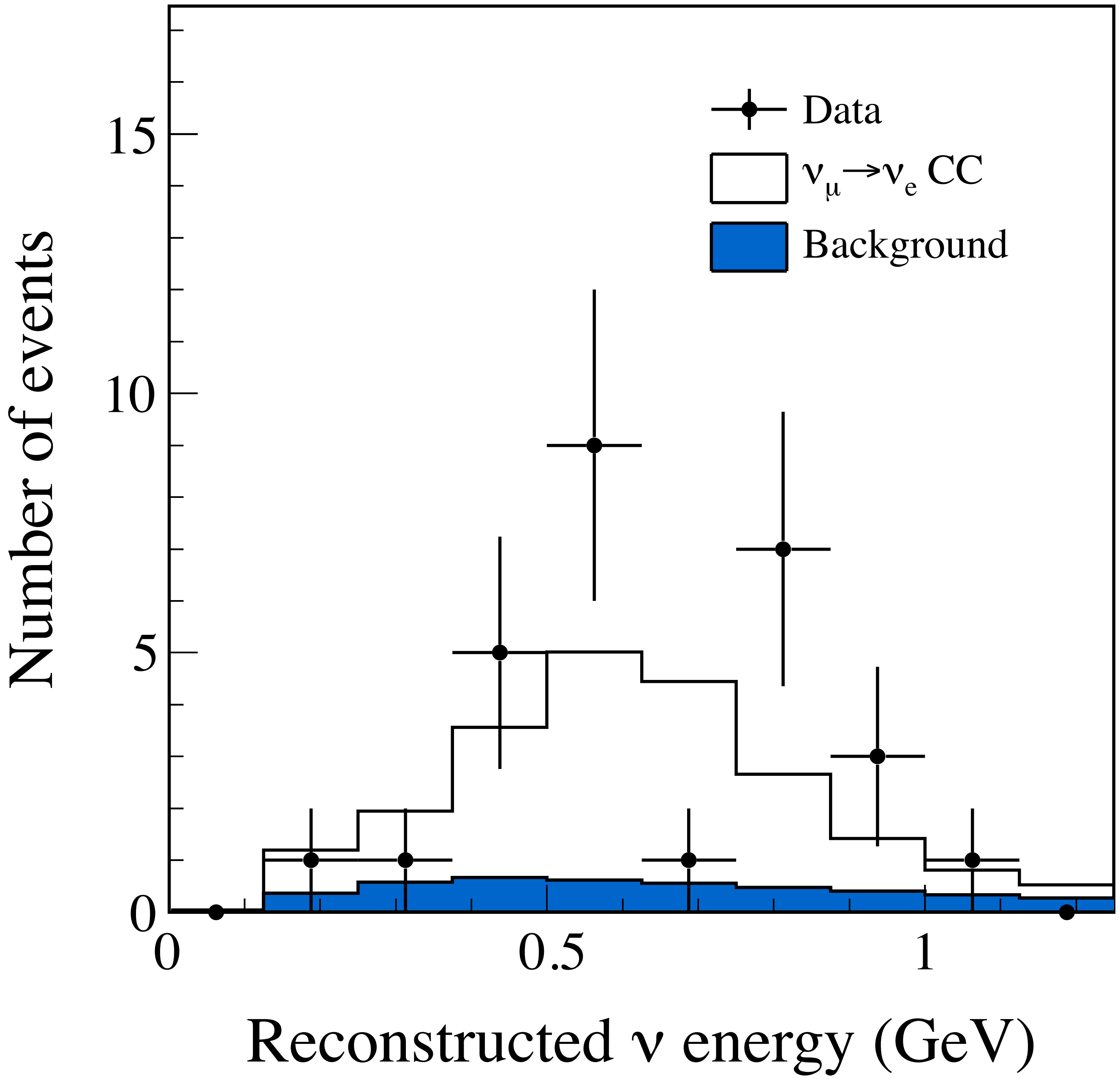
# Systematic uncertainties on T2K: Power and limits of near detectors

Kendall Mahn
Michigan State University

# Electron neutrino appearance




| | MC total | $\nu_\mu + \overline{\nu}_\mu$ CC | $\nu_e + \overline{\nu}_e$ CC | $\nu + \bar{\nu}$ NC | $\nu_\mu \to \nu_e$ CC |
|---|---|---|---|---|---|
| interactions in FV | 656.83 | 325.67 | 15.97 | 288.11 | 27.07 |
| FCFV | 372.35 | 247.75 | 15.36 | 83.02 | 26.22 |
| (1) single ring | 198.44 | 142.44 | 9.82 | 23.46 | 22.72 |
| (2) electron-like | 54.17 | 5.63 | 9.74 | 16.35 | 22.45 |
| (3) $E_{\mathrm{vis}} > 100\,\mathrm{MeV}$ | 49.36 | 3.66 | 9.68 | 13.99 | 22.04 |
| (4) no Michel election | 40.03 | 0.69 | 7.87 | 11.84 | 19.63 |
| (5) $E_\nu^{\mathrm{rec}} < 1250\,\mathrm{MeV}$ | 31.76 | 0.21 | 3.73 | 8.99 | 18.82 |
| (6) not $\pi^0$-like | 21.59 | 0.07 | 3.24 | 0.96 | 17.32 |

Phys. Rev. D 91, 072010 (2015)
arxiv: 1502.01550

**Dominant background and signal are predominantly CCQE-like**

Negligible numu contamination, small NC backgrounds

# An overly generic oscillation analysis

$$N_{FD}^{\alpha\to\beta}(\mathbf{p}_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(\mathbf{p}_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(\mathbf{p}_{true}) \times R_i(\mathbf{p}_{true};\mathbf{p}_{reco})$$

1. Far detector rate depends on:
    1. Flux (Phi), cross section processes (sigma), efficiency (epsilon)
    2. Correct association of reconstructed objects to true kinematics of an event (R)

# An overly generic oscillation analysis

$$N_{FD}^{\alpha\to\beta}(\mathbf{p}_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(\mathbf{p}_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(\mathbf{p}_{true}) \times R_i(\mathbf{p}_{true};\mathbf{p}_{reco})$$

$$N_{ND}^{\alpha}(\mathbf{p}_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\alpha^i(\mathbf{p}_{true}) \times \epsilon_\alpha(\mathbf{p}_{true}) \times R_i(\mathbf{p}_{true};\mathbf{p}_{reco})|,$$

Near detector provides event rate (constrains flux, cross section and (some) of the detector response)

Inherent difficulties:

1. nue appearance (but ND measures numu rate)

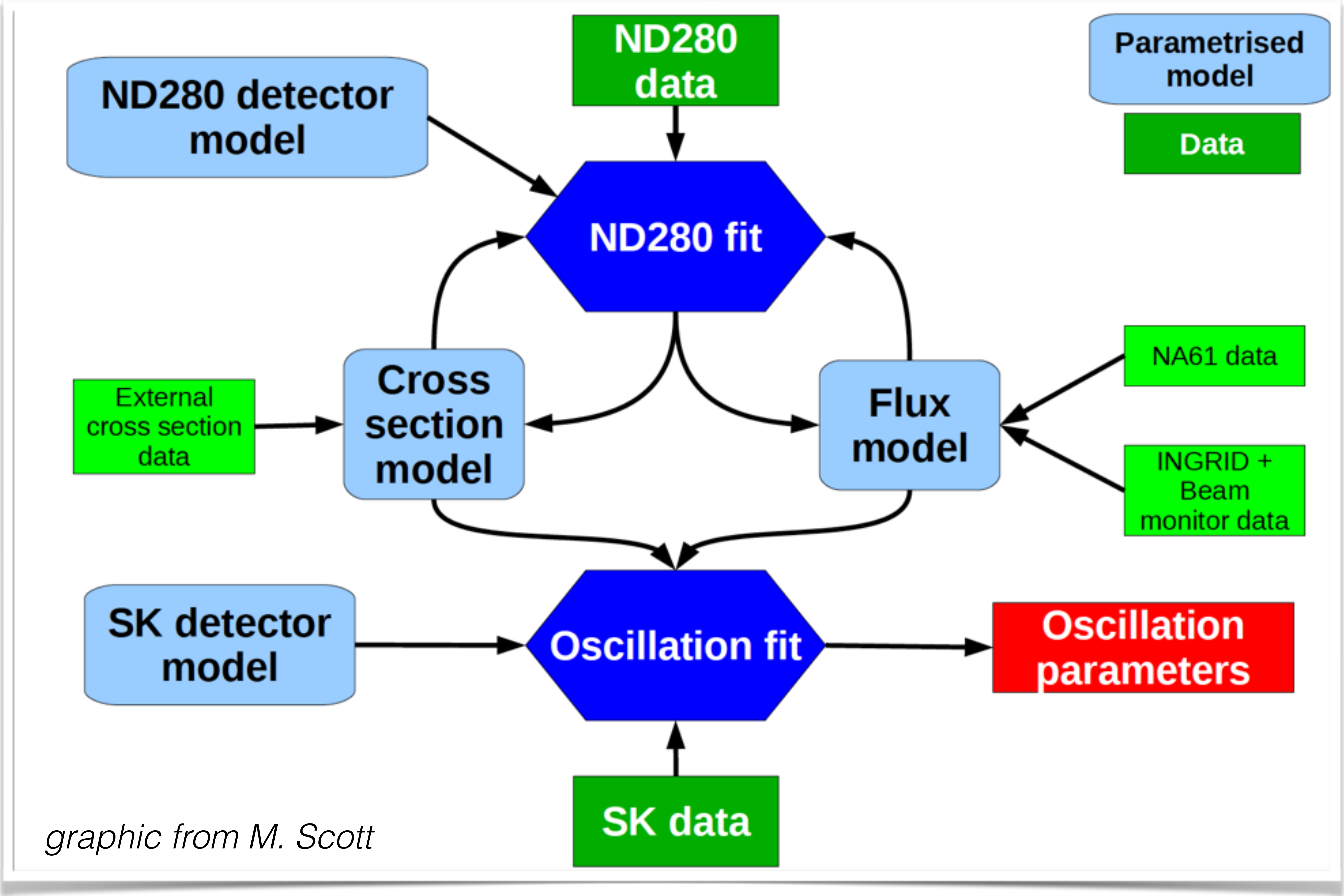
2. Not pure flavor beam (neutrino and antineutrino contributions)

3. Oscillation probability in FD equation => energy dependance of sum is different

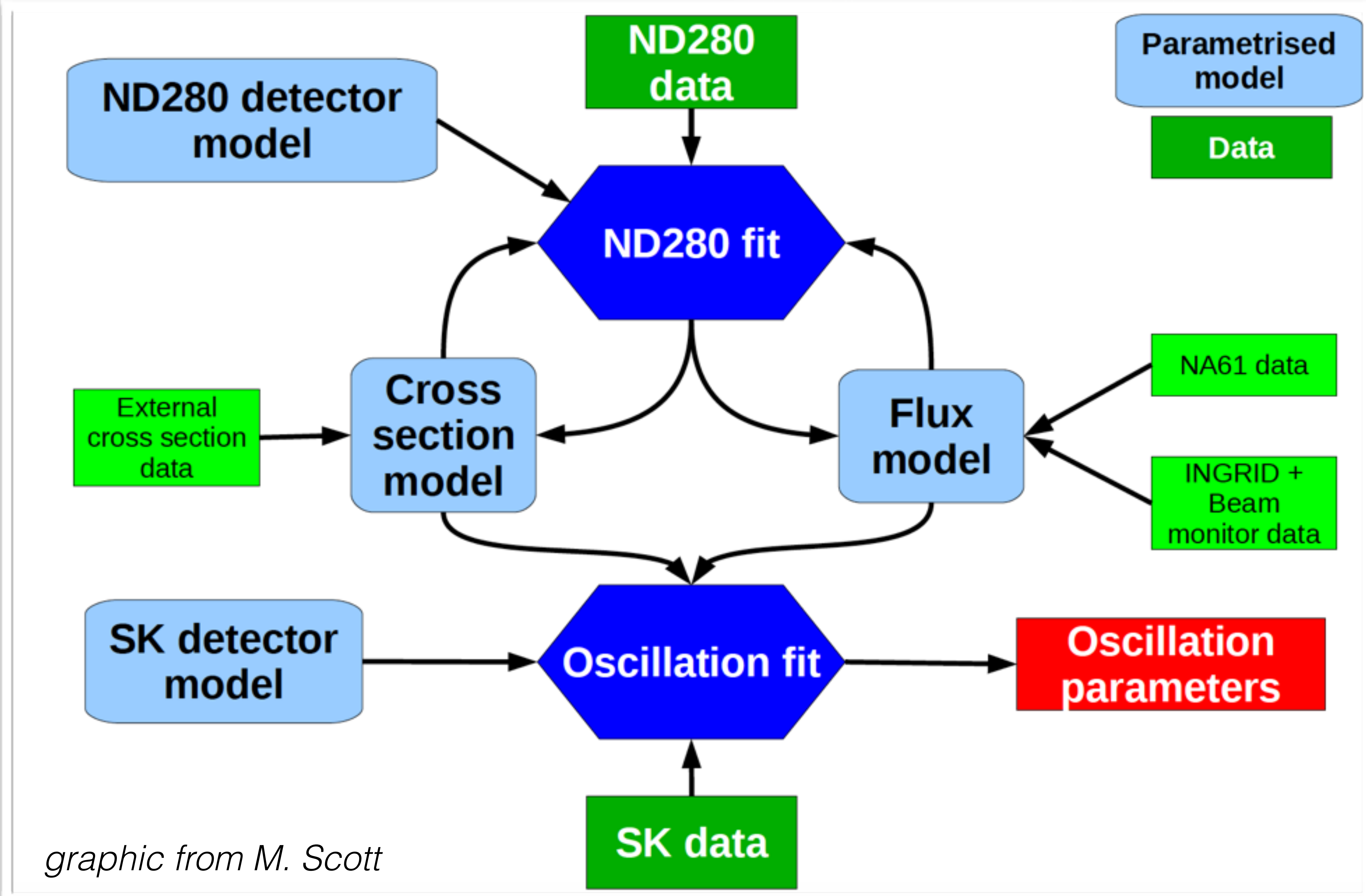
4. Wide flux spectrum (not possible to isolate cross section processes)

5. Small differences in flux and detector response of ND and FD

6. Correct association between true and reconstructed variables




*Reliance on model and **parameterization***




***More than 1 ND: value of theory, "service"***

*data in "ND" fit*

# Flux at ND and FD (2012 analysis)

| Neutrino Mode | Trkr. $\nu_\mu$ CCQE | Trkr. $\nu_\mu$ CCnQE | SK $\nu_e$ Sig. | SK $\nu_e$ CC intrinsic Bgnd. | SK $\nu_e$ NC Bgnd. |
|---|---|---|---|---|---|
| $\pi^+ \to \nu_\mu + \mu^+$ | 82.2% | 45.8% | 99.3% | 1.1% | 70.3% |
| $\mu^+ \to \nu_e + e^+ + \bar{\nu_\mu}$ | <1% | <1% | <0.1% | 66.0% | <0.1% |
| $K^{+,0} \to \nu_e + X$ | <1% | <1% | <0.1% | 33.0% | <0.1% |
| $K^{+,0} \to \nu_\mu + X$ | 17.4% | 53.4% | 0.7% | – | 29.7% |

Off-axis neutrino beam:

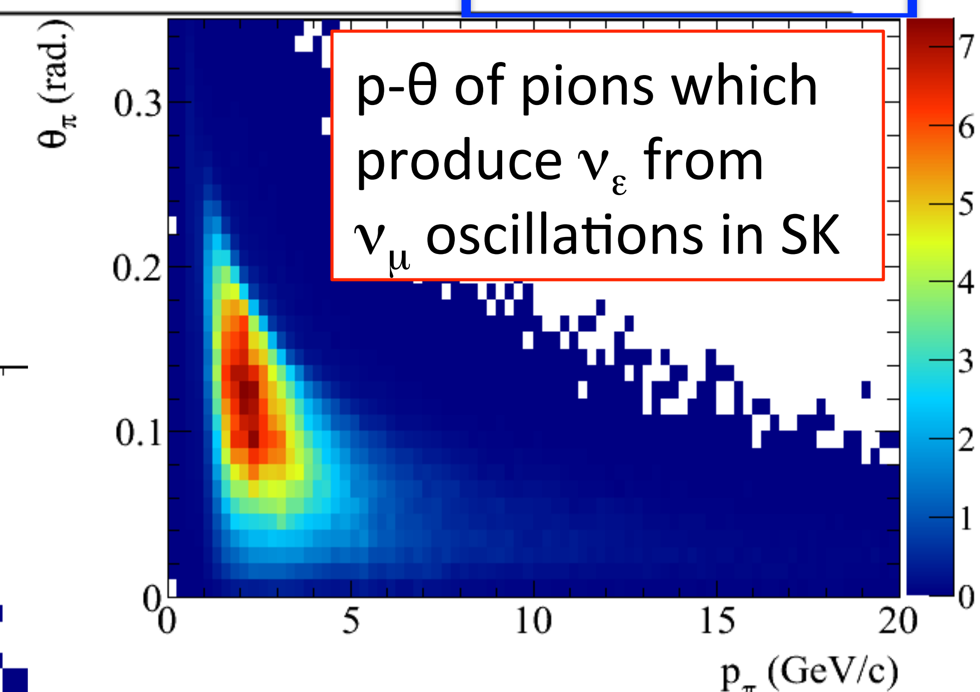
1. Geant3/FLUKA simulation
2. Parameterized as normalizations per Enu bin
3. Critical information from NA61, on-axis near detector (INGRID), beam line monitoring (T2K flux prediction: Phys. Rev. D 87, 012001 (2013) includes references, details)

***DUNE: What external flux information is expected?***

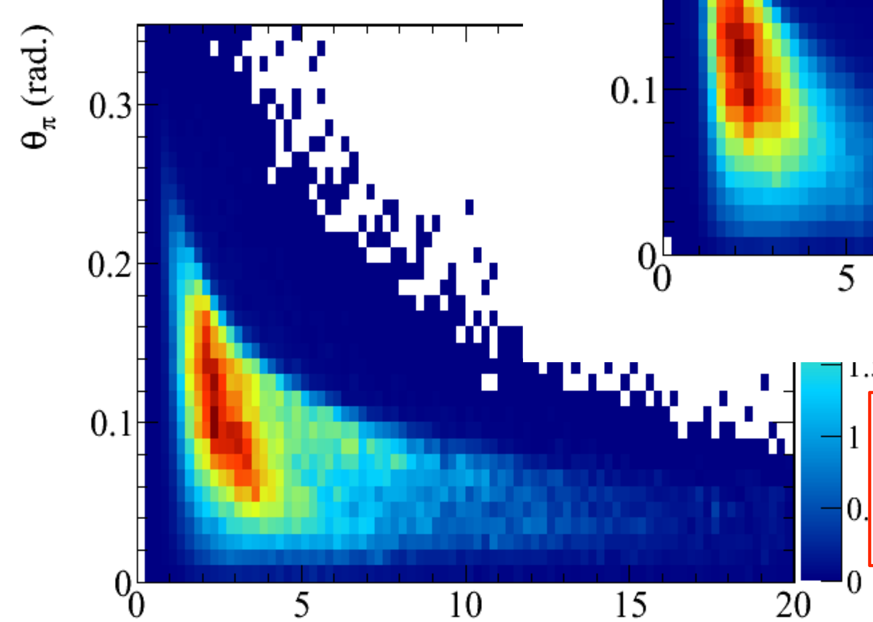
# Flux at ND and FD (2012 analysis)

| Neutrino Mode | Trkr. $\nu_\mu$ CCQE | Trkr. $\nu_\mu$ CCnQE | SK $\nu_e$ Sig. | SK $\nu_e$ CC intrinsic Bgnd. | SK $\nu_e$ NC Bgnd. |
|---|---|---|---|---|---|
| $\pi^+ \to \nu_\mu + \mu^+$ | 82.2% | 45.8% | 99.3% | 1.1% | 70.3% |
| $\mu^+ \to \nu_e + e^+ + \bar{\nu_\mu}$ | <1% | <1% | <0.1% | 66.0% | <0.1% |
| $K^{+,0} \to \nu_e + X$ | <1% | <1% | <0.1% | 33.0% | <0.1% |
| $K^{+,0} \to \nu_\mu + X$ | 17.4% | 53.4% | 0.7% | – | 29.7% |

SK signal and NC background events come from $\nu_\mu$ flux directly measured at ND




p-θ of pions which produce $\nu_e$ from $\nu_\mu$ oscillations in SK

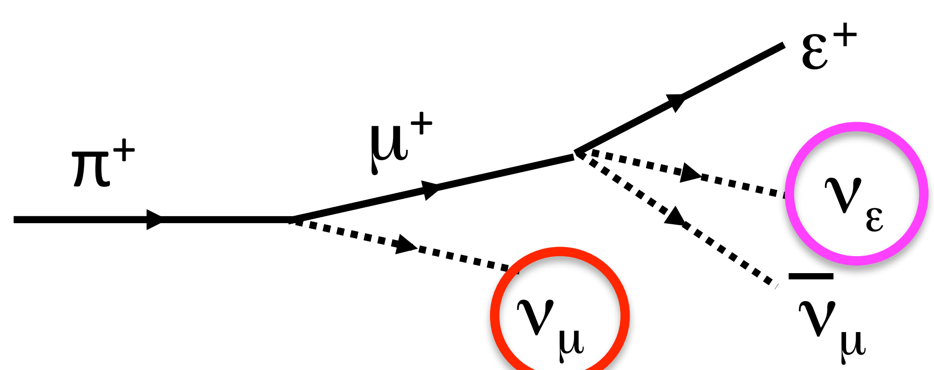


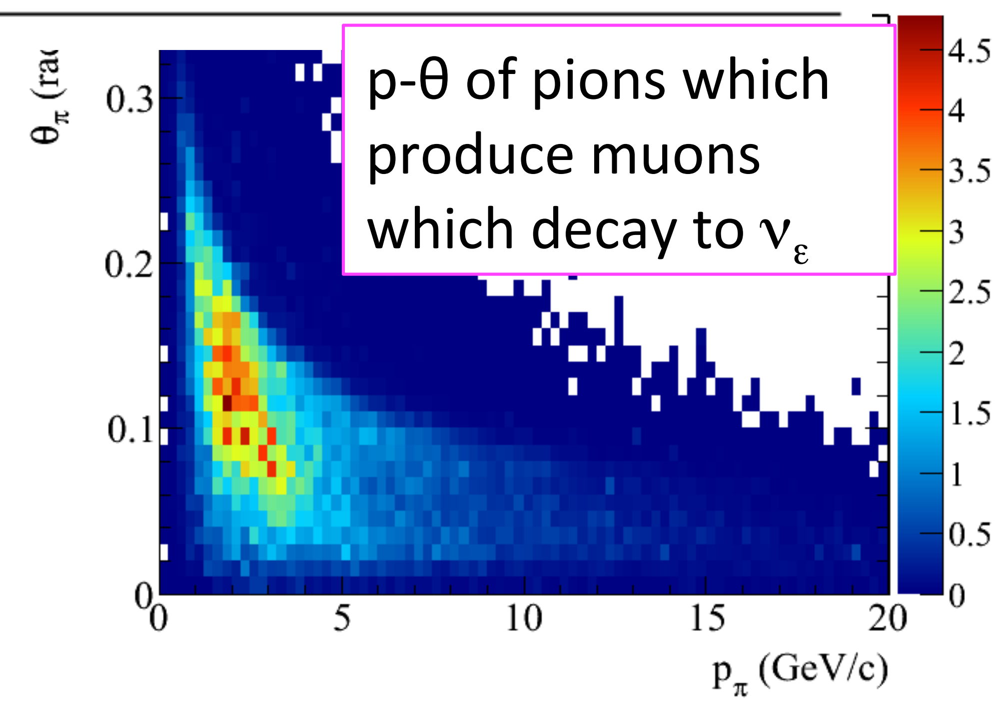

p-θ of pions which produce $\nu_\mu$ in ND

# Flux at ND and FD (2012 analysis)

| Neutrino Mode | Trkr. $\nu_\mu$ CCQE | Trkr. $\nu_\mu$ CCnQE | SK $\nu_e$ Sig. | SK $\nu_e$ CC intrinsic Bgnd. | SK $\nu_e$ NC Bgnd. |
|---|---|---|---|---|---|
| $\pi^+ \rightarrow \nu_\mu + \mu^+$ | 82.2% | 45.8% | 99.3% | 1.1% | 70.3% |
| $\mu^+ \rightarrow \nu_e + e^+ + \bar{\nu_\mu}$ | <1% | <1% | <0.1% | 66.0% | <0.1% |
| $K^{+,0} \rightarrow \nu_e + X$ | <1% | <1% | <0.1% | 33.0% | <0.1% |
| $K^{+,0} \rightarrow \nu_\mu + X$ | 17.4% | 53.4% | 0.7% | – | 29.7% |

CC background from beam $\nu_\varepsilon$ is strongly correlated with $\nu_\mu$ flux at ND:



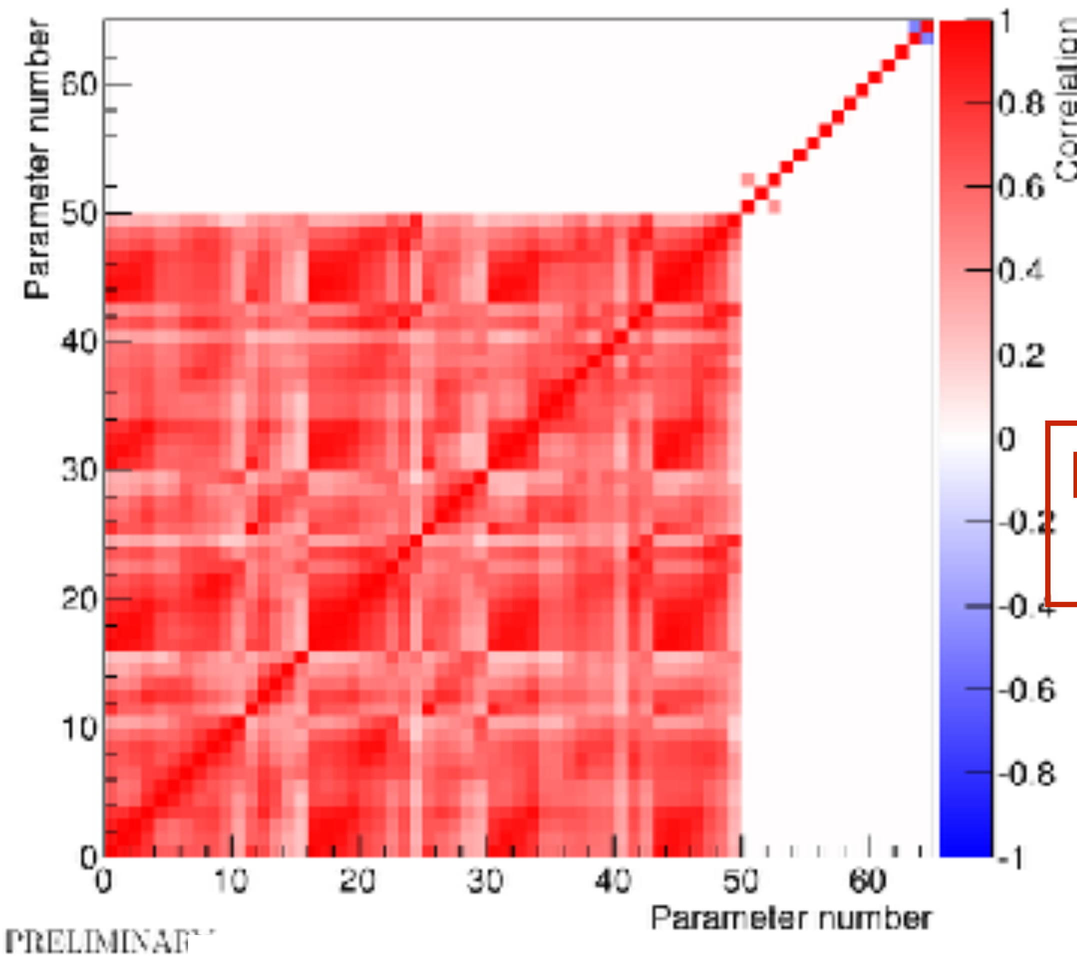

p-θ of pions which produce $\nu_\mu$ in ND

***DUNE: What is the physics overlap of expected ND samples?***

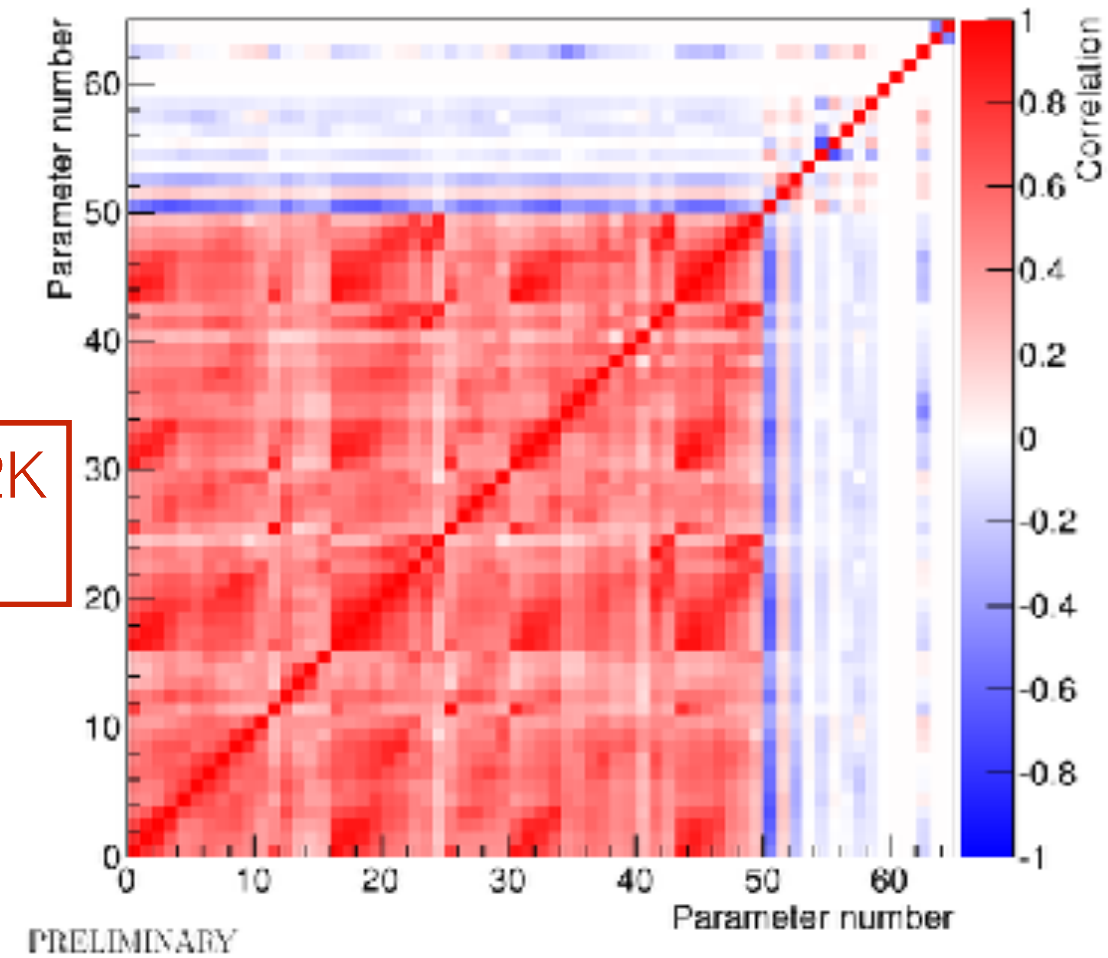
# See-saw between flux and cross section

$$N_{FD}^{\alpha\rightarrow\beta}(\mathbf{p}_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(\mathbf{p}_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(\mathbf{p}_{true}) \times R_i(\mathbf{p}_{true};\mathbf{p}_{reco})$$

$$N_{ND}^{\alpha}(\mathbf{p}_{reco}) = \sum \phi_\alpha(E_{true}) \times \sigma_\alpha^i(\mathbf{p}_{true}) \times \epsilon_\alpha(\mathbf{p}_{true}) \times R_i(\mathbf{p}_{true};\mathbf{p}_{reco})|,$$



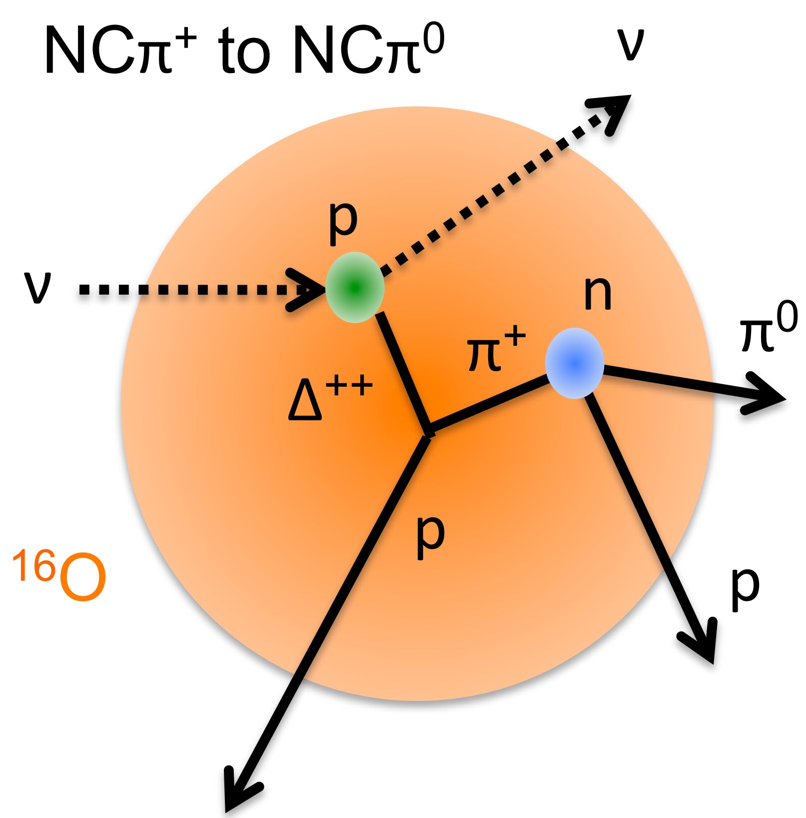

Preliminary, T2K collaboration

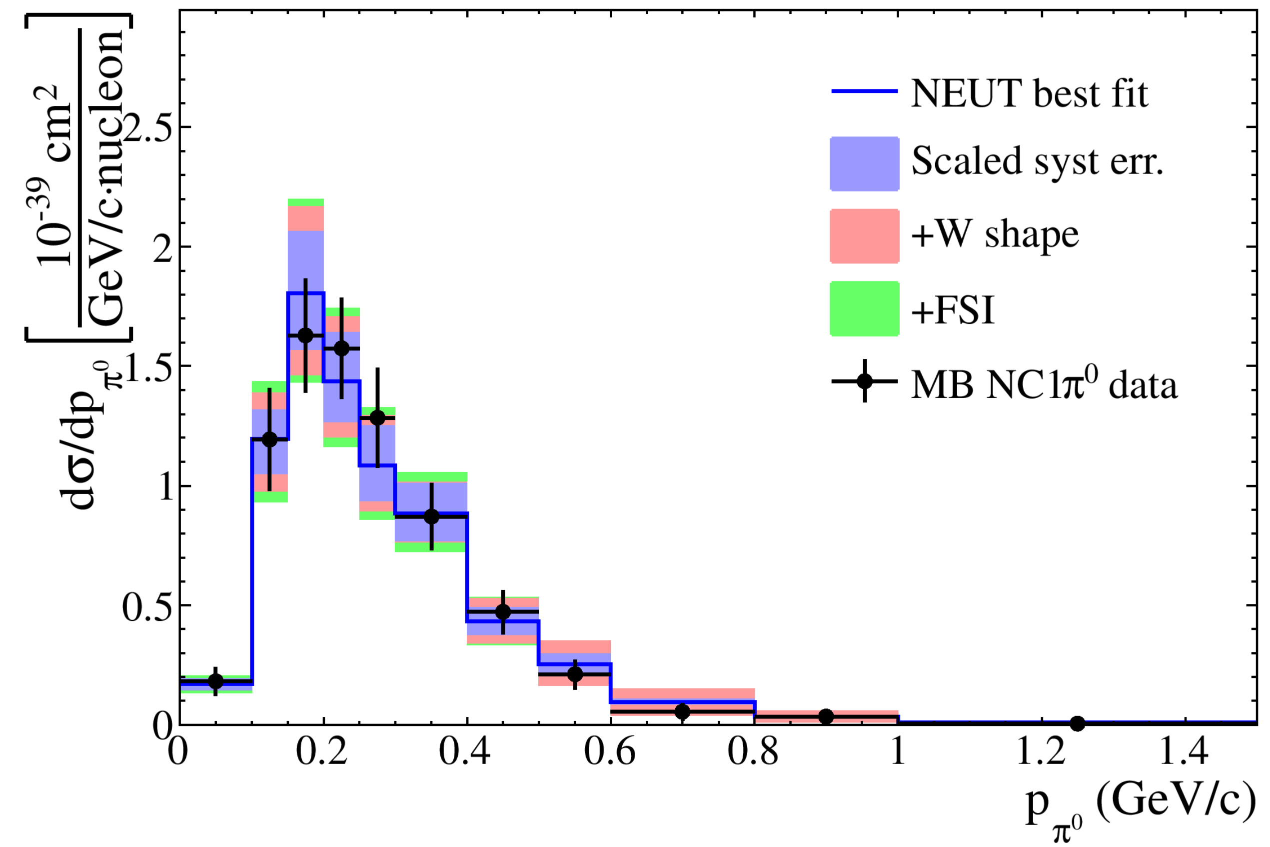



$\phi_\alpha(E_{true})$ $\sigma_\beta^i(\mathbf{p}_{true})$

**DUNE: How does nue-e scattering break this by direct flux determination?**

# Cross section model parameterization




- Base model for each interaction-level (nucleon processes)
- Artificial separation of initial state, final state physics for each
- Compare model, uncertainties nucleon, nuclear target data
- Complexity from importance of process (QE vs. DIS), theoretical or empirical lack of understanding

# Cross section model parameterization

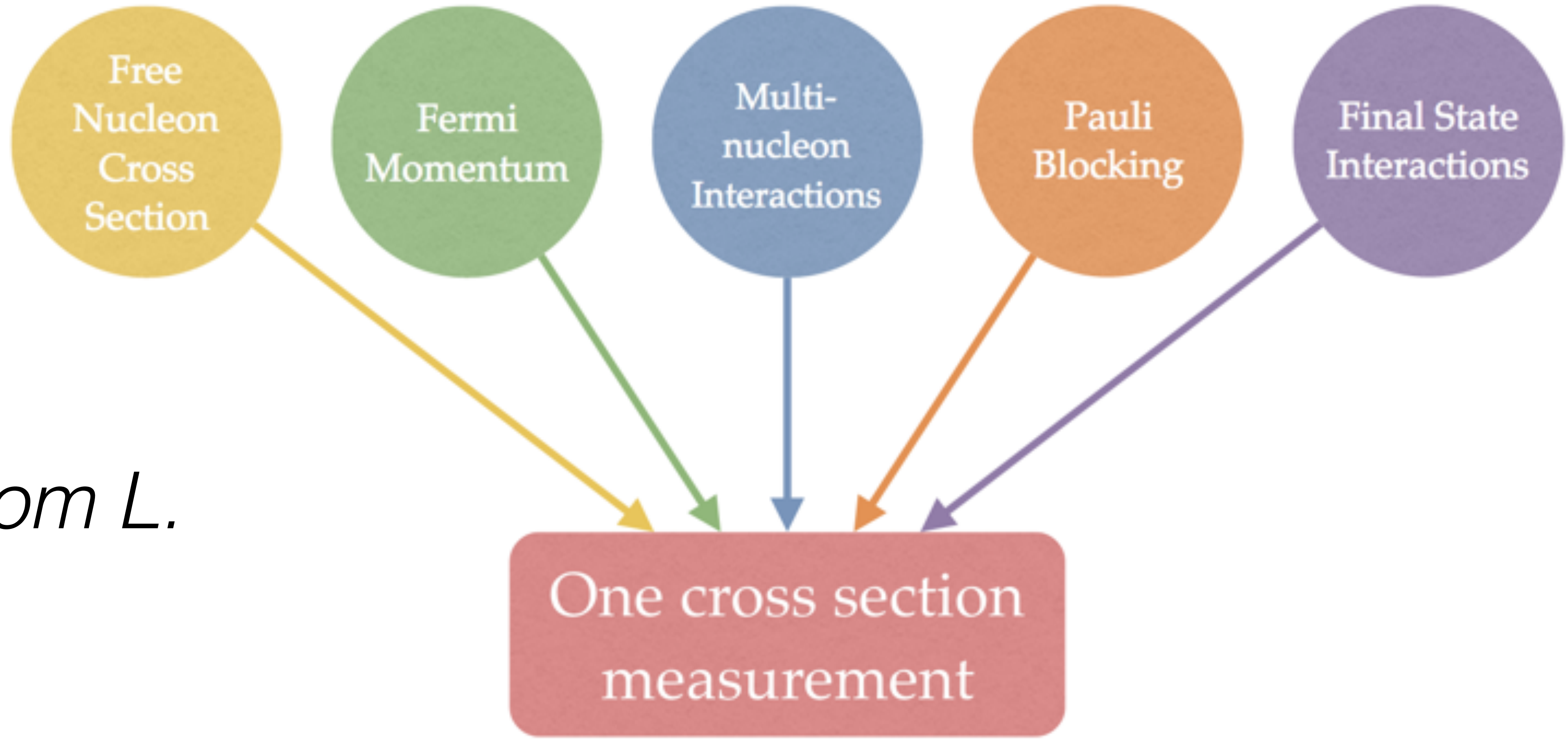



*Image from L. Fields*

- Model sets efficiency/acceptance of signal and background
- Hidden physics, or mistakes?

***DUNE: What are the true degrees of freedom?***

*Does that change how we use ND?*

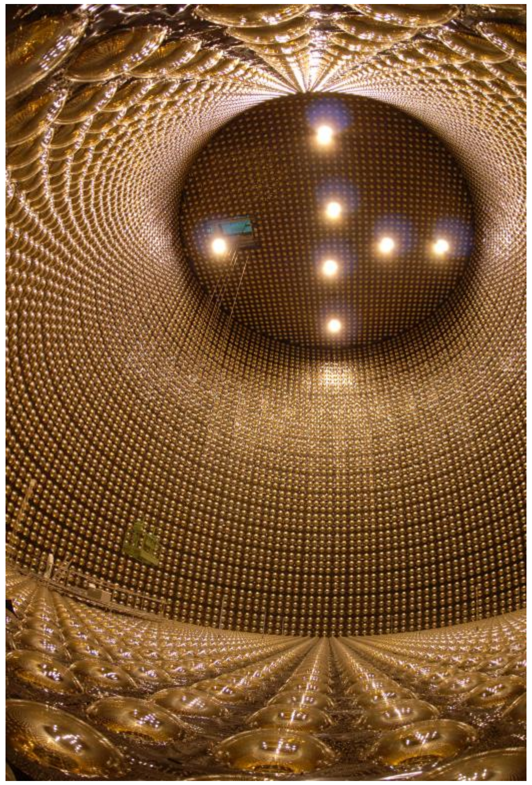
# Cross section model limitation examples

- Not easy to measure NC single photon production -> 1% uncertainty
- numu/nue cross section differences -> 3%
- Single nucleon measurements: Inconsistencies? Precision sufficient?

***DUNE: What are we almost entirely reliant on the model for?***

***Are there (new) measurements which we can do with ND?***

# ND vs. FD comparison

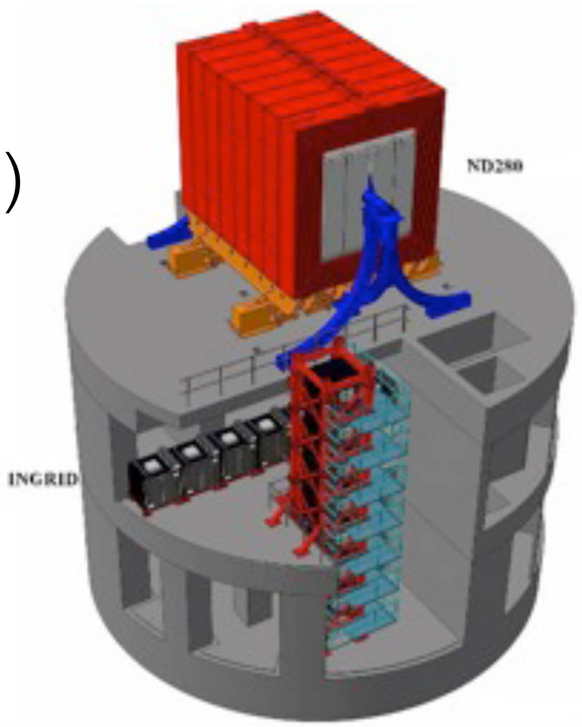


Off-axis beam => both on-axis and off-axis near detectors but focus on off-axis here (sorry INGRID!)

Far detector (SK) technology is Water Cherenkov

Off-axis near detector (ND280) technology is tracking

Details in Nucl. Instrum. Meth. A 659, 106 (2011)




Good:

PID

Momentum resolution

Water target

**Sign selection**

**Similar selected topologies to FD**

Challenging:

**Acceptance**

Dead material

Secondary interactions

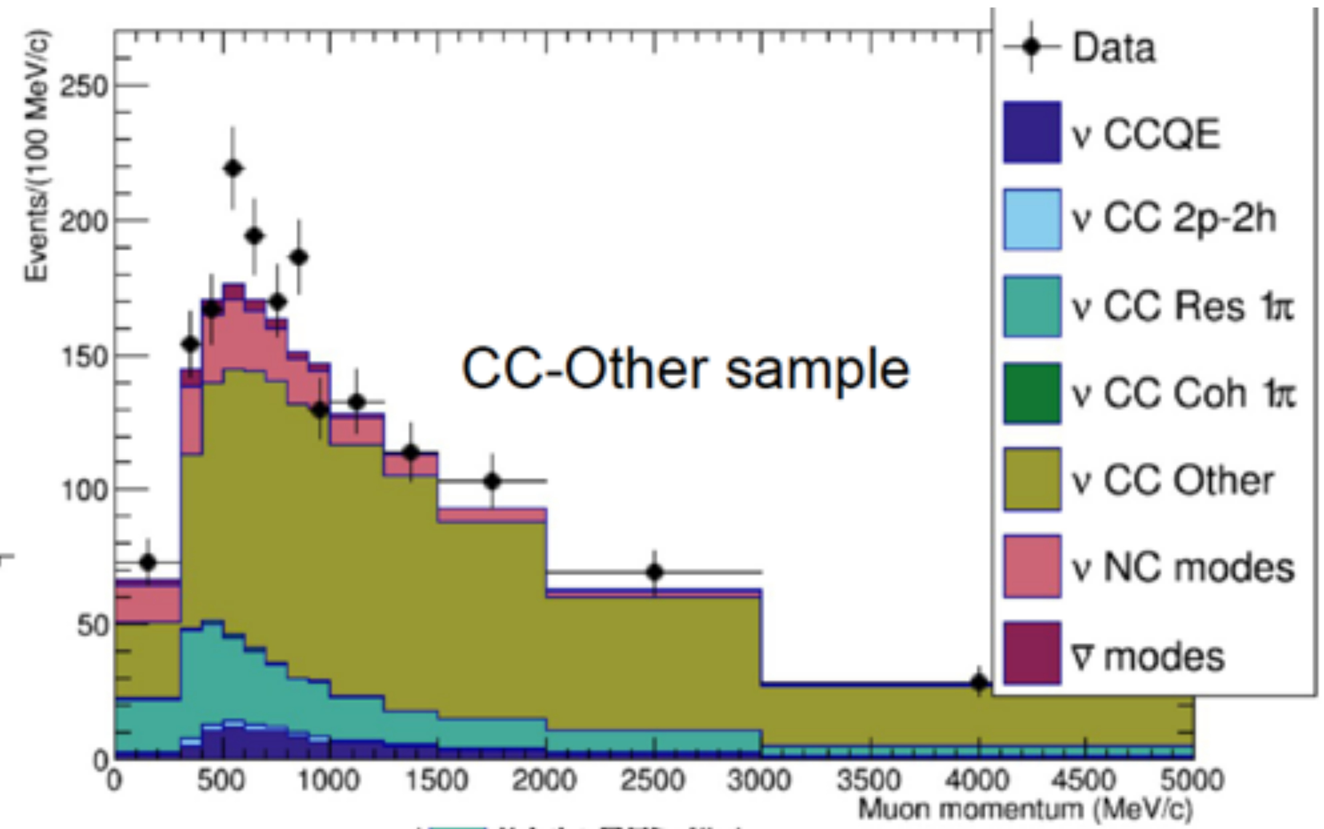
NC backgrounds

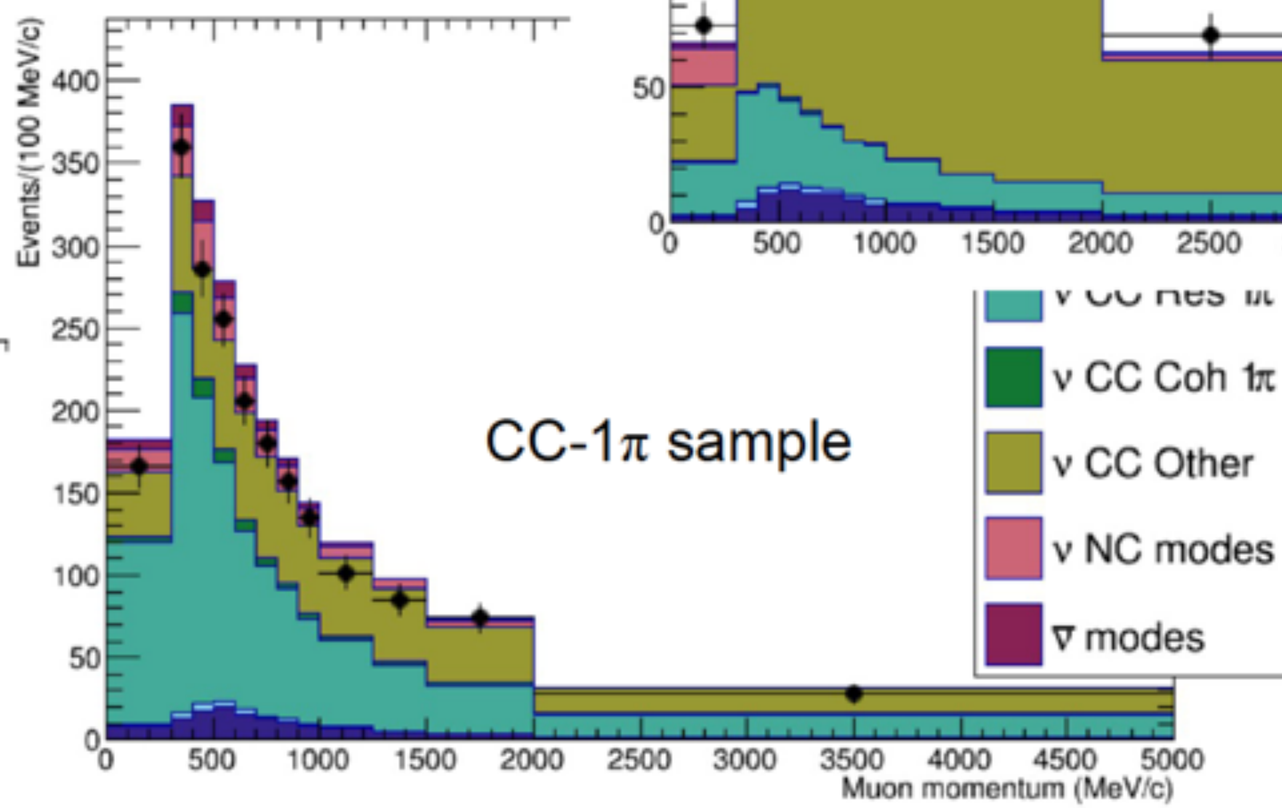
# ND samples and FD

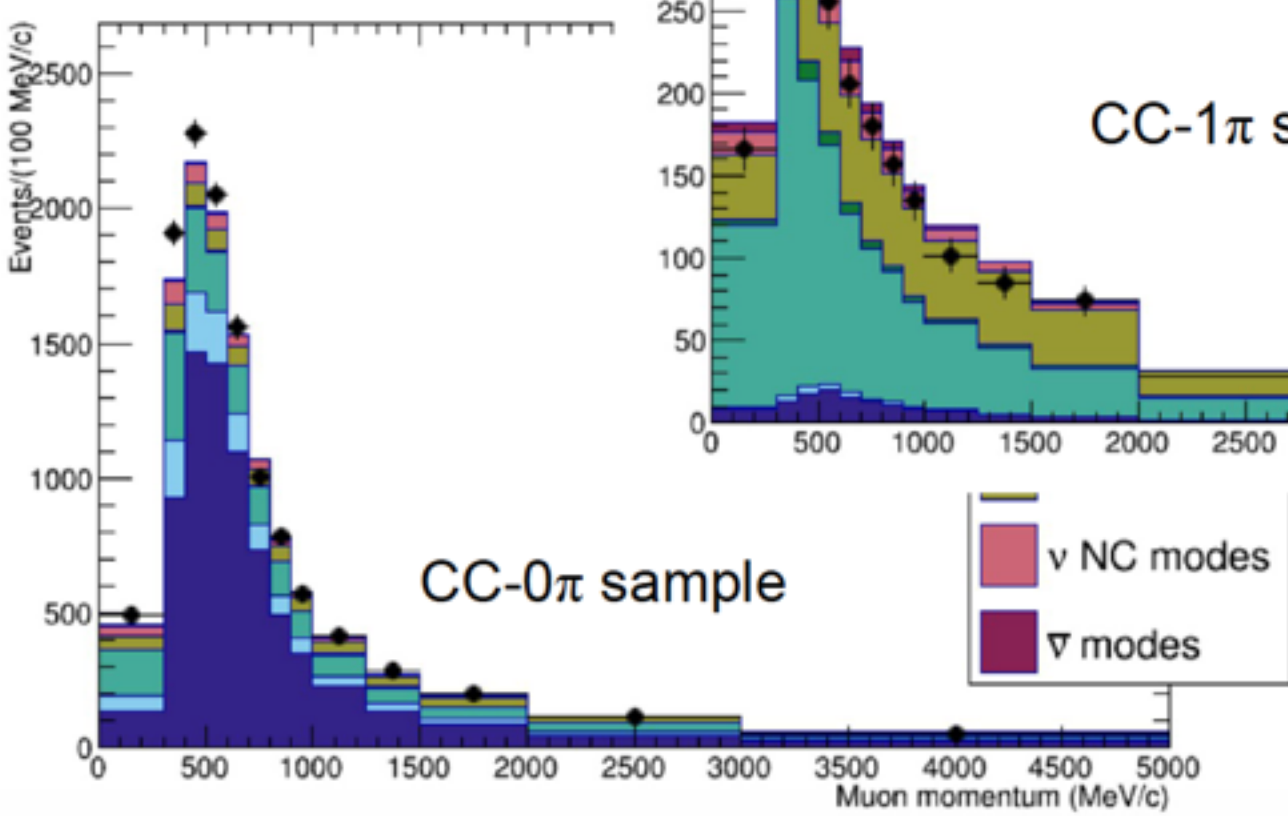
**Selection:**

- Identify highest momentum muon-like track
- Separate by number of tagged pions
- No proton information (yet) – poorly understood model

*slide from M. Scott*



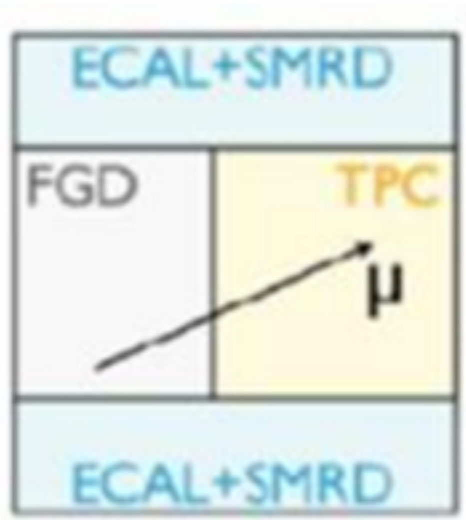



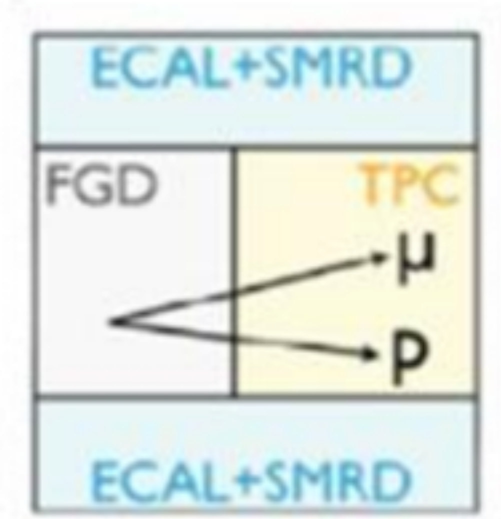



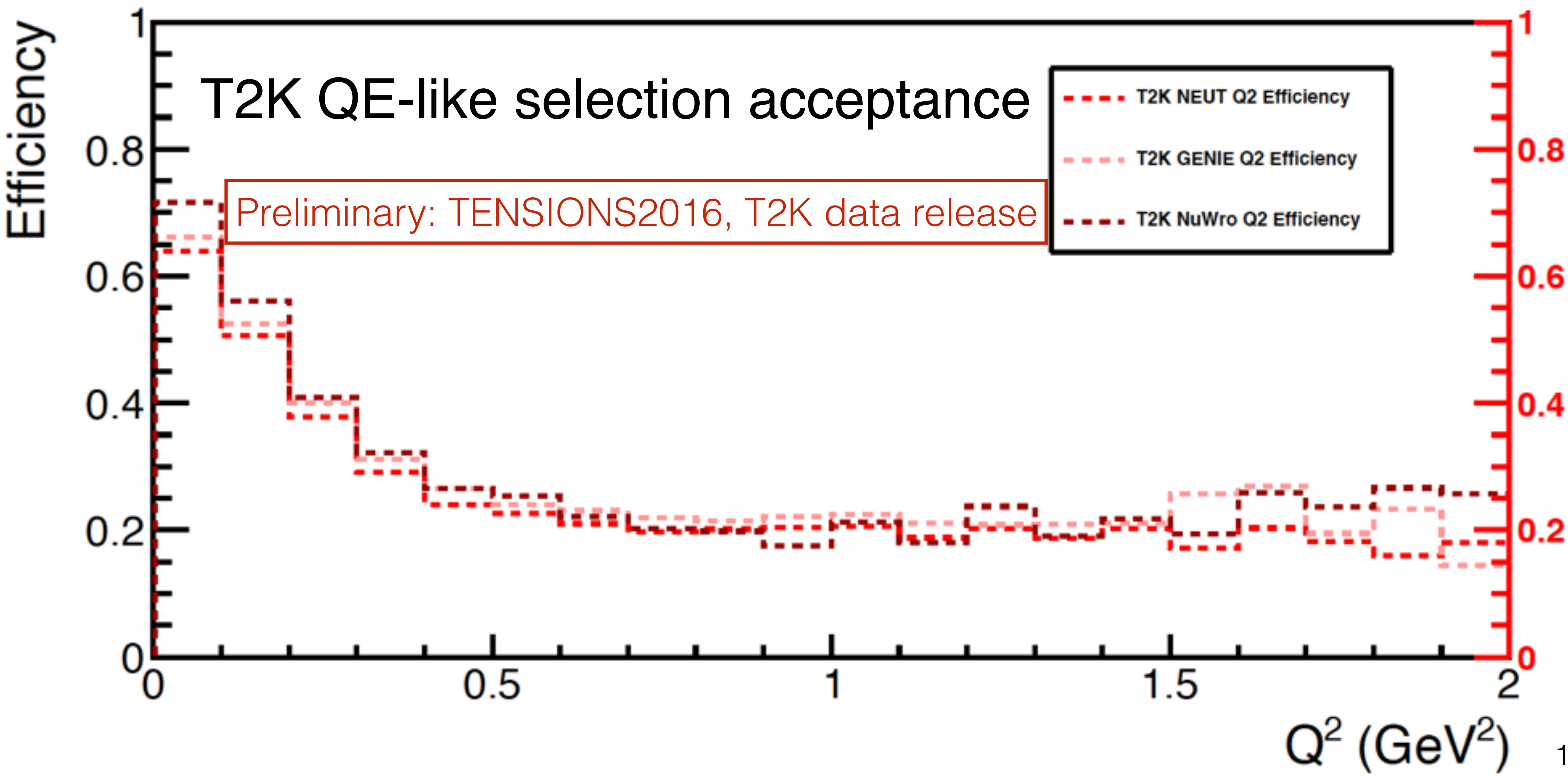

Preliminary, T2K collaboration

Also: RHC (nu,nubar samples)

**Region 0** **Region 1**



# Power of ND in oscillation analysis

TABLE II. Systematic uncertainty on the predicted event rate at the far detector.

| Source [%] | $\nu_\mu$ | $\nu_e$ | $\overline{\nu}_\mu$ | $\overline{\nu}_e$ |
|---|---|---|---|---|
| ND280-unconstrained cross section | 0.7 | 3.0 | 0.8 | 3.3 |
| Flux and ND280-constrained cross section | 2.8 | 2.9 | 3.3 | 3.2 |
| SK detector systematics | 3.9 | 2.4 | 3.3 | 3.1 |
| Final or secondary hadron interactions | 1.5 | 2.5 | 2.1 | 2.5 |
| Total | 5.0 | 5.4 | 5.2 | 6.2 |

arXiv: 1701.00432v1

1. Cross section systematics uncertainties which affect extrapolation (not constrained by ND)

2. Uncertainties from flux + some cross section uncertainties (constrained by ND)

3. FD detector systematic uncertainties (not constrainable in T2K's configuration)

4. Final state interaction, "secondary" interactions of hadrons in FD (not currently constrained)

# Perspectives for DUNE

**Focus on differences from T2K experience. What challenges do we know about and how will new ND mitigate them?**

- How significant are OOFV/cosmics/pileup? What insight from NOvA on tackling these?
- What theory-led issues do we have? Example: numu/nue differences.
    - Experimental: 3% uncertainty? What is the overall sample size of a CC nue selection in each ND?
- How important are threshold/acceptance effects? -> *ND TF initial studies*
- Are there other small but poorly known components of the model?
    - Thoughtful investigation of NC backgrounds at ND, FD

# References

Wealth of information in t2k-experiment.org under Publications tab. Most recent long paper:
Phys. Rev. D 91, 072010 (2015) arxiv: 1502.01550

# Backup

# Example: Limit of ND, Final State Interactions

| True Topology | CC-inclusive | CC0$\pi$-like | CC1$\pi^+$-like | CCOther-like |
|---|---|---|---|---|
| CC0$\pi$ | 51.5% | 72.4% | 6.4% | 5.8% |
| CC1$\pi^+$ | 15.0% | 8.6% | 49.2% | 7.8% |
| CCOther | 24.2% | 11.5% | 31.0% | 73.6% |
| non-$\nu_\mu$ CC | 4.1% | 2.3% | 6.8% | 8.7% |
| Out of FGD1 FV | 5.2% | 5.2% | 6.6% | 4.1% |

Good: Selection of samples according to "final state topology", can be pure!

*Benefit of ND with: good particle identification, lack of dead (no instrumentation) regions, timing and vertex information*

Bad: Final state interactions migrate events between observable final states.

Different flux at ND and FD due to oscillation changes this rate

*A correct FSI model is needed to extract oscillation probabilities. ND helps but doesn't "solve" this problem.*

# Energy estimators // Energy Reconstruction

$$E_\nu^{cal} = \epsilon_n + E_\ell + \sum_i (E_{\mathbf{p}'_i} - M) + \sum_j E_{\mathbf{h}'_j}$$

Calorimetric estimation of energy depends on:

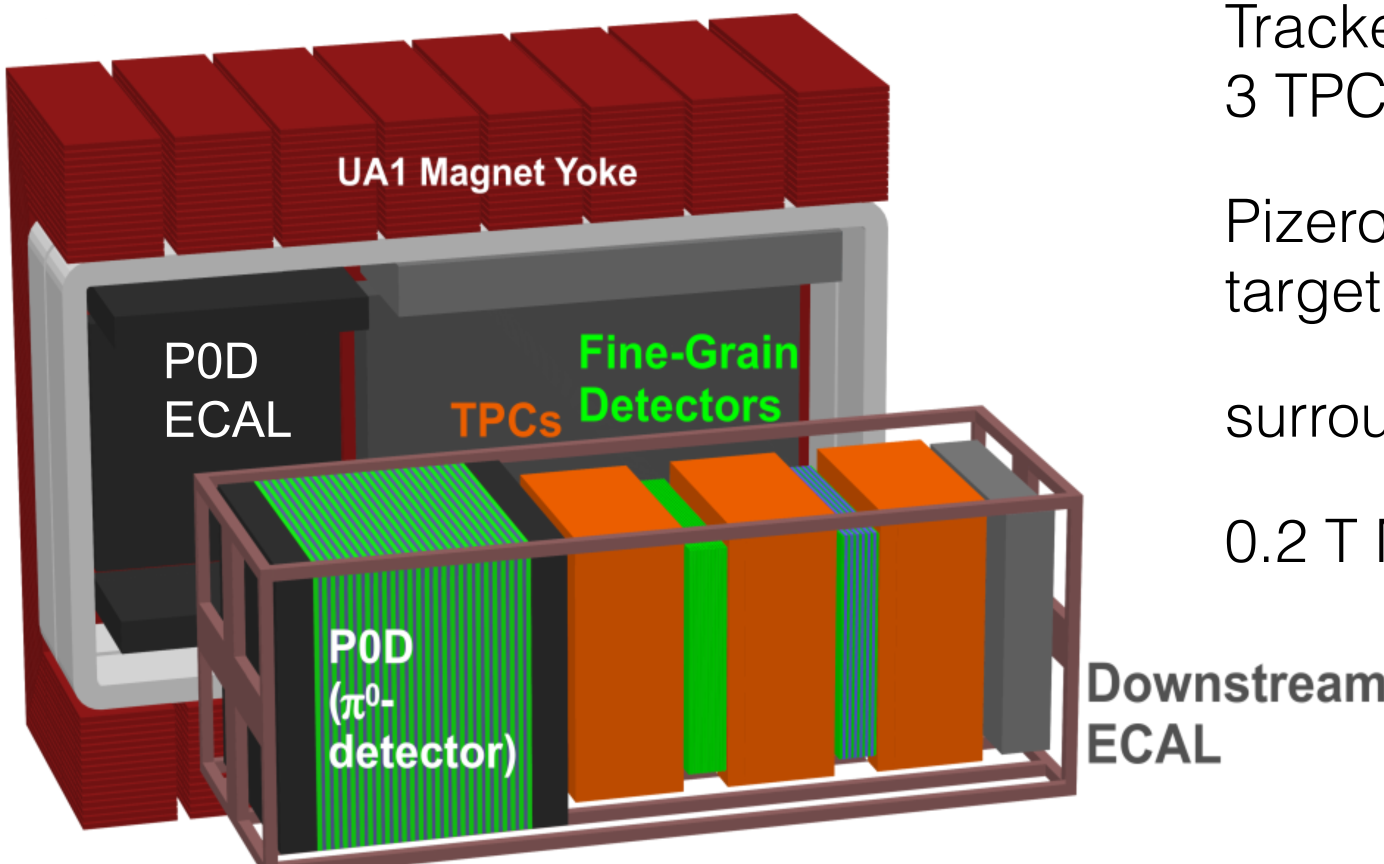
1. Nuclear properties/cross section model (separation energy epsilon n)
2. Kinetic energy of nucleons (Ep-M) (since ejected from nucleus)
3. Total energy of the mesons (Eh) (since produced in the process)

Low threshold is important to get all mesons, nucleons

Neutrons and proton mis-reconstruction is important

Understanding response of detector to particles is crucial

# Off-axis near detectors: ND280

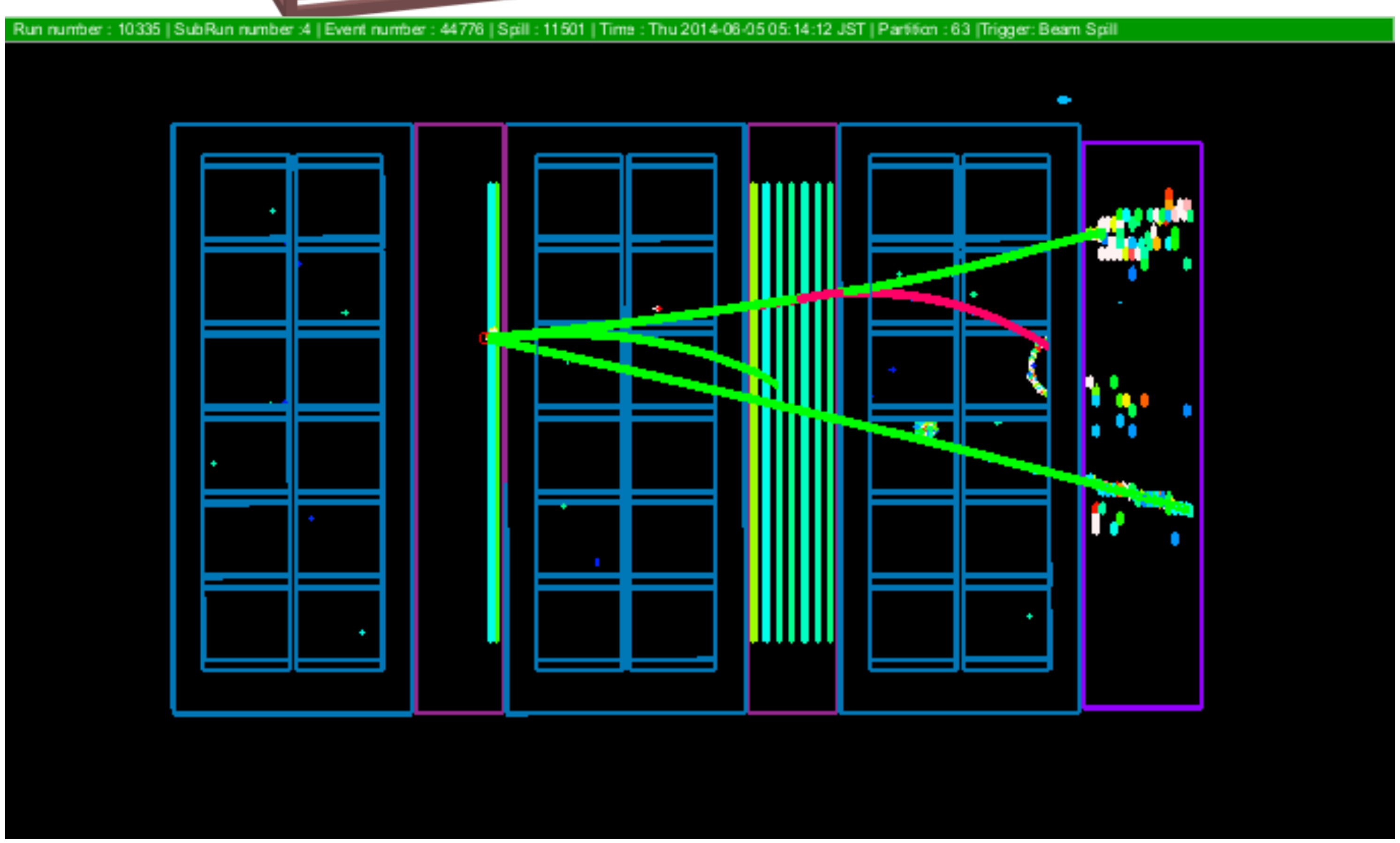



Tracker: 2 FGDs (scintillator and water targets) and 3 TPCs

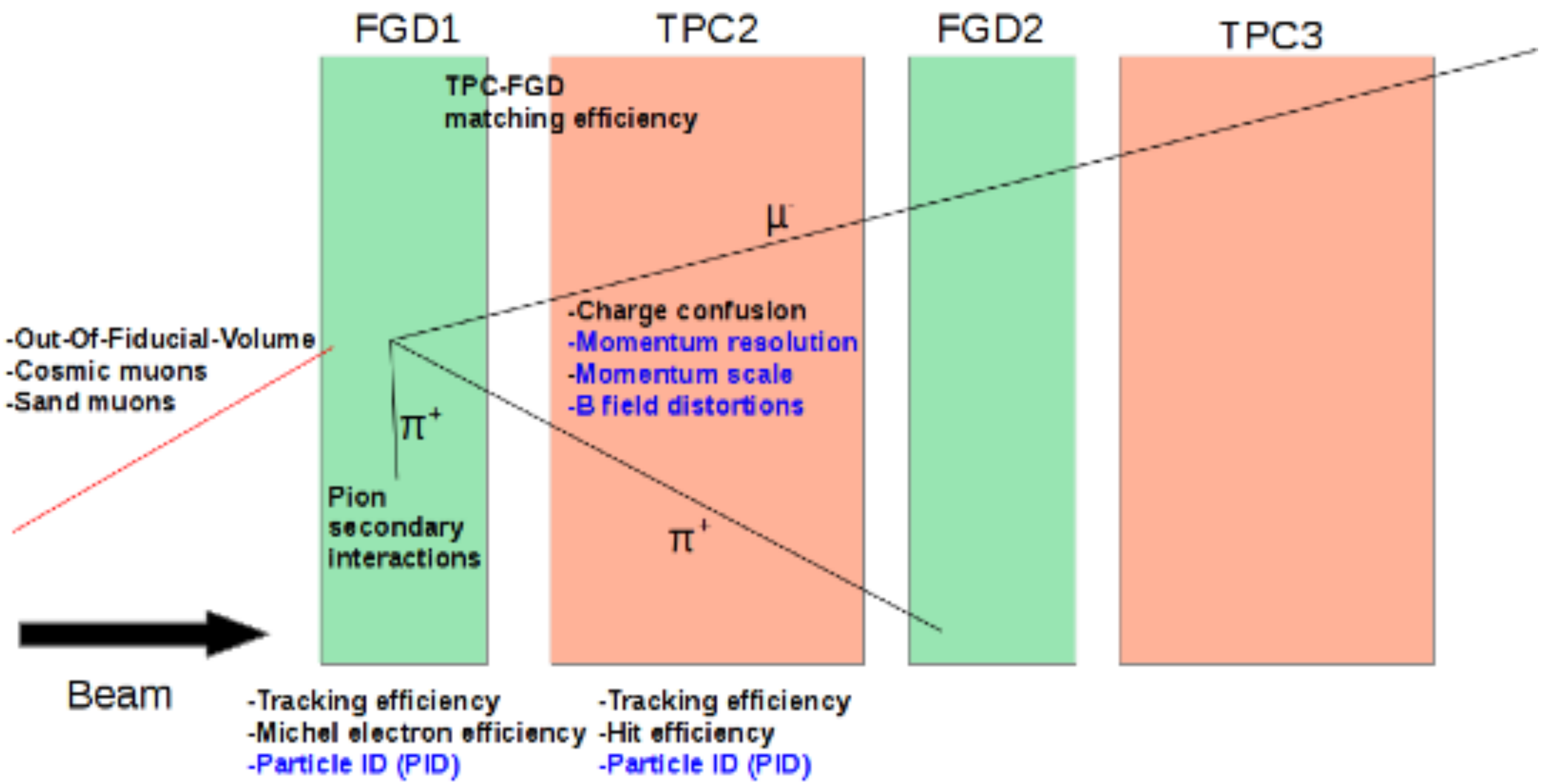
Pizero-Detector scintillator-tracker with water targets,

surrounding Electromagnetic Calorimeters (ECALs)

0.2 T Magnet instrumented with scintillator (SMRD)



# Detector uncertainties




Largest uncertainty in some regions of phase space is OOFV and secondary interactions of pions in detector (SI)

- Important role of test beam response and external measurements
- ND detectors where secondary interactions can be identified (and correlated) helps

Acceptable in ND280: B field, PID, hit and tracking efficiency. Extensive use of "control" samples and dedicated measurements (Phys. Rev. D 91, 072010 (2015), arXiv:1502.01550)

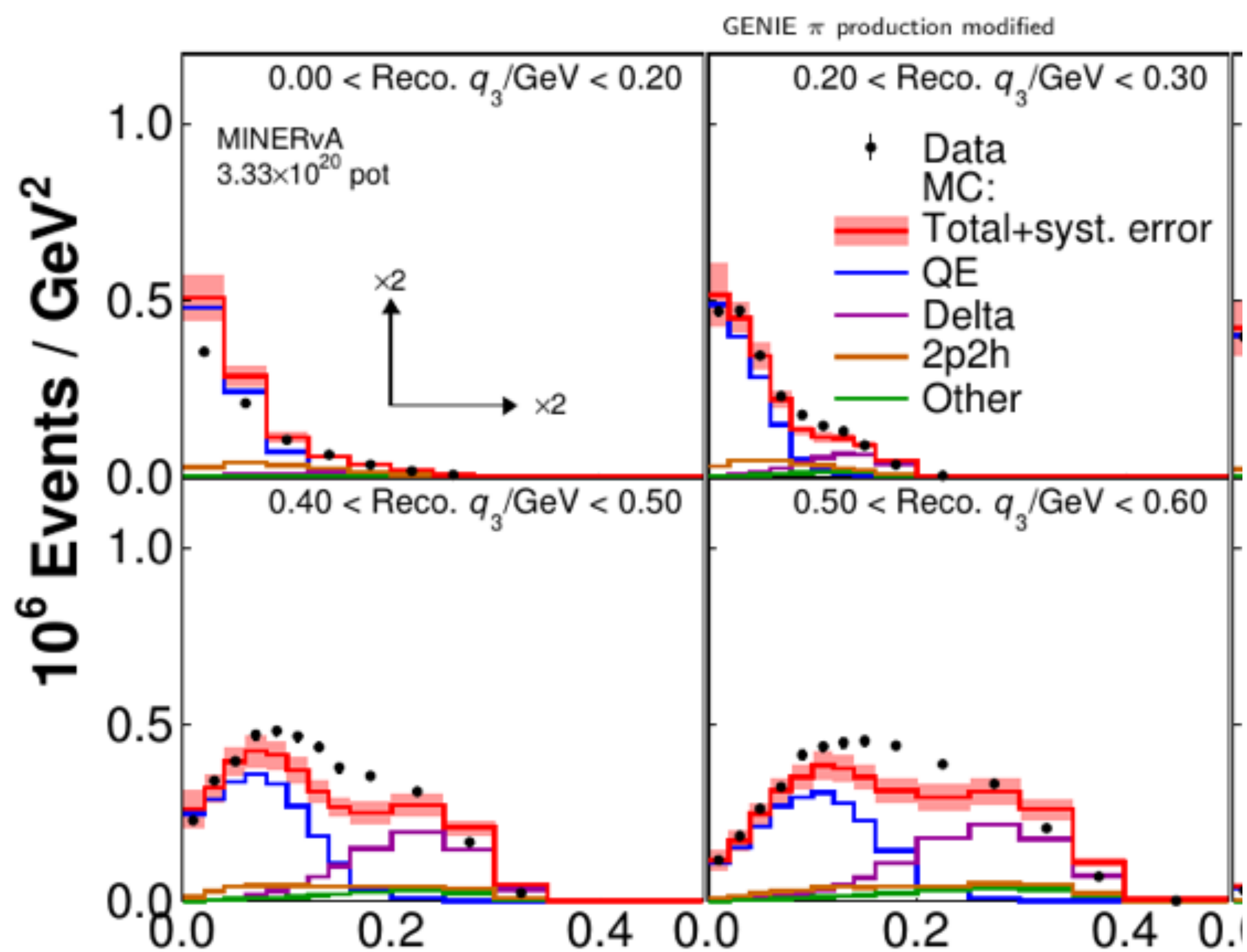
# Inactive ("dead") material

Lots of neutrino interactions in concrete, sand, **magnet** and dead material of detector (~5% p7)

*Improved with better global timing across the detector (is it entering or exiting?) but always an issue at some level (glue, bar coating, electronics, central cathode)*

Fully active targets or fiducial volume can reduce this, see NOvA or MINERvA (PRL 116, 071802, plot from NuInt2015)

Take careful measurements of the detector as built.



# Observable final state mix

| True Topology | CC-inclusive | CC0$\pi$-like | CC1$\pi^+$-like | CCOther-like |
|---|---|---|---|---|
| CC0$\pi$ | 51.5% | 72.4% | 6.4% | 5.8% |
| CC1$\pi^+$ | 15.0% | 8.6% | 49.2% | 7.8% |
| CCOther | 24.2% | 11.5% | 31.0% | 73.6% |
| non-$\nu_\mu$ CC | 4.1% | 2.3% | 6.8% | 8.7% |
| Out of FGD1 FV | 5.2% | 5.2% | 6.6% | 4.1% |

Good: Selection of samples according to “final state topology”, can be pure!

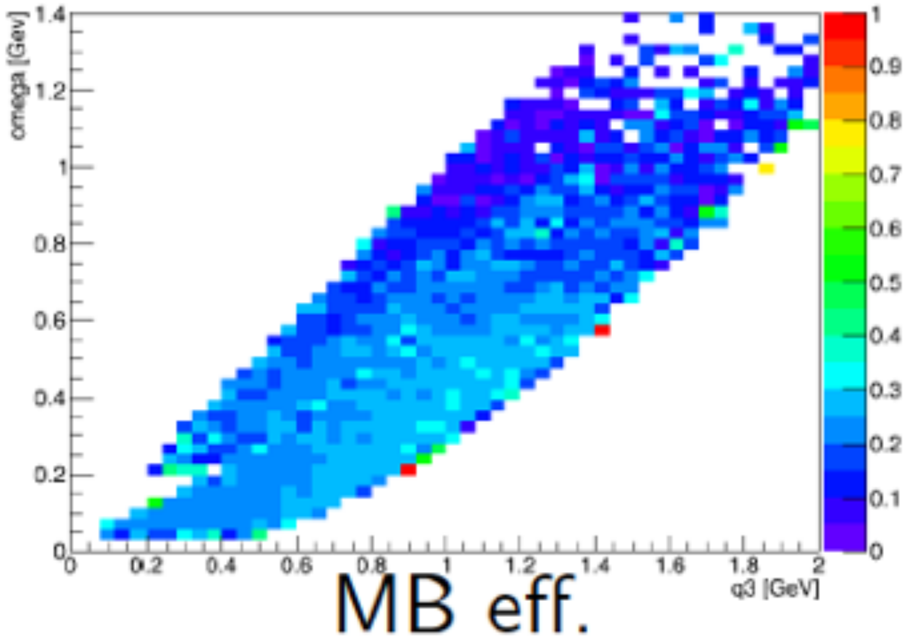
*Benefit of ND with: good particle identification, lack of dead (no instrumentation) regions, timing and vertex information*

Bad: Final state interactions migrate events between observable final states.

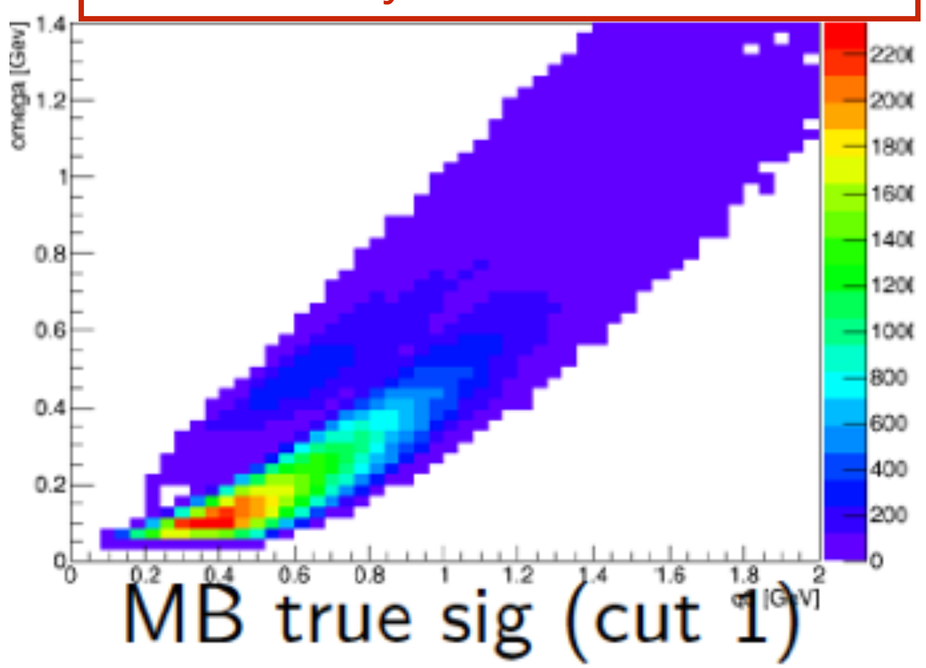
Different flux at ND and FD due to oscillation changes this rate

*A correct FSI model is needed to extract oscillation probabilities. ND helps but doesn’t “solve” this problem.*

# Acceptance

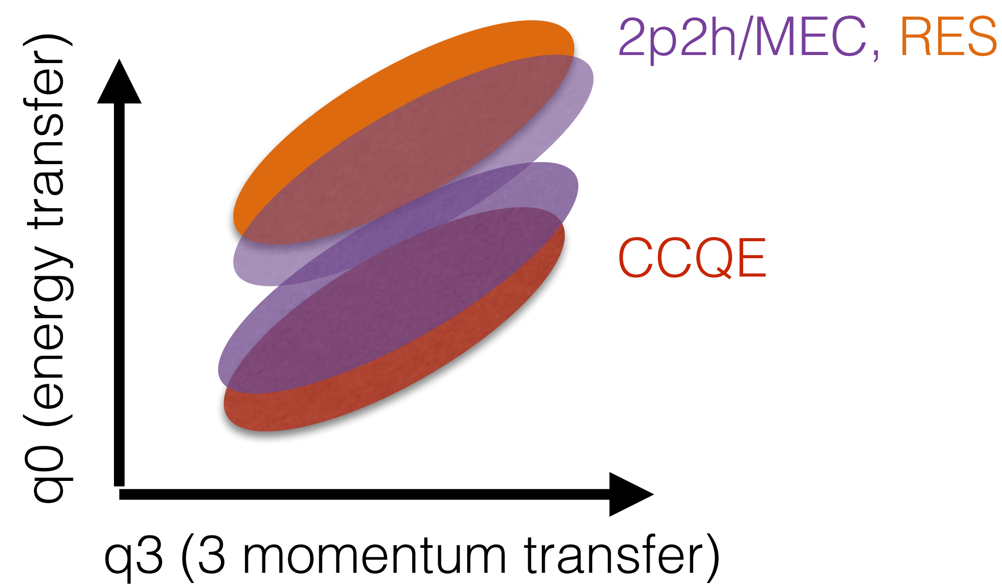



Preliminary: TENSIONS2016



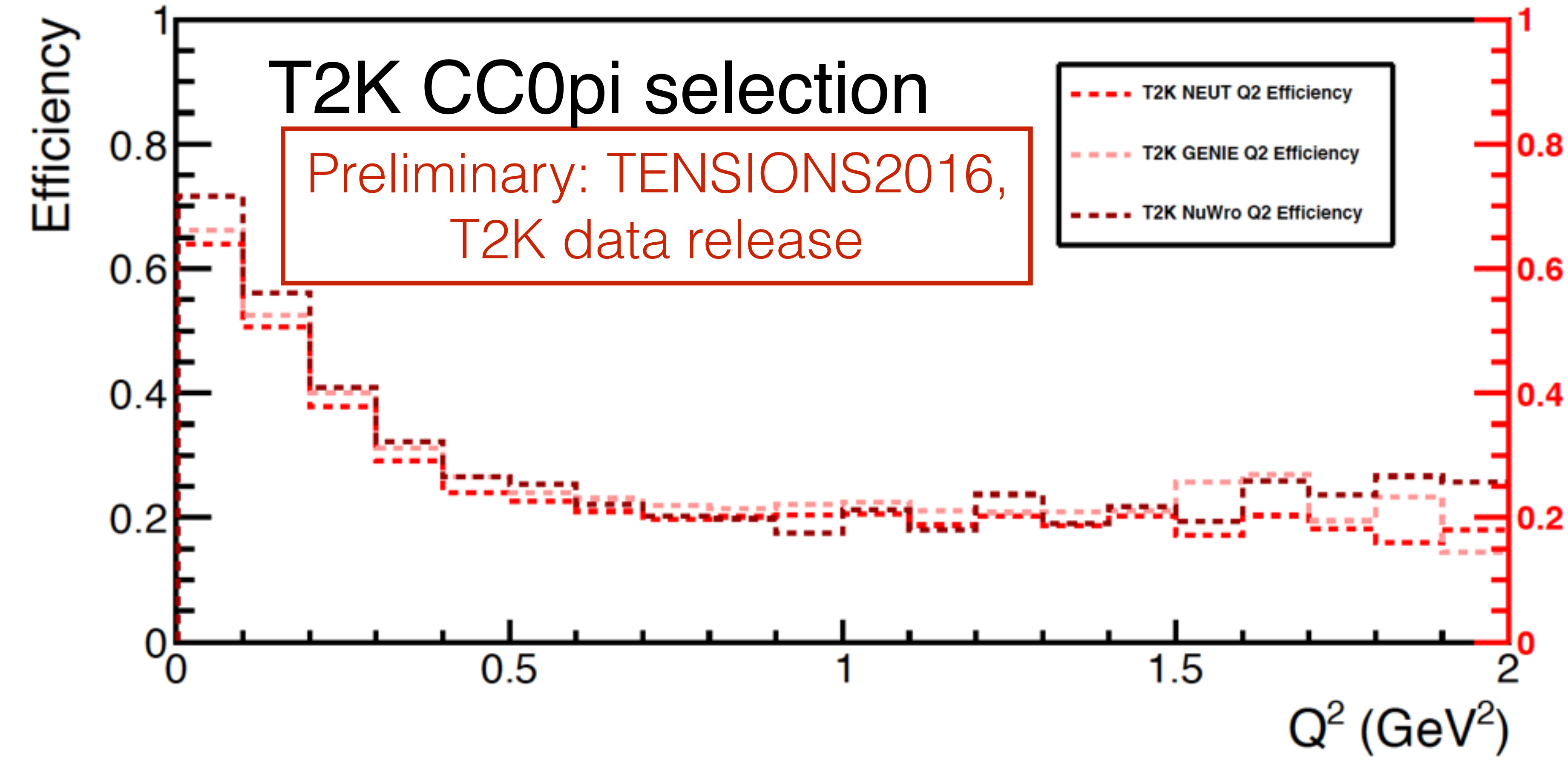

MiniBooNE detector (4π, Cherenkov)

- Efficiency quite flat in cross section physics of interest: q0-q3, $Q^2$
- Accepts most momentum and all angle. Limited from muon range, which is "easy" to measure




*Changing efficiency can couple to cross section model and increase systematic uncertainty*

# Acceptance




Difficult for ND280 tracking detector to achieve 4pi coverage due to inherent geometrical/charge deposit effects

Major challenge only recently addressed— backwards going tracks— thanks to improved timing and reconstruction approaches

Can develop samples which are less sensitive to cross section model (see above) but must proceed carefully

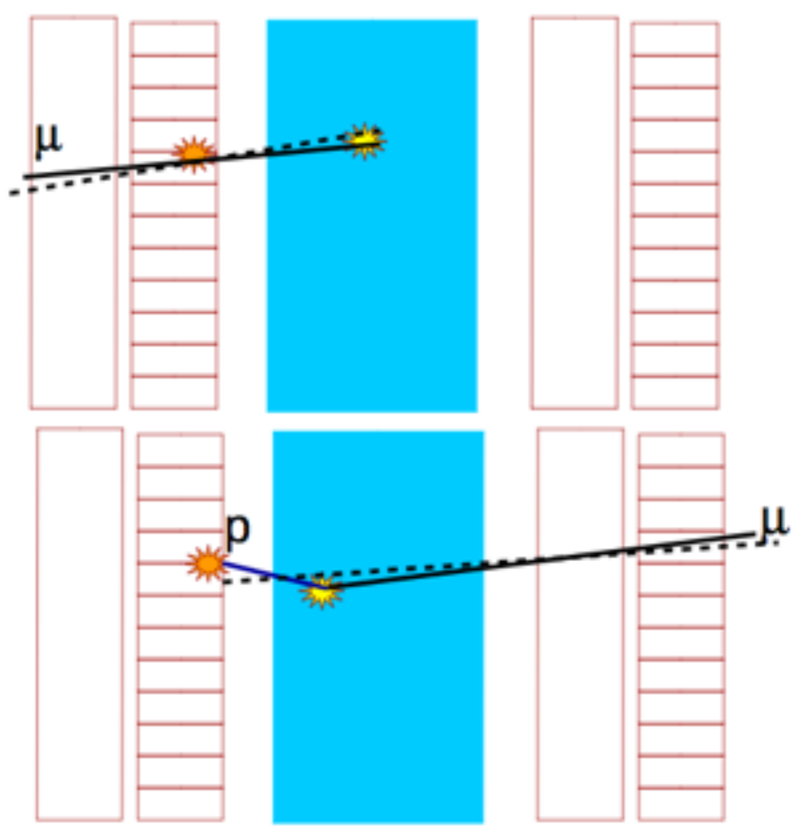
# Different target materials

ND280 has water and scintillator targets

Useful! Compare cross section model to range of existing experiments with different beams (CH) and to FD (water) for validation of cross section model

Challenges in isolating water target interactions:

- “Identical”: Difficulty in relative detector systematics between FGD1 (scintillator) and FGD2 (scintillator and water)
- Migration between samples (example from T2K collaborator, F. Gizzarelli)




i) **backward muon** → vertex upstream of the passive material (ie vertex in y layer)

ii) **backward proton** reconstructed as a single track with the forward muon → vertex upstream of the passive material (ie vertex in y layer)