Status of Charged-pion Cross-section Measurements from NOvA

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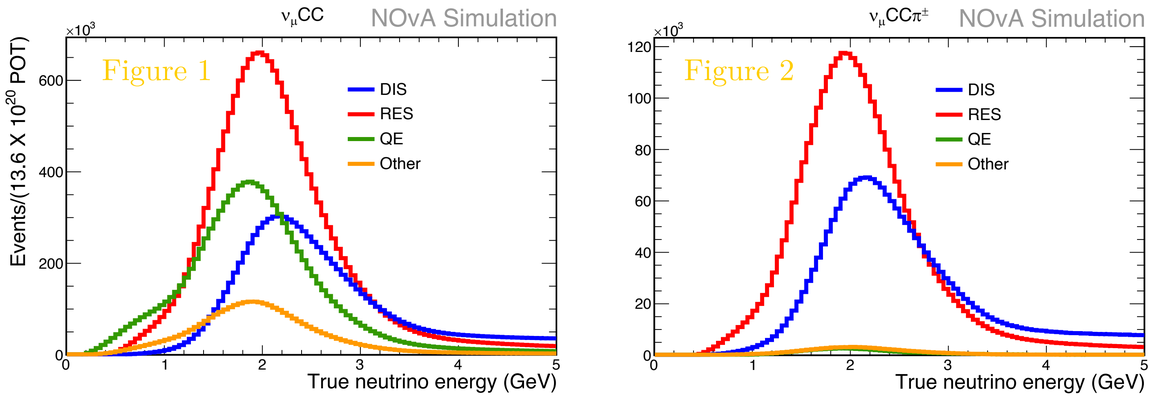
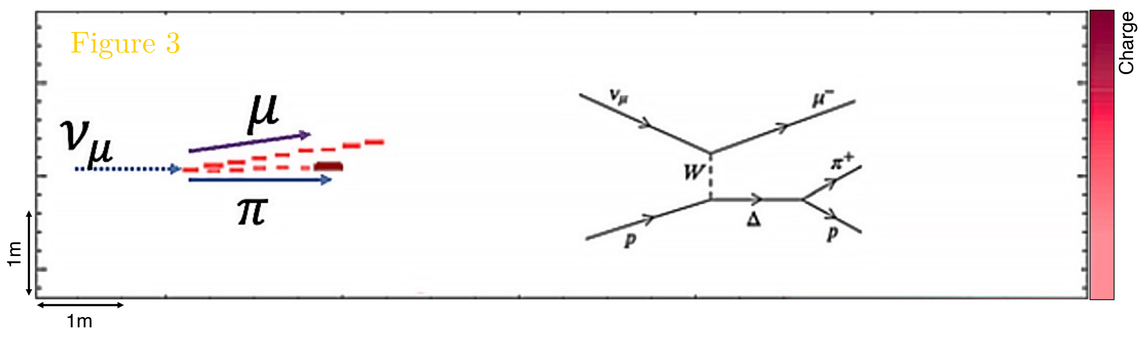
(1) NOvA (NuMI Off-Axis ν_e Appearance Expt.)

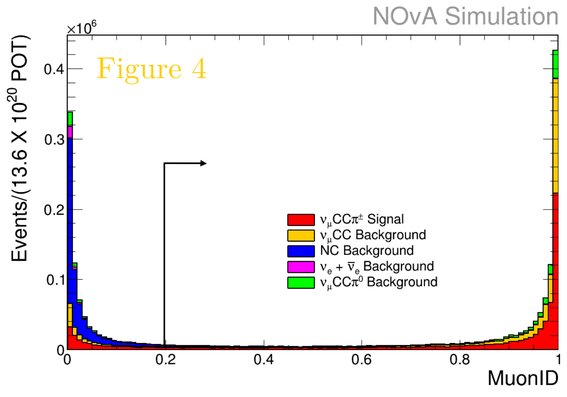
- NOvA is a long-baseline neutrino oscillation experiment aiming to determine mass hierarchy, oscillation parameters, and CP violation phase.
- The NOvA experiment consists of
  - **14-kton far detector**, located in Ash River, MN.
  - **0.3-kton near detector** located at Fermilab.
- Near detector exposed to **1-3 GeV muon-type (95% pure) neutrinos** from NuMI.
  - **Significant QE, RES, DIS and MEC** interactions (Figure 1, GENIE3).
- Inclusive charged-current charged-pion production gives access to dominant RES and DIS channels (Figure 2).

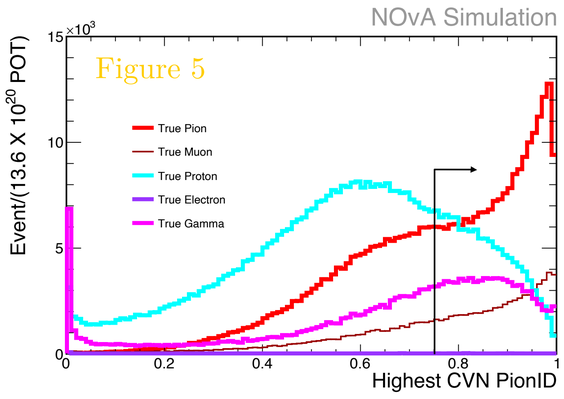




(2) Inclusive ν_μCC $\pi^\pm$ selection

- A simulated ν_μCC $\pi^\pm$ event in NOvA is shown in Figure 3.
- Require reconstructed interaction **vertex containment** in fiducial volume, **containment of visible energy**, and **at least two "prongs"** (reconstructed candidate particles).
- Prong particle likelihood is scored using deep-learning based CVN (Convolutional Visual Network)
  - Muon candidate prong identified **by MuonID score > 0.2** (Figure 4).
  - Candidate pion prong identified by highest **PionID score > 0.75** (Figure 5).





(3) Particle kinematic reconstruction

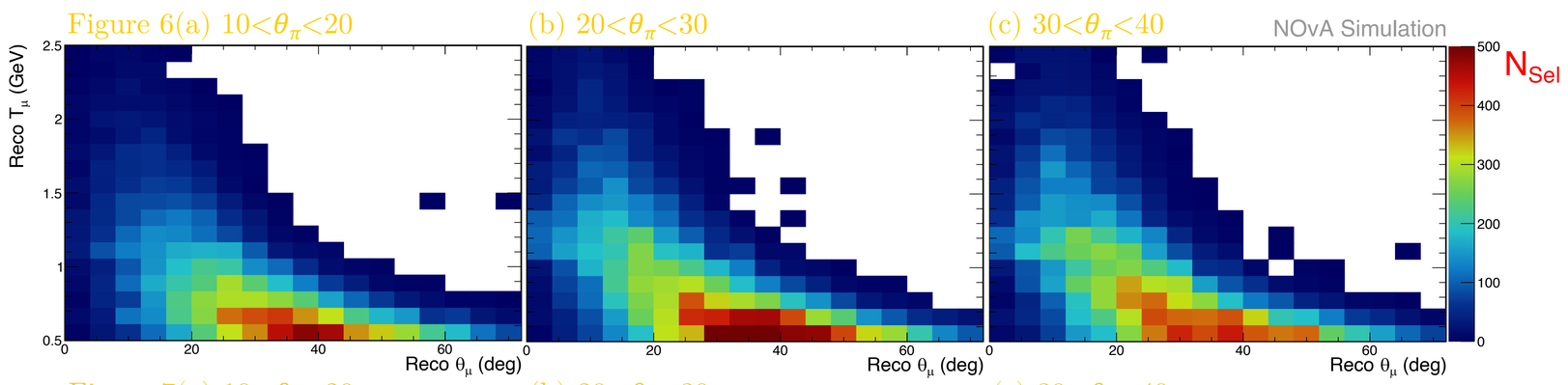
- Particle energies are determined calorimetrically from visible prong energy.
  - **~ 4-5% resolution on muon energy.**
  - **~100-150 MeV resolution on pion energy**
- Particle direction is determined from Hough Transform + Kalman Filter.
  - **~2-5 degree resolution on muons angle.**
  - **10-15 degree resolution on pion angle.**

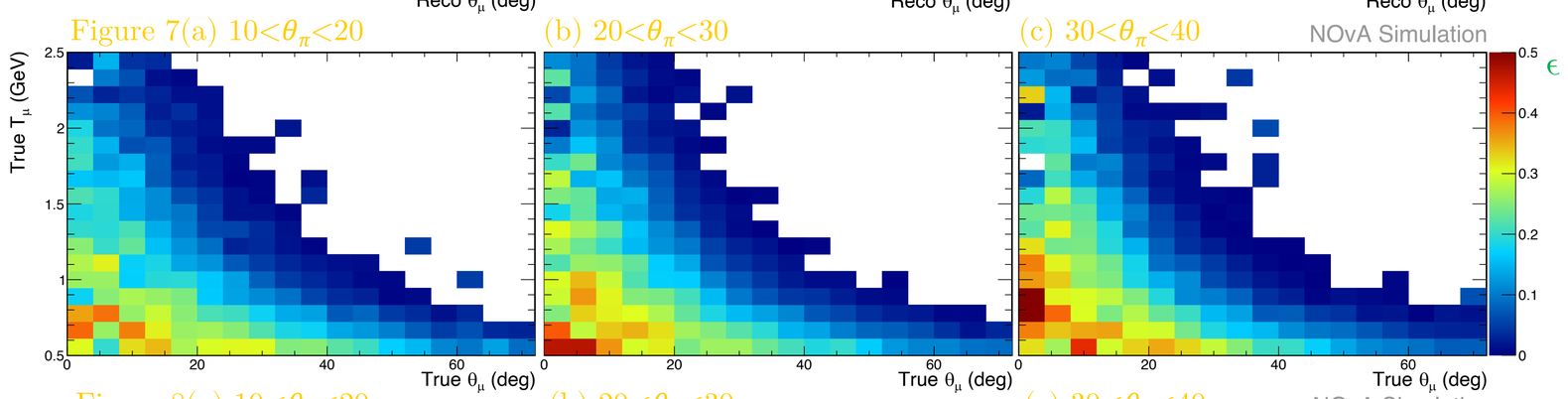
(4) Studying Differential Cross-Section Measurement

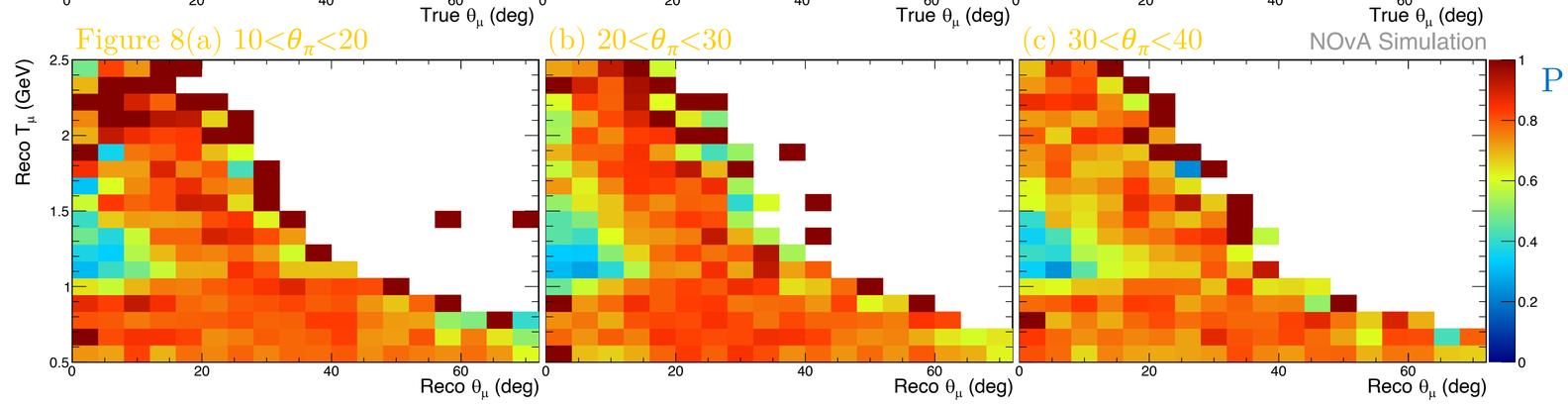
- We are exploring a cross-section measurement differential in the kinematics of the muon and leading pion.
- Figures 6-8 show N_{sel} **(selected events)**, P **(signal/background)**, and ϵ **(selected signal/true signal count)** respectively which contribute to the cross-section as:

$$\sigma = \frac{N_{sel} \times P}{N_t \times \Phi \times \epsilon}$$

- From resolution and statistics from 13.6 x 10^{20} POT, an initial binning is under study:
  - T_μ : 18 bins from 0.5 to 2.5 GeV
  - θ_μ: 18 bins from 0 to 72 degree
  - T_π : 3 variable bins from 0.2 to 0.73
  - θ_π : 8 variable bin from 0 to 90 degree
- Figures 6-8 show the muon kinematic space for selected pions with $350 < T_\pi < 550$ (MeV) and (a) $10<\theta_\pi<20$, (b) $20<\theta_\pi<30$, and (c) $30<\theta_\pi<40$ (deg).





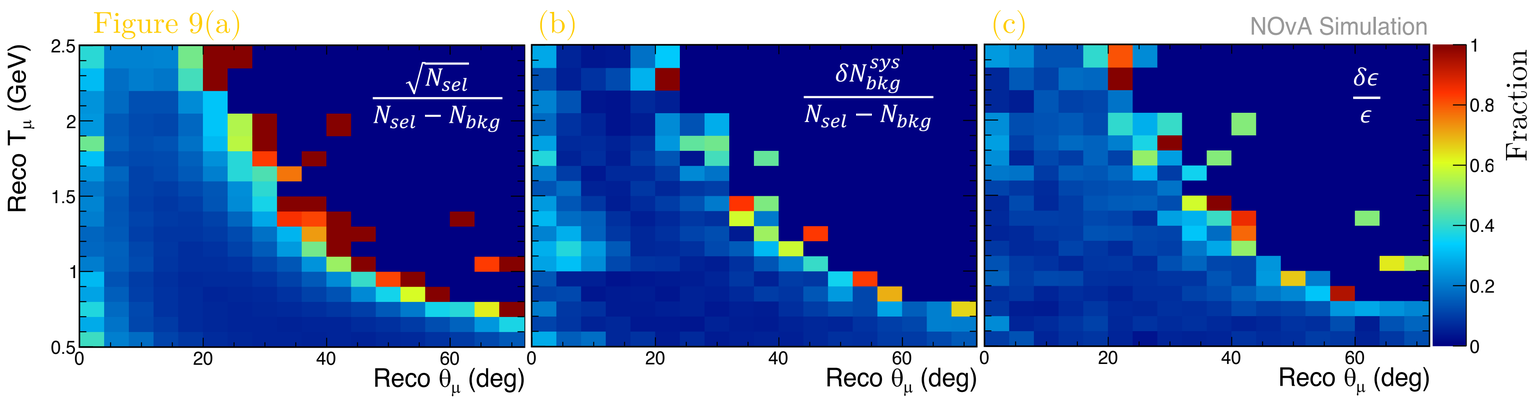


(5) Uncertainty Studies

- Initial statistical and systematic uncertainties (including GENIE interaction uncertainties and detector modeling effects) were studied and are shown in Figure 9 for $350 < T_\pi < 550\ (MeV)$ and $30<\theta_\pi<40$.
  a) Statistical uncertainties are below 20% for most of the space.
  b) Background uncertainties before constraints are comparable to statistical uncertainties.
  c) Uncertainties on the efficiency are also comparable to statistical uncertainties in phase-space shown.

(6) Future Work

- Study unfolding.
  - Transition events from reconstructed quantities into their true quantities.
- Continue systematic uncertainty evaluation and data-driven constraints.
- Optimize/assess kinematic binning including inclusion of low and high energy pions which have reduced efficiencies.



Check out the NOvA live event display.

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