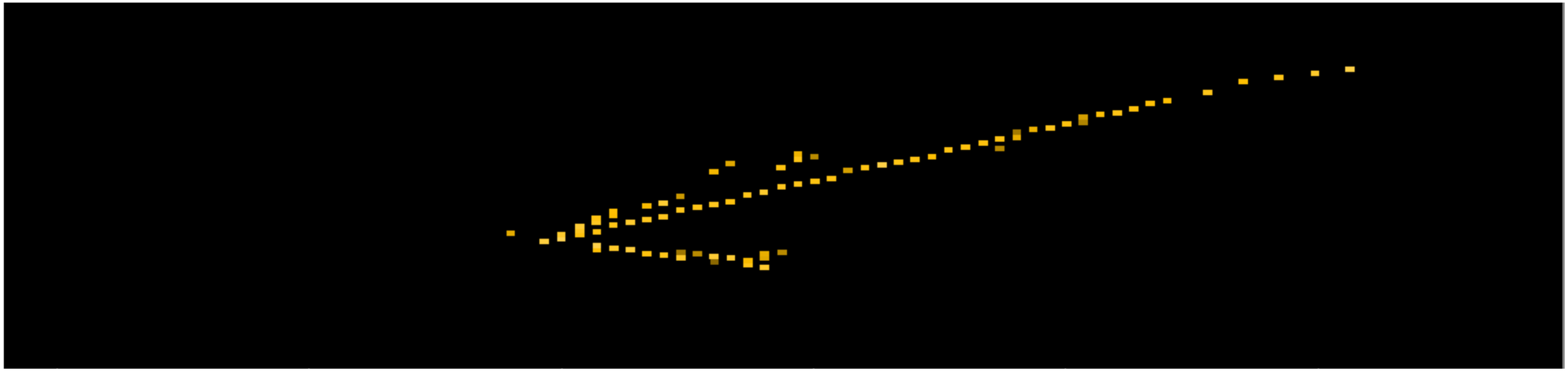
Muon-neutrino charged-current interactions at the NOvA near detector



Leonidas Aliaga (on behalf of the NOvA Collaboration)

The 22nd International Workshop on Neutrinos from Accelerators (NuFact 2021)

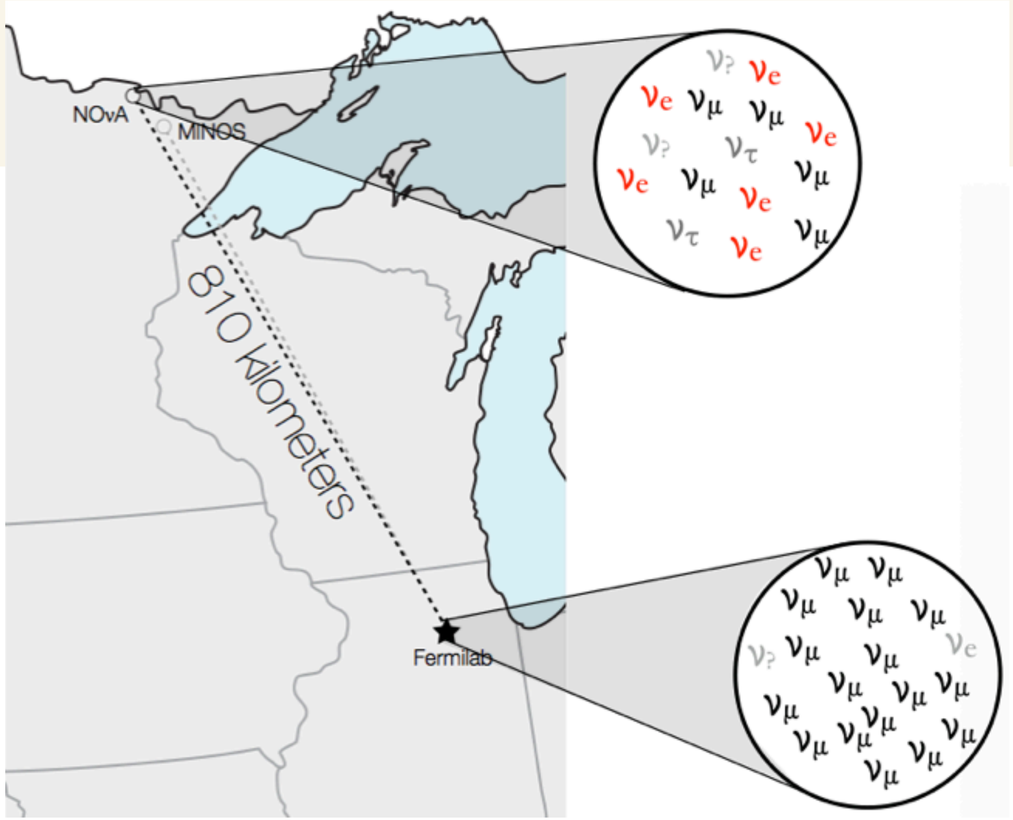
September 9, 2021

The NOvA experiment

» NOvA is a long-baseline neutrino oscillation experiment

» 2 detectors: 14.6 mrad off-axis and 810 km apart

- *Designed to measure for* $\nu_\mu \longrightarrow \nu_e$ *: detectors provide excellent imaging of both* ν_μ *and* ν_e *CC events*



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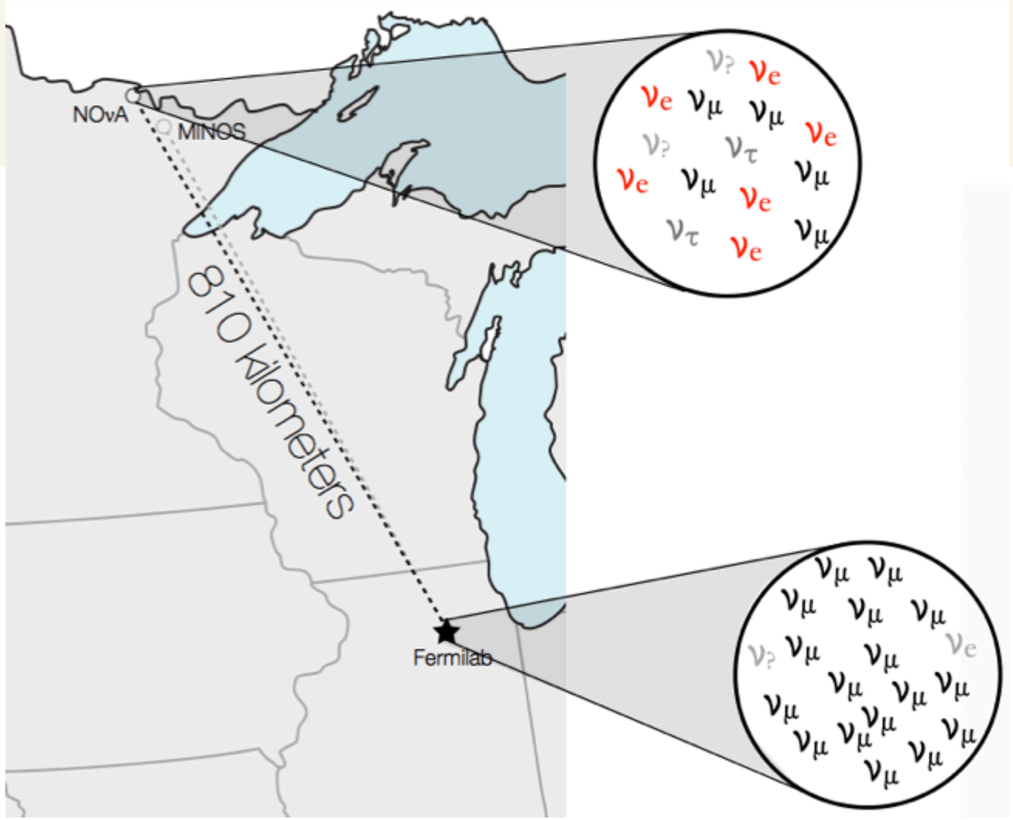
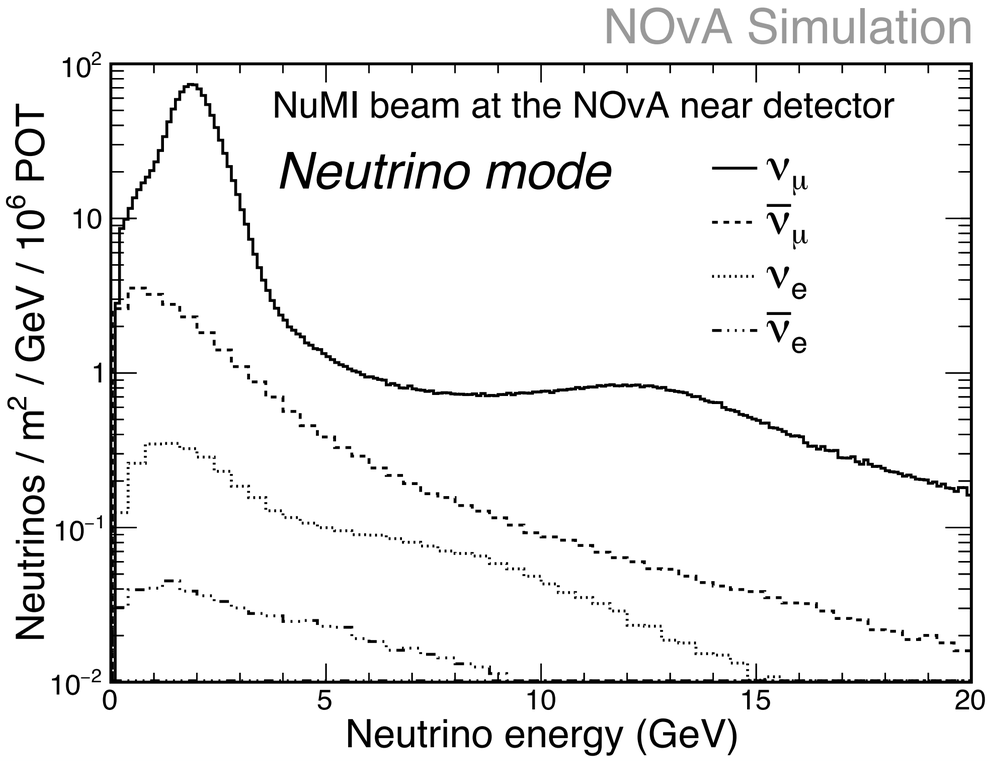


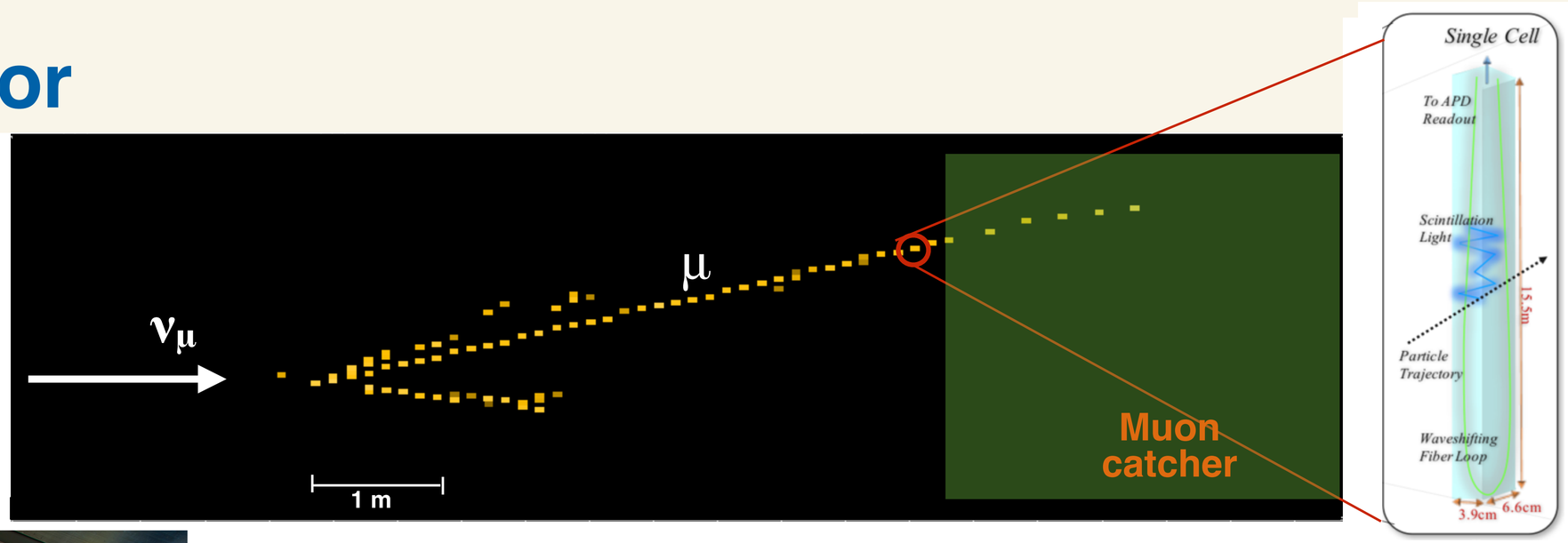


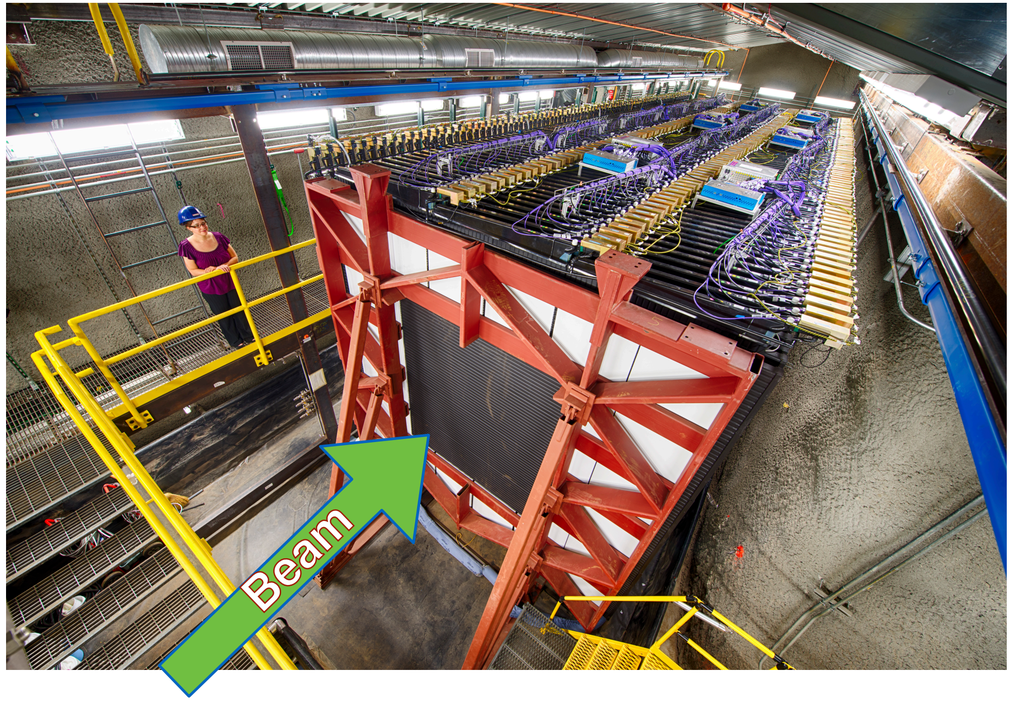
- **94% pure ν_μ**, 5% $\bar{\nu}_\mu$, and 1% $\nu_e + \bar{\nu}_e$ in neutrino mode
- **92% pure $\bar{\nu}_\mu$**, 7% ν_μ, and 1% $\nu_e + \bar{\nu}_e$ in antineutrino mode

High neutrino flux at the Near Detector *provides a rich data set for* ***cross-section measurements***

NOvA Near Detector

The ND is **1 km** from source, **underground** at Fermilab.





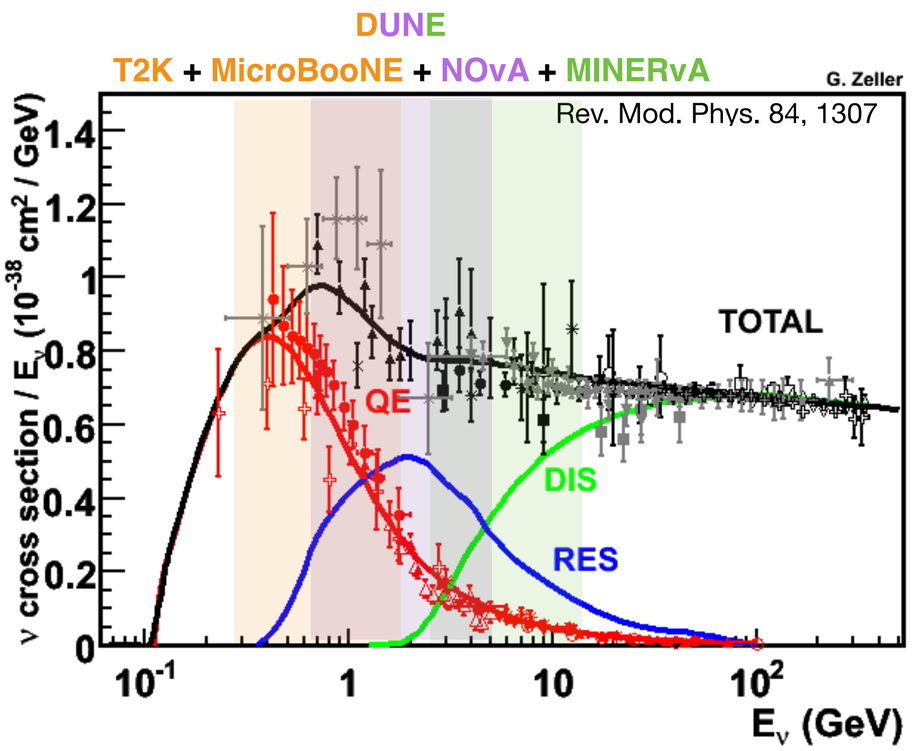
PVC cells filled with **liquid scintillator, 193 ton** fully active mass and 97 ton downstream muon catcher

Alternating planes of orthogonal views

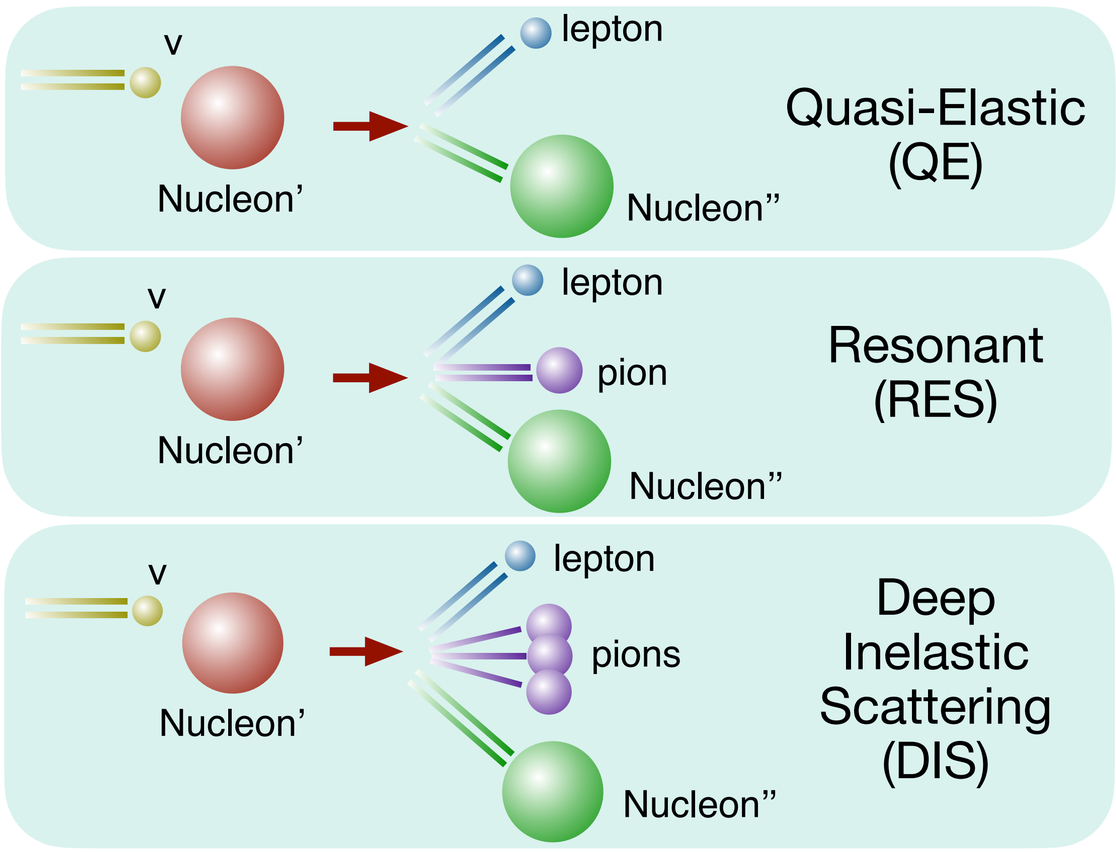
Low-Z, fine-grained: 1 plane ~ 0.15 X_0

C	Cl	H	O	Ti
67%	16%	11%	3%	3%

Neutrino interactions at the few-GeV region



NOvA flux peaks between 1 and 5 GeV:
it is the transition region between interaction processes.

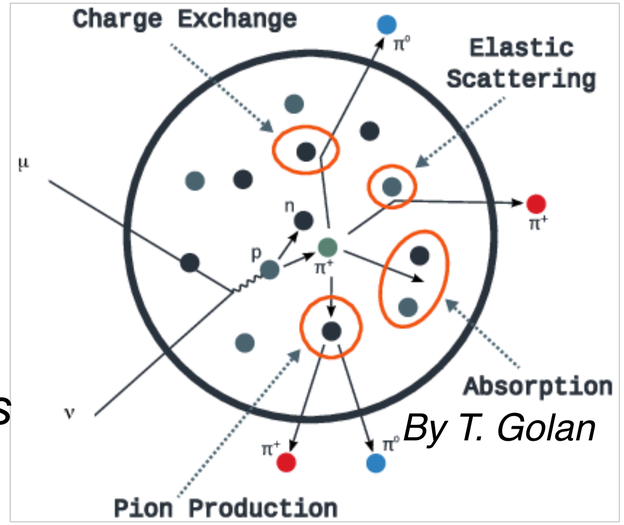


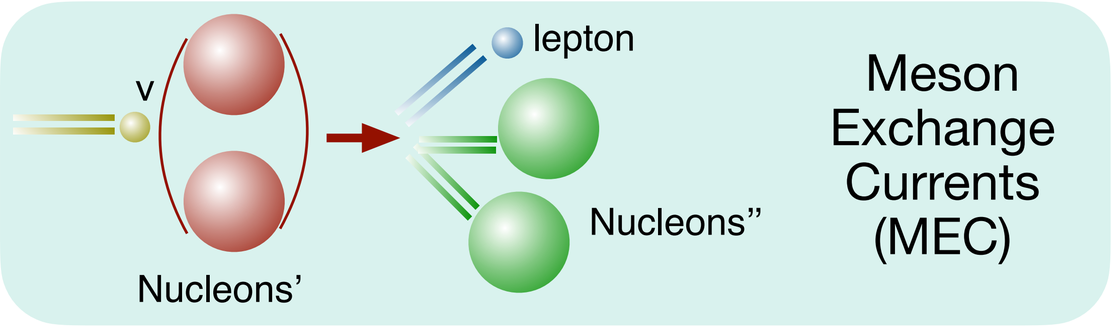
Neutrino interactions at the few-GeV region

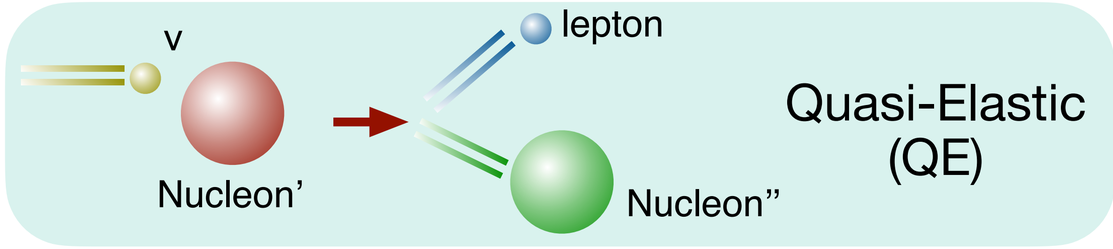
These interactions happen inside the nuclear media.

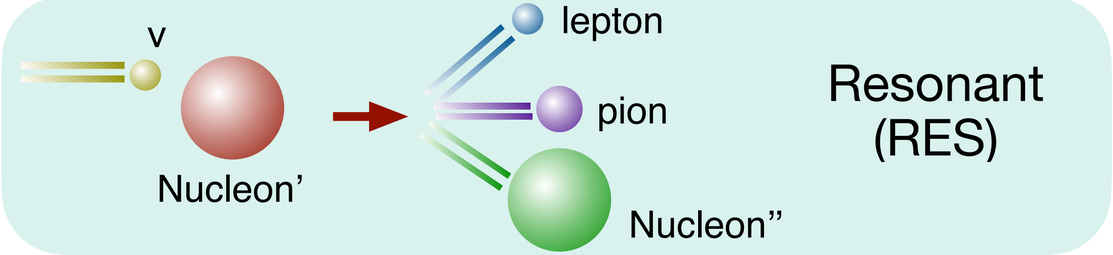
nuclear physics is important (and hard).

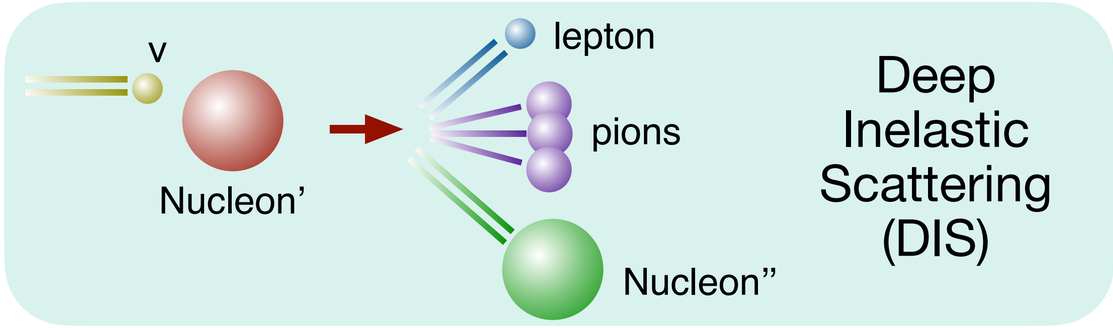
The theory to describe this process is incomplete. Models are still under construction.











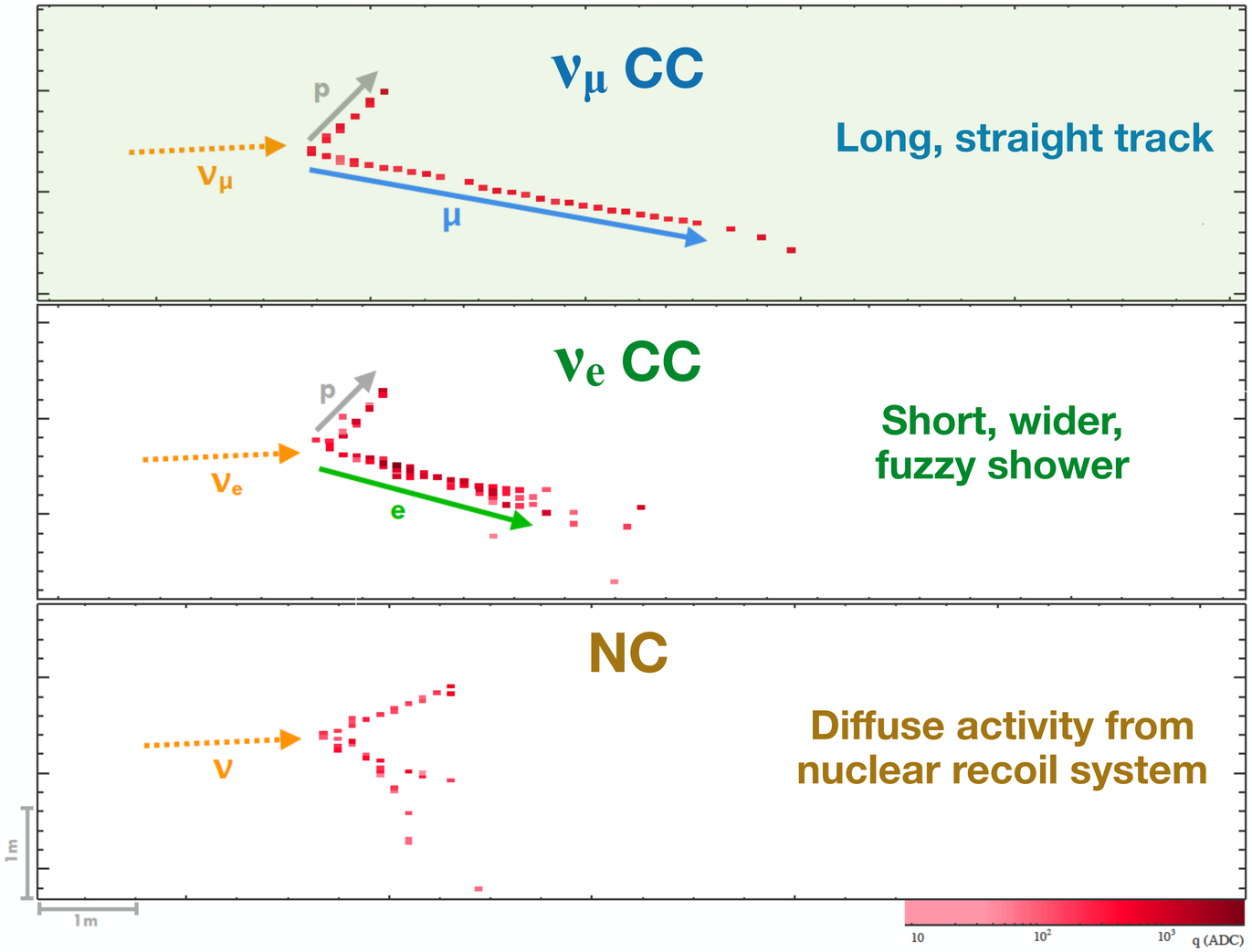
Neutrino cross-section measurements at NOvA

Energy range

Detector technology

Statistics

} Unique environment for cross-section measurements



Neutrino cross-section measurements at NOvA

Energy range
Detector technology
Statistics

} Unique environment for cross-section measurements

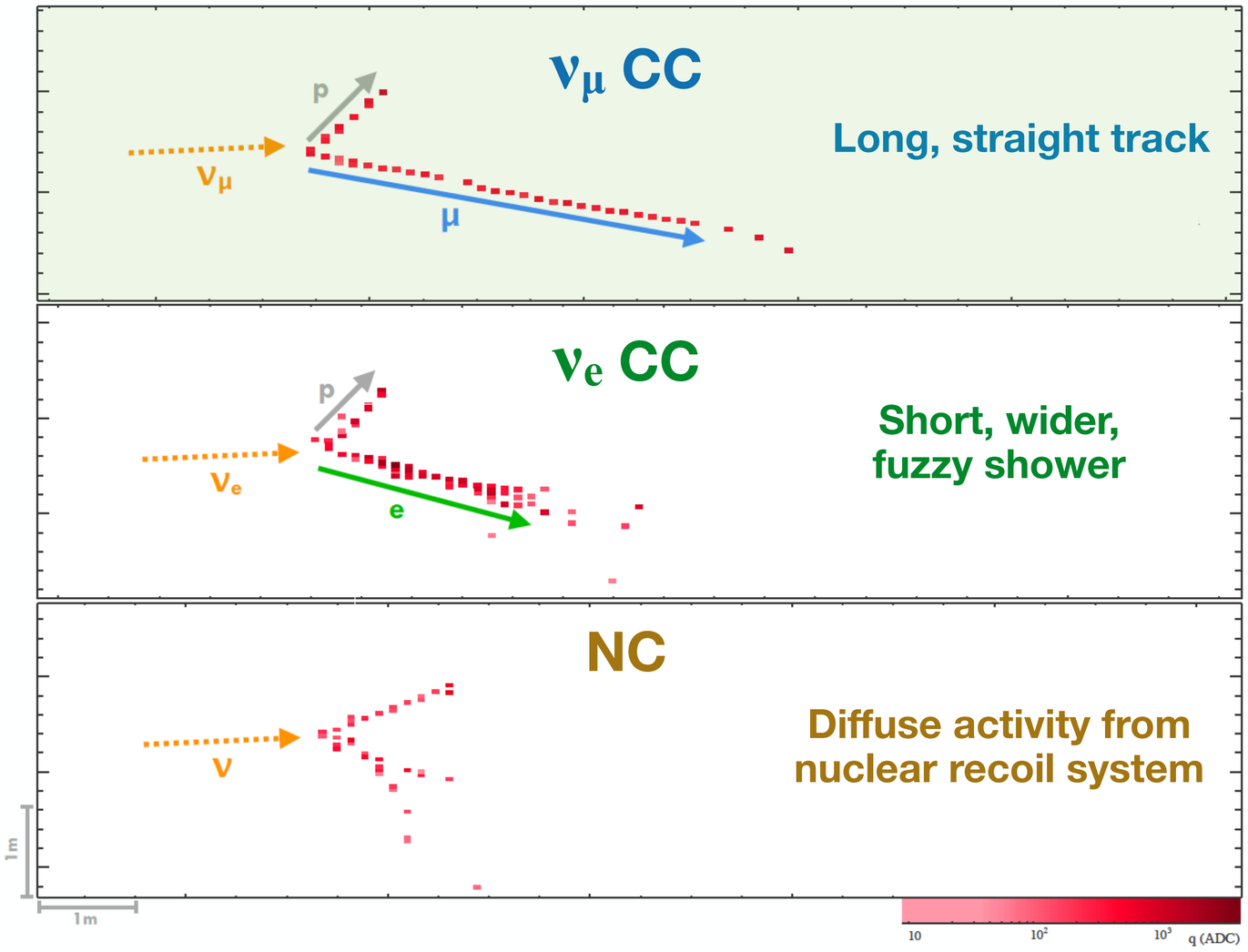
This talk

ν_μ - CC Inclusive

ν_μ - CC with low hadronic activity

See also next talk

Interactions with electromagnetic shower in the NOvA ND (B. Ramson)



NOvA Simulation

$$\frac{d\sigma}{dx_i} = \frac{\sum_j U_{ij}^{-1}(N_j^{\mathrm{sel}} \times P_j)}{\epsilon_i N_{\mathrm{T}} \ \Phi \ \Delta x_i}$$

We rely on simulations for optimizing the **selection**, applying **corrections for the background**, **smearing** and **efficiency** and for the **flux normalization**.

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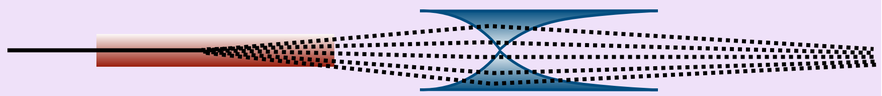
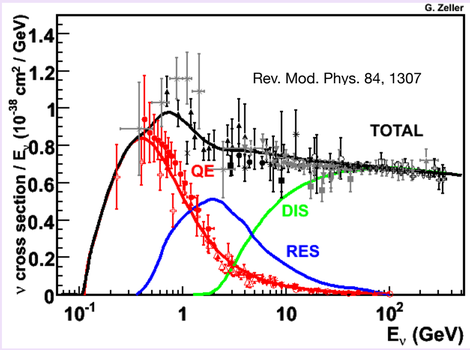
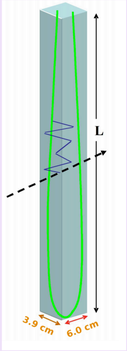


Beamline and Flux: G4NuMI

ν-A modelling: GENIE



Detector response: GEANT4



Readout electronics & DAQ: Custom simulation routines

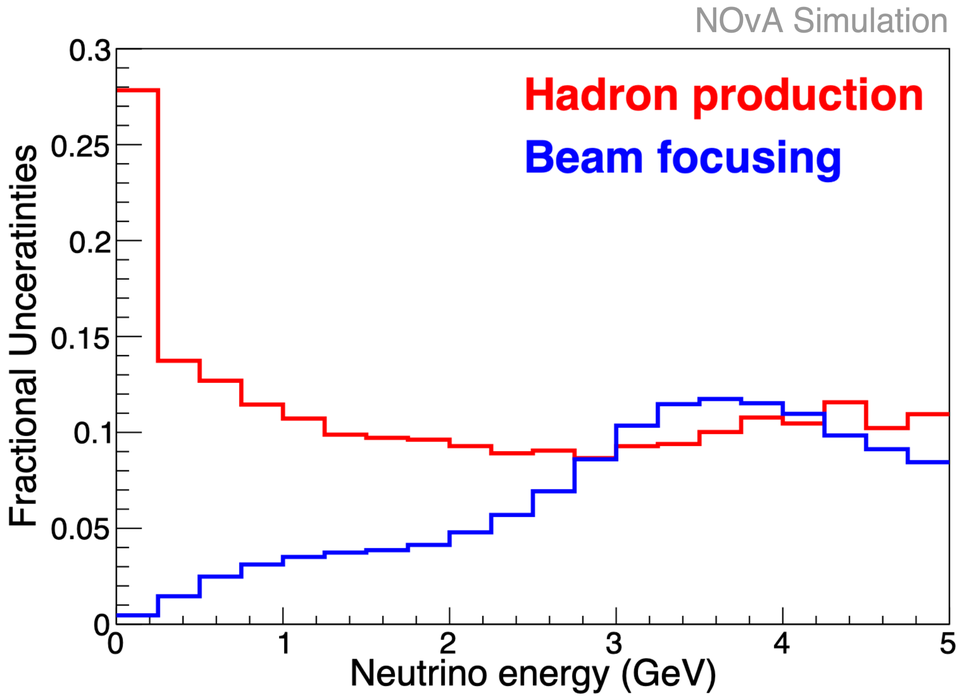
NuMI beam prediction

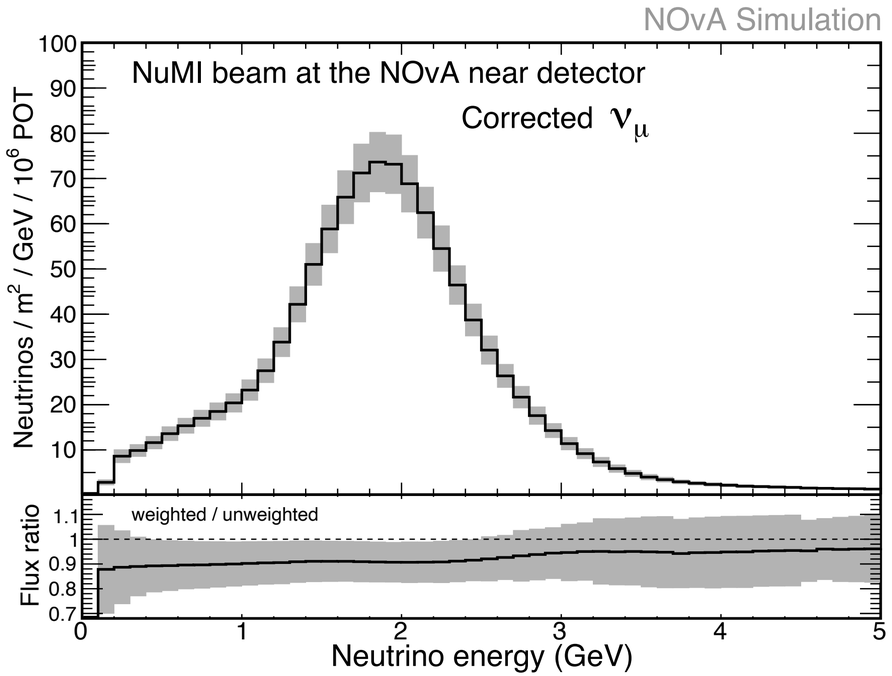
Hadron production model is constrained with external measurements on thin target data (NA49)

» *Same technique developed by **MINERvA** (Phys. Rev. D94, 092005)*

» *The uncertainty based on these external measurements results in a **~10% normalization uncertainty***

Beam focusing uncertainty is sub-dominant around the peak (below 2.5 GeV)





The NOvA 2019 GENIE Tune

- We use NOvA and external data to tune interaction model.
- These analyses use GENIE 2.12.2

» Correct QE to account for low Q^2 suppression.

» Apply low Q^2 suppression to Res baryon production.

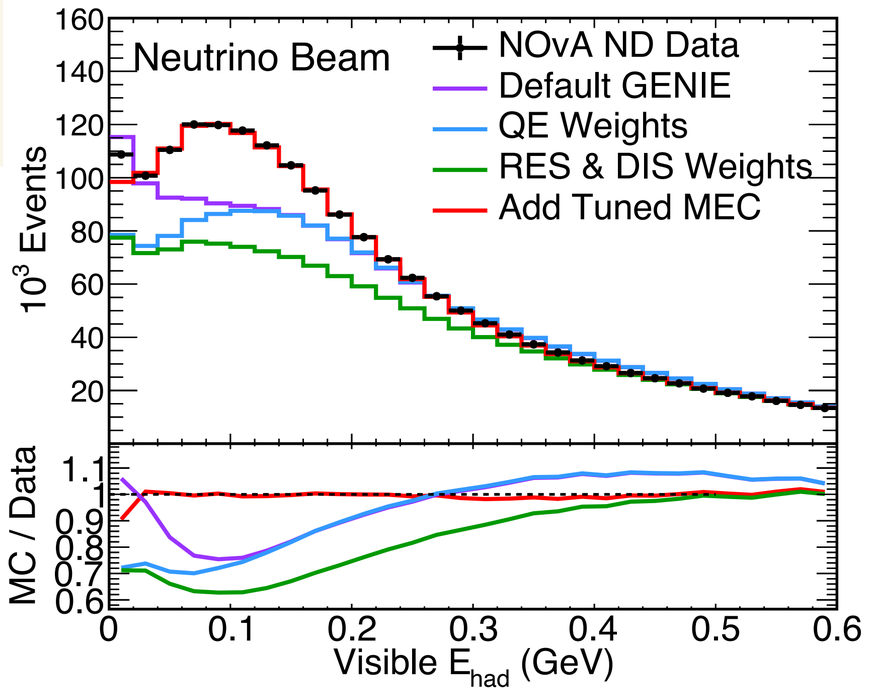
» Non resonant inelastic scattering (DIS) at W>1.7 GeV/c^2) weighted up 10% based on NOvA data.

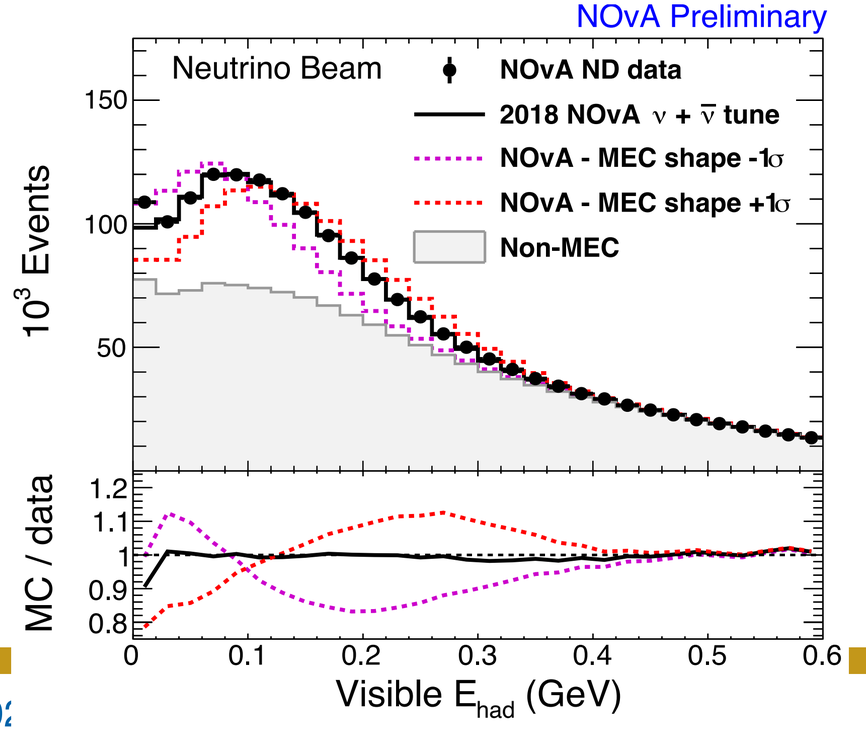
» "Empirical MEC" based on NOvA ND data to account for multi-nucleon knockout (2p2h).

Same tune that was used in the NOvA 2019 analysis

Eur. Phys. J. C 80, 1119 (2020)

Our analyses are constructed to be insensitive to this tuning

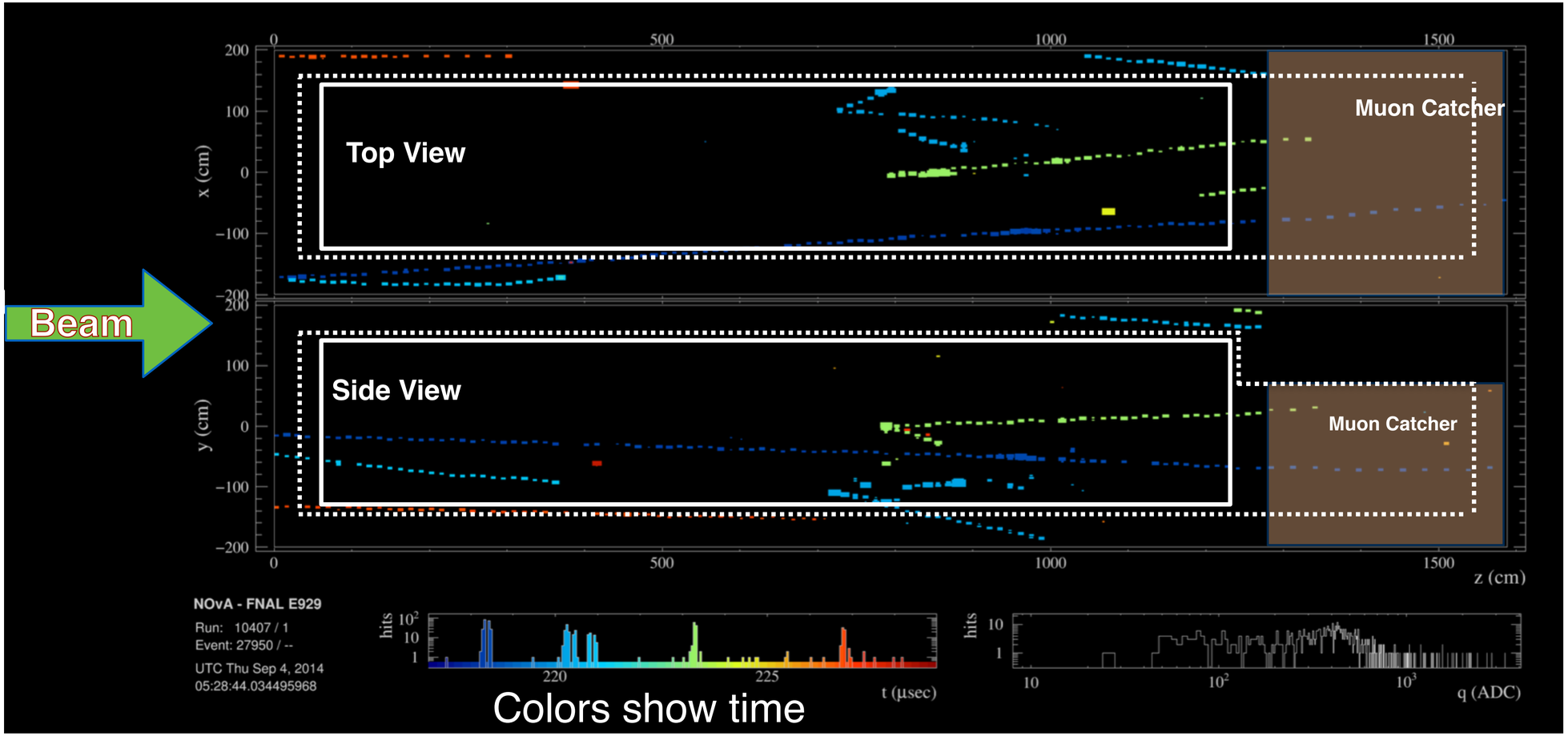




ν_μ - CC Inclusive

Containment and fiducial

Muon candidates should be contained in the **active region + Muon Catcher** and any other track only in the active region to avoid shower leaking.

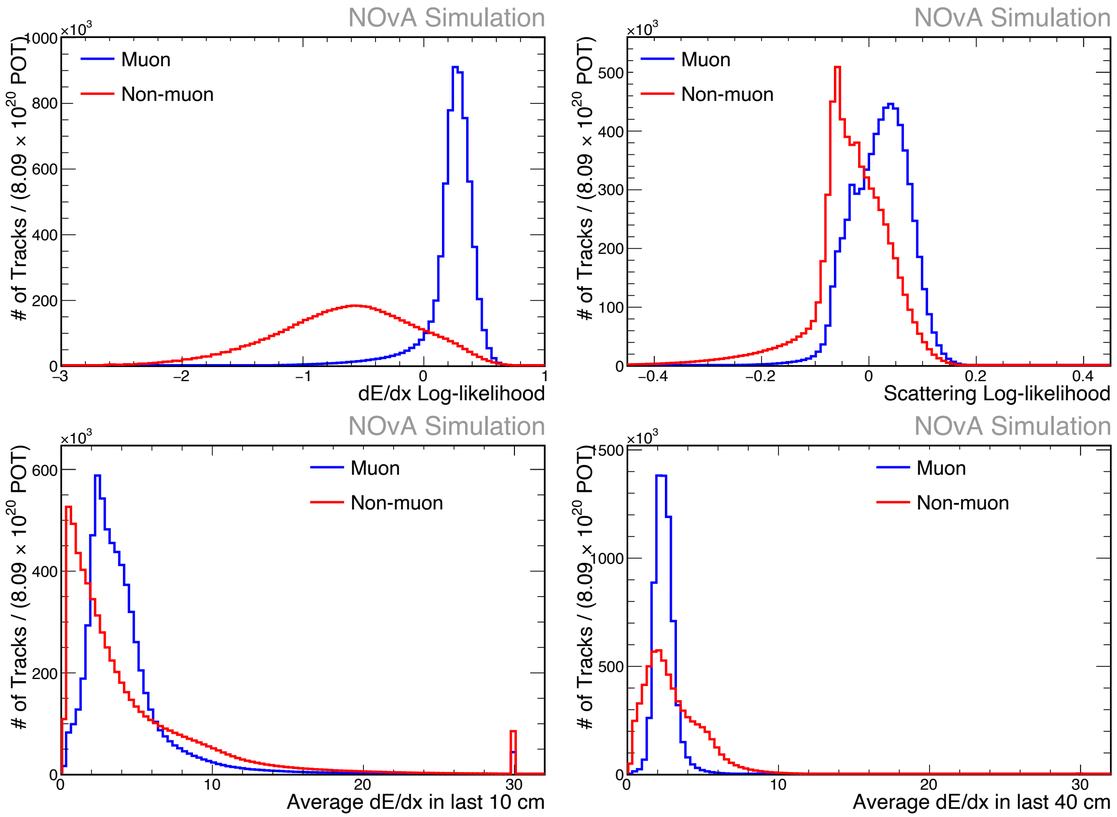


- These **preselection criteria select 23% of signal events**

Vertices should be inside a **fully active** (fiducial) region to cut rock muons

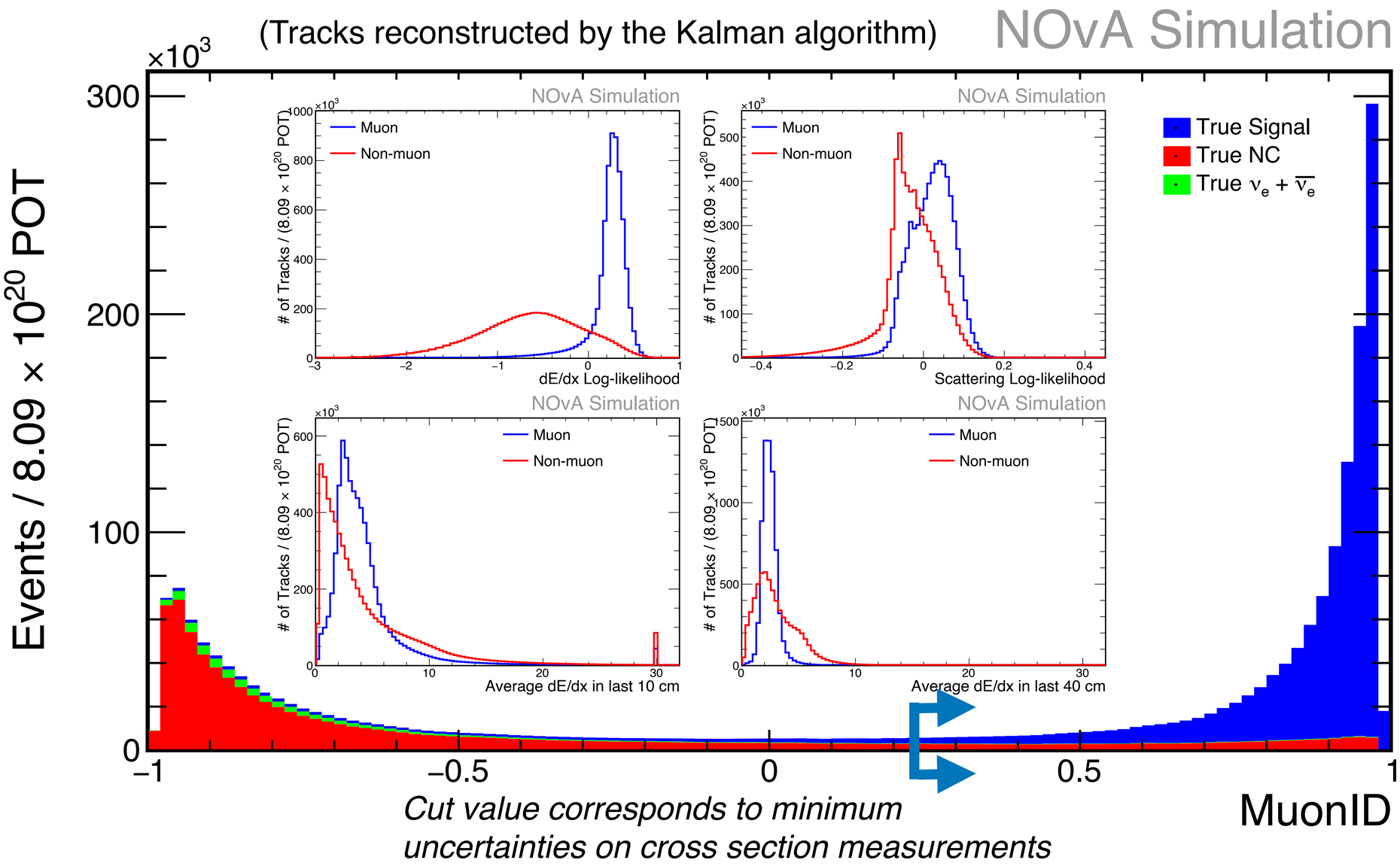
Muon identification

(Tracks reconstructed by the Kalman algorithm)



- **Preselection**: events fully contained and with vertex in fiducial volume.
- **Muon ID** calculated with a Boosted Decision Tree

Muon identification



Cut value corresponds to minimum uncertainties on cross section measurements

- **Preselection**: events fully contained and with vertex in fiducial volume.
- **Muon ID** calculated with a Boosted Decision Tree.
- Cut value corresponds to **minimum uncertainties on cross section** measurement.
- Sample has **97% purity** and **~98% efficiency** with respect to preselection.

ν_μ CC Inclusive

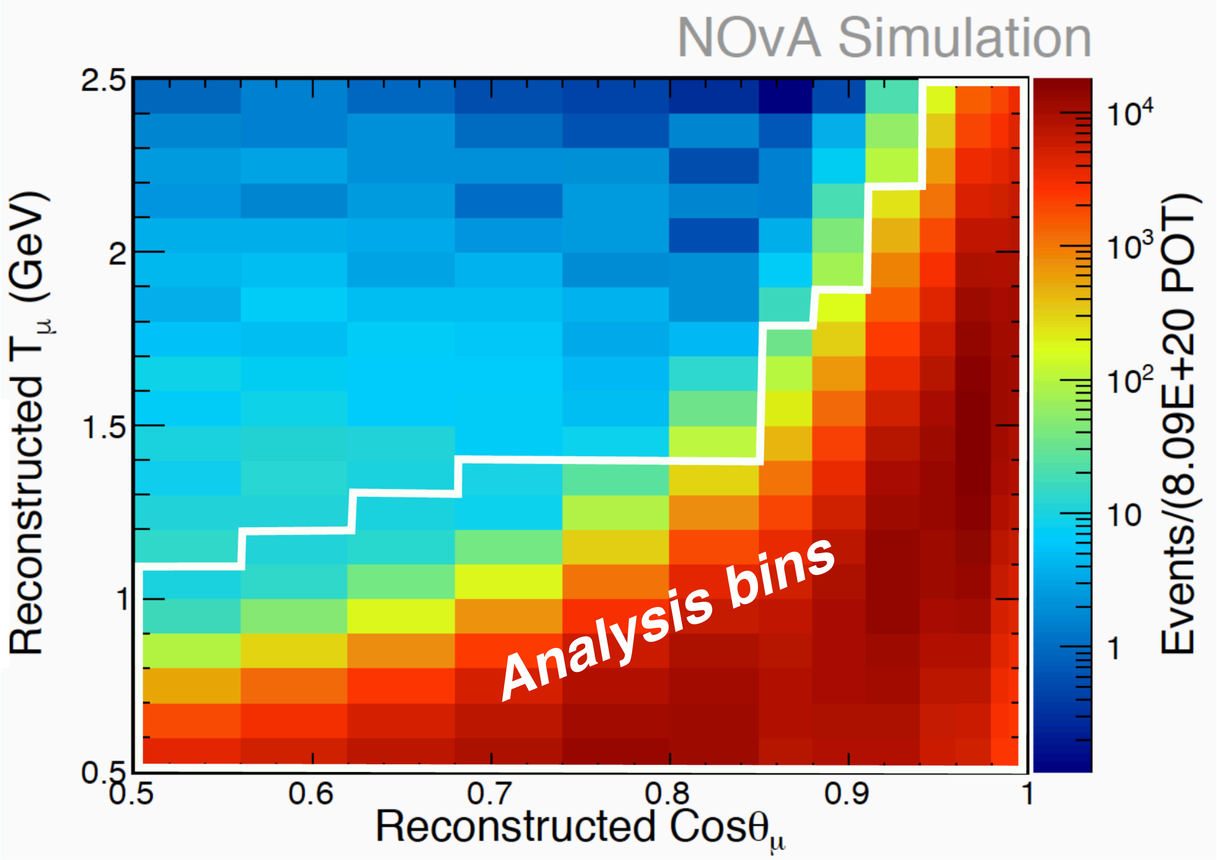
$$\left(\frac{d^2\sigma}{d\cos\theta_\mu dT_\mu}\right)_i = \sum_k \left(\frac{\sum_j U^{-1}_{ijk}(N^{\mathrm{sel}}(\cos\theta_\mu, T_\mu, E_{\mathrm{avail}})_j P(\cos\theta_\mu, T_\mu, E_{\mathrm{avail}})_j)}{N_{\mathrm{t}}\Phi\epsilon(\cos\theta_\mu, T_\mu, E_{\mathrm{avail}})_{ik}\Delta\cos\theta_{\mu_i}\Delta T_{\mu_i}}\right)$$

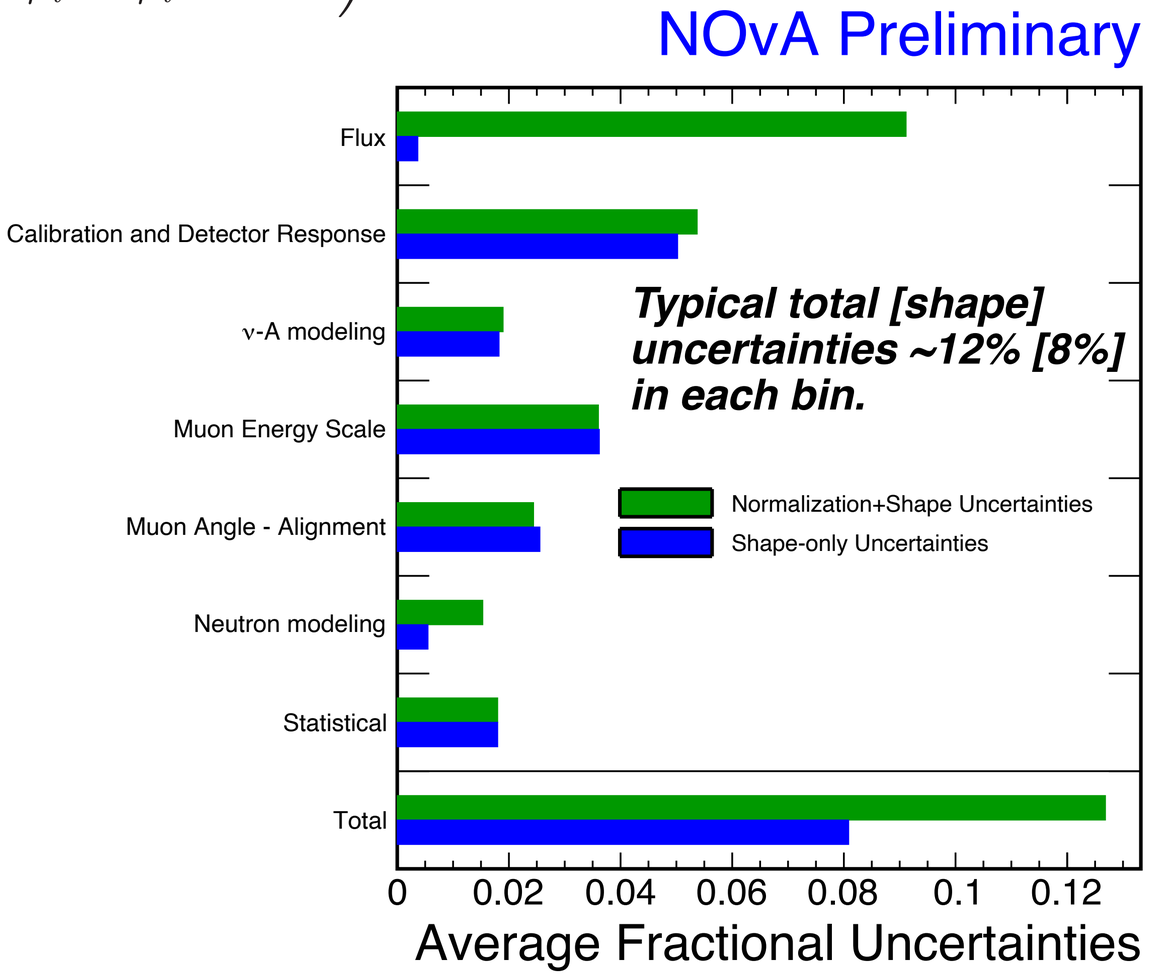
***E_{avail}**: total energy of all observable final state hadrons*

*Analysis is done in (T_μ, $\cos\theta_\mu$, E_{avail}) and then projected to **muon kinematics***

ν_μ CC Inclusive

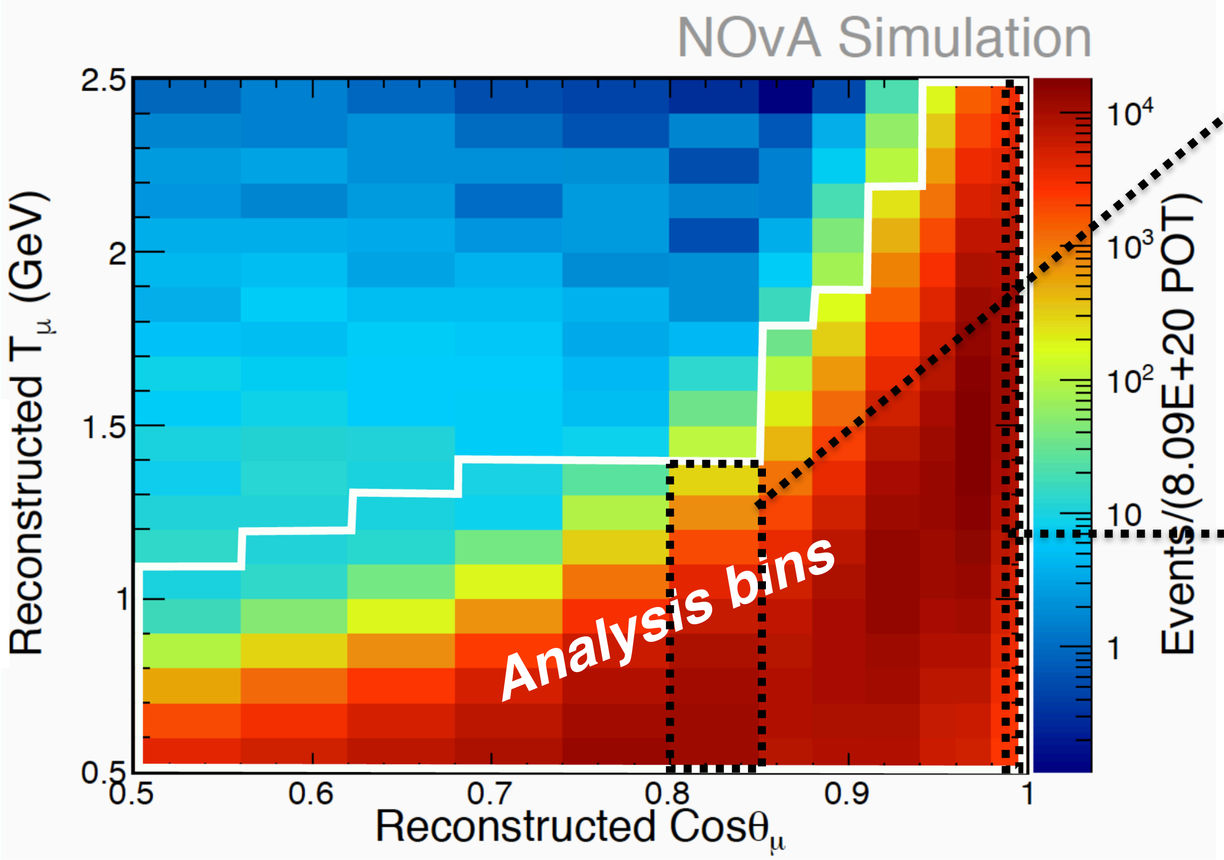
$$\left(\frac{d^2\sigma}{d\cos\theta_\mu dT_\mu}\right)_i = \sum_k \left(\frac{\sum_j U^{-1}_{ijk}(N^{\rm sel}(\cos\theta_\mu, T_\mu, E_{\rm avail})_j P(\cos\theta_\mu, T_\mu, E_{\rm avail})_j)}{N_{\rm t}\Phi\epsilon(\cos\theta_\mu, T_\mu, E_{\rm avail})_{ik}\Delta\cos\theta_{\mu_i}\Delta T_{\mu_i}}\right)$$



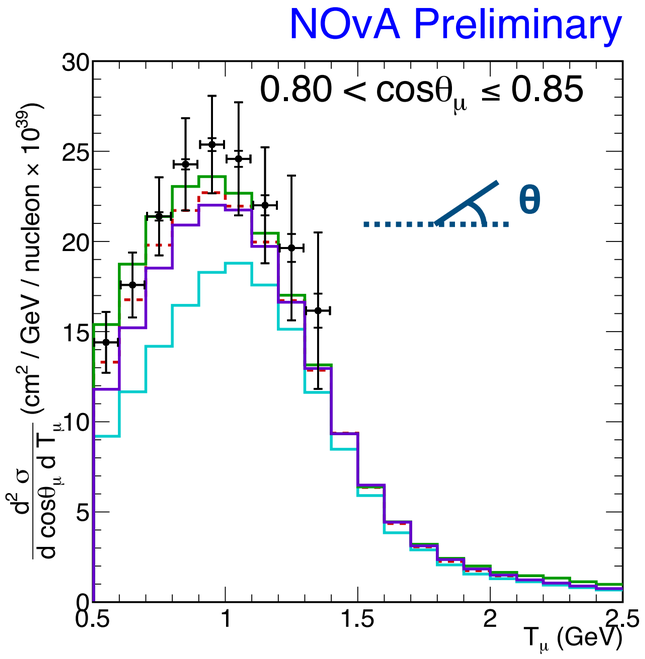


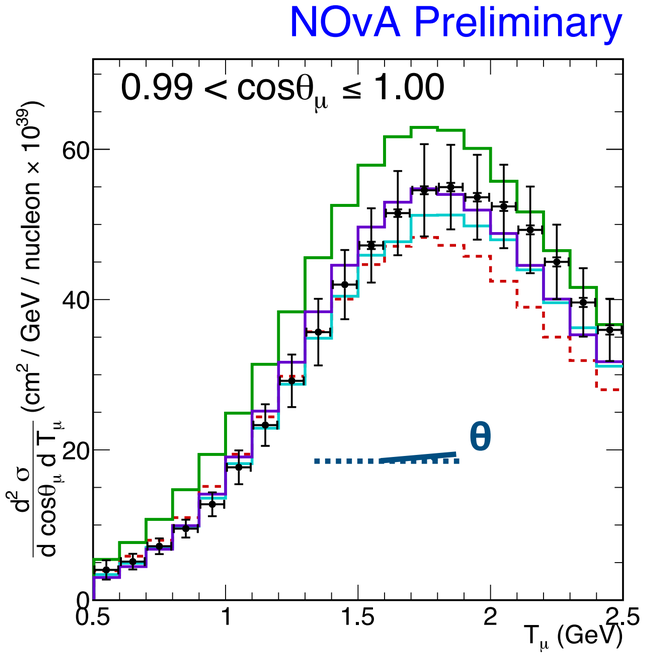
ν_μ CC Inclusive: Example of 2 cosine slices

Draft publication is under Collaboration review



Presented in Fermilab JETP Seminar, July, 2020





- Data (Stat. + Syst.)
- GENIE 3.00.06*
- GiBUU 2019
- NEUT 5.4.0
- NuWro 2019

» Out of the box generator comparisons.

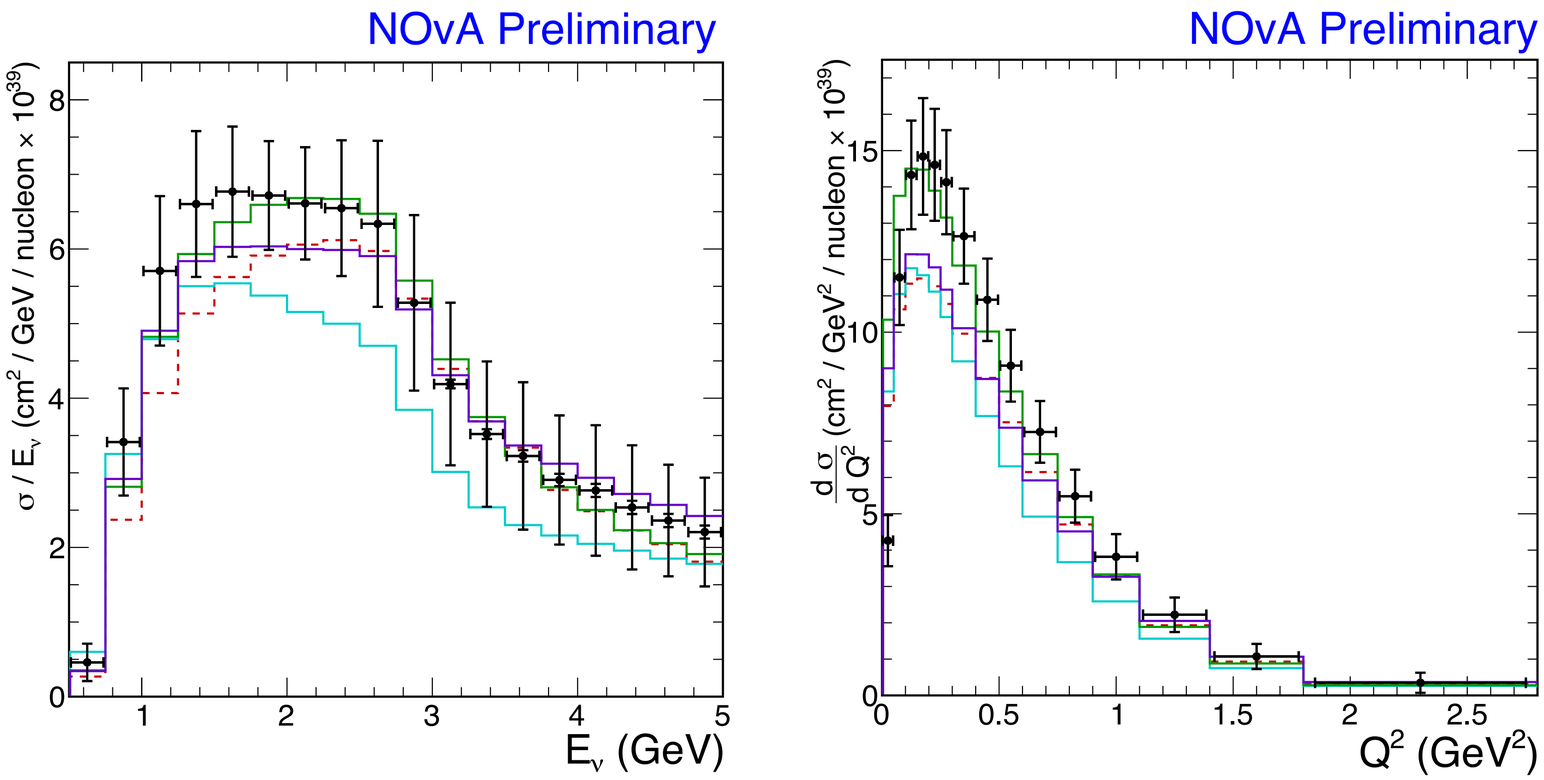
» All generators reproduce well the shape of our data.

» We notice an overall normalization difference in GiBUU.

***N18_10j_02_11a:** G18_10j_00_000 and G18_10b_02_11a

ν_μ CC Inclusive: E_ν and Q^2

Draft publication is under Collaboration review



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» E_ν and Q^2 are extracted only over the range of muon kinematics reported in the differential measurements.

» Good agreement between data and predictions for E_ν

» We observe a low Q^2 suppression that is not well modeled by any generator

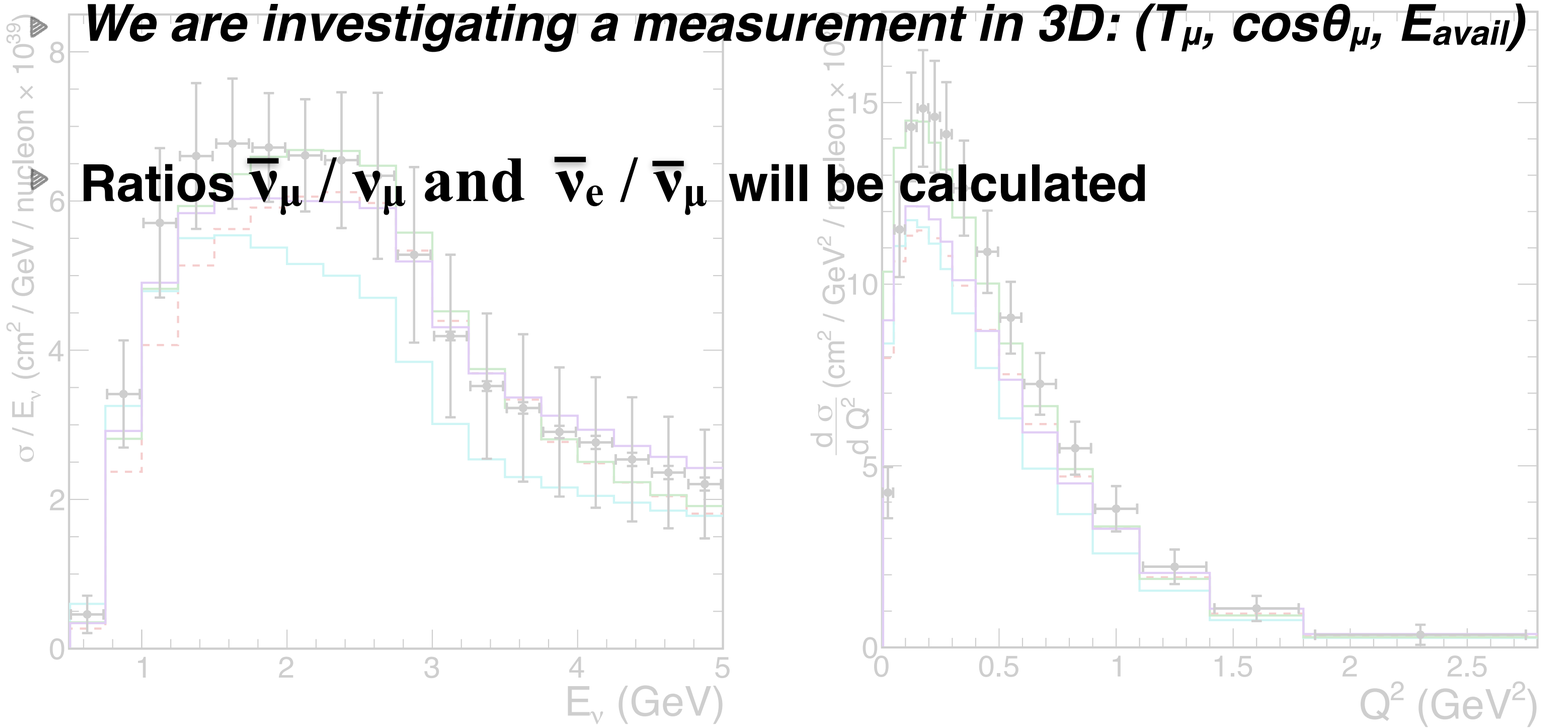
Presented in Fermilab JETP Seminar, July, 2020

***N18_10j_02_11a:**
G18_10j_00_000 and G18_10b_02_11a

$\bar{\nu}_\mu$ CC Inclusive

Draft publication is under Collaboration review

- ***Analysis is similar to the muon-neutrino***
- ***We are investigating a measurement in 3D: (T_μ, $\cos\theta_\mu$, E_{avail})***
- **Ratios $\bar{\nu}_\mu$ / ν_μ and $\bar{\nu}_e$ / $\bar{\nu}_\mu$ will be calculated**



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*N18_10j_02_11a:
G18_10j_00_000 and G18_10b_02_11a

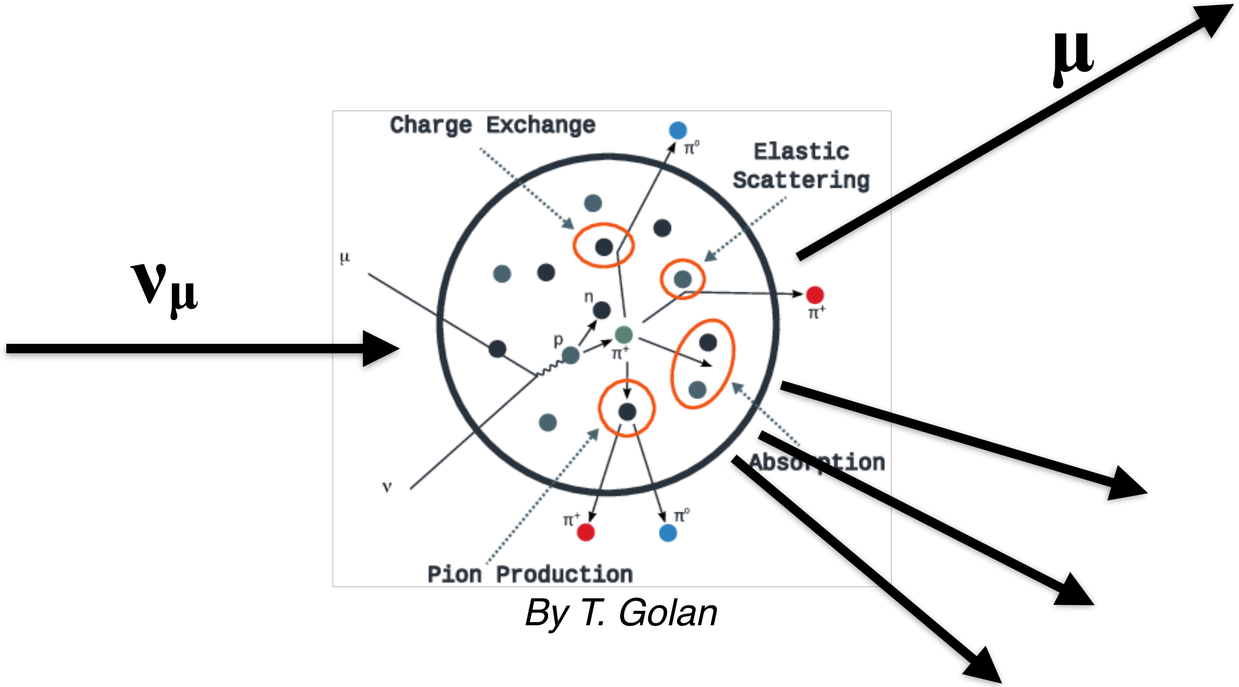
Presented in Fermilab JETP Seminar, July, 2020

Beyond the inclusive measurements

I showed the status of the inclusive CC cross sections in NOvA

$$\sigma_{\mathrm{CC}}^{\mathrm{inclusive}}(E_\nu) = \sigma_{\mathrm{CC}}^{\mathrm{QE}} + \sigma_{\mathrm{CC}}^{\mathrm{MEC}} + \sigma_{\mathrm{CC}}^{\mathrm{Res}} + \sigma_{\mathrm{CC}}^{\mathrm{DIS}} + \sigma_{\mathrm{CC}}^{\mathrm{Coh}}$$

NOvA is actively working on different exclusive channels with neutrino and antineutrino for CC and NC



By T. Golan

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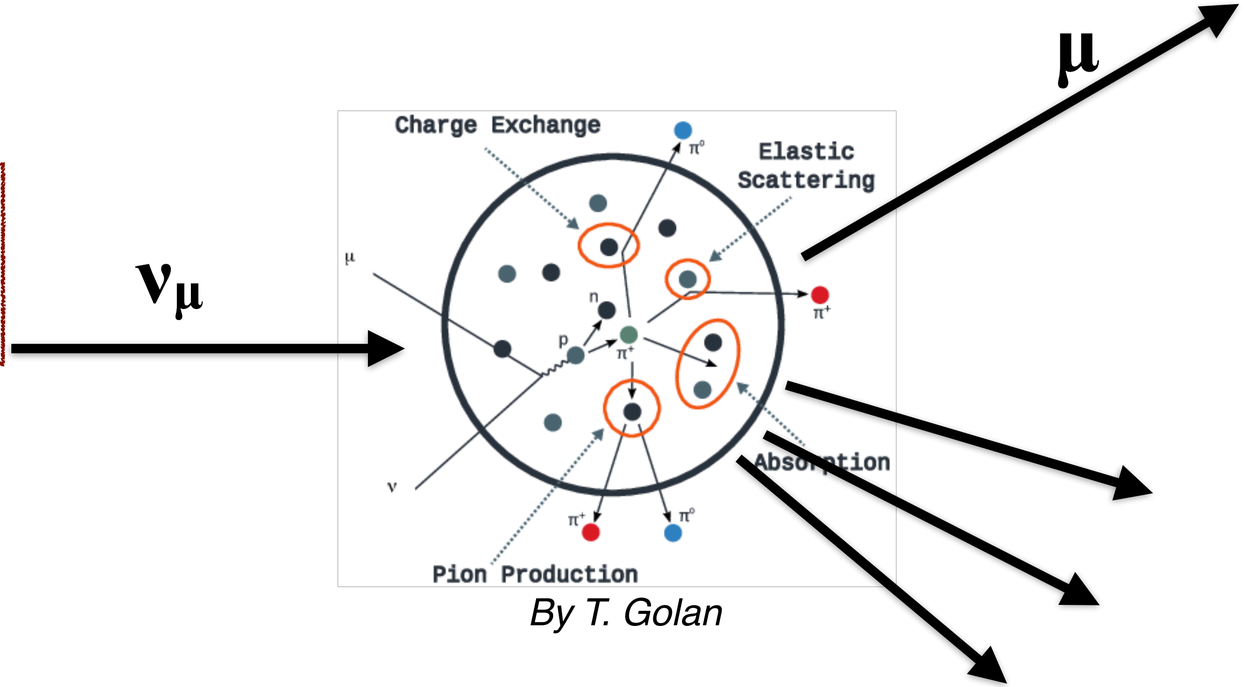
NOvA is actively working on different exclusive channels with neutrino and antineutrino for CC and NC

There are two areas of analyses:

- **ν_μ-CC with low hadronic activity (ν_μ-CC low-had):** suitable for nuclear effect studies

- Different channels of semi in[ex]clusive neutral and charged **pion / pion-less / proton** production for CC and NC



By T. Golan

ν_μ - CC with low hadronic activity

ν_μ-CC low-had: why is this measurement interesting?

It is sensitive to MEC contributions

It characterizes neutrino interactions with pion and proton with low kinetic energies

We plan to measure

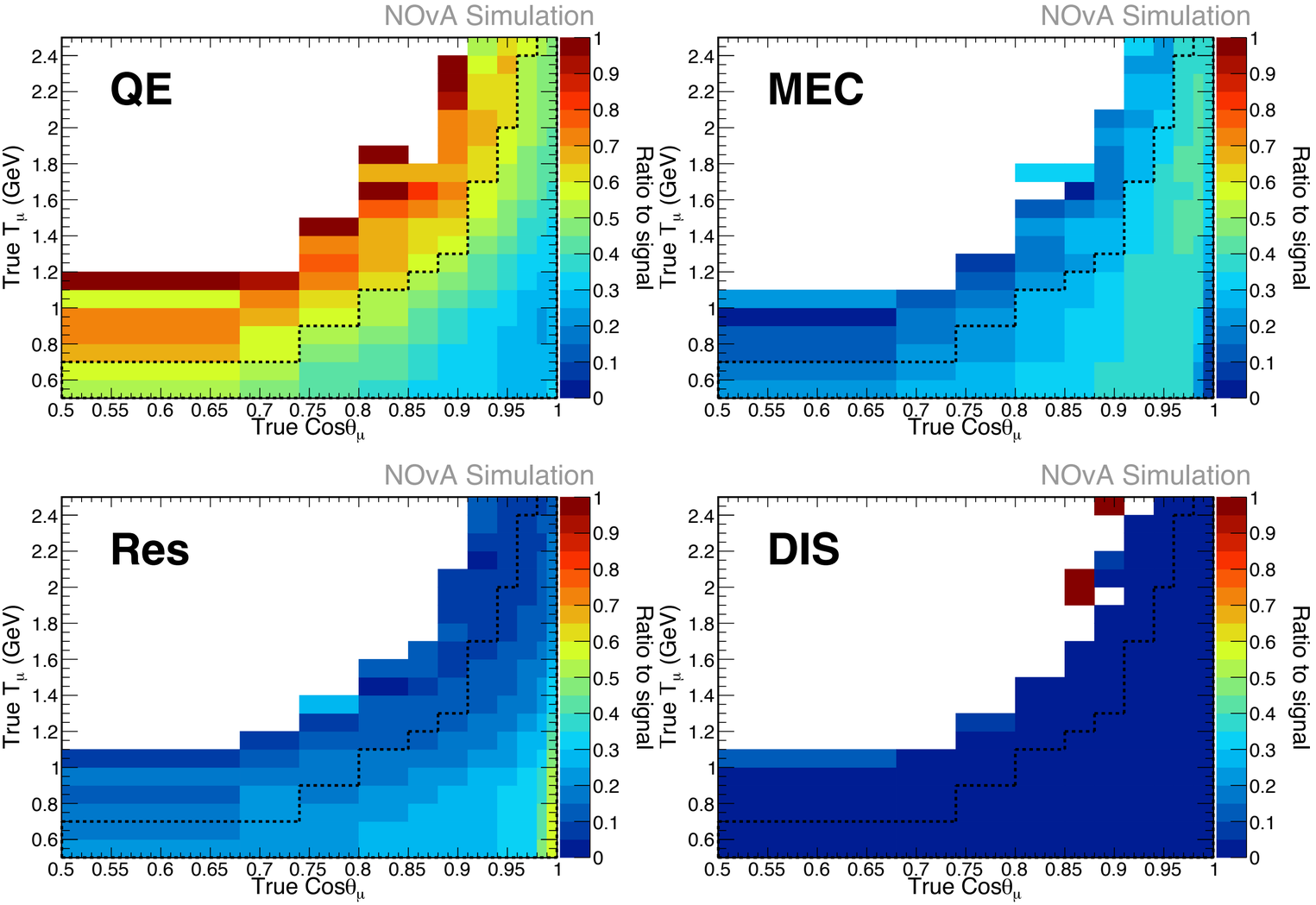
» Cross sections of ν_μ - CC interactions with low hadronic activity in 2D: ($\cos\theta_\mu$, T_μ)

- *Total and shape comparison of measurements with generators*
- *Close examination to the phase space regions that are sensitive to MEC*

» Additionally, we want to test nuclear effects by comparing E_ν^{QE} *(assuming QE interactions and using muon kinematics) vs* E_ν^{Cal} (using calorimetry on all detected particles)

ν_μ-CC low-had: interaction modes

Fraction of interactions to total selected events

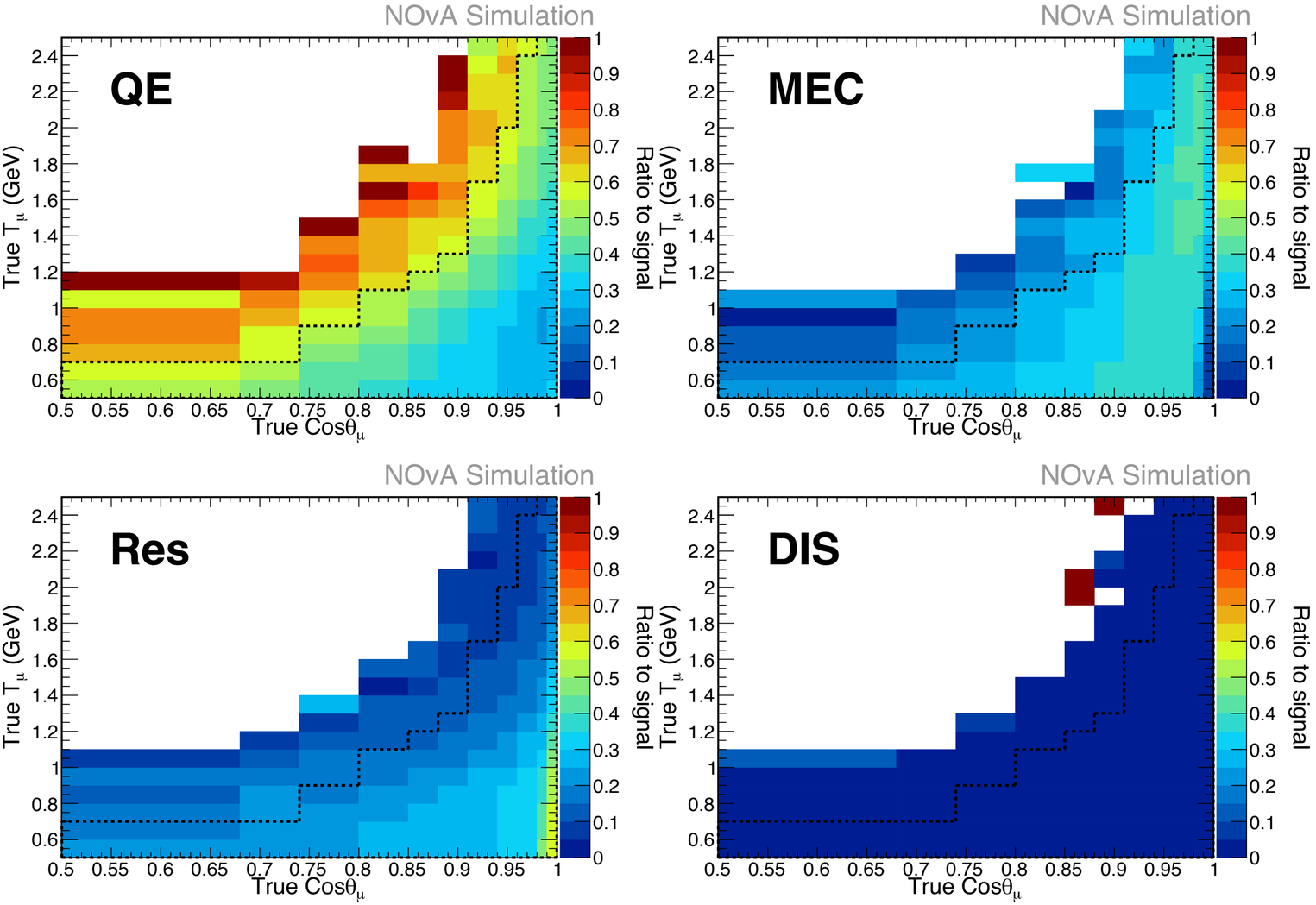


Selection: ***ν_μ CC with 1 track***

QE	MEC	Res	DIS	COH
39.7%	33.7%	23.0%	2.5%	1.1%

ν_μ-CC low-had: interaction modes

Fraction of interactions to total selected events



Selection: ***ν_μ CC with 1 track***

QE	MEC	Res	DIS	COH
39.7%	33.7%	23.0%	2.5%	1.1%

Low hadronic activity is defined by finding the minimum uncertainty on the total cross section:

Signal: ***ν_μ CC*** *with*
T_{proton}^{max} = 250 MeV, T_{pion}^{max} = 175 MeV

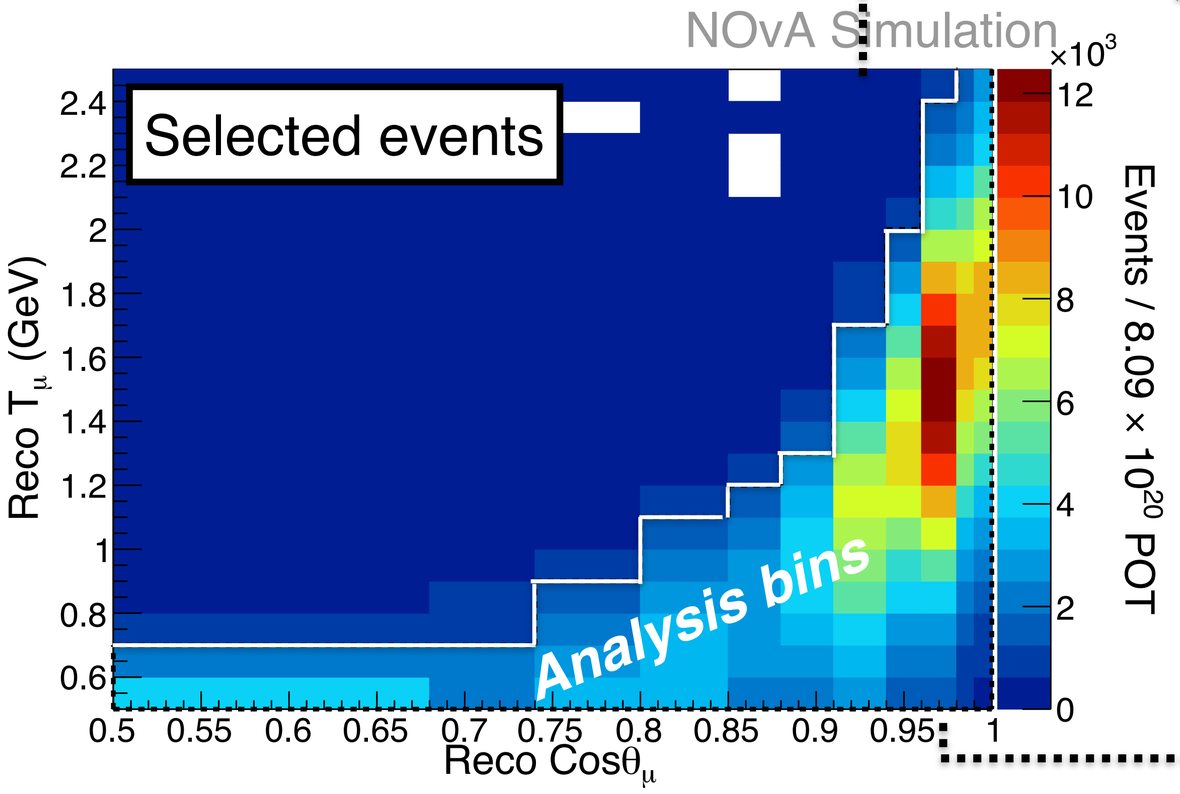
Purity is > 80% in most of the analysis bins

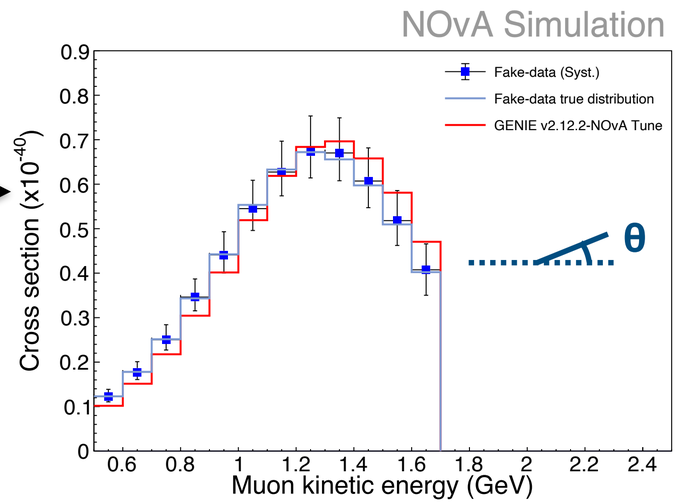
Cross section using mock-data

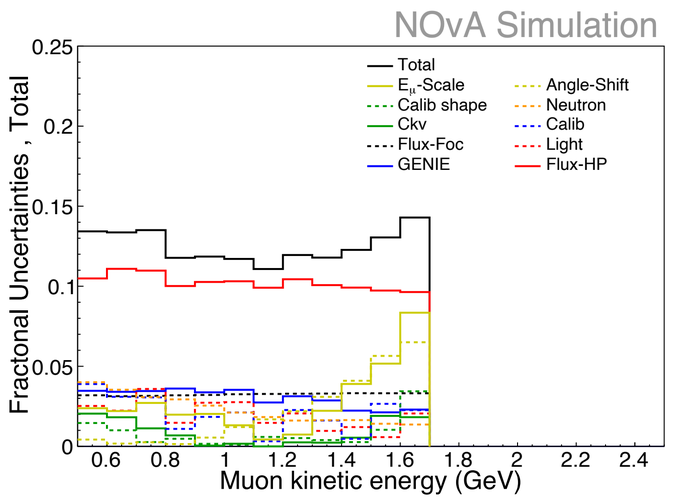
» The expected uncertainties are small enough to make cross-section measurements

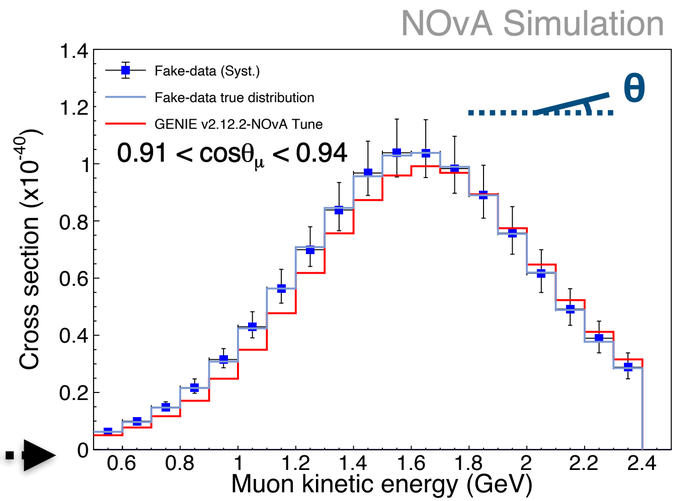
» The full analysis chain has been built

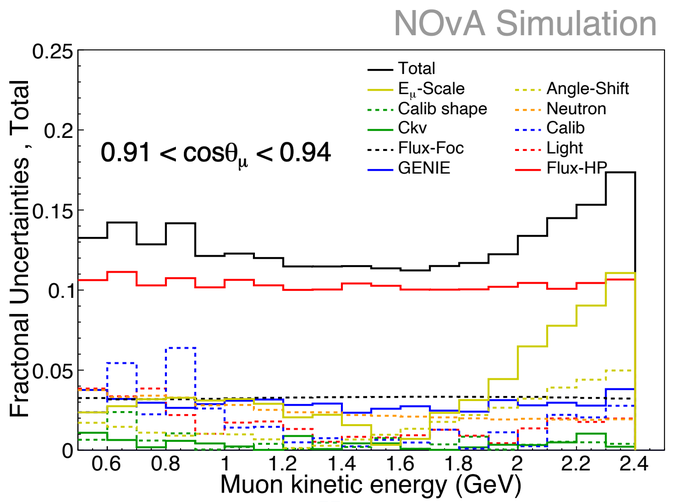
Analysis is currently under Collaboration review











Summary and conclusions

» The NOvA experiment has an excellent opportunity to make a high precision and a broad set of neutrino-nucleus cross-section measurements

» This talk showed:

- ν_μ - CC Inclusive was recently presented and the publication will follow soon
- ν_μ - CC with low hadronic activity is actively being analyzed and we expect results in a short term

» ν_e - CC and exclusive CC and NC channels including pion final states measurements have quick progress

Stay tuned !

Thank you!

MAY 2020

Backup

Available energy and interaction modes