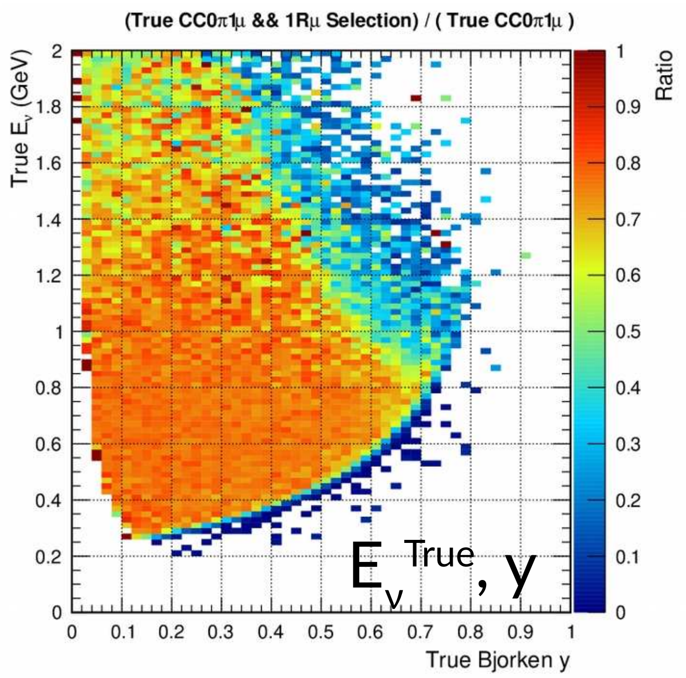


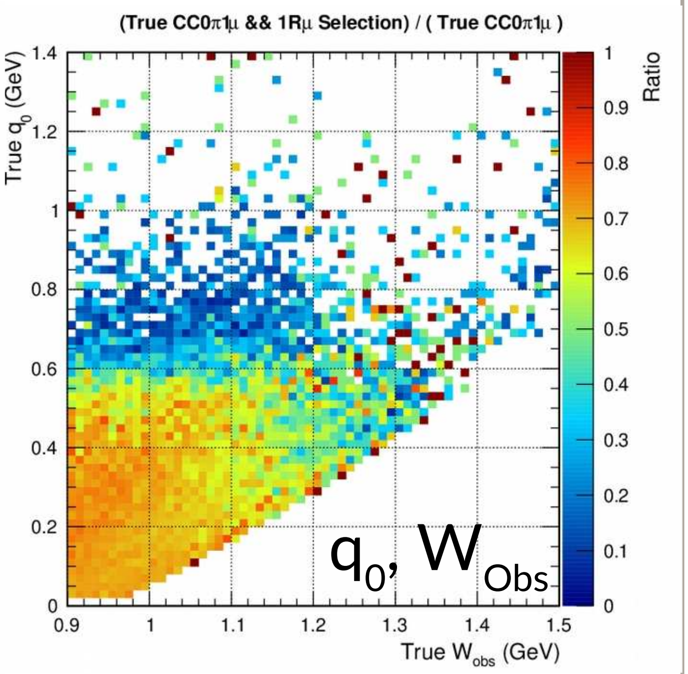
Roughly Cherenkov threshold for pions

SK 1Rμ different variables

- Event has <u>true 1μ0π selection</u>, and <u>reco SK 1Rμ selection</u>
- Acceptance in different variables



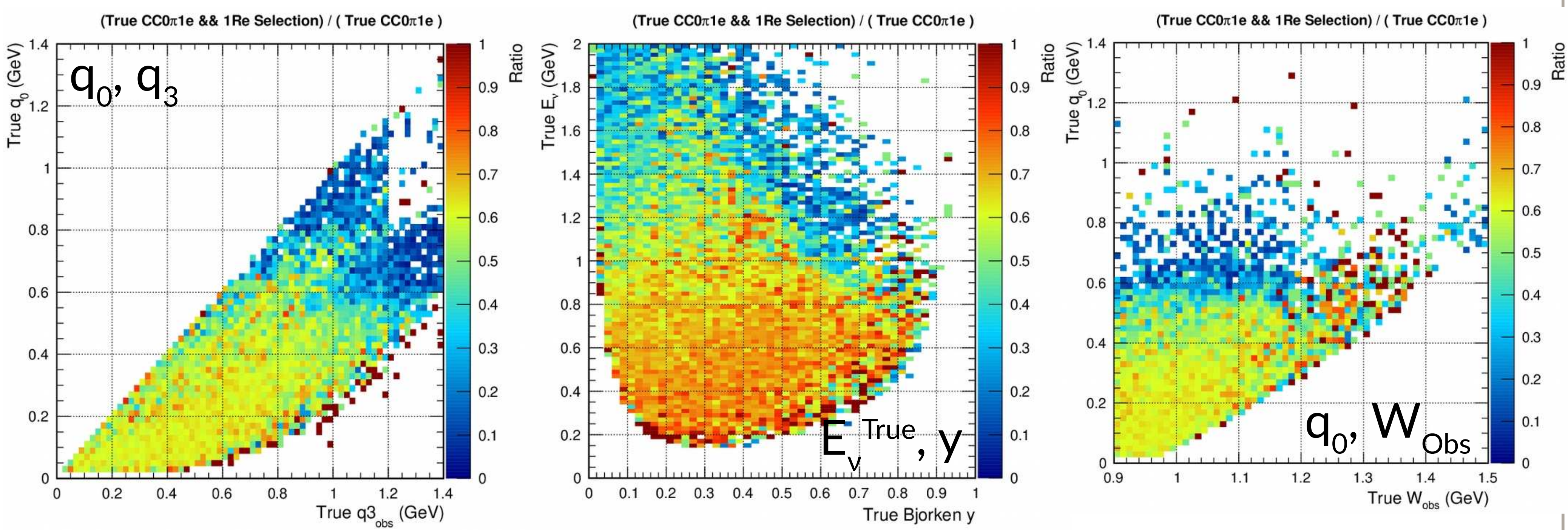




- Generally very good acceptance, about 70-90%

SK 1Re different variables

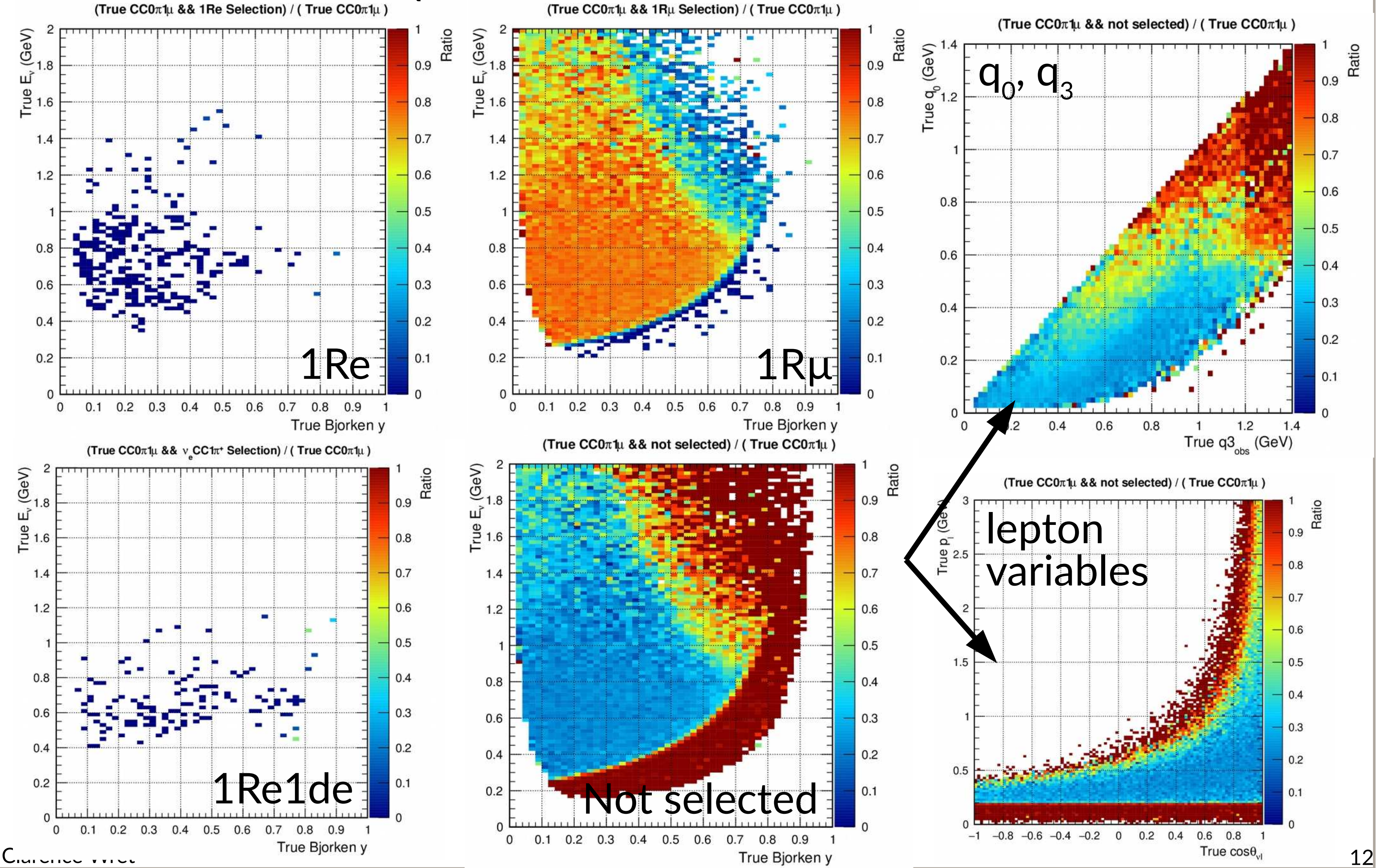
- Event has <u>true 1e0π selection</u>, and <u>reco SK 1Re selection</u>
- Acceptance in different variables



- Generally good acceptance, 60-70% efficient

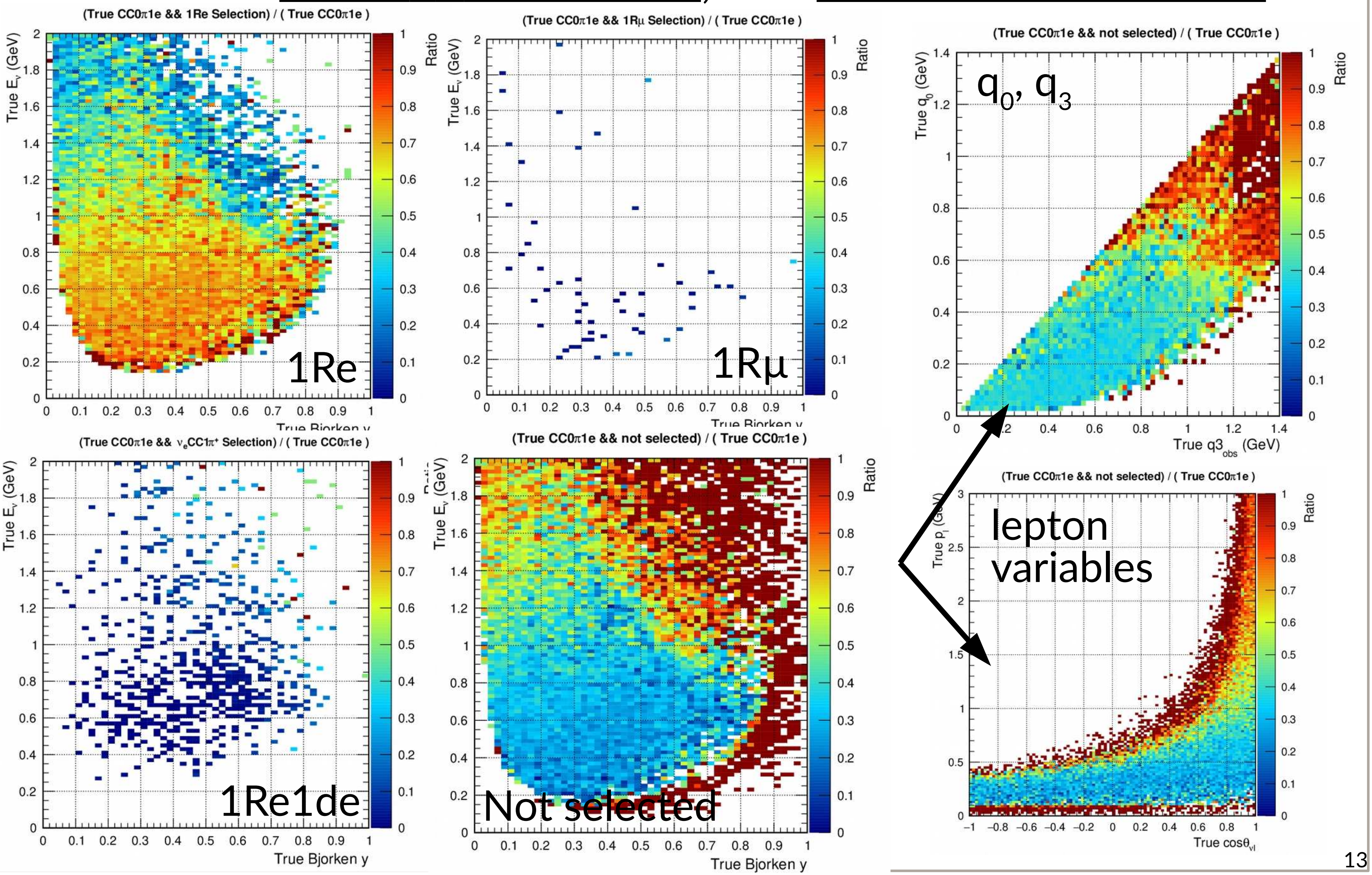
SK 1Rμ mis-reco

- Event has true 1μ0π selection, and recoed as selection x



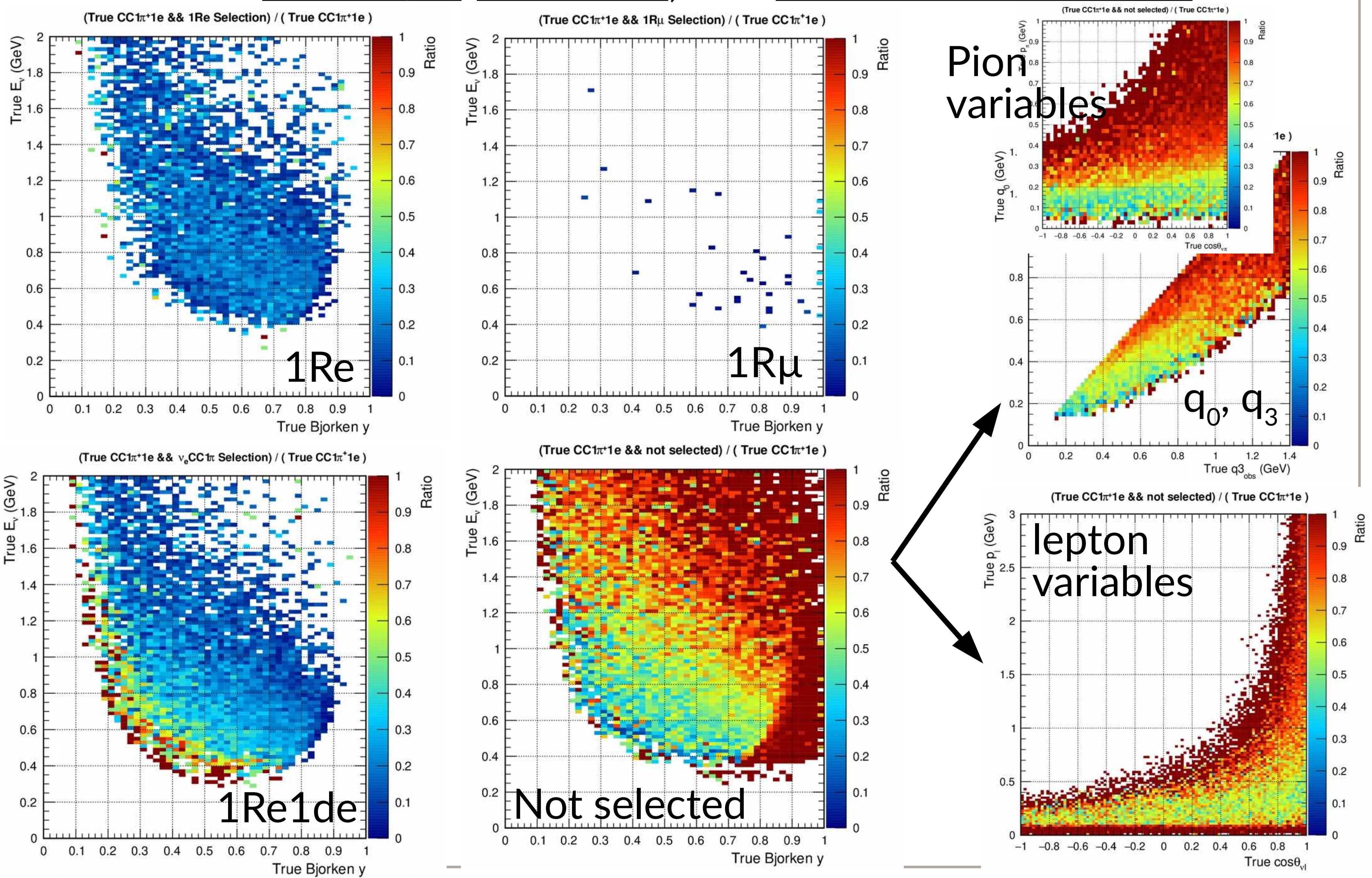
SK 1Re mis-reco

- Event has true 1e0π selection, and recoed as selection x



SK 1Re1de mis-reco

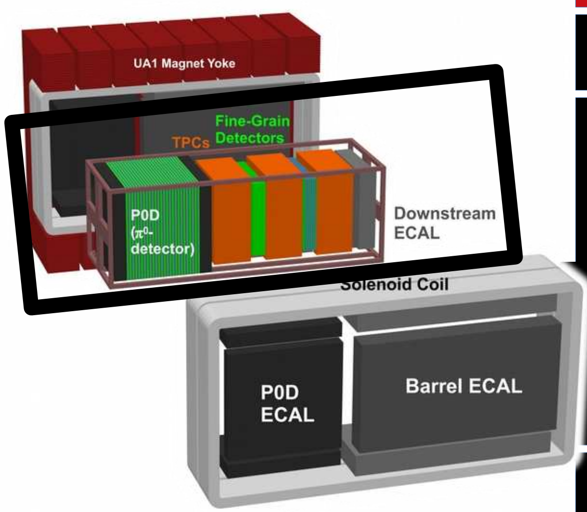
- Event has <u>true 1e1π⁺ selection</u>, and <u>recoed as selection x</u>

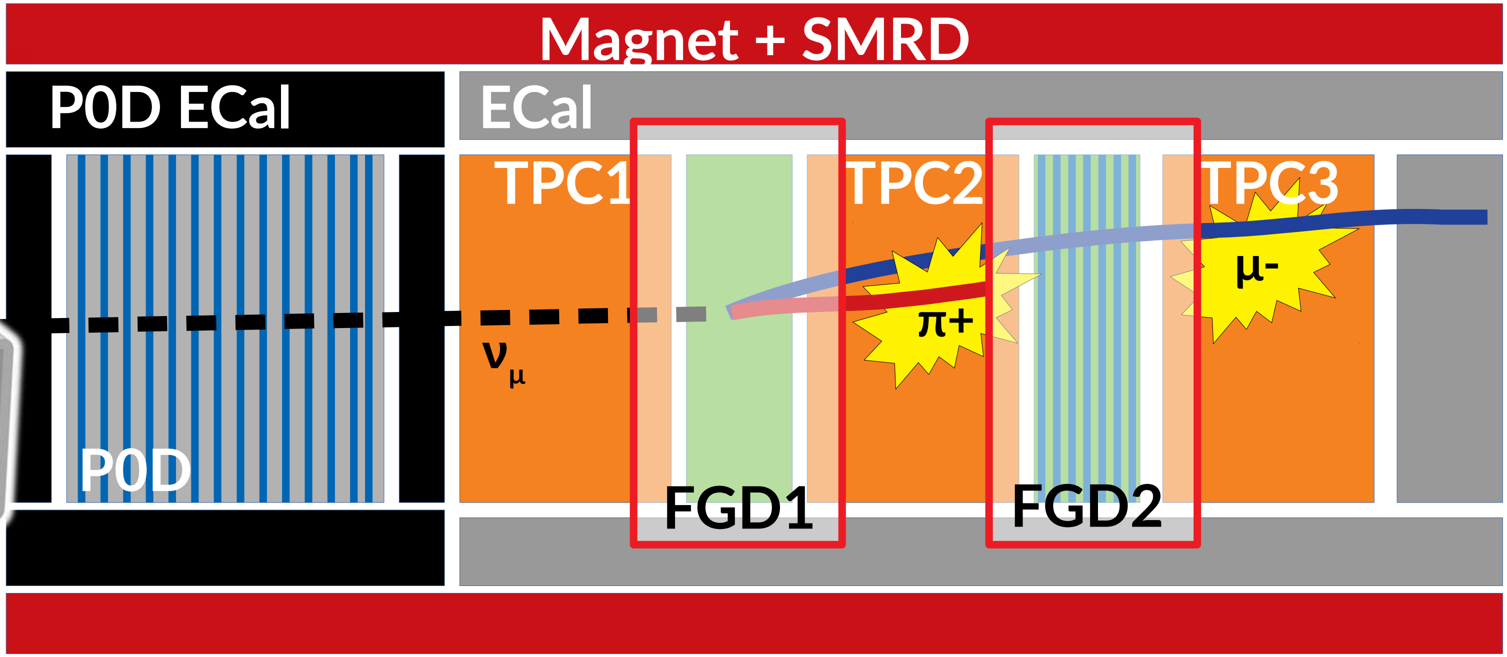


SK conclusions

- Efficiencies largely flat in $\cos\theta_{lep}$ for all selections
- 1Rμ 85-95%, 1Re 65-80%, 1Re 1.d.e. 20% of $1e1\pi^{\pm}$
- Fall-off at higher momentum due to containment and E_{rec} cut
  - Flat until p~0.8 GeV for 1Re, p~1.2 GeV for 1Rμ
- Very seldom (<0.5%) mis-reconstruct topology
  - Most missed events are not reconstructed at all
- Efficiency mostly flat in neutrino energy, q_0, q_3 and y
  - High q_0 and y efficiency is not flat, but small fraction of events in that region
- 1Re 1.d.e. selection tags true $1e1\pi^{+}$ with 40-50% efficiency for pions with low momentum
  - Does not select high momentum pions by design

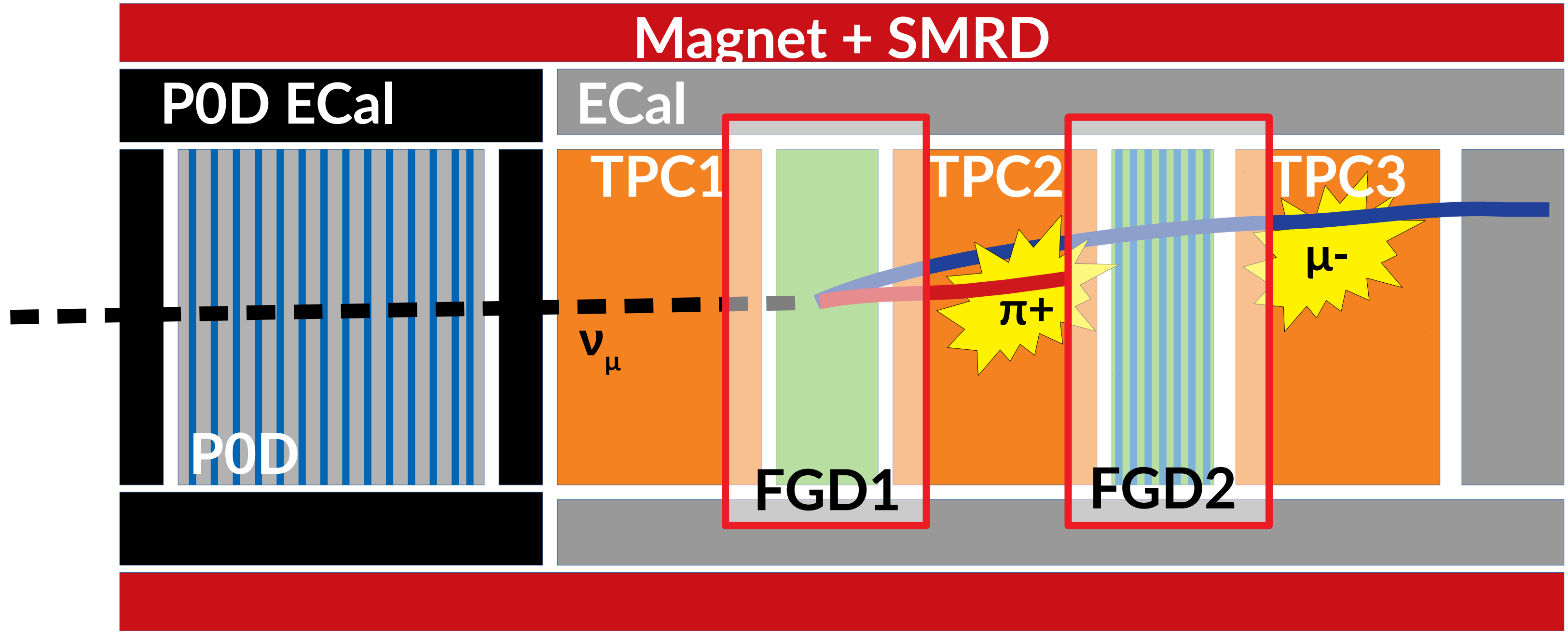
ND280 selections





- ND280 uses FGD1 and FGD2 as targets and the TPCs for tracking
- 2018 and earlier: oscillation analyses do not use the ECals, P0D, or SMRD for particle tracking in an event
  - This will change soon!
  - Use SMRD and ECal as veto for cosmics, but not included in assigning PID and measuring kinematics

ND280 selections

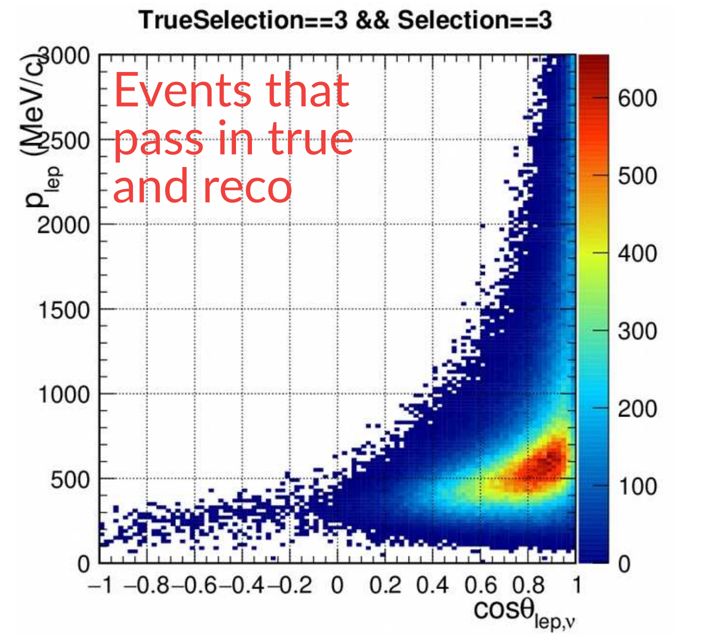


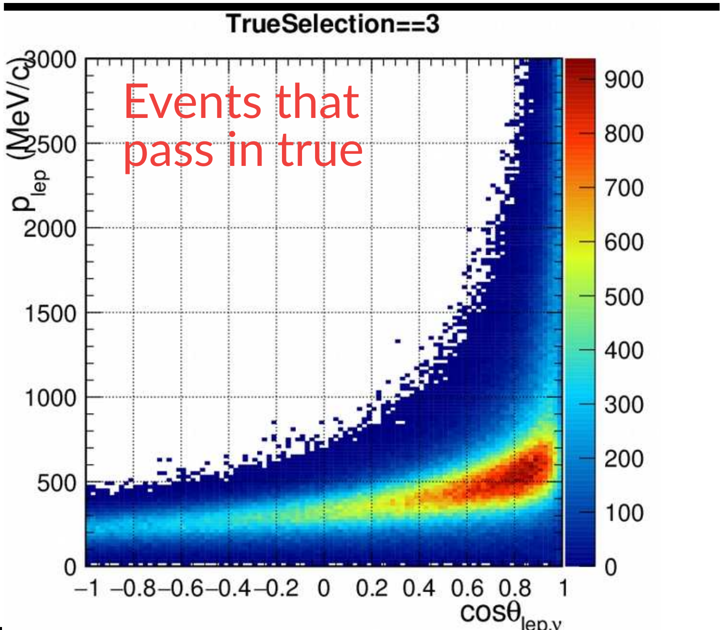
- All selections are CC-only: select muon* as high momentum negative(positive) track with muon PID
- Selection on reconstructed pion multiplicity**
  - CC0π, CC1π, CCOther: constrain signal and background model
  - CCOther soaks up $N(\pi^{\pm}) > 1$, $N(\pi^{0}) > 0$
- Split by FGD1/2, FHC/RHC, Pion mult., Neutrino/anti-neutrino (for RHC): <u>18 selections</u>

*electron selection under development, not included yet
**TPC track, FGD-contained track, delayed FGD Michel

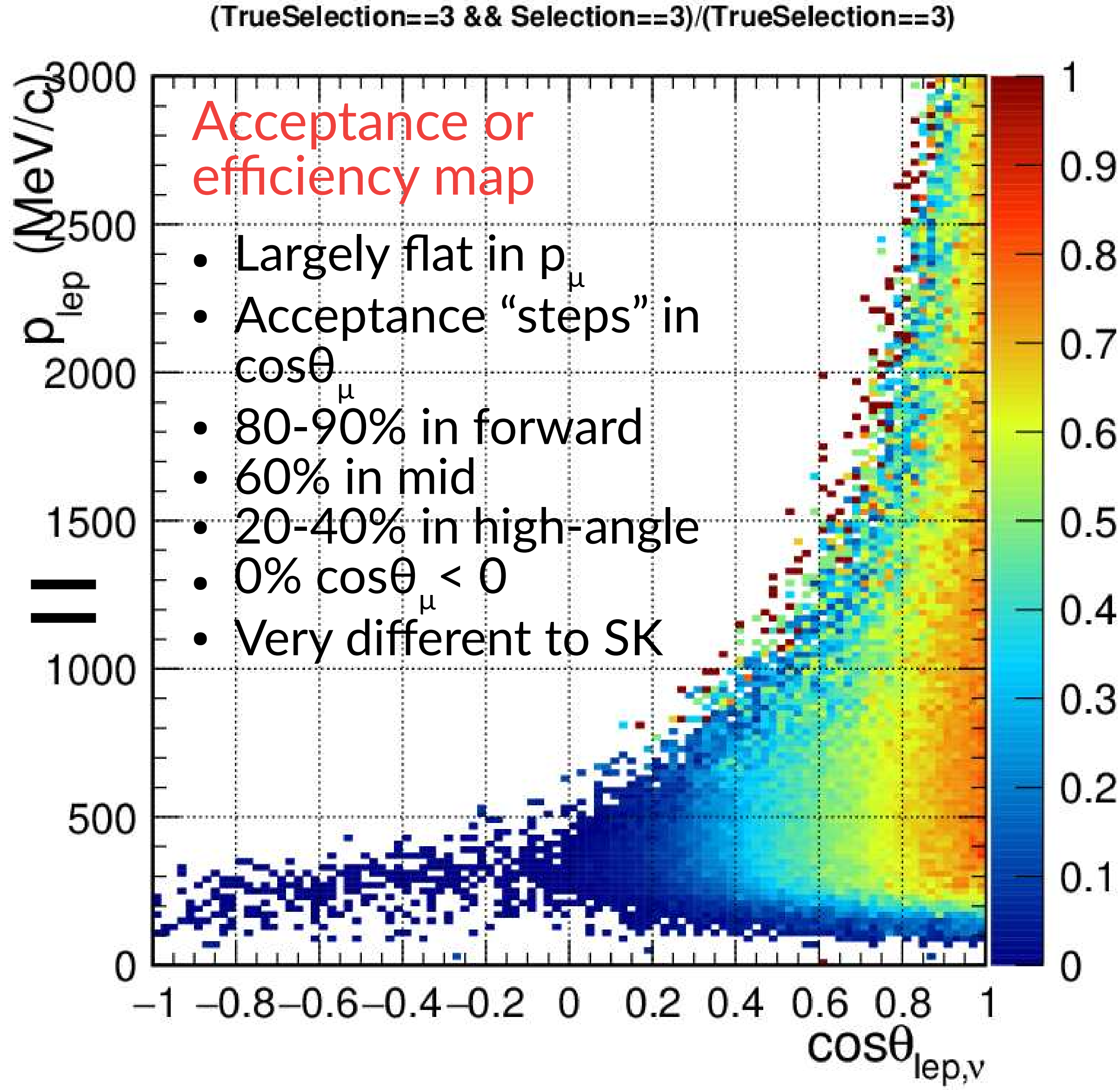
ND280 FGD1 CC0π

- Event has <u>true ND280 FGD1 CC0π</u>, and <u>reco ND280 FGD1 CC0π</u>





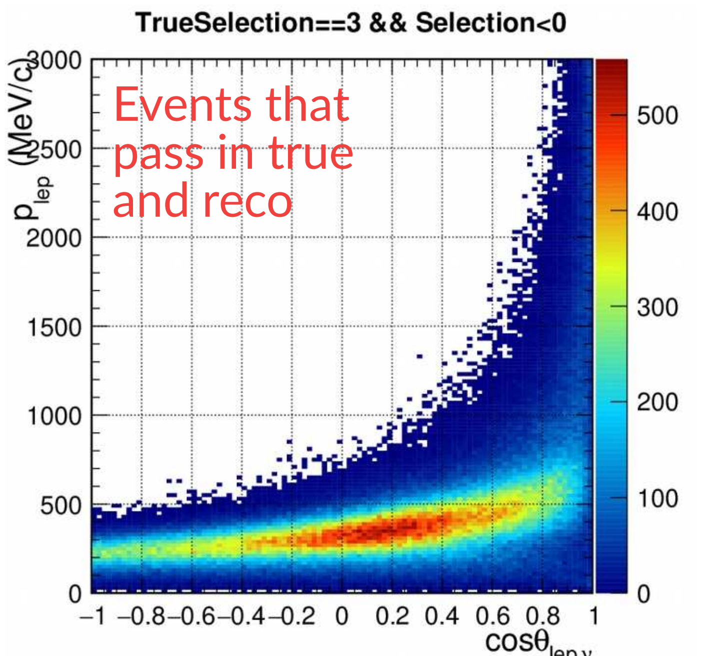
=

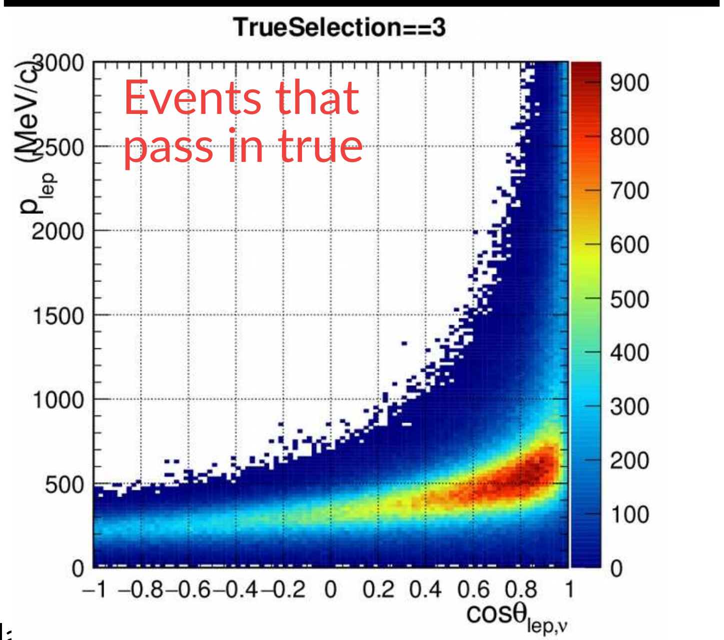


- Largely flat in p_μ
- Acceptance "steps" in $\cos\theta_\mu$
- 80-90% in forward
- 60% in mid
- 20-40% in high-angle
- 0% $\cos\theta_\mu < 0$
- Very different to SK

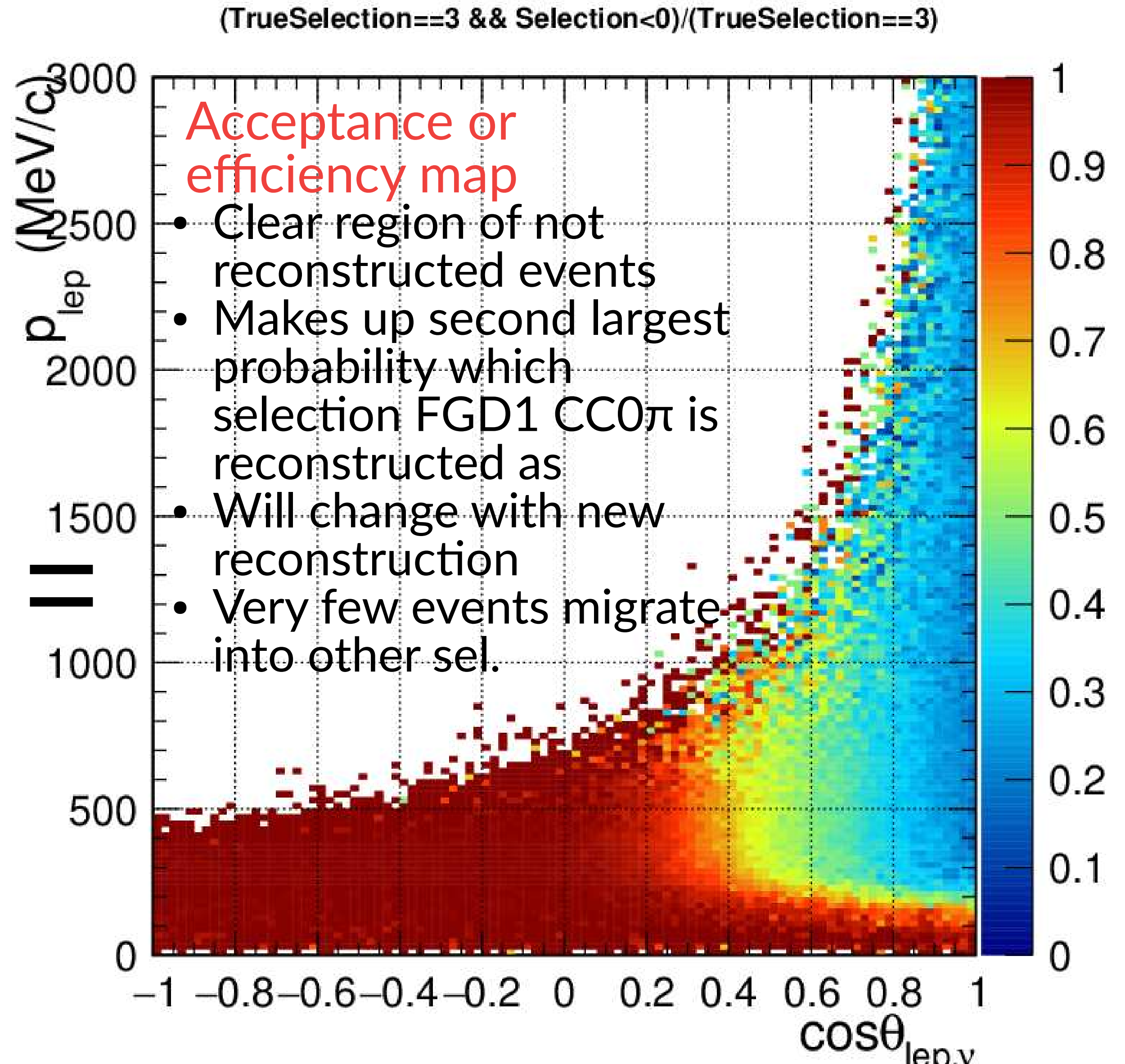
ND280 FGD1 CC0π

- Event has true ND280 FGD1 CC0π, and reco no ND280 selection



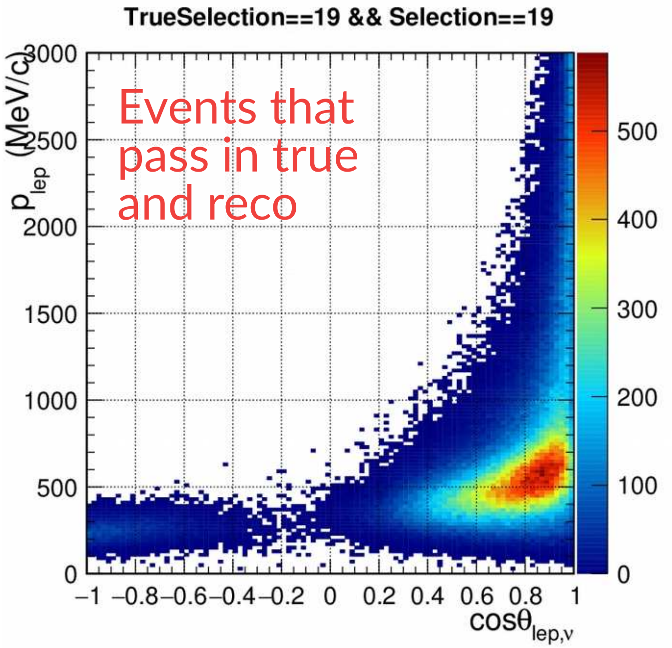


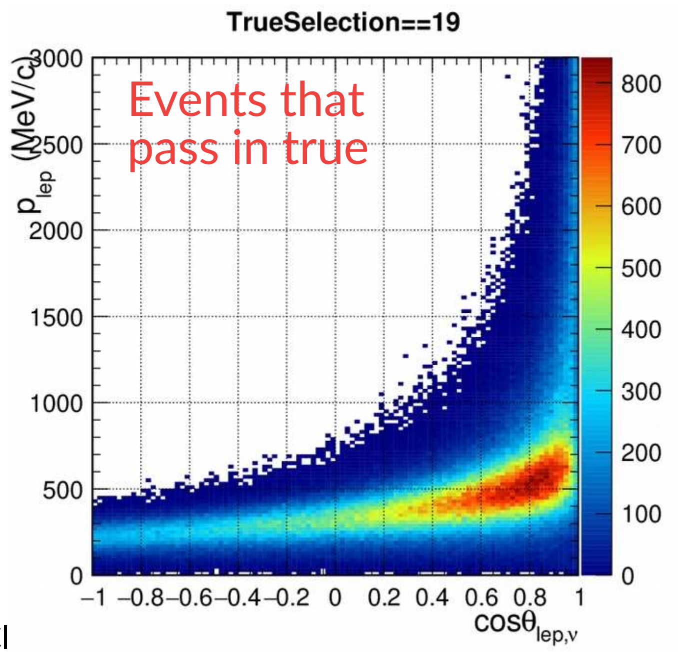
=



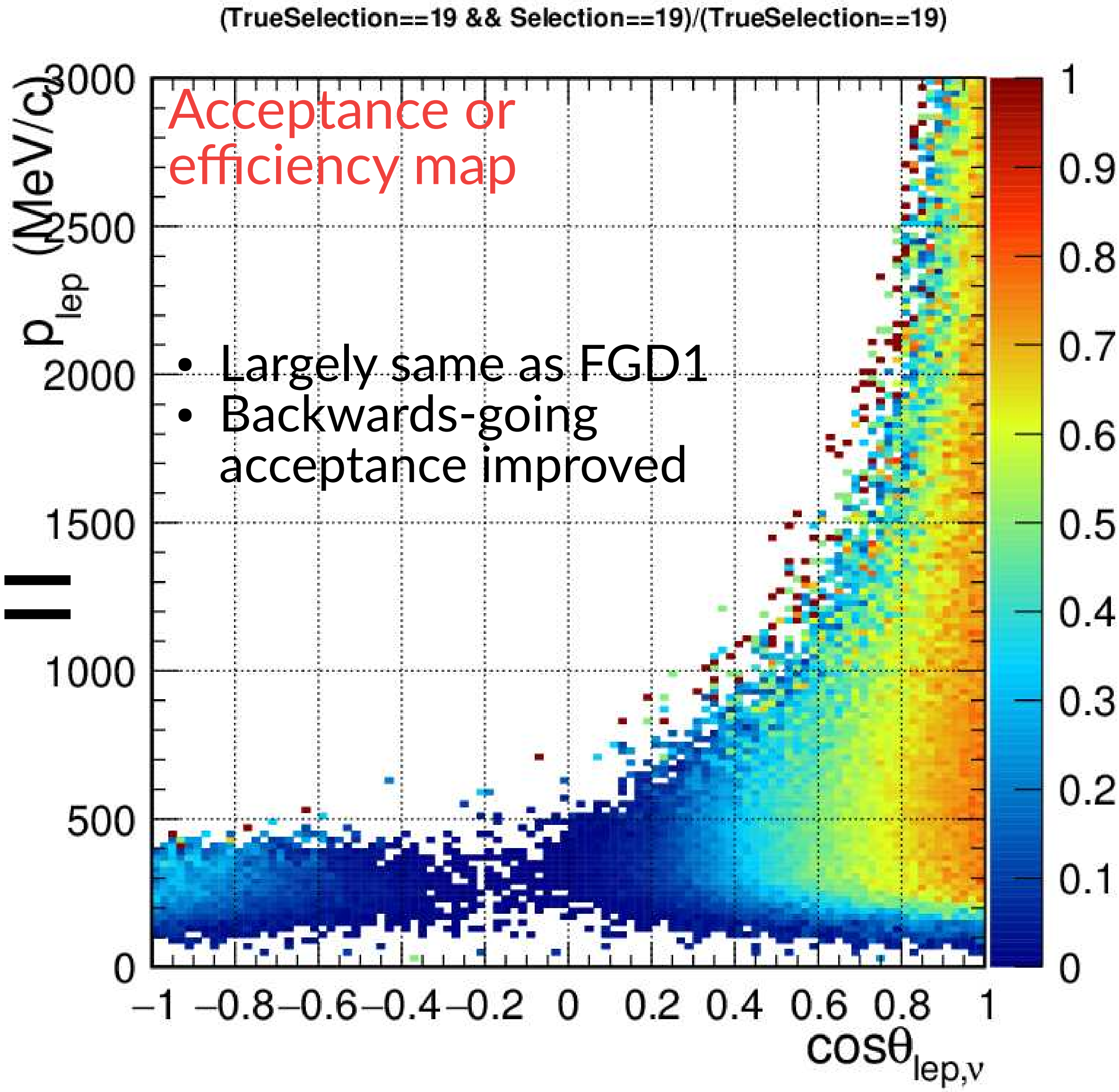
ND280 FGD2 CC0π

- Event has <u>true ND280 FGD2 CC0π</u>, and <u>reco ND280 FGD2 CC0π</u>





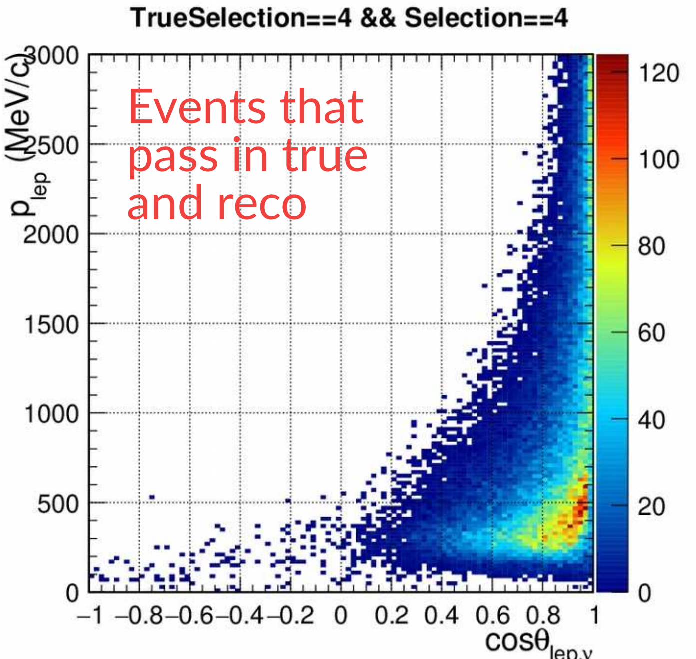
=

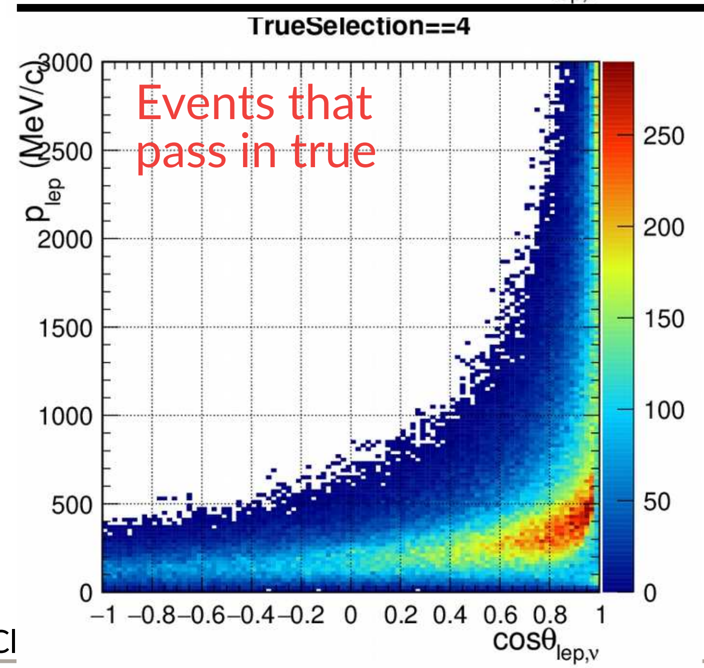


- Largely same as FGD1
- Backwards-going acceptance improved

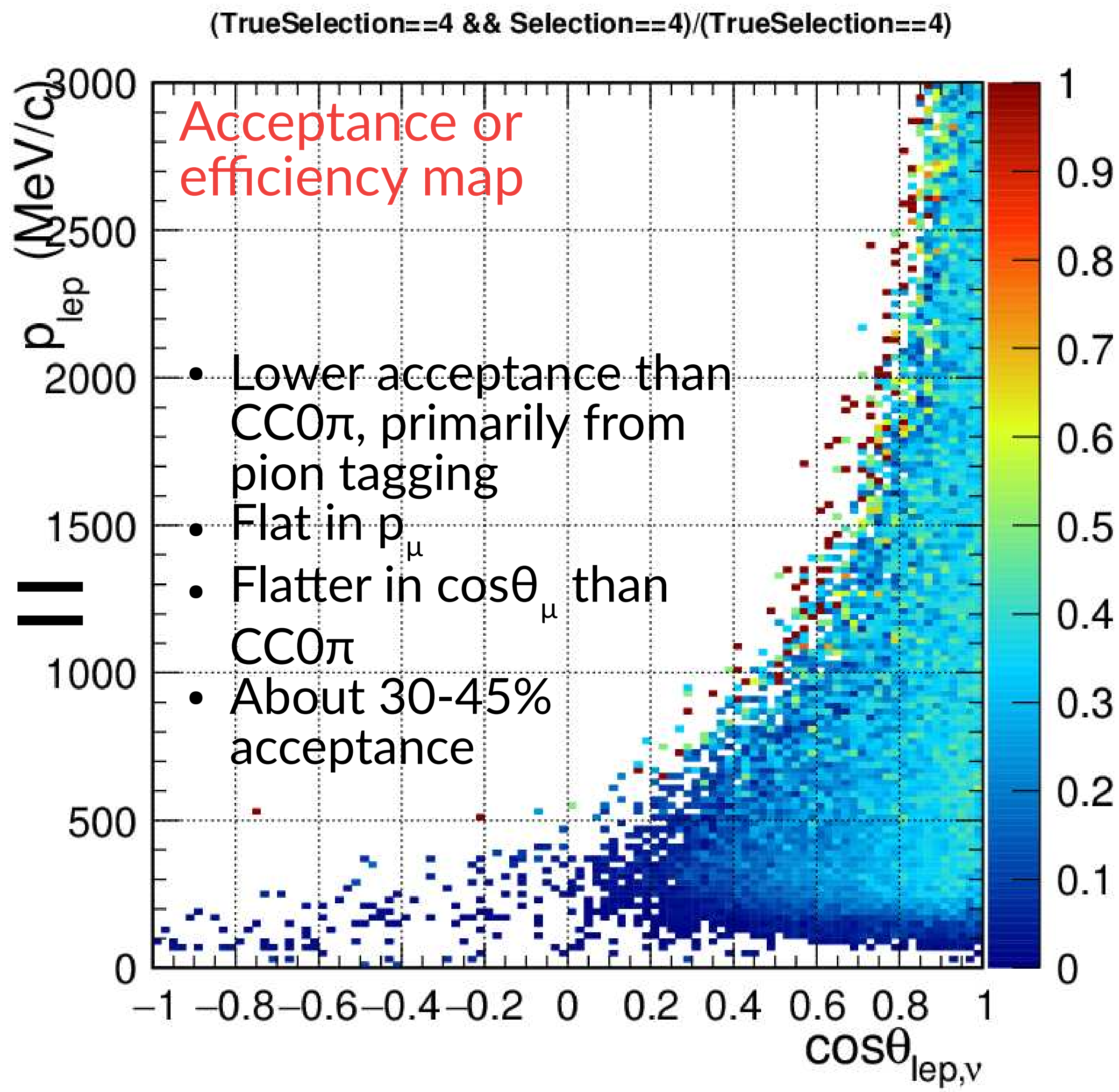
ND280 FGD1 CC1π

- Event has true ND280 FGD1 CC1π, and reco ND280 FGD1 CC1π





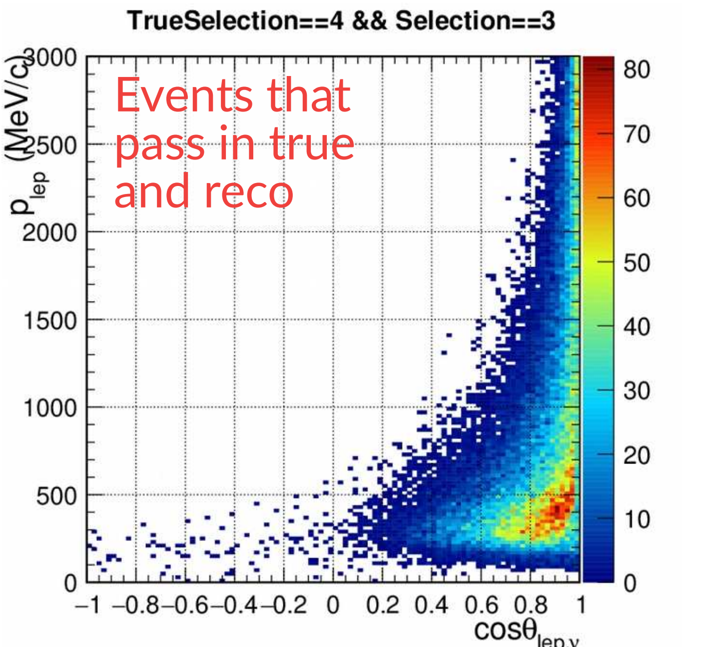
=

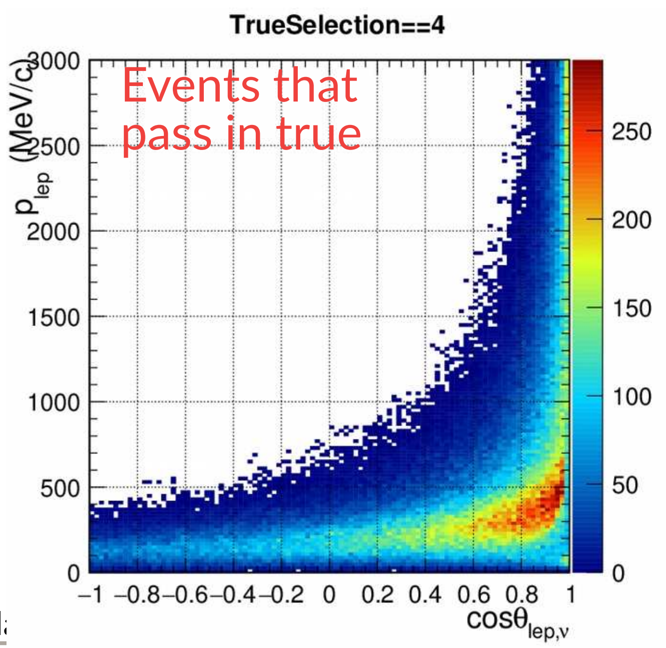


- Lower acceptance than CC0π, primarily from pion tagging
- Flat in p_μ
- Flatter in $\cos\theta_\mu$ than CC0π
- About 30-45% acceptance

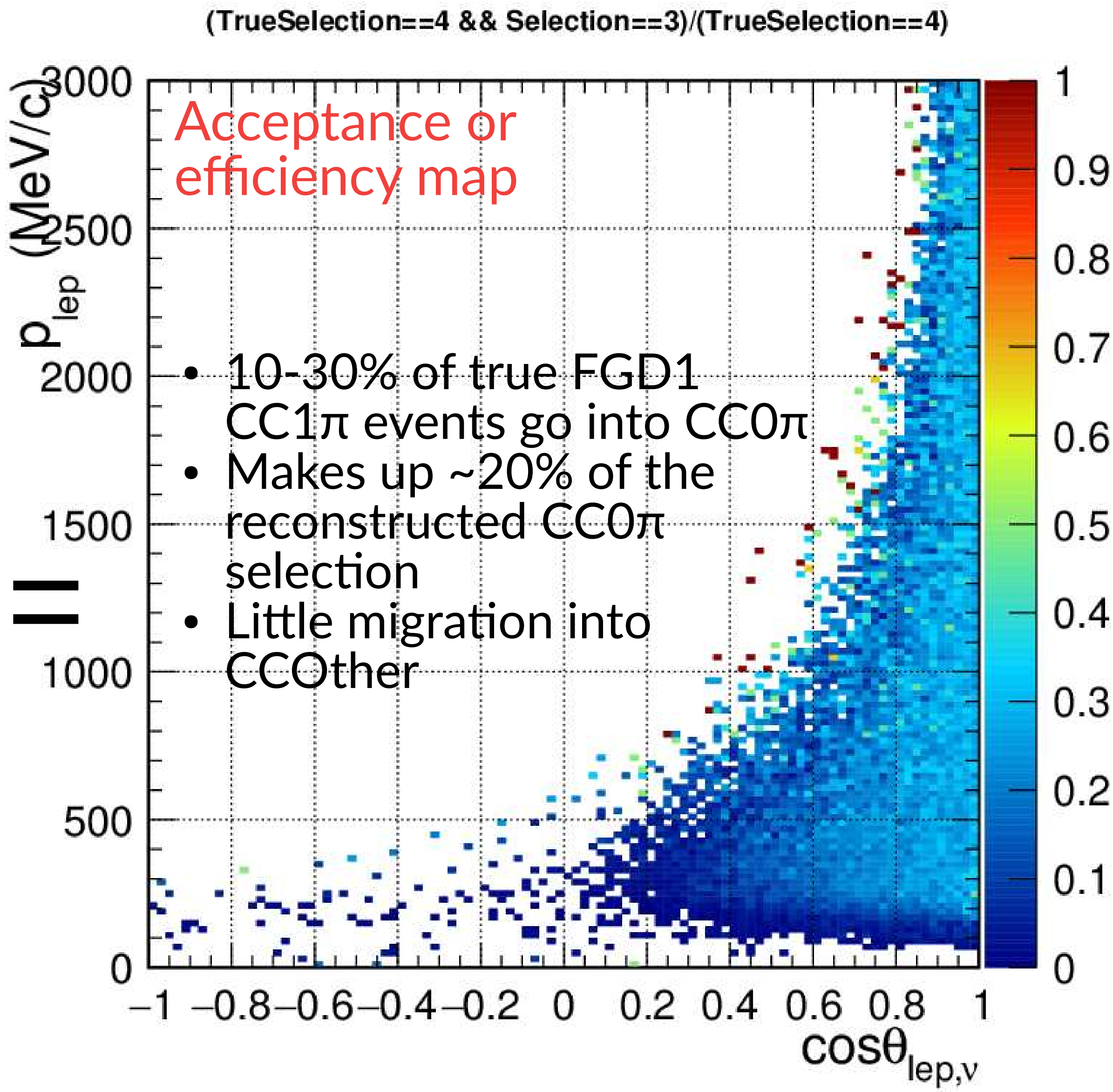
ND280 FGD1 CC1π

- Event has true ND280 FGD1 CC1π, and reco ND280 FGD1 CC0π





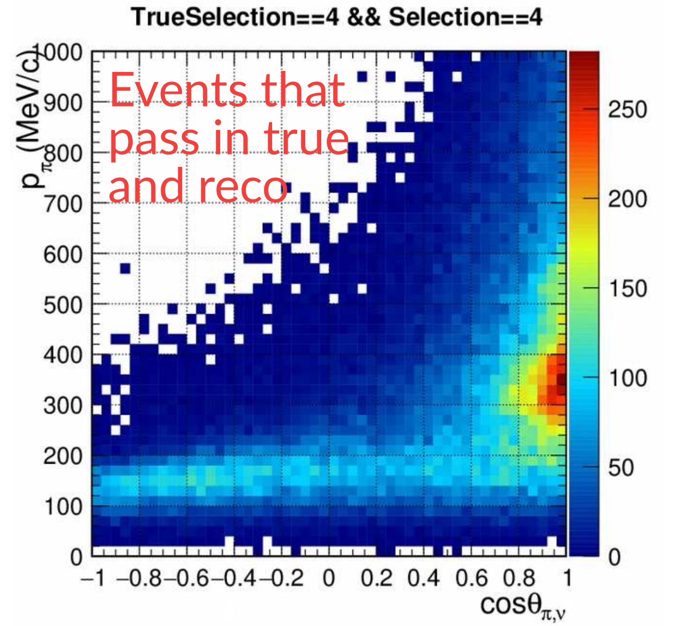
=

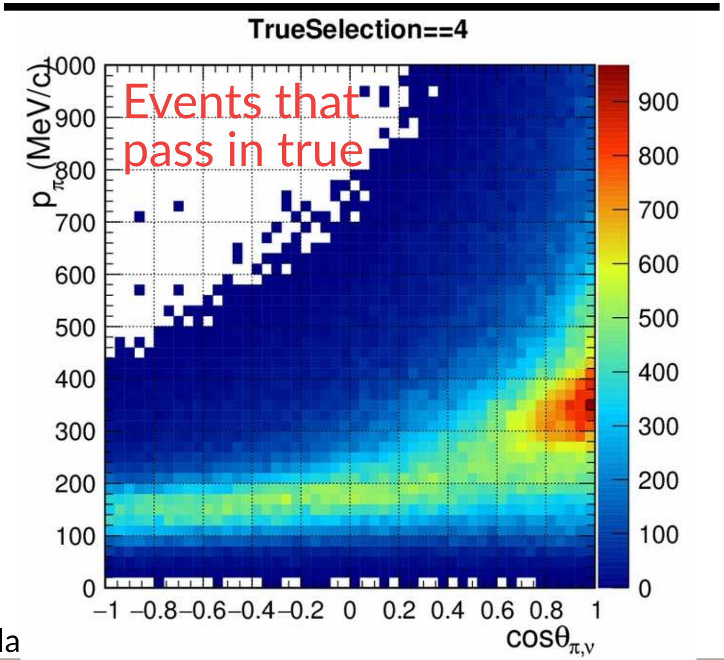


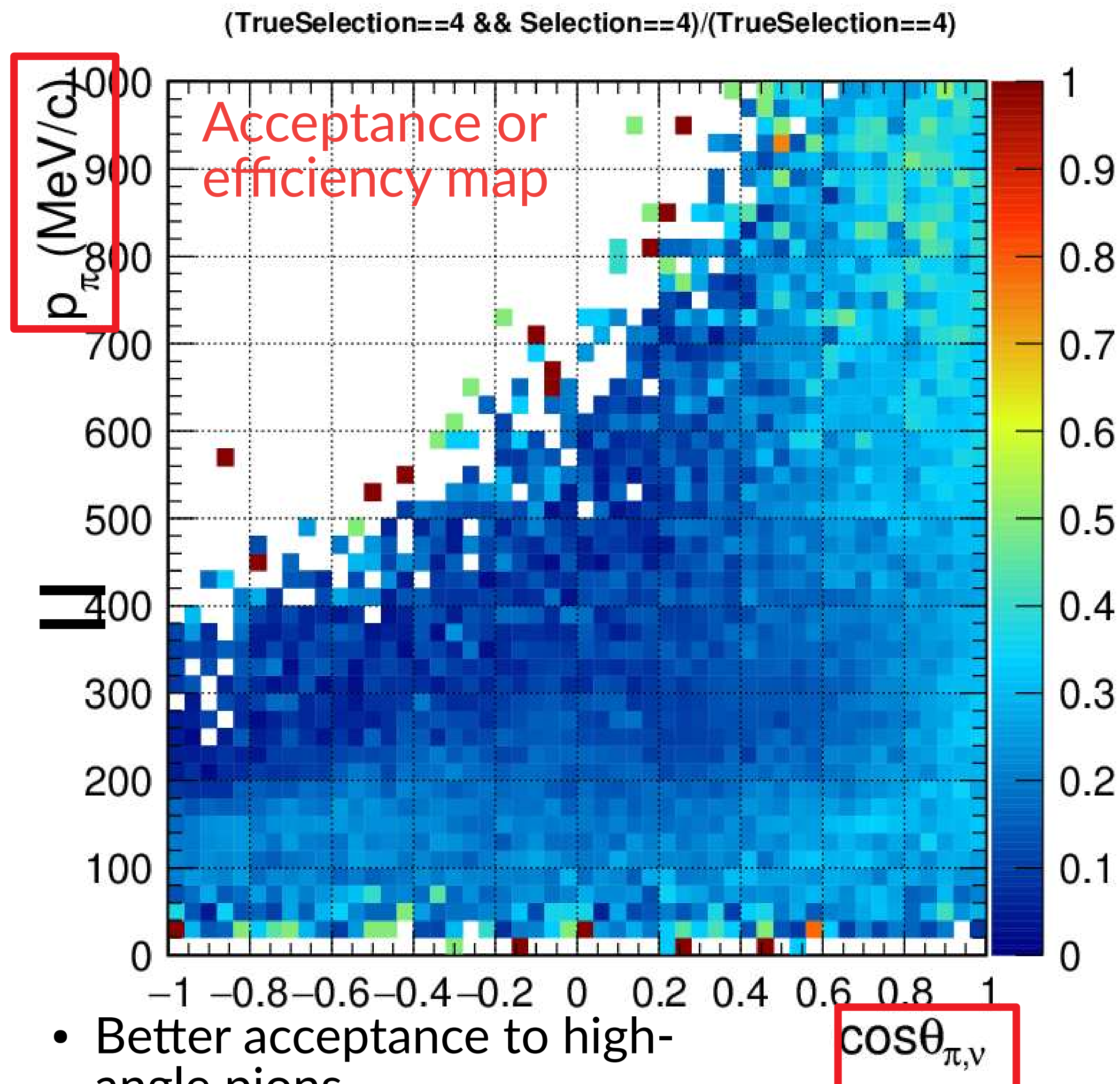
- 10-30% of true FGD1 CC1π events go into CC0π
- Makes up ~20% of the reconstructed CC0π selection
- Little migration into CCOther

ND280 FGD1 CC1π pion

- Event has true ND280 FGD1 CC1π, and reco ND280 FGD1 CC1π



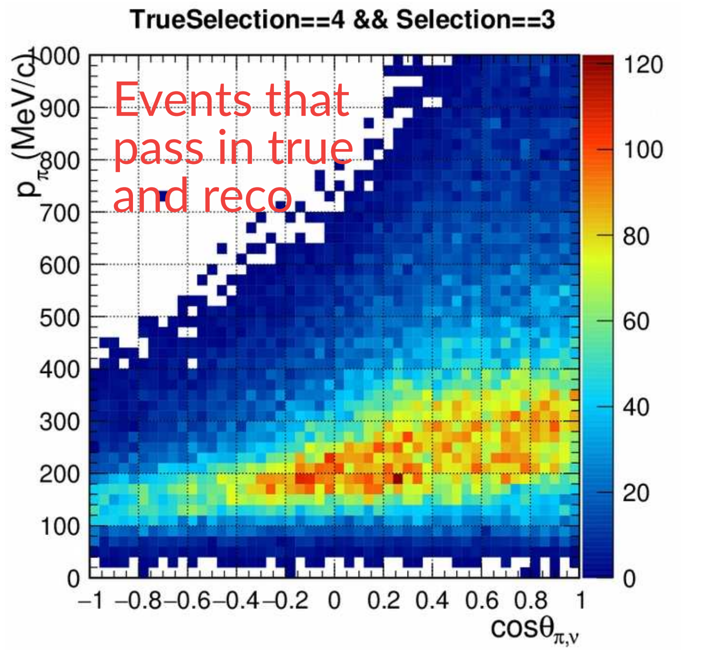


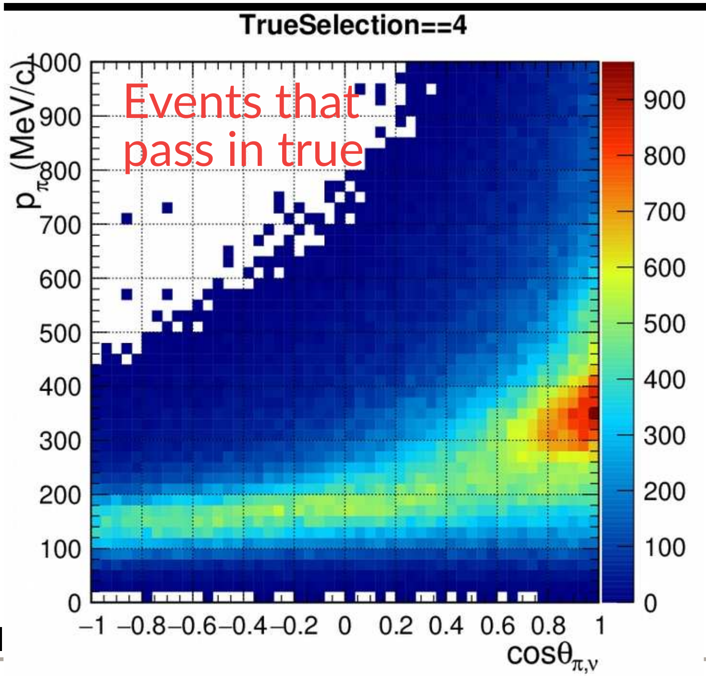


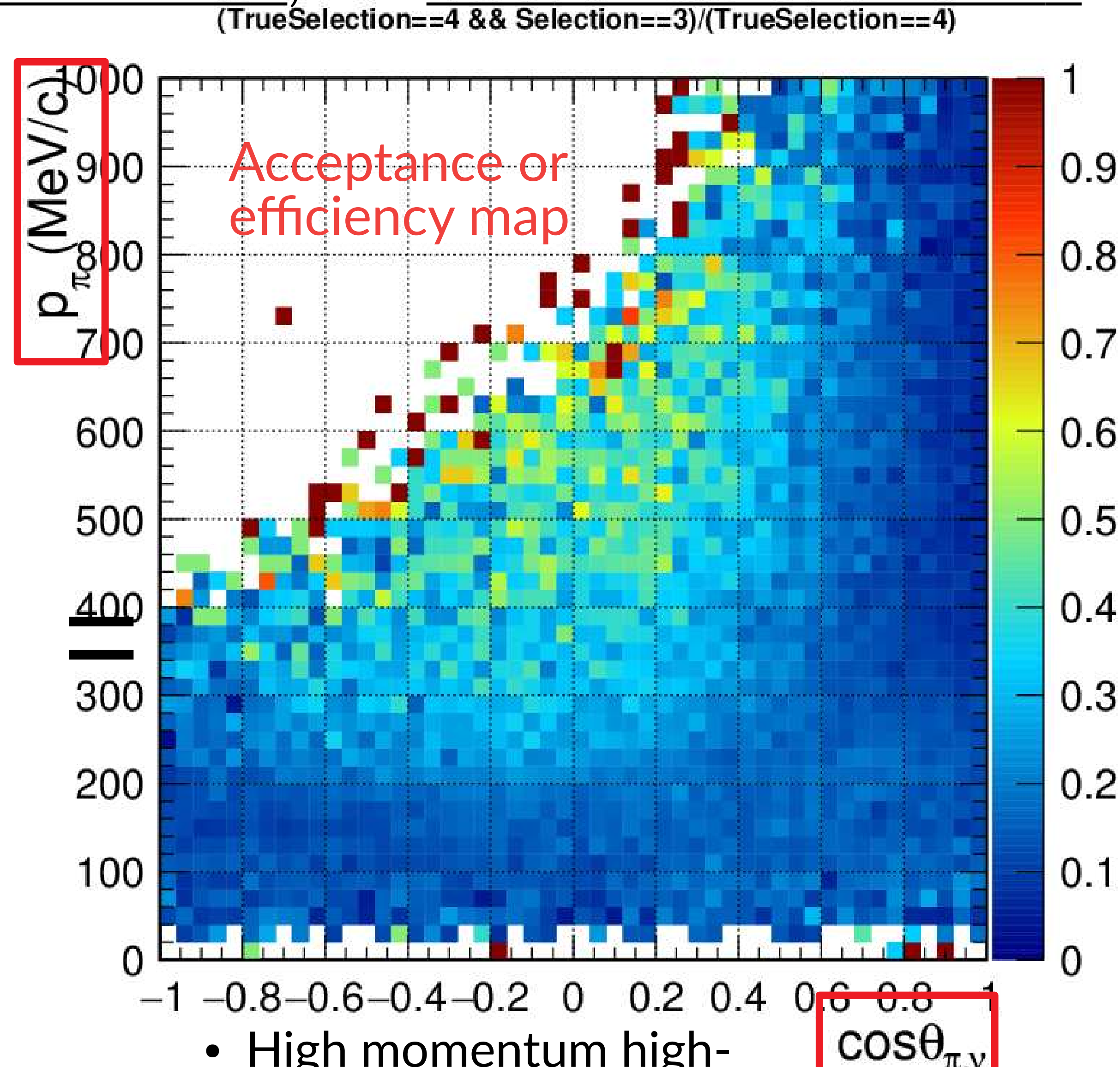
- Better acceptance to high-angle pions
- From Michel and FGD-contained pion tag

ND280 FGD1 CC1π pion

- Event has true ND280 FGD1 CC1π, and reco ND280 FGD1 CC0π



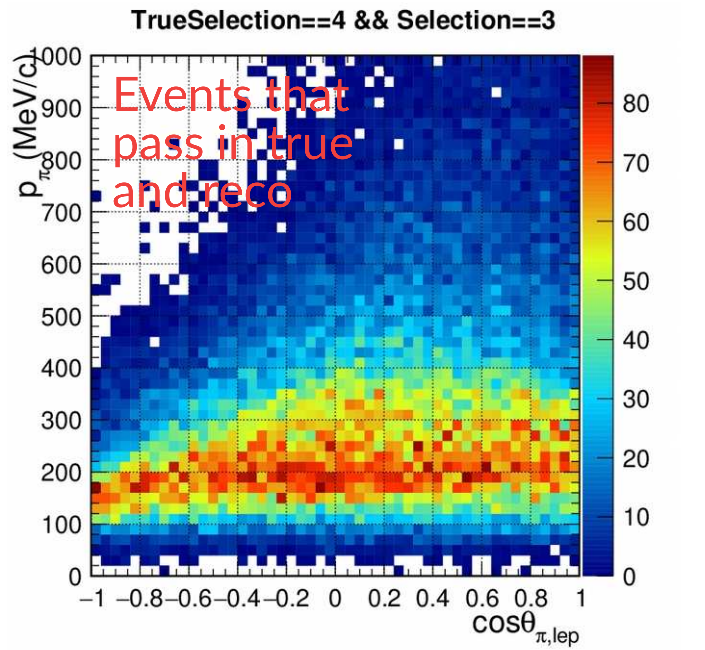


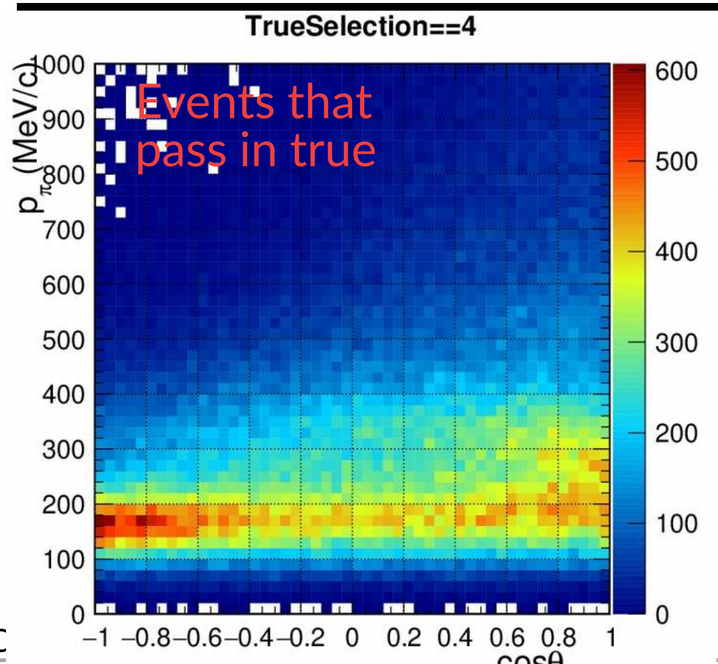


- High momentum high-angle pions likely to escape FGD: can't tag with FGD contained or Michel

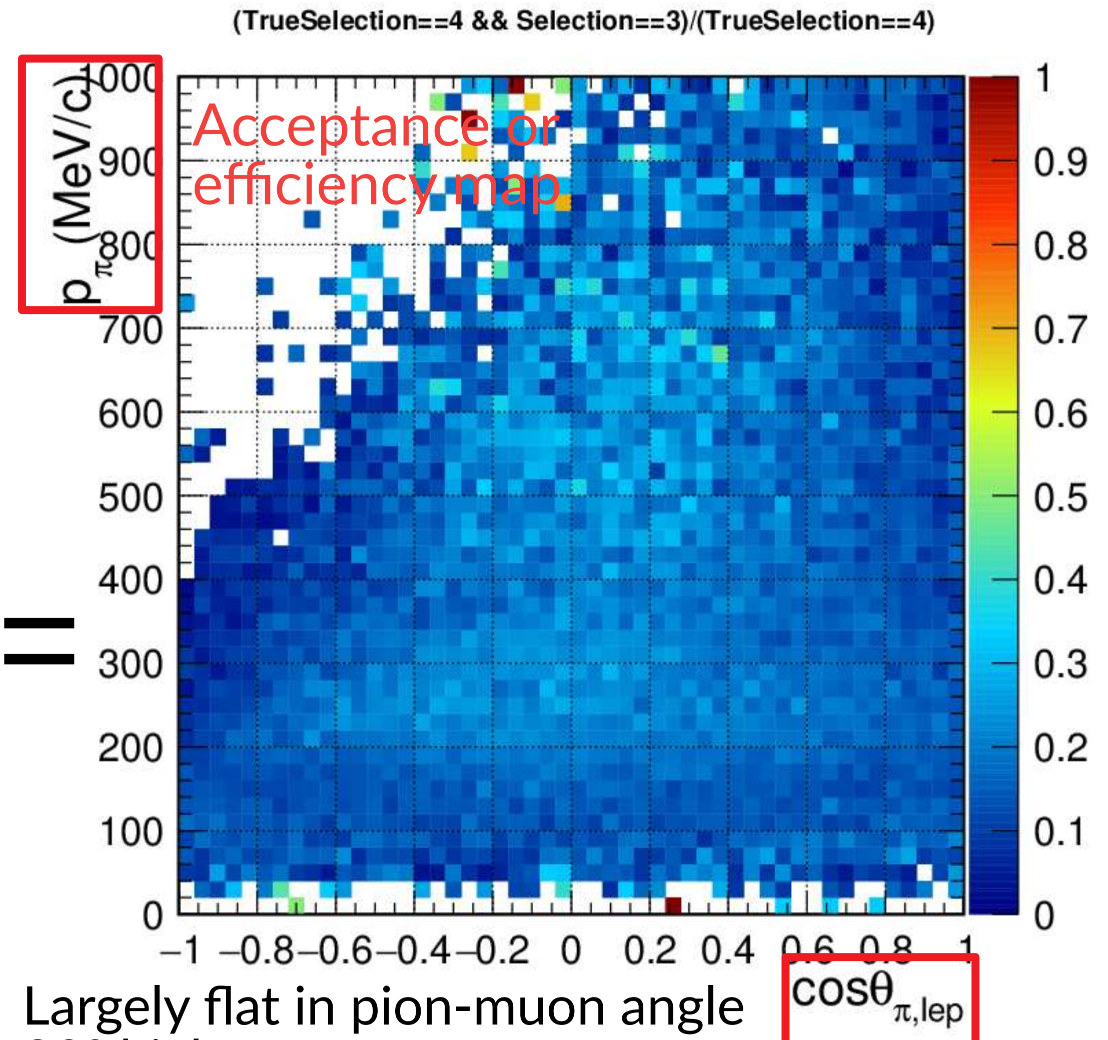
ND280 FGD1 CC1π pion

- Event has true ND280 FGD1 CC1π, and reco ND280 FGD1 CC0π





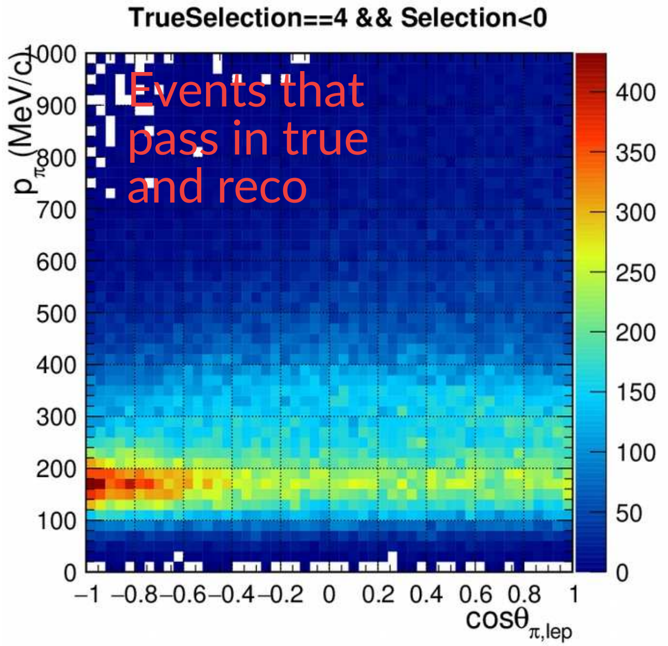
=

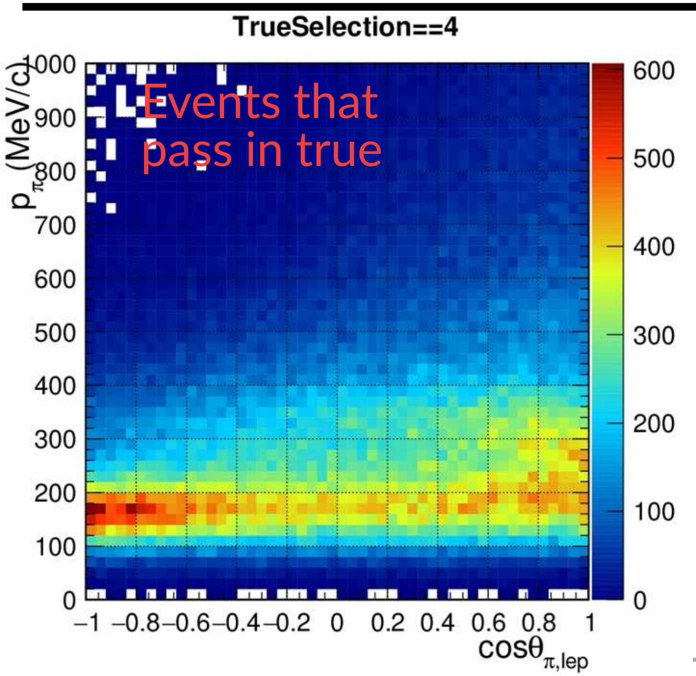


- Largely flat in pion-muon angle
- 90° highest acceptance:
  - Muon missed and pion tagged as lepton
  - Muon tagged and pion not (high-angle high-momentum)

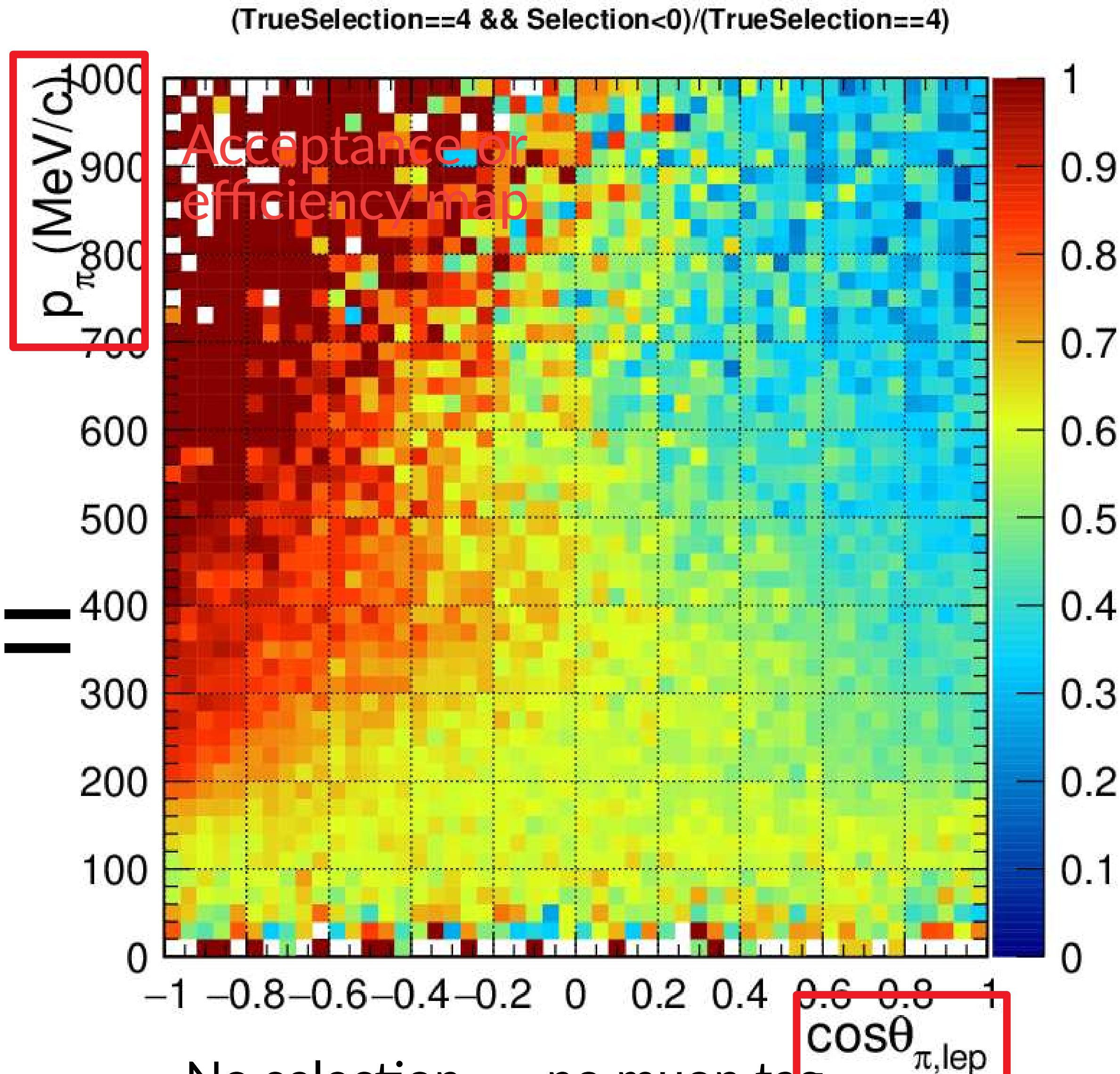
ND280 FGD1 CC1π pion

- Event has true ND280 FGD1 CC1π, and reco no ND280 selection





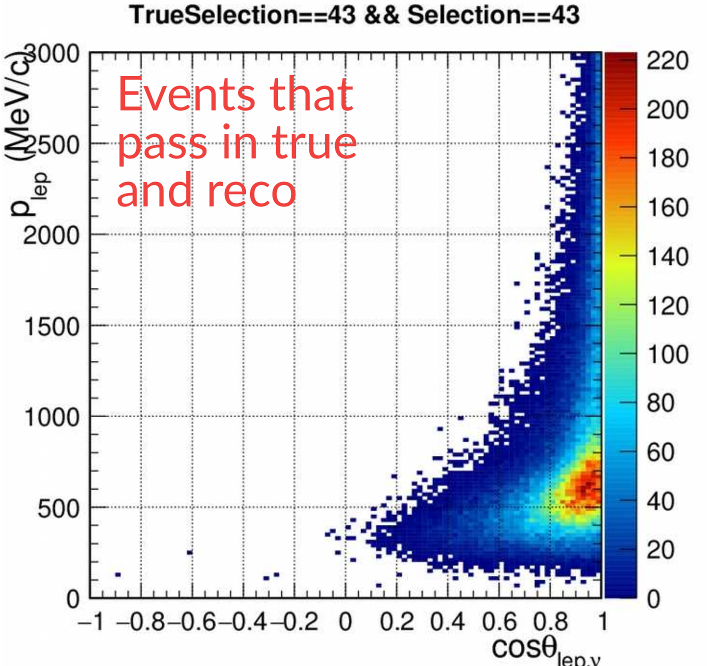
=

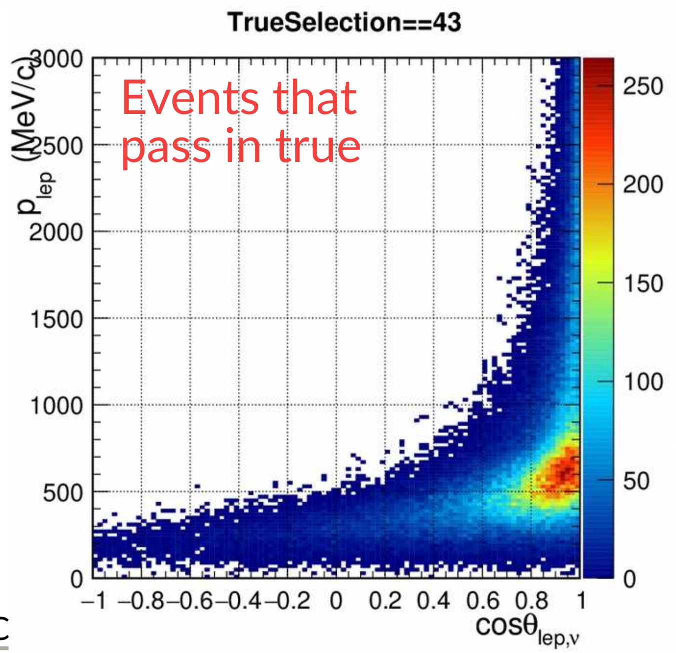


- No selection == no muon tag
- Shape largely due muon/pion correlation in interaction model

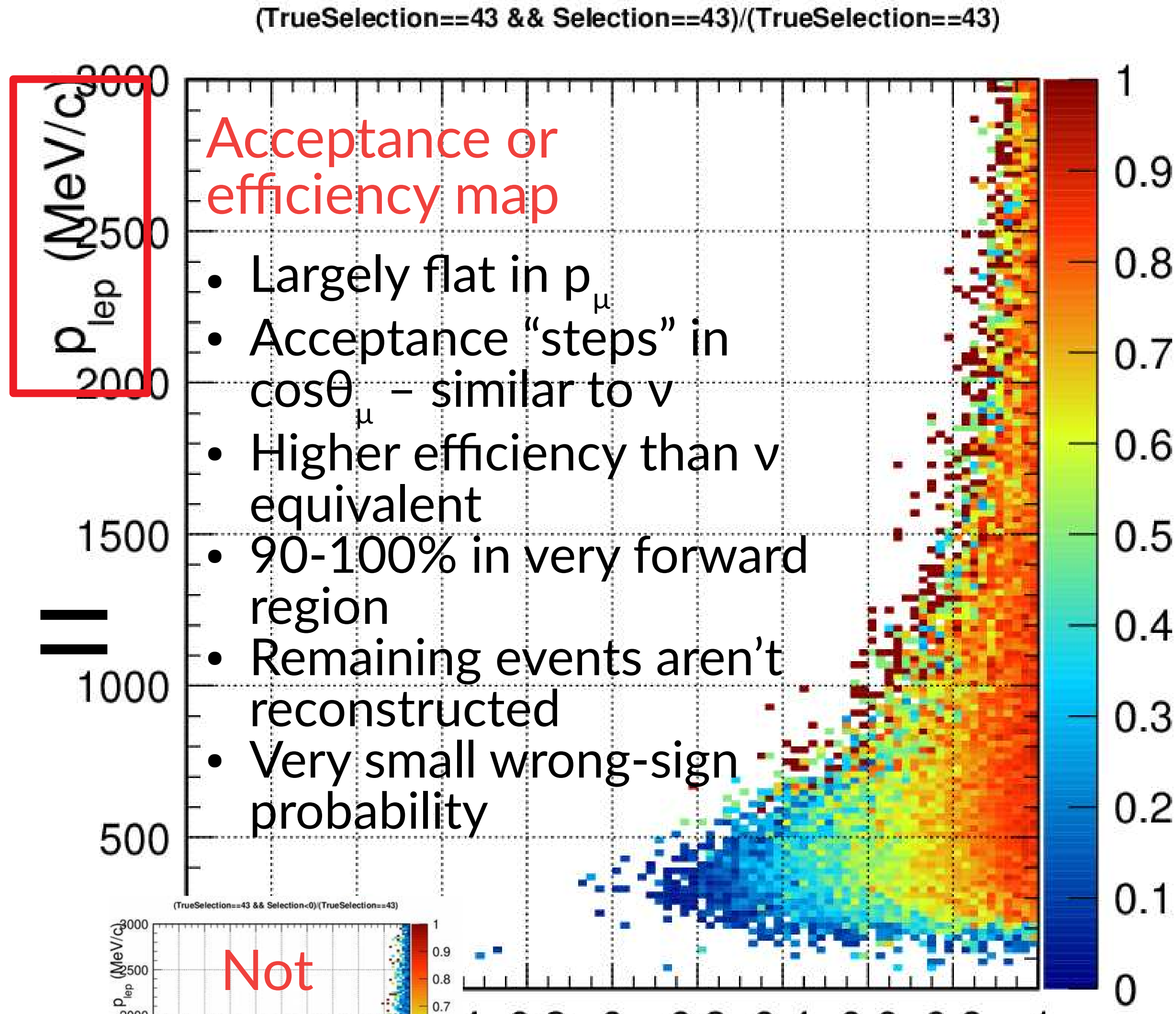
ND280 FGD1 CC0π anti-ν

- Event has true ND280 FGD1 CC0π anti-ν, and reco ND280 FGD1 CC0π anti-ν

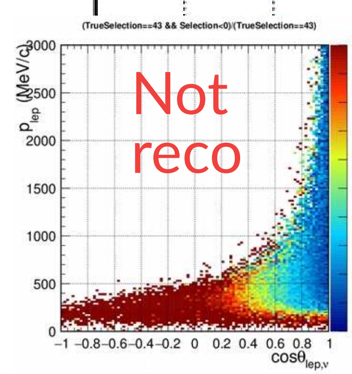




=

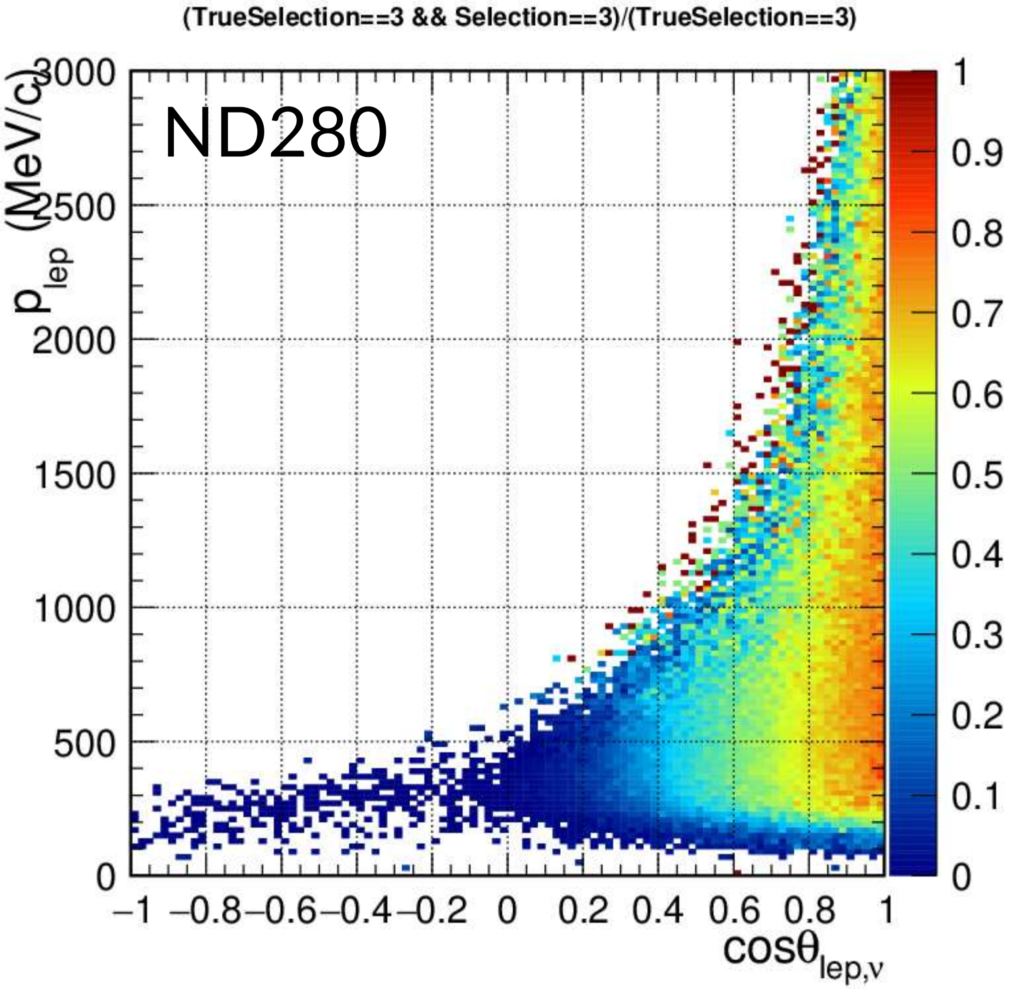


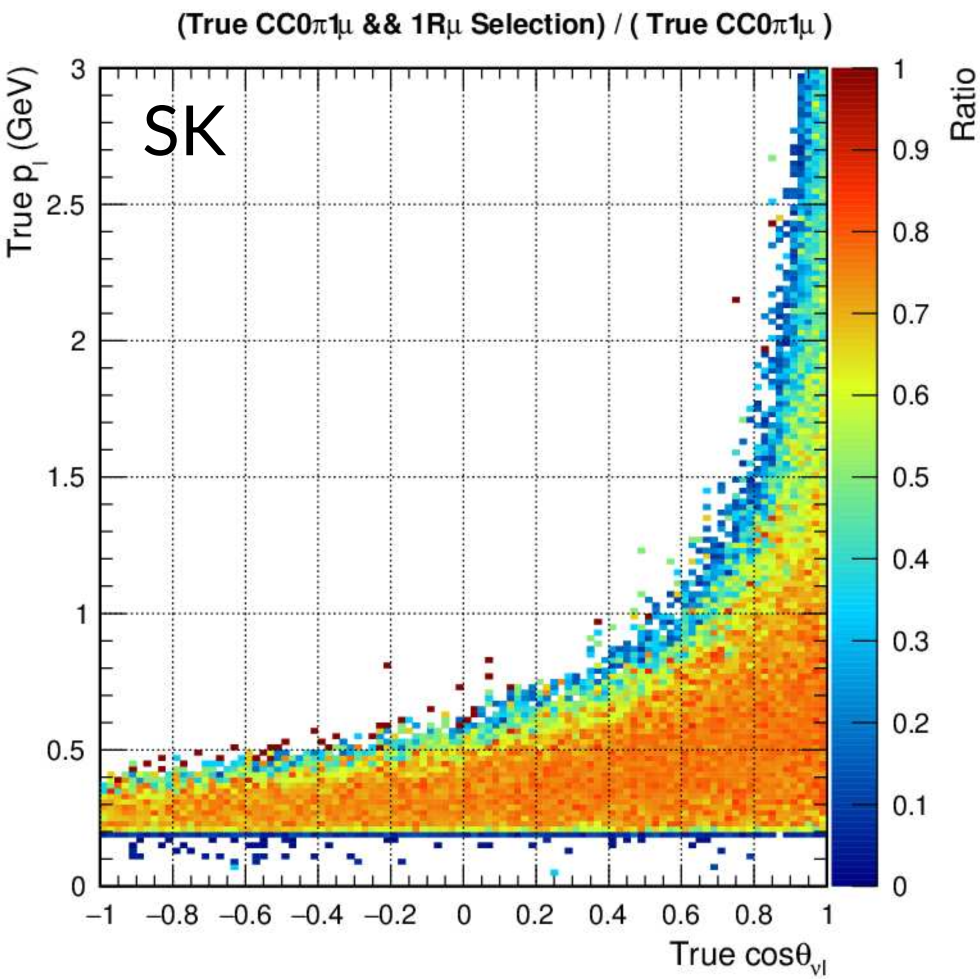
- Largely flat in p_{μ}
- Acceptance "steps" in $\cos\theta_{\mu}$ – similar to ν
- Higher efficiency than ν equivalent
- 90-100% in very forward region
- Remaining events aren't reconstructed
- Very small wrong-sign probability



ND280 vs SK

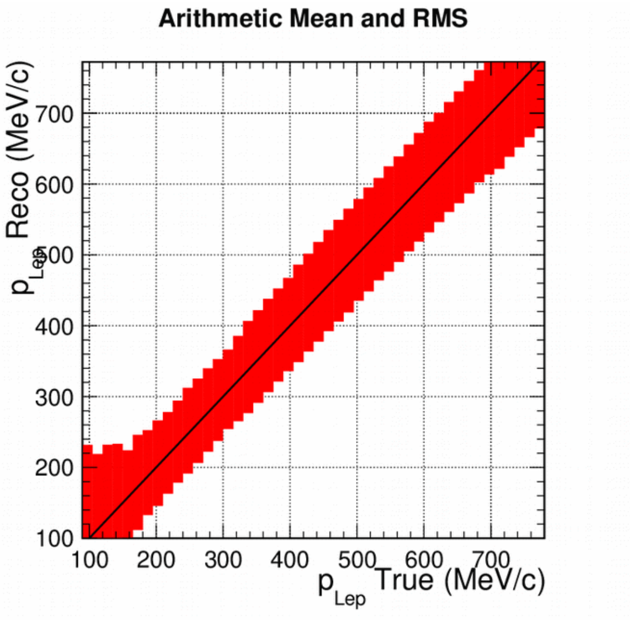
- SK event has true 1μ0π selection, and reco SK 1Rμ selection
- ND280 event has true FGD1 CC0π selection, and reco FGD1 CC0π selection

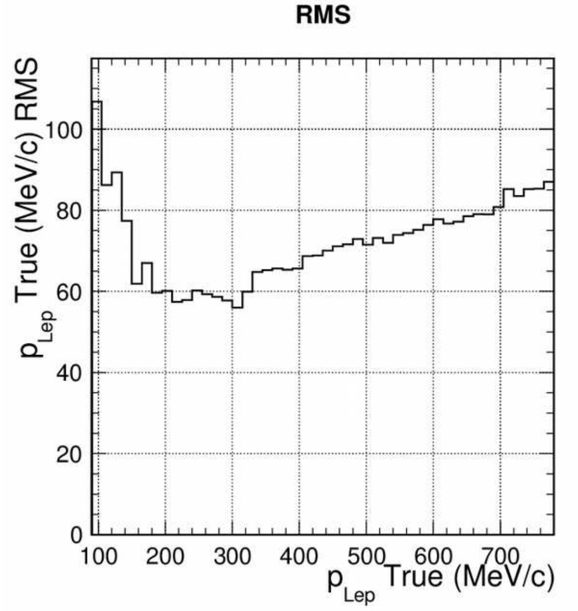




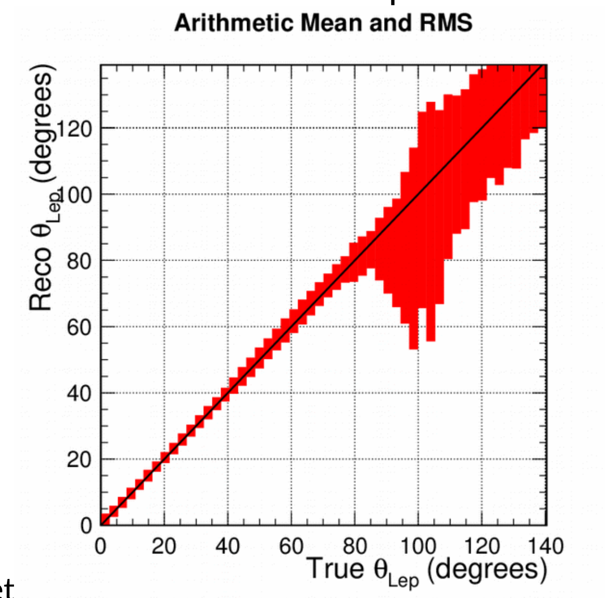
ND280 lepton resolution

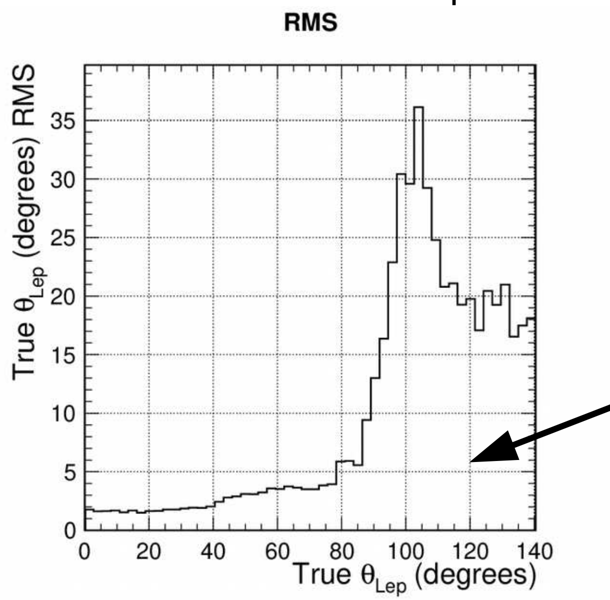
- Above p=150 MeV/c unbiased central value, Δp=55-95 MeV





- Unbiased until θ_{lep}=80°, and $\Delta\theta_{lep}$=1.5-2° until θ_{lep}= 40°

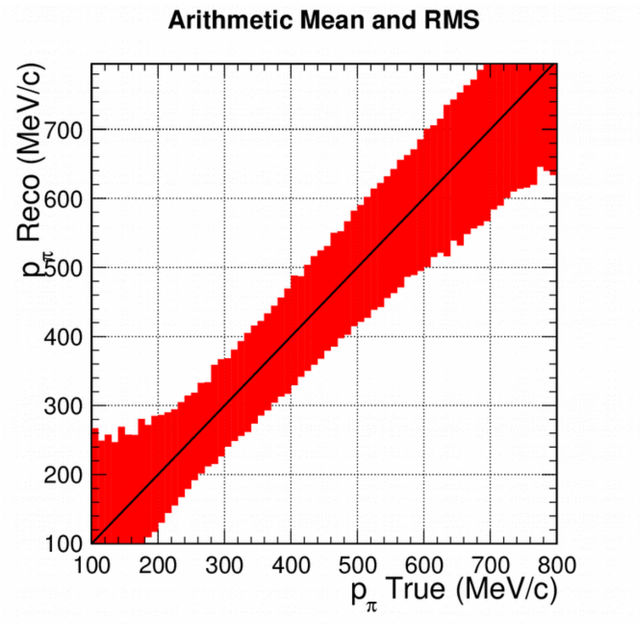


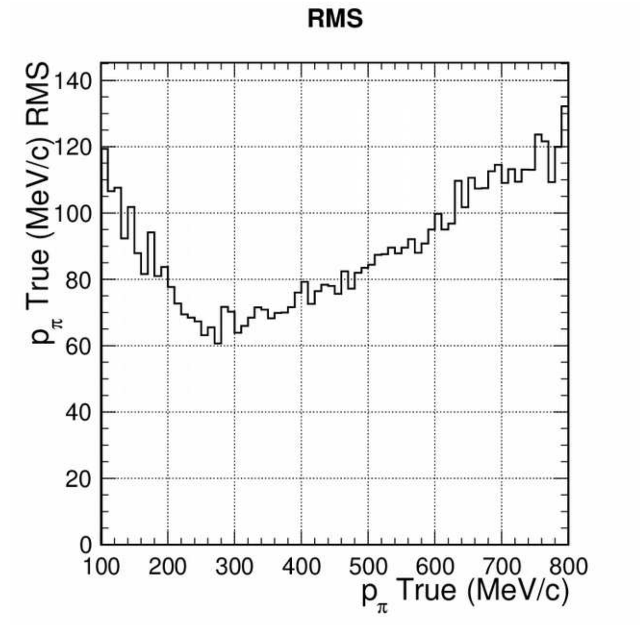


Expected to improve with full FGD + TPC + Ecal + SMRD reco (aka 4π)

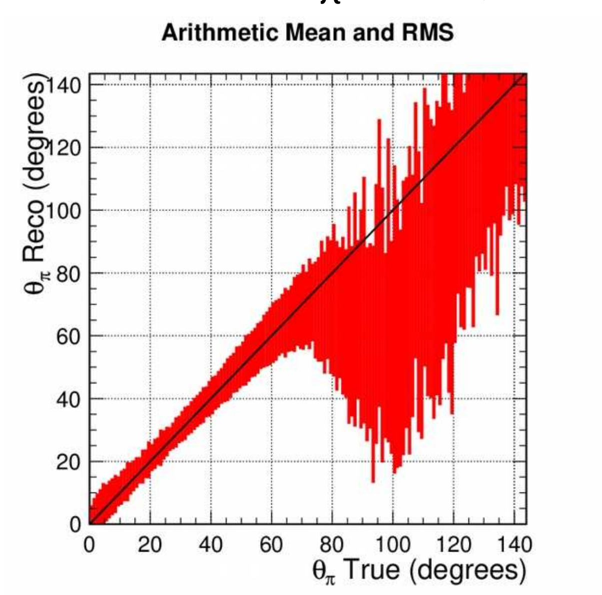
ND280 pion resolution

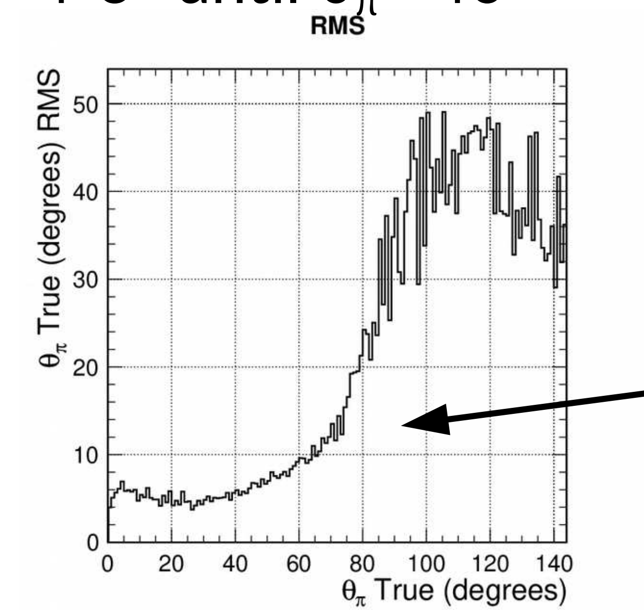
- Above p=170 MeV/c unbiased central value, Δp=60-120 MeV





- Unbiased until θ_π=60°, and $\Delta\theta_\pi$=4-6° until θ_π= 40°





Expected to improve with full FGD + TPC + Ecal + SMRD reco (aka 4π)

Summary

- ND280 and SK acceptance maps presented
- SK has very good 1Rμ/1Re discrimination: very seldom see migrations
  - Second largest probability is to not be selected
- SK has flat acceptance in $\cos\theta_{lep}$, tails off in momentum above 0.8 GeV for 1Re, 1.2 GeV for 1Rμ
- SK 1Re 1de catches below Cherenkov threshold pions at 40-50% efficiency, and drops sharply for higher momentum pions
- ND280 has very different acceptance to SK:
  - Very efficient in forward region, very low in high-angle and backward region. Largely flat in p_{Lep} for constant $\cos\theta_{lep}$
- ND280 sees small migration of true 0π events
- ND280 true 1π events enter 0π selection when high-angle/backward and/or high-momentum pions: collinear not a big problem
- ND280 anti-neutrino largely similar to neutrino
- Summary document available

Thanks

ND280 event counts

T2K run 2-6, 2017-18 analyses, pre-tune

Sample	Nominal MC
FGD1 CC0π ν_μ	16723.80
FGD1 CC1π ν_μ	4381.47
FGD1 CCOther ν_μ	3943.95
FGD2 CC0π ν_μ	16959.30
FGD2 CC1π ν_μ	3564.23
FGD2 CCOther ν_μ	3570.94
FGD1 CC1Track $\bar{\nu}_\mu$	3587.77
FGD1 CCNTrack $\bar{\nu}_\mu$	1066.91
FGD2 CC1Track $\bar{\nu}_\mu$	3618.29
FGD2 CCNTrack $\bar{\nu}_\mu$	1077.24
FGD1 CC1Track ν_μ in RHC	1272.17
FGD1 CCNTrack ν_μ in RHC	1357.45
FGD2 CC1Track ν_μ in RHC	1262.63
FGD2 CCNTrack ν_μ in RHC	1246.71
Total	63632.86

N.B. MC subject to model parameters: these are just meant to be indicative!

T2K run 2-8, 2018- analyses, pre-tune

Sample	Nominal MC
FGD1 0π	31529.3
FGD1 1π	7998.1
FGD1 other	6793.68
FGD2 0π	31734
FGD2 1π	6419.04
FGD2 other	6562.75
FGD1 $\bar{\nu}_\mu$ 0π	6371.34
FGD1 $\bar{\nu}_\mu$ 1π	533.253
FGD1 $\bar{\nu}_\mu$ other	1023.36
FGD2 $\bar{\nu}_\mu$ 0π	6283.35
FGD2 $\bar{\nu}_\mu$ 1π	483.508
FGD2 $\bar{\nu}_\mu$ other	943.956
FGD1 ν_μ RHC 0π	2485.51
FGD1 ν_μ RHC 1π	855.911
FGD1 ν_μ RHC other	804.647
FGD2 ν_μ RHC 0π	2553.51
FGD2 ν_μ RHC 1π	679.99
FGD2 ν_μ RHC other	792.166
Total	114847

SK event counts

T2K run 2-8, 2018- analyses, pre-tune

SK sample		ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$	ν_e signal	$\bar{\nu}_e$ signal	Total
FHC 1R$_\mu$	Unosc.	1032.20133	0.22571	29.27574	0.02277	0.00000	0.00000	1061.72555
	Osc. A	226.32063	0.22530	15.09567	0.02275	0.05801	0.00028	241.72264
	Osc. B	236.96139	0.22530	15.23470	0.02275	0.03979	0.00036	252.48428
FHC 1R$_e$	Unosc.	5.53636	8.06040	0.24202	0.37171	0.00000	0.00000	14.21050
	Osc. A	4.54691	7.50513	0.22423	0.35192	50.37052	0.34829	63.34700
	Osc. B	4.55877	7.50513	0.22439	0.35192	34.75386	0.41848	47.81254
FHC CC-1π^+	Unosc.	1.44498	1.09939	0.03577	0.01001	0.00000	0.00000	2.59015
	Osc. A	0.50014	1.02353	0.02400	0.00960	6.13047	0.00695	7.69469
	Osc. B	0.51191	1.02353	0.02413	0.00960	4.42335	0.00840	6.00092
RHC 1R$_\mu$	Unosc.	47.05223	0.03926	146.83759	0.02617	0.00000	0.00000	193.95525
	Osc. A	22.70539	0.03920	36.51955	0.02612	0.00152	0.00207	59.29385
	Osc. B	22.97233	0.03920	37.82922	0.02612	0.00115	0.00258	60.87061
RHC 1R$_e$	Unosc.	0.46046	0.69453	0.83340	1.10271	0.00000	0.00000	3.09109
	Osc. A	0.42091	0.65028	0.70965	1.03854	1.20541	3.27052	7.29531
	Osc. B	0.42130	0.65028	0.71097	1.03854	0.87909	3.88051	7.58068

N.B. MC subject to model parameters: these are just meant to be indicative!

ND280 muon selection

- Pre-selection (event quality, fiducial volume, upstream background, broken track cuts)
- Muon PID cut in TPC

Define pull of energy loss from expectation

$$\delta_i = \frac{C_T^{obs} - C_T^{exp}}{\sigma^{exp}}$$

From test-beam studies of the TPCs, characterise energy loss

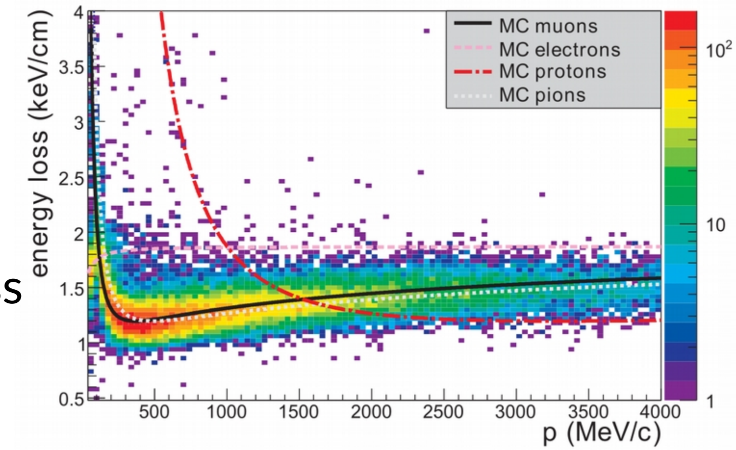
$$C_T^{exp} = \frac{53.87\ \text{ADC}}{\beta^{2.283}}\left(5.551 - \beta^{2.283} - \log\left[0.001913 + \frac{1}{(\beta\gamma)^{1.249}}\right]\right)$$

Form likelihoods for particle types

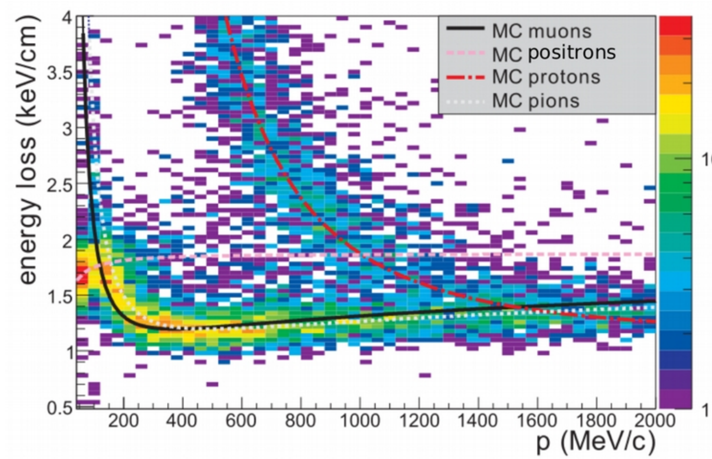
$$\mathcal{L}_i = \frac{e^{-\delta_i^2}}{\sum_n e^{-\delta_n^2}} \qquad n = \mu, \pi, e, p$$

Impose likelihood cuts

$$\mathcal{L}_{MIP} = \frac{\mathcal{L}_\mu + \mathcal{L}_\pi}{1 - \mathcal{L}_p} > 0.8 \qquad \mathcal{L}_\mu > 0.05$$



(a) Negative particles



(b) Positive particles

SK selection

1Rμ

1. Fully-contained in SK fiducial volume: classified by OD activity and total PMT hits as fully contained events; *wall* > 50cm, *towall* > 250cm. Here "wall" is the distance between vertex and the nearest ID wall; "towall" is the distance between the vertex and ID wall along the direction at which the particle (in the case of multiple rings, it refers to the particle with the most energetic ring) travels
2. Number of rings found by the fiTQun multi-ring fitter is one
3. The ring is identified as muon-like by the single-ring fitter: $\ln(L_e/L_\mu) < 0.2 \times p_e$, where $\ln L_e$ is the fiTQun single-ring e-like hypothesis log likelihood, $\ln L_\mu$ single-ring μ-like log likelihood, and p_e reconstructed electron momentum of single-ring e-like hypothesis
4. Reconstructed muon momentum of the single-ring μ-like hypothesis p_μ is larger than 200 MeV/c
5. Number of sub-events (identified by hits timing clusters) is 1 or 2 (i.e. number of decay electrons is 0 or 1).
6. fiTQun π^+ rejection cut: $\ln(L_{\pi^+}/L_\mu) < 0.15 \times p_\mu$, where $\ln L_{\pi^+}$ is the log likelihood of fiTQun single-ring π^+ hypothesis

1Re

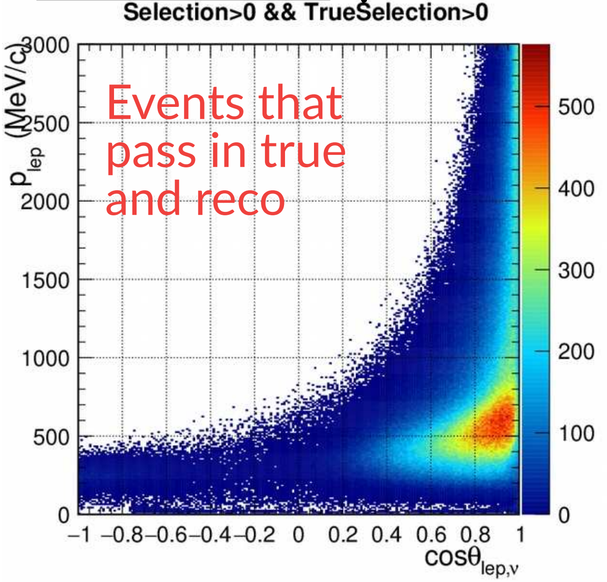
1. Fully-contained in SK fiducial volume: *wall* > 80cm, *towall* > 170cm
2. Number of rings found by the fiTQun multi-ring fitter is one
3. The ring is identified as electron-like by the single-ring fitter: $\ln(L_e/L_\mu) > 0.2 \times p_e$, where $\ln L_e$ is the fiTQun single-ring e-like log likelihood, $\ln L_\mu$ single-ring μ-like log likelihood, and p_e reconstructed electron momentum of single-ring e-like hypothesis
4. Visible energy (fiTQun single-ring e-like hypothesis reconstructed energy) is greater than 100 MeV. In practice, we use fiTQun reconstructed single-ring electron momentum as the visible energy.
5. Number of decay electron is 0.
6. Reconstructed neutrino energy E_{rec} is less than 1250 MeV
7. fiTQun π^0 rejection cut: $\ln(L_{\pi^0}/L_e) < 175 - 0.875 \times m_{\pi^0}$, where $\ln L_{\pi^0}$ is the likelihood from fiTQun dedicated π^0 fit, and m_{π^0} the fitted π^0 mass.

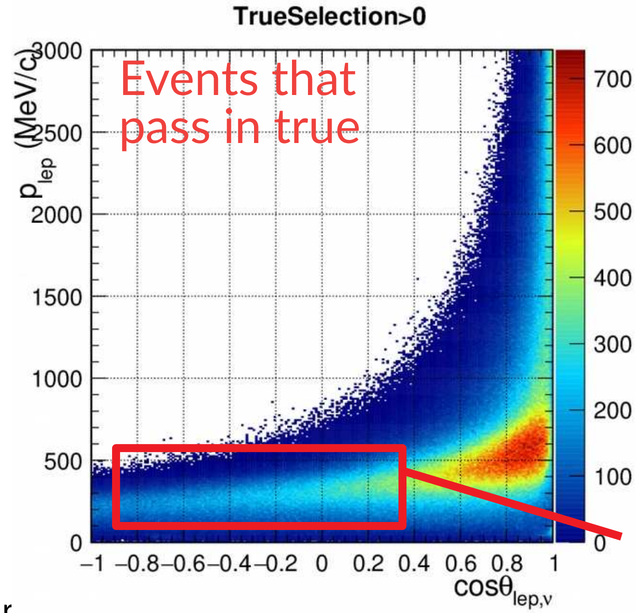
1Re1de

1. Fully-contained in SK fiducial volume: *wall* > 50cm, *towall* > 270cm
2. Number of rings found by the fiTQun multi-ring fitter is one
3. The ring is identified as electron-like by the single-ring fitter: $\ln(L_e/L_\mu) > 0.2 \times p_e(\mathrm{MeV})$, where $\ln L_e$ is the fiTQun single-ring e-like log likelihood, $\ln L_\mu$ single-ring μ-like log likelihood, and p_e reconstructed electron momentum of single-ring e-like hypothesis
4. Visible energy (fiTQun single-ring e-like hypothesis reconstructed energy) is greater than 100 MeV
5. Number of sub-events is 2 (number of decay electron is 1).
6. Reconstructed neutrino energy E_{rec} is less than 1250 MeV
7. fiTQun π^0 rejection cut: $\ln(L_{\pi^0}/L_e) < 175 - 0.875 \times m_{\pi^0}$, where $\ln L_{\pi^0}$ is the likelihood from fiTQun dedicated π^0 fit, and m_{π^0} the fitted π^0 mass in MeV.

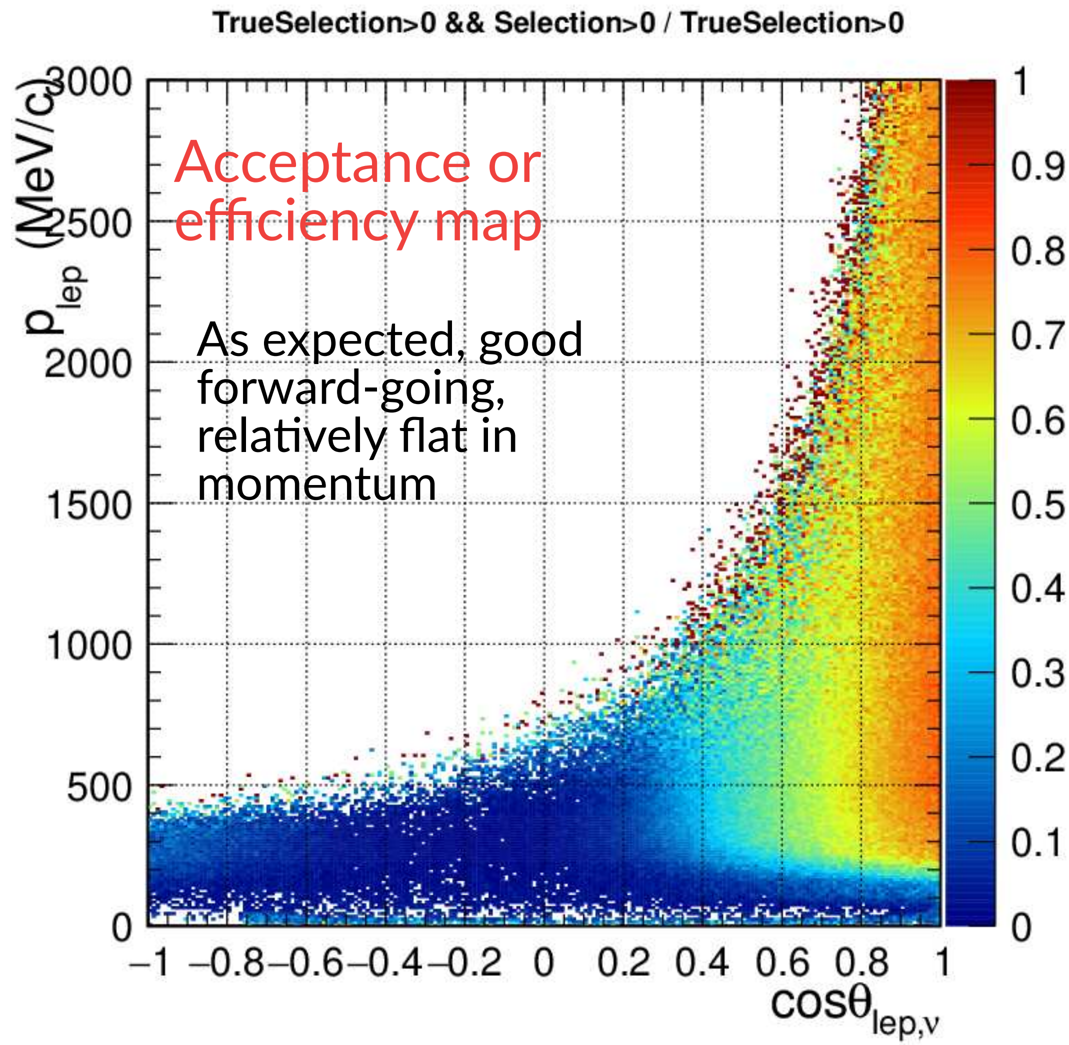
ND280 CC-inclusive

- Event has <u>any true ND280 selection</u>, and <u>any reco ND280 selection</u> (not necessarily the same)





=



Backwards region missed by ND280 reconstruction

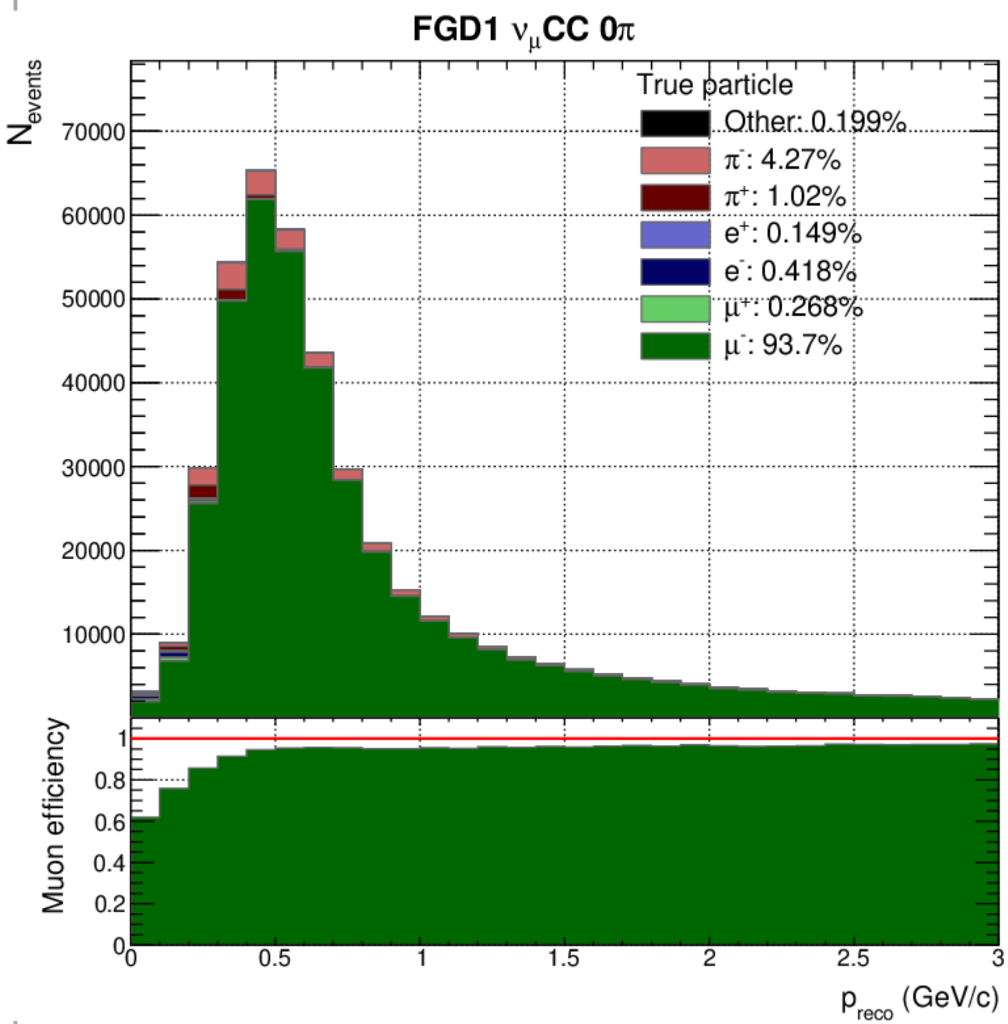
Dimensionalities

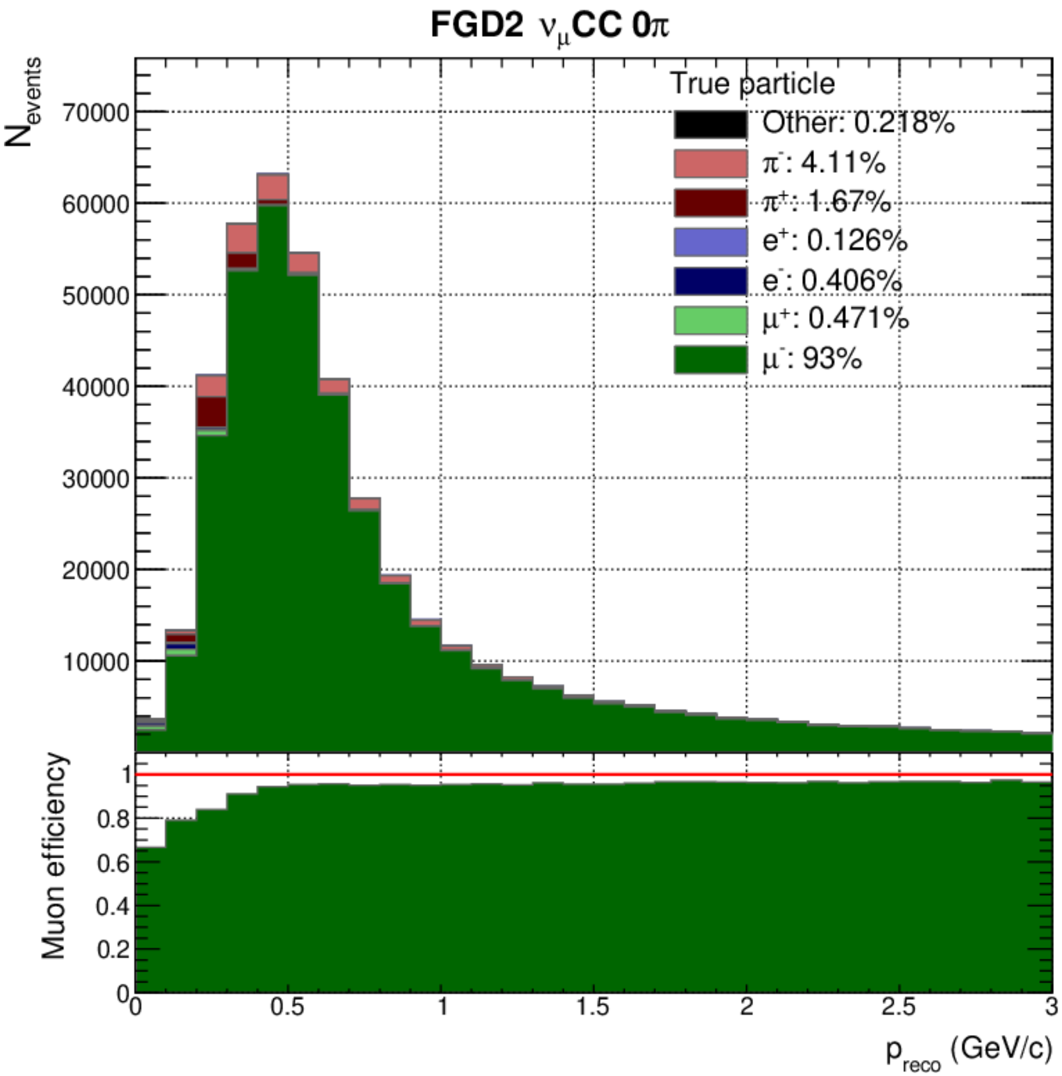
- Would be ideal to have map in 5D, e.g. pmu, cosmu, ppi, cospi, cosmupi
- Ran out of MC statistics **VERY** quickly (ND280 is ~3M, SK is ~3M)
  - Required coarser binning
  - But then characterisation in regions of large change in acceptance is poorly modelled
  - Also signal and background often populate different regions of the kinematics: different binning for different acceptances?
  - Was deemed too big a task for even a 3D map
  - The 3D map exhibited large biases in trying to reproduce the ppi distribution using plep, costheta_lep and cos_pi,nu
- Settled for 2D maps with uniform binning
  - Use the map whose kinematics you want to look at
- Could release full TTree of passed/not passed

Lepton tagging

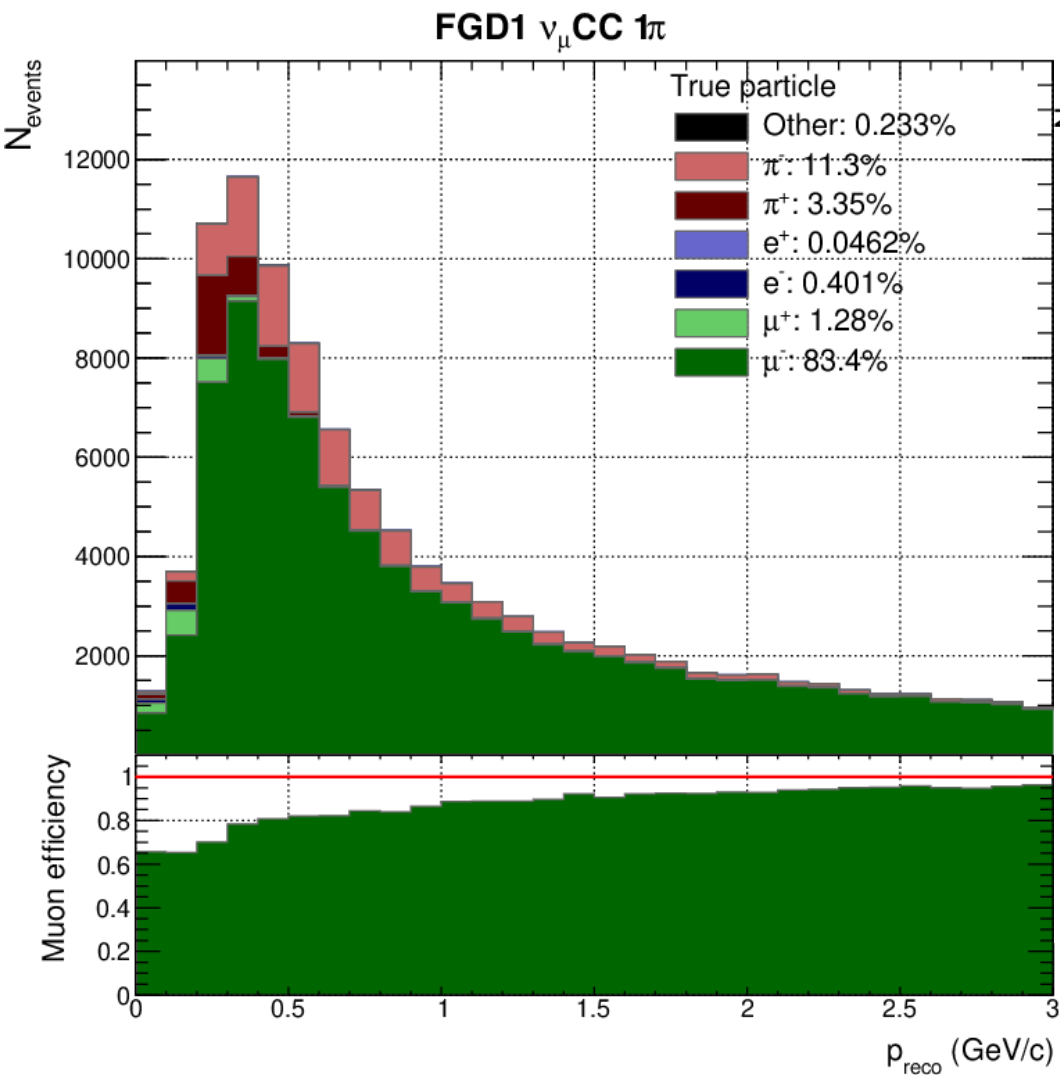
- Take the selected lepton candidate from reconstruction
- Look at its reconstructed momentum
- Look at its true particle ID

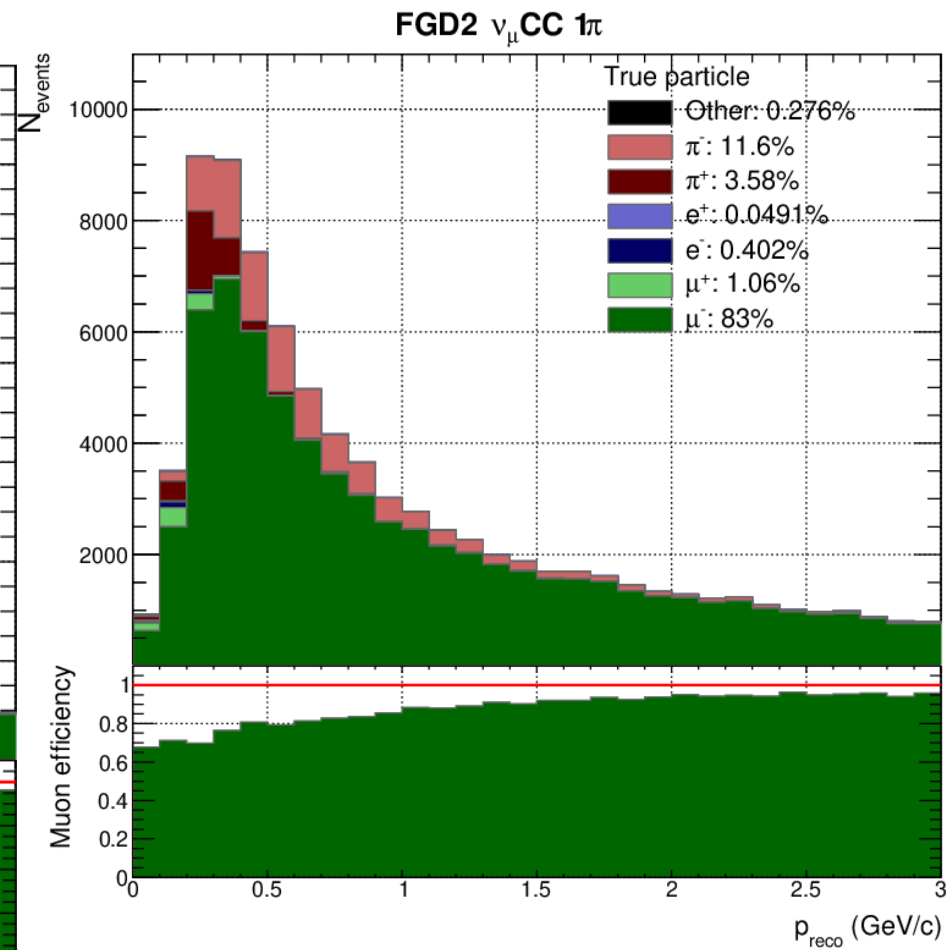
Lepton tagging



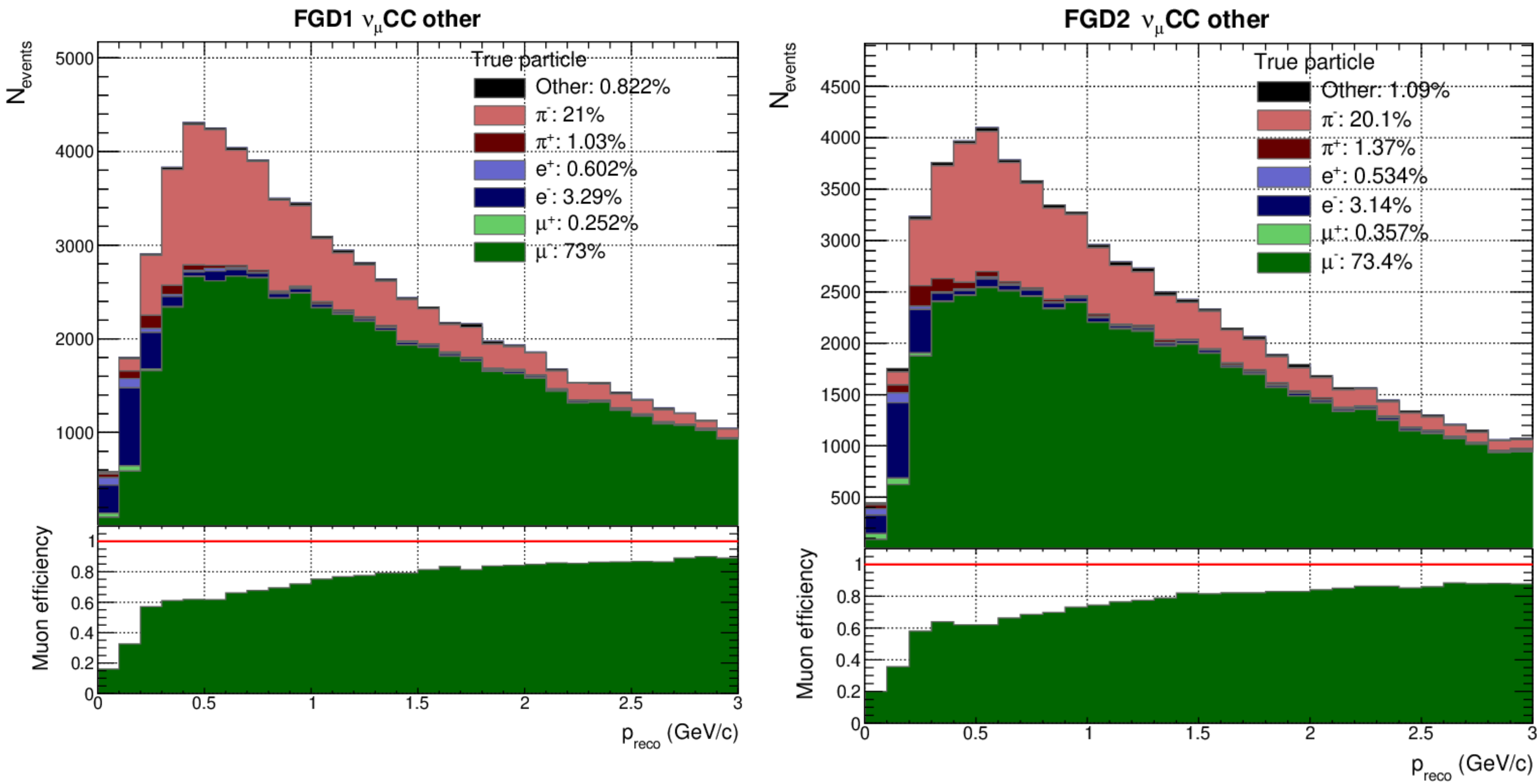


Lepton tagging

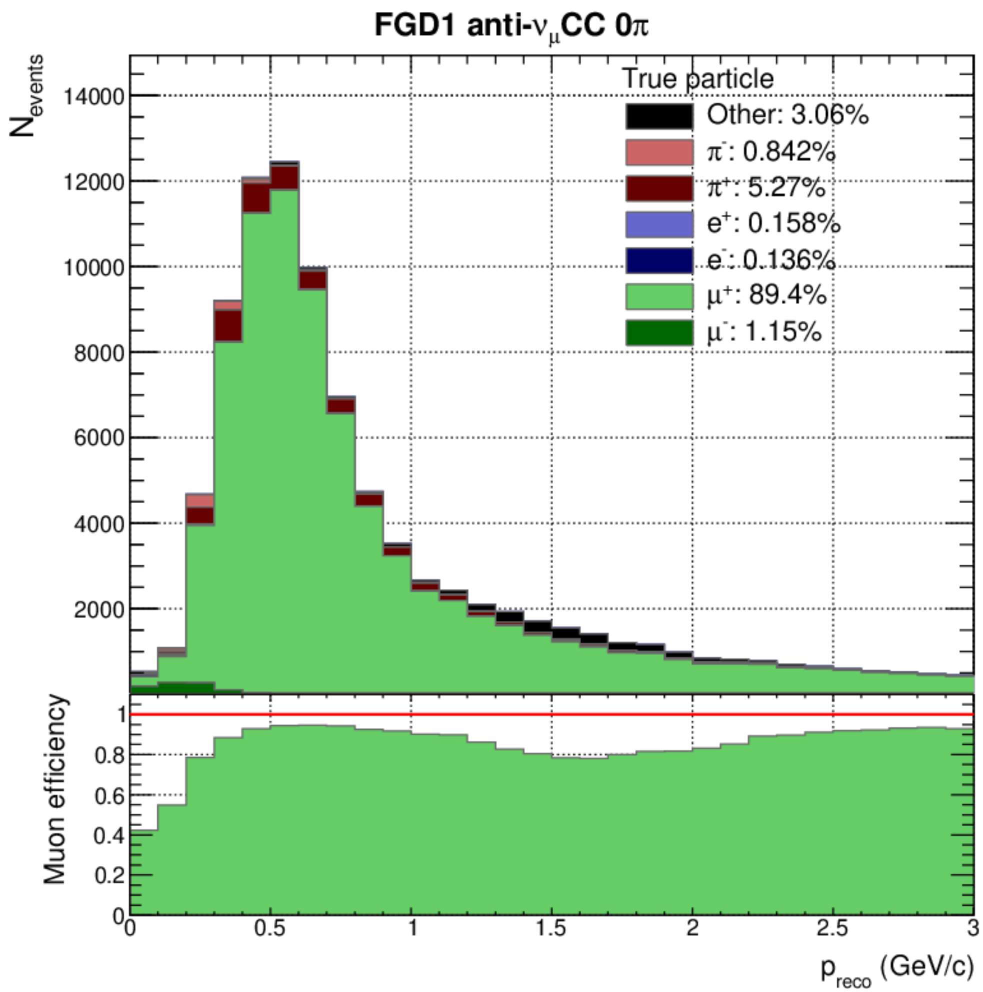


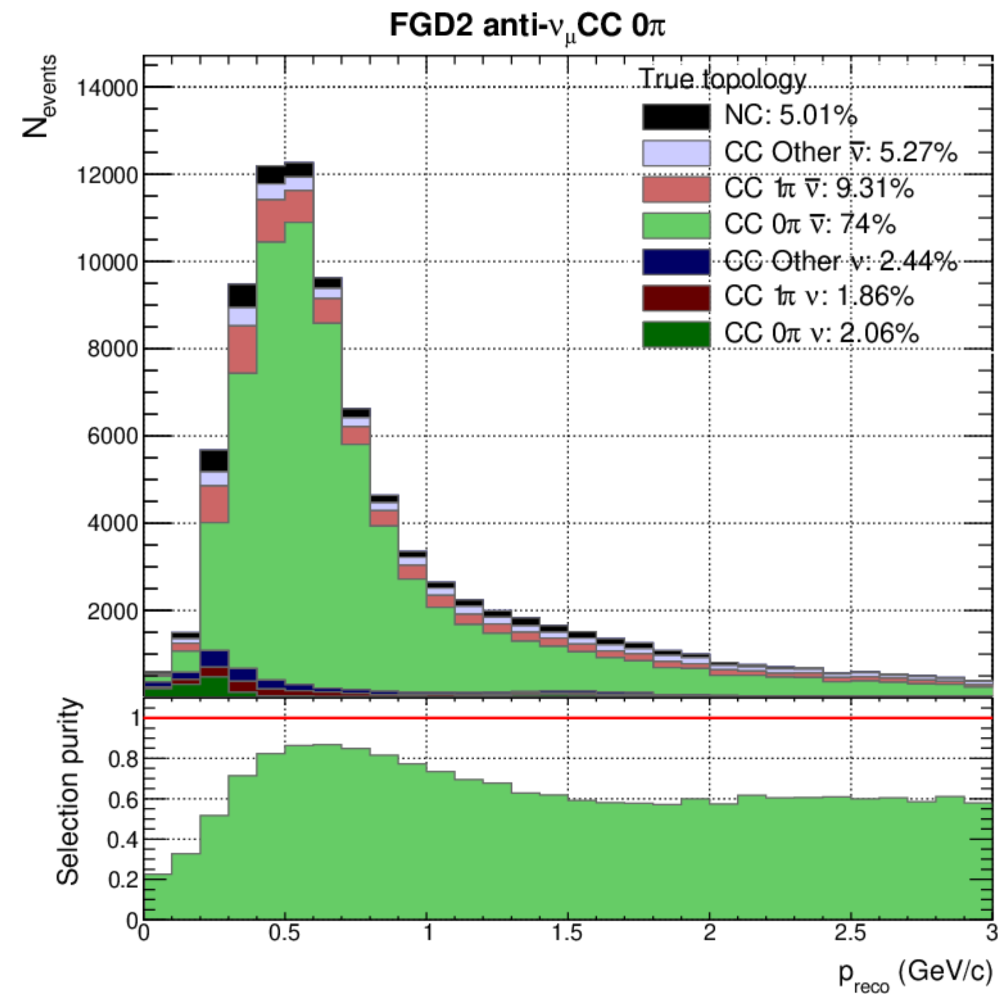


Lepton tagging

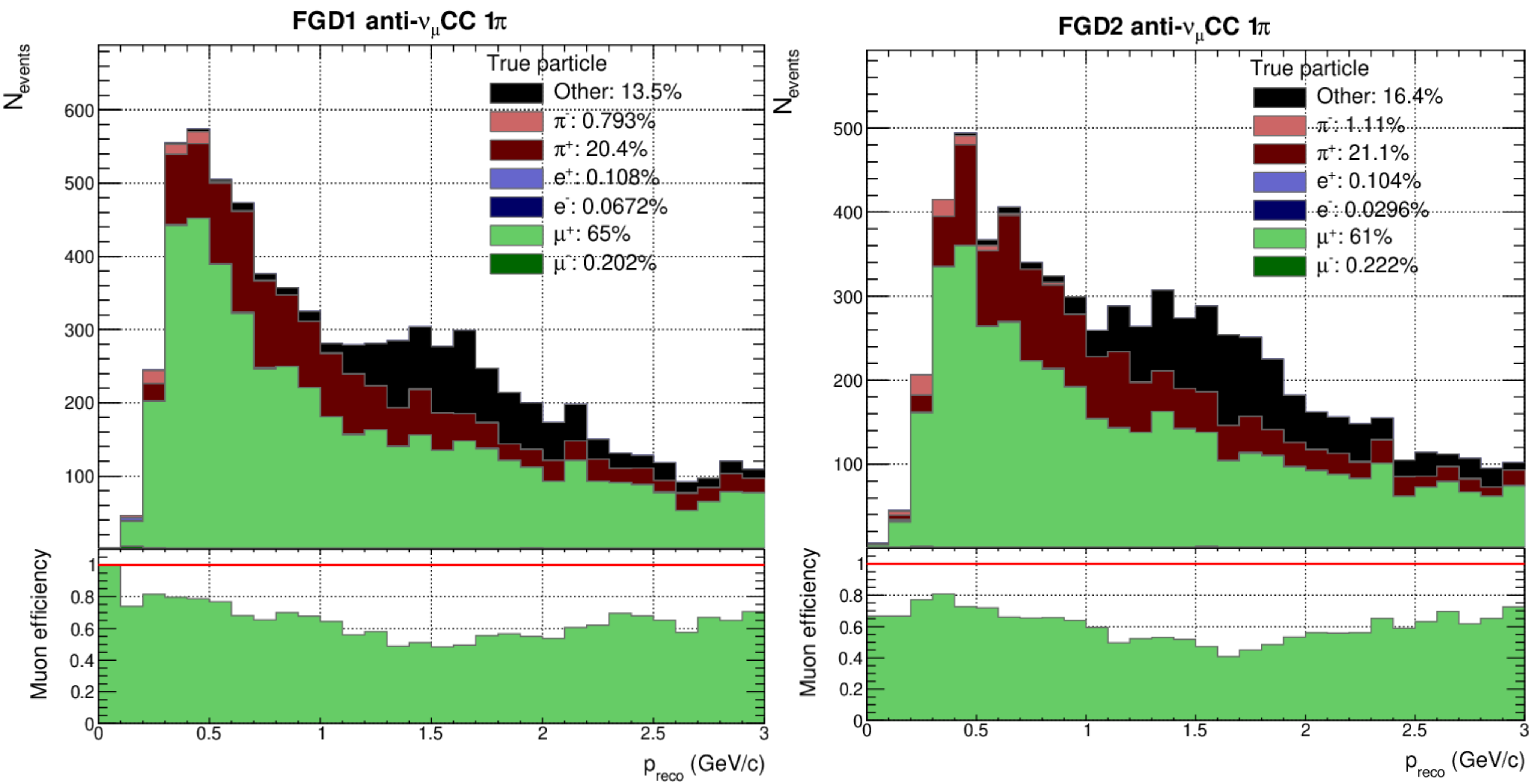


Lepton tagging

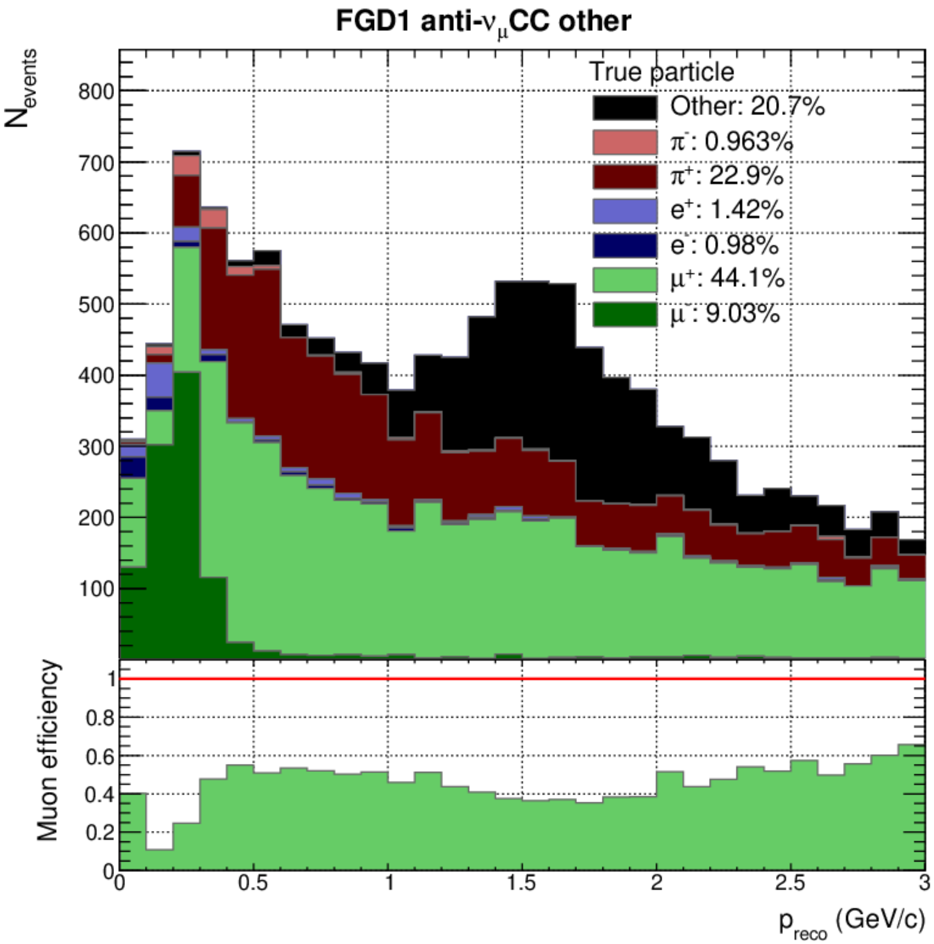


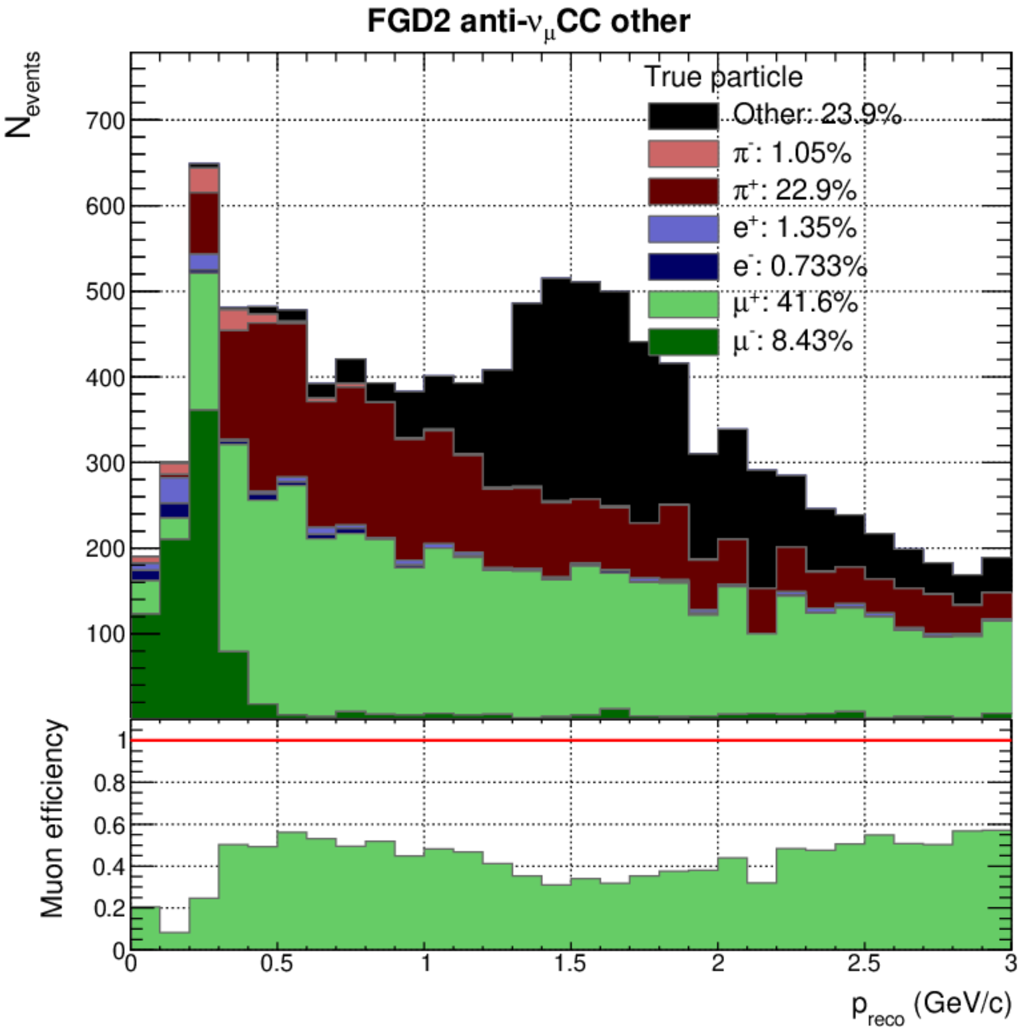


Lepton tagging

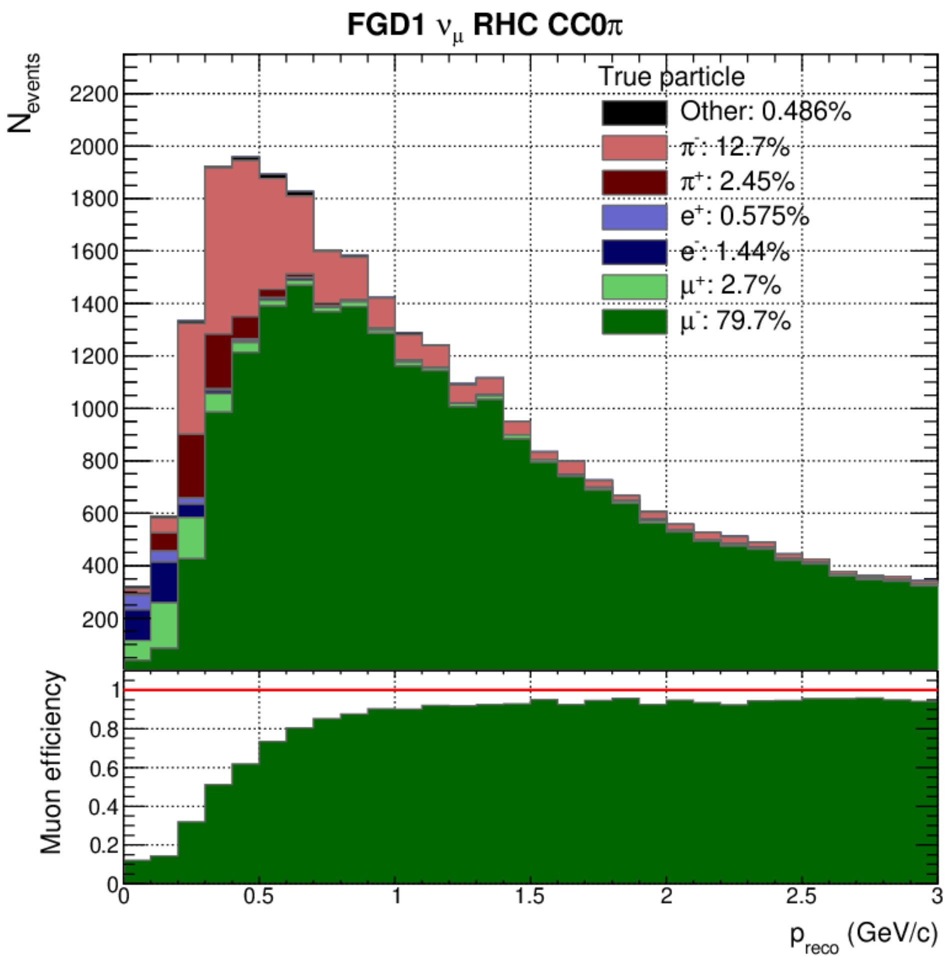


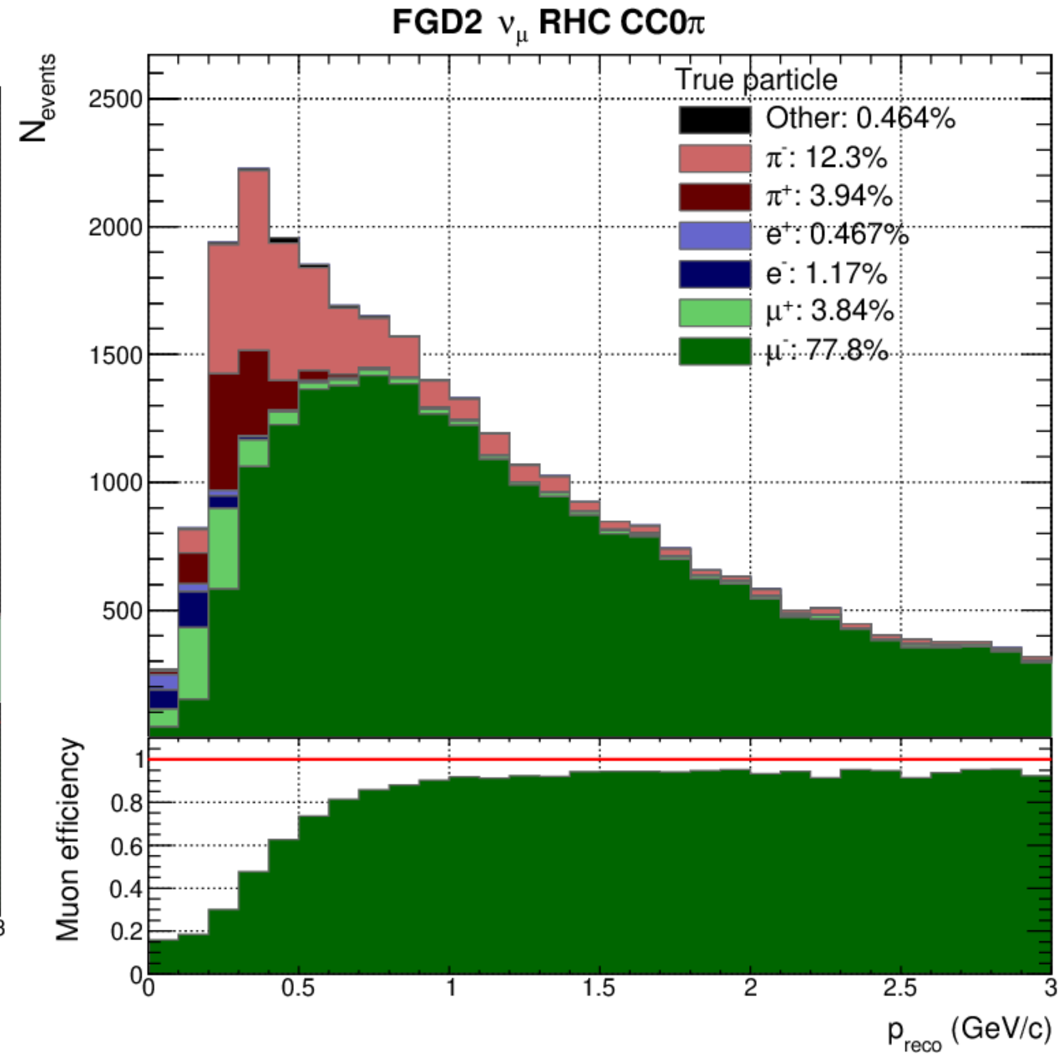
Lepton tagging



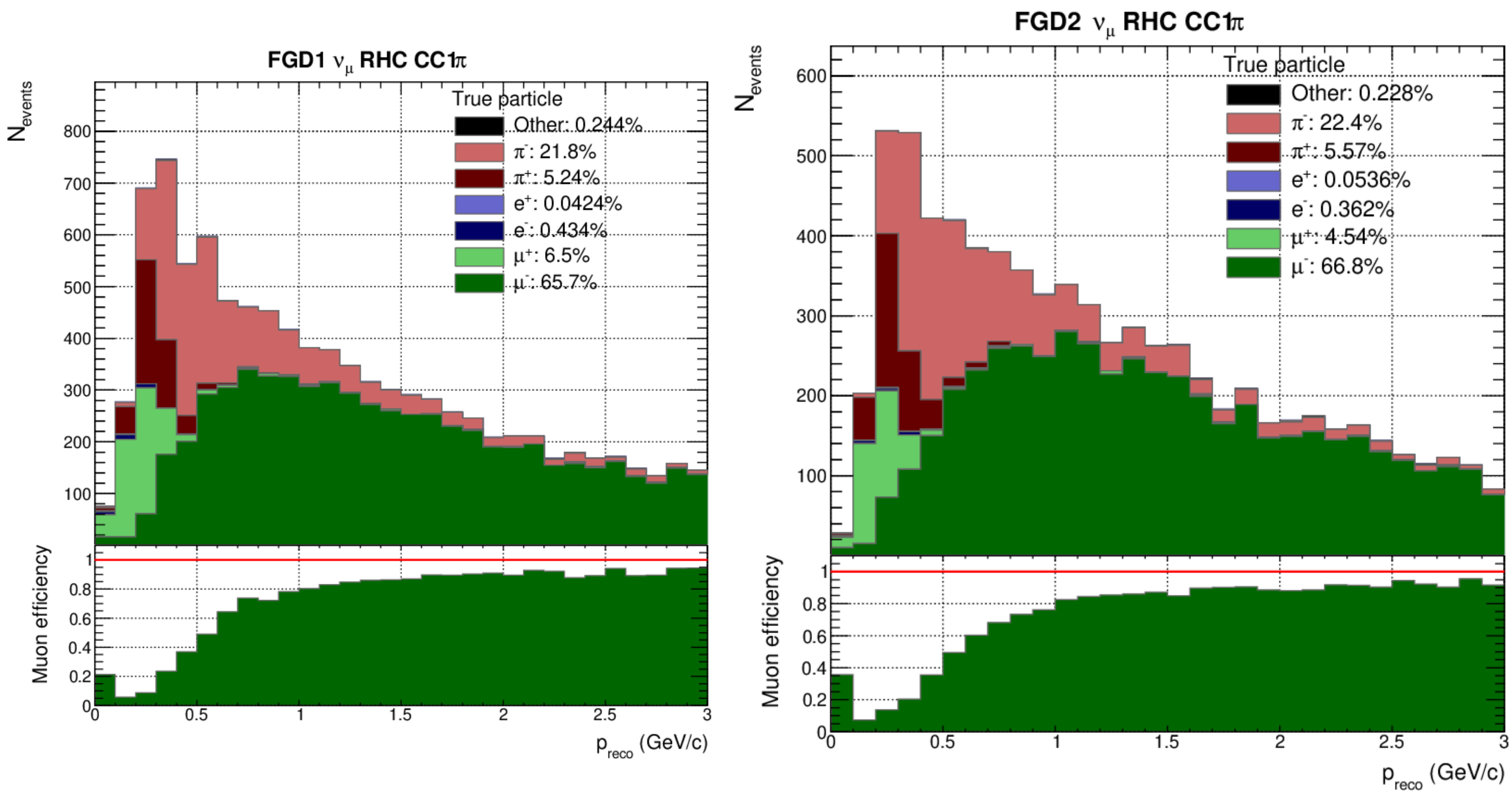


Lepton tagging





Lepton tagging



Lepton tagging