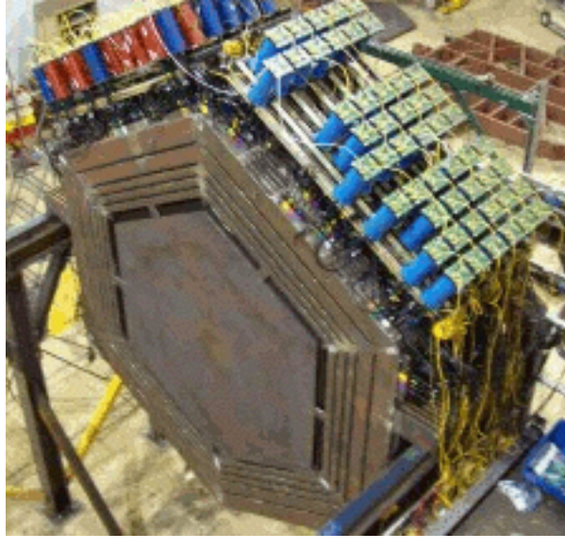


MINER*ν*A Experiment

Jiyeon Han (Univ. of Pittsburgh)
on behalf of MINER*ν*A Collaboration

8 June 2017 / 50th Annual Fermilab User's Meeting

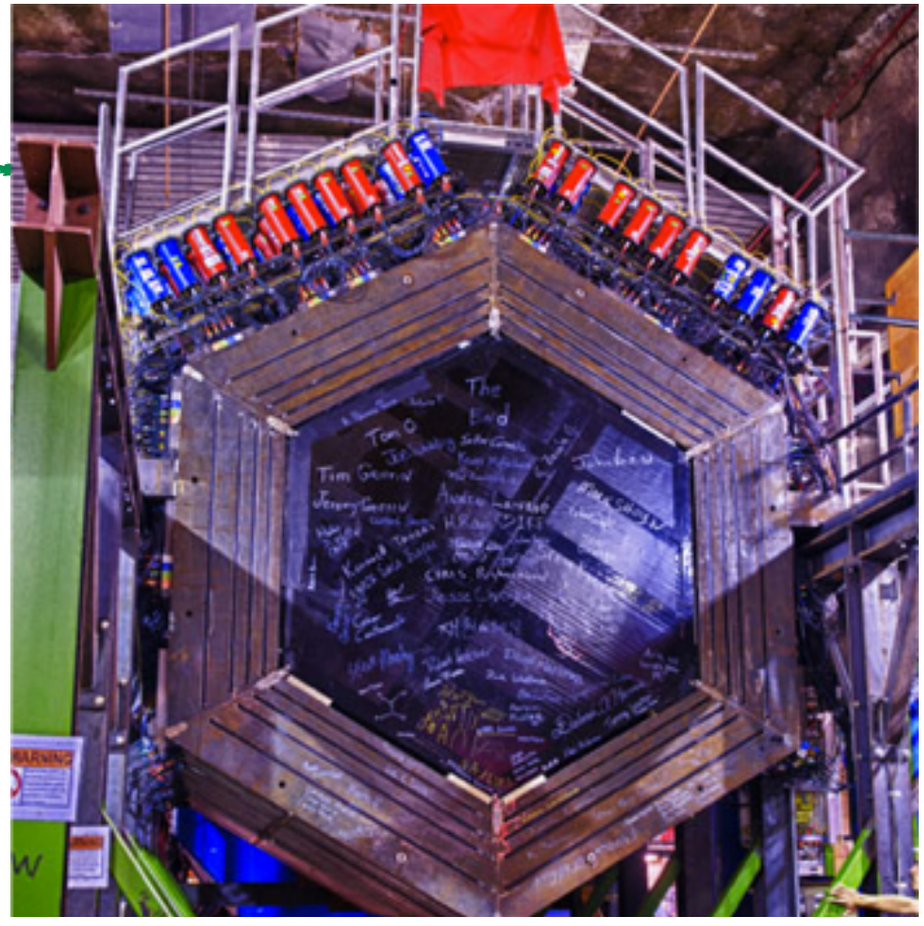
MINERvA Experiment

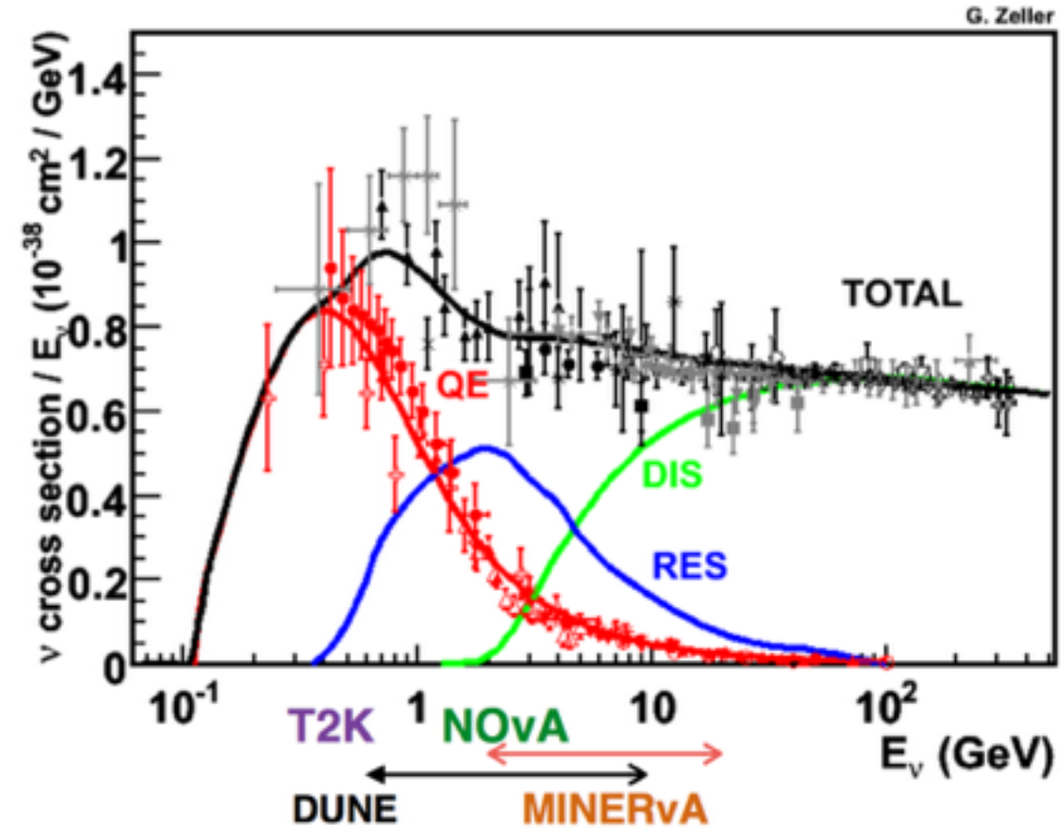
- Scintillator-based detector in on-axis NuMI beam
- MINERvA experiment was designed to perform high-precision measurements of neutrino interactions on a wide variety of materials
- High precision measurement of neutrino interactions in E_ν = 1 ~10 GeV

⇒ *Useful inputs for neutrino oscillation measurements (ν_μ disappearance, ν_e appearance)*

- Study of nuclear effect via measurements on many nuclei in the same beam
- Probe the structure of proton/neutron and the strong force dynamics that affects neutrino-nucleon interactions

⇒ *Important to improve modeling in generators*



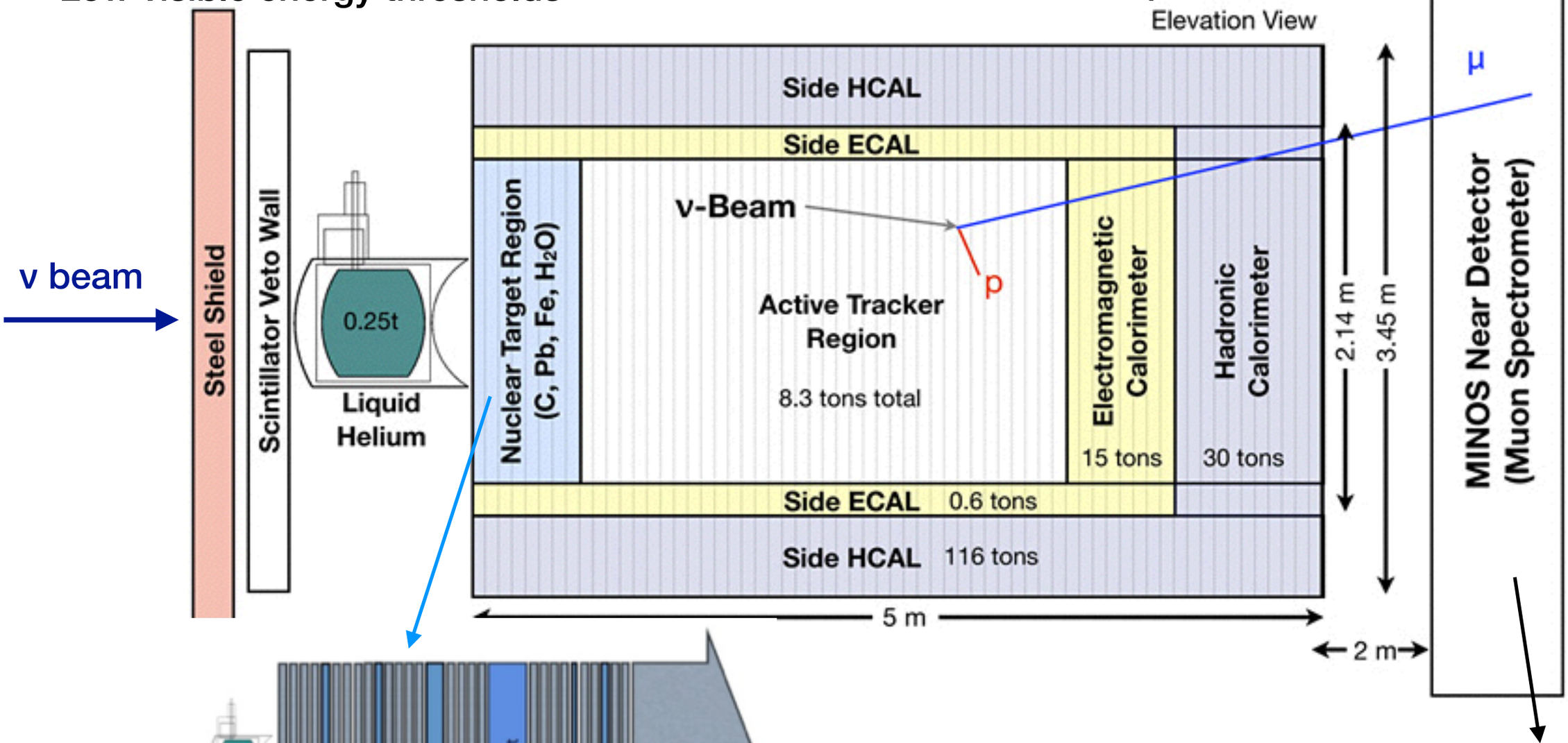


J.A. Formaggio, G. Zeller, Reviews of Modern Physics, 84 (2012)

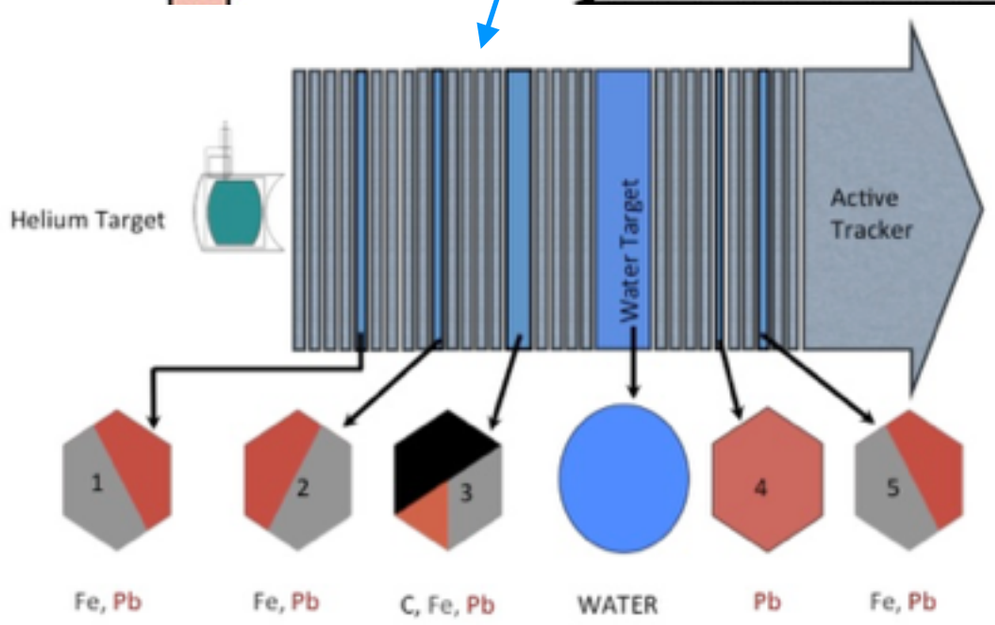
MINERvA Detector

Solid Scintillator Tracker :
Measure track, Particle ID, calorimetric E
Low visible energy thresholds

ECAL, HCAL :
Measure energy deposit from EM/hadronic particle



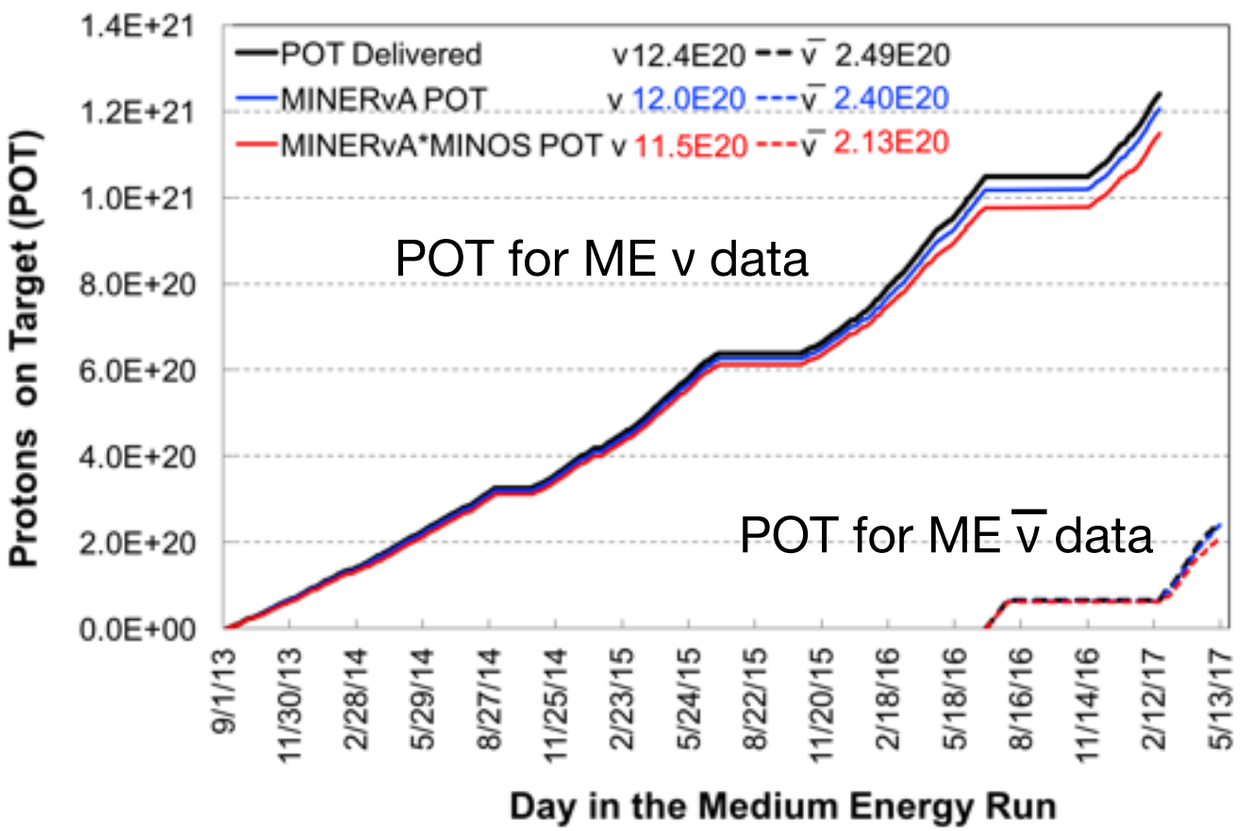
MINOS detector :
Determine muon charge / momentum

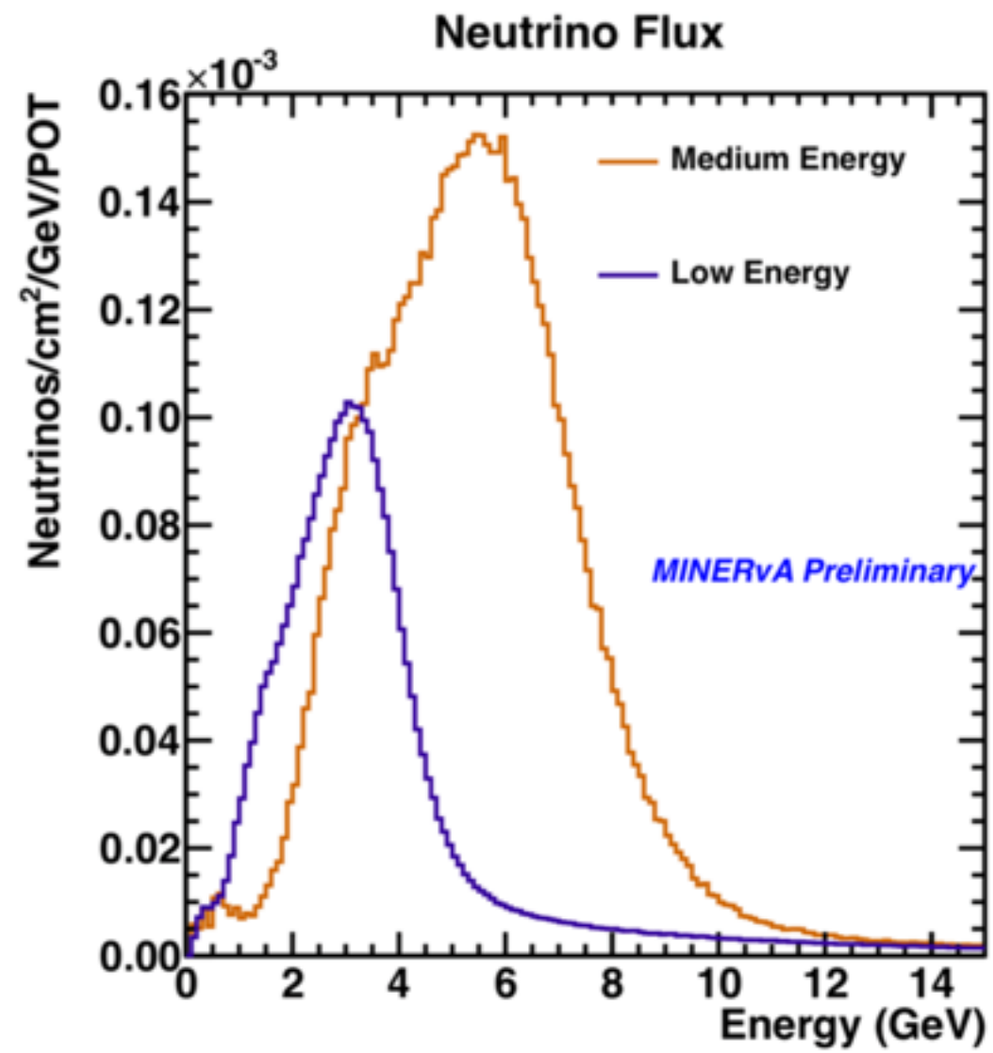


Various Nuclear Targets :
Pure C, Fe, Pb, Liquid Helium, water used
Allow measurement on different nuclei

Neutrino Beam in Medium Energy

- Medium energy (ME) ν data taking since 2013, started $\bar{\nu}$ data on Feb, 20, 2017





LE beam power : 250kW, 3.98×10^{20} POT

ME beam power : 650kW, 1.22×10^{21} POT

⇒ ME data provides a high statistics data sample for DIS analysis

ME data has ~3 times more POT

It covers higher neutrino energy region

Physics program since last year

- **Publication in 2016 ~ 2017** :
  - "Direct Measurement of Nuclear Dependence of Charged Current Quasielastic-like Neutrino Interactions using MINERvA", arXiv:1705.03791
  - **"Measurement of the antineutrino to neutrino charged-current interaction cross section ratio in MINERvA", PRD 95, 072009 (2017)**
  - "Measurement of Neutral-current K+ production by neutrinos using MINERvA", submitted to Phys. Rev. L
  - "Measurements of the inclusive Neutrino and Antineutrino Charged Current Cross Sections in MINERvA using the Low-ν Flux Method", Phys. Rev. D 94, 112007 (2016)
  - "Measurement of Partonic Nuclear Effects in Deep Inelastic Neutrino Scattering using MINERvA", PRD 93, 071101 (2016)
  - "Neutrino Flux Predictions for the NuMI Beam", Phys. Rev. D 94, 092005 (2016)
  - "First evidence of coherent K+ meson production in neutrino-nucleus scattering", Phys. Rev. Lett. 117, 061802 (2016)
  - "Measurement of K+ production in charged-current ν_μ interactions", Phys. Rev. D 94 012002 (2016)
  - "Cross sections for neutrino and antineutrino induced pion production on hydrocarbon in the few GeV region using MINERvA", Phys. Rev. D 94, 052005 (2016)
  - "Evidence for diffractive neutral pion production from hydrogen in Neutrino Interactions on hydrocarbon", Phys. Rev. Lett. 117, 111801 (2016)
  - "Measurement of Neutrino Flux using Neutrino-Electron Elastic Scattering", Phys. Rev. D 93, 112007 (2016)
  - "Measurement of Partonic Nuclear Effects in Deep-Inelastic Neutrino Scattering using MINERvA", Phys. Rev. D 93, 071101 (2016)
  - "Identification of nuclear effects in neutrino-carbon interactions at low three-momentum transfer", Phys. Rev. Lett. 116, 071802 (2016)
  - "Measurement of electron neutrino quasielastic and quasielastic-like scattering on hydrocarbon at average Ev of 3.6 GeV", Phys. Rev. Lett. 116. 081802 (2016)

- **Wine and cheese seminars at FNAL** :
  - **06/17/16 Cheryl Patrick (Northwestern) : Antineutrino charged current quasi-elastic scattering at MINERvA**
  - **10/07/16 Minerba Betancourt (FNAL) : Nuclear dependence of quasi-elastic scattering at MINERvA**
  - **03/03/17 Dan Ruterbories (Rochester) : From exclusive to inclusive and back again : the most elastic interactions of neutrinos at MINERvA**
  - **Ozgur Altinok's talk scheduled on July 7th, 2017 : CCProtonPi0 measurement from MINERvA**

Physics highlights from LE analyses

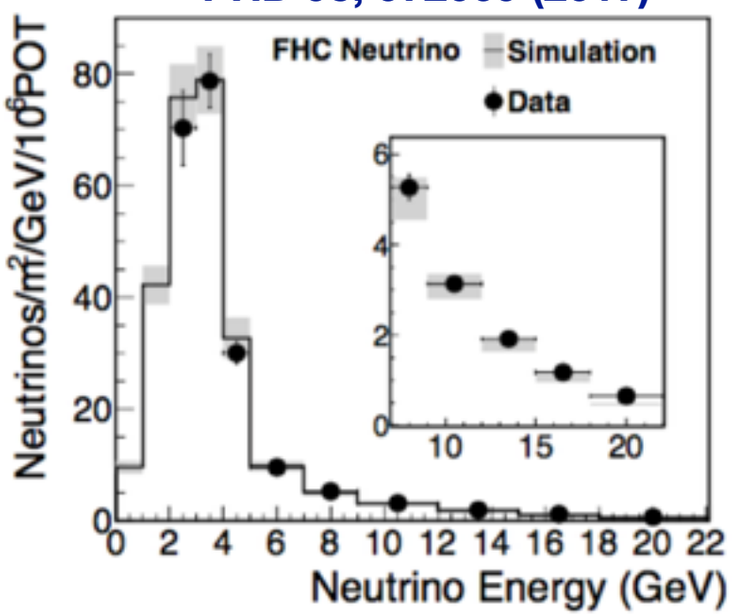
- NuMI Flux measurement with low-ν method
- Cross section measurement of quasi elastic scattering
  - Modeling improvement in simulation
  - Double differential cross section of quasi elastic ν_μ, $\overline{\nu}_\mu$ scattering
  - Nuclear dependence of cross section measurement

NuMI Flux Measurement

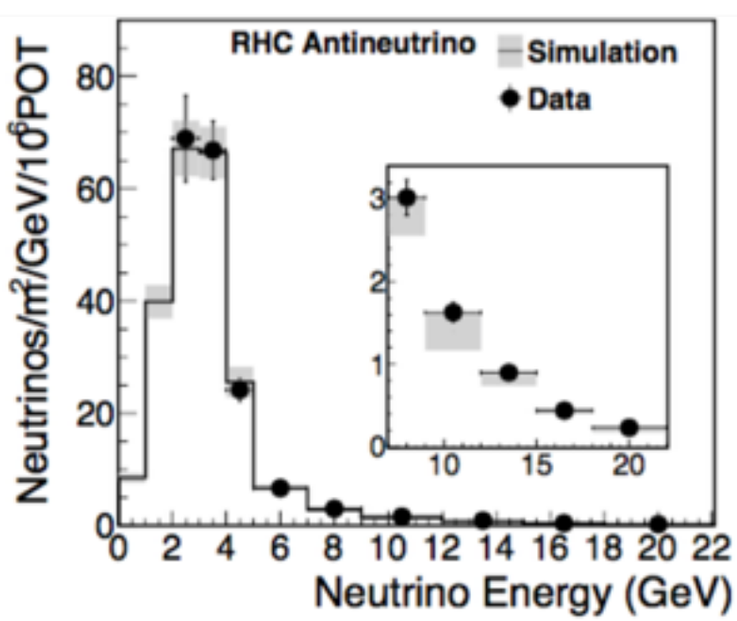
- Neutrino flux is measured using low-ν method
  - Flux is approximately constant as a function of E_ν in low hadronic energy (ν)
- Low-ν method confirms the flux simulation : PRD 95, 072009(2017), PRD 93, 112007(2016)
  - Systematic uncertainty is further improved in the latest flux measurement
  - Low-ν method is sensitive to multi-nucleon interaction models

PRD 95, 072009 (2017)

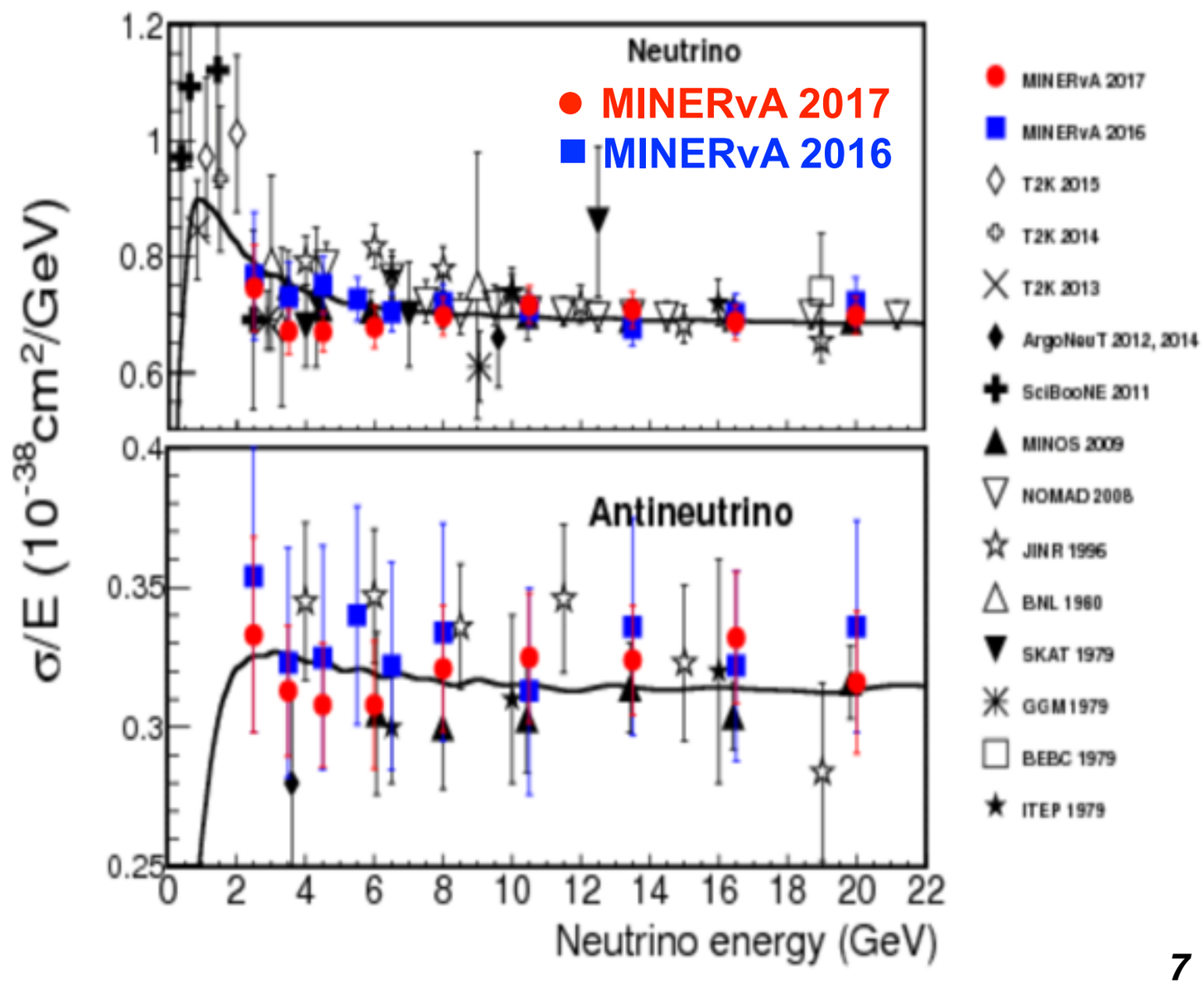
ν mode



$\bar{\nu}$ mode



Low-ν inclusive cross section in E_ν

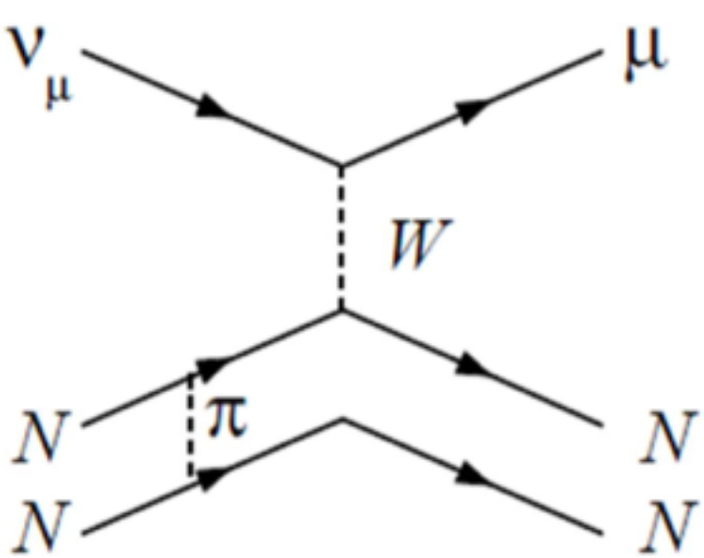


Modeling Improvement in Simulation

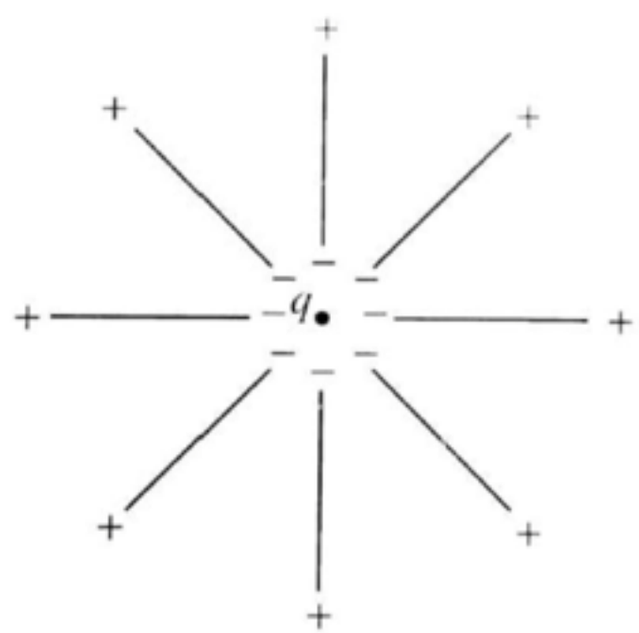
- Previous measurements indicated that simulation didn't describe data well
- Improve modeling in simulation
  - ***Multi-nucleon effect (2p2h) is reweighed based on low recoil data***
    - The optional (non-default) Valencia 2p2h model in GENIE appears to underestimate 2p2h
  - ***Nuclear screening effect is added to account for polarization of nucleus***
    - Polarization of nucleus screens electroweak coupling of W
  - ***Non-resonance pion production rate is tuned using deuterium data***
    - Non-resonance pion production is over-estimated in default GENIE

⇒ ***Tuned simulation is used for cross section measurements, which describes data better***

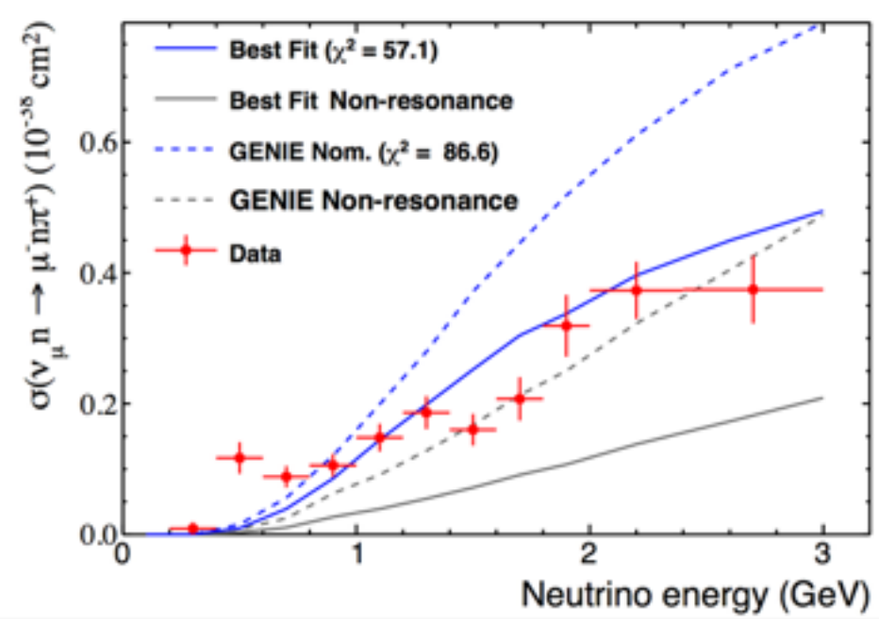
Multi-nucleon effect (2p2h)



Nuclear screening



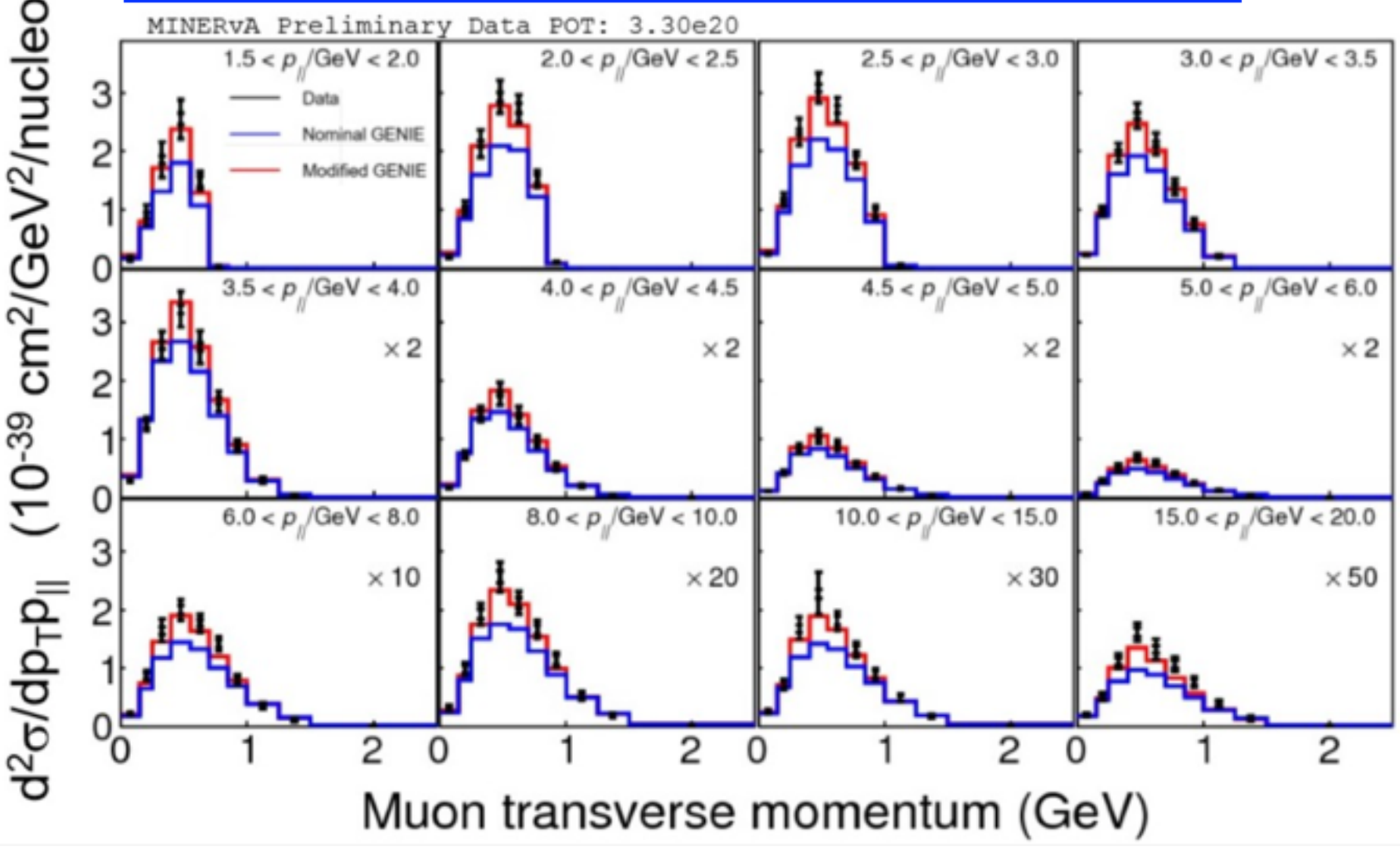
Non-Resonance Pion Production



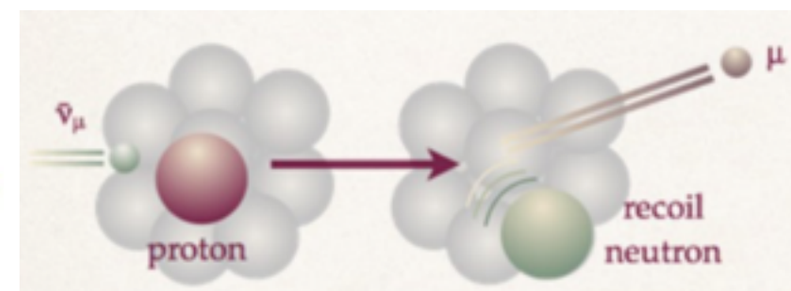
Double Differential Cross Section of Quasi Elastic ν_μ Process

- Differential cross section of Q^2 for CCQE events accounts for multinuclear effect
- Measure $d^2\sigma/dp_T p_{||}$ and $d\sigma/dQ^2$, $d\sigma/dE_\nu$ with CCQE-like signal definition
- **Muon variables (p_T, $p_{||}$) are used instead of Q^2, E_ν to reduce model dependence**

Wine and Cheese seminar by Dan Rutherboris 03/03/17



CCQE-like events (signal) :



- Any number of nucleons
- No pions, heavy baryons etc

Mateus Carneiro will present more details in poster session!!

- Results agree with modified GENIE except low and high Q^2 (p_T), E_ν ($p_{||}$) region
  ⇒ Still, need to improve simulation

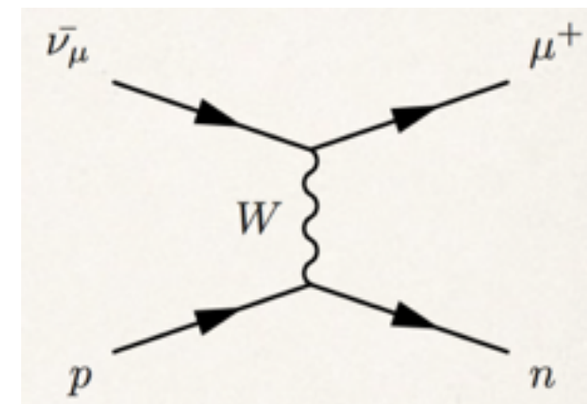
Double differential cross section of quasi elastic $\bar{\nu}_\mu$ process

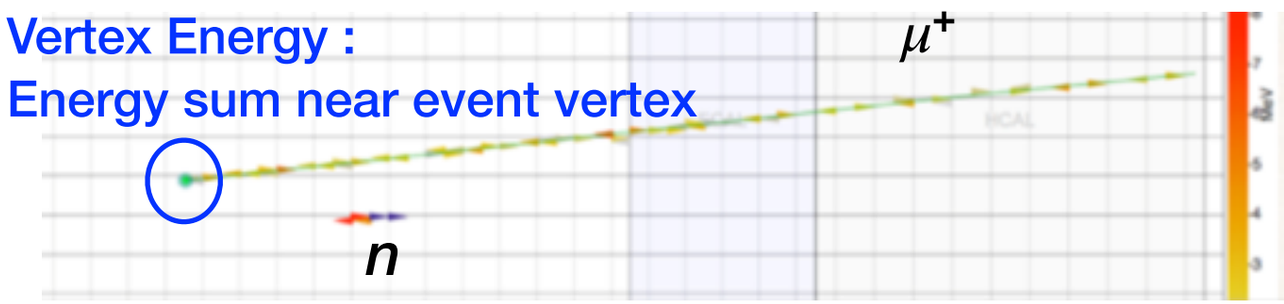
- Measured $d^2\sigma/dp_T p_{||}$ for quasi elastic anti-neutrino process with LE data (1.02×10^{20} POT)
  - Found that data had excess around p_T = 0.5 GeV

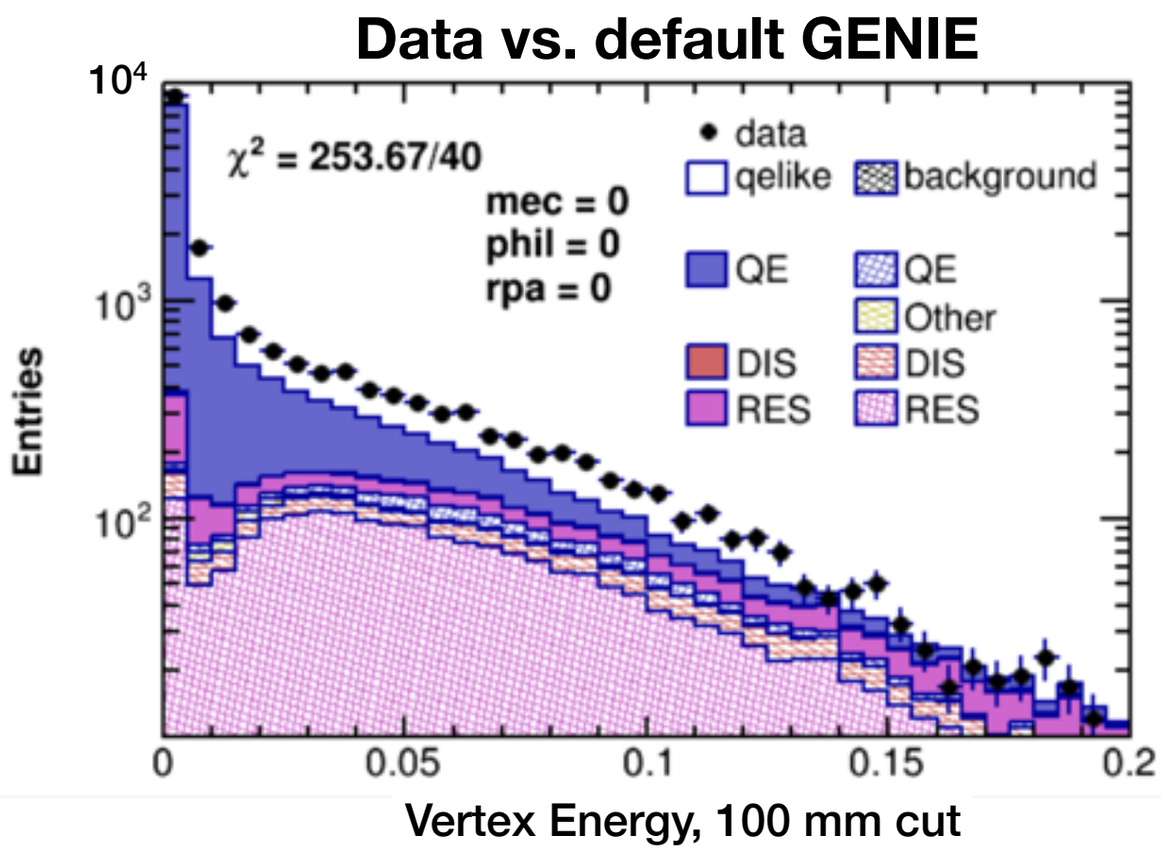
Wine and Cheese seminar by Cheryl Patrick on 06/17/16

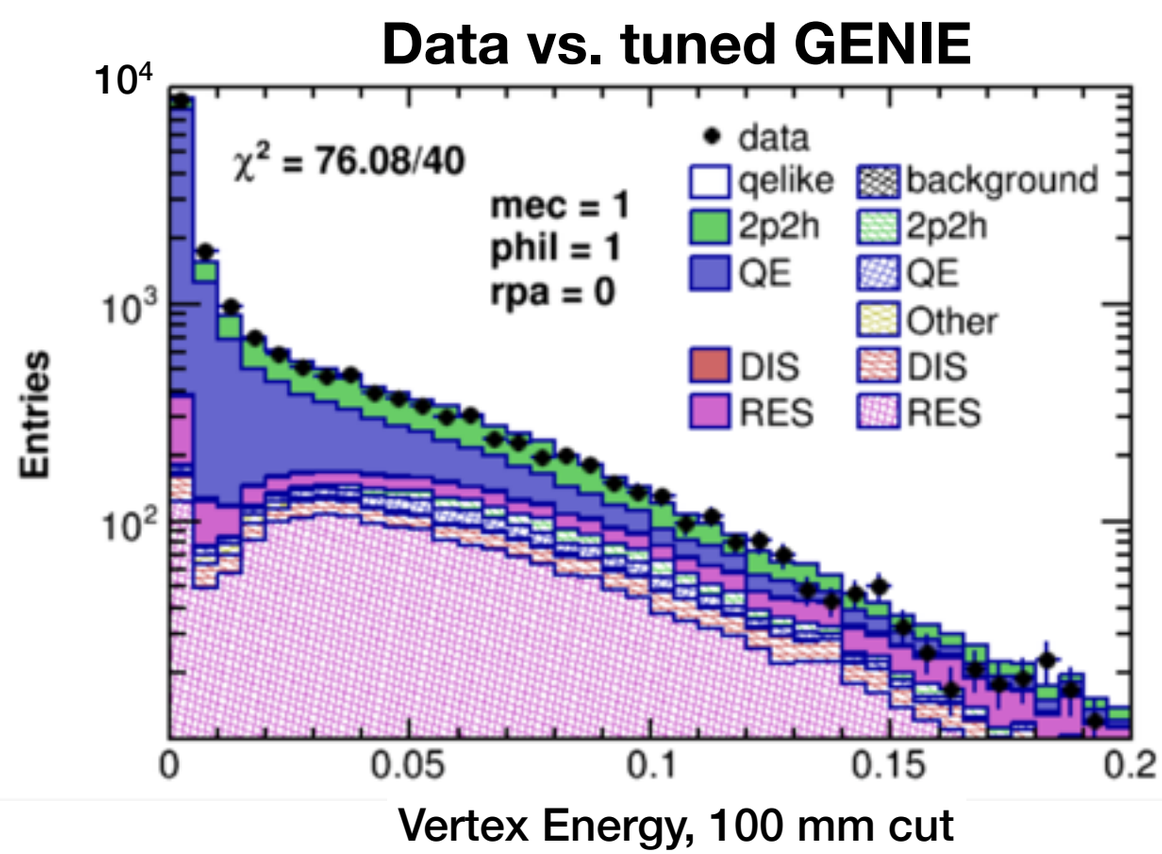
- Further work to understand the difference between data and MC

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$









⇒ ***Tuned MC for nuclear effect, nuclear screening options has better description of data***

Nuclear Dependence of Quasi Elastic Scattering

- Differential cross section of CCQE-like events on different target

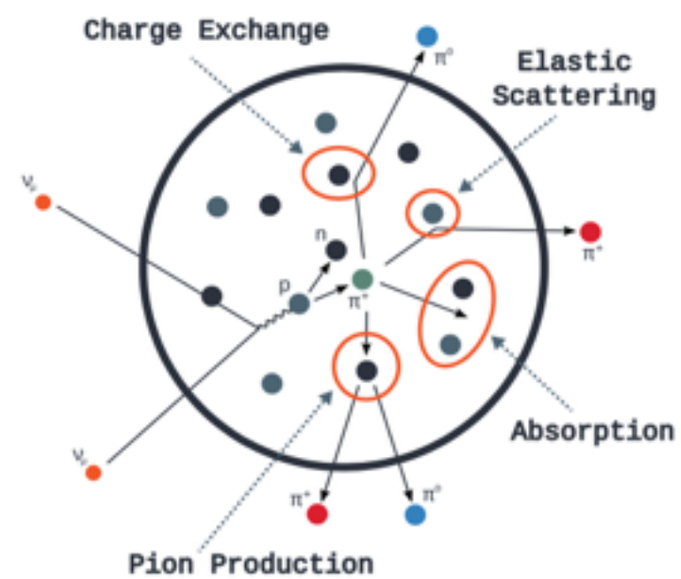
Important to understand neutrino interactions with nuclei for precision oscillation measurement

⇒ **Need a reliable nuclear model in simulation**

Argon interaction falls between carbon and iron

Important to have a good model for FSI effect on different nucleus in future experiments

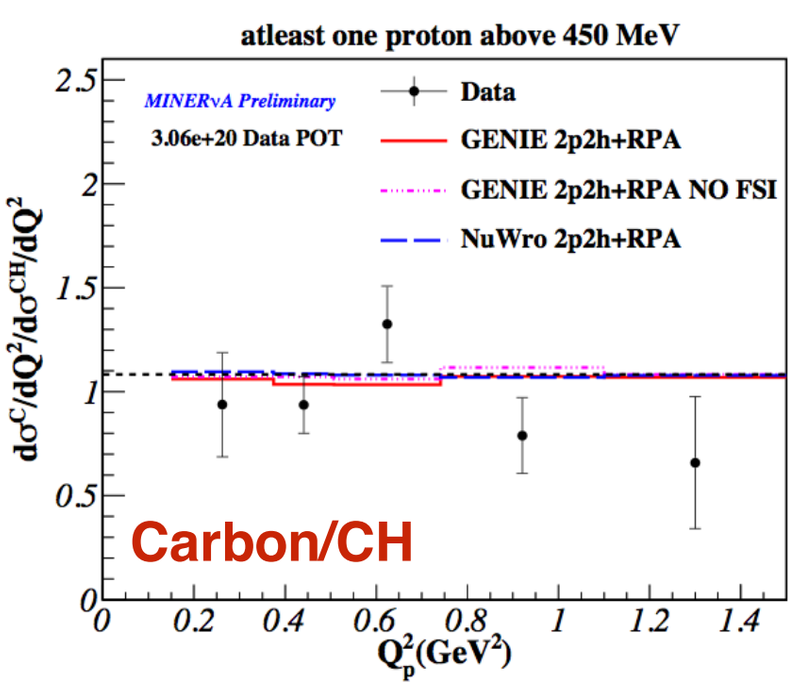
Final State Interactions

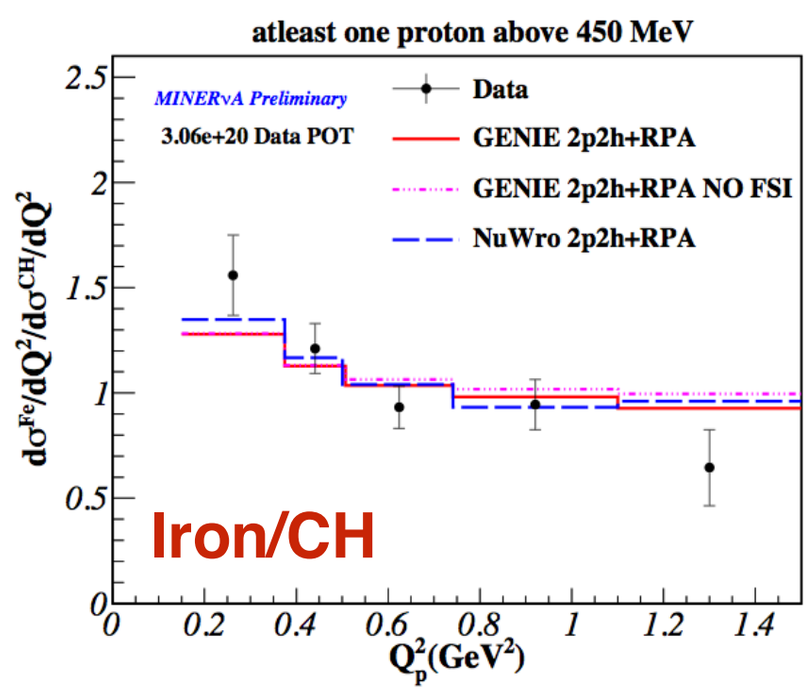


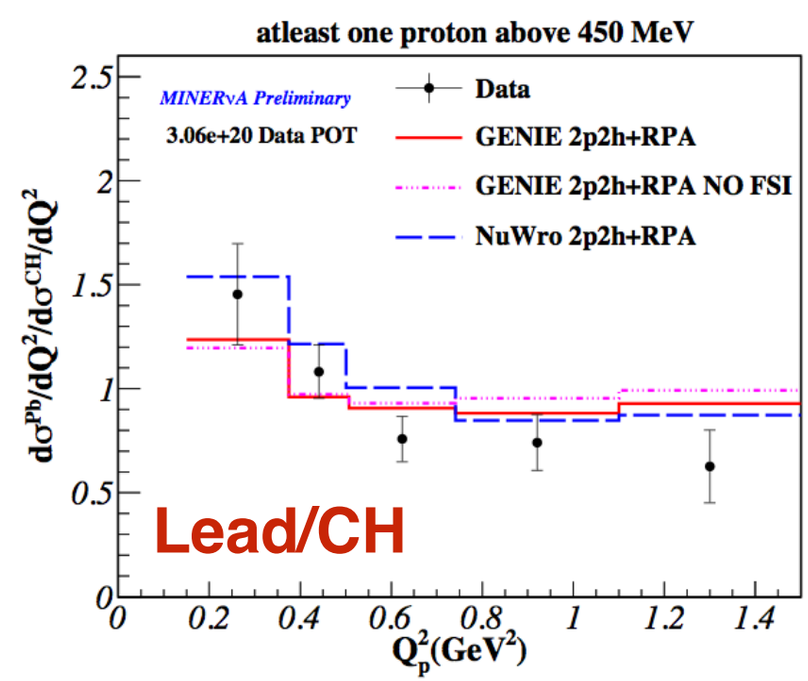
$$Q_p^2 = (M')^2 - M_p^2 + 2M'(T_p + M_p - M')$$

: Q_p^2 is affected by final state interactions (FSI)

Wine and Cheese seminar by Minerba Betancourt on 10/07/16







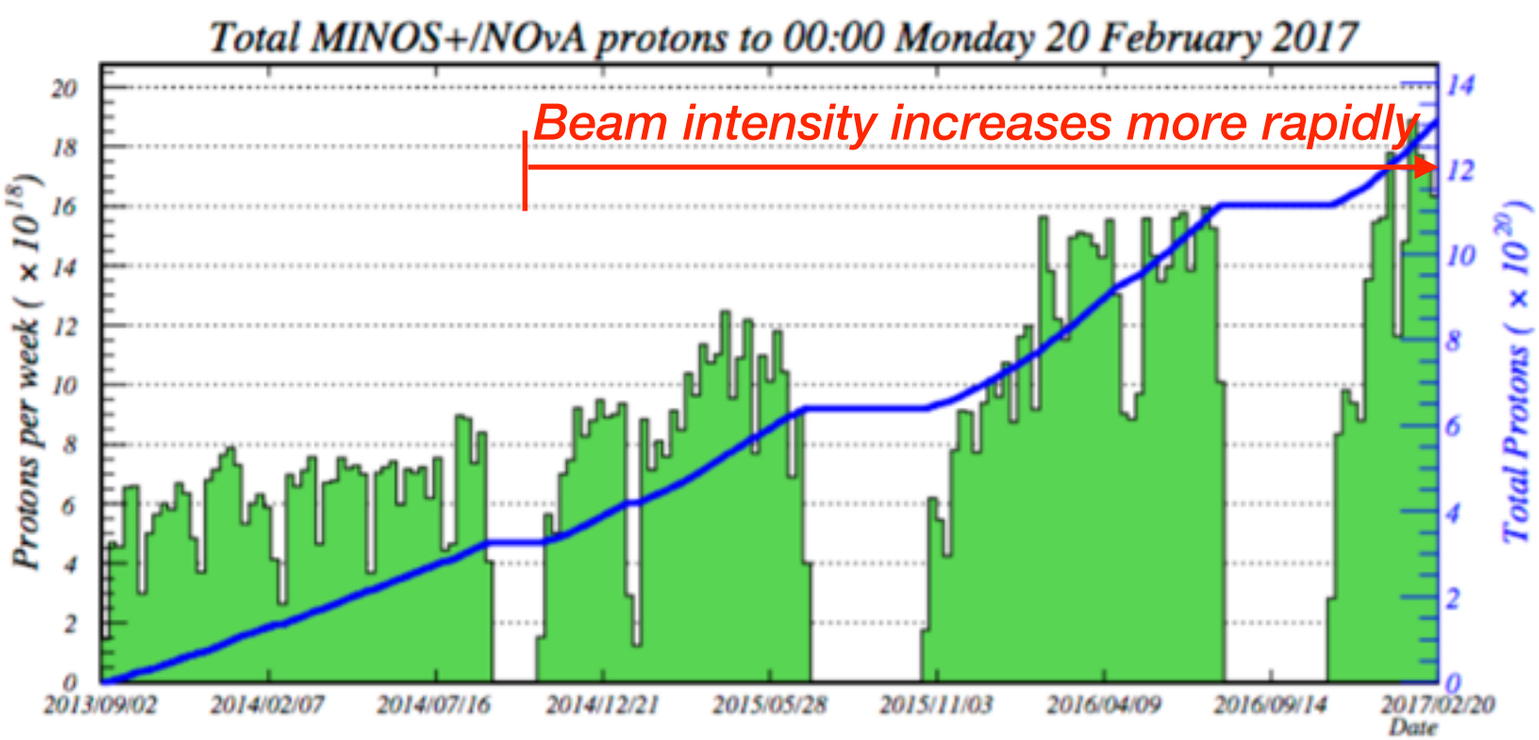
Iron and lead have larger excess than CH in low Q_p^2 / NuWro with FSI describes data better than GENIE

What's next?

- MINERvA is having fruitful period and is publishing the valuable measurements
  - Finishing up LE analysis and moving forward with ME data
  - ME data has higher intensity ⇒ important effect in ME data
  - Lots of activities and efforts are on-going to understand ME data
    - Large scale of MC production with realistic overlay scenario
    - ME test beam study, validation study, etc
- ME samples will have higher statistical precision (3x POT) and higher energy…
- ***Expect ME results to***

  ⇒ ***Improve sensitivity in probing the nuclear effects***

  ⇒ ***Further improve model descriptions for theory and for oscillation experiments***



Poster sessions from MINERvA
- CCQE ν_μ by Mateus Carneiro
- CCQE ν_e by Jiyeon Han
- Neutrino trident production by Jose Becerra

From the MINERvA Collaboration …

Measurements with high statistics in ME is underway

Stay tuned!!

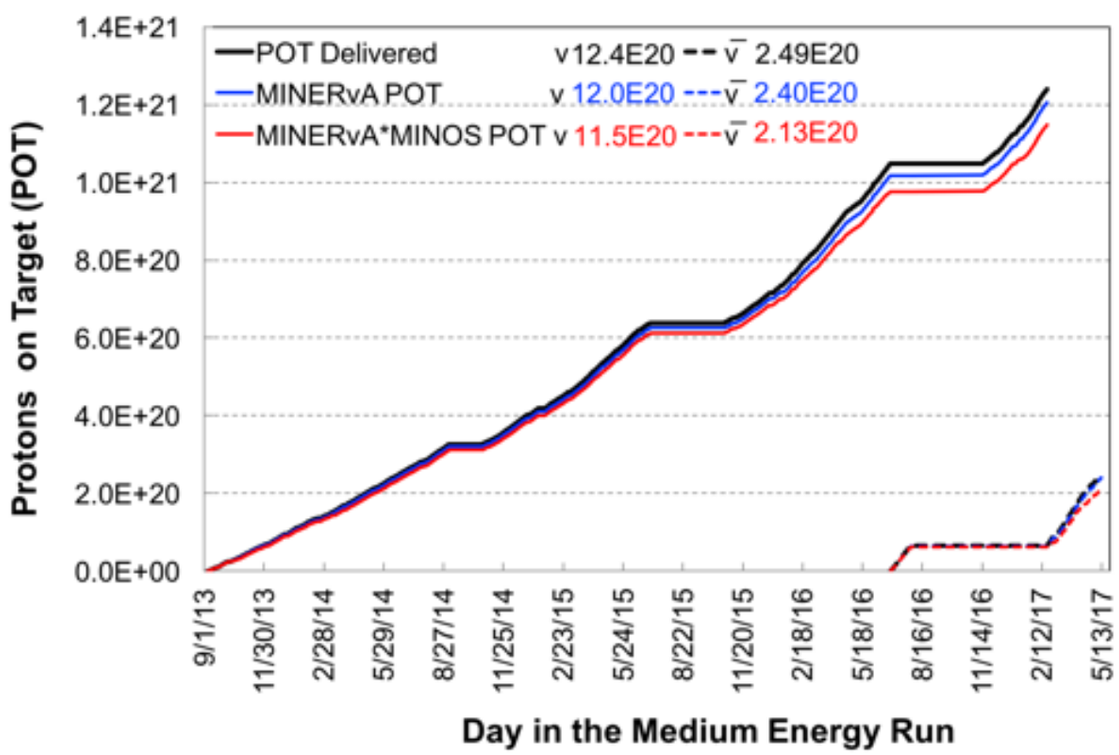
Thanks to Fermilab divisions and sections for all of their support!!

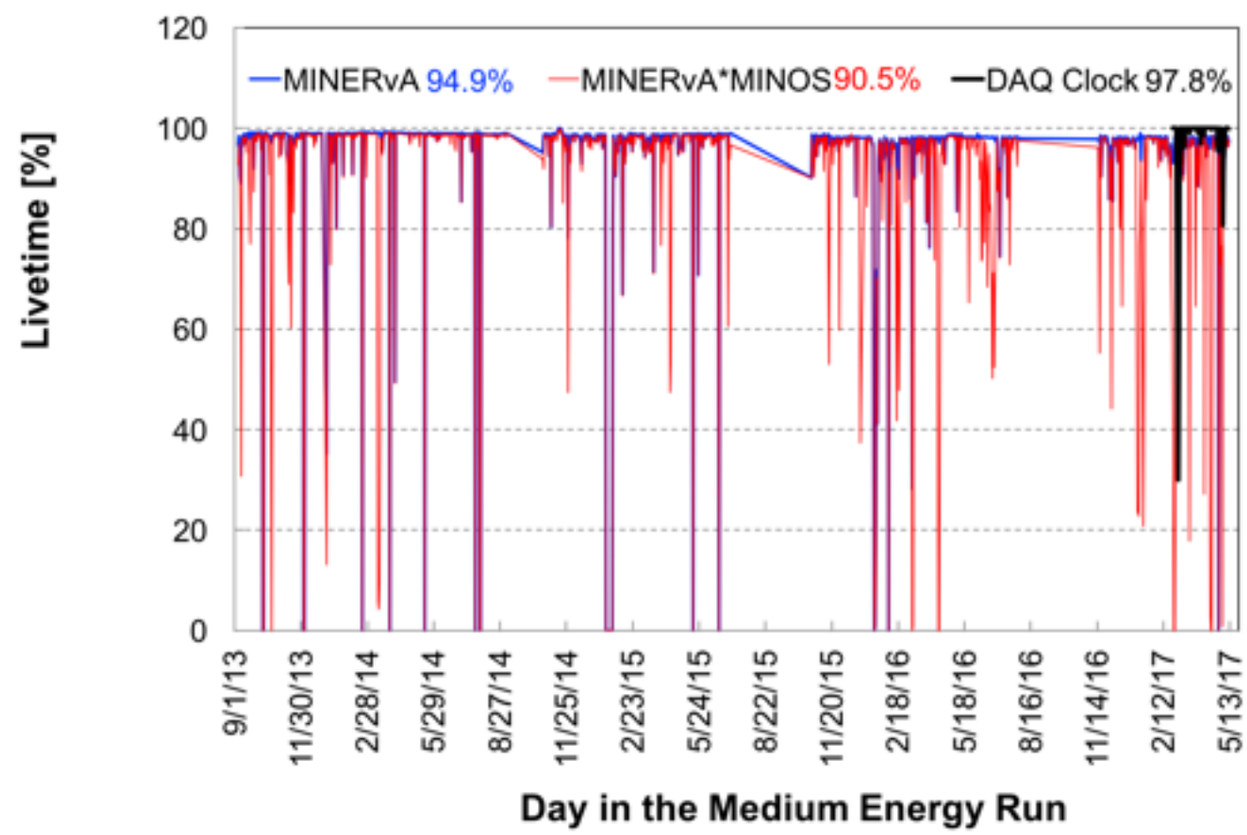
Accelerator Division
Computing Division
Particle Physics Division
Neutrino Division
ESH&Q Section

Back-up Slides

MINERvA detector performance

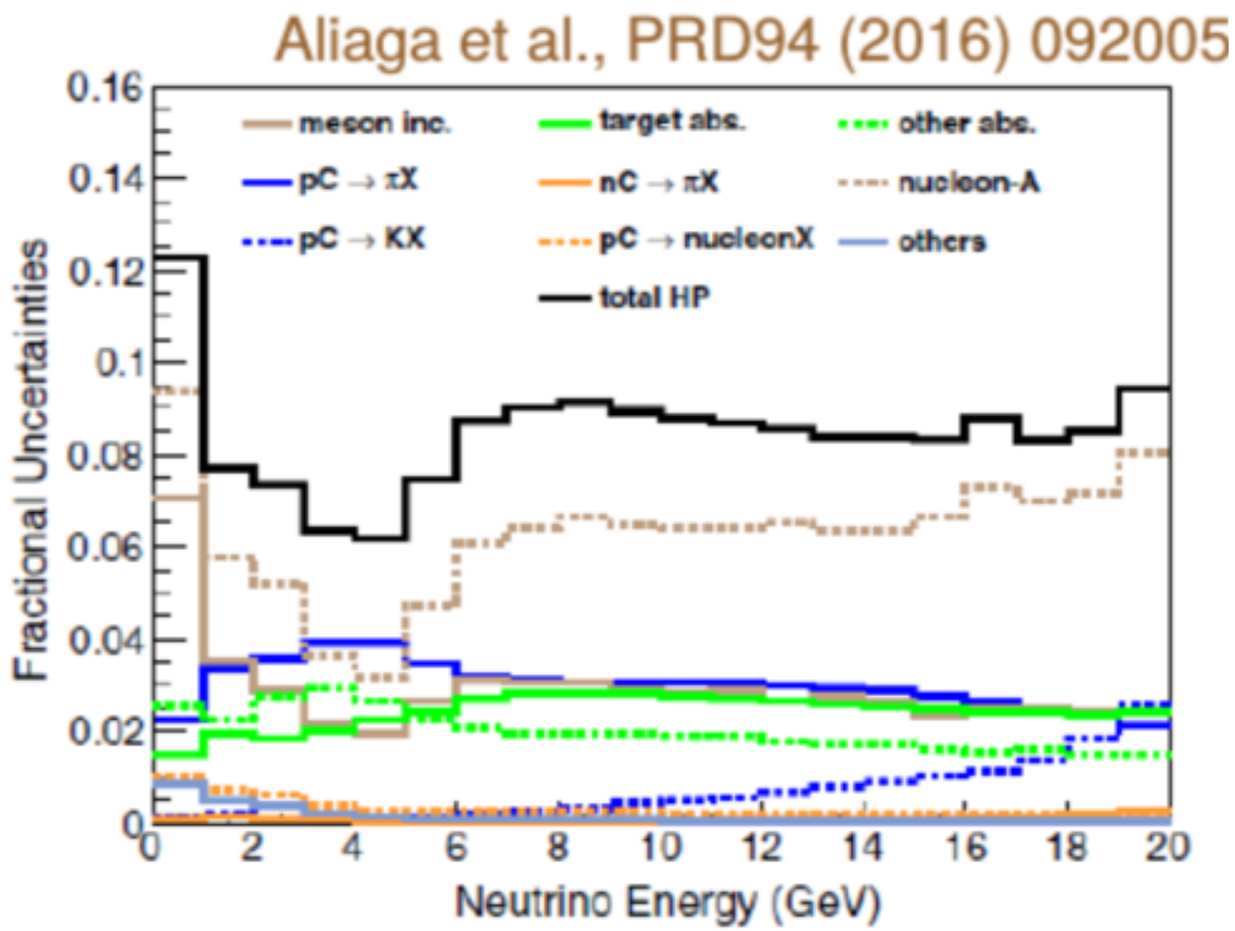
- Detector performance
  - MINERvA is running well with high data taking efficiency
  - We took over MINOS detector and have operated since last year
  - Total data taking efficiency (MINERvA × MINOS) is higher than 90%

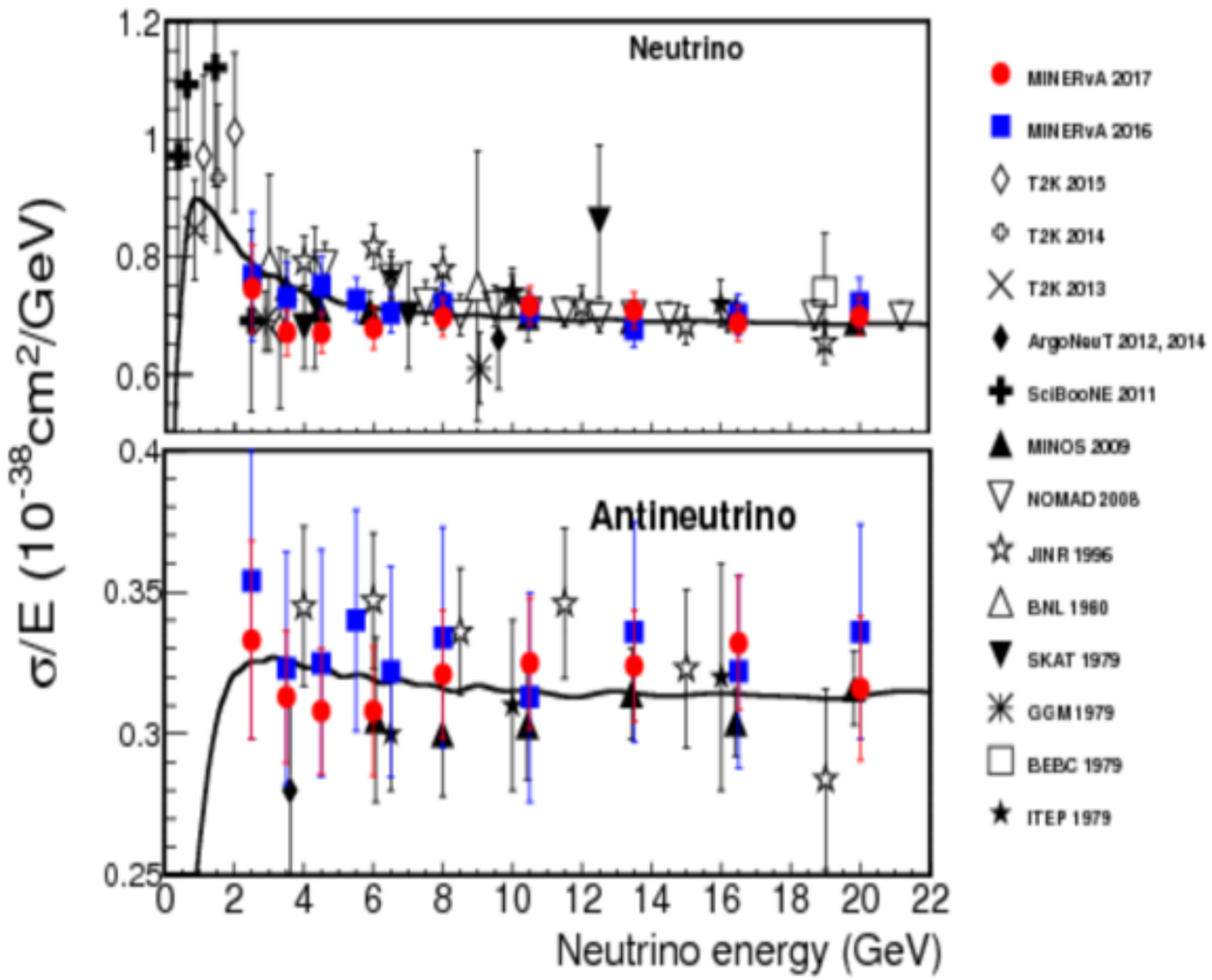




New Flux Prediction : systematic uncertainty

- Fractional uncertainties comparison





Systematic uncertainty is further improved in 2 low-nu measurements

- Systematic uncertainty includes :
  - Focusing uncertainties
  - Hadronic interactions
  - Beam line absorption

- External hadro production data used for constraint
  - Thin target pion production (NA49)
  - NuMI target pion production (MIPP)

→ **Additional constraints from measurements is expected to reduce the error down to ~5%**

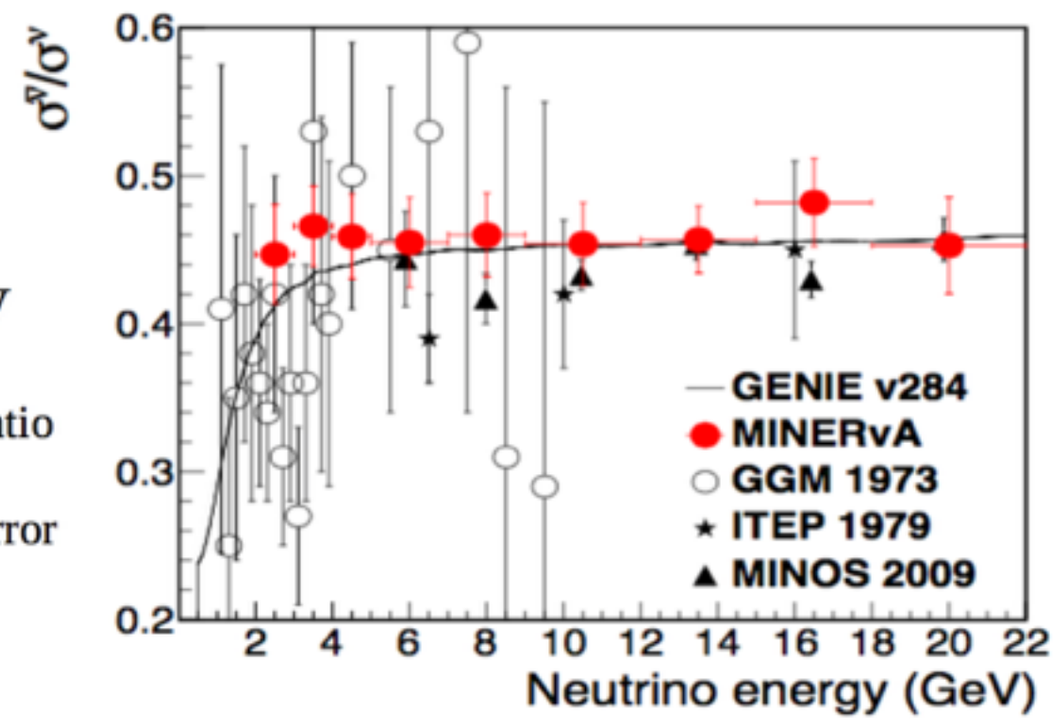
Flux measurement using low-nu method

- CC inclusive cross section ratio, $R_{CC} = \sigma^{\bar{\nu}}/\sigma^{\nu}$

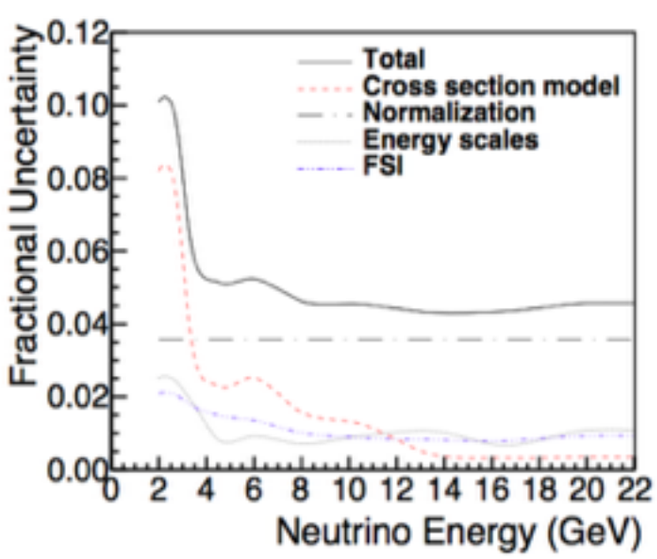
Long-baseline oscillation experiments will measure a ratio of oscillation probability to constrain CP violation

$$\mathcal{A}_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

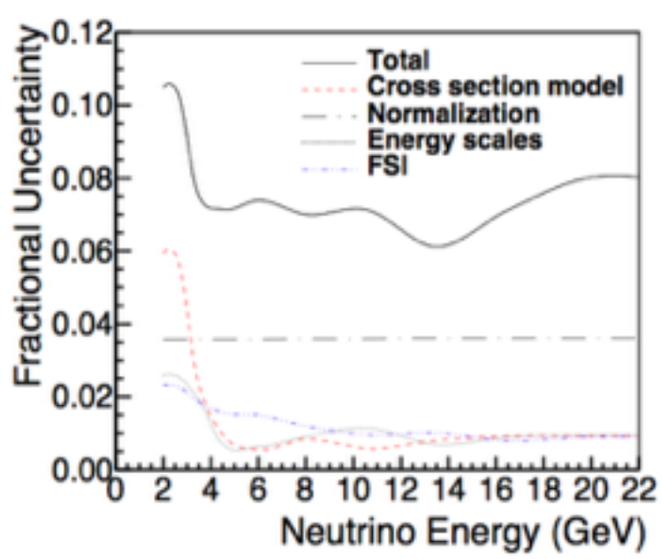
- Most precise measurement below 6 GeV
  - Many systematic uncertainties cancel in the ratio
  - Antineutrino statistical precision dominates error



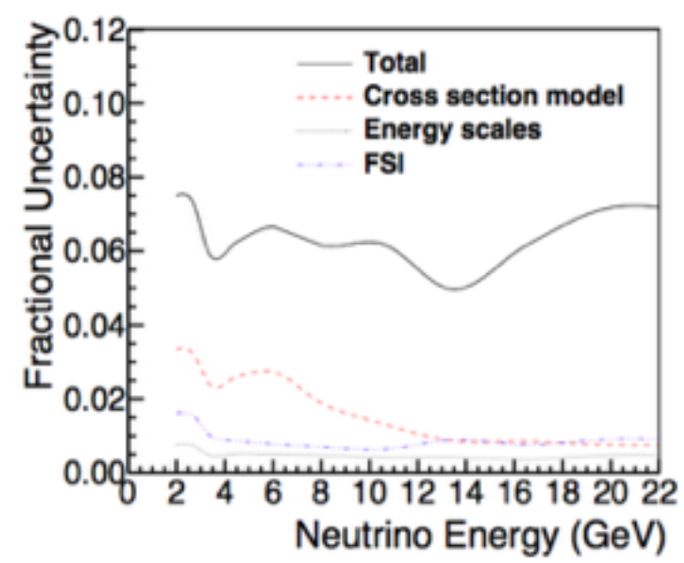
Systematic uncertainty components :



σ^{ν}



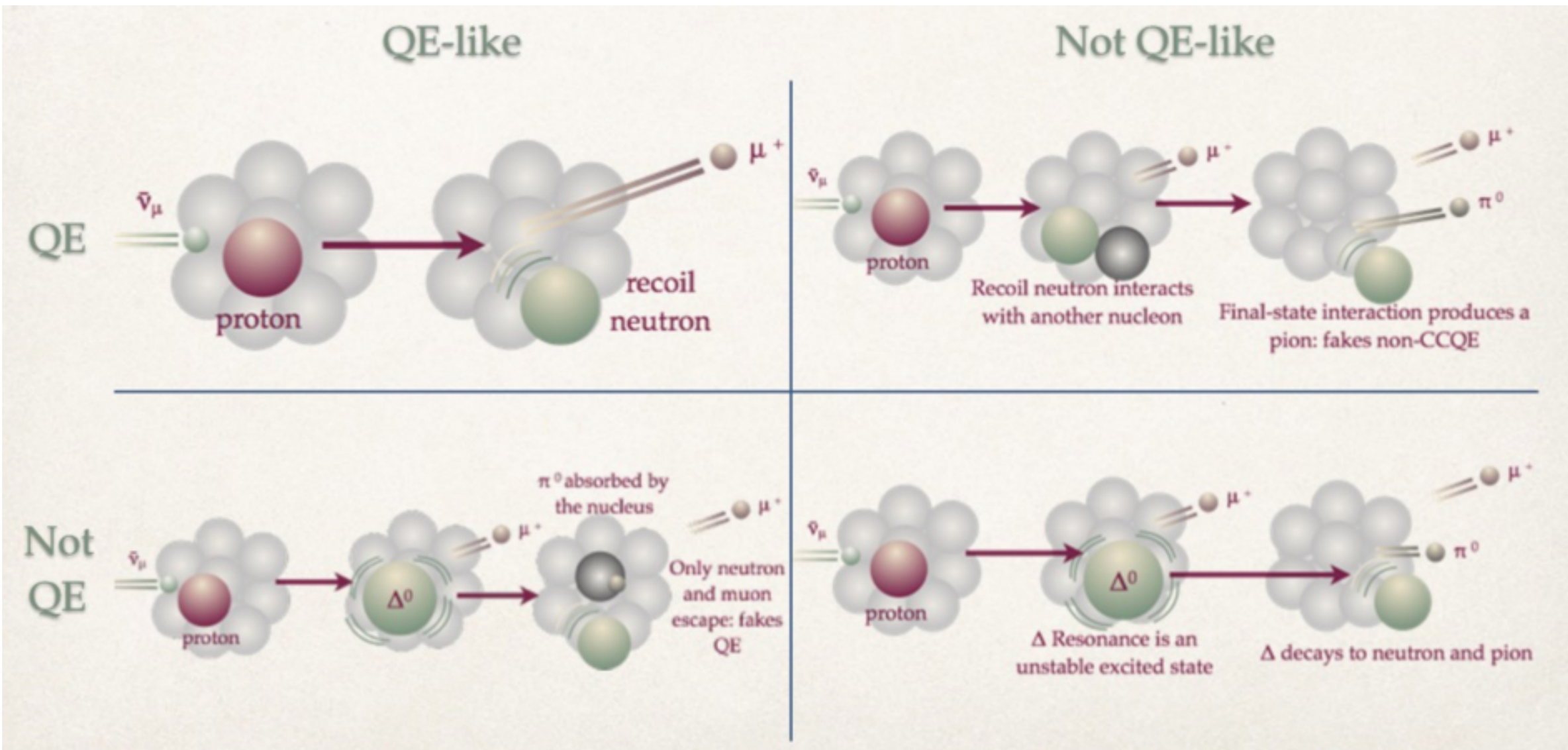
$\sigma^{\bar{\nu}}$



$R_{CC} = \sigma^{\bar{\nu}}/\sigma^{\nu}$

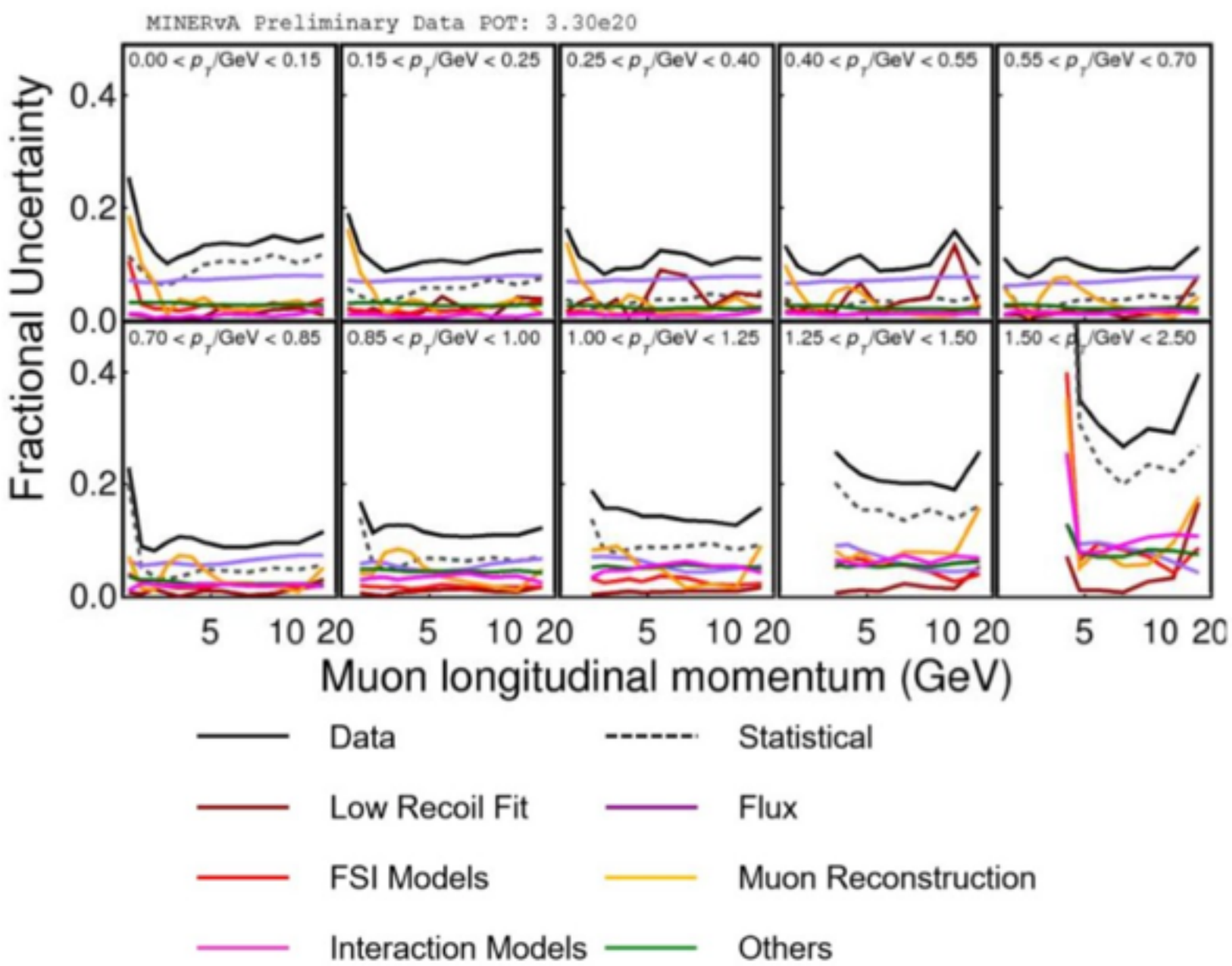
CCQE-like Events Definition

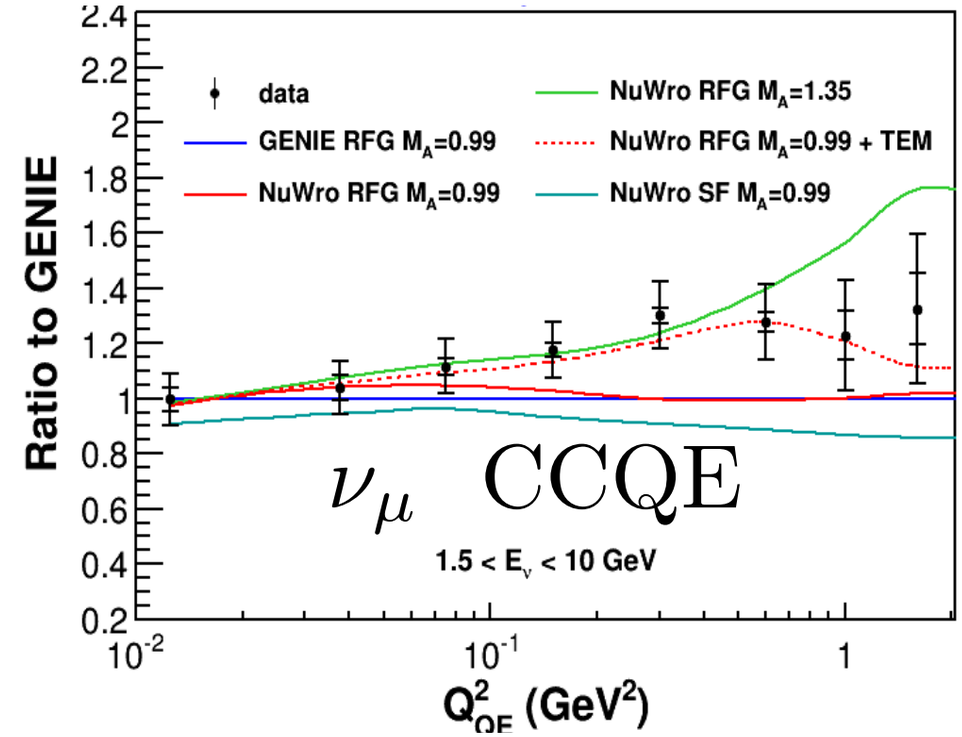
- CCQE-like events is defined as
  - Any number of nucleons
  - No pions, heavy baryons etc

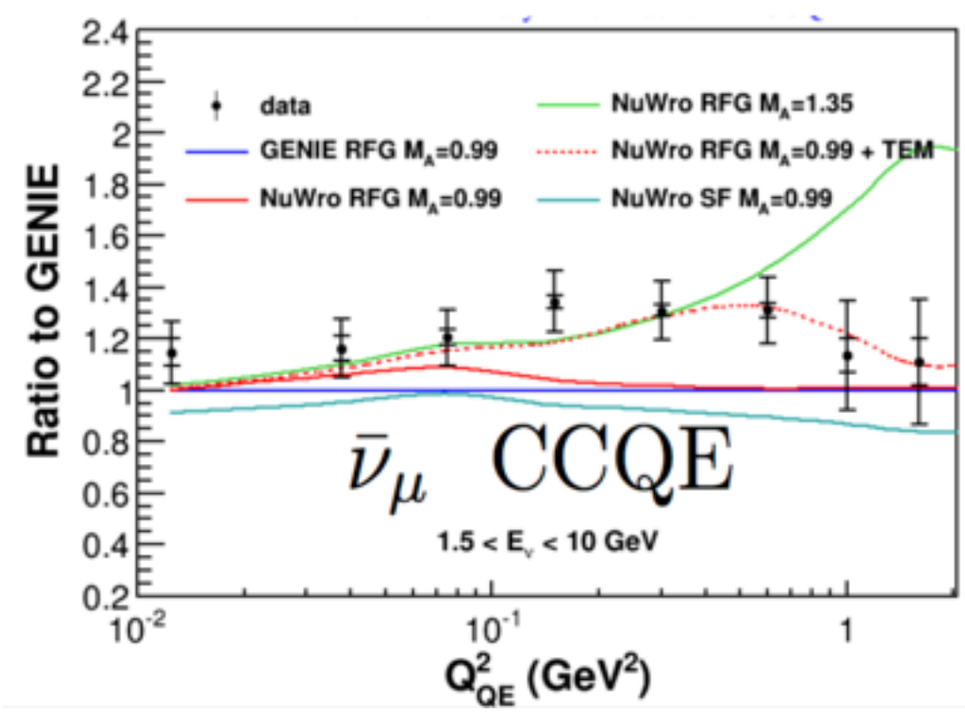


CCQE Cross Section Measurement (I)

- Systematic uncertainty of $d^2\sigma/dp_T p_{||}$ measurement

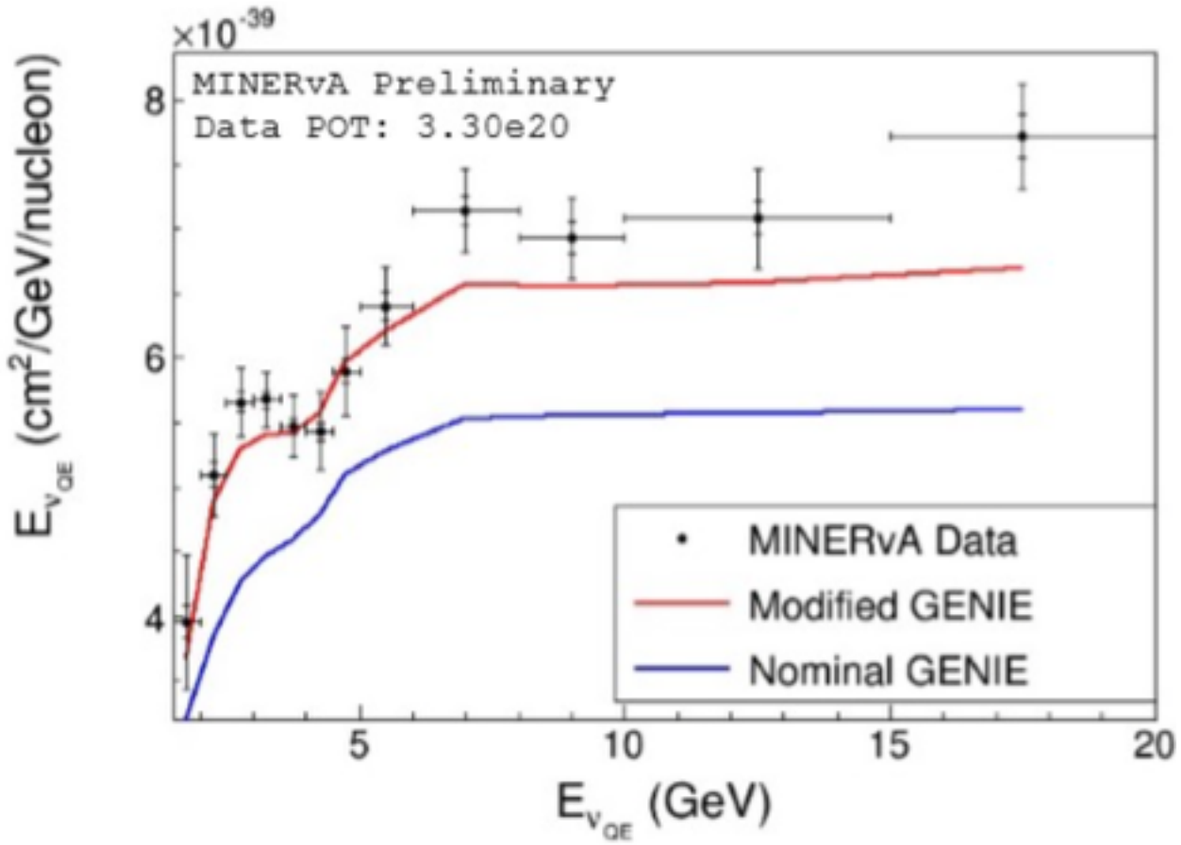


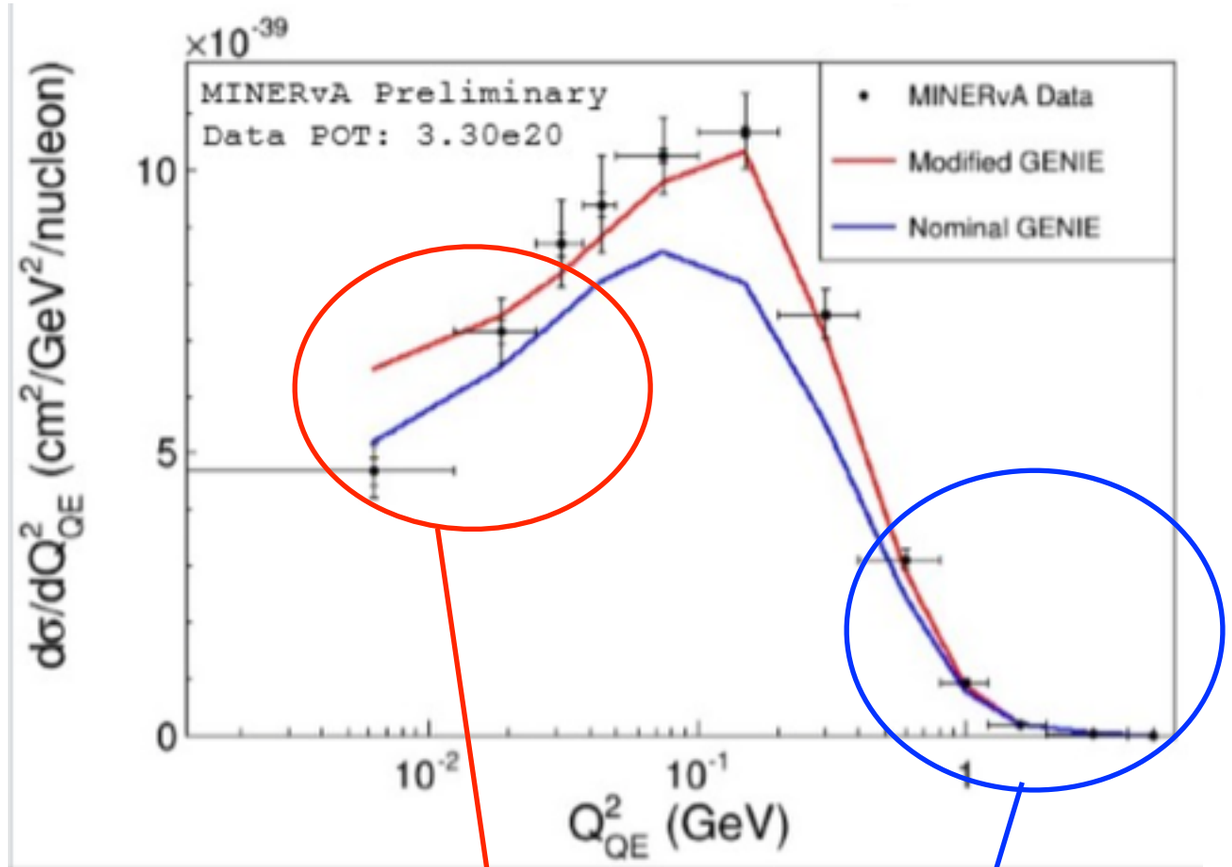


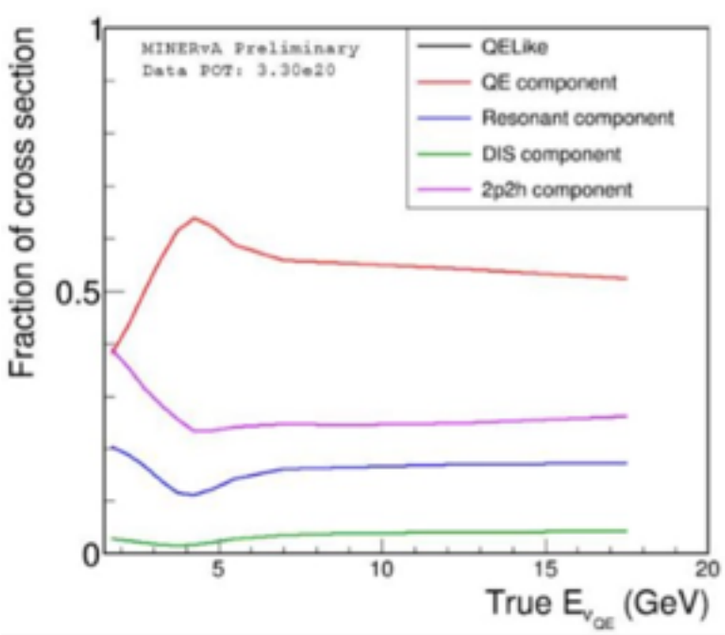


CCQE Cross Section Measurement (II)

- Differential cross section in E_ν and Q^2 of CCQE-like events







Fractions of non-QE components changes rapidly, which might biased $E_{\nu,QE}$

Mis-modeling of the falling edge of the focusing peak might affect this effect, too

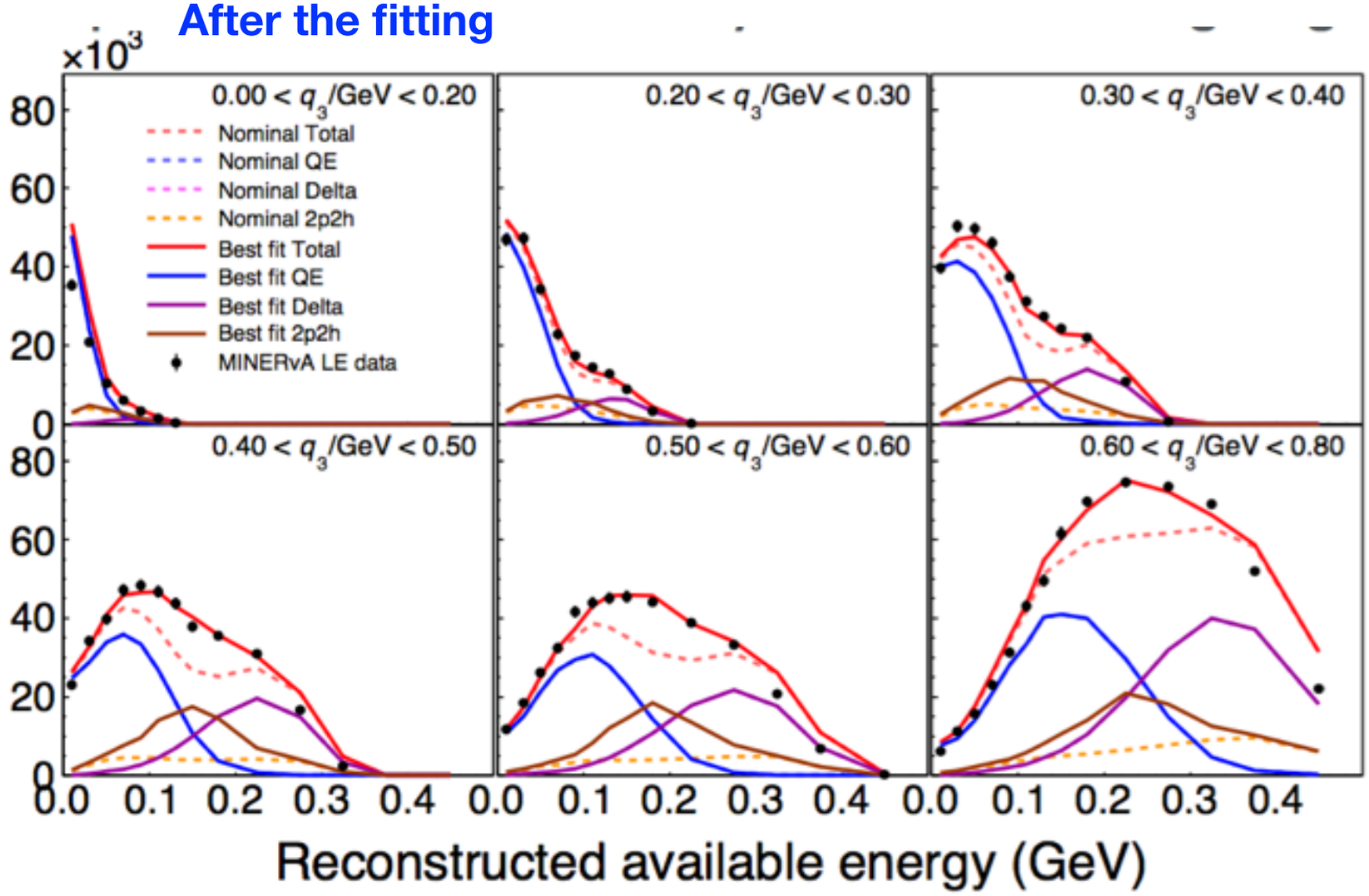
Discrepancy shown up in low recoil analysis as well

Discrepancy potentially due to the dipole axial form factor

2p2h modeling

- Adding 2p2h model : fit data in 2D (q_0, q_3)
  - Gaussian fit used in true variables as a reweighing function applied to 2p2h component
  - QE and RES component is fixed

After the fitting

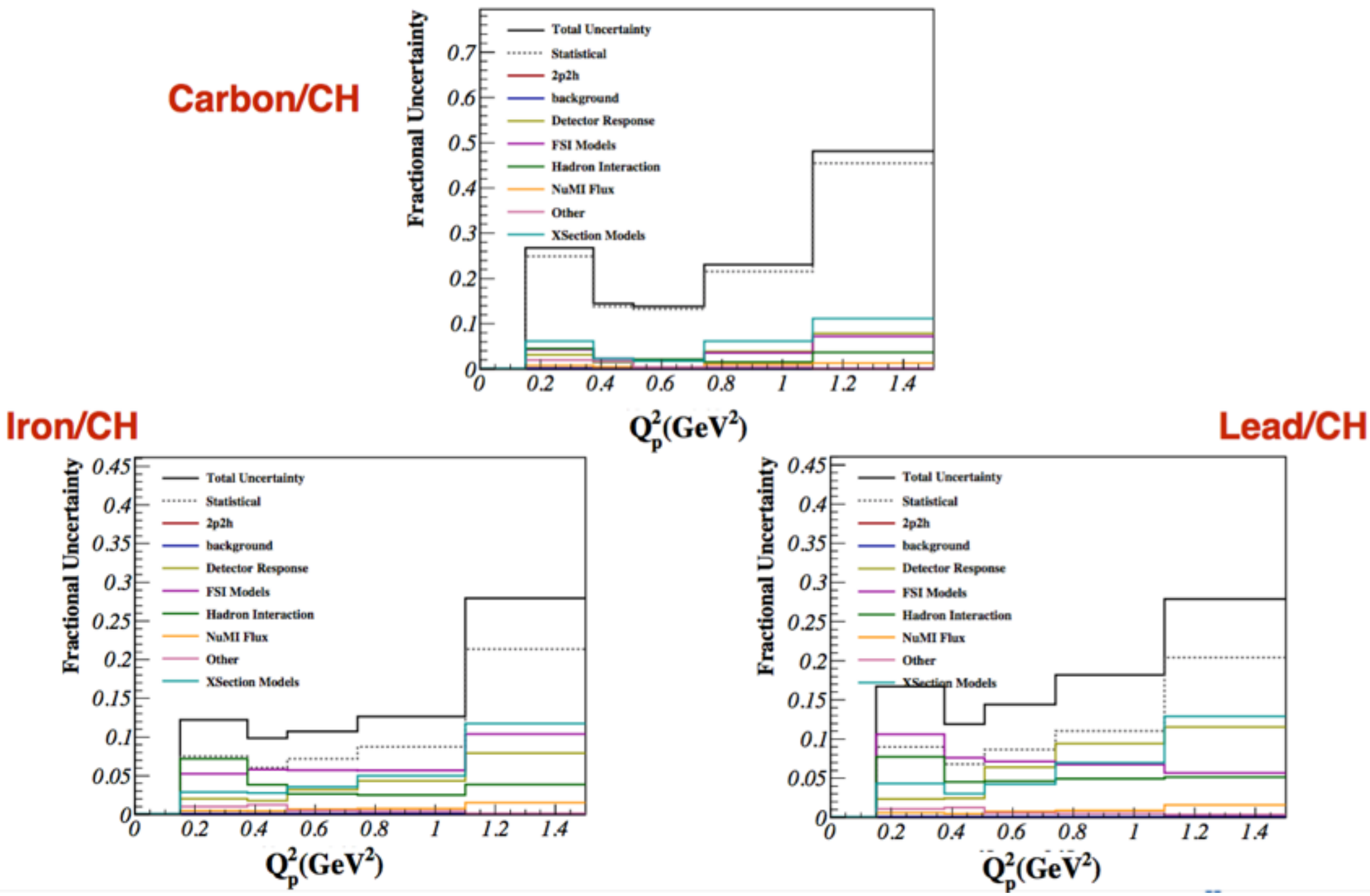


2p2h component increased more in larger q_3 region

Dashed line : original component
Solid line : reweighed component

Nuclear dependence cross section for CCQE

- Systematic uncertainty contribution for the measurement



- Leading sources are statistical error and modeling (hadron interaction, 2p2h)

Neutral / Charged Current K^+ production

- Complementary measurement for K^+ production
- NC and CC K+ processes are very sensitive to Kaon Final State Interaction (FSI)

NC reactions : backgrounds for $p \rightarrow K^+ \nu$ search

$\nu p \rightarrow \nu K^+ \Lambda$

$\nu n \rightarrow \nu K^+ \Sigma^-$

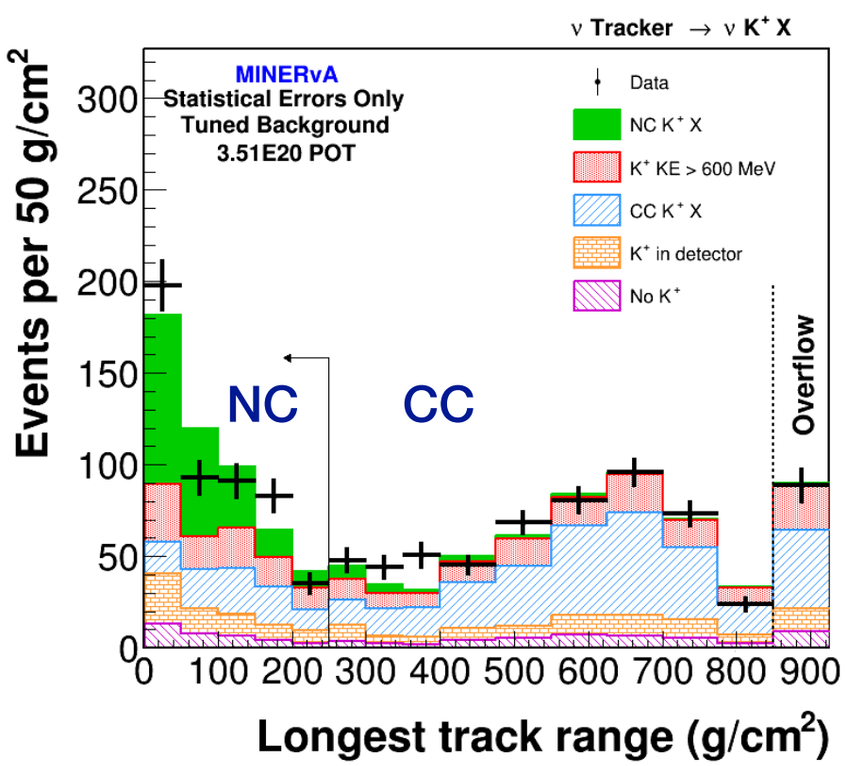
Not visible in Cherenkov detectors due to Cherenkov threshold

⇒ fake the signal process

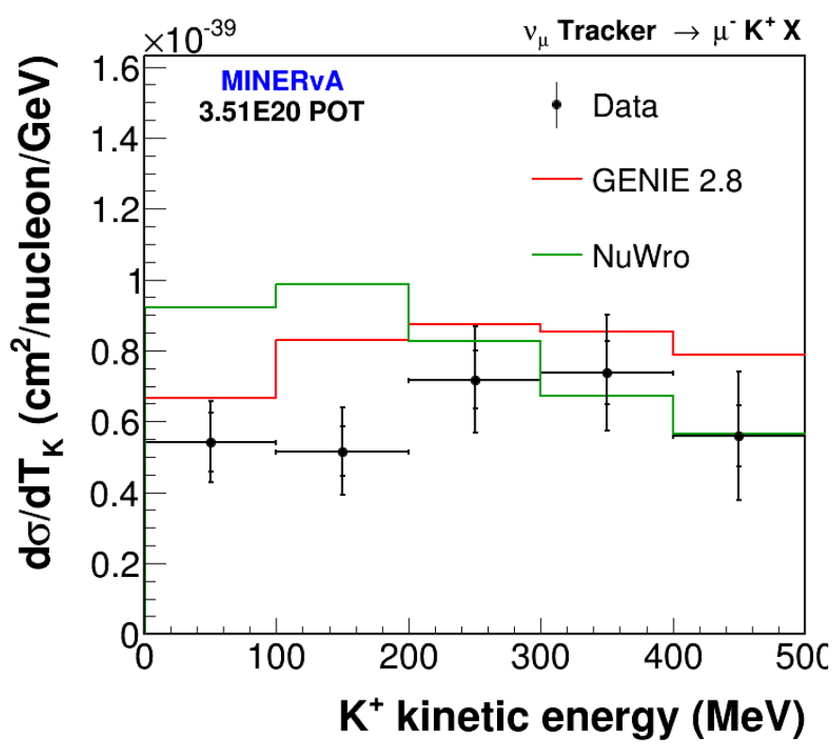
VS.

CC reactions are not generally background because they produce detectable charge lepton

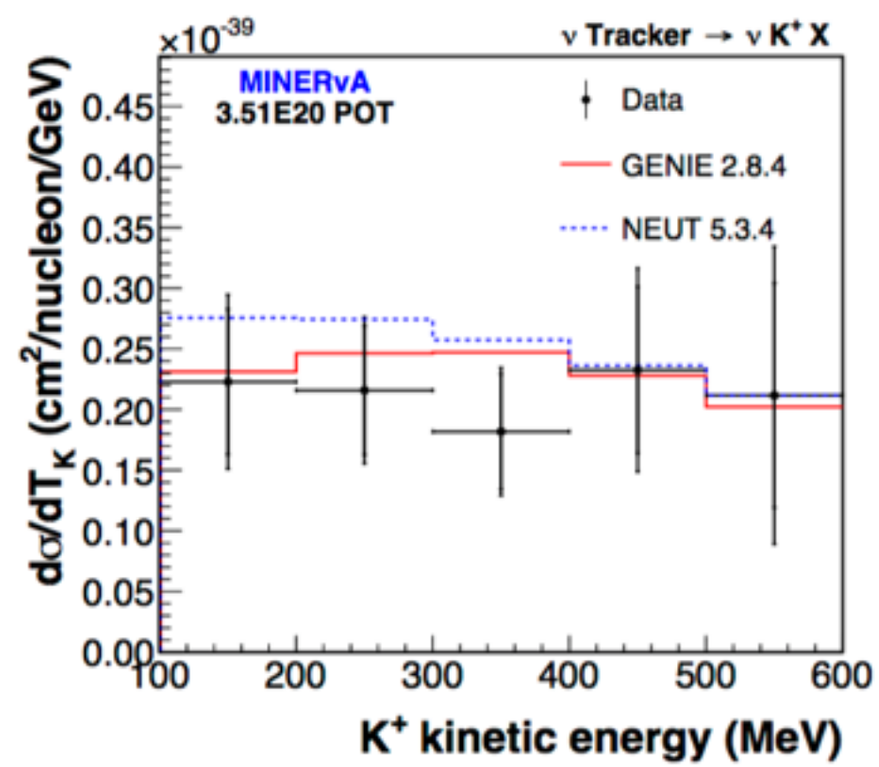
- NC and CC processes are separated by range of longest reconstructed track
- CC K+ production rate is underestimated by simulations (GENIE and NuWro) in low E
- NC K^+ appears to be well modeled by GENIE



CC K^+ (PRD 94 012002 (2016))



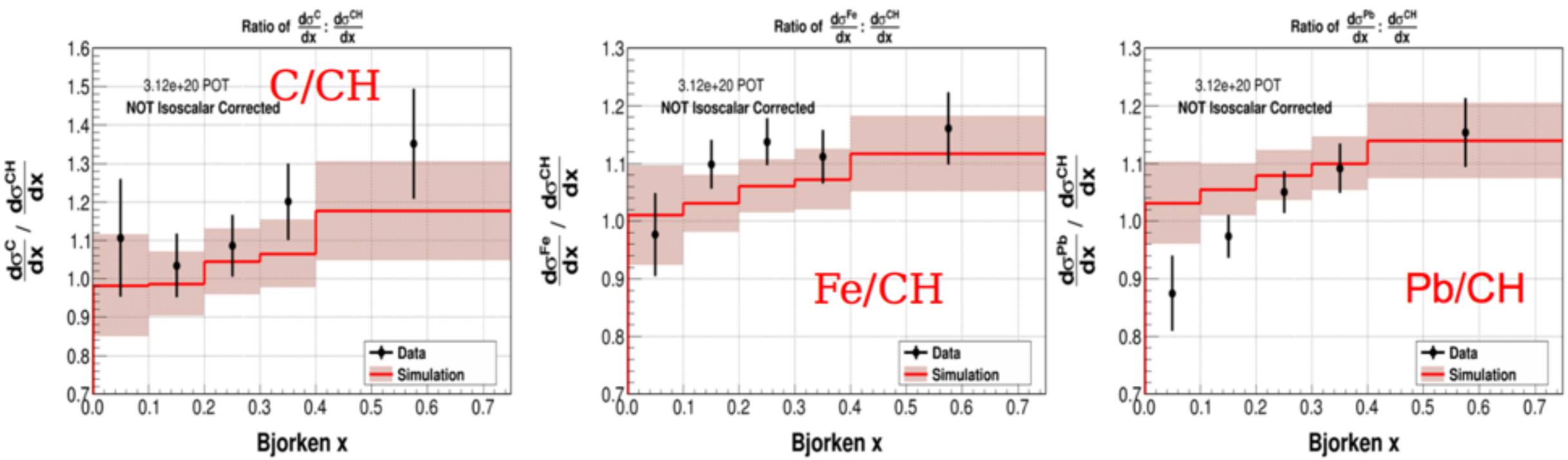
NC K^+ (arXiv:1611.0224)



DIS Inclusive measurement

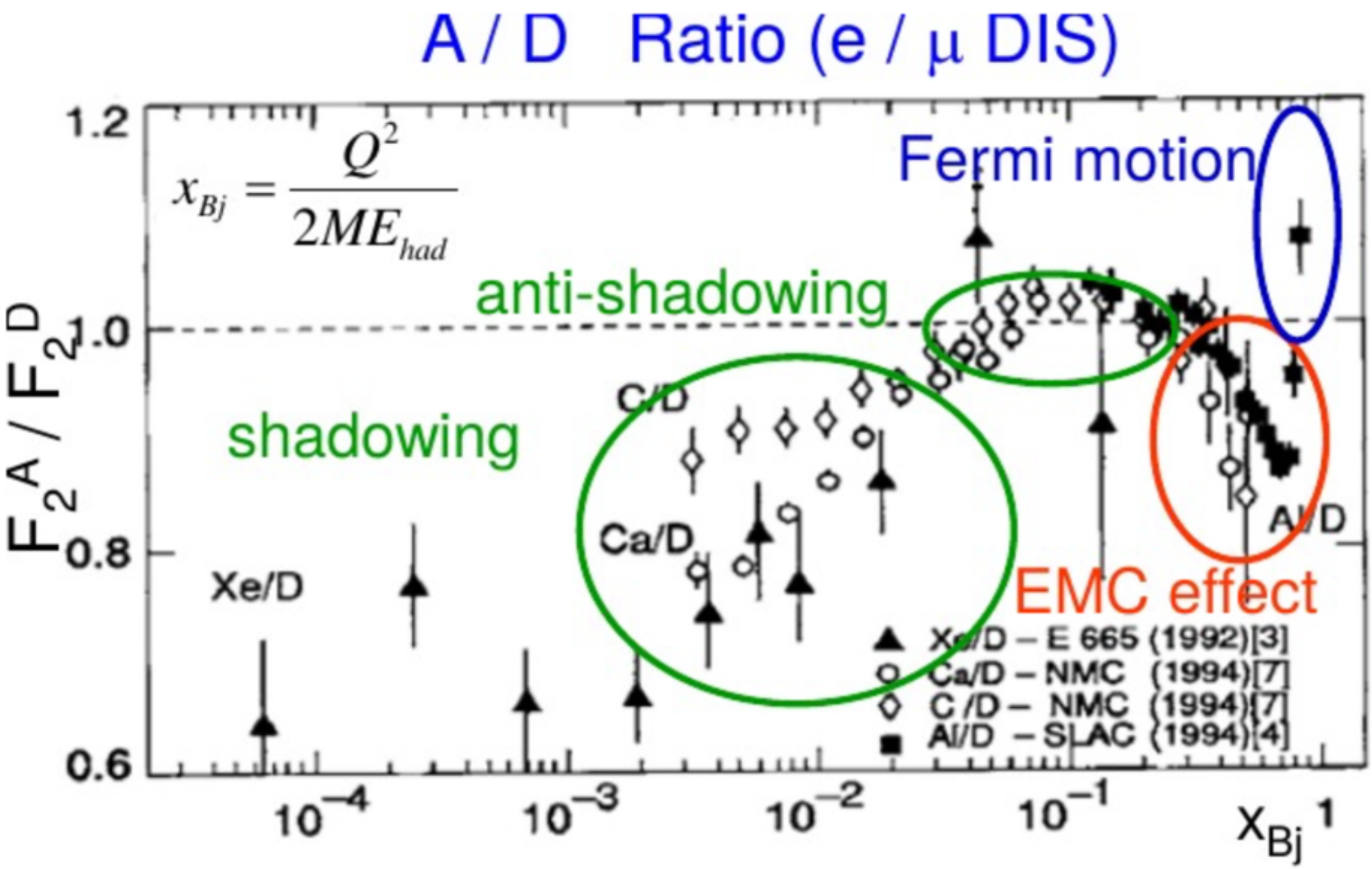
- MINERvA is the first experiment to look for "EMC effect" in neutrino scattering
  - "EMC effect" describes DIS of muons on deuteron and on iron
- Measure the cross section on different target and the ratio to scintillator(CH) cross section
  - Ratio of cross section cancels the common systematic uncertainty, reduces error by ~1/2

PRD 93, 071101 (2016)



- No clear evidence of discrepancy with model (GENIE 2.6.2, no EMC effect included)
  - Statistically limited in LE → ME analysis is underway with much higher statistics
- Deviation at low x in Pb target implies additional nuclear shadowing effect required

Nuclear dependence measurement of CCQE scattering is also available in MINERvA :
Wine and Cheese seminar on Oct. 7th, 2016 by Minerba Betancourt

Nuclear Shadow Effect

- Shadowing effect mostly affects low x region